Search for High Mass SM Higgs at the Tevatron

Les Rencontres de Physique
de la Vallee D'Aoste
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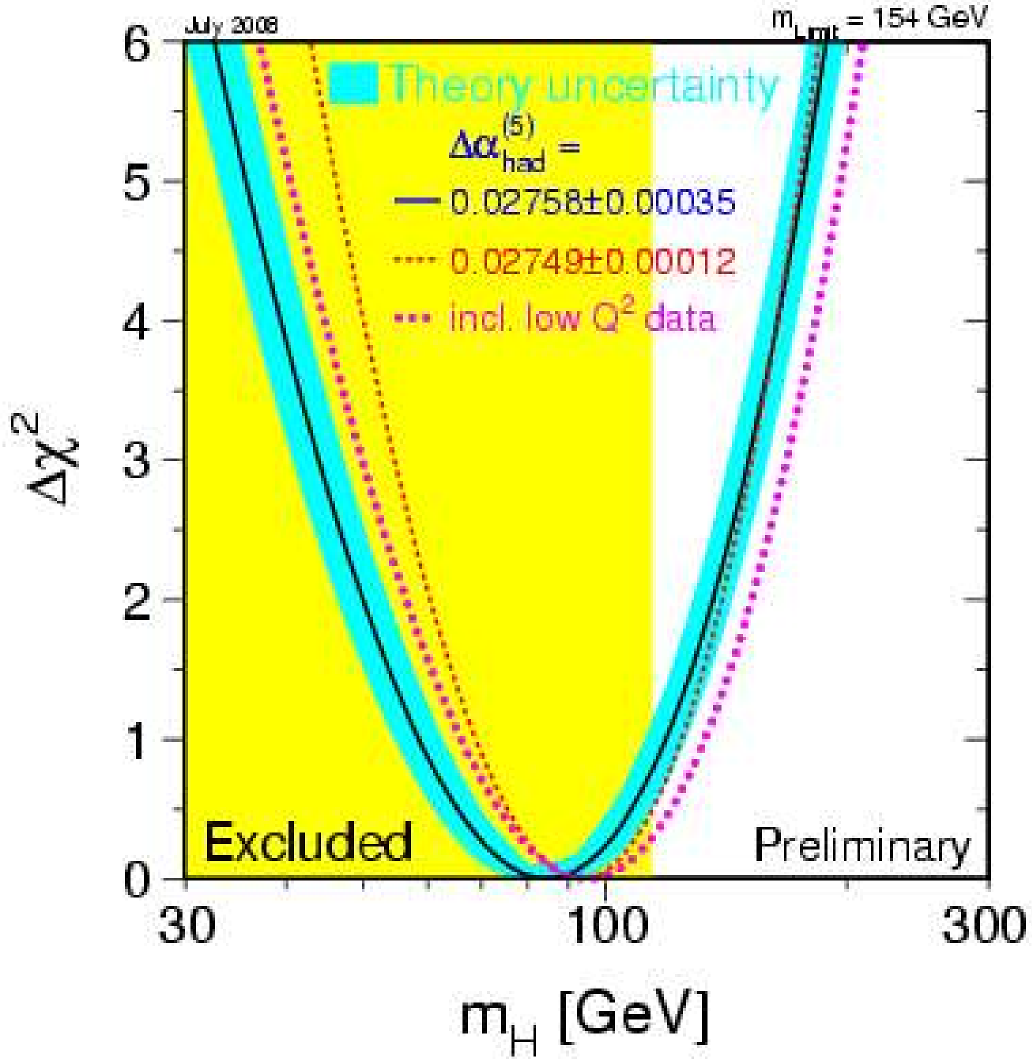
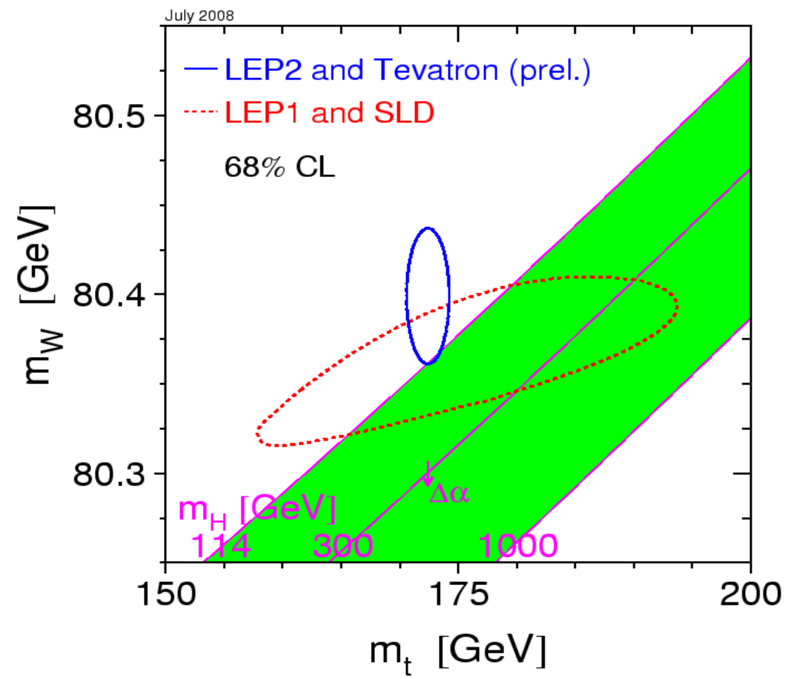
for the CDF and D0 Collaborations

SM Higgs Boson





- Direct Limit (LEP)

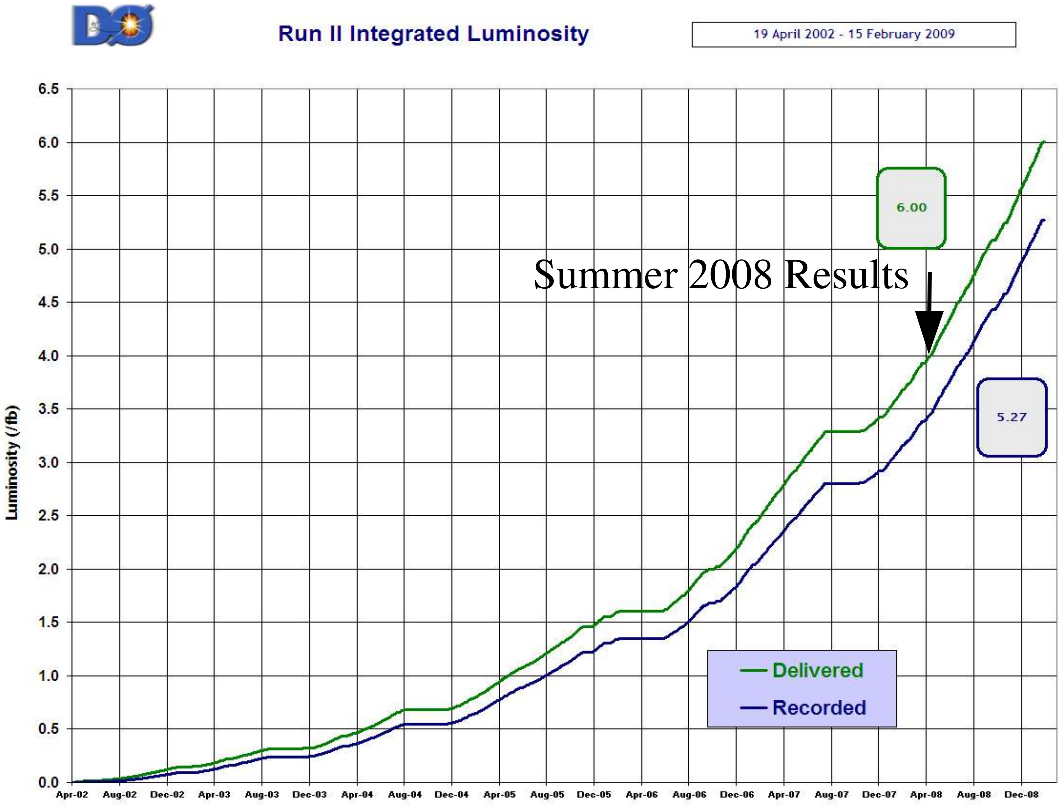
  $M_H > 114$ GeV

- Indirect Limit

  $M_H = 84^{+34}_{-26}$ GeV

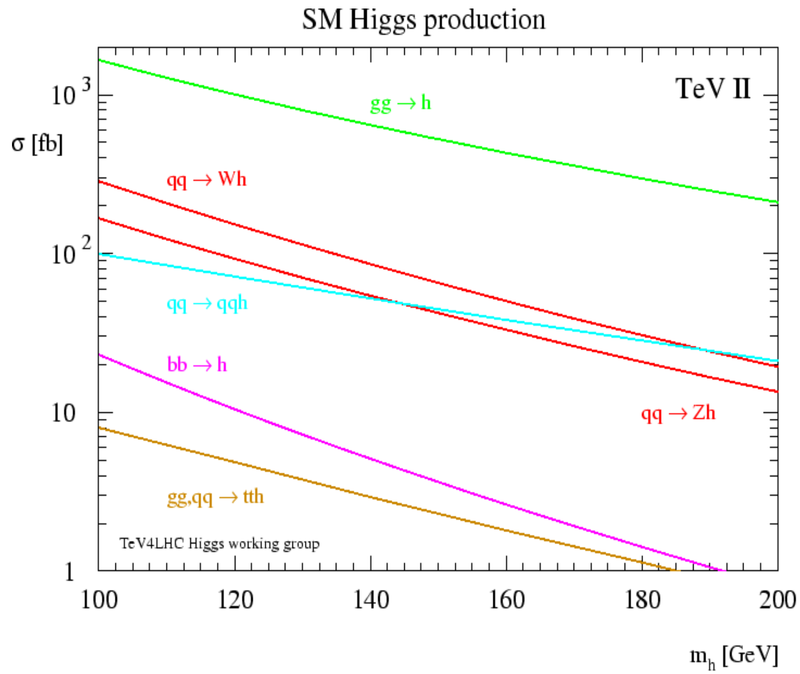
  $M_H < 154$ GeV @ 95% CL

Fermilab Tevatron

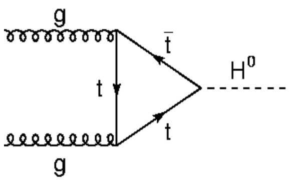


- $\bar{p}p$ collisions @ $\sqrt{s}$=1.96 TeV.
- CDF and D0 general purpose experiments.

