High Mass Higgs at the Tevatron

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(FNAL)

On behalf of CDF and D0 collaborations

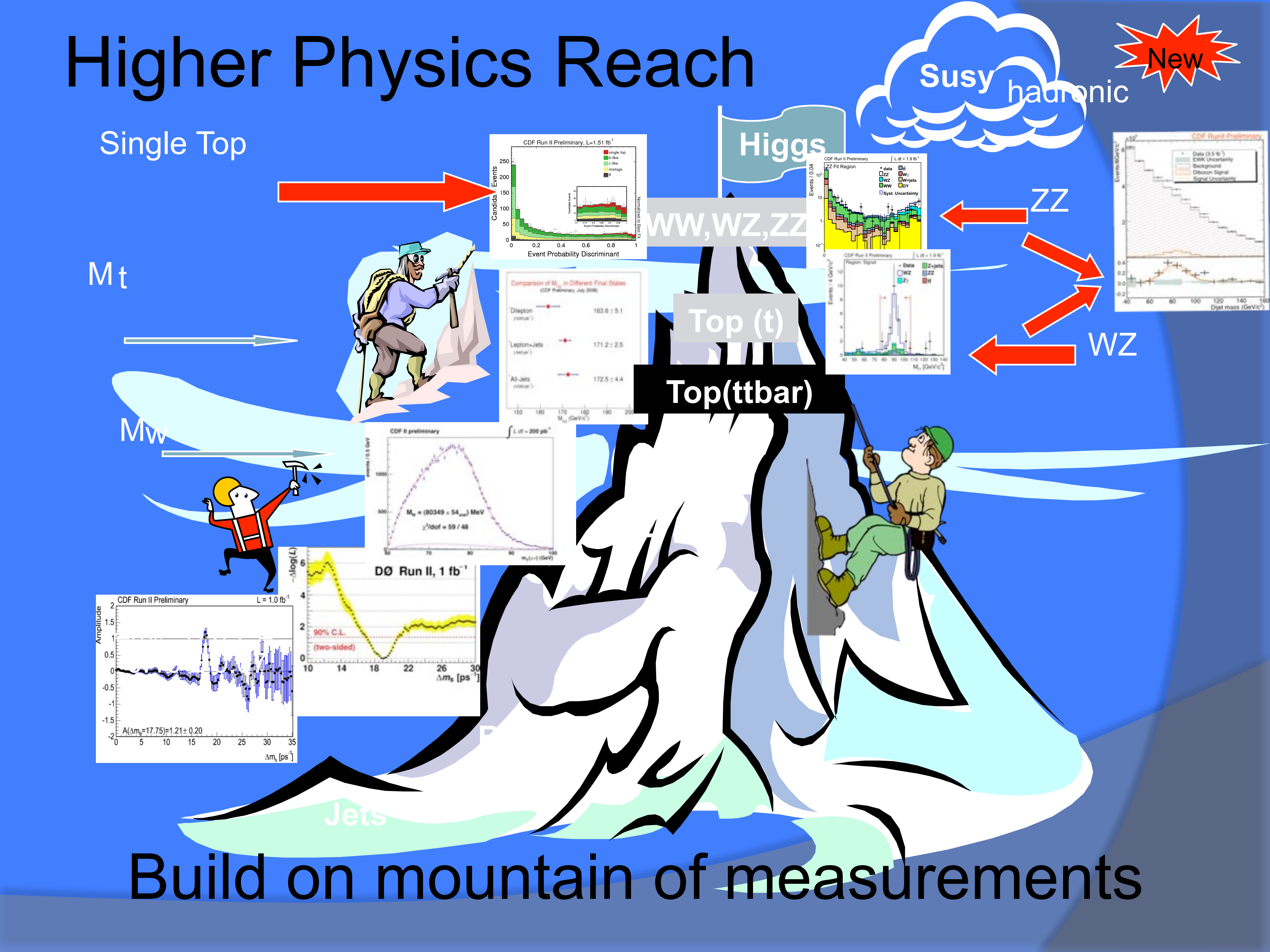
Outline:

- What is “high mass” Higgs ?

- Search strategies
  - Understanding signal and backgrounds
  - Systematic uncertainties

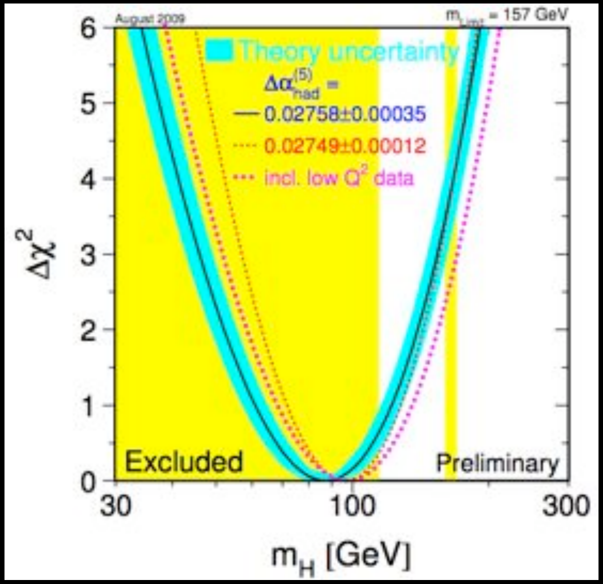
- Results
  - SM search
  - 4th generation interpretation
  - New channels

- Prospects and projections



Higher Physics Reach
Susy
hadronic
New
Single Top
Higgs
WW,WZ,ZZ
ZZ
WZ
Mt
Top (t)
Top(ttbar)
Mw
Jets
CDF Run II Preliminary, L=1.51 fb^{-1}
Event Probability Discriminant
CDF II preliminary
M_W = (80349 ± 54$_{stat}$) MeV
χ^2/dof = 59 / 48
DØ Run II, 1 fb^{-1}
90% C.L.
(two-sided)
Δm_s [ps^{-1}]
CDF Run II Preliminary
L = 1.0 fb^{-1}
Amplitude
A(Δm_s=17.75)=1.21± 0.20
CDF RunII Preliminary
Dijet mass (GeV/c^2)
Build on mountain of measurements

We know where to look:



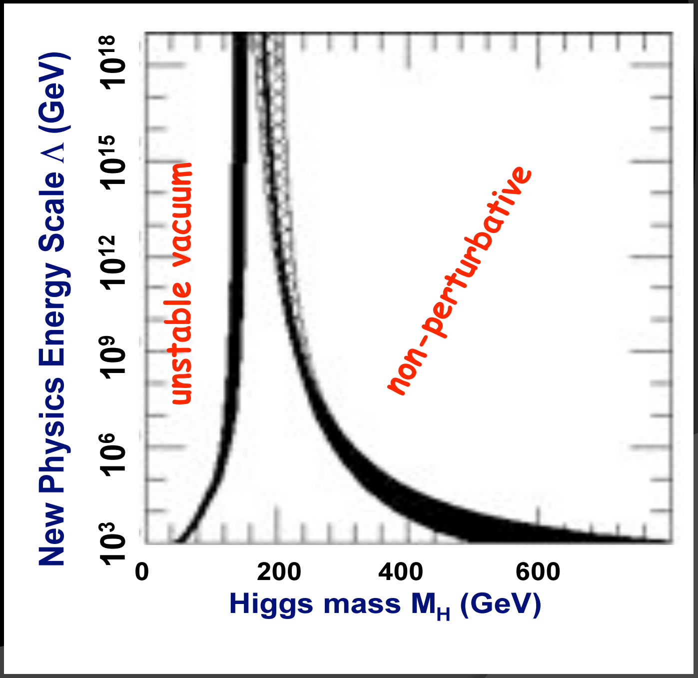
Higgs:

Direct search at LEP:

m_H>114 GeV @ 95%CL

Including indirect electroweak constraints

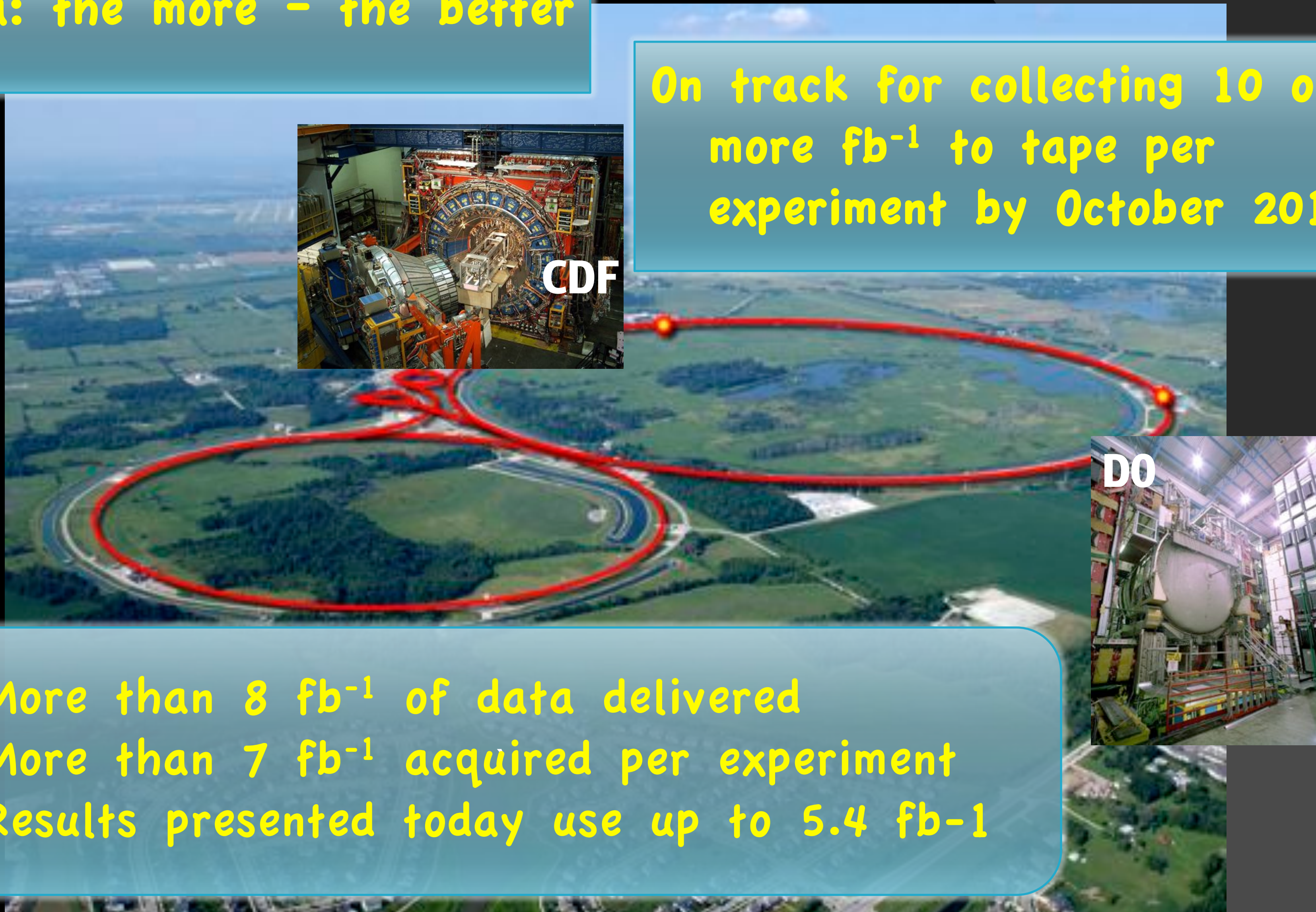
- m_H<185 GeV @ 95%CL
- Can change significantly beyond Standard Model



