Searches for an high mass Higgs boson in the $H \rightarrow WW$ channel at the CDF experiment

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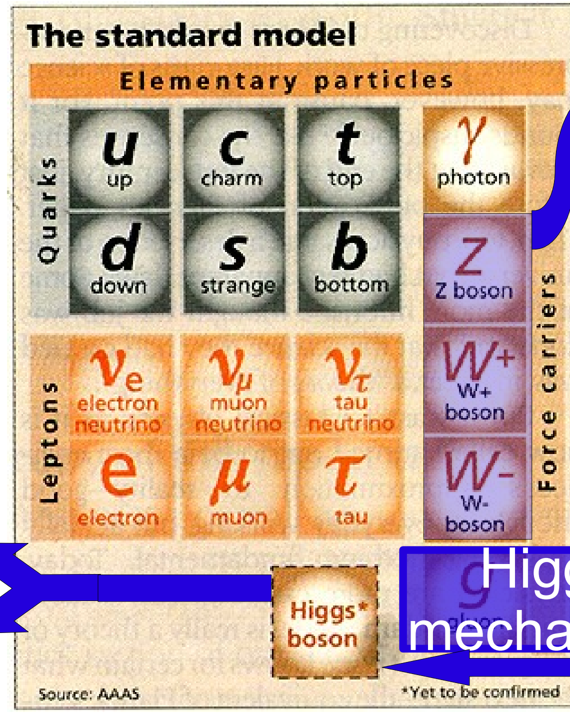
The Higgs mechanism

SM unifies weak and electro-magnetic interactions



Experimentally: massiveness of weak field carriers

EWK symmetry breaking

Higgs mechanism

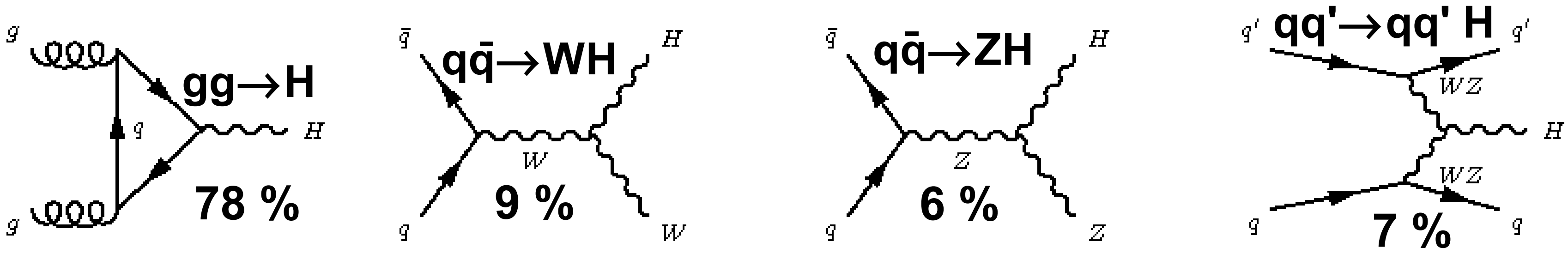
its mass is a free parameter

existence yet to be confirmed

- **Explaining the EW symmetry breaking is a major goal for particle physics nowadays, and Tevatron can probe it!**
- **Finding the Higgs boson → a good proof that this mechanism is the one that nature chose**

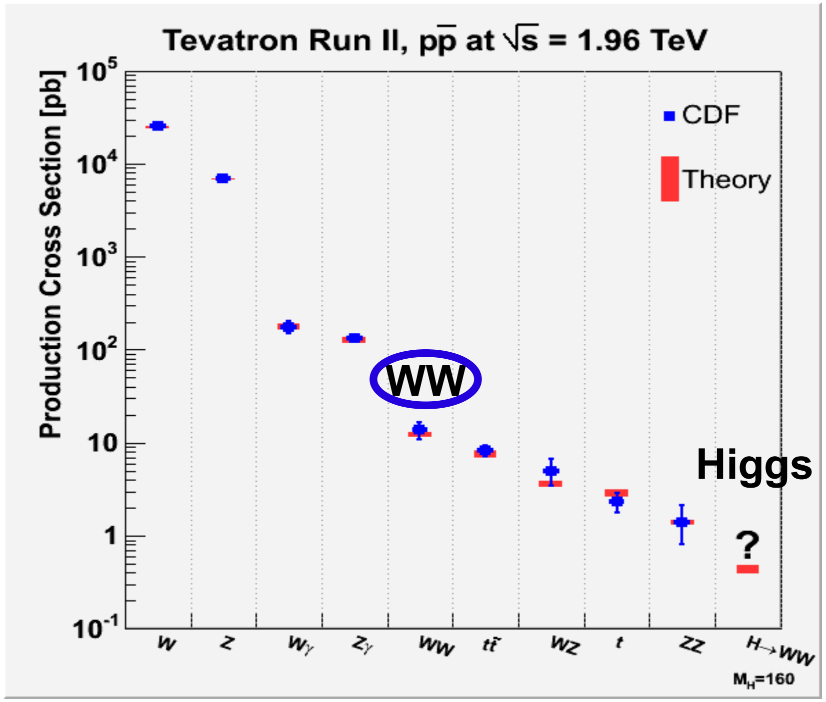
Higgs production

- **Four main production mechanisms at Tevatron:**

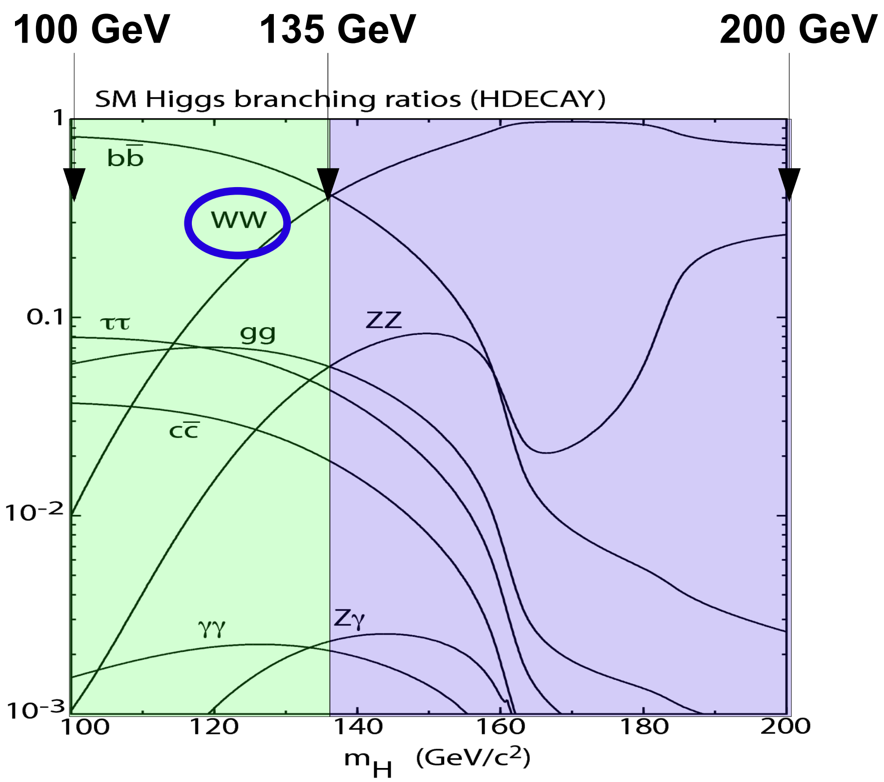


- **As sensitivity increases all of them become important!**
- **Lots of measurements down to ~pb processes**

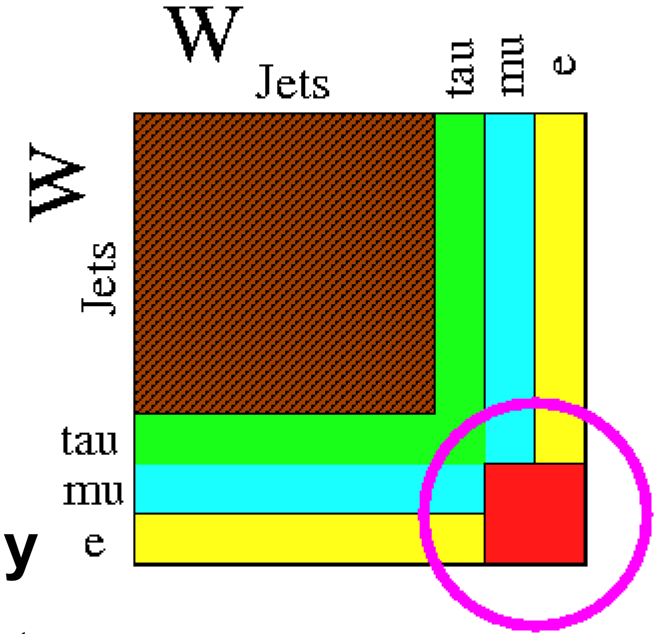
$$\sigma_{SM}^{m_H=160\,GeV} \sim 0.6\ pb$$



- **For $m_H > 135$ GeV/c² H → WW dominant**
  - This is how we define high mass Higgs searches at Tevatron
  - Still contributes significantly to Higgs searches down to 120 GeV/c²



