The Search for VH $\rightarrow$ VWW Standard Model Higgs Production in the Trilepton Signature with 5.9fb^{-1}

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Collider Detector at Fermilab

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Summary

1. Standard Model & The Higgs Boson
   - The Standard Model of Particle Physics
   - Symmetries in the Standard Model
   - EW Symmetry Breaking & the Higgs
   - Higgs & Non-zero Mass
   - Trilepton Higgs Signal
2. Tevatron & Collider Detector at Fermilab (CDF)
   - Tevatron
   - CDF
3. The Experimental Data
4. The Trilepton Analysis in $H \rightarrow WW$
   - Improved Acceptance
   - Events in the $H \rightarrow WW$ Trilepton Regions
   - NeuroBayes Neural Network
   - Statistics and Confidence Level Limits
   - Results
5. Conclusion

A defense presented in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
(Dept. of Physics)
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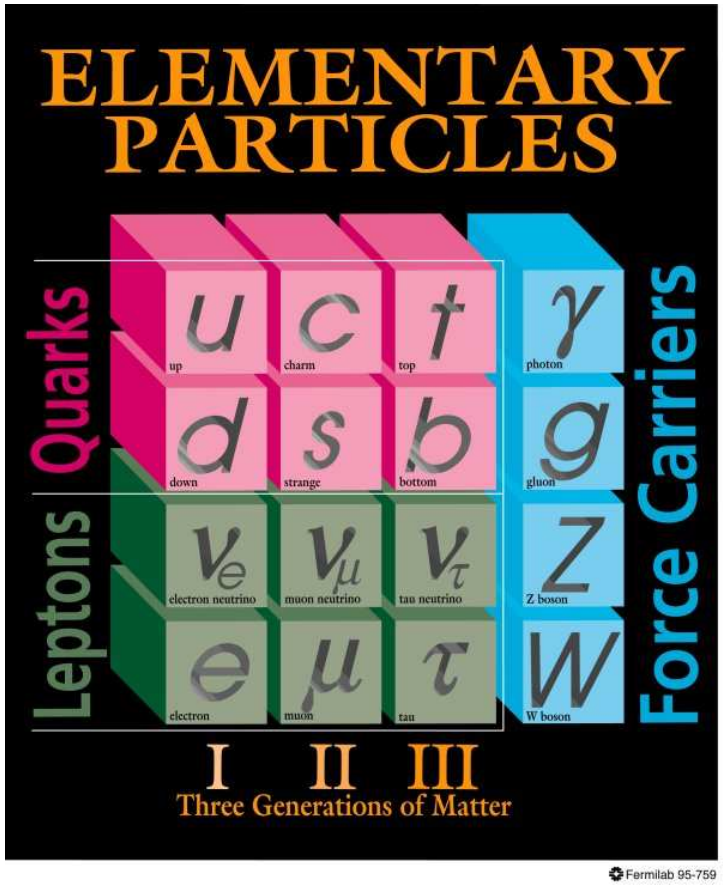
UNIVERSITY OF WISCONSIN-MADISON
JASON MICHAEL NETT

The Known Universe

- The *known universe* is composed of the fundamental particles of the Standard Model of particle physics.
- One particle is missing from this table: the Higgs Boson



The Standard Model's Structure

The Standard Model is based on the gauge group formed from the product space of three unitary gauge groups:

$$\underbrace{SU(3)_C}_{\text{QCD}} \times \underbrace{SU(2)_L \times U(1)_Y}_{\text{electroweak}}$$

- "C" refers to color charge of QCD (not discussed here)
- "L" refers to left-handed weak doublets of $SU(2)$
- "Y" refers to right-handed weak singlets of $U(1)$

Standard Model Forces

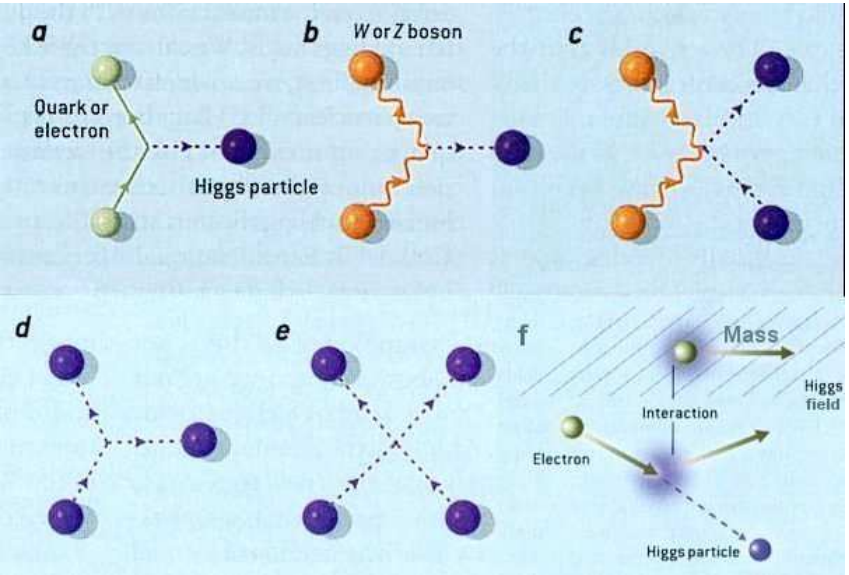
The Standard Model described 3 (of 4) forces of nature: electromagnetism, weak, strong–all arise from symmetries of the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$

- EM, *photons* (γ): The gauge boson of the $SU(2)_L \times U(1)_Y$ group which manifests as the electromagnetic force.
- Weak, W^+, W^-, Z^0: The gauge bosons of the $SU(2)_L \times U(1)_Y$ group which manifest as the weak force.
- Strong, *gluons* (g): The gauge bosons of the $SU(3)_C$ group which manifest as the strong force.

The Unknown Part of the Known Universe

The Higgs mechanism was postulated to resolve several problems:

- origin of spontaneous electroweak symmetry breaking
- symmetry breaking generates weak boson and fermion masses
- also important for quark mixing



(The Higgs boson was postulated in 1964 separately by Peter Higgs [5, 6]; by Francois Englert and Robert Brout [2]; and by Gerald Guralnik, C.R. Hagan, and T.W.B. Kibble[4])

Lagrangians: The Foundation

In a Q.F.T., a "lagrangian density" is postulated with the form:

$\mathcal{L}(\phi, \partial_\mu \phi) =$ Kinetic Energy (density) $-$ Potential Energy (density)

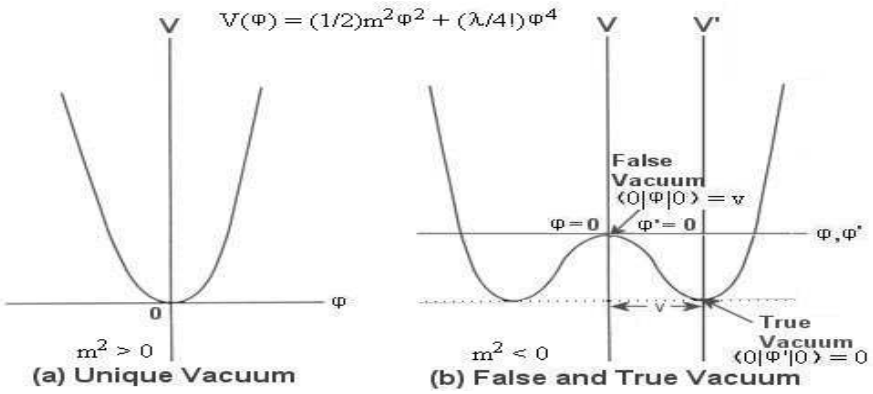
Symmetries of the Lagrangian

BUT, we are concerned with symmetries of the Lagrangian density here.
First, a simple example; then the real deal:

Definition

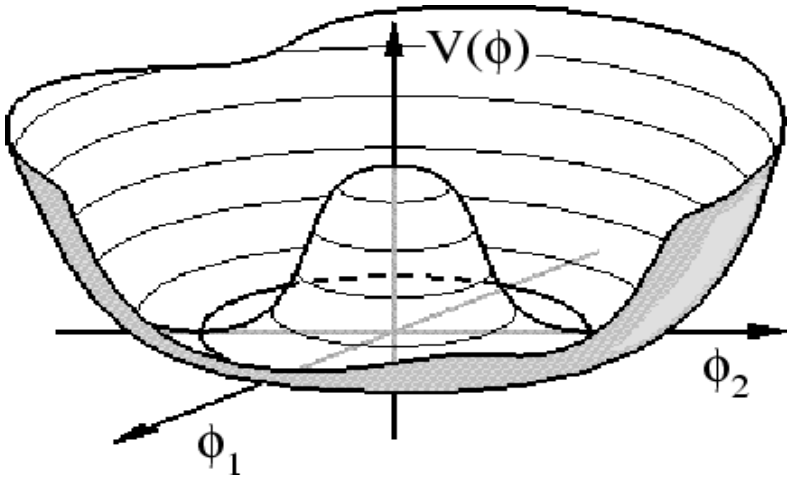
Single Complex Scalar ('no spin') Particle Universe: Consider a single scalar complex particle field $\phi(x) = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$. It's lagrangian is

$$\mathcal{L} = \underbrace{(\partial_\mu \phi)^\dagger (\partial^\mu \phi)}_{\text{Kinetic}} - \underbrace{m_0^2 \phi^\dagger \phi}_{\text{rest mass}} - \underbrace{\frac{1}{4}\lambda \left(\phi^\dagger \phi\right)^2}_{\text{Interaction}}$$



Symmetries of the Lagrangian

- Higgs physics is a *broken* symmetry: $m^2 < 0$.
- Finding particle states:
  - Set ϕ to minima
  - Compute quantized oscillations from minima
  - Massive Particles: Oscillations "up" the potential well
  - Massless Particles: Oscillations "within" minima manifold
- *Problem:* Which point on minima manifold?!



Symmetries of the Lagrangian

By the circular symmetry of the minima manifold, choose:

$$\phi(x) = \underbrace{\frac{v + h(x)}{\sqrt{2}}}_{\text{Radial Perturbation}} \cdot \underbrace{e^{\frac{i}{v}\theta(x)}}_{\text{Angular Perturbation}}$$

$$v \equiv \text{Radius of minima manifold circle}$$

What does this choice do to the lagrangian?

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu h)^2}_{\text{Radial, Kinetic}} + \underbrace{\frac{1}{2}(\partial_\mu \theta)^2}_{\text{Angular, Kinetic}} - \underbrace{\frac{1}{2}m_0^2 h^2}_{\text{Radial, particle mass}} + \cdots + \text{interaction terms}$$

Result: Two particles, one massive Higgs-like and one massless.

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$U(1)$ Global & Local Symmetry

Definition

Recall that $U(1)$ is the group of rotations in the complex plane. Our lagrangian is invariant to *global* $U(1)$ transformtions ($\phi \to \phi' = e^{i\alpha}\phi$), but not to *local* $U(1)$ transformations ($\phi \to \phi' = e^{i\alpha(x)}\phi$).

- The lagrangian can be altered/repostulated to impose symmetry under local transformations
- *Why?* In nature, the forces appear to arise from insisting upon *local* gauge symmetry.
- *How?* Replace the derivative with a covariant derivative

Definition

To make the complex scalar particle lagrangian invariant to local $U(1)$ gauge transformations replace the derivative with a *covariant derivative*:

$$\partial_\mu \to D_\mu = \partial_\mu + iqA_\mu$$

Hence, we introduce a new *gauge* field A_μ.

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Imposing local $U(1)$ gauge invariance yields:

$$\mathcal{L} = [(\partial^\mu + iqA^\mu)\phi]^\dagger [(\partial_\mu + iqA_\mu)\phi] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\lambda(\phi^\dagger\phi)^2 - m_0^2(\phi^\dagger\phi)$$

$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu$$

New field A_μ, precursor of the photon!

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EW Symmetry Breaking & the Higgs

Recap

- Assuming $m^2 < 0 \Rightarrow$ broken symmetry in the potential changes particle spectrum
- Imposing *local* gauge invariance $\Rightarrow$ new interacting "gauge field" (precursor of force carrying particles)

For Higgs in electroweak physics

- Assuming $m^2 < 0$ lead to more complicated minima manifold and particle spectrum.
- Instead of $U(1)$ we have $SU(2) \times U(1)$, leading to four gauge fields: photon (EM) and $W^{\pm}, Z$ bosons (weak force)
- Assuming spin $1/2$ fermions rather than spinless complex scalar particles.

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Massive W-bosons and Higgs Interaction

Key Point: Higgs Mechanism leads to two terms

$$\underbrace{m_W^2 W_\mu^\dagger W^\mu}_{W\text{-boson mass}} + \underbrace{g m_W W_\mu^\dagger W^\mu H}_{W\text{-Higgs interaction}}$$

Meaning:

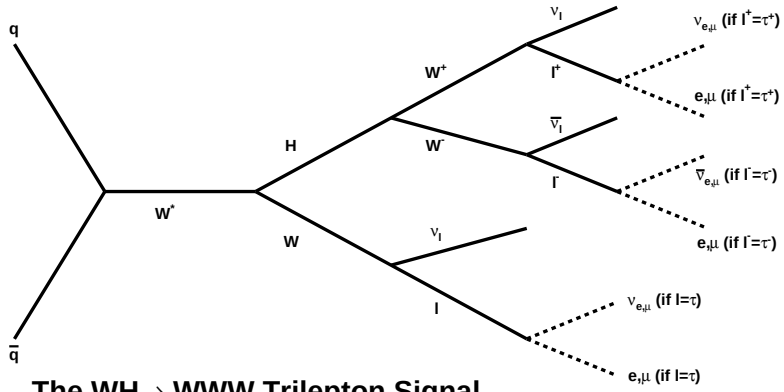
- W has nonzero mass
- High mass of W related to strong coupling with Higgs
- We look for the Higgs decaying to WW

Higgs Also Important for:

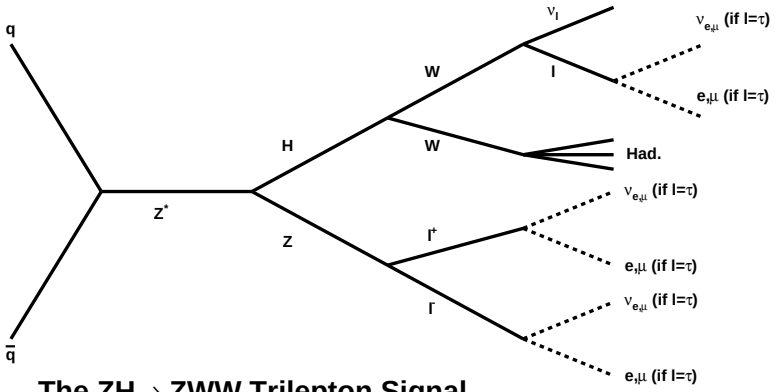
- Nonzero fermion masses
- Quark mixing

Trilepton Higgs Signal

That's why we need it. Where do we find it?



The WH→ WWW Trilepton Signal

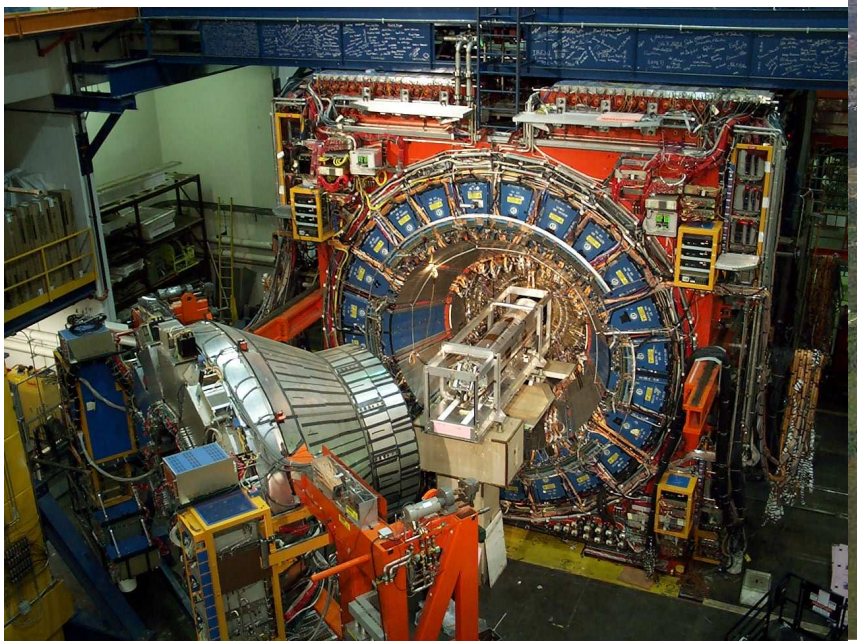


The ZH→ ZWW Trilepton Signal

"Associated Production with a Weak Vector Boson"

Experiment

How do we find it?



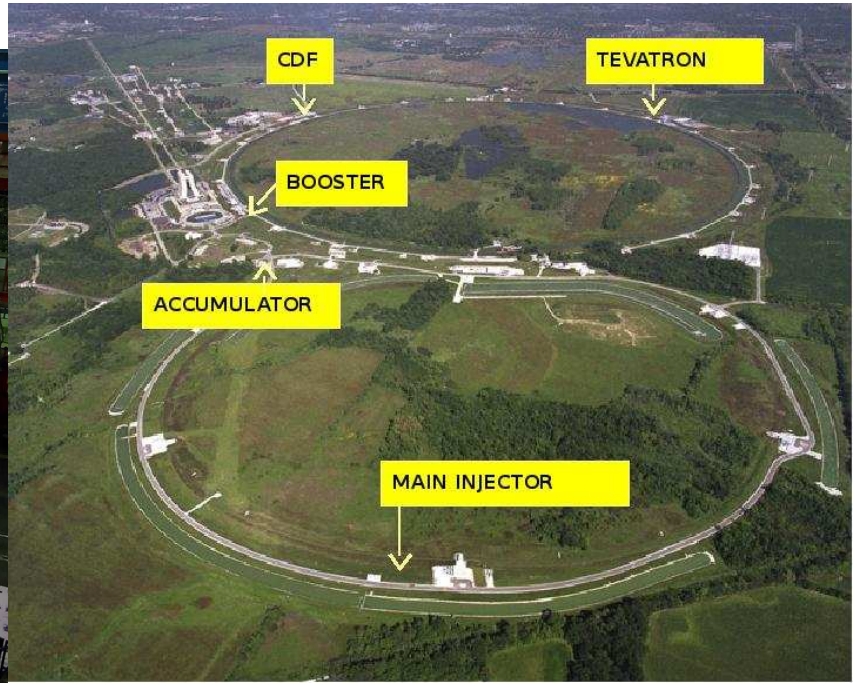
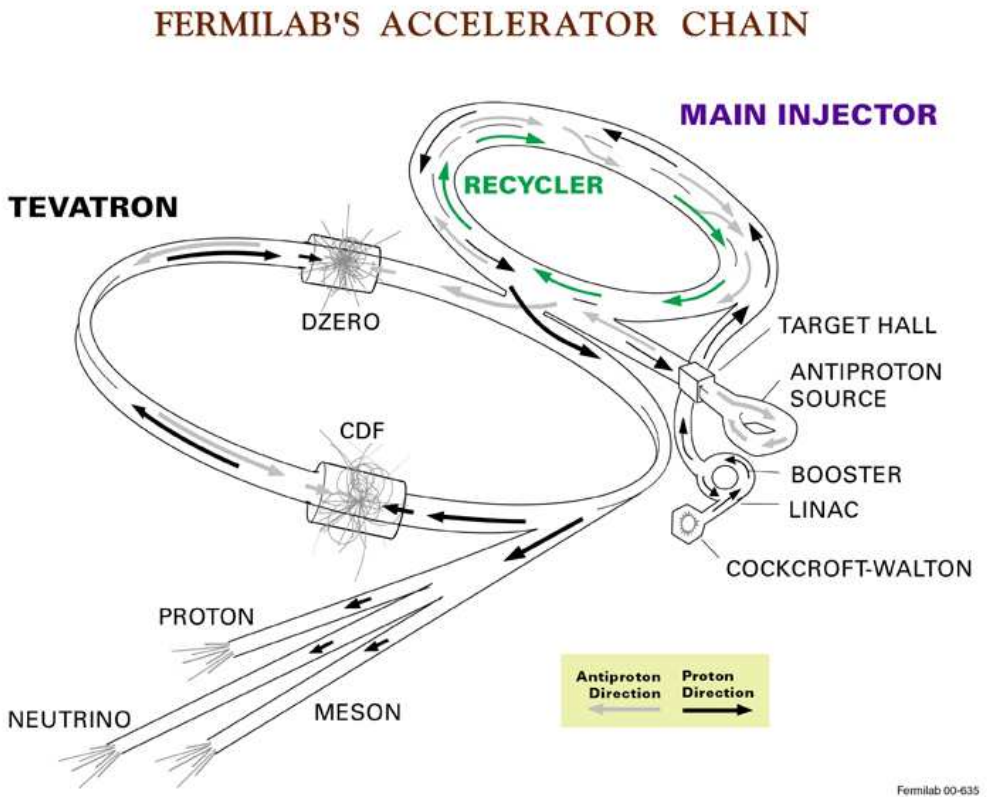


Figure: CDF (left) & Tevatron (right)

Tevatron: Proton-Antiproton Collider

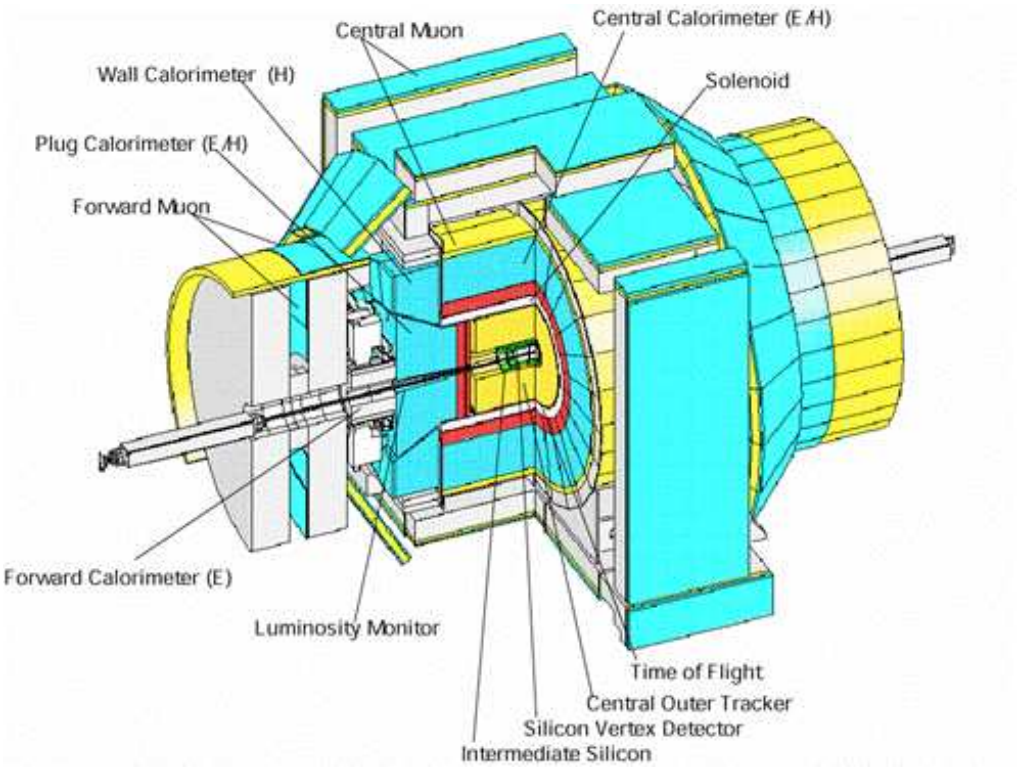
1. Cockcroft-Walton: H^- gas ions accelerate to 750 keV.
2. LINAC: Acc. to 400 MeV, discrete bunches, e^- stripped to protons only.
3. Booster: First synchrotron (circular acc.) boosts to 8 GeV.
4. Main Injector: Larger synchrotron. Boost some p to 150 GeV, use other to form $\bar{p}$'s.
5. Tevatron: Parallel circular beams of protons and anti-protons, colliding at CDF and D0 experiments.



CDF: Collider Detector

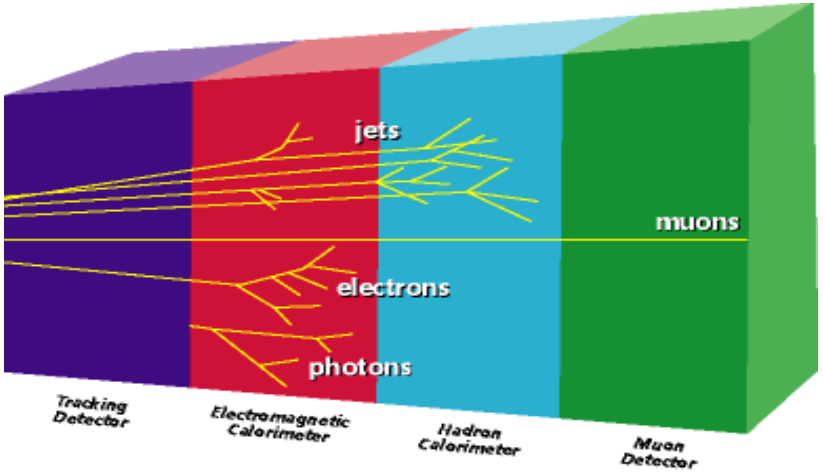
CDF has many components, but we are most interested in LEPTONS

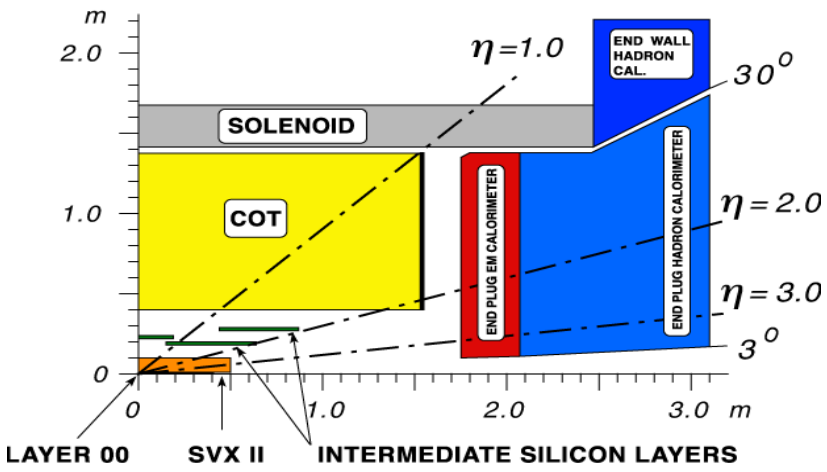
- Tracking: Trace paths of charged particle, high-brow game of 'connect the dots'
- Calorimeters: Absorb high energy particles, measure the energy.
- Muons: Only stuff to punch through everything, so extra track detectors on outer shell.



CDF: High Energy Objects

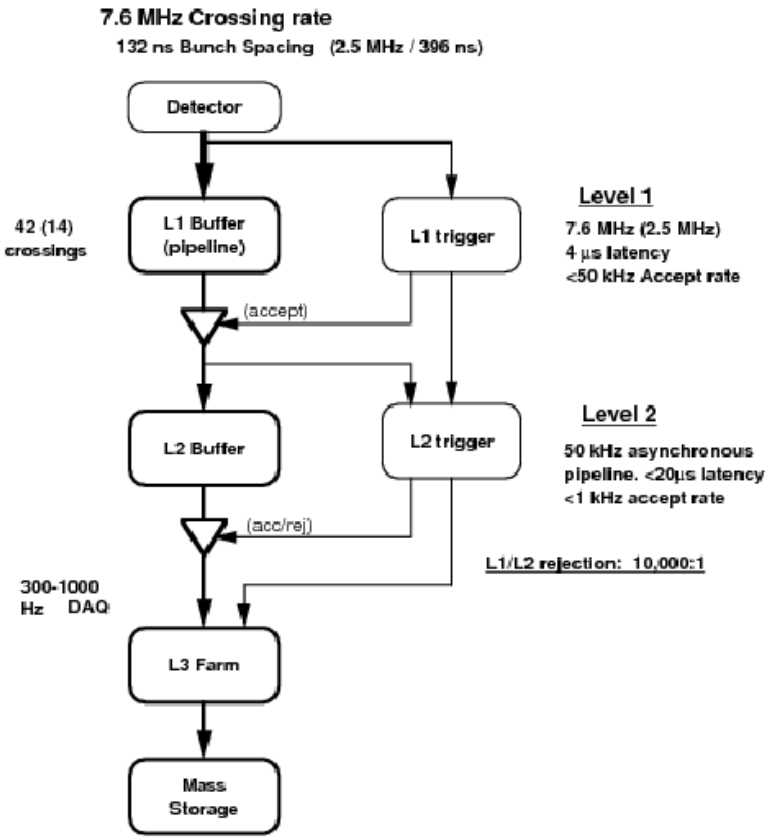
- Leptons
  - Electrons: Tracking + EM Calorimeter
  - Muons: Tracking + "Muon Stub"
- Jets: Tight "spray" of particles, usually from QCD–EM & Hadronic Calorimeter
- Photons: No Track + EM Calorimeter, (*not used in this analysis)*
- Missing Energy ($\not{E}_T$): Neutrinos are not detected, $\not{E}_T$ inferred from conservation of energy in plane transverse to beam





Filter out the junk

- Collision frequency: 2.5 MHz.
- 3-Lepton events are very rare: $\sim$ 100 total after many years.
- Filter: Three-level "trigger" system records only interesting collisions
  - Level 1: 25 kHz
  - Level 2: 800 Hz
  - Level 3: 100 Hz



Triggers & Datasets

Triggers–or "Datasets"–Used In This Analysis

- **Central Electrons** *Travel* $\sim$ *perpendicular to beamline*
- **Central Muons** (CMUP, CMX, MUON_CMP_PHIGAP)
- **Forward Electrons** (MET_PEM)*Travel* $\sim$ *small angle to beamline*

Intro. to $H \to WW$

Experimental Higgs search split into two groups:

- Low Higgs Mass Search:
  - $(114 < m_H \lesssim 135\ \mathrm{GeV}/c^2)$
  - $H \to b\bar{b}$ "Heavy quark decay"
- High Higgs Mass Search:
  - $(135 \lesssim m_H < 200\ \mathrm{GeV}/c^2)$
  - $H \to WW$ "Vector boson decay"
  - $gg \to H \to WW$ is strongest Higgs production, so previously studied only 2-lepton events.
  - **WE NOW ADD**

$$VH \to VWW \to \text{'3-leptons} + \not{E}_T\text{'}$$

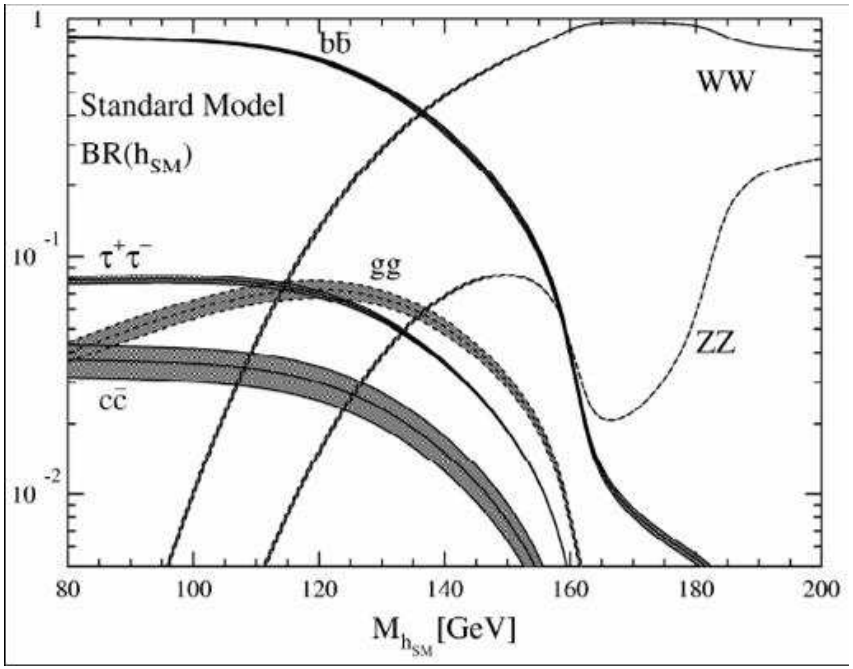


Figure: Standard Model branching ratios for the Higgs boson at the Tevatron as computed by the HDECAY algorithm [1].

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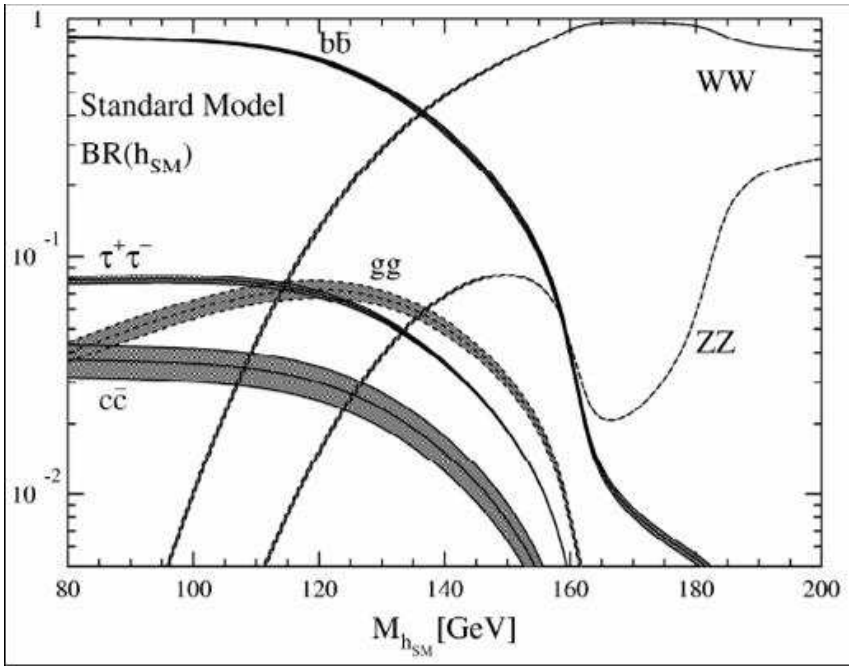

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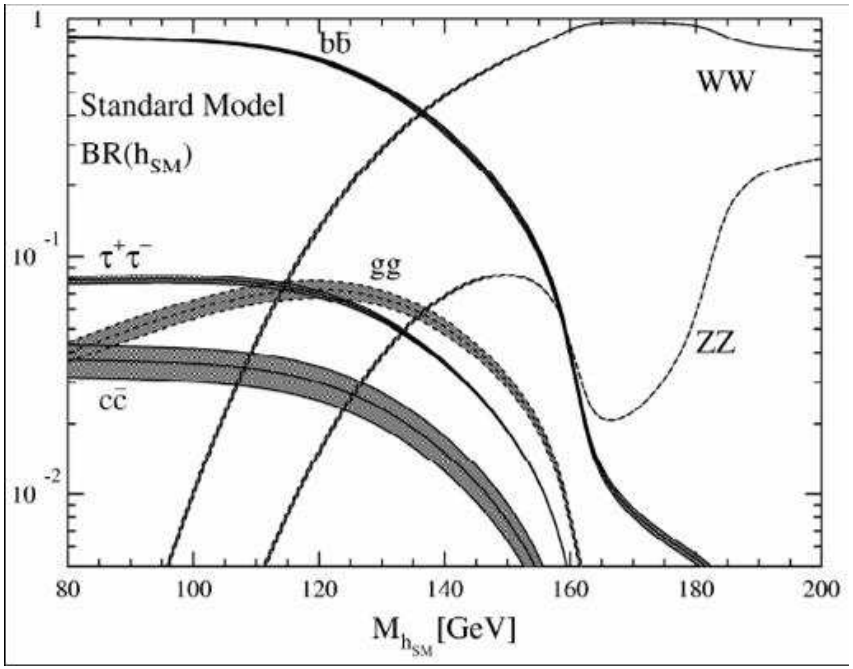

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Improved Acceptance

Based purely on cross sections (effectively the production rate) and branching ratios (decay rates),how much will trileptons add?

UNITS:

- Cross Section ("barns"): Defined "10^{-24} cm^2"–Probability of producing interaction b/w colliding p and $\bar{p}$.
- Luminosity ("$\#/(cm^2 \cdot s)$"): Number of particles crossing a unit of area per time.
- Data amount = Integrated luminosity ("barns^{-1}"): Number of particles that have crossed a unit of area over a period of time

Events

$$\text{Produced} = \text{XSec}\left(10^{-24}\text{cm}^2\right) \cdot \text{I.L.}\left(\frac{1}{10^{-24}\text{cm}^2}\right) = \text{XSec(femtobarn)} \cdot \text{I.L.}\left(\frac{1}{femtobarn}\right)$$

Improved Acceptance

Based purely on cross sections (effectively the production rate) and branching ratios (decay rates),how much will trileptons add?

- $\sigma_{\text{ggH165}} \cdot \mathcal{BR}(H \to WW) \cdot P(W \to l)^2 = 0.02653\text{pb}$
- $\sigma_{\text{WH165}} \cdot \mathcal{BR}(H \to WW) \cdot P(W \to l)^3 = 7.425 \times 10^{-4}\text{pb}$
- $\sigma_{\text{ZH165}} \cdot \mathcal{BR}(H \to WW) \cdot P(Z \to ll) \cdot 2 \cdot P(W \to l, W \to \text{had.}) = 8.054 \times 10^{-4}\text{pb}$
- *Expect $\sim$ 5.8% more events compared to dilepton events from gluon fusion*

Whittle down the Datasets

We have high energy lepton datasets, what do we do with them?

- Triggered datasets roughly identify high energy leptons, jets, and $\not{E}_T$
- Pass more sophisticated reconstruction cuts (see dissertation for details)
- Select 3-lepton events
- Identify Background Processes (produce signal-like signature)

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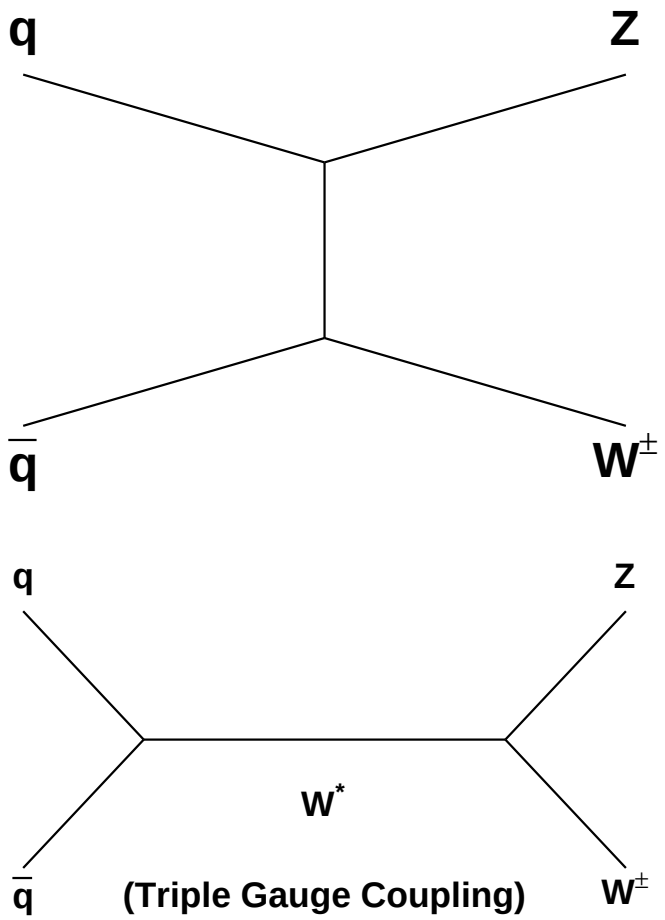
Background Overview

1. WZ Diboson
2. ZZ Diboson
3. Z+Jets: $Z \rightarrow ll$ +Small portion of events have a jet fake a 3rd lepton signature
4. $Z\gamma$: $Z \rightarrow ll$ +Small portion of events have the γ convert to $e\bar{e}$ pair for the 3rd lepton signature
5. $t\bar{t} \rightarrow Wb, W\bar{b}$

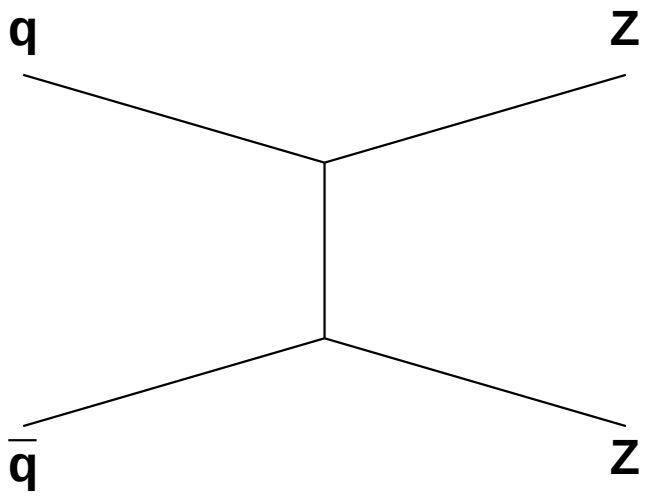
Background (1/5): *WZ*

- Only background to provide exactly 3 leptons $+\not{E}_T$
- Dominant background
- Modelled by monte carlo simulation



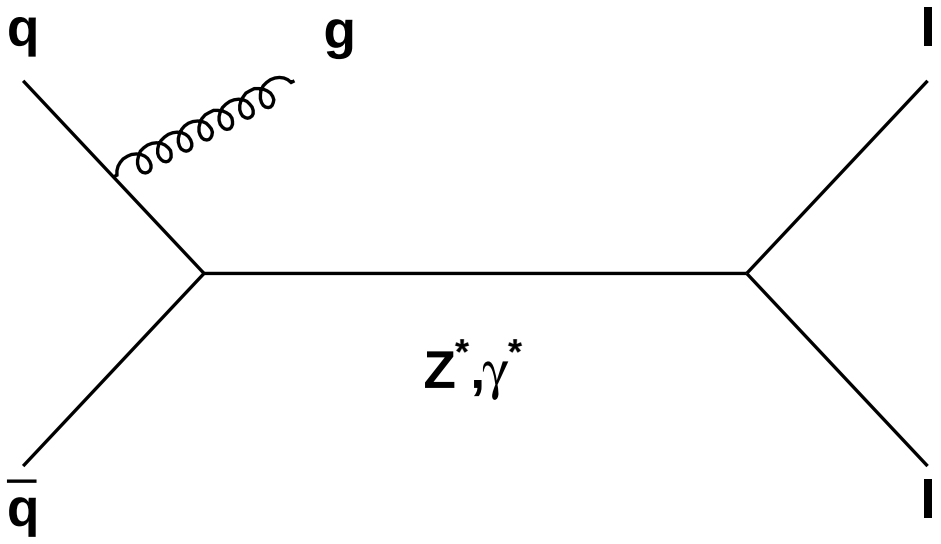
Background (2/5): *ZZ*

- Contributes from $ZZ \rightarrow llll$, with one not found ("reconstructed")
- A "lost" lepton counts towards $\not{E}_T$, so looks similar to *WZ*
- Modelled by monte carlo simulation



Background (3/5): $Z+$Jets

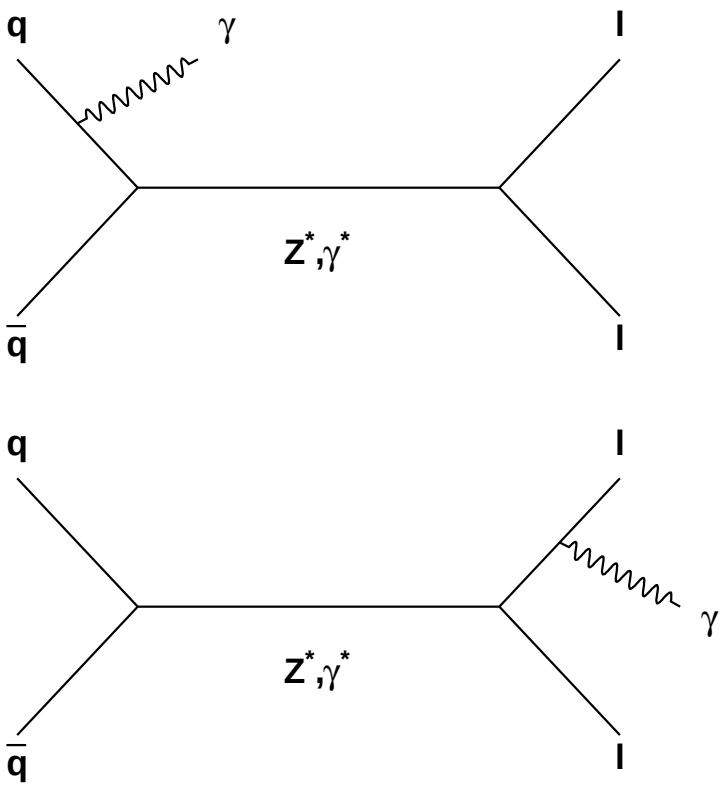
Drell-Yan ($Z \rightarrow ll$) w/ QCD jets, where a jet "fakes" a lepton signature w/ $\sim$ 1% to 5% prob., depending on p_T



- *NOT* simulated by monte carlo, estimated from jet data.
- *"fake rate"*$\approx$(# fully fake lepton I.D.)/(# could potentially fake lepton I.D.)

Background (4/5): $Z\gamma$

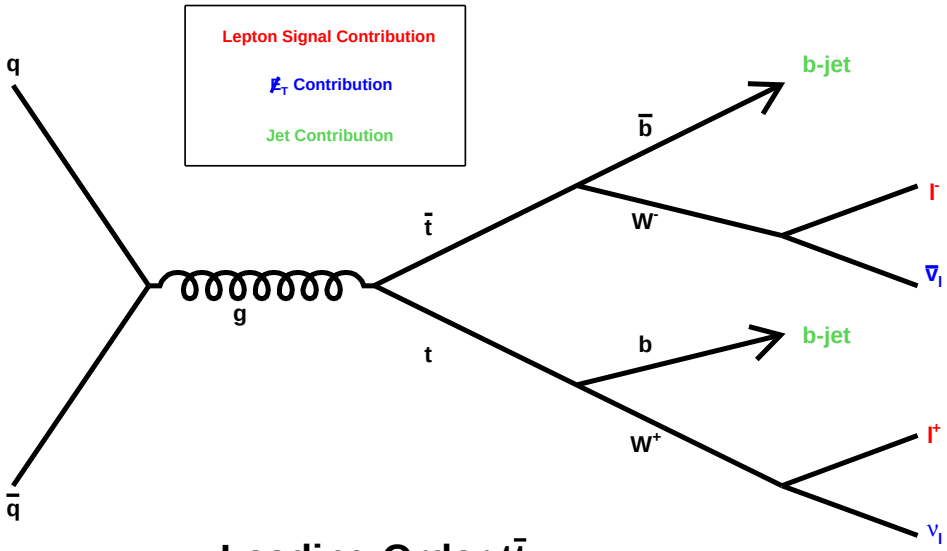
- Modelled by monte carlo simulation
- ISR: "Initial-state radiated" The 2 Z-leptons sum to the Z-mass
- FSR: "Final-state radiated" The 3-body Z-leptons + photon sum to the Z-mass
- 3rd lepton: Photon converts to electron-pair in calorimeter.



Background (5/5): $t\bar{t}$

*V*irtually negligible

Each top quark decays to $W + b$, providing 2 leptons from W's, 3rd lepton signature provided by a b-quark jet.

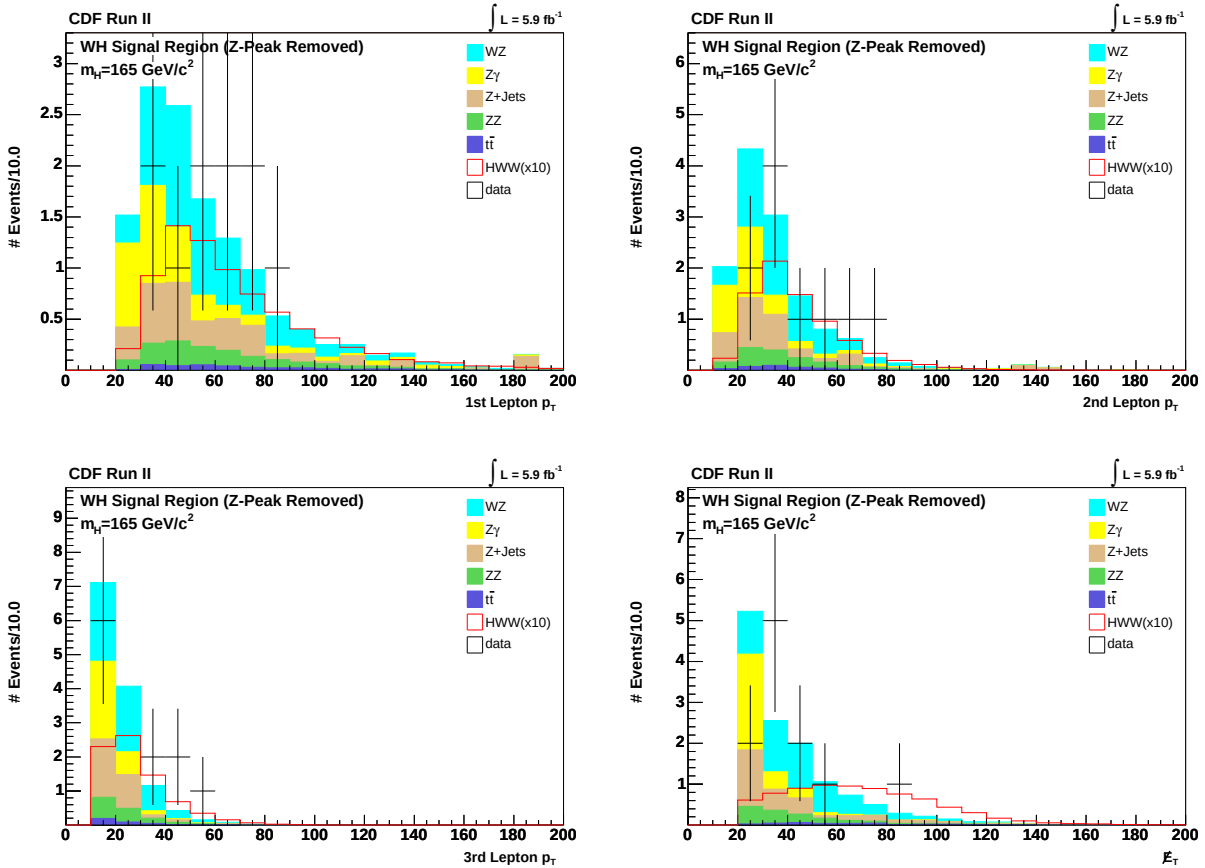


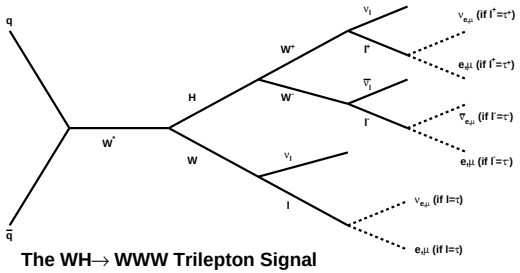
Leading Order $t\bar{t}$

- Modelled by monte carlo simulation
- Fake rate from b-jets not well-known, so largy systematic error assigned

Signal Region: *WH*

- 3 leptons
- Z-Peak is removed ($m_{ll} \notin [76.0, 106.0]$ GeV)
- $\not{E}_T > 20.0$ GeV
- Any number of jets

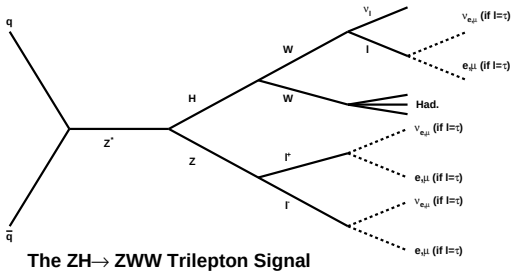


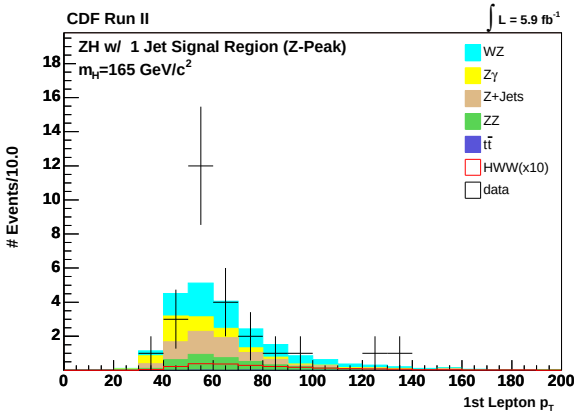


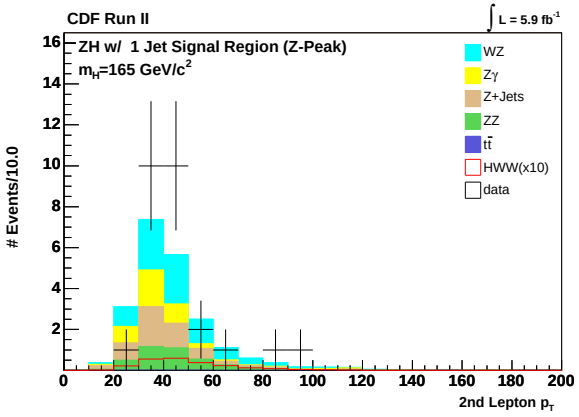
The WH→ WWW Trilepton Signal

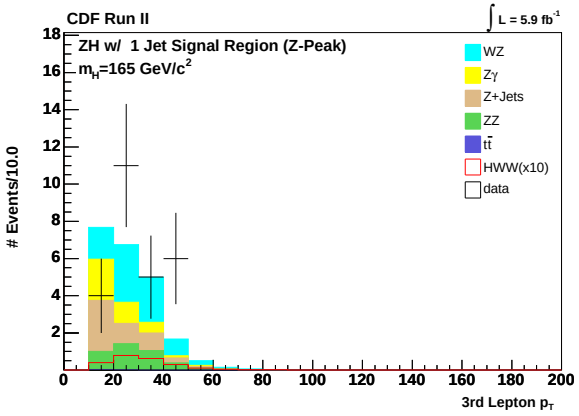
Signal Region: ZH-1 Jet

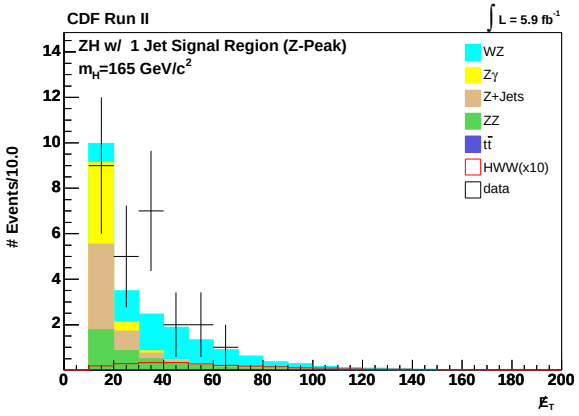
- 3 leptons
- Z-Peak is selected ($m_{ll} \in [76.0, 106.0]$ GeV)
- $\not{E}_T > 10.0$ GeV
- Number of jets = 1 (1 jet not detected)





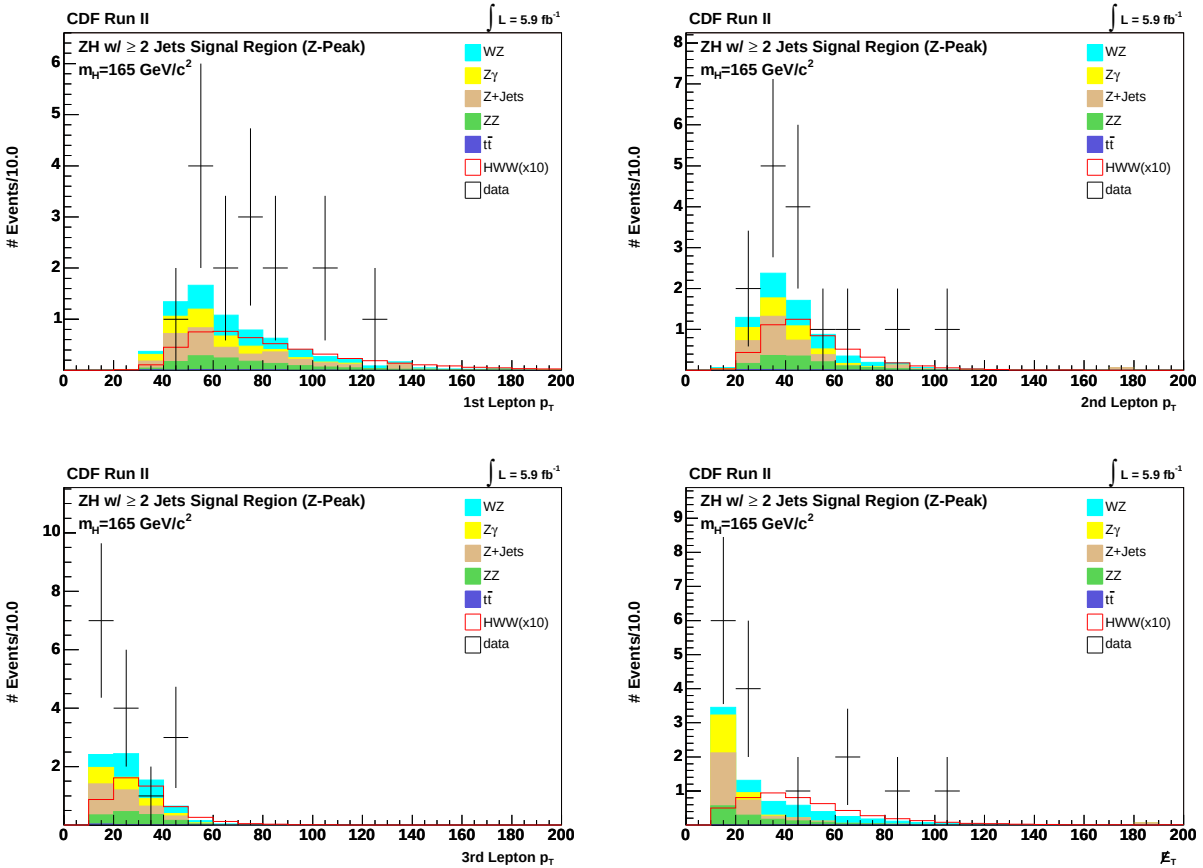


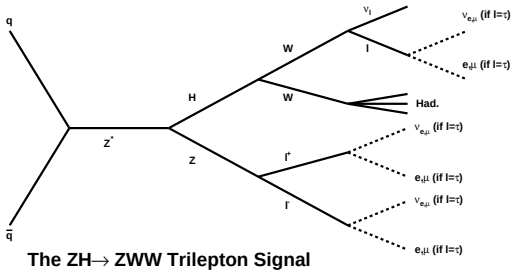




Signal Region: $ZH \geq 2$ Jet

- 3 leptons
- Z-Peak is selected ($m_{ll} \in [76.0, 106.0]$ GeV)
- $\not{E}_T > 10.0$ GeV
- Number of jets ≥ 2





The ZH→ ZWW Trilepton Signal

Signal Event Count For 5.9fb^{-1}

CDF Run II $\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$

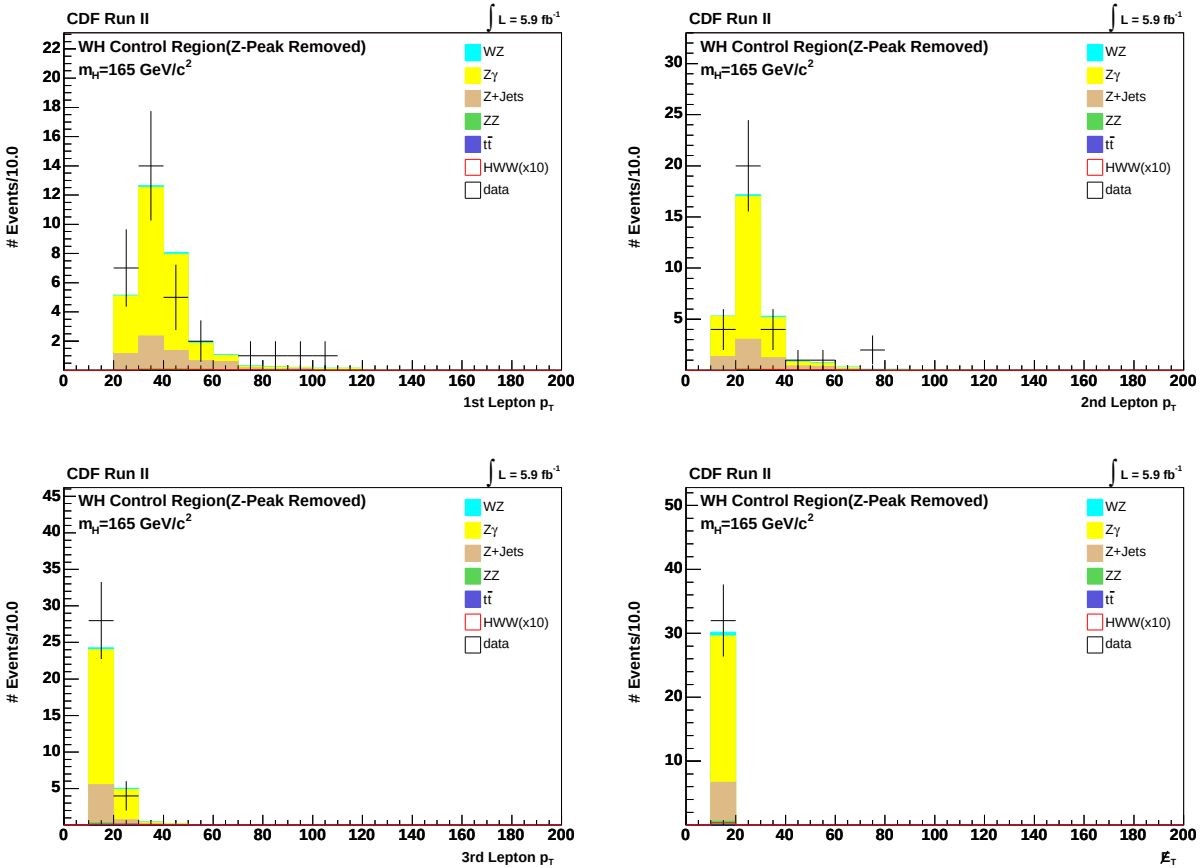
($m_H = 165\ \mathrm{GeV}/c^2$)	**WH**			**ZH (NJet$=1$)**			**ZH (NJet≥ 2)**		
WZ	5.35	$\pm$	0.75	8.53	$\pm$	1.37	2.28	$\pm$	0.52
ZZ	1.30	$\pm$	0.18	3.97	$\pm$	0.57	1.32	$\pm$	0.25
$Z\gamma$	3.13	$\pm$	0.62	4.14	$\pm$	0.86	1.36	$\pm$	0.37
Fakes (WW,Z+Jets)	2.92	$\pm$	0.72	5.13	$\pm$	1.32	2.27	$\pm$	0.58
$t\bar{t}$	0.37	$\pm$	0.12	0.07	$\pm$	0.02	0.08	$\pm$	0.03
Total Background	13.1	$\pm$	1.46	21.8	$\pm$	2.69	7.30	$\pm$	1.19
WH	0.61	$\pm$	0.08	0.03	$\pm$	0.004	0.008	$\pm$	0.002
ZH	0.16	$\pm$	0.02	0.20	$\pm$	0.03	0.49	$\pm$	0.07
Total Signal	0.77	$\pm$	0.10	0.23	$\pm$	0.03	0.50	$\pm$	0.07
Data	11			26			15		

High Mass

Expected trilepton signal: ~ 1.5 events. Compare to $gg \to H$: $1.5/28 = 5.4$, close to the 5.8 from earlier.

