Tevatron Searches for Standard Model Higgs at High Mass

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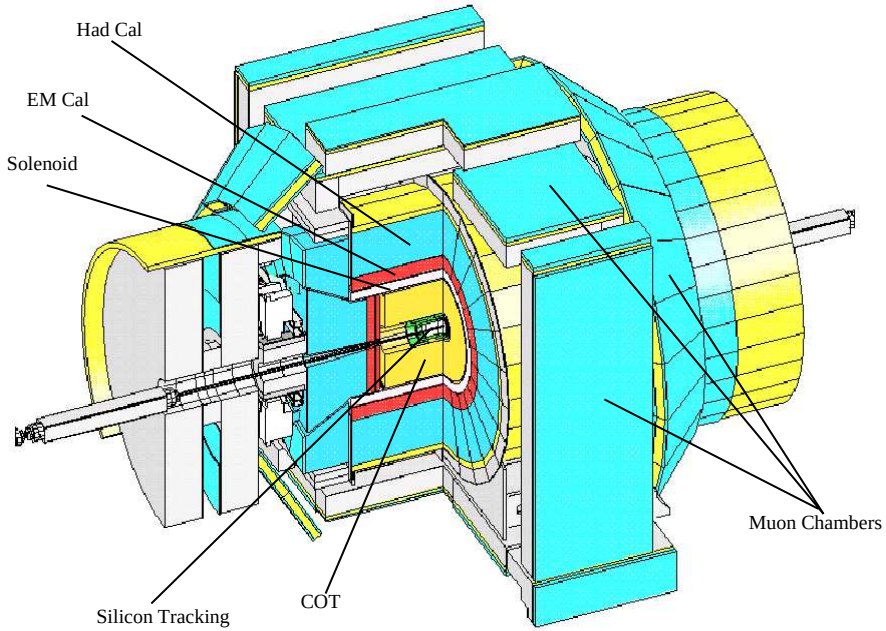
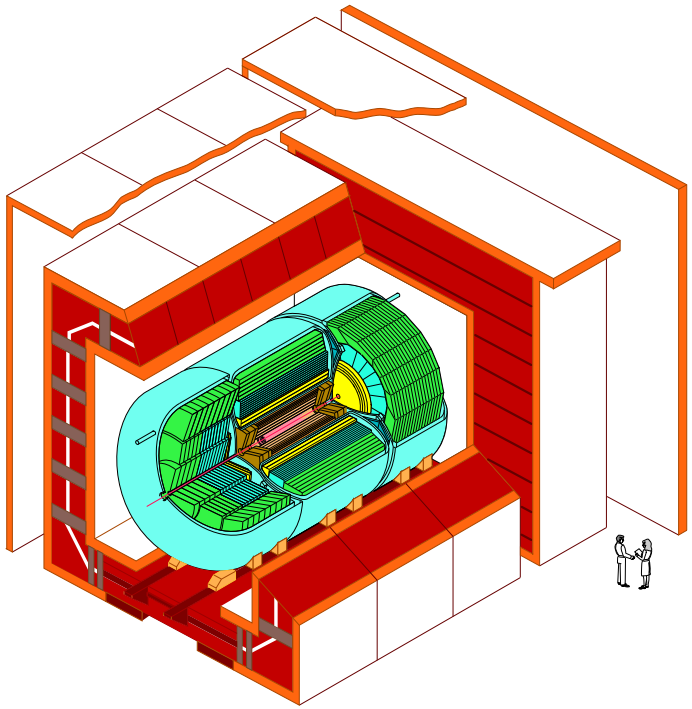
CDF & D0 Detectors



- Silicon tracking
- Drift chamber/Fiber tracker
- Electromagnetic & Hadronic Calorimetry
- Muon Chambers



DØ Detector

- Tevatron: $p \rightarrow \times \leftarrow \bar{p}$ $\sqrt{s} = 1.96$ TeV
- Delivered luminosity to date: ≈ 3.8 fb^{-1}
- Analysis shown here use up to 2.4 fb^{-1}

Standard Model and the Higgs

The standard model needs a Higgs or Higgs-like mechanism

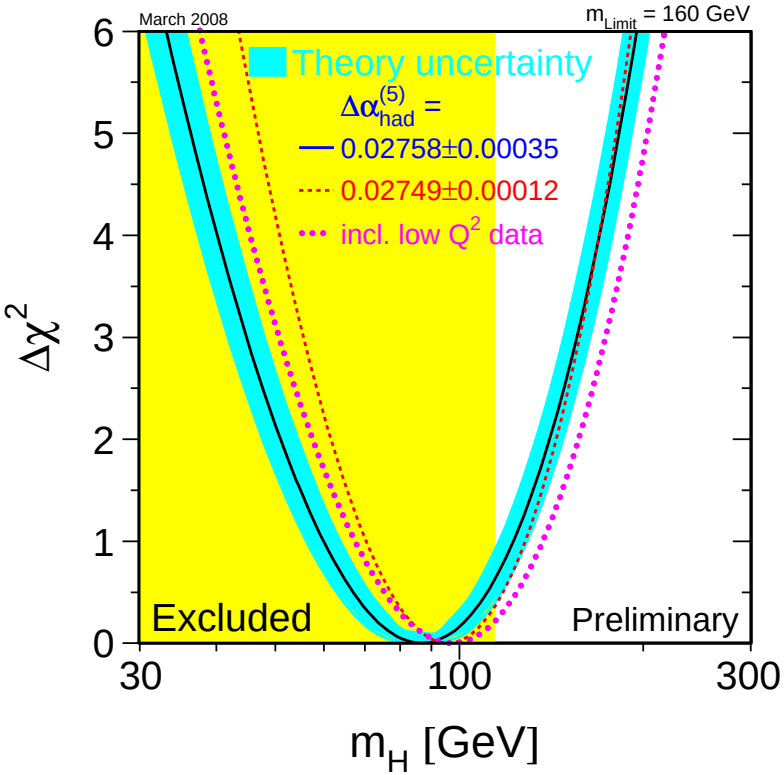
- To explain electroweak symmetry breaking
- And give particles mass