SM Higgs has a very narrow window of opportunity to be self-sufficient due to a fine-tuned (apparently accidental) cancellation of large correction factors

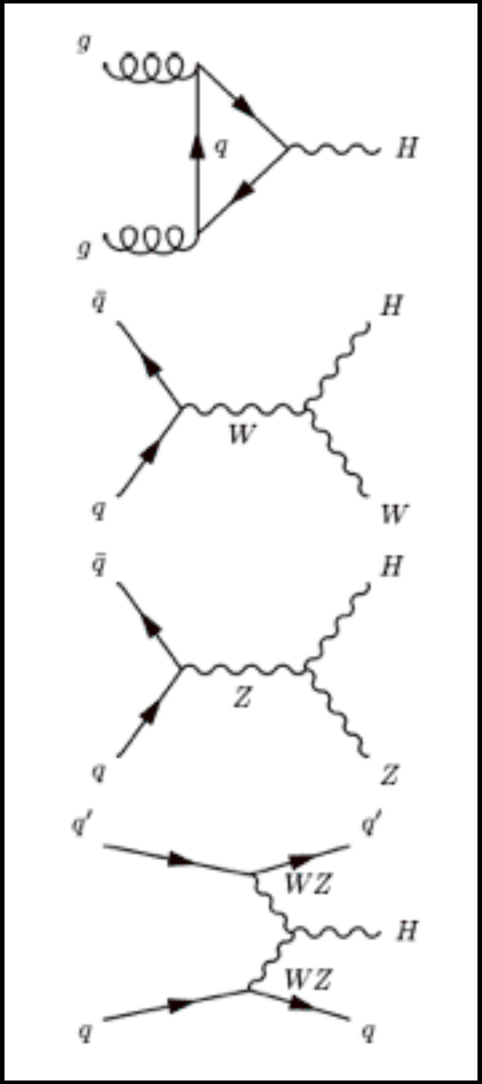
Data: the more – the better

On track for collecting 10 or more fb^{-1} to tape per experiment by October 2011



More than 8 fb^{-1} of data delivered
More than 7 fb^{-1} acquired per experiment
Results presented today use up to 5.4 fb-1

SM Higgs at the Tevatron



@Mh=160 GeV

ggH (78 %)

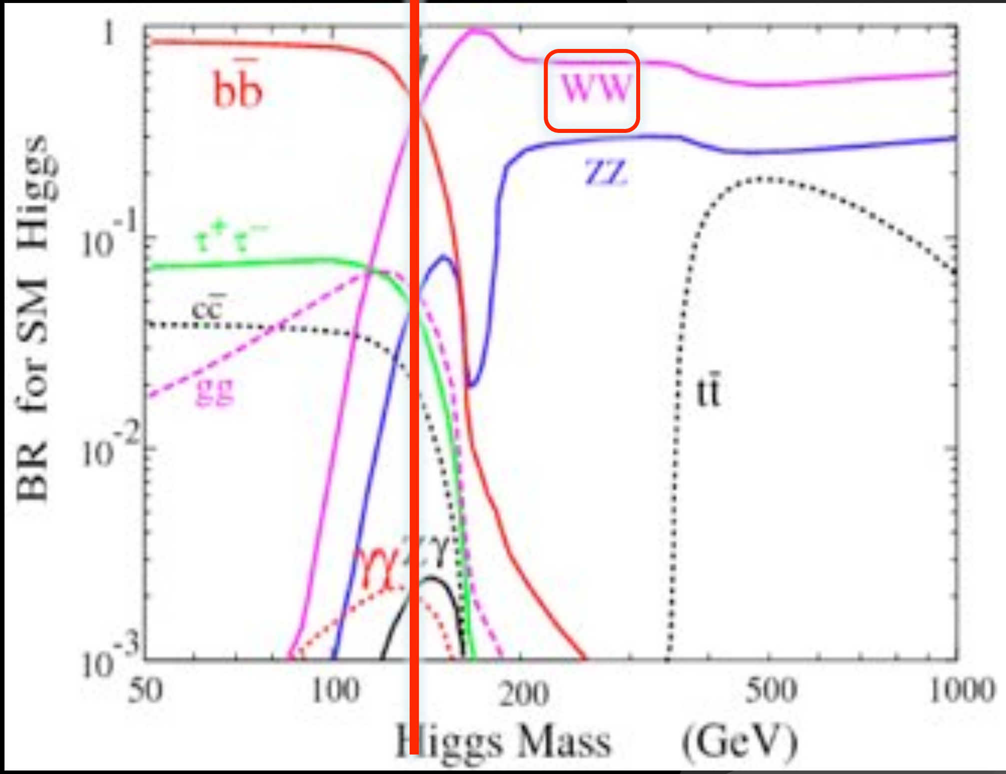
WH (9 %)

ZH (6 %)

VBF (7 %)

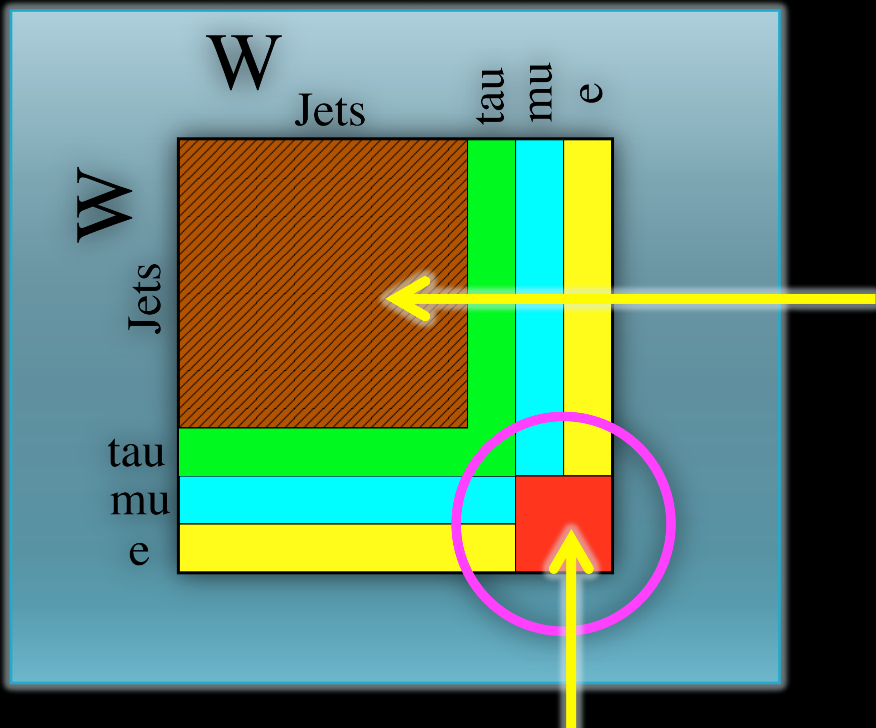
Low Mass

High Mass



- WW dominates at $M_H > 135$ GeV
- Contributes to Higgs searches down to 120 GeV/c^2

H→WW Final States



BR(W→hadrons)~68%
But large QCD background
Not used now, work in progress

We select both W decaying leptonically:

- BR(WW→ee,$\mu\mu$,eμ)~6%
- Easy and clean triggers on single electron or muon
- Partially includes τ's
- Dedicated analysis looks at hadronic tau decays (later in this talk)

General Analysis Strategy

High Pt
Electron and Muon
data

Verify modeling of
main BGs →

Control regions

Apply loose
dilepton+MET
selection ↓

Signal Region
S/B ~1/60

S/B ~1/25

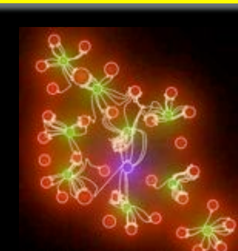
→ Channel1

→ Channel2

→ ....

Separate into channels
based on lepton purity, S/B
ratio

Multivariate
Techniques →



S/B ~1/1

Template1

Templatel2

....

↓

Systematics
and correlations

←

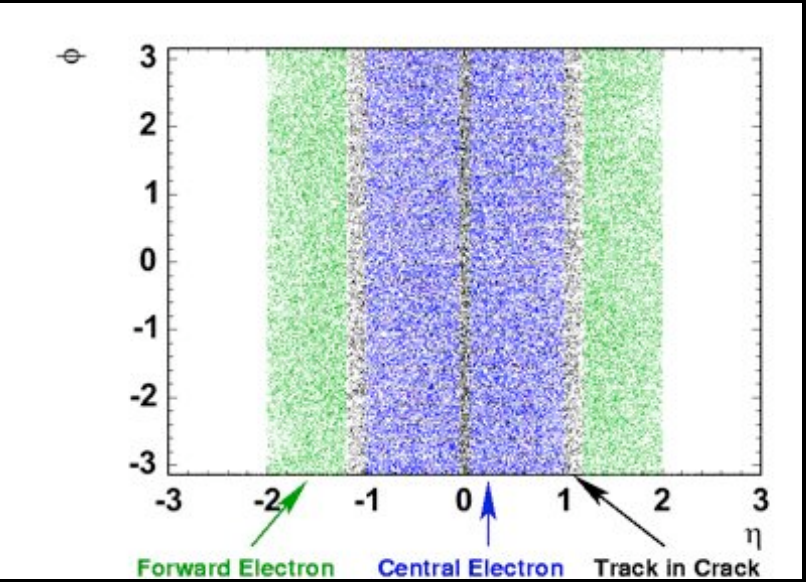
Results:
Limits or signal
significance

Extended lepton types

CDF example

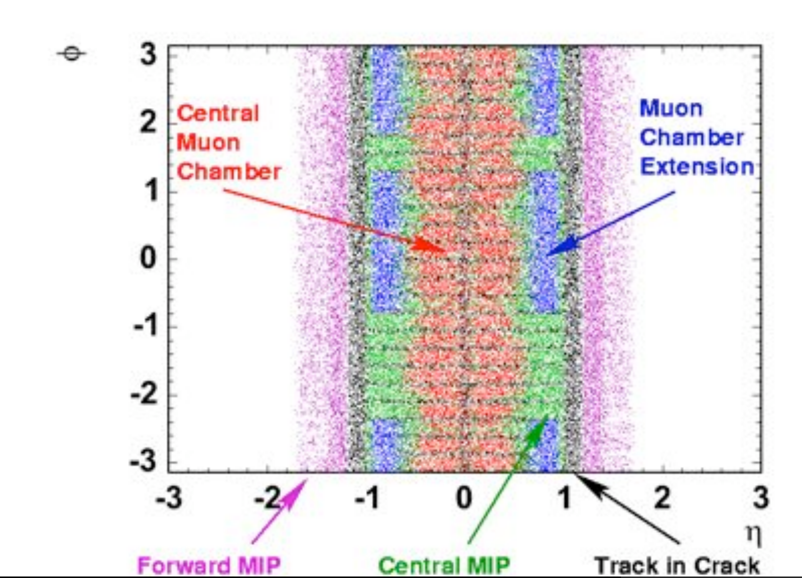
Signal acceptance is crucial !!!