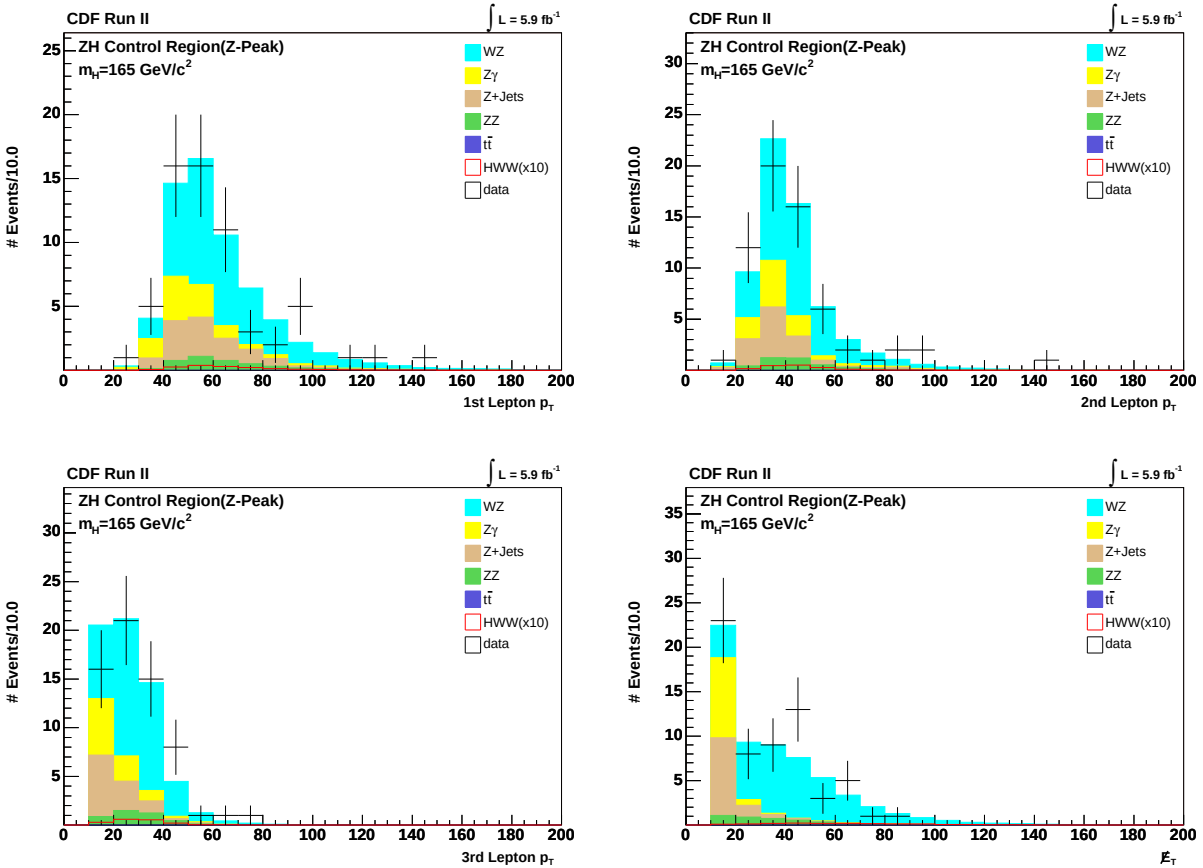
Control Region: *WH*

- 3 leptons
- Z-Peak is removed ($m_{ll} \notin [76.0, 106.0]$ GeV)
- $10.0 < \not{E}_T < 20.0$ GeV
- Any number of jets
- For study of $Z\gamma$ background



Control Region: *ZH*

- 3 leptons
- Z-Peak is selected ($m_{ll} \in [76.0, 106.0]$ GeV)
- $\not{E}_T > 10.0$ GeV
- Number of jets = 0
- For study of WZ, Z+Jets backgrounds
- Side project: WZ cross section measured at 3.7 ± 0.8 pb (*in preparation for publication*)



Control Event Count

CDF Run II $\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$

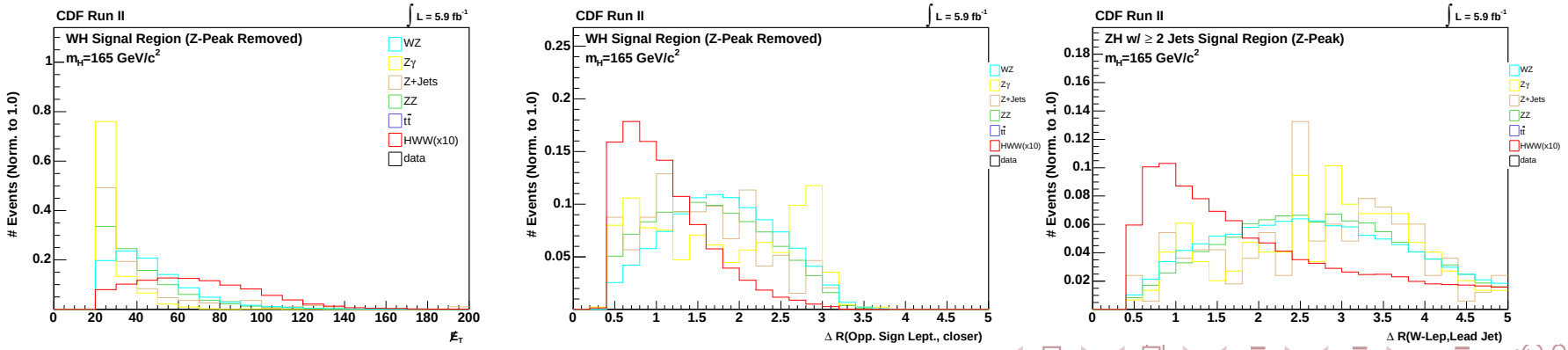
($m_H = 165\ \mathrm{GeV}/c^2$)	**WH Control Region**			**ZH Control Region**		
WZ	0.60	$\pm$	0.08	37.8	$\pm$	7.32
ZZ	0.60	$\pm$	0.08	4.23	$\pm$	0.01
$Z\gamma$	22.9	$\pm$	4.56	9.92	$\pm$	2.10
Fakes (WW,Z+Jets)	6.07	$\pm$	1.51	10.9	$\pm$	3.27
$t\bar{t}$	0.02	$\pm$	0.005	0.002	$\pm$	0.0004
Total Background	30.2	$\pm$	4.84	62.9	$\pm$	9.59
WH	0.03	$\pm$	0.004	0.10	$\pm$	0.02
ZH	0.01	$\pm$	0.002	0.07	$\pm$	0.01
Total Signal	0.04	$\pm$	0.005	0.17	$\pm$	0.03
Data	32			63		

High Mass

Table: Event count for the signal and background processes in the trilepton control regions for $5.9\mathrm{fb}^{-1}$ of collected data

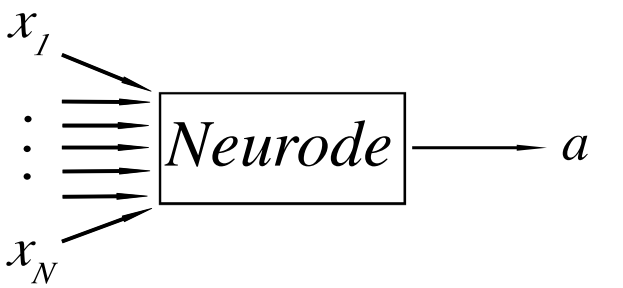
Separating Signals From Backgrounds

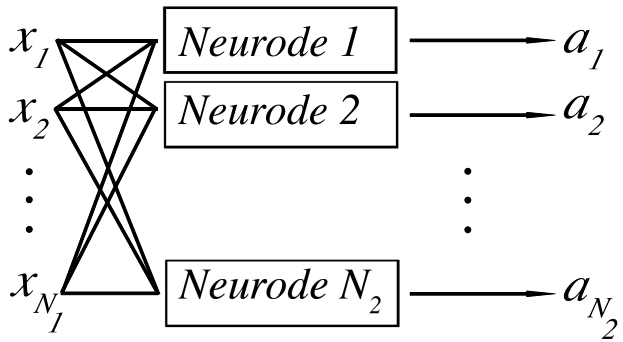
- Cuts are finished, but can do more to isolate signal-like events
- Many physical quantities show separated, though overlapping, distributions
- Neural Network: Input many distributions w/ small separations, output one distribution with larger separation.
- Neural Networks "train" on simulated signal

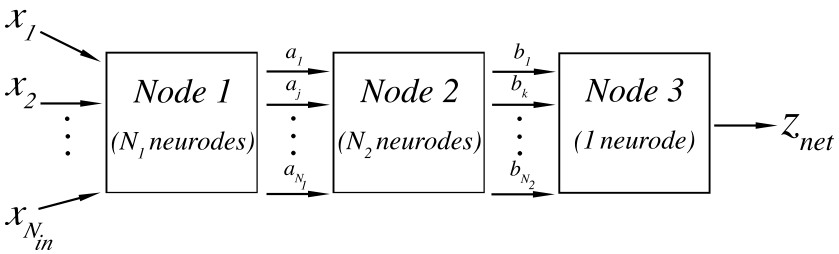


“NeuroBayes” Neural Network

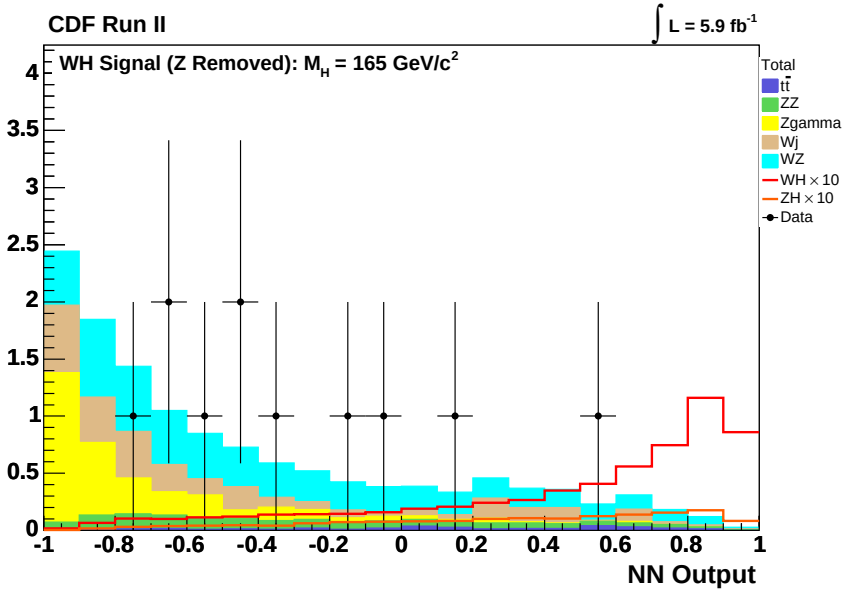
- High parallel information processing system
- Structure: “neurode”⊂“network node”⊂“neural net”
- Use many distributions with smaller separations to make single distribution with large separation
- Input: Some N_{in} variables
- Output: $z_{\text{net}} \in (-1, 1)$

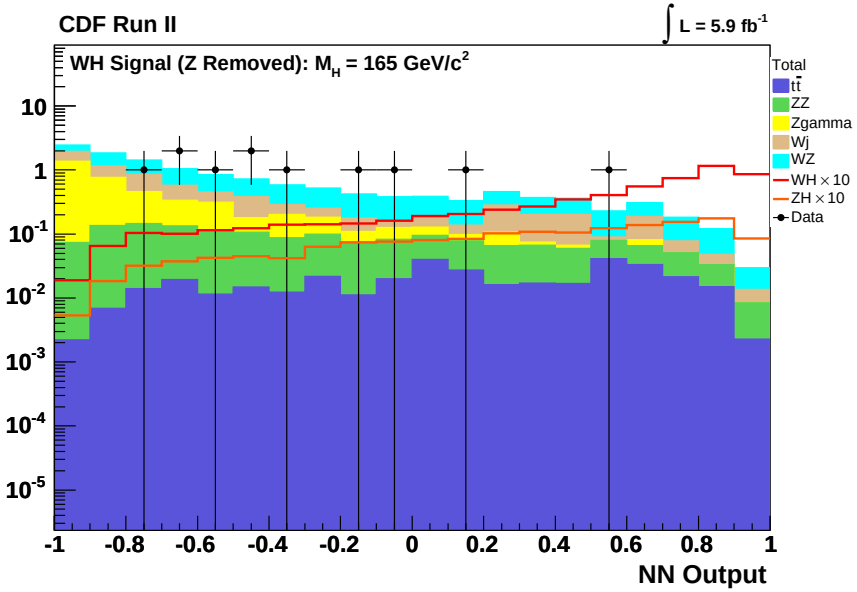




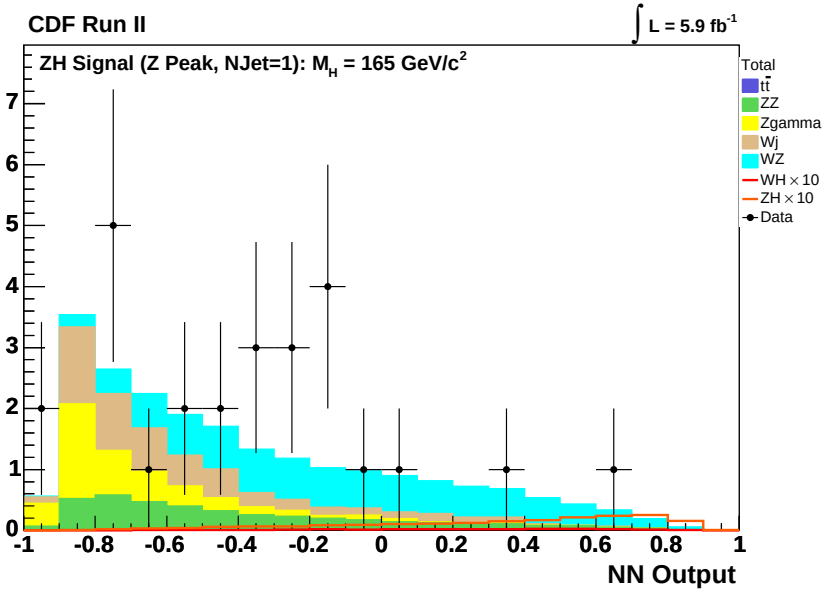


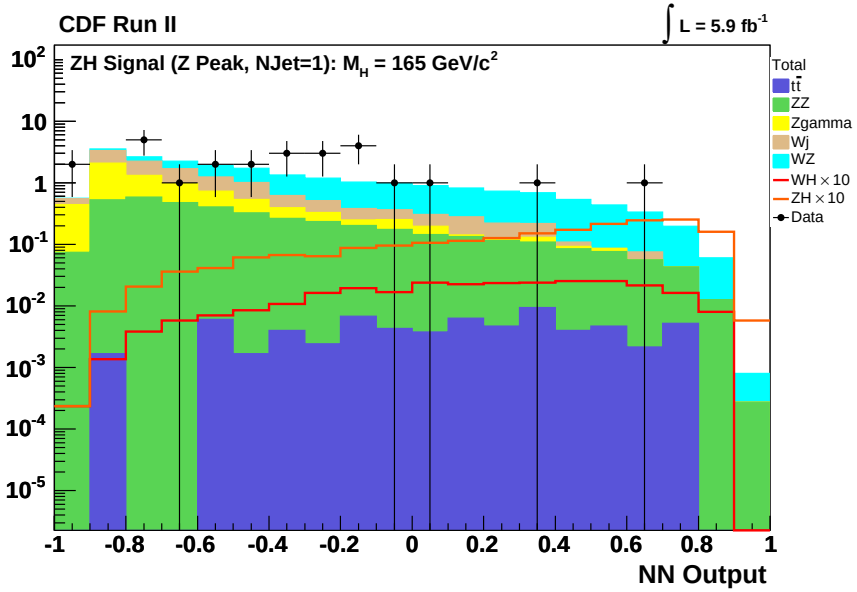
Neural Net Output: *WH* Signal Analysis



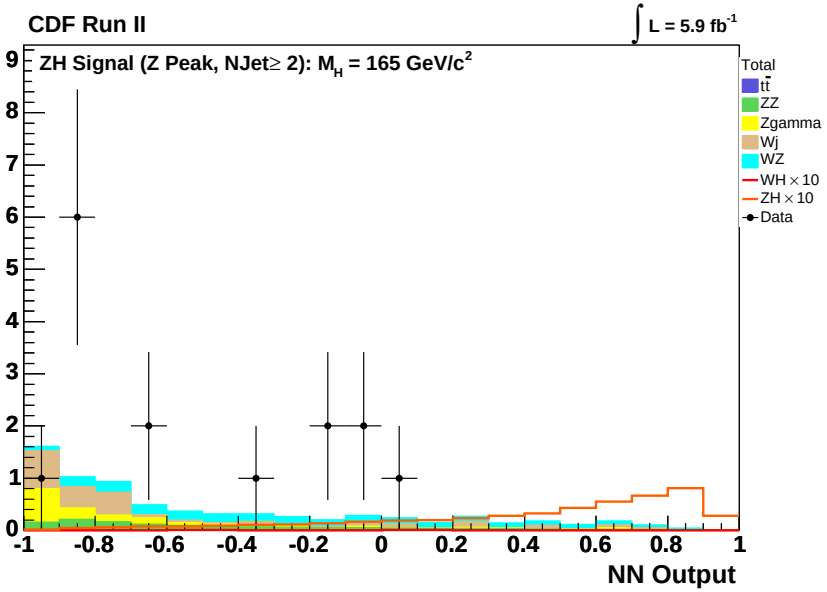


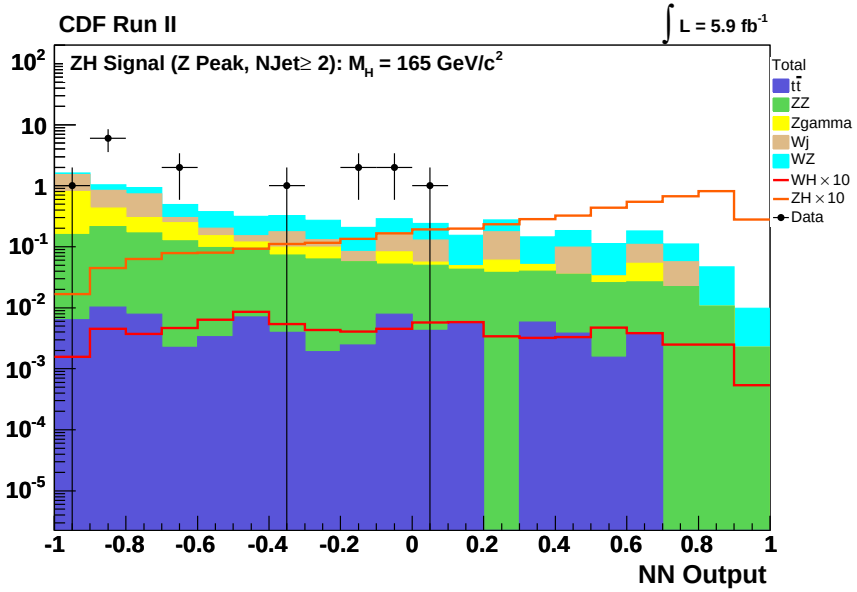
Neural Net Output: *ZH*-1 Jet Signal Analysis





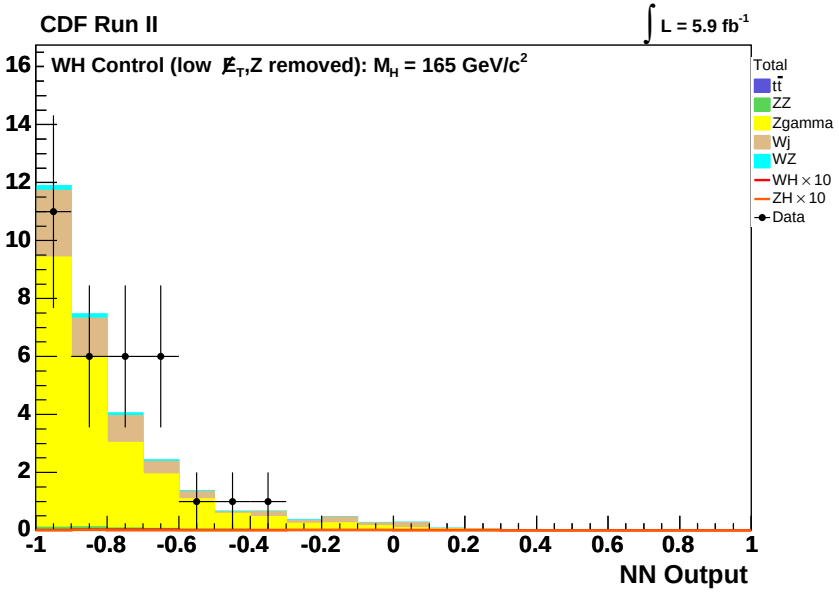
Neural Net Output: $ZH \geq 2$ Jet Signal Analysis

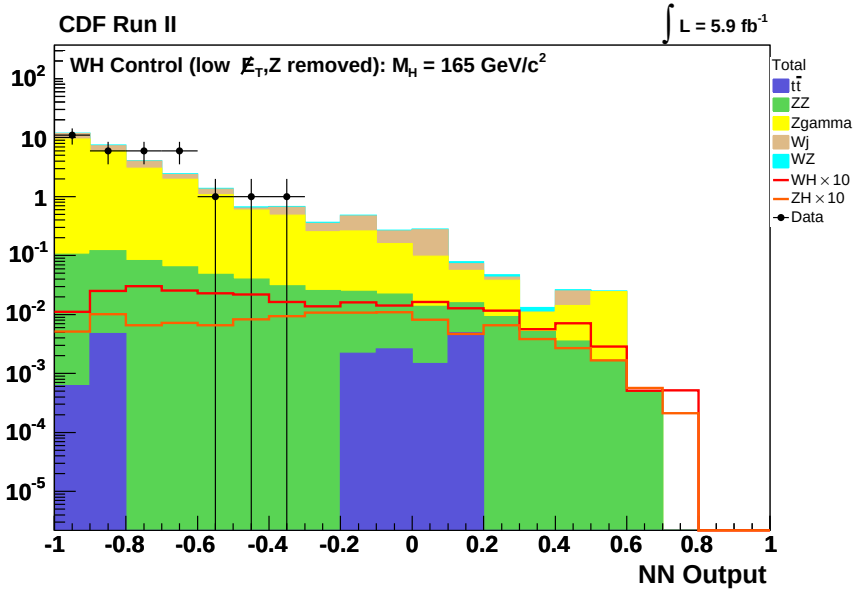




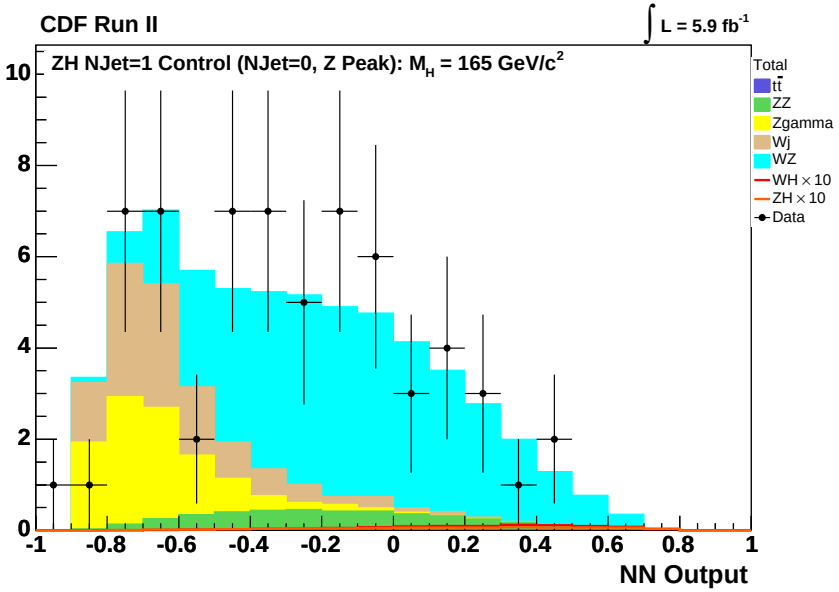
- Recall: Neural Networks "train" on a simulated signal to separate signal from background
- Control regions are also used to test the training, expected to be heavy in background (left) and sparse in signal (right)
- Let's run the control region through neural networks trained on the signal regions.

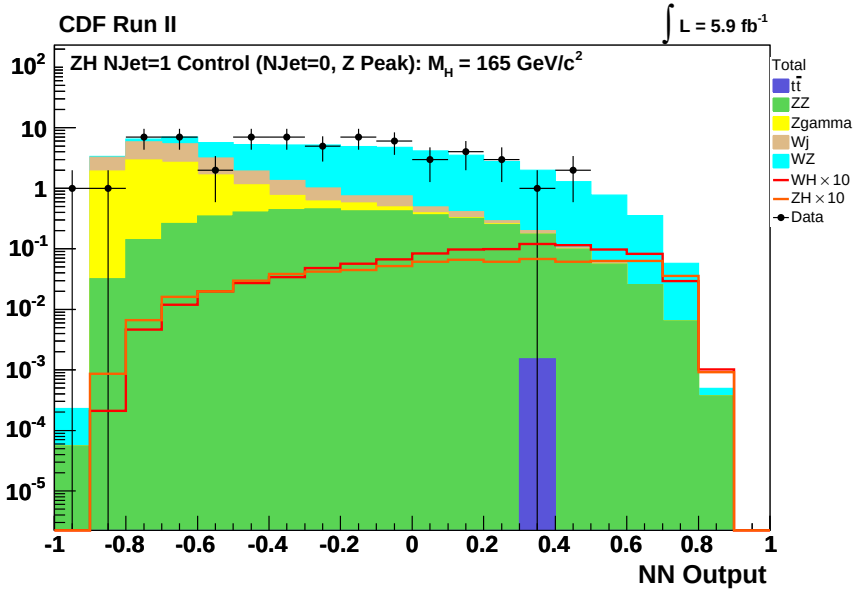
Neural Net Output: *WH* Control (Low $\not\!\!E_T$)



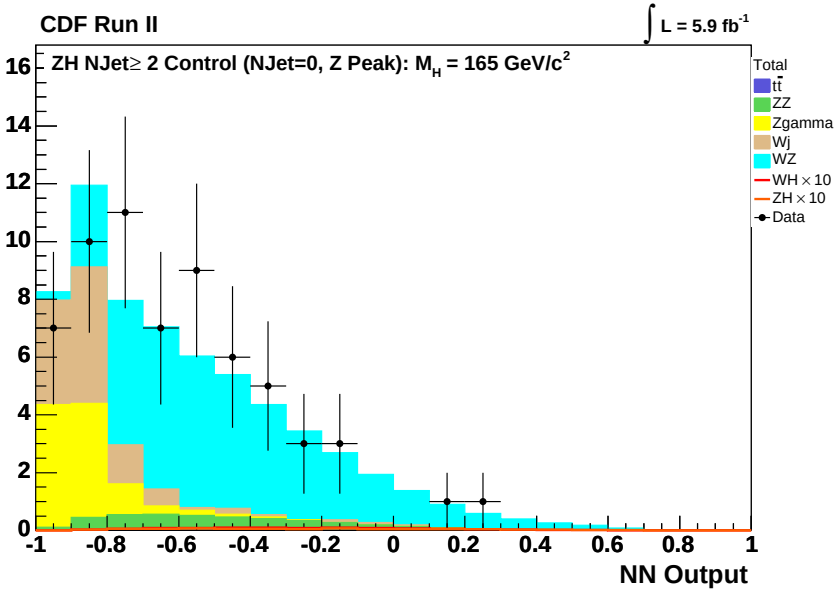


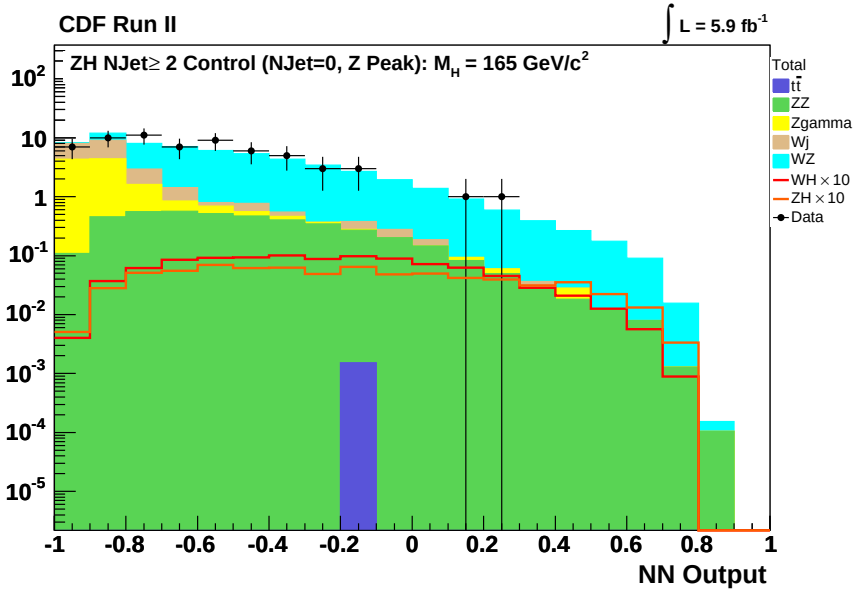
Neural Net Output: *ZH*-1 Jet Control (NJet= 0)





Neural Net Output: $ZH \geq 2$ Jet Control (NJet$=0$)





Systematic Errors

Systematic Uncertainty	WZ	ZZ	$Z\gamma$	$t\bar{t}$	Fakes	WH	ZH
Diboson Acceptance	0.100	0.100					
$t\bar{t}$ Higher Order Diagrams				0.100			
Higgs Higher Order Diagrams						0.100	0.100
PDF Model	0.027	0.027	0.027	0.021		0.012	0.009
Lepton ID Efficiencies	0.020	0.020	0.020	0.020		0.020	0.020
Trigger Efficiences	0.021	0.021	0.021	0.020		0.021	0.021
Light Jet Fake Rates					$\sim 0.25^d$		
b-Jet Fake Rate[c]				[b]			
Luminosity	0.059	0.059	0.059	0.059		0.059	0.059
MC Run Dependence			0.050[c]				
Jet Energy Scale	[a]	[a]	[a]	[a]	[a]	[a]	[a]
$Z\gamma$ Conversion			0.10				
σ_{Diboson}	0.060	0.060					
$\sigma_{t\bar{t}}$				0.100			
σ_{VH}						0.050	0.050
$\sigma_{Z\gamma}$			0.010[c]				

[a] JES systematic errors are measured individually to each process and in each region. See table **??**.

[b] WH: 0.273, ZH(1 Jet): 0.420, $ZH(\geq 2$ Jets): 0.222

[c] New to trilepton analysis, not in dilepton analysis.

[d] WH: 0.248, ZH(1 Jet): 0.258, $ZH(\geq 2$ Jets): 0.253

Systematic Errors

Most Important Systematics:

- Cross section: Theoretical errors on cross sections used in MC modelling
- Higher order diagrams: Higgs processes generated with PYTHIA at (LO+ pheno model of parton showering), accounts for variations from MC@NLO modelling.
- Jet Energy Scale: Inherent uncertainty on measuring the energy of jets. Varying the measured energy within errors changes number of jets counted per event, changing the region an event falls in.
- Fake Rate: Estimating the rate at which jets fake a lepton signature is difficult, so a large 25% error is assumed.

Confidence Level Limits

- *Goal:* Compute the significance of a signal or set an exclusion if one is not observed. We set exclusion limits here.
- *Compare data to two hypotheses:*
  - The background *only* assumption
  - The background + *signal* assumption
- *95% Confidence Level Exclusion:* This exclusion should be found no more than 5% of the time when a real signal is present.

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Confidence Level Limits: Likelihood Ratio

Definition

The *likelihood ratio* is the ratio of the likelihood function for the background-plus-signal hypothesis to the likelihood function for the background-only hypothesis.

$$X = \prod_{i=1}^{n} \frac{\frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i}}{d_i!}}{\frac{e^{-b_i} b_i^{d_i}}{d_i!}} \tag{1}$$

where s_i = signal expectation in the i-th bin of the neural net score, b_i = background expectation, d_i = number of events observed in data.

Confidence Level Limits: Defined

Definition

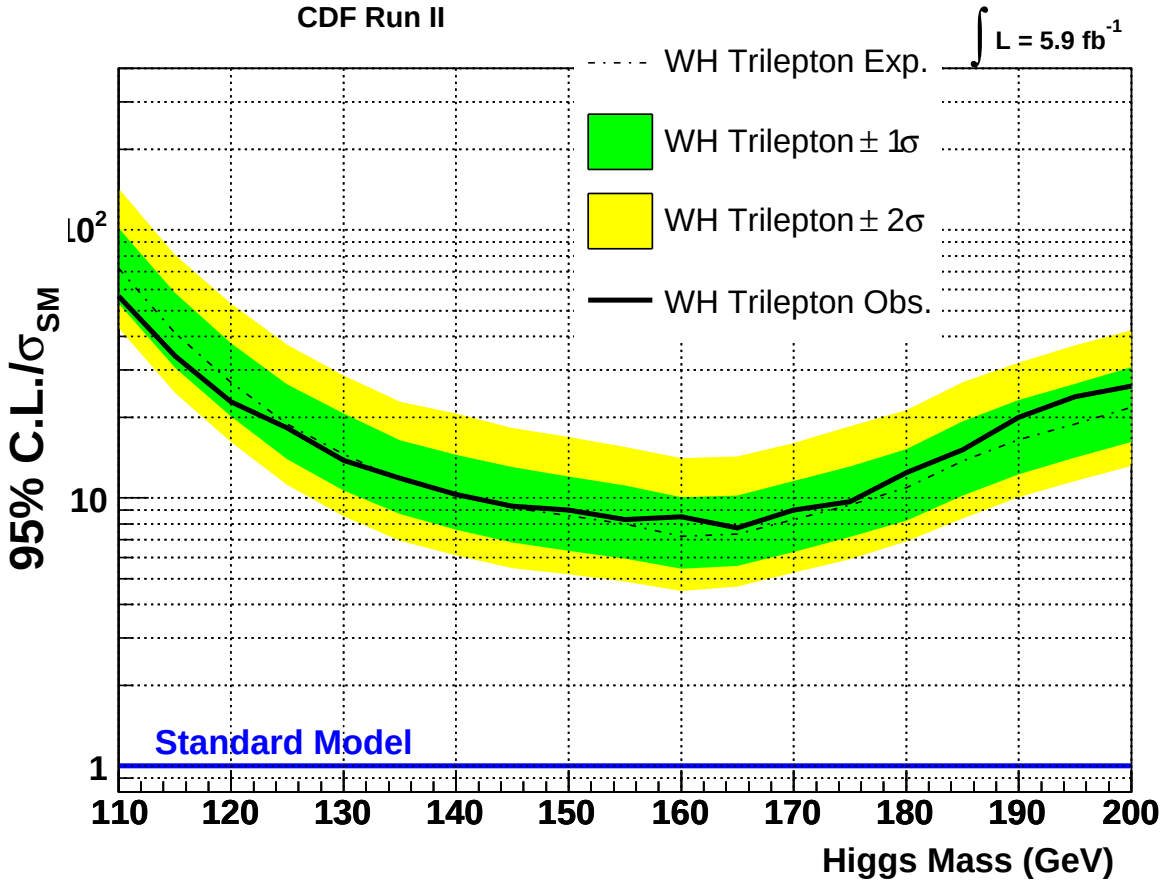
The *confidence level* for exclusion of the signal-plus-background hypothesis is the prob. of the likelihood ratio X being $\leq$ to the likelihood ratio of the data $X_{\text{obs.}}$.

$$CL_{s+b} = P_{s+b}(X \leq X_{\text{obs.}}) \tag{2}$$

$$P_{s+b}(X \leq X_{\text{obs.}}) = \sum_{X(\{d_i'\}) \leq X(\{d_i\})} \prod_{i=1}^{n} \frac{e^{-(s_i+b_i)}(s_i+b_i)^{d_i'}}{d_i'!} \tag{3}$$

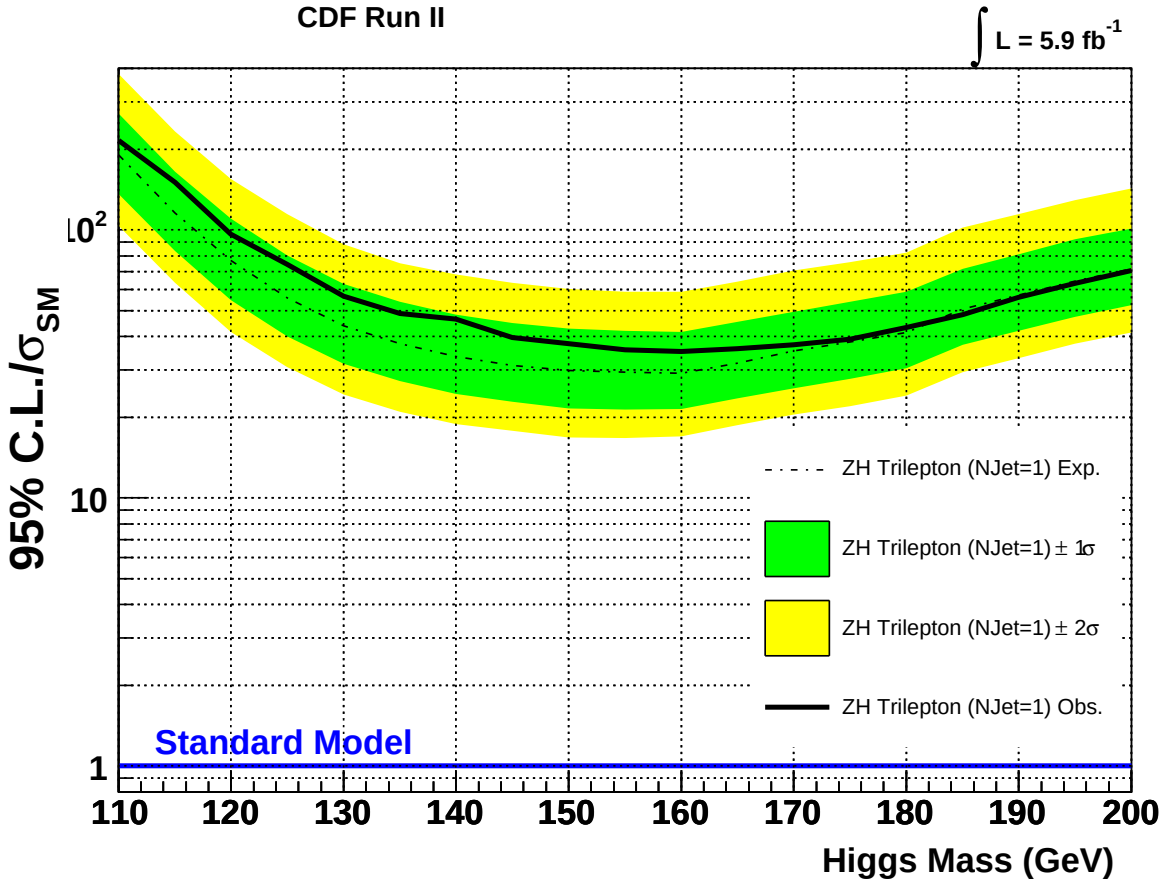
where $X(\{d_i\})$ is for the observed candidates for each channel $\{d_i\}$ and the sum is over final outcomes $\{d_i'\}$ with test statistic value $\leq$ the observed one [7].

WH Limits



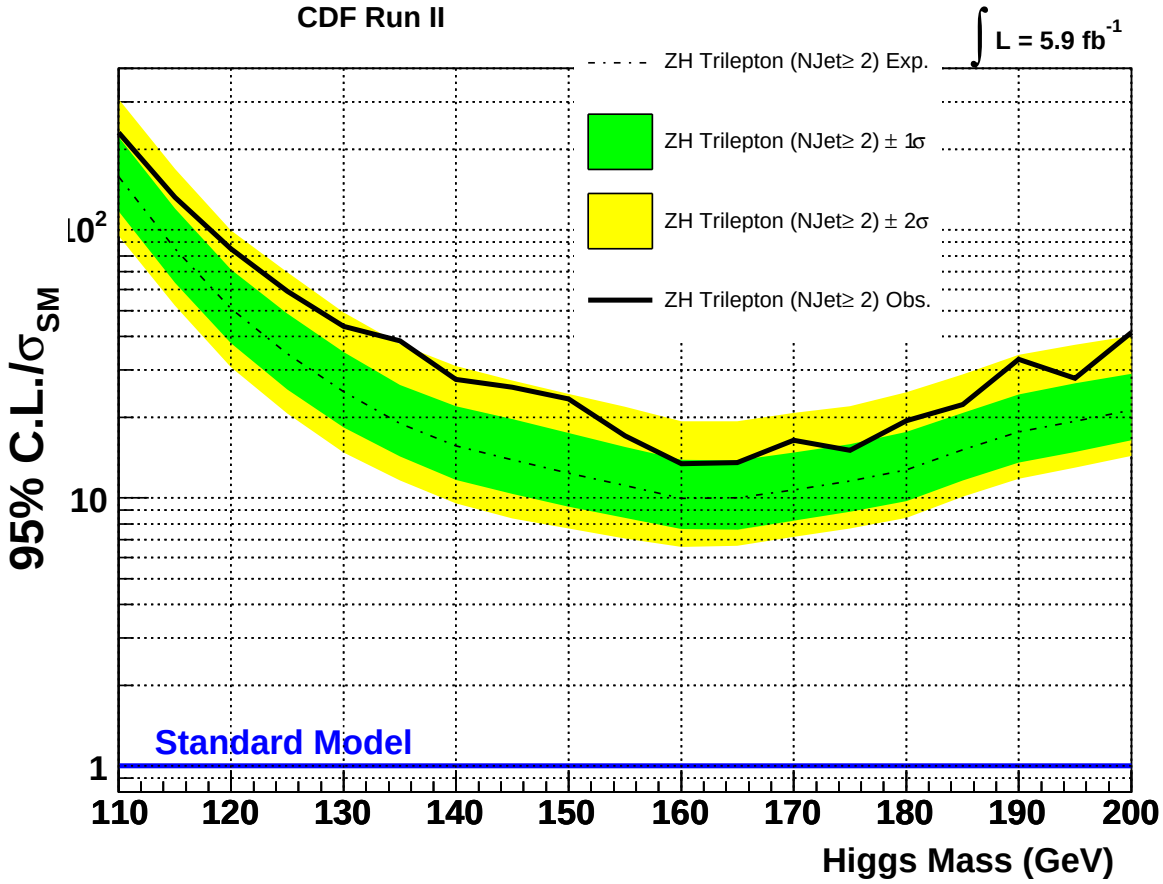
m_H	Exp.	Obs.
130	15	14
135	12	12
140	10	11
145	9.3	9.6
150	8.6	9.6
155	7.9	8.5
160	7.3	8.1
165	7.4	8.0
170	8.5	9.1
175	9.4	10
180	11	13

ZH-1 Jet Limits



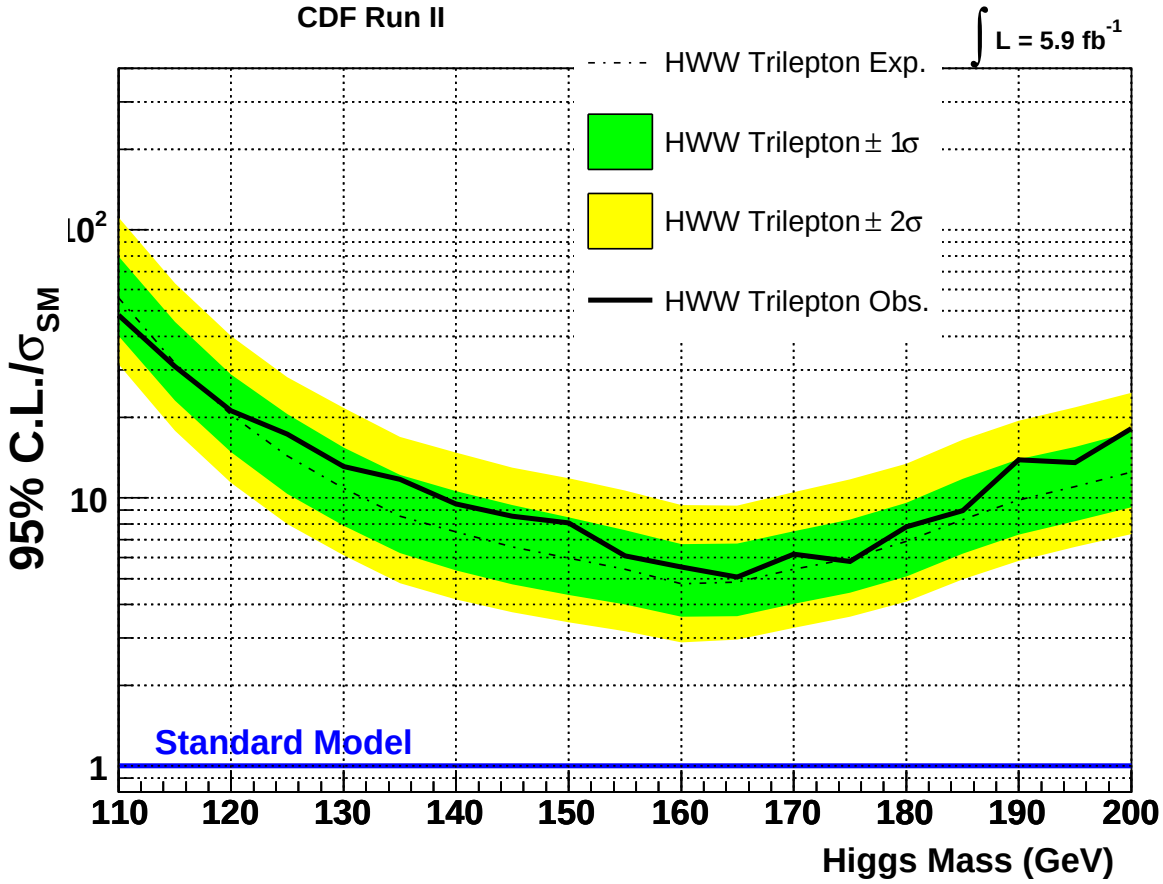
m_H	Exp.	Obs.
130	44	57
135	37	49
140	34	47
145	31	40
150	30	38
155	29	36
160	29	35
165	32	36
170	35	38
175	38	39
180	41	44

$ZH \geq 2$ Jets Limits



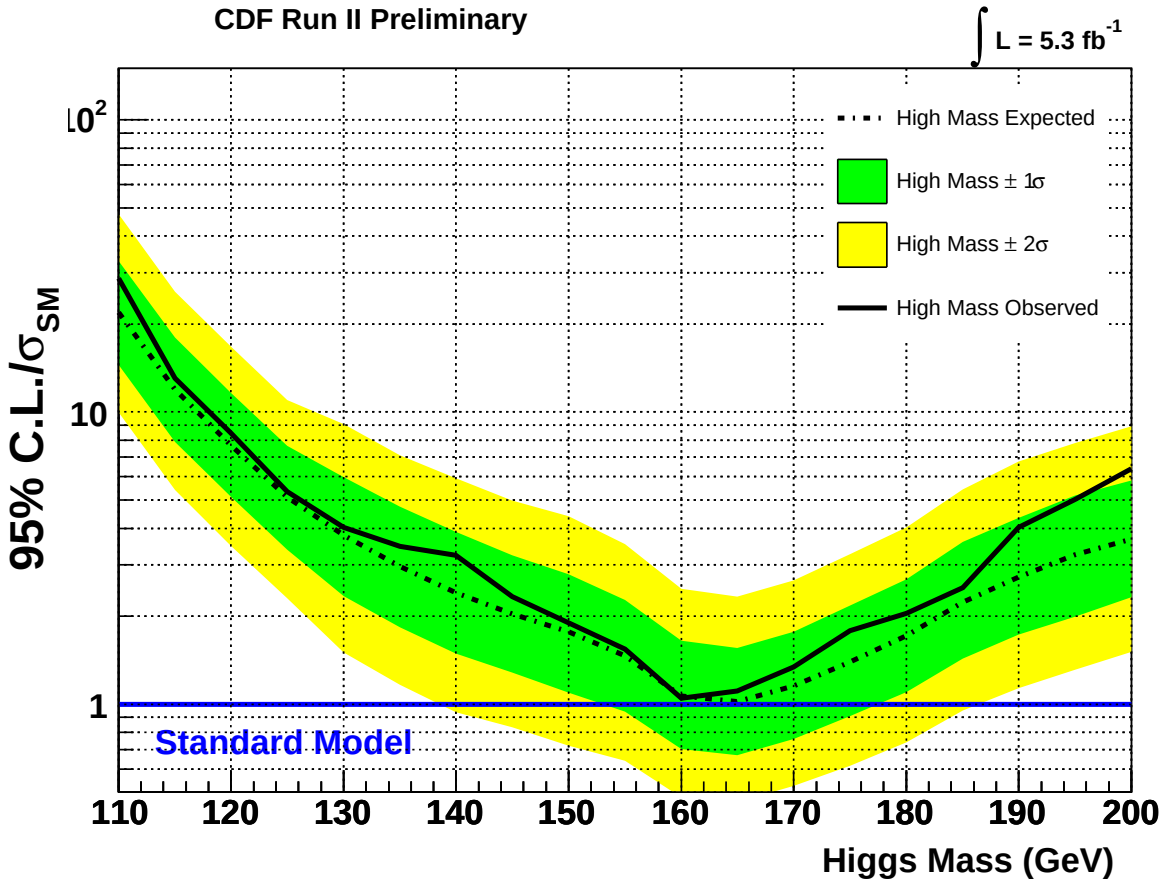
m_H	Exp.	Obs.
130	26	43
135	20	38
140	16	27
145	14	26
150	13	23
155	11	17
160	10	13
165	10	13
170	11	16
175	12	14
180	13	19

Combined Trilepton Limits



m_H	Exp.	Obs.
130	11	13
135	8.7	12
140	7.5	9.4
145	6.7	8.7
150	6.1	8.3
155	5.4	6.1
160	4.9	5.1
165	4.9	5.1
170	5.6	6.1
175	6.1	6.0
180	6.9	8.1

CDF-*Only* $H \rightarrow WW$ Limits (w/ 5.3fb^{-1})



m_H	Exp.	Obs.
130	3.78	4.02
135	2.95	3.47
140	2.40	3.23
145	2.04	2.33
150	1.77	1.89
155	1.47	1.54
160	1.07	1.05
165	1.02	1.11
170	1.15	1.34
175	1.39	1.78
180	1.72	2.05

Conclusion

- The $H \rightarrow WW$ trilepton analysis is a new addition to the search for the SM Higgs boson.
- WH and ZH Combined trilepton limits reach $4.9\times$ S.M. sensitivity alone in 5.9/fb

BACKUP

Lagrangians: The Foundation

In a Q.F.T., a "lagrangian density" is postulated with the form:

$$\mathcal{L}(\phi, \partial_\mu \phi) = \text{Kinetic Energy (density)} - \text{Potential Energy (density)}$$

Consequantial physics results from...

Definition

Principle of Least Action: When a system evolves from one given path to another between times t_1 and t_2, it does so along the path for which $S = \int \mathcal{L}(\phi, \partial_\mu \phi) d^4x$ is an extremum (typically a minimum). i.e. $\delta S = 0$

This translates into...

Definition

Euler-Lagrange equation of motion:

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} \right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0$$

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Higgs & Non-zero Fermion Mass

Fact

Only left-handed spin-1/2 fields enter into weak interactions.

How do we deal with this mathematically?