Direct searches at LEP tell us

$$M_H > 114.4 \text{ GeV} \text{ @ 95\% C.L.}$$

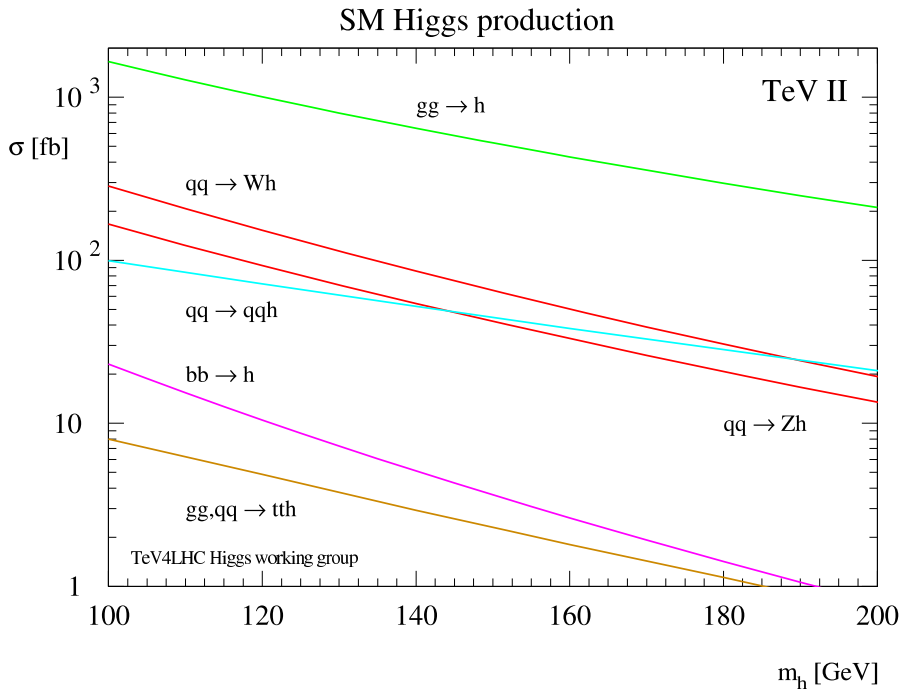
Indirect constraints from EW data prefer a lighter higgs, but combined with the LEP lower limit gives an upper limit of

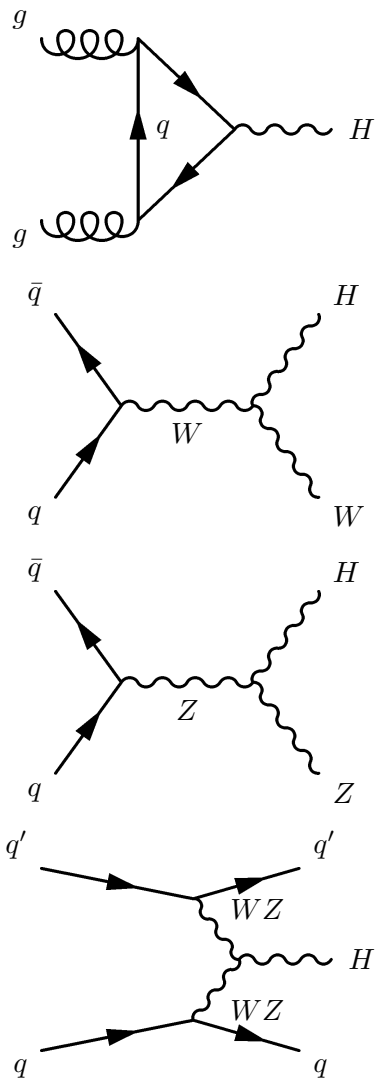
$$M_H < 190 \text{ GeV}$$



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)

