Searches for an high mass Higgs boson and Higgs searches combination

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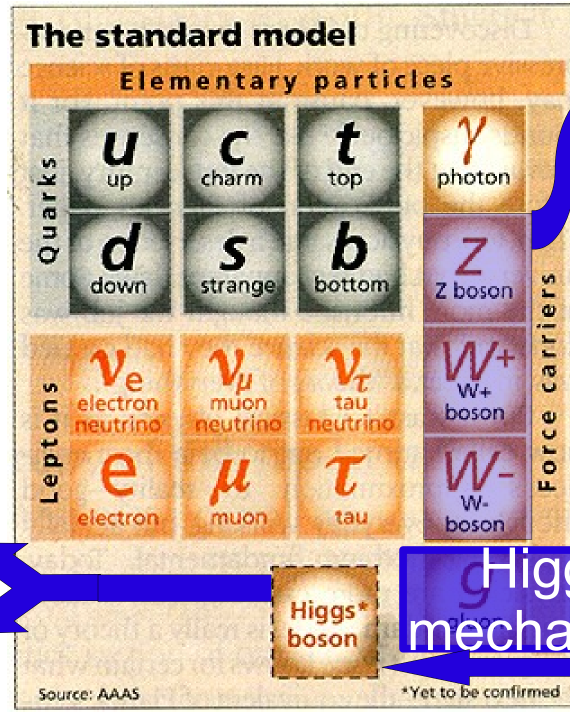
The Higgs mechanism

SM unifies weak and electro-magnetic interactions

its mass is a free parameter

existence yet to be confirmed



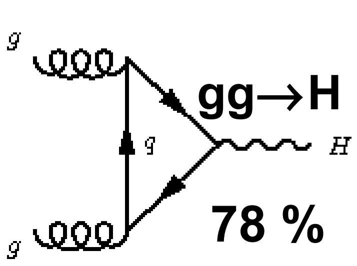
Experimentally: massiveness of weak field carriers

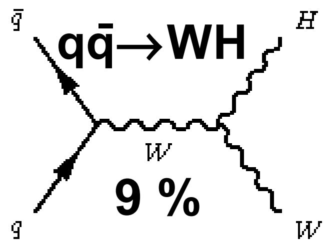
EWK symmetry breaking

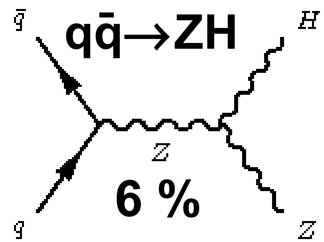
Higgs mechanism

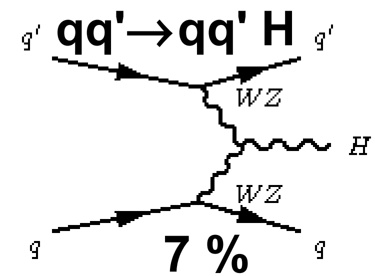
- **Explaining the EW symmetry breaking is a major goal for particle physics nowadays, and Tevatron can probe it!**
- **Finding the Higgs boson → a good proof that this mechanism is the one that nature chose**

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



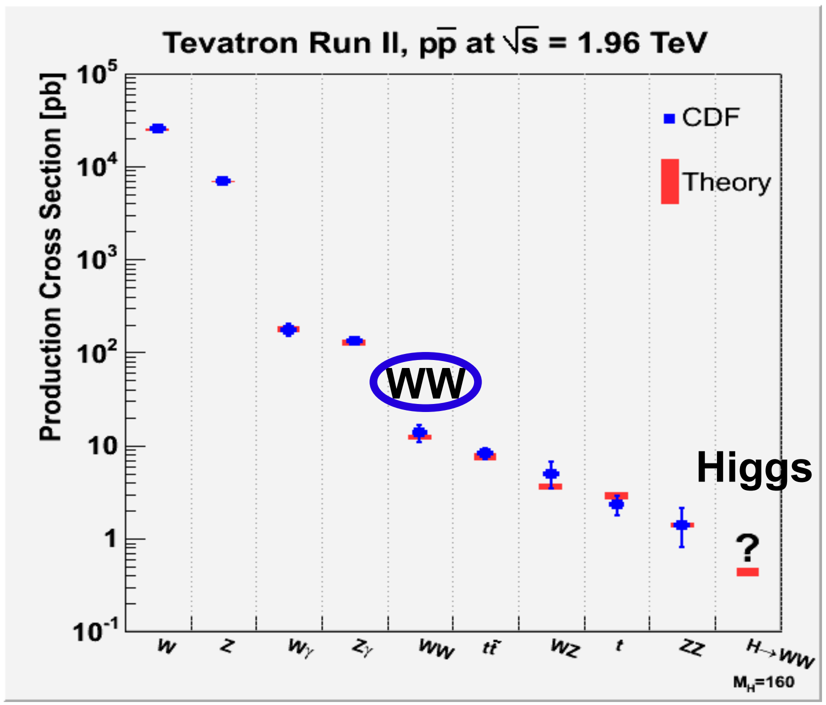




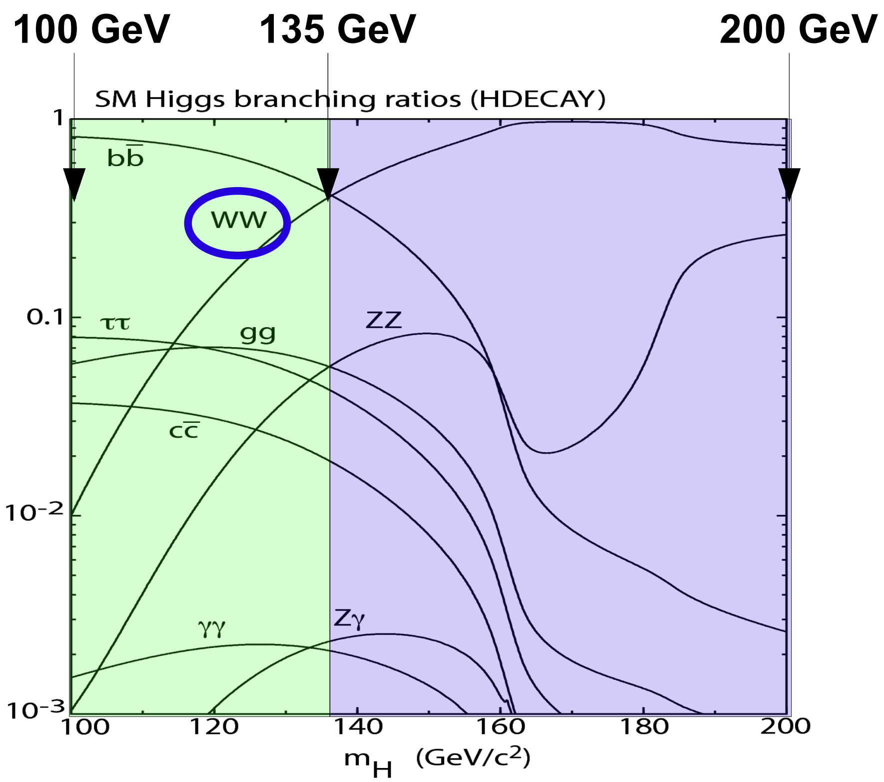


- **As sensitivity increases all of them become important!**
- **Lots of measurements down to ~pb processes**

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

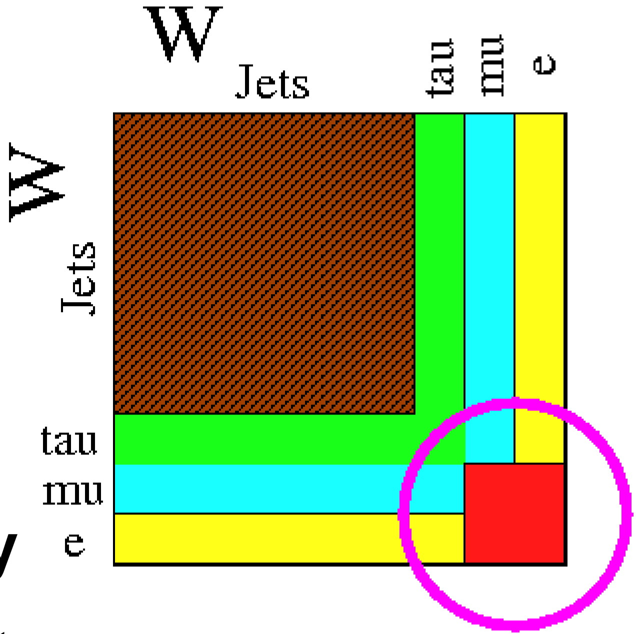


- **For m_H > 135 GeV/c² H → WW dominant**
  - This is how we define high mass Higgs searches at Tevatron
  - Still contributes significantly to Higgs searches down to 120 GeV/c²



Final state: H → WW → lνlν

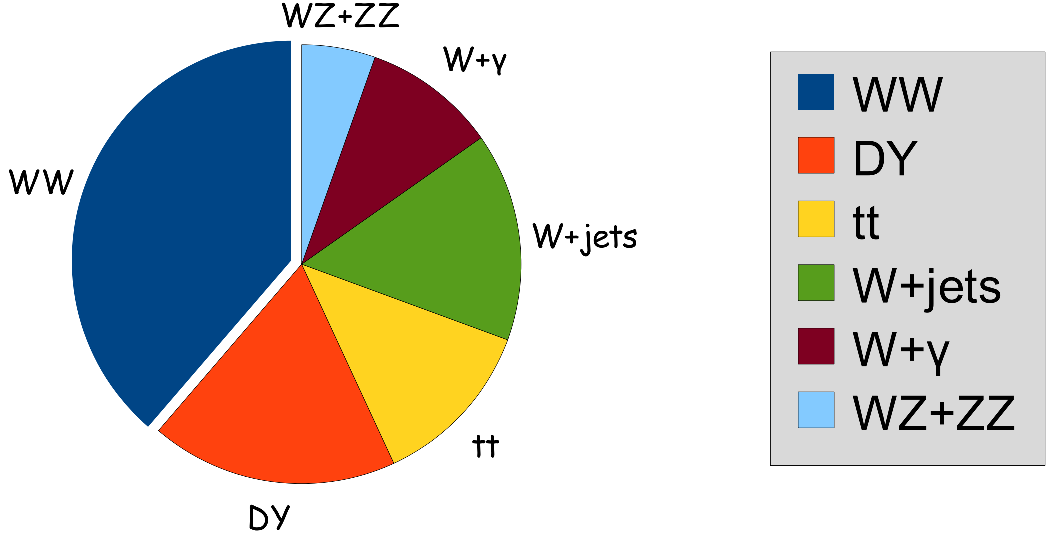
- **W decays**
  - BR(W→l ν) ~ 32%
  - BR(W→hadrons) ~ 68%
- **Hadronic modes have large QCD background: not used.**
- **We select both W decaying leptonically**