Definition

Define the *left and right handed projection operators* that create purely left (ψ_L) or right (ψ_R) spin fields out of a general field ψ:

$$\psi_L = \left(\frac{1-\gamma_5}{2}\right)\psi$$

$$\psi_R = \left(\frac{1+\gamma_5}{2}\right)\psi$$

Fact

Therefore, the symmetry group for WEAK interactions is $SU(2)_L \times U(1)$[3, 9, 8]

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For a spin $1/2$ particle ψ, assume the Dirac lagrangian (instead of the Klein-Gordon lagrangian from before):

$$\mathcal{L} = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi \tag{4}$$

(*where the γ_μ are 4×4 anti-commuting matrices supporting Lorentz group algebra*)

WHY WE NEED THE HIGGS MECHANISM:

Fact

A Dirac mass term has mixed left and right fields, but electroweak requires $SU(2)_L$ invariance:

$$-m\bar{\psi}\psi = -m\left(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L\right)$$

So mass terms contradict needed symmetry, but universe filled with massive particles

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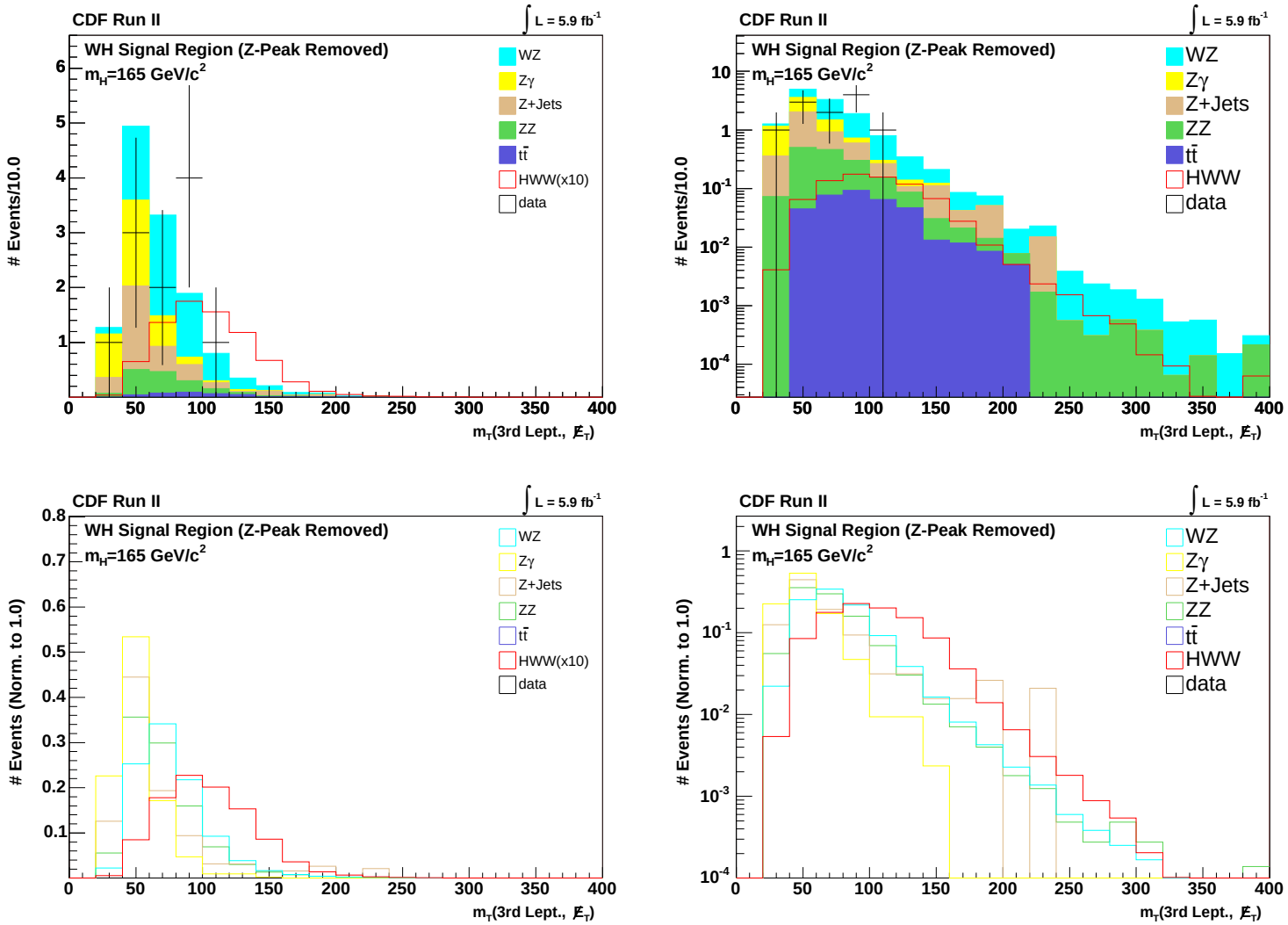
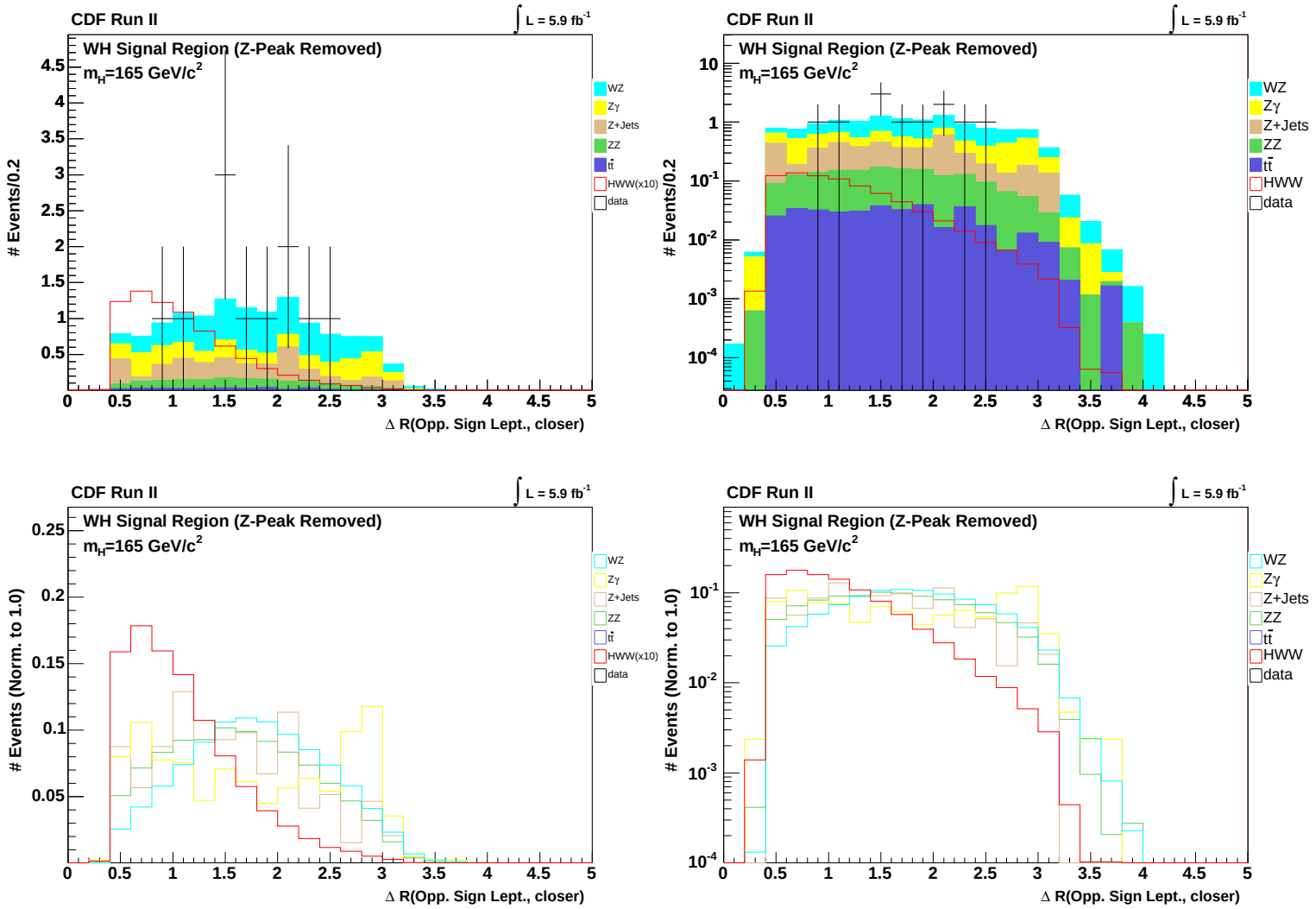
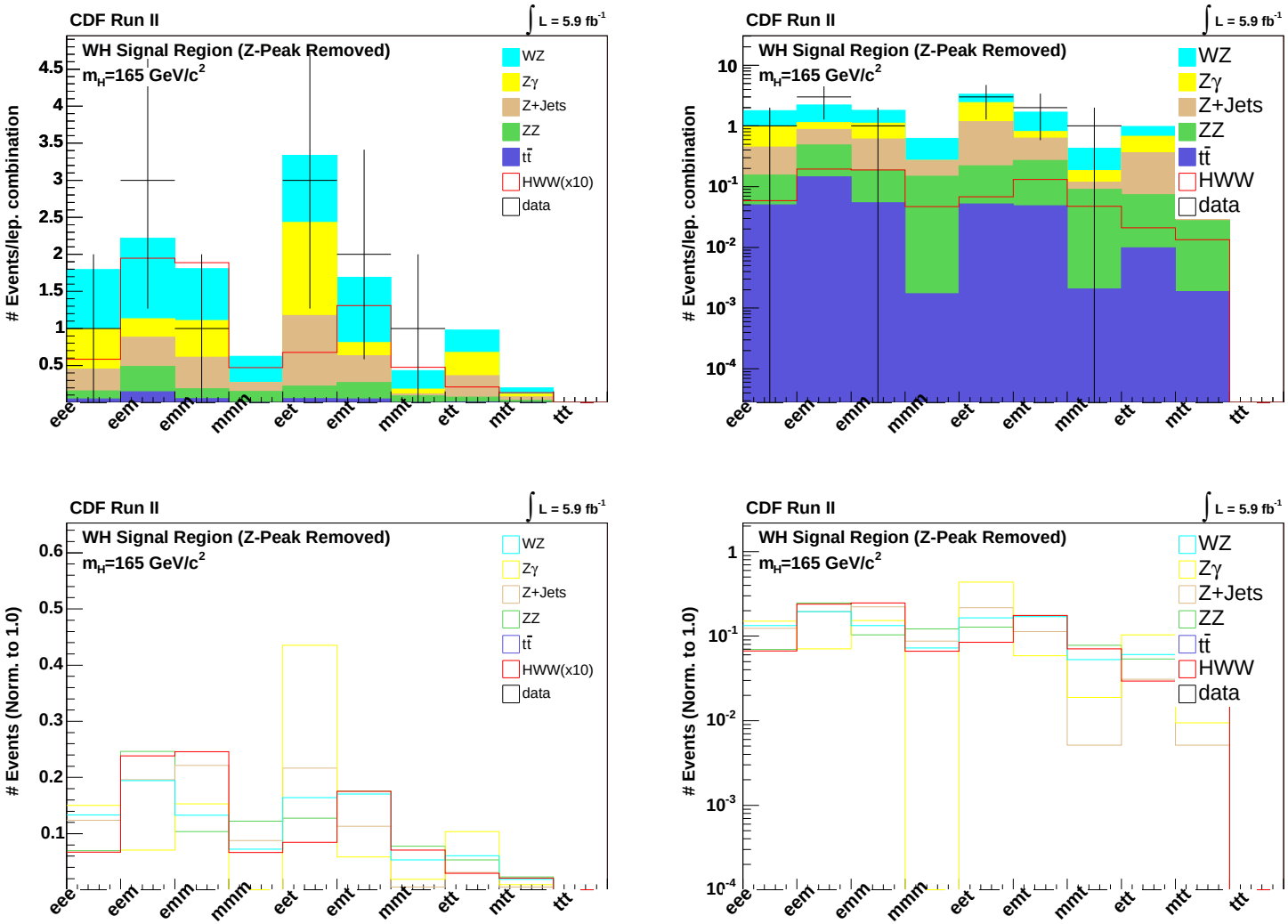
WH Signal: m_T (3rd Lep.,$\not{E}_T$)



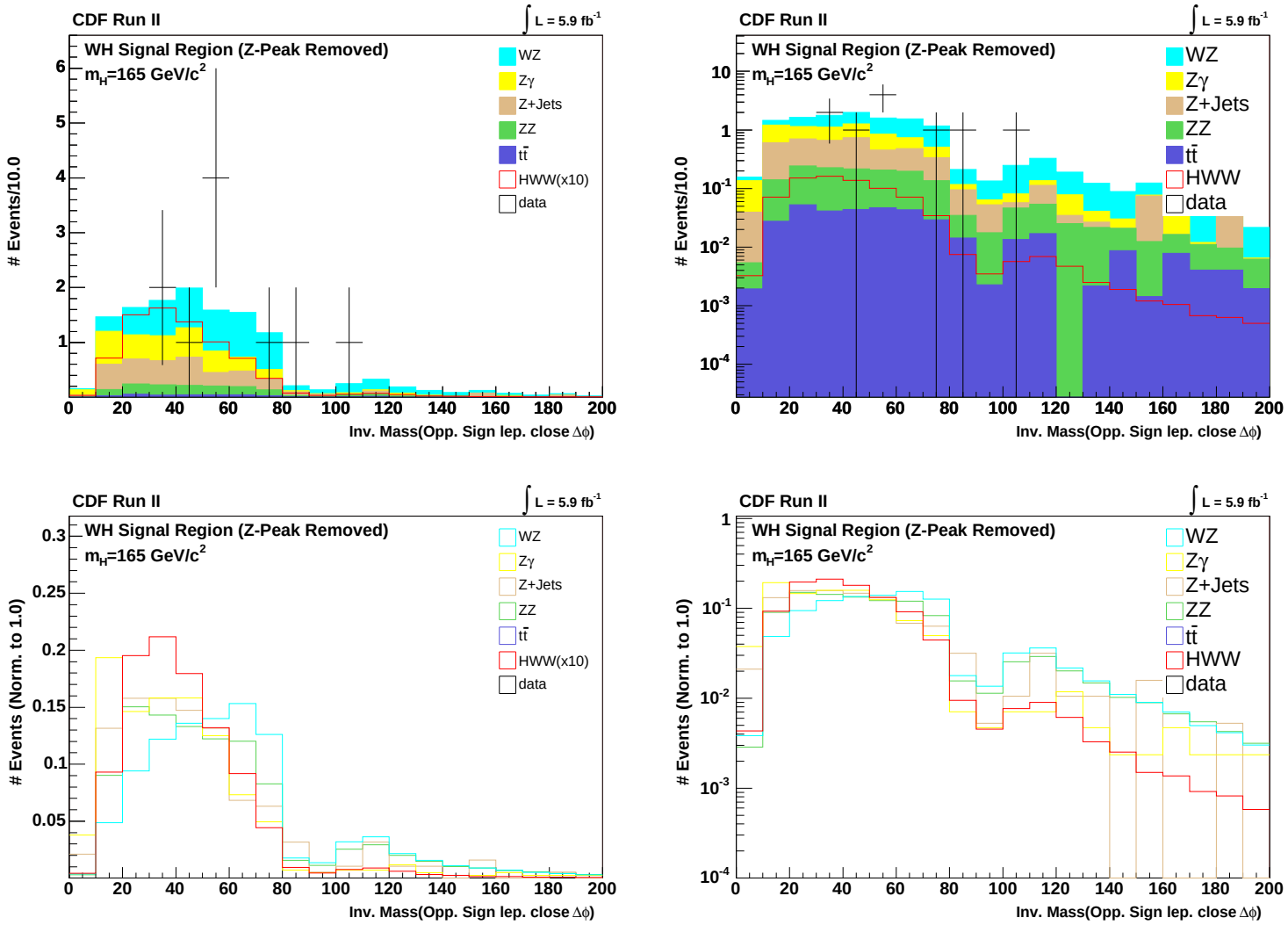
WH Signal: ΔR Opp. Sign Close



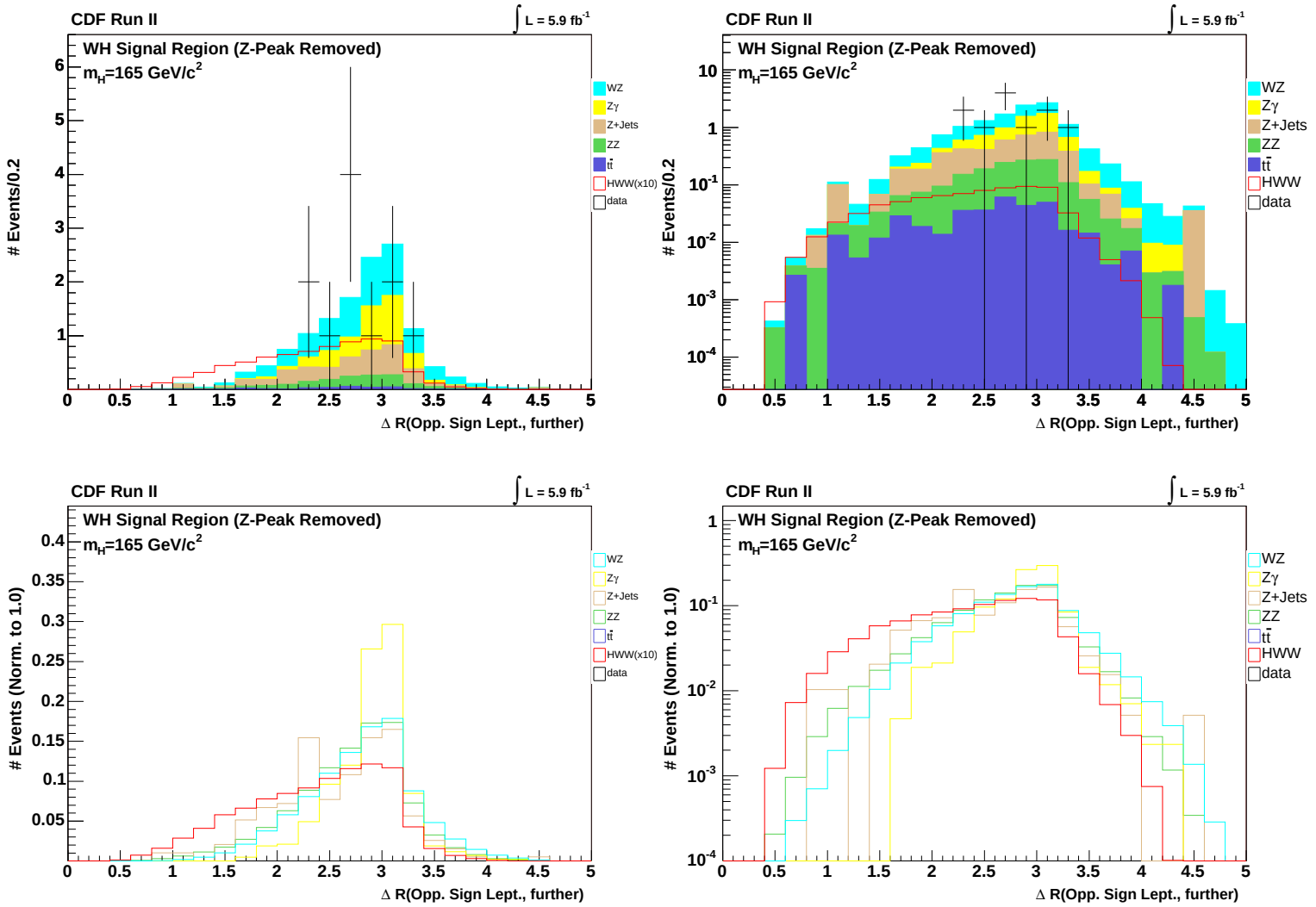
WH Signal: Lepton Type Combinations



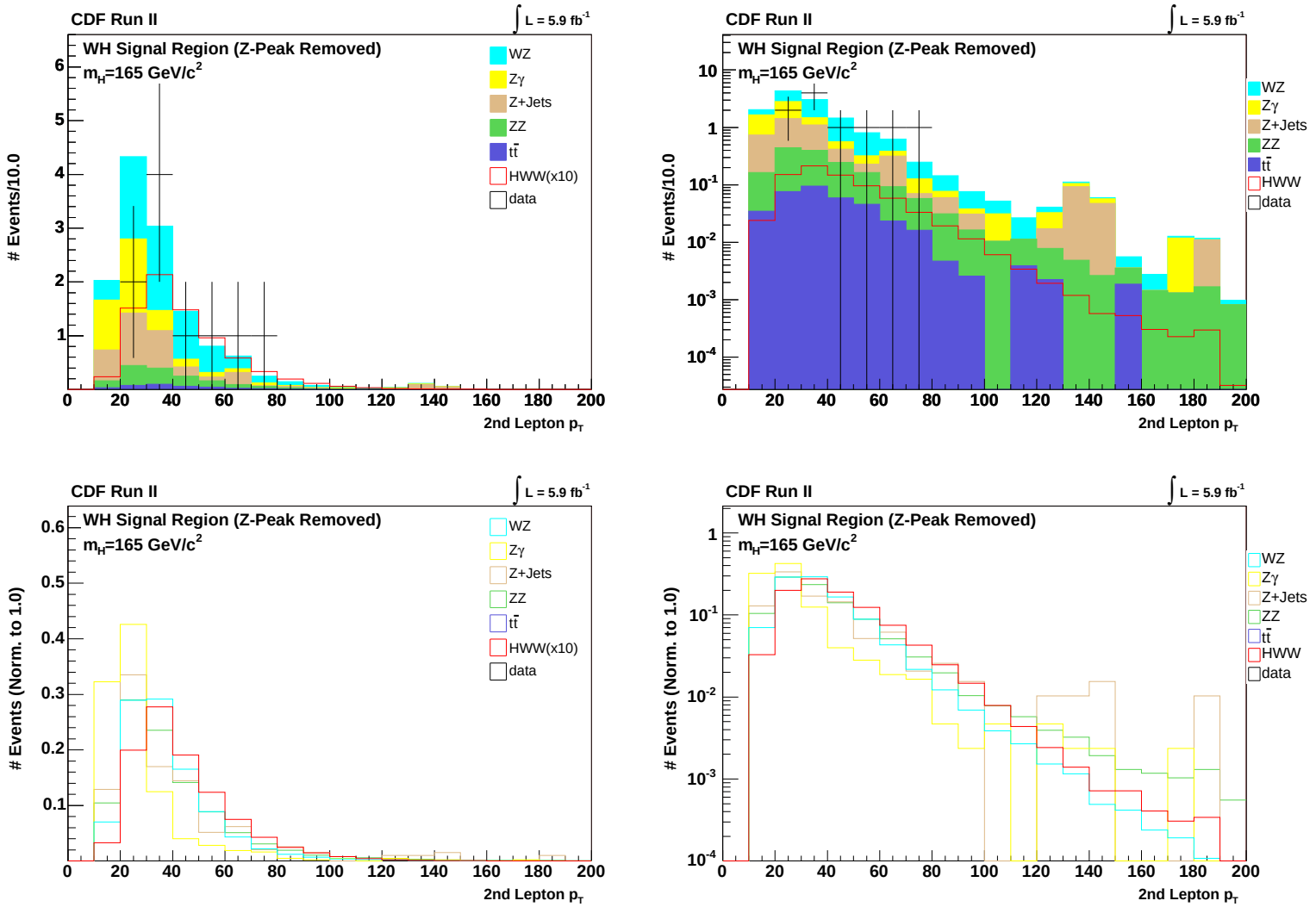
WH Signal: Dimass Opp. Sign Lepton (closer by ϕ)



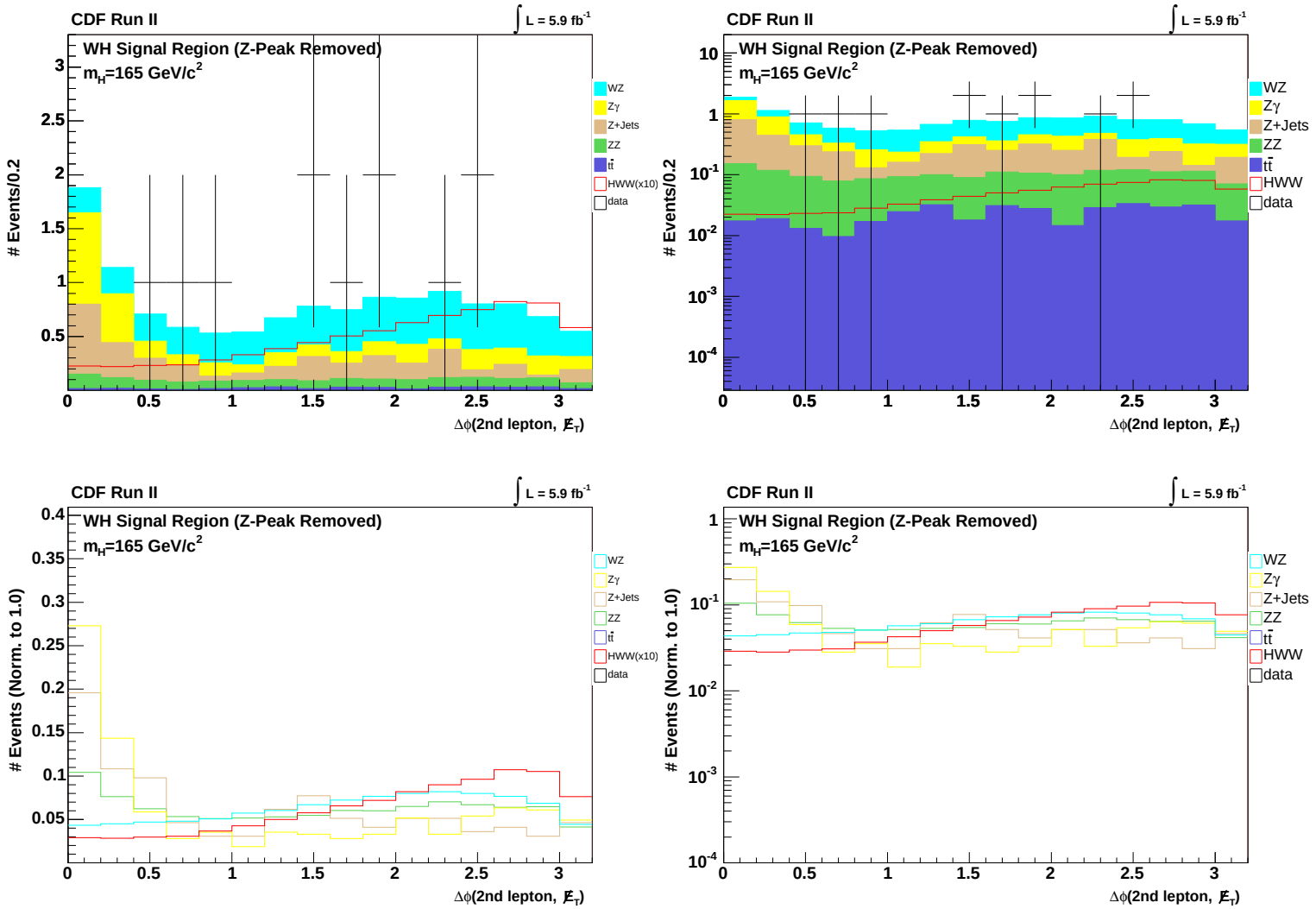
WH Signal: ΔR Opp. Sign. Leptons Far



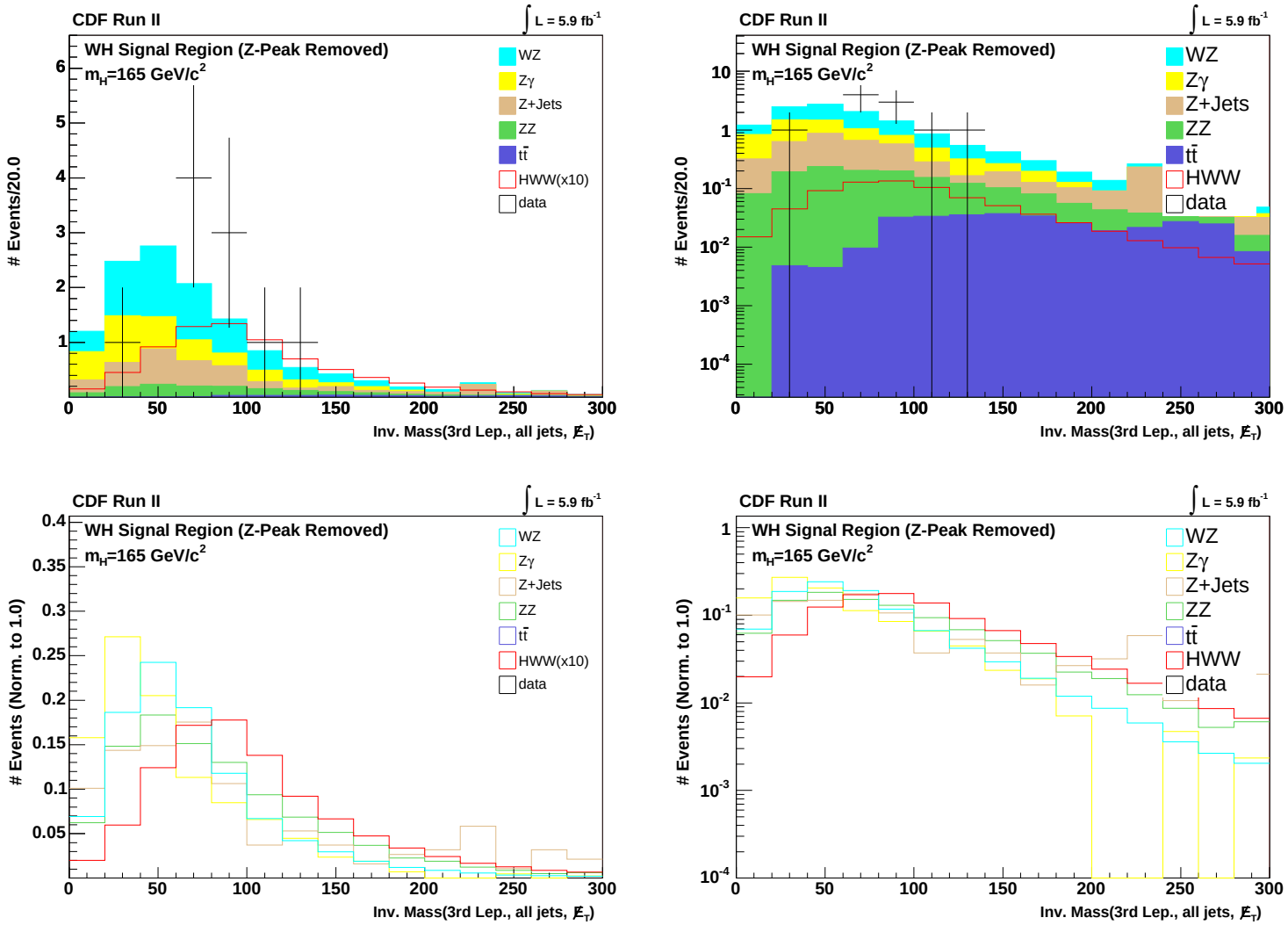
WH Signal: 2nd Lepton p_T



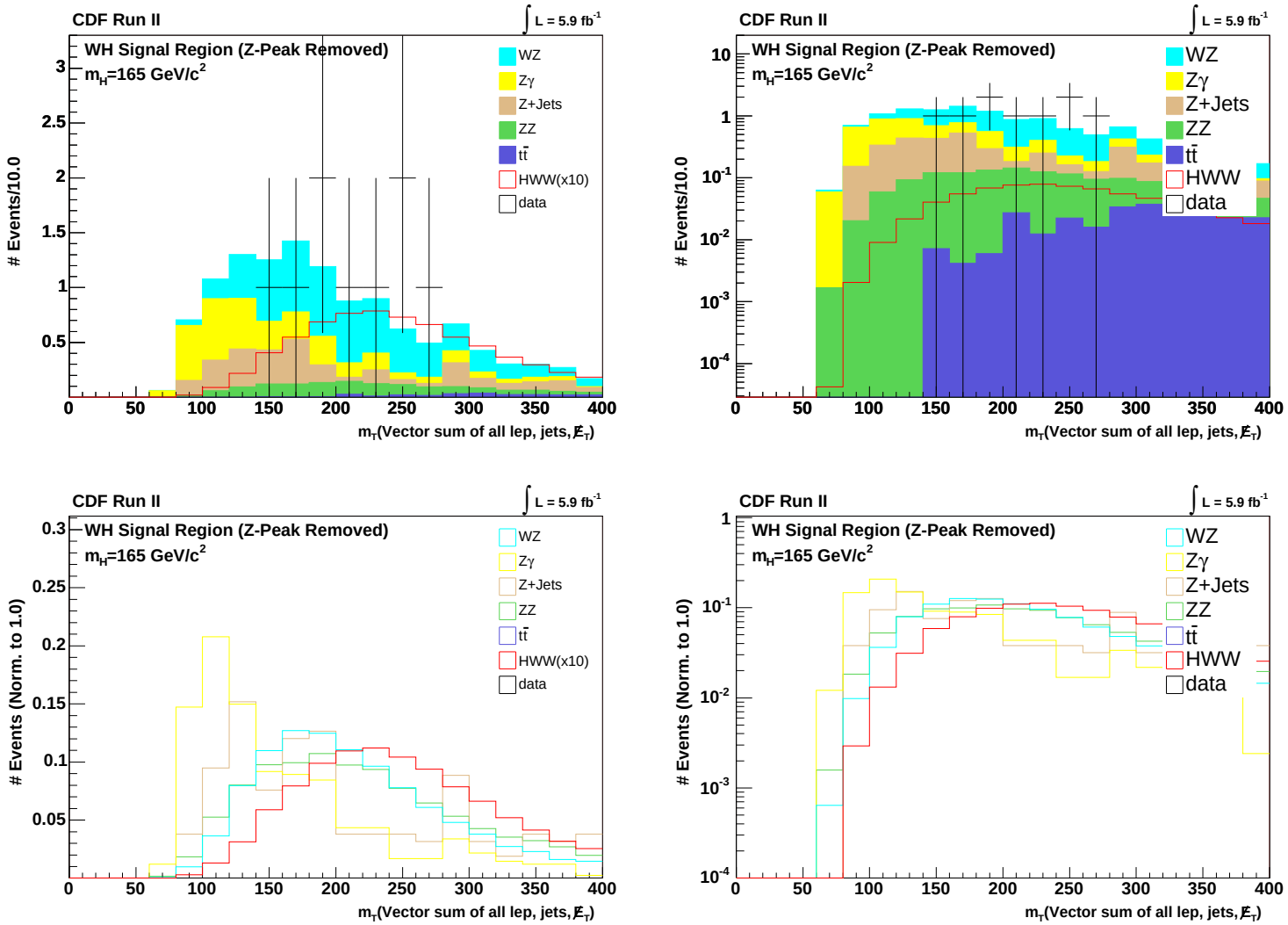
WH Signal: $\Delta\phi$ (2nd Lep, $\not\!\!E_T$)



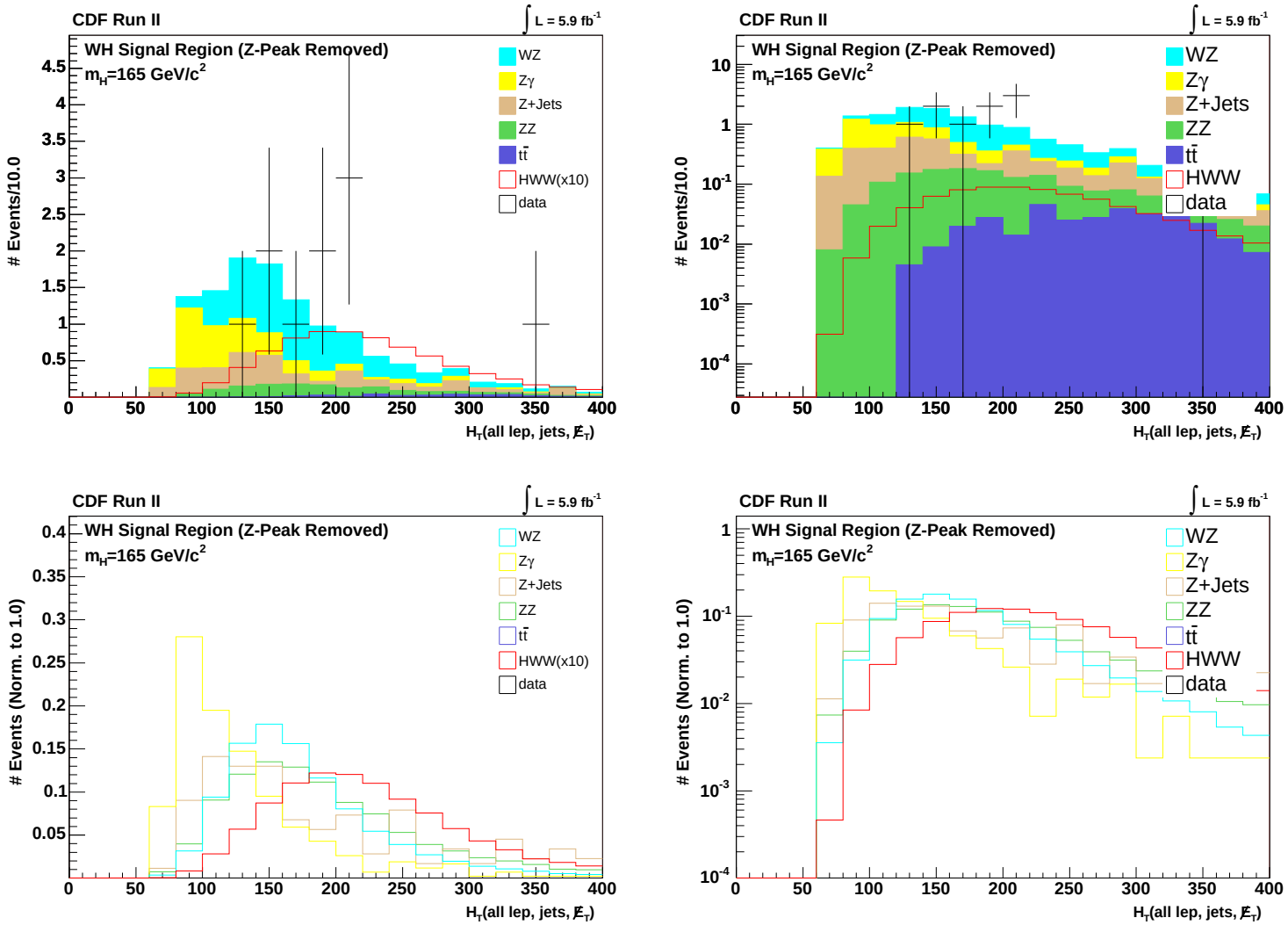
WH Signal: Inv. Mass(3rd Lep,$\not\!\!E_T$,Jets)



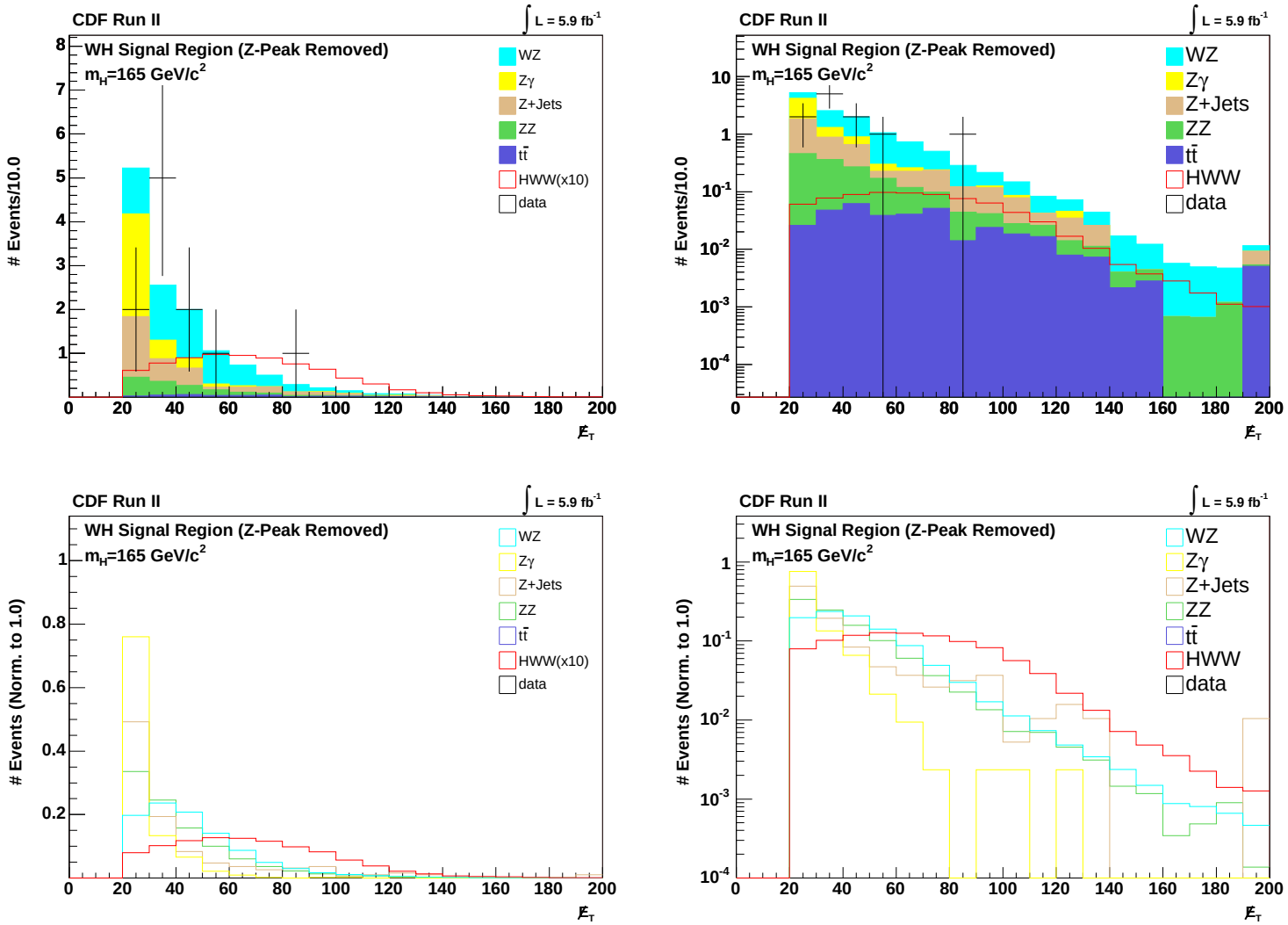
WH Signal: m_T(all Lep.,$\not{E}_T$, Jets)



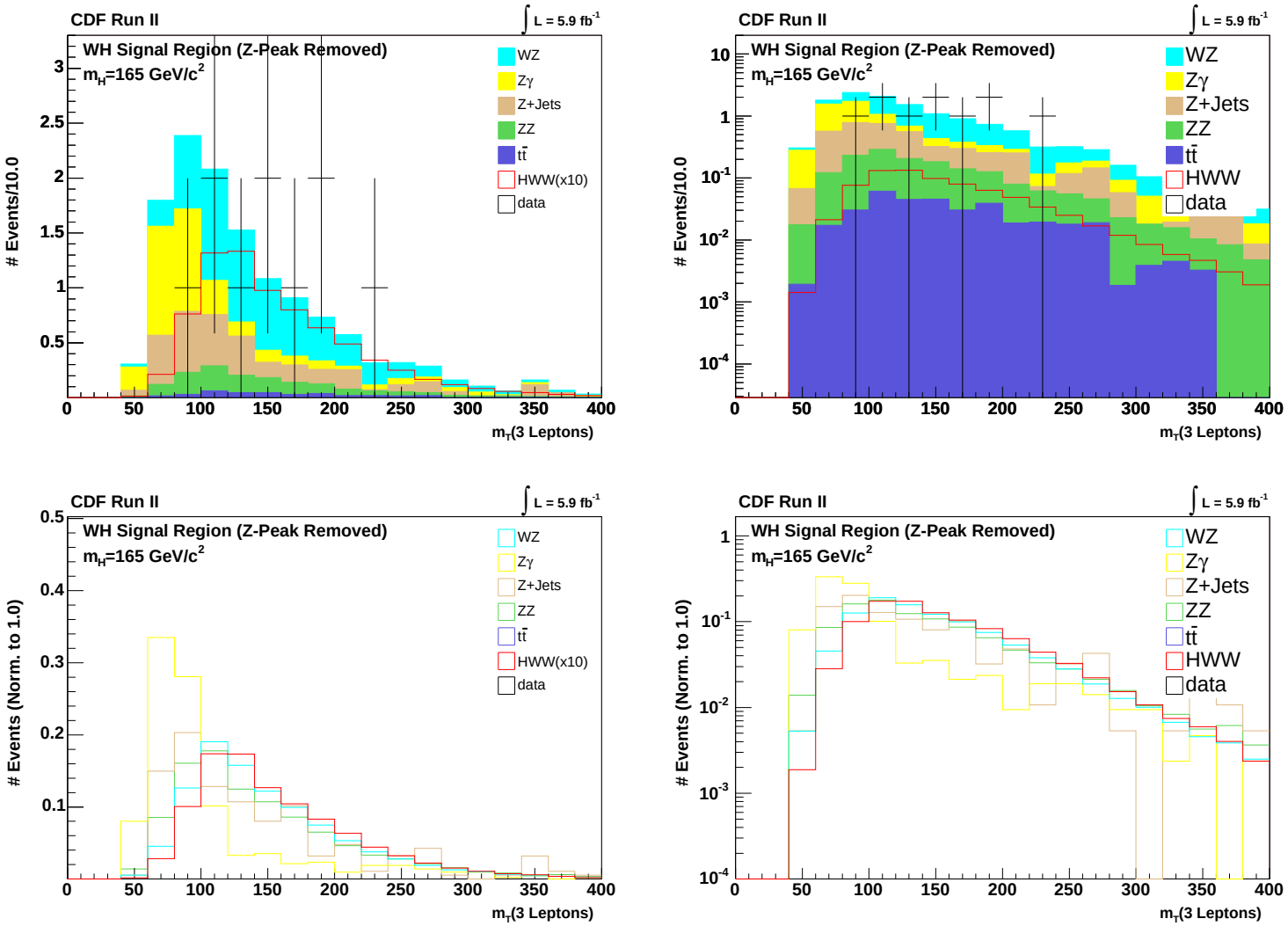
WH Signal: H_T


CDF Run II
∫ L = 5.9 fb⁻¹
WH Signal Region (Z-Peak Removed)
m_H=165 GeV/c²
WZ
Zγ
Z+Jets
ZZ
tt̄
HWW(x10)
HWW
data
# Events/10.0
# Events (Norm. to 1.0)
H_T(all lep, jets, ∅̸_T)

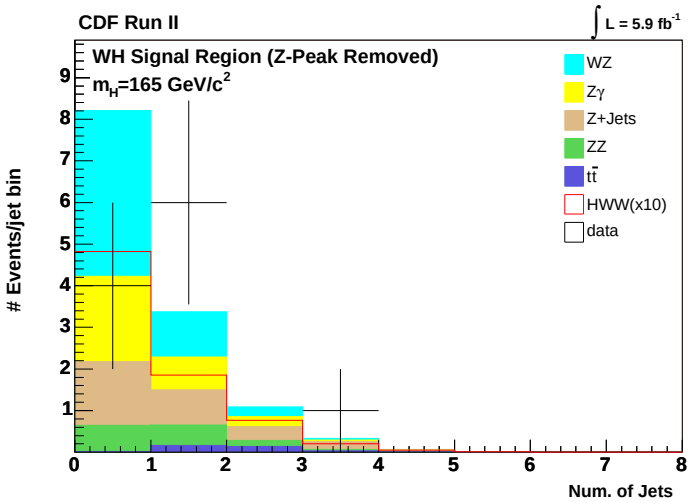
WH Signal: $\not\!\!E_T$

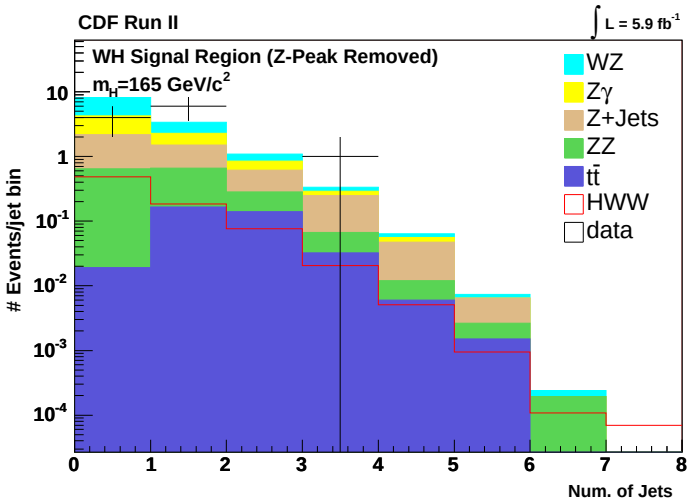


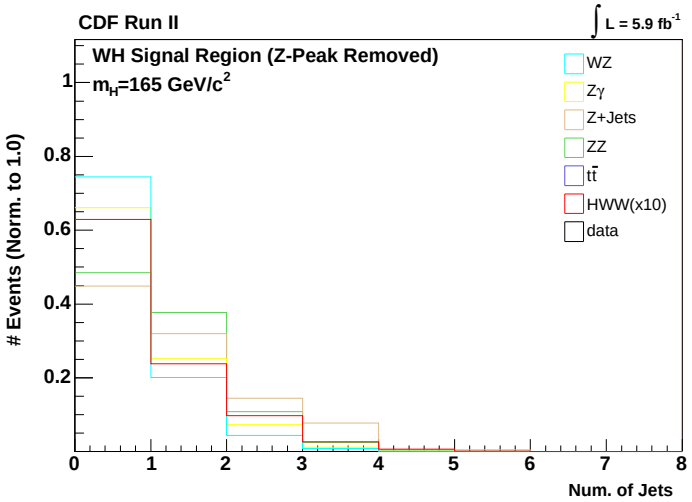
WH Signal: m_T trimass

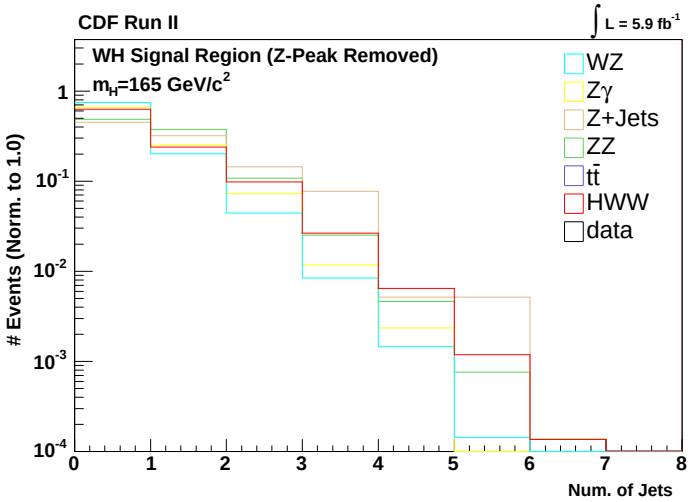


WH Signal: NJet

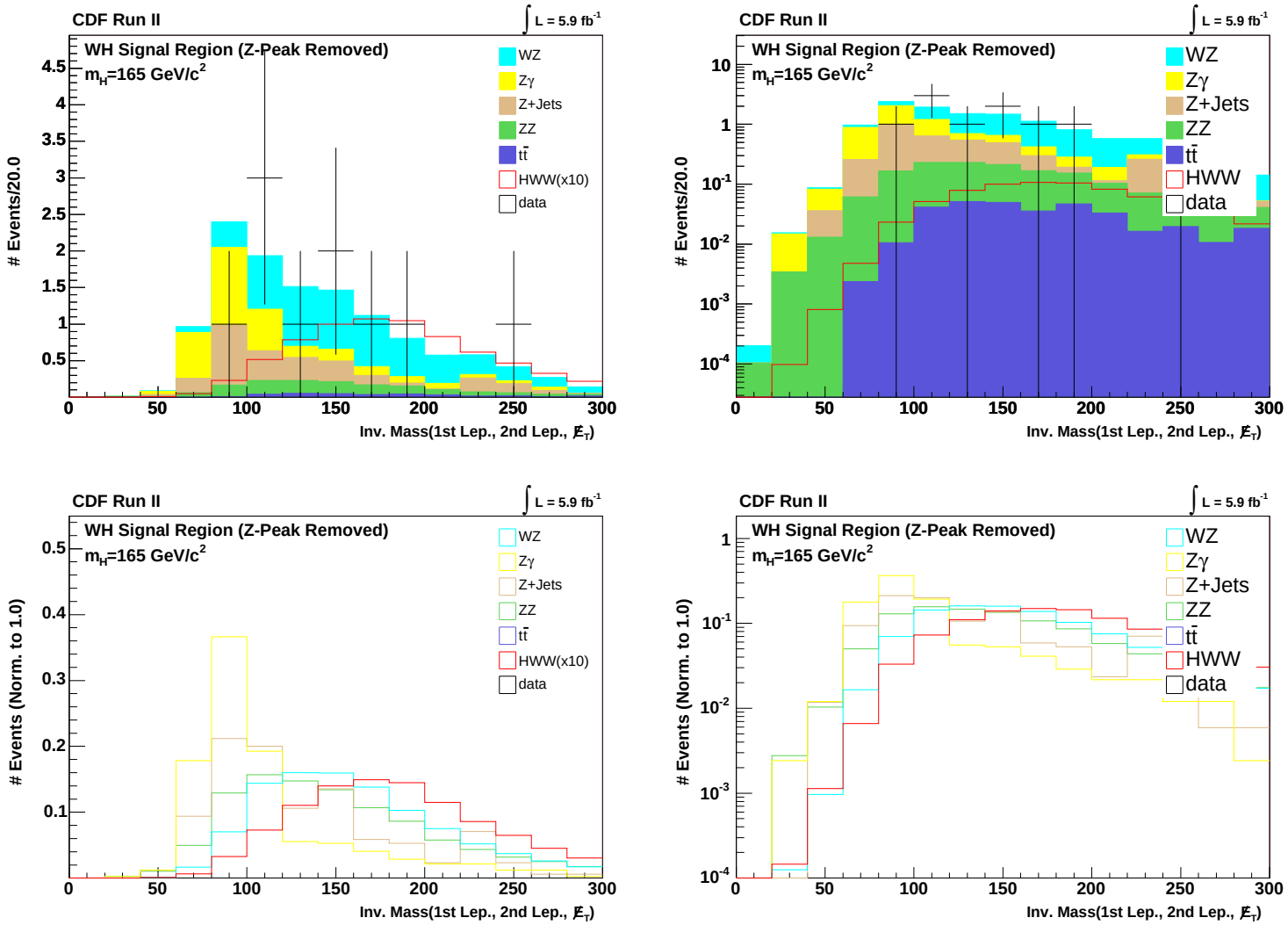




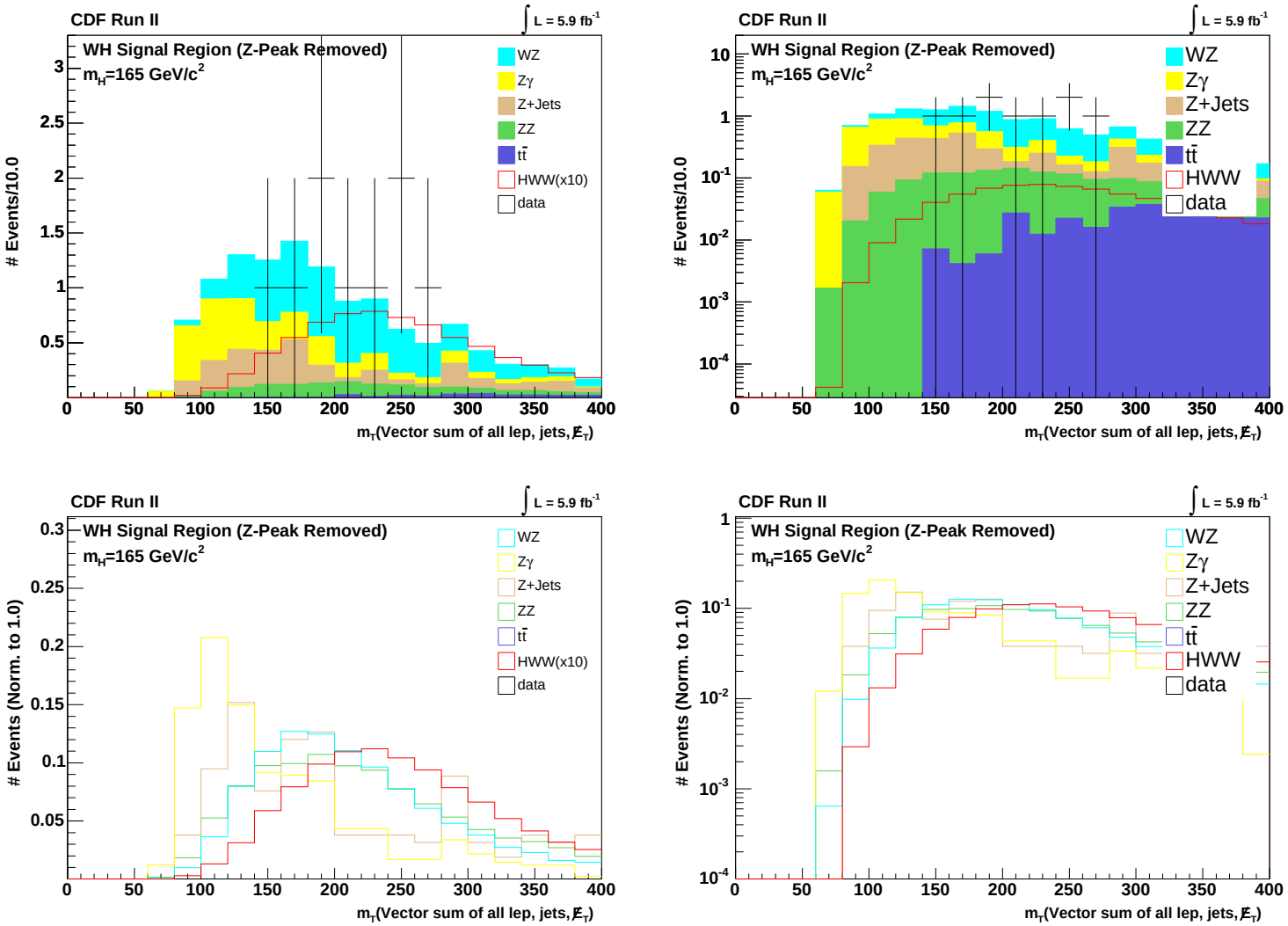




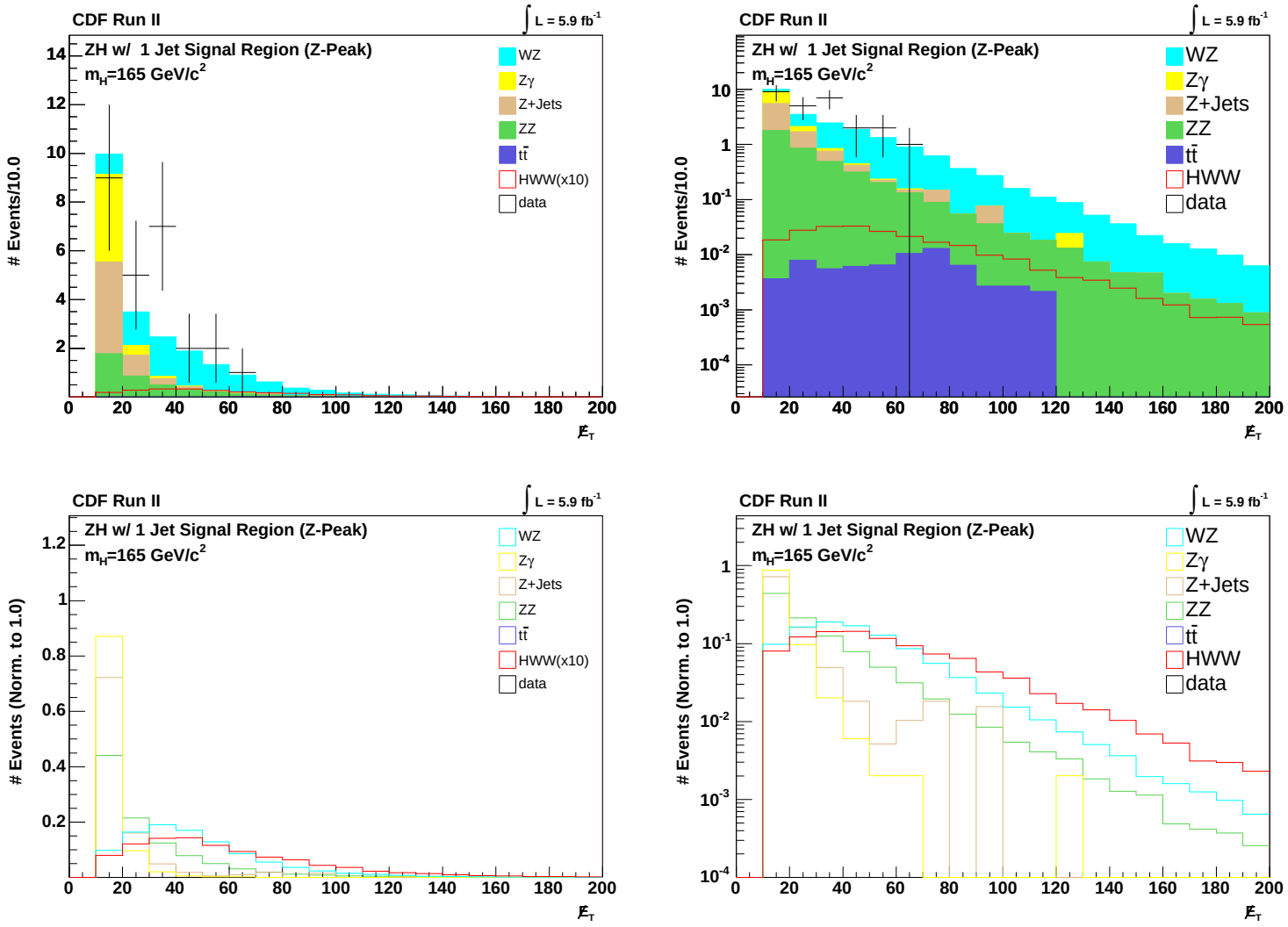
WH Signal: Inv. Mass(1st Lep., 2nd Lep., $\not\!\!E_T$)