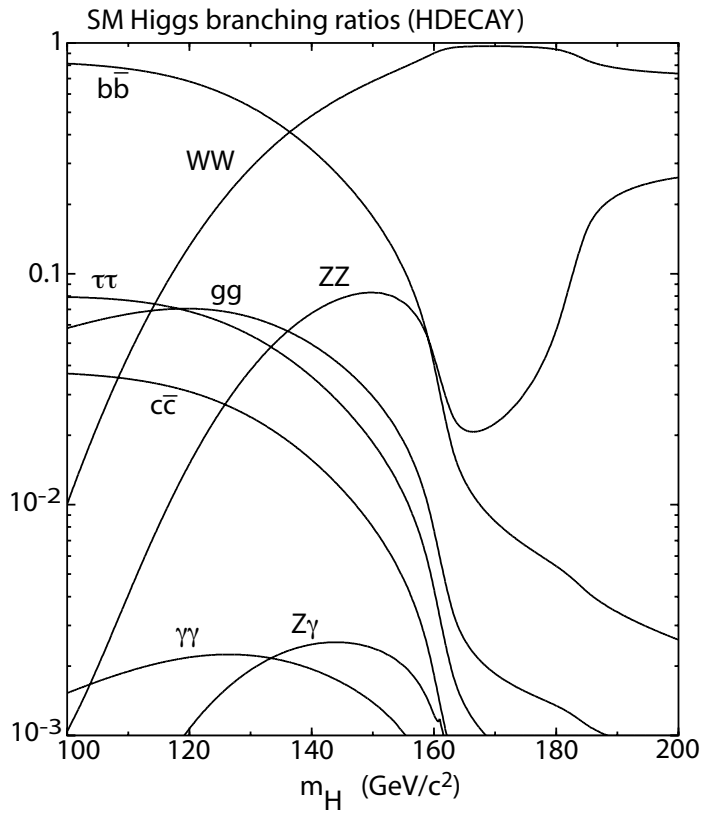


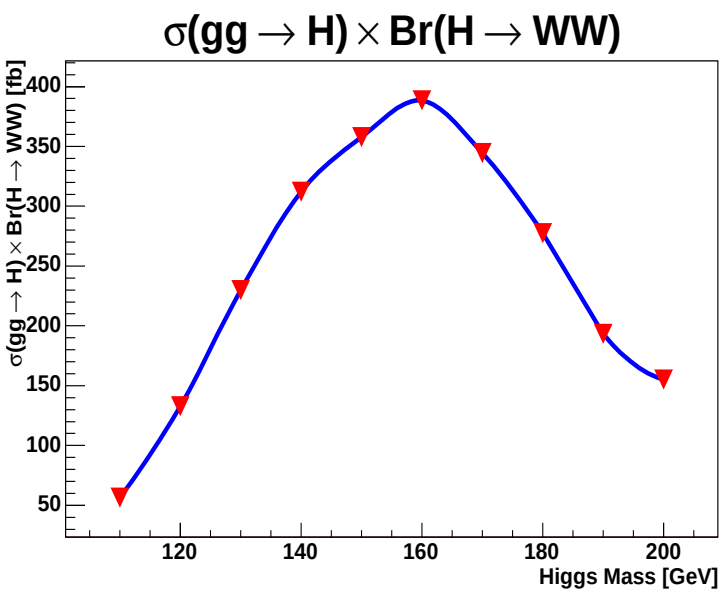


Standard Model Higgs Decay

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^-

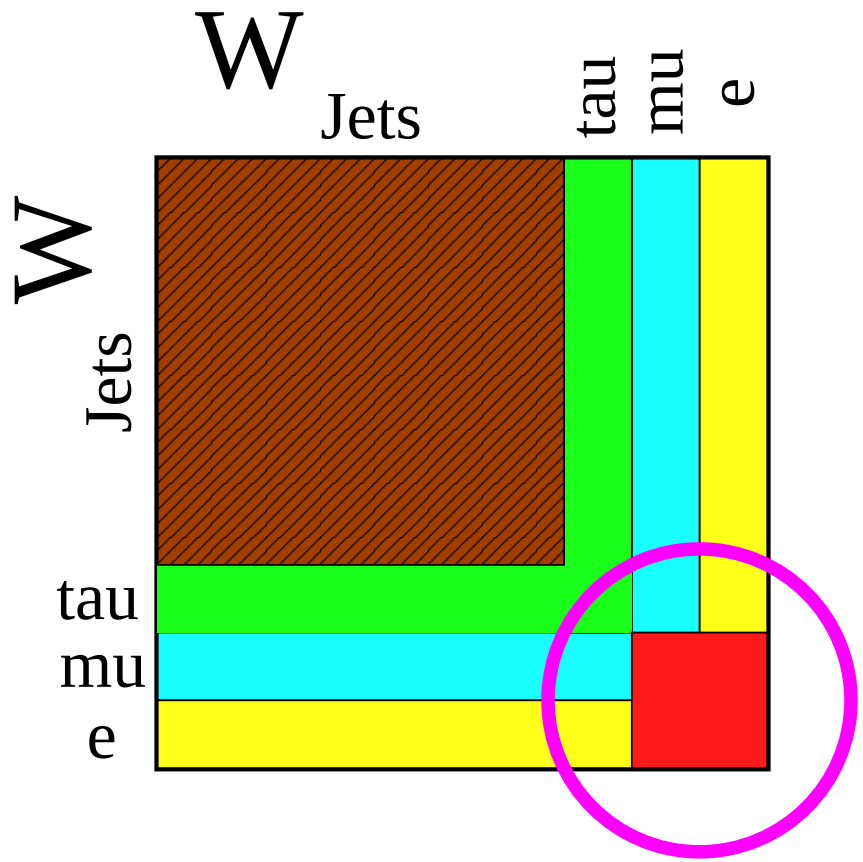




- For $gg \to H \to W^+W^-$ $\sigma \times BR$
  - Peak sensitivity for $m_H = 160$ GeV
  - Comparable sensitivity to $VH \to Vb\bar{b}$ at 130 GeV

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

- W **Decay Modes**
  - Leptonic 33% (e, μ, τ)
  - Hadronic 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



D0 $WH \rightarrow WWW$

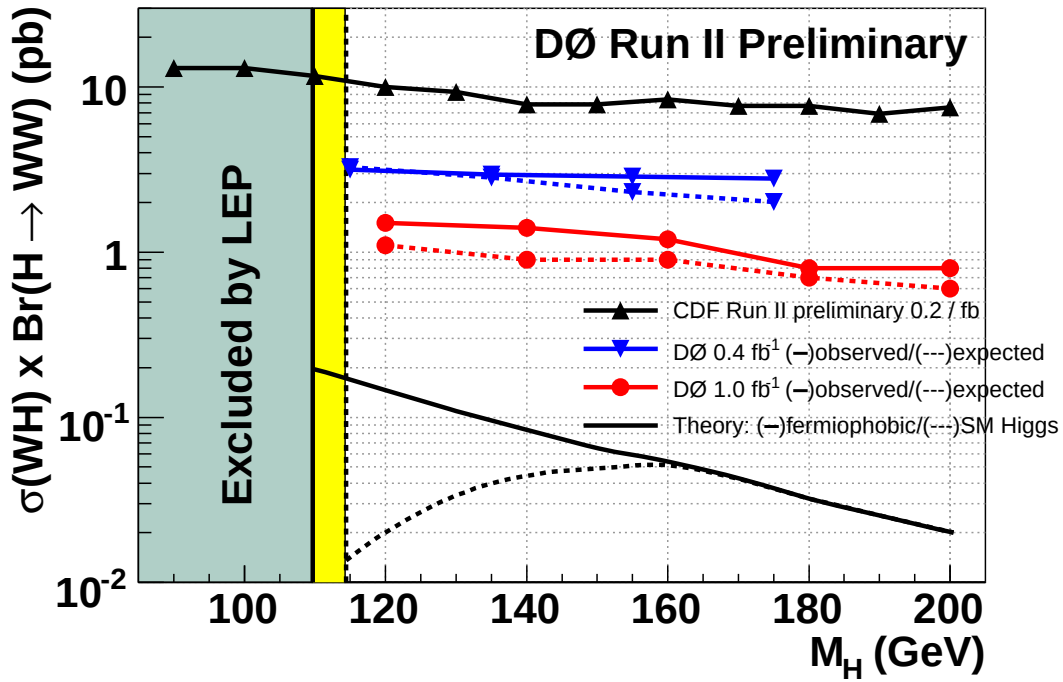
Search for $WH \rightarrow W^{\pm}W^{*}W^{*} \rightarrow l^{\pm}l^{\pm} + X$ using 1 fb^{-1}

- Look for 2 like-sign leptons (ee, $e\mu$, $\mu\mu$)
- Largest background is charge misidentification (mostly from Drell-Yan)

Discriminant is 2-D likelihood using $\Delta\phi_{ll}$, m_{ll}, $\not{E}_T$, $\Delta\phi^{min}_{\not{E}_T}$, $\not{E}_T^{had}$