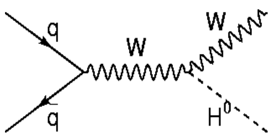
Higgs Production and Decay at the Tevatron



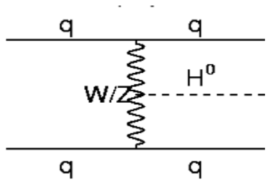
- Gluon Fusion



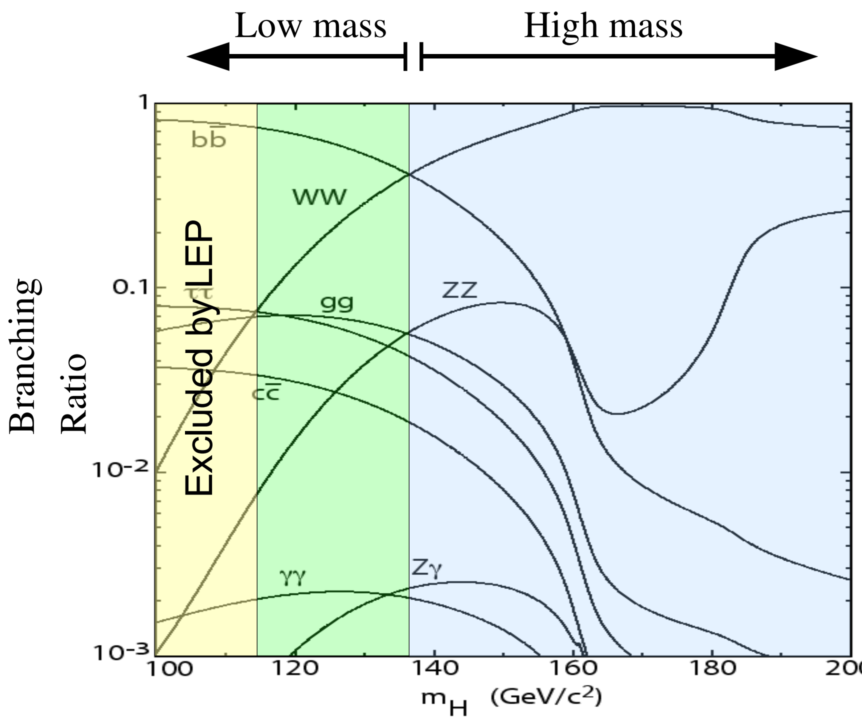
- Associated Production



- Vector Boson Fusion



- $H \rightarrow WW$ dominant decay for $m_H > 135$ GeV ("high mass").
- $H \rightarrow b\bar{b}$ dominant decay for $m_H < 135$ GeV ("low mass").



Experimental Higgs Search Channels

High Mass

Low Mass

- $H \to WW \to \ell\ell$
- $WH \to WWW \to \ell^+\ell^+$
- $H \to \gamma\gamma$
- $WH \to \ell\nu bb$
- $ZH \to \ell\ell bb$
- $ZH \to \nu\nu bb$
- $HX \to \tau\tau jj$
- $VH \to bbjj$
- $WH \to \tau\nu bb$
- $ttH \to ttbb$

Summer 2008 Tevatron
High Mass Combination

Winter 2008 Tevatron
Low + High Mass Combination

Tevatron High Mass Channels

Channel	Integrated Luminosity (fb^{-1})			
	Summer 2008		Winter 2009	
	CDF	D0	CDF	D0
$H \to WW \to \ell\ell$	3.0	3.0	3.6	3.0
$WH \to WWW \to \ell^+\ell^+$	1.9	1.1	3.6	1.1

- Additional results and new Tevatron combination expected soon.

$H \rightarrow WW$

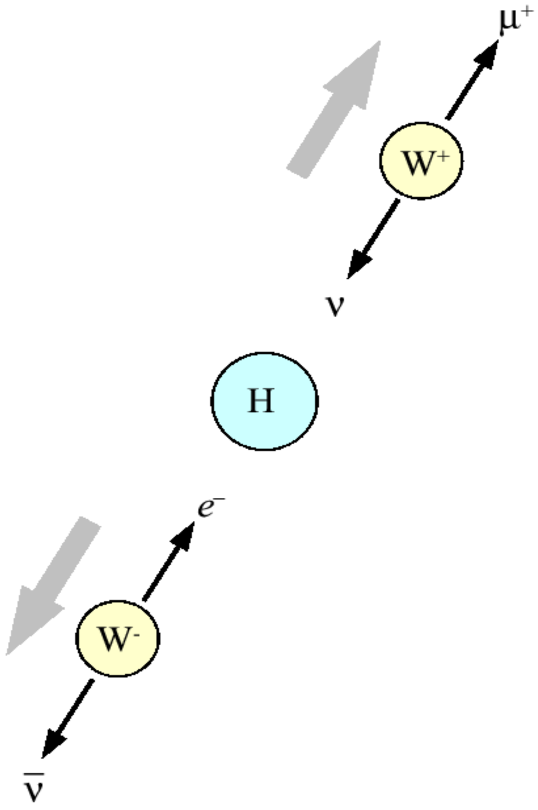
- Most sensitive Higgs channel at the Tevatron.
  - Highest sensitivity around M_H=160 GeV.
- Signature two high p_T leptons (ℓ=e or μ) and missing E_T.
- Backgrounds: WW, WZ, ZZ, tt, W+γ/jets, $Z \rightarrow \ell\ell$, $Z \rightarrow \tau\tau$, QCD.
- Strategies.
  - Good lepton id and missing E_T resolution.
  - WW is a fundamental physics background, and one of the largest backgrounds. Spin correlation ($\Delta\phi_{\ell\ell}$)is the best single variable for discriminating H and WW.
  - All subchannels and both experiments make use of advanced multivariate techniques to get best possible signal / background discrimination.

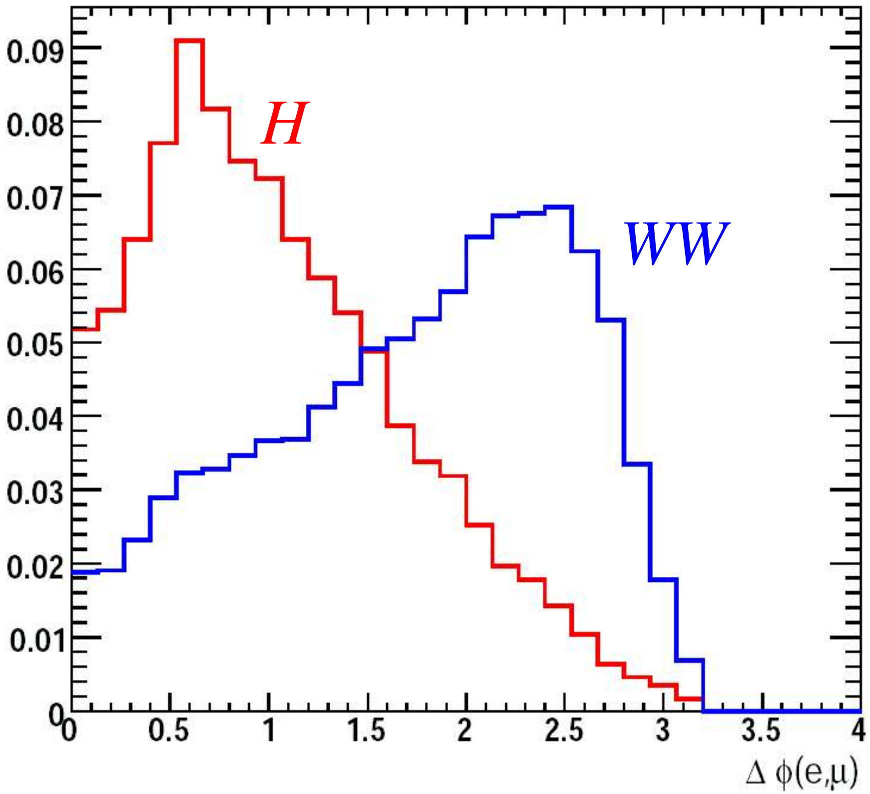
$H \to WW$ Systematic Errors

- Theoretical.
  - Total cross sections (H, WW, W+jets).
  - Differential cross sections (p_T(Z), p_T(W)).
  - PDFs.
- Simulation.
  - Lepton / jet / missing E_T energy scale & resolution.
  - Lepton id efficiencies.
- Fake backgrounds / fake rates.
- Luminosity.

Spin Correlation in $H \rightarrow WW$

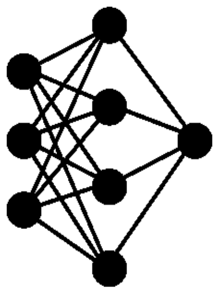
- Leptons from $H \rightarrow WW \rightarrow \ell\ell$ tend to be emitted in the same direction (i.e. small $\Delta\phi(\ell,\ell)$).



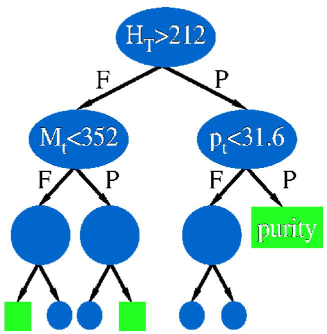


Multivariate Analysis Techniques

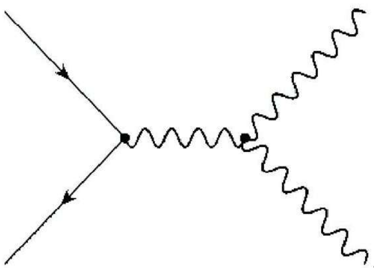
- Neural Networks (NN).
  - Works well. Time-tested – have been used successfully for many years.



- Boosted Decision Trees (BDT).
  - Relatively recent. Popularity has grown enormously recently.



- Matrix Element (ME).
  - Highly efficient for specific signals / backgrounds.
  - Computationally costly.
  - Can be used as input to other techniques.