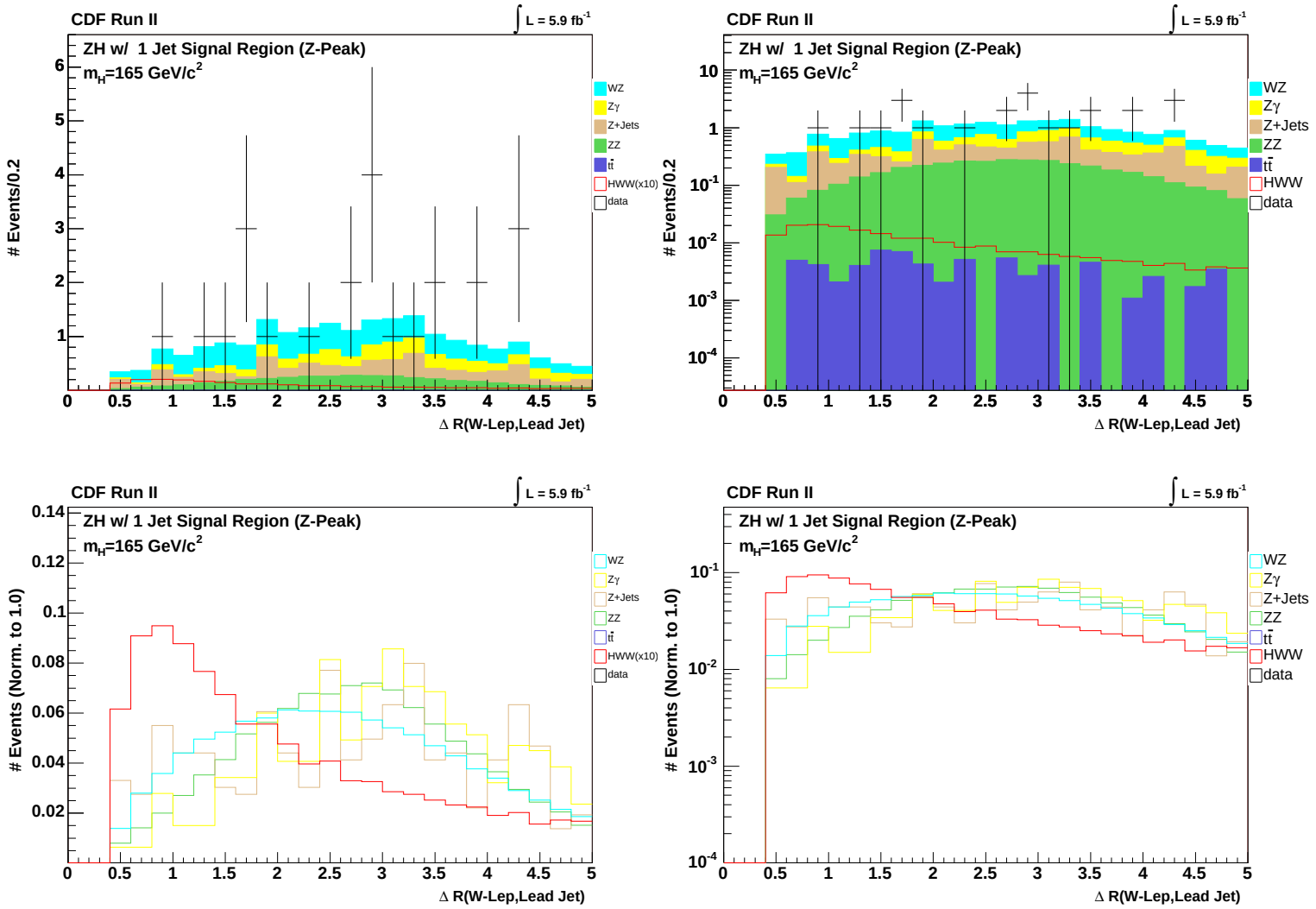
WH Signal: m_T (all leptons, jets, $\not{E}_T$)



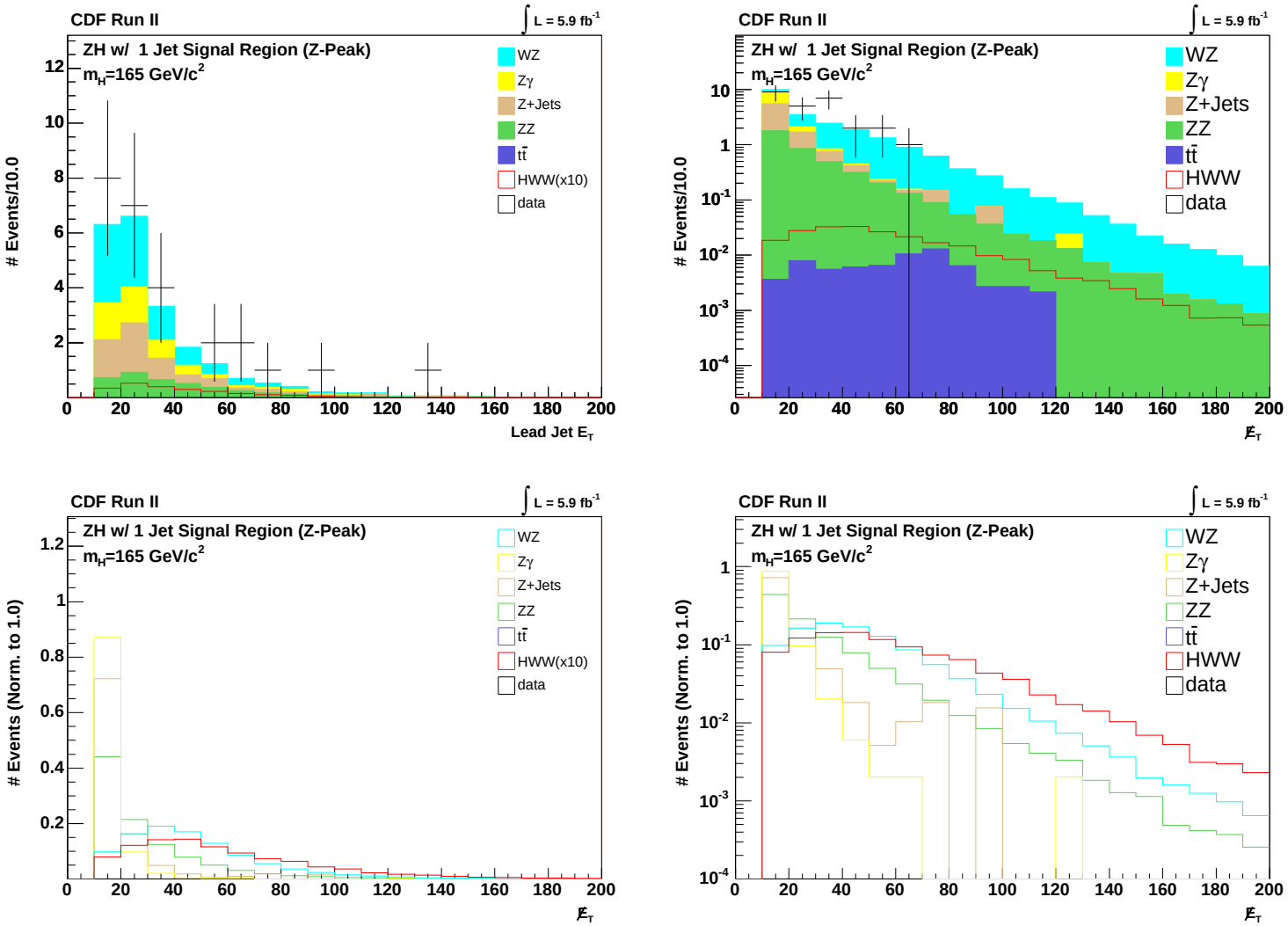
ZH 1 Jet Signal: $\not\!\!E_T$



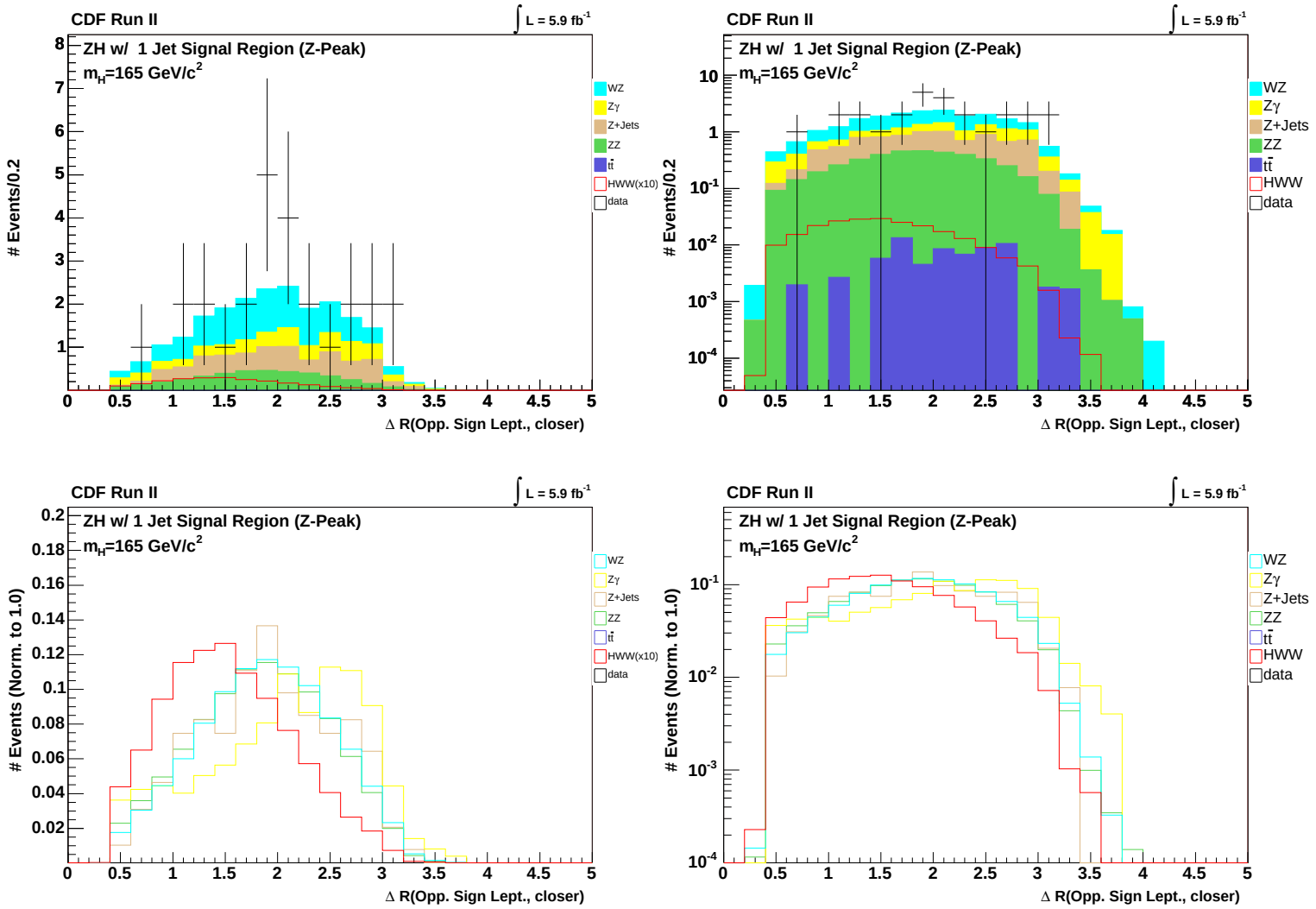
ZH 1 Jet Signal: ΔR(*W*-Lep, Lead Jet)



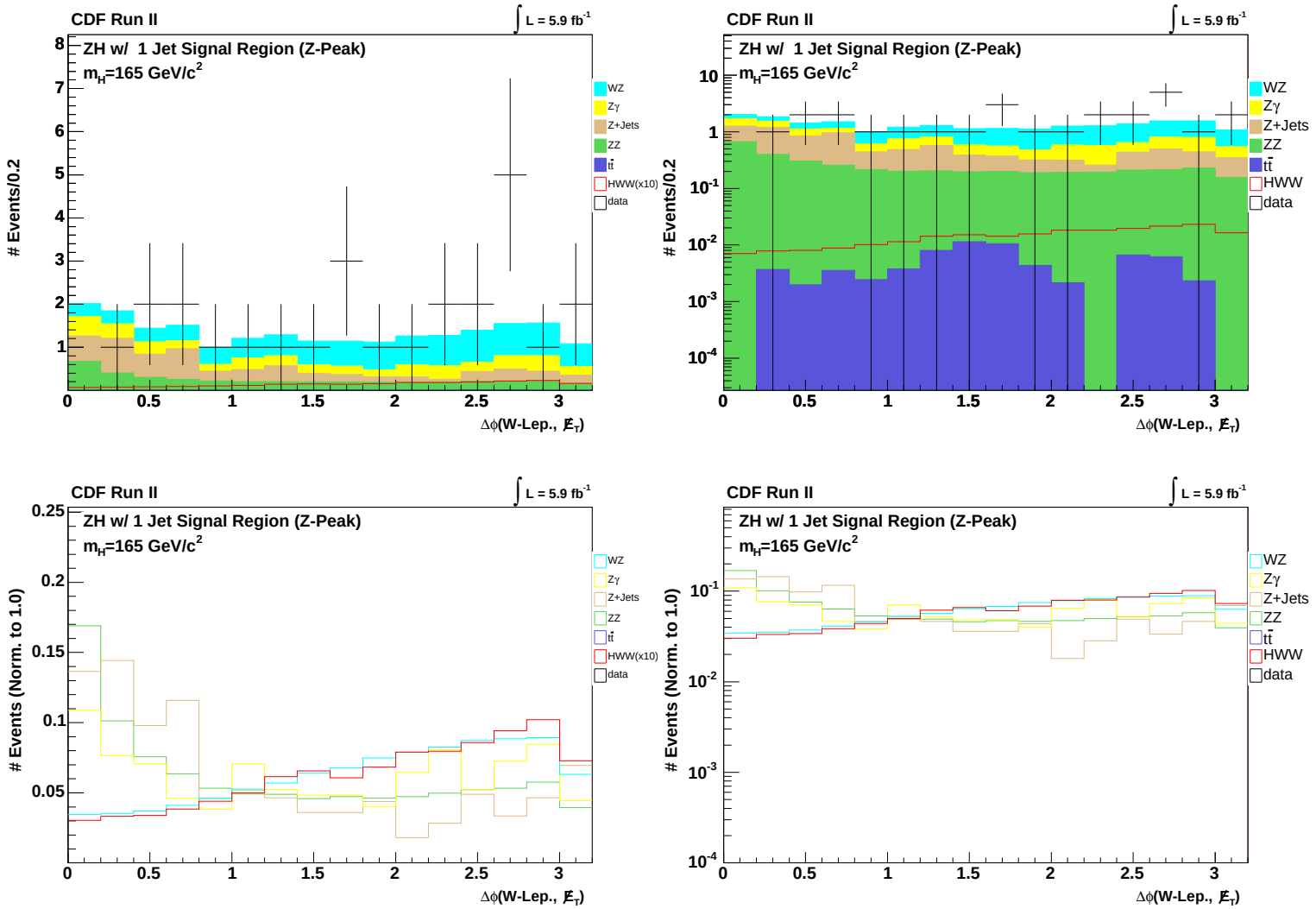
ZH 1 Jet Signal: Lead Jet E_T



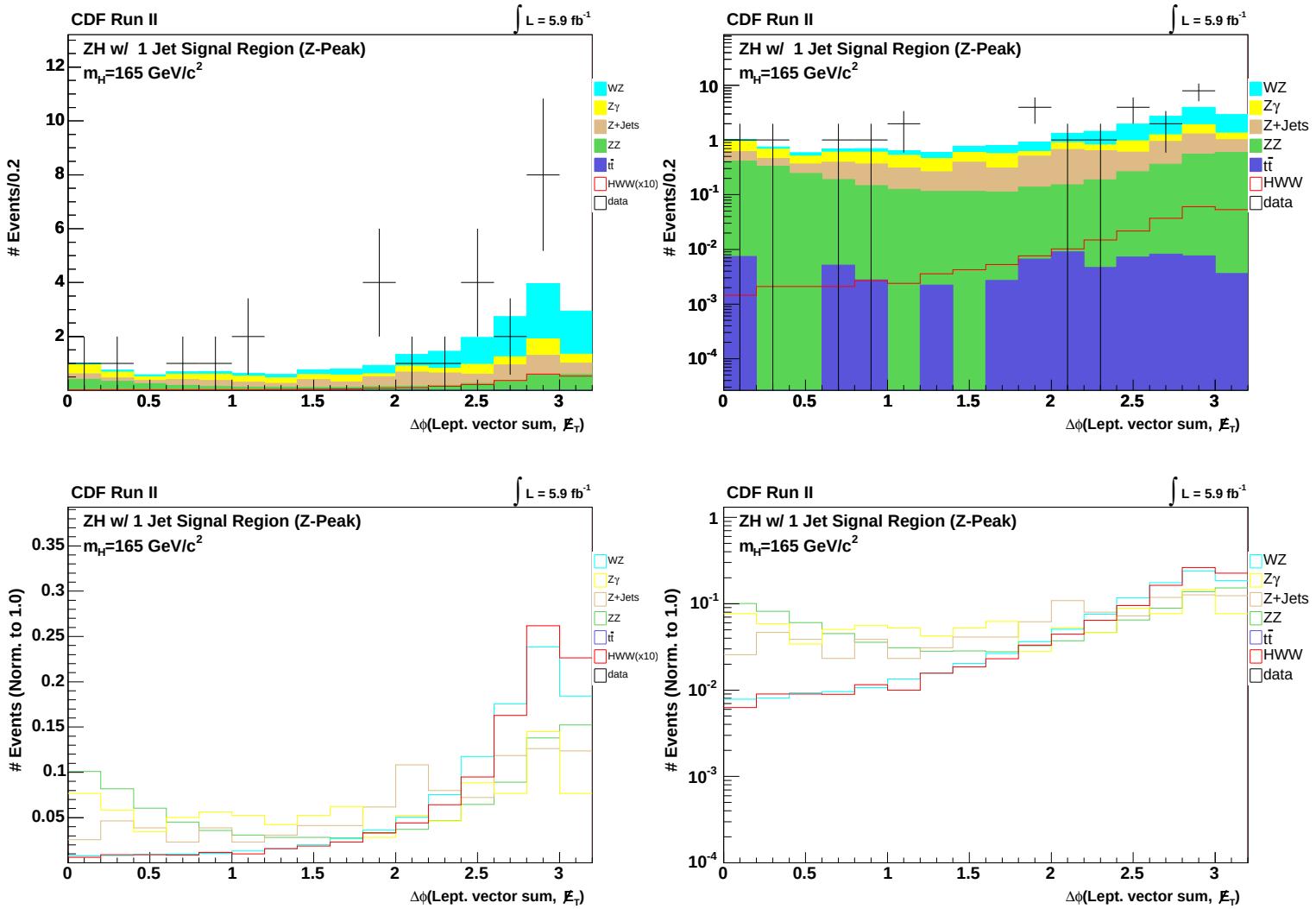
ZH 1 Jet Signal: ΔR Opp. Sign Close



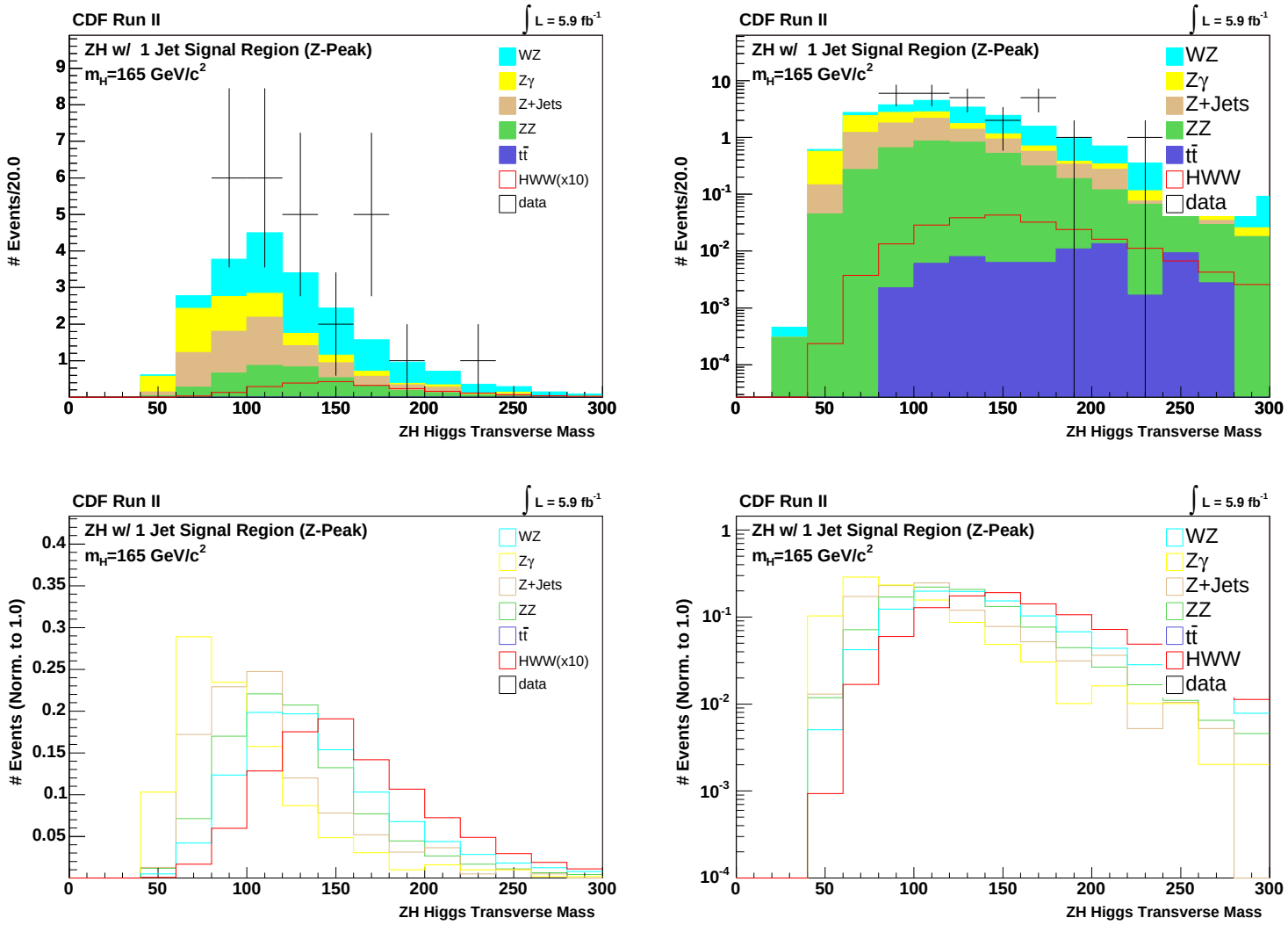
ZH 1 Jet Signal: $\Delta\phi(W\text{-Lep}, \not{E}_T)$



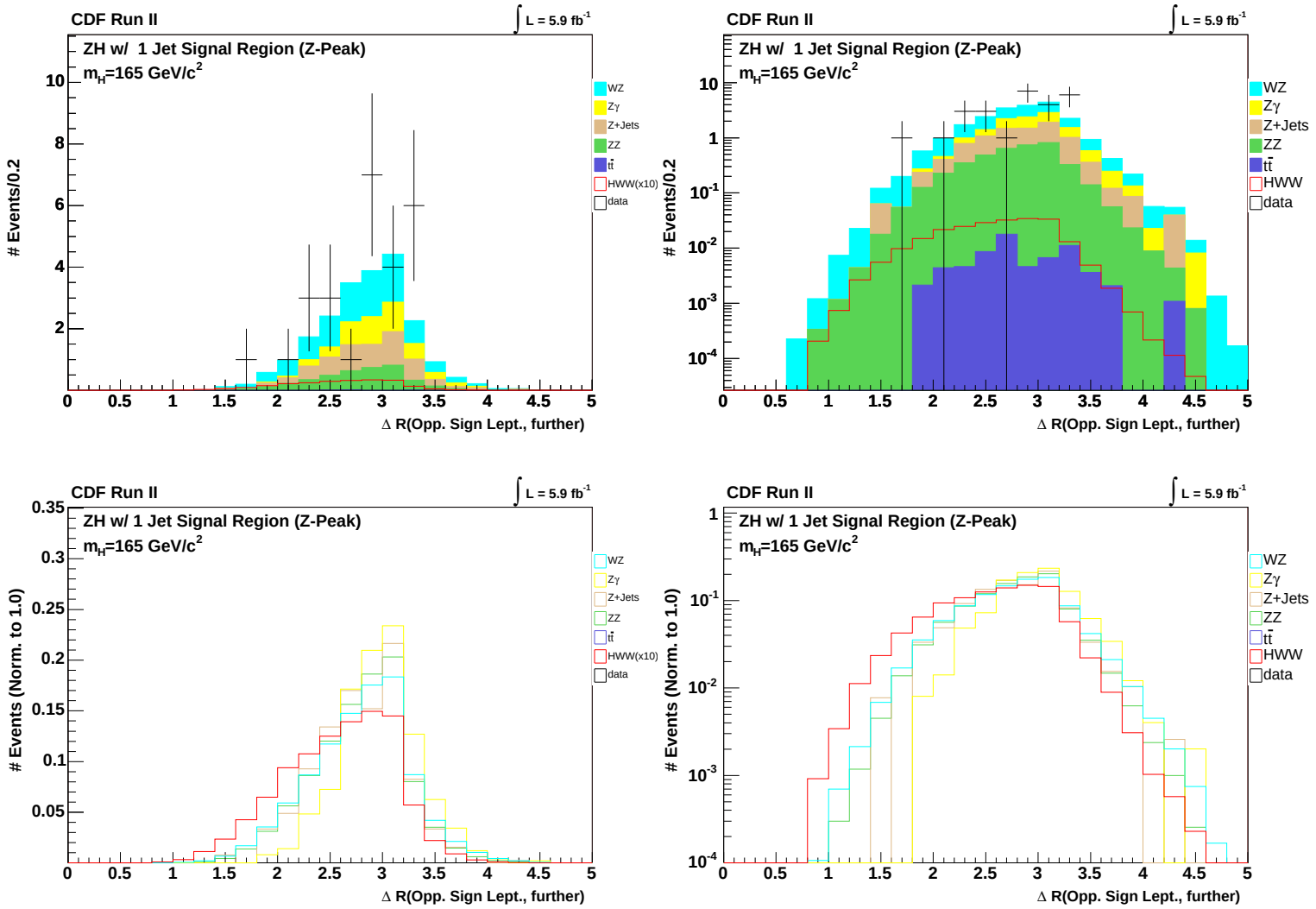
ZH 1 Jet Signal: $\Delta\phi$(Lepton sum, $\not\!\!E_T$)



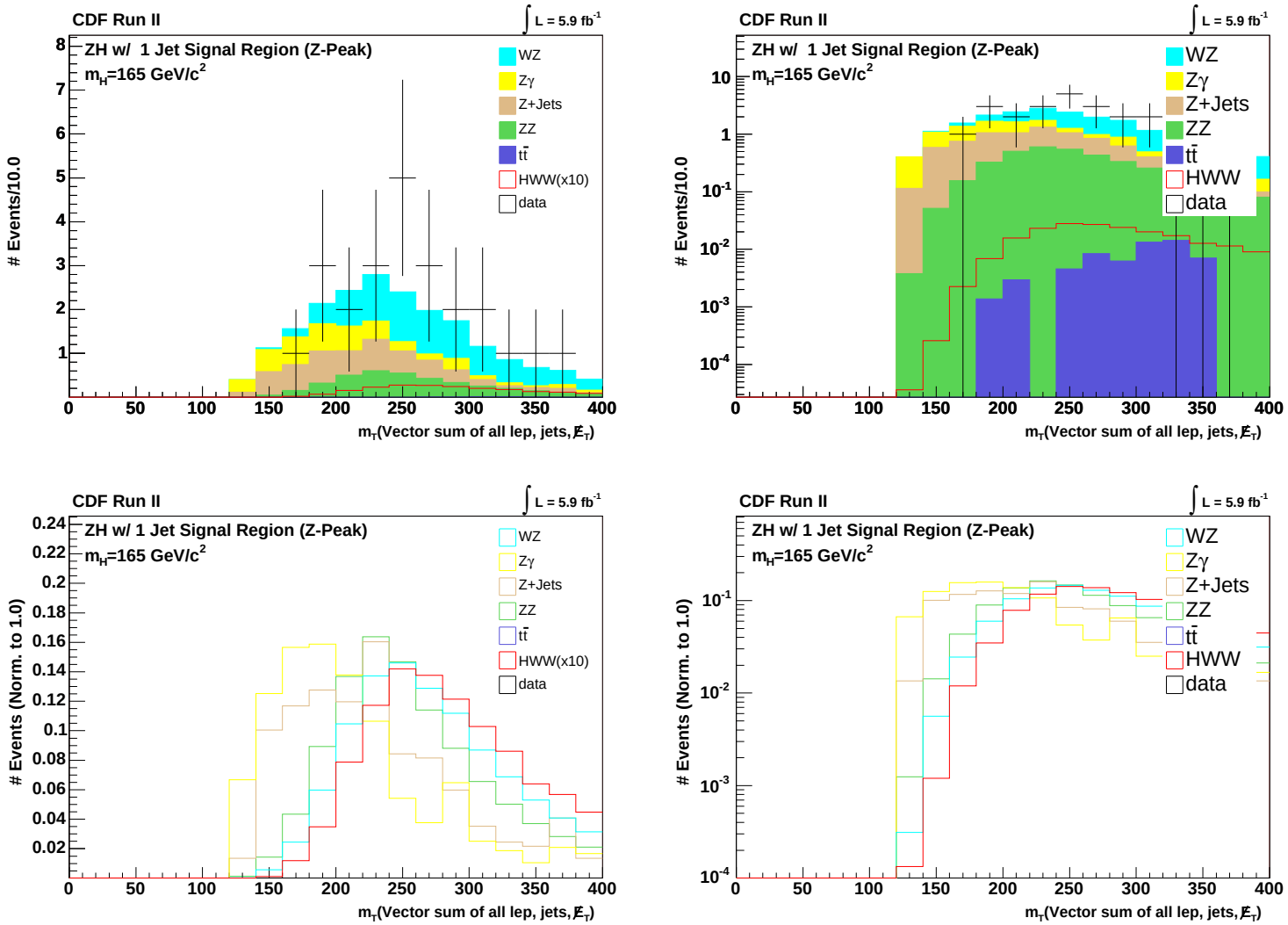
ZH 1 Jet Signal: *ZH* Higgs Mass



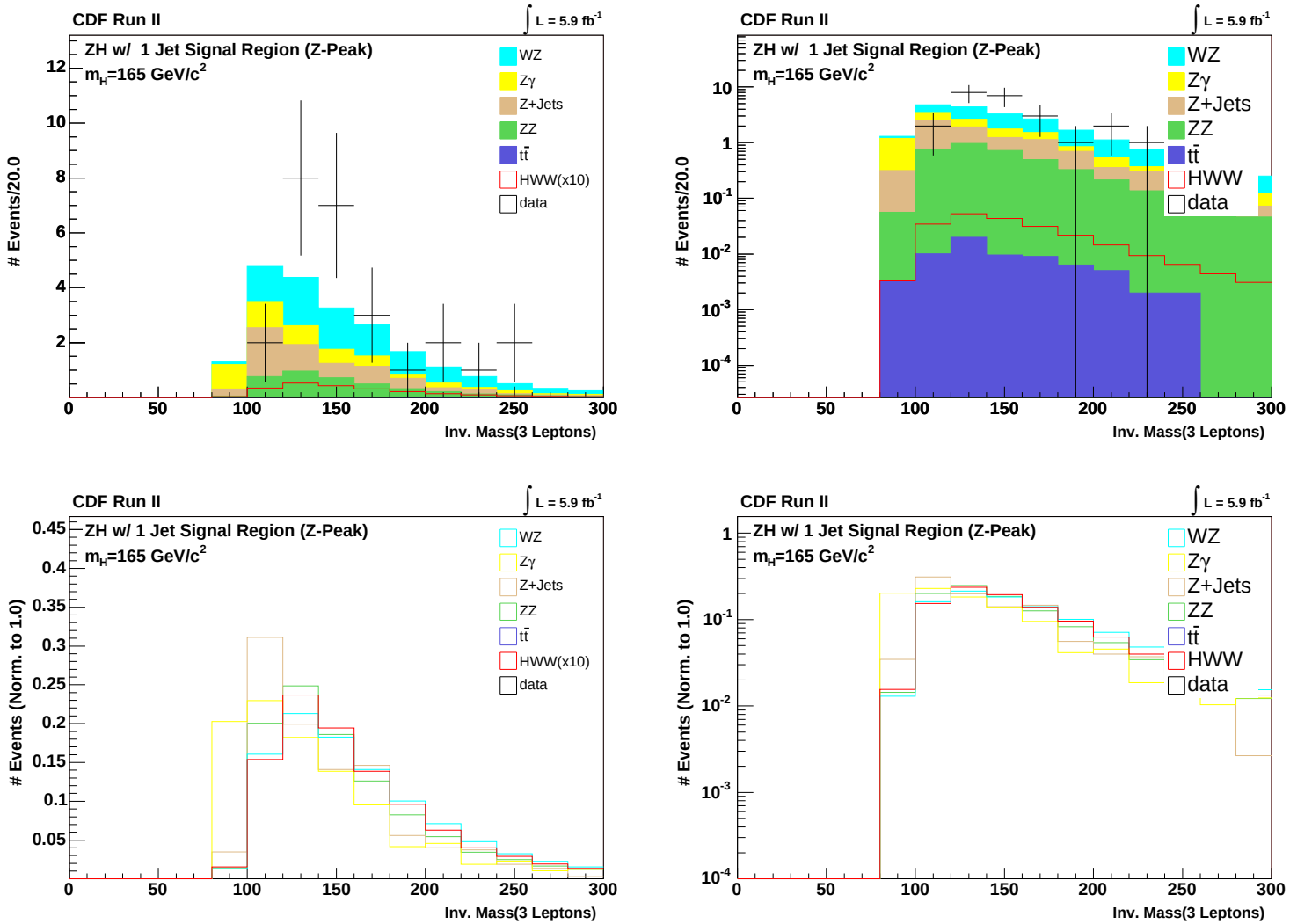
ZH 1 Jet Signal: ΔR(Opp. Sign Far Lep)



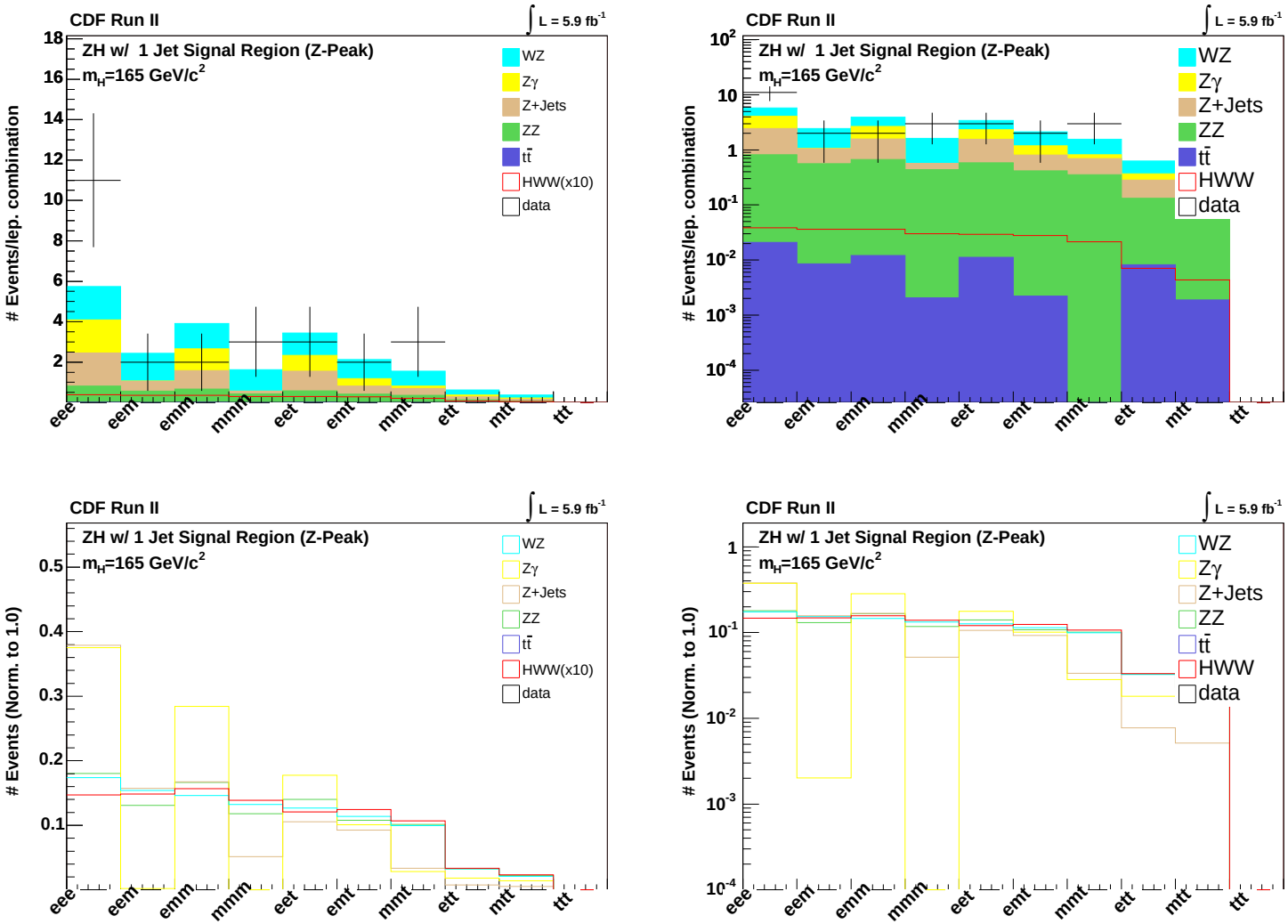
ZH 1 Jet Signal: m_T(All Lep, $\not\!\!E_T$, Jets)



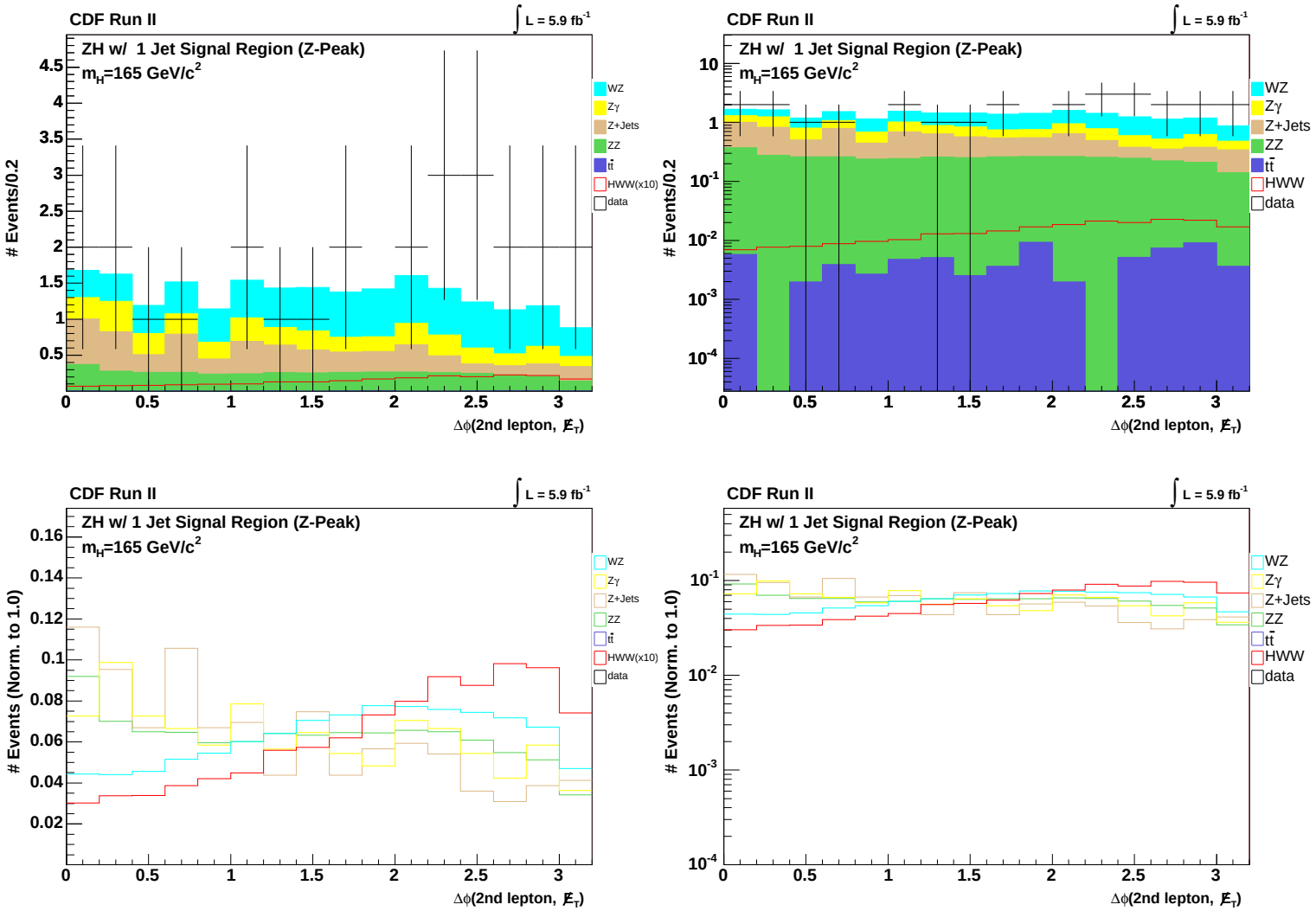
ZH 1 Jet Signal: Inv. Mass (all lep)



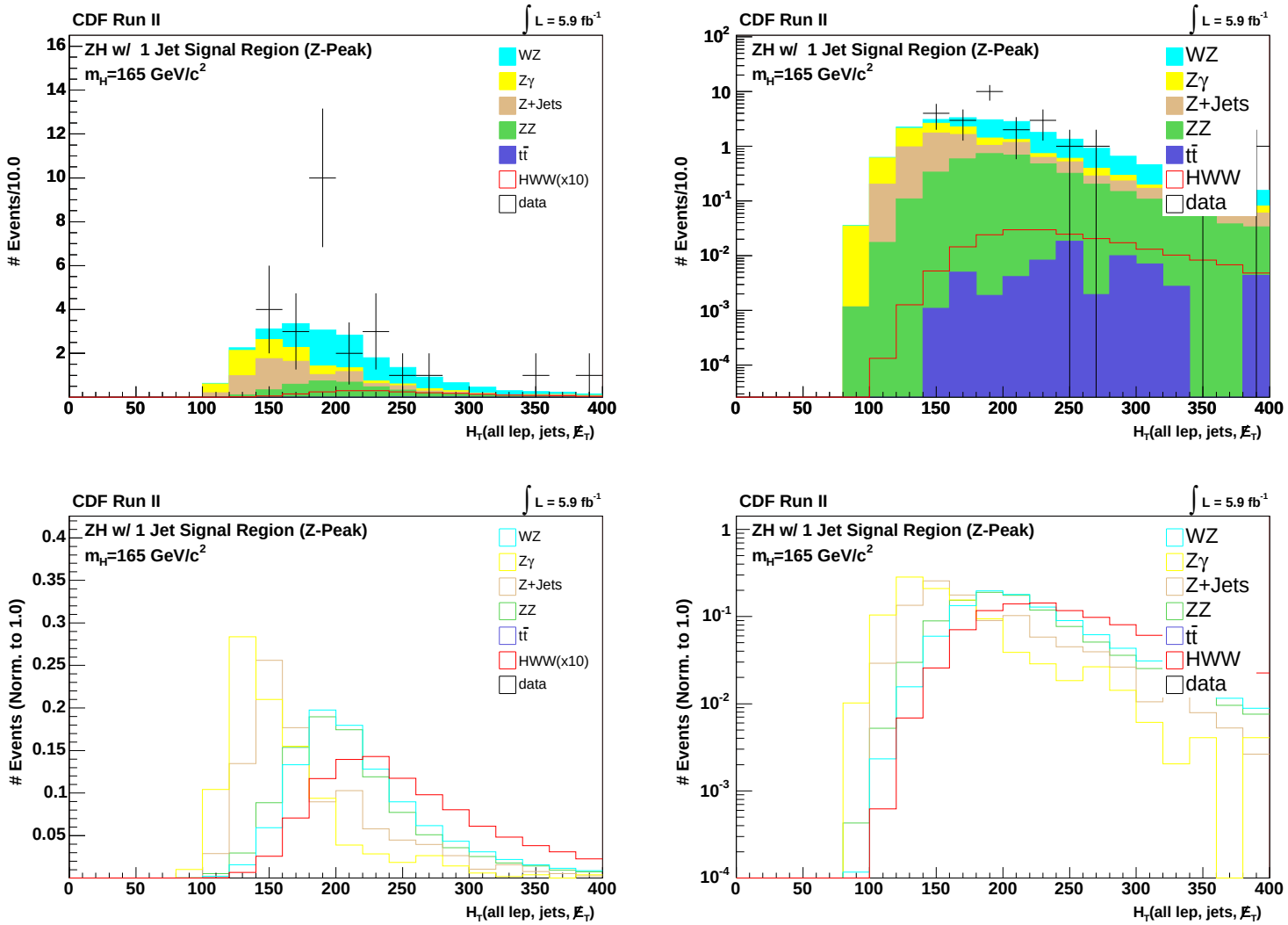
ZH 1 Jet Signal: Lepton Type Combinations



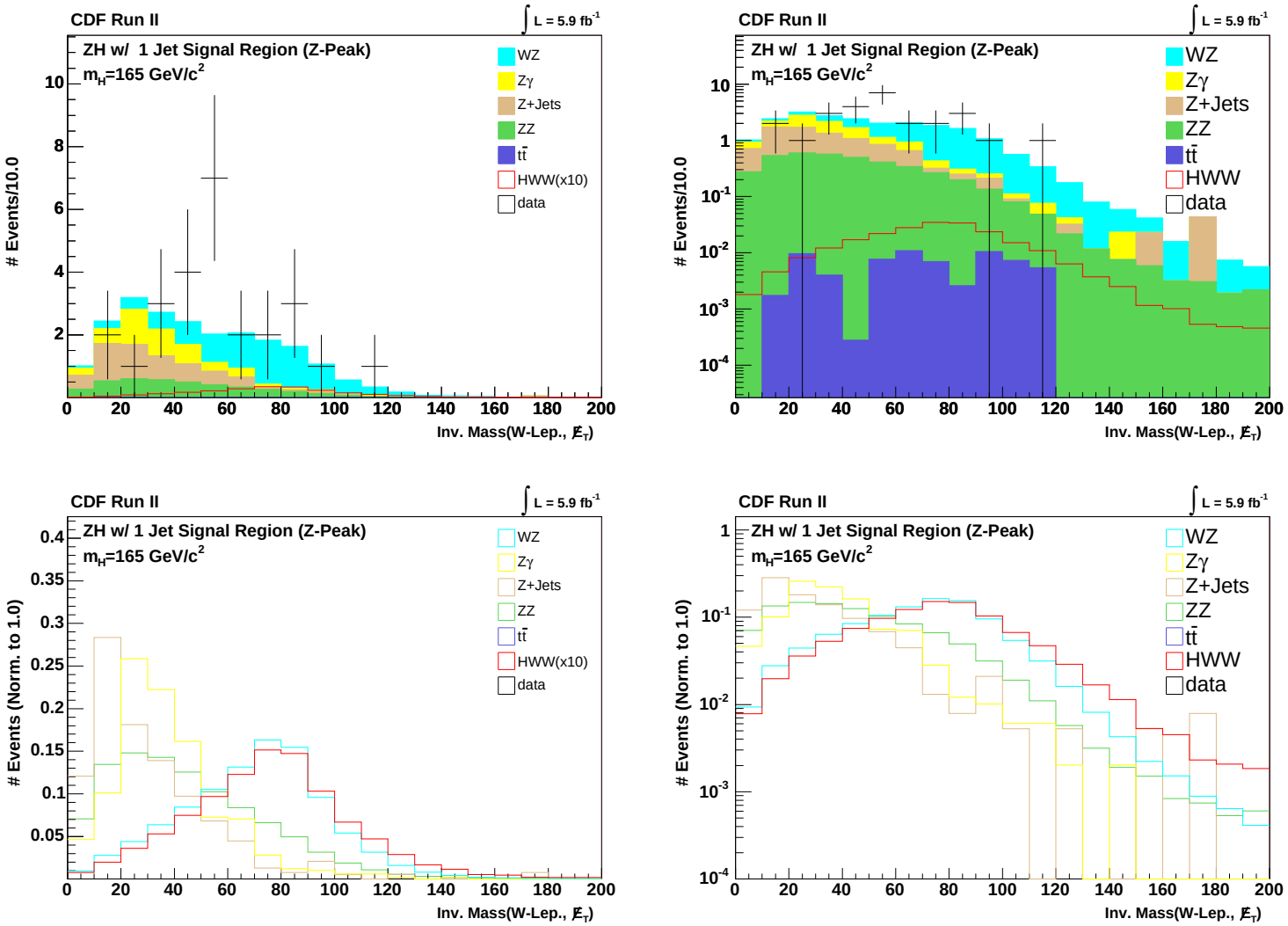
ZH 1 Jet Signal: $\Delta\phi$(2nd Lep, $\not\!\!E_T$)



