Searches for High Mass Higgs at the Tevatron

WW^* final states

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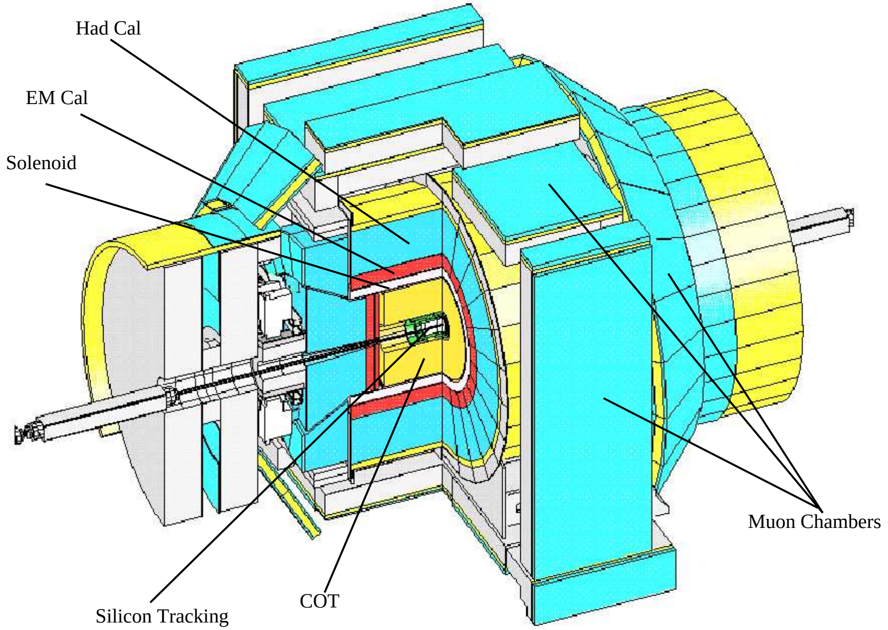
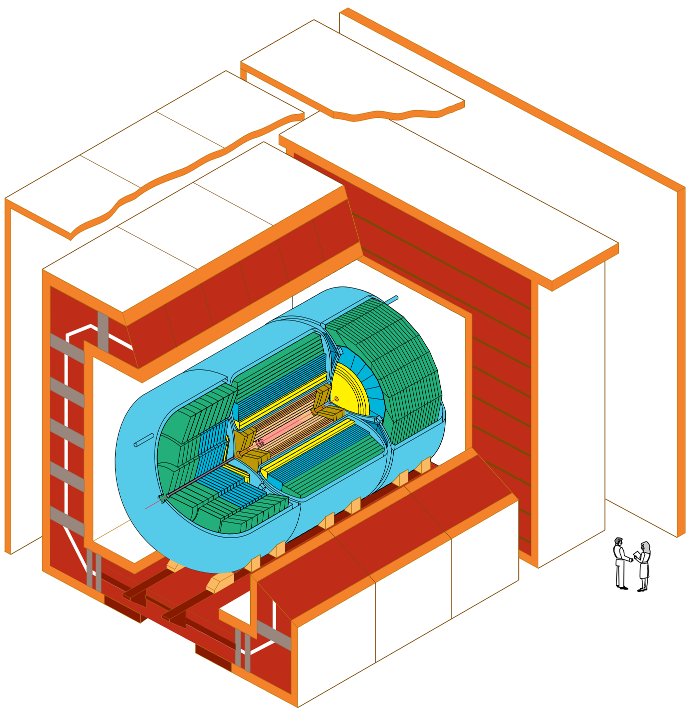
CDF & D0 Detectors



- Silicon tracking
- Drift chamber/Fiber tracker
- EM & Had Calorimetry
- Muon Chambers



DØ Detector

- Tevatron: $p \rightarrow \times \leftarrow \bar{p}$ $\sqrt{s} = 1.96$ TeV
- Delivered luminosity to date: ≈ 6.9 fb^{-1}
- Analysis shown here use up to 4.8 fb^{-1}

Standard Model and the Higgs

The standard model needs a Higgs or Higgs-like mechanism

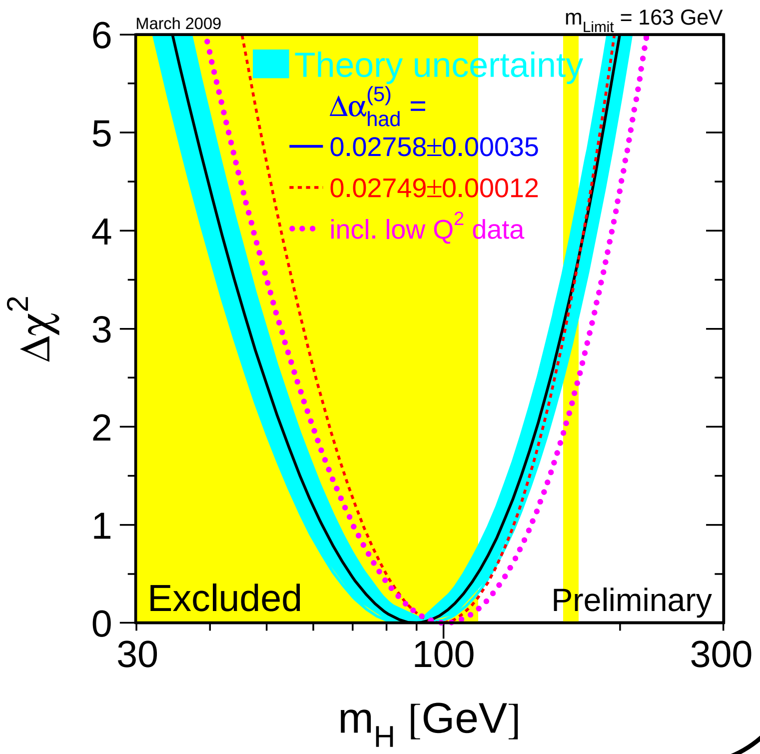
- To explain electroweak symmetry breaking
- And give particles mass

Direct searches at LEP tell us

$M_H > 114.4$ GeV @ 95% C.L.

Indirect constraints from EW data prefer a lighter higgs, but combined with the LEP lower limit gives an upper limit of

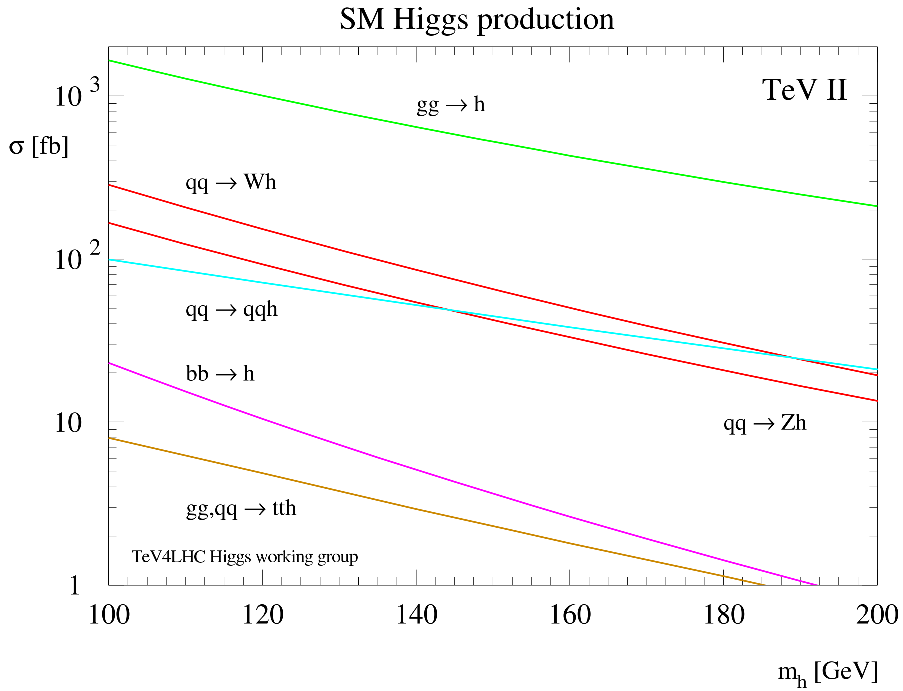
$M_H < 191$ GeV

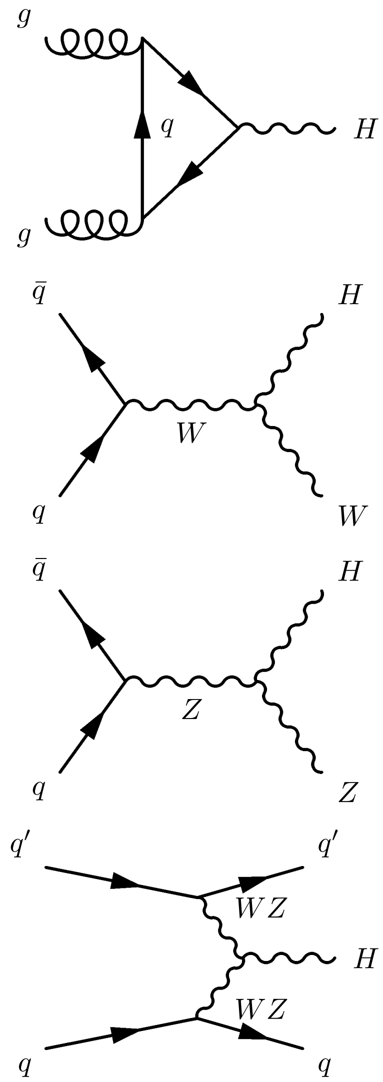


Standard Model Higgs Production

- Four main production mechanisms
- Gluon fusion is the dominant process at the Tevatron
- Associated production (particularly useful for light Higgs for better S/B)