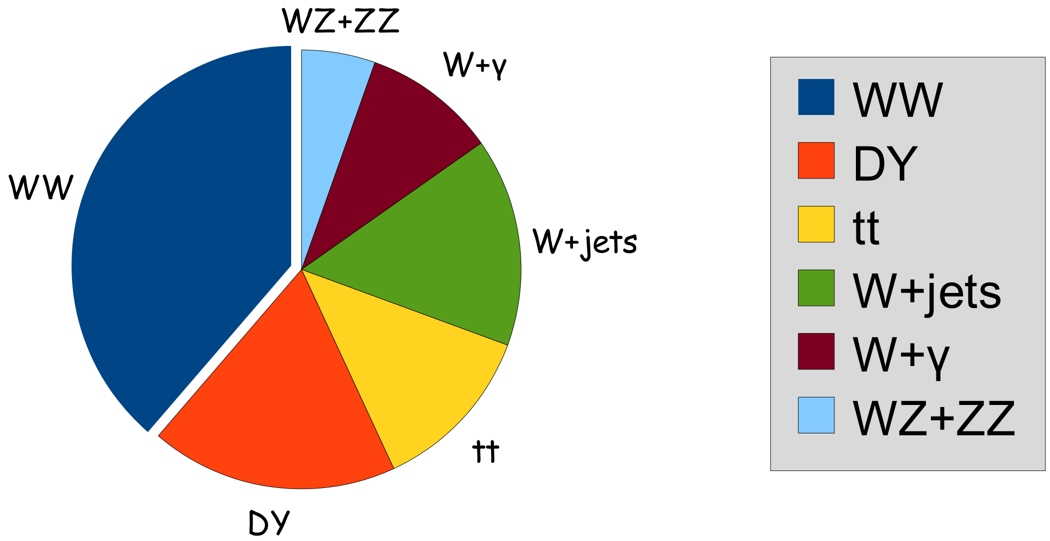
Final state: H → WW → lνlν



- **W decays**
  - BR(W→l ν) ~ 32%
  - BR(W→hadrons) ~ 68%
- **Hadronic modes have large QCD background: not used.**
- **We select both W decaying leptonically**
  - Easy and clean triggers on single electron or muon
    - Manageable trigger cross section at hadronic colliders
    - Clean signature, exploiting good tracking and muon systems of CDF
  - Partially includes $\tau \rightarrow (e,\mu)$
  - Overall BR for WW pair to di-lepton (e or μ) ~ 6%

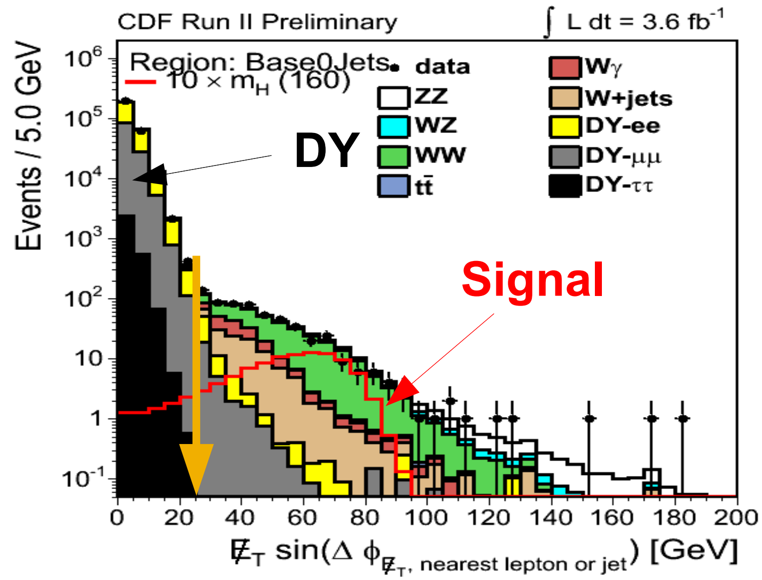
Sample composition

- **Main background contributions**



- **Background modeling**
  - Data-driven modeling whenever possible: W+jets
  - Most processes modeled with Pythia⊗Geant3 Monte Carlo
    - Exception is WW: MC@NLO
    - Cross sections normalized to (N)NLO calculation

- **In order to enhance signal/background ratio, require:**
  - Two opposite sign, isolated electrons or muons
    - p_T > 20 GeV/c for trigger lepton, p_T > 10 GeV/c for the 2nd lepton
  - Significant Missing E_T
    - reject Drell-Yan events
  - m(ll) > 16 GeV/c^2
    - reject heavy flavor decays



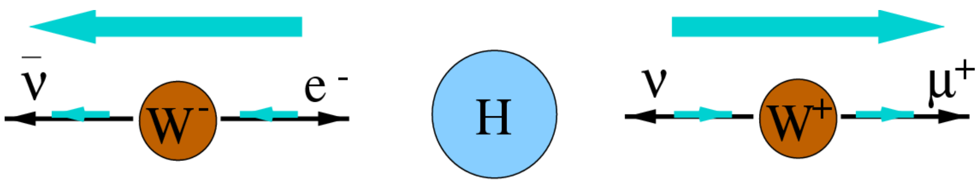
CDF RunII Preliminary $\int \mathcal{L} = 3.6\ fb^{-1}$, $M_H = 160$ GeV

$\mathcal{L}$ (fb^{-1})	Signal	Background	$S/\sqrt{B}$	Data
3.6	19.3 ± 2.4	1088 ± 105	0.59	1085

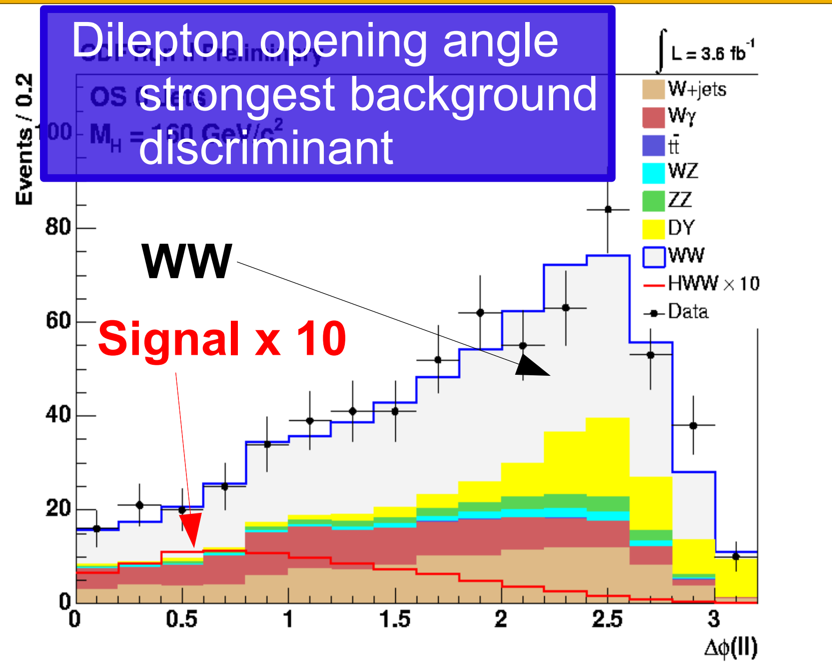
- **A simple counting experiment is not enough..**

Improving S/√B

- **Study the kinematics:**
  - Spin 1 particles (WW pair) from spin-0 Higgs boson



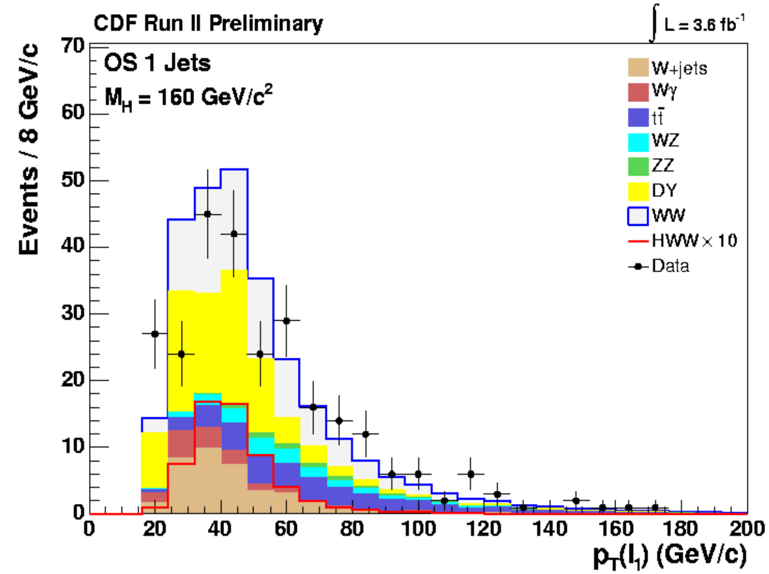
Spin correlation:
Leptons go in the same direction



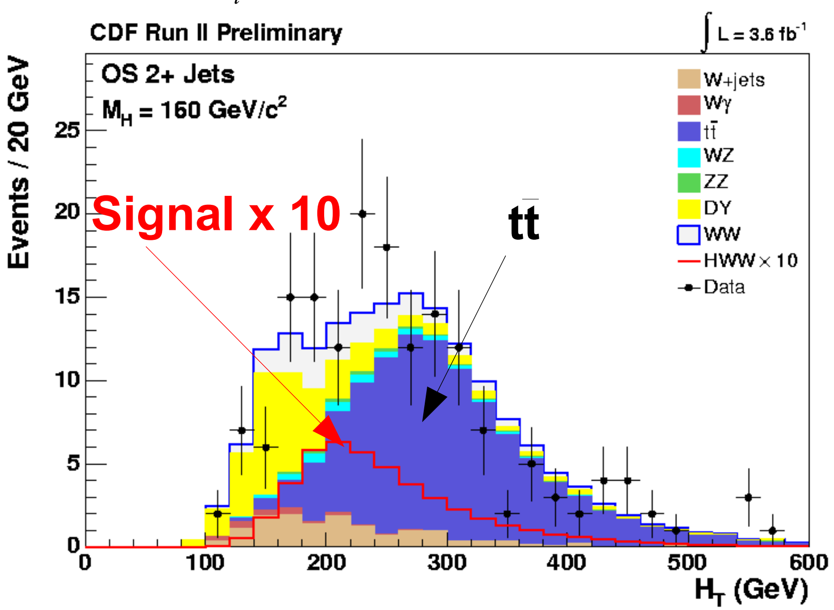
- **Use multivariate techniques (Neural Networks) to separate signal and background**
  - one NN for each Higgs mass hypothesis to probe
  - Divide the analysis in different channels by jet (E_T > 15 GeV, $|\eta|$ < 2.5) multiplicity: **0,1,2+ Jets**
  - optimize Neural Network inputs for each channel