95% C.L. At $m_H = 160$ GeV

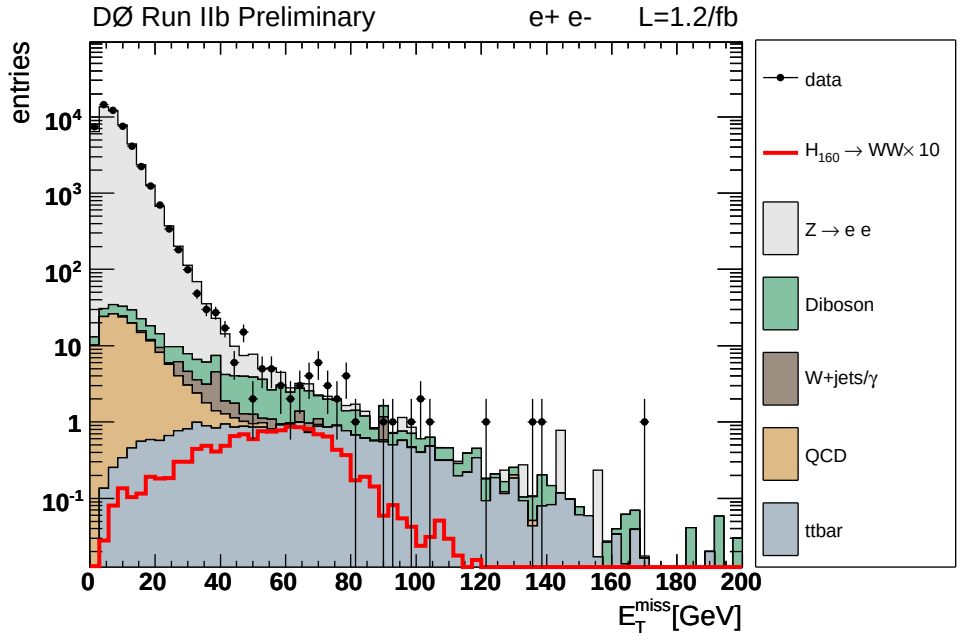
- Expected/$\sigma_{SM} = 18$
- Observed/$\sigma_{SM} = 24$



SM Backgrounds

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

- Main background is $Z/\gamma^* \rightarrow ll$
- CDF & D0 suppress this by requiring significant $\not{E}_T$



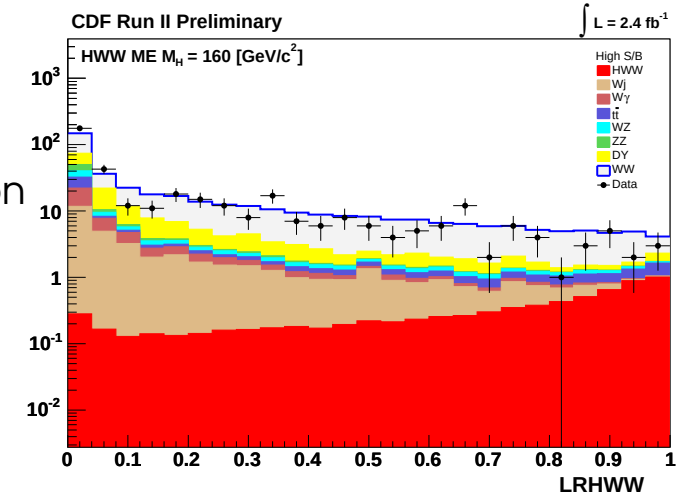
After Drell-Yan suppression the main backgrounds are:

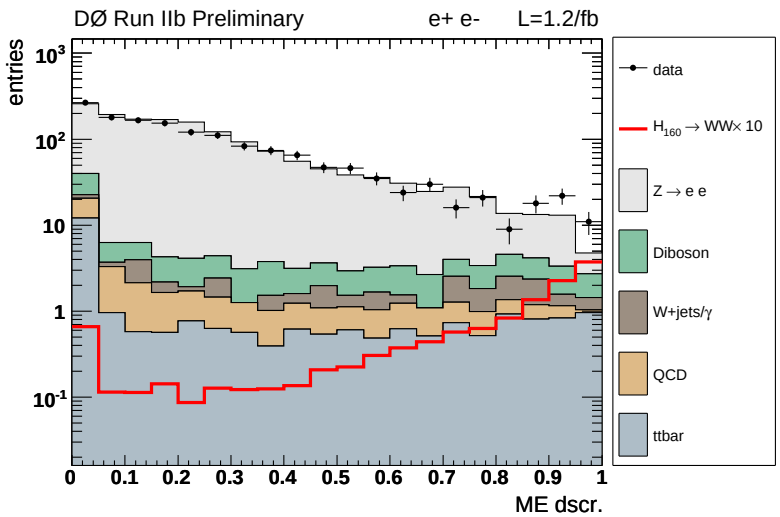
- Diboson production - WW, WZ, ZZ
- Top pair production - $t\bar{t}$
- $W+$ jets - where a jet is misidentified as a lepton
- $W\gamma$ - where the photon is misidentified as a lepton (typically an electron)

Matrix Elements at CDF & D0

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

$\vec{x}_{obs}$	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

D0 models 2 modes:

- HWW and WW

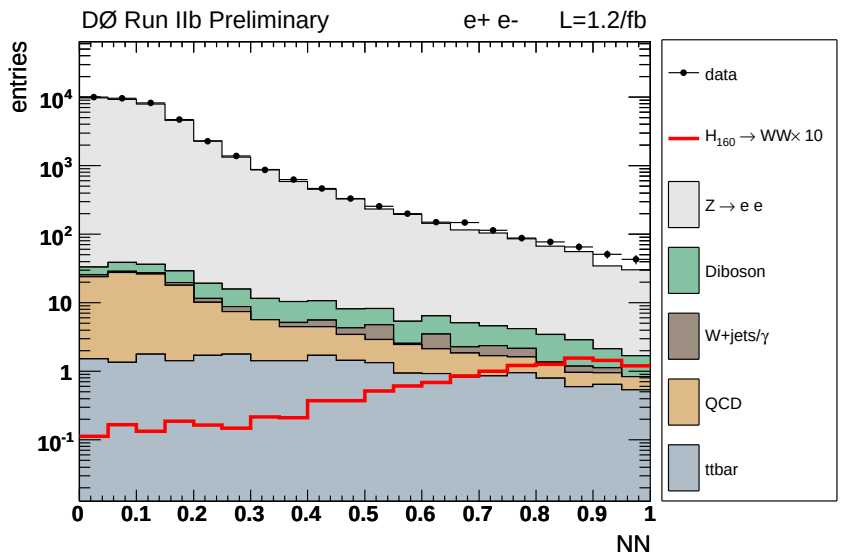
Use a Likelihood Ratio

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

D0 $H \rightarrow WW$

To better separate signal from background D0 uses neural networks

- Separate neural networks for ee, $e\mu$, and $\mu\mu$ for each mass
- Trained against weighted sample of all backgrounds for ee and $e\mu$
- Trained against main WW and $W+$ jets backgrounds for $\mu\mu$
- Between 11 and 15 input variables are used including
  - Lepton P_T, $\not{E}_T$, M_{ll}, $\Delta\phi_{ll}$, ΔR_{ll}, and ME_{disc} (slide 8)

