Heavy Higgs Boson Searches at the Tevatron

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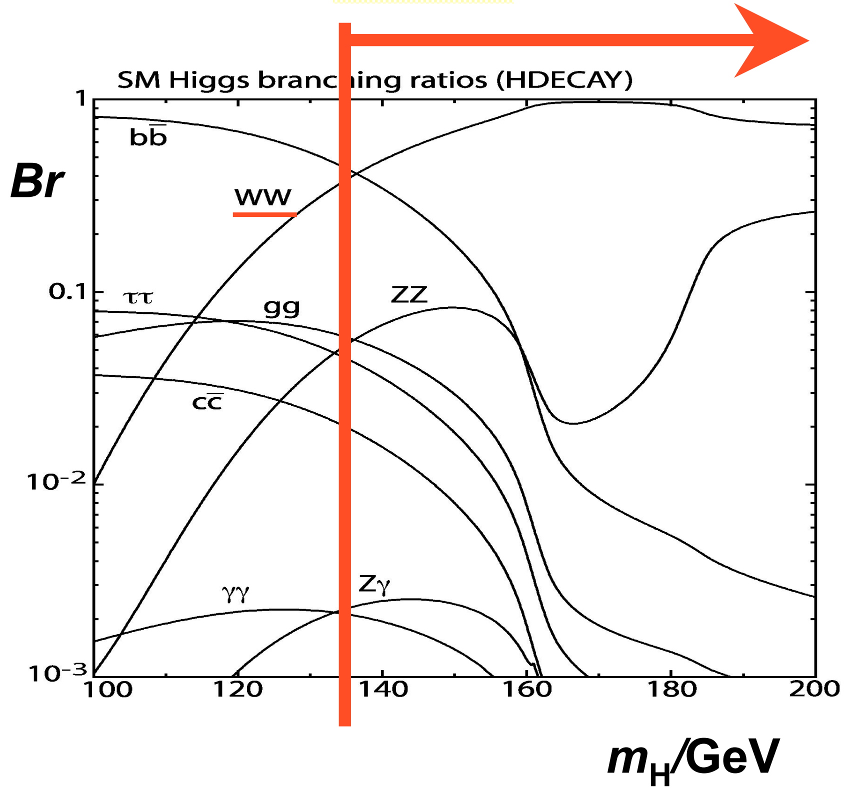
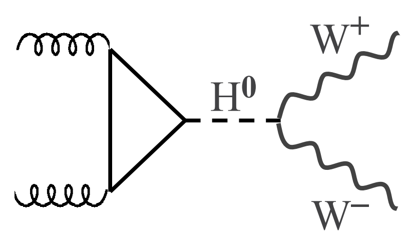
Higgs-Maxwell workshop, 13 February 2008

- $H \rightarrow WW$ channel
- Limit-setting
- Analysis techniques
- Analysis stability
- Improving sensitivity
- Current limits
- Projections

Decay

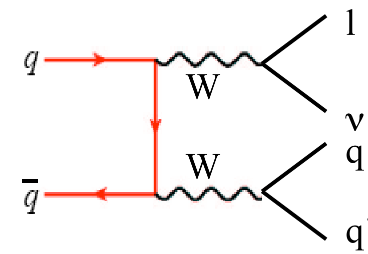


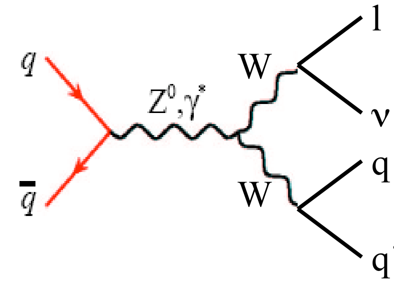


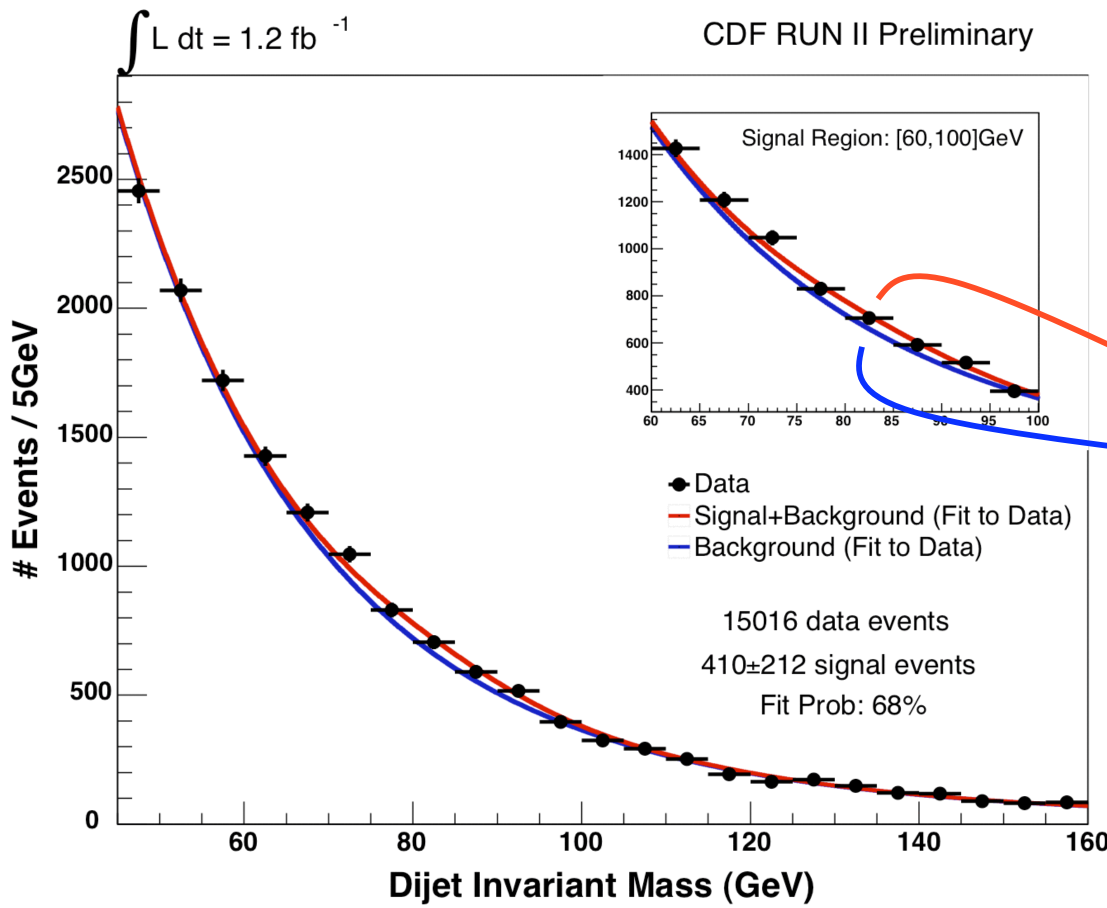
***Br*(W→ lν) ≈ 0.32**
***Br*(W→ jj) ≈ 0.68**

Hadronic Ws?

WW→ lνjj





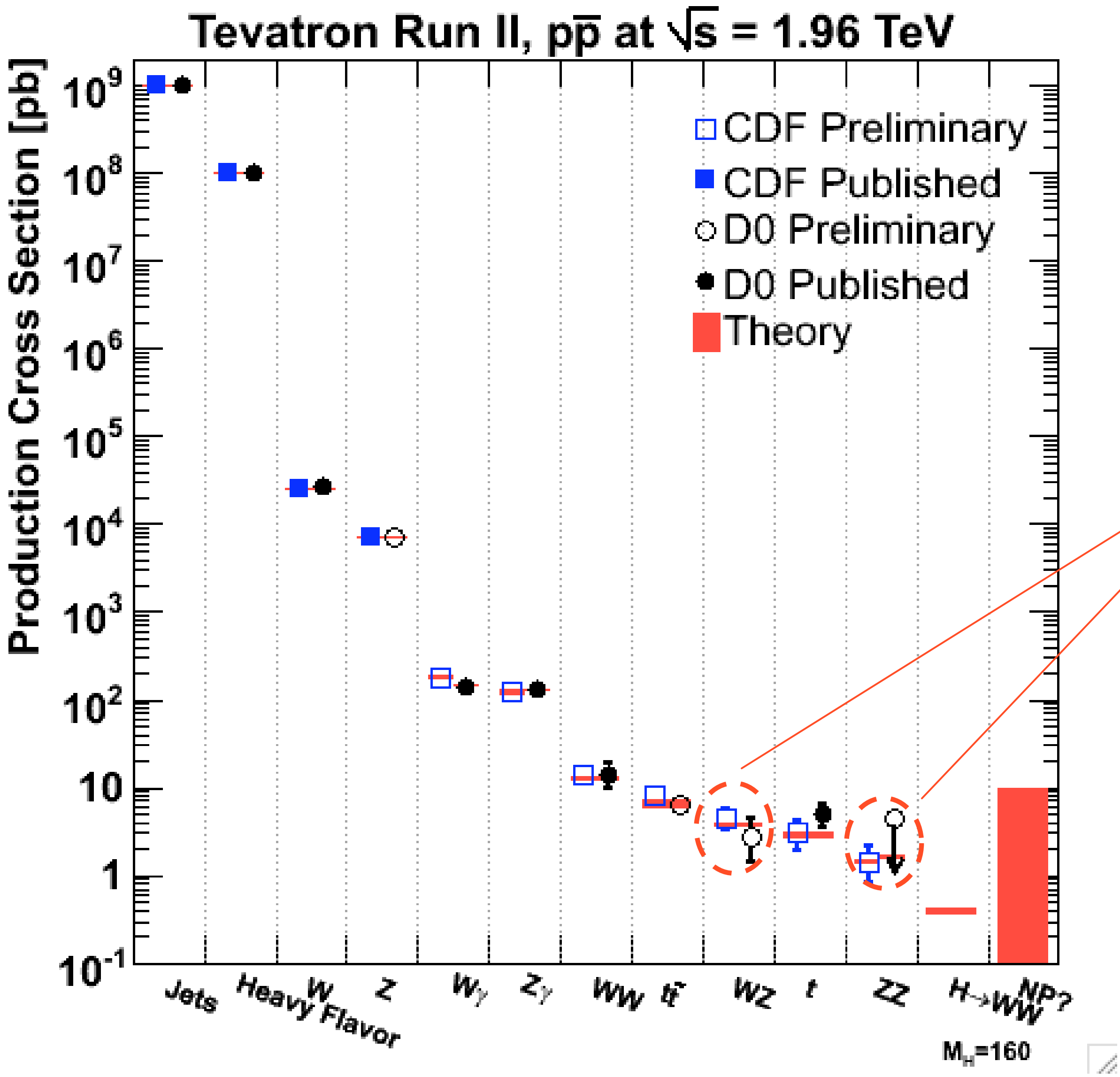


Signal + background

Background only!

Leptonic final states for our Higgs search

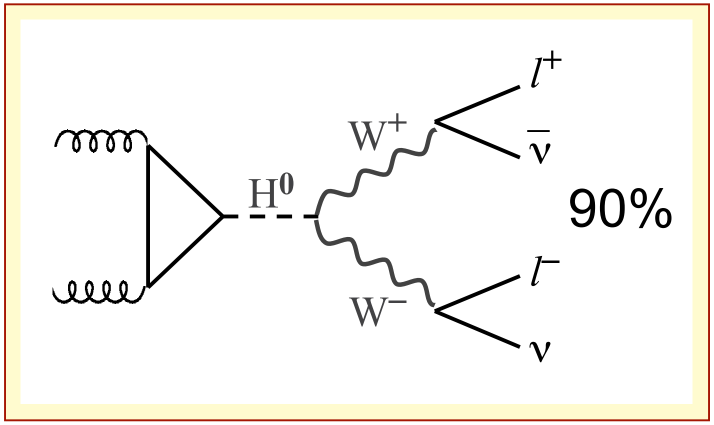
A physics programme

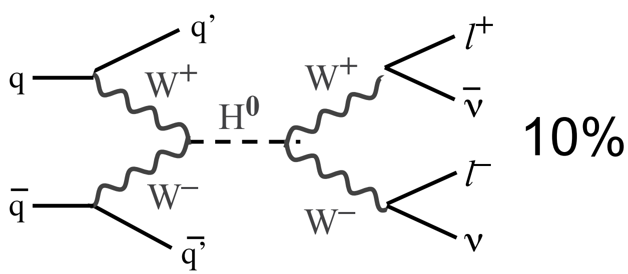


Using leptonic decay channels

$$\sigma(p\bar{p}\rightarrow ZZ) \approx 3 \times \sigma(p\bar{p}\rightarrow H)$$

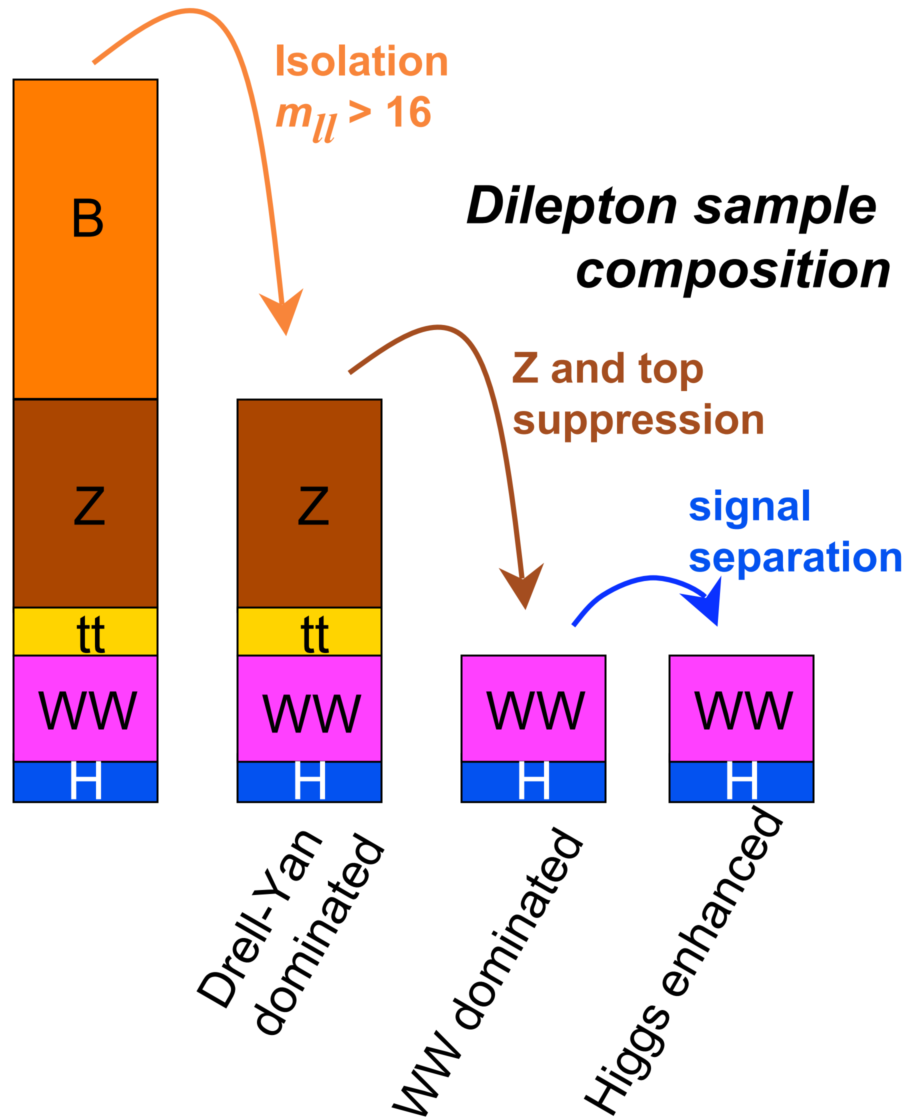
H→WW





ee, eμ, μμ ; $\not{E}_T$

(also $\mu\tau_{had}$ from D0)