See talks by: Michele Giunta, Michael Mulhearn

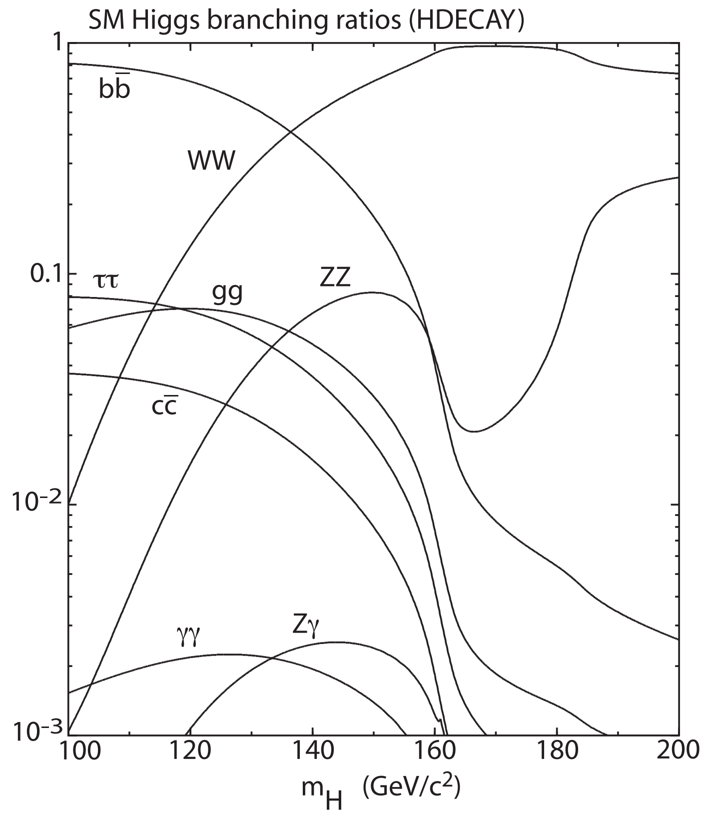


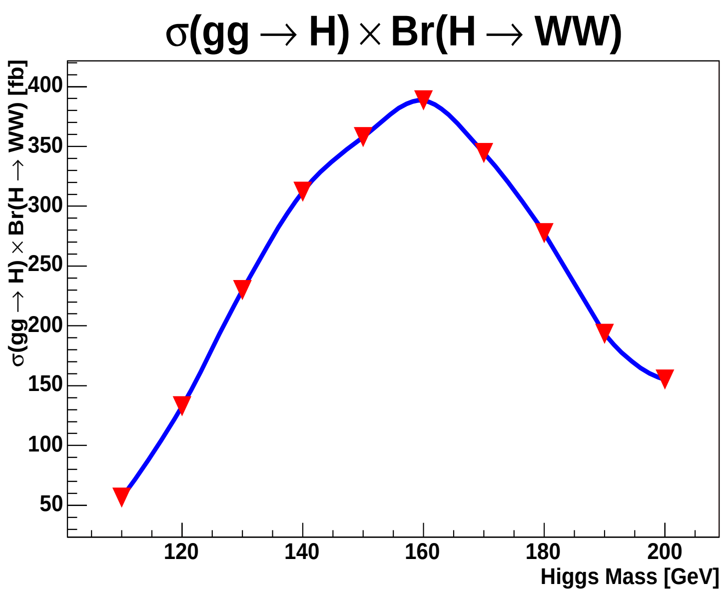


Standard Model Higgs Decay

Higgs decay modes depend on m_H

- For $m_H < 135$ GeV
  - Higgs decays predominantly to $b\bar{b}$
- For $m_H > 135$ GeV
  - Higgs decays mainly to W^+W^-

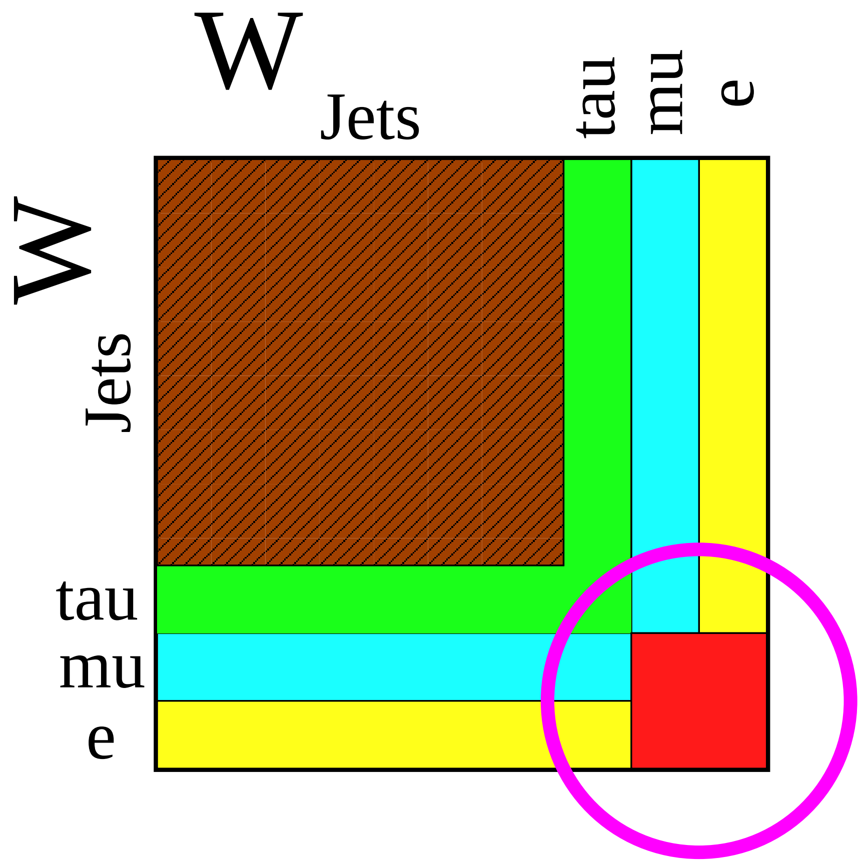




- For $gg \to H \to W^+W^-$ $\sigma \times BR$
  - Peak sensitivity for $m_H = 165$ GeV
  - Comparable sensitivity to individual low mass analyses at 125 GeV

$H \rightarrow W^+W^-$ Final States

- W **Decay Modes**
  - Leptonically 33% (e, μ, τ)
  - Hadronically 67%
- Dilepton (e, μ): $BR = 5\%$
  Very small BR, clean, easily triggerable
  Sensitive to $\tau \rightarrow (e, \mu)$
- Lepton + τ_{had}: $BR = 4\%$
  Of potential use at CDF and D0
- Lepton + Jets: $BR = 30\%$
  Large BR, but large W + multi-jets backgrounds
- All Hadronic: $BR = 45\%$
  Largest BR, but huge QCD backgrounds



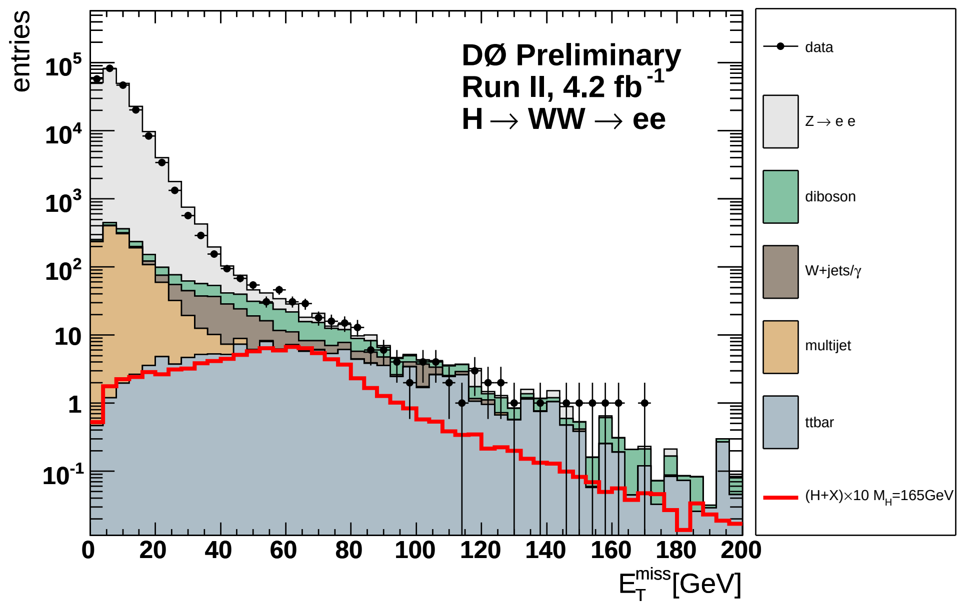
SM Backgrounds

The final state we are interested in is the Dilepton final state:
For $H \to WW \to l\nu l\nu$

- Largest background: $Z/\gamma^* \to \ell\ell$
- CDF & D0 suppress this by requiring significant $\not{E}_T$

After Drell-Yan suppression the main backgrounds are:

- Diboson production - WW, WZ, ZZ
- Top pair production - $t\bar{t}$



- $W+$ jets - where a jet is misidentified as a lepton
- $W\gamma$ - where the photon is misidentified as a lepton (typically an electron)