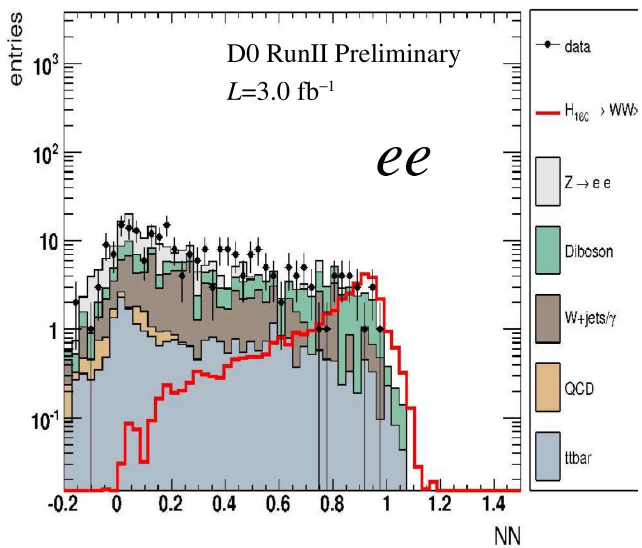
$H \to WW$ Event Selection

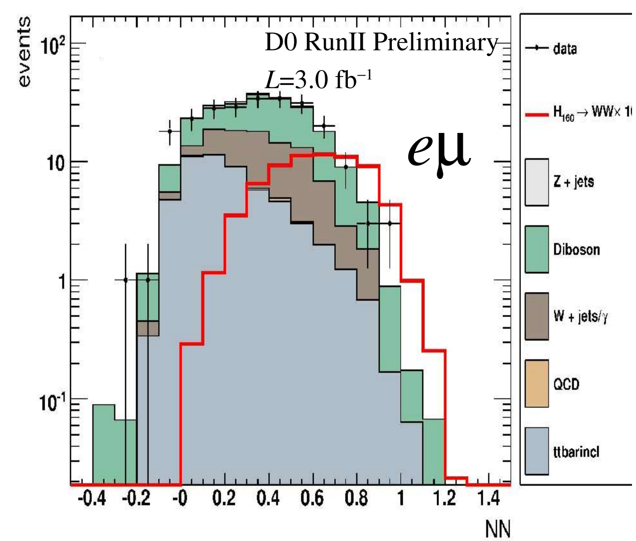
	ee	*eμ*	*μμ*
Leptons (preselection)	$p_T(\mu) > 10$ GeV, $p_T(e) > 15$ GeV, $M_{\ell\ell} > 15$ GeV		
$\not{E}_T$ (GeV)	>20	>20	>20
$\not{E}_T^{Scaled}$	>7	>6	>5
$M_T^{min}(\ell, \not{E}_T)$ (GeV)	>20	>30	>20
$\Delta\phi(\ell,\ell)$	<2.0	<2.0	<2.5

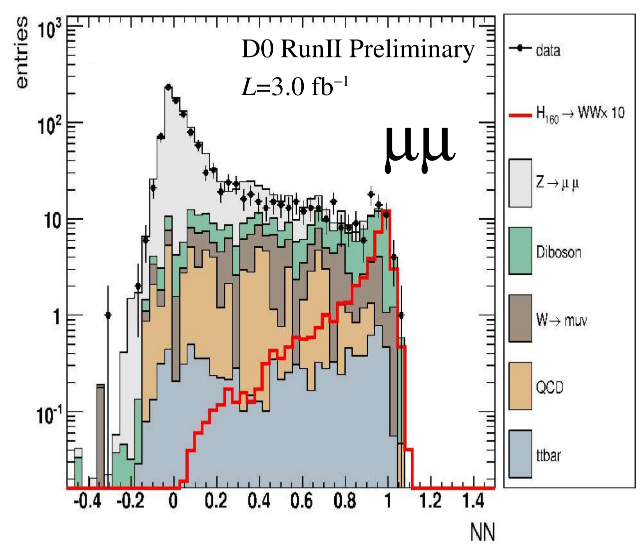
	$e\mu$ pre-selection	$e\mu$ final	ee pre-selection	ee final	$\mu\mu$ pre-selection	$\mu\mu$ final
$Z \to ee$	209.0 ± 3.0	0.72 ± 0.16	160463 ± 264	73.6 ± 5.1	–	–
$Z \to \mu\mu$	151.1 ± 0.6	2.14 ± 0.06	-	-	256432 ± 230	957 ± 14
$Z \to \tau\tau$	2312 ± 2	2.45 ± 0.05	835 ± 8	1.0 ± 0.3	1968 ± 11	5.5 ± 0.5
$t\bar{t}$	187.5 ± 0.2	54.2 ± 0.1	96.9 ± 0.2	28.5 ± 0.1	19.4 ± 0.1	10.1 ± 0.1
$W + jets$	163.4 ± 5.3	60.1 ± 3.2	174 ± 7	72.0 ± 4.3	149 ± 3	85.8 ± 2.1
WW	285.6 ± 0.1	108.0 ± 0.1	127.5 ± 0.4	45.7 ± 0.2	162.9 ± 0.5	91.3 ± 0.3
WZ	14.8 ± 0.1	4.9 ± 0.1	89.6 ± 0.8	7.6 ± 0.2	51.6 ± 0.5	16.2 ± 0.3
ZZ	3.47 ± 0.01	0.49 ± 0.01	73.5 ± 0.3	5.4 ± 0.1	43.0 ± 0.2	13.5 ± 0.1
Multi-jet	190 ± 168	1 ± 8	2322 ± 193	4.3 ± 8.3	945 ± 31	63.6 ± 8.0
Signal ($m_H = 160$ GeV)	9.0 ± 0.1	6.9 ± 0.1	4.40 ± 0.01	3.49 ± 0.01	4.7 ± 0.1	4.09 ± 0.06
Total Background	3516 ± 168	234 ± 9	164181 ± 327	238 ± 11	259770 ± 232	1242 ± 16
Data	3706	234	164290	236	263743	1147

$H \rightarrow WW$ NN Analysis

- Neural network analysis makes use of 14 input variables.

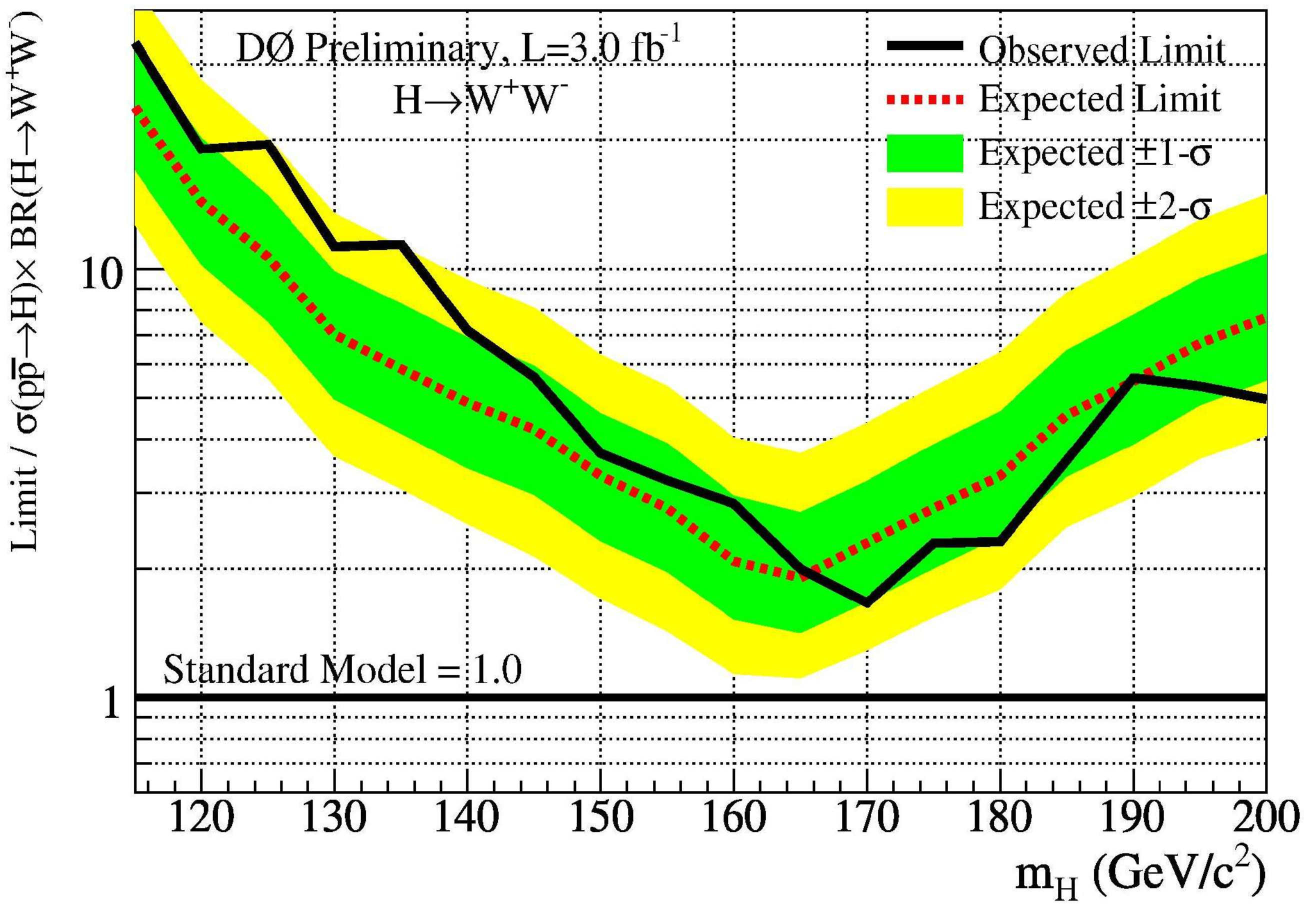






$H \to WW$ Result

- Upper limit on σ×BR set using entire NN output distribution for all channels using modified frequentist method (CLs method).

