CDF/PHYS/EXOTIC/CDFR/10???
November 30, 2009
Version 1.0

Search for VH → VWW SM Higgs Production in the Trilepton Signature

Doug Benjamin, Mark Kruse

Duke University

Eric James, Sergo Jindariani, Britney Rutherford

Fermilab

Roman Lysak

IEP SAS, Slovakia

Dean Andrew Hidas

Rutgers University

Aidan Robson, Rick St. Denis, Peter Bussey

University of Glasgow

Matthew Herndon, Jason Nett[1], Jennifer Pursley

University of Wisconsin, Madison

Maria d'Errico, Simone Pagan Griso, Donatella Lucchesi

INFN and University of Padova

[1]Contact: Jason Nett jnett@wisc.edu

Abstract

We present here the first search for Standard Model $VH \rightarrow VWW \rightarrow l\nu l\nu l\nu$ production, where V is the W and Z weak vector bosons, using 4.8 fb^{-1} of integrated luminosity. This analysis adds to the existing CDF HWW group's dilepton analysis two new regions characterized by a **tri**-lepton signature, which are chosen to isolate the $WH \rightarrow WWW$ and $ZH \rightarrow ZWW$ associated production signals in the three-lepton bin. As such, we define two new regions denoted trilepton-*NoZPeak* (for the WH-centered analysis) and trilepton-*InZPeak* (for the ZH-centered analysis) with which we expect to contribute an additional $\sim 5.8\%$ acceptance to the current $H \rightarrow WW$ dilepton analysis. The trilepton-*InZPeak* region is defined by events having at least one lepton pairing (among three possible pairings) with opposite-sign, same flavor, and a dilepton invariant mass within $[91.0, 101.0]$ GeV–a 10 GeV window around the Z-boson mass. The trilepton-*NoZPeak* region is then defined by those trilepton events which do not match the *InZPeak* definition.

These two new regions are poised to make a substantial contribution to the $H \rightarrow WW$ group result. The *NoZPeak* analysis expected limits reach 9.2 times the standard model limit; the trilepton-*InZPeak* analysis is set at 12.5 times the expected standard model limit; and the combined trilepton analysis is set at 6.23 times the expected standard model limit. Finally, for the combined $H \rightarrow WW$ analysis result, in the 165 GeV bin the limit drops from 1.28[2] to 1.12. As such, we are poised to begin excluding the standard model Higgs boson at 95% confidence level with CDF-only analyses in short order.

[2]CDF Note 9928

Contents

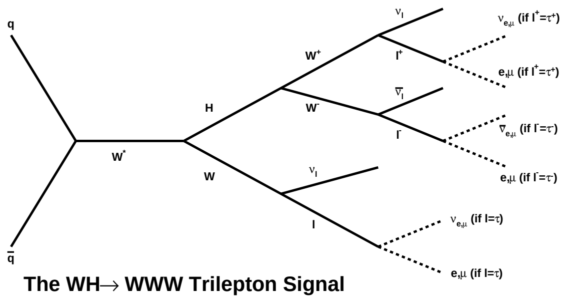

Figure 1: WH associated production trilepton signal topology

1 Introduction

We present here the first iteration of a search for Standard Model $VH \to VWW \to l\nu l\nu l\nu$ production, where V is the W and Z weak vector bosons, using 4.8 fb^{-1} of integrated luminosity. This note focuses on two channels chosen specifically to isolate the $WH \to WWW$ and $ZH \to ZWW$ associated production processes because of their unique characteristics. Consider the three leptons as ordered by their transverse momentum p_T (or transverse energy E_T for electrons) such that the highest p_T lepton is the 1$^{\text{st}}$ and the lowest p_T lepton is the 3$^{\text{rd}}$. First, we filter trilepton events into an *InZPeak* category if any of the three possible dilepton pairings (that is, pairing the 1$^{\text{st}}$ lepton with the 2$^{\text{nd}}$ lepton; the 1$^{\text{st}}$ lepton with the 3$^{\text{rd}}$ lepton; or the 2$^{\text{nd}}$ lepton with the 3$^{\text{rd}}$ lepton) has an invariant mass value that falls within a 10 GeV window of the Z boson mass at 91 GeV and also have opposite signs and same flavor. This *InZPeak* analysis focuses on the ZH signal process. The rest of the trileptons events–those that do not have any of the three dilepton invariant mass values near the Z boson mass–are directed toward the *NoZPeak* analysis, which focuses on the WH signal process. These regions are new to the $H \to WW$ analysis group.

Additionally, the *NoZPeak* region has a missing energy cut of $\not\!\!E_T > 20$ GeV. This cut drastically reduces the $Z\gamma$ background contribution and also provides a *NoZPeak* control region in $10.0GeV < \not\!\!E_T < 20.0$. Because the $WH \to WWW \to l\nu l\nu l\nu$ event topology has three $W \to l\nu$ decays, the missing energy is relatively large and a negligible amount of signal is lost from moving the $\not\!\!E_T$ cut up to 20.0 GeV from 10.0 GeV.

The *InZPeak* region has somewhat larger backgrounds than the *NoZPeak* region and is topologically similar to the most signficant background, WZ. However, for a $ZH \to ZWW$ event to produce a three-lepton signature we either have one of the W-leptons decaying hadronically or–less frequently–we have a $ZH \to ZWW \to llll$ physics event that loses one of it's leptons to an area of the detector that is incapable of reconstructing a track (detector holes or too far forward in pseudorapidity) but is still recorded by the calorimeter system. Therefore, ZH trilepton events inherently have a higher number of jets than the backgrounds and very little signal in the NJet= 0 bin. This characteristic of the ZH trilepton signal allows us to create a control region for the *InZPeak* analysis in the NJet= 0 bin with very little signal loss.

The three lepton + $\not\!\!E_T$ signature with an unspecified number of jet is a relatively complex event topology that introduces a correspondingly large number of variables that describe the event. This is a fortuitous circumstance as it allows the formulation of many complex variables that powerfully discriminate the signals from backgrounds in both of these new *NoZPeak* and *InZPeak* trilepton regions. Together, they represent a strong addition to the search for the standard model Higgs boson.

2 Motivation for Trileptons

The productions cross sections for WH and ZH may be small relative to the gluon fusion cross section of the current $H \rightarrow WW$ analysis, but until now the trilepton signature has been completely unexplored, the uniqueness of the trilepton signature keeps background low, and every little bit counts as we push toward the standard model limit.

Leptons decaying from a W-boson are physically detectable from an experimental point of view if the W decays to an electron, a muon, or a tau provided that the tau goes on to decay to an electron or muon. Given a generic W-boson, the probability of getting a lepton via any of these decays is : [3]

$$\begin{aligned} P(W \rightarrow l) &= P(W \rightarrow e) + P(W \rightarrow \mu) + P(W \rightarrow \tau)\left[P(\tau \rightarrow e) + P(\tau \rightarrow \mu)\right] \\ &= 0.2528 \end{aligned}$$

The relevant cross sections are (from tables 2, 3, and see [4])

- $\sigma_{\mathrm{ggH}} = 0.4607$ pb
- $\sigma_{\mathrm{WH}} = 0.0510$ pb
- $\sigma_{\mathrm{ZH}} = 0.0331$ pb

The dominant mode for the current $H \rightarrow WW$ group analysis is gluon fusion in the two-lepton bin, which has an expected yield of:

$$\sigma_{\mathrm{ggH}} \cdot \mathcal{BR}(H \rightarrow WW) \cdot P(W \rightarrow l)^2 = 0.02653\mathrm{pb}$$

By comparision, the expected yield for WH associated production in the three-lepton bin is:

$$\sigma_{\mathrm{WH}} \cdot \mathcal{BR}(H \rightarrow WW) \cdot P(W \rightarrow l)^3 = 7.425 \times 10^{-4}\mathrm{pb}$$

or 2.8% the yield of the current analysis.

ZH associated production may have a smaller cross section than WH, but given one such event there is a higher probability of producing three leptons. In this case, the Z decays to two leptons so we need only one of the two Higgs-W-bosons to decay leptonically

[3] Basic decay values are from PDG Particle Physics Booklet (July 2006), Institute of Physics

[4] CDF Note 9863

mode	Period	Stntuple	$\sigma \times \mathcal{B}$ (pb)	K-factor[a]	Filter Eff
WZ	0-23	we0s6d,we0scd,we0shd we0sld,we0sod,we0sbf we0shf	3.46×0.101	1.0	0.754
ZZ	0-23	we0s7d,we0sdd,we0sid we0smd, we0spd,we0scf we0sif	1.511	1.0	0.233
$t\bar{t}$	0-11	te0s2z	7.9×0.1027	1.0	1.0
$Z\gamma$					

[a] If cross section is NLO, then K-factor is one.
[b] Gen5 tarball for period 0.
[c] $m_{ll} > 20$.
[d] $m_{ll} > 10$.
[e] $10 < m_{ll} < 20$.

Table 1: Monte Carlo samples used in this analysis

and there are two ways for this to happen:

$$P(W \to l, W \to l) = P(W \to l)^2 = 0.06391$$
$$P(W \to l, W \to \text{had.}) = P(W \to l)\,[1 - P(W \to l)] = 0.1889$$
$$P(W \to \text{had.}, W \to l) = P(W \to l)\,[1 - P(W \to l)] = 0.1889$$
$$P(W \to \text{had.}, W \to \text{had.}) = [1 - P(W \to l)]^2 = 0.5583$$

[5] So the expected ZH yield is

$$\sigma_{\text{ZH}} \cdot \mathcal{BR}(H \to WW) \cdot P(Z \to ll) \cdot 2 \cdot P(W \to l, W \to \text{had.}) = 7.425 \times 10^{-4}\text{pb}$$

or 3.0% of the current $H \to WW$ dilepton analysis. Thus, based on cross sections and branching ratios alone we pursued this trilepton analysis expecting to contribute another $\sim 5.8\%$ to the current $H \to WW$ dilepton analysis.

Incidentally, one of the future improvements to this analysis is to accept τ leptons directly. Noting that the above prediction assumes that vector boson decays to τ's result in a detectable lepton only if that τ decays to an electron or muon, if we repeat the prediction assuming we accept hadronically decaying taus into the trilepton analysis, then the 5.8% becomes 11.0%.

[5] Observe that 0.06391+0.1889+0.1889+0.5583=1.0

$M_H(GeV^2)$	Period	Stntuple	σ (pb)	BR ($H \to WW$)	Filter Efficiency
110	0-23	fhgs4a,fhgs6a	0.2075	0.0441	0.6880
120	0-23	fhgs4b,fhgs6b	0.1529	0.1320	0.6978
130	0-23	fhgs4c,fhgs6c	0.1141	0.2869	0.7032
140	0-23	fhgs4d,fhgs6d	0.0860	0.4833	0.7065
150	0-23	fhgs4e,fhgs6e	0.0654	0.6817	0.7085
160	0-23	fhgs4f,fhgs6f	0.0510	0.9011	0.7108
170	0-23	fhgs4g,fhgs6g	0.0389	0.9653	0.7125
180	0-23	fhgs4h,fhgs6h	0.0306	0.9345	0.7141
190	0-23	fhgs4i,fhgs6i	0.0243	0.7761	0.7151
200	0-23	fhgs4j,fhgs6j	0.0193	0.7347	0.7165
145	0-23	fhgs4o,fhgs6o	0.0749	0.5731	0.7075
155	0-23	fhgs4p,fhgs6p	0.0572	0.8007	0.7098
165	0-23	fhgs4q,fhgs6q	0.0441	0.9566	0.7114
175	0-23	fhgs4r,fhgs6r	0.0344	0.9505	0.7130

Table 2: Associated Higgs production with a W boson (from CDF Note 9863).

$M_H(GeV^2)$	Period	Stntuple	σ (pb)	BR ($H \to WW$)	Filter Efficiency
110	0-23	uhgs4a,uhgs6a	0.1236	0.0441	0.6930
120	0-23	uhgs4b,uhgs6b	0.0927	0.1320	0.7031
130	0-23	uhgs4c,uhgs6c	0.0705	0.2869	0.7087
140	0-23	uhgs4d,uhgs6d	0.0542	0.4833	0.7122
150	0-23	uhgs4e,uhgs6e	0.0421	0.6817	0.7151
160	0-23	uhgs4f,uhgs6f	0.0331	0.9011	0.7172
170	0-23	uhgs4g,uhgs6g	0.0261	0.9653	0.7184
180	0-23	uhgs4h,uhgs6h	0.0208	0.9345	0.7204
190	0-23	uhgs4i,uhgs6i	0.0166	0.7761	0.7220
200	0-23	uhgs4j,uhgs6j	0.0135	0.7347	0.7239
145	0-23	uhgs4o,uhgs6o	0.0477	0.5731	0.7135
155	0-23	uhgs4p,uhgs6p	0.0373	0.8007	0.7155
165	0-23	uhgs4q,uhgs6q	0.0294	0.9566	0.7183
175	0-23	uhgs4r,uhgs6r	0.0233	0.9505	0.7196

Table 3: Associated Higgs production with a Z boson (from CDF Note 9863).

3 Event Summary and Signatures of the *NoZPeak* and *InZPeak* Trilepton Regions

3.1 Trilepton Signal Regions Defined

The current $H \rightarrow WW$ group analysis is constrained only to the study of events with exactly two leptons, which focuses primarily on the gluon fusion Higgs boson signal because of its large cross section relative to associated production. The trilepton analysis, however, focuses virtually entirely on the two associated production channels because there are three vector bosons that may all decay leptonically, whereas the gluon fusion and vector boson fusion signals do not contribute a real third lepton. Monte Carlo signal simulation does indicate that gluon fusion and vector-boson fusion have negligible contribution to the three-lepton bin. Thus, we are left with two signals to study: a $WH \rightarrow WWW \rightarrow l\nu, l\nu, l\nu$ signal and a $ZH \rightarrow ZWW \rightarrow l\nu, l\nu, l\nu$, jet signal. With two signals we naturally define two new trilepton signal regions attempting to isolate each, ameliorating the effort to discriminate each from background based on their unique characteristics.

The Z-boson may decay to two detectable leptons, as opposed to the W-boson which decays to a lepton and a neutrino that cannot be detected directly, so we begin by defining the trilepton *InZPeak* region for the ZH signal. Each event in question has exactly three leptons that may be combined into exactly three lepton pairs. If any of the three lepton-pairs of an event have opposite sign, same flavor, and a dilepton invariant mass within a 10.0 GeV window of the Z-boson mass at 91 GeV–that is, $m_{ll} \in [81.0, 101.0]$ GeV–then the event is directed towards the *InZPeak* analysis. All other trilepton events are directed towards the *NoZPeak* analysis. Observe in table 4 that $\sim 77\%$ of the signal in the *NoZPeak* region is WH, while $\sim 96\%$ of the signal in the *InZPeak* region is ZH. We will see in section 4 how this division allows us to focus on the unique characteristic of each signal for discrimination from the background in the NeuroBayes neural net treatment.

3.2 Backgrounds

Both regions of this trilepton analysis have five background categories considered: WZ, ZZ, $Z\gamma$ (replacing Drell-Yan), Fakes (data-based WW and Z+jets), and $t\bar{t}$. Each is summarized in table 4 along with the predicted signal for a $m_H = 160$ GeV standard model Higgs boson and the data.

3.2.1 Heavy Dibosons: WZ, ZZ

The WZ and ZZ diboson contributions provide three physical leptons, with WZ being the dominant background in both trilepton signal regions. Both samples are Pythia-based,

Process	NoZPeak	InZPeak
WZ	$5.92 \pm 0.81_{\mathrm{syst}}$	$7.69 \pm 1.05_{\mathrm{syst}}$
ZZ	$1.28 \pm 0.17_{\mathrm{syst}}$	$3.96 \pm 0.54_{\mathrm{syst}}$
$Z\gamma$	$2.04 \pm 0.36_{\mathrm{syst}}$	$2.73 \pm 0.49_{\mathrm{syst}}$
Fakes (WW, W+Jets, Z+Jets)	$2.28 \pm 0.68_{\mathrm{syst}}$	$6.54 \pm 1.96_{\mathrm{syst}}$
$t\bar{t}$	$0.14 \pm 0.02_{\mathrm{syst}}$	0.02
$WH160$ Signal	$0.53 \pm 0.13_{\mathrm{syst}}$	0.02
$ZH160$ Signal	$0.16 \pm 0.04_{\mathrm{syst}}$	$0.51 \pm 0.12_{\mathrm{syst}}$
Background Stack	$11.7 \pm 1.32_{\mathrm{syst}}$	$20.9 \pm 2.64_{\mathrm{syst}}$
data(4.8 fb^{-1})	12	27

Table 4: Background and Signal Counts for the *NoZPeak* and *InZPeak* Trilepton Regions.

where the W is allowed to decay inclusively and the Z is forced to decay leptonically (electron, muon, or tau pairs)[6].

3.2.2 $Z\gamma$

The $Z\gamma$ background in the trilepton analyses replaces the Drell Yan contribution of the dilepton analyses and is created by the Bauer generator. We acquire a third lepton from a Drell Yan process when either an initial or final state radiated photon undergoes a conversion and showers in the calorimeter for the third lepton. As such, the $Z\gamma$ is the restriction of Drell Yan to those events which do radiate a photon for the purpose of working with a larger statistical sample.

3.2.3 Fakes(WW, Z+Jets)

In the dilepton analysis, the "Fakes" category is measured from single high p_T lepton data (rather than MC) and assumed to have a W+jets event topology, where the one lepton is from the W-boson. This data sample is then scaled down by the predicted rate of which a jet will fake a second lepton in the detector.

Similarly, for the trilepton analyses we are interested in processes that produce two physical lepton and contribute a third fake lepton from the jets. Two high p_T lepton data is dominated by WW and Z+jets. First note that we do not consider simulated WW background as the dilepton analyses do to avoid double counting the process. Second, because the rate at which a jet is expected to fake a lepton is on the order of $1-5\%$, the rate at which such an event is expected to fake two leptons is drastically lower: $0.01-0.25\%$. As such, we consider the contribution of W+jets with one real lepton and two faked lepton to be negligible for the trilepton analyses.

[6] CDF Note 9863

3.2.4 $t\bar{t}$

Though the contribution from $t\bar{t}$ is small, we do consider it in this analysis. This background falls into the three lepton bin by having two W boson decaying to physical leptons and two b-jets that may occasionally fake a third lepton. The rate at which specifically a b-jet–as opposed to light jets–fakes a lepton is not well studied, so we use a monte carlo $t\bar{t}$ sample and look directly in the three lepton bin instead of applying a fake rate.

3.2.5 Correction to Simulation and Fake Rates

To properly weight events from simulation and scale data-based backgrounds, we follow the same standard procedures that the rest of the $H \to WW$ group as described in CDF Note 9863.

3.3 Signal Yields in the *NoZPeak* and *InZPeak* Regions

Although we have defined two signal trilepton signal regions to separately focus on the WH and ZH associated production channels, both regions do contain both signal and are summarized for all generated masses in table 5.

m_H GeV	*NoZPeak*			*InZPeak*		
	WH	ZH	Total	WH	ZH	Total
110	0.05	0.02	0.07	0.002	0.06	0.06
120	0.15	0.05	0.20	0.004	0.15	0.15
130	0.28	0.09	0.37	0.008	0.29	0.30
140	0.40	0.12	0.52	0.01	0.41	0.42
145	0.44	0.14	0.58	0.02	0.45	0.47
150	0.47	0.14	0.61	0.02	0.48	0.50
155	0.50	0.16	0.66	0.02	0.51	0.53
160	0.53	0.16	0.69	0.02	0.51	0.53
165	0.50	0.15	0.65	0.02	0.49	0.52
170	0.45	0.14	0.59	0.02	0.46	0.48
175	0.40	0.13	0.53	0.02	0.42	0.44
180	0.35	0.11	0.46	0.02	0.38	0.40
190	0.24	0.08	0.32	0.01	0.27	0.28
200	0.18	0.06	0.24	0.01	0.22	0.23

Table 5: Signal Summary

3.4 Control Regions

Verifying that monte carlo simulation is properly modelled requires verification with data in a region where signal is expected to be negligible–that is, "control regions." The control regions we chose for both the *NoZPeak* and *InZPeak* trilepton regions contain minimal signal (see table 6) so cutting them out of the analyses drastically cuts down the background to discriminate against in addition to providing a verification of modelling. They are:

- *NoZPeak* Control Region: $10.0 < \not{E}_T < 20.0$
- *InZPeak* Control Region: Number of Jets= 0

The topology of WH associated production in the trilepton channel also contains at least three neutrinos (more if $W \rightarrow \tau\nu_\tau \rightarrow l_{e,\mu}\nu_{e,\mu}\nu_\tau$ decays are involved), resulting in high missing energy values (see figure 12). Thus, a low $\not{E}_T$ region is a natural choice for a control of the *NoZPeak* trilepton analysis, which also drastically cuts down the $Z\gamma$ and Fakes backgrounds.