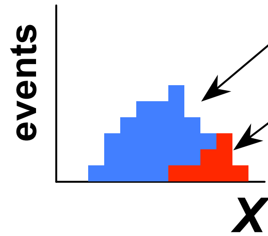


Limit setting

Isolation
m_{ll} > 16 or 25

Z and top suppression

signal separation

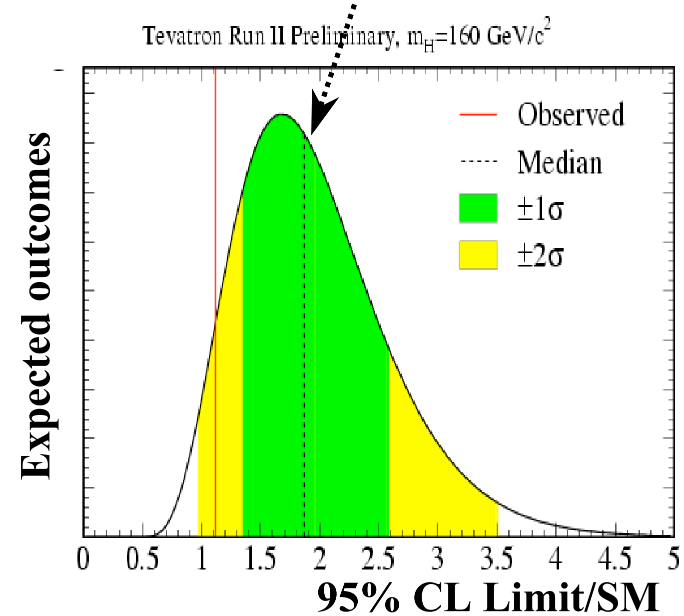


X = some observable

H_1=SM+Higgs of mass m_H
H_0=SM only

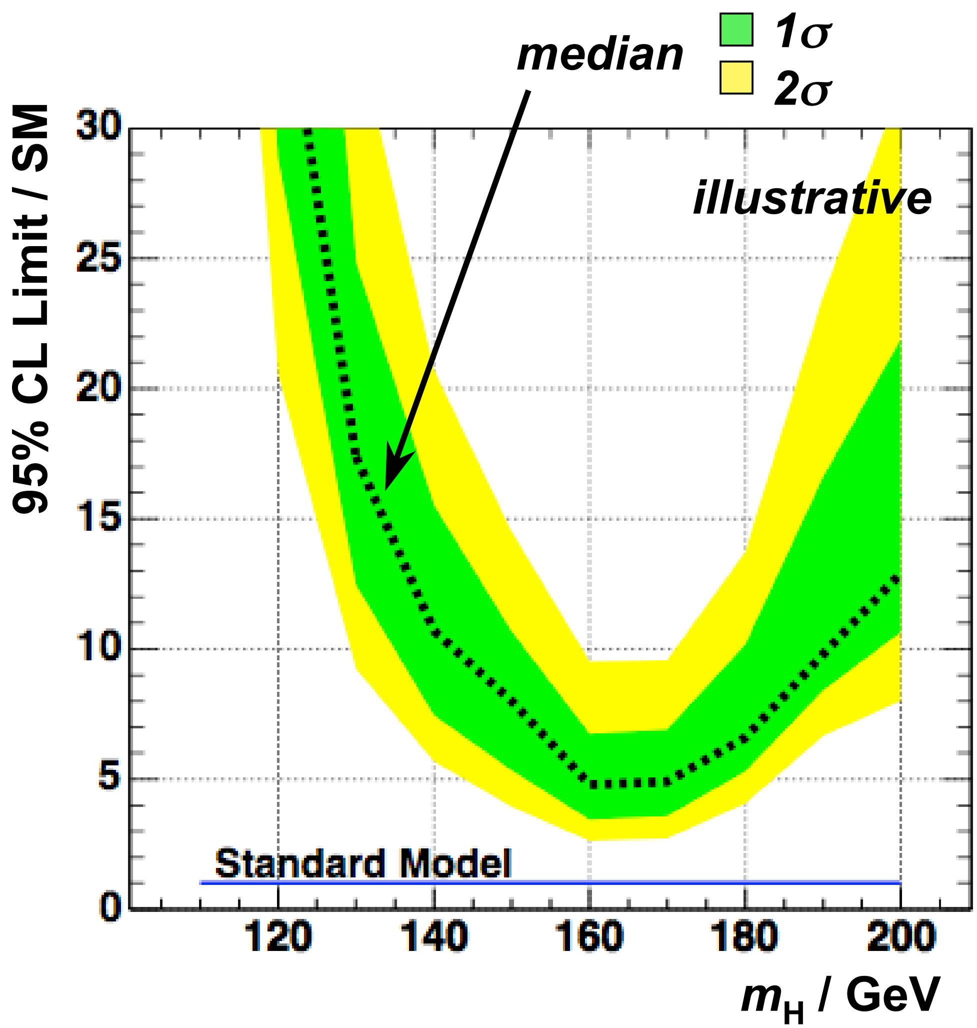
- *Construct test statistic Q = P(data|H_1)/P(data|H_0)*
  $-2\ln Q = \chi^2(\text{data}|H_1) - \chi^2(\text{data}|H_0)$,
  marginalized over nuisance params except σ_H
- *Find 95th percentile of resulting σ_H distribution – this is 95% CL upper limit.*
- *When computed with collider data this is the "observed limit"*
- *Repeat for pseudoexperiments drawn from expected distributions to build up expected outcomes*
- *Median of expected outcomes is "expected limit"*

Median = expected limit

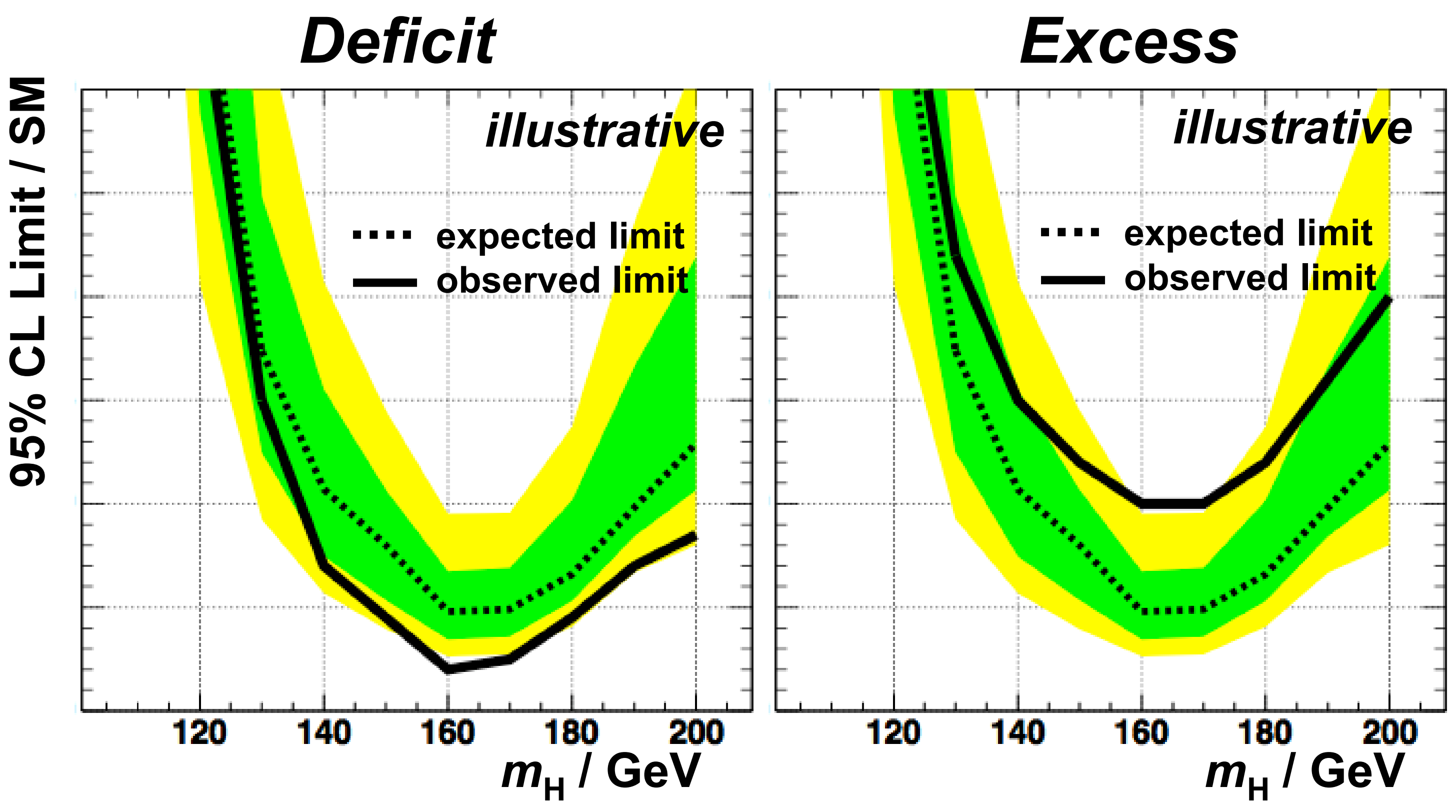


Limit setting (2)

Repeat for different values of m_H → build up exclusion plot



What have we found?



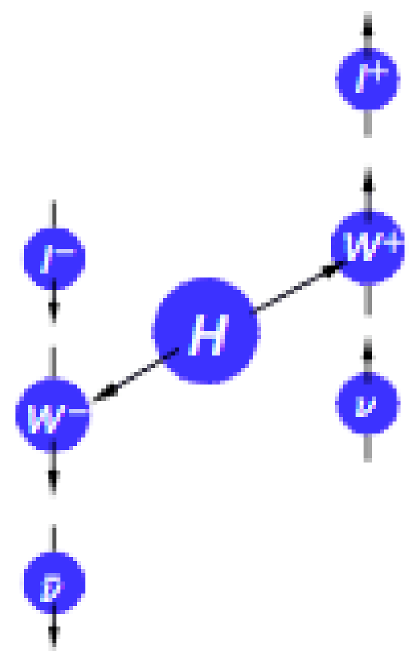
Overview of Analyses

Cut-based analysis

Spin structure WW vs H->WW … lepton $\Delta\phi$

Parity violation
Higgs is scalar ⇒ charged leptons go in ~ same direction

Low masses: one W off-shell so one lepton lower in energy



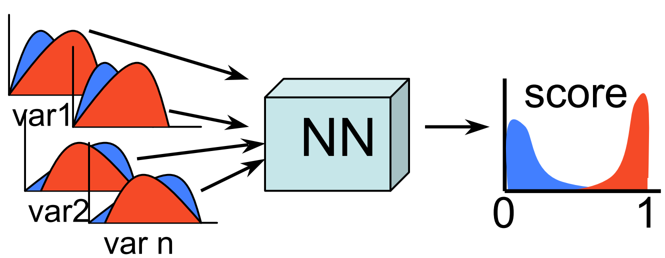
Overview of Analyses

Cut-based analysis

Spin structure WW vs H->WW … lepton $\Delta\phi$

Extend sensitivity

Neural net approach (CDF and D0)



Matrix element approach (CDF)

$$d\sigma \propto \int \sum f^a(x,Q^2)\ f^b(x,Q^2)\ |M^{ab}(\Phi_4;\alpha)|^2 \ldots$$

Matrix element method

- Use LO matrix element (MCFM) to compute event probability

$\boldsymbol{x}_{\mathbf{obs}}$: $\begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}_{\mathrm{lep1}}$ $\begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix}_{\mathrm{lep2}}$

$\not{E}_x$, $\not{E}_y$

(with true values $\boldsymbol{y}$)

LO $|\mathbf{M}|^2$:

H→WW→$l\nu l\nu$

WW→$l\nu l\nu$

ZZ→$ll\nu\nu$

W+parton→$l\nu$+jet

Wγ→$l\nu$+γ

parton →lepton fake rate

γ conversion rate

$\not{E}_T$ model

lepton energy resn

$$P(x_{\rm obs}) = \frac{1}{<\sigma>} \int \frac{d\sigma_{\rm th}(y)}{dy} \epsilon(y) G(x_{\rm obs}, y) dy$$

- Compute likelihood ratio discriminator

$$R = \frac{P_{\rm s}}{P_{\rm s} + \sum_i k_{\rm b}{}^i P_{\rm b}{}^i}$$

k_b is relative fraction of expected background contrib.

P_s computed for each m_H

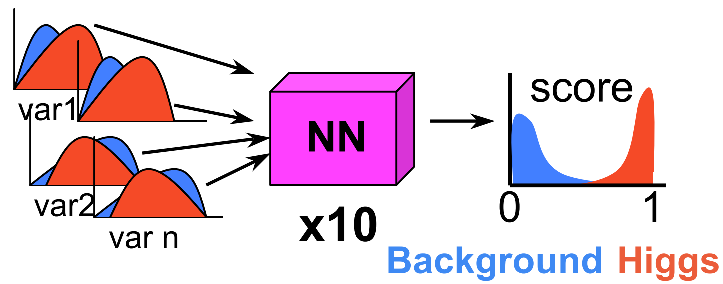
- Fit templates (separately for high S/B and low S/B dilepton types)

Neural network method

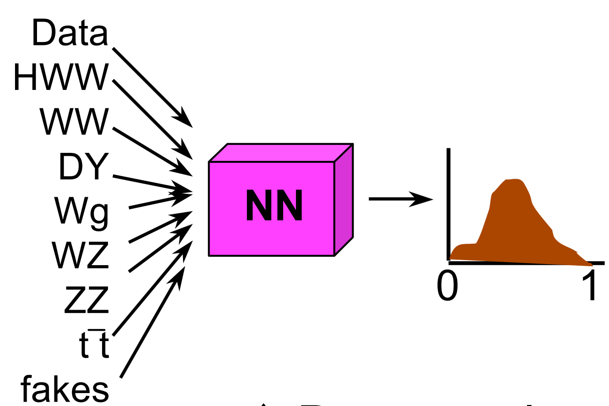
- Various versions. Current:
- Apply preselection (eg $\not{E}_T$ to remove Drell-Yan)
- Train on {all backgrounds / WW} against Higgs
  m_H=110,120…160…200 { possibly separate ee,eμ,μμ }

$\not{E}_T$	E_T^{jet1}
ΣE_T	$\Delta R_{\text{leptons}}$
m_{ll}	$\Delta\phi_{\text{leptons}}$
E^{lep1}	$\Delta\phi\,\not{E}_{T\ \text{lep or jet}}$
E^{lep2}	E_T^{jet2}
$\not{E}_T$sig	N_{jets}

Most recent CDF "combined ME/NN" analysis also uses ME LRs as NN input variables



- Pass signal/all backgrounds through net
- Form templates



- Pass templates and data to fitter

What have we found???

Last summer, CDF had 3 analyses:
Matrix Element, Neurobayes Neural Net, TMVA Neural Net

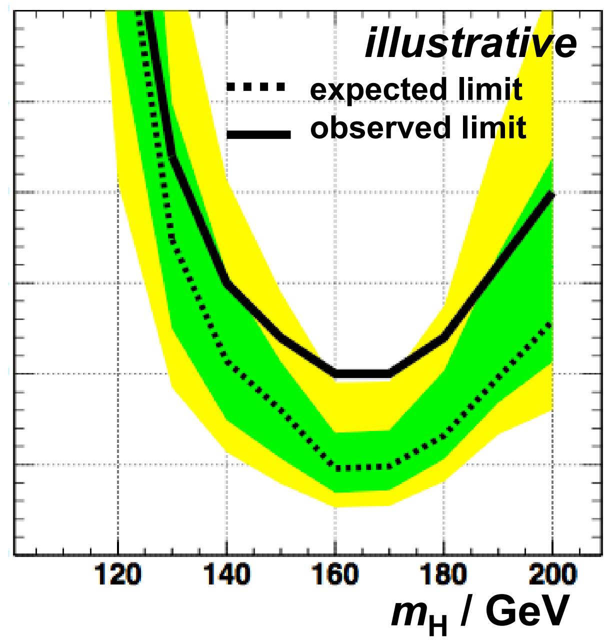
- ***expected sensitivities all similar***
- ***input distributions: well modeled***
- ***observed limits...***

What have we found???

Last summer, CDF had 3 analyses:
Matrix Element, Neurobayes Neural Net, TMVA Neural Net

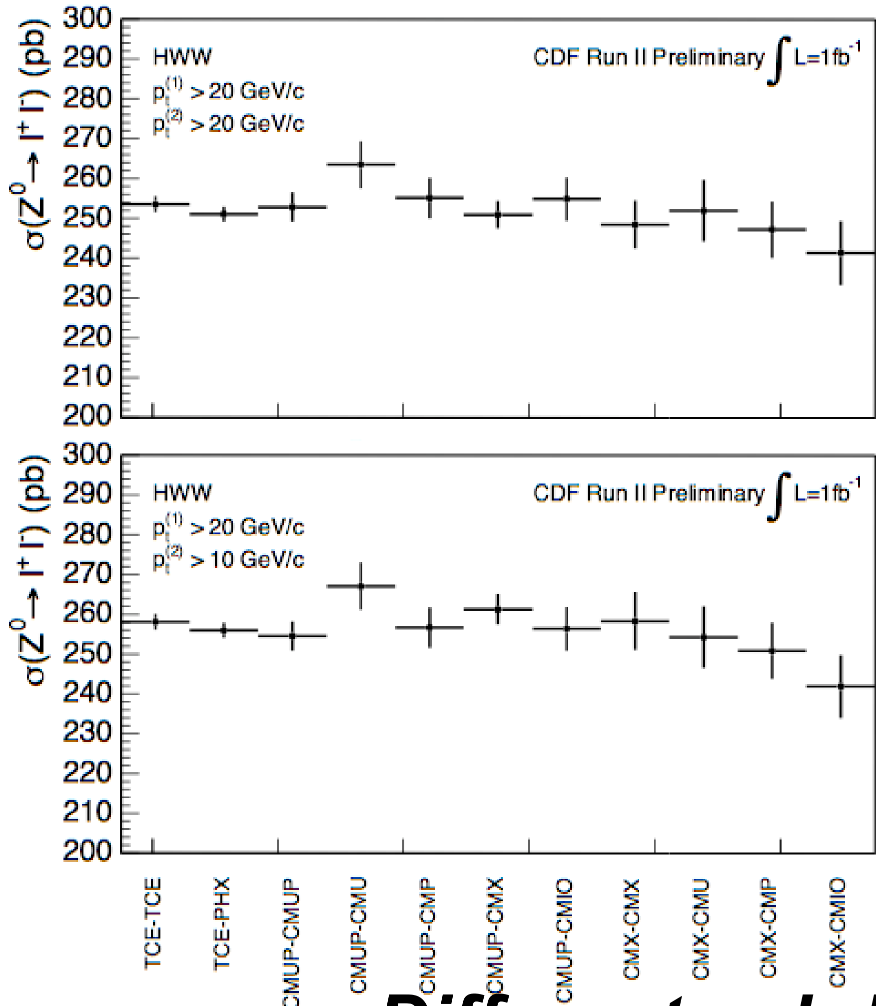
- ***expected sensitivities all similar***
- ***input distributions: well modeled***
- ***observed limits...***

Excess in one of the 3 analyses!