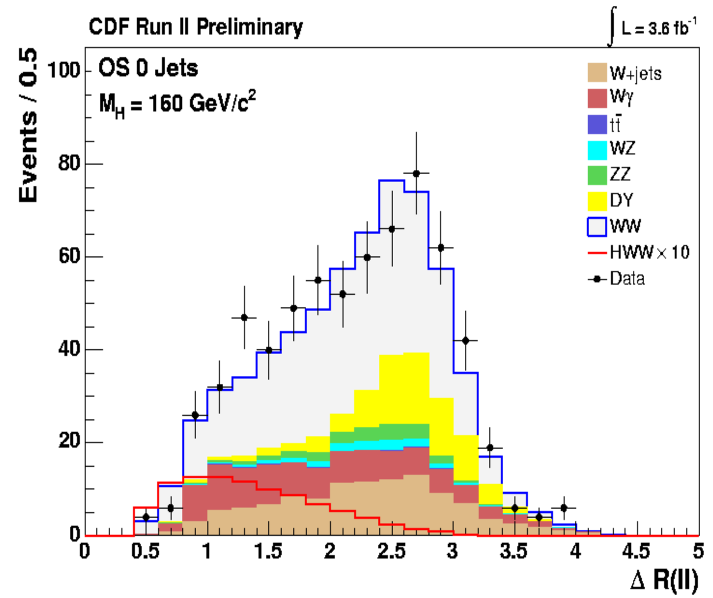
Neural Network inputs

- **Three different kind of inputs:**
  - Lepton-specific ($p_T(l)$, …)
  - Angular ($\Delta\phi(l,l)$, $\Delta\phi(l,\not{E}_T)$, …)
  - Kinematics ($\not{E}_T$, H_T, …)



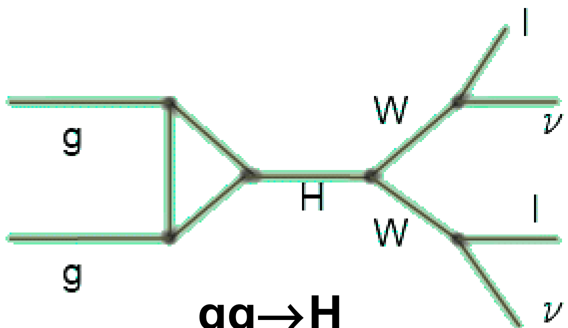
$$H_T = \sum_i |E_T(l_i)| + |E_T(jet_i)| + |\not{E}_T|$$





$gg \rightarrow H \rightarrow WW$: 0 Jets

- **Signal from gluon fusion**



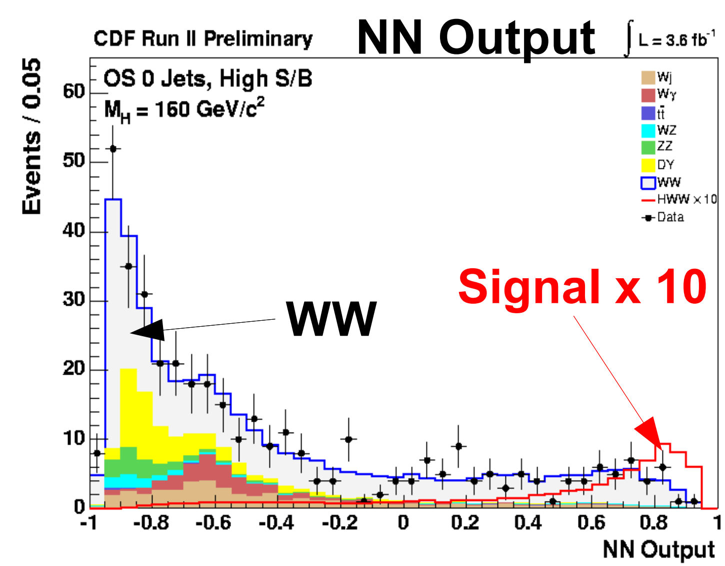
gg→H

- **Main background: WW**

- **Use also Matrix Element probabilities as input to the NN**
  - LO theoretical cross section calculations convoluted with experimental resolution for detecting each object

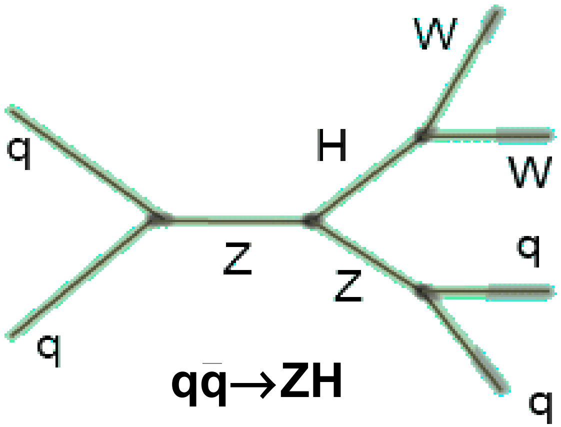
CDF Run II Preliminary	$\int \mathcal{L} = 3.6\ \mathrm{fb}^{-1}$
$M_H = 160\ \mathrm{GeV}/c^2$	
$t\bar{t}$	1.35 ± 0.21
DY	80 ± 18
WW	318 ± 35
WZ	14 ± 1.9
ZZ	20.7 ± 2.8
W+jets	113 ± 27
$W\gamma$	92 ± 25
Total Background	637 ± 67
$gg \rightarrow H$	9.5 ± 1.4
Total Signal	9.5 ± 1.4
Data	654

OS 0 Jets



WW + 1 jet

- **Final states with 1 jet**
  - 22% of the signal from (W/Z)H and Vector Boson Fusion (VBF)
  - WW still a dominant background

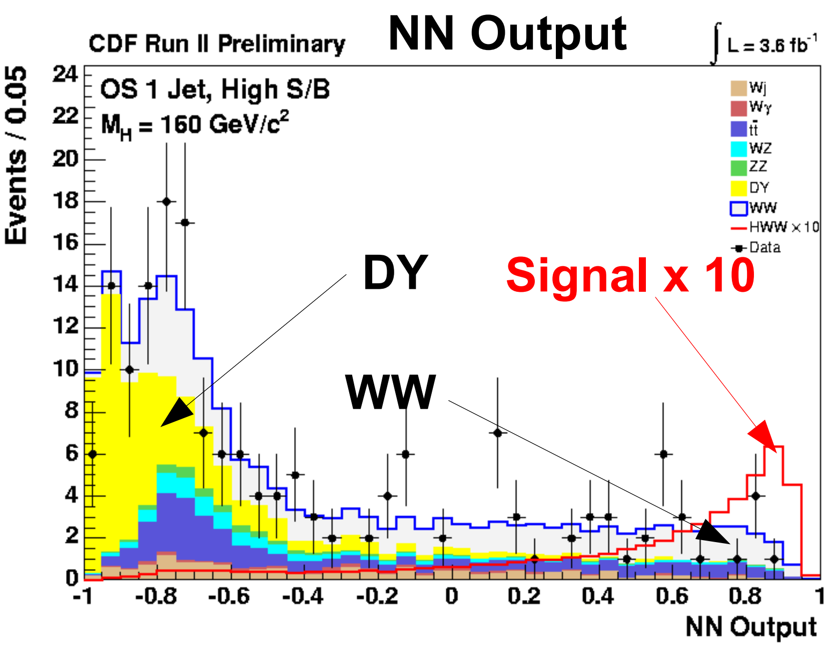


CDF Run II Preliminary $\int \mathcal{L} = 3.6\ \text{fb}^{-1}$

$M_H = 160\ \text{GeV}/c^2$

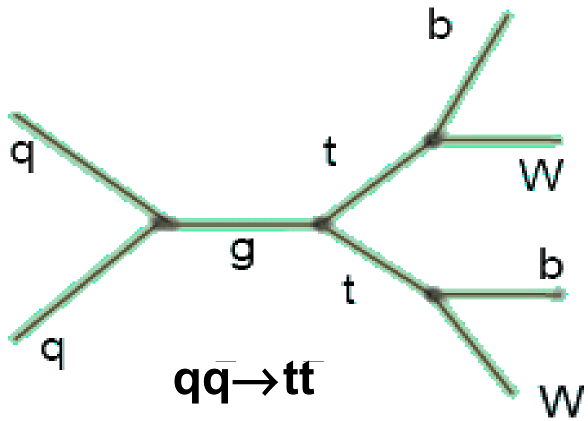
$t\bar{t}$	34.9	±	5.5
DY	85	±	27
WW	85.3	±	9.1
WZ	14.5	±	2.0
ZZ	5.48	±	0.75
W+jets	40	±	10
$W\gamma$	13.2	±	4.0
Total Background	278	±	35
$gg \to H$	4.70	±	0.72
WH	0.661	±	0.086
ZH	0.244	±	0.032
VBF	0.381	±	0.061
Total Signal	5.98	±	0.78
Data	262		

OS 1 Jet



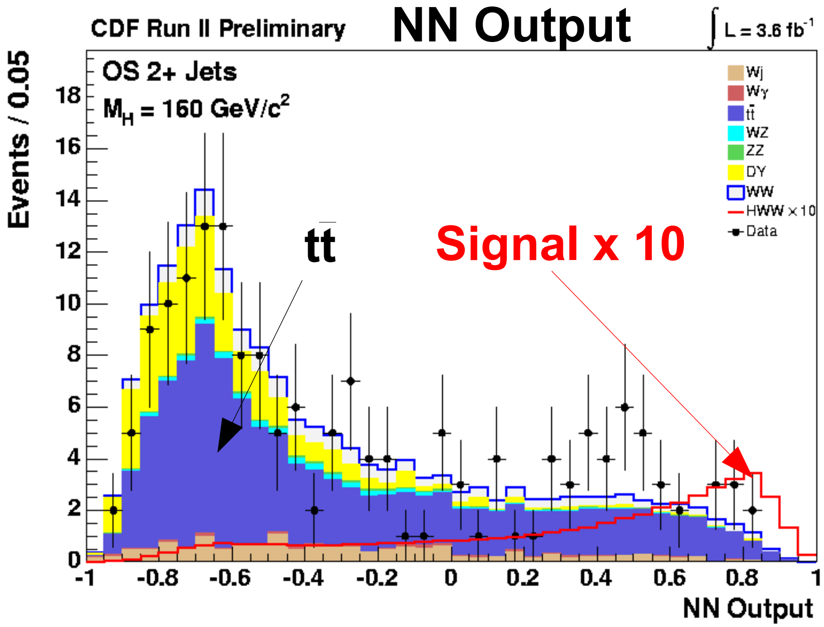
WW + 2 or more jets

- **Final states with 2 or more jets:**
  - (W/Z)H and VBF are 62% of the total signal
  - Veto identified b-jets to reduce $t\bar{t}$