Similarly, the topology of ZH associated production–while also having inherently high $\not{E}_T$– lends to a preference for at least one or two jets (see figures 30 and 17) since one of the two Higgs-W-bosons decays hadronically. Only $\sim 10\%$ of the trilepton ZH signal is present in the NJet= 0 bin, but much of it's most dominant background, WZ, is. Thus, the NJet= 0 bin is a natural choice for the control region of the *InZPeak* trilepton analysis. Unfortunately, there are several nefarious difficulties that arise from this choice that must be discussed. First, four of the discriminating variables chosen in the neural network treatment discussed in section 4 are undefined when NJet= 0 (though can be powerful discriminators among those events that do have at least one jet, serving as yet another argument for this choice of control region) and NJet must be excluded as a discriminating variable as well since the control region allows it only one possible value by definition (a variable cannot be used to discriminate background from signal when both background and signal must have identical values for that variable). The neural network result for the control region of *InZPeak* has the following removed from the list of discriminating variables:

- NJet
- E_T of the leading jet
- ΔR between the W-lepton and the leading jet. Denote the two leptons with dilepton invariant mass $\in [81.0, 101.0]$ GeV (the definition of the *InZPeak* region) as the Z-leptons, then the other lepton is denoted the W-lepton.
- Transverse mass of the vector sum of all jets
- Transverse mass of the W-lepton and the $\not{E}_T$

Further, with the $t\bar{t}$ background being borderline negligible already, our monte carlo sample of $t\bar{t}$ does not contain a single trilepton event in this control region. Summarily, to obtain a neural network result for this *InZPeak* control region we had to retrain a neural network on the signal region (NJet ≥ 1) excluding both the five aforementioned discriminating variables and the $t\bar{t}$ background.

To support the claim that this neural network result for the *InZPeak* control region is valid, we first emphasize that the $t\bar{t}$ contribution to the signal region is only 0.02 events expected in 4.8fb^{-1} of data compared to a total background of 20.9 ± 2.64. Second, we chose 16 discriminating variables for the signal region, so losing these five is a serious but not critical loss; the total correlation to target drops from 61.9% to 52.2%.

While this choice of control region poses challenges, we are rewarded with both a cut that excludes a large portion of the backgrounds with minimal signal loss and with several powerful discriminating variables that would be ill-defined otherwise.

Process	NoZPeak	InZPeak
WZ	$0.70 \pm 0.10_{\text{syst}}$	$27.7 \pm 3.78_{\text{syst}}$
ZZ	$0.66 \pm 0.09_{\text{syst}}$	$3.10 \pm 0.42_{\text{syst}}$
$Z\gamma$	$16.8 \pm 3.77_{\text{syst}}$	$4.82 \pm 1.08_{\text{syst}}$
Fakes (WW, W+Jets, Z+Jets)	$6.34 \pm 1.90_{\text{syst}}$	$7.22 \pm 2.16_{\text{syst}}$
$t\bar{t}$	0.005	-
WH160 Signal	0.02	$0.05 \pm 0.007_{\text{syst}}$
ZH160 Signal	0.01	$0.06 \pm 0.007_{\text{syst}}$
Background Stack	$24.5 \pm 4.26_{\text{syst}}$	$42.8 \pm 5.02_{\text{syst}}$
data(4.8 fb^{-1})	22	45

Table 6: Event Count of the Control Regions.

We provide here the fits for the discriminating variables in the *NoZPeak* and *InZPeak* trilepton control regions to data[7].

[7]Detailed definitions of each variable are provided in section 4.

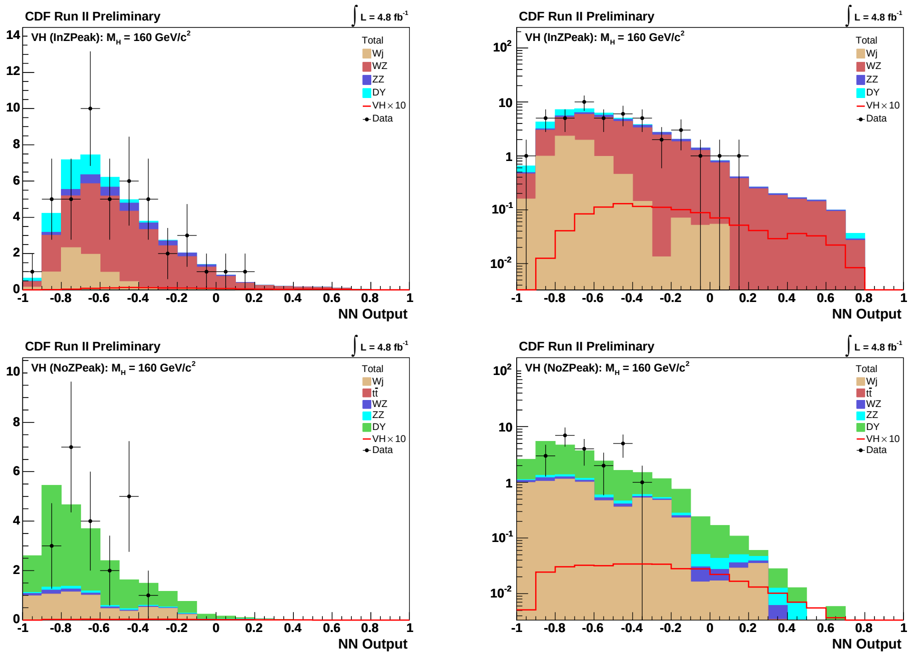

Figure 2: *NoZPeak* Control Region (10.0 GeV $< \not{E}_T <$ 20.0 GeV) and *InZpeak* Control Region (NJet$=0$) neural net results against samples trained on signal regions.

4 Results

4.1 Neural Net Training and Results

The trilepton $H \rightarrow WW$ analyes rely on the NeuroBayes neural network package to discriminate signal from background; we do not attempt the Matrix Element method in this study. We use 13 input variables for the *NoZPeak* analysis and 16 for the *InZPeak* analysis. The neural net results can be seen in figures 3, 4, 5, and 6.

Because the interaction topology under consideration involves three leptons and also because we do not separate the analyses by jet bin (aside from reserving the NJet=0 bin for the *InZPeak* control region), the signatures of the signal regions under consideration involve many potentially complex variables whose discriminatory power must be explored. As such, a larger than usual quantity of discriminating variables are used to train the NeuroBayes neural nets and we have found no reason yet to believe that fewer variables would be any benefit.

NoZPeak Variable Descriptions/Details:

- ΔR b/w Opp. Sign Close Leptons: With three leptons there are three possible pairings of leptons. Events with all three leptons having the same sign are rejected from this analysis, so every event has two possible pairings of opposite-signed leptons. Of those two pairings, this variable is the ΔR value of the pairing with lower ΔR value.

- $\not{E}_T$: Missing Transverse Energy

- H_T: Sum of the transverse energies of all three leptons, the $\not{E}_T$, and all jets.

- Dimass b/w Opp. Sign Close by ϕ: Dilepton invariant mass of the opposite-signed lepton pair that is closer in the ϕ coordinate.

- $\Delta\phi$(Lep2,$\not{E}_T$): The magnitude of the difference in ϕ between the 2^{nd} lepton by p_T and the $\not{E}_T$.

- Inv. Mass(Lep3,$\not{E}_T$,Jets): Invariant mass of the vector sum of the 3^{rd} lepton, $\not{E}_T$, and Jets.

- m_T(Leptons,$\not{E}_T$,Jets): Transverse mass of the vector sum of all three leptons, $\not{E}_T$, and all jets.

- p_T of the 2^{nd} lepton by p_T.

- ΔR Opp. Sign Far Leptons: With three leptons there are three possible pairings of leptons. Events with all three leptons having the same sign are rejected from this analysis, so every event has two possible pairings of opposite-signed leptons.

Of those two pairings, this variable is the ΔR value of the pairing with higher ΔR value.

- m_T Trilepton Mass: Transverse mass of the vector sum of the three leptons.
- NJet: The number of jets in the event. For this use of NJet, all events with NJet $\geq$ 2 jets are thrown into the NJet = 2 bin.
- m_T (Lep3, $\not\!\!E_T$): Transverse mass of the vector sum of the 3$^{\text{rd}}$ lepton and the $\not\!\!E_T$.
- Inv. Mass(Lep1,Lep2,$\not\!\!E_T$): Invariant mass of the vector sum of the 1$^{\text{st}}$ lepton, 2$^{\text{nd}}$ lepton, and $\not\!\!E_T$.

InZPeak Variable Descriptions/Details:

- NJet: The number of jets in the event.
- $\not\!\!E_T$: Missing Transverse Energy
- Lead Jet E_T: Transverse energy of the leading jet. Note that the control region for *InZPeak* is NJet = 0, so all events in the signal region must have at least one jet by definition. Also, for this use of NJet, all events with NJet $\geq$ 2 jets are thrown into the NJet = 2 bin.
- ΔR(W-Lep, Lead Jet): The *InZPeak* region is defined by having one lepton paring (opposite signed, same flavor) near the Z boson mass. Denote the one other lepton not in this pairing as the W-lepton. This variable is then the ΔR between the W-lepton and the leading jet.
- $\Delta\phi$(Leptons,$\not\!\!E_T$): $\Delta\phi$ between the vector sum of the three leptons and the $\not\!\!E_T$.
- H_T(Leptons,$\not\!\!E_T$,Jets): Sum of E_T of all three leptons, $\not\!\!E_T$, and all jets.
- m_T(Leptons,$\not\!\!E_T$,Jets): Transverse mass of the vector sum of all three leptons, $\not\!\!E_T$, and all jets.
- $\Delta\phi$(Lep2,$\not\!\!E_T$): The magnitude of the difference in ϕ between the 2$^{\text{nd}}$ lepton by p_T and the $\not\!\!E_T$.
- ΔR b/w Opp. Sign Close Leptons: With three leptons there are three possible pairings of leptons. Events with all three leptons having the same sign are rejected from this analysis, so every event has two possible pairings of opposite-signed leptons. Of those two pairings, this variable is the ΔR value of the pairing with lower ΔR value.
- Trimass:The invariant mass of the vector sum of the three leptons.

- Inv. Mass(Lep3,$\not{E}_T$,Jets): Invariant mass of the vector sum of the 3$^{\text{rd}}$ lepton, $\not{E}_T$, and Jets.

- Dimass(W-Lep,$\not{E}_T$): The *InZPeak* region is defined by having one lepton paring (opposite signed, same flavor) near the Z boson mass. Denote the one other lepton not in this pairing as the W-lepton. This variable is then the invariant mass of the vector sum of the W-lepton and the $\not{E}_T$.

- m_T Jets: Transverse mass of the vector sum of all jets. Note that the control region for *InZPeak* is NJet = 0, so all events in the signal region must have at least one jet by definition.

- m_T(W-Lep,$\not{E}_T$): Transverse mass of the vector sum of the W-lepton and the $\not{E}_T$.

- $\Delta\phi$(Z-Leptons,W-Lepton): ΔR between the vector sum of the two leptons whose dimass is near the Z-boson mass, and the other lepton.

- ΔR Opp. Sign Far Leptons: With three leptons there are three possible pairings of leptons. Events with all three leptons having the same sign are rejected from this analysis, so every event has two possible pairings of opposite-signed leptons. Of those two pairings, this variable is the ΔR value of the pairing with higher ΔR value.

Variable(*NoZPeak*)	110	120	130	140	145	150	155
ΔR b/w Opp. Sign Close Lept.	12.4	40.8	9.69	40.2	41.4	40.8	43.1
$\not\!\!E_T$	26.0	21.2	33.8	25.7	26.2	28.1	28.9
Dimass b/w Opp. Sign Close by ϕ	41.0	14.9	29.7	9.52	8.14	12.7	11.6
H_T	3.38	3.82	16.1	11.9	13.1	9.14	9.38
$\Delta\phi$(Lep2,$\not\!\!E_T$)	5.77	6.48	7.60	6.67	6.47	7.74	8.94
m_T(Leptons,$\not\!\!E_T$,Jets)	(0.38)	2.08	4.84	5.46	5.99	6.33	7.42
$p_T 2^{\mathrm{nd}}$ Lepton	2.77	5.06	3.26	5.12	3.08	4.57	6.88
Inv. Mass(Lep3,$\not\!\!E_T$,Jets)	2.05	2.46	4.34	4.51	4.57	7.84	6.64
ΔR Opp. Sign Far Lept.	9.24	11.0	12.6	9.93	10.9	6.31	6.67
NJet	7.24	7.30	3.64	3.16	3.27	3.04	3.11
m_T Trilepton Mass	(0.52)	2.62	3.78	3.85	6.62	6.67	4.44
m_T (Lep3, $\not\!\!E_T$)	3.38	2.13	(0.80)	(0.04)	(0.90)	2.32	3.17
Inv. Mass(Lep1,Lep2,$\not\!\!E_T$)	8.38	8.34	4.51	2.69	4.16	1.75	1.56
Variable(*NoZPeak*)	160	165	170	175	180	190	200
ΔR b/w Opp. Sign Close Lept.	45.7	47.1	31.5	29.0	27.3	19.5	17.3
$\not\!\!E_T$	29.8	11.3	45.9	46.4	47.0	48.0	21.6
Dimass b/w Opp. Sign Close by ϕ	12.4	10.9	8.61	8.11	7.31	6.78	5.14
H_T	10.5	11.3	6.05	13.4	16.4	22.7	49.7
$\Delta\phi$(Lep2,$\not\!\!E_T$)	9.49	8.81	9.19	9.41	7.70	7.37	6.58
m_T(Leptons,$\not\!\!E_T$,Jets)	8.08	8.57	9.93	8.35	8.67	9.54	10.7
$p_T 2^{\mathrm{nd}}$ Lepton	7.85	4.59	8.48	8.57	4.66	8.28	8.45
Inv. Mass(Lep3,$\not\!\!E_T$,Jets)	6.99	7.63	12.7	10.0	8.67	8.72	7.34
ΔR Opp. Sign Far Lept.	6.30	5.65	5.79	5.18	5.25	5.54	5.01
NJet	4.58	3.09	3.67	3.36	3.50	2.72	2.25
m_T Trilepton Mass	4.59	7.55	4.65	4.57	7.70	3.98	3.23
m_T (Lep3, $\not\!\!E_T$)	3.77	4.14	4.46	3.64	3.68	3.05	1.85
Inv. Mass(Lep1,Lep2,$\not\!\!E_T$)	3.15	1.98	1.52	(0.90)	(0.77)	(0.26)	1.67

Table 7: *NoZPeak* Significance: The variables are ordered by their significance as discriminating variables for the NeuroBayes neural net trained at the 160 GeV signal. Values in parentheses (*) indicate the input variable was not used for the given m_H.

Variable(*InZPeak*)	110	120	130	140	145	150	155
NJet	23.6	29.7	33.2	37.6	39.6	41.1	43.2
$\not{E}_T$	8.07	9.35	13.4	22.7	23.3	23.6	24.8
Lead Jet E_T	3.76	7.23	14.5	12.0	16.3	17.3	17.9
ΔR(W-Lep, Lead Jet)	19.2	17.4	16.7	13.6	13.8	13.0	12.7
$\Delta\phi$(Leptons,$\not{E}_T$)	21.3	20.5	19.1	10.9	10.2	12.4	11.6
m_T(Leptons,$\not{E}_T$,Jets)	3.50	1.05	5.96	5.86	4.93	3.93	9.26
$\Delta\phi$(Lep2,$\not{E}_T$)	4.42	3.64	4.54	5.31	4.81	4.85	5.60
ΔR b/w Opp. Sign Close Lept.	13.8	13.9	10.7	14.6	11.7	10.9	7.10
Trimass	11.6	9.50	9.14	6.83	6.96	6.96	6.35
Inv. Mass(Lep3,$\not{E}_T$,Jets)	7.29	2.78	(0.23)	1.91	1.47	1.94	4.67
H_T(Leptons,$\not{E}_T$,Jets)	(0.48)	(0.95)	2.68	6.38	7.14	6.93	5.81
m_T Jets	(1.01)	2.38	(1.01)	(0.98)	(0.18)	2.36	2.49
Dimass(W-Lep,$\not{E}_T$)	2.02	(0.07)	2.05	2.80	2.76	2.34	3.09
m_T(W-Lep,$\not{E}_T$)	6.55	4.46	(0.72)	1.78	3.44	3.99	3.56
ΔR Opp. Sign Far Lept.	2.82	3.25	2.60	2.40	2.36	2.61	1.83
$\Delta\phi$(Z-Leptons,W-Lepton)	1.55	(1.82)	1.43	(1.19)	2.54	2.64	2.09

Variable(*InZPeak*)	160	165	170	175	180	190	200
NJet	45.8	46.6	46.8	47.4	25.8	24.7	22.2
$\not{E}_T$	26.7	27.8	27.8	28.4	15.0	13.9	12.7
Lead Jet E_T	19.2	19.0	19.5	20.1	12.2	11.6	10.6
ΔR(W-Lep, Lead Jet)	13.2	12.7	12.1	11.0	7.84	5.53	4.48
$\Delta\phi$(Leptons,$\not{E}_T$)	12.0	13.2	12.1	11.0	9.72	7.55	6.82
m_T(Leptons,$\not{E}_T$,Jets)	8.62	9.39	9.09	8.52	10.9	9.81	9.26
$\Delta\phi$(Lep2,$\not{E}_T$)	8.19	8.11	8.02	6.67	5.48	5.17	4.52
ΔR b/w Opp. Sign Close Lept.	6.54	6.06	5.23	4.95	4.52	3.63	2.81
Trimass	5.84	5.04	4.87	4.87	4.52	3.07	2.66
Inv. Mass(Lep3,$\not{E}_T$,Jets)	5.84	6.64	6.60	6.23	6.81	6.93	7.32
H_T(Leptons,$\not{E}_T$,Jets)	5.02	5.86	7.97	9.66	51.1	54.4	58.7
m_T Jets	4.28	4.58	4.88	4.79	4.31	3.38	2.53
Dimass(W-Lep,$\not{E}_T$)	4.08	4.22	4.68	4.54	3.88	3.98	3.25
m_T(W-Lep,$\not{E}_T$)	3.11	2.62	3.28	2.68	3.24	2.93	3.00
ΔR Opp. Sign Far Lept.	2.94	2.61	2.34	2.02	2.45	1.40	1.32
$\Delta\phi$(Z-Leptons,W-Lepton)	2.60	2.59	2.94	1.98	2.07	1.32	1.35

Table 8: *InZPeak* Significance: The variables are ordered by their significance as discriminating variables for the NeuroBayes neural net trained at the 160 GeV signal. Values in parentheses (*) indicate the input variable was not used for the given m_H.