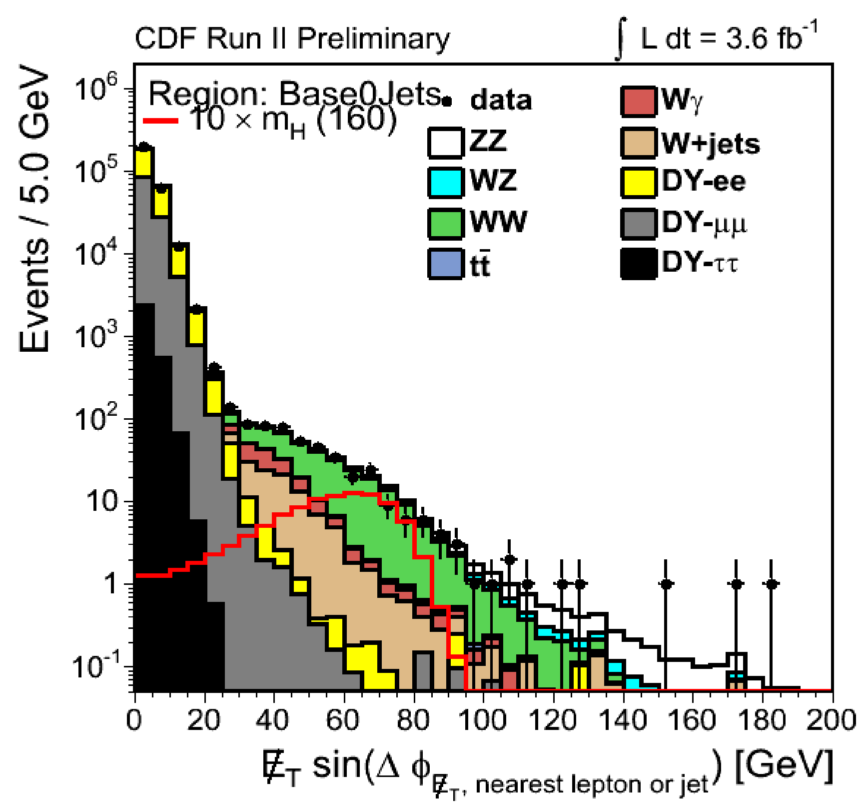


Expected limit is 2.1 times SM at M_H=160 GeV

$H \rightarrow WW$ Event Selection

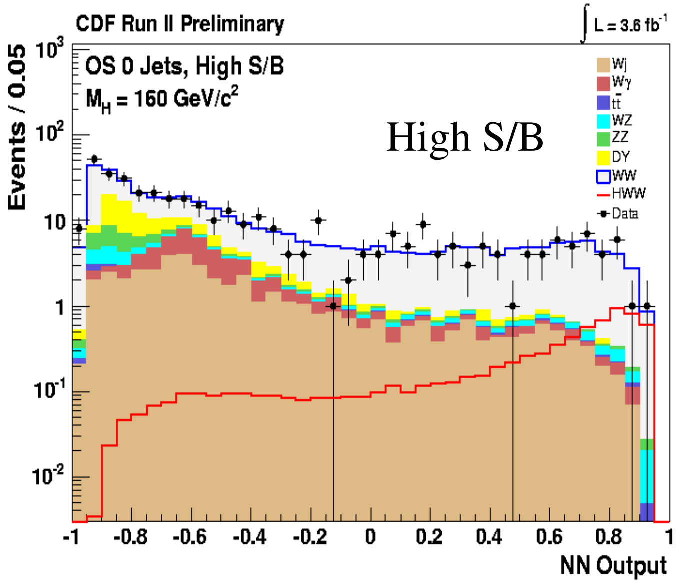
	ee	$e\mu$	$\mu\mu$
Leptons	$p_{T1} > 20$ GeV, $p_{T2} > 10$ GeV, $M_{\ell\ell} > 16$ GeV		
$\not{E}_{T\mathrm{spec}}$ (GeV)	>25	>15	>25
$\not{E}_{T\mathrm{spec}} = \not{E}_T \sin\{\min[\pi/2, \Delta\phi(\not{E}_T, \ell j)]\}$			

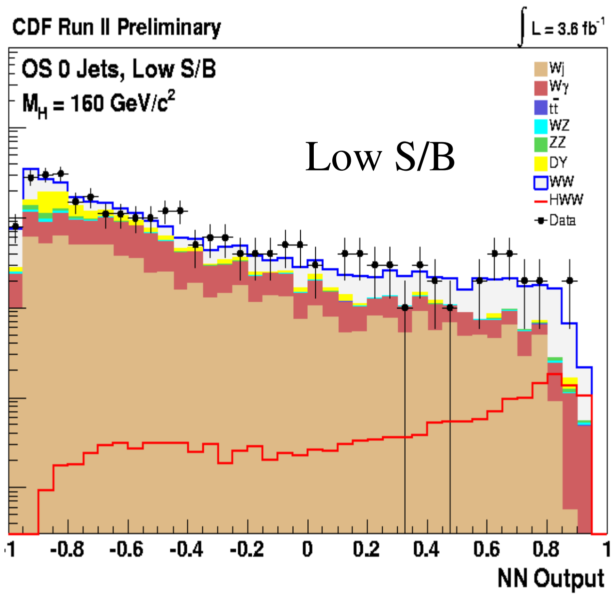
- Separate NN analysis for 0, 1, and ≥2 jets.
- 1 and 2 jets includes VBF and VH contributions to signal.
- Also separate NN analysis for high and low S/B events based on lepton quality for 0 and 1 jets.



$H \rightarrow WW$ 0 jets NN Analysis

- Neural network analysis makes use of 5 input variables, including $\Delta\phi_{\ell\ell}$ and H vs. WW matrix element likelihood ratio (LRHWW).
- Separate NN for high and low S/B lepton id.



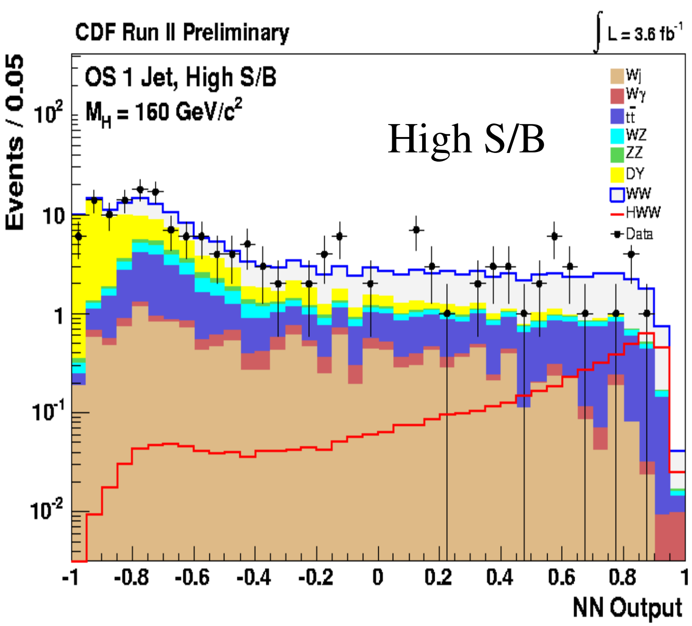


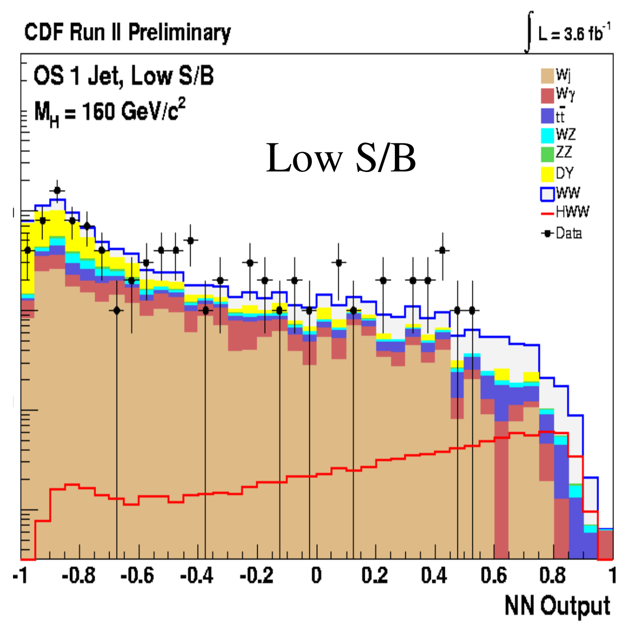
CDF Run II Preliminary	$\int \mathcal{L} = 3.6$ fb^{-1}		
$M_H = 160$ GeV/c^2			
$t\bar{t}$	1.35	±	0.21
DY	80	±	18
WW	318	±	35
WZ	13.8	±	1.9
ZZ	20.7	±	2.8
W+jets	113	±	27
$W\gamma$	92	±	25
Total Background	637	±	67
Total Signal	9.5	±	1.4
Data	651		

OS 0 Jets

$H \to WW$ 1 jets NN Analysis

- Neural network analysis makes use of 8 input variables (LRHWW not included for >0 jets).
- Separate NN for high and low S/B lepton id.



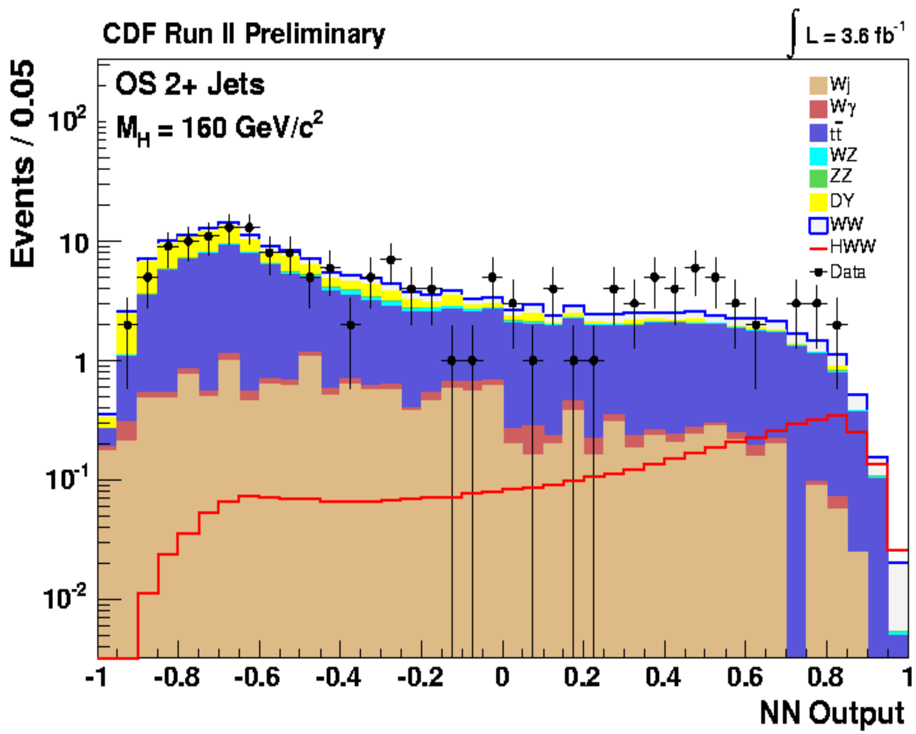


CDF Run II Preliminary	$\int \mathcal{L} = 3.6$ fb^{-1}		
$M_H = 160$ GeV$/c^2$			
$t\bar{t}$	34.9	$\pm$	5.5
DY	85	$\pm$	27
WW	85.3	$\pm$	9.1
WZ	14.5	$\pm$	2.0
ZZ	5.48	$\pm$	0.75
W+jets	40	$\pm$	10
$W\gamma$	13.2	$\pm$	4.0
Total Background	278	$\pm$	35
Total Signal	5.98	$\pm$	0.78
Data	262		

OS 1 Jet

$H \rightarrow WW$ 2+ jets NN Analysis

- Neural network analysis makes use of 8 input variables.
- High and low S/B lepton id not used for ≥2 jets.