  - 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

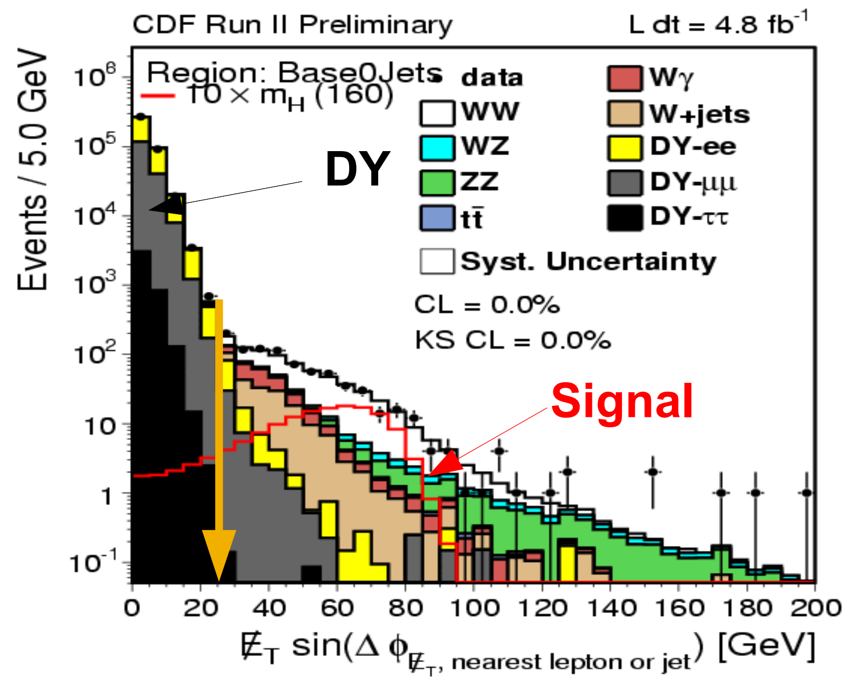
- **Main background contributions**



- **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

Event selection

- **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 2[rd] lepton
  - Significant Missing E_T
    - reject Drell-Yan events
  - m(ll) > 16 GeV/c²
    - reject heavy flavor decays



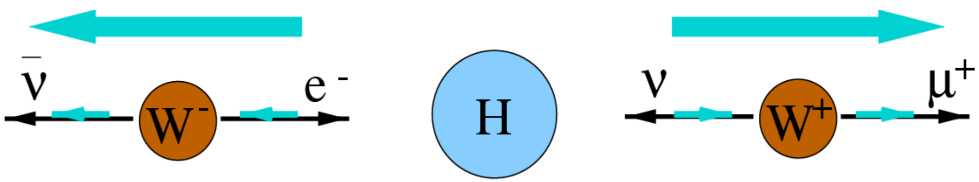
CDF RunII Preliminary $\int \mathcal{L} = 4.8\ \text{fb}^{-1}$, $M_H = 165$ GeV

$\mathcal{L}$ (fb^{-1})	Signal	Background	$S/\sqrt{B}$	Data
4.8	27.2 ± 4.9	1550 ± 130	0.69	1567

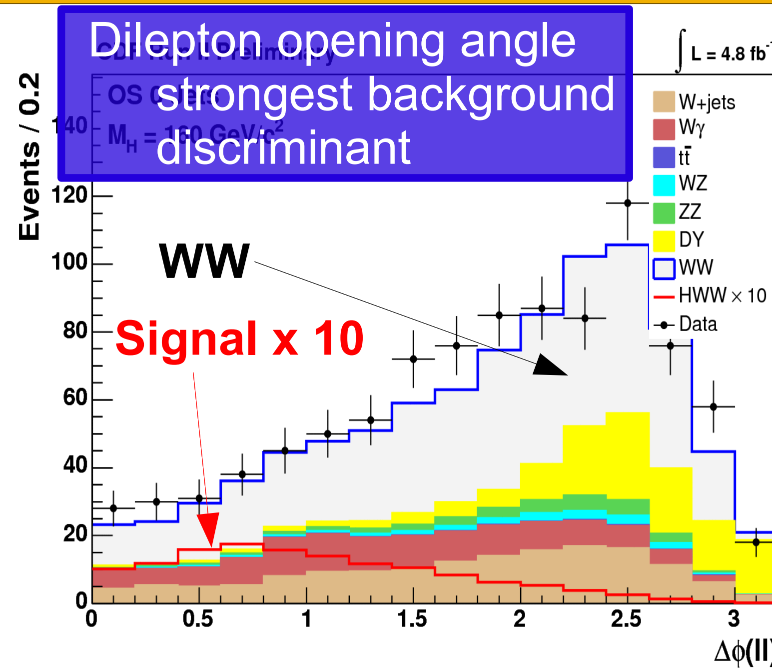
- **A simple counting experiment is not enough..**

Improving S/√B

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



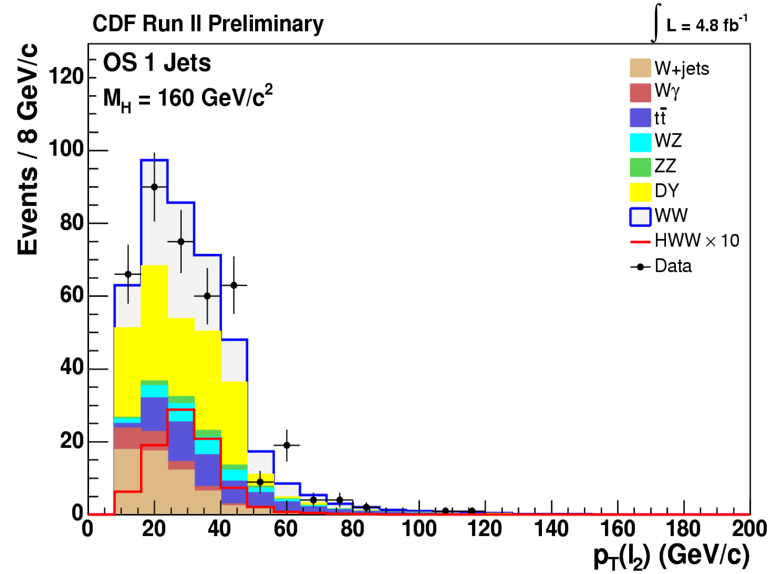
Spin correlation:
Leptons go in the same direction



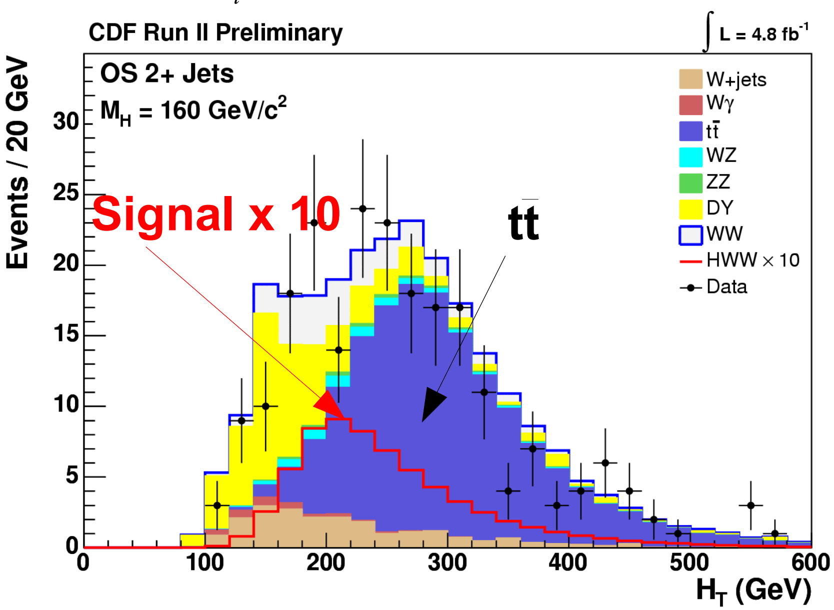
- **Use multivariate techniques (Neural Networks) to separate signal and background**
  - one NN for each Higgs mass hypothesis to probe
  - Divide the analysis in different channels by jet (E_T > 15 GeV, $|\eta|$ < 2.5) multiplicity: **0,1,2+ Jets**
  - optimize Neural Network inputs for each channel

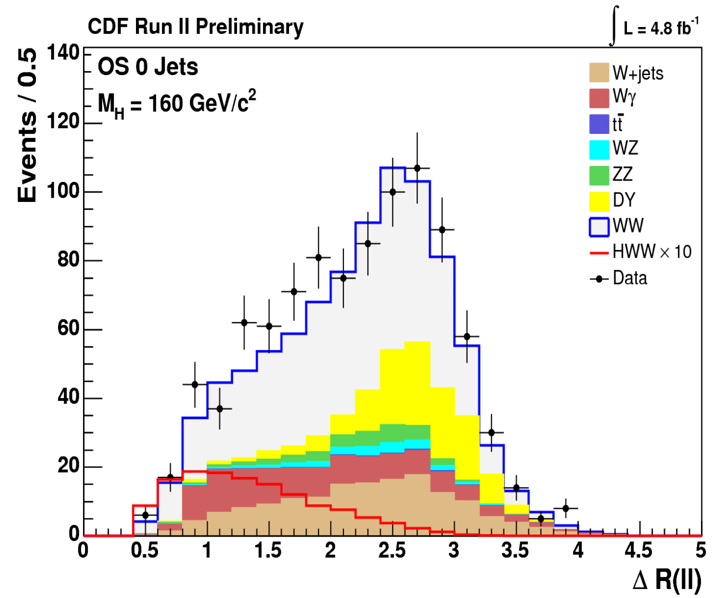
Neural Network inputs

- **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, ...)