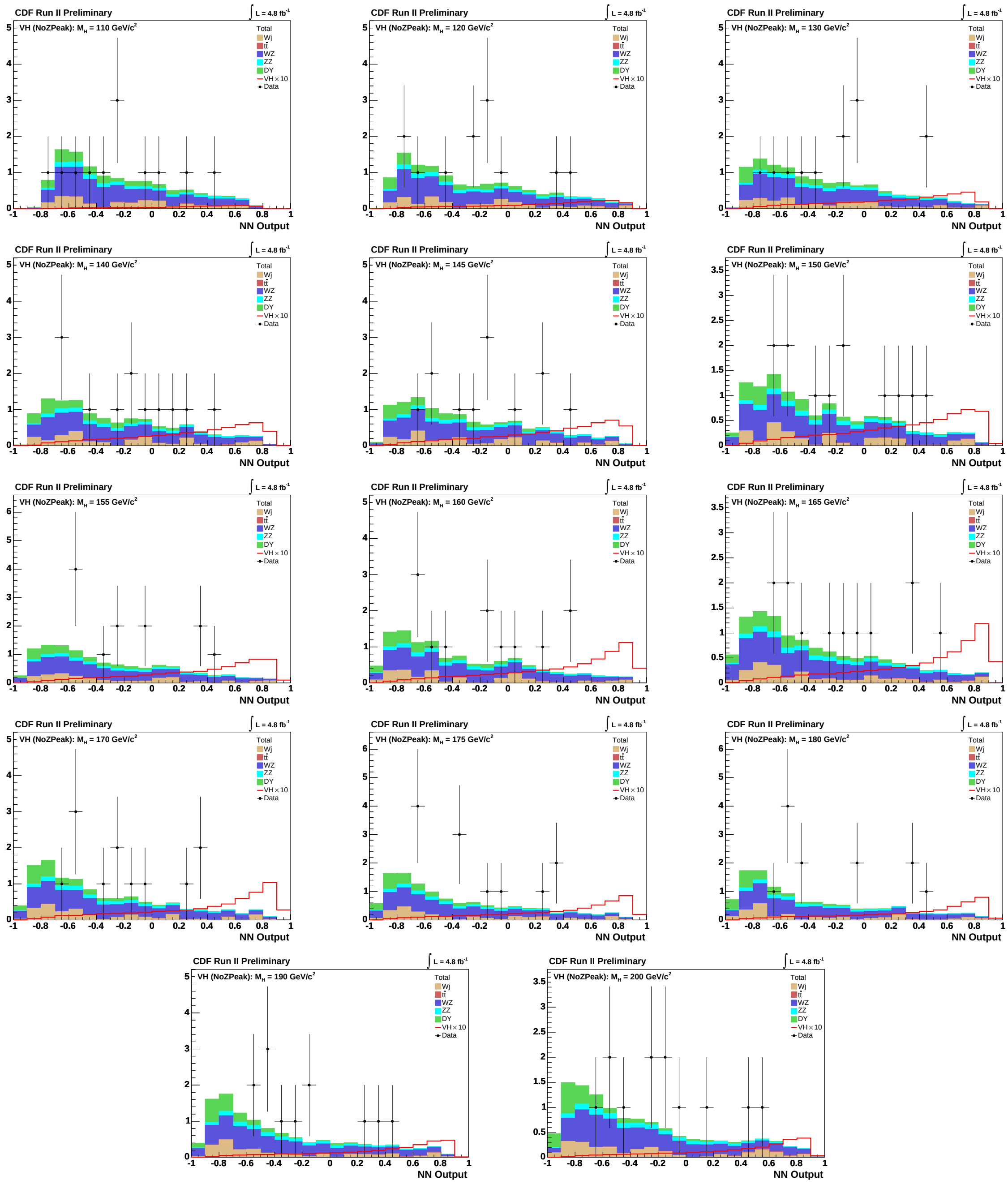

Figure 3: Trilepton *NoZPeak* NeuroBayes Neural Network output (linear scale)

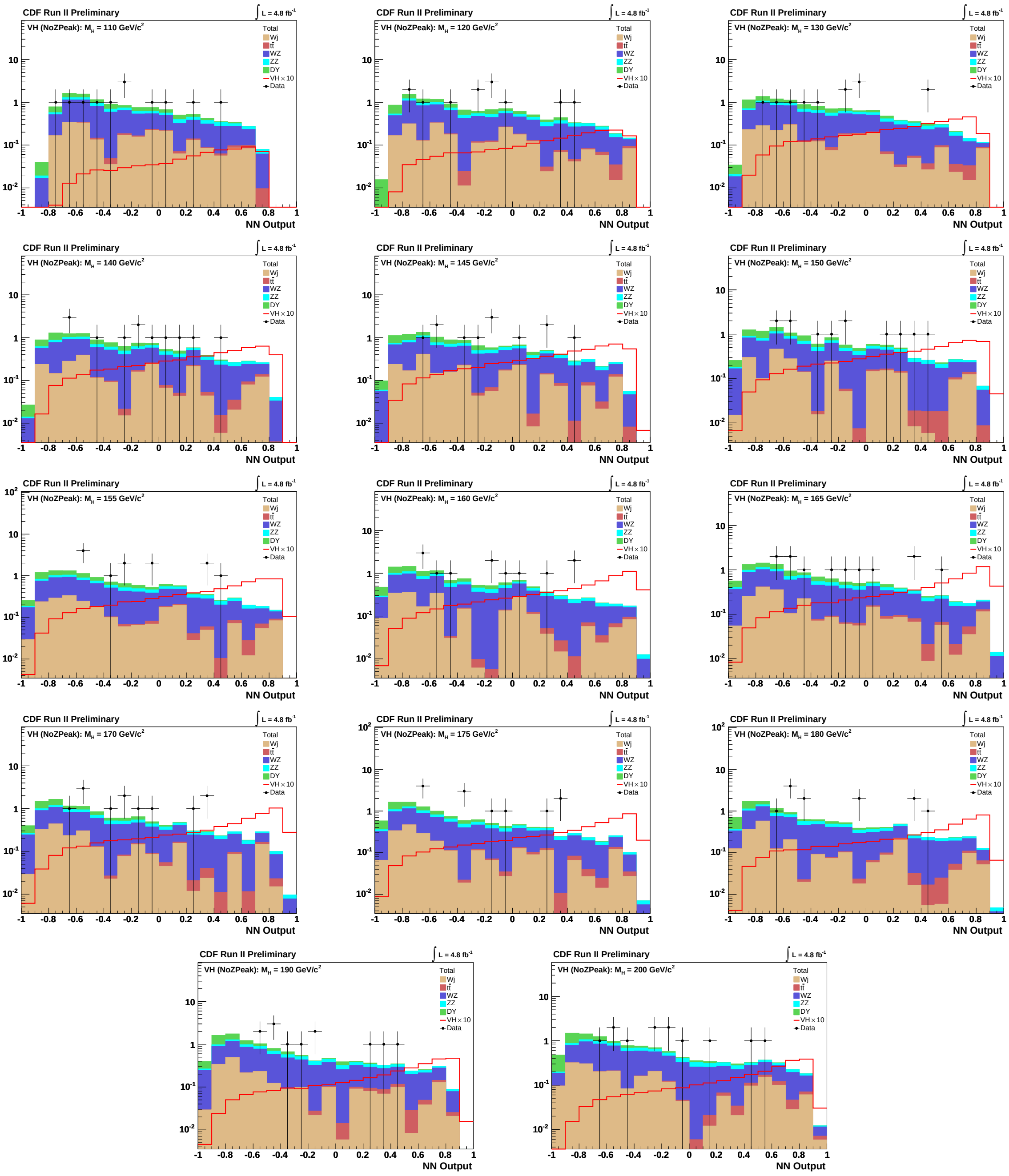

Figure 4: Trilepton *NoZPeak* NeuroBayes Neural Network output (logarithmic scale)

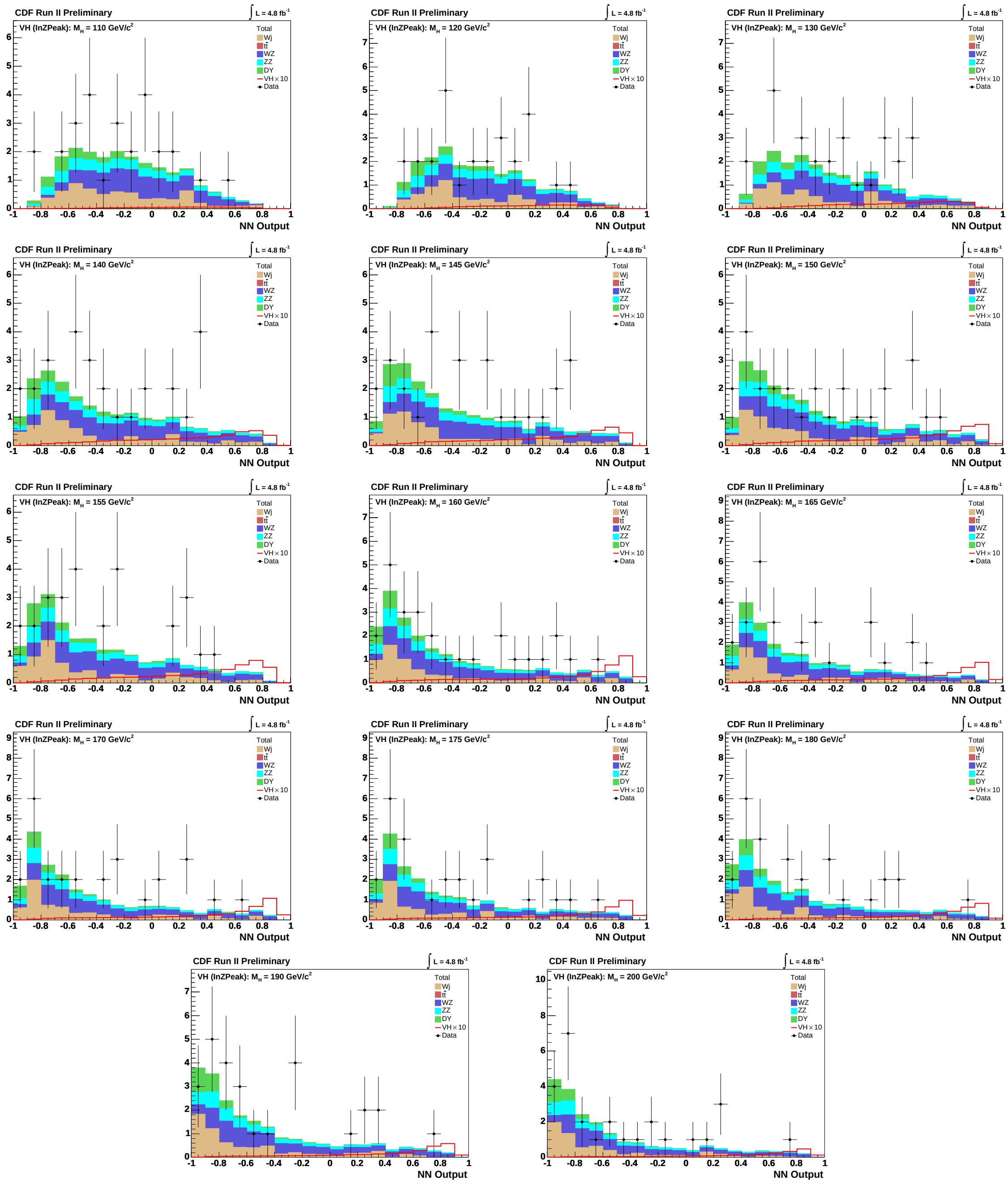

Figure 5: Trilepton *InZPeak* NeuroBayes Neural Network output (linear scale)

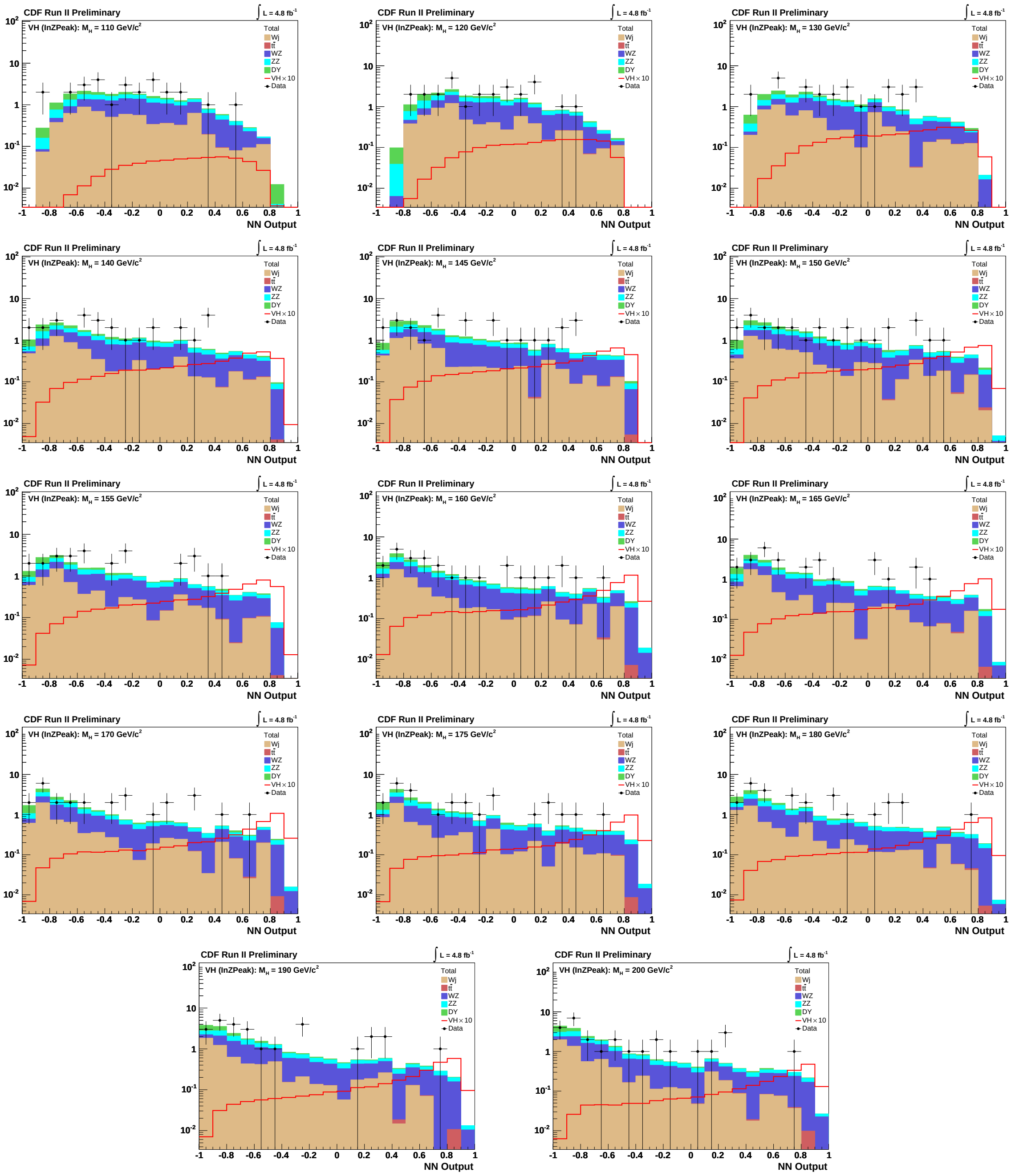

Figure 6: Trilepton *InZPeak* NeuroBayes Neural Network output (logarithmic scale)

4.2 Limit Summary

Systematic Uncertainty	WZ	ZZ	$Z\gamma$	$t\bar{t}$	Fakes	WH	ZH
DiboAcc	0.100	0.100					
TtbarAcc				0.100			
EWKHiggs						0.100	0.100
FlatPDF	0.027	0.041	0.041*	0.021		0.012	0.009
LeptonID	0.020	0.020	0.019*	0.020		0.020	0.020
TriggerEff	0.021	0.021	0.034*	0.020		0.021	0.021
Fake					0.300		
Luminosity	0.059	0.059	0.059*	0.059		0.059	0.059
MCRunDep		0.050	0.050*				
$Z\gamma$ Acc.*			0.110*				
$W\gamma$ Scale			0.120*				
σ_{Diboson}	0.060	0.060					
$\sigma_{t\bar{t}}$				0.100			
σ_{VH}						0.050	0.050
$\sigma_{\text{Z}\gamma}$*			0.050*				

Table 9: Systematic Uncertainties: Standard values for systematics used in other $H \to WW$ analyses are used wherever applicable. Since $Z\gamma$ is a new background contribution replacing Drell Yan in the trilepton analyses, new values had to be determined and are marked with (*).

The results of this trilepton analysis present a significant contribution to the $H \to WW$ combined result. We are poised to solidify and expand the window of standard model Higgs boson exclusion within $163 < m_H < 166$ GeV[8]. In the 160 GeV bin, the trilepton-*NoZPeak* analysis limits are set at 8.91 times the expected standard model limit; the trilepton-*InZPeak* analysis is set at 12.5 times the expected standard model limit; and the combined trilepton analysis is set at 6.23 times the expected standard model limit. Finally, for the combined $H \to WW$ analysis result, in the 165 GeV bin the limit drops from 1.28[9] to 1.12. As such, we are poised to begin excluding the standard model Higgs boson at 95% confidence level with CDF-only analyses in short order.

The limit calculations presented were computed with `HWWLimit` version of `MCLimit`. Expected limits were calculated in each case with 10,000 iterations of 10,000 pseudoexperiments (1000 iterations of 1000 pseudoexperiments performed 10 times), while 500,000 iterations were performed for the observed results. The systematic uncertainties used are summarized in table 9. Most values used are standard to all $H \to WW$ analyses, but

[8] CDF Note 9998

[9] CDF Note 9928

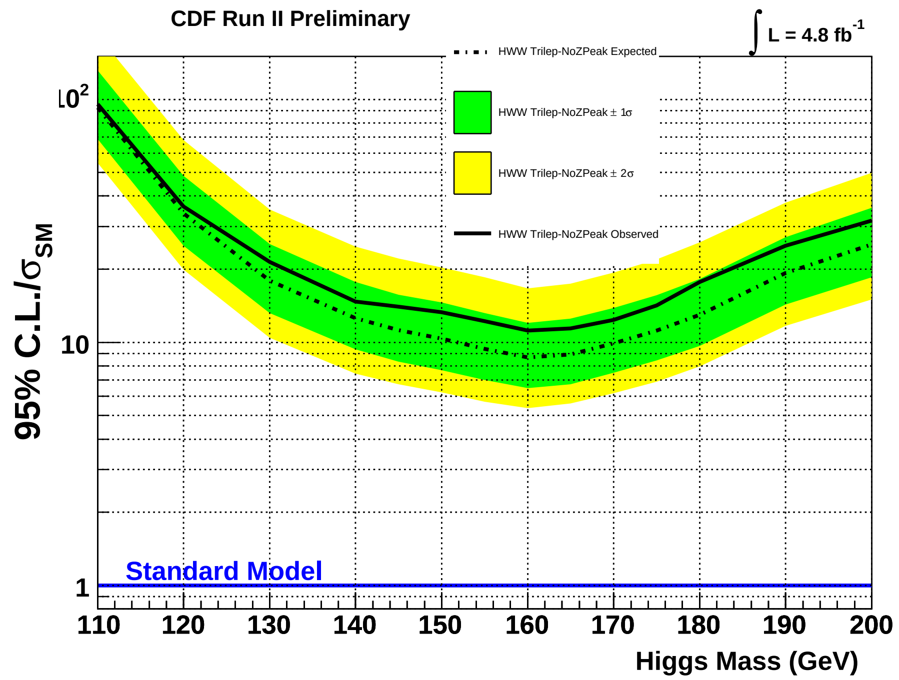

Figure 7: Trilepton *NoZPeak* Region Limits

since $Z\gamma$ is a new background in this analysis there are several new systematics particular to this analysis. First, note that the $W\gamma$ background is already scaled down by 14% in other $H \rightarrow WW$ analyses due to known mismodelling of photon conversions. We are using the same scale factor for the $Z\gamma$ contribution since the same photon conversion affect is assumed, as such we use the same systematic error associated with this scale factor. Second, we have for $W\gamma$ the systematic `WgamAcc`, which accounts for poor MC modeling beyond leading order. Likewise, we assume the same error of 11% for a new `ZgamAcc` systematic since both are modelled by the Bauer MC generator.