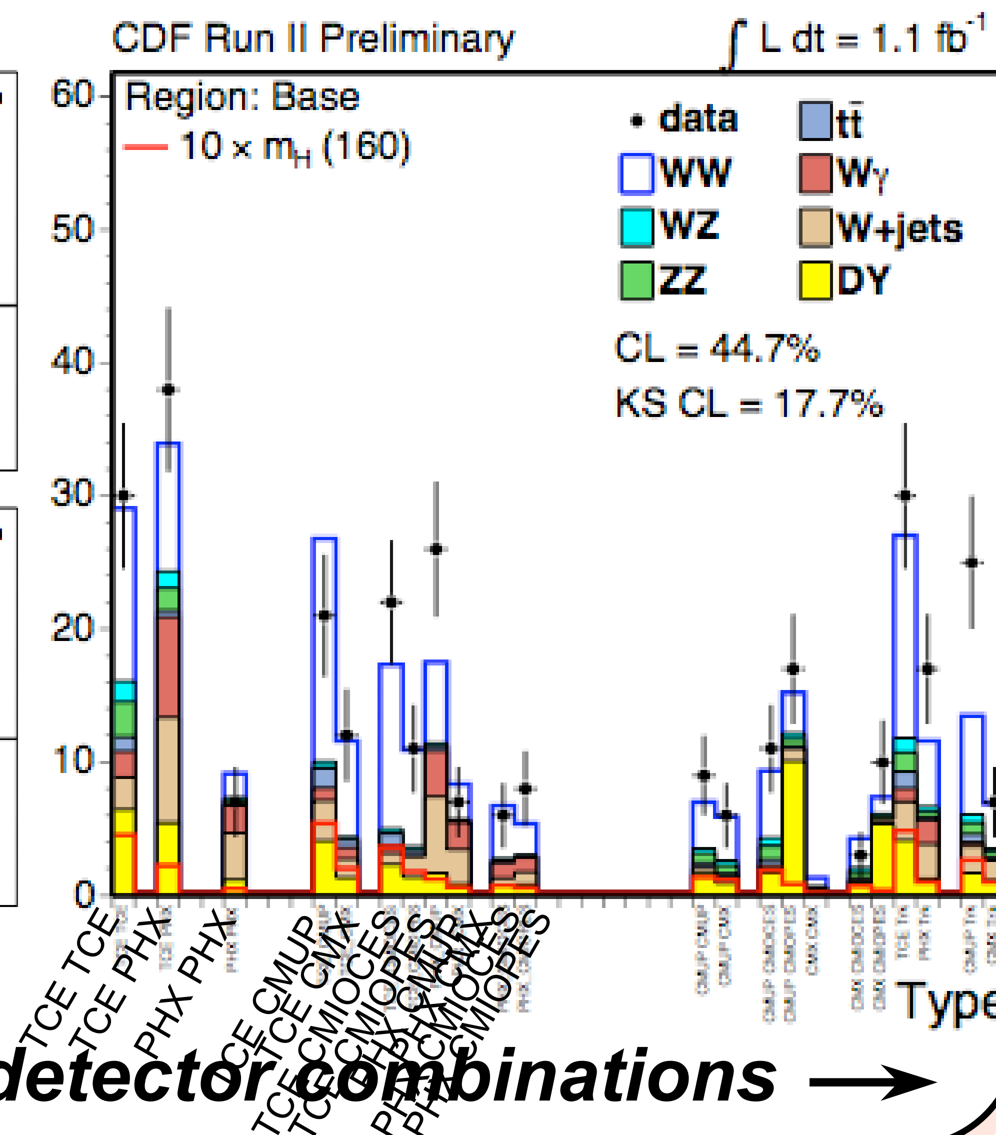


Grounding in SM measurements

Neural net:



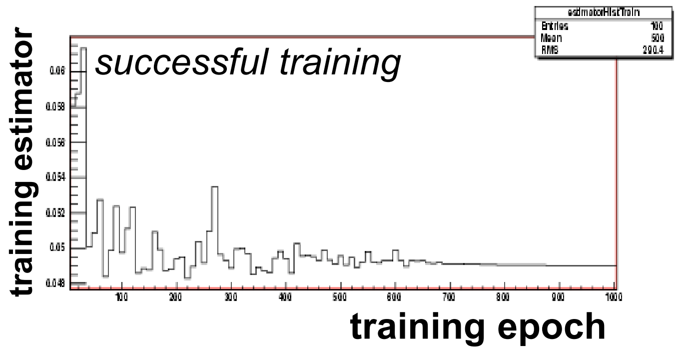
Matrix element:

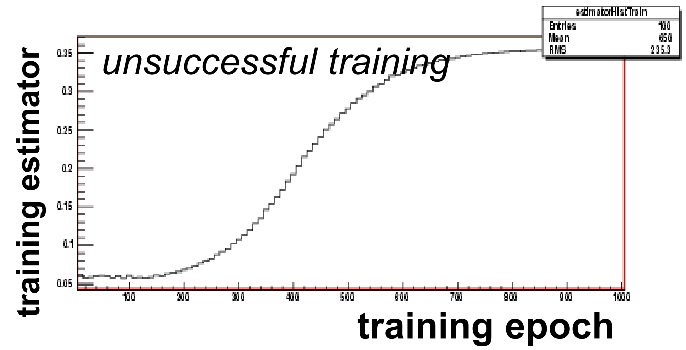


Different subdetector combinations

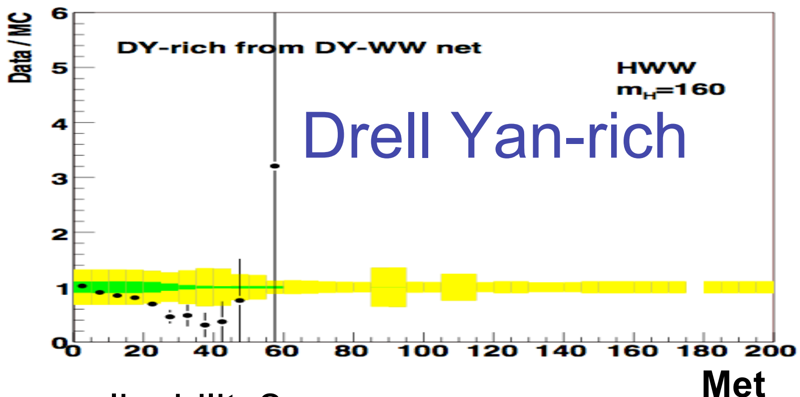
Assessing NN stability

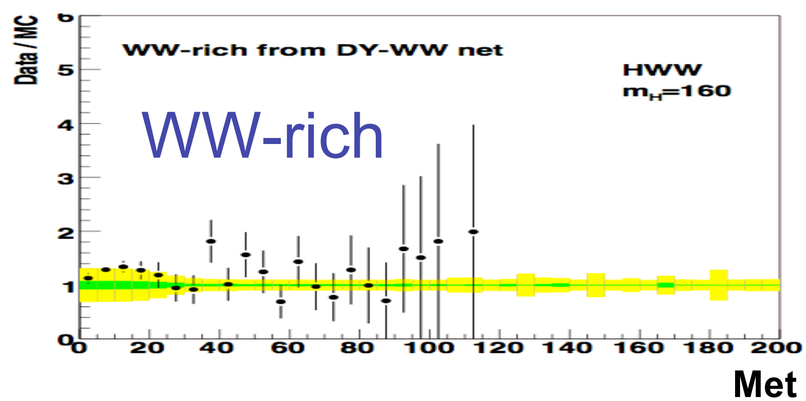
- ***convergence***





- ***rogue variables***
  - had checked data-simulation agreement in as many regions as possible





  - applicability?
  - and how to identify variable that affects observed limit but not expected limit, without biasing result?
  - traced to variable that depended on unclustered energy

- ***control regions…***

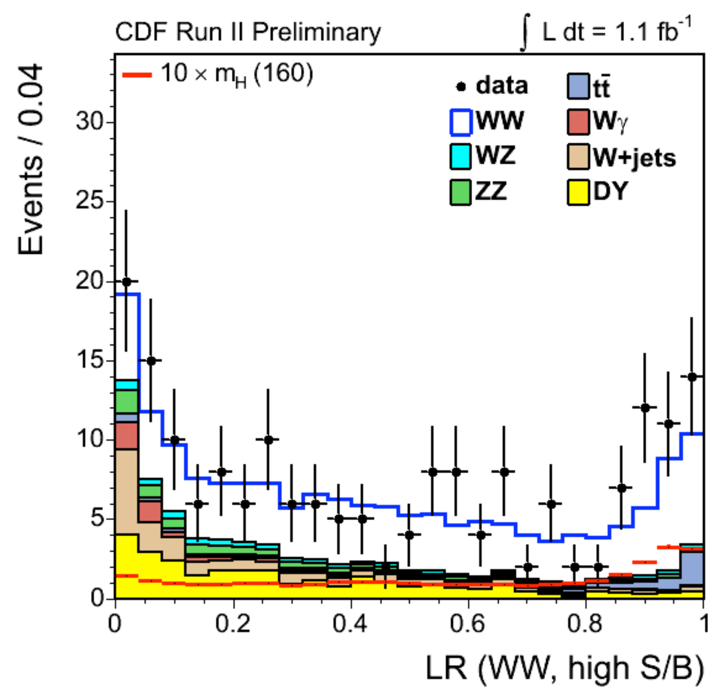
Complementarity

- ***exploit different sensitivities of matrix element / neural net***
  – ME is leading order
    - remove variables that use jet information from neural net for comparison

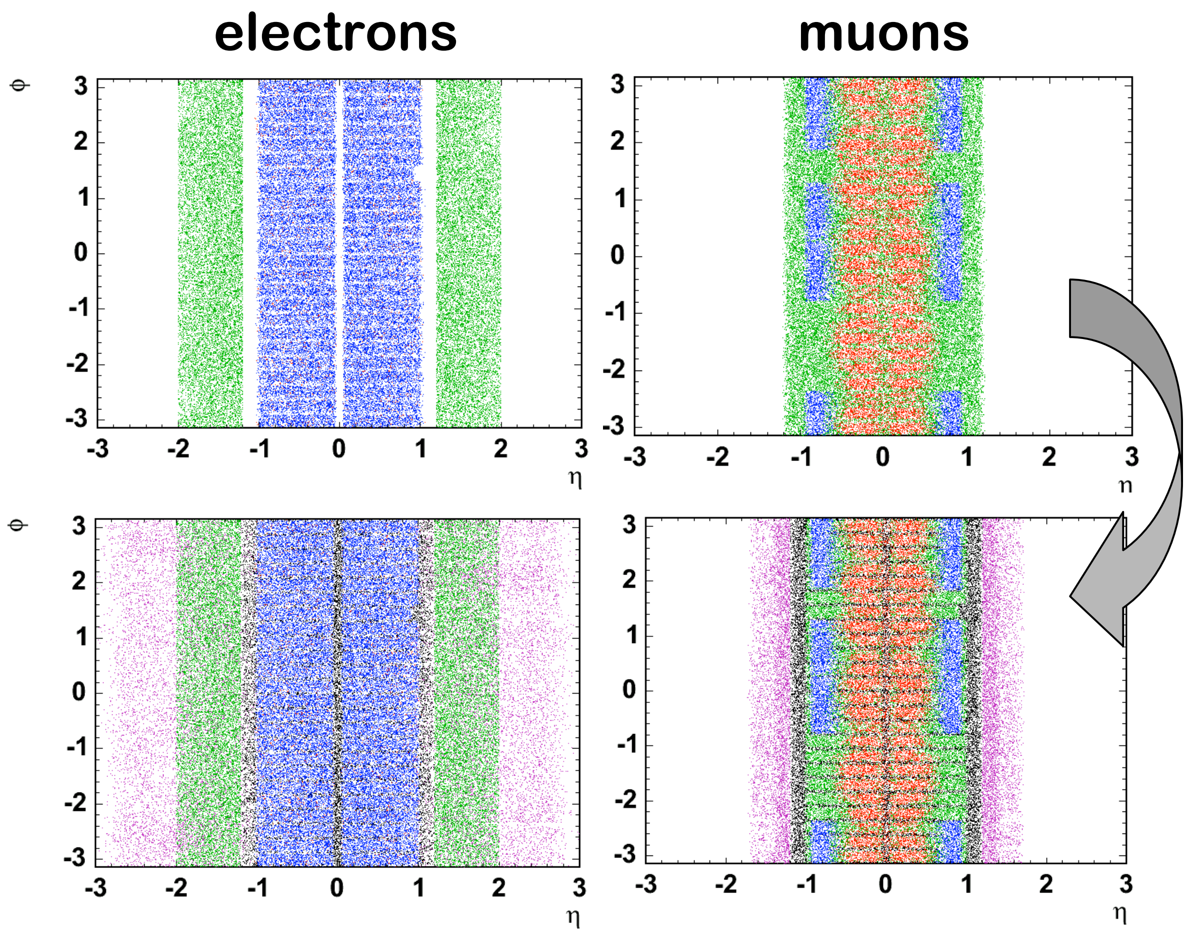
- ***verify matrix element method: cycle signal***

Redefine discriminant for WW hypothesis:

$$R' = \frac{P_{\mathrm{WW}}}{P_{\mathrm{WW}} + \sum_i k_{\mathrm{b}}^i P_{\mathrm{b}}^i}$$



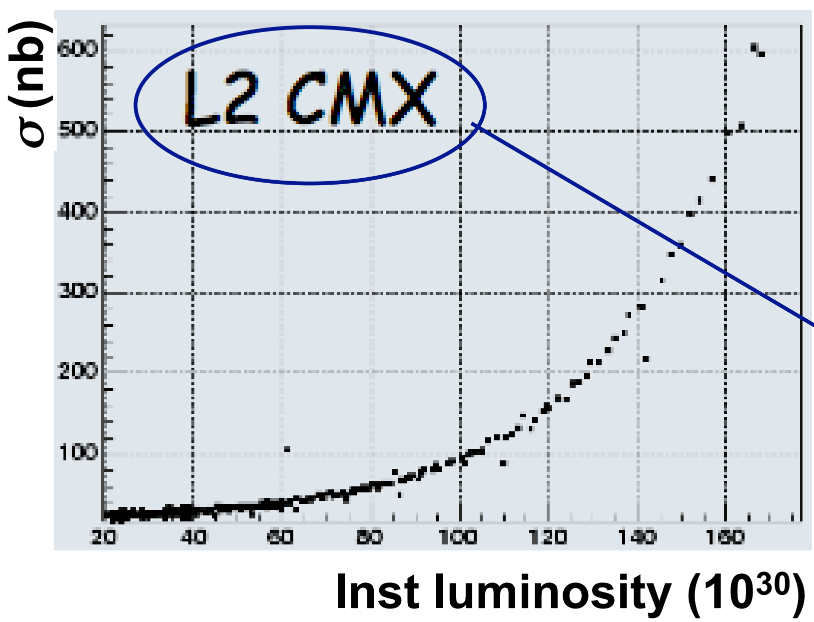
Lepton coverage

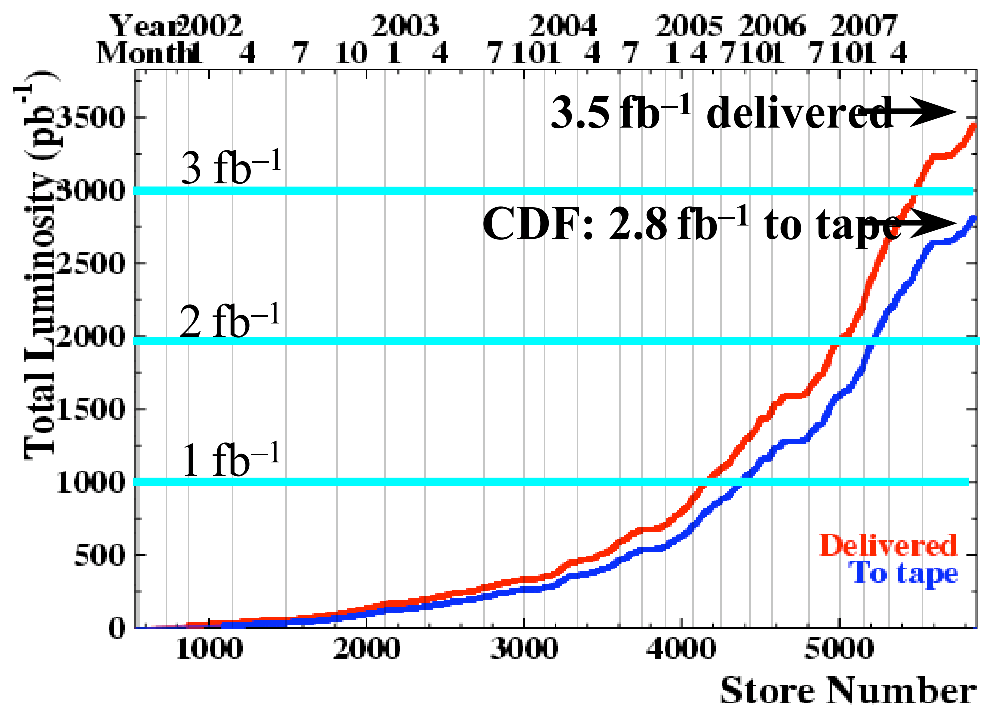


Increased acceptance by adding plug calorimeter (no tracking) and tracks pointing to cracks