Electron ID



- Central Electrons
- Forward Electrons
- Isolated Tracks

Muon ID



- Central Muons
- Minimum Ionizing Tracks, fiducial to:
  - Central calorimeter
  - Forward calorimeter
- Isolated Tracks

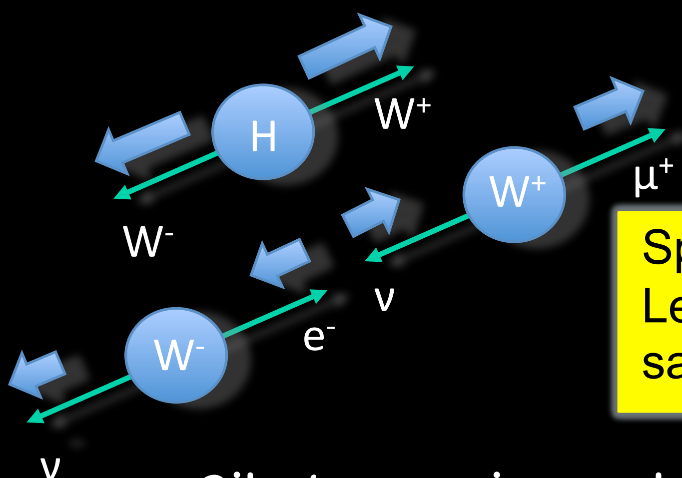
Signal vs Background

- $S/\sqrt{B}$ ~0.6, so simple counting analysis isn't enough

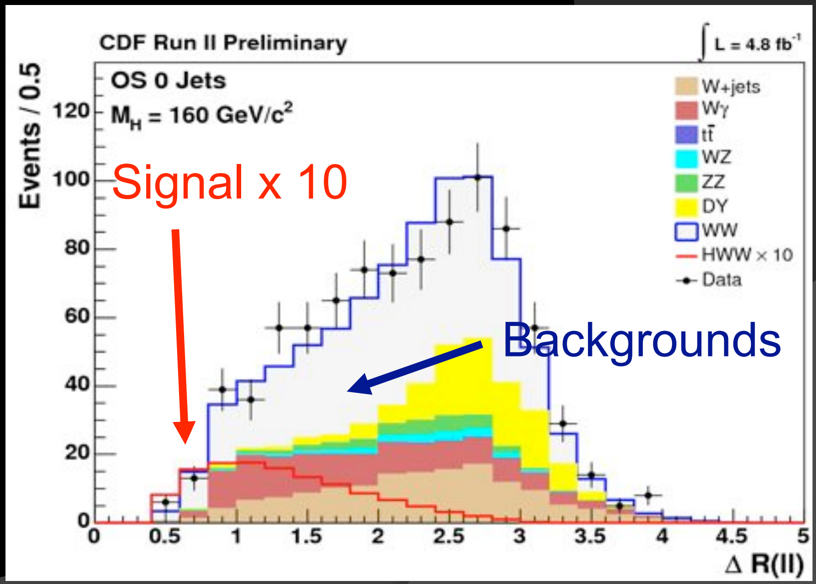
- Both experiments use multivariate techniques to discriminate between signal and background:
  - Matrix Element (ME), Neural Networks (NN)
  - Each channel and M_H hypothesis has its own NN

CDF Run II Preliminary $\int \mathcal{L} = 4.8$ fb^{-1}			
$M_H = 165$ GeV/c^2			
$t\bar{t}$	196	±	32
DY	342	±	61
WW	605	±	65
WZ	54.8	±	7.5
ZZ	42.3	±	5.8
W+jets	278	±	70
$W\gamma$	191	±	27
Total Background	1710	±	140
$gg \to H$	22.3	±	4.8
WH	4.38	±	0.57
ZH	1.59	±	0.21
VBF	1.61	±	0.26
Total Signal	29.8	±	5.1
Data	1733		

High Mass



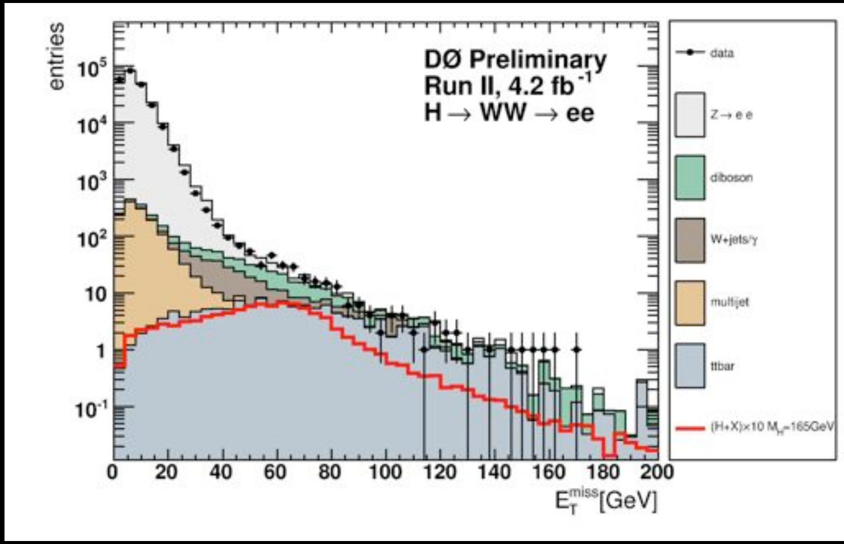
Spin correlation: Leptons go in the same direction



Dilepton opening angle is the strongest background discriminant

Physics Backgrounds

- Z->ll is the largest background but suppressed by requiring large missing E_T:



- After the suppression, the main backgrounds are:
  - Diboson production – WW, WZ, ZZ
  - W+jets where a jet fakes a lepton
  - W+γ where the photon fakes a lepton
  - tt and single top

Modeling:

WW
MC@NLO at CDF
Pythia/Sherpa at D0

Z->ll
Pythia at CDF
Alpgen at D0

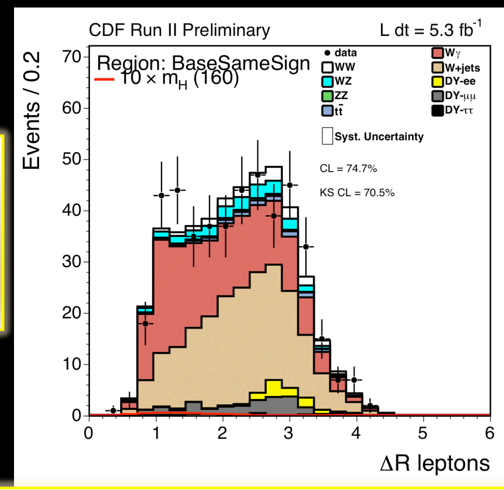
W+jets
data-driven at CDF
Aplgen at D0

W+gamma
Baur at CDF
Alpgen at D0

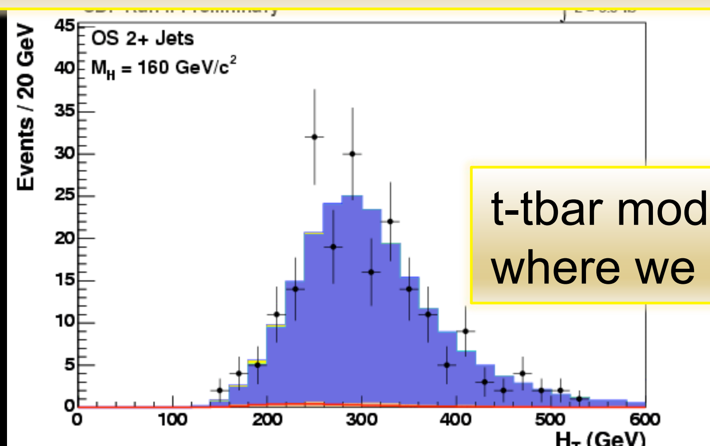
ZZ, WZ, tt, single top & Signal
Pythia

Control…

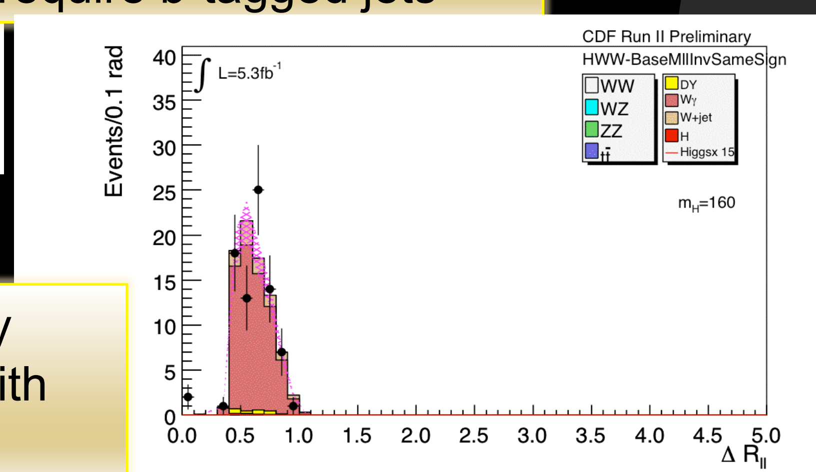
- Focus on system boost (P_T) and angular distributions (dR, $d\varphi$)
- Isolate each background in dedicated control region orthogonal to the signal region



W+jets modeling tested by inverting the opposite sign requirement



t-tbar modeling tested in the region where we require b-tagged jets

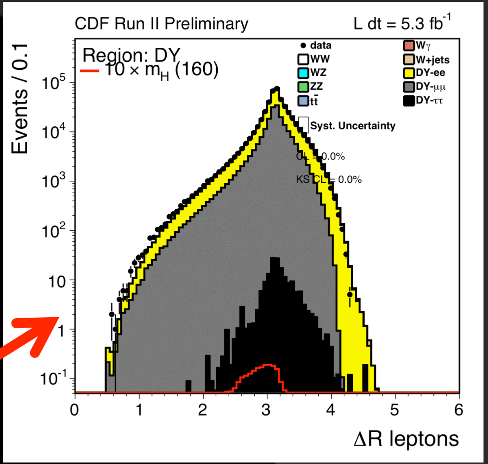


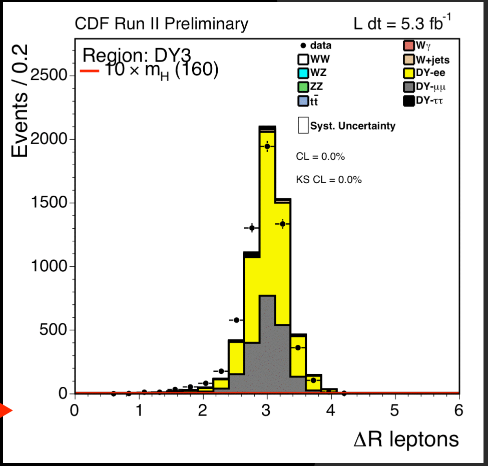
W+gamma modeling tested by requiring same sign leptons with low M_{ll}