Sensitivity(*NoZPeak*)	110	120	130	140	145	150	155
$^{+2\sigma}/_{\sigma_{\mathrm{SM}}}$	183	68.1	35.1	24.7	22.1	20.3	18.5
$^{+1\sigma}/_{\sigma_{\mathrm{SM}}}$	131	48.3	25.3	17.7	15.7	14.6	13.2
$^{\mathbf{Median}}/_{\sigma_{\mathbf{SM}}}$	**92.4**	**34.0**	**18.0**	**12.6**	**11.2**	**10.4**	**9.39**
$^{-1\sigma}/_{\sigma_{\mathrm{SM}}}$	68.4	25.0	13.2	9.35	8.32	7.67	7.00
$^{-2\sigma}/_{\sigma_{\mathrm{SM}}}$	54.7	19.8	10.4	7.42	6.72	6.22	5.70
$^{\mathbf{Observed}}/_{\sigma_{\mathbf{SM}}}$	**95.3**	**36.2**	**21.4**	**14.7**	**14.0**	**13.3**	**12.2**
Sensitivity(*NoZPeak*)	160	165	170	175	180	190	200
$^{+2\sigma}/_{\sigma_{\mathrm{SM}}}$	16.6	17.4	19.3	21.9	25.8	37.5	49.8
$^{+1\sigma}/_{\sigma_{\mathrm{SM}}}$	12.0	12.5	13.8	15.6	18.2	27.1	35.8
$^{\mathbf{Median}}/_{\sigma_{\mathbf{SM}}}$	**8.66**	**8.91**	**9.89**	**11.2**	**13.0**	**19.3**	**25.3**
$^{-1\sigma}/_{\sigma_{\mathrm{SM}}}$	6.48	6.73	7.49	8.43	9.68	14.3	18.6
$^{-2\sigma}/_{\sigma_{\mathrm{SM}}}$	5.35	5.60	6.17	6.90	7.98	11.7	15.0
$^{\mathbf{Observed}}/_{\sigma_{\mathbf{SM}}}$	**11.2**	**11.4**	**12.4**	**14.2**	**17.7**	**25.0**	**31.8**

Table 10: Trilepton *NoZPeak* Region Expected Sensitivity

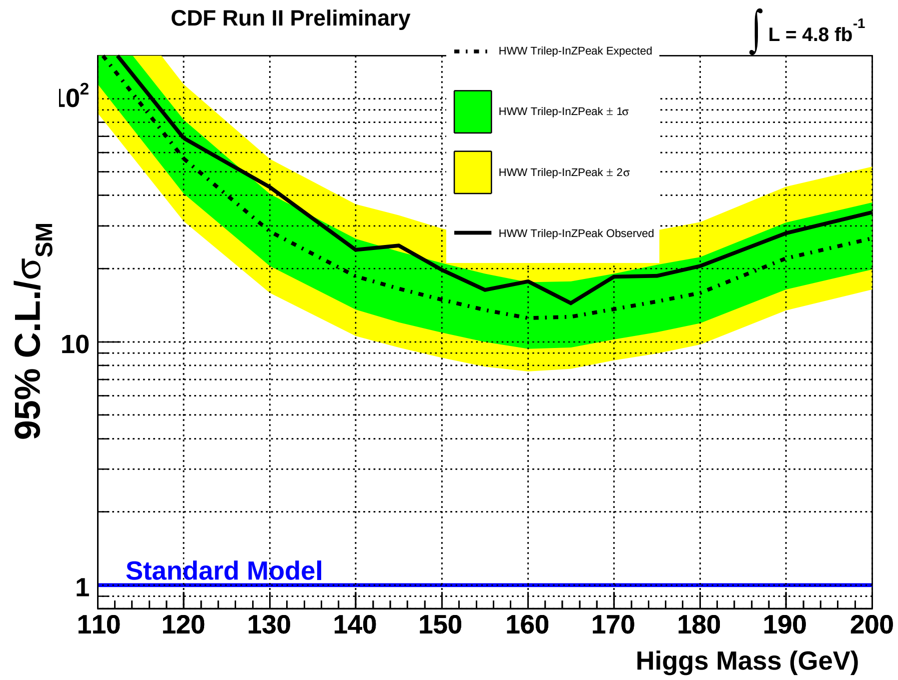

Figure 8: Trilepton *InZPeak* Region Limits

Sensitivity(*NoZPeak*)	110	120	130	140	145	150	155
$^{+2\sigma}/_{\sigma_{SM}}$	325	114	56.5	36.7	33.1	29.2	26.3
$^{+1\sigma}/_{\sigma_{SM}}$	227.	82.0	40.6	26.6	23.5	21.1	19.1
Median$/_{\sigma_{SM}}$	**159**	**56.7**	**28.4**	**18.6**	**16.5**	**14.9**	**13.5**
$^{-1\sigma}/_{\sigma_{SM}}$	114	40.7	20.5	13.6	12.0	10.9	9.97
$^{-2\sigma}/_{\sigma_{SM}}$	87.1	31.4	15.9	10.5	9.48	8.62	7.90
Observed$/_{\sigma_{SM}}$	**190**	**68.9**	**43.2**	**23.9**	**24.8**	**19.8**	**16.3**
Sensitivity(*NoZPeak*)	160	165	170	175	180	190	200
$^{+2\sigma}/_{\sigma_{SM}}$	24.7	24.6	26.2	28.8	31.1	43.5	52.4
$^{+1\sigma}/_{\sigma_{SM}}$	17.6	17.8	19.0	20.7	22.3	31.0	37.4
Median$/_{\sigma_{SM}}$	**12.5**	**12.7**	**13.7**	**14.6**	**15.9**	**22.0**	**26.6**
$^{-1\sigma}/_{\sigma_{SM}}$	9.37	9.48	10.2	11.0	11.9	16.4	19.8
$^{-2\sigma}/_{\sigma_{SM}}$	7.55	7.75	8.41	8.95	9.74	13.5	16.4
Observed$/_{\sigma_{SM}}$	**17.7**	**14.4**	**18.6**	**18.7**	**20.5**	**27.9**	**34.1**

Table 11: Trilepton *InZPeak* Region Expected Sensitivity

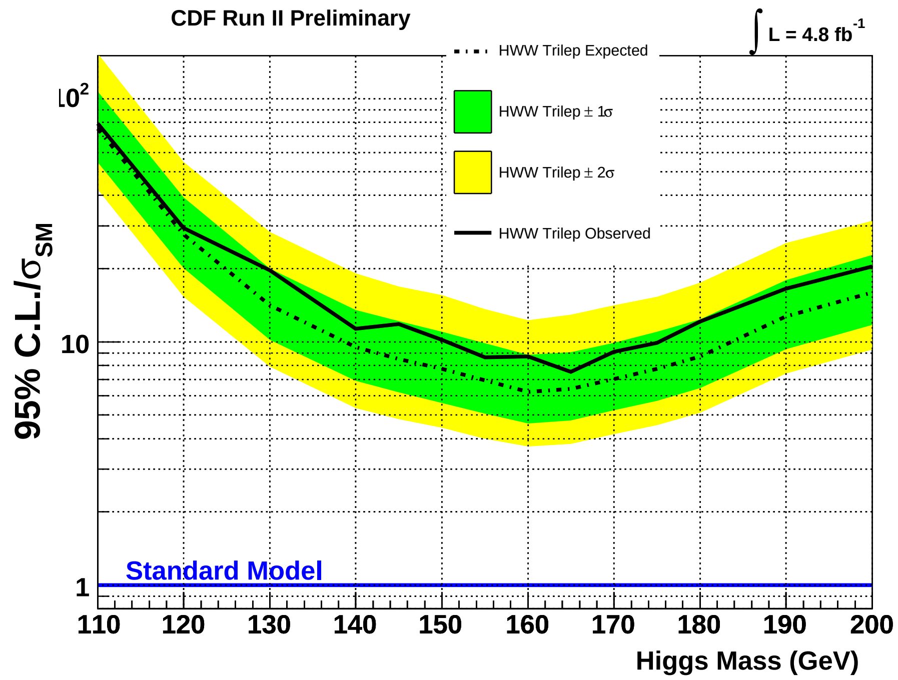

Figure 9: Trilepton Combined Limits

Sensitivity($NoZPeak$)	110	120	130	140	145	150	155
$^{+2\sigma}/_{\sigma_{SM}}$	153	54.9	28.4	19.2	16.9	15.5	13.6
$^{+1\sigma}/_{\sigma_{SM}}$	107	39.2	20.0	13.5	12.2	11.0	9.88
Median$/_{\sigma_{SM}}$	**75.3**	**27.6**	**14.1**	**9.51**	**8.50**	**7.75**	**6.94**
$^{-1\sigma}/_{\sigma_{SM}}$	54.8	20.1	10.2	6.92	6.21	5.62	5.06
$^{-2\sigma}/_{\sigma_{SM}}$	42.3	15.3	7.89	5.34	4.81	4.43	3.99
Observed$/_{\sigma_{SM}}$	**78.8**	**29.4**	**19.7**	**11.3**	**11.8**	**10.2**	**8.62**
Sensitivity($NoZPeak$)	160	165	170	175	180	190	200
$^{+2\sigma}/_{\sigma_{SM}}$	12.3	12.9	14.1	15.3	17.5	25.5	31.5
$^{+1\sigma}/_{\sigma_{SM}}$	8.83	9.07	9.91	11.0	12.4	18.0	22.7
Median$/_{\sigma_{SM}}$	**6.23**	**6.42**	**7.03**	**7.74**	**8.71**	**12.7**	**16.0**
$^{-1\sigma}/_{\sigma_{SM}}$	4.61	4.75	5.24	5.72	6.45	9.34	11.7
$^{-2\sigma}/_{\sigma_{SM}}$	3.72	3.81	4.18	4.55	5.11	7.42	9.28
Observed$/_{\sigma_{SM}}$	**8.70**	**7.52**	**9.10**	**9.91**	**12.1**	**16.5**	**20.4**

Table 12: Trilepton Combined Expected Sensitivity

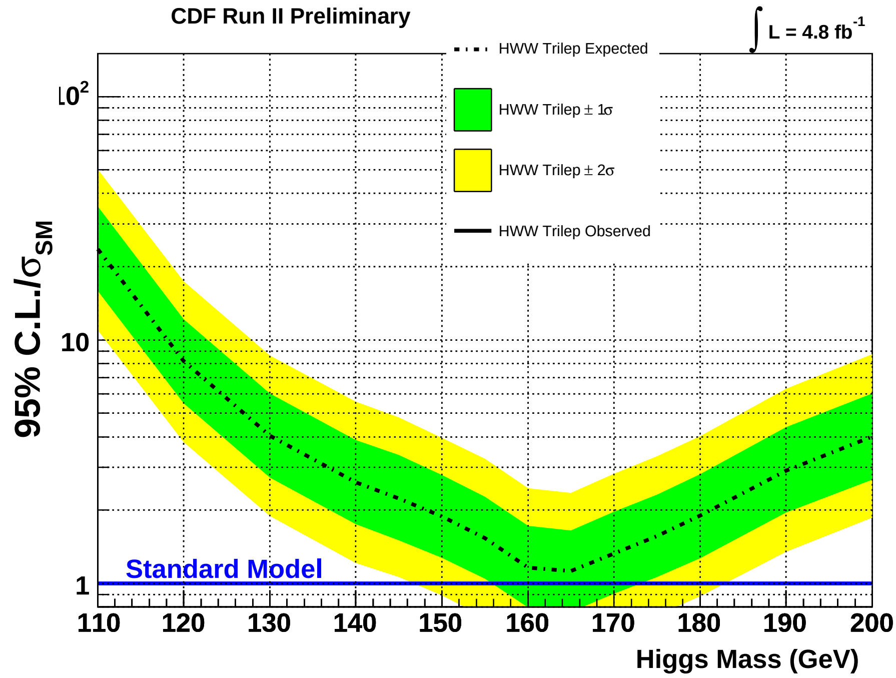

Figure 10: HWW+Trilepton Combined Limits

Sensitivity($NoZPeak$)	110	120	130	140	145	150	155
$+2\sigma/\sigma_{SM}$	50.2	17.4	8.63	5.58	4.81	3.97	3.25
$+1\sigma/\sigma_{SM}$	35.3	12.2	6.02	3.88	3.37	2.79	2.26
Median$/\sigma_{SM}$	**23.6**	**8.20**	**4.05**	**2.60**	**2.24**	**1.88**	**1.53**
$-1\sigma/\sigma_{SM}$	15.9	5.50	2.72	1.75	1.51	1.27	1.04
$-2\sigma/\sigma_{SM}$	11.0	3.80	1.89	1.21	1.06	0.89	0.72
Observed$/\sigma_{SM}$	-	-	-	-	-	-	-
Sensitivity($NoZPeak$)	160	165	170	175	180	190	200
$+2\sigma/\sigma_{SM}$	2.46	2.35	2.82	3.33	4.03	6.31	8.73
$+1\sigma/\sigma_{SM}$	1.72	1.65	1.97	2.31	2.81	4.39	6.03
Median$/\sigma_{SM}$	**1.16**	**1.12**	**1.33**	**1.57**	**1.90**	**2.90**	**4.00**
$-1\sigma/\sigma_{SM}$	0.80	0.76	0.91	1.06	1.27	1.96	2.67
$-2\sigma/\sigma_{SM}$	0.56	0.55	0.65	0.74	0.89	1.35	1.86
Observed$/\sigma_{SM}$	-	-	-	-	-	-	-

Table 13: HWW w/ Trileptons Combined Expected Sensitivity

5 Appendix

5.1 Appendix: Neural Net Input Variables

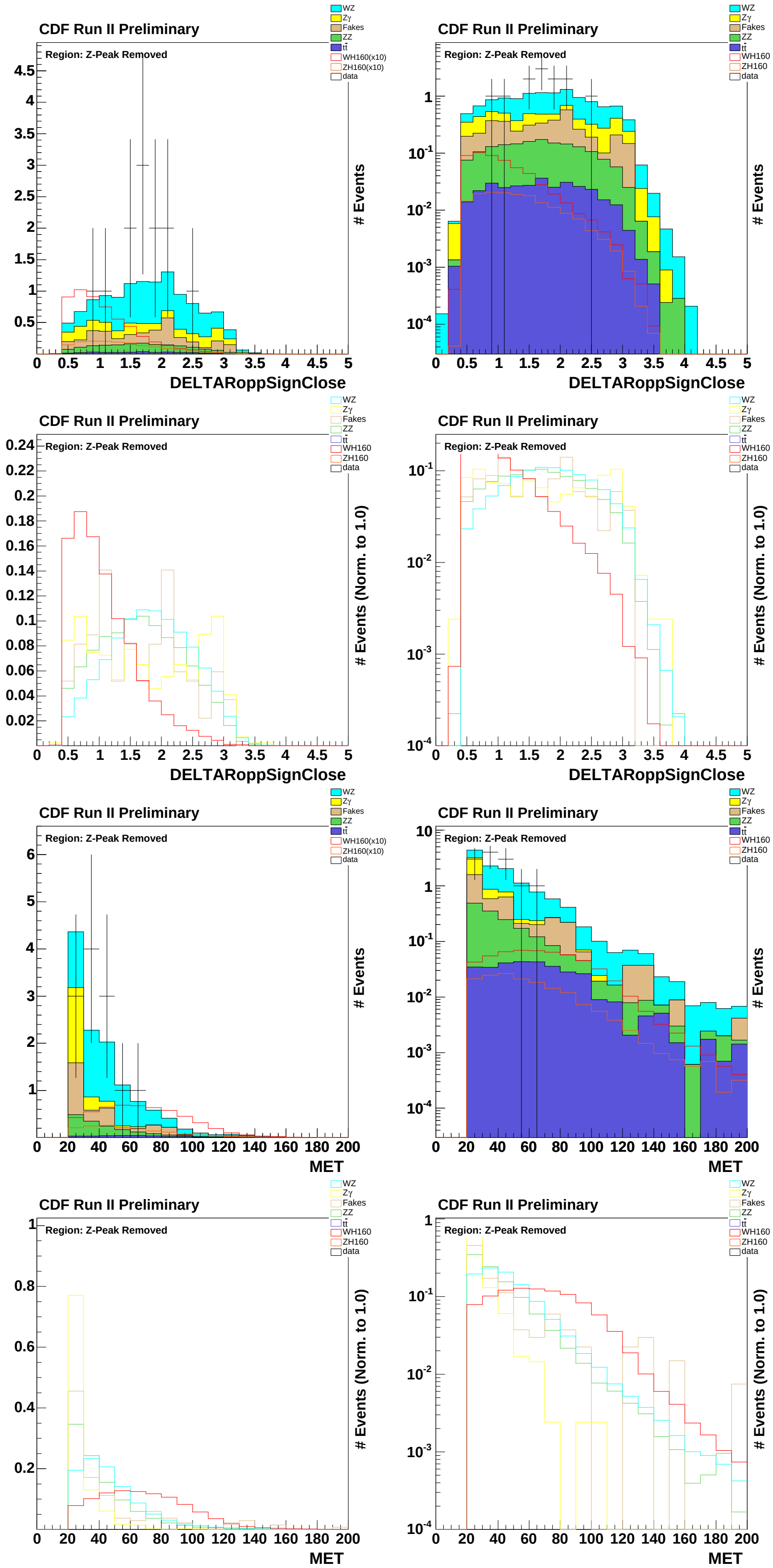

Figure 11: *NoZPeak* Signal Region (10.0 GeV < $\not\!\!E_T$ < 20.0 GeV): ΔR Opp. Sign Close Leptons, $\not\!\!E_T$.

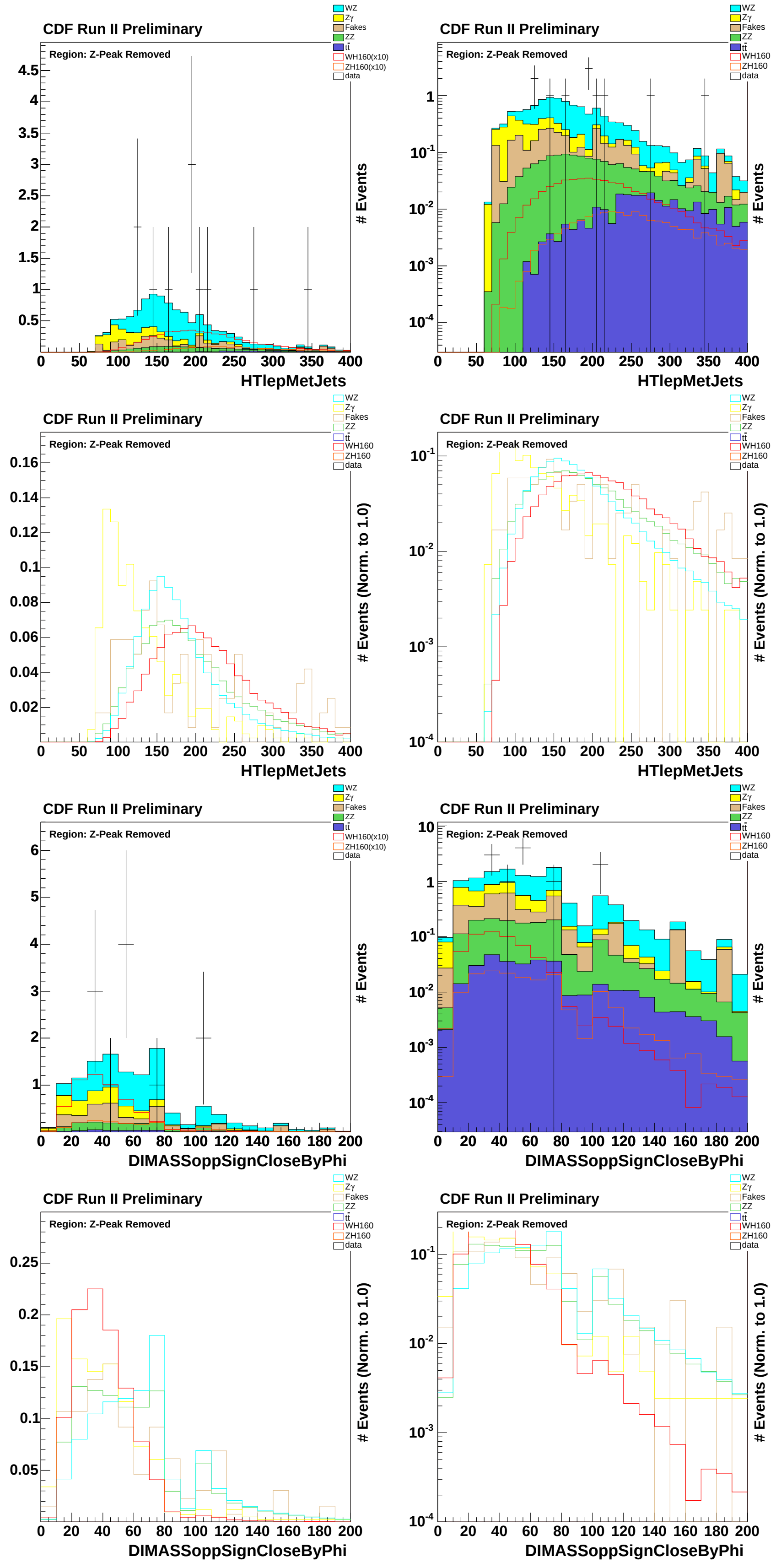

Figure 12: *NoZPeak* Signal Region (10.0 GeV $< \not\!\!E_T <$ 20.0 GeV): H_T(all leptons, $\not\!\!E_T$, all jets), Dimass Opp. Sign Leptons (closer pair in ϕ).

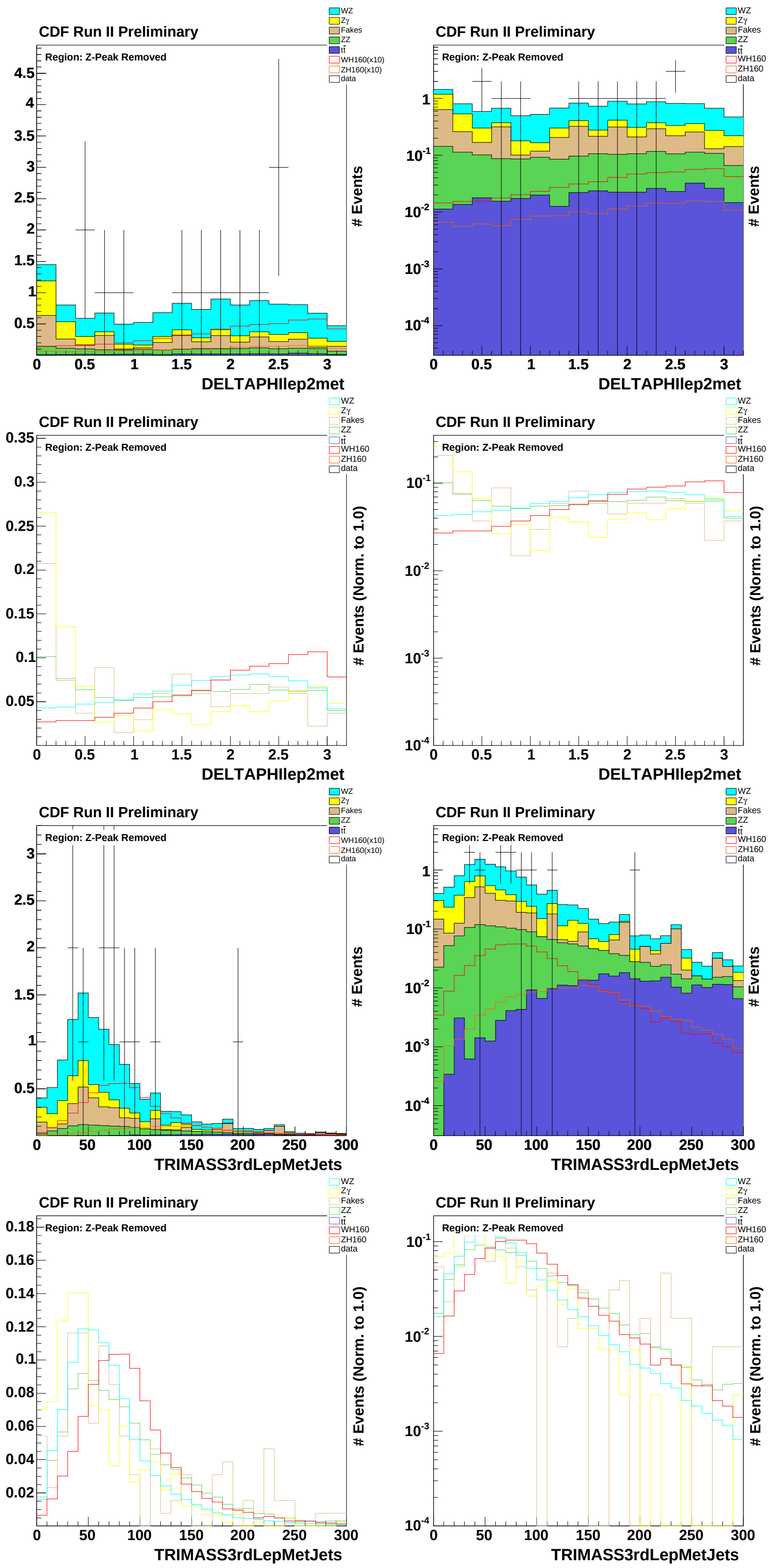

Figure 13: *NoZPeak* Signal Region (10.0 GeV < $\not\!\!E_T$ < 20.0 GeV): $\Delta\phi$ between the 2$^{\rm nd}$ lepton and $\not\!\!E_T$, Inv. mass of the 3$^{\rm rd}$ lepton+$\not\!\!E_T$+Jets.