CDF Run II Preliminary	$\int \mathcal{L} = 3.6\ \mathrm{fb}^{-1}$		
$M_H = 160$ 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
$gg \to H$	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	

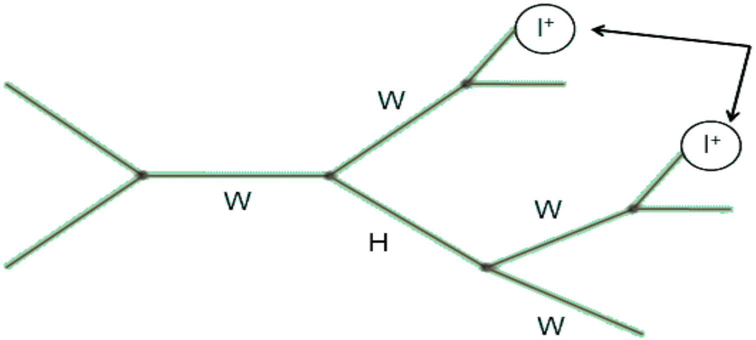
OS 2+ Jets



Same Sign: additional Higgs acceptance

To further increase Higgs acceptance, events with two same-sign leptons are separately analyzed

- **$WH \rightarrow WWW \rightarrow l^{\pm} l^{\pm} + X$ is the main signal contribution**



- **Dominant Backgrounds:**
  - Lepton charge misidentification
  - jets faking leptons
- **Analysis technique similar to Opposite Sign analysis**
  - Require at least 1 jet
  - Remove Missing E_T cut

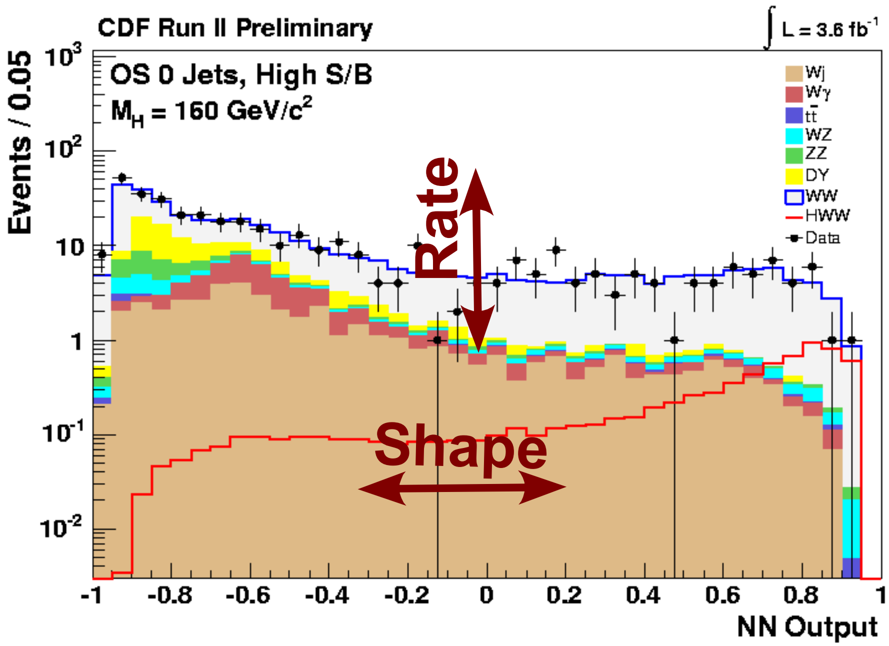
CDF Run II Preliminary $\int \mathcal{L} = 3.6\ \text{fb}^{-1}$

$M_H = 160\ \text{GeV}/c^2$			
$t\bar{t}$	0.11	±	0.03
DY	11.99	±	3.65
WW	0.020	±	0.005
WZ	6.82	±	0.93
ZZ	1.44	±	0.20
W+jets	22.45	±	6.73
$W\gamma$	3.23	±	1.00
Total Background	**46.07**	±	**8.02**
WH	1.19	±	0.16
ZH	0.19	±	0.02
Total Signal	**1.38**	±	**0.18**
Data		**41**	

SS 1+ Jets

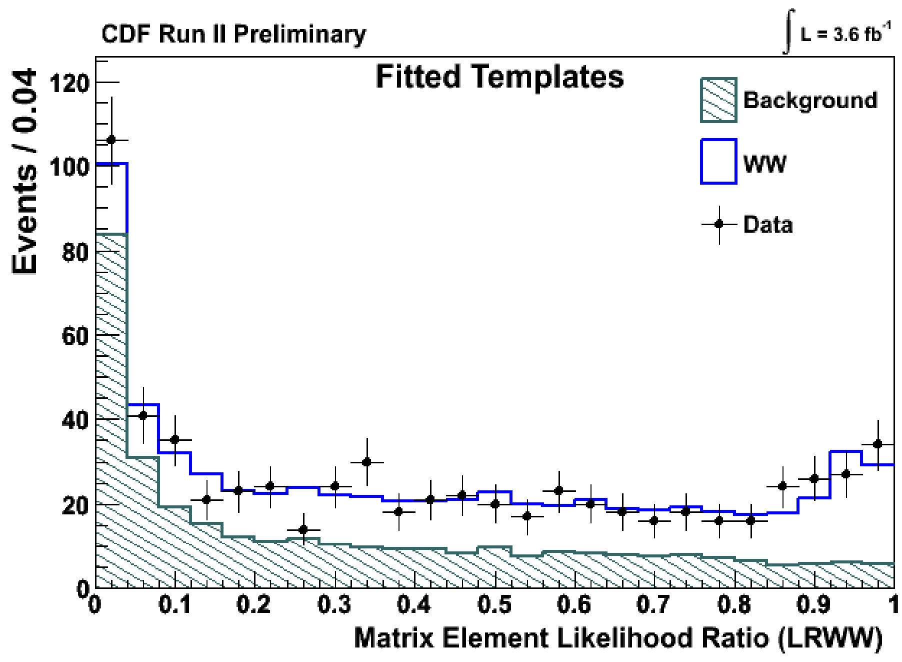
Systematics uncertainties

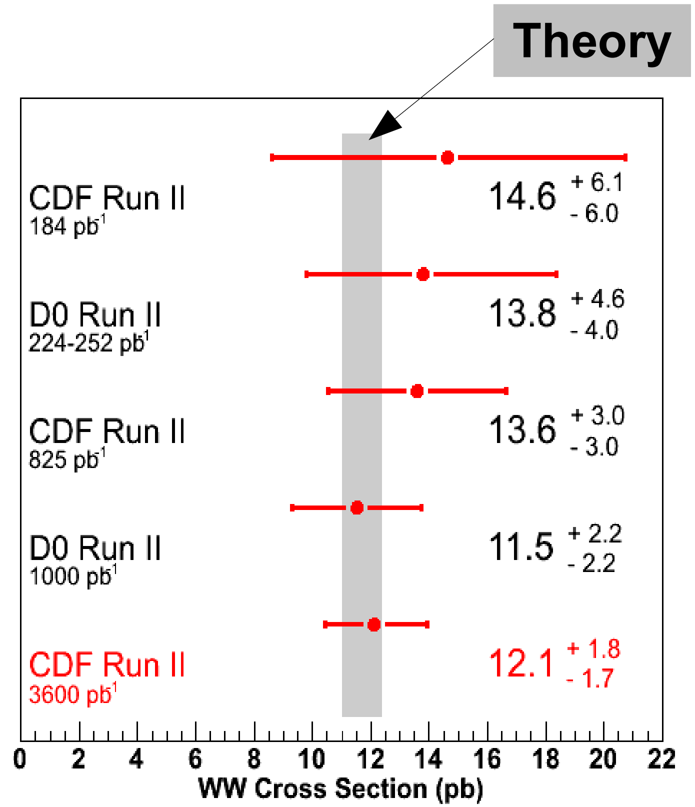
- **Two main classes of systematics uncertainties**
  - **Rate systematics**: Dominant. Affects normalization of NN output distribution. Major contributors are theoretical cross section errors.
  - **Shape systematics**: Found to be negligible up to now. Modify shape of NN output distribution. One example is Jet Energy Scale.



WW cross section measurement

- **Same data sample and same techniques used for Higgs search**





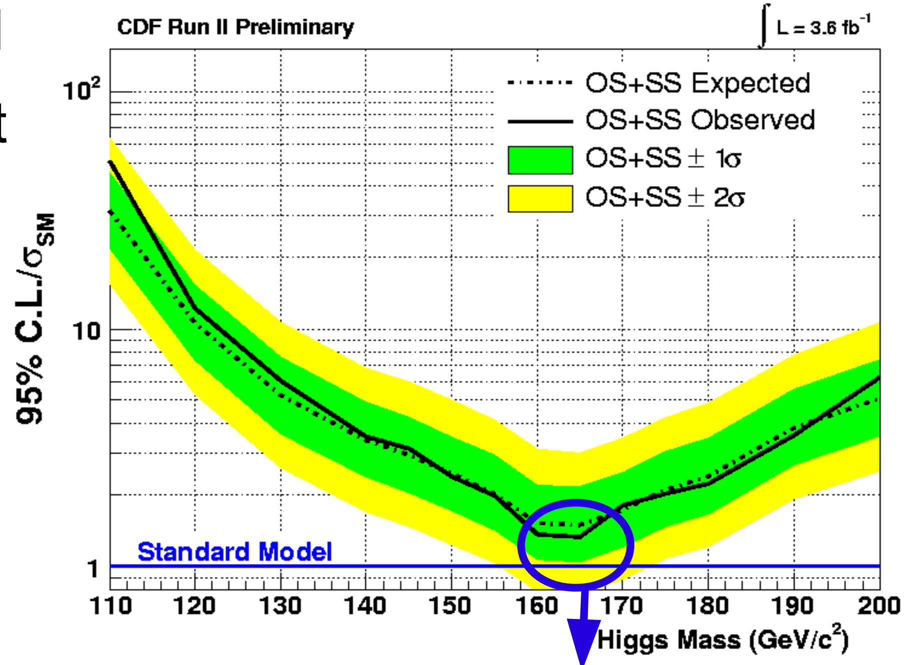
NEW

$$\sigma(p\bar{p}\rightarrow WW)=12.1^{+1.8}_{-1.7}\ pb$$

CDF Public Note 9753, PRL in progress

$H \rightarrow WW$ results

- **Use NN output distributions to calculate 95% CL upper limits in the 110 < m_H < 200 GeV/c^2 mass range**
  - using a pure Bayesian method
  - perform a counting experiment for each bin of the NN outputs
  - include systematics, accounts correlations among channels



m_H = 165 GeV	σ / σ_{SM}	
Channel	Expected Limits	Observed Limit
OS 0 Jets	2.4	2.4
OS 1 Jet	2.8	2.1
OS 2+ Jets	3.6	5.5
SS 1+Jets	7.6	5.4