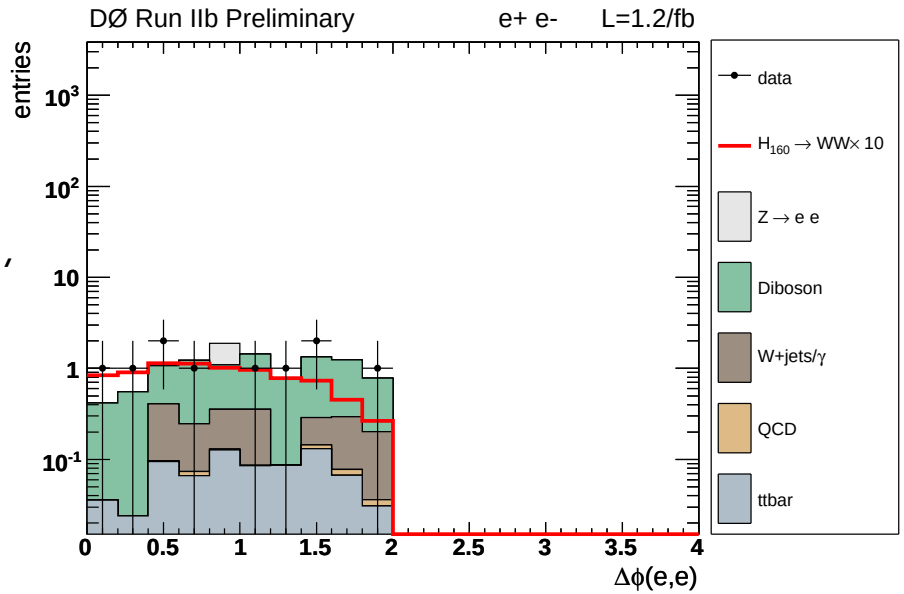


D0 $H \rightarrow WW$

Further cuts are then applied including cuts on

- Minimum transverse mass $(l, \not{E}_T)$, $\not{E}_T$, M_{ll}, $\Delta\phi_{ll}$ (*right*)

These cuts are optimized by individual channel for different m_H



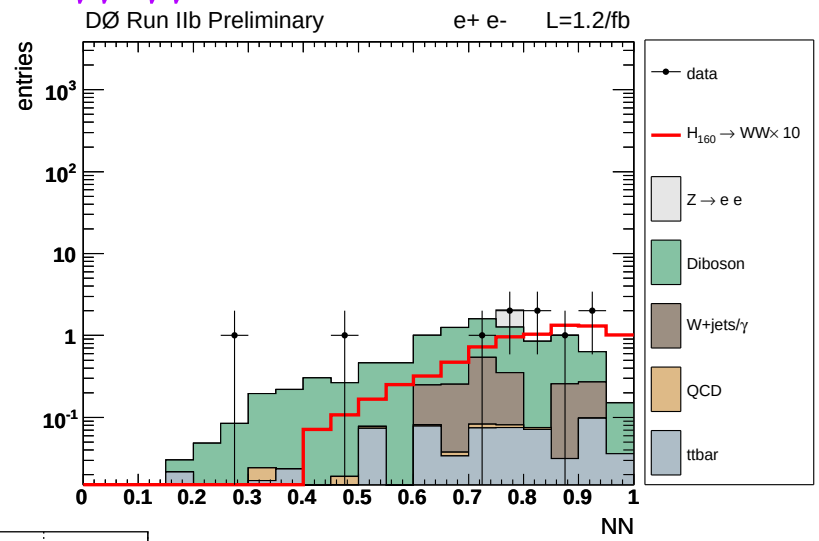
	ee	$e\mu$	$\mu\mu$
$Z \rightarrow ee$	0.8 ± 0.6	0 ± 0	-
$Z \rightarrow \mu\mu$	-	0.39 ± 0.25	632.6 ± 10.6
$Z \rightarrow \tau\tau$	0 ± 0	0 ± 0	30.8 ± 2.4
$t\bar{t}$	0.75 ± 0.1	$24. \pm 0.2$	25.1 ± 0.4
W+jets	1.5 ± 1.0	3.0 ± 1.1	66.7 ± 9.7
WW	7.4 ± 0.4	14.6 ± 0.6	46.2 ± 0.4
WZ	0.07 ± 0.05	0.66 ± 0.18	8.72 ± 0.6
ZZ	0.14 ± 0.05	0.02 ± 0.02	7.19 ± 0.3
Multijet	0.04 ± 0.7	0 ± 0.5	14.5 ± 2.1
$H \rightarrow WW$	0.82 ± 0.02	1.76 ± 0.04	2.08 ± 0.03
Total BG	$10.7 \pm 1.7 \pm 1.7$	$21.1 \pm 1.3 \pm 3.4$	$831.8 \pm 29 \pm 34$
Data	10	18	839

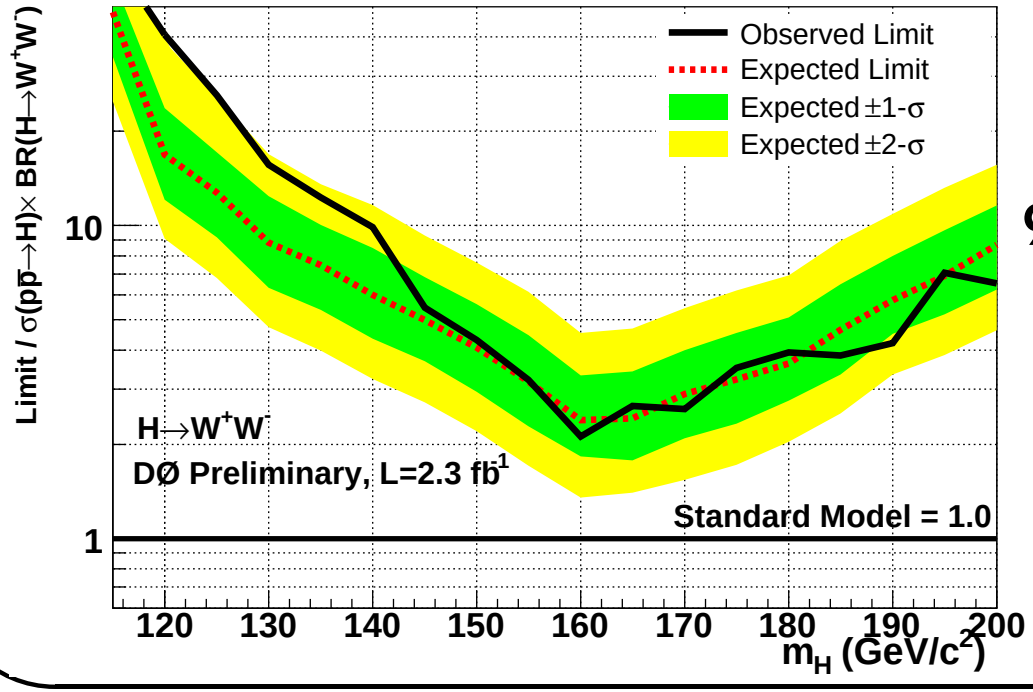
Signal/Background

$m_H = 160$ GeV/c^2	
ee	0.82 / 10.7
$e\mu$	1.76 / 21.1
$\mu\mu$	2.08 / 831.8

D0 $H \rightarrow WW$

- D0 final discriminant is NN output
- Example from ee channel
- This Run 2b analysis combined with Run 2a (below)