σ_{WW} **recently been measured by CDF and DØ and agrees well with SM**

Analysis Strategy

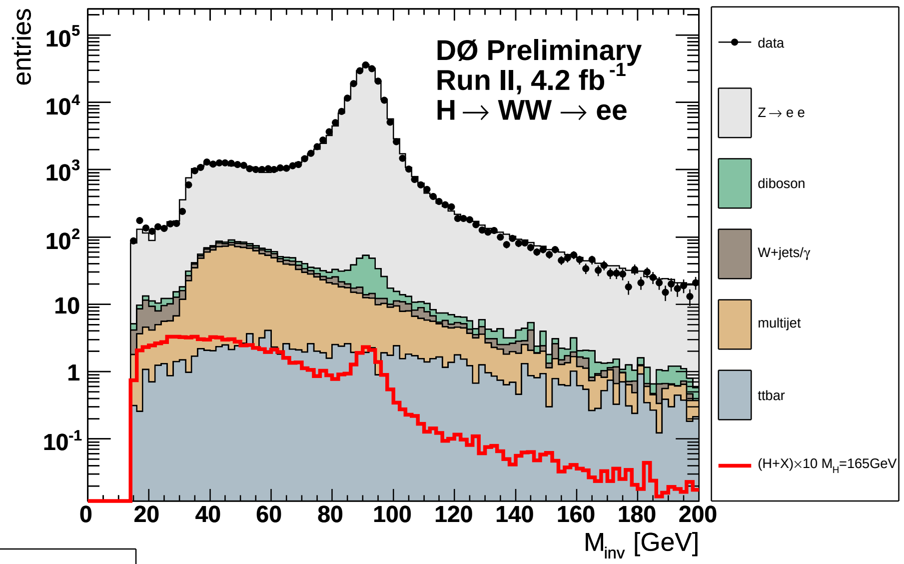
In general terms, the analysis strategy for $H \to WW$ searches involving 2 leptons in the final state at the tevatron is:

- Reduce the otherwise overwhelming Drell-Yan contribution (Cut out events with low $\not{E}_T$)
- Maximize the signal acceptance
  - Extend lepton selection
  - Add signal production mechanisms
- Separate signal from remaining background using some advanced multivariate technique
  - NN, Matrix element calculations, likelihood discriminants
- When there is no excess observed
  - Set limits on SM Higgs production at 95% CL

In the analyses shown here D0 separates by lepton pair type $(ee, e\mu, \mu\mu)$ whereas CDF separates by jet multiplicity

D0 $H \rightarrow WW$ (ee)

At *pre-selection*:
Require 2 High-P_T electrons
$P_T > 15$ GeV and $M_{e^+e^-} > 15$ GeV
$M_{\ell^+\ell^-}$ spectrum from ee channel ⟶

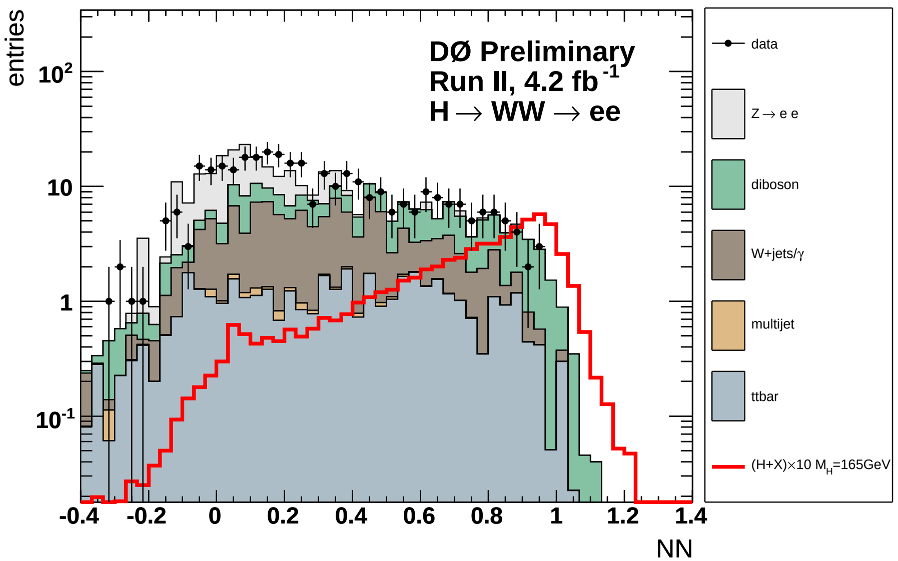


Full selection includes:

$\not\!\!E_T > 20$ GeV $\quad \not\!\!E_T^{scaled} > 6$

$M_T^{min}(e, \not\!\!E_T) > 20 \quad \Delta\phi(e,e) < 2)$

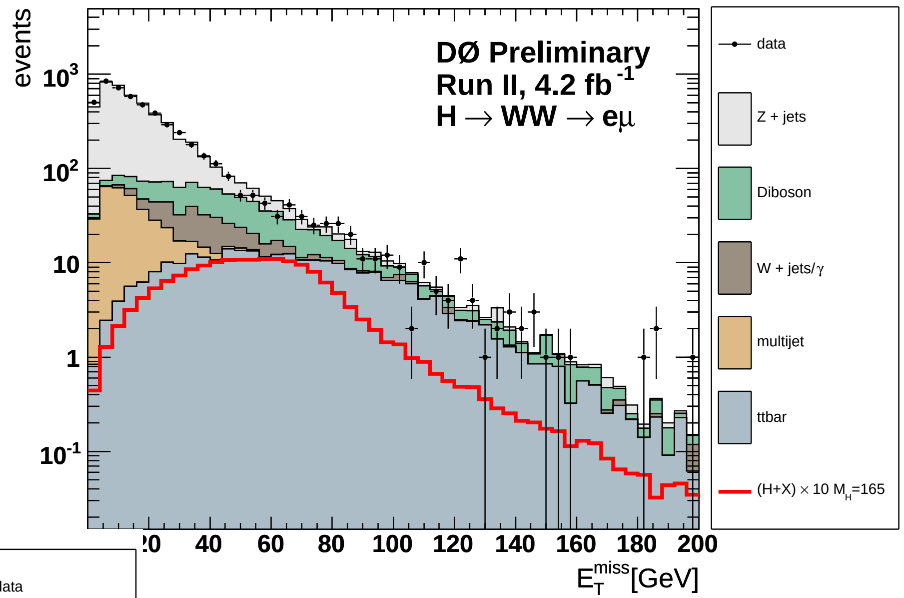
NN output for ee channel (below)



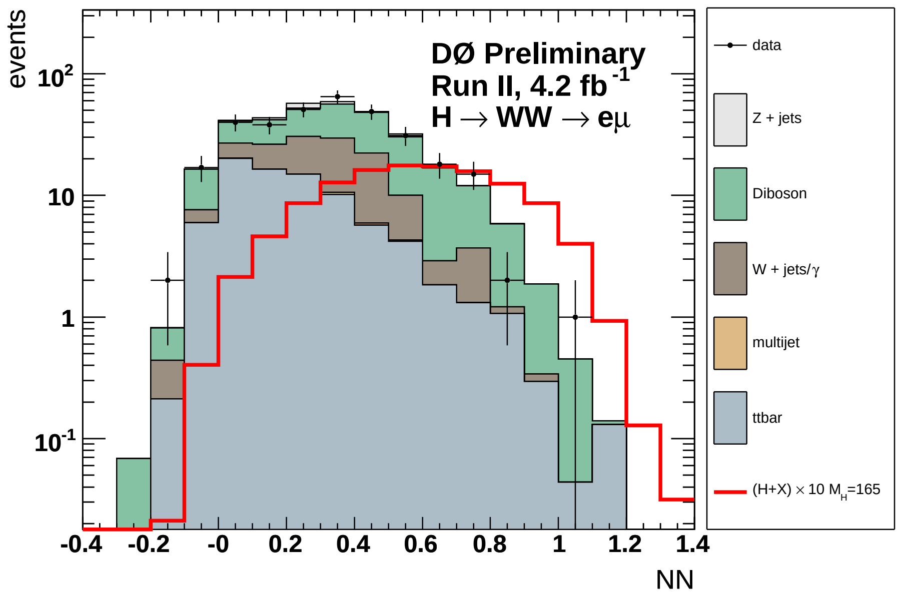
	Preselection			Full Selection		
$Z \rightarrow ee$	218695	±	704	108	±	704
$Z \rightarrow \tau\tau$	1135	±	16	1.4	±	16
$t\bar{t}$	131.4	±	1.4	39.9	±	1.4
W+jets	241	±	5	98	±	5
WW	172.2	±	2.6	66.8	±	2.6
WZ	112.5	±	0.2	9.68	±	0.2
ZZ	98.2	±	0.2	7.68	±	0.2
Multijet	1351	±	55	1.7	±	2.0
HWW (165 GeV)	9.45	±	0.01	6.13	±	0.01
Total Background	221937	±	707	332	±	15
Data	**221530**			**336**		

D0 $H \rightarrow WW$ $(e\mu)$

At *pre-selection*:
Require 2 High-P_T leptons
$P_T^e > 15$ GeV $P_T^\mu > 10$ GeV
and $M_{e^\pm\mu^\mp} > 15$ GeV
$\not\!\!E_T$ spectrum from $e\mu$ channel ⟶



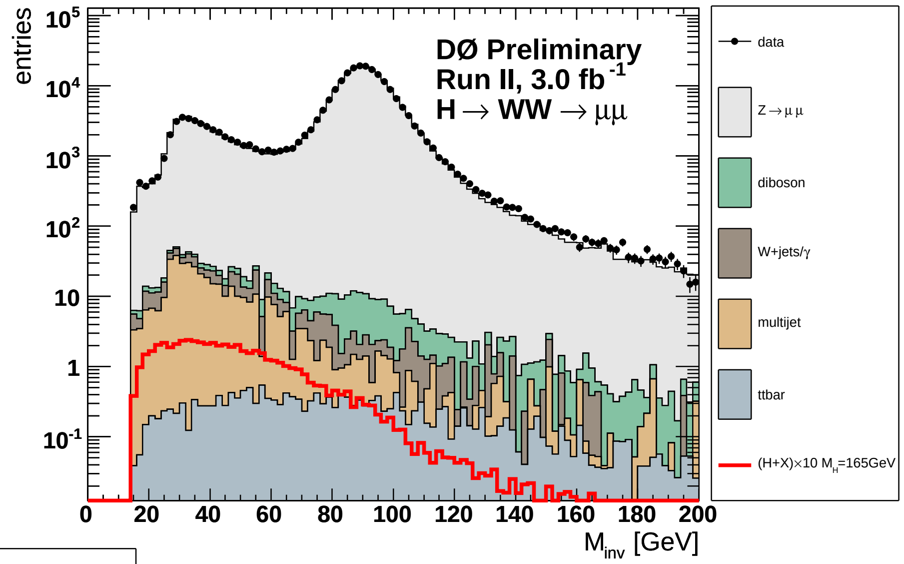
Full selection:
Same as ee channel
NN output for $e\mu$ channel (below)