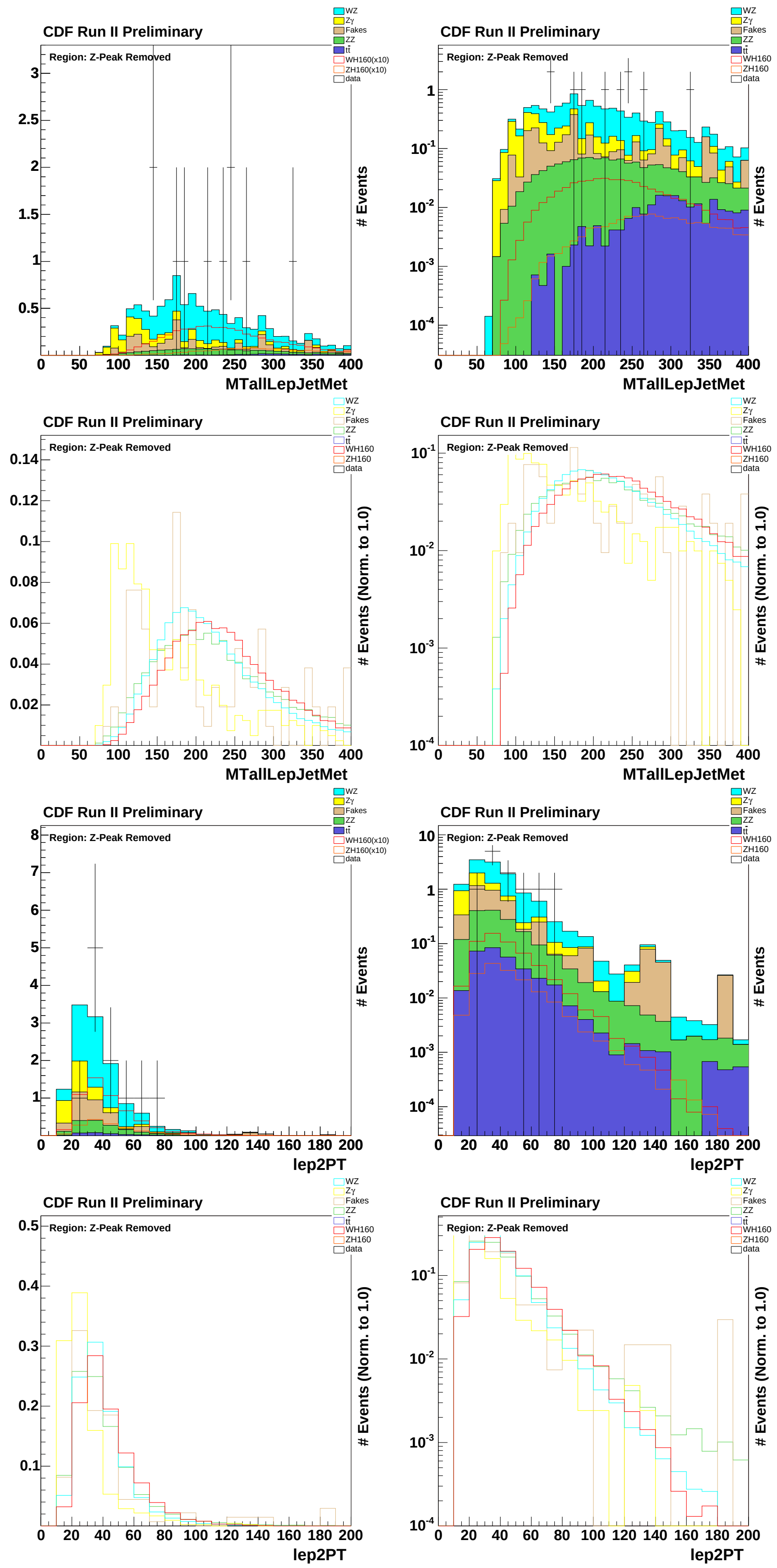

Figure 14: *NoZPeak* Signal Region (10.0 GeV $< \not{E}_T <$ 20.0 GeV): m_T(Leptons,$\not{E}_T$,Jets), p_T of 2$^{\rm nd}$ Lepton

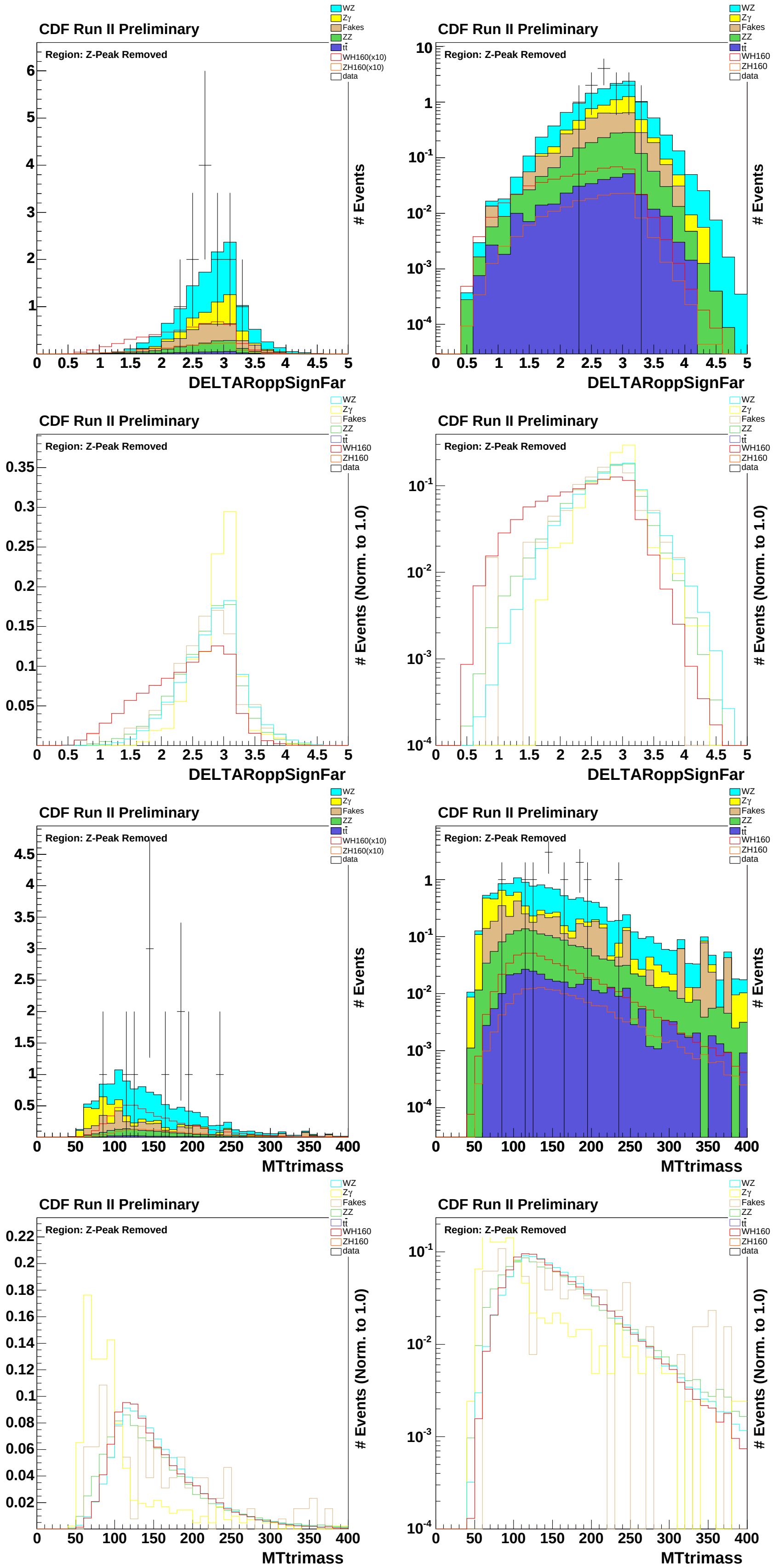

Figure 15: *NoZPeak* Signal Region (10.0 GeV < $\not{E}_T$ < 20.0 GeV): ΔR Opp. Sign Far Leptons, m_T Trilepton Mass.

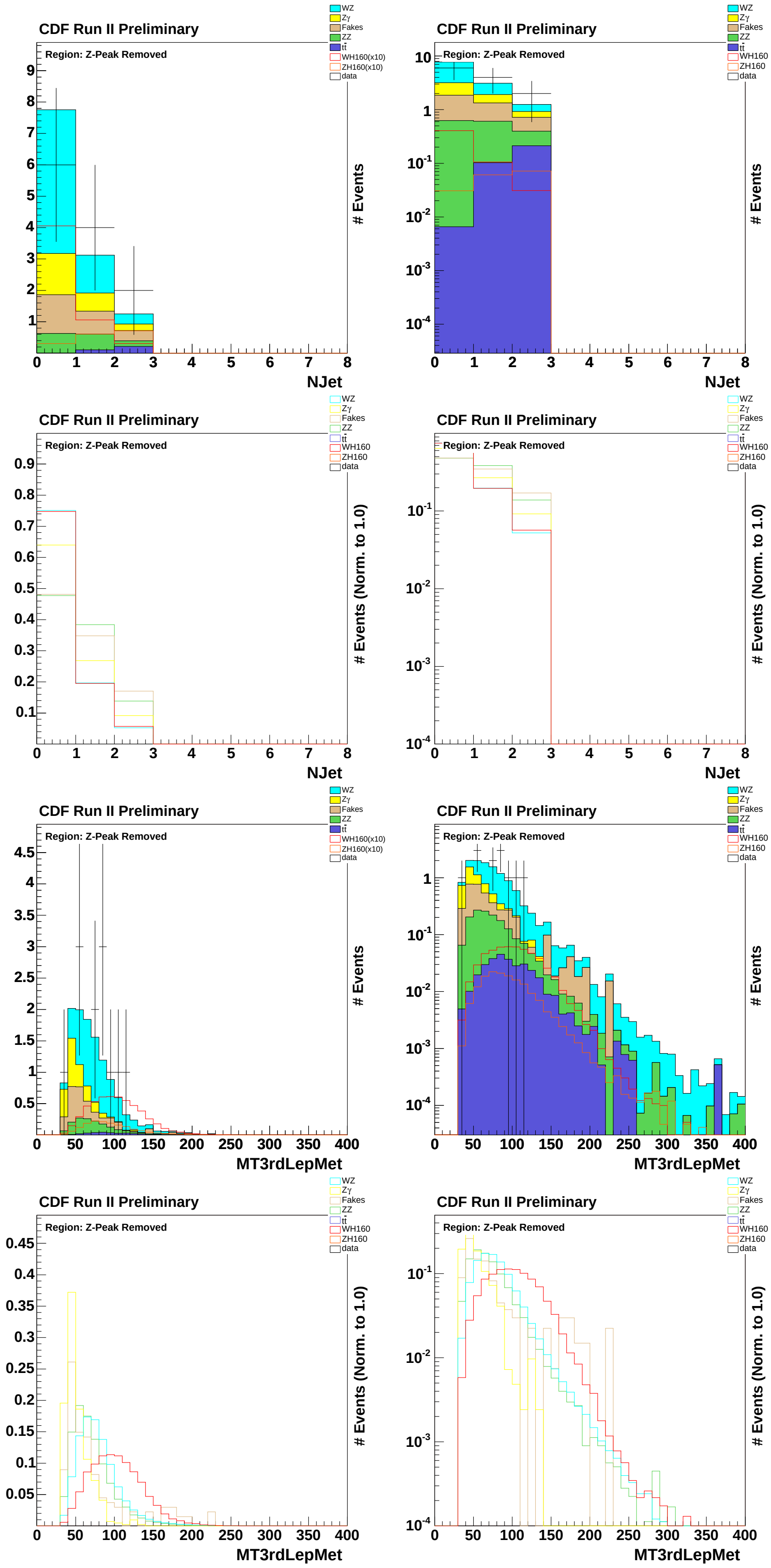

Figure 16: *NoZPeak* Signal Region (10.0 GeV < $\not\!\!E_T$ < 20.0 GeV): NJet (note that the 0-jet bin is not used in the analysis), m_T (Lep3, $\not\!\!E_T$).

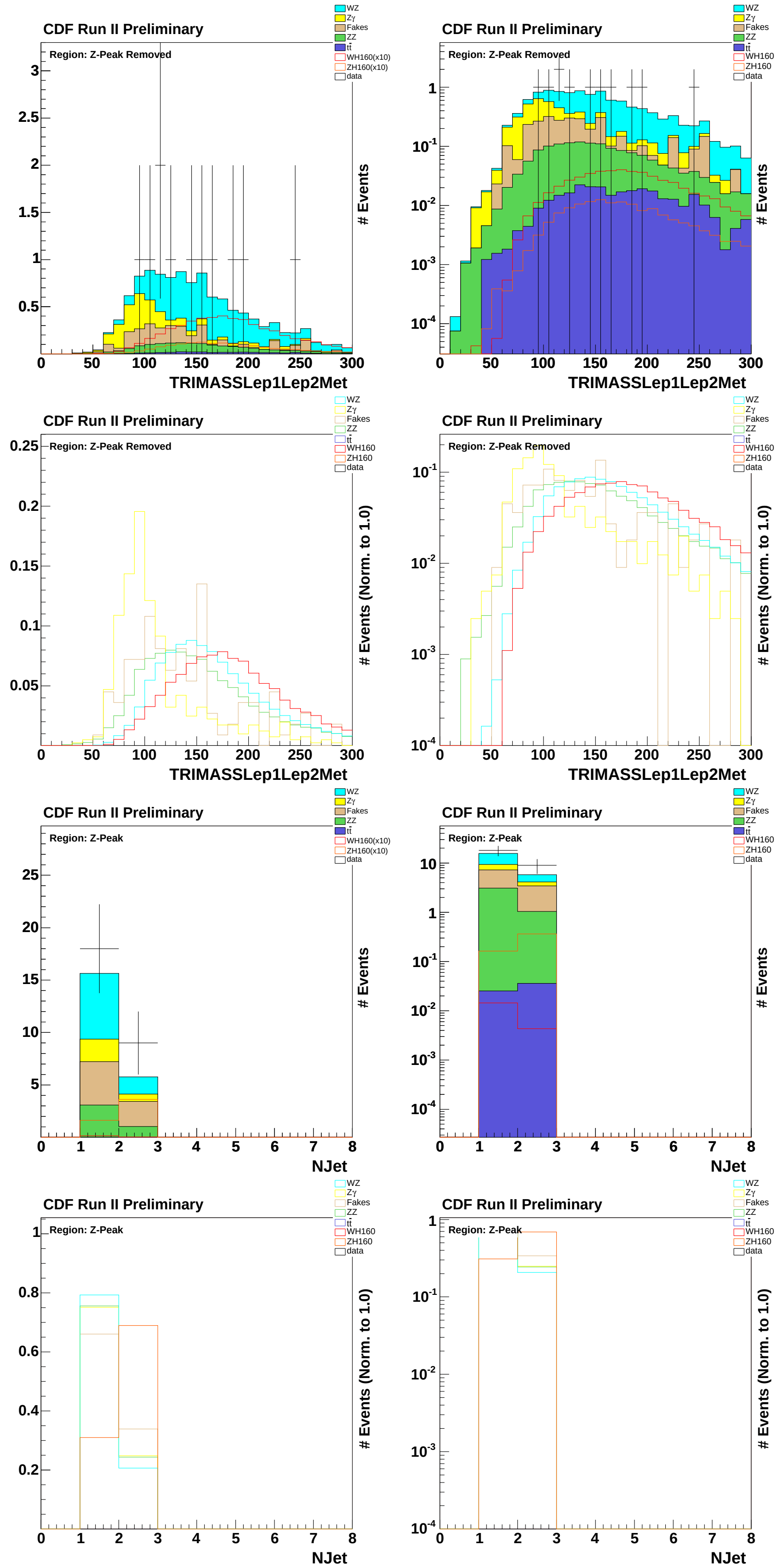

Figure 17: *NoZPeak* Signal Region (10.0 GeV $<$ $\not\!\!E_T$ $<$ 20.0 GeV): Inv. Mass(Lep1,Lep2,$\not\!\!E_T$). *InZPeak* Signal Region (NJet $\neq 0$): NJet.

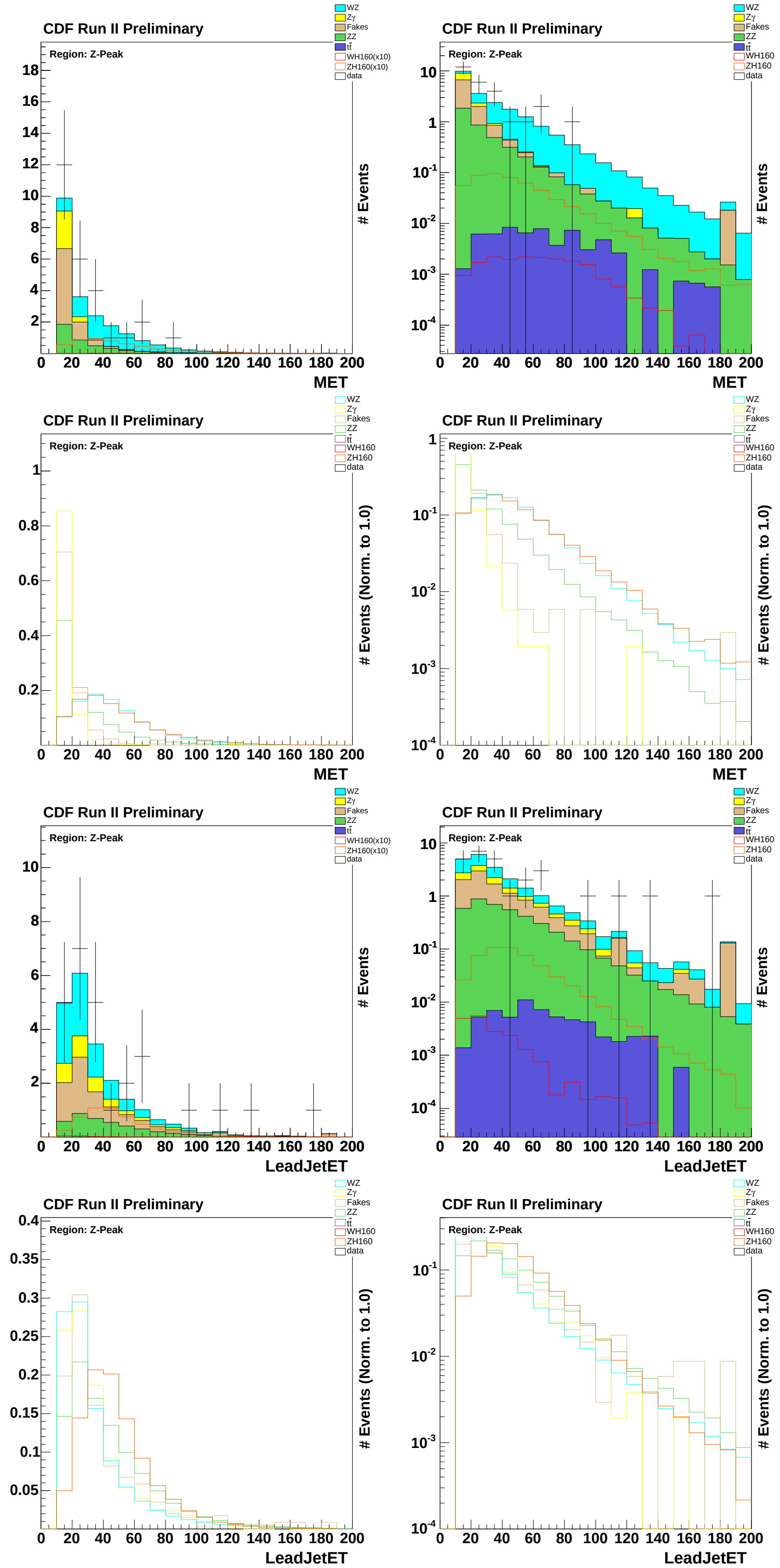

Figure 18: *InZPeak* Signal Region (NJet $\neq 0$): $\not\!\!E_T$, Lead Jet E_T.