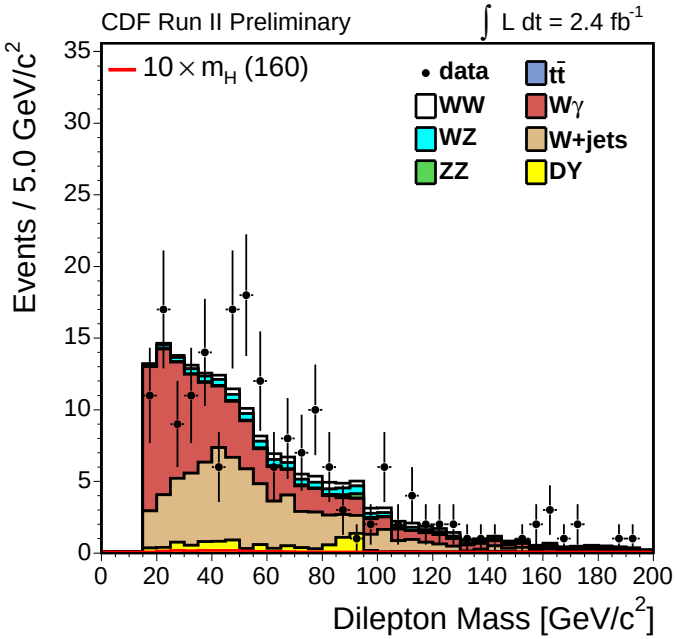
95% C.L. ($M_H = 160$ GeV)

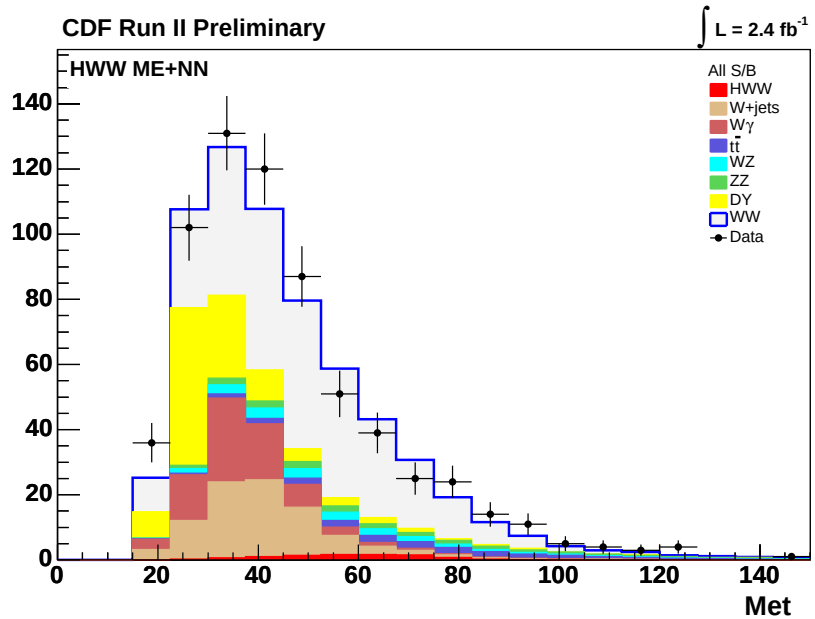
- Expected/σ_{SM} = 2.4
- Observed/σ_{SM} = 2.1

CDF $H \rightarrow WW$

Event selection

- 2 Opposite sign high-P_T leptons (electrons or muons)
  - $P_T^1 > 20$, $P_T^2 > 10$ GeV
- 0 or 1 jet
- Require significant $\not{E}_T$





← Cross checks - one of many

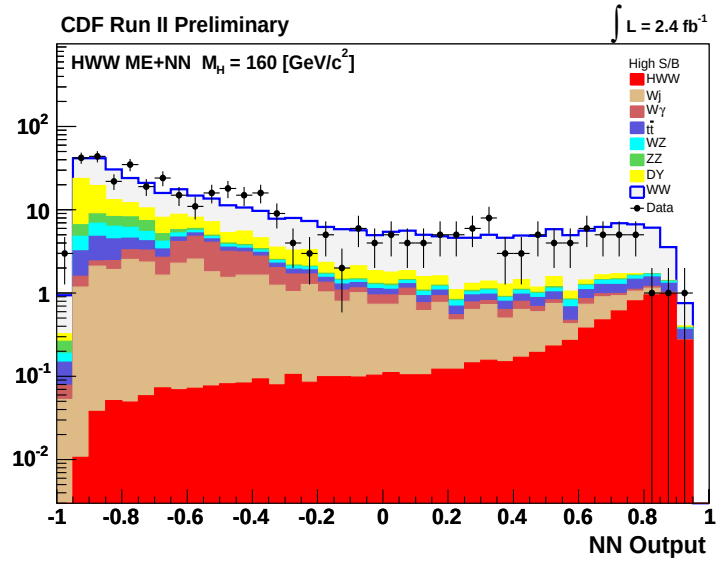
- Look at same sign leptons
- A good measure of $W\gamma$ and W+jet predictions
- Predict 177 ± 26
- Observe 195

CDF $H \to WW$

CDF trains a NN on weighted sum of all backgrounds at each m_H

11 input variables which include

- 5 Matrix element likelihood ratios (slide 8)
- $\not{E}_T$, $\Delta\phi_{ll}$, ΔR_{ll} , m_{ll}