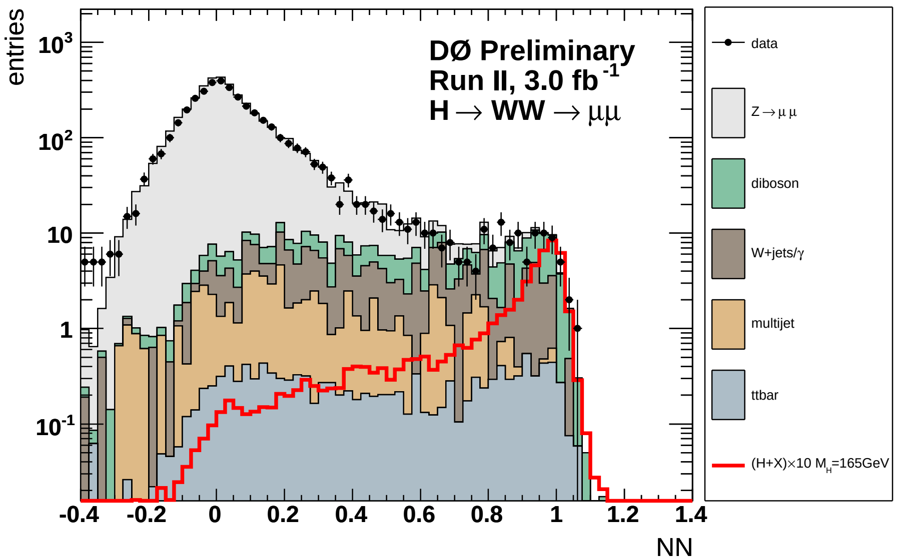
	Preselection			Full Selection		
$Z \rightarrow ee$	280.6	±	3.3	0	+	1
$Z \rightarrow \mu\mu$	274.6	±	0.9	5.8	±	0.1
$Z \rightarrow \tau\tau$	3260	±	3	7.3	±	0.1
$t\bar{t}$	272.0	±	0.3	82.5	±	0.1
W+jets	183	±	4	78.6	±	2.8
WW	421	±	0.1	154.7	±	0.1
WZ	20.5	±	0.1	6.6	±	0.1
ZZ	5.3	±	0.1	0.60	±	0.01
Multijet	279	±	168	1.1	±	9.6
HWW (165 GeV)	17.1	±	0.01	12.2	±	0.1
Total Background	4995	±	168	337	±	10
Data	**4995**			**329**		

D0 $H \rightarrow WW$ $(\mu\mu)$

At *pre-selection*:
requiring 2 High-P_T muons
$P_T^1 > 15$ GeV, $P_T^2 > 10$ and $M_{\mu^+\mu^-} > 15$ GeV
$N_{jet} < 2$ for $P_T^{jet} > 15$ GeV, $\Delta R(\mu, jet) > 0.1$
$M_{\mu^+\mu^-}$ spectrum from $\mu\mu$ channel $\longrightarrow$



Full selection includes:
$N_{jet} = 0$: $P_T^{\mu\mu} > 20$ GeV
$N_{jet} = 1$: $\not{E}_T > 20$ GeV
NN output for ee channel (below)

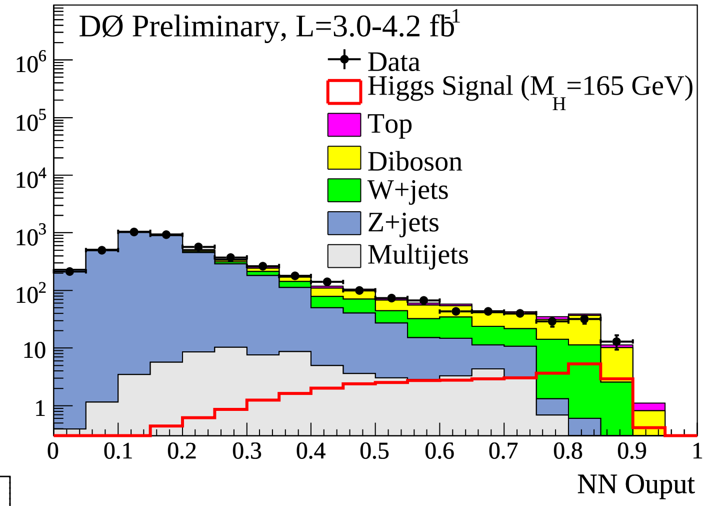


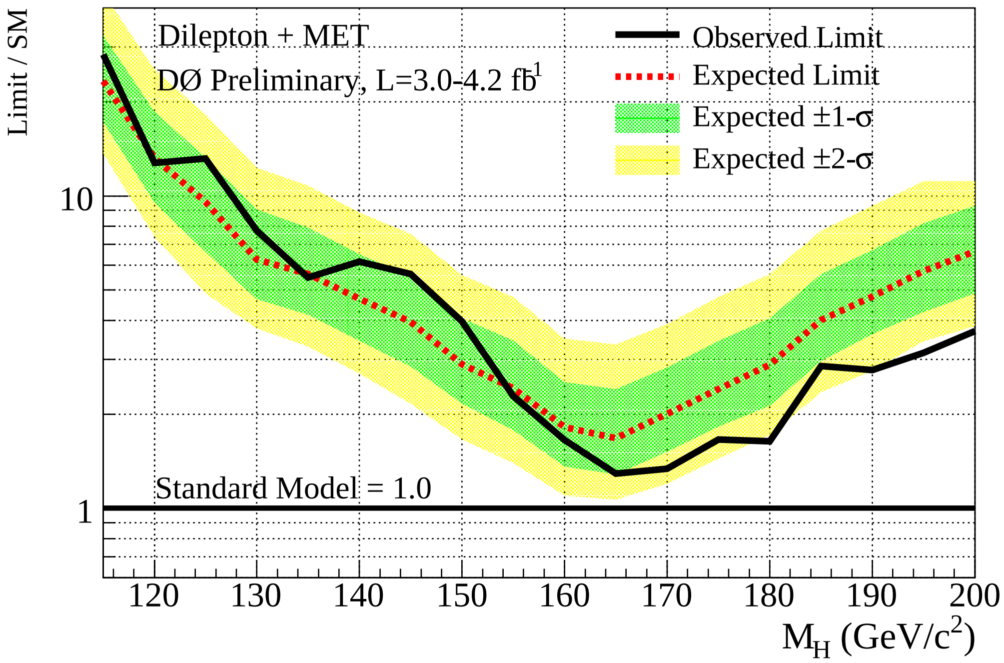
	Preselection			Full Selection		
$Z \rightarrow \mu\mu$	235670	$\pm$	158	3921	$\pm$	22
$Z \rightarrow \tau\tau$	1735	$\pm$	10	66	$\pm$	2
$t\bar{t}$	19.93	$\pm$	0.05	12.55	$\pm$	0.04
W+jets	214	$\pm$	7	134	$\pm$	5
WW	159	$\pm$	0.3	92.8	$\pm$	0.3
WZ	47.3	$\pm$	0.5	19.4	$\pm$	0.3
ZZ	40.5	$\pm$	0.2	15.1	$\pm$	0.1
Multijet	386	$\pm$	20	64	$\pm$	8
HWW (165 GeV)	5.43	$\pm$	0.01	4.85	$\pm$	0.01
Total Background	238272	$\pm$	159	4325	$\pm$	24
Data	**239923**			**4084**		

D0 $H \to WW$

To better separate signal from background D0 uses neural networks

- Separate NNs for ee, $e\mu$, and $\mu\mu$ for each mass
- Trained against weighted sample of all BGs
- 12 to 14 inputs are used including
  - Lepton P_T, $\not{E}_T$, $M_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta R_{\ell\ell}$, and $\Delta\phi(\not{E}_T, \ell)$





95% C.L. ($M_H = 165$ GeV)

- **Expected/σ_{SM} = 1.7**
- **Observed/σ_{SM} = 1.3**

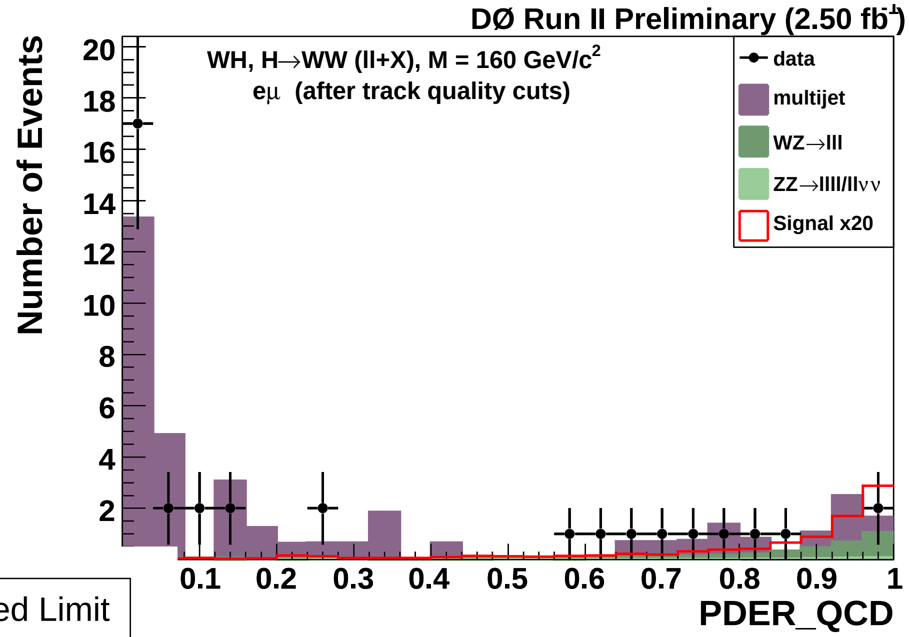
D0 $WH \rightarrow WWW \rightarrow \ell^{\pm}\ell^{\pm} + X$