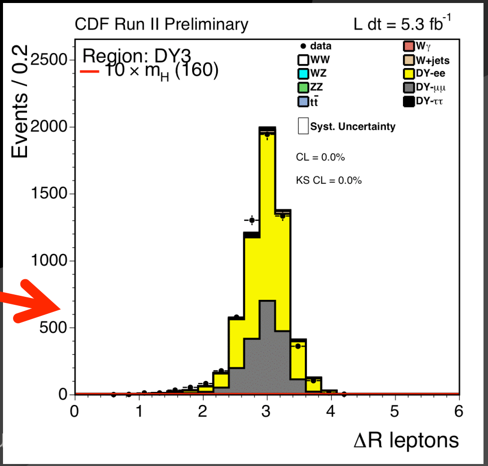
More control…

- Multivariate techniques can easily distinguish DY from signal based on Missing ET (MET) distributions
- DY with fake MET can be a problem

- Use PYTHIA incorporating CDF-specific tunings
  - Good match with inclusive Z pT (boost) observed in data
- However, selection based on missing E_T requirement leads to large disagreement between data and MC
- Tune MC in intermediate missing E_T range
  - Obtain good modeling of kinematic variable shapes

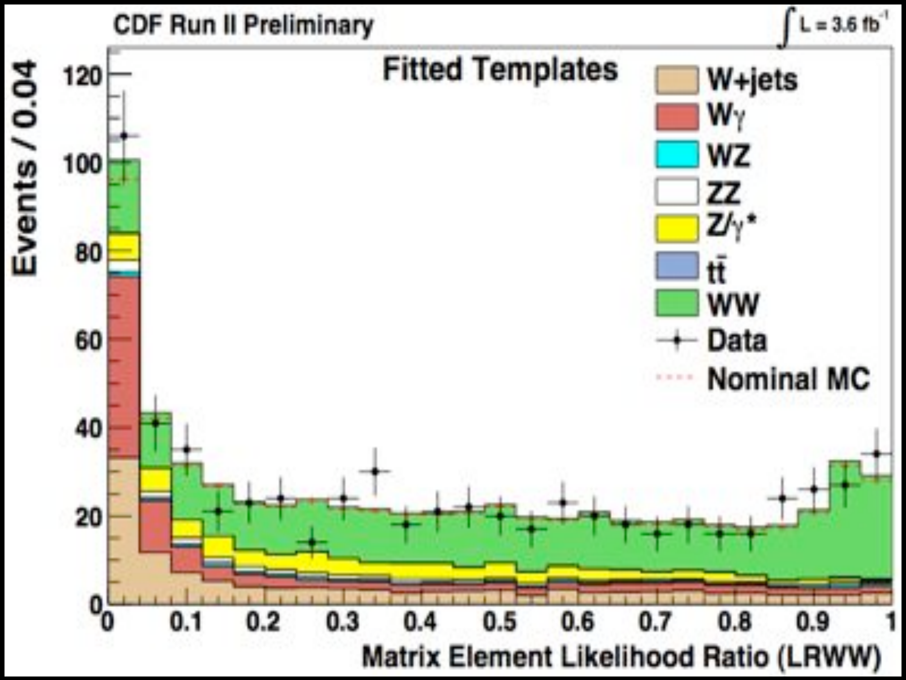






Even More control…

- In case of heavy dibosons we were not able to define dedicated control regions
- We use cross-section measurements and compare them to theory to check modeling for these backgrounds



- Measure WW cross section using events with no jets
- Maximum likelihood fit to WW likelihood ratio distribution
  - Systematic uncertainties included as Gaussian constraints in fit

$$\sigma(p\bar{p} \rightarrow WW) = 12.1 \pm 0.9\ (\text{stat.})^{+1.6}_{-1.4}\ (\text{syst.})\ [\text{pb}]$$

Syst. **includes** 5.9% luminosity uncertainty

$\sigma(ZZ)=1.56^{+0.8}_{-0.63}(\text{stat})\pm 0.25(\text{syst})$ [pb]

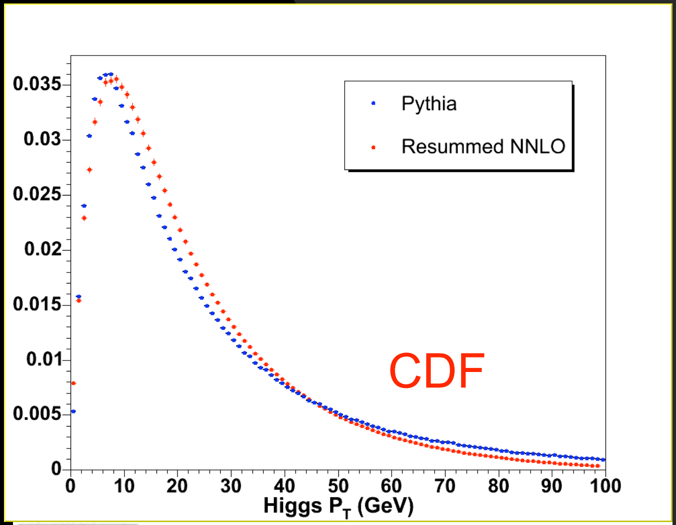
Signal

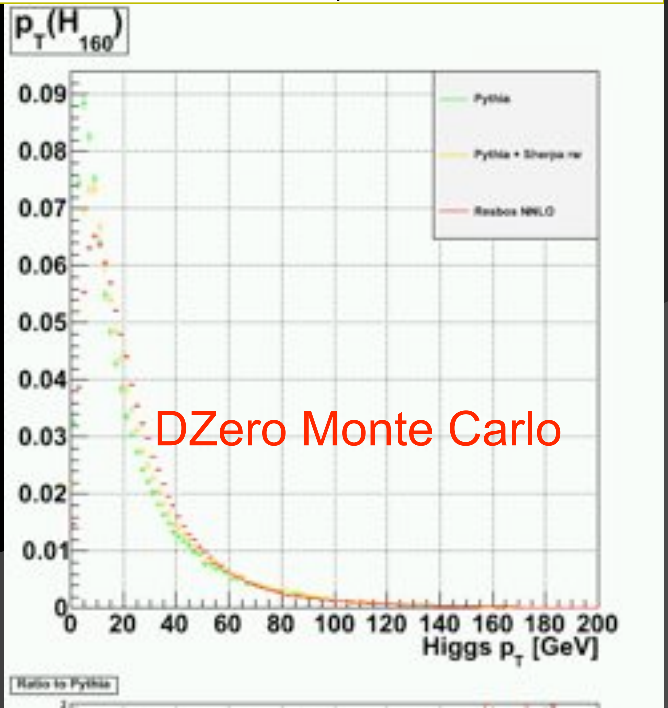
- Tevatron limits and exclusion range also depend significantly on theoretical Higgs production cross sections (gluon fusion, in particular, at high mass)
- Currently use inclusive cross section calculations of de Florian and Grazzini (arXiv:0901.2427v2)
  - Soft-gluon resummation to NNLL
  - Proper treatment of b-quarks to NLO
  - Inclusion of two-loop electroweak effects
  - MRSTW2008 Parton Density Functions
- In good agreement with calculations of Anastasiou, Boughezal, and Petriello (arXiv: 0811.3458v2)
- We rely on NLO calculations for VH and VBF

Signal, more on the gluon fusion

Anastasiou et al., arXiv:0905.3529v2

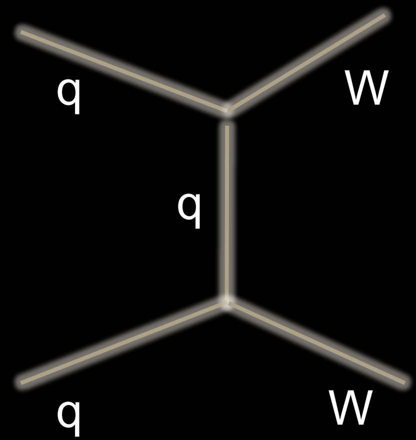
- Event kinematics Modeled using Pythia which is LO with soft gluon resummations
- Re-weight the PYTHIA events at generator to match the Higgs p_T spectrum obtained from:
  - the NNLL calculation (CDF)
  - RESBOS (D0)
- Since our signal acceptance is determined from this re-weighted event sample, we believe that normalizing to the NNLL inclusive cross section is self-consistent

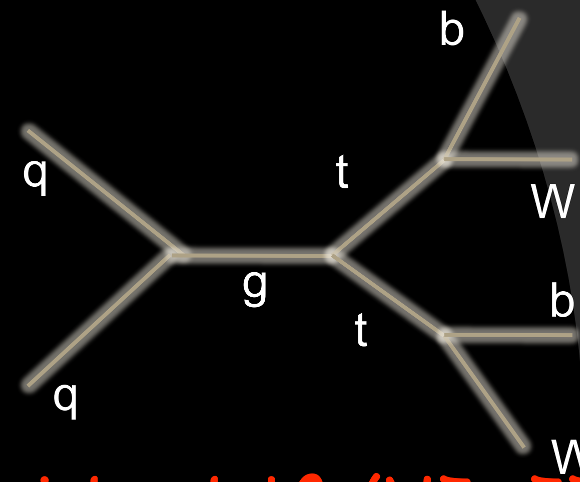




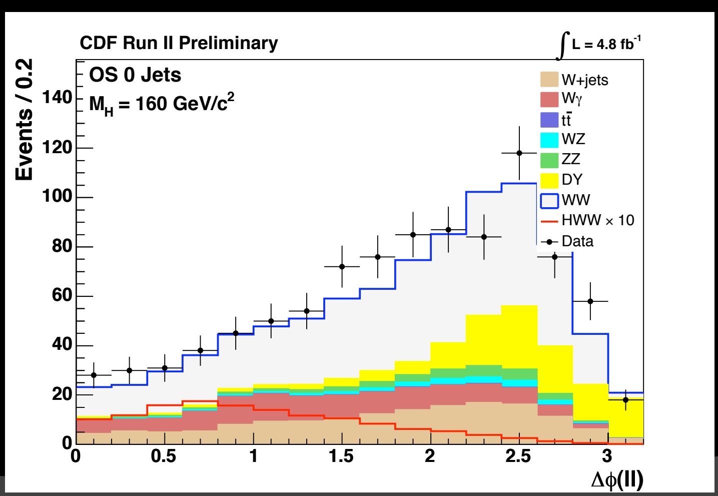
Optimize S/B:

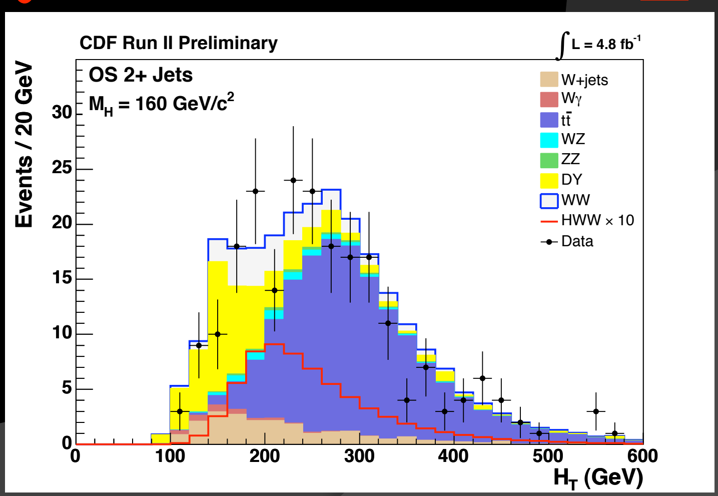
- Separate analysis into channels by S/B ratio and lepton purity
  - CDF – by jet multiplicity: 0, 1 and 2+ jets