Luminosity

Higher statistics…
… but affects trigger rates



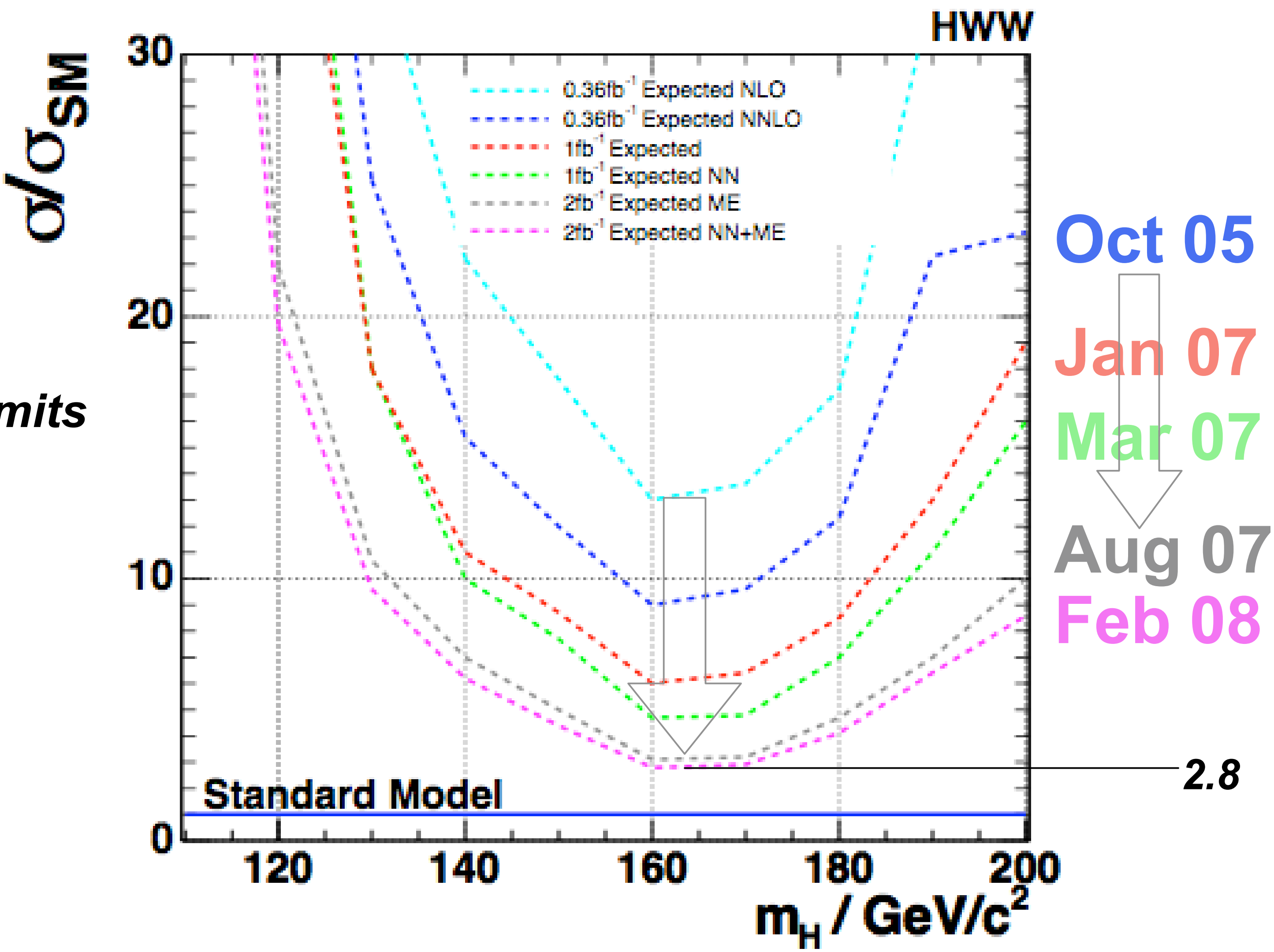


a trigger consisting of hits in the "CMX" muon system, matched to a track

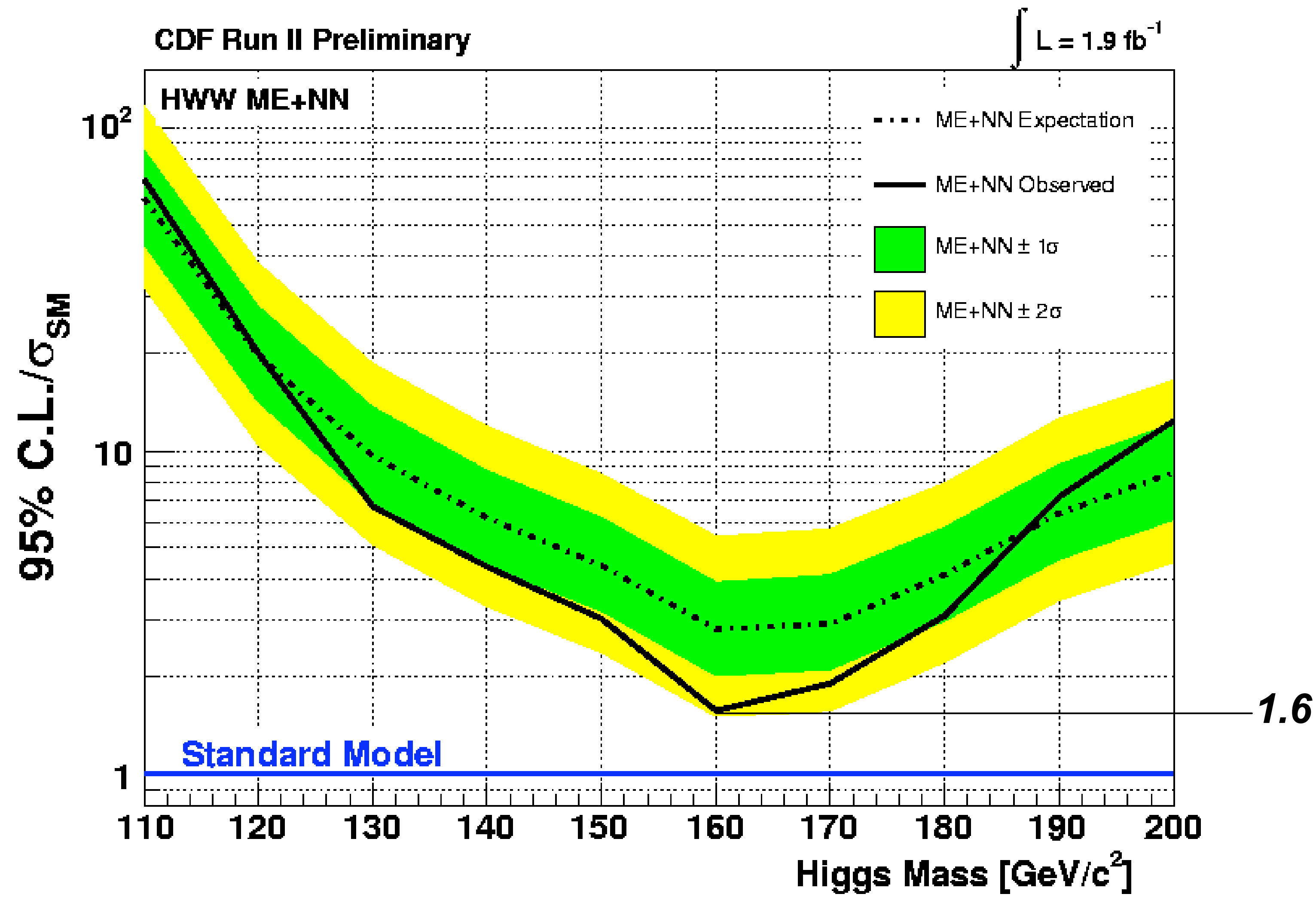
- ***recent hardware upgrades***
- ***clever prescale strategies***
  - – complicate analysis!

CDF limit development

Expected limits



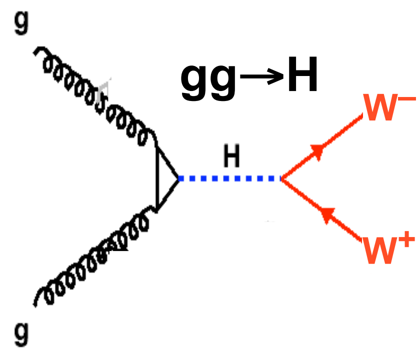
CDF limit

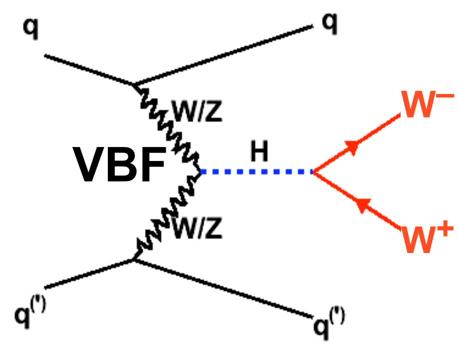


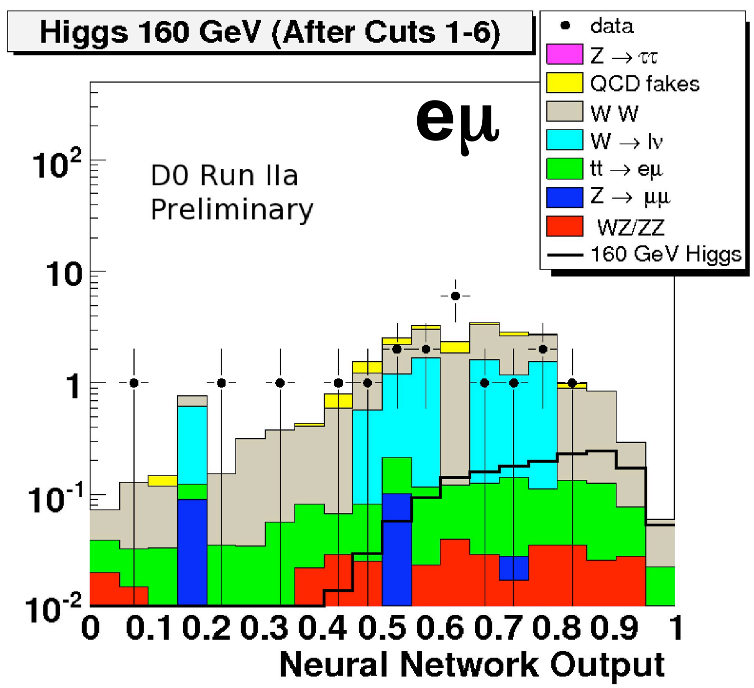
CDF Run II Preliminary
∫ L = 1.9 fb^{-1}
HWW ME+NN
ME+NN Expectation
ME+NN Observed
ME+NN ± 1σ
ME+NN ± 2σ
1.6
Standard Model
10^2
10
1
110
120
130
140
150
160
170
180
190
200
Higgs Mass [GeV/c^2]
95% C.L./σ_{SM}

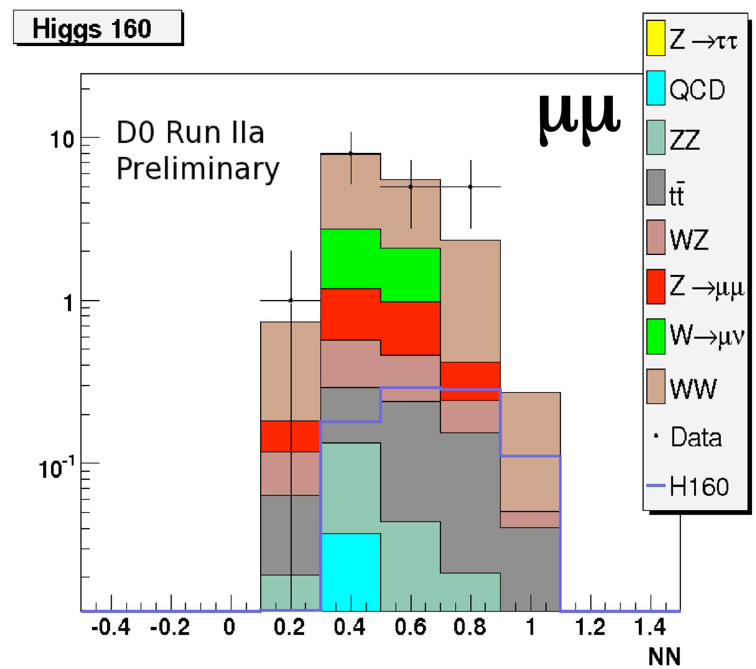
D0 H→WW (e/μ)

- ee, eμ channels 1.1fb^{-1} ; μμ channel 1.7fb^{-1}
- includes VBF









CDF Run II Preliminary $\int \mathcal{L} = 1.9 fb^{-1}$

$M_H(GeV/c^2)$	110	120	130	140	150	160	170	180	190	200
$-2\sigma/\sigma_{SM}$	32.0	10.4	5.1	3.3	2.4	1.5	1.6	2.2	3.4	4.5
$-1\sigma/\sigma_{SM}$	43.2	14.1	6.8	4.4	3.2	2.0	2.1	3.0	4.6	6.1
Median/σ_{SM}	**60.5**	**19.7**	**9.6**	**6.2**	**4.4**	$\boxed{\textbf{2.8}}$	**2.9**	**4.1**	**6.4**	**8.6**
$+1\sigma/\sigma_{SM}$	85.2	28.1	13.7	8.7	6.2	3.9	4.1	5.8	9.1	12.2
$+2\sigma/\sigma_{SM}$	117.2	38.2	18.7	12.0	8.5	5.4	5.7	8.0	12.6	16.6
Observed/σ_{SM}	**69.2**	**20.1**	**6.7**	**4.4**	**3.0**	**1.6**	**1.9**	**3.1**	**7.2**	**12.4**

HWW ME+NN

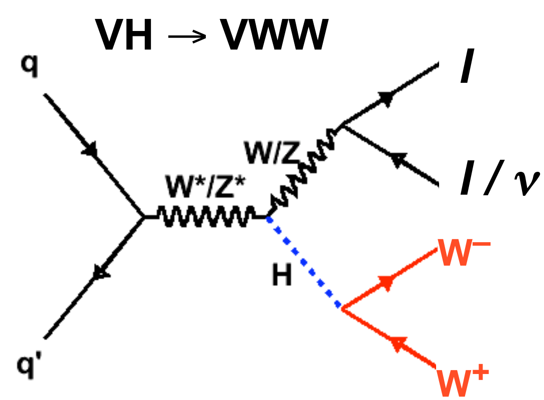
D0 RunIIa+b Preliminary

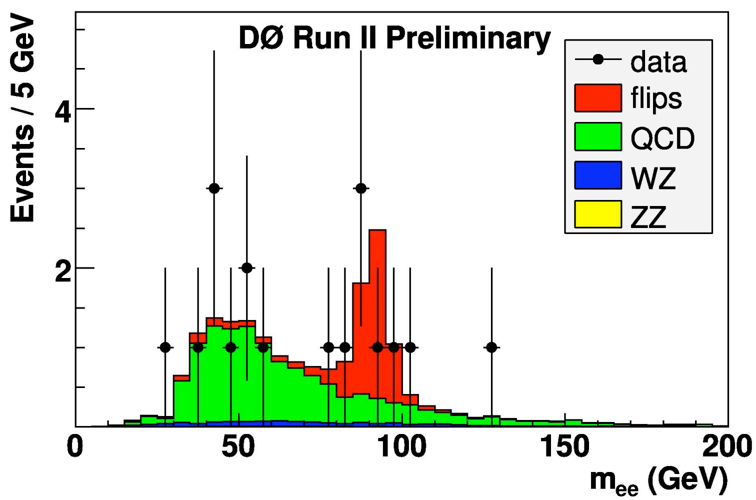
m_H (GeV)	120	140	160	180	200
Median /σ_{SM}	22.2	6.7	$\boxed{2.8}$	4.4	9.7
Observed /σ_{SM}	47.3	12.0	2.4	4.7	11.1

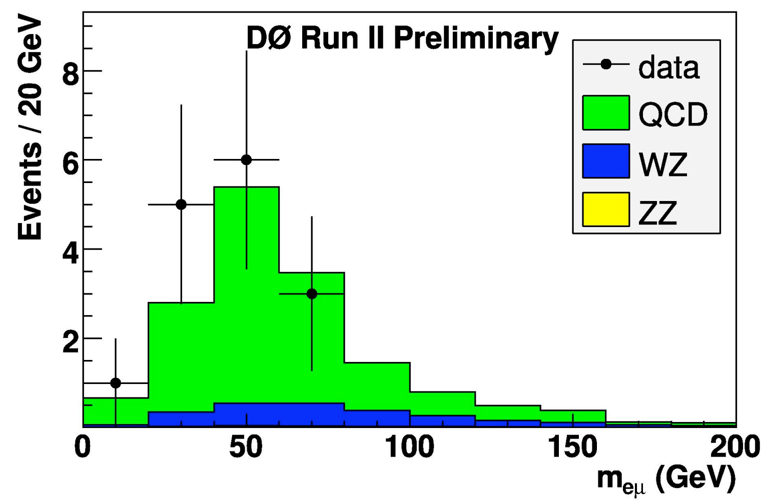
D0: Other channels

- **H→WW $\mu\tau_{had}$ channel 1fb^{-1}**
  – select τ using neural net
  – event likelihoods to separate signal
  (not currently contributing to overall limit)

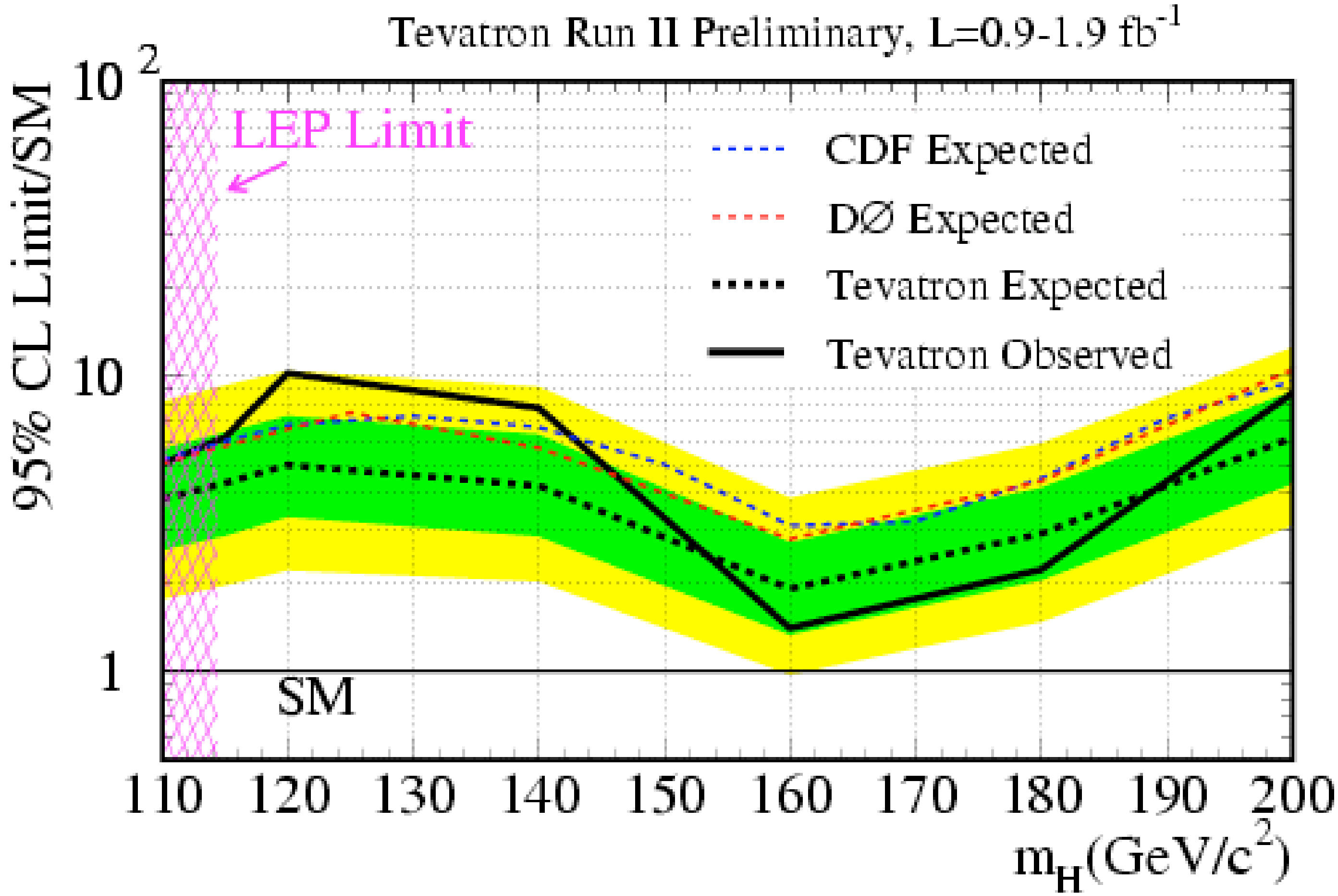
- **VH→VWW 1.1fb^{-1}**
  search for $l^{\pm}\nu l'^{\pm}\nu$+X (like-sign dileptons)
  2d likelihood: physics/instrumental backgrounds







Current limit



Improving sensitivity: high m_H

High mass Higgs (~160 GeV)