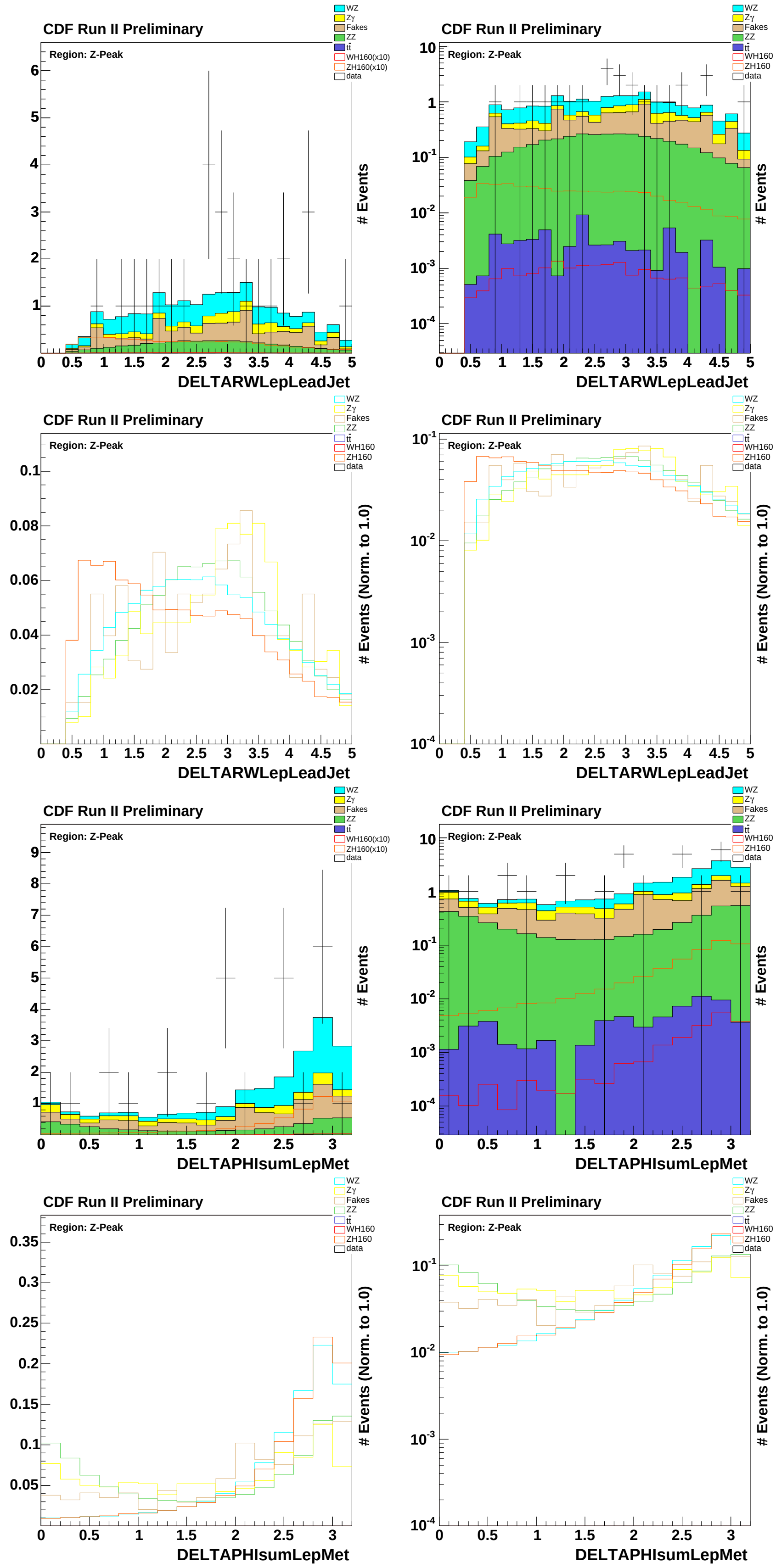

Figure 19: *InZPeak* Signal Region (NJet $\neq 0$): $\Delta R(W\text{-Lep, Lead Jet})$, $\Delta\phi(\text{Leptons}, \not{E}_T)$.

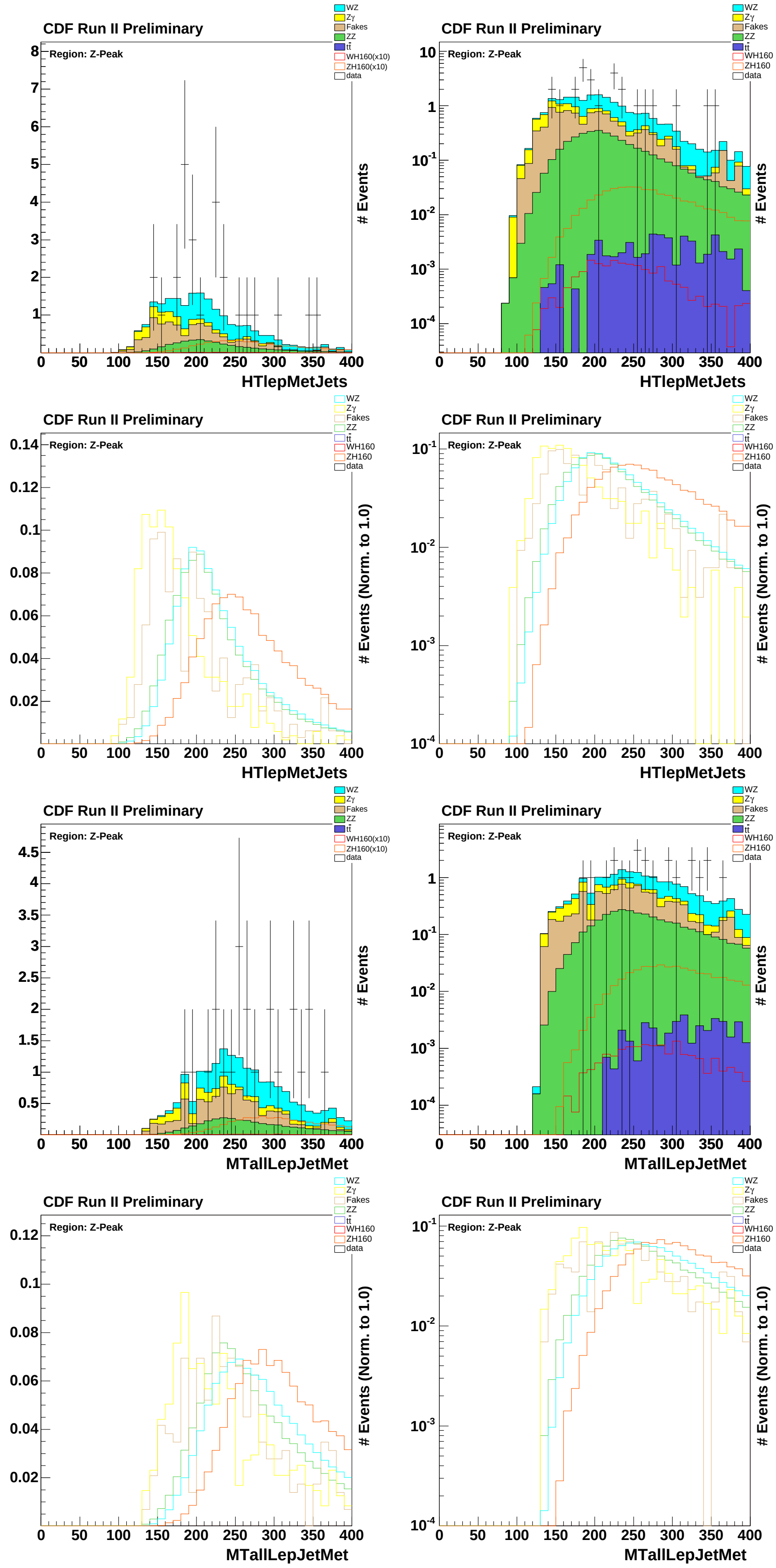

Figure 20: *InZPeak* Signal Region (NJet $\neq$ 0): H_T(Leptons,$\not\!\!E_T$,Jets), m_T(Leptons,$\not\!\!E_T$,Jets).

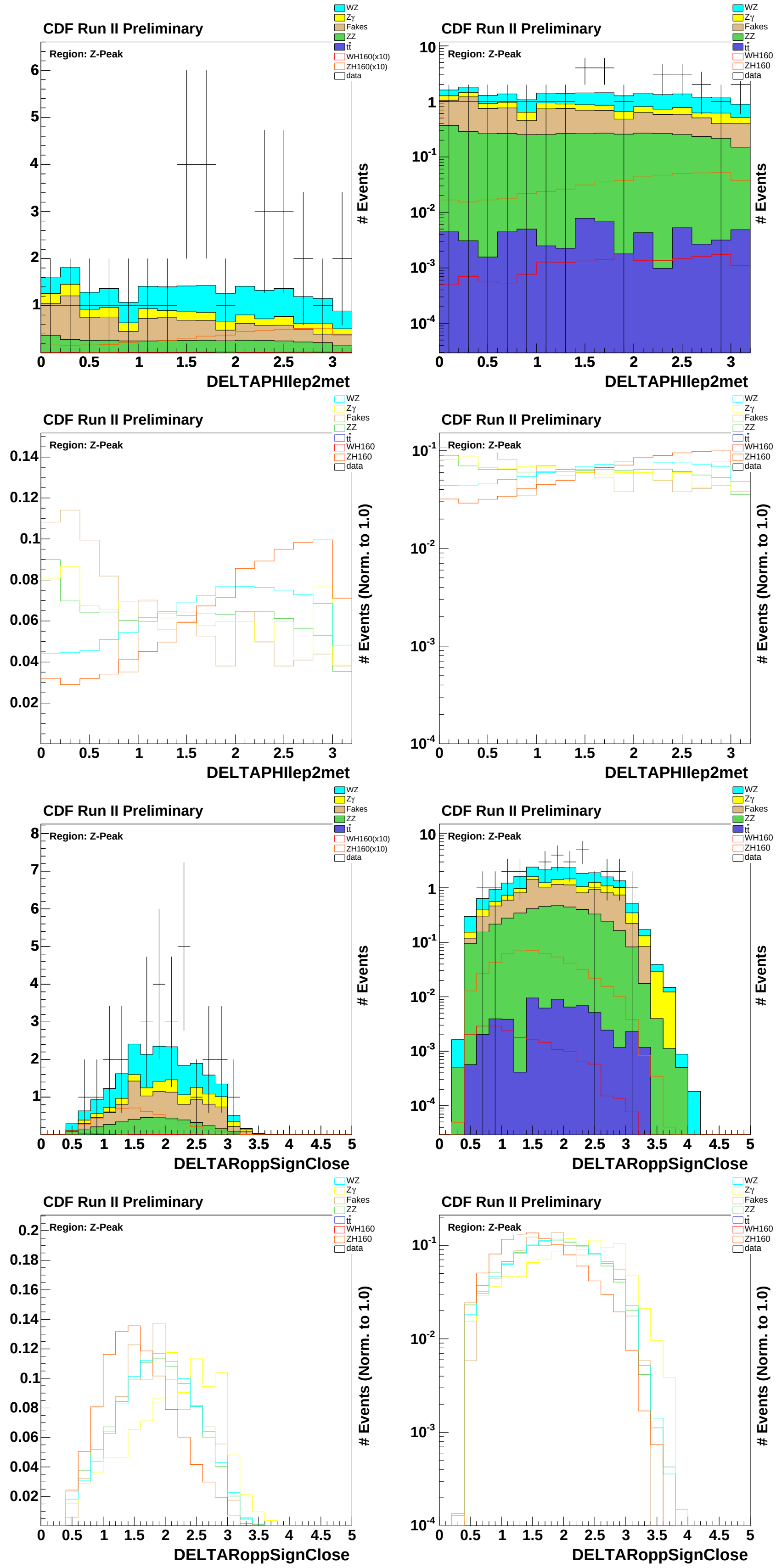

Figure 21: *InZPeak* Signal Region (NJet $\neq 0$): $\Delta\phi$(Lep2,$\not\!\!E_T$), ΔR b/w Opp. Sign Close Leptons.

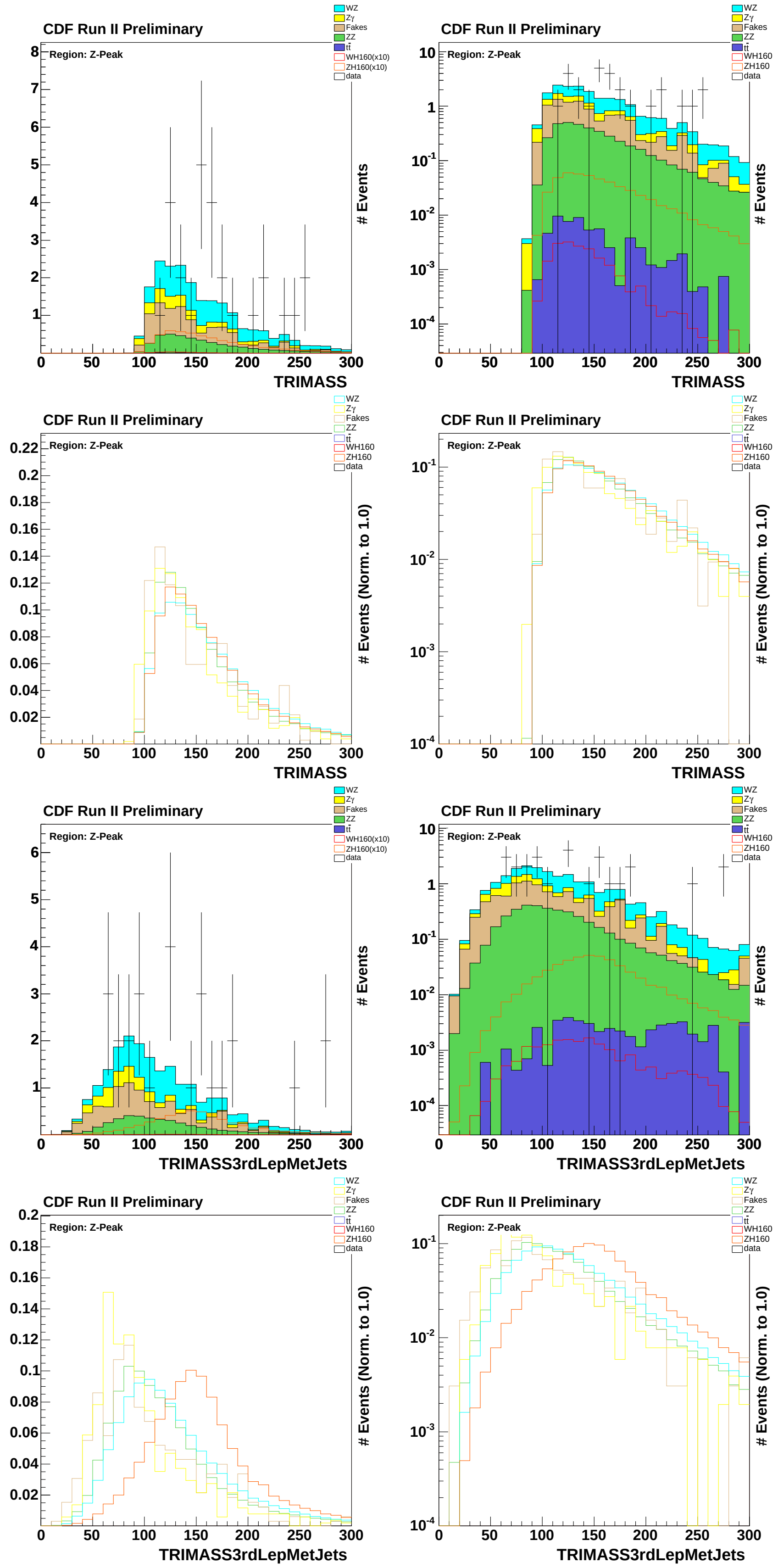

Figure 22: *InZPeak* Signal Region (NJet $\neq$ 0): Trilepton Invariant Mass, Inv. Mass(Lep3,$\not\!\!E_T$,Jets).

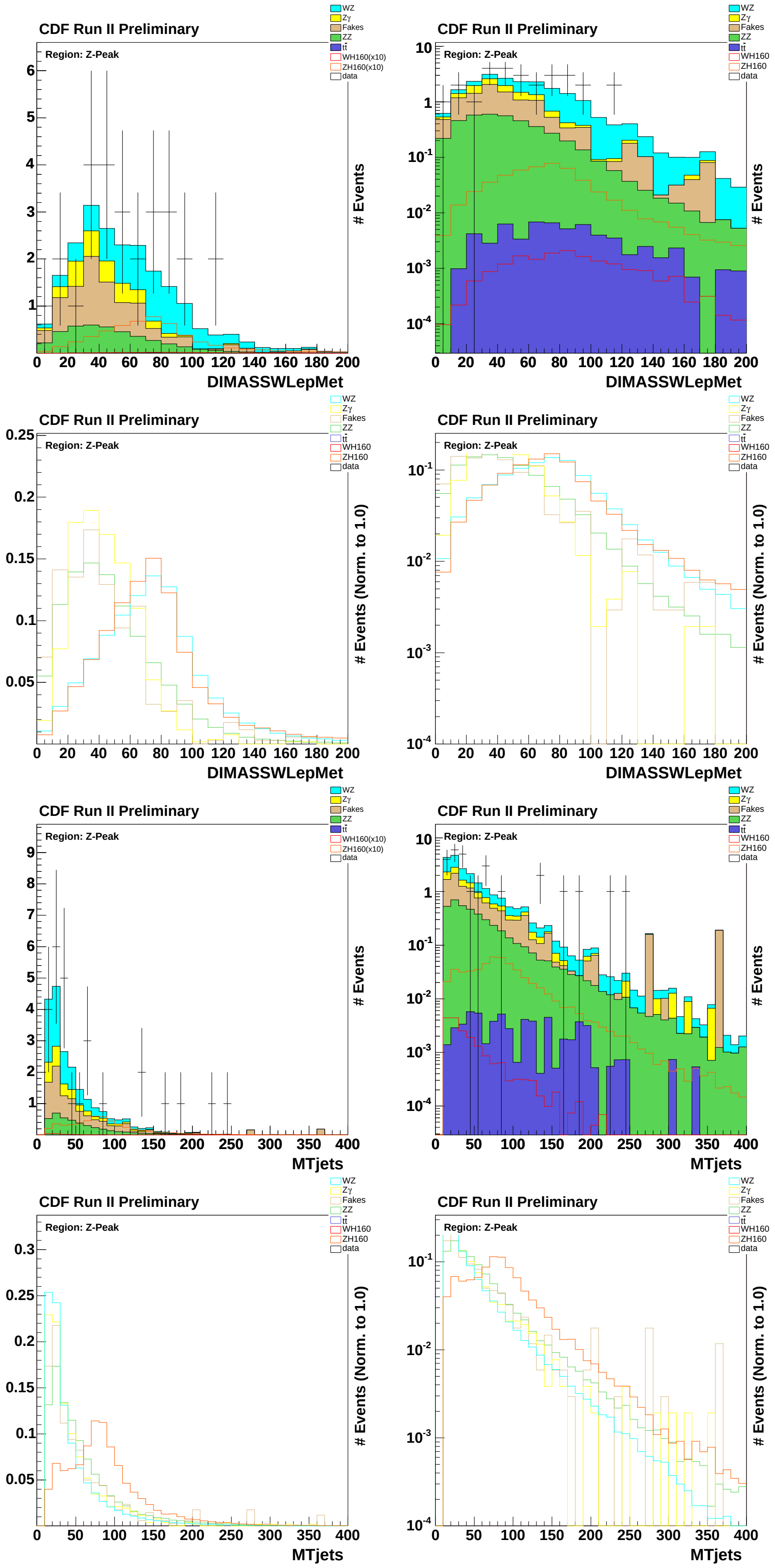

Figure 23: *InZPeak* Signal Region (NJet $\neq 0$): Dimass(W-Lep,$\not\!\!E_T$), m_T Jets.