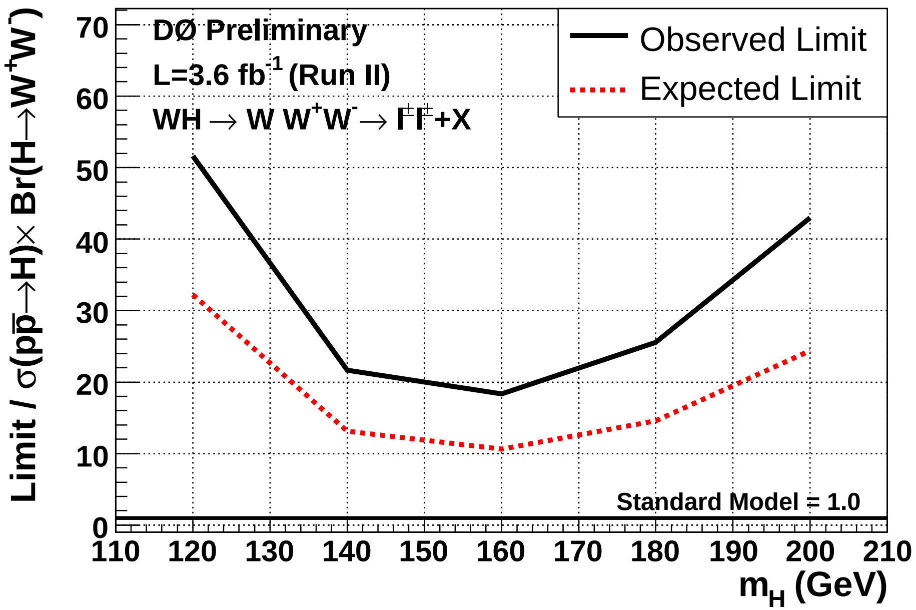
At *pre-selection*:
2 High-P_T leptons same charge

Define a multidimensional likelihood

- Good separation of Signal and Multijet BG

$e^{\pm}\mu^{\pm}$ likelihood based discriminant $\longrightarrow$





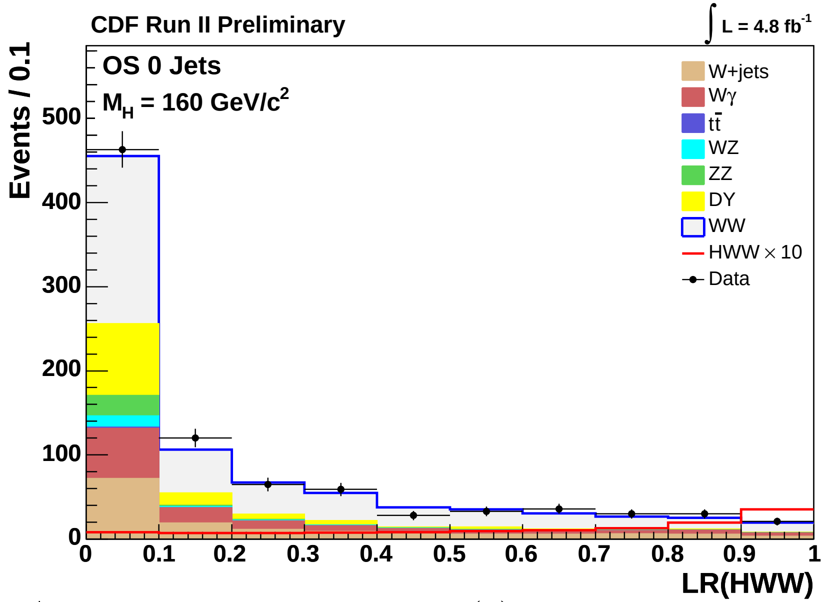
Signal / Background	
ee	0.18 / 23.6
$e\mu$	0.35 / 39.2
$\mu\mu$	0.18 / 12.3

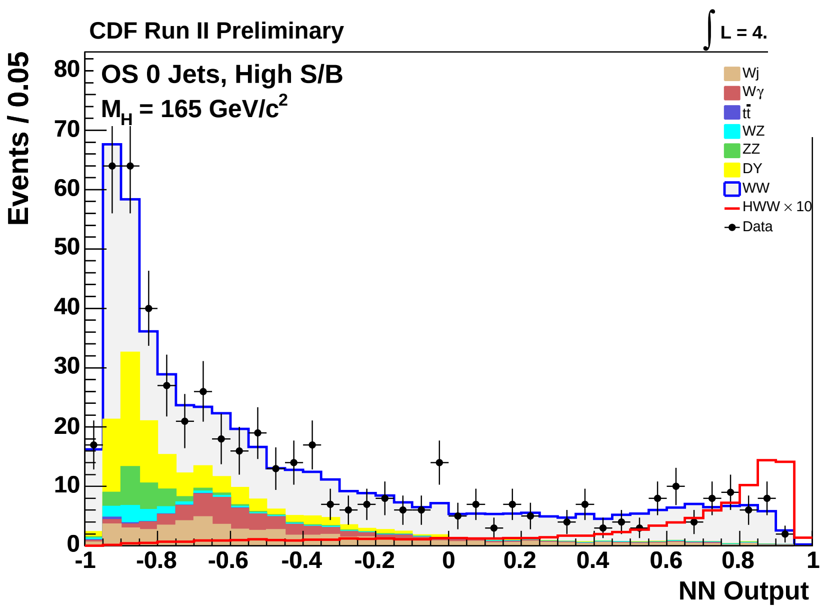
$\longleftarrow$ **Limits for** $WH \rightarrow WWW$

CDF $H \to WW$: 0-Jet

CDF requires 2 high-P_T leptons $P_T^1 > 20$, $P_T^2 > 10$ GeV and significant $\not{E}_T$

- Jet : $P_T > 15$ GeV and $|\eta| < 2.5$
- Makes use of leading order matrix element based likelihood ratios (LR) $\longrightarrow$
- Signal / BG : 11.8 / 858
- Final discriminant is NN (below)





$$P(\vec{x}_{obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}}\, \varepsilon(\vec{y})\, G(\vec{x}_{obs}, \vec{y})\, d\vec{y}$$

CDF models 5 modes:

∘ HWW, WW, ZZ, $W\gamma$, W+jet

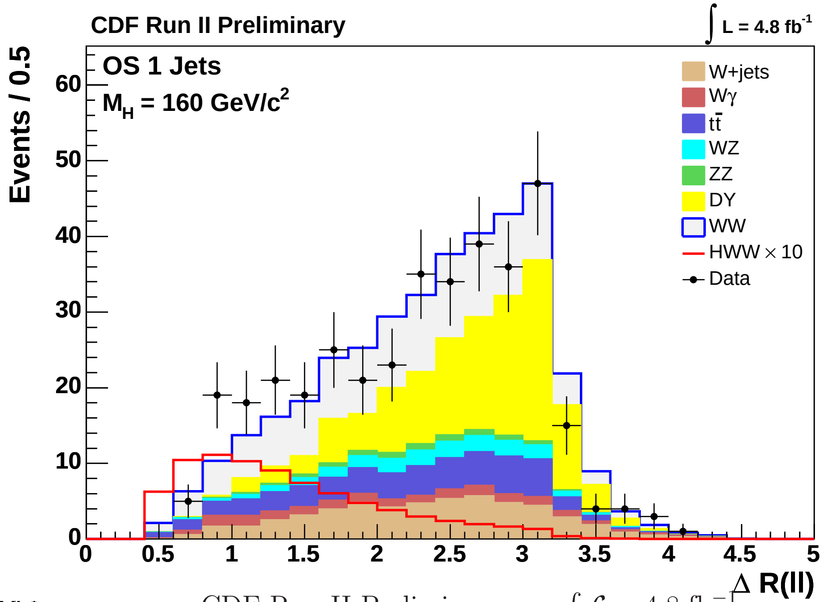
Use a Likelihood Ratio

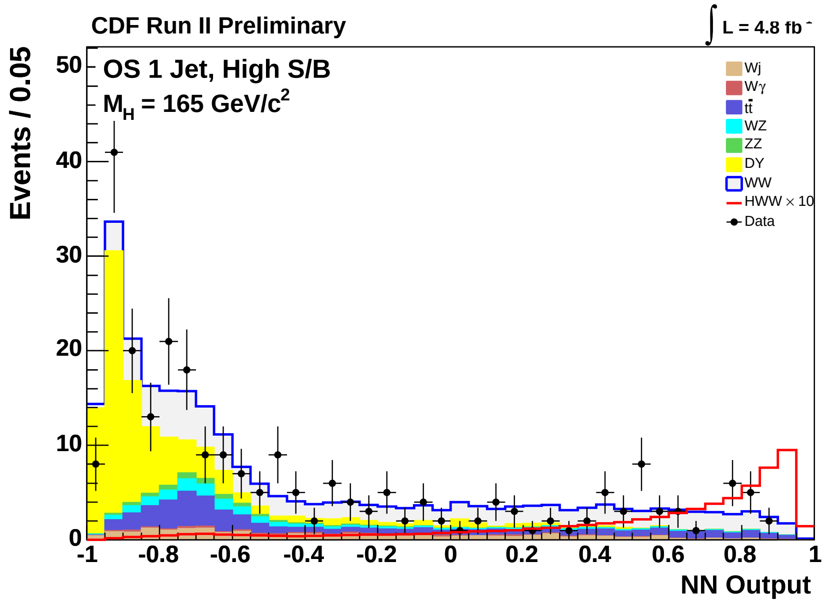
$$LR_m = \frac{P_m(\vec{x}_{obs})}{P_m(\vec{x}_{obs}) + \sum_i k_i P_i(\vec{x}_{obs})}$$