0 jets at LO (<u>WW</u>, DY, W+γ) **2 jets at LO (WZ, ZZ, <u>$t\bar{t}$</u>)**

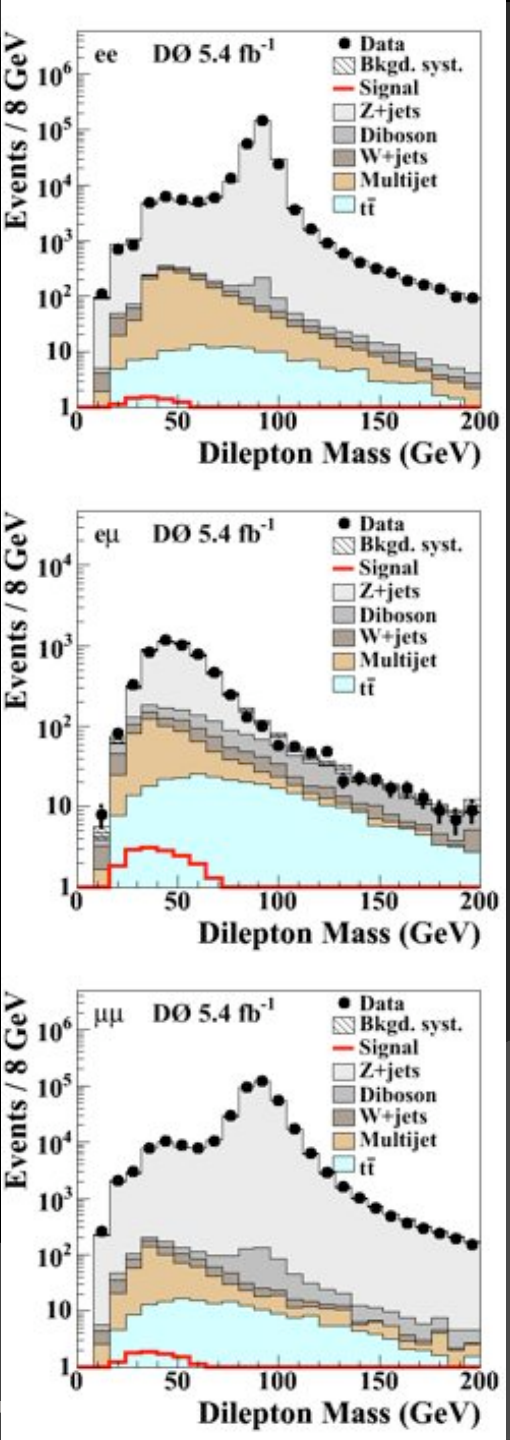




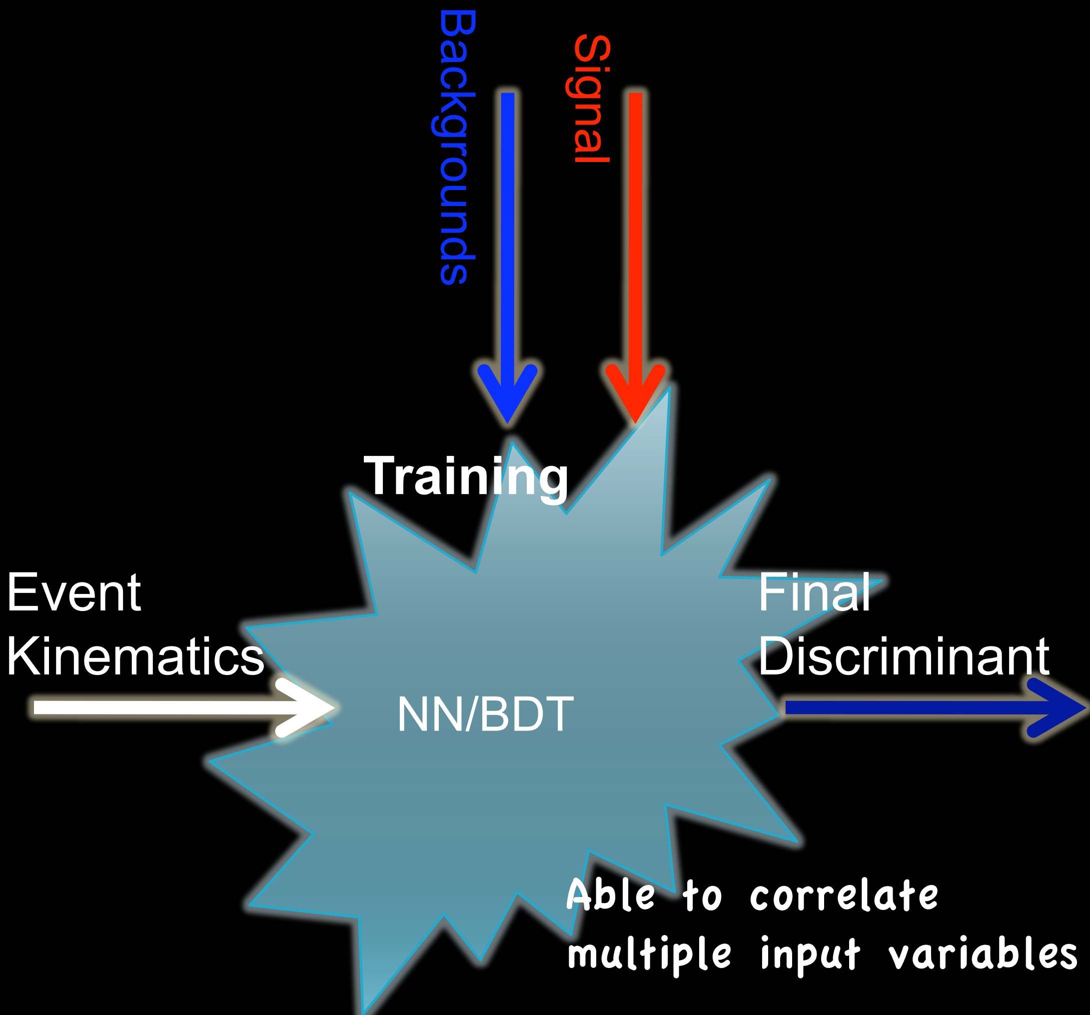
Optimize S/B:

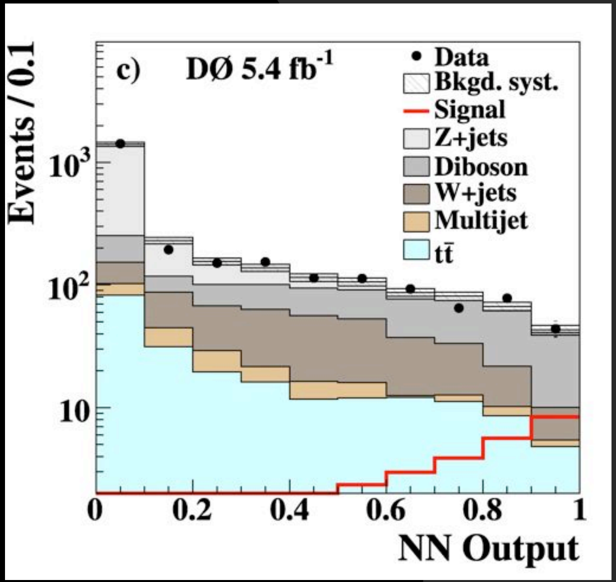
- Separate analysis into channels by S/B ratio and lepton purity
  - D0 – by di-lepton flavor: ee, eμ, μμ

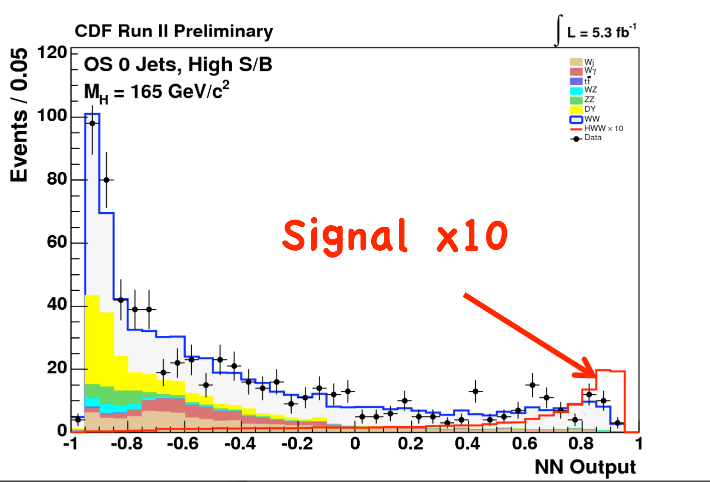
- Background composition depends on dilepton flavor:
  - electroweak WW in eμ channel
  - Z+jets is largest in ee and μμ channels (however it can be distinguished by low missing ET), while WW is still most difficult to separate from the signal



Final optimization:



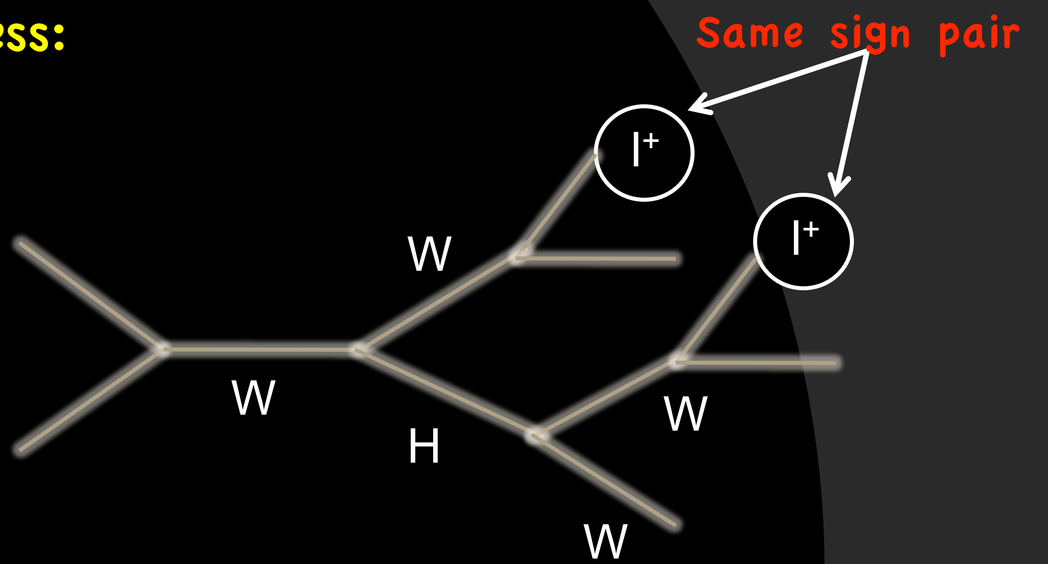


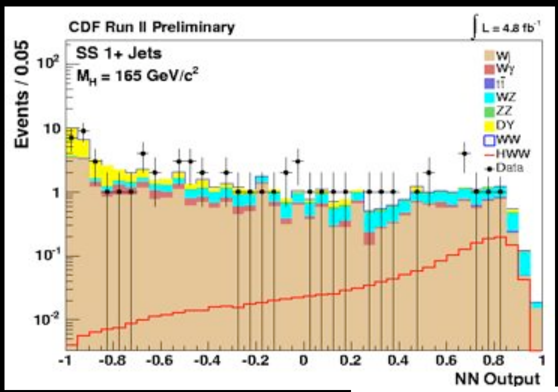


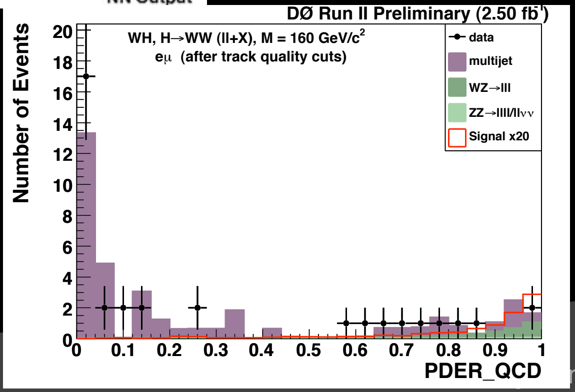
Additional Acceptance

Select two same-sign leptons to increase signal acceptance

- Main contributing signal process:
  - WH→ WWW→ ll+X
- Main backgrounds:
  - lepton charge misID
  - jets faking leptons