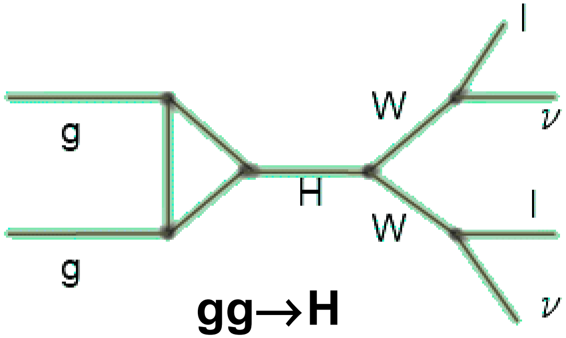
$$H_T = \sum_i |E_T(l_i)| + |E_T(jet_i)| + |\not{E}_T|$$





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

- **Signal from gluon fusion**



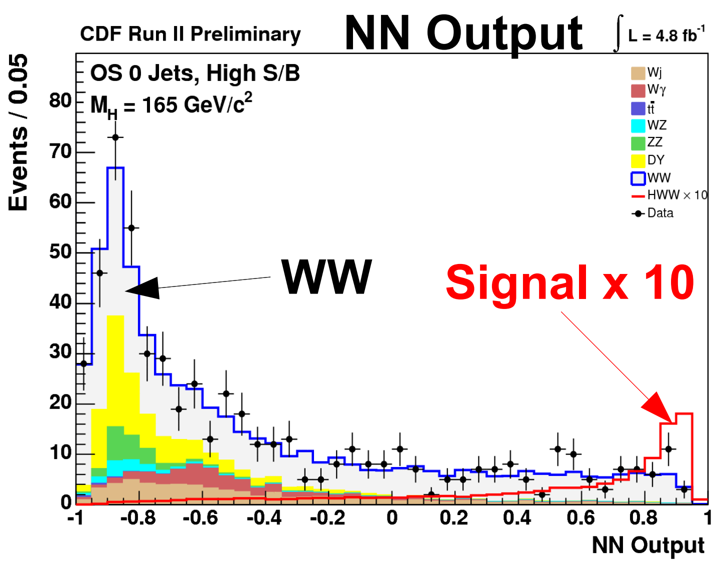
- **Main background: WW**

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

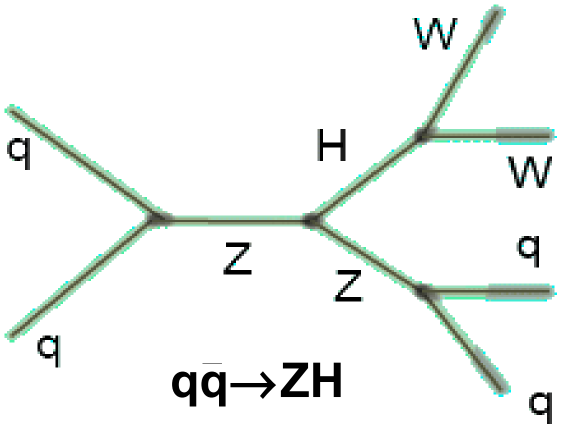
CDF Run II Preliminary $\int \mathcal{L} = 4.8\ \text{fb}^{-1}$

$M_H = 165\ \text{GeV}/c^2$			
$t\bar{t}$	1.99	±	0.31
DY	128	±	30
WW	447	±	48
WZ	19.7	±	2.7
ZZ	29.9	±	4.1
W+jets	154	±	37
$W\gamma$	112	±	19
Total Background	893	±	79
$gg \to H$	12.6	±	1.7
Total Signal	12.6	±	1.7
Data	950		

OS 0 Jets



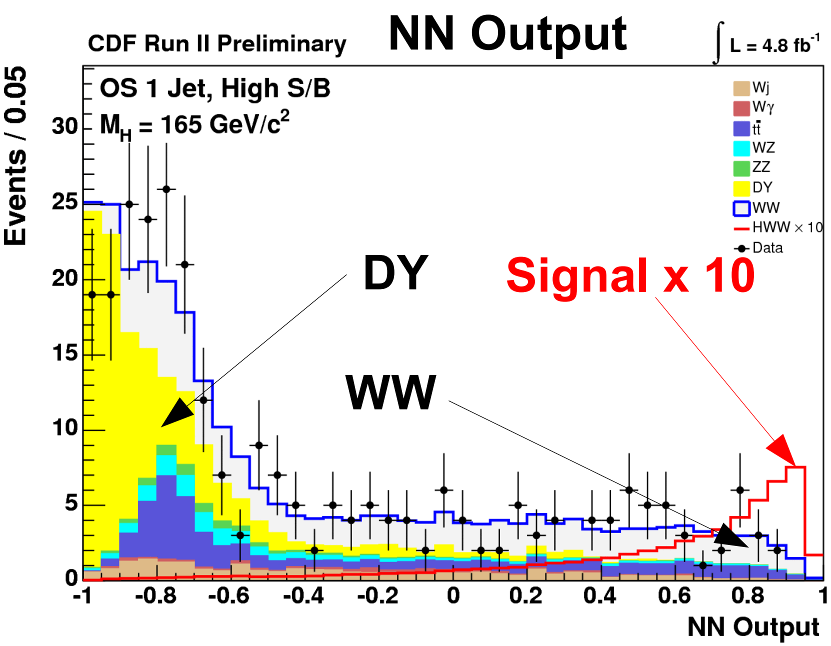
- **Final states with 1 jet**
  - 22% of the signal from (W/Z)H and Vector Boson Fusion (VBF)
  - WW still a dominant background



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

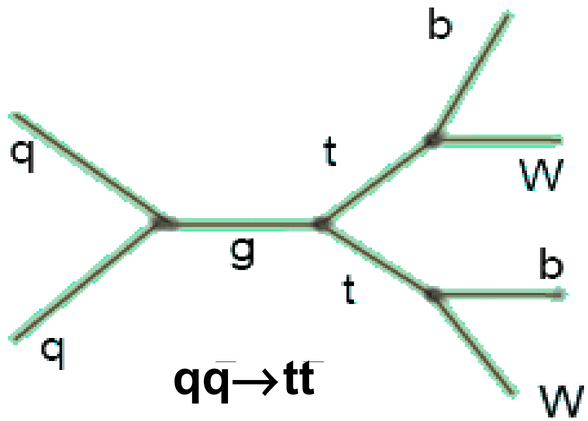
$M_H = 165\ \mathrm{GeV}/c^2$			
$t\bar{t}$	48.4	±	7.6
DY	133	±	42
WW	121	±	13
WZ	20.0	±	2.7
ZZ	8.0	±	1.1
W+jets	59	±	15
$W\gamma$	16.2	±	3.6
Total Background	406	±	52
$gg \rightarrow H$	6.4	±	1.7
WH	0.87	±	0.11
ZH	0.339	±	0.044
VBF	0.565	±	0.090
Total Signal	8.2	±	1.7
Data	393		

OS 1 Jet



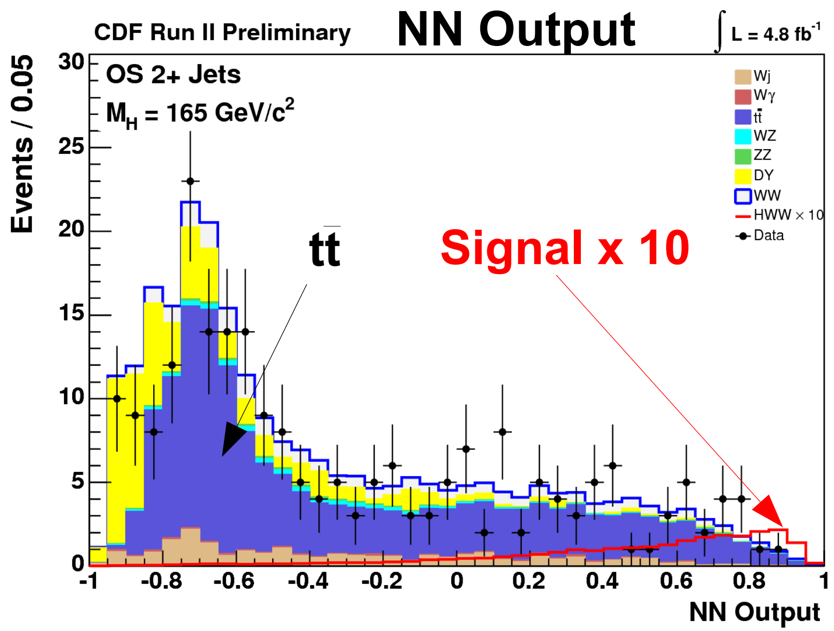
WW + 2 or more jets

- **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	$\int \mathcal{L} = 4.8$ fb^{-1}		
$M_H = 165$ GeV$/c^2$			
$t\bar{t}$	145	±	24
DY	51	±	17
WW	25.6	±	5.8
WZ	5.30	±	0.73
ZZ	2.36	±	0.32
W+jets	21.9	±	5.9
$W\gamma$	2.72	±	0.67
Total Background	254	±	33
$gg \to H$	2.5	±	1.7
WH	1.90	±	0.25
ZH	0.99	±	0.13
VBF	1.04	±	0.17
Total Signal	6.4	±	1.8
Data	224		

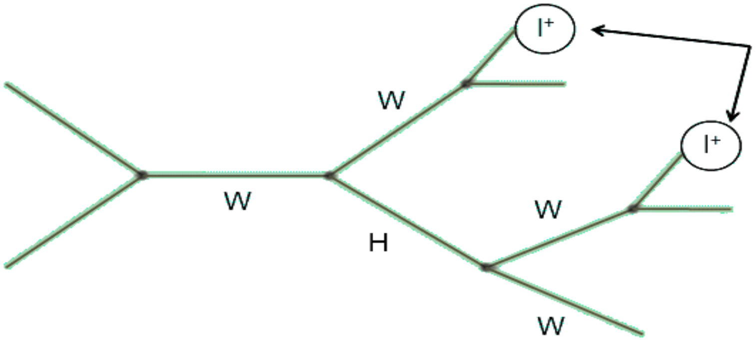
OS 2+ Jets



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 $\int \mathcal{L} = 4.8\ \text{fb}^{-1}$

$M_H = 165\ \text{GeV}/c^2$			
$t\bar{t}$	0.242	±	0.068
DY	26.7	±	8.1
WW	0.039	±	0.010
WZ	9.5	±	1.3
ZZ	1.98	±	0.27
W+jets	34	±	10
$W\gamma$	4.34	±	0.99
Total Background	76	±	13
WH	1.61	±	0.21
ZH	0.261	±	0.034
Total Signal	1.87	±	0.24
Data		81	