M_H = 165 GeV/c^2

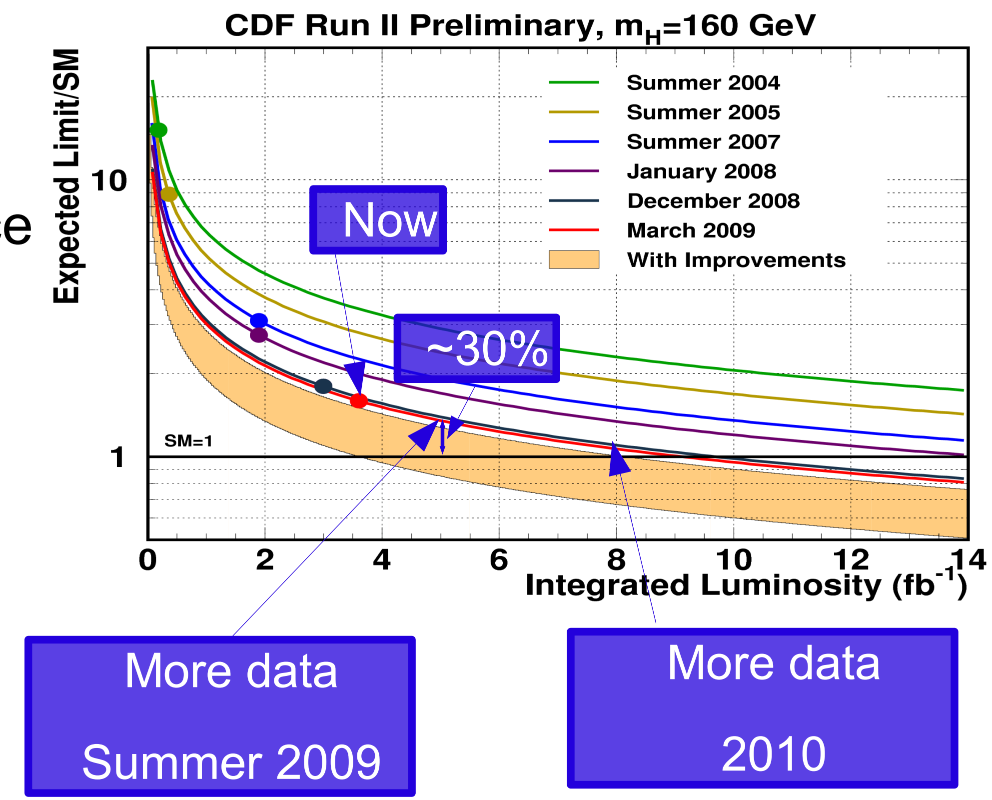
Observed Limit: 1.3 x σ_{SM}

Expected Limit: 1.5 x σ_{SM}

CDF approaching SM sensitivity!

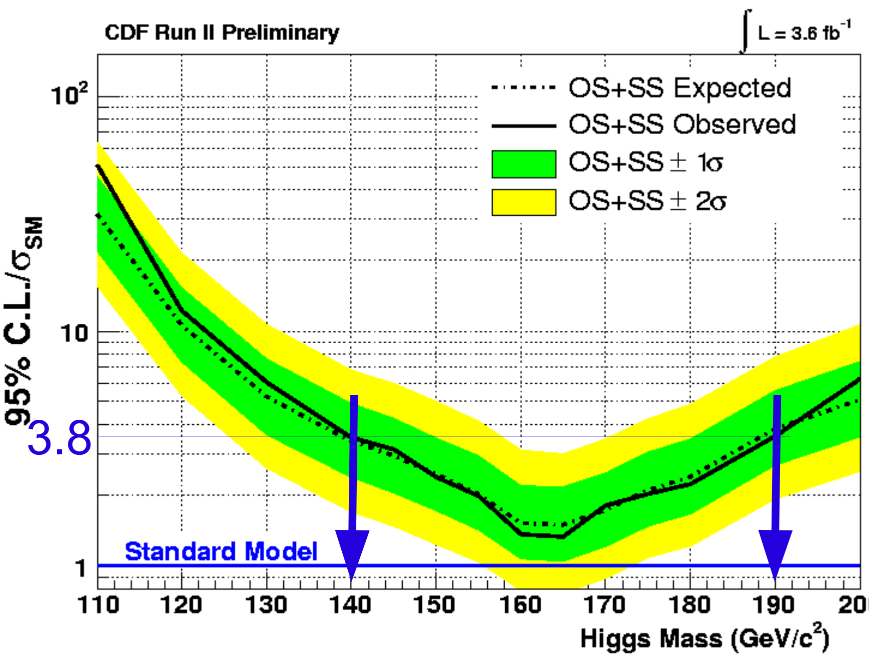
CDF Public Note 9764 – PRL in progress

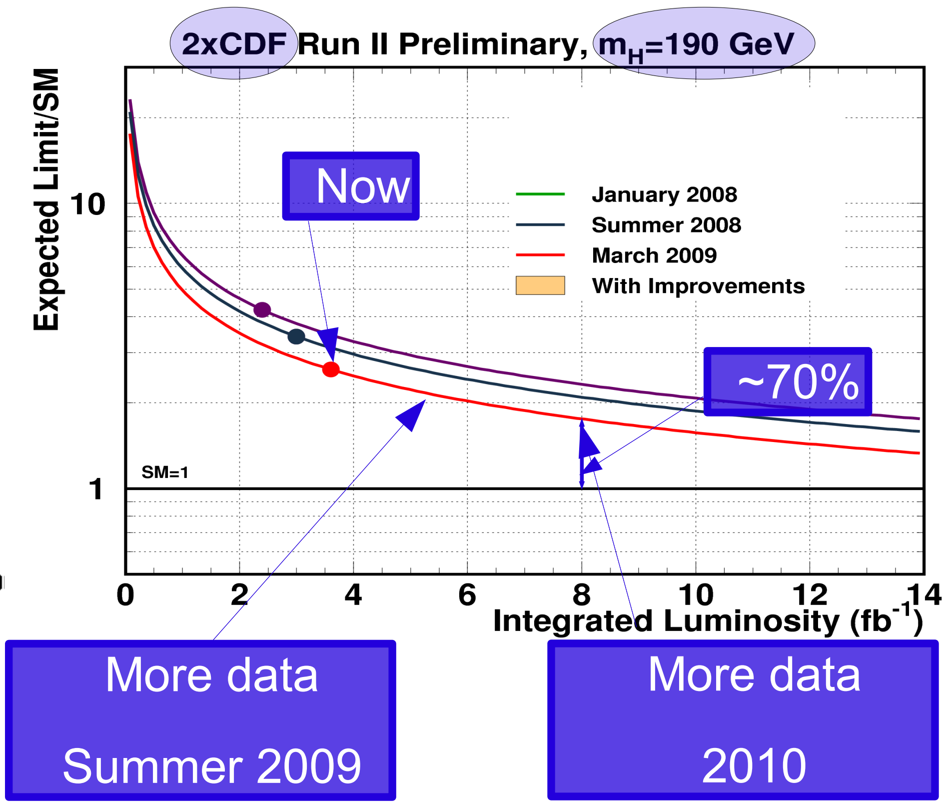
- **Ongoing improvements**
  - increase lepton acceptance
  - add new triggers
  - lowering Missing E_T requirements
  - adding 3 lepton events



- **Goal: reach single-experiment exclusion – short term**

Additional improvements





- **More challenging**
  - in combination with D0 need to improve 70%
  - H → ZZ could also be a viable resource
- **Goal: SM sensitivity combining with D0 – longer term**

Conclusions

- **H → WW has been proven to be an excellent way to search for an high mass Higgs boson at CDF**
  - Current limits are $1.3 \cdot \sigma_{SM}$ @ $m_H = 165$ GeV/c^2
- **Analysis is improving faster and faster**
  - rapid incorporation of new data
  - **sensitivity increasing faster than luminosity scaling**
- **Aim to reach single experiment SM sensitivity for a wide mass range**