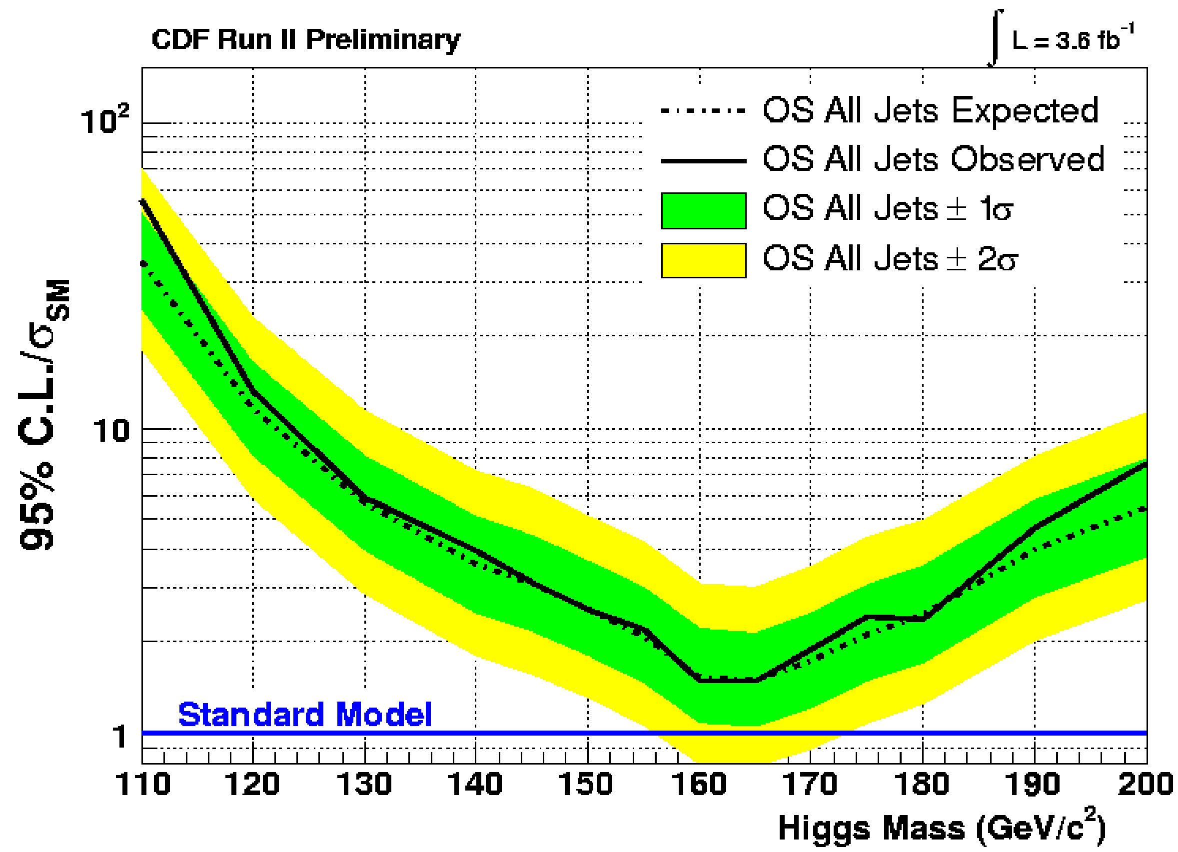


CDF Run II Preliminary	$\int \mathcal{L} = 3.6\ \mathrm{fb}^{-1}$		
$M_H = 160\ \mathrm{GeV}/c^2$			
$t\bar{t}$	100	±	17
DY	33	±	11
WW	17.6	±	4.0
WZ	3.76	±	0.52
ZZ	1.62	±	0.22
W+jets	14.7	±	4.0
$W\gamma$	2.12	±	0.70
Total Background	173	±	23
$gg \rightarrow H$	1.75	±	0.30
WH	1.39	±	0.18
ZH	0.693	±	0.090
VBF	0.70	±	0.11
Total Signal	4.53	±	0.52
Data	169		

OS 2+ Jets

$H \rightarrow WW$ Result

- Upper limit on σ×BR obtained likelihood fit of all five NN output distributions.



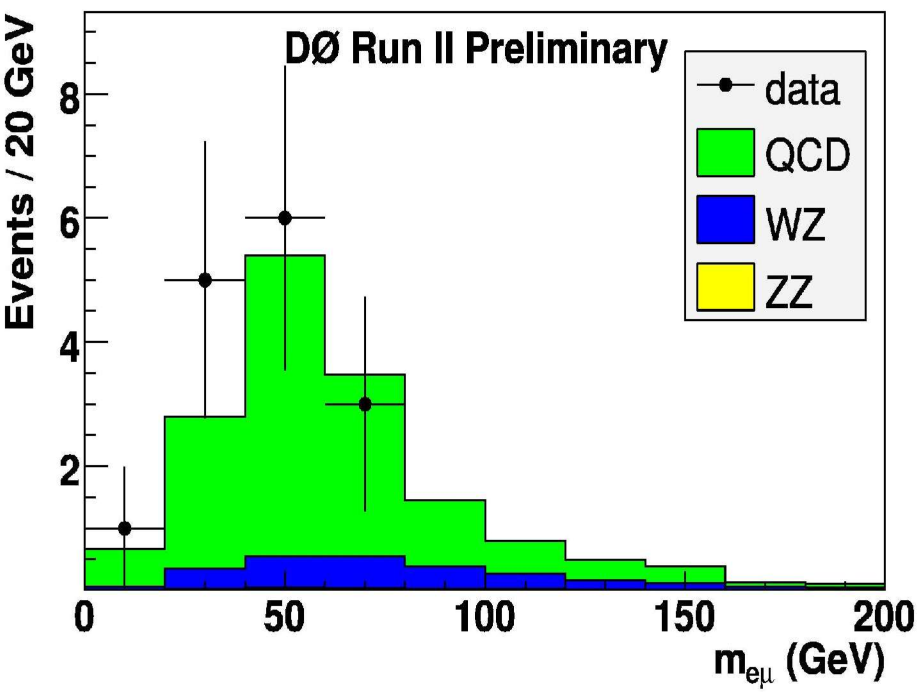
Expected limit is 1.48 times SM at M_H=160 GeV

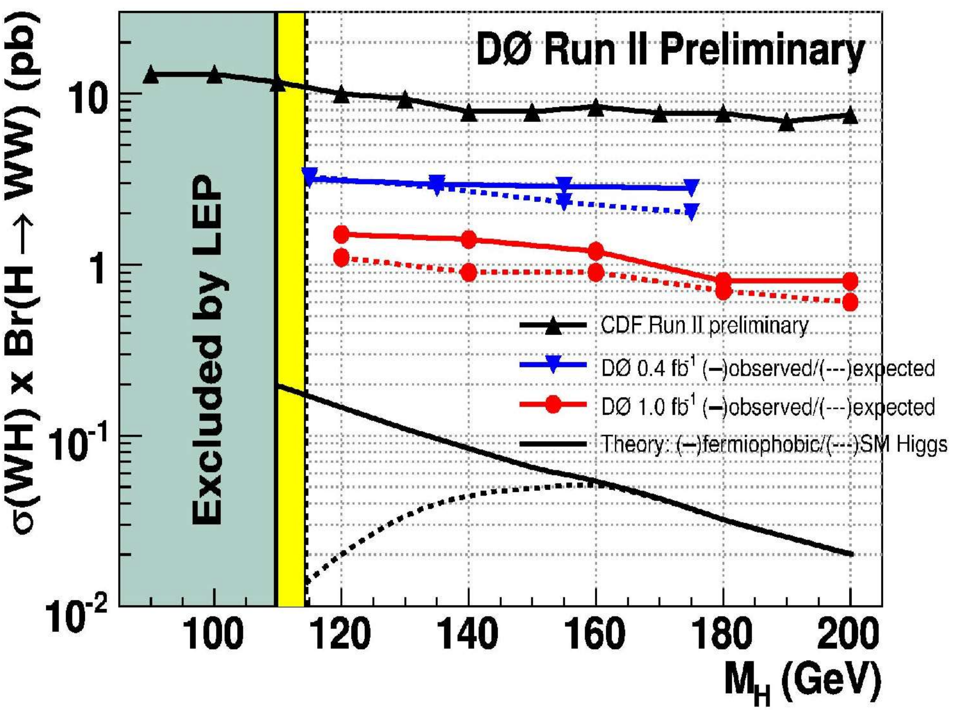
$WH \rightarrow WWW \rightarrow \ell^+ \ell^+$

- Signature two like-sign high p_T leptons ($\ell = e$ or μ).
- Smaller σ×BR than $H \rightarrow WW$ but very low SM background.
- Backgrounds: *WZ, ZZ*, *W*+γ/jets, QCD, charge flips.
  - Instrumental backgrounds (fakes and charge flips) are dominant.

$WH \rightarrow WWW \rightarrow \ell^+ \ell^+$

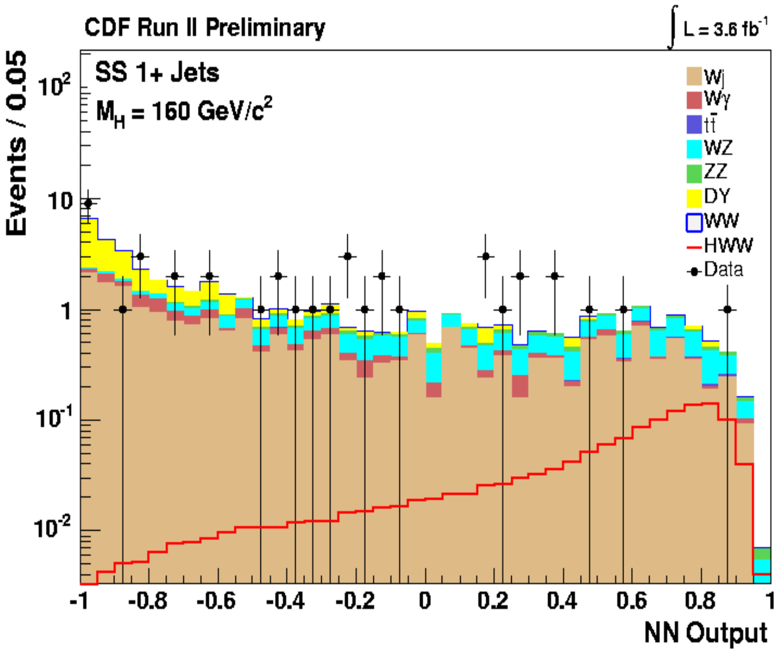
- Event selection: $p_T(e) > 15$ GeV, $p_T(\mu) > 15$ GeV.
- Upper limit on $\sigma \times BR$ from 2D multivariate likelihood fit.
  - Expected limit is 17 times SM at M_H=160 GeV.