CDF $H \to WW$: 1-Jet

For events containing 1 jet:

- VH and VBF become significant
- Makes use of kinematic variables such as $M_{\ell\ell}$, $P_T(\ell)$s, $E(\ell_1)$ $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$ $\longrightarrow$
- Final discriminant is NN (below)





CDF Run II Preliminary $\int \mathcal{L} = 4.8$ fb^{-1}

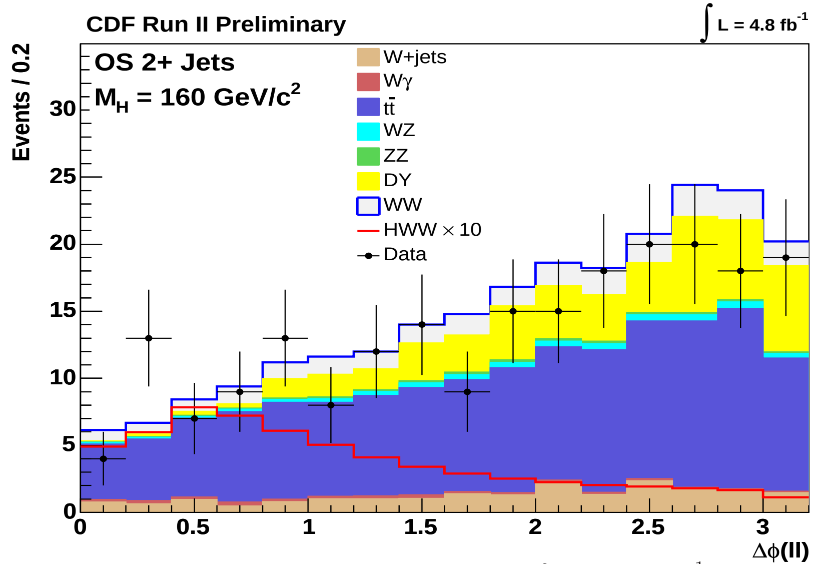
$M_H = 165$ GeV$/c^2$			
$t\bar{t}$	46.6	$\pm$	7.3
DY	123	$\pm$	39
WW	115	$\pm$	12
WZ	19.5	$\pm$	2.7
ZZ	7.5	$\pm$	1.0
W+jets	55	$\pm$	14
$W\gamma$	17.5	$\pm$	5.3
Total Background	383	$\pm$	49
$gg \to H$	5.96	$\pm$	0.91
WH	0.82	$\pm$	0.11
ZH	0.317	$\pm$	0.041
VBF	0.528	$\pm$	0.084
Total Signal	7.63	$\pm$	0.99
Data		368	

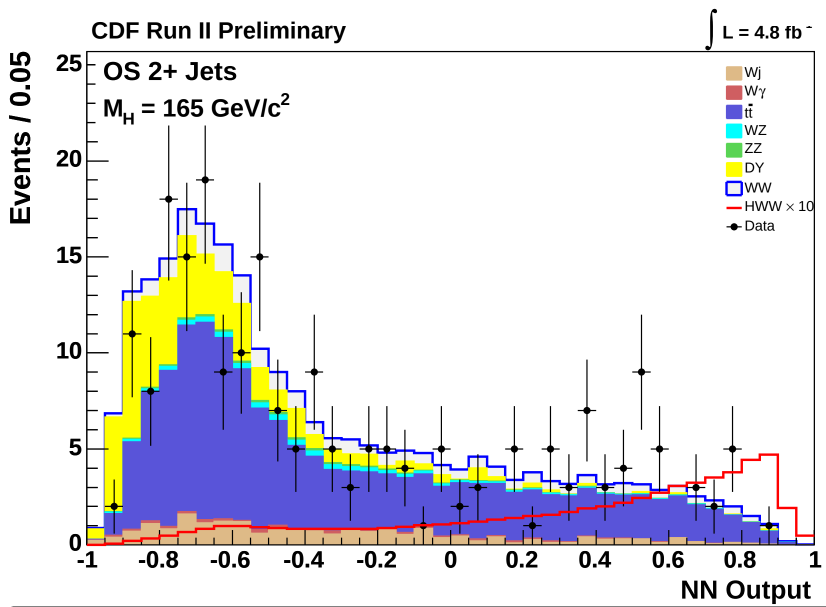
OS 1 Jet

CDF $H \rightarrow WW$: ≥ 2-Jet

For events containing ≥ 2 jets:

- VH and VBF significant
- Veto events with secondary vertices $\rightarrow$ Reduce $t\bar{t}$
- Makes use of kinematic variables such as $M_{\ell\ell}$, $P_T(\ell)$s, ΔR, $\Delta\phi_{\ell\ell}$ $\longrightarrow$
- Final discriminant is NN (below)





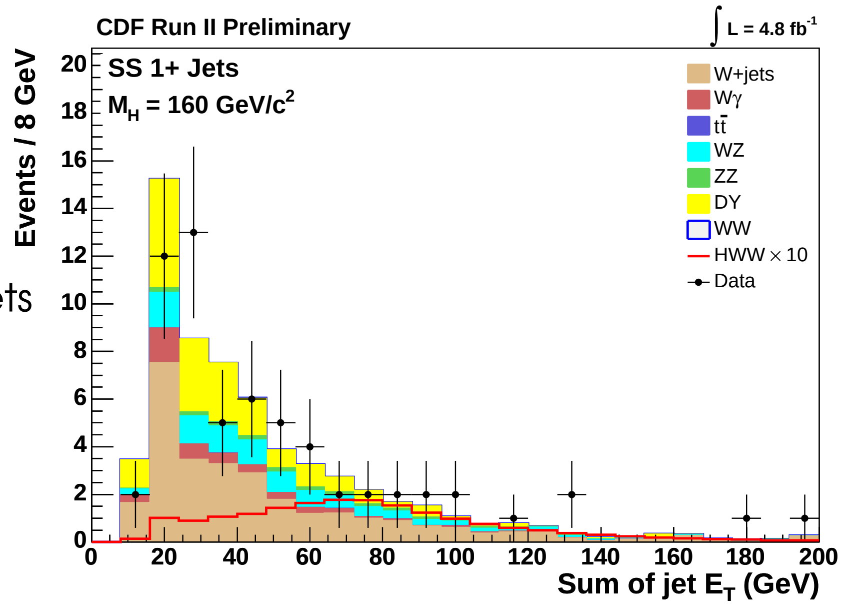
CDF Run II Preliminary	$\int \mathcal{L} = 4.8$ fb^{-1}		
$M_H = 165$ GeV$/c^2$			
$t\bar{t}$	137	±	23
DY	46	±	15
WW	24.0	±	5.4
WZ	5.13	±	0.71
ZZ	2.22	±	0.30
W+jets	20.2	±	5.5
$W\gamma$	2.98	±	0.98
Total Background	237	±	31
$gg \rightarrow H$	2.29	±	0.39
WH	1.76	±	0.23
ZH	0.93	±	0.12
VBF	0.97	±	0.16
Total Signal	5.96	±	0.68
Data	214		

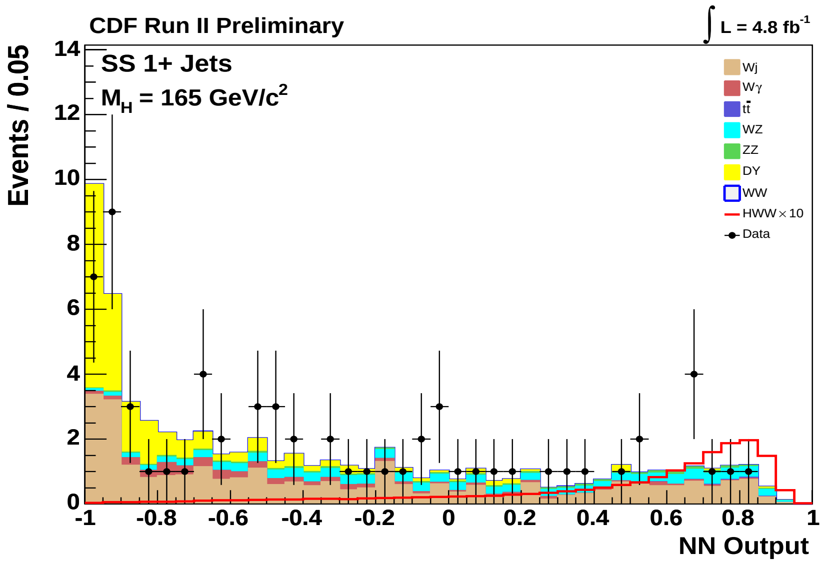
OS 2+ Jets

CDF $H \to WW$: Like Charge ≥ 1-Jet

For events containing ≥ 1 jet:

- 2 like charge leptons $P_T > 20$ GeV
- VH and VBF significant
- Dominant backgrounds is from W+jets
- Makes use of kinematic variables such as $M_{\ell\ell}$, $P_T(\ell)$s, $\Delta\phi_{\ell\ell}$, $\sum E_T^{jets}$ $\longrightarrow$
- Final discriminant is NN (below)