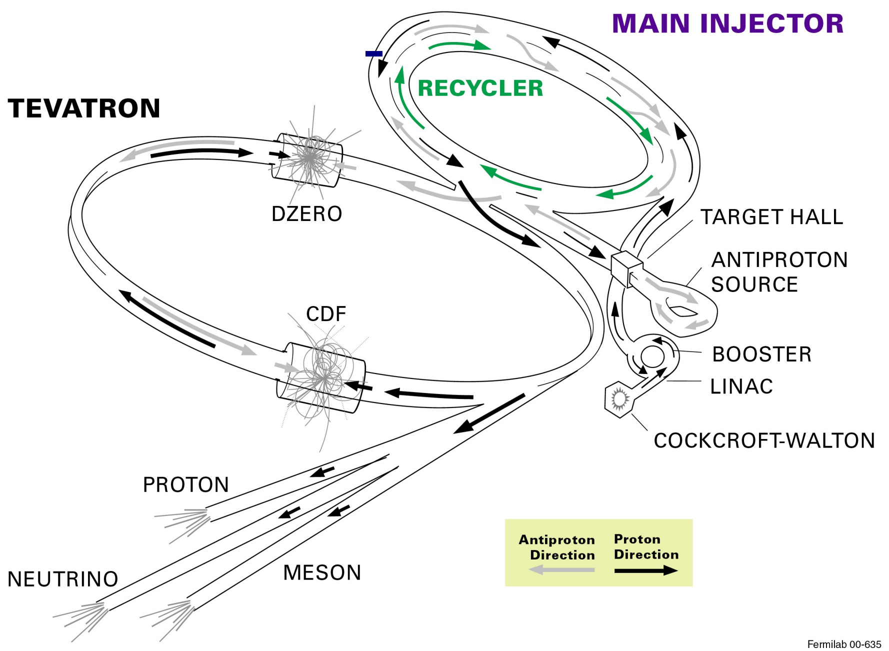
Backup

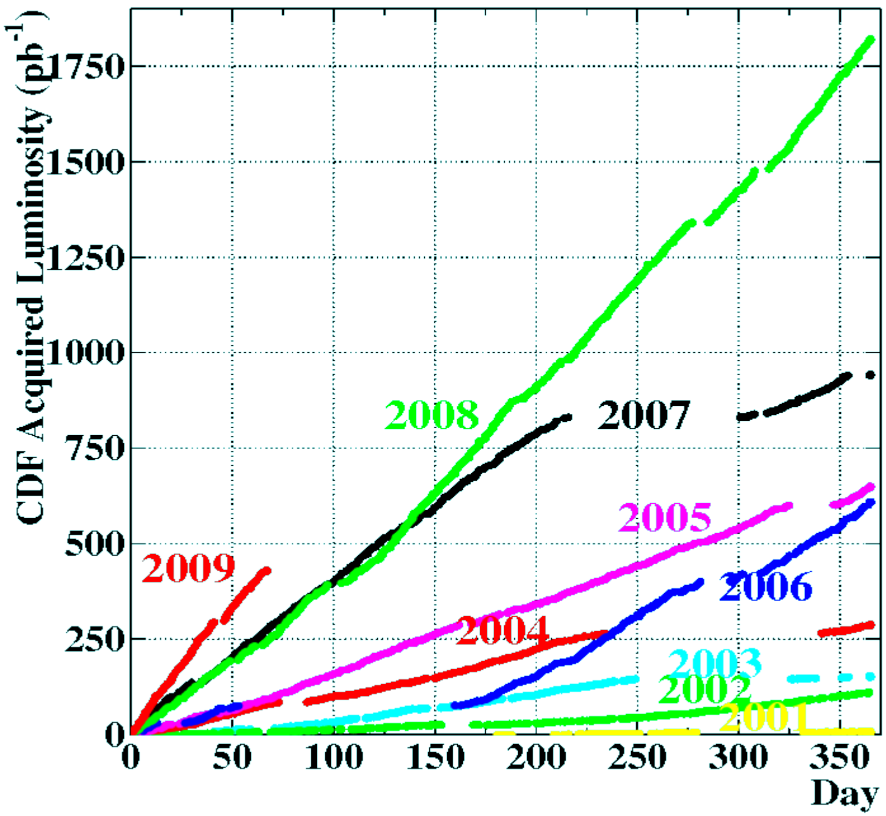
Backup index

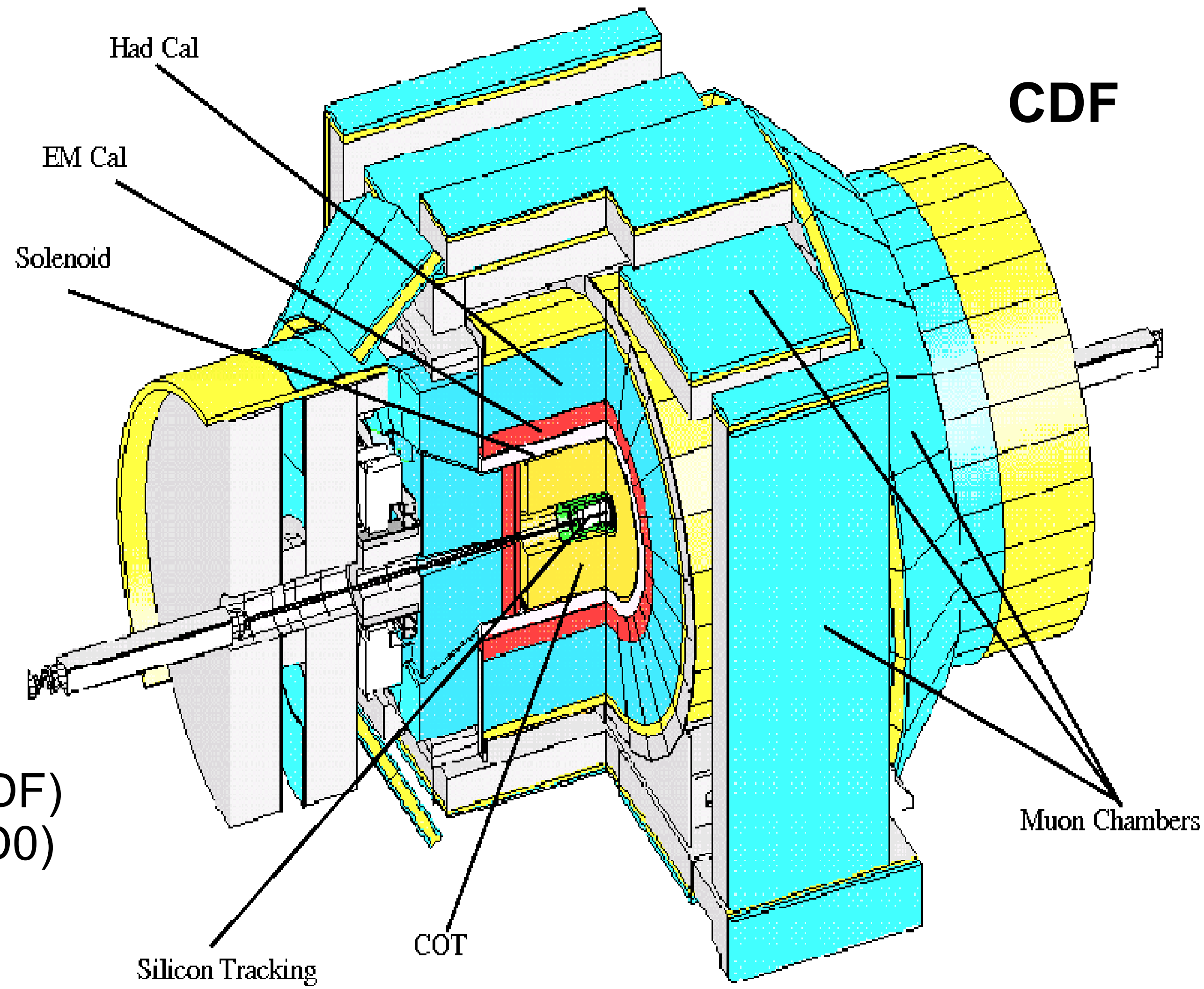
- **Tevatron**
- **CDF**
- **X-sec table and references**
- **Details for CDF H→WW analyses**
  - Systematic tables
  - Matrix Element calculation
  - CDF limits table
- **Improvements in plots**
- **Combination**
  - Bayesian approach - details
  - CDF combination results

Tevatron Performance

FERMILAB'S ACCELERATOR CHAIN

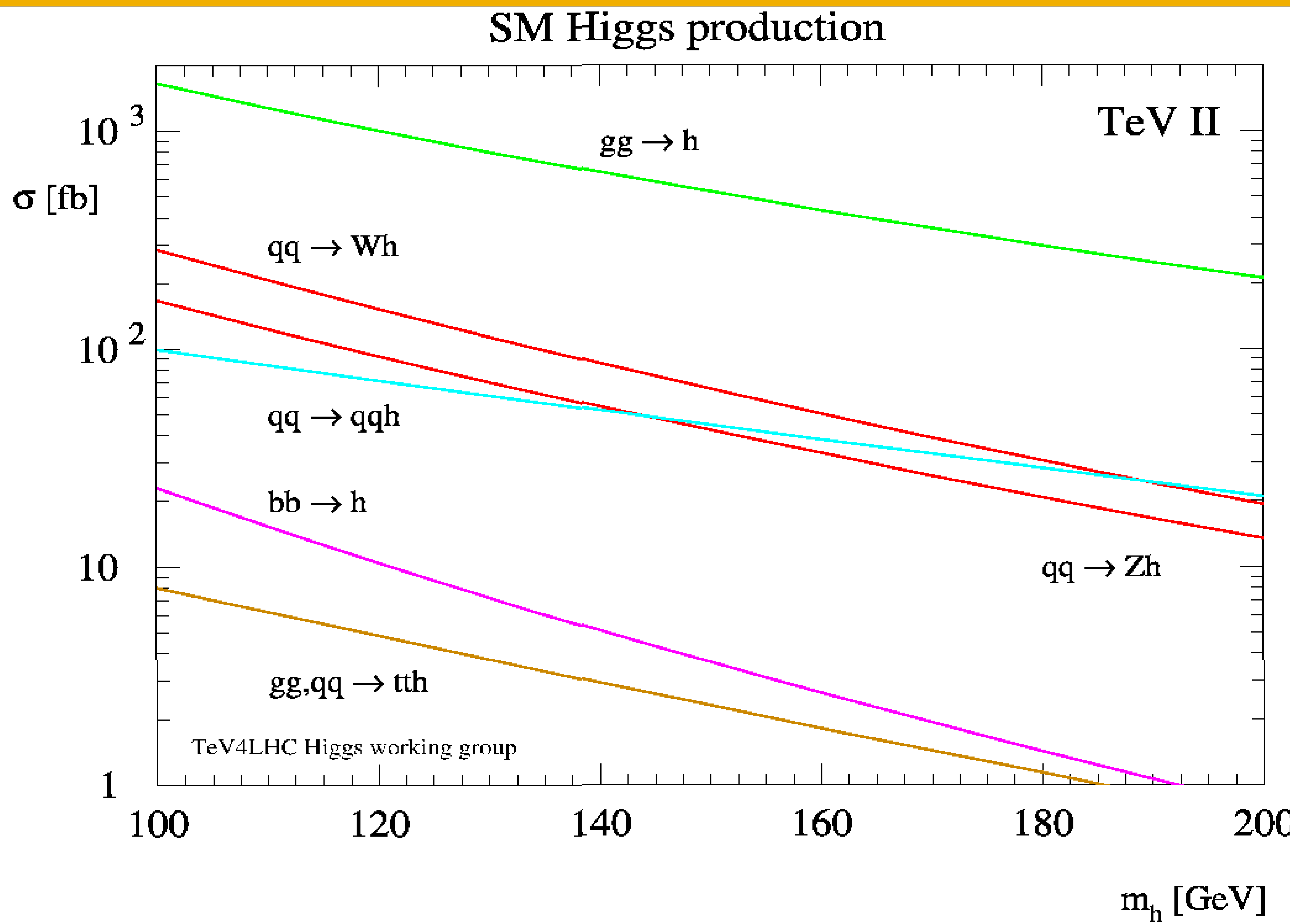






- Tracking:
  - Silicon detectors
  - drift chamber (CDF) or fiber tracker (D0)
- Calorimeter
- Muon detectors