- CDF final discriminant is NN output

CDF Run II Preliminary	$\int \mathcal{L} = 2.4\,\mathrm{fb}^{-1}$		
$M_H = 160\ \mathrm{GeV}/c^2$			
$H \to WW$	9.5	$\pm$	1.1
WW	300.3	$\pm$	38.1
WZ	20.5	$\pm$	3.1
ZZ	18.2	$\pm$	2.7
$t\bar{t}$	20.8	$\pm$	3.8
DY	104.0	$\pm$	23.0
$W\gamma$	72.4	$\pm$	18.7
$W + \mathrm{jets}$	89.2	$\pm$	22.8
Total BG	**626**	$\pm$	**54**
Data	**661**		

HWW ME+NN

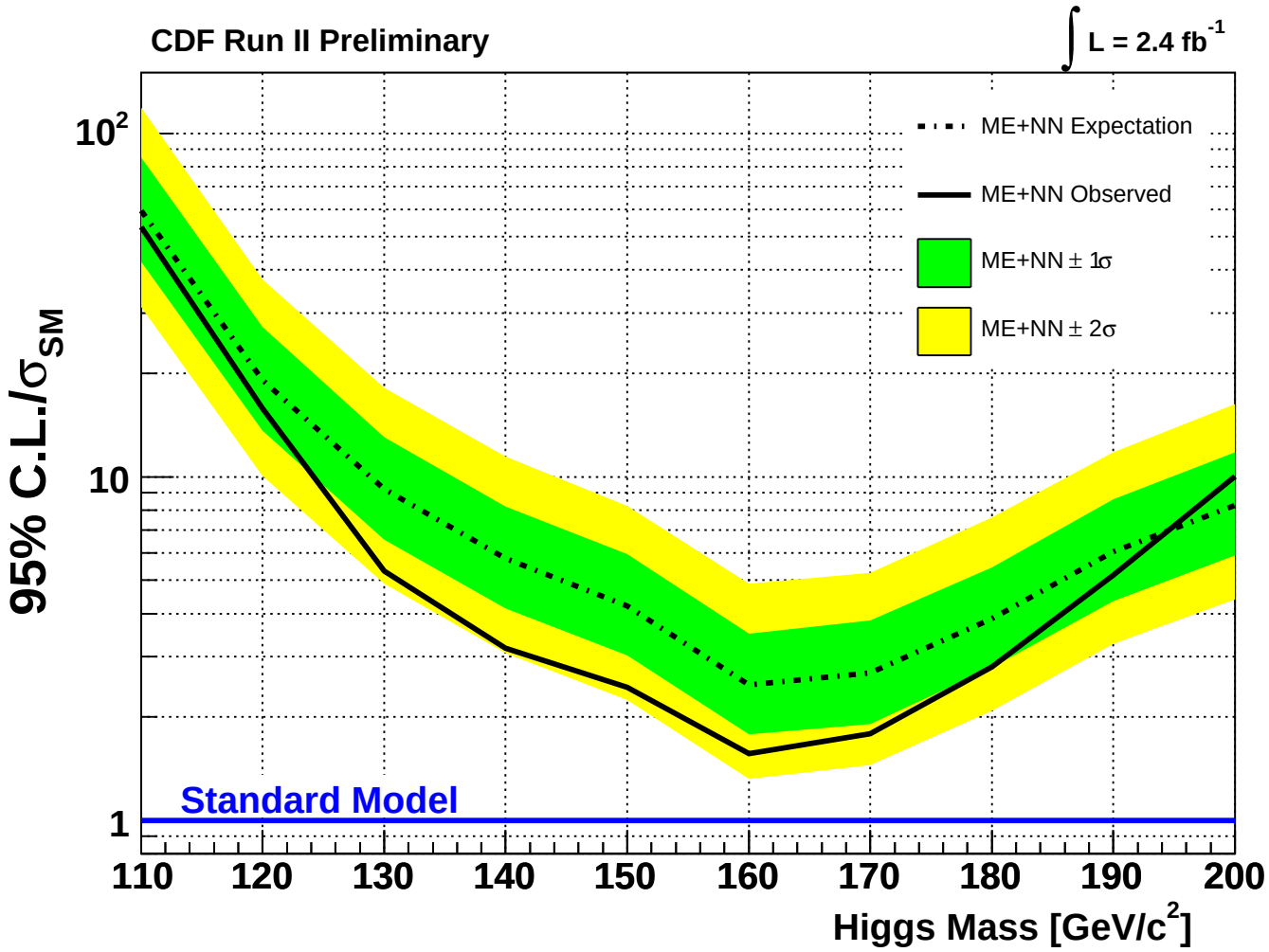
At $m_H = 160$ GeV expect

- 9.5 signal events
- 626 background

CDF $H \rightarrow WW$

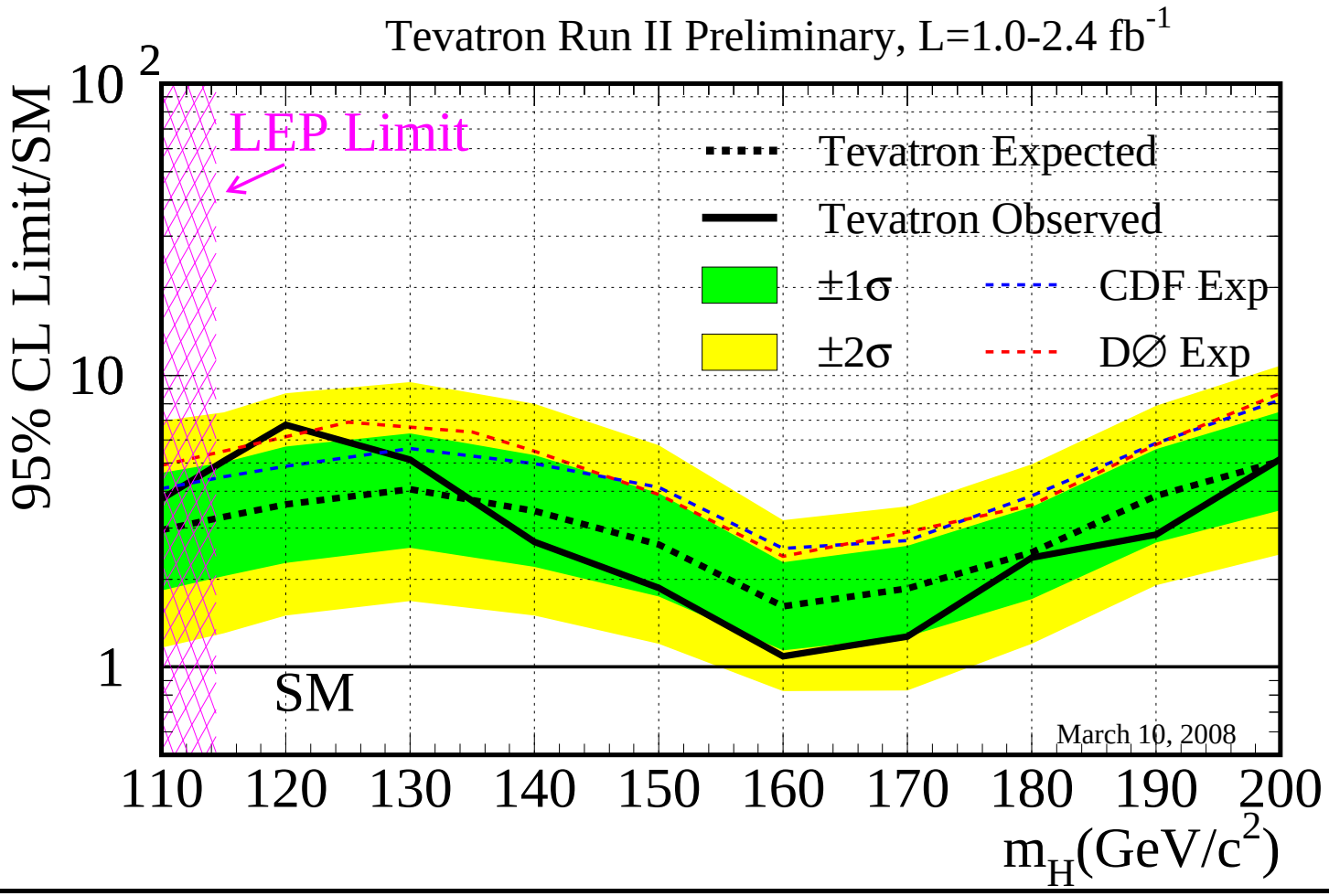
95% C.L. ($M_H = 160$ GeV)