SS 1+ Jets

Even more: lowering m(ll) selection

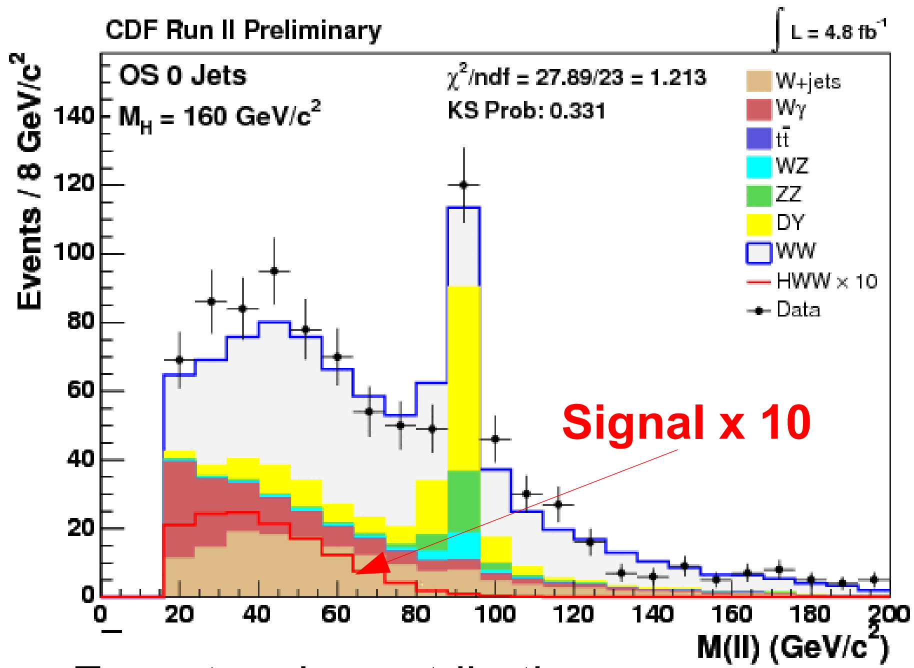
NEW

- **Exploit the still significant signal with m(ll) < 16 GeV**
  - OS leptons, missing E_T
- **Dominant background: W+γ**
  - SS leptons: W+γ control region used to normalize its rate prediction (reduce systematics)

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

$M_H = 165\ \text{GeV}/c^2$			
$t\bar{t}$	0.330	$\pm$	0.052
DY	3.56	$\pm$	0.85
WW	10.9	$\pm$	1.3
WZ	0.284	$\pm$	0.041
ZZ	0.107	$\pm$	0.015
W+jets	9.9	$\pm$	2.4
$W\gamma$	55.9	$\pm$	6.7
Total Background	80.9	$\pm$	7.3
$gg \to H$	0.75	$\pm$	0.12
Total Signal	0.75	$\pm$	0.12
Data		85	

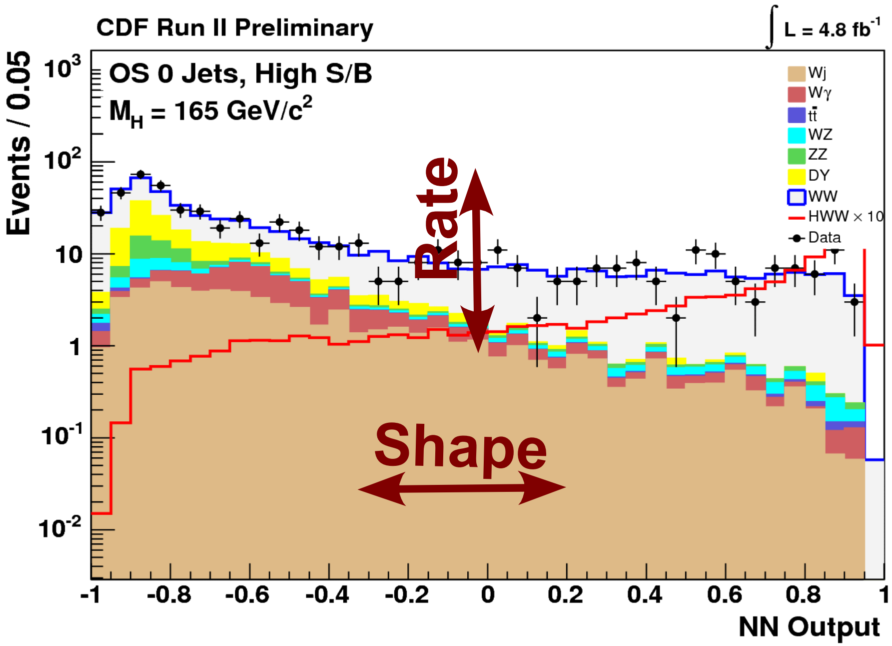
OS low M(ll)



- Expect main contribution from gg→H signal
- Improve results especially for lower m_H

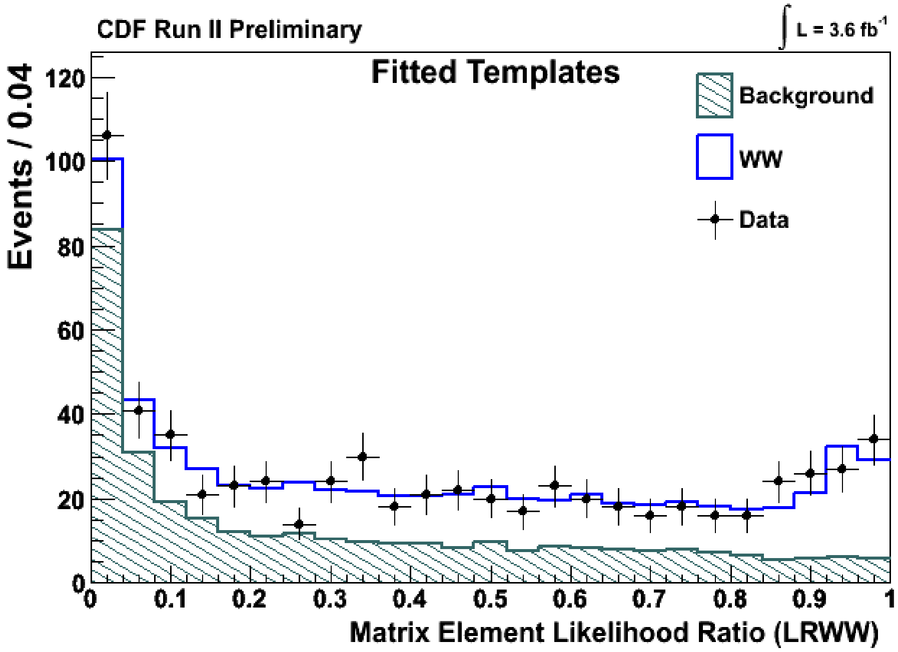
Systematics uncertainties

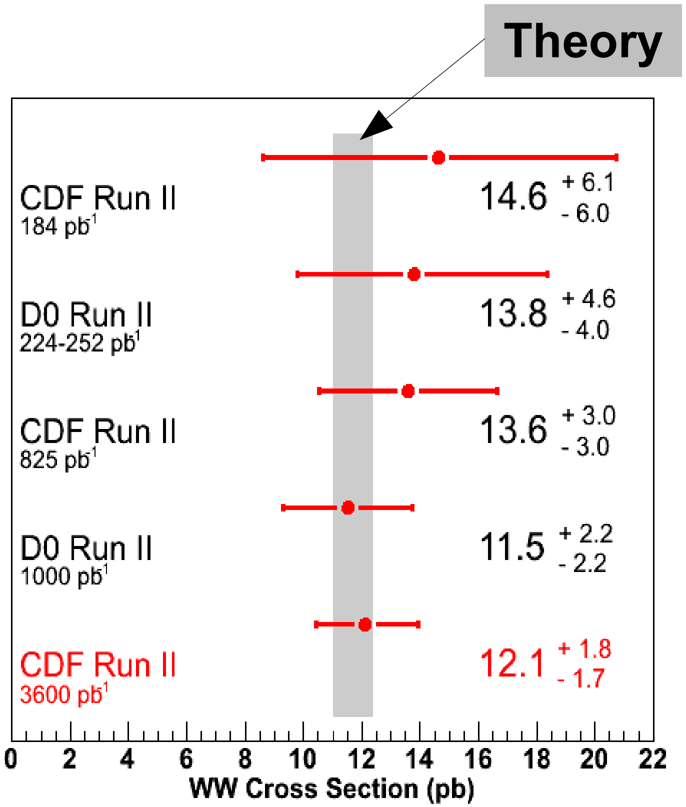
- **Two main classes of systematics uncertainties**
  - **Rate systematics**: Dominant. Affects normalization of NN output distribution. Major contributors are theoretical cross section errors.
  - **Shape systematics**: Found to be negligible up to now. Modify shape of NN output distribution. One example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



WW cross section measurement

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

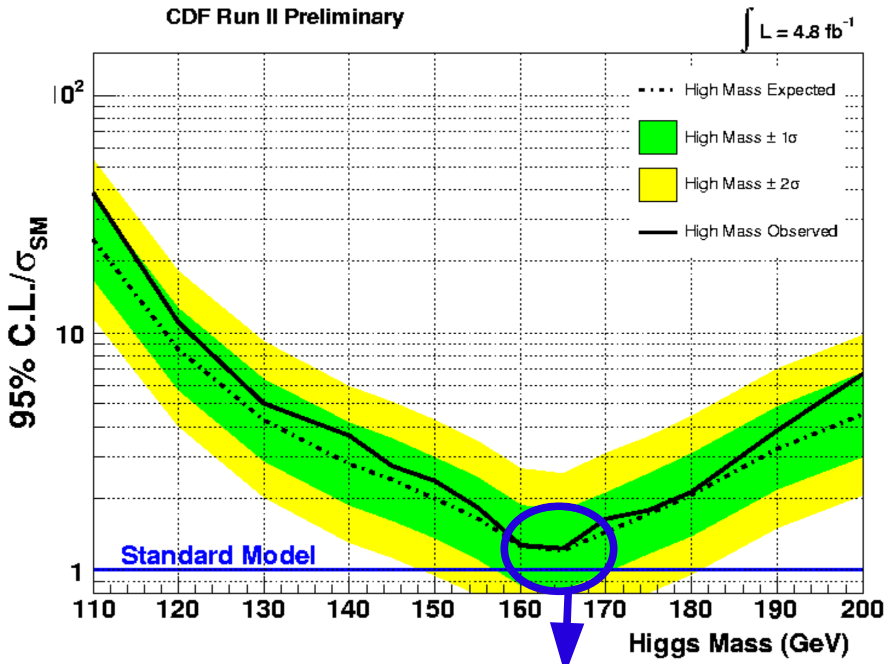




$$\sigma(p\bar{p}\rightarrow WW) = 12.1^{+1.8}_{-1.7}\, pb$$

CDF Public Note 9753, PRL in progress

- **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	2.0	2.8
OS 1 Jet	2.5	1.9
OS 2+ Jets	3.3	4.5
SS 1+Jets	6.4	4.9
OS low m(ll)	13.1	8.8