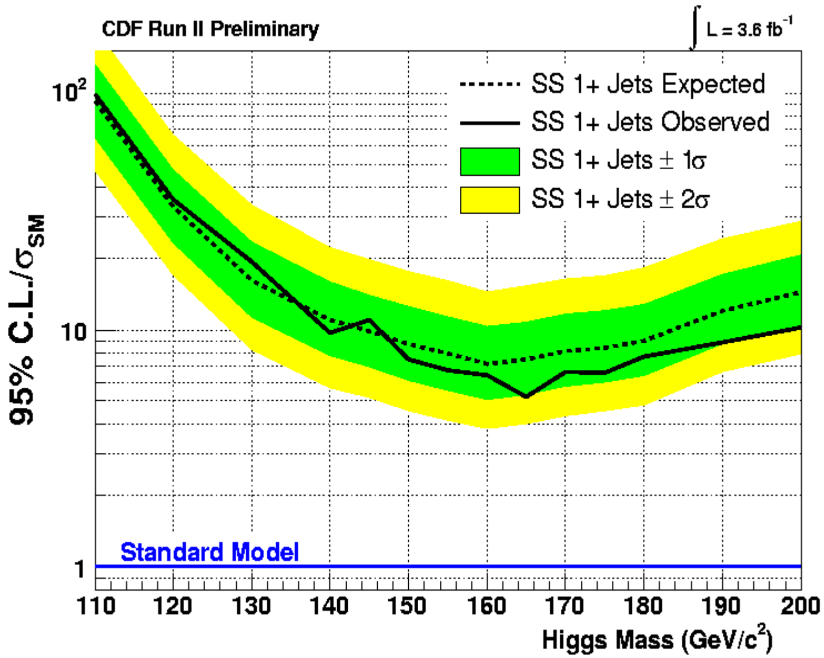




$WH \rightarrow WWW \rightarrow \ell^+ \ell^+$

- Event selection: $p_{T1} > 20$ GeV, $p_{T2} > 20$ GeV.
- Multivariate analysis using 13-variable NN.
  - Expected limit is 7.2 times SM at M_H=160 GeV.





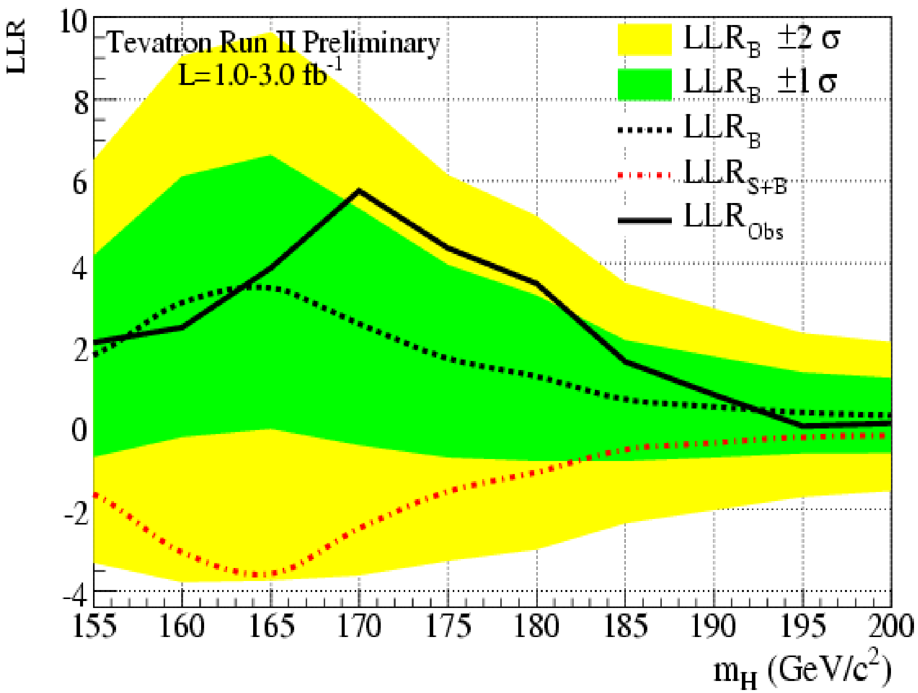
Tevatron High Mass Combination

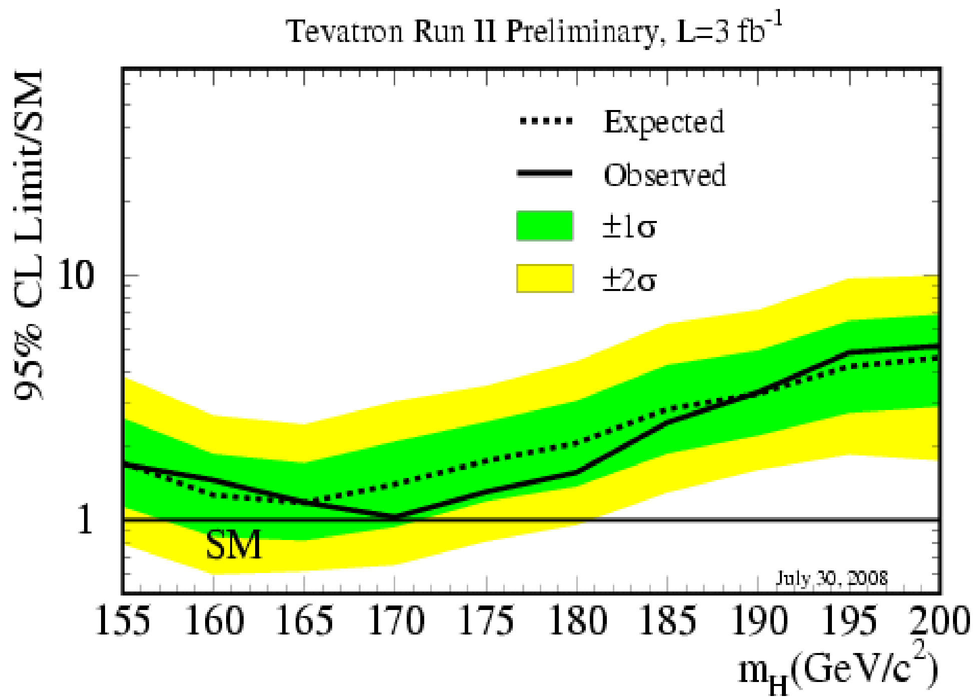
- CDF and D0 results from *WW* and *WWW* channels are combined into single Higgs limit.
  - Bayesian and modified frequentist (CLs) methods using LLR test statistic.

$$LLR(M_H) = -2\ln\frac{p(data|M_H)}{p(data|Null)}$$

  - Correlated systematic errors taken into account.
- Most recent high mass combination includes results from summer 2008.