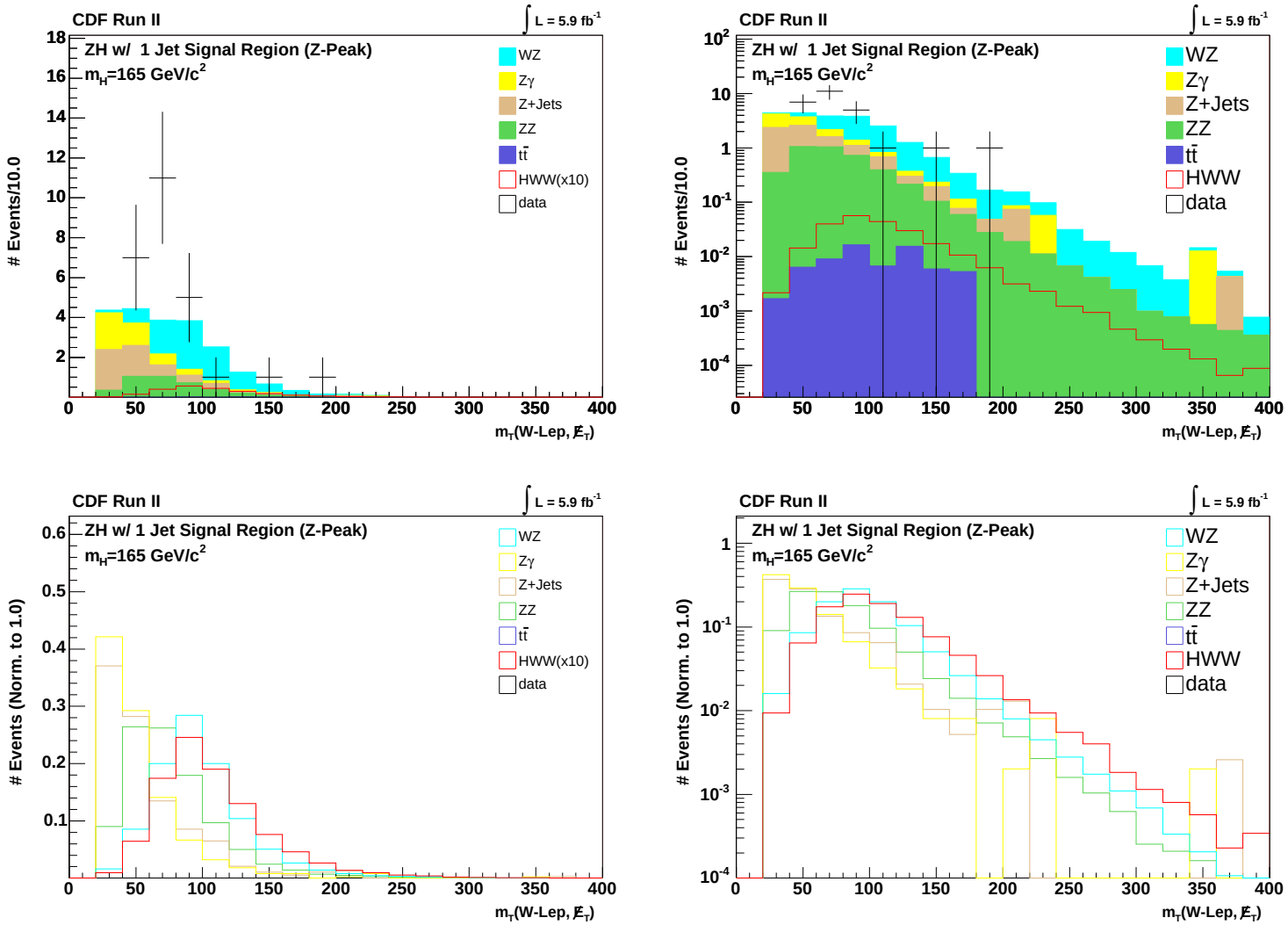
ZH 1 Jet Signal: H_T



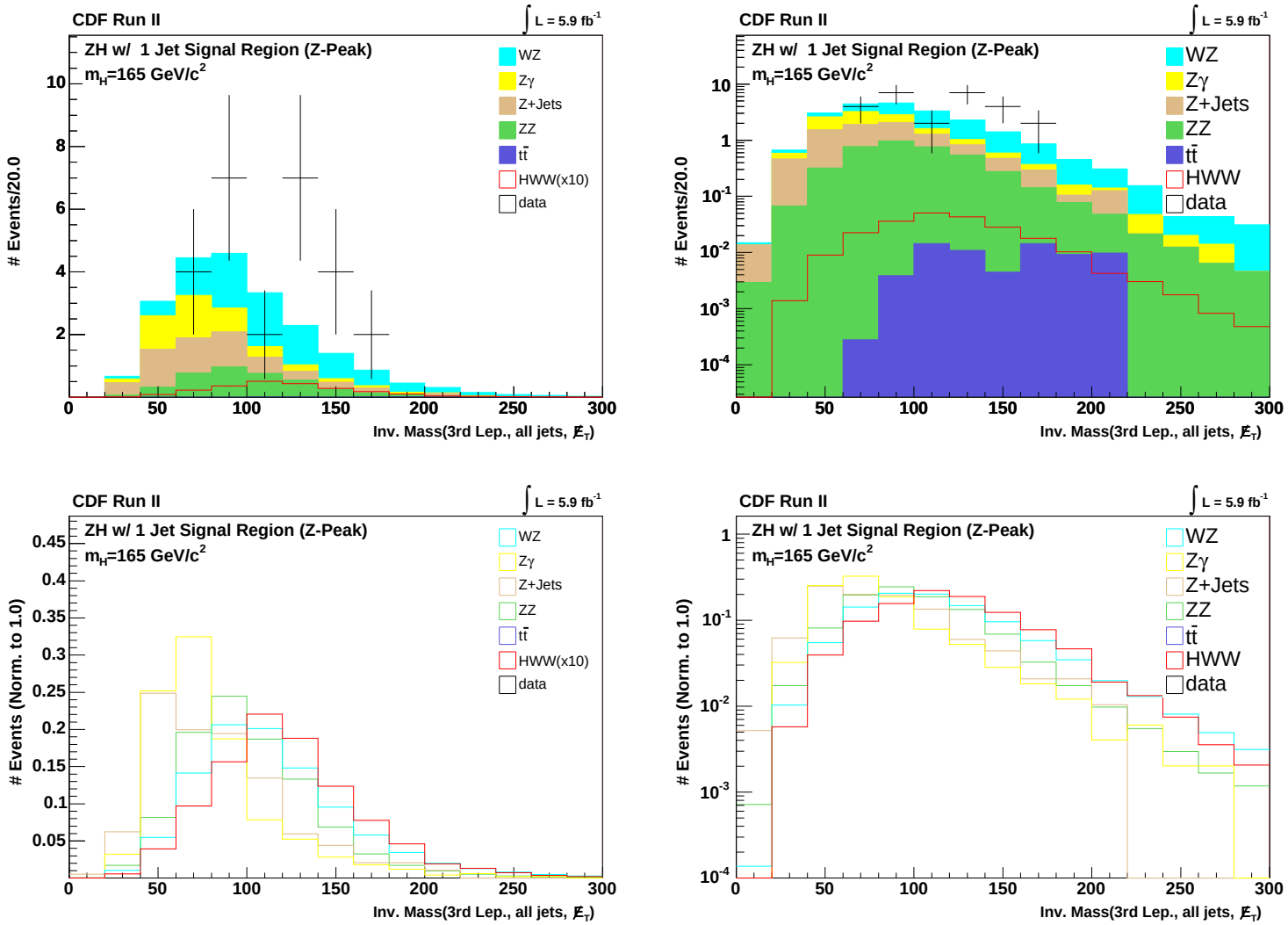
ZH 1 Jet Signal: Inv. Mass (W-lep, $\not{E}_T$)



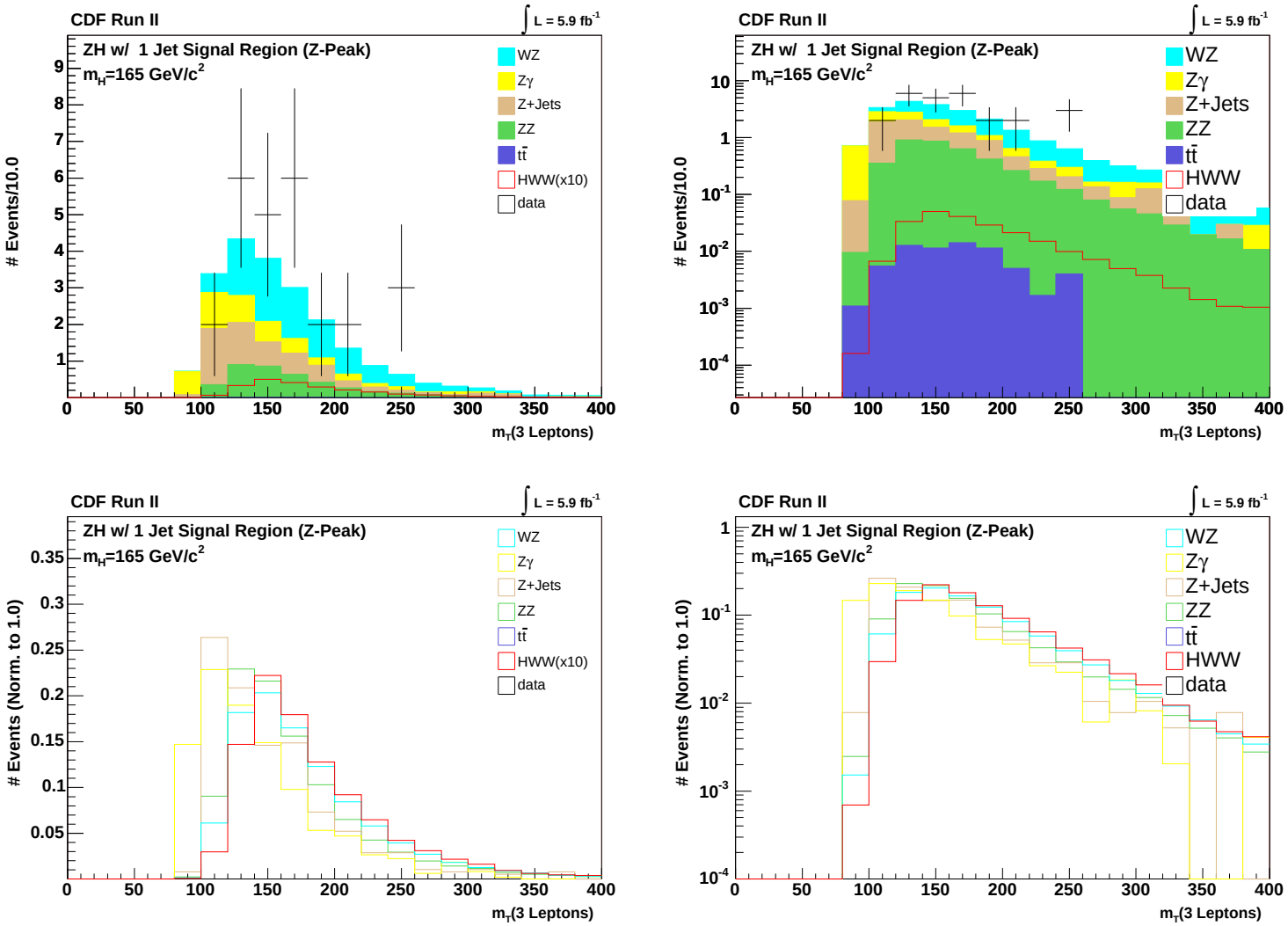
ZH 1 Jet Signal: m_T (W-lep, $\not{E}_T$)



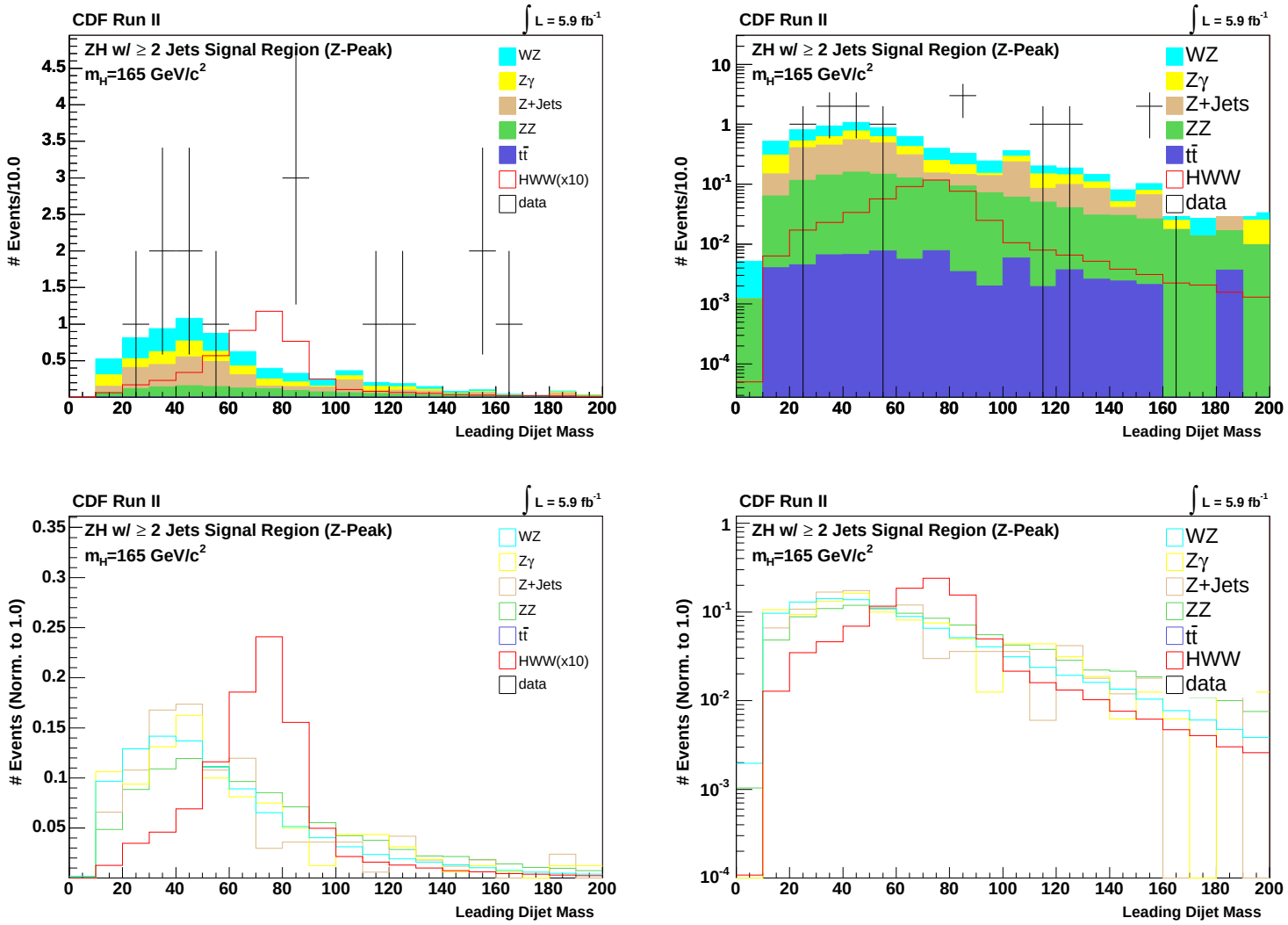
ZH 1 Jet Signal: Inv. Mass (lep 3, $\not\!\!E_T$, Jets)



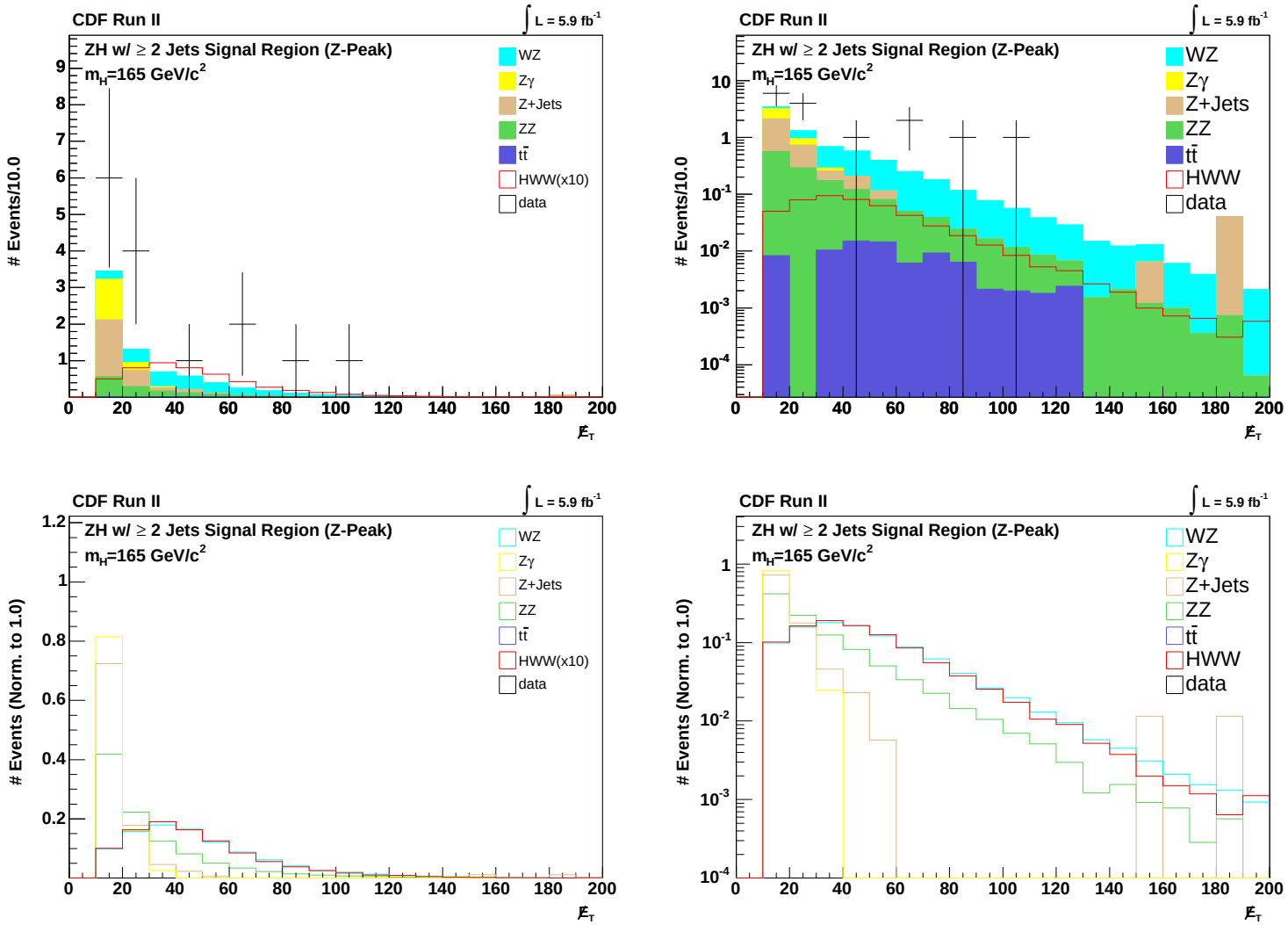
ZH 1 Jet Signal: m_T(3 leptons)



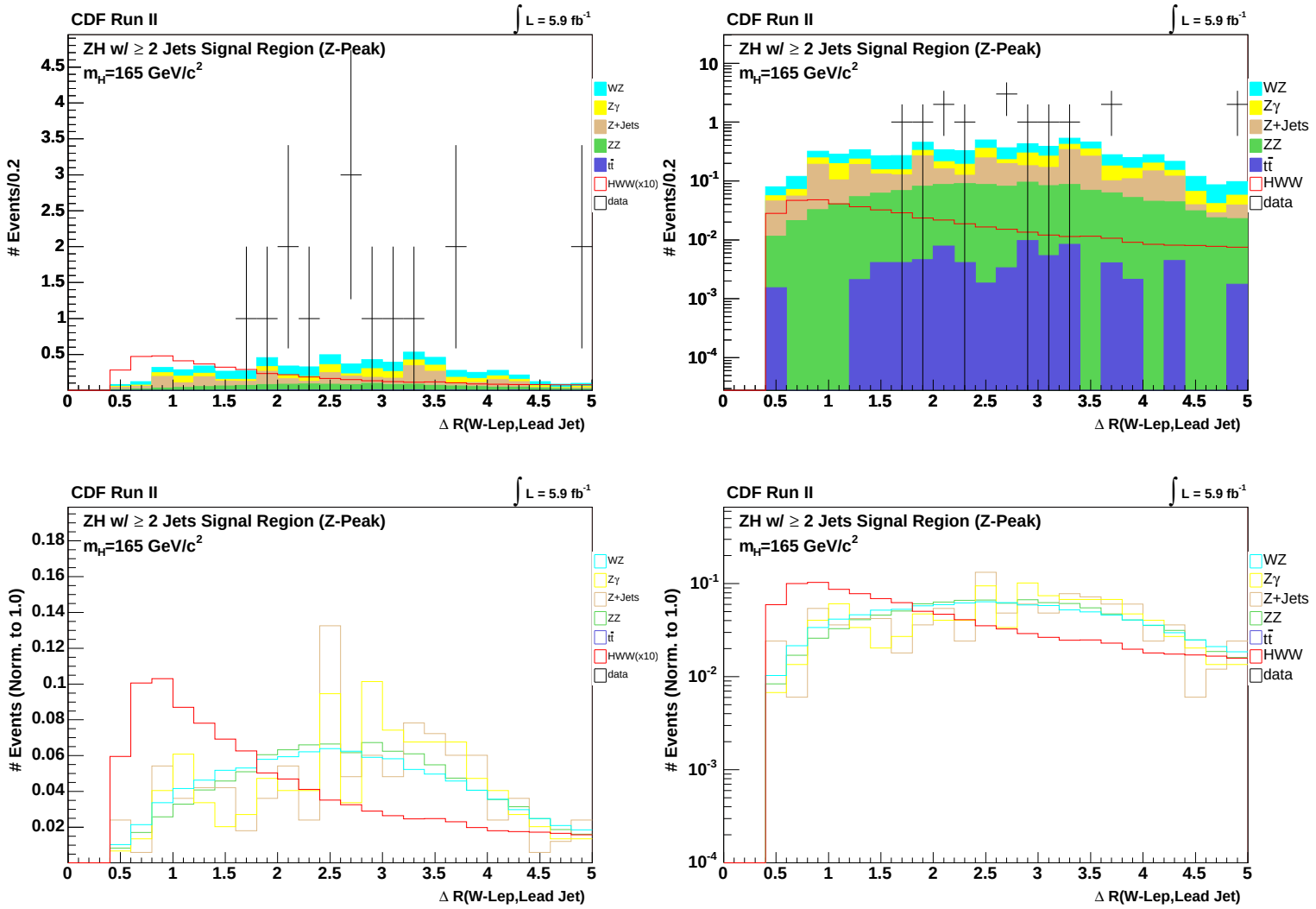
$ZH \geq 2$ Jet Signal: Inv. Mass(1st & 2nd Jets)



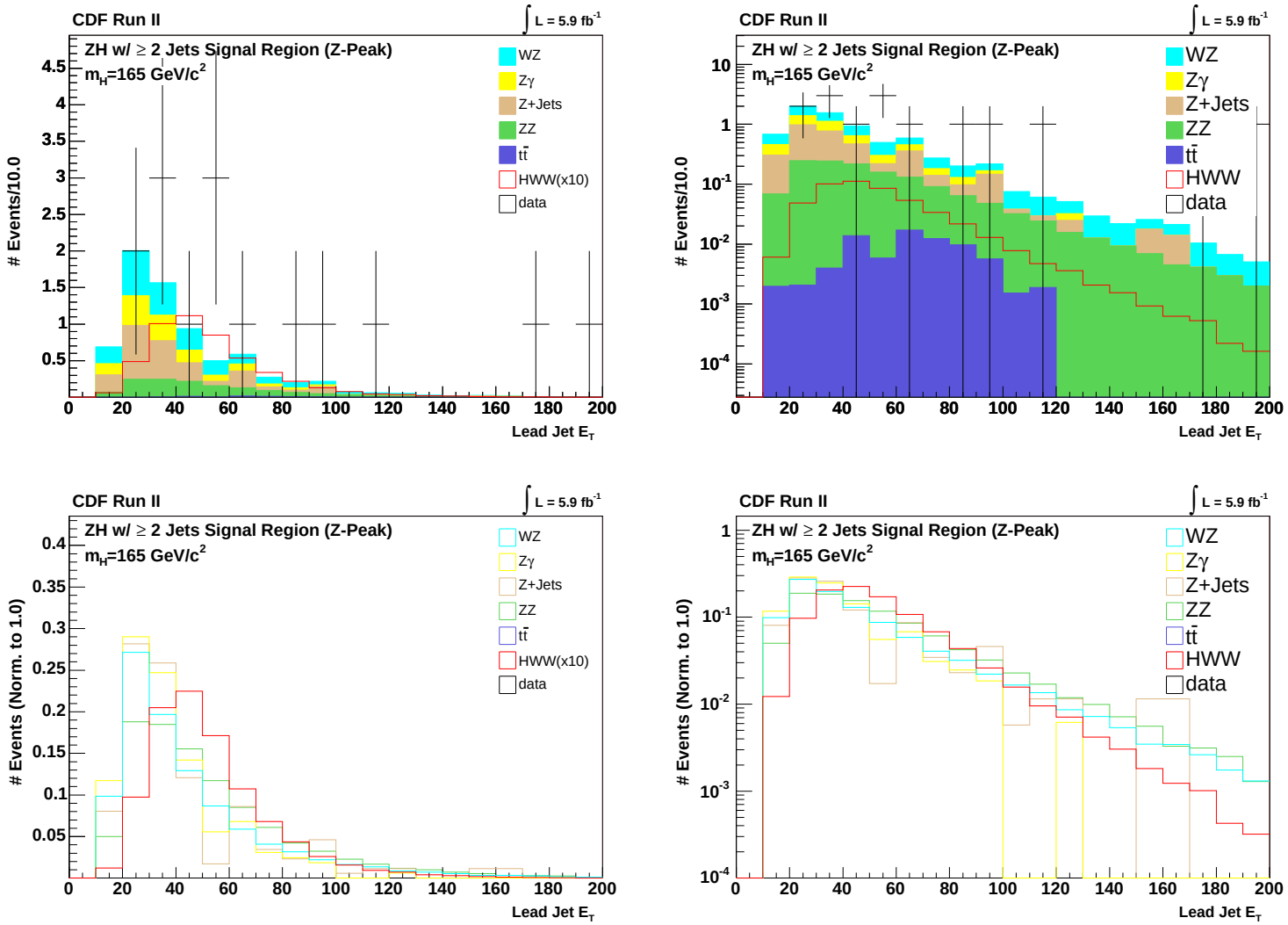
$ZH \geq 2$ Jet Signal: $\not\!\!E_T$



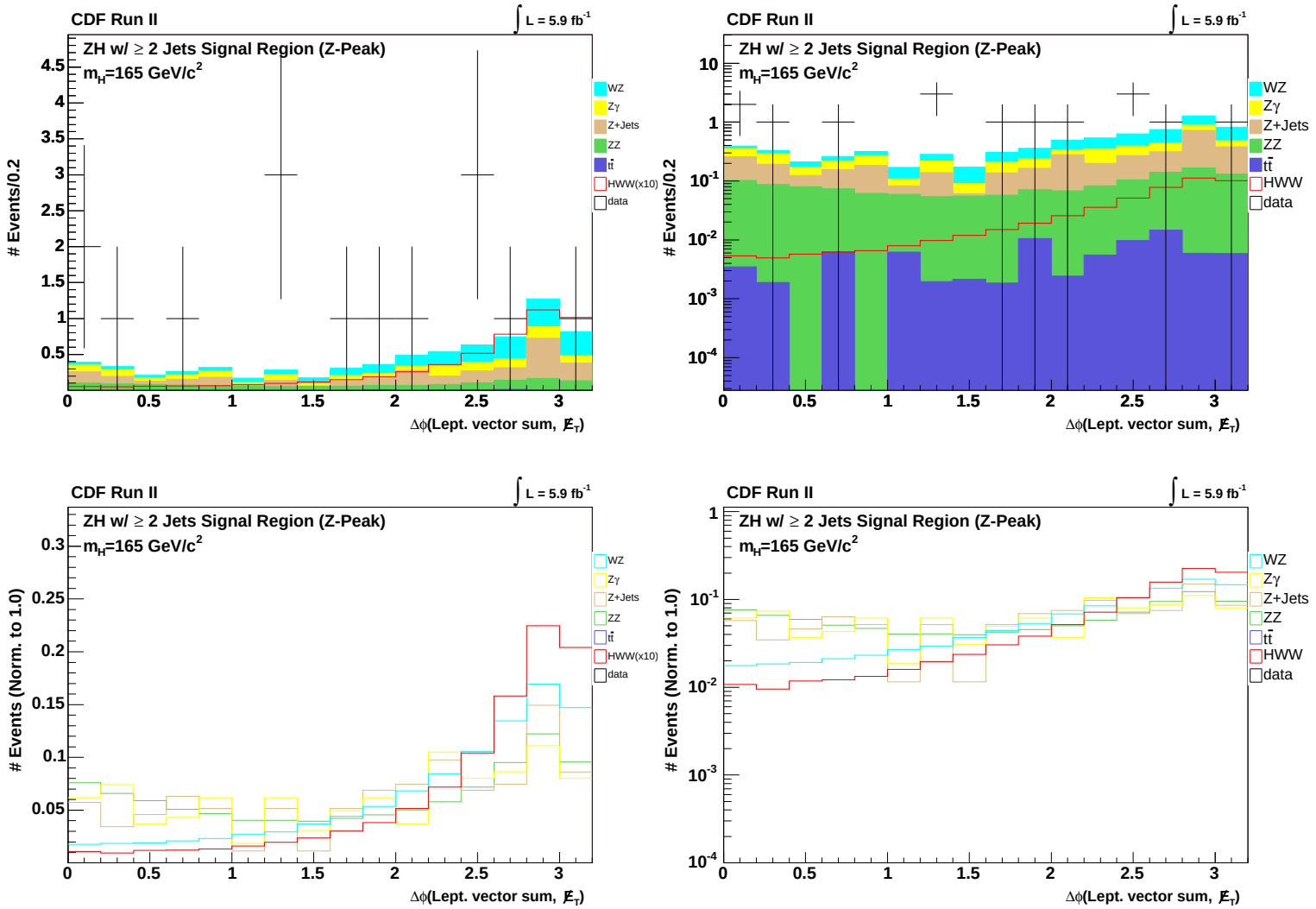
$ZH \geq 2$ Jet Signal: $\Delta R(W\text{-Lep, Lead Jet})$



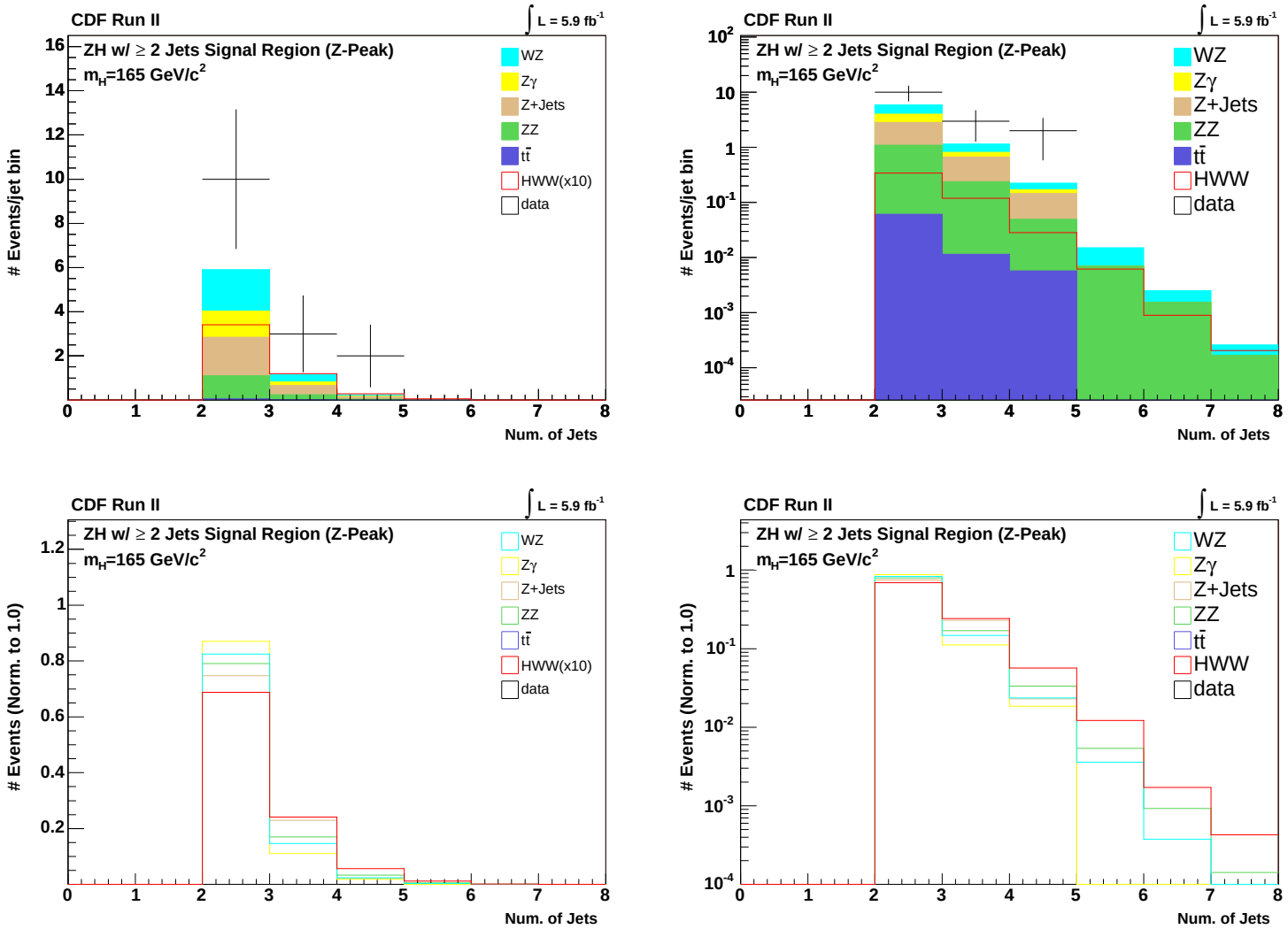
$ZH \geq 2$ Jet Signal: Lead Jet E_T



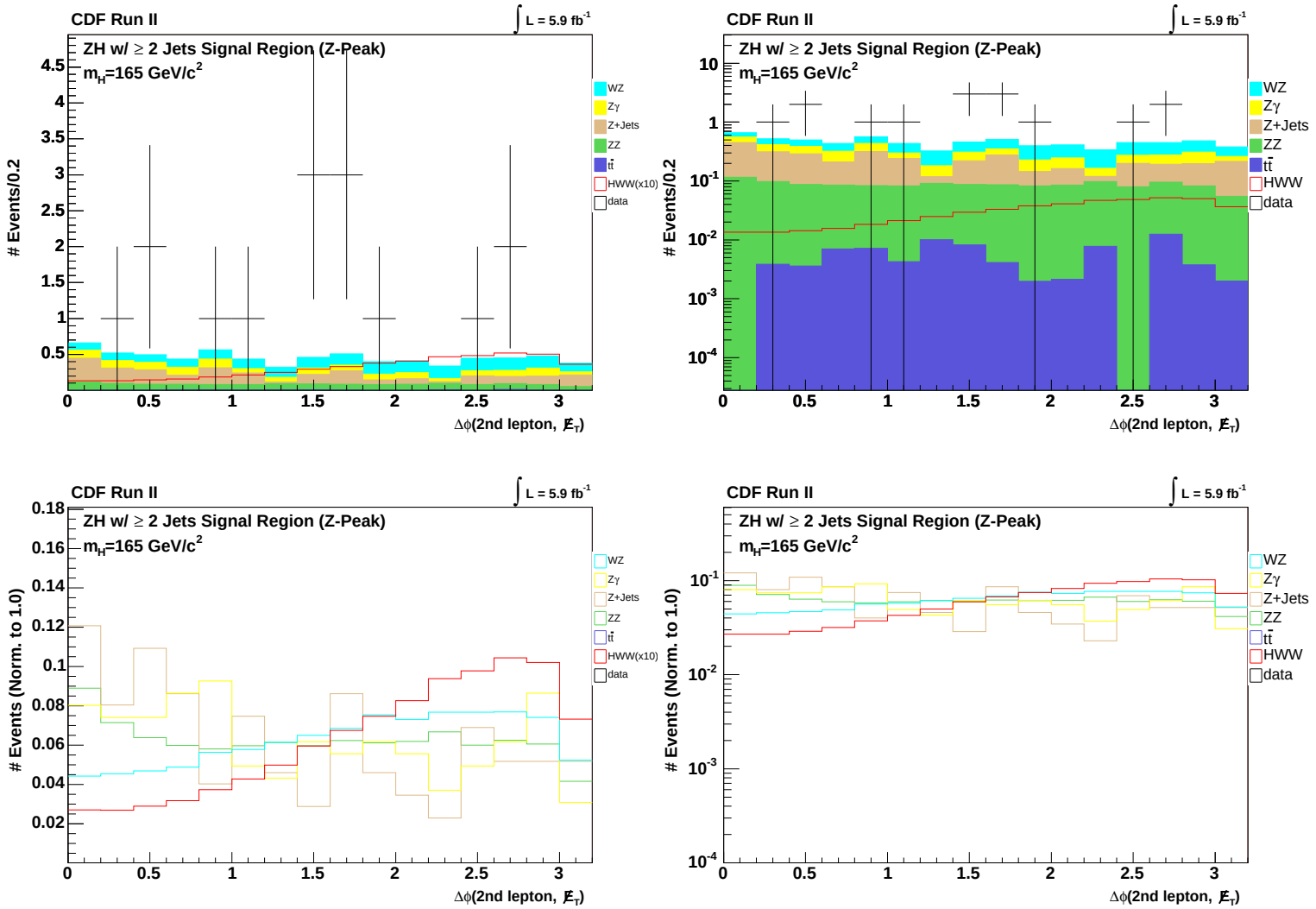
$ZH \geq 2$ Jet Signal: $\Delta\phi$(Lep sum, $\not\!\!E_T$)



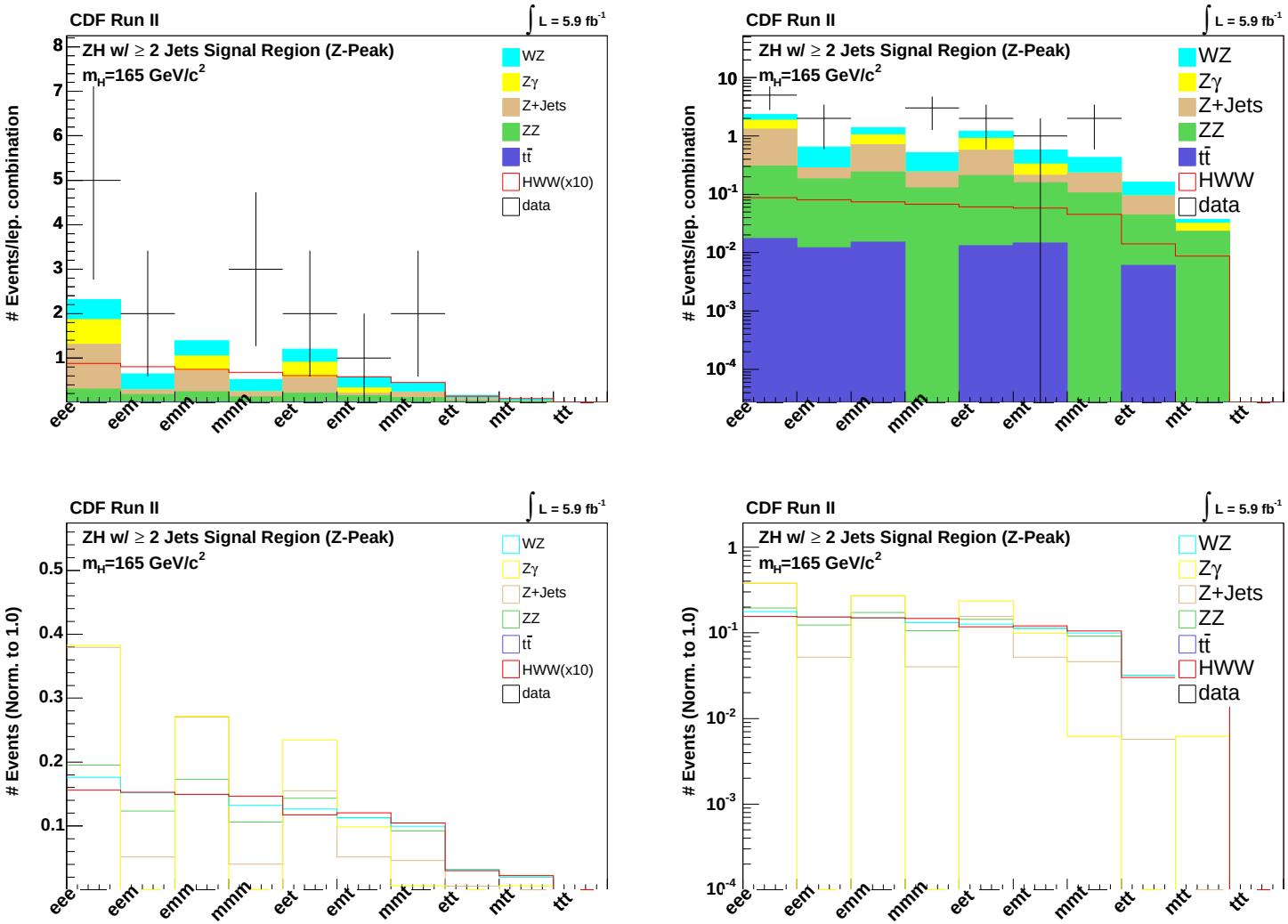
$ZH \geq 2$ Jet Signal: Number of Jets



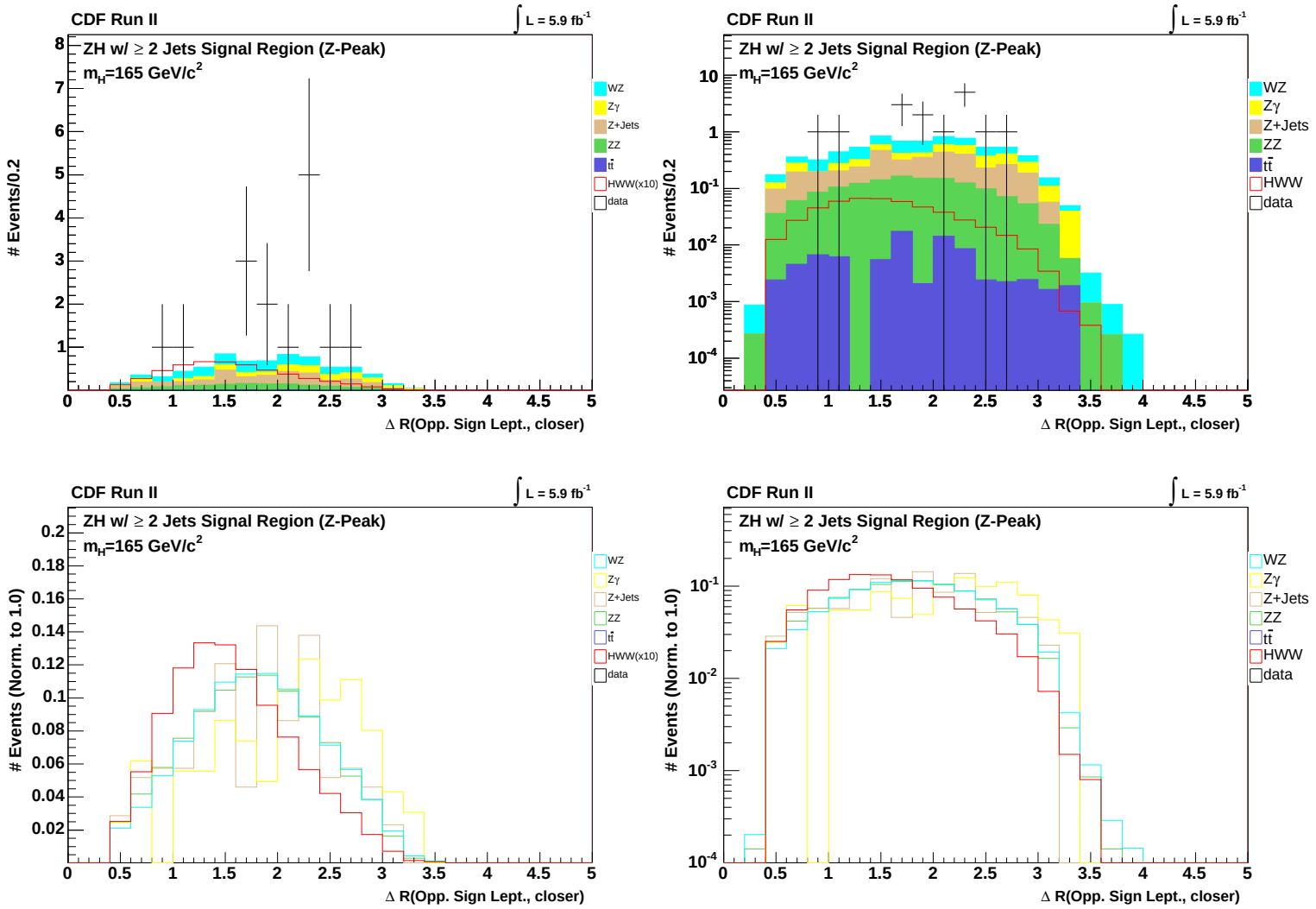
$ZH \geq 2$ Jet Signal: $\Delta\phi(2^{nd}$ Lep, $\not\!\!E_T)$



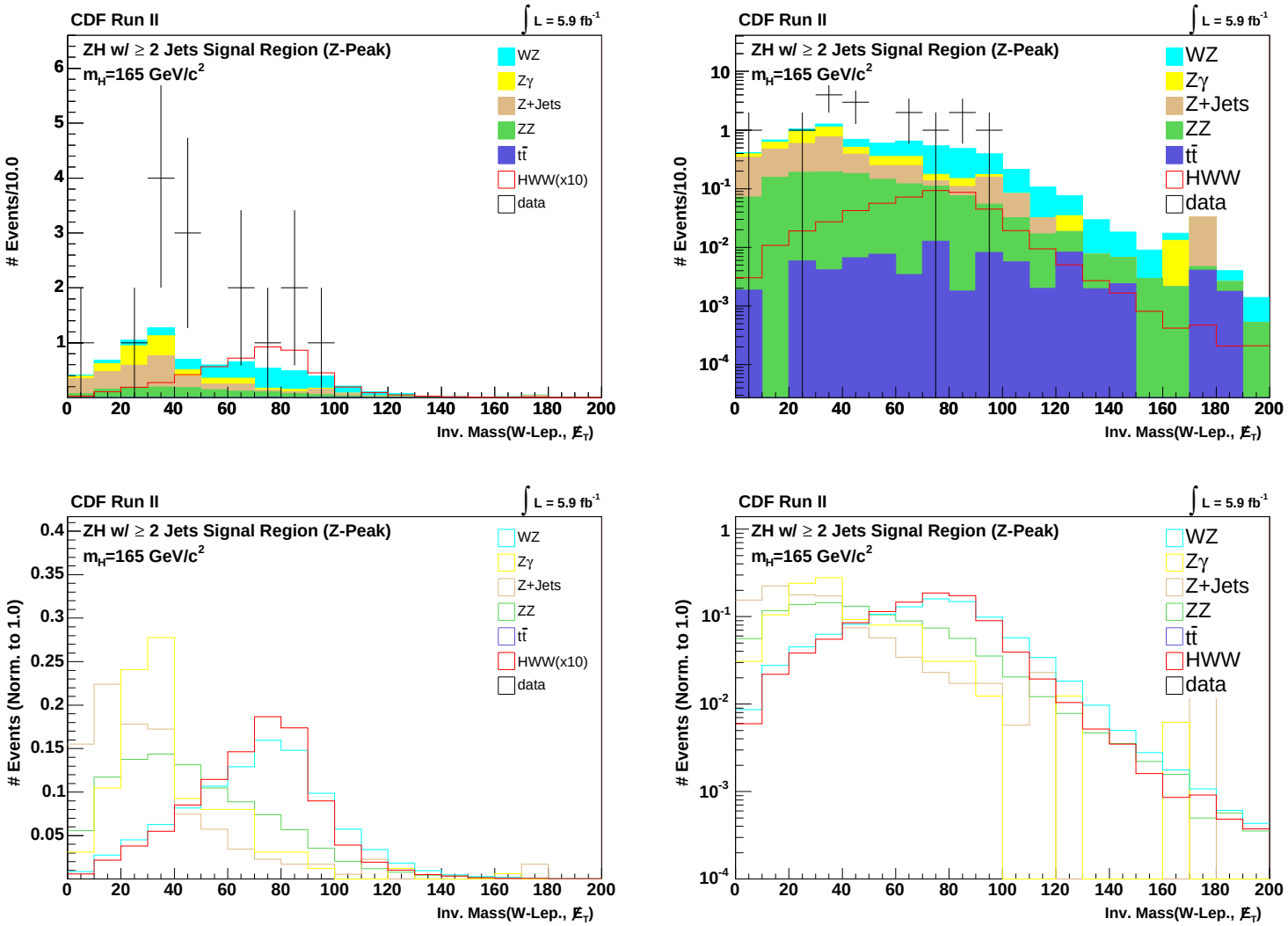
$ZH \geq 2$ Jet Signal: Lepton Type Combinations



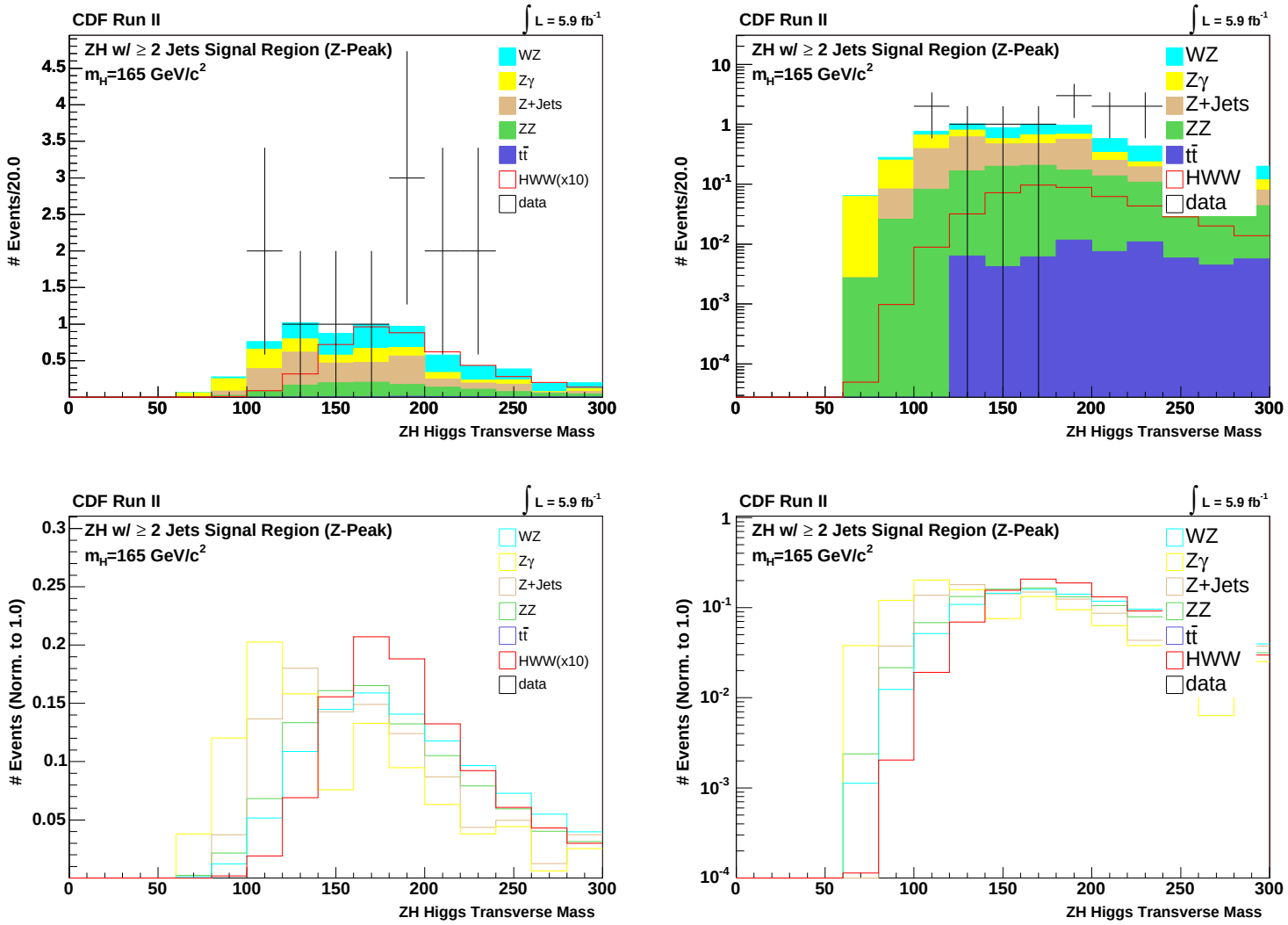
$ZH \geq 2$ Jet Signal: ΔR Opp. Sign Close



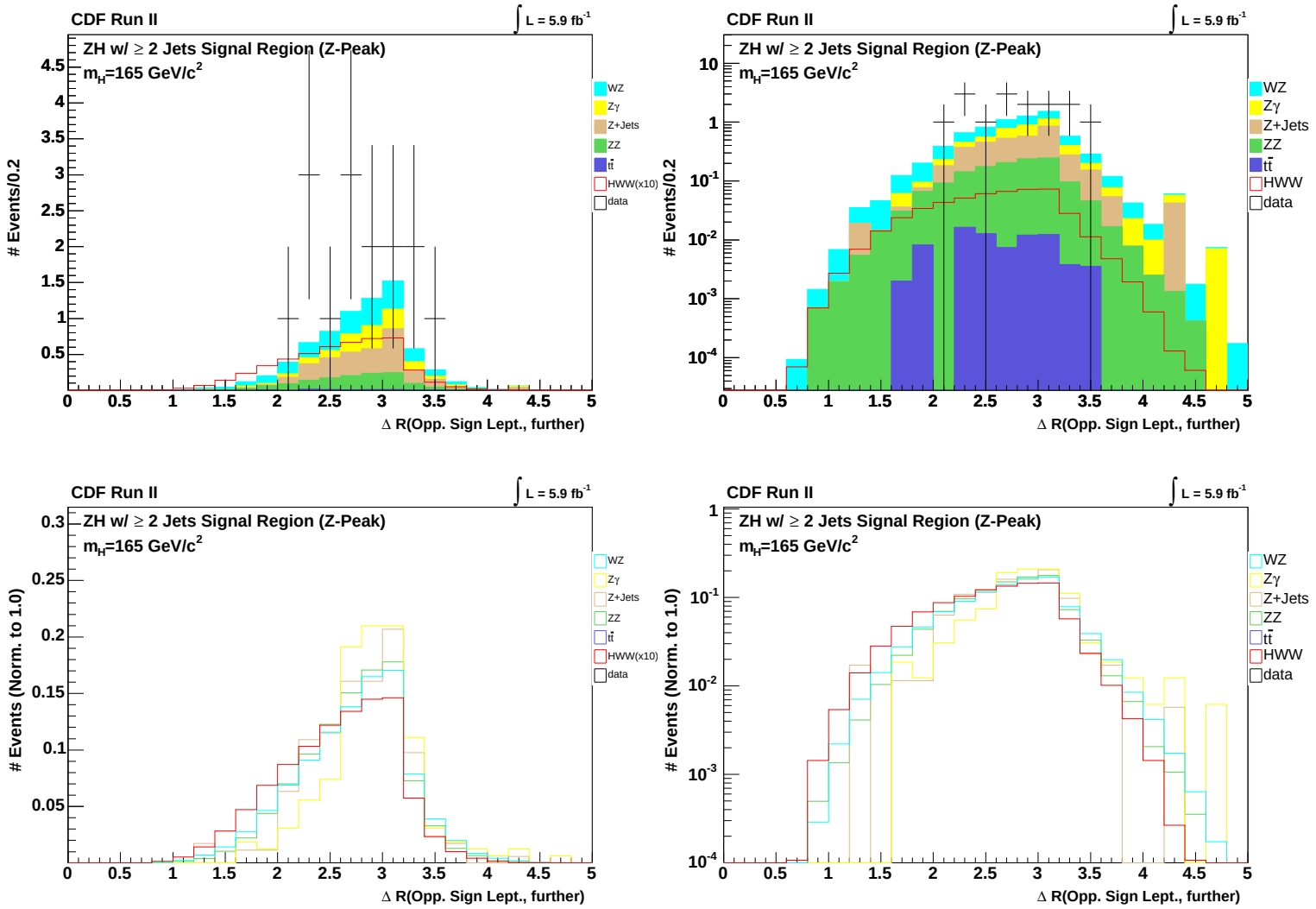
$ZH \geq 2$ Jet Signal: Inv. Mass (W-Lep, $\not\!\!E_T$)



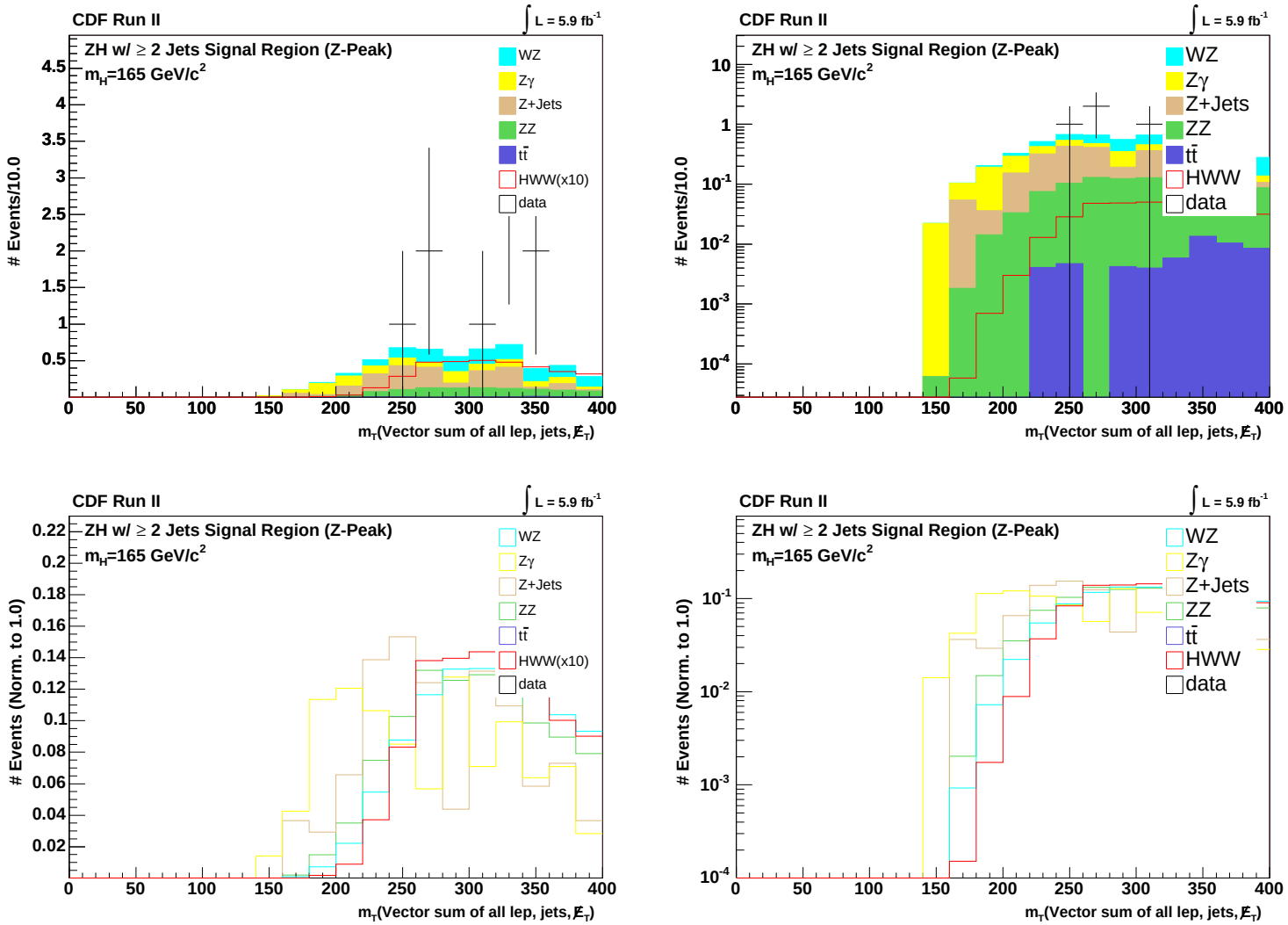
$ZH \geq 2$ Jet Signal: Higgs Mass



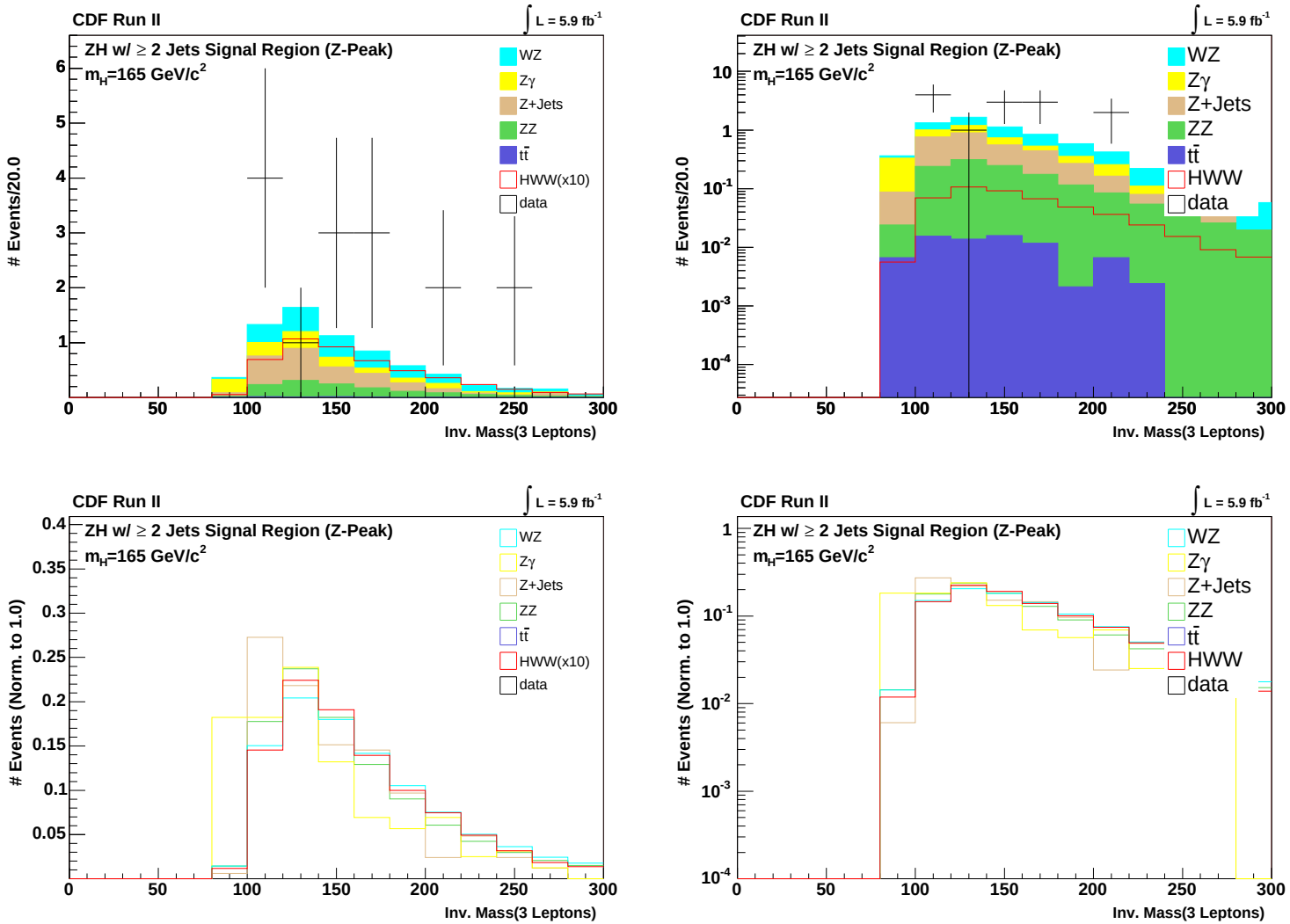
$ZH \geq 2$ Jet Signal: ΔR Opp. Sign Far