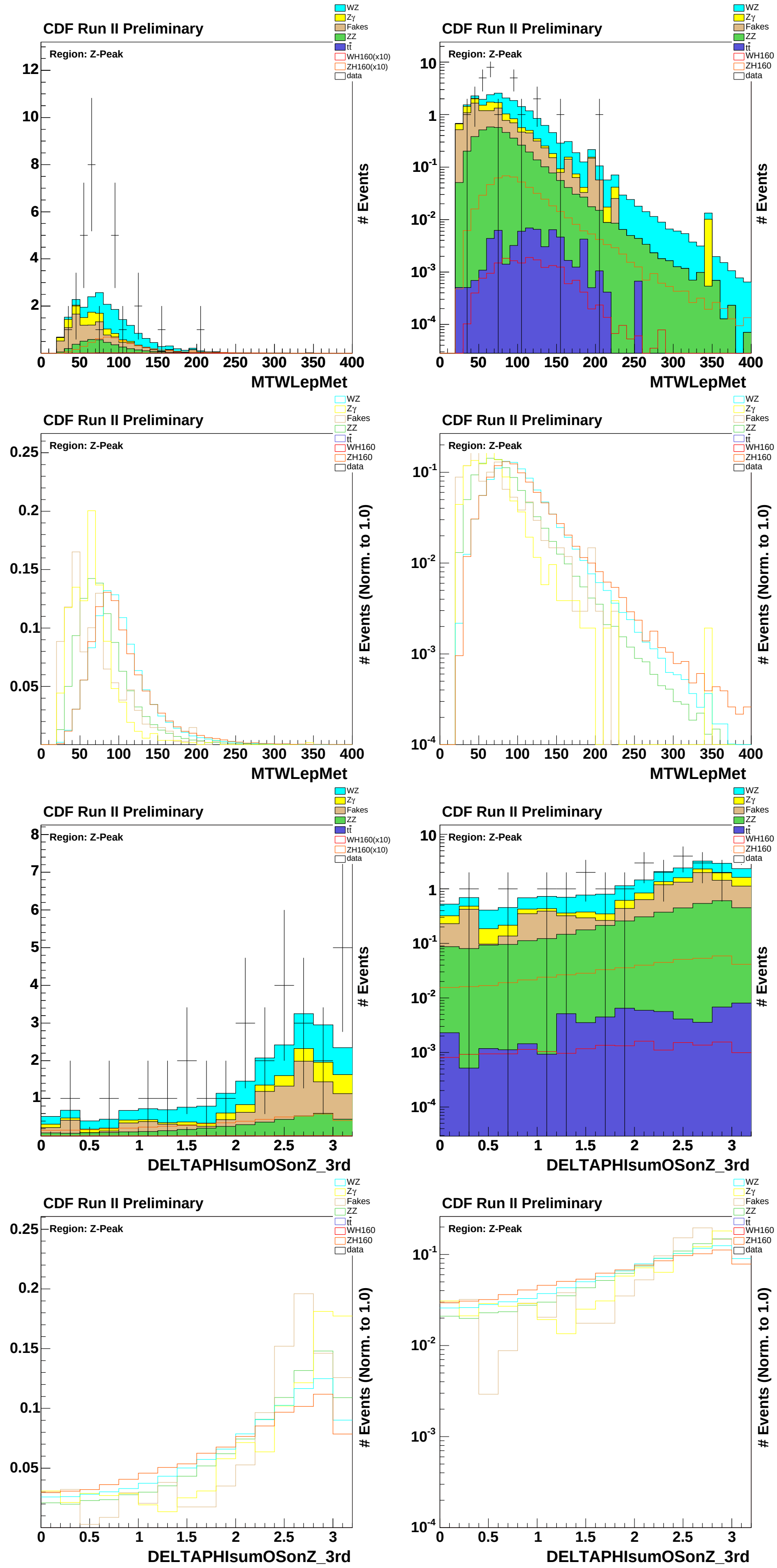

Figure 24: *InZPeak* Signal Region (NJet $\neq$ 0): $m_T(W\text{-Lep},\not{E}_T)$, $\Delta\phi(Z\text{-Leptons},W\text{-Lepton})$.

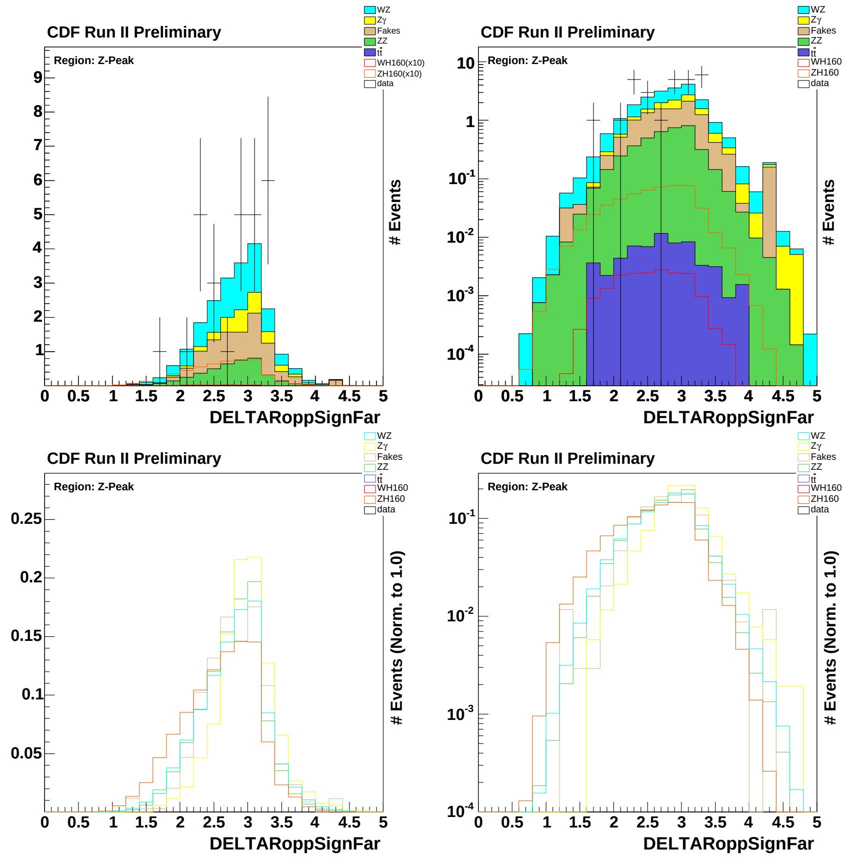

Figure 25: *InZPeak* Signal Region (NJet $\neq 0$): ΔR Opp. Sign Far Leptons.

5.2 Appendix: Input Variables in Control Regions

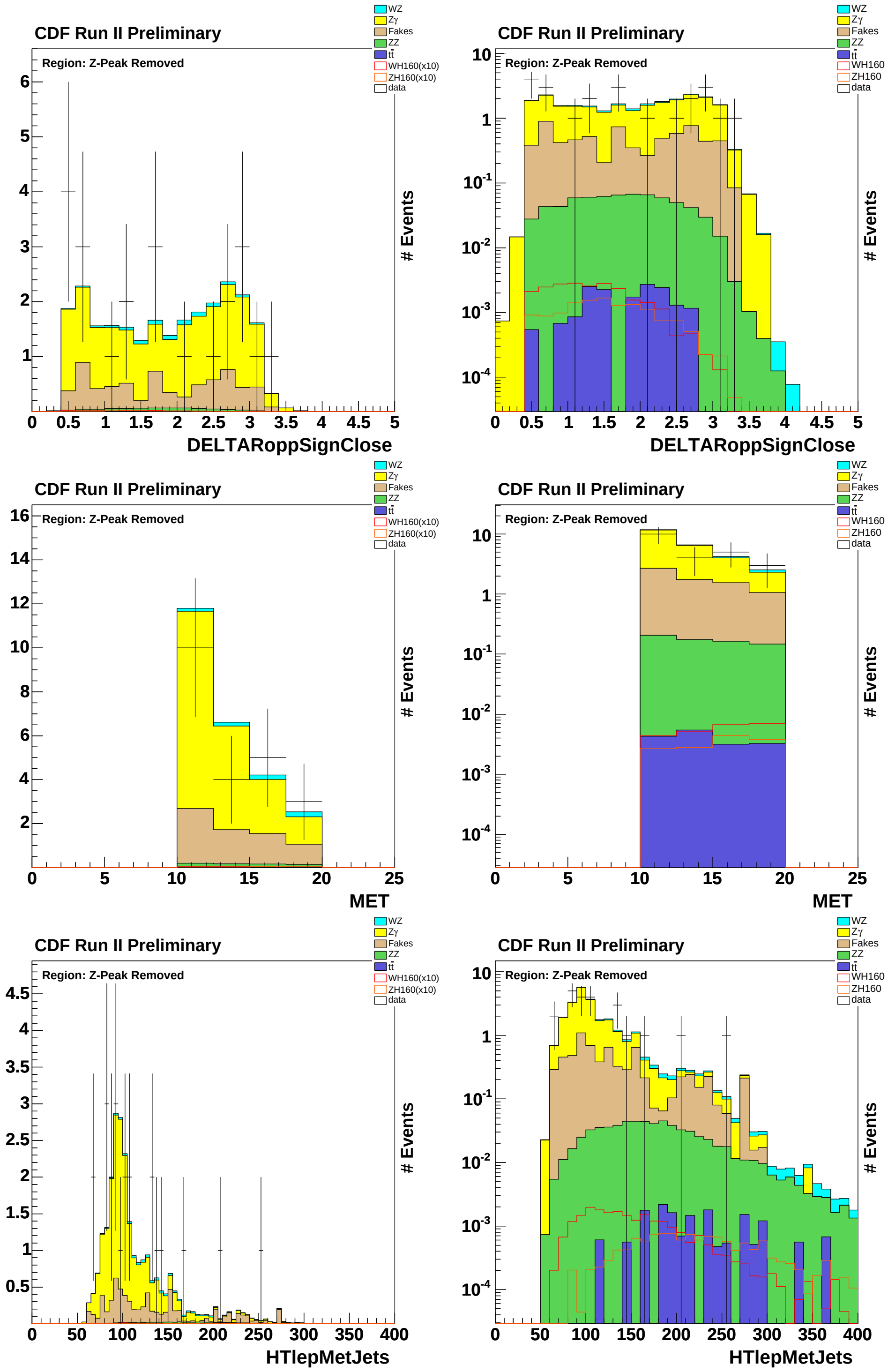

Figure 26: *NoZPeak* Control Region (10.0 GeV < $\not\!\!E_T$ < 20.0 GeV): ΔR Opp. Sign Close Leptons, $\not\!\!E_T$, H_T(all leptons, $\not\!\!E_T$, all jets).

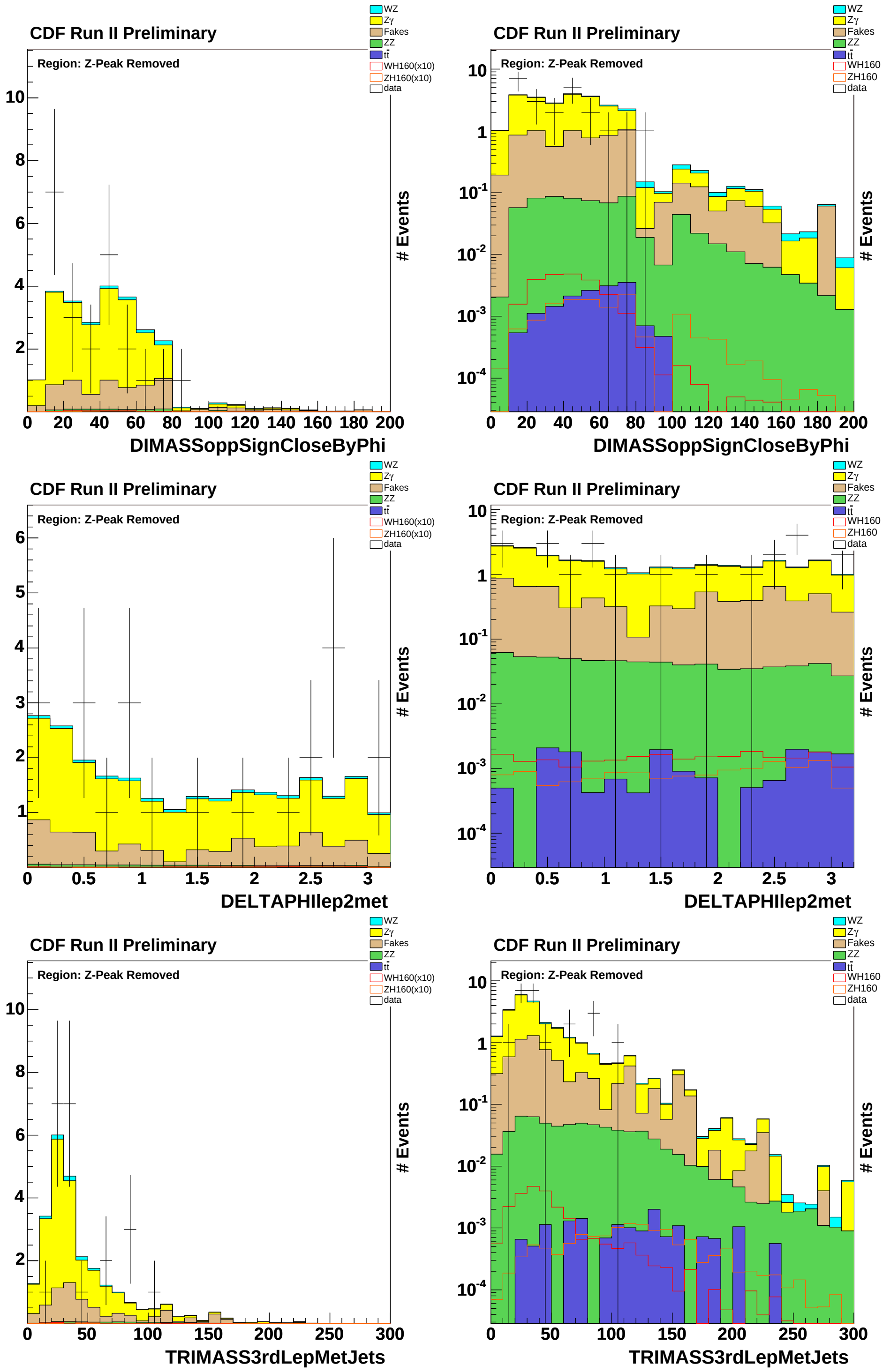

Figure 27: *NoZPeak* Control Region (10.0 GeV < $\not\!\!E_T$ < 20.0 GeV): Dimass Opp. Sign Leptons (closer pair in ϕ), $\Delta\phi$ between the 2$^{\text{nd}}$ lepton and $\not\!\!E_T$, Inv. mass of the 3$^{\text{rd}}$ lepton+ $\not\!\!E_T$+Jets.

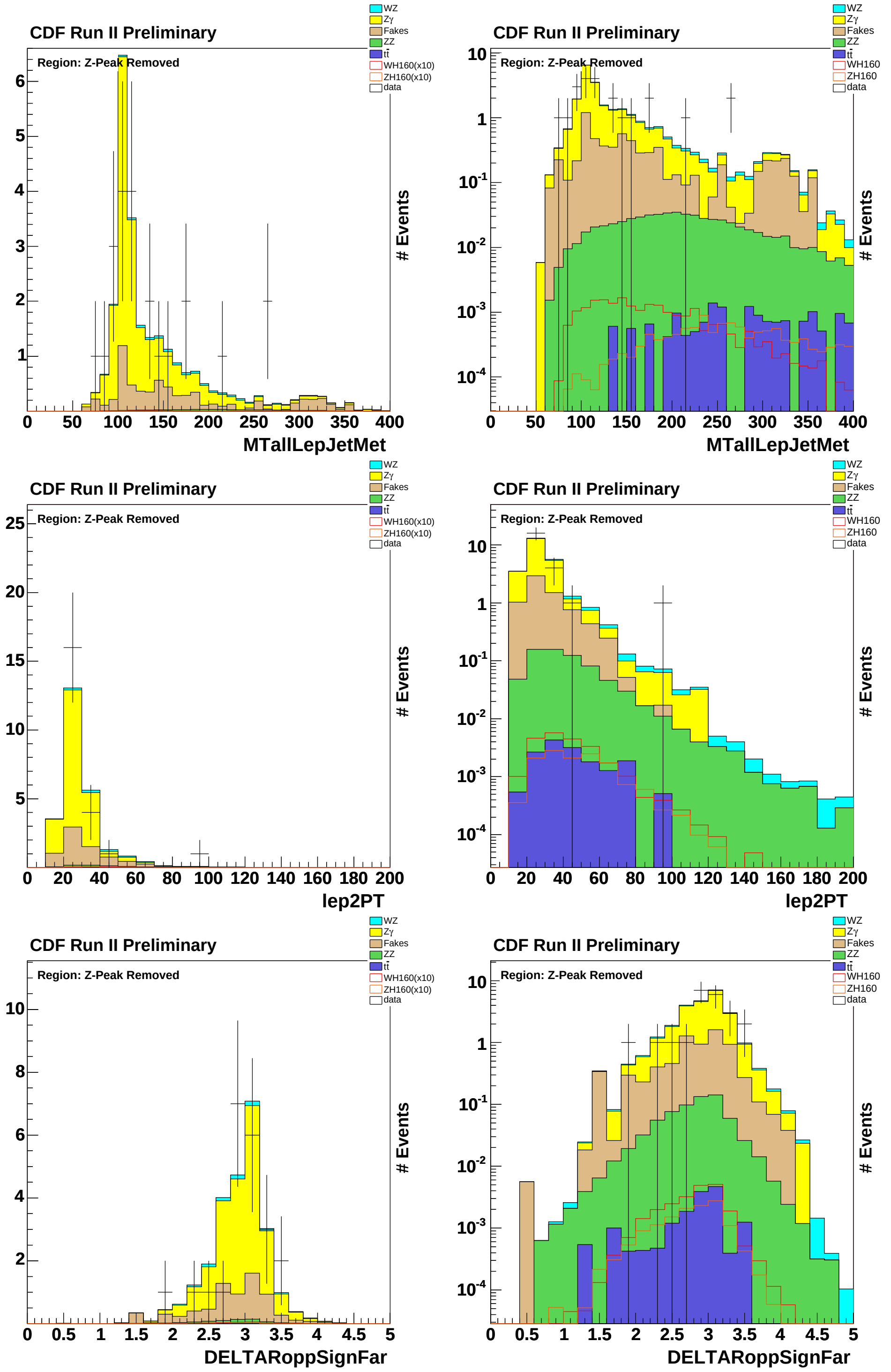

Figure 28: *NoZPeak* Control Region (10.0 GeV < $\not{E}_T$ < 20.0 GeV): m_T(Leptons,$\not{E}_T$,Jets), p_T of 2$^{\text{nd}}$ Lepton, ΔR Opp. Sign Far Leptons.

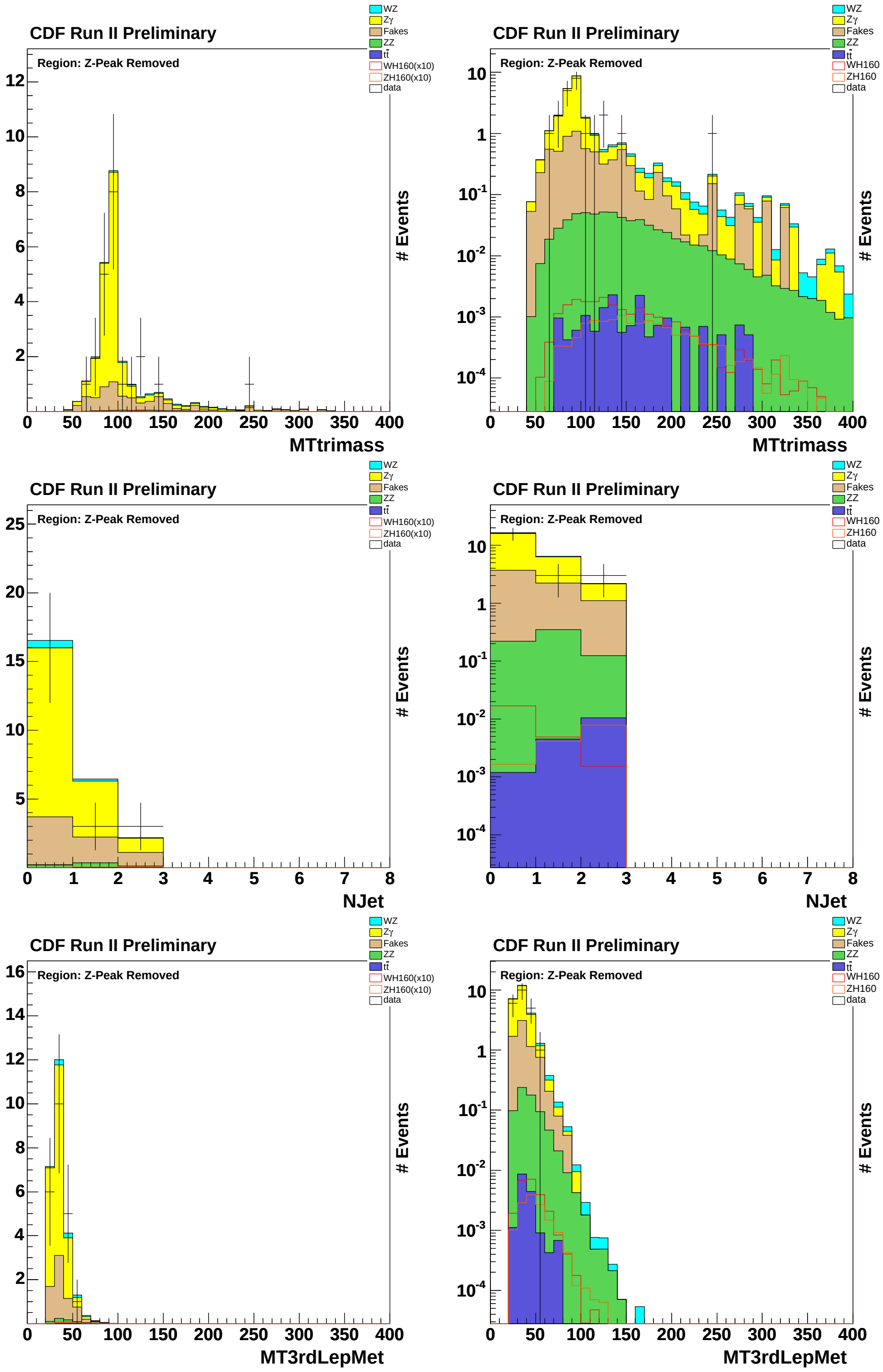

Figure 29: *NoZPeak* Control Region (10.0 GeV < $\not{E}_T$ < 20.0 GeV): m_T Trilepton Mass, NJet, m_T (Lep3, $\not{E}_T$).