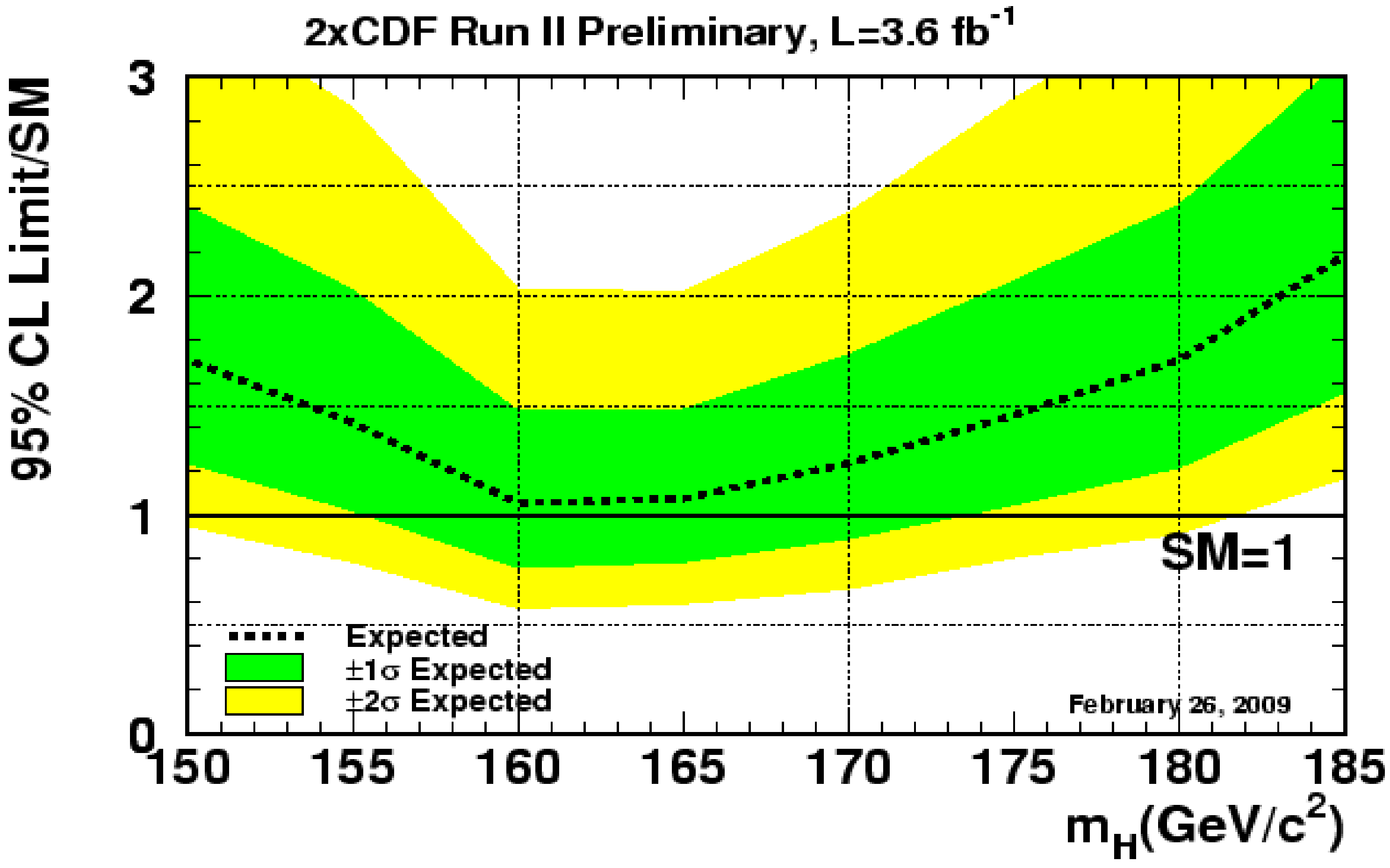
Tevatraon High Mass Combination Result





SM Higgs excluded at 95% CL for M_H=170 GeV

Updated High Mass Combination Preview

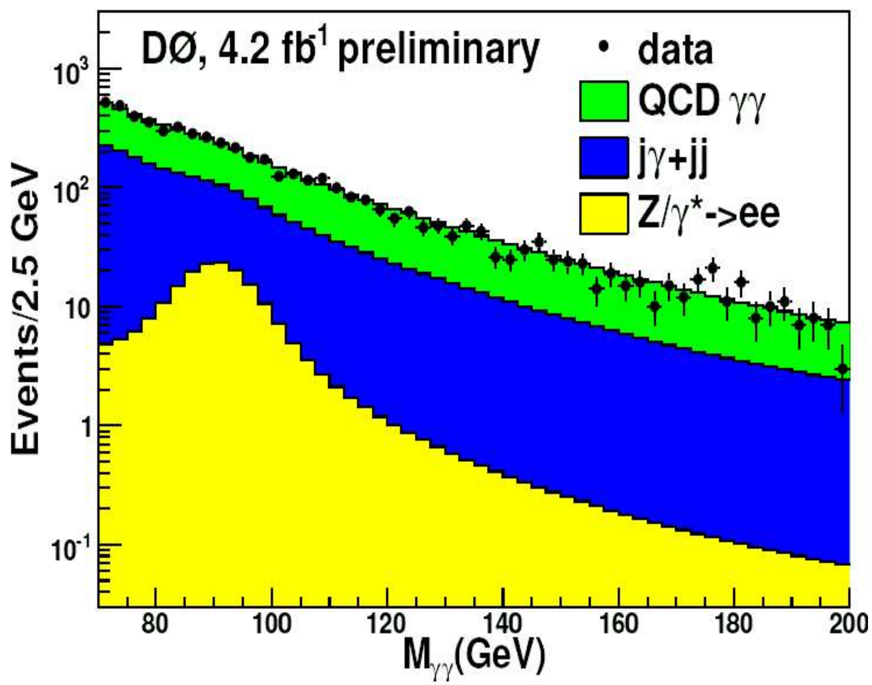


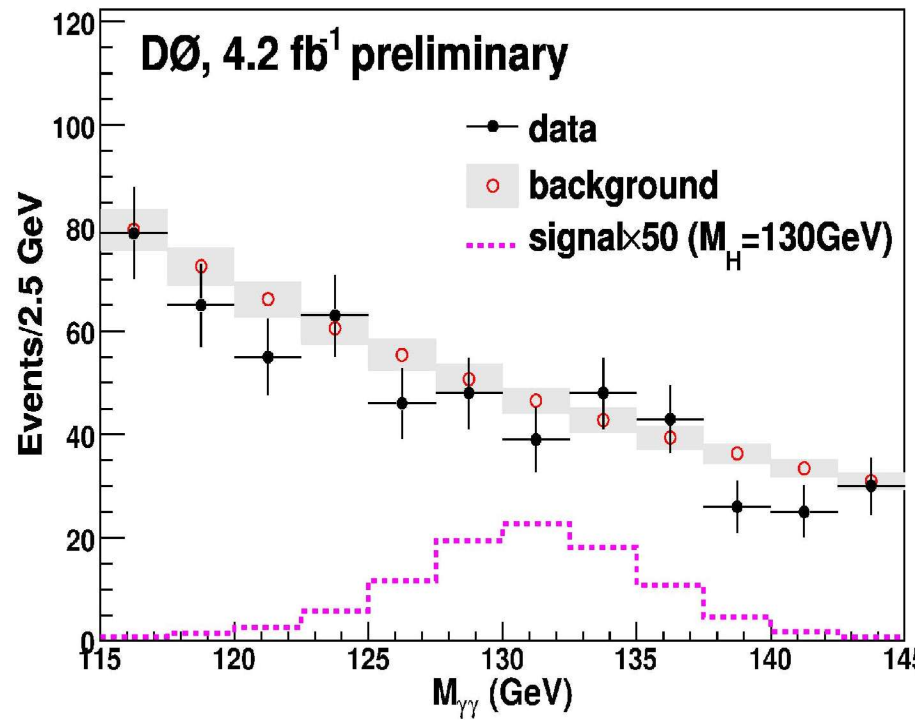
$H \to \gamma\gamma$

- Low branching ratio, but sensitive in intermediate mass range.
  - Flat sensitivity for intermediate mass M_H ~120–130 GeV.
  - Sensitive to gluon fusion production for low M_H.
  - Fermiphobic interpretation also available.
- Signature two high p_T γ's.
- Backgrounds: $Z/\gamma^* \to ee$, γ+jets, dijet, nonresonant $\gamma\gamma$.
  - Nonresonant $\gamma\gamma$ is irreducible physics background.
- Strategies.
  - Good photon id.
    - Need best possible rejection of $e \to \gamma$ and jet$\to \gamma$ fake photons.
  - Look for narrow invariant mass peak.

$H \rightarrow \gamma\gamma$ Event Selection

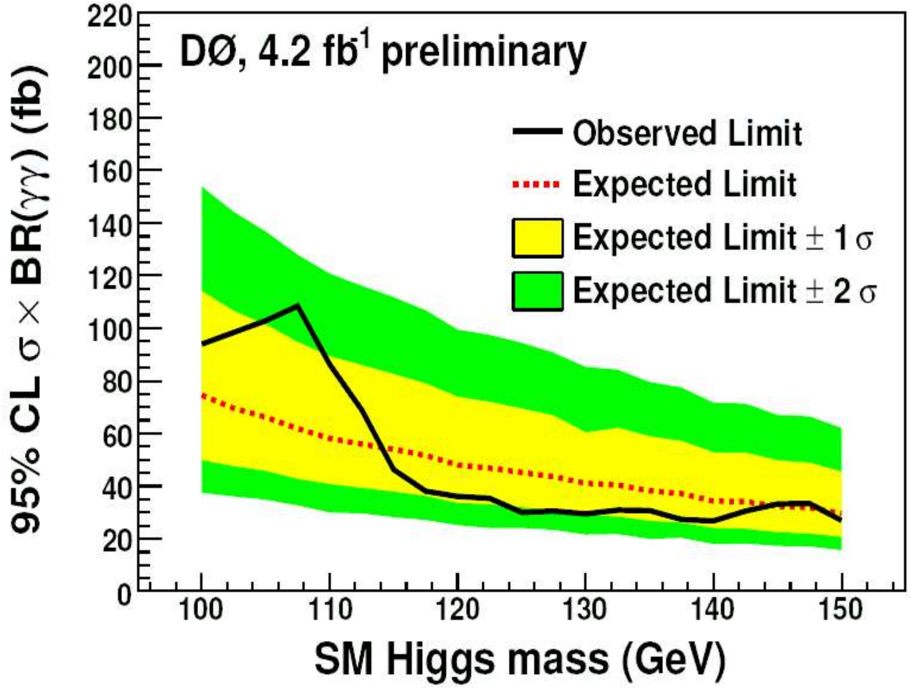
- Require tight photon id and $p_T > 25$ GeV and $|\eta| < 1.1$.