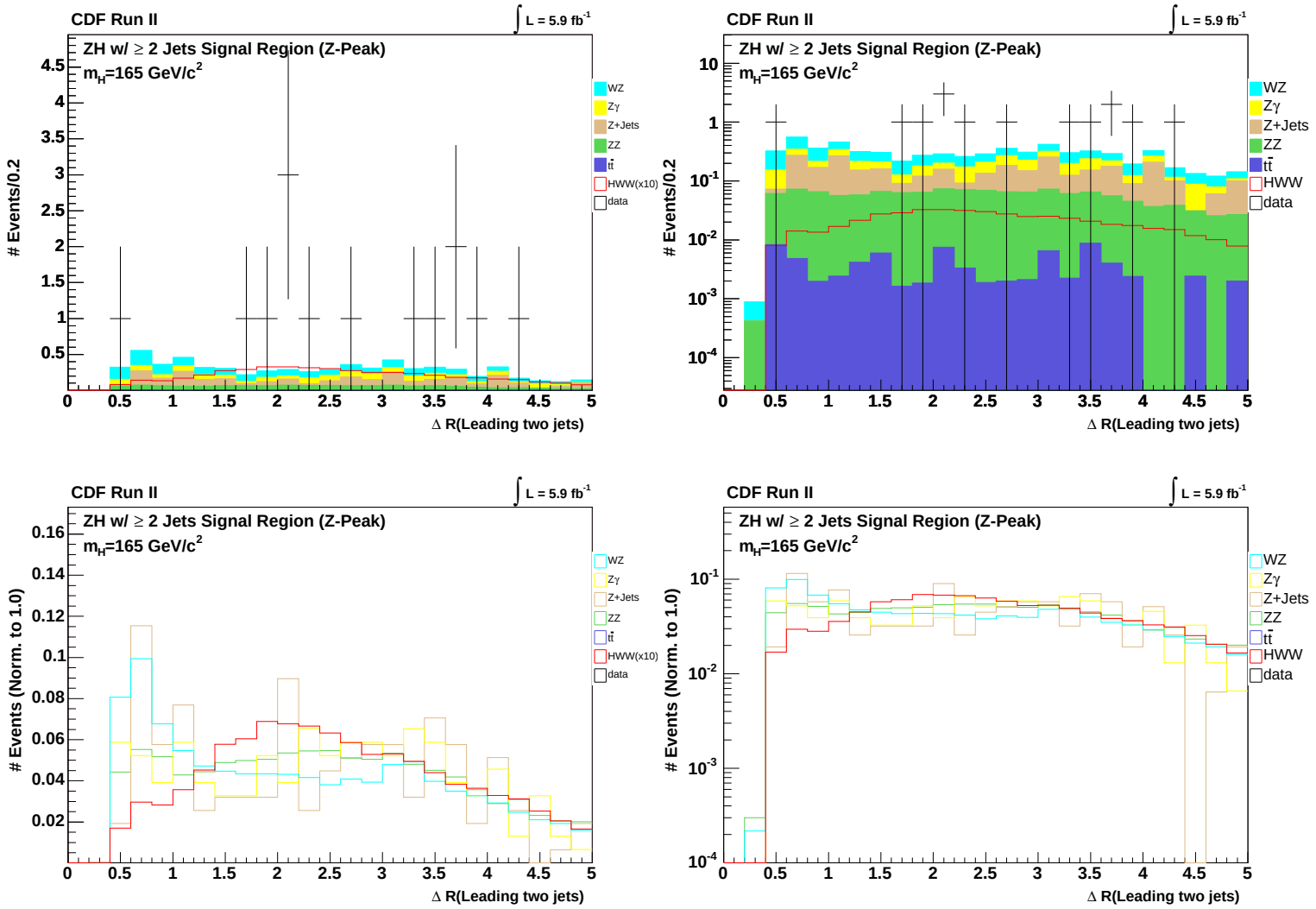
$ZH \geq 2$ Jet Signal: m_T(Leptons, $\not\!\!E_T$, Jets)



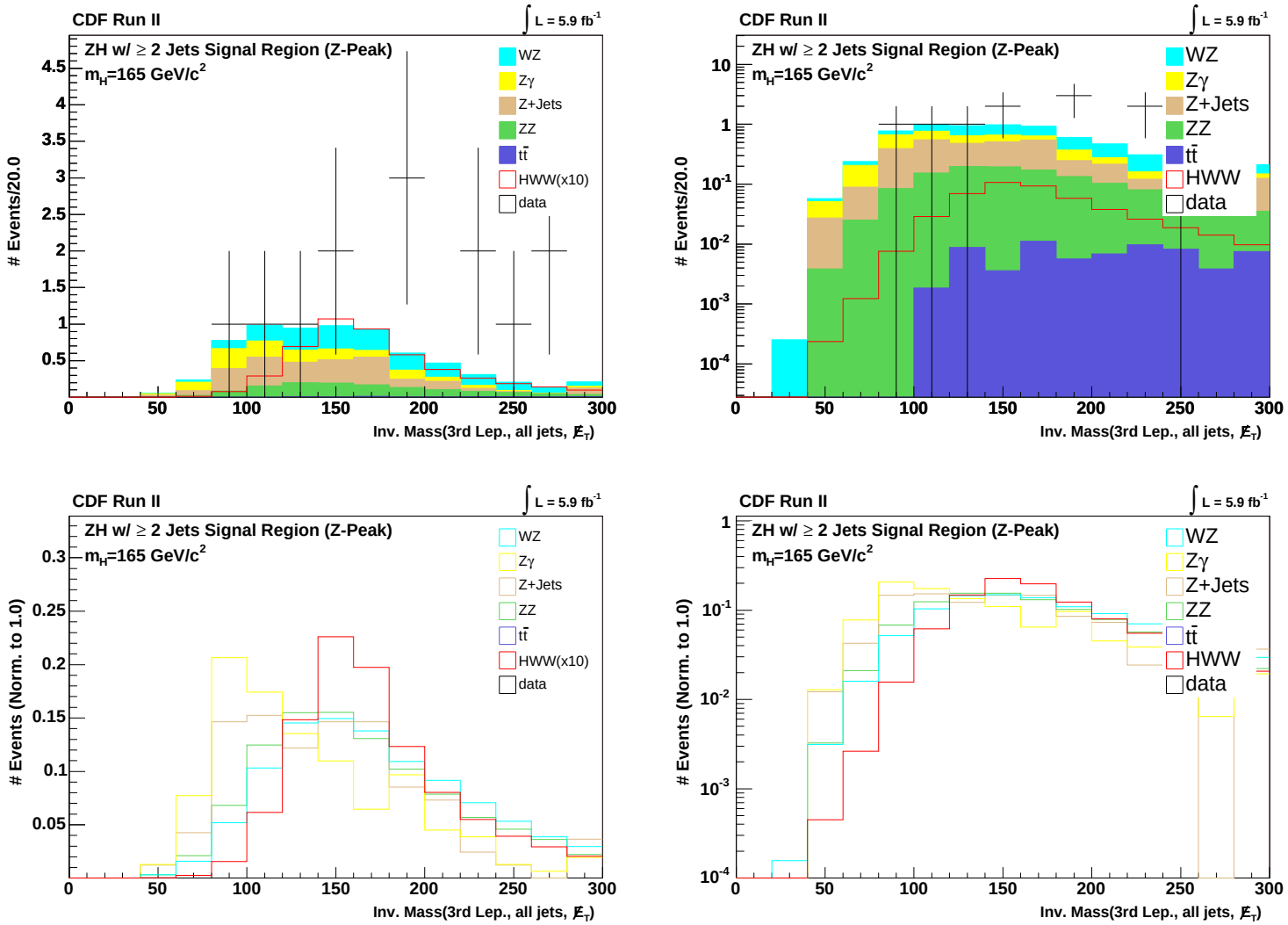
$ZH \geq 2$ Jet Signal: Inv. Mass (all leptons)



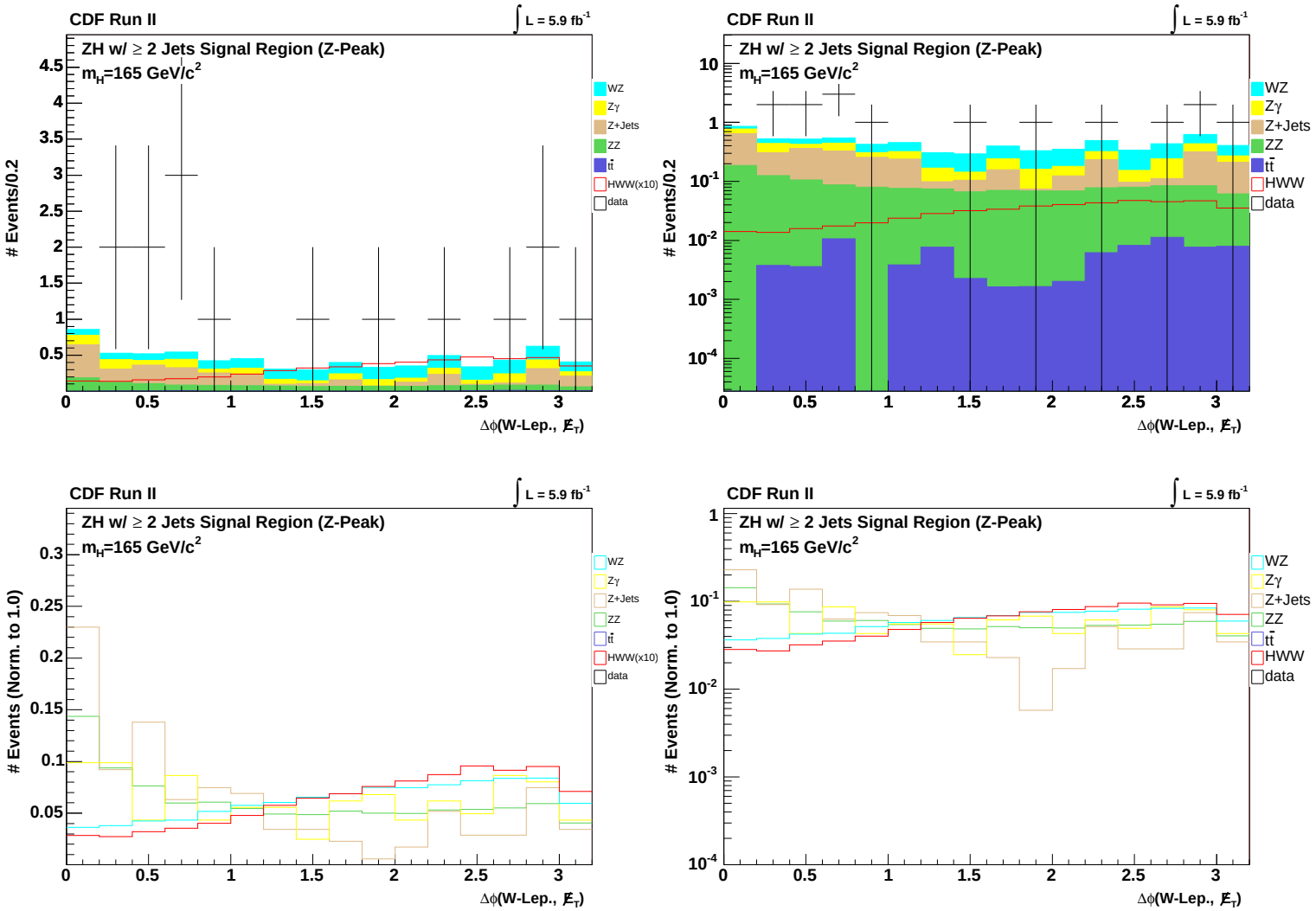
$ZH \geq 2$ Jet Signal: ΔR(1st and 2nd Jets)



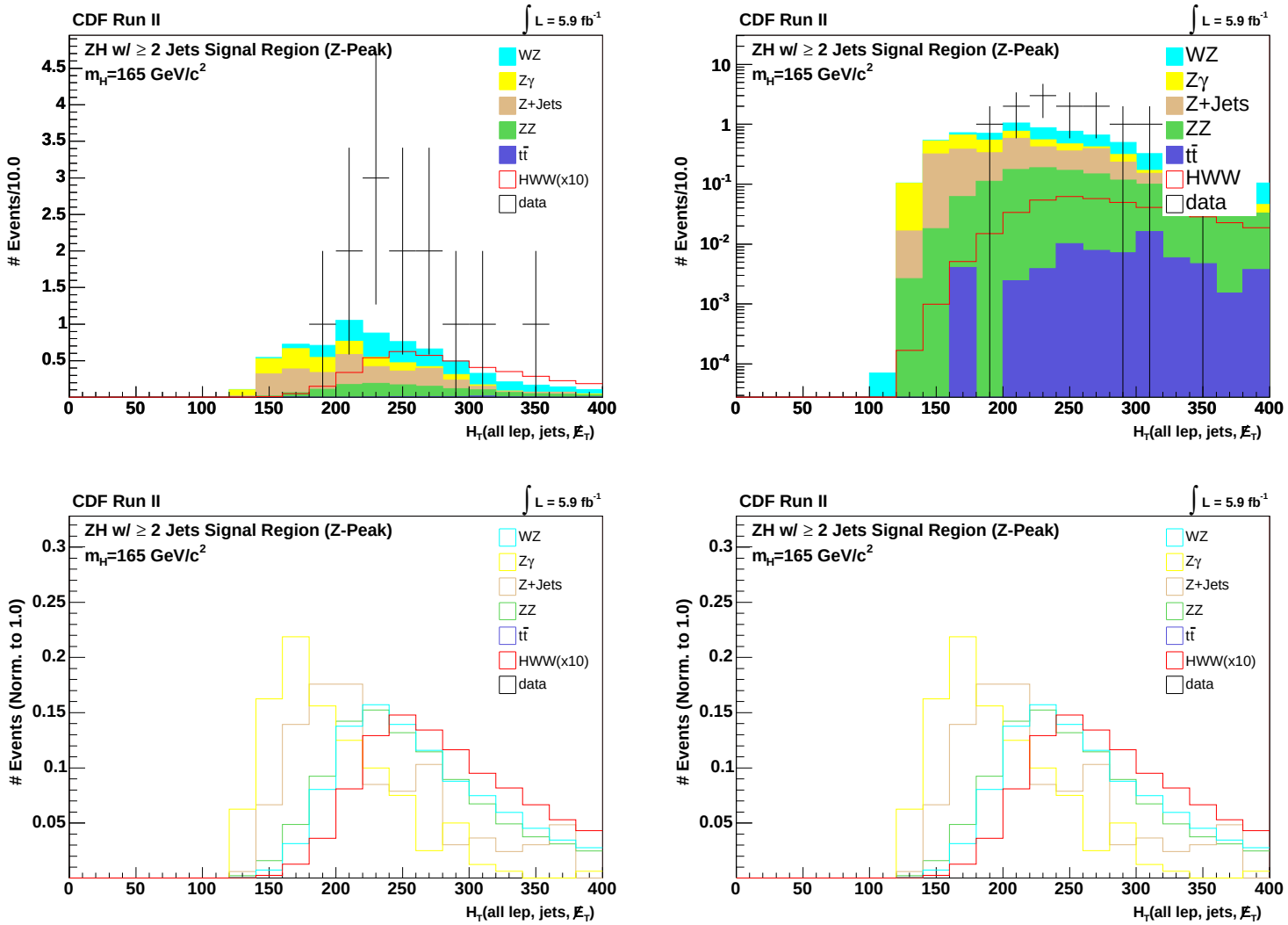
$ZH \geq 2$ Jet Signal: Inv. Mass (3rd Lep, $\not\!\!E_T$, Jets)



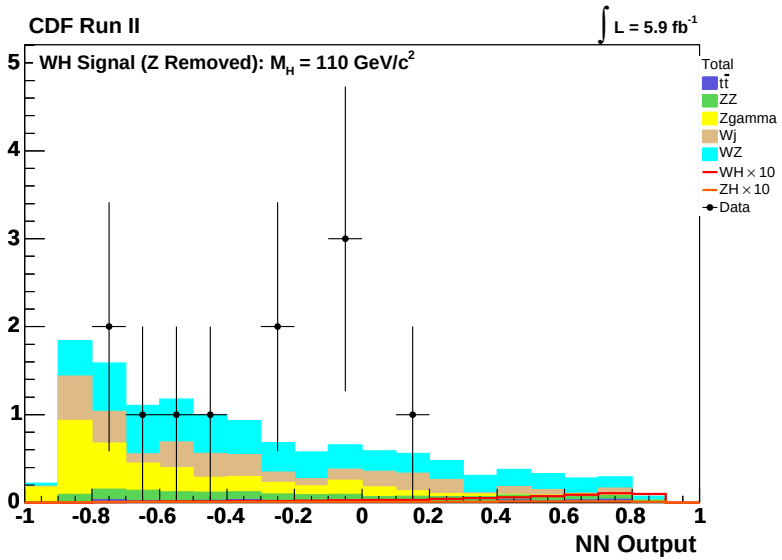
$ZH \geq 2$ Jet Signal: $\Delta\phi$ (W-Lep,$\not\!\!E_T$)

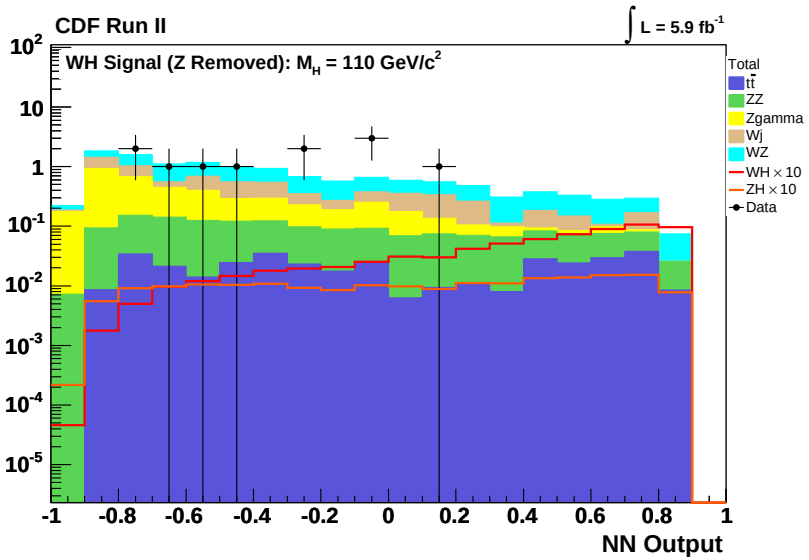


$ZH \geq 2$ Jet Signal: H_T

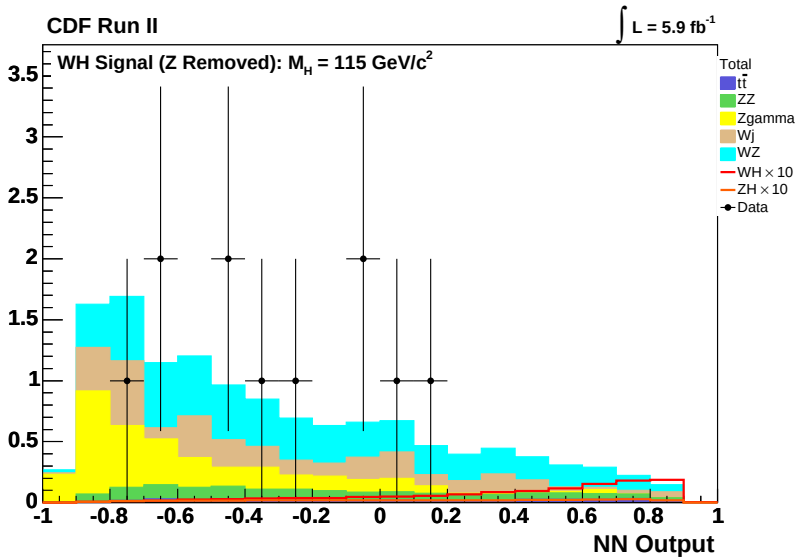


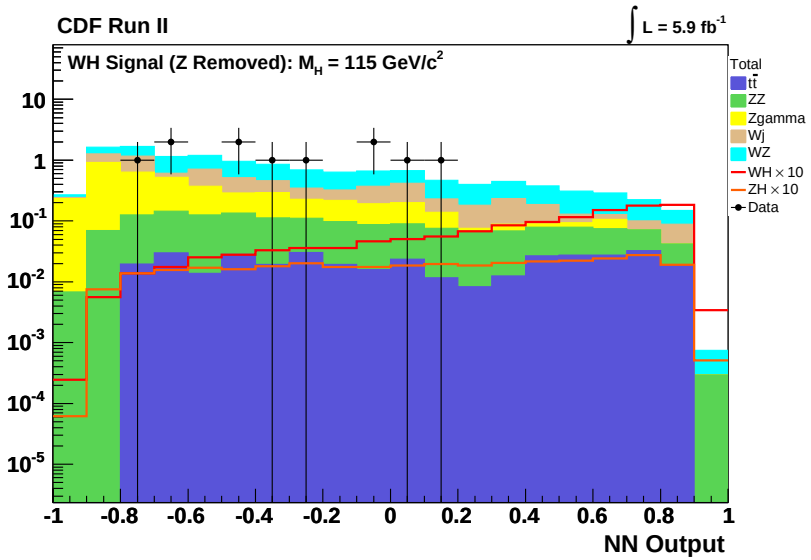
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 110 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

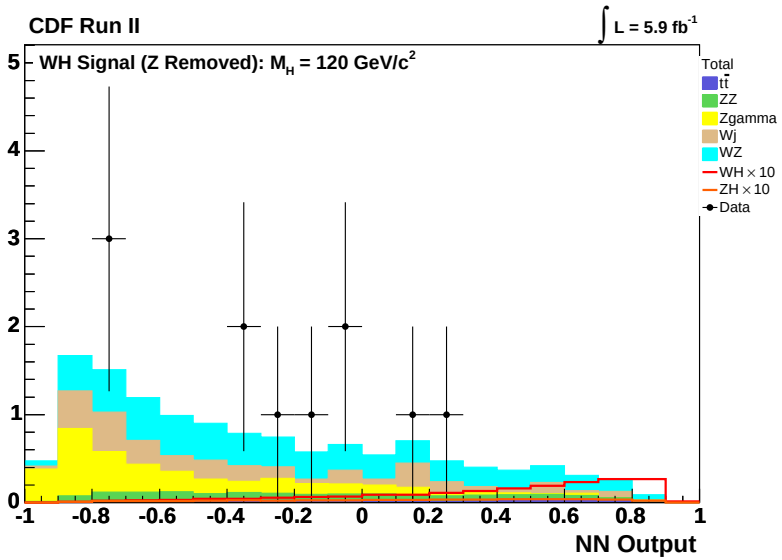

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 110 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

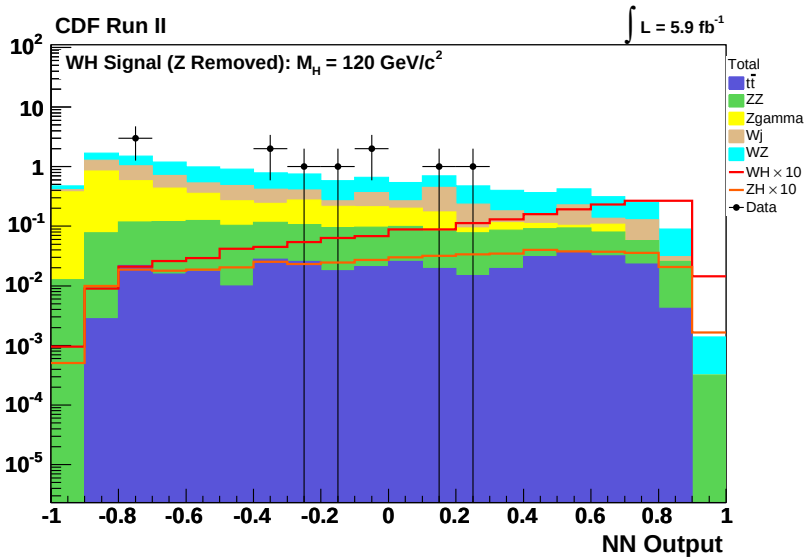
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 115 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

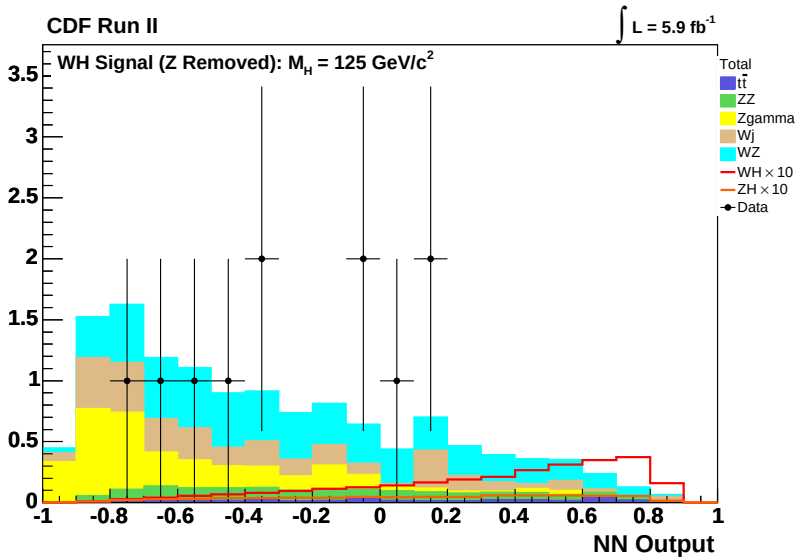

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 115 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

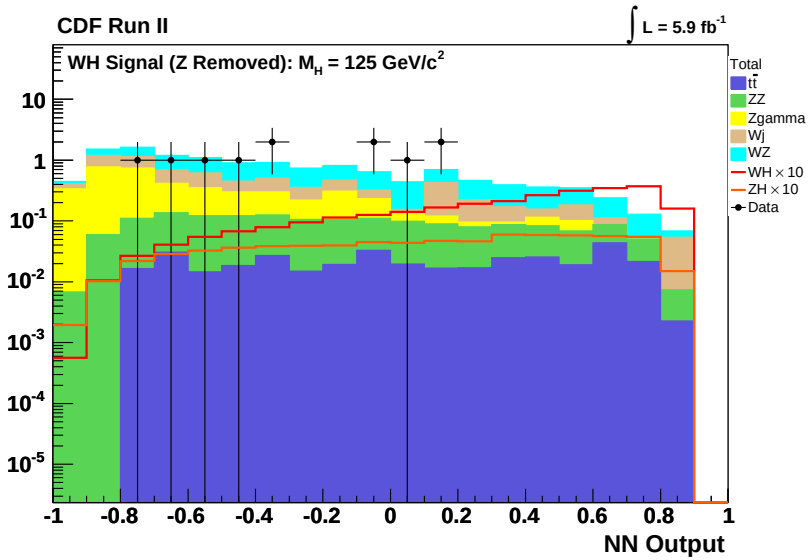
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 120 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

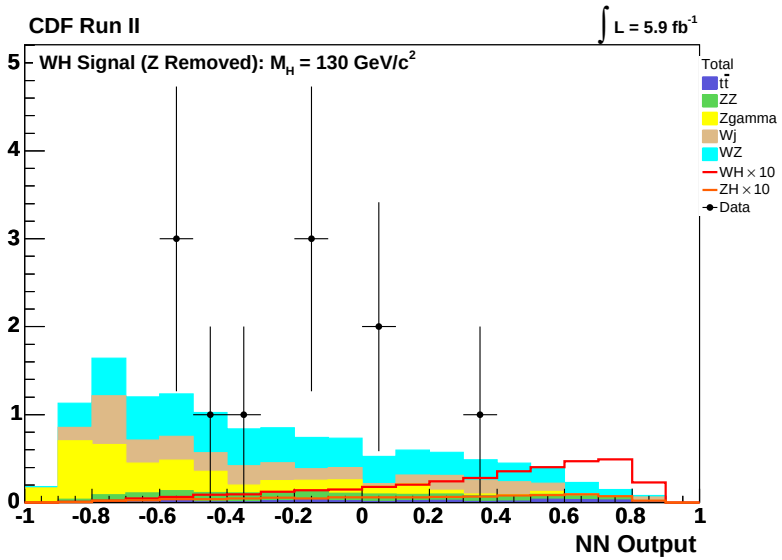

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 120 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

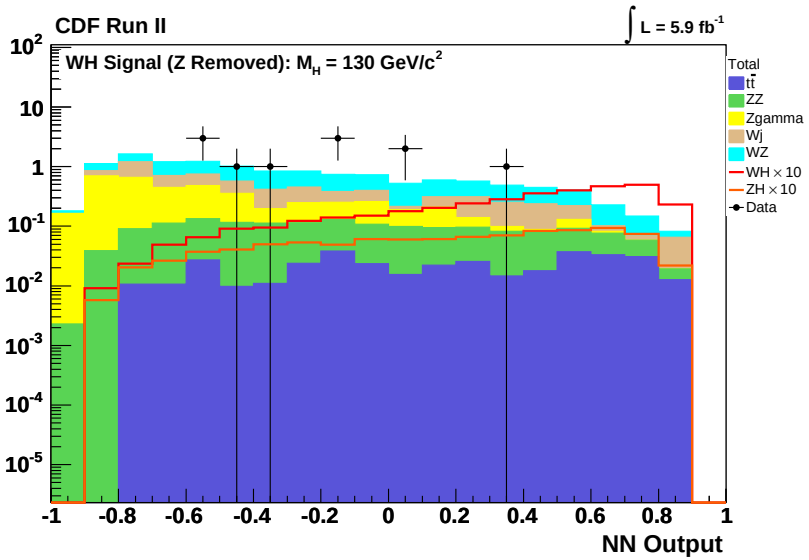
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 125 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

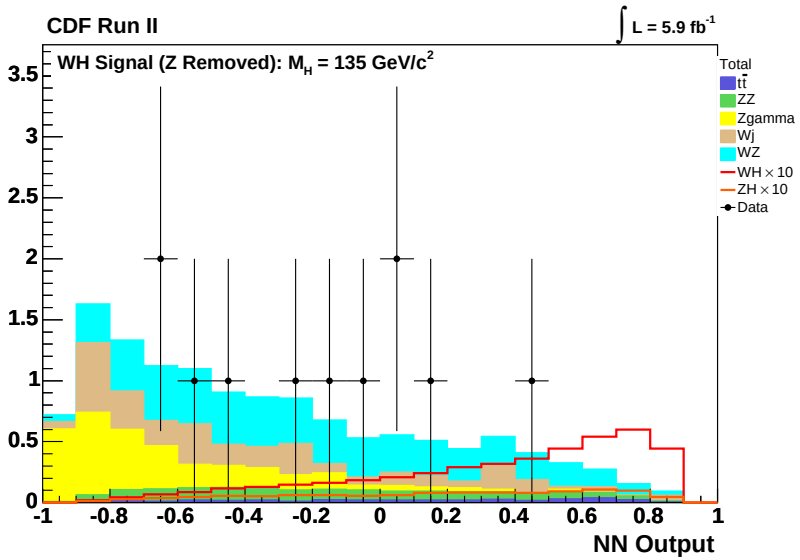

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 125 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

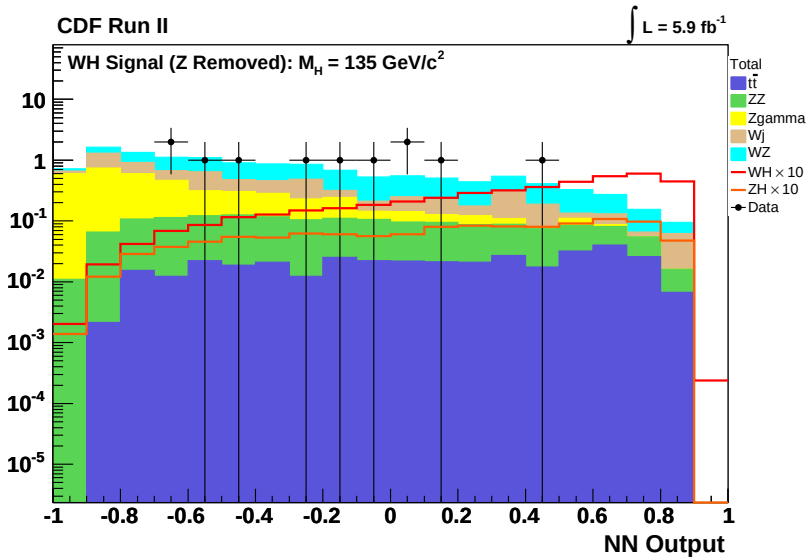
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 130 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

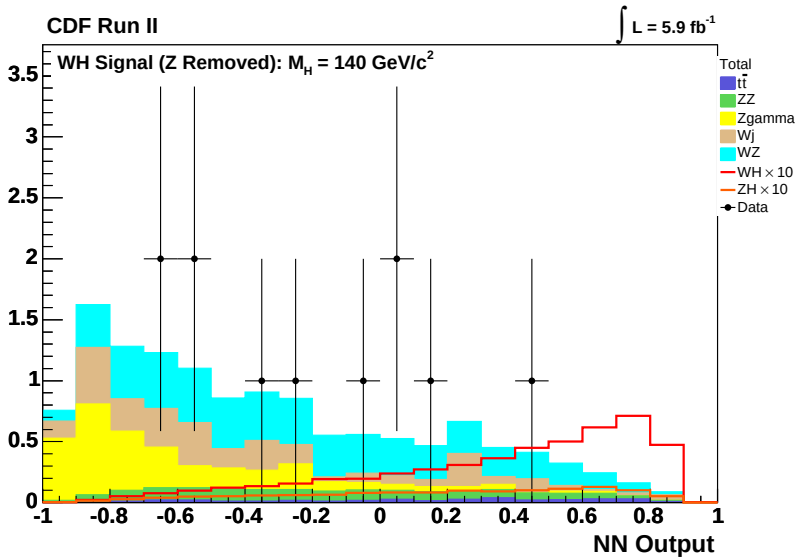

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 130 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

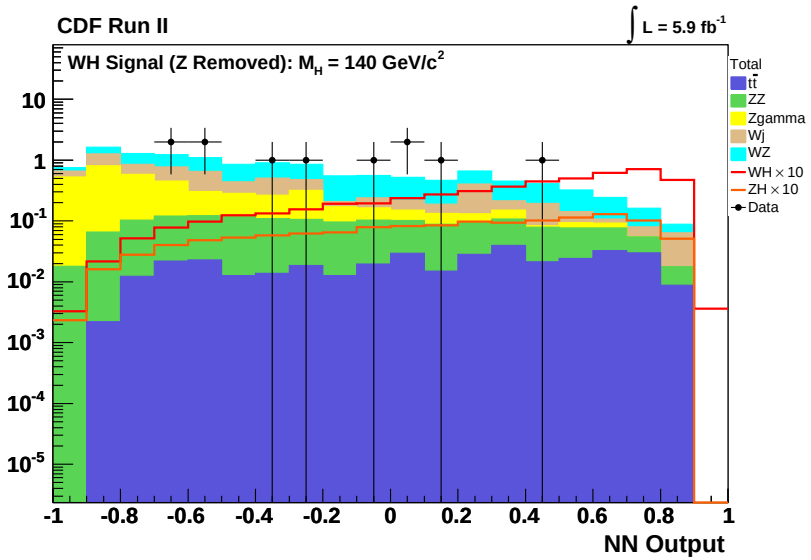
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 135 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

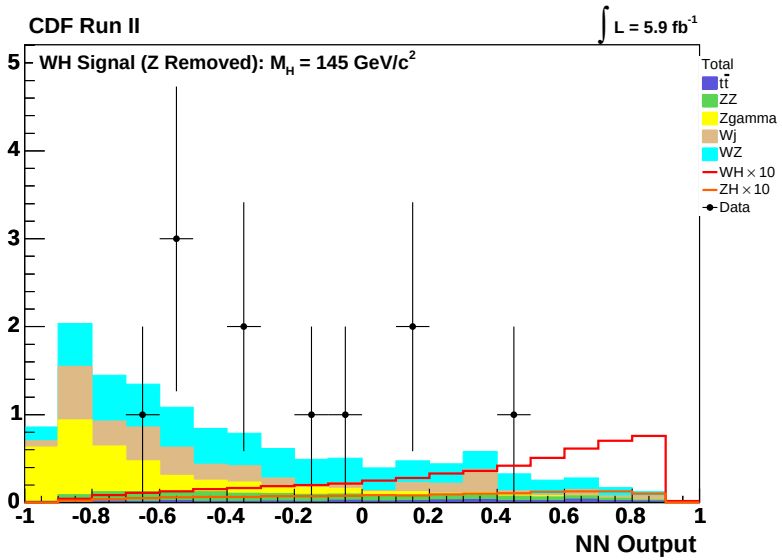

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 135 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

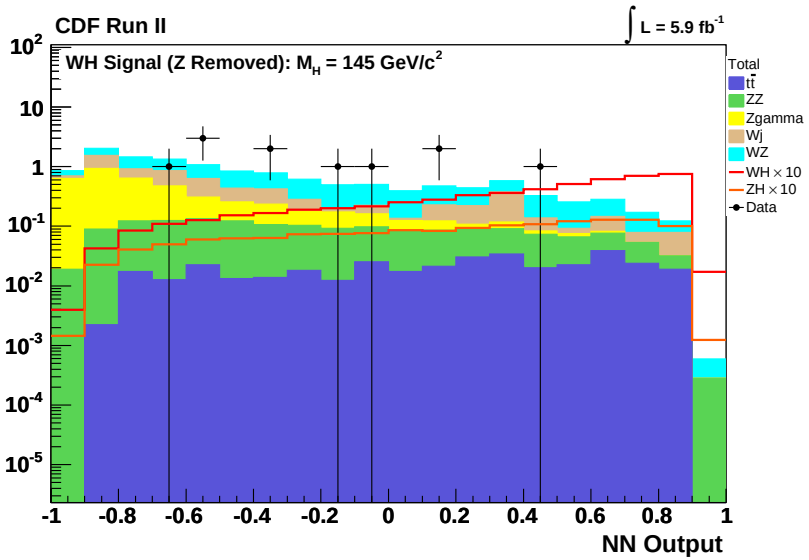
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 140 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

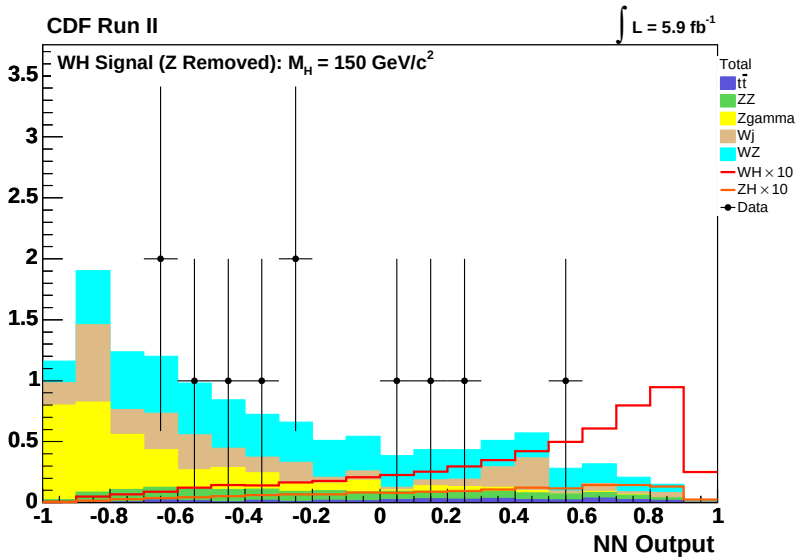

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 140 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

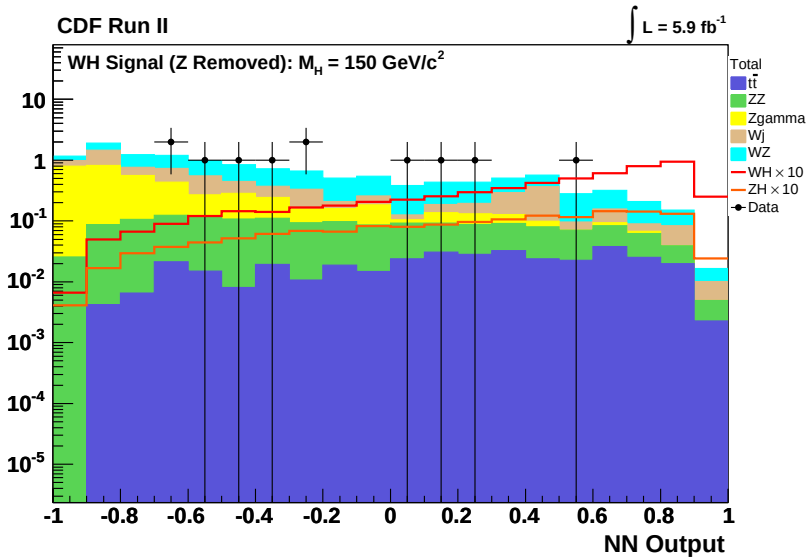
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 145 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

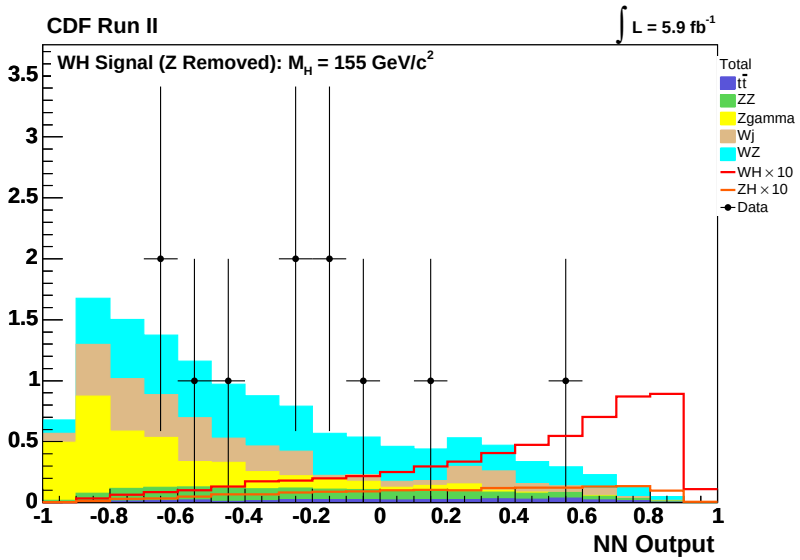

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 145 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

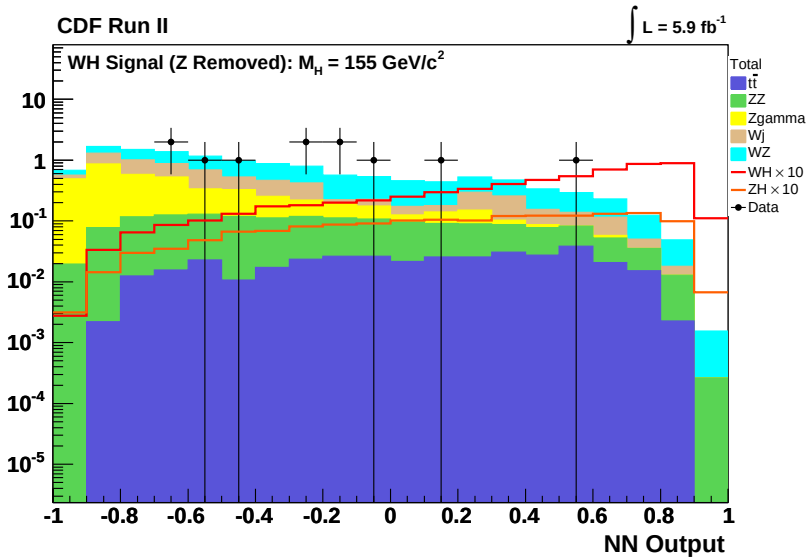
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 150 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

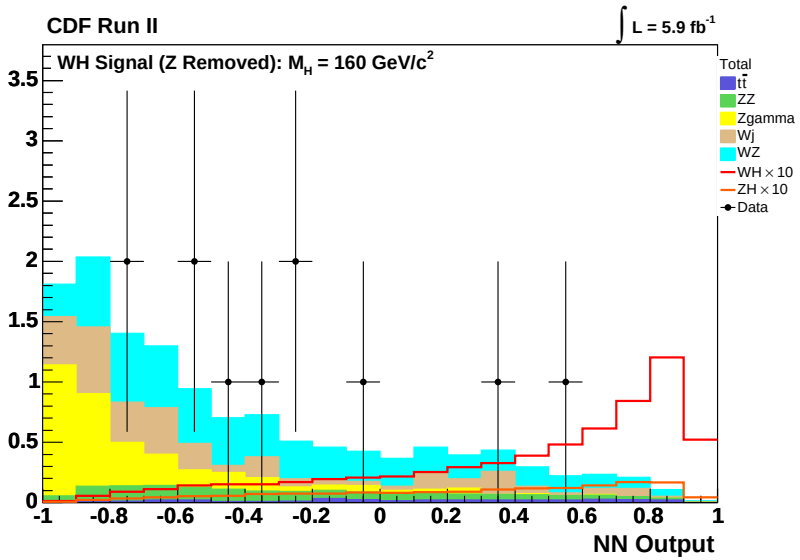

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 150 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

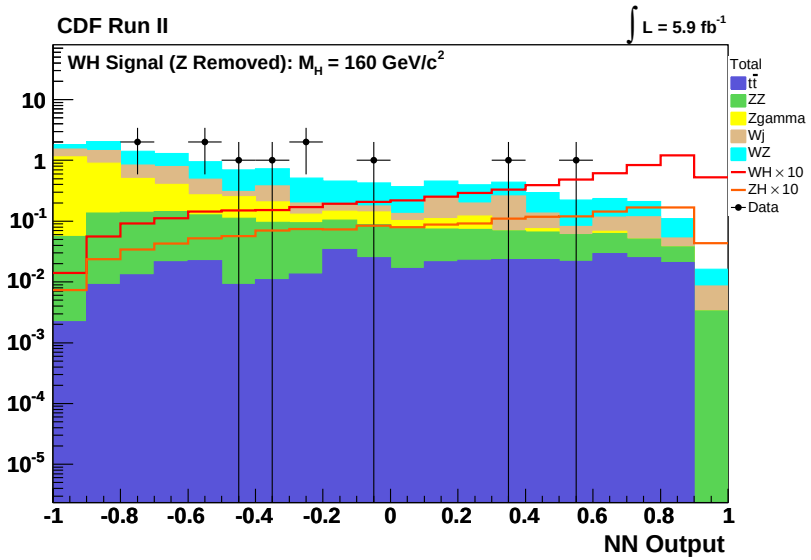
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 155 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

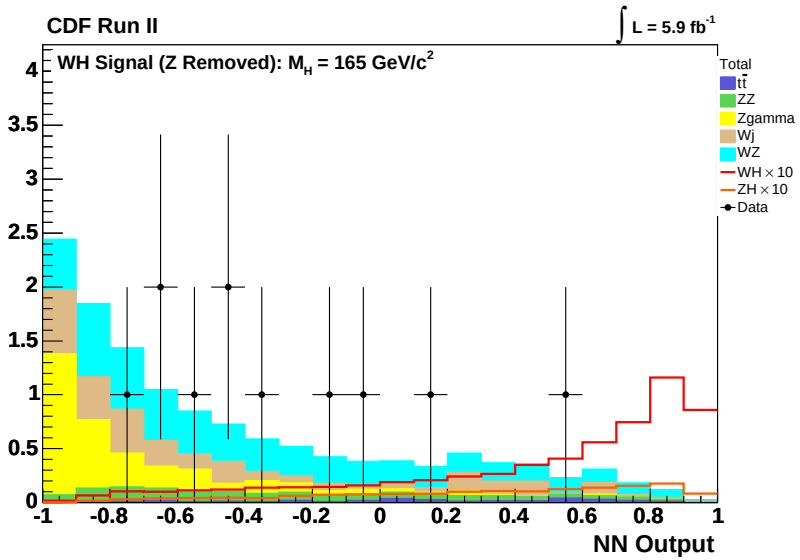

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 155 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

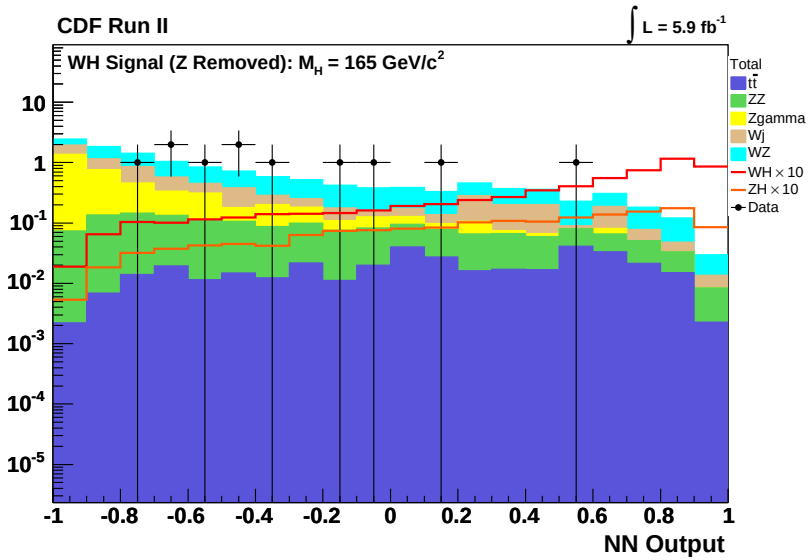
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 160 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

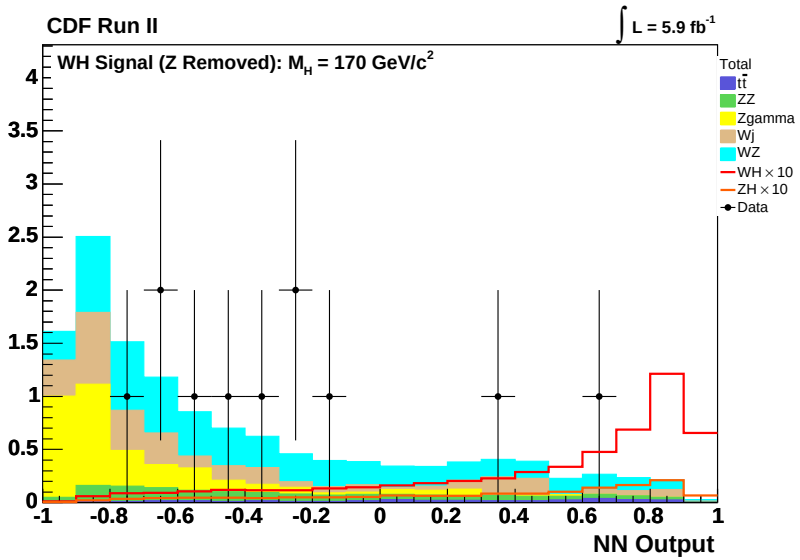

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 160 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

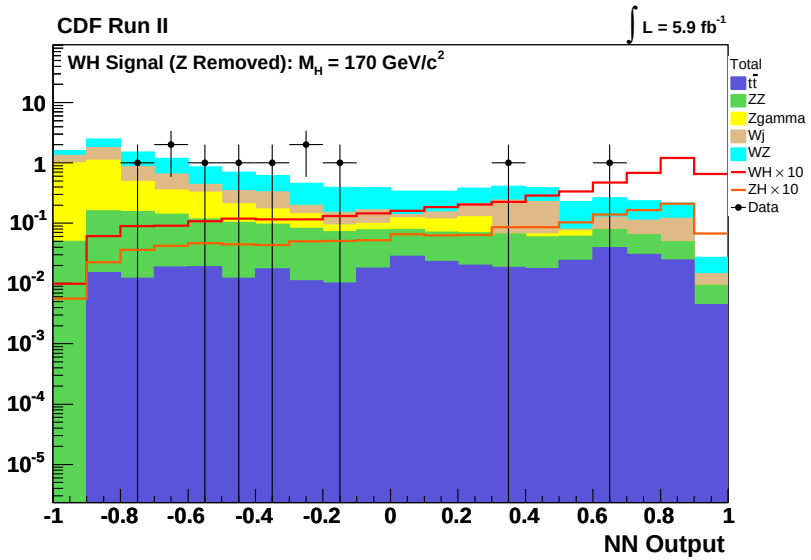
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 165 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

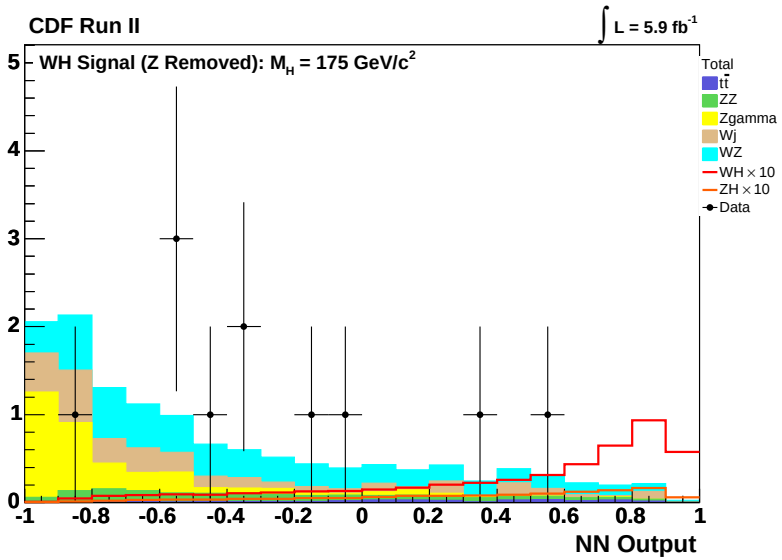

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 165 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