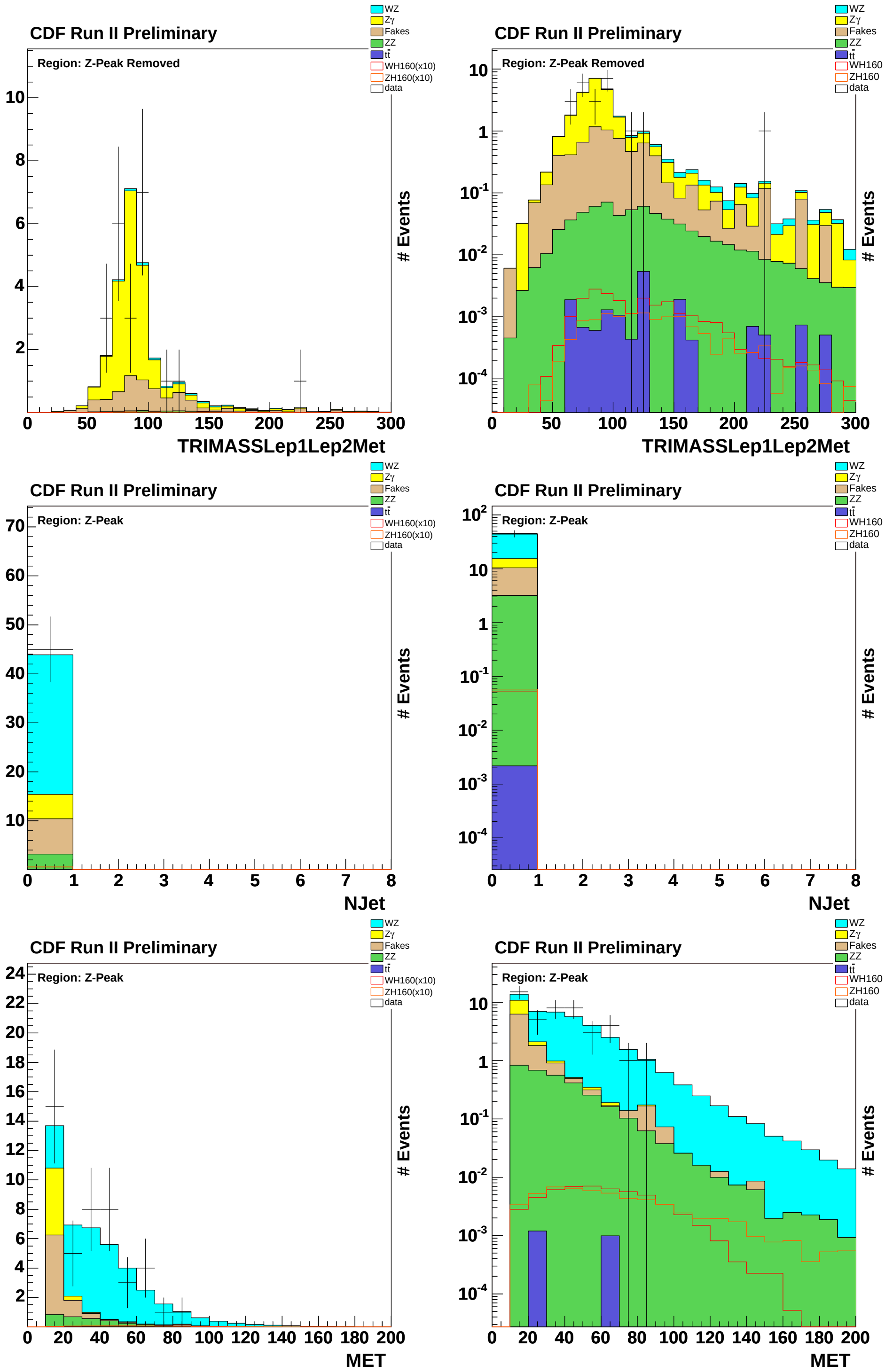

Figure 30: *NoZPeak* Control Region (10.0 GeV < $\not\!\!E_T$ < 20.0 GeV): Inv. Mass(Lep1,Lep2,$\not\!\!E_T$). *InZPeak* Control Region (NJet=0): NJet, $\not\!\!E_T$.

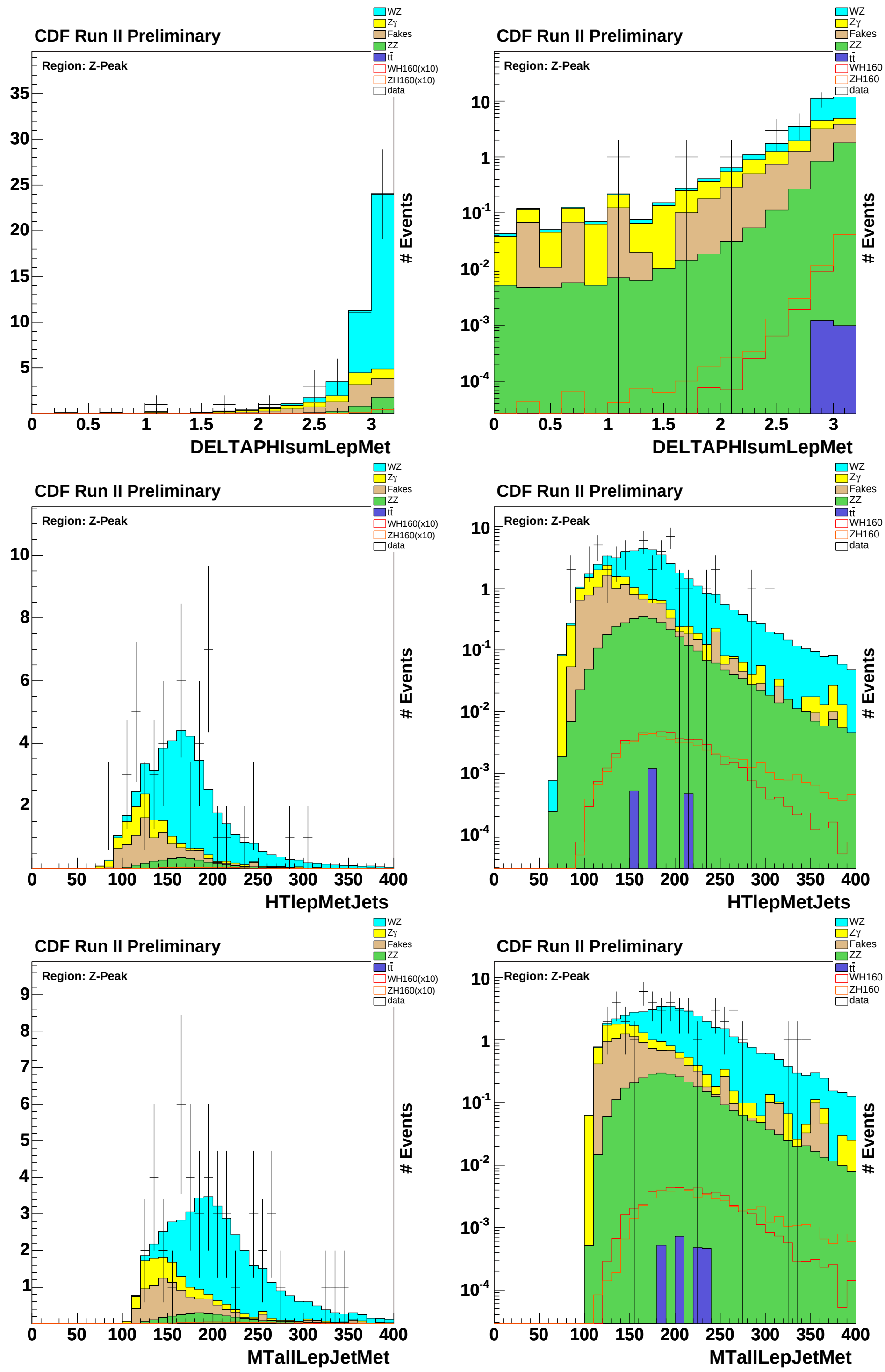

Figure 31: *InZPeak* Control Region (NJet=0): $\Delta\phi(\text{Leptons},\not\!\!E_T)$, $H_T(\text{Leptons},\not\!\!E_T,\text{Jets})$, $m_T(\text{Leptons},\not\!\!E_T,\text{Jets})$

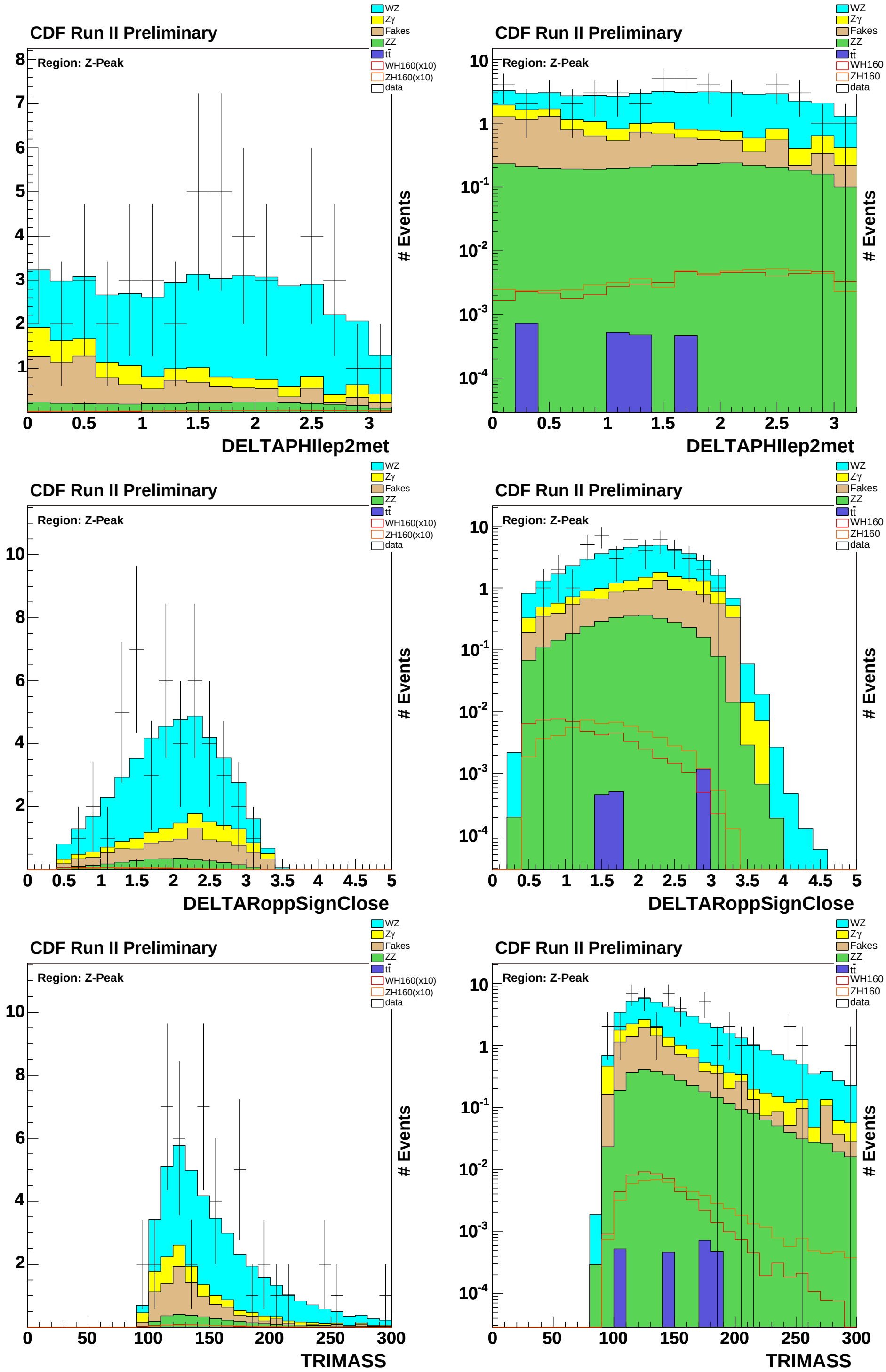

Figure 32: *InZPeak* Control Region (NJet=0): $\Delta\phi(\text{Lep2},\not\!\!E_T)$, ΔR b/w Opp. Sign Close Lept, trilepton invariant mass.

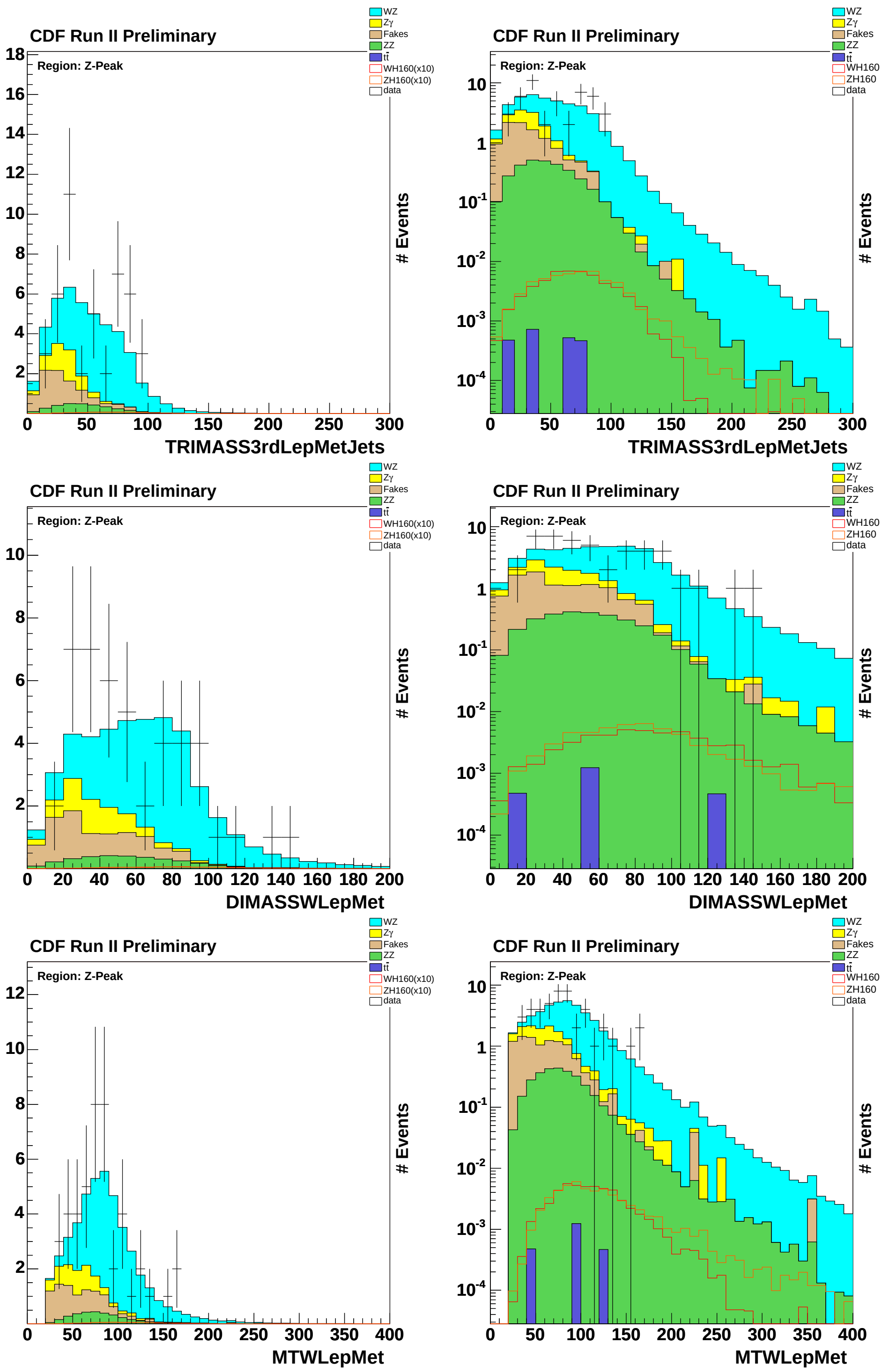

Figure 33: *InZPeak* Control Region (NJet=0): Inv. Mass(Lep3,$\not\!\!E_T$,Jets), Dimass(W-Lep,$\not\!\!E_T$), m_T(W-Lep,$\not\!\!E_T$).

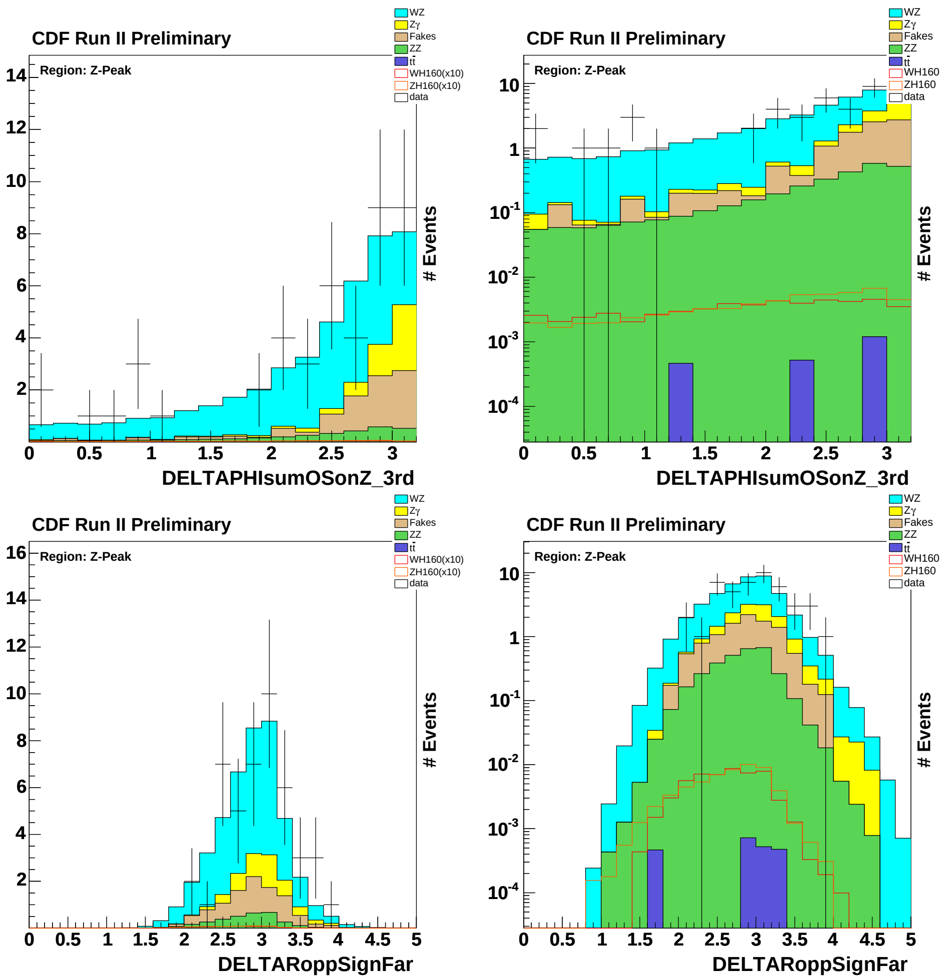

Figure 34: *InZPeak* Control Region (NJet=0): $\Delta\phi(Z\text{-Leptons},W\text{-Lepton})$, ΔR Opp. Sign Far Leptons.