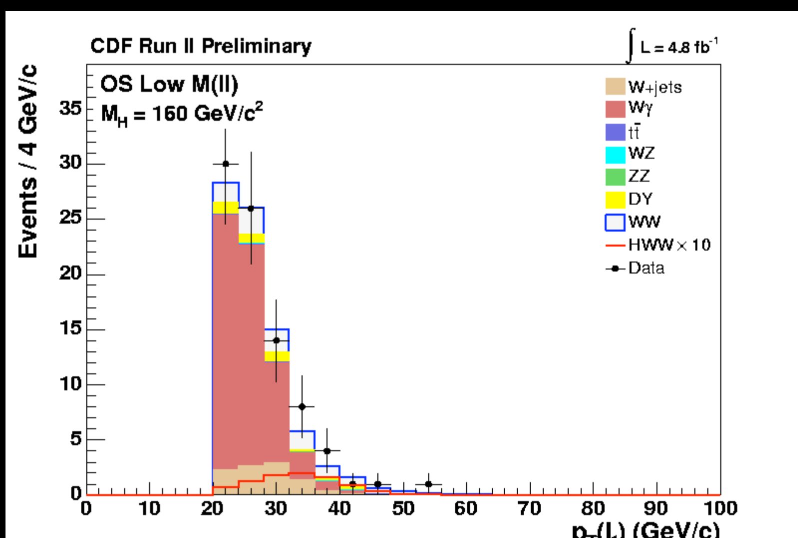
- CDF Same-Sign analysis uses 4.8 fb-1 of data and techniques are similar to opposite sign analysis
- D0 analysis uses 3.6 fb-1 and likelihood discriminant
- This channel adds ~10% to sensitivity at high mass

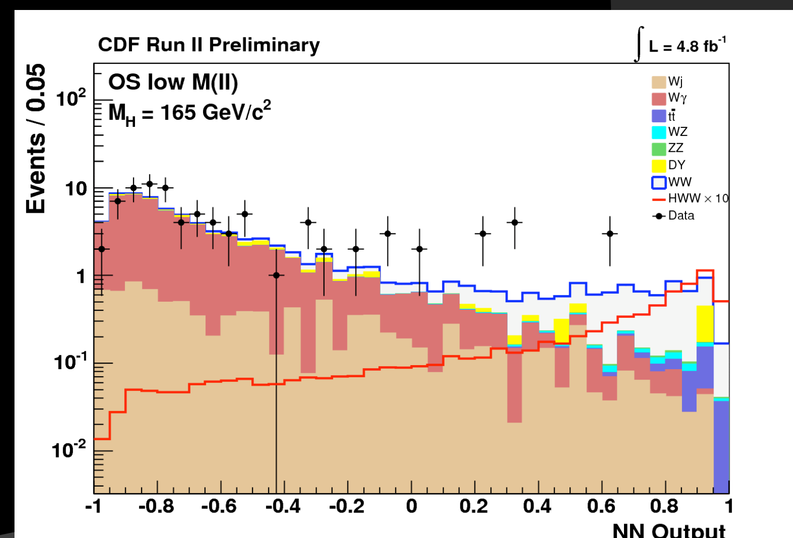
And more acceptance

- Similar event selection, but Mll<16 GeV/c2
- Different background composition:
  - dominant background W+γ where γ fakes a lepton
- Similar techniques (NN) applied
  - lepton Pt- one of the most powerful variables

CDF Run II Preliminary $\int \mathcal{L} = 4.8\ \text{fb}^{-1}$			
$M_H = 165\ \text{GeV}/c^2$			
$t\bar{t}$	0.330	±	0.052
DY	3.56	±	0.85
WW	10.9	±	1.3
WZ	0.284	±	0.041
ZZ	0.107	±	0.015
W+jets	9.9	±	2.4
$W\gamma$	55.9	±	6.7
Total Background	80.9	±	7.3
$gg \to H$	0.75	±	0.12
Total Signal	0.75	±	0.12
Data		85	

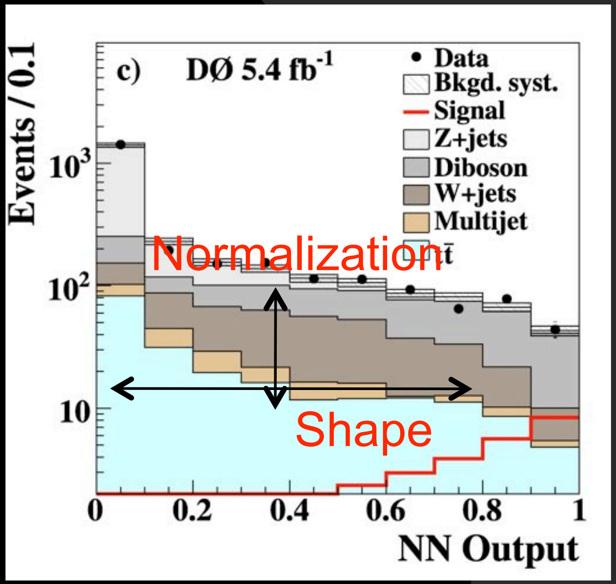
OS low M(ll)

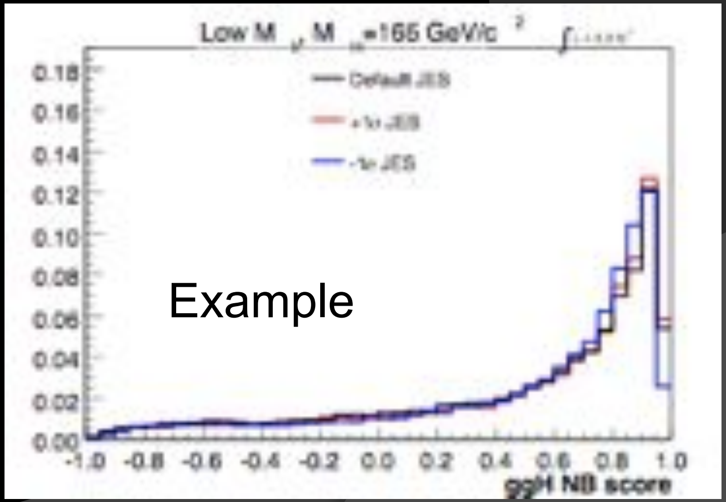




Systematic uncertainties:

- We consider uncertainties both on the normalization of each signal/background process and on the shapes of the final discriminant templates for each signal/ background process
- Correlations in uncertainties between different channels are properly accounted for in the minimization procedure
  - A single channel can constrain an individual uncertainty parameter across all channels



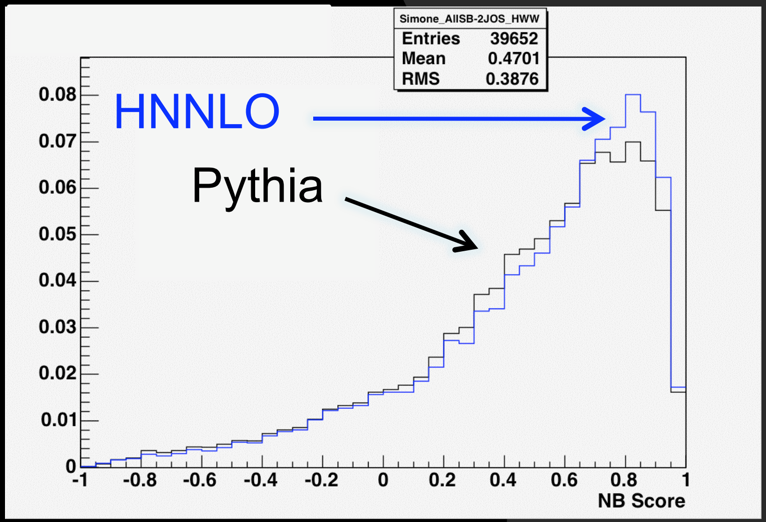


Gluon fusion x-section uncertainties:

- The uncertainties assigned to the cross section prediction also have an important effect on limits
- To estimate effect of higher-order QCD radiative corrections vary μ_F and μ_R between $0.5m_H$ and $2.0m_H$ within the constraint $0.5 < \mu_F/\mu_R < 2.0$
- To estimate effect of PDF model use 40 alternative error sets associated with MSTW2008 NNLO PDF
- Since CDF separates high mass search channels by number of reconstructed jets, topology dependent scale factor uncertainties are required (Anastasiou et al., arXiv:0905.3529v2). Not required for D0.