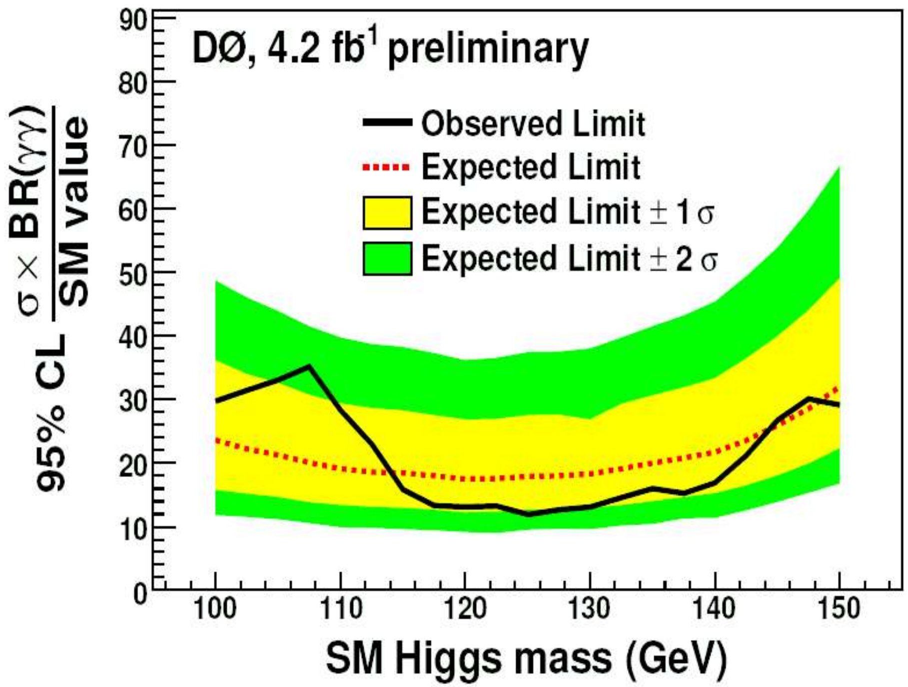




$H \to \gamma\gamma$ Result

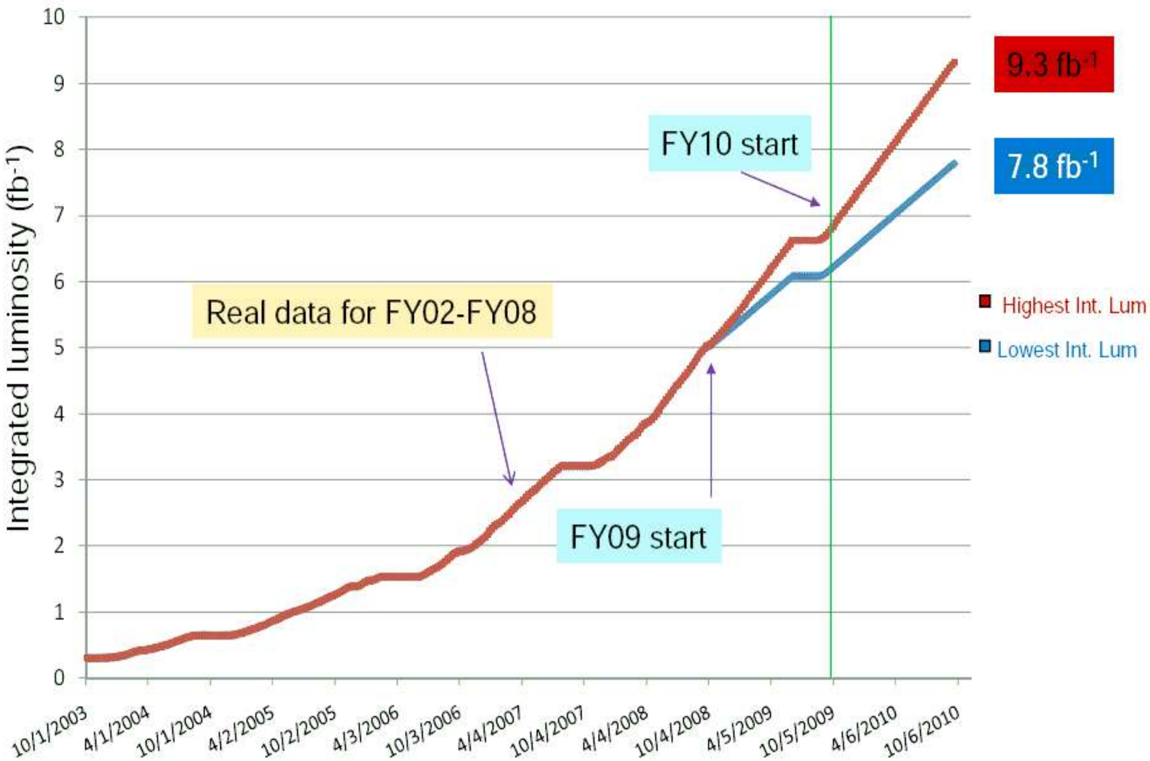
- Limit extracted using expected lineshape.
  - Use sidebands around $M_H \pm 15$ GeV to fix background normalization.





- Expected limit is 18.3 times SM at M_H=130 GeV.
- Observed limit is 13.1 times SM at M_H=130 GeV.

Prospects



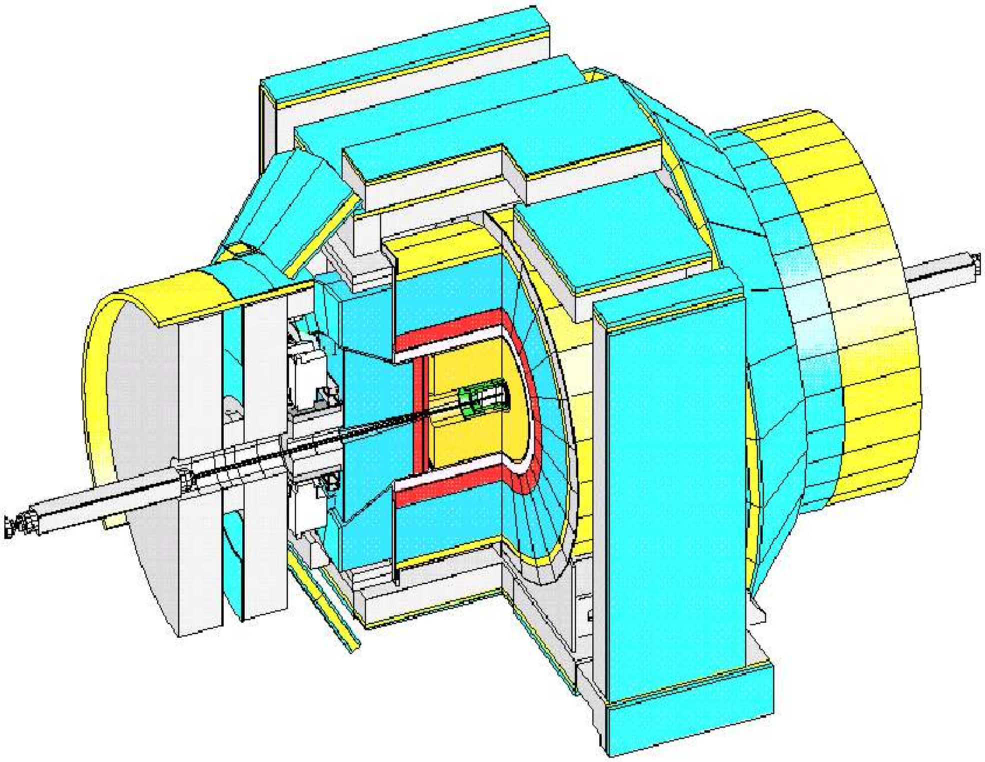
- Tevatron and experiments are running well.
- Experiments have ~6 fb^{-1} delivered today (~5.3 fb^{-1} recorded).
- Expect 8-9 $fb^{-1}$of integrated luminosity per experiment delivered (7-8 fb^{-1} recorded) by end of FY10 (more if Tevatron runs in 2011).
- Analysis improvements will likely improve Higgs sensitivity faster than luminosity scaling.

Summary

- SM Higgs excluded at 95% CL at M_H=170 GeV.
- Updated results with up to 4 fb^{-1} and updated Tevatron combination are expected soon.
- Tevatron and experiments are continuing to run well.
  - CDF and D0 currently have recorded about 5 fb^{-1} of data.
  - Expect 7–8 fb^{-1} or more of analyzed data eventually.

Backup Slides

CDF Detector

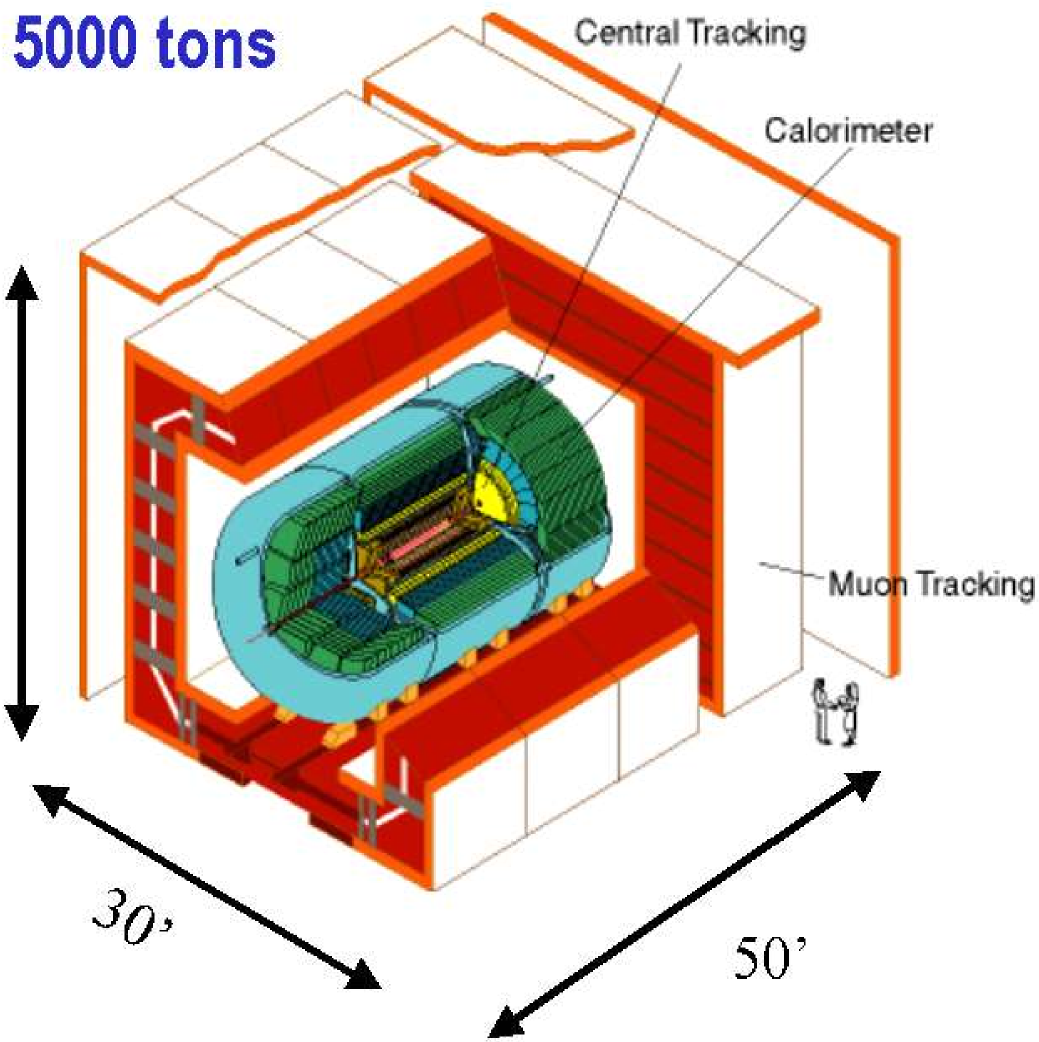


Tracking
- Solenoid magnet
- Silicon vertex detector
- Wire drift chamber
- $|\eta| < 2.5$

Calorimeter
- $|\eta| < 4$

Muon system
- $|\eta| < 1.5$

D0 Detector



Tracking
- Solenoid magnet
- Silicon vertex detector
- Scintillating fiber tracker
- $|\eta| < 3$

LAr-U Calorimeter
- $|\eta| < 4$

Muon system
- $|\eta| < 2$

$H \rightarrow WW$ Systematic Errors

Systematic Error	Signal (%)	Background (%)
Jet Energy Scale & Resolution	0.3	1
Lepton ID Efficiency	5.7–8	5.7–8
Jet ID Efficiency		6
Theory σ's	4	5
$p_T(Z)$		1–5
$p_T(W)$	6.8	3
PDFs	4	4
Fake backgrounds		
Integrated Luminosity	6.5	6.5

$H \to WW$ Systematic Errors

Systematic Error	Signal (%)	Background (%)
Jet Energy Scale	4.6–8.7	1.1
Lepton Energy Scale	2.5–3.1	
Lepton ID & trigger efficiency	2	2
Missing E_T modeling	1	1–5
γ Conversion modeling		20 ($W\gamma$)
Theory σ's	12	5–10
PDFs	5.1	
Fake backgrounds		4
Integrated Luminosity	5.9	5.9

Tevatron High Mass Combination 90% and 95% CL Exclusions