M_H = 165 GeV/c^2

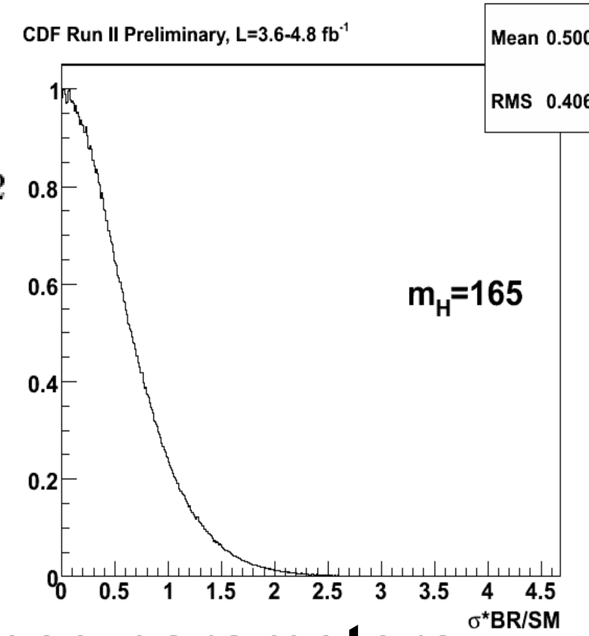
Observed Limit: **1.2 x σ_{SM}**

Expected Limit: **1.2 x σ_{SM}**

CDF Public Note 9887 – PRL in progress

Higgs searches combination

- **Straight-forward in principle to extend the method to combine all CDF measurements**



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

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

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

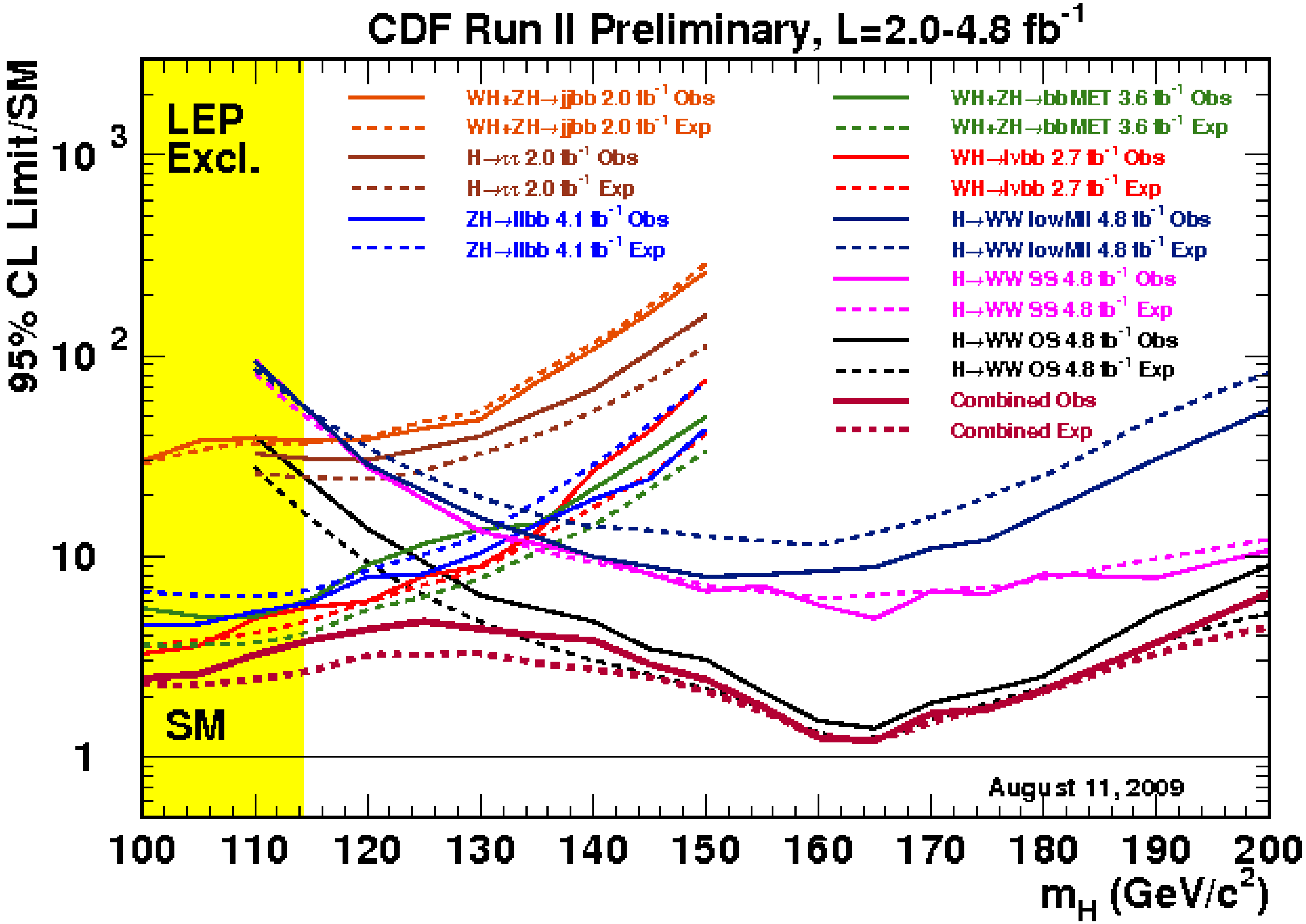
$$n_i = \text{“observed” events}$$

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

- **95% CL limits on R integrating out nuisance parameters**
  - ***correlate systematics among different channels!***
- **Practically very challenging: CPU intensive calculations**
  - Ex. just H → WW takes ~ 1 year of a modern CPU time
  - change integration method: Markov Chains v.s. Monte Carlo sampling

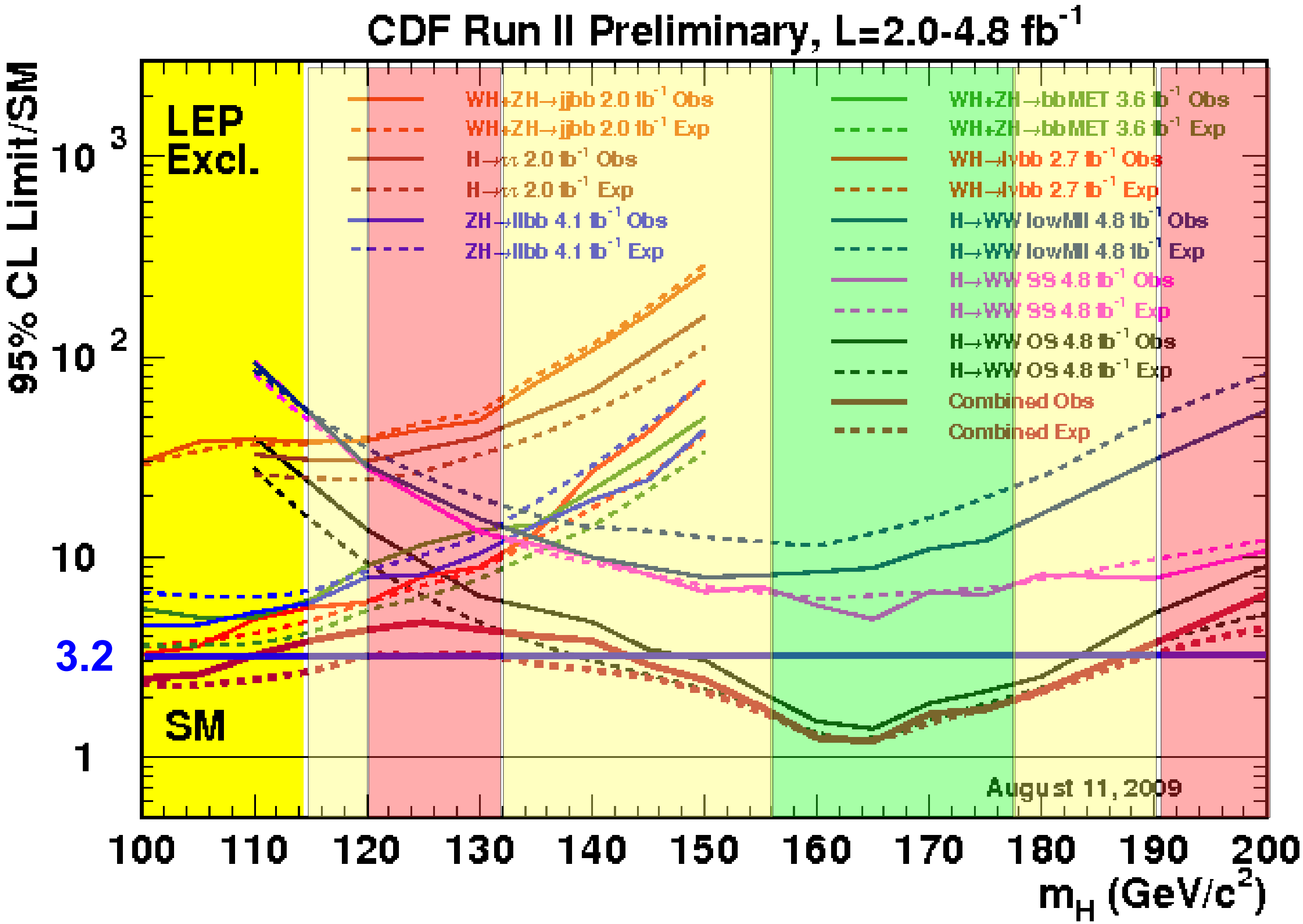
CDF overall picture: Summer 2009!