%'s are in sensitivity

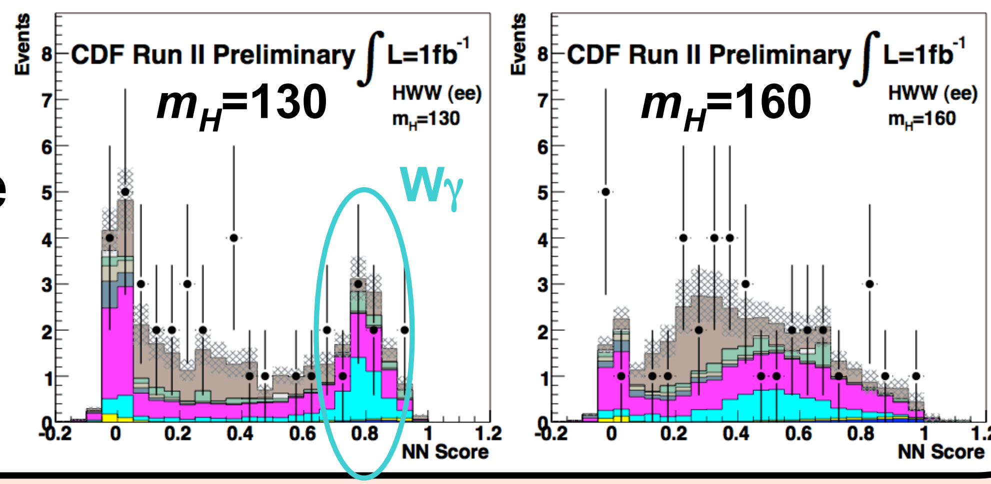
CDF range of achievable improvements

- 10-20% from hadronic taus in W decay (including better id)
  - Ongoing studies
- 25-40% VH→VWW and VBF (jj in final state)
  - Expect good S/B
  - Ongoing studies
- 10-15% more triggers (existing triggers)+ more leptons

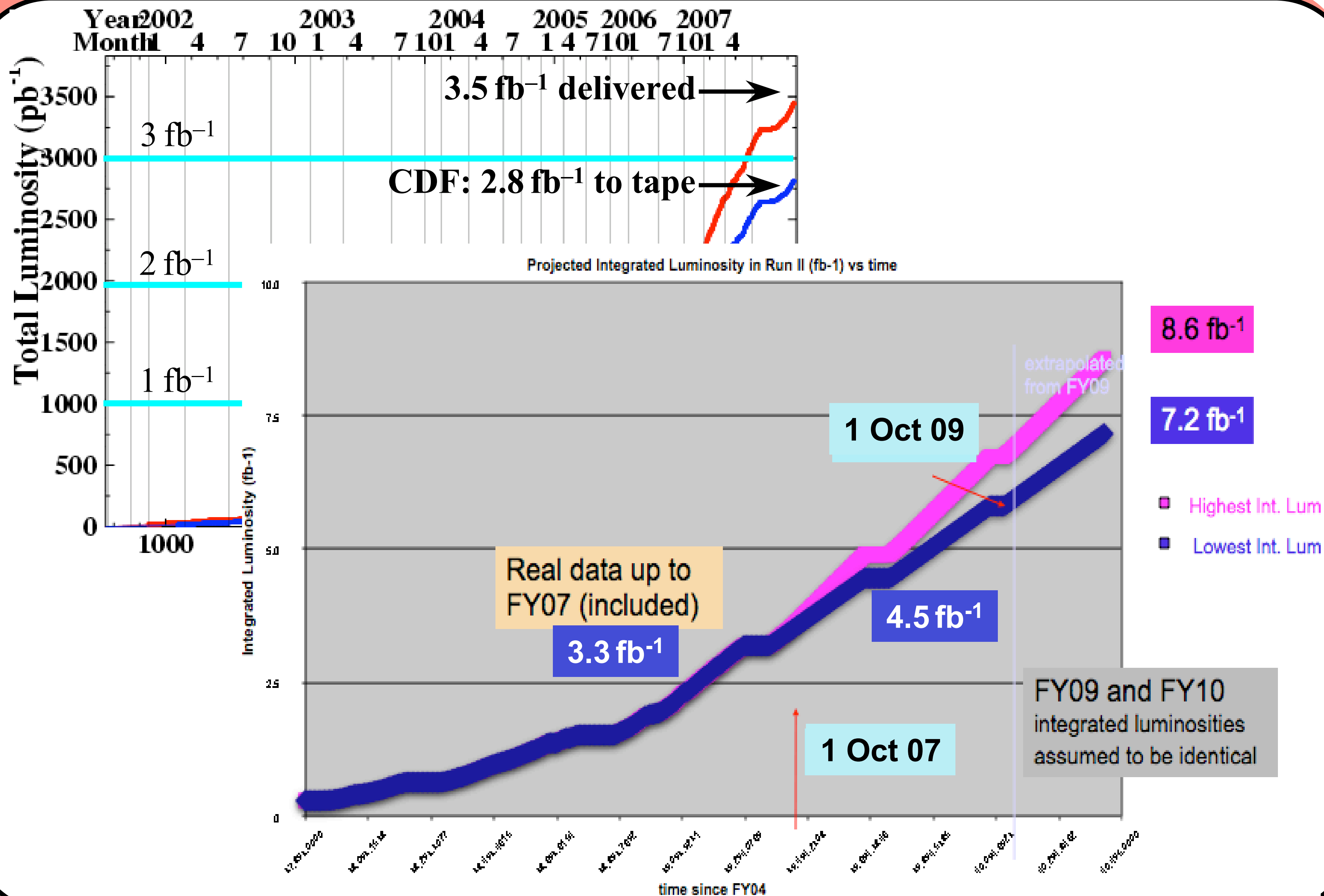
Improvements from x1.5 to x2 in sensitivity
All improvements validated on analysis/studies with real data/tools

+ Increase WW analysis sensitivity at lower masses

ee



Luminosity

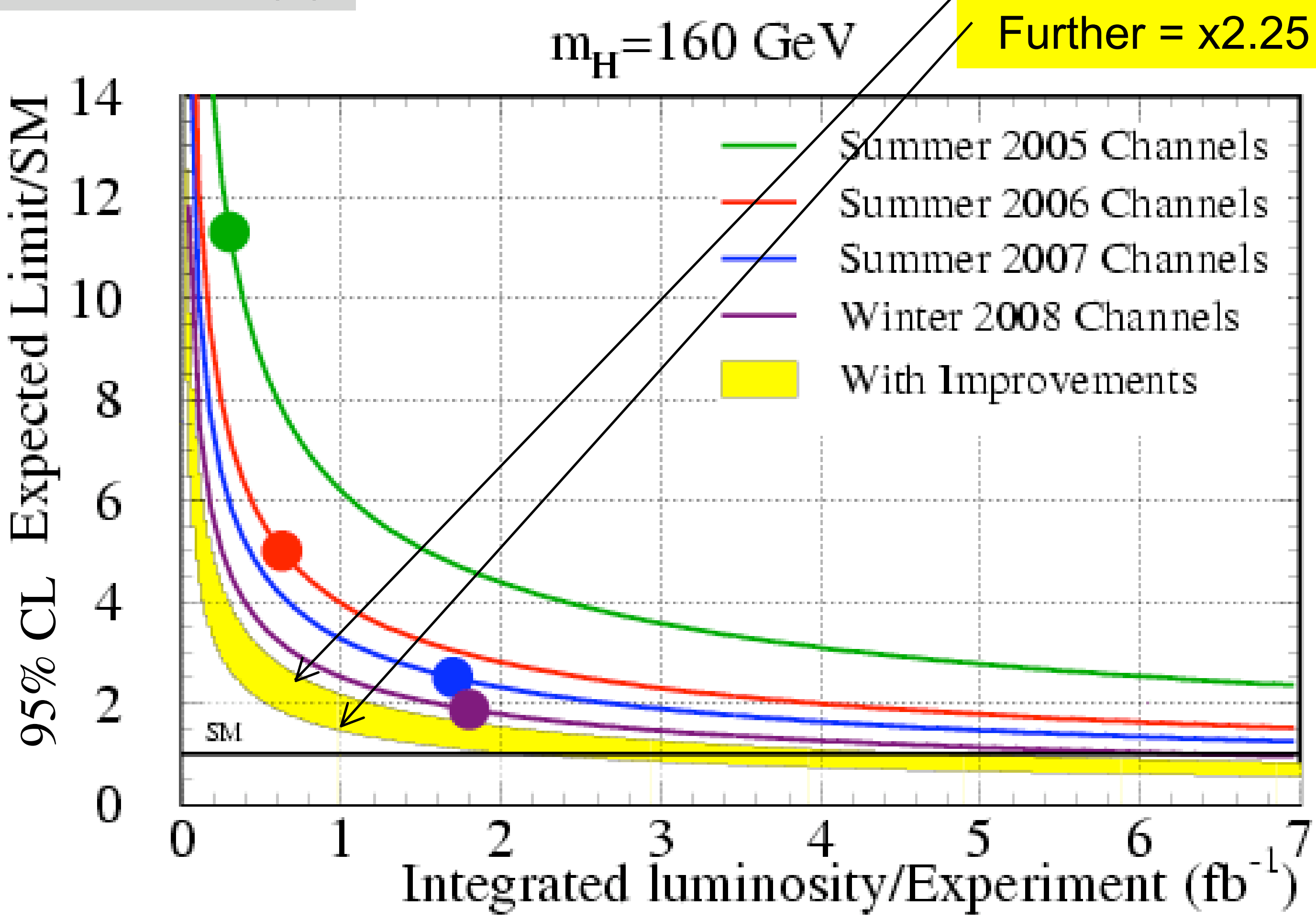


Year 2002 2003 2004 2005 2006 2007
Month 1 4 7 10 1 4 7 10 1 4 7 1 4 7 10 1 7 10 1 4
Total Luminosity (pb^{-1})
3.5 fb^{-1} delivered
CDF: 2.8 fb^{-1} to tape
3 fb^{-1}
2 fb^{-1}
1 fb^{-1}
Projected Integrated Luminosity in Run II (fb-1) vs time
Integrated Luminosity (fb-1)
time since FY04
8.6 fb^{-1}
7.2 fb^{-1}
extrapolated from FY09
Highest Int. Lum
Lowest Int. Lum
1 Oct 09
Real data up to FY07 (included)
3.3 fb^{-1}
4.5 fb^{-1}
1 Oct 07
FY09 and FY10 integrated luminosities assumed to be identical

Achievable Sensitivity

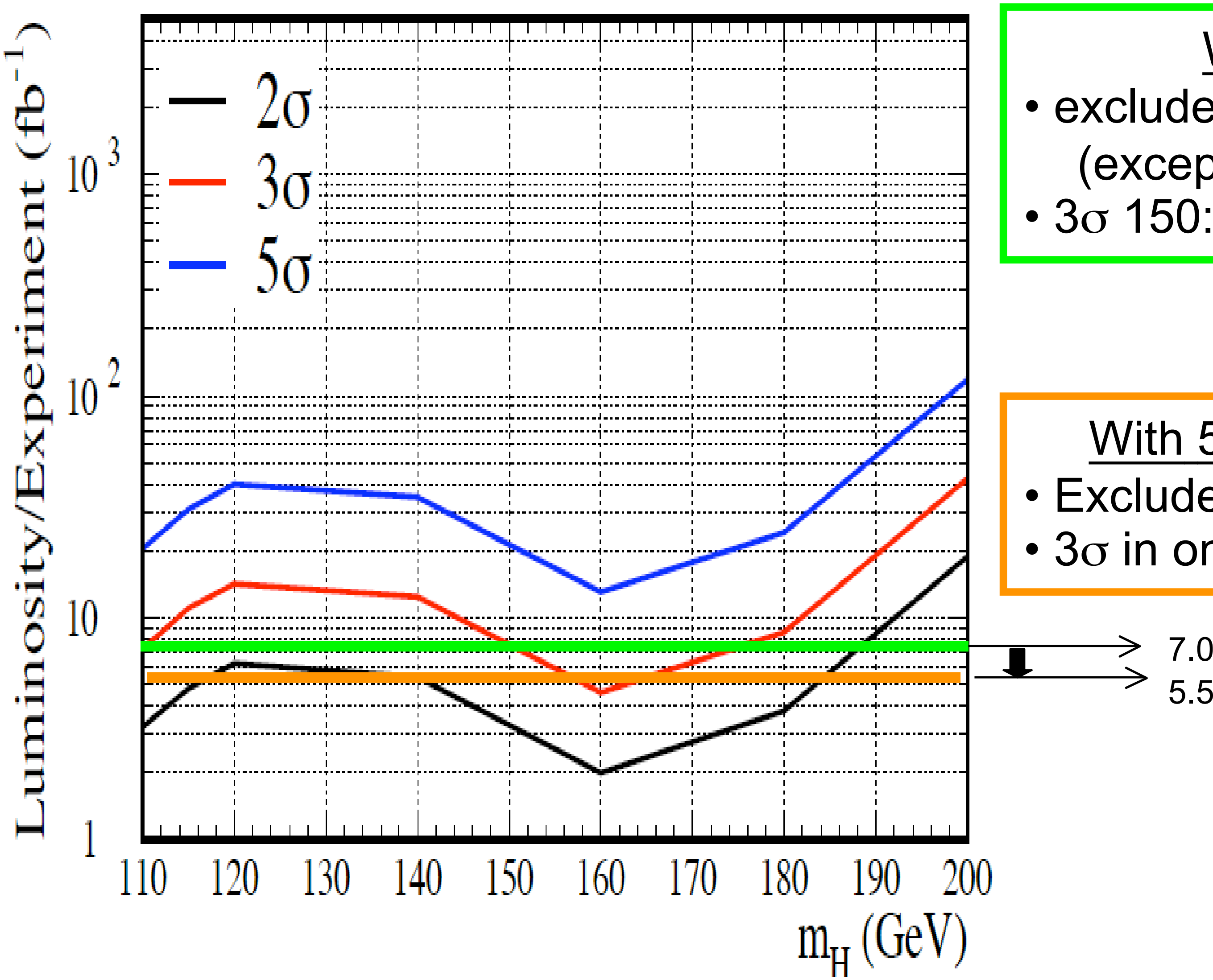
CDF+D0 combined
- curves are sqrt(L)

Sensitivity factors
Minimum = x1.5
Further = x2.25



Backup...

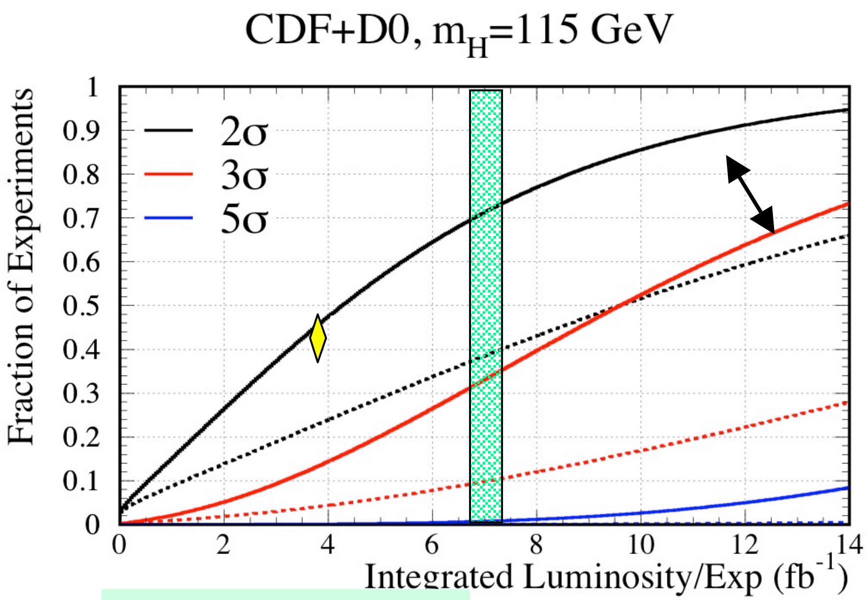
Exclusion region grows



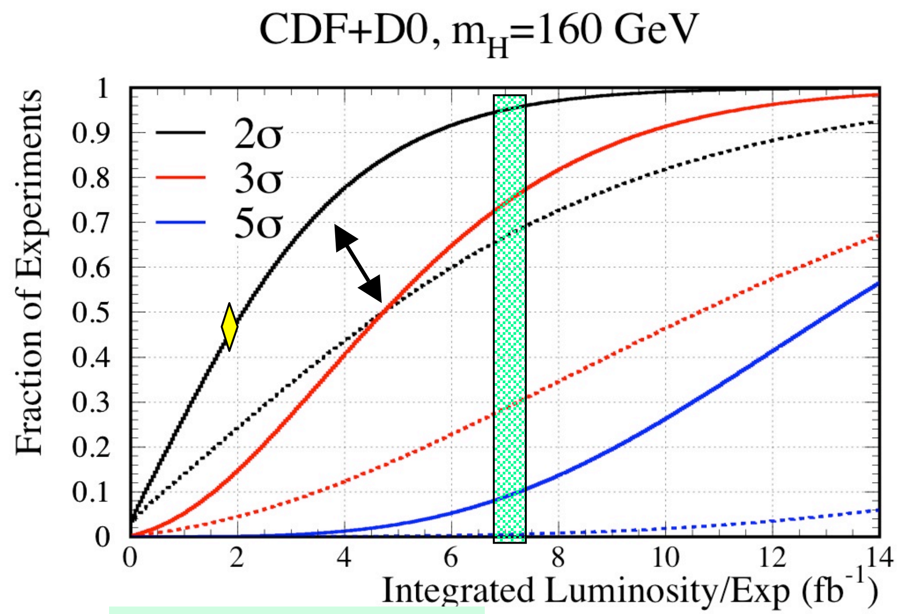
With 7 fb^{-1}
- exclude all masses (except real mass)
- 3σ 150:170

With 5.5 fb^{-1} tougher:
- Exclude 140:180 range
- 3σ in one point: 160

Do we have to get lucky?



Analyzed Lum.



Analyzed Lum.

Solid lines = 2.25 improvement
Dash lines = 1.50 improvement

<u>“further” @ 115 GeV</u>

7 fb^{-1} => 70% experiments w/2σ
30% experiments w/3σ

<u>“further” @ 160 GeV</u>

7 fb^{-1} => 95% experiments w/2σ
75% experiments w/ 3σ

October 2007

~~March 2007~~

Scenario from ~~Feb 2006~~

2008

~~LHC 2007: Pilot Run, Z,W calib? 200pb^{-1}~~

~~2009~~ 2010

LHC ~~2008~~: Physics, 1fb^{-1}

2008

Tev ~~2007~~: 4fb^{-1} : HWW 4x3: at SM limit in the 140-170 range. TOP and W Mass improved as well, so SM fit limits narrower.