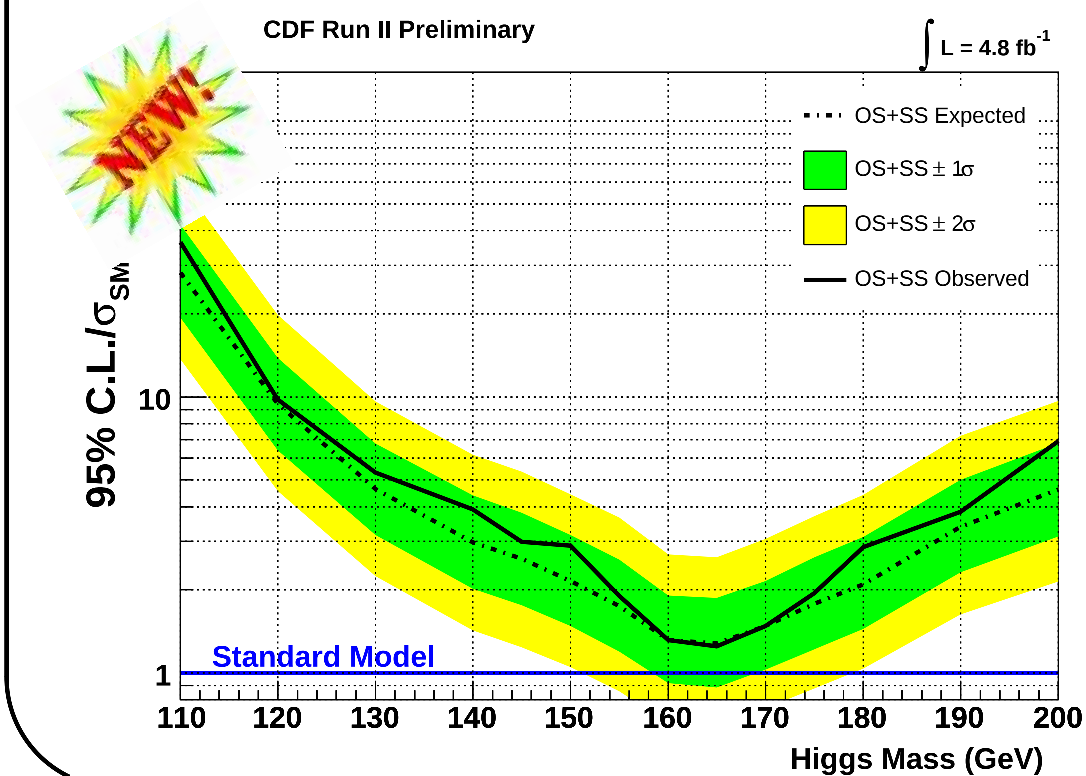
CDF Run II Preliminary	$\int \mathcal{L} = 4.8$ fb^{-1}		
	$M_H = 165$ GeV$/c^2$		
$t\bar{t}$	0.146	$\pm$	0.041
DY	17.2	$\pm$	5.3
WW	0.026	$\pm$	0.007
WZ	9.1	$\pm$	1.2
ZZ	1.96	$\pm$	0.27
W+jets	29.3	$\pm$	8.8
$W\gamma$	4.2	$\pm$	1.3
Total Background	62	$\pm$	11
WH	1.49	$\pm$	0.19
ZH	0.250	$\pm$	0.033
Total Signal	1.74	$\pm$	0.23
Data		64	

SS 1+ Jets

CDF $H \to WW$

Using up to 4.8 fb^{-1} of data CDF sets limits on SM Higgs production at 95% CL

- Separate NNs for each channel for each mass
- Using all relavent production mechanisms
- Combine all channels (below)



CDF Run II Preliminary	$\int \mathcal{L} = 4.8$ fb^{-1}		
$M_H = 165$ GeV$/c^2$			
$t\bar{t}$	185	±	30
DY	304	±	55
WW	563	±	59
WZ	52.4	±	7.2
ZZ	39.8	±	5.4
W+jets	249	±	63
$W\gamma$	147	±	39
Total Background	1541	±	148
$gg \to H$	20.0	±	2.9
WH	4.06	±	0.53
ZH	1.50	±	0.19
VBF	1.50	±	0.24
Total Signal	27.1	±	3.2
Data	1531		

OS+SS

95% C.L. ($M_H = 165$ GeV)

- **Expected/σ_{SM} = 1.28**
- **Observed/σ_{SM} = 1.25**

Systematic Uncertainties

Many systematic uncertainties are considered and evaluated by both experiments. The dominant uncertainties are typically

- Theoretical cross section uncertainties for signal and background
  - Range from 5-12%
- Acceptance uncertainty from limited order MC (5-10%)
- W+jets, uncertainty in how often a jet is misidentified as a lepton (20-30%)
- Jet modeling (5-20%)
- Luminosity ≈6%

Uncertainties are correlated, uncorrelated, and anti-correlated appropraitly

Several shape systematics are investigated including jet energy scale, jet reconstruction, P_T^{WW}, P_T^H, P_T^Z

Tevatron Combination

Have had great success combining the results from CDF and D0 over the past several years

For Tevatron combination results please see the next talk by Bjoern Penning

(New CDF result will be incorperated in the next Tevatron combination for Lepton-Photon)

Conclusions

- CDF & D0 both making rapid progress in high mass Higgs searches
- Many improvements added over the last few years are bringing each experiment closer and closer to SM sensativity
- Expecting an updated combination for Lepton-Photon

The Tevatron has reached standard model exclusion in the most sensitive mass region

Backup

CDF Matrix Elements

$$P(\vec{x}_{obs}) = \frac{1}{\langle\sigma\rangle} \int \frac{d\sigma_{th}(\vec{y})}{d\vec{y}} \, \varepsilon(\vec{y}) \, G(\vec{x}_{obs}, \vec{y}) \, d\vec{y}$$

$\vec{x}_{obs}$	Observed leptons and $\not{E}_T$
$\vec{y}$	True lepton 4-vectors (l, ν)
σ_{th}	Leading order theoretical cross-section
$\varepsilon(\vec{y})$	Efficiency & acceptance
$G(\vec{x}_{obs}, \vec{y})$	Resolution effects
$1/\langle\sigma\rangle$	Normalization

CDF models 5 modes:

- HWW, WW, ZZ, $W\gamma$, W+jet

Use a Likelihood Ratio

$$LR_m = \frac{P_m(\vec{x}_{obs})}{P_m(\vec{x}_{obs}) + \sum_i k_i P_i(\vec{x}_{obs})}$$

D0 $H \rightarrow WW$

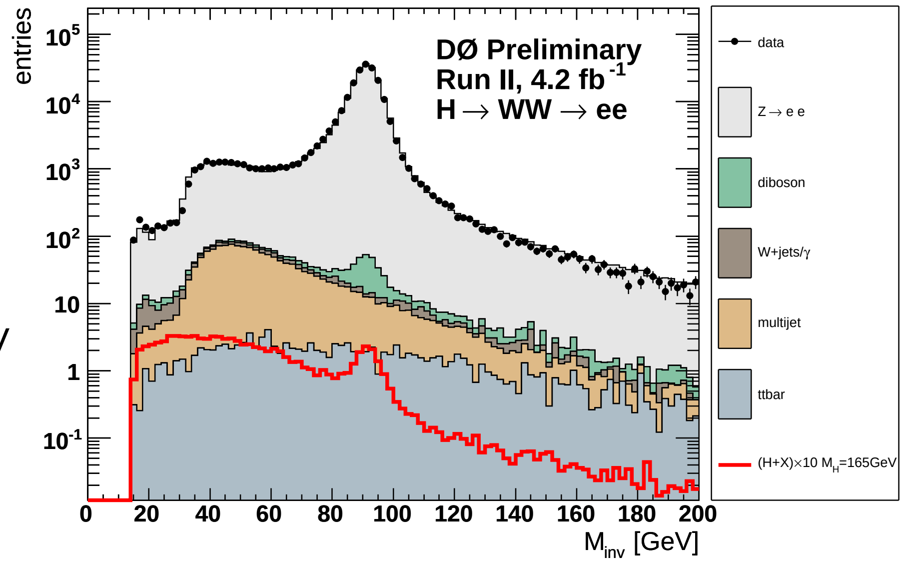
At *pre-selection*:

Require 2 High-P_T leptons (e or μ)

$P_T > 15$ GeV $(e), 10$ GeV (μ)

- $M_{\ell^+\ell^-} > 15$ GeV
- $\mu\mu$: $N_{jets} < 2$, where $P_T^{jet} > 15$ GeV & $\Delta R(\mu, jet) > 0.1$

$M_{\ell^+\ell^-}$ spectrum from ee channel $\longrightarrow$



Pre-Selection									
	ee			$e\mu$			$\mu\mu$		
$Z \rightarrow ee$	218695	±	704	280.6	±	3.3		-	
$Z \rightarrow \mu\mu$		-		274.6	±	0.9	4235670	±	158
$Z \rightarrow \tau\tau$	1135	±	16	3260	±	3	1735	±	10
$t\bar{t}$	131.4	±	1.4	272.0	±	0.3	19.93	±	0.05
W+jets	241	±	5	183	±	4	214	±	7
WW	172.2	±	2.6	421.2	±	0.1	159.0	±	0.3
WZ	112.5	±	0.2	20.5	±	0.1	47.3	±	0.5
ZZ	98.2	±	0.2	5.3	±	0.1	40.5	±	0.2
Signal ($M_H = 165$ GeV)	9.45	±	0.01	17.1	±	0.01	5.43	±	0.01
Total Background	221937	±	707	4995	±	168	238272	±	159
Data	**221530**			**4995**			**239923**		