CDF Combination on Higgs searches

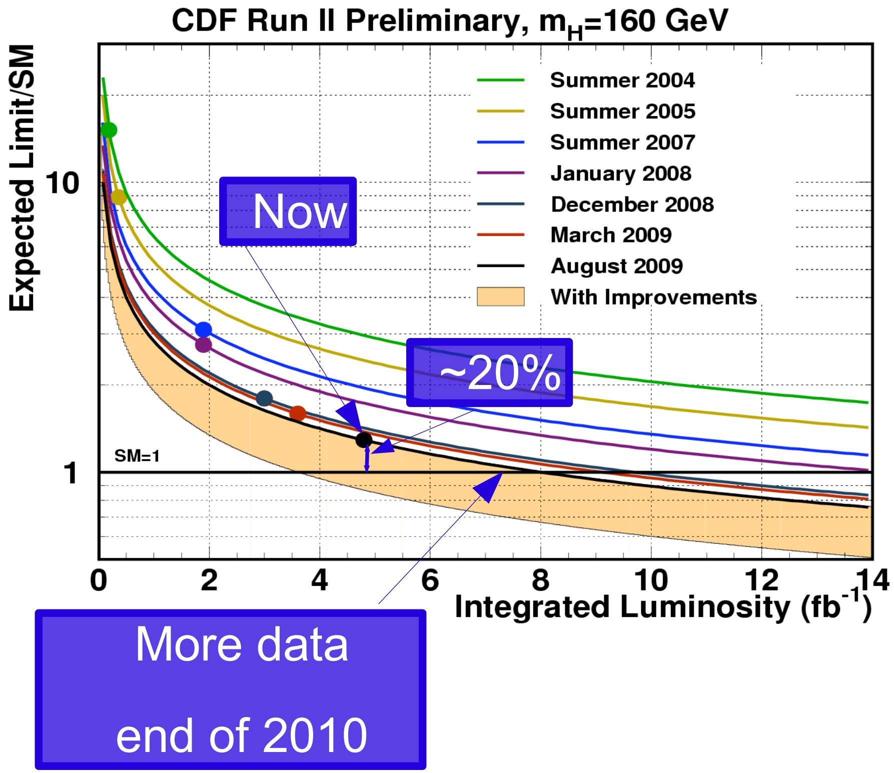


CDF overall picture: Summer 2009!

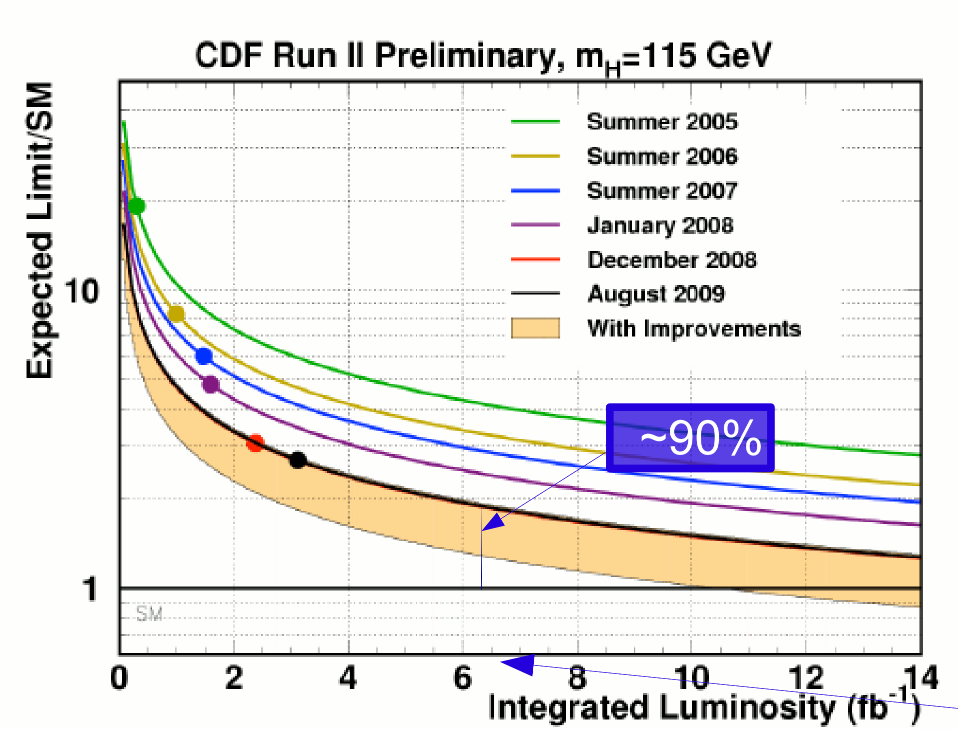
CDF Combination on Higgs searches

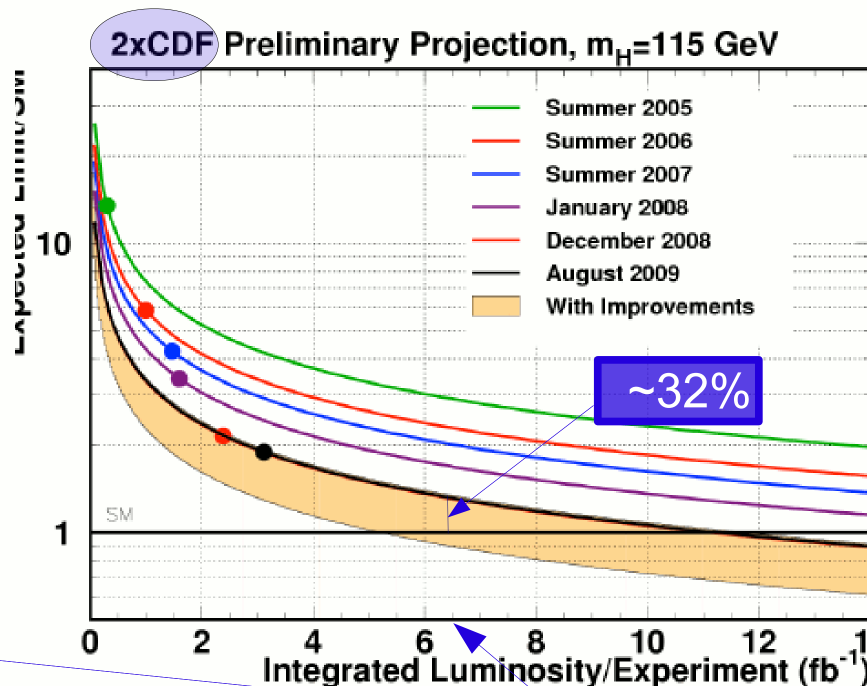


- **+20% going from Winter to Summer '09!**
- **At m_H ~ 160 GeV CDF is near!**
- **Ongoing improvements**
  - lowering Missing E_T requirements for H → WW
    - can open the road for H → ZZ also!
  - adding 3 lepton events
  - include hadronic τ decays
- **Goal: reach single-experiment SM sensitivity soon!**



The future of m_H=115 GeV



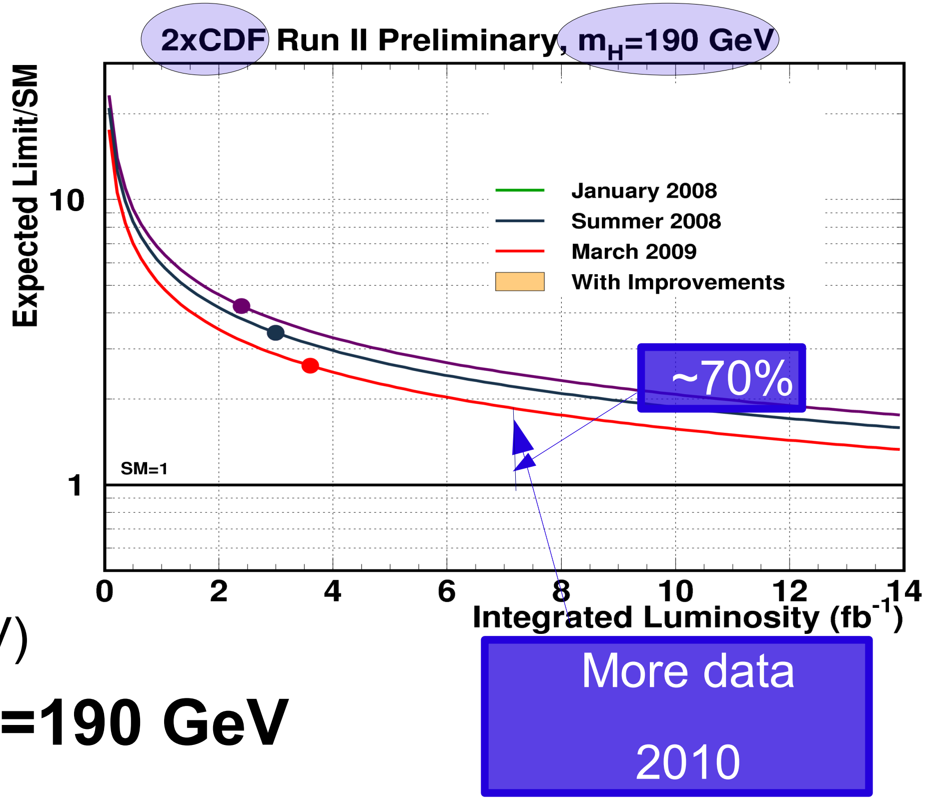


More data end of 2010

- **More challenging**
  - Need to improve ~30% on (most important) analyses!
  - Or find out something new (and assume D0 will do the same)
  - P.s. New WH analyses not included yet in the combination (few %)
- **Goal: SM sensitivity combining with D0 – longer term ?**

The future of m_H=190 GeV

- **Not easy to think how to improve so much:**
  - in combination with D0 need to improve 70%!
  - H → ZZ could also be a viable resource, but do not expect a big impact
    - first sensitivity studies not so promising at 190 GeV)



- **m_H=130 GeV is as far as m_H=190 GeV**
  - H → WW could be tried to be a bit more optimized for this (SS and the new lower m(ll) analysis did a good job)
  - … but need to improve both high and low mass analyses
- **If we want SM here we really need new (good) ideas!**

Conclusions

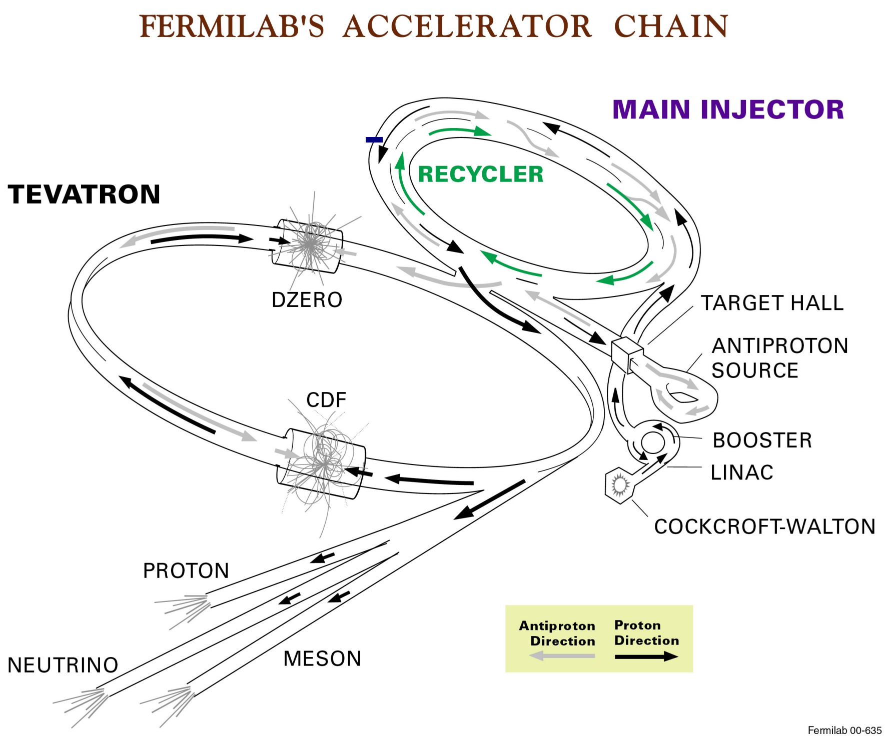
- **H → WW has been proven to be an excellent way to search for an high mass Higgs boson at CDF**
  - Current limits are $1.2 \cdot \sigma_{SM}$ @ m_H=165 GeV/c^2
- **Analysis is improving faster and faster**
  - rapid incorporation of new data
  - **sensitivity increasing faster than luminosity scaling**
- **CDF itself is ~< 3xSM in the 110-190 GeV range**
  - realistically need to combine with D0,
  - add data!! (about 7.3fb^{-1} of good data exp. by 2010, 2011?)
  - improve/add analyses and develop new ideas
- **Aim to reach SM sensitivity for a wide mass range**