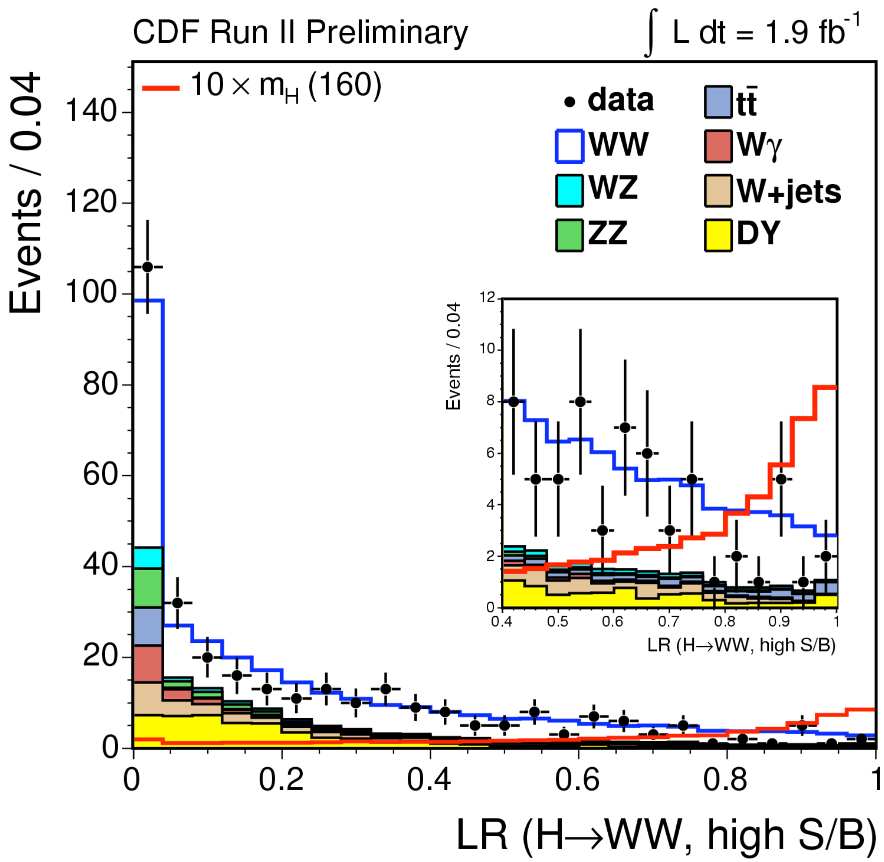
- Deviations building from expected limit: we focus on this range for ATLAS ~~2009~~. Perhaps SM fit narrowing on this range.
- Higgs is 130-150 OR 170-185. Perhaps SM Fit excludes upper range.

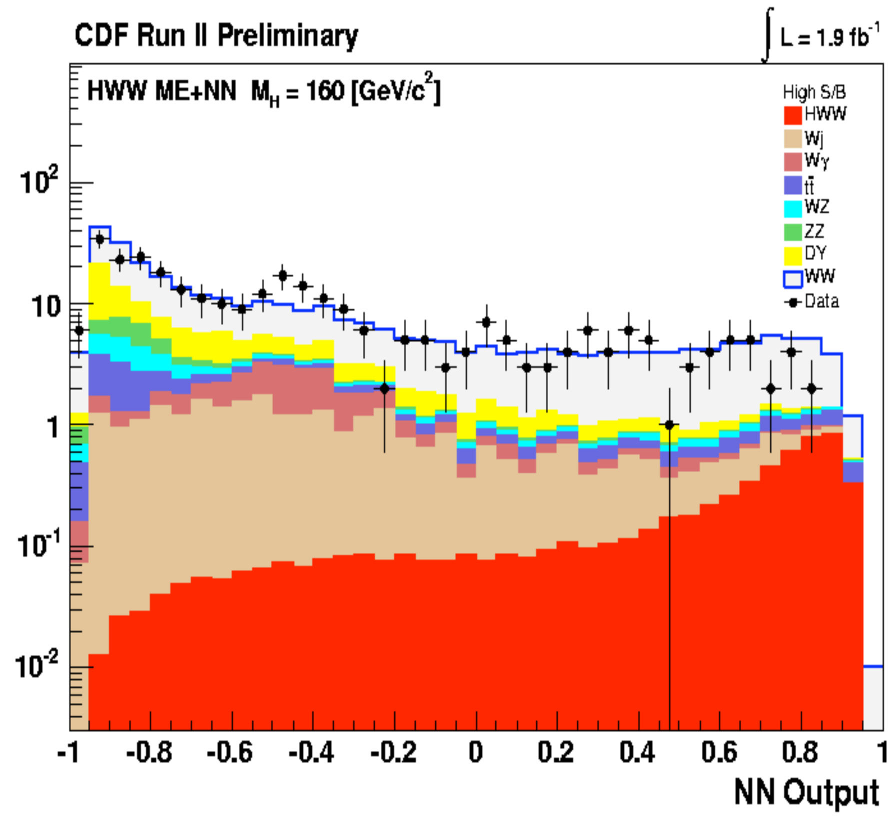
Tev 2009: 3σ at 116: ATLAS ~~2011~~? for discovery.

CDF keeps running!?

LHC 2010: 10fb^{-1} : Discover it for > 130.

CDF H →WW





expected signal events

CDF Run II Preliminary $\int \mathcal{L} = 1.9 fb^{-1}$

Category	Higgs Mass (GeV)									
	110	120	130	140	150	160	170	180	190	200
High S/B	0.3	1.1	2.4	3.9	5.1	6.3	6.2	5.0	3.6	2.8
Low S/B	0.1	0.3	0.6	0.9	1.2	1.4	1.4	1.2	0.9	0.7

HWW ME+NN

Systematics: CDF H→WW

%	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Higgs
$\not{E}_T$ Modeling	1.0	1.0	1.0	1.0	20.0	1.0	-	1.0
Conversions	-	-	-	-	-	20.0	-	-
NLO Acceptance	5.5	10.0	10.0	10.0	5.0	10.0	-	10.0
Cross-section	10.0	10.0	10.0	15.0	5.0	10.0	-	-
PDF Uncertainty	1.9	2.7	2.7	2.1	4.1	2.2	-	2.2
LepId $\pm 1\sigma$	1.5	1.4	1.3	1.5	1.5	1.2	-	1.5
Trigger Eff	2.1	2.1	2.1	2.0	3.4	7.0	-	3.3
Total	11.9	14.7	14.6	18.4	21.9	25.6	22.5	10.9

Systematics: D0 H→WW

DØ: $H \to WW \to \ell^{\pm}\ell'^{\mp}$ Analysis

Contribution	H	Diboson	$Z/\gamma^* \to \ell\ell$	$W + jet/\gamma$	$t\bar{t}$	QCD
Lepton ID .	$^{+8}_{-5}$	$^{+8}_{-5}$	$^{+8}_{-5}$	$^{+8}_{-5}$	$^{+8}_{-5}$	–
Momentum smearing	2–11	2–11	2–11	2–11	2–11	–
Trigger	5	5	5	5	5	–
Jet Energy Scale	5	10	10	10	10	–
Cross Section	4	4	4	4	4	–
PDF Uncertainty	4	4	4	4	4	–
Normalization	–	–	–	20	–	20

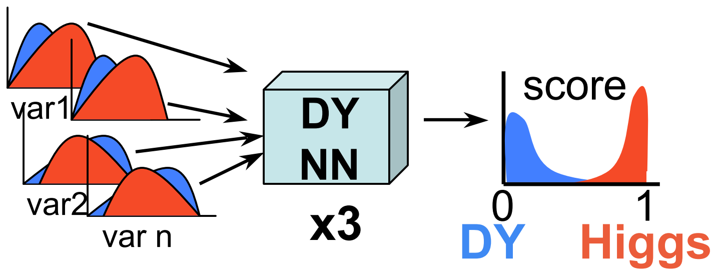
Systematics: WH→WWW

DØ: $WH \to WWW \to \ell^{\pm}\ell'^{\pm}$ Analysis.

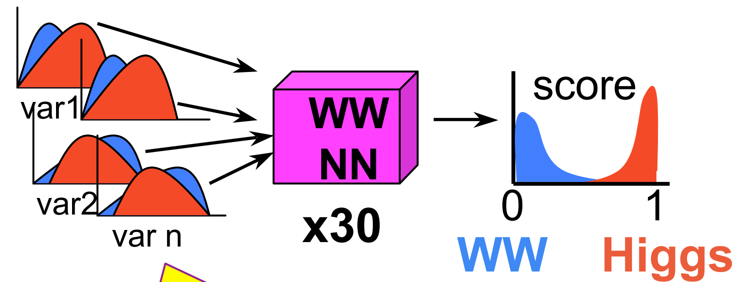
Contribution	WH	WZ/ZZ	Charge flips	QCD
Lepton ID/Reco. eff	10	10	0	0
Trigger eff.	5	5	0	0
Cross Section	6	7	0	0
Normalization	0	6	0	0
Instrumental-ee (ee final state)	0	0	32	15
Instrumental-em ($e\mu$ final state)	0	0	0	18
Instrumental-mm ($\mu\mu$ final state)	0	0	${}^{+290}_{-100}$	32

Neural network method TMVA

- Use TMVA neural nets twice
- Train on Drell-Yan and Higgs m_H=160 ee,eμ,μμ

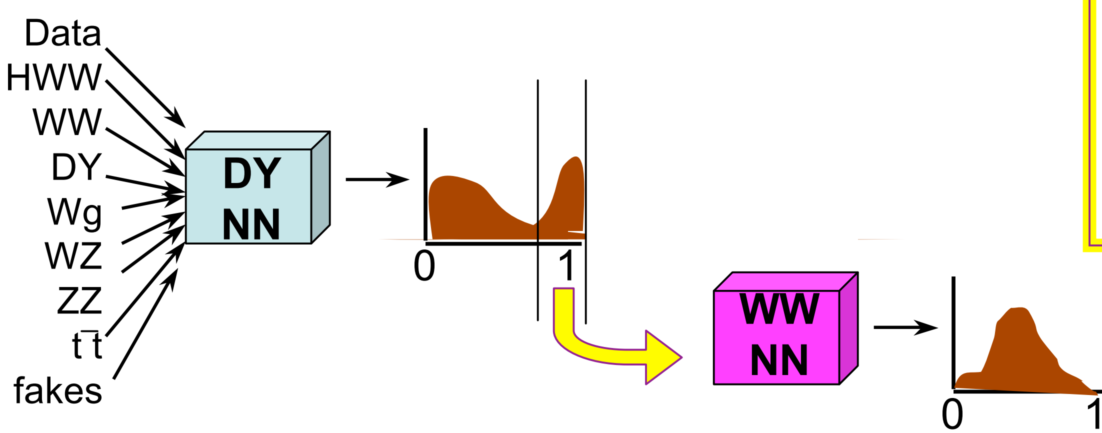


- Train on WW and Higgs m_H=110,120…160…200; ee,eμ,μμ



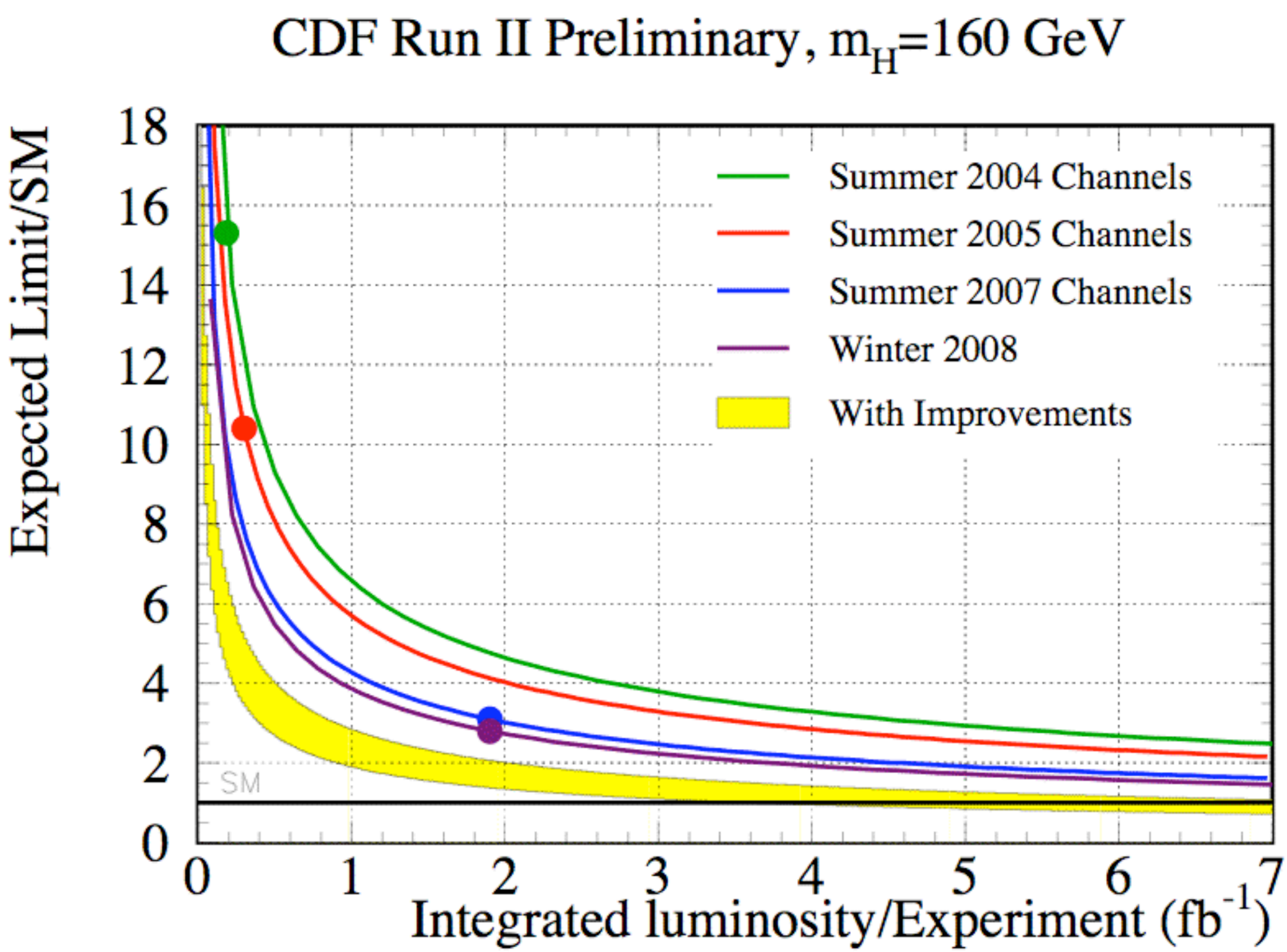
$\not{E}_T$	E_T^{jet1}
ΣE_T	$\Delta R_{\text{leptons}}$
m_{ll}	$\Delta\phi_{\text{leptons}}$
E^{lep1}	$\Delta\phi\,\not{E}_{T\text{ lep or jet}}$
E^{lep2}	E_T^{jet2}
$\not{E}_T\text{sig}$	N_{jets}

- Pass signal/data/background through DY–H net
- Cut
- Pass remaining events through WW–H net



- Fit templates

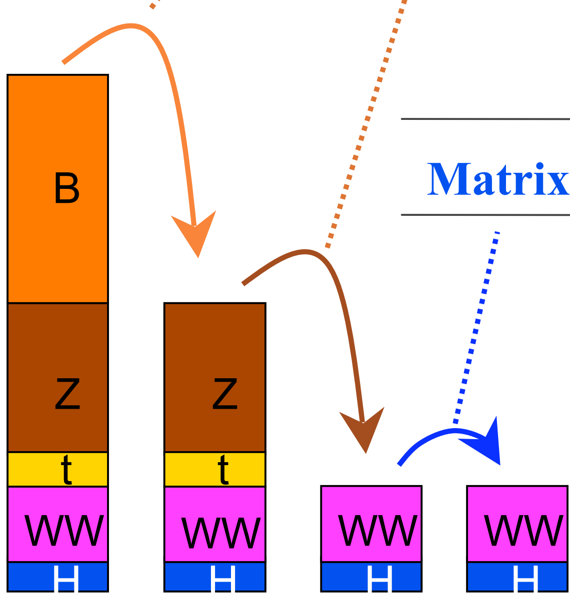
Achievable sensitivity (CDF only)



Selection

Matrix Element	*Neural Net*
Isolation 20GeV/10GeV	
m_{ll}>25 GeV	m_{ll}>16 GeV
Metspecial >25(ee,μμ) >15(eμ) Njets<=1	Njets(E_T>15)=0 || Njets(E_T<55)=1 || Njets(E_T<40)=2 DY–Higgs neural net
Matrix element discriminator	WW–Higgs neural net

Cosmic rejection
Opposite sign



Selection

Leptons:

Matrix element

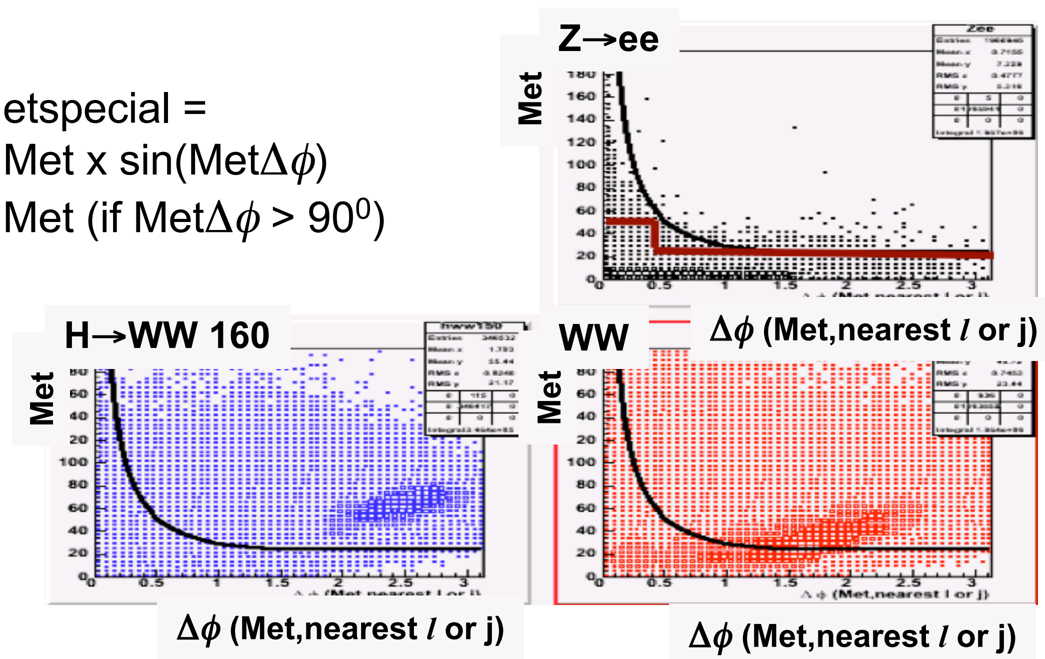
Using extended lepton coverage from WZ observation