Expected/σ_{SM} = 2.5 Observed/σ_{SM} = 1.6



Tevatron Combination

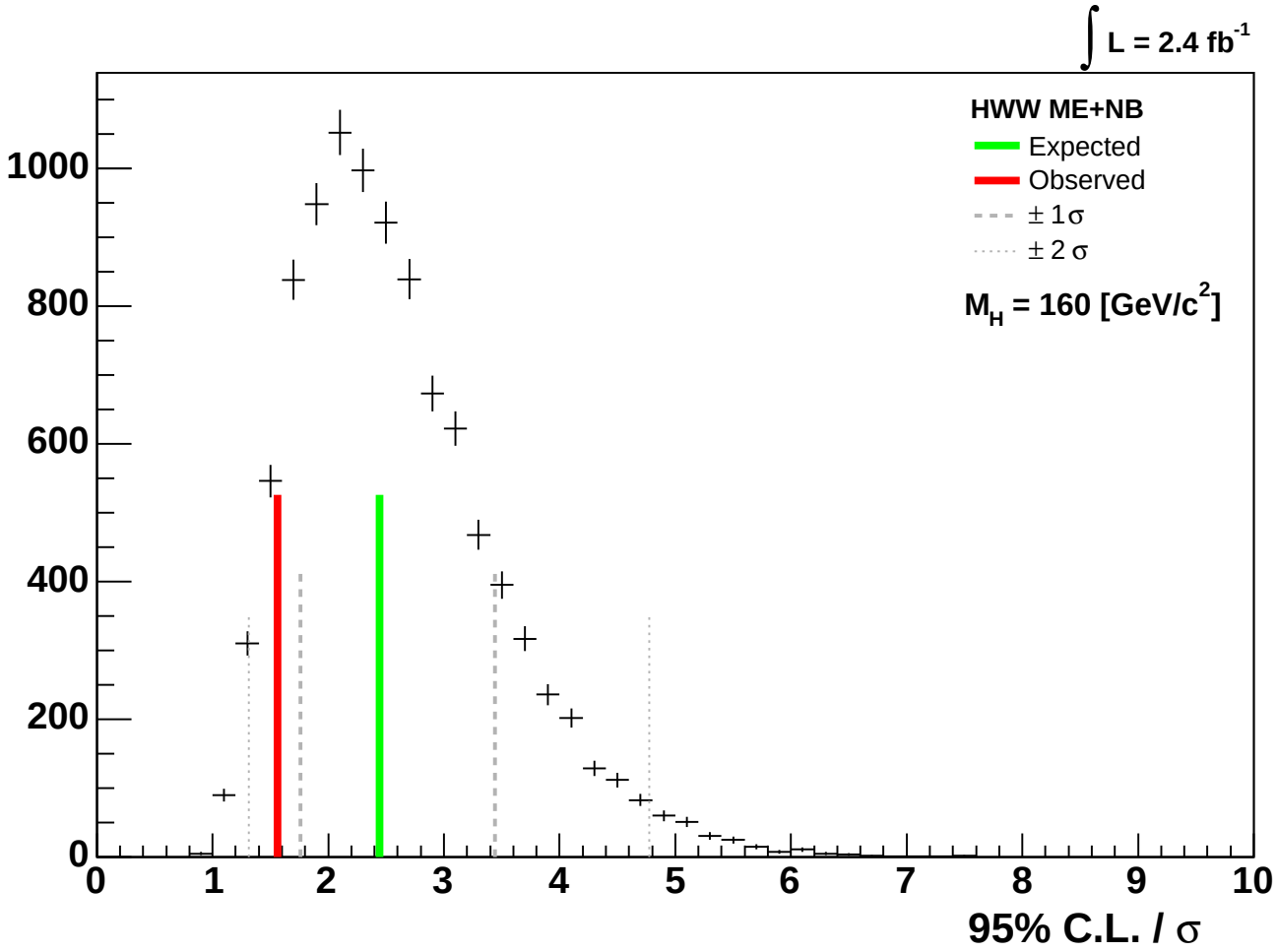
At $M_H = 160$ GeV Expected/σ_{SM} = **1.6**, Observed/σ_{SM} = **1.1**



Conclusions

- CDF & D0 making rapid progress in high mass searches
- Great collaboration between CDF and D0 in higgs combination results
  - Tevatron Expected 95% C.L. /σ_{SM} ($m_H = 160$ GeV) = 1.6
  - Tevatron Observed 95% C.L. /σ_{SM} ($m_H = 160$ GeV) = 1.1
- Significant improvements on the way

The Tevatron is quickly approaching standard model sensitivity around $m_H = 160$ GeV/c^2

Backup

Pseudo Experiments (CDF) $M_H = 160$ GeV