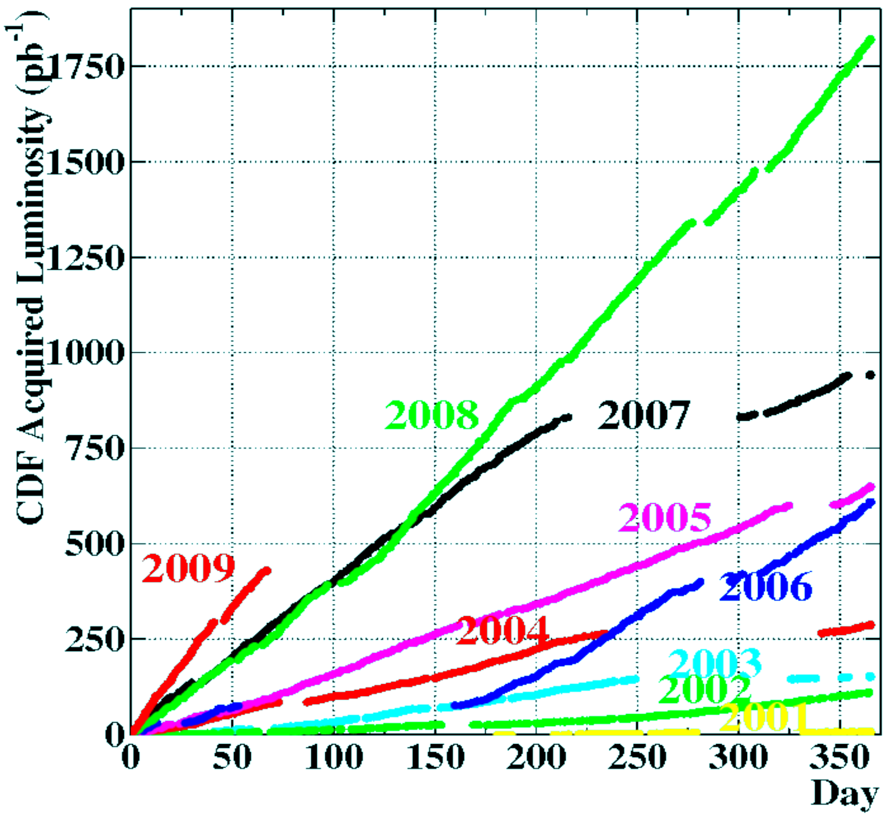
Backup

Tevatron combination

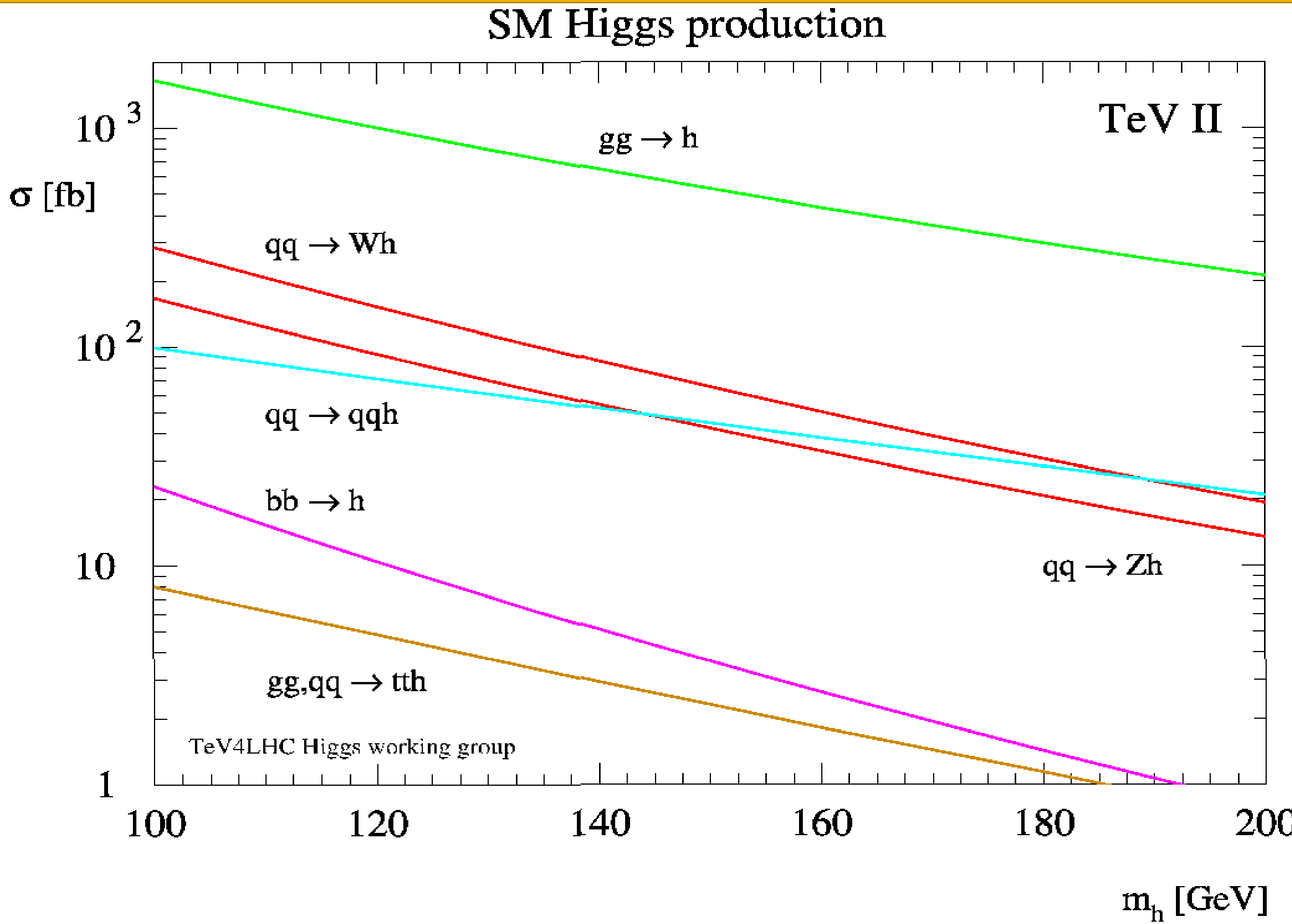
- **Last Tevatron combination released in March 2009**
  - Excluded at 95%CL m_H=160-170 GeV !!!
  - Expected limit was $1.1x\sigma_{SM}$ at 165 GeV
- **Preliminary results shows we achieve SM sensitivity with updated CDF analysis and old D0 one (T. Junk, HDG)**
- **CDF released for the summer great updates:**
  - HWW, ZH (met+bb), ZH(llbb) analyses were updated/improved
  - WH not already in combination but almost ready to-go
- **D0 updated its WH analysis, no other significant updates**
- **Getting ready for a new combination before Winter '10**

Tevatron Performance





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 (0J)

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet(s)	$gg \to H$
Cross Section								
Scale								7.0
PDF Model								7.7
Total	*6.0*	*6.0*	*6.0*	10.0	5.0			10.4
Acceptance								
Scale (leptons)								2.5
Scale (jets)								4.6
PDF Model (leptons)	1.9	2.7	2.7	2.1	4.1			1.5
PDF Model (jets)								0.9
Higher-order Diagrams	*5.0*	*10.0*	*10.0*	10.0		11.0		
Missing Et Modeling					21.0			
$W\gamma$ Scaling						12.0		
Jet Fake Rates (Low/High S/B)							21.5/27.7	
Jet Modeling	-1.0					*-4.0*		
MC Run Dependence	2.8							
Lepton ID Efficiencies	2.0	1.7	2.0	2.0	1.9			1.9
Trigger Efficiencies	2.1	2.1	2.1	2.0	3.4			3.3
Luminosity	5.9	5.9	5.9	5.9	5.9			5.9

CDF Analysis: Systematcs (1J)

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet(s)	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								23.5			
PDF Model								7.7			
Total	*6.0*	*6.0*	*6.0*	10.0	5.0			24.7	**5.0**	**5.0**	10.0
Acceptance											
Scale (leptons)								2.8			
Scale (jets)								-5.1			
PDF Model (leptons)	1.9	2.7	2.7	2.1	4.1			1.7	1.2	0.9	2.2
PDF Model (jets)								-1.9			
Higher-order Diagrams	*5.0*	*10.0*	*10.0*	10.0		11.0			**10.0**	**10.0**	**10.0**
Missing Et Modeling					30.0						
$W\gamma$ Scaling						12.0					
Jet Fake Rates (Low/High S/B)							22.2/31.5				
Jet Modeling	-1.0					*15.0*					
MC Run Dependence	1.0										
Lepton ID Efficiencies	2.0	2.0	2.2	1.8	2.0			1.9	1.9	1.9	1.9
Trigger Efficiencies	2.1	2.1	2.1	2.0	3.4			3.3	2.1	2.1	3.3
Luminosity	5.9	5.9	5.9	5.9	5.9			5.9	5.9	5.9	5.9

CDF Analysis: Systematcs (2J)