Neural net

Using standard leptons

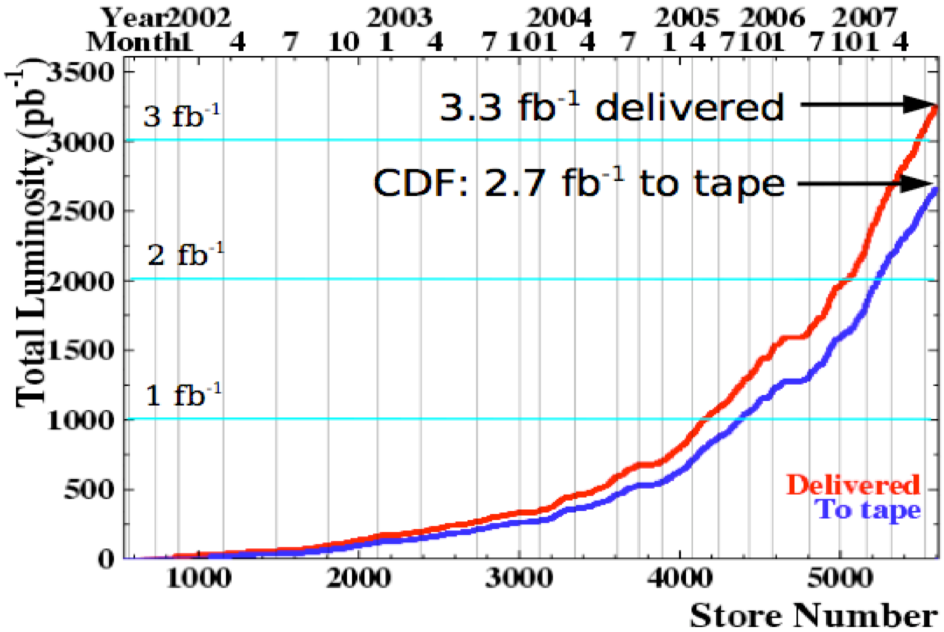
"Metspecial":
(Matrix element)

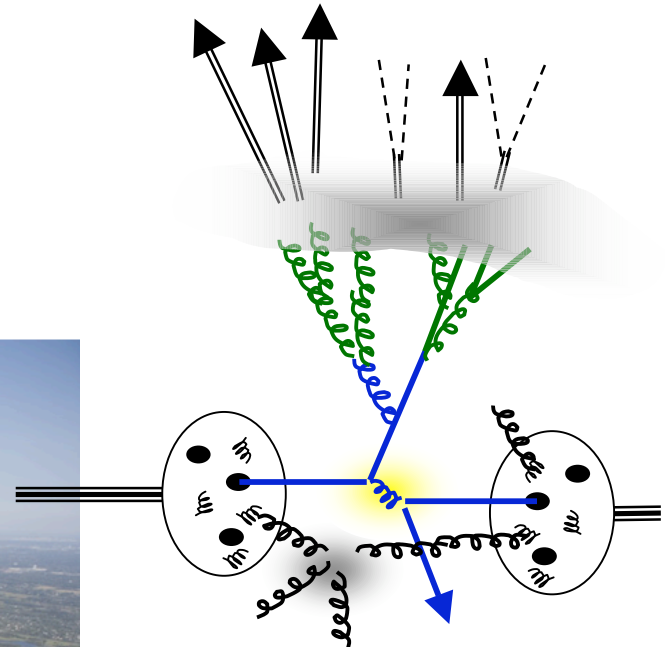
Metspecial =
  Met x sin(Met$\Delta\phi$)
  Met (if Met$\Delta\phi > 90^0$)



Avoid Met pointing along lepton or jet direction

Tevatron

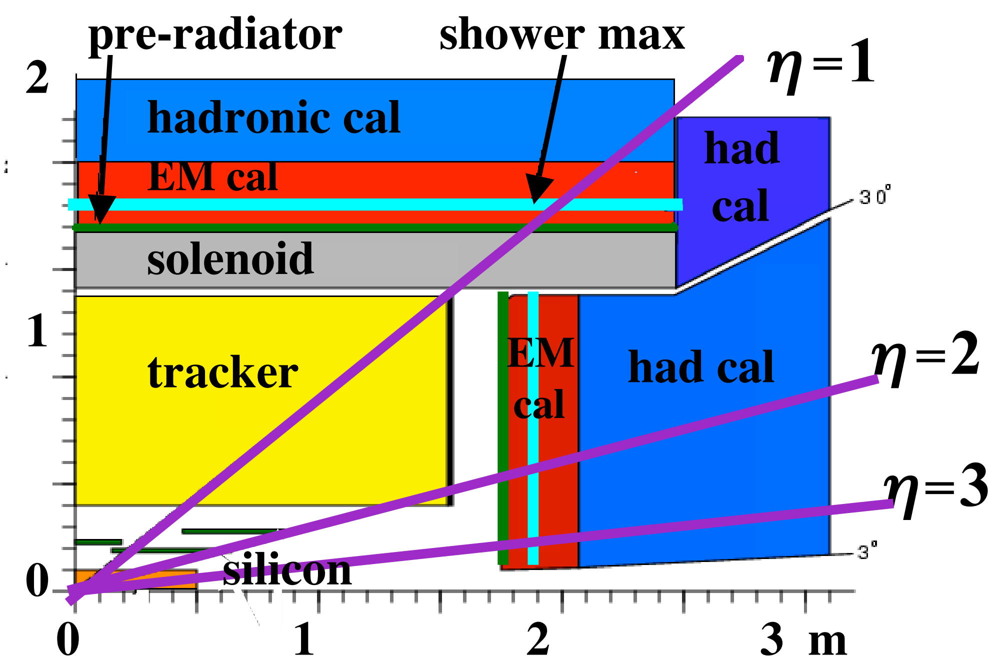


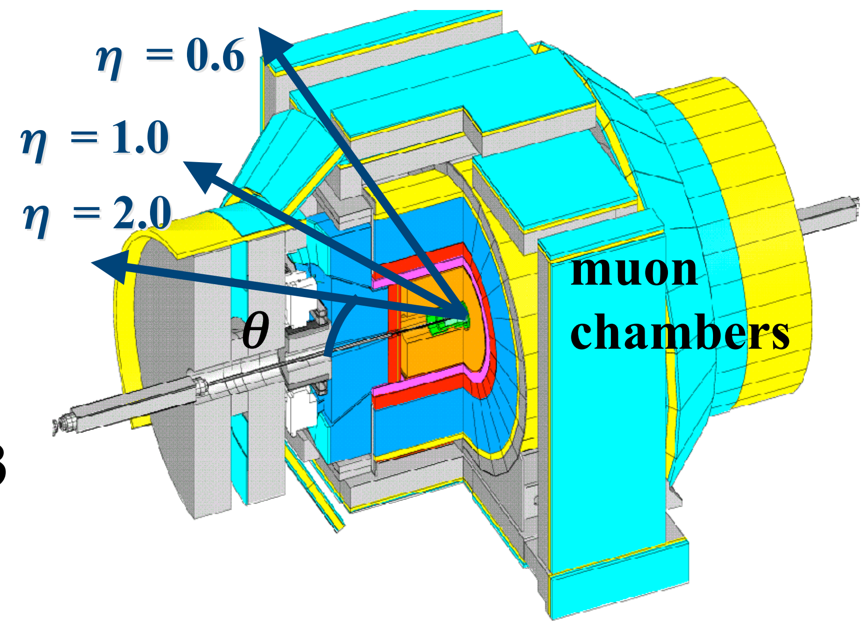


proton–antiproton

$\sqrt{s}$ = 1.96TeV

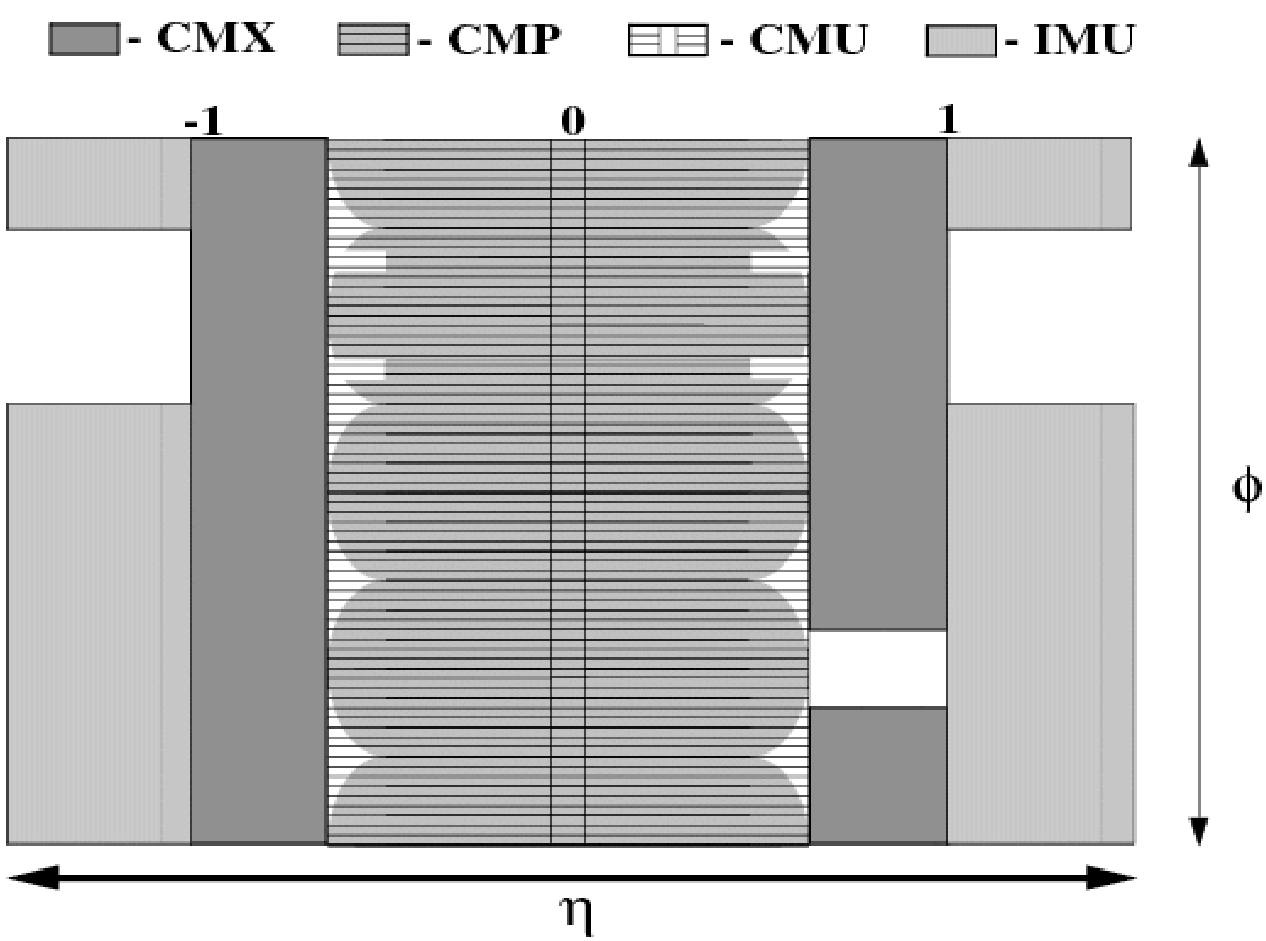
CDF



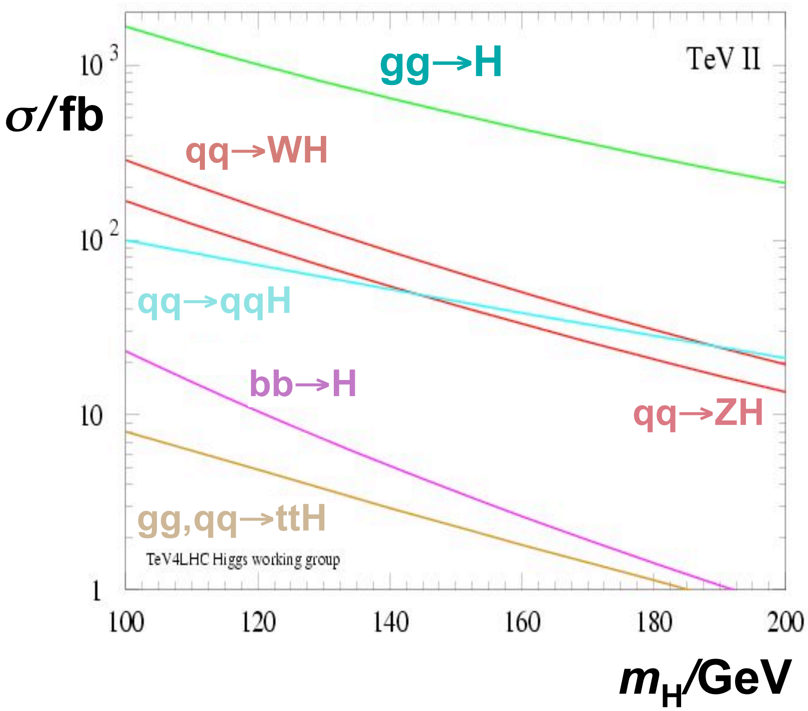


Drift chamber to $|\eta|<1$
Further tracking from Si
Calorimeter to $|\eta|<3$
Muon system to $|\eta|<1.5$