Signal / Background

ee	9.45 / 221937
$e\mu$	17.1 / 4995
$\mu\mu$	5.43 / 238272

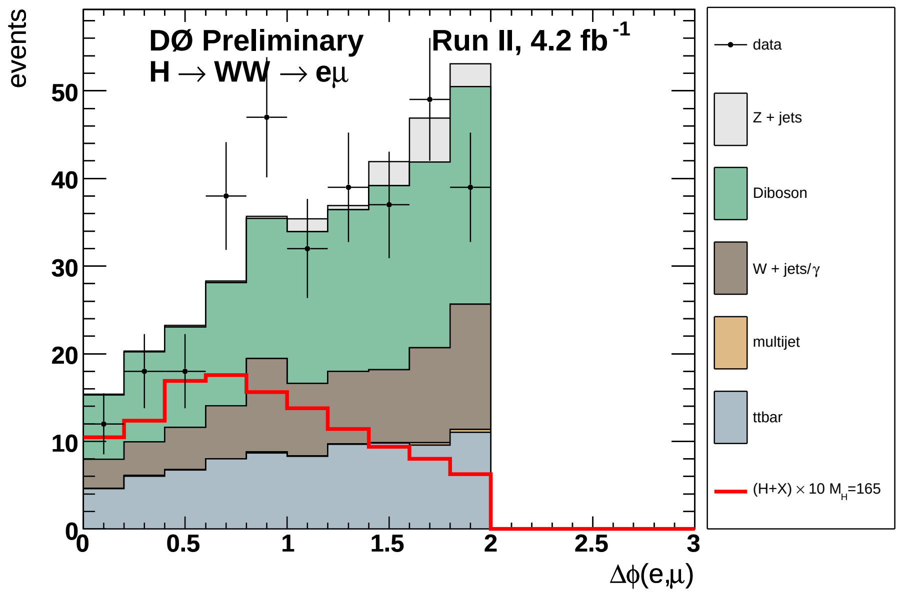
D0 $H \to WW$

Further cuts are then applied including cuts on

- $M_T^{min}(\ell, \not\!\!E_T)$, $\not\!\!E_T$, $M_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $N^{jets}(\mu\mu)$

These cuts are optimized by individual channel for difference m_H

Dilepton azimuthal separation $\longrightarrow$



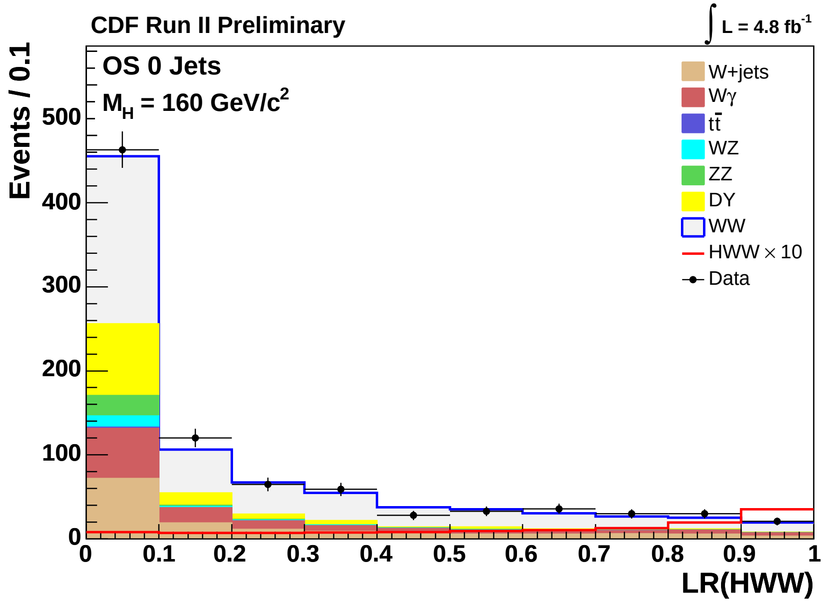
Full Selection	ee			eμ			μμ		
$Z \to ee$	108	±	14	0.0	+	0.1		-	
$Z \to \mu\mu$		–		5.8	±	0.1	3921	±	22
$Z \to \tau\tau$	1.4	±	0.5	7.3	±	0.1	66	±	2
$t\bar{t}$	39.9	±	0.8	272.0	±	0.3	12.55	±	0.04
W+jets	98.3	±	3	78.6	±	2.8	134	±	5
WW	66.8	±	1.6	154.7	±	0.1	92.8	±	0.3
WZ	9.68	±	0.05	6.6	±	0.1	19.4	±	0.3
ZZ	7.68	±	0.07	0.60	±	0.01	15.1	±	0.1
Signal ($M_H = 165$ GeV)	6.13	±	0.01	12.2	±	0.1	4.85	±	0.01
Total Background	332	±	15	337	±	10	4325	±	24
Data	**336**			**329**			**4084**		

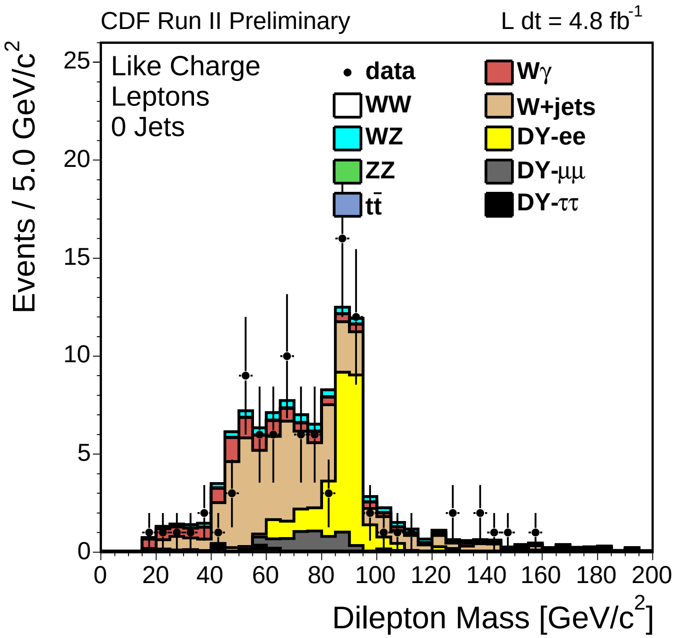
Signal / Background	
ee	6.13 / 332
$e\mu$	12.2 / 337
$\mu\mu$	4.85 / 4325

CDF $H \to WW$

CDF requires 2 high-P_T leptons $P_T^1 > 20$, $P_T^2 > 10$ GeV and significant $\not{E}_T$

- Opposite and same charge ℓ
- Separated by jet multiplicity
- Makes use of leading order matrix element based likelihood ratios (LR) $\longrightarrow$





$\longleftarrow$ Cross checks (Same charge leptons)

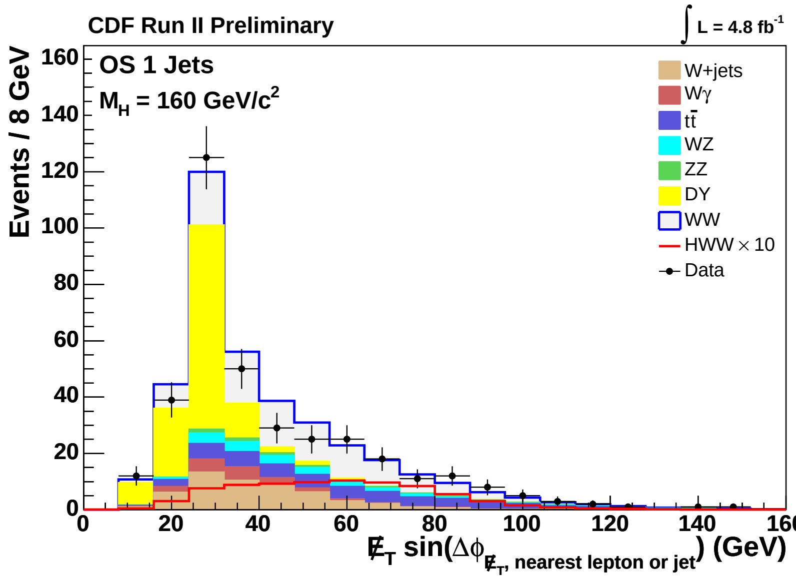
- One of many orthogonal "regions"
- A good measure of $W\gamma$, W+jet predictions, and charge mis-ID

Several channels used: 0,1,$\geq$2 Jets, Same Charge (Above: example from 0-Jet)

CDF $H \to WW$

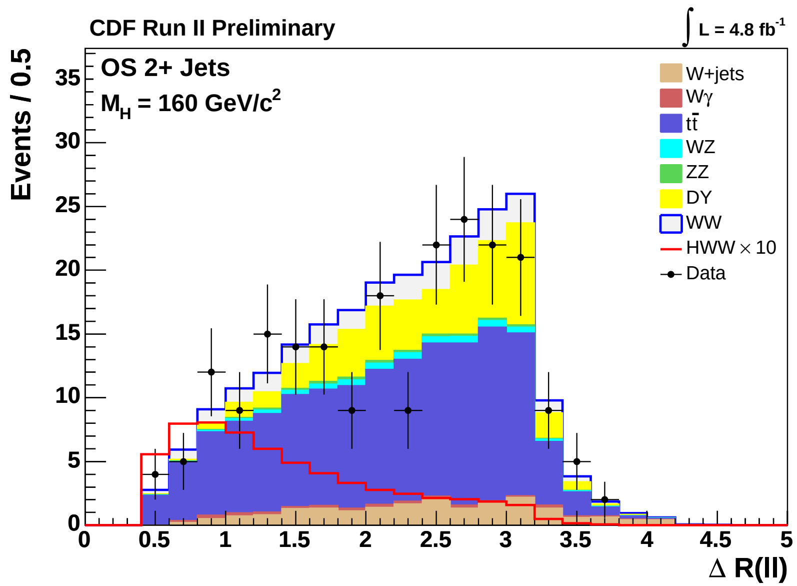
1-jet Channel (right)

- In the 1-jet channel VH and VBF are more significant
- "Significant" $\not\!\!E_T$ for 1-jet channel $\longrightarrow$



≥ 2 jet channel (below)

- Veto events with secondary vertices to reduce $t\bar{t}$



All Channels Combined

CDF Run II Preliminary	$\int \mathcal{L} = 4.8\ \mathrm{fb}^{-1}$		
$M_H = 165\ \mathrm{GeV}/c^2$			
Total Background	1541	$\pm$	148
$gg \to H$	20.0	$\pm$	2.9
WH	4.06	$\pm$	0.53
ZH	1.50	$\pm$	0.19
VBF	1.50	$\pm$	0.24
Total Signal	27.1	$\pm$	3.2
Data	1531		

OS+SS