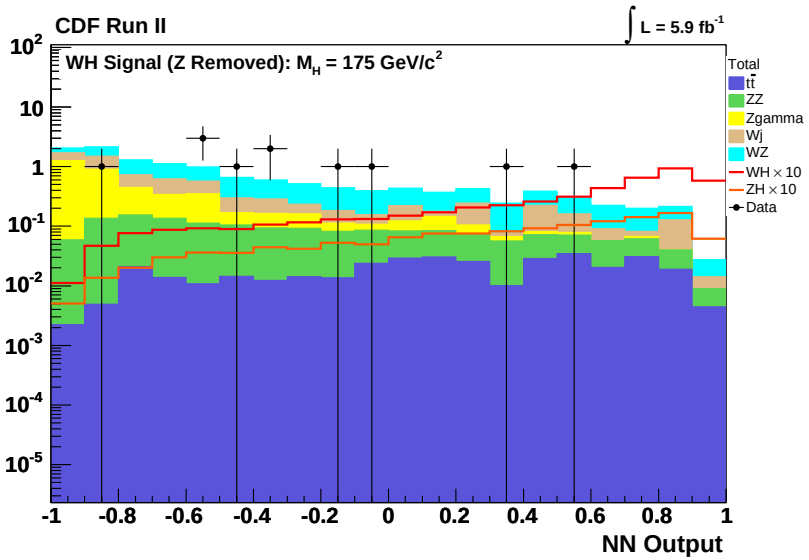
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 170 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

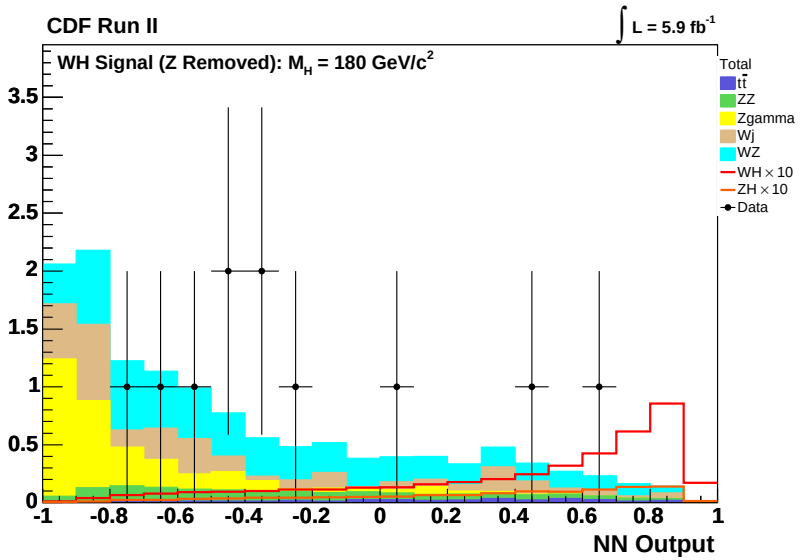

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 170 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

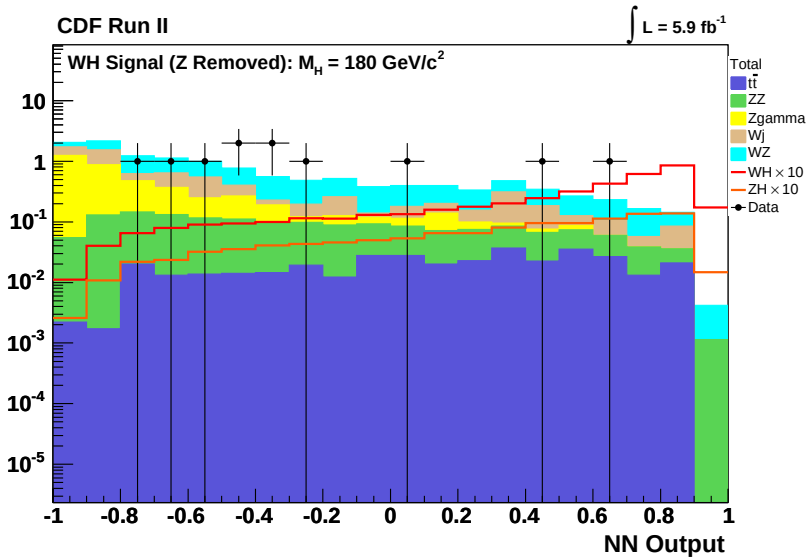
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 175 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

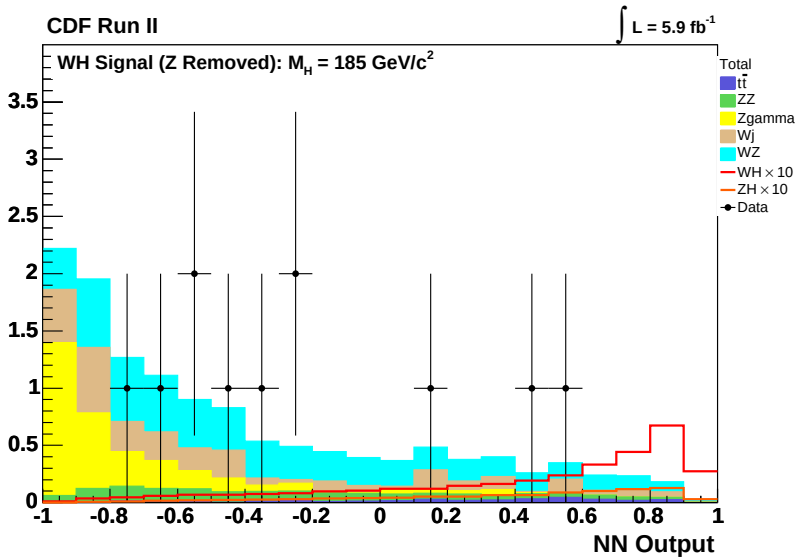

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 175 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

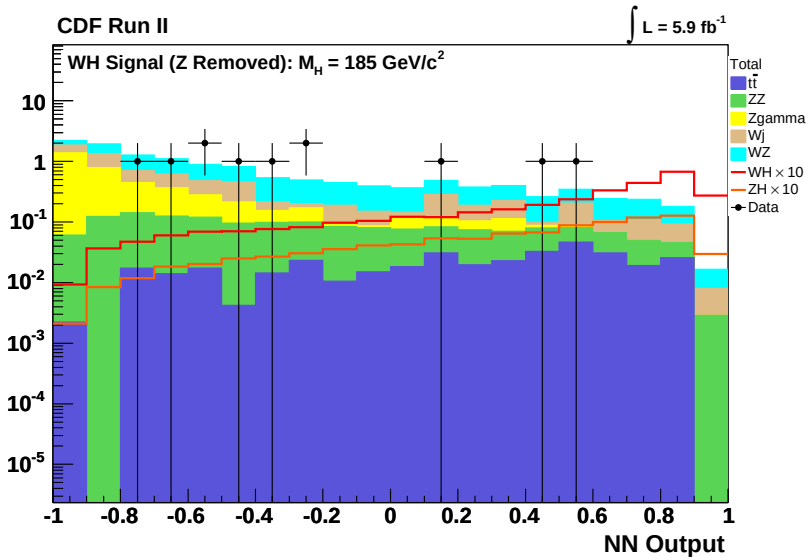
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 180 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

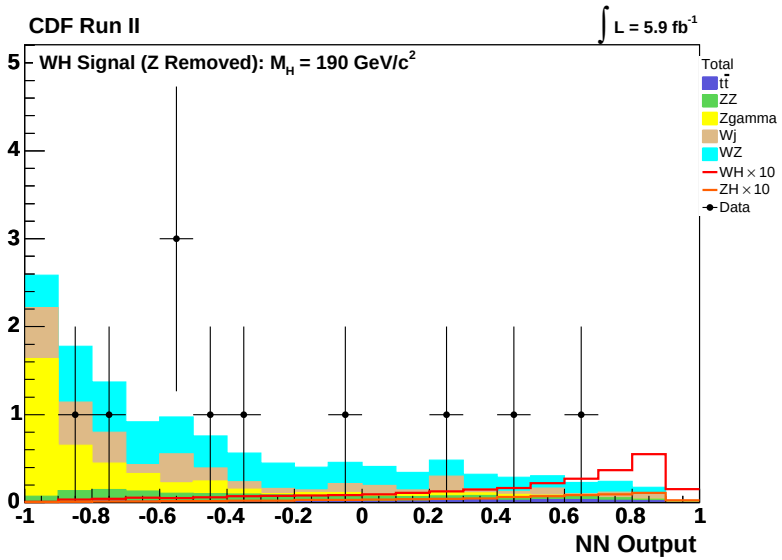

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 180 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

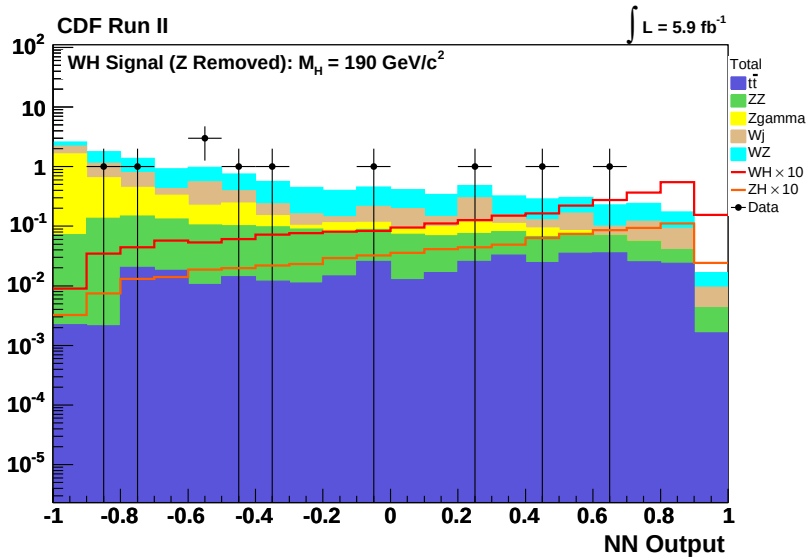
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 185 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

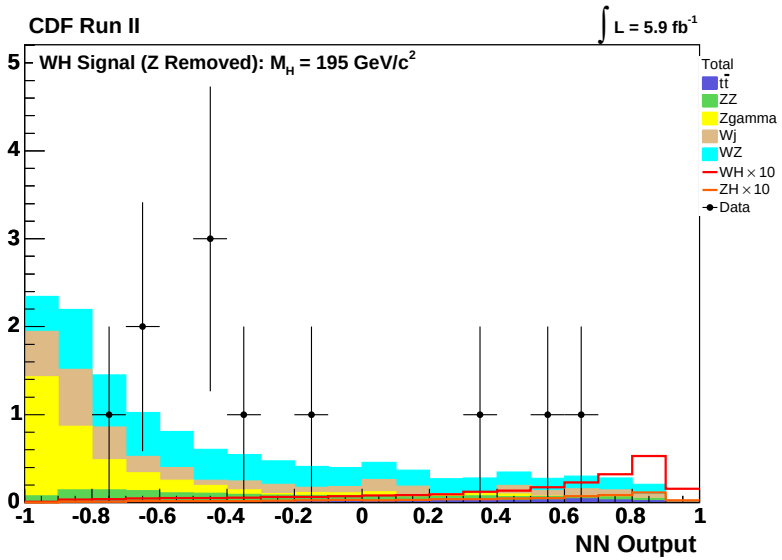

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 185 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

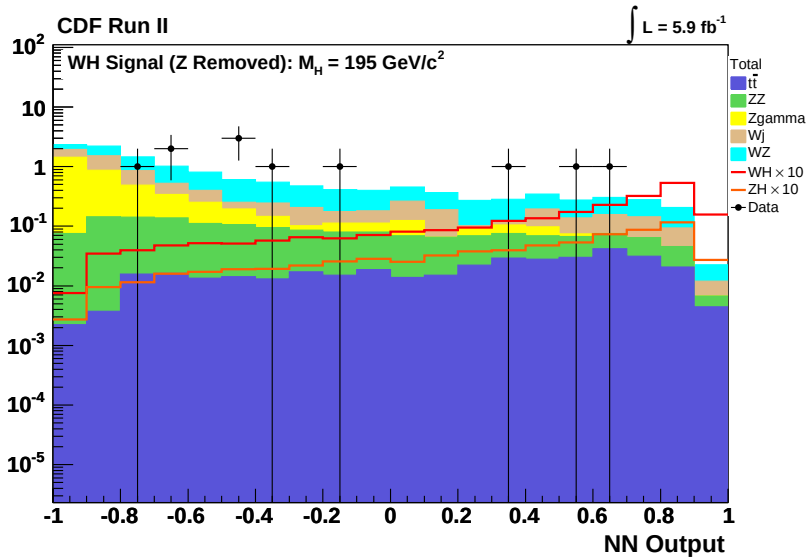
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 190 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

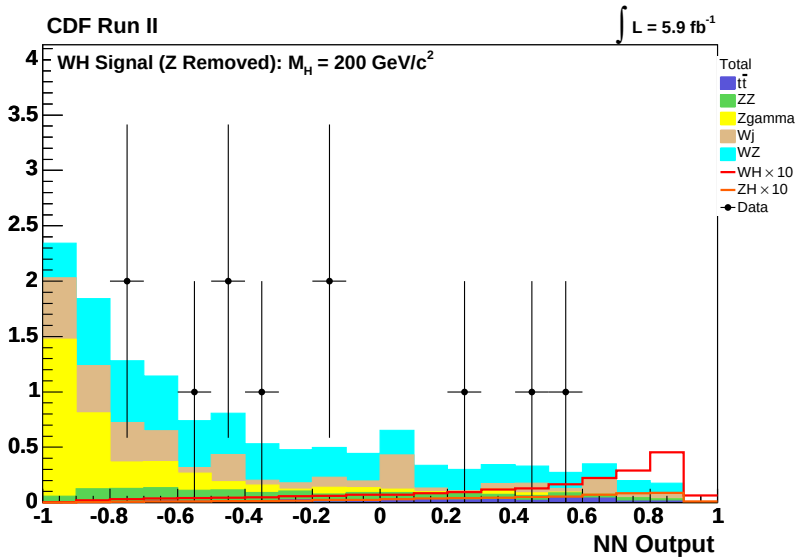

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 190 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

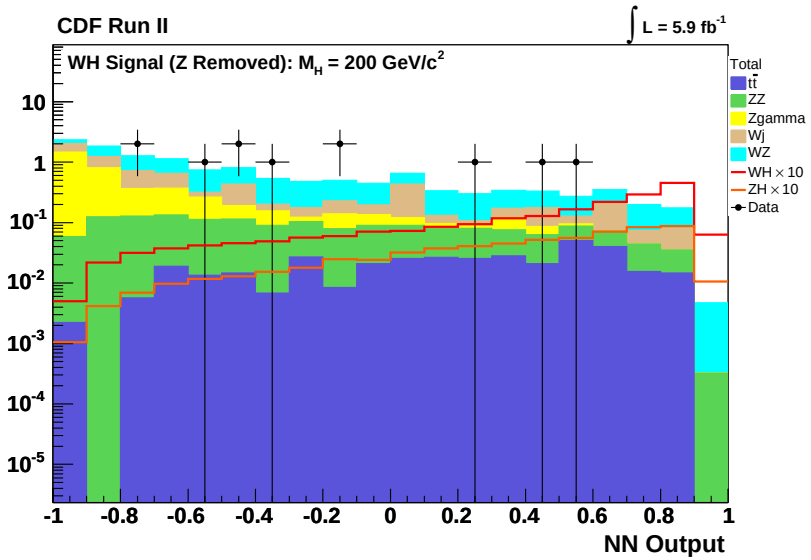
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 195 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

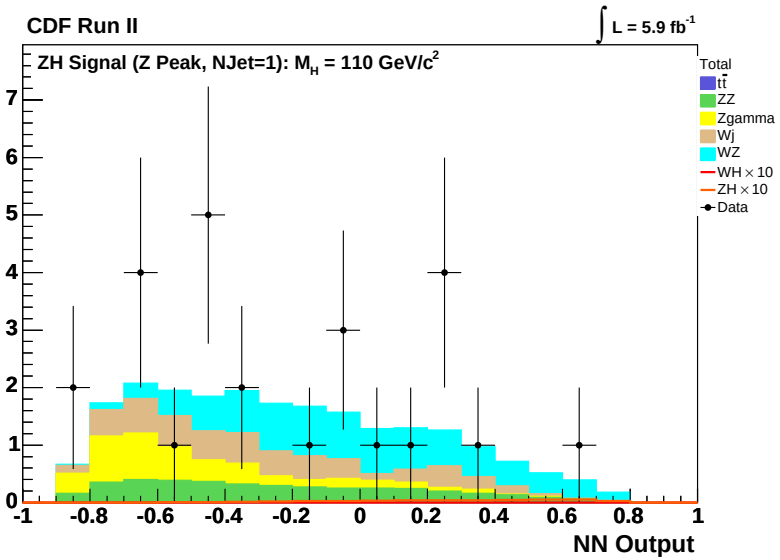

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 195 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

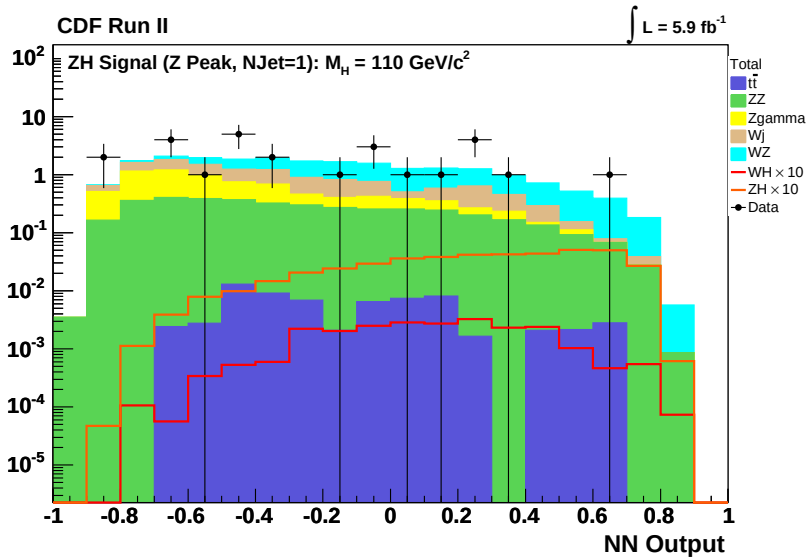
NN *WH*


CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 200 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

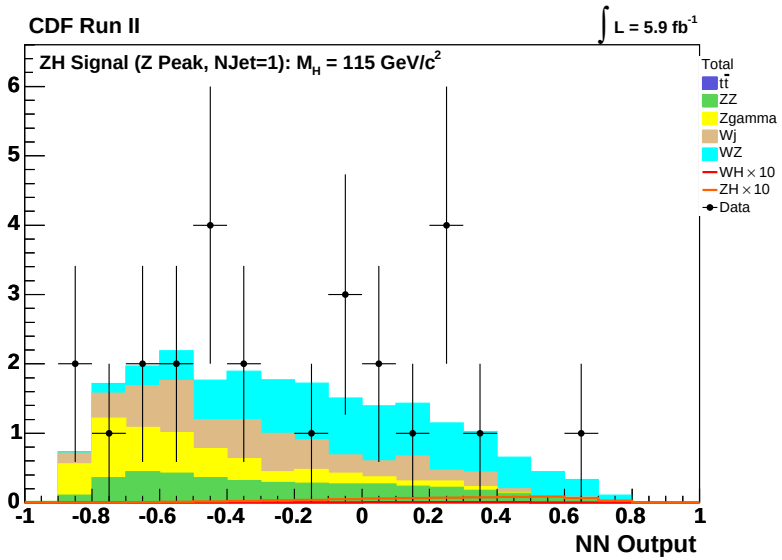

CDF Run II
∫ L = 5.9 fb-1
WH Signal (Z Removed): MH = 200 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

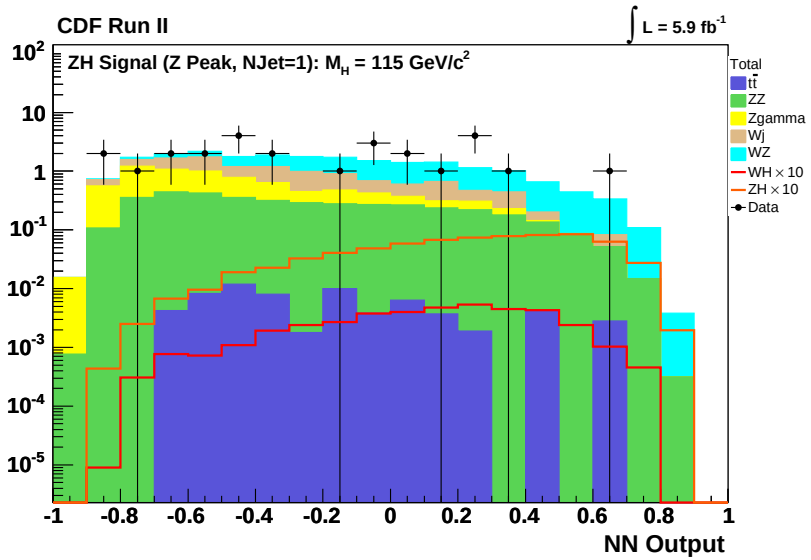
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 110 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

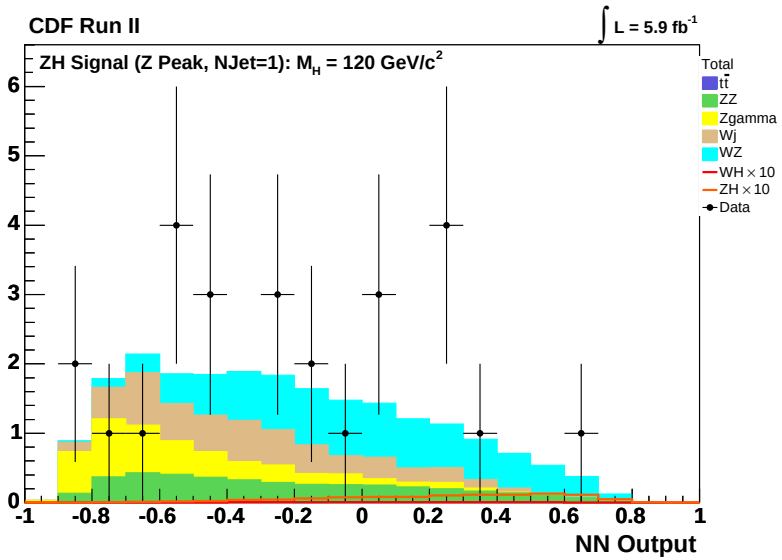

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 110 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

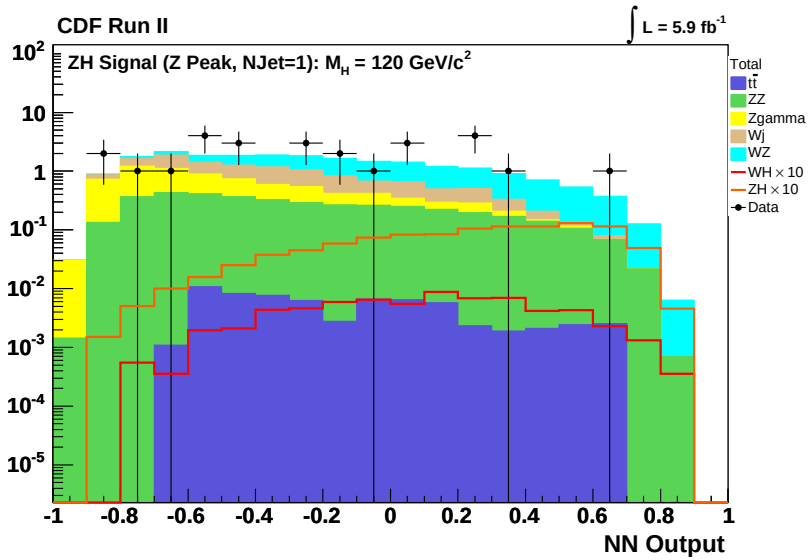
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 115 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

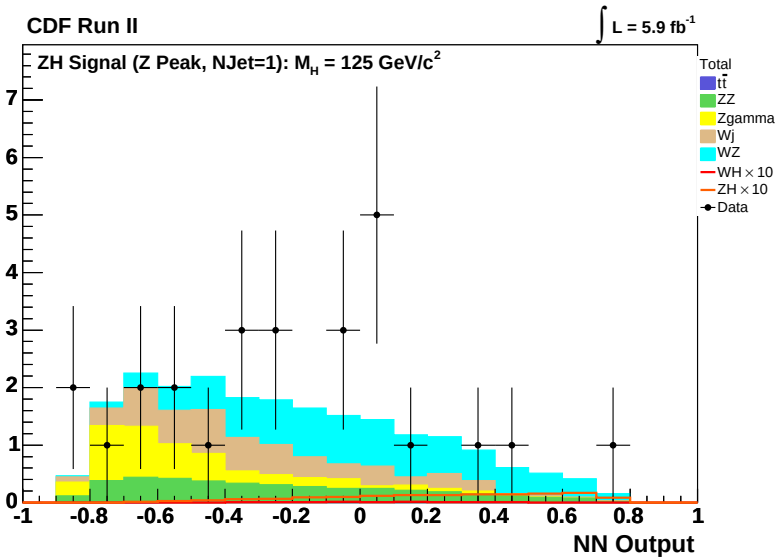

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 115 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

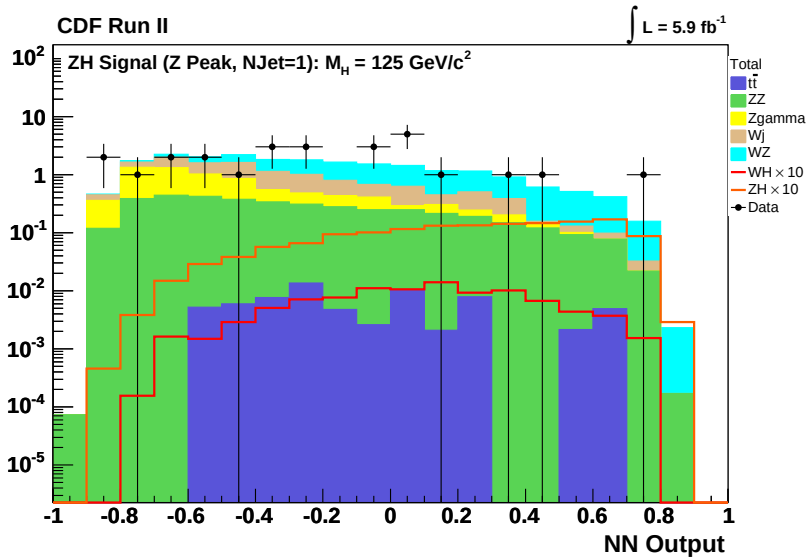
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 120 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

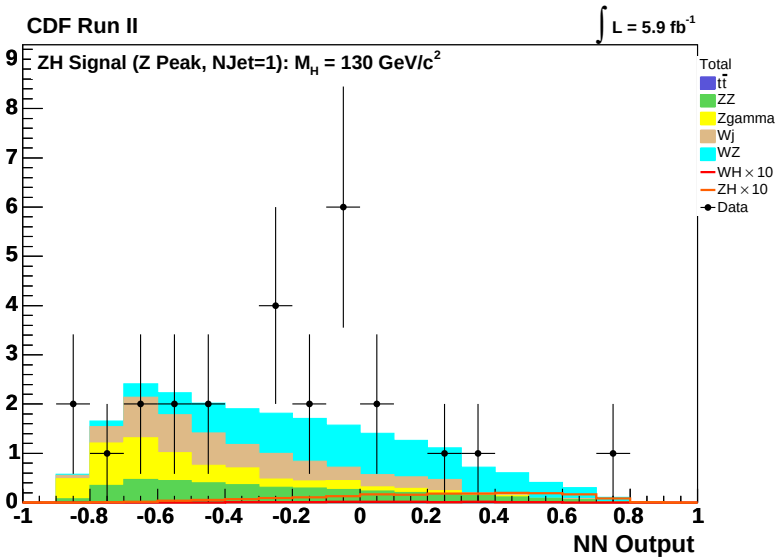

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 120 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

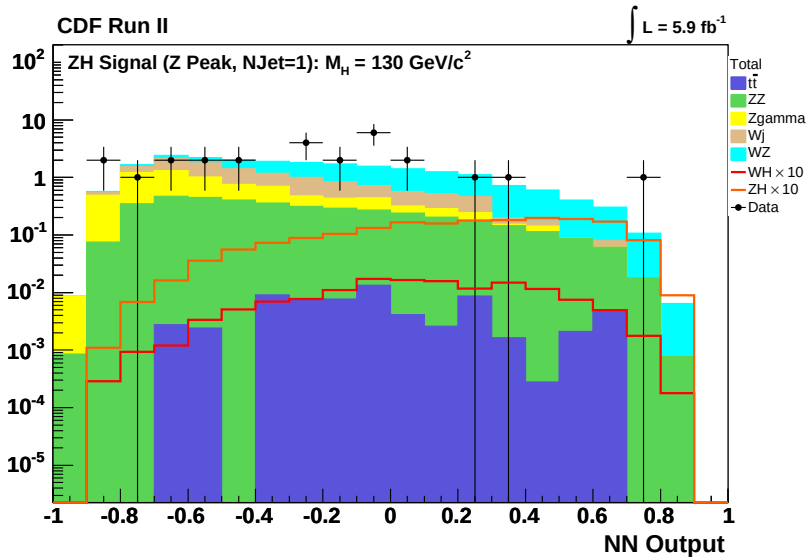
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 125 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

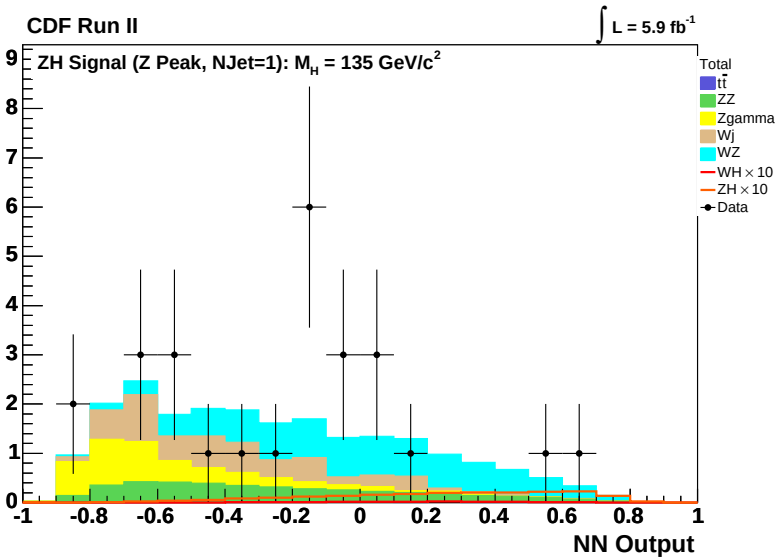

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 125 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

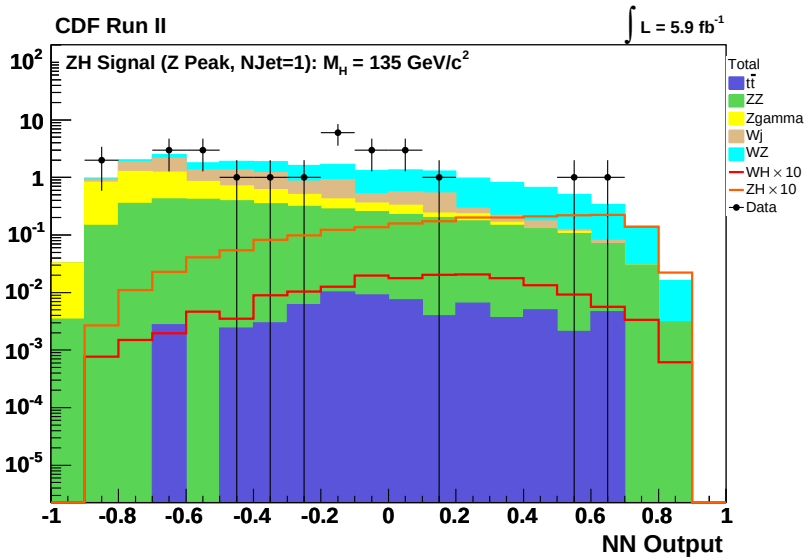
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 130 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

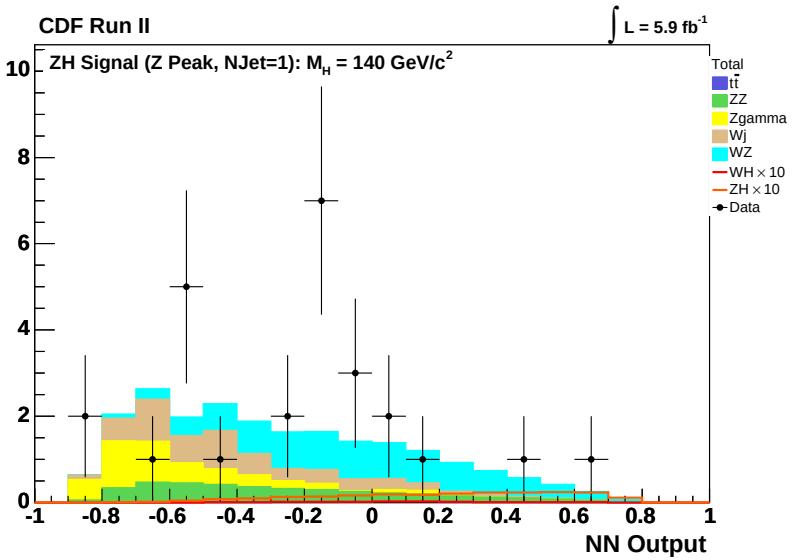

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 130 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

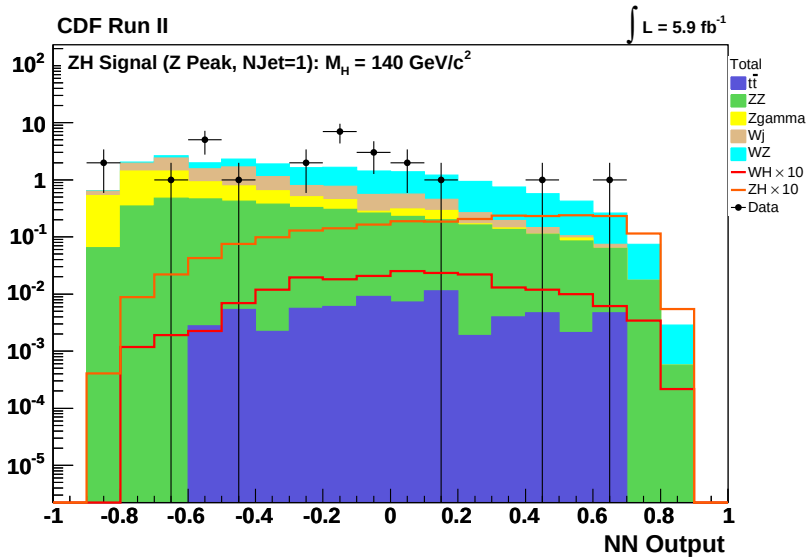
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 135 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

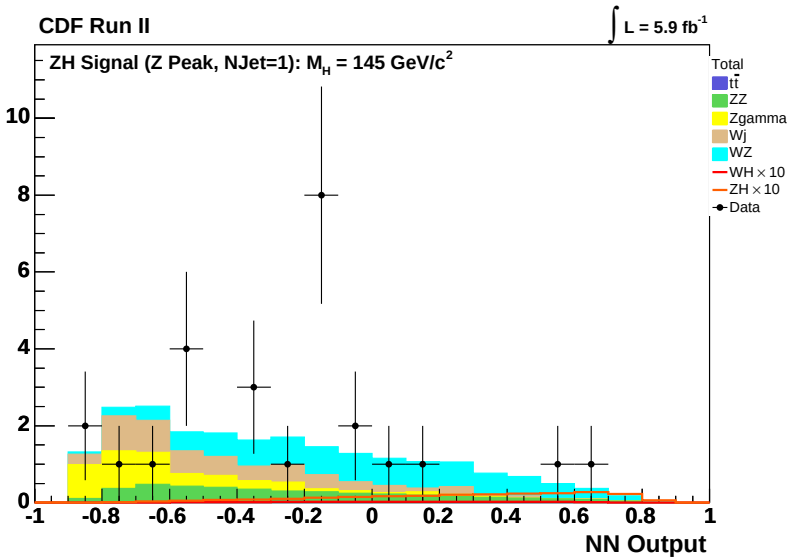

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 135 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

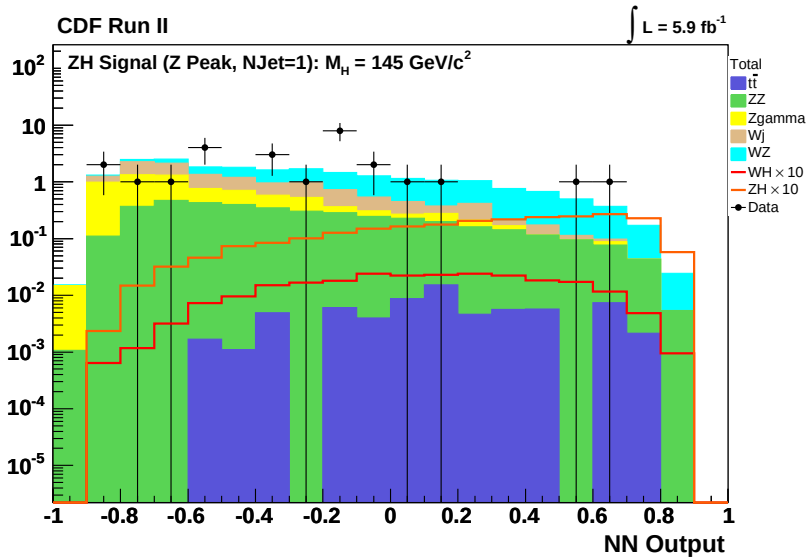
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 140 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

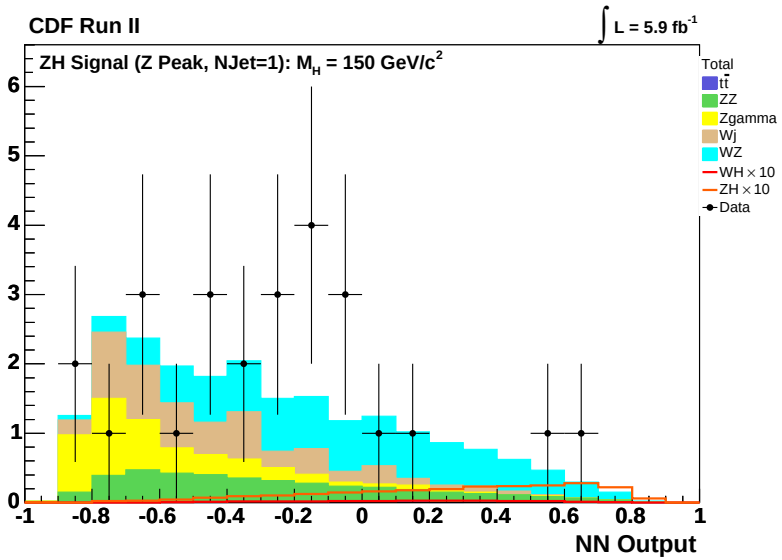

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 140 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

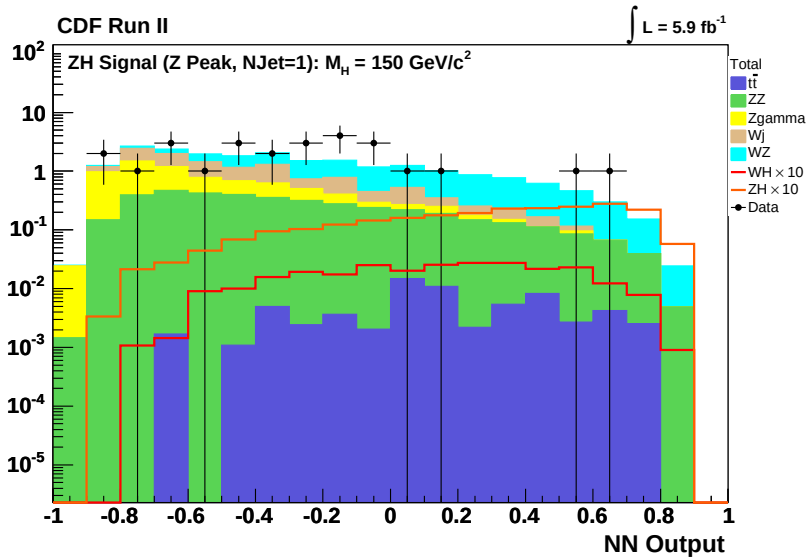
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 145 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

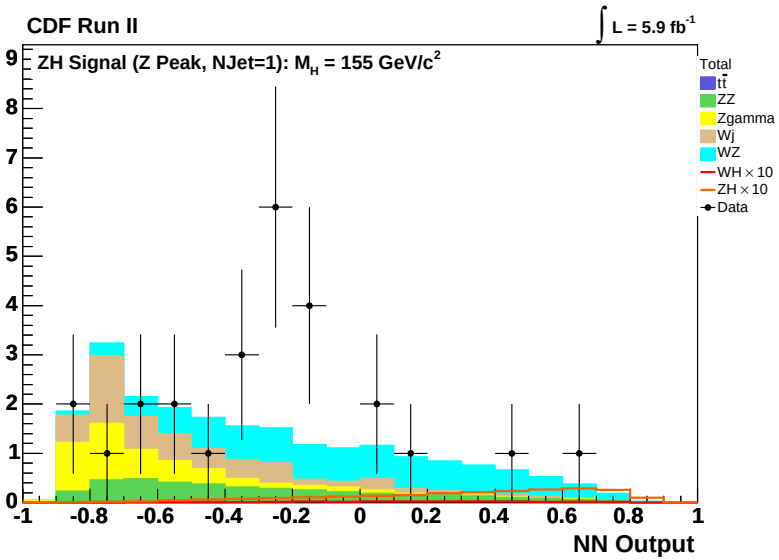

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 145 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

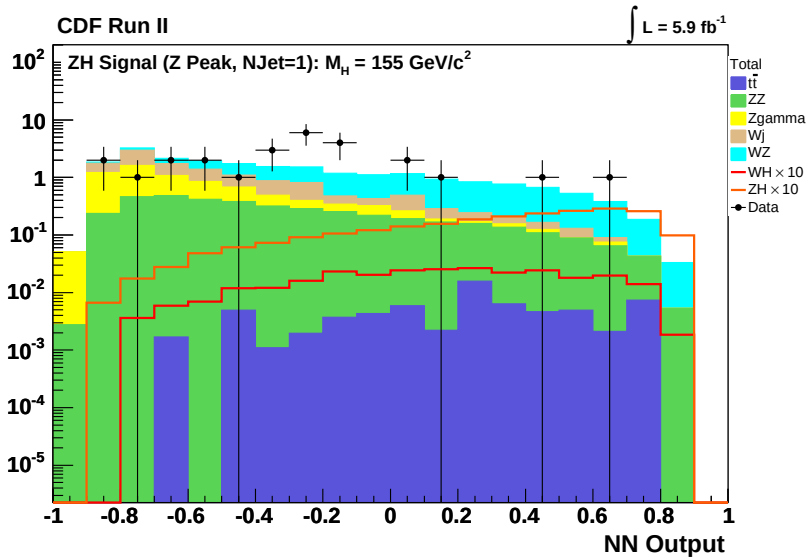
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 150 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

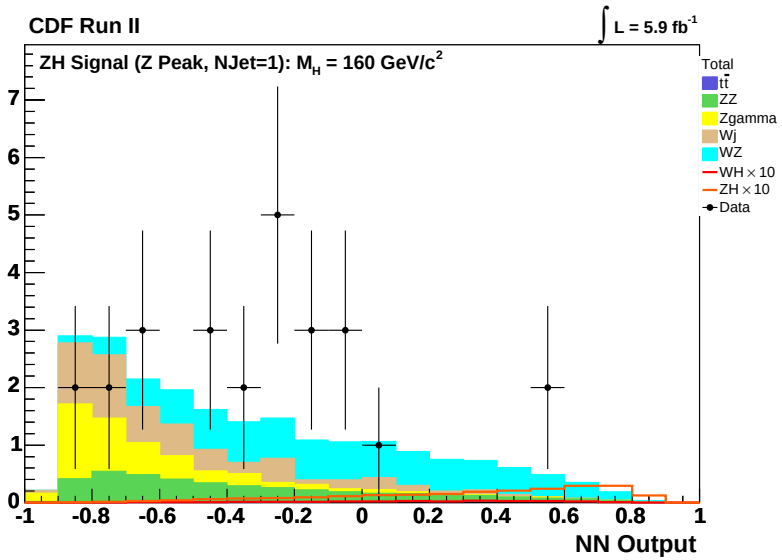

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 150 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

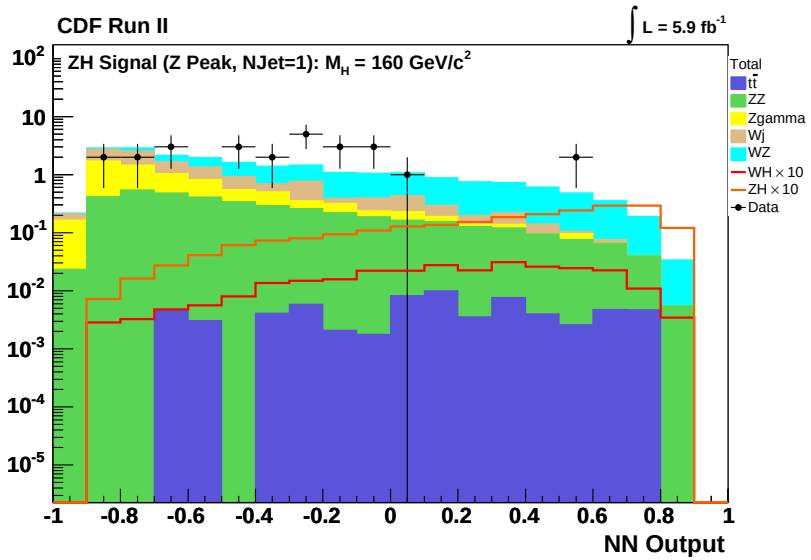
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 155 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

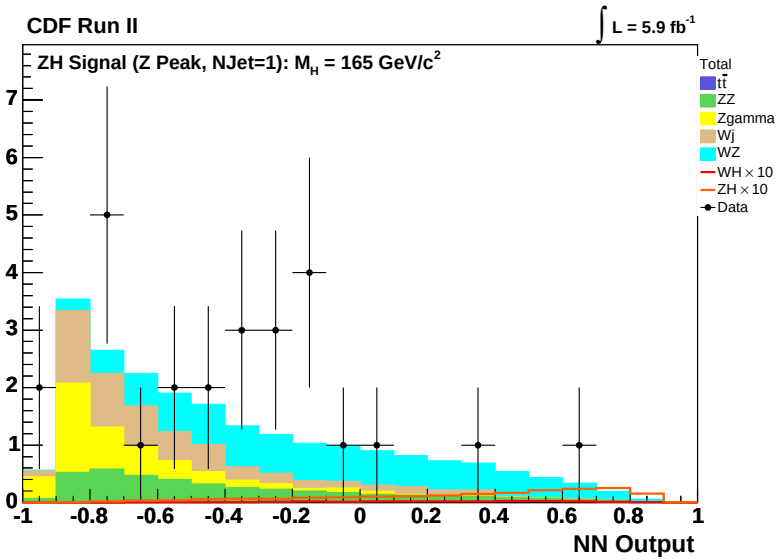

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 155 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

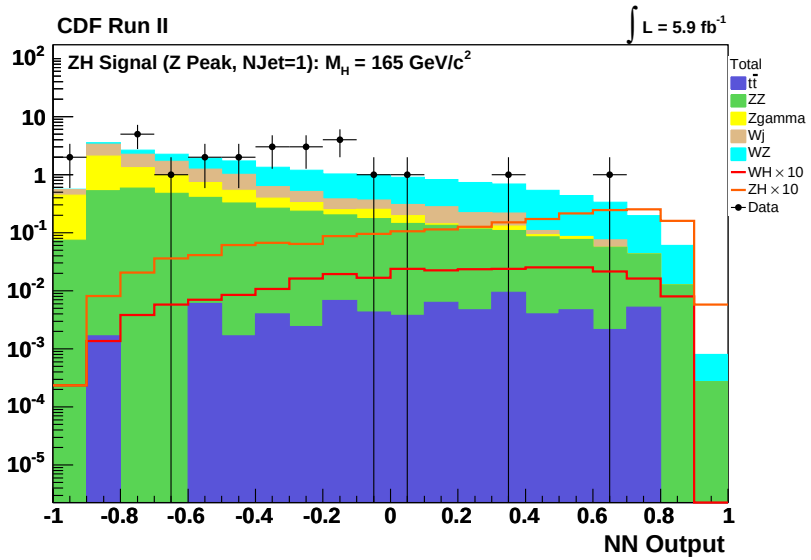
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 160 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

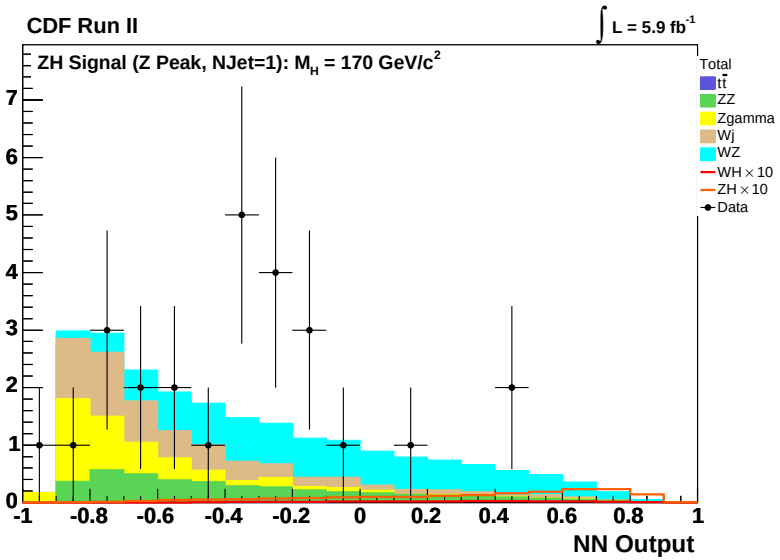

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 160 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

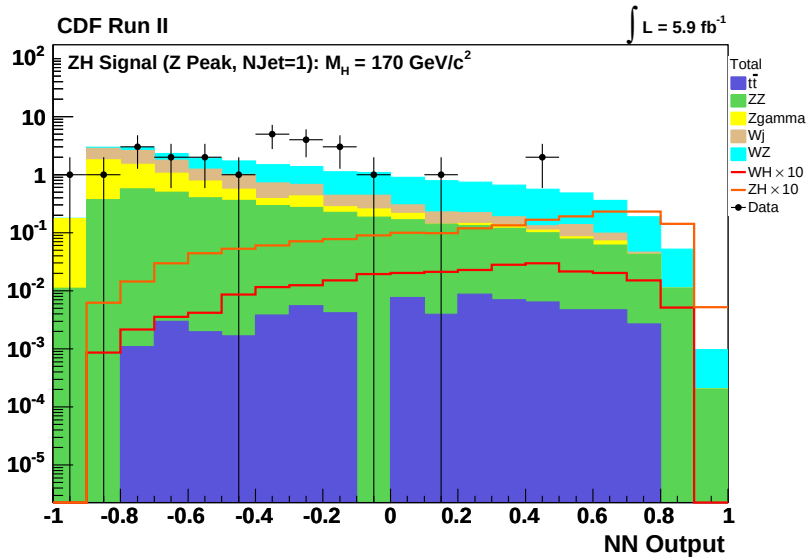
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 165 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

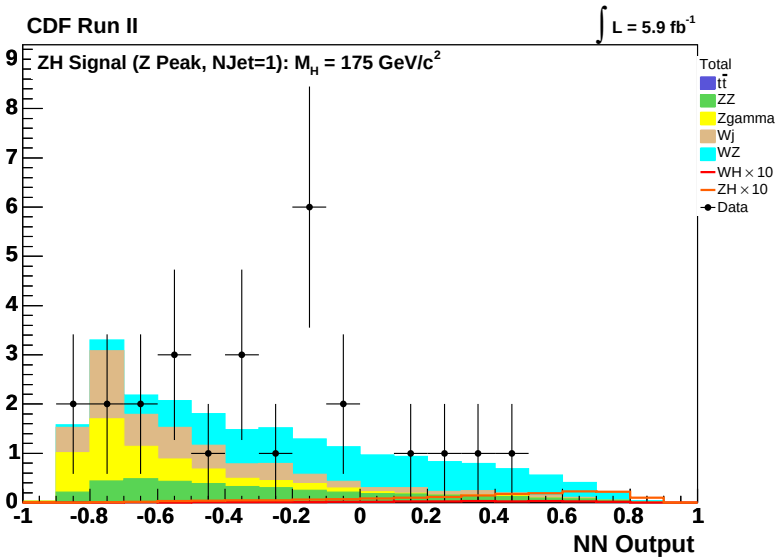

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 165 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

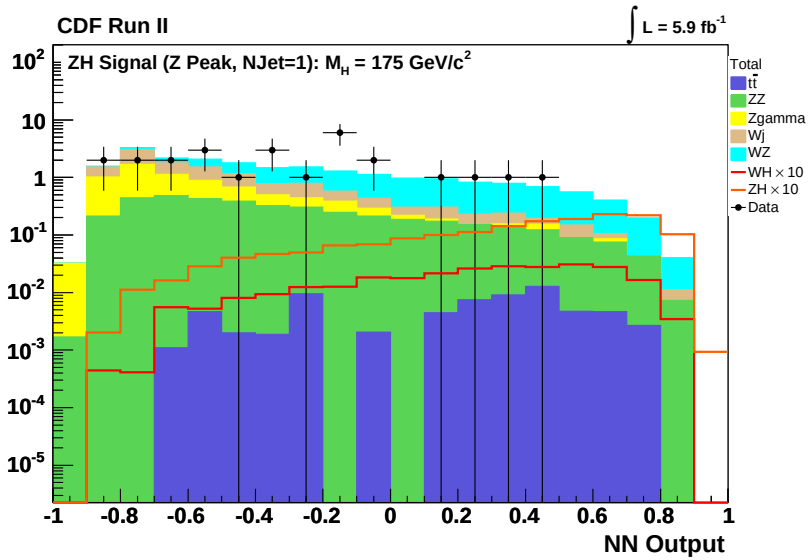
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 170 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

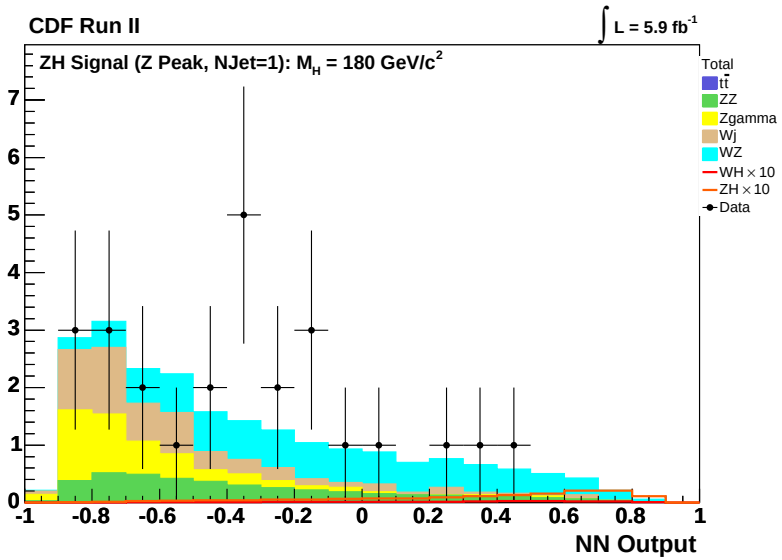

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 170 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

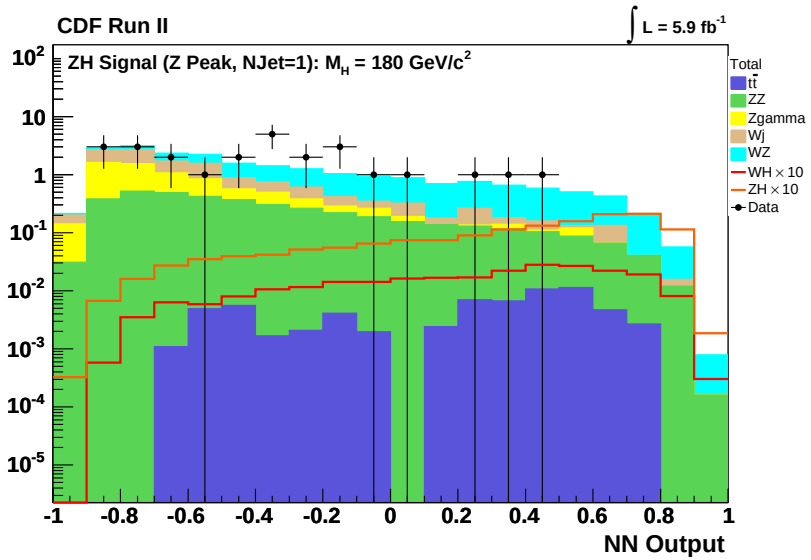
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 175 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

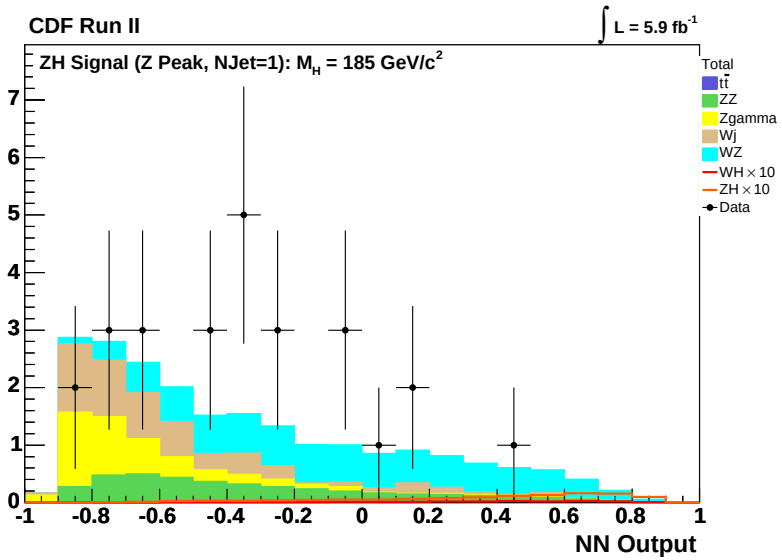

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 175 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