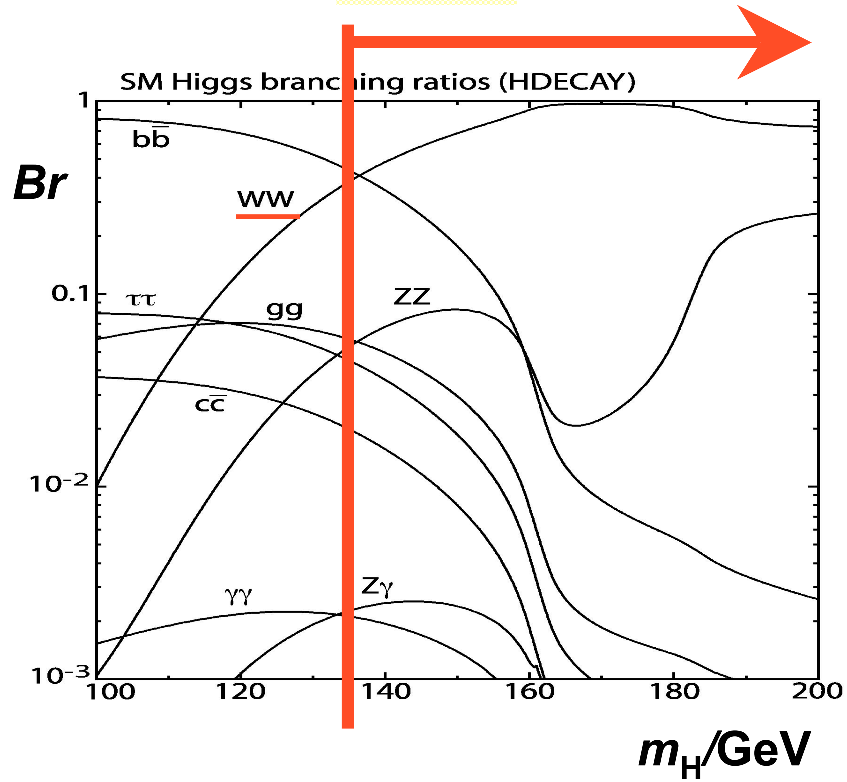
CDF muon patchwork

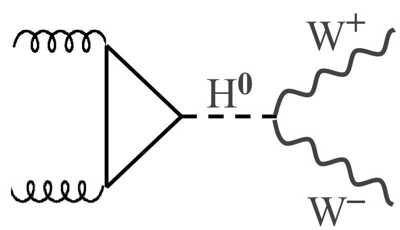


Production



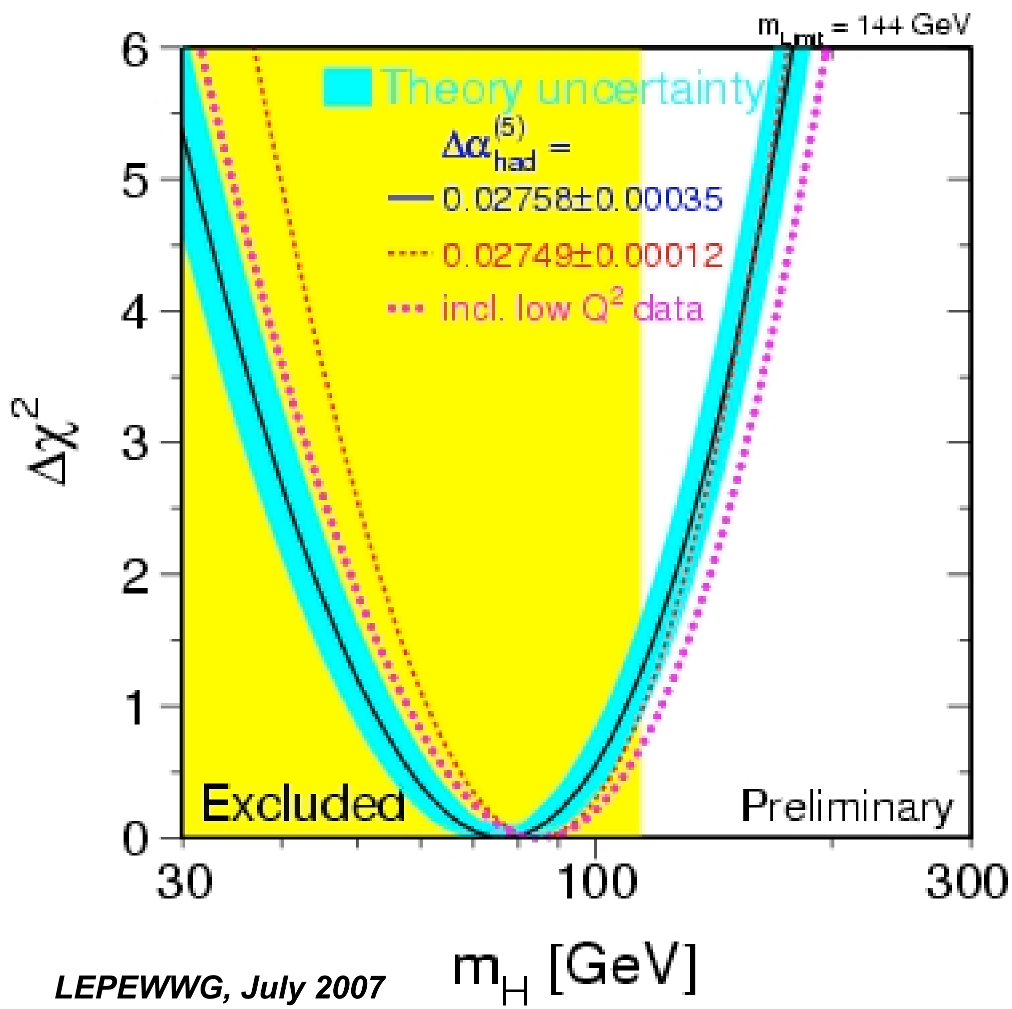
Decay





***Br*(W→ lν) ≈ 0.32**
***Br*(W→ jj) ≈ 0.68**

Precision EWK fits

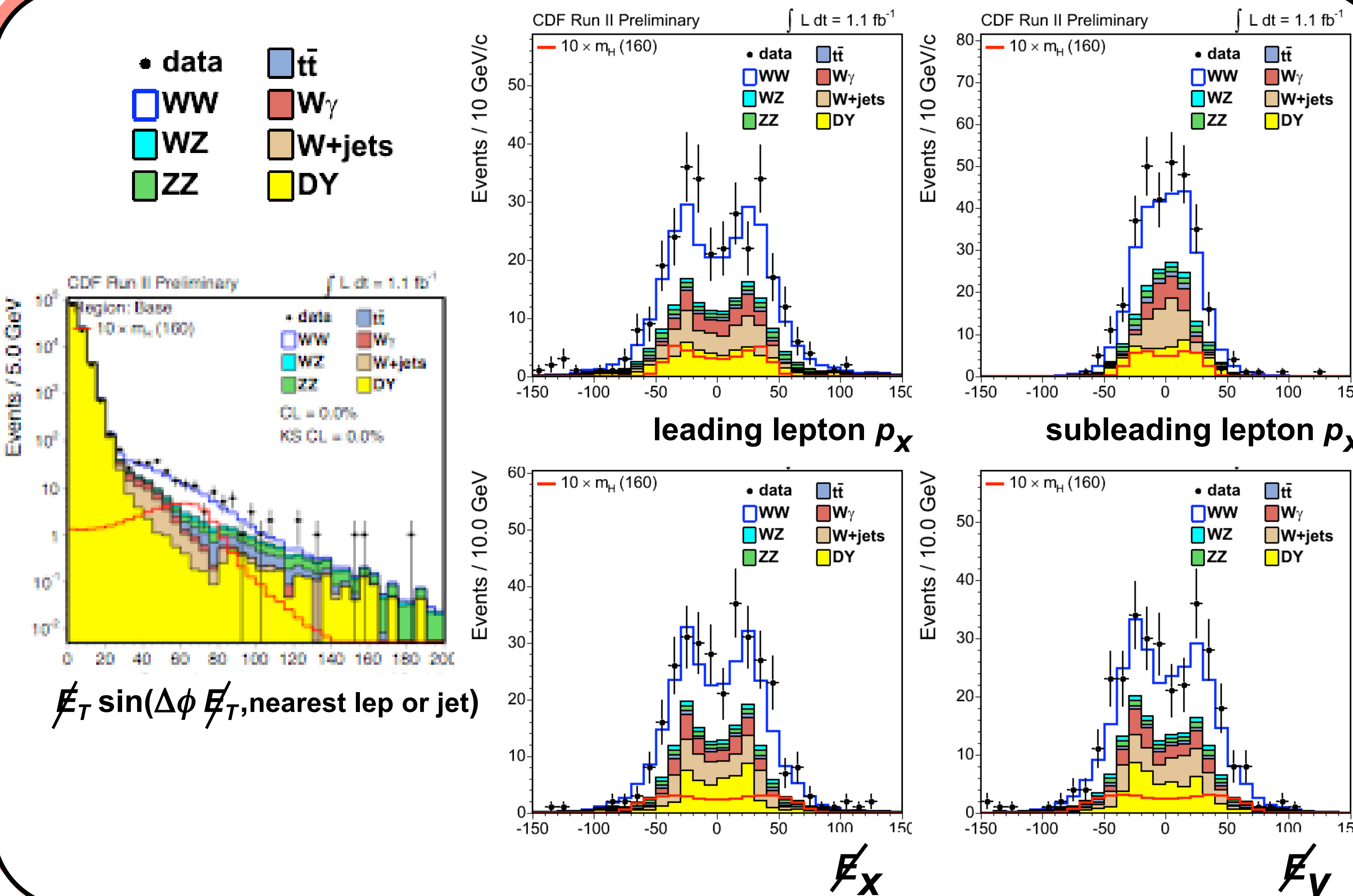


LEPEWWG, July 2007

1-sided 95%CL upper limit 144 GeV

increases to 182 GeV including LEP direct exclusion to 114GeV

ME Input Variables



Higgs yields

Category	Higgs Mass (GeV) 110	120	130	140	150	160	170	180	190	200
$e\ e$	0.1	0.3	0.6	0.9	1.2	1.4	1.4	1.1	0.8	0.6
$e\ \mu$	0.2	0.6	1.3	2.0	2.6	3.1	3.0	2.5	1.8	1.4
$\mu\ \mu$	0.1	0.2	0.5	0.8	1.1	1.3	1.3	1.0	0.7	0.6
e trk	0.0	0.2	0.4	0.7	0.9	1.2	1.2	1.0	0.7	0.6
μ trk	0.0	0.1	0.2	0.4	0.6	0.8	0.7	0.6	0.4	0.3
Total	0.4	1.3	3.0	4.8	6.4	$\boxed{7.8}$	7.6	6.2	4.4	3.5

Matrix element analysis 2/fb

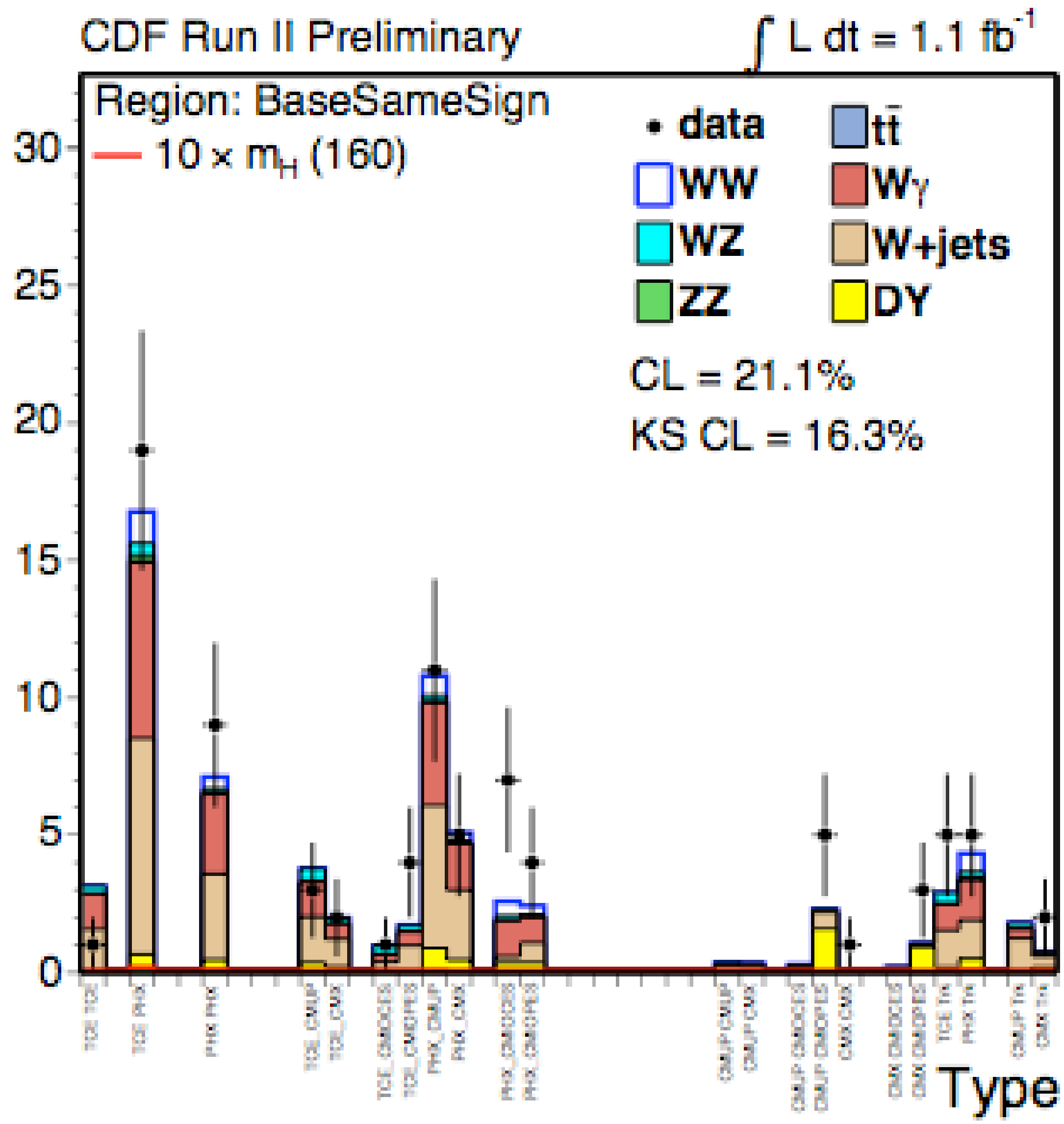
Category	m_H / GeV 110	120	130	140	150	160	170	180	190	200
ee	0.0	0.1	0.3	0.5	0.6	0.7	0.7	0.6	0.4	0.4
$e\mu$	0.1	0.3	0.6	1.0	1.3	1.6	1.6	1.3	1.0	0.8
$\mu\mu$	0.0	0.1	0.2	0.4	0.5	0.6	0.6	0.5	0.4	0.3
e trk	0.0	0.1	0.2	0.3	0.5	0.6	0.6	0.5	0.4	0.3
μ trk	0.0	0.0	0.1	0.2	0.3	0.4	0.4	0.3	0.2	0.2
total	0.2	0.6	1.4	2.4	3.2	$\boxed{3.9}$	3.9	3.3	2.4	2.0

Matrix element analysis 1/fb

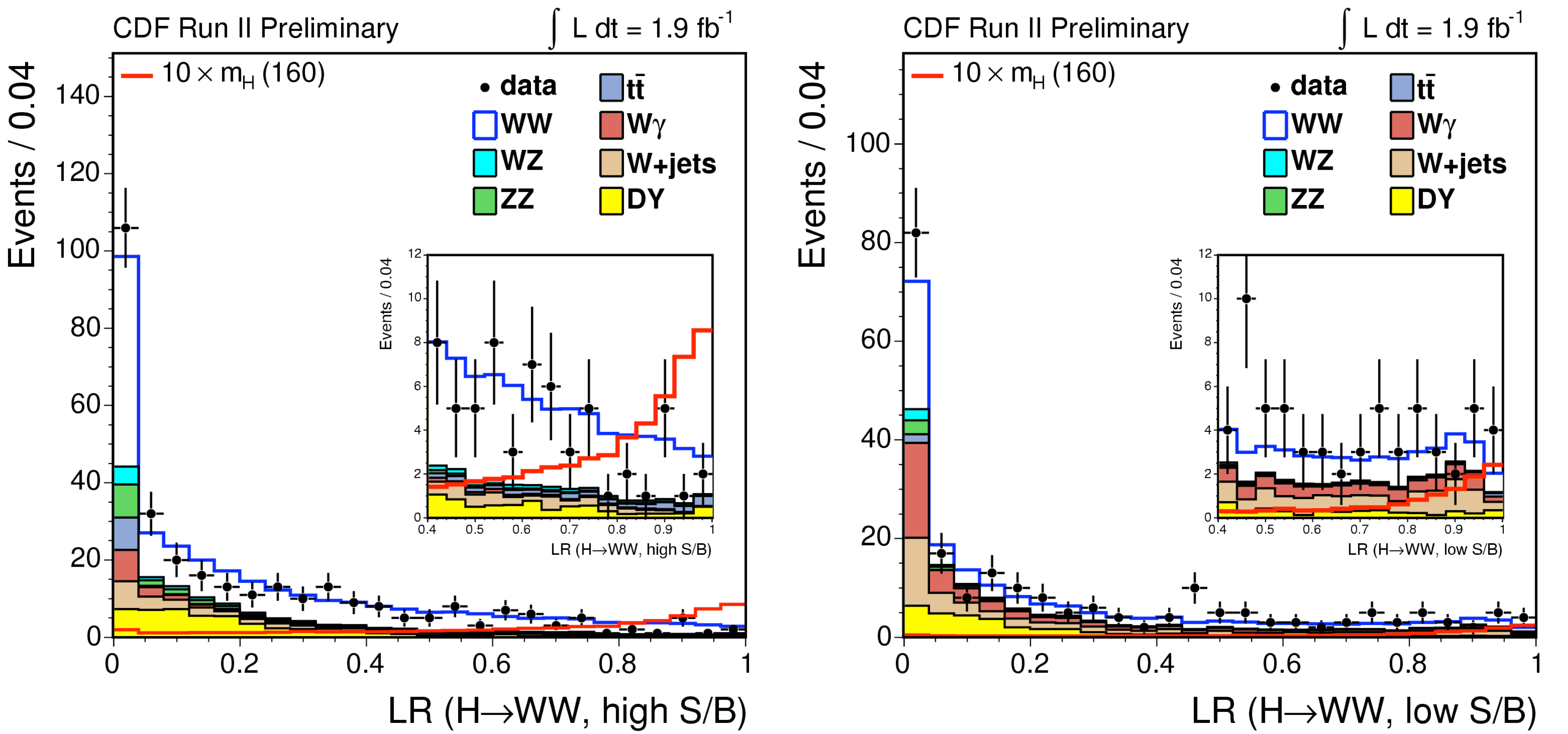
Category	m_H / GeV 110	120	130	140	150	160	170	180	190	200
ee	0.0	0.1	0.2	0.4	0.5	0.6	0.6	0.4	0.3	0.2
$e\mu$	0.1	0.2	0.2	0.3	0.4	0.6	0.6	0.4	0.3	0.2
$\mu\mu$	0.0	0.1	0.2	0.3	0.4	0.6	0.6	0.4	0.3	0.2
total	0.2	0.3	0.9	1.5	1.9	$\boxed{2.5}$	2.4	1.8	1.3	0.9

Neural net analysis 1/fb

ME same sign


CDF Run II Preliminary
$\int L\,dt = 1.1\ fb^{-1}$
Region: BaseSameSign
10 × m_H (160)
data
$t\bar{t}$
WW
Wγ
WZ
W+jets
ZZ
DY
CL = 21.1%
KS CL = 16.3%
Type

ME Likelihood Ratio



Systematics

Dilepton Process	Source	Uncertainty(%)
All	Correlated Luminosity	4
	Uncorrelated Luminosity	4
	Lepton Trigger	1
	Track Isolation	2
Higgs	α_s	3
	NNLO(σ/σ_{SM} only)	10
WW	Jet Veto,PDF/Q^2 on σ_{WW}	8
	Generator	4
Non-WW	Generator	6
	Drell Yan $\not{E}_T$	30
	Drell Yan $M_{ll} < 25\mathrm{GeV}/c^2$	5

(neural net)

Higgs			
Source	Uncertainty (%)		
	ee	e μ	$\mu\mu$
Lepton ID, Trigger,Iso	2.1	1.2	1.2
Non-WW			
Source	Uncertainty (%)		
	ee	e μ	$\mu\mu$
Lepton ID, Trigger,Iso	4.1	3.2	5.8
WW			
Source	Uncertainty (%)		
	ee	e μ	$\mu\mu$
Lepton ID, Trigger,Iso	2.1	1.2	1.2

Shape uncertainties (***neural net***):

- JES
- Lepton Energy Scale
- ISR
- PDF
- Fakes

40 weights stored per event (Higgs and all backgrounds!)

– and similar for matrix element analysis

Systematics

Common uncertainties treated as nuisance parameters:

Luminosity
Track isolation
Higgs: α_s, NNLO
WW: Jet veto, PDF/Q^2, generator
DY: Met modeling, low mass modeling

Shape uncertainties:

Higgs			
Source	Uncertainty (%)		
	ee	$e\mu$	$\mu\mu$
Jet Energy Scale	$-0.0+0.0$	$-0.0+0.0$	$-0.0+0.0$
Lepton Energy Scale	$-0.3-0.4$	$-0.1+0.0$	$-0.0+0.1$
ISR	$-0.6+0.2$	$-0.6+0.2$	$-0.2+0.7$
PDF	$-8.1+8.9$	$-7.7+8.4$	$-7.4+8.2$
Non-WW			
Source	Uncertainty (%)		
	ee	$e\mu$	$\mu\mu$
Jet Energy Scale	$-0.1+2.7$	$-0.4+9.9$	$-0.5+0.8$
Lepton Energy Scale	$-1.0+1.7$	$-0.5+0.2$	$-2.0-0.7$
ISR	$-0.2+0.2$	$-2.2+1.2$	-2.7+1.4
Fakes	± 9.1	± 14.5	± 0.7
PDF	$-4.1+4.9$	$-4.5+5.1$	$-4.4+5.3$
WW			
Source	Uncertainty (%)		
	ee	$e\mu$	$\mu\mu$
Jet Energy Scale	± 0.0	$-0.0+0.0$	$-0.0+0.0$
Lepton Energy Scale	$-0.3-0.3$	$-0.0+0.1$	$-0.0+0.0$
ISR	$-3.8+2.0$	$-3.8+2.0$	$-3.9+2.0$
PDF	$-4.2+4.5$	$-4.3+4.6$	$-4.3+4.7$

NN: low-mass, low m_{ll}

Sensitivity to low m_H from low m_{ll}

n Higgs events	m_H		
	110	160	200
$16 < m_{ll} < 25$	0.05	0.49	0.08
$16 < m_{ll} < 200$	0.21	3.0	1.3
$25 < m_{ll} < 200$	0.16	2.5	1.2
low mass fraction	30%	20%	6%