Higgs Production at the Tevatron



Higgs production x-sections

- **New ggH signal x-sections by Florian at Grazzini (arXiv:0901.2427), Anastasiou *et al.* (*arXiv:0811.3458*)**
  - included NNLL σ(gg→H), latest MSTW2008 pdf, 2-loop ewk corrections, exact b-quark treatment @ NLO

M_H (GeV/c^2)	$\sigma_{gg\to H}$ (pb)	σ_{WH} (pb)	σ_{ZH} (pb)	σ_{VBF} (pb)	$\mathrm{Br}_{\mathrm{H}\to\mathrm{WW}}$
110	1.413	0.208	0.124	0.084	0.044
120	1.093	0.153	0.093	0.072	0.132
130	0.858	0.114	0.071	0.061	0.287
140	0.682	0.086	0.054	0.052	0.483
145	0.611	0.075	0.048	0.048	0.573
150	0.548	0.065	0.042	0.045	0.682
155	0.492	0.057	0.037	0.041	0.801
160	0.439	0.051	0.033	0.038	0.901
165	0.389	0.044	0.029	0.035	0.957
170	0.349	0.039	0.026	0.033	0.965
175	0.314	0.034	0.023	0.031	0.951
180	0.283	0.031	0.021	0.028	0.935
190	0.231	0.024	0.017	0.024	0.776
200	0.192	0.019	0.014	0.021	0.735

CDF Analysis: Systematcs (1J)

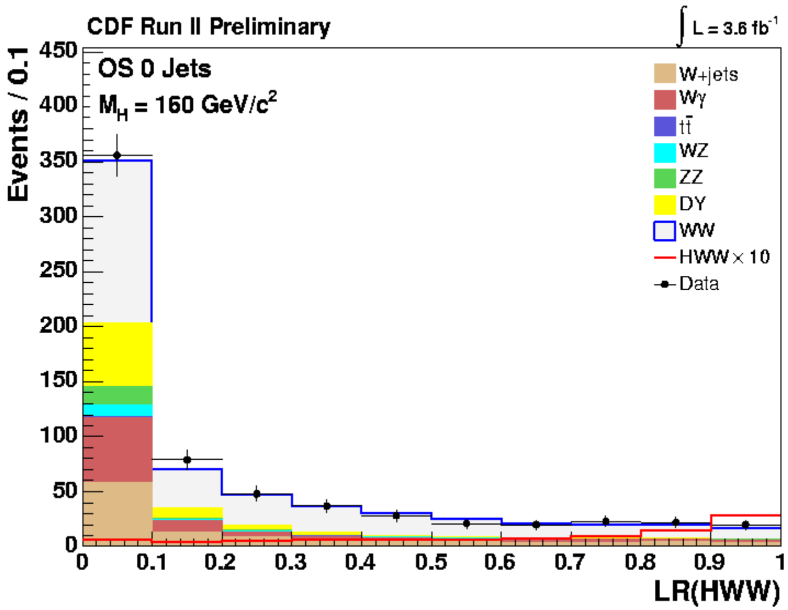
Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet
Cross Section							
Scale							
PDF Model							
Total	6.0%	6.0%	6.0%	10.0%	5.0%	10.0%	
Acceptance							
Scale							
PDF Model	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%	
Higher-order Diagrams	5.0%	10.0%	10.0%	10.0%		10.0%	
Jet Modeling	-1.0%				30.0%	15.0%	
Conversion Modeling						20.0%	
Jet Fake Rates							
(Low S/B)							22.2%
(High S/B)							31.5%
MC Run Dependence	1.9%			1.0%		2.4%	
Lepton ID Efficiencies	2.0%	2.0%	2.2%	1.8%	2.0%	2.0%	
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%	7.0%	
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%	5.9%	

Uncertainty Source	$gg \to H$	WH	ZH	VBF
Cross Section				
Scale	10.9%			
PDF Model	5.1%			
Total	12.0%	5.0%	5.0%	10.0%
Acceptance				
Scale (leptons)	2.8%			
Scale (jets)	-5.1%			
PDF Model (leptons)	1.7%	1.2%	0.9%	2.2%
PDF Model (jets)	-1.9%			
EWK Higher-order Diagrams		10.0%	10.0%	10.0%
Lepton ID Efficiencies	1.9%	1.9%	1.9%	1.9%
Trigger Efficiencies	3.3%	2.1%	2.1%	3.3%
Luminosity	5.9%	5.9%	5.9%	5.9%

Matrix Elements at CDF (0J only)

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

$\vec{x}_{obs}$	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

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

CDF Limits

- **New x-sec: OS+SS**

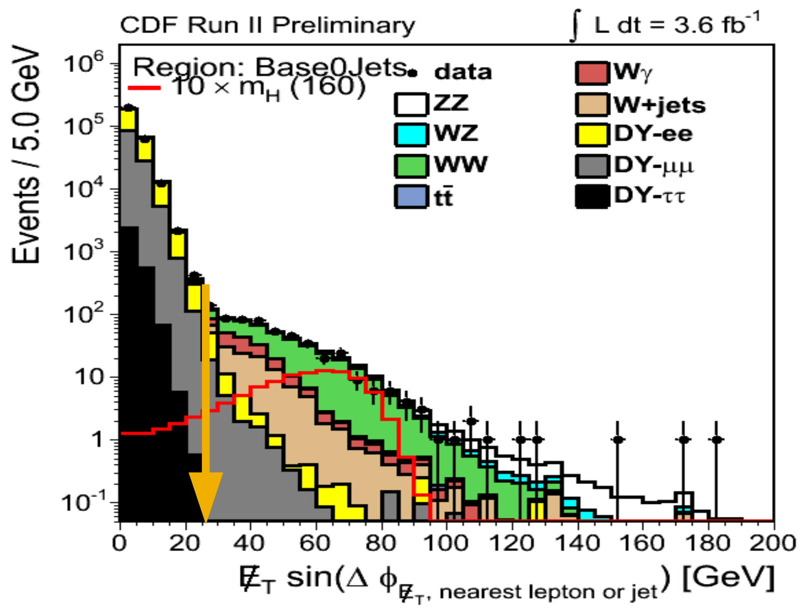
OS+SS	110	120	130	140	145	150	155	160	165	170	175	180	190	200
$-2\sigma/\sigma_{SM}$	15.48	5.31	2.60	1.69	1.47	1.23	1.04	0.79	0.77	0.88	1.08	1.21	1.92	2.52
$-1\sigma/\sigma_{SM}$	21.85	7.39	3.61	2.38	2.04	1.72	1.42	1.07	1.05	1.21	1.47	1.66	2.68	3.54
Median/$\sigma_{\mathbf{SM}}$	**31.48**	**10.62**	**5.26**	**3.40**	**2.94**	**2.46**	**2.02**	**1.52**	**1.50**	**1.73**	**2.10**	**2.40**	**3.84**	**5.11**
$+1\sigma/\sigma_{SM}$	45.61	15.32	7.61	4.92	4.26	3.51	2.95	2.19	2.18	2.49	3.05	3.47	5.59	7.43
$+2\sigma/\sigma_{SM}$	63.79	21.54	10.71	6.82	6.01	5.02	4.14	3.12	3.00	3.49	4.24	4.88	7.78	10.66
Observed/$\sigma_{\mathbf{SM}}$	**51.05**	**12.22**	**6.06**	**3.52**	**3.14**	**2.39**	**1.99**	**1.37**	**1.33**	**1.81**	**2.02**	**2.23**	**3.56**	**6.24**