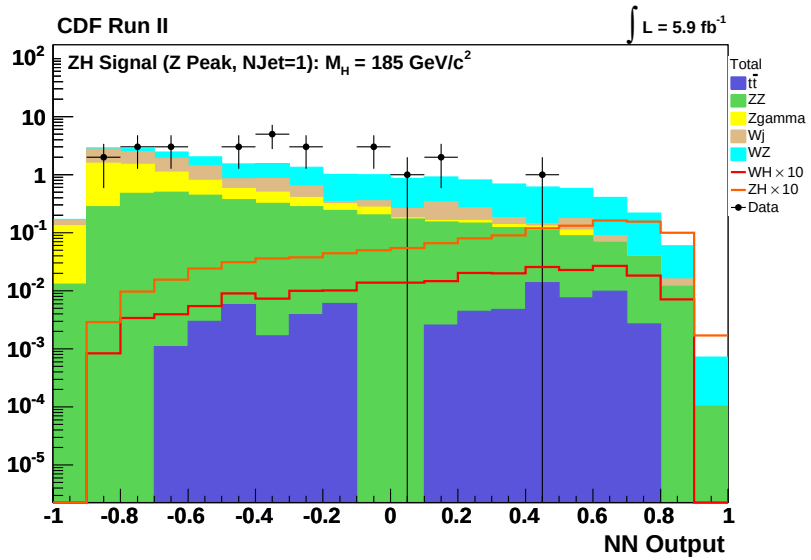
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 180 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

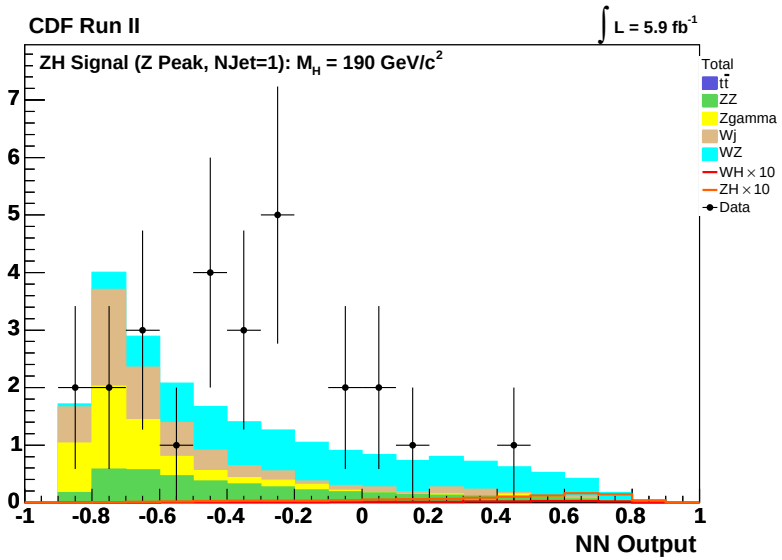

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 180 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

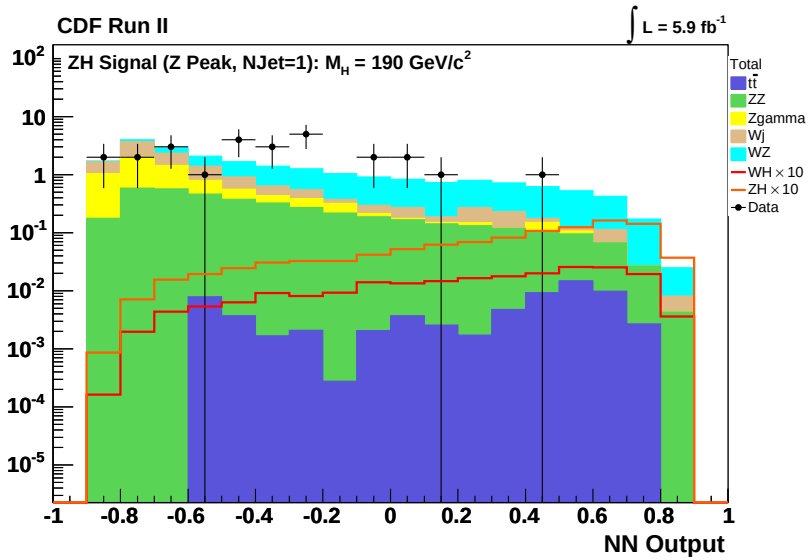
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 185 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

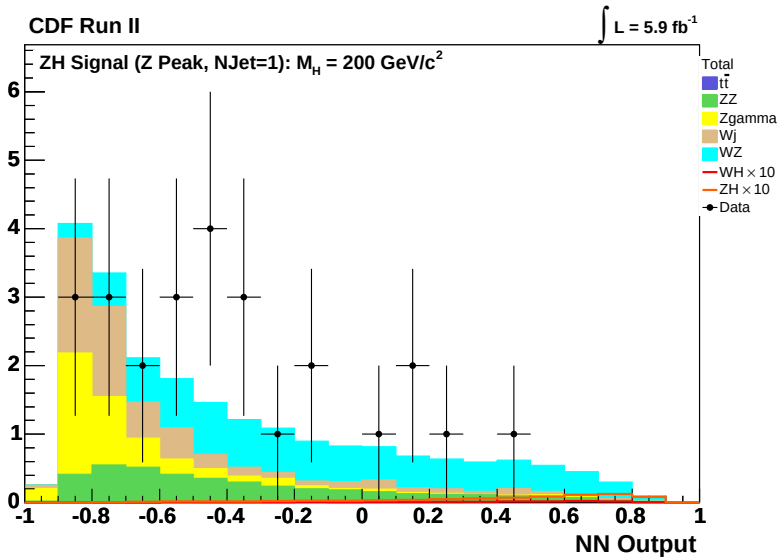

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 185 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

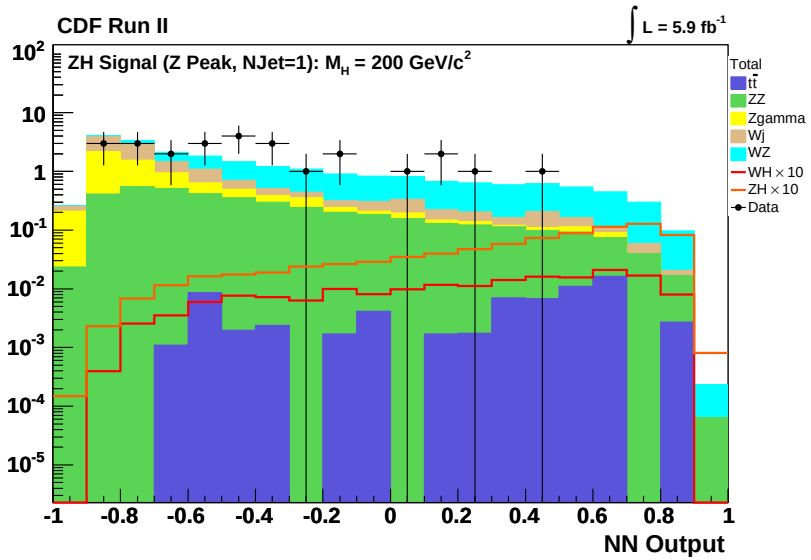
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 190 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

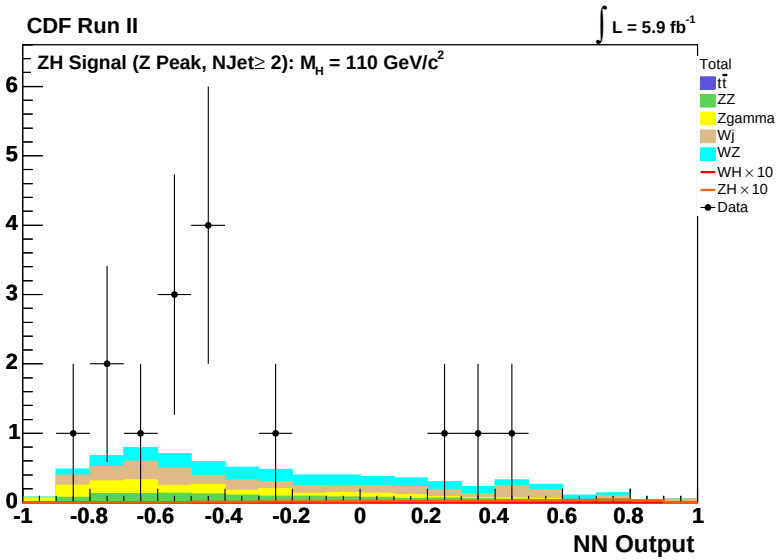

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 190 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

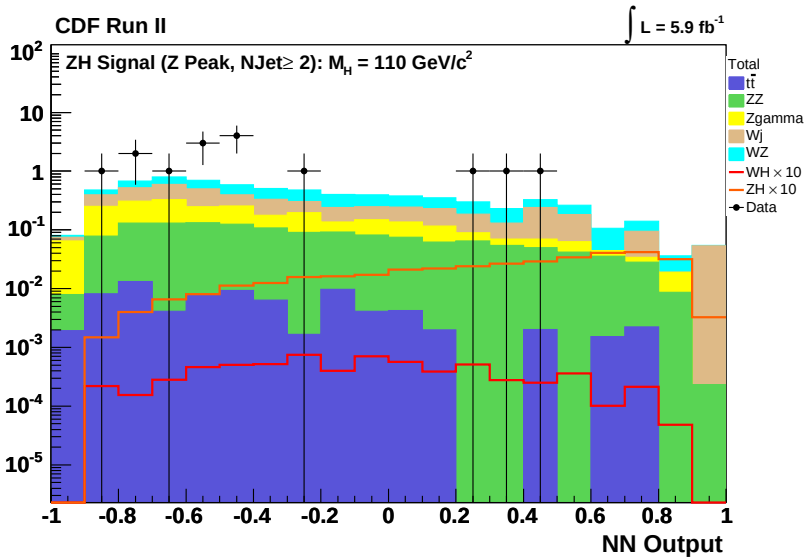
NN *ZH* 1 Jet


CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 200 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

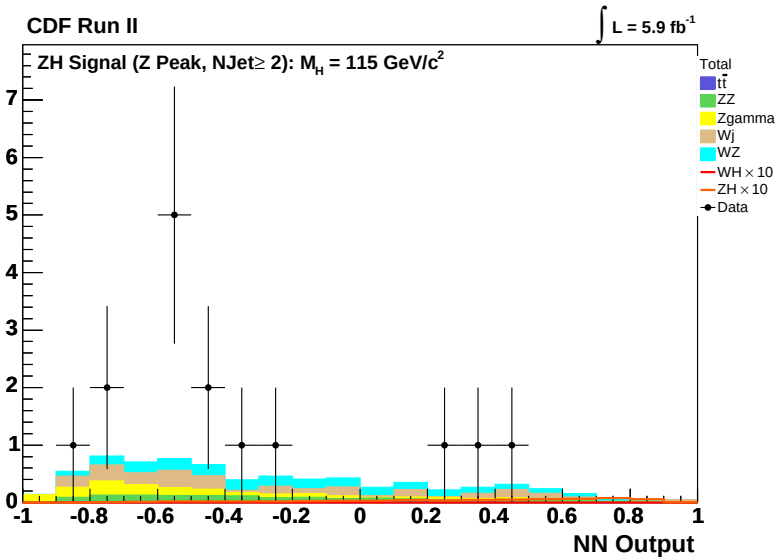

CDF Run II
∫ L = 5.9 fb-1
ZH Signal (Z Peak, NJet=1): MH = 200 GeV/c2
Total
tt̄
ZZ
Zgamma
Wj
WZ
WH × 10
ZH × 10
Data
NN Output

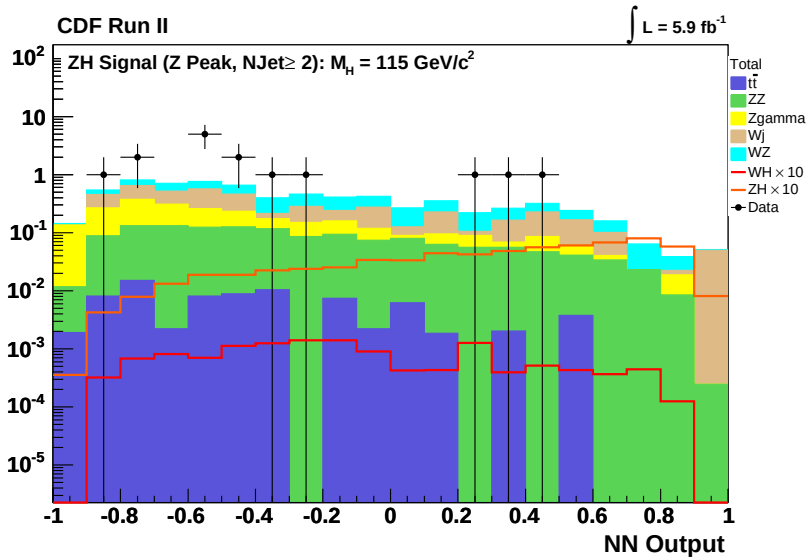
NN $ZH \geq 2$ Jets



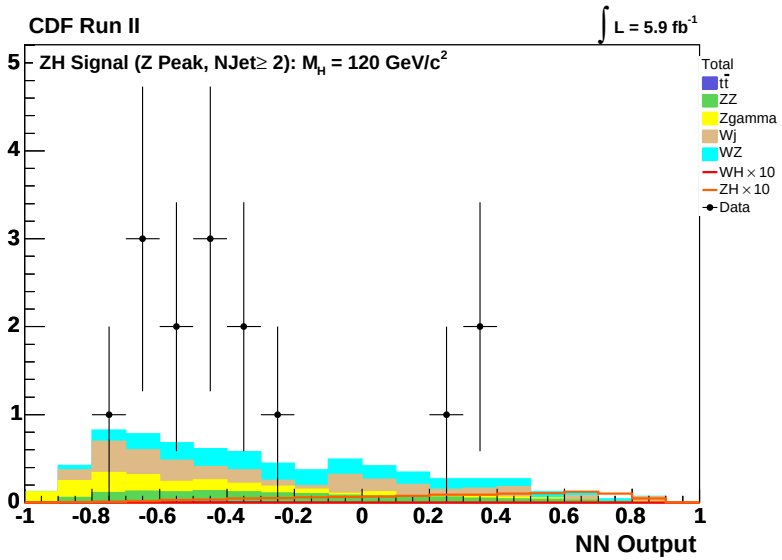


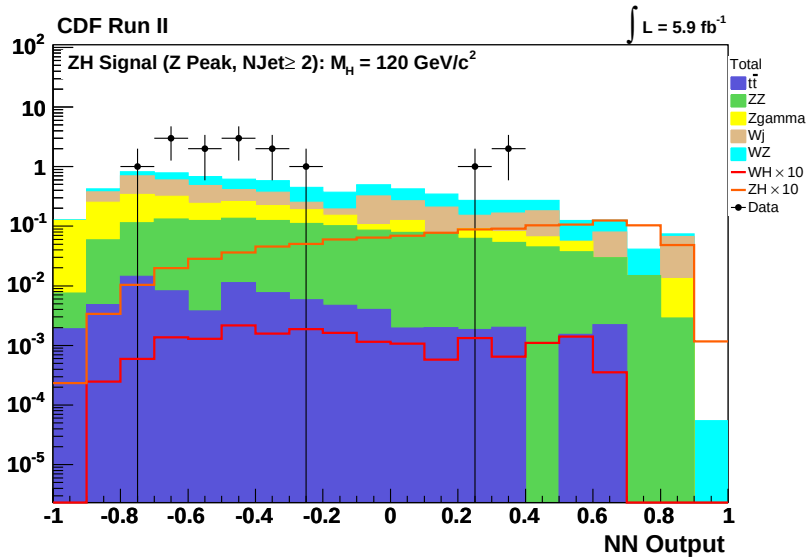
NN $ZH \geq 2$ Jets



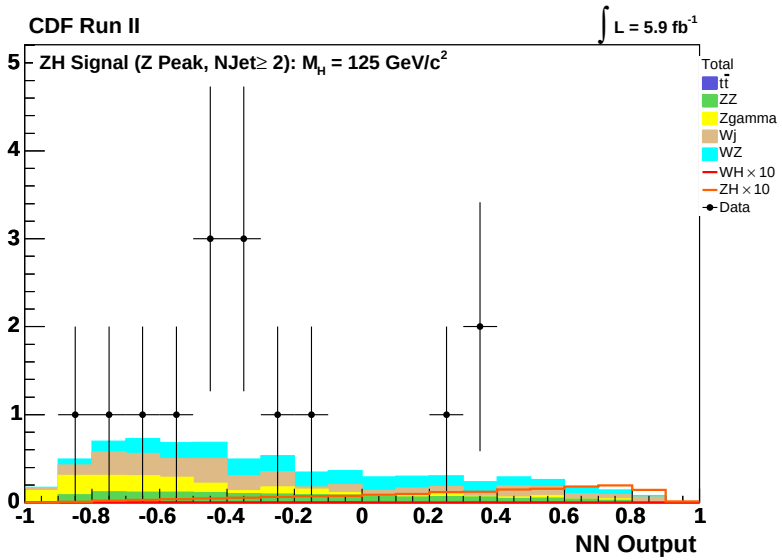


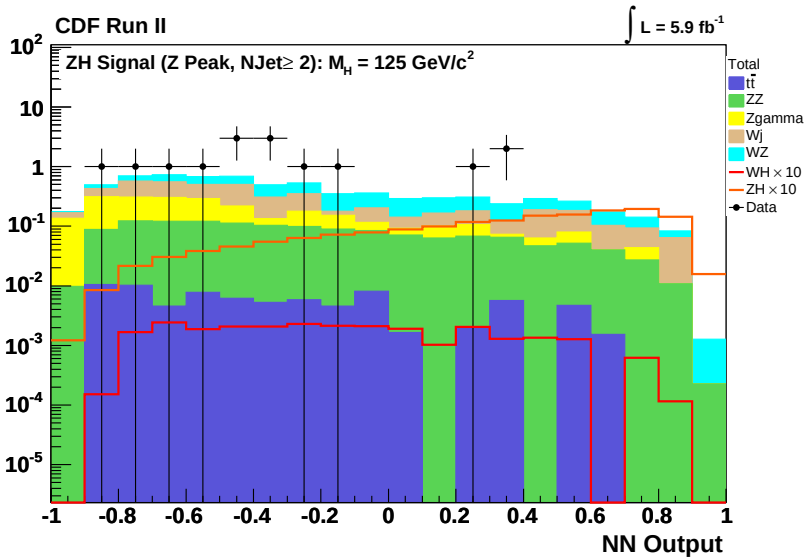
NN $ZH \geq 2$ Jets



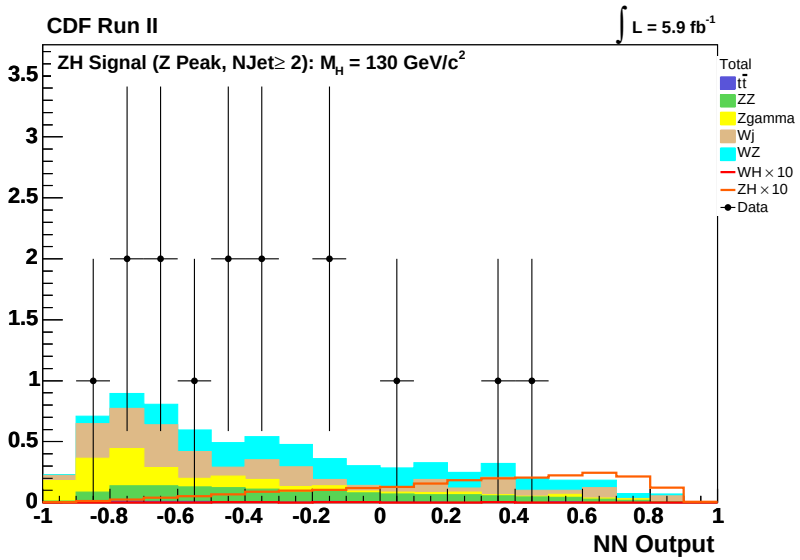


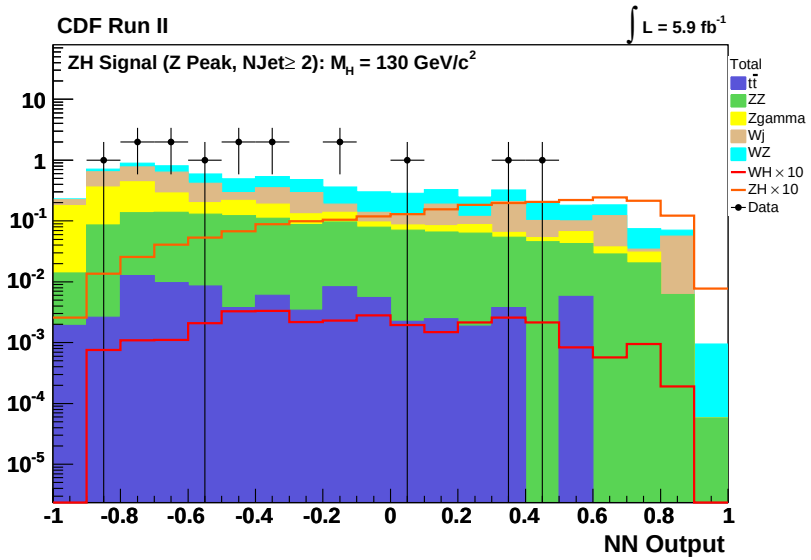
NN $ZH \geq 2$ Jets



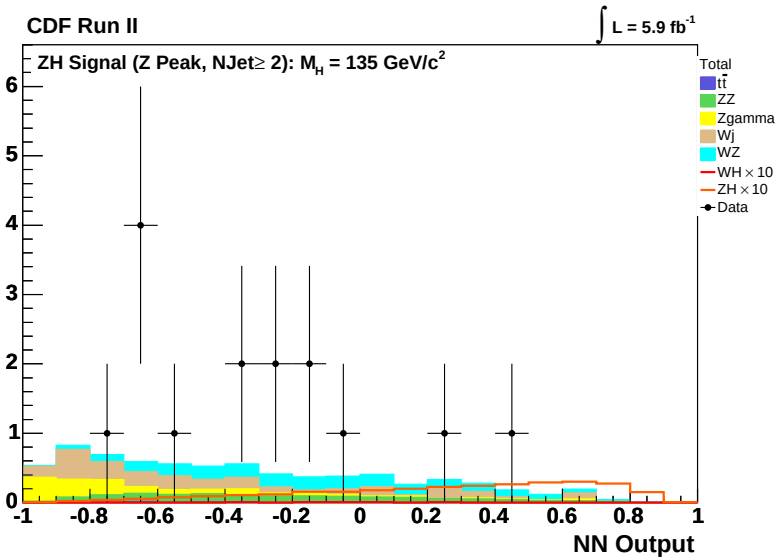


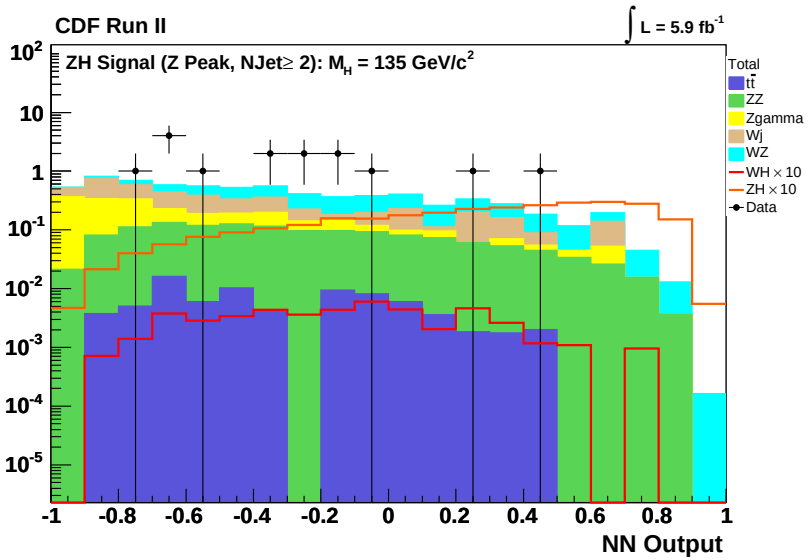
NN $ZH \geq 2$ Jets



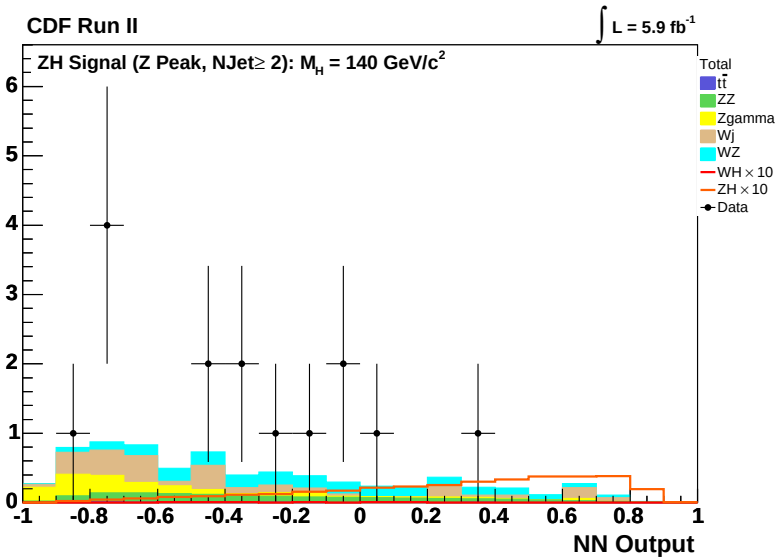


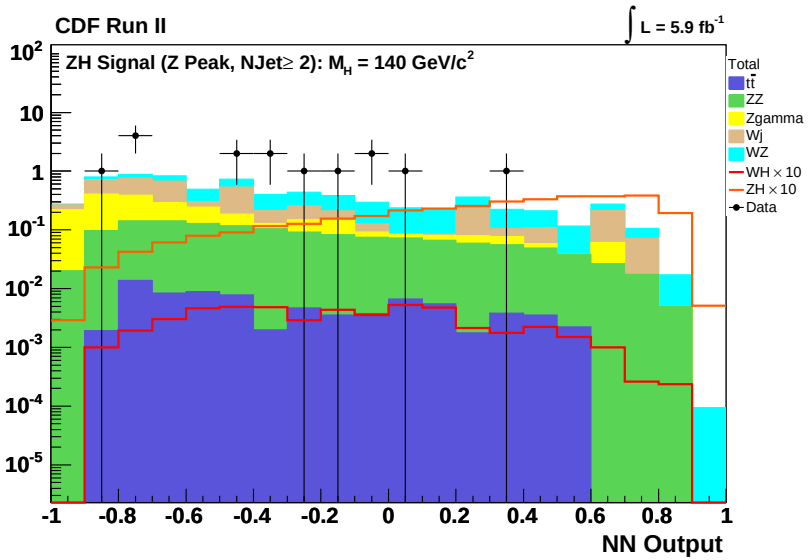
NN $ZH \geq 2$ Jets



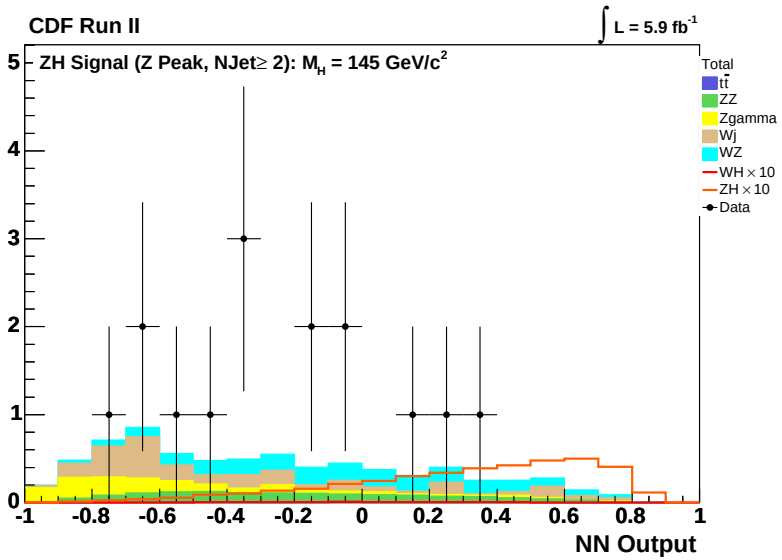


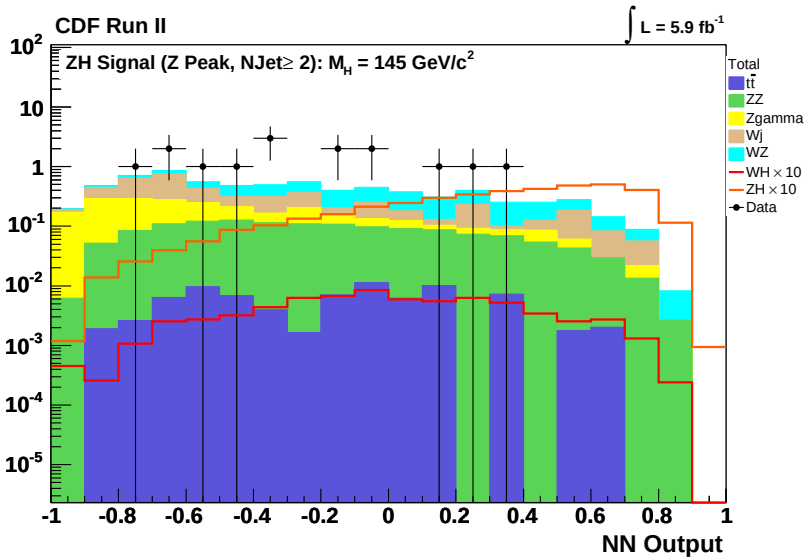
NN $ZH \geq 2$ Jets



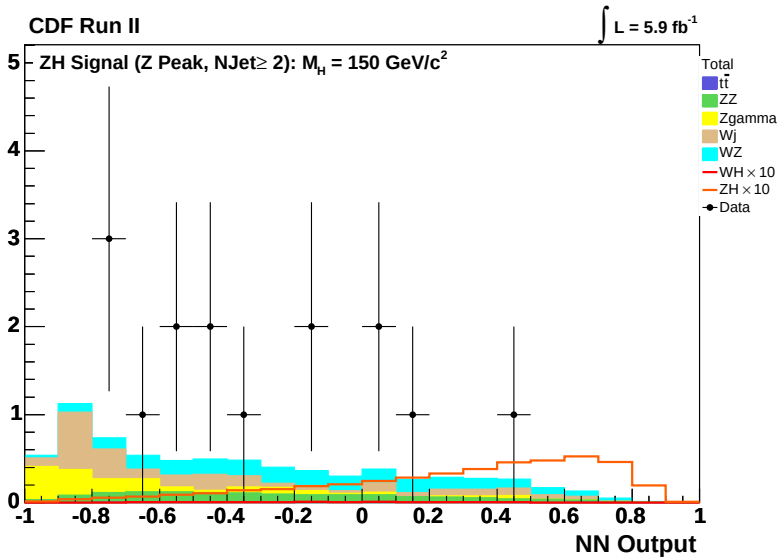


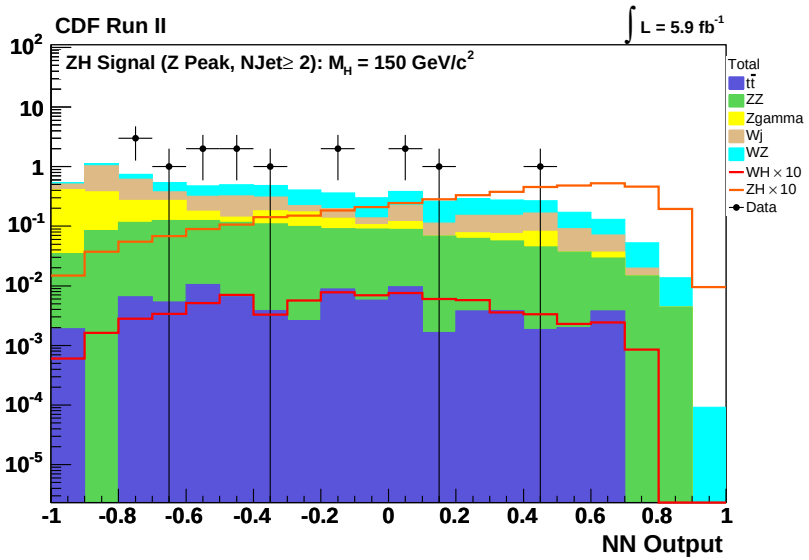
NN $ZH \geq 2$ Jets



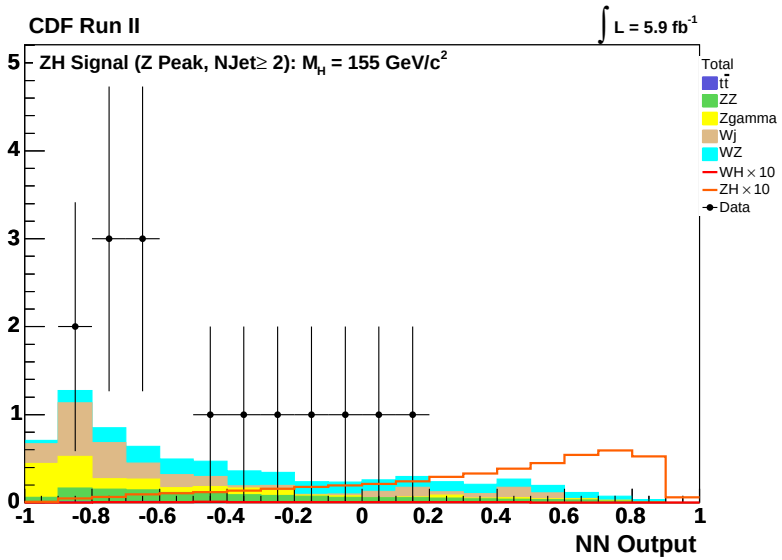


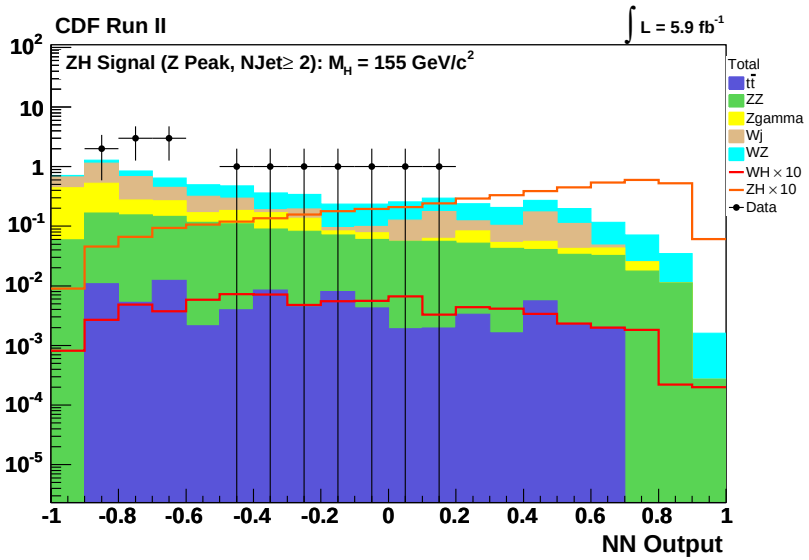
NN $ZH \geq 2$ Jets



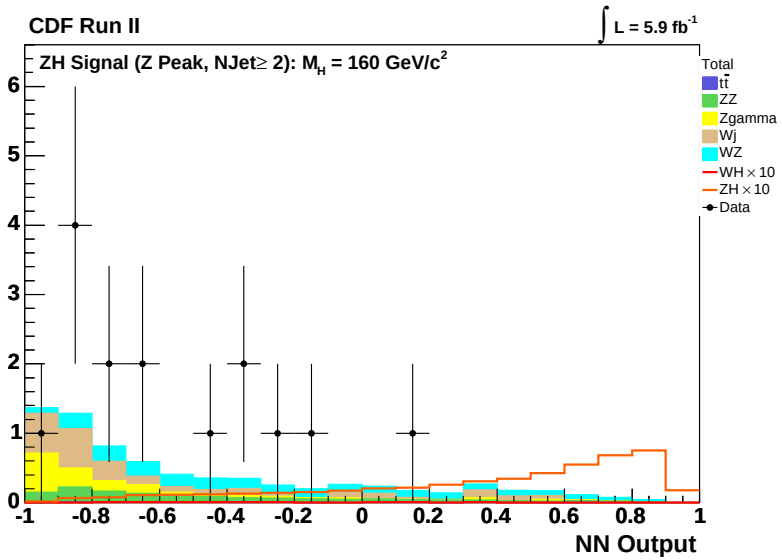


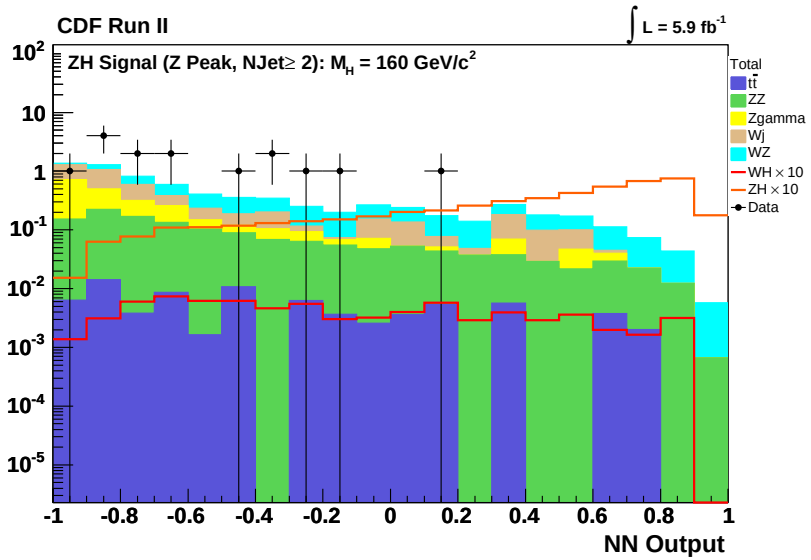
NN $ZH \geq 2$ Jets



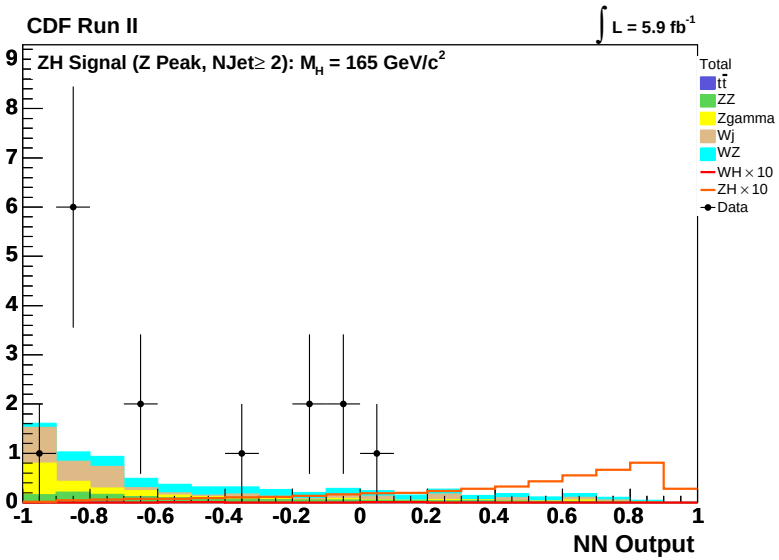


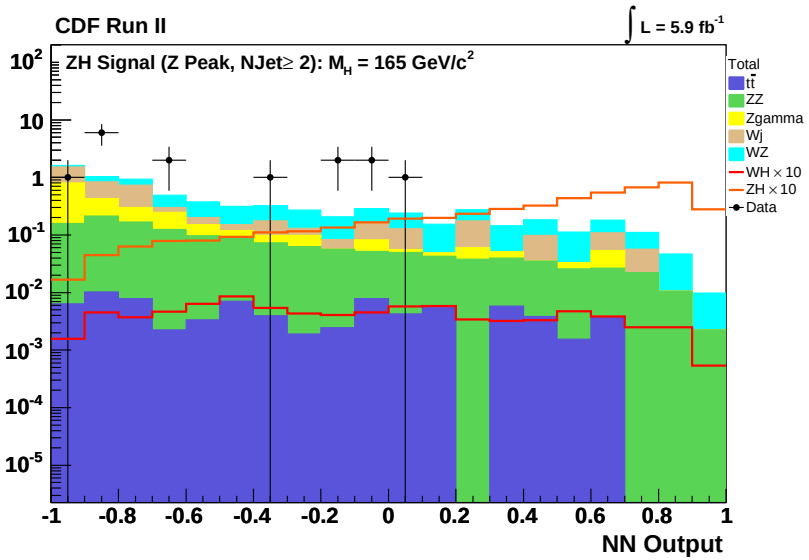
NN $ZH \geq 2$ Jets



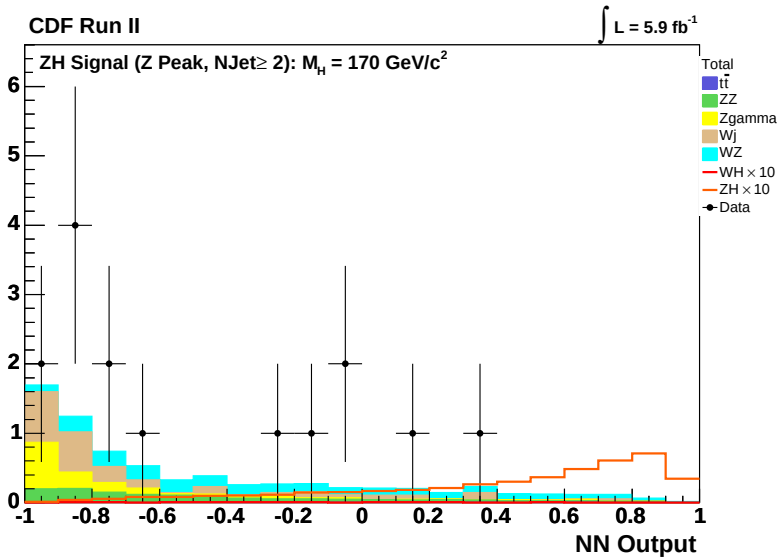


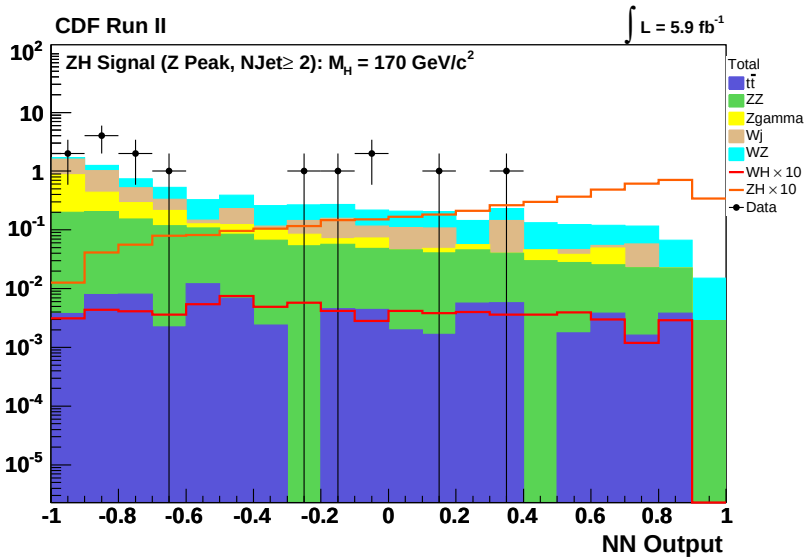
NN $ZH \geq 2$ Jets



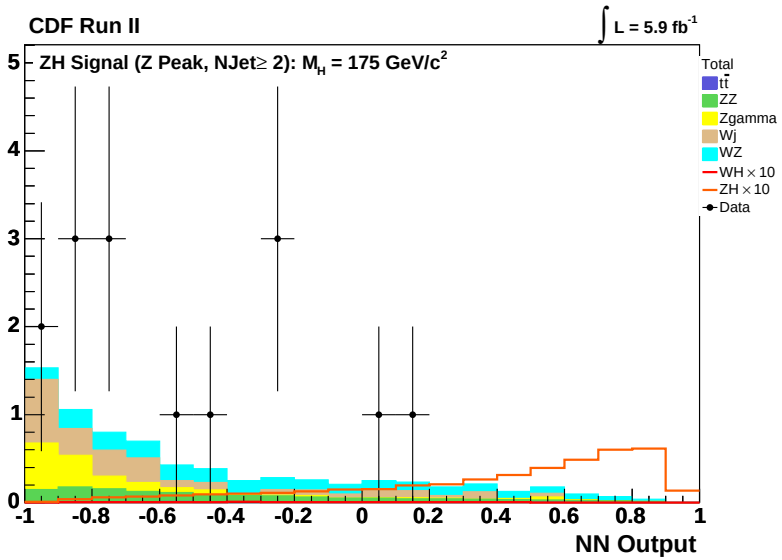


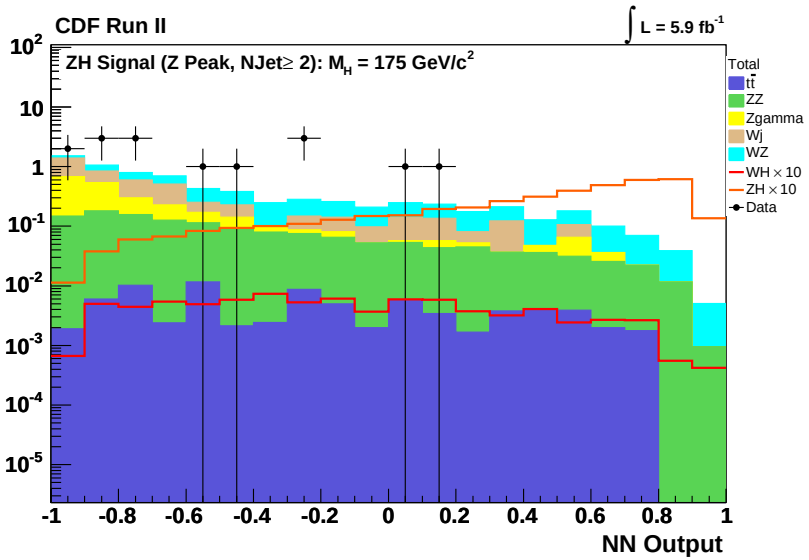
NN $ZH \geq 2$ Jets



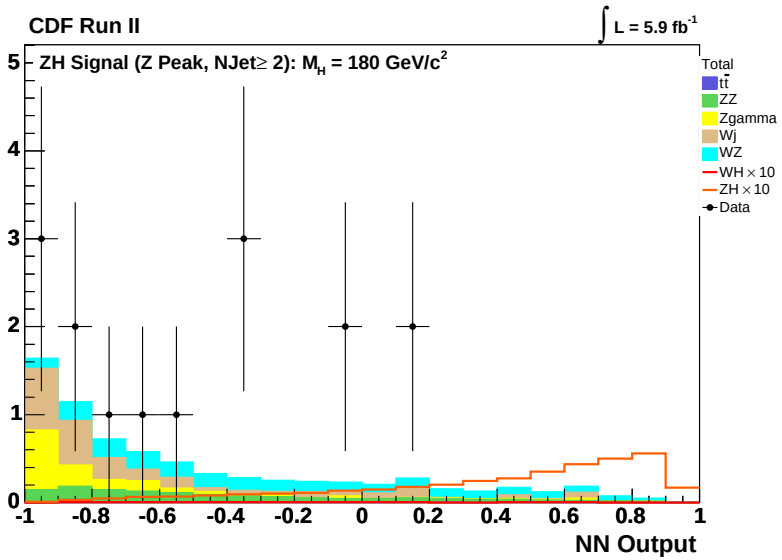


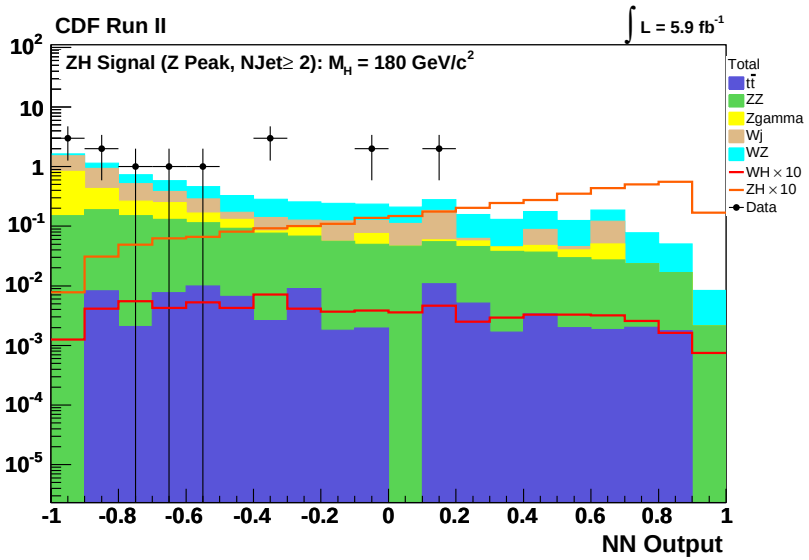
NN $ZH \geq 2$ Jets



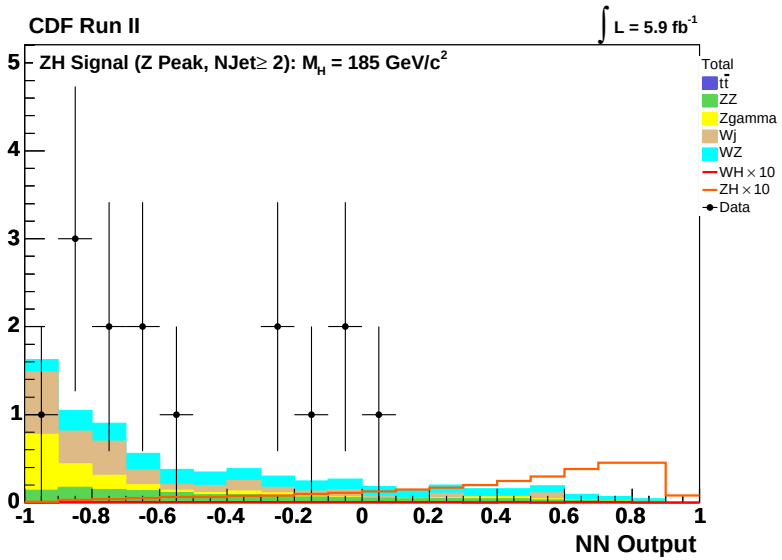


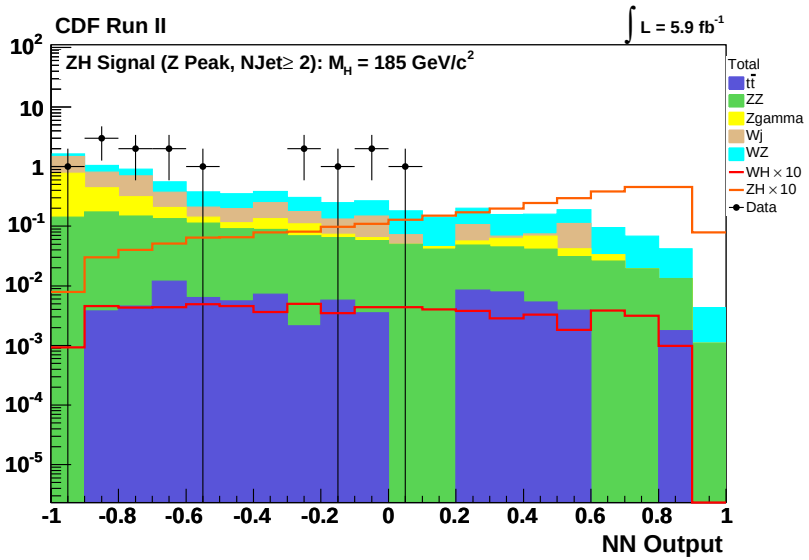
NN $ZH \geq 2$ Jets



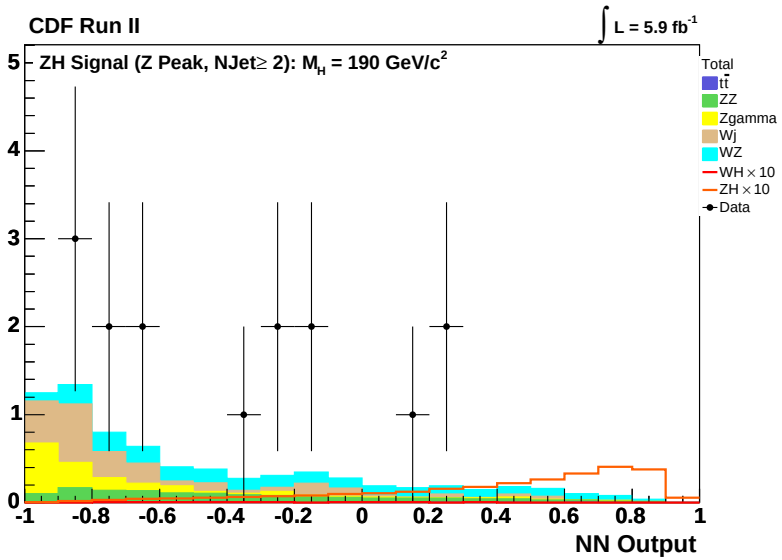


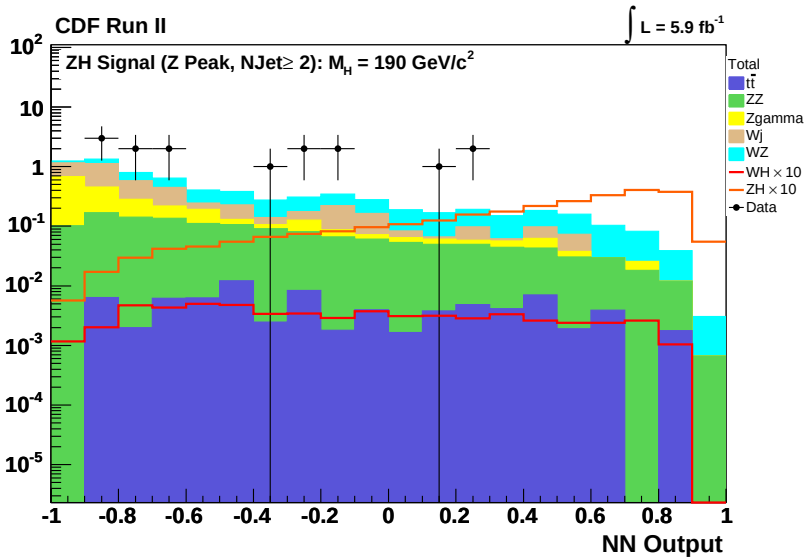
NN $ZH \geq 2$ Jets



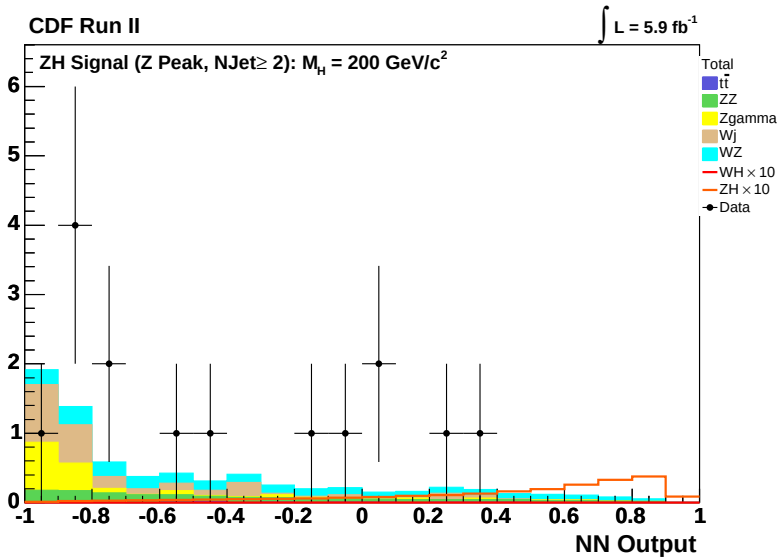


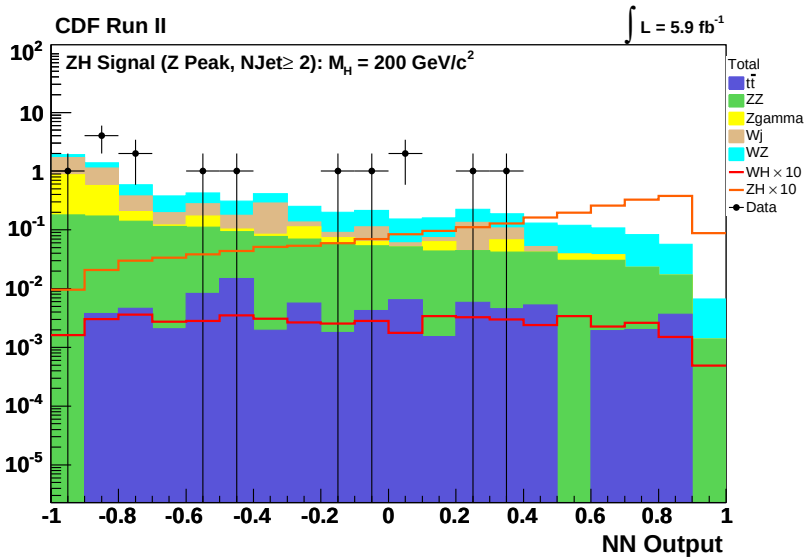
NN $ZH \geq 2$ Jets





NN $ZH \geq 2$ Jets





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