Gluon fusion acceptance uncertainties:

- In addition to the cut-dependent scale uncertainties that we assign to the gluon fusion cross section, we also assign scale and PDF uncertainties on the acceptance
- HNNLO program is used to quantify variations in the H p_T spectrum as a function of scale and PDF choices
- We apply additional re-weightings to the PYTHIA event sample to match the variations and assign uncertainties based on observed changes in signal acceptance



Method allows us to assign shape uncertainties to our signal templates

Fall 2009 results

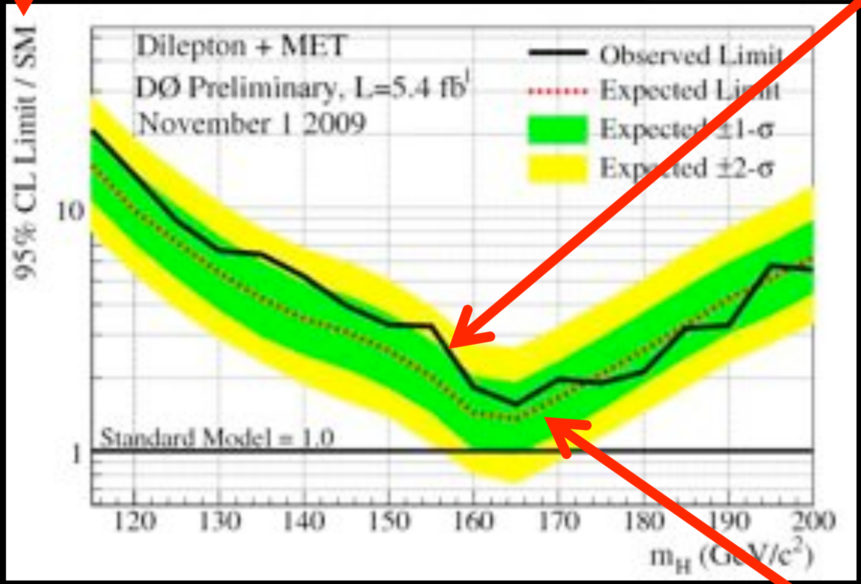
At Mh=165 GeV

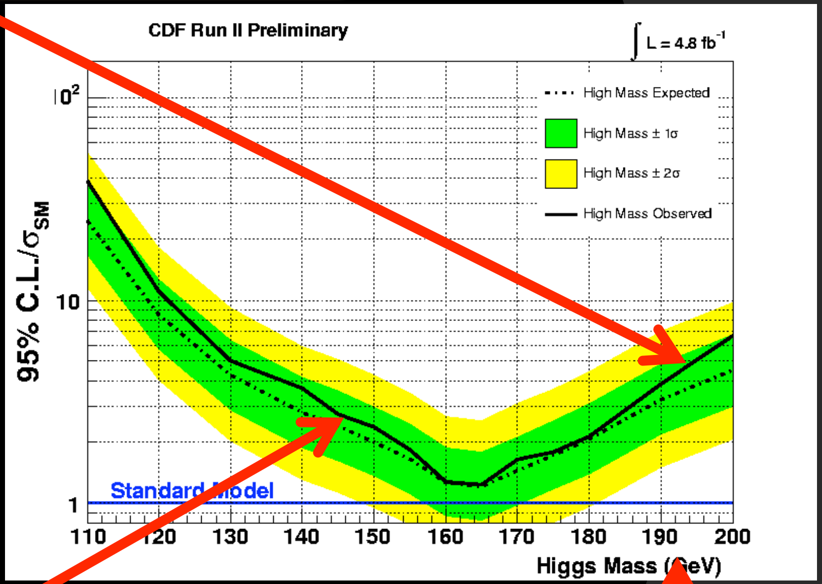
CDF: Exp/σ_{SM}: 1.19 Obs/σ_{SM}: 1.18

D0: Exp/σ_{SM}: 1.36 Obs/σ_{SM}: 1.55

Upper cross section limit for Higgs production relative to SM prediction

Observed limit (solid line) from data

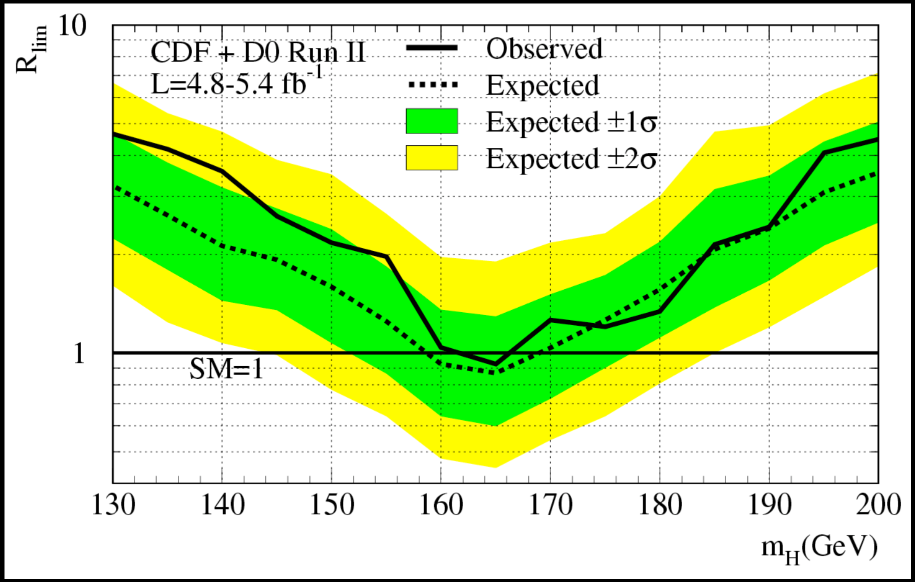


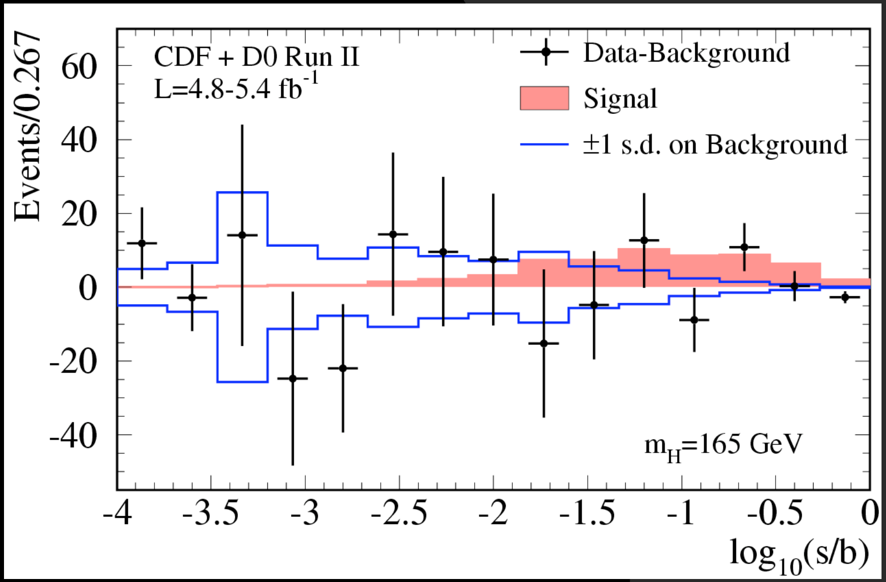


Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

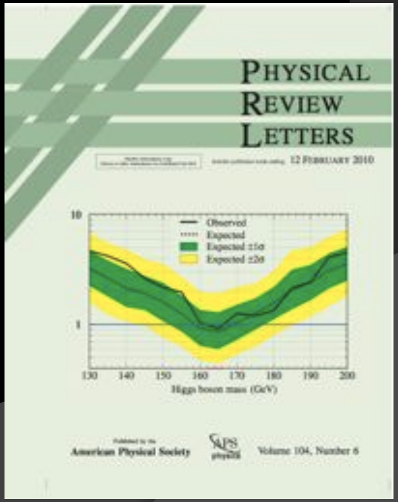
Analysis repeated using different signal templates for each m_H between 100 and 200 GeV in 5 GeV steps

Fall 2009 combination:



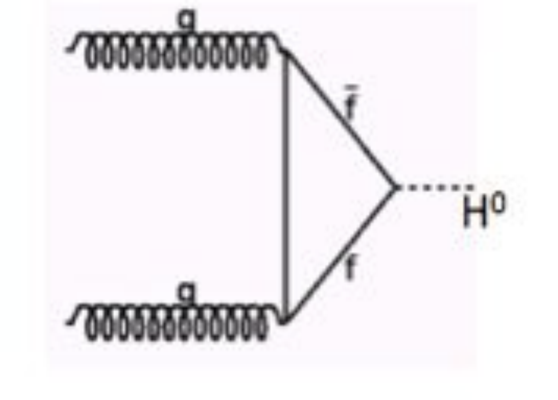


- Phys. Rev. Lett. 104, 061802 (2010)
- Observed exclusion 162 < m_H < 166 GeV
- Expected exclusion 159 < m_H < 169 GeV

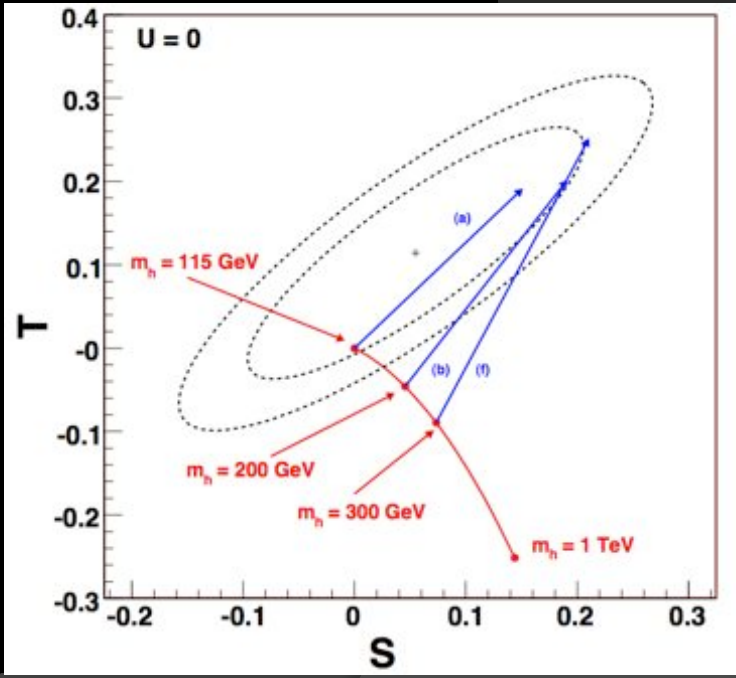


Going beyond SM:

… or what if there are 4 generations of fermions ?



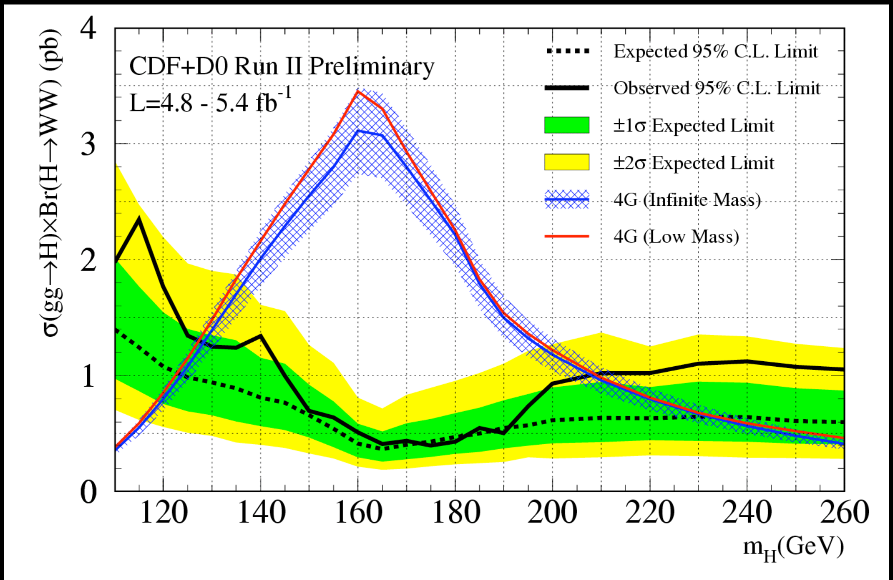
Four Generations and Higgs Physics
Kribs, Tait, Spannowsky, Plehn
Phys.Rev.D76:075016,2007.
arXiv:0706.3718 [hep-ph]