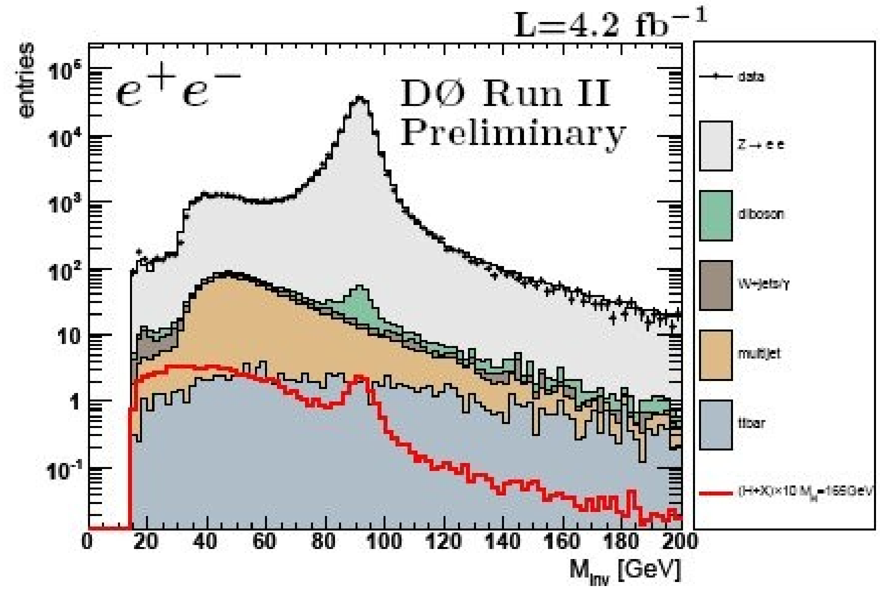
- **ICHEP x-sec: OS+SS**

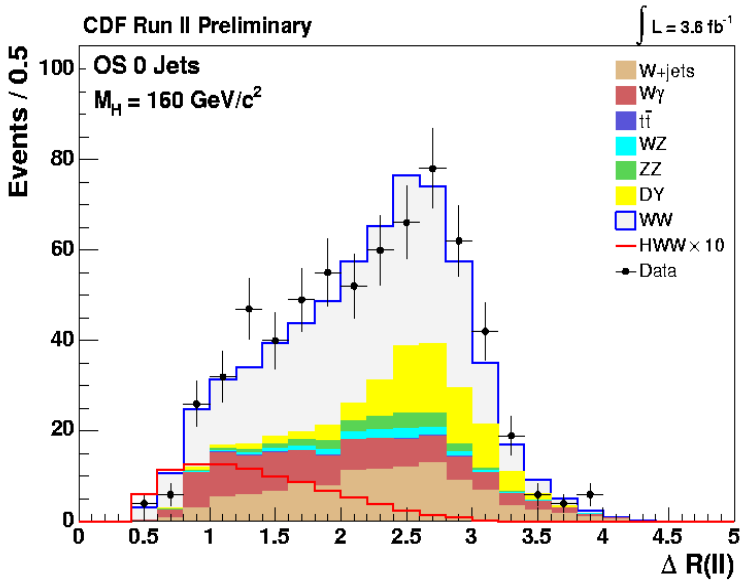
OS+SS	110	120	130	140	145	150	155	160	165	170	175	180	190	200
$-2\sigma/\sigma_{SM}$	16.26	5.45	2.62	1.71	1.44	1.23	1.00	0.75	0.74	0.85	1.00	1.17	1.82	2.39
$-1\sigma/\sigma_{SM}$	22.78	7.43	3.69	2.35	2.01	1.71	1.38	1.03	1.02	1.16	1.39	1.60	2.53	3.36
Median/$\sigma_{\mathbf{SM}}$	**32.40**	**10.79**	**5.31**	**3.36**	**2.92**	**2.44**	**1.97**	**1.47**	**1.45**	**1.66**	**2.00**	**2.31**	**3.65**	**4.89**
$+1\sigma/\sigma_{SM}$	47.08	15.64	7.66	4.86	4.20	3.52	2.87	2.14	2.08	2.38	2.88	3.36	5.33	7.11
$+2\sigma/\sigma_{SM}$	66.21	21.71	10.63	6.91	5.89	4.96	4.03	2.96	2.95	3.36	4.09	4.76	7.49	10.08
Observed/$\sigma_{\mathbf{SM}}$	**52.20**	**12.58**	**5.88**	**3.56**	**3.11**	**2.31**	**1.91**	**1.37**	**1.29**	**1.67**	**2.01**	**2.03**	**3.59**	**5.94**

  - New pdf MSTW 2008
  - Better treatment of b-quark
  - 2-loop ewk corrections and NNLL x-sec already incuded

Improvements in Plots







- **Lower Missing E_T**
- **Lower m(ll)**
- **Lepton isolation**
- **Tri-lepton events**
- **Improve lepton acceptance/purity (and add new triggers)**

- **CDF and D0 combination: Bayesian method**

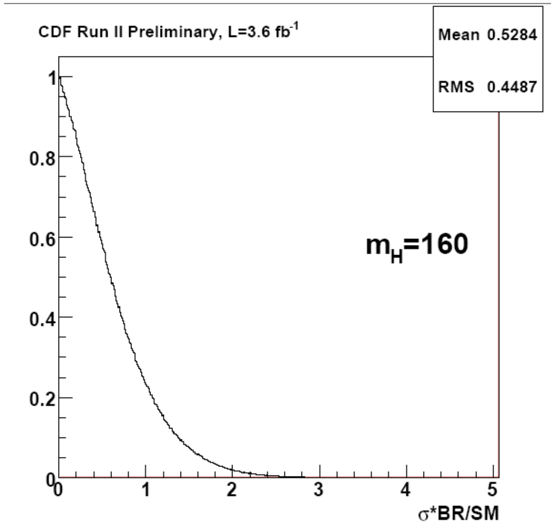
$$\mathcal{L}(R) \times \pi(\vec{\theta}) = \prod_{i=1}^{N_C \cdot Nbins} \mu_i^{n_i} e^{-\mu_i}/n_i! \times \prod_{k=1}^{n_{NP}} e^{-\theta_k^2/2}$$

$$\mu_i = R \times s_i(\vec{\theta}) + b_i(\vec{\theta}) = \text{expected events}$$

$$R = \text{Signal in } \sigma_{SM} \text{ units}$$

$$n_i = \text{“observed” events}$$

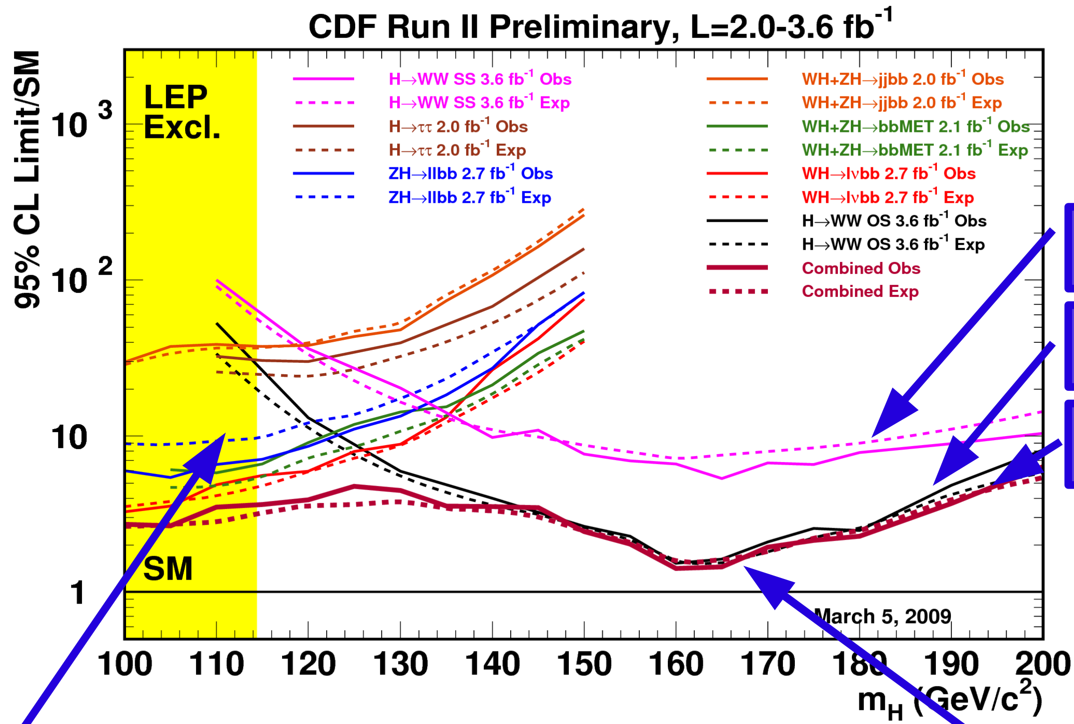
$$\vec{\theta} = \text{Nuisance parameters}$$



Extract 95% CL limits on R integrating out nuisance parameters

- ***It's not just a √2 factor: correlate systematics among experiments***

CDF Combination on Higgs searches



Same sign

Opposite sign

Combination

Low mass searches:

lots of analyses contributing

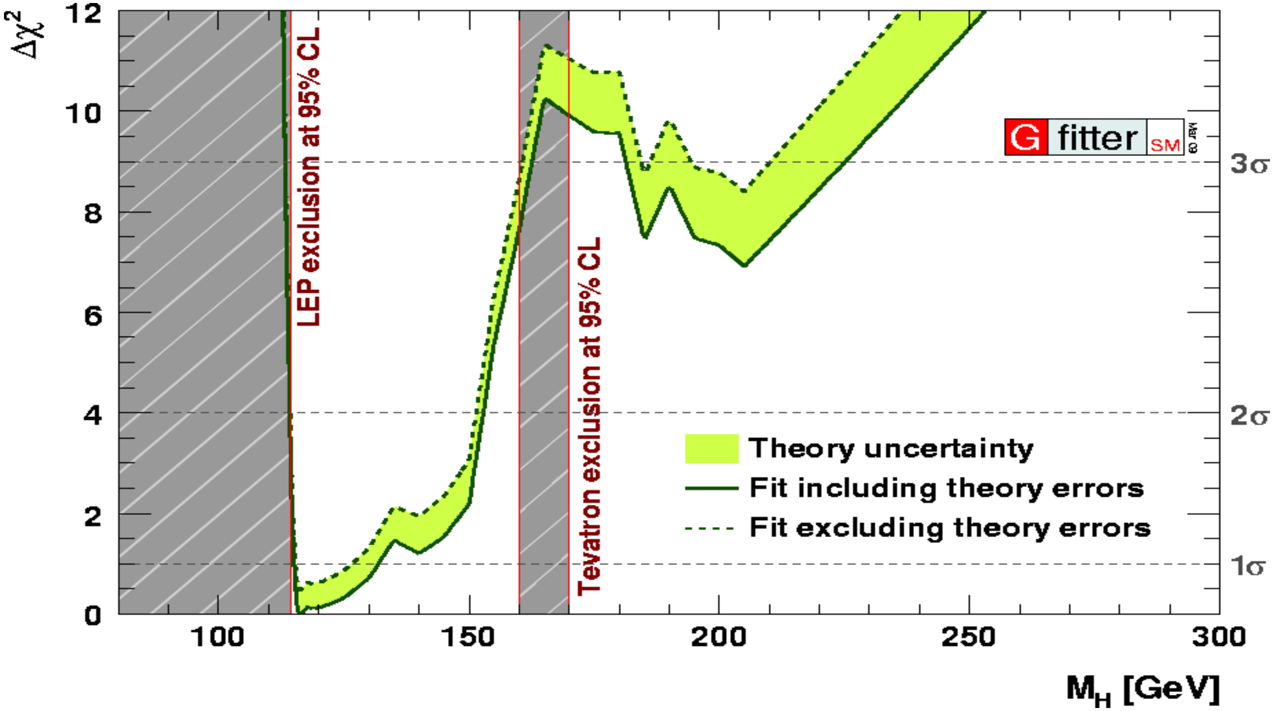
High mass searches:

$H \rightarrow WW$ dominates

http://www-cdf.fnal.gov/physics/new/hdg/results/combcdf_mar09/

Cornering the Higgs

- **Combining with D0 colleagues we achieved the first SM Higgs boson exclusion above LEP limits (see Wade's talk)**



- **Considering also indirect constraints from EWK precision measurements**