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet(s)	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								67.5			
PDF Model								7.7			
Total	*6.0*	*6.0*	*6.0*	10.0	5.0			67.9	**5.0**	**5.0**	10.0
Acceptance											
Scale (leptons)								3.1			
Scale (jets)								-8.7			
PDF Model (leptons)	1.9	2.7	2.7	2.1	4.1			2.0	1.2	0.9	2.2
PDF Model (jets)								-2.8			
Higher-order Diagrams	*5.0*	*10.0*	*10.0*	10.0		11.0			**10.0**	**10.0**	**10.0**
Missing Et Modeling					32.0						
$W\gamma$ Scaling						12.0					
Jet Fake Rates							27.1				
Jet Modeling	20.0					*18.5*					
b-tag veto				5.4							
MC Run Dependence	1.5										
Lepton ID Efficiencies	1.9	2.9	1.9	1.9	1.9			1.9	1.9	1.9	1.9
Trigger Efficiencies	2.1	2.1	2.1	2.0	3.4			3.3	2.1	2.1	3.3
Luminosity	5.9	5.9	5.9	5.9	5.9			5.9	5.9	5.9	5.9

CDF Analysis: Systematcs (SS)

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet(s)	WH	ZH
Cross Section									
Scale									
PDF Model									
Total	*6.0*	*6.0*	*6.0*	10.0	5.0			**5.0**	**5.0**
Acceptance									
Scale (leptons)									
Scale (jets)									
PDF Model (leptons)	1.9	2.7	2.7	2.1	4.1			1.2	0.9
PDF Model (jets)									
Higher-order Diagrams	*5.0*	*10.0*	*10.0*	10.0		11.0		**10.0**	**10.0**
Missing Et Modeling					17.0				
$W\gamma$ Scaling						12.0			
Jet Fake Rates							30.0		
Jet Modeling	3.0					*16.0*			
Charge Misassignment	16.5			16.5	16.5				
MC Run Dependence	1.0								
Lepton ID Efficiencies	2.0	2.0	2.0	2.0	2.0			2.0	2.0
Trigger Efficiencies	2.1	2.1	2.1	2.0	3.4			2.1	2.1
Luminosity	5.9	5.9	5.9	5.9	5.9			5.9	5.9

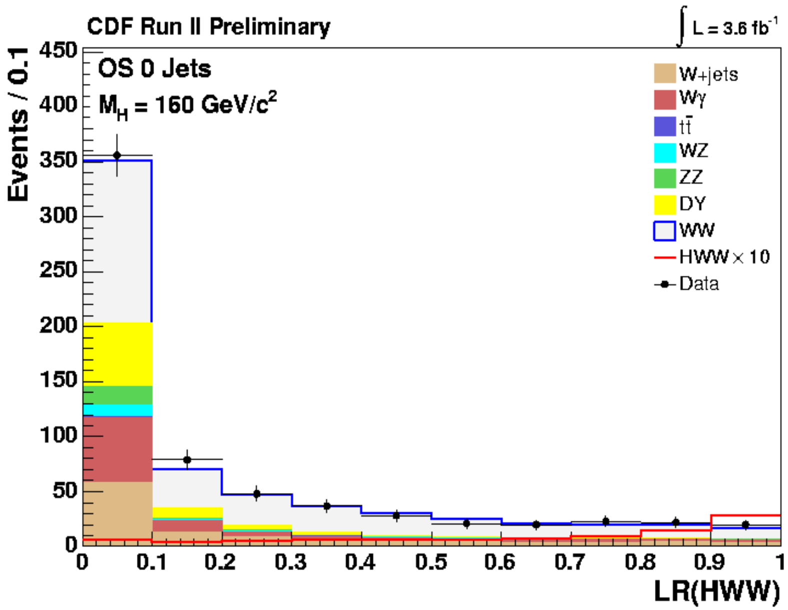
CDF Analysis: Systematcs (low mll)

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet(s)	$gg \rightarrow H$
Cross Section								
Scale								12.0
PDF Model								7.7
Total	*6.0*	*6.0*	*6.0*	10.0	5.0			14.3
Acceptance								
Scale (leptons)								2.6
Scale (jets)								1.1
PDF Model (leptons)	1.9	2.7	2.7	2.1	4.1			1.7
PDF Model (jets)								0.3
Higher-order Diagrams	*5.5*	*11.0*	*11.0*	10.0				
Missing Et Modeling					22.0			
$W\gamma$ Scaling						12.0		
Jet Fake Rates							24.1	
Jet Modeling	-1.0							
MC Run Dependence	5.0							
Lepton ID Efficiencies	2.0	1.7	2.0	2.0	1.9			1.9
Trigger Efficiencies	2.1	2.1	2.1	2.0	3.4			3.3
Luminosity	5.9	5.9	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

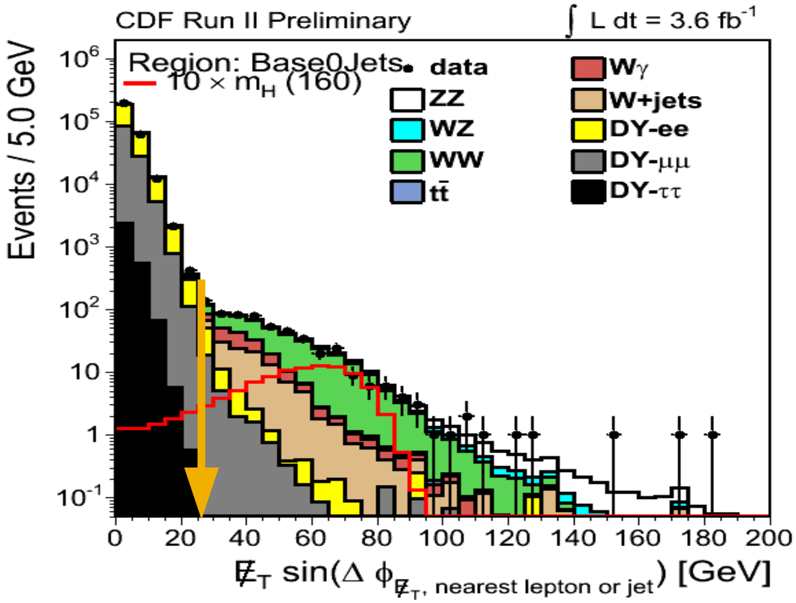
D0 models 2 modes:

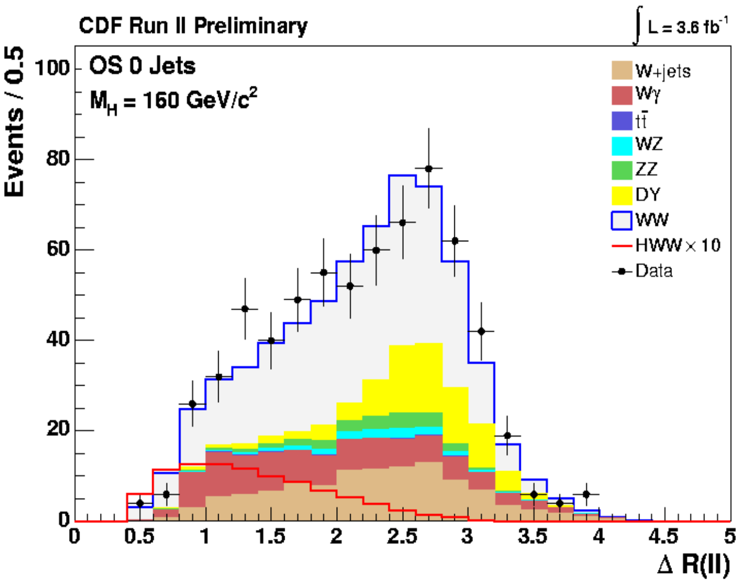
- HWW and WW

Use a Likelihood Ratio

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

Improvements in Plots

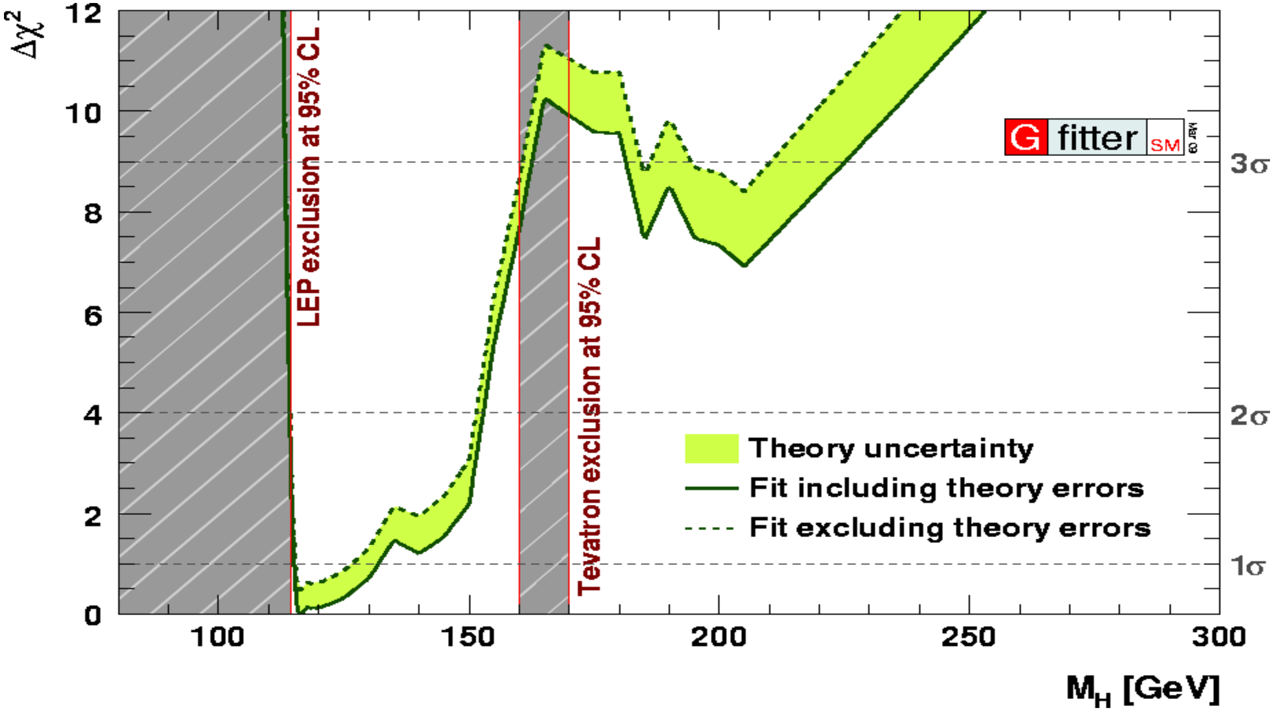




- **Lower Missing E_T**
- **Lepton isolation**
- **Tri-lepton events**

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**