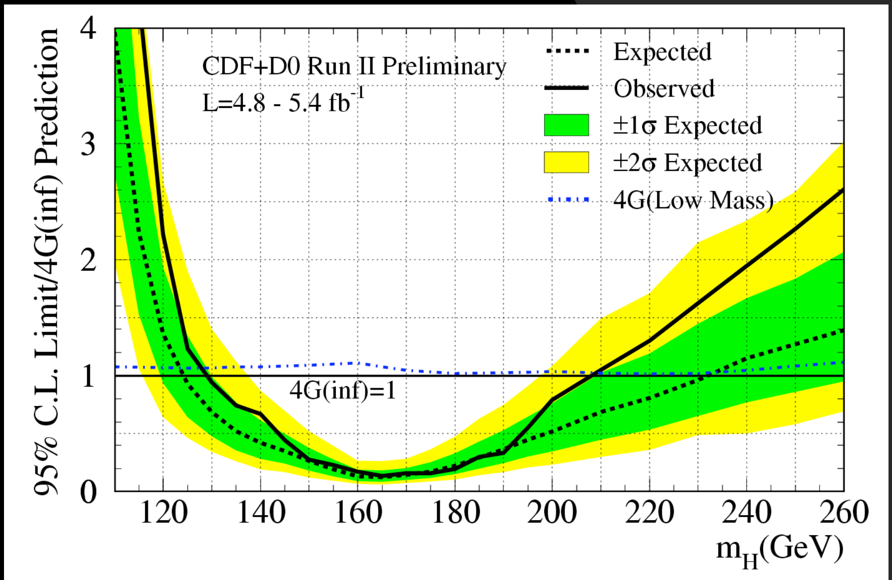


- Presence of additional high mass quarks enhances gg→H production by as much as a factor of nine - also modifies Higgs branching ratios
- Small modifications to default CDF/D0 high mass searches
  - Remove WH, ZH, and VBF signal contributions : retrain discriminates for gg→H only

Going beyond SM:

… or what if there are 4 generations of fermions ?



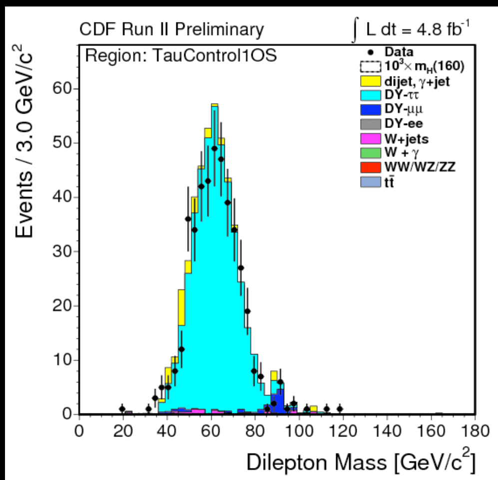


- Cross section times branching ratio limits for gg→H→WW
- Theoretical predictions from Anastasiou, Boughezal, and Furlan - arXiv:1003.4677 [hep-ph] (2010)
- Observed exclusion 130 < m_H < 210 GeV

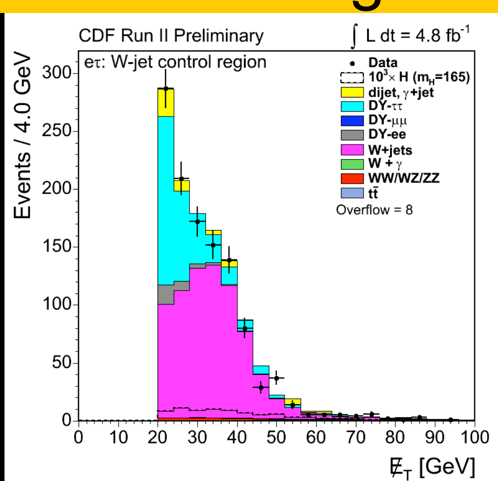
Getting better: WW→ετνν,μτνν

New Channel for CDF

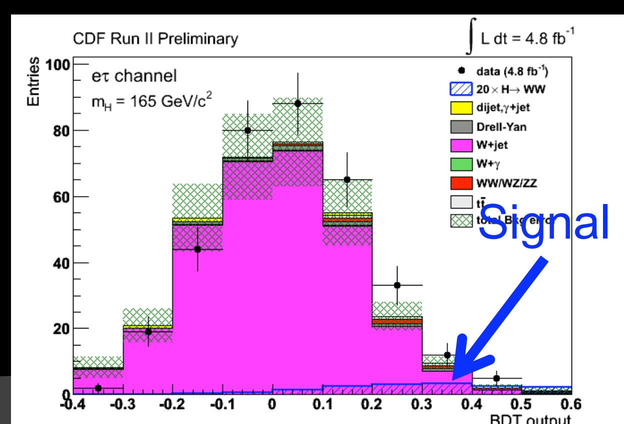
CDF has made further steps to improve SM anal…

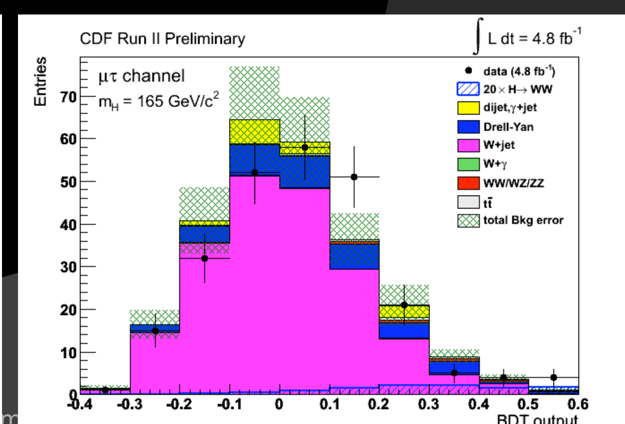


Control Regions



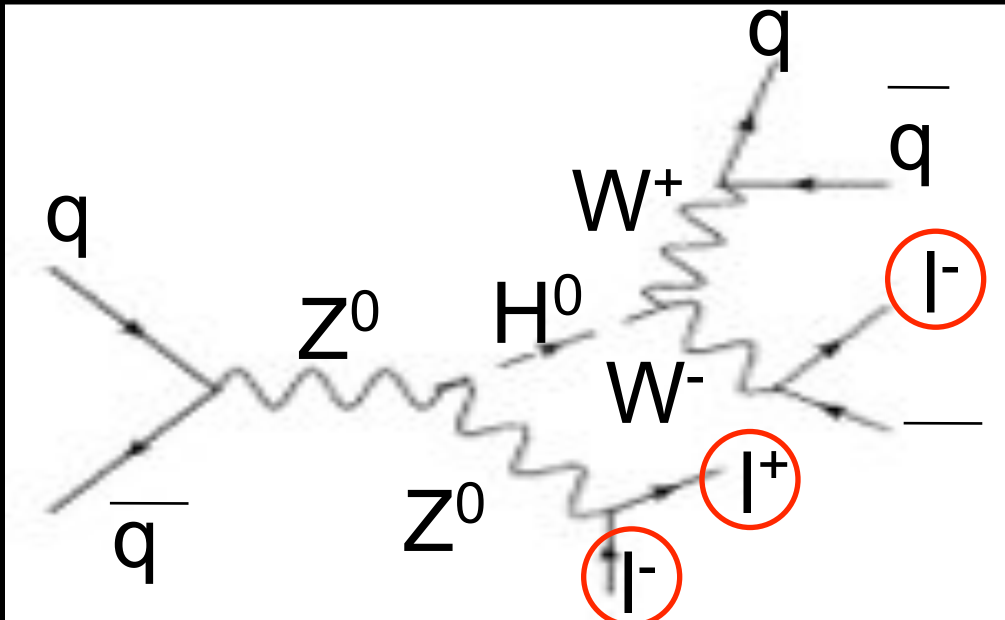
- Look at τ's decaying hadronically
- Special control regions to understand W+jets and Z->ττ background modeling
- Expected signal, 1.8 events
- Main BG – W+jets
- Adds few % to analysis sensitivity



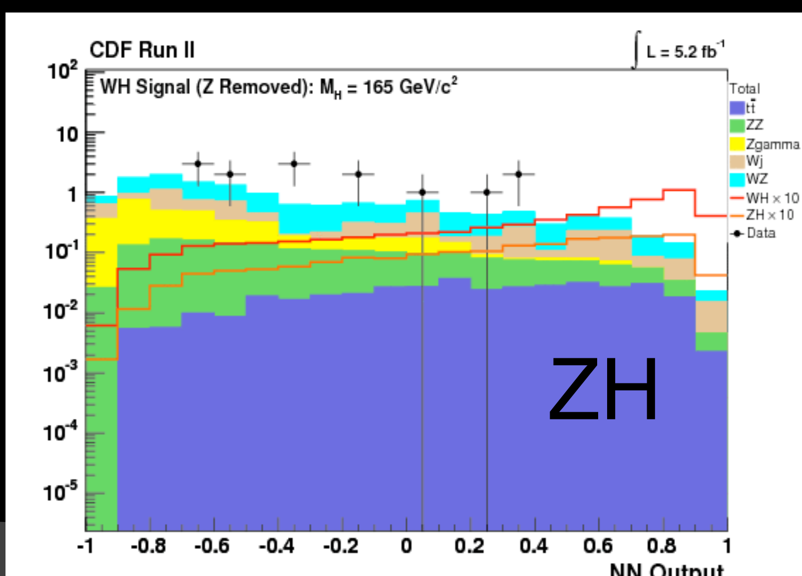


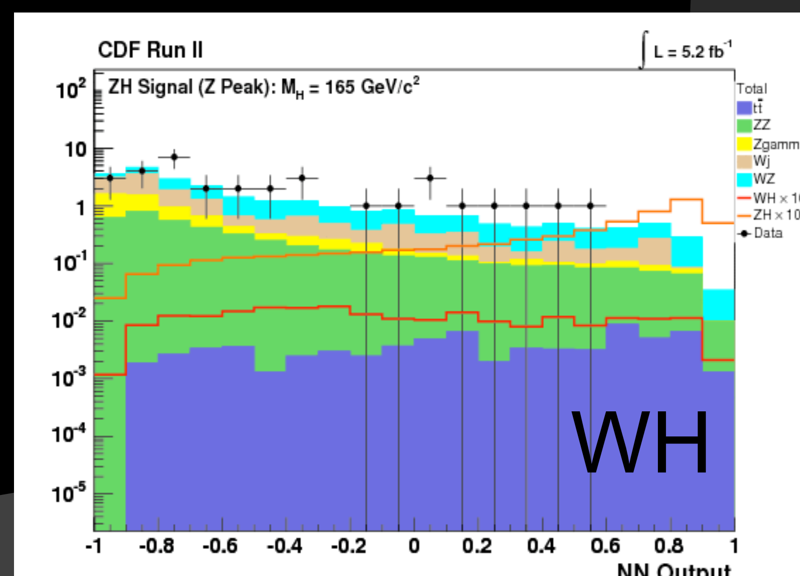
No channel left behind:

New Channel for CDF



- Trileptons:
  - WH -> lllνν
  - ZH -> Z(ll)W(qq)W(lν)
- In events with 2 jets use M_W as constraint
- Sensitivity of ~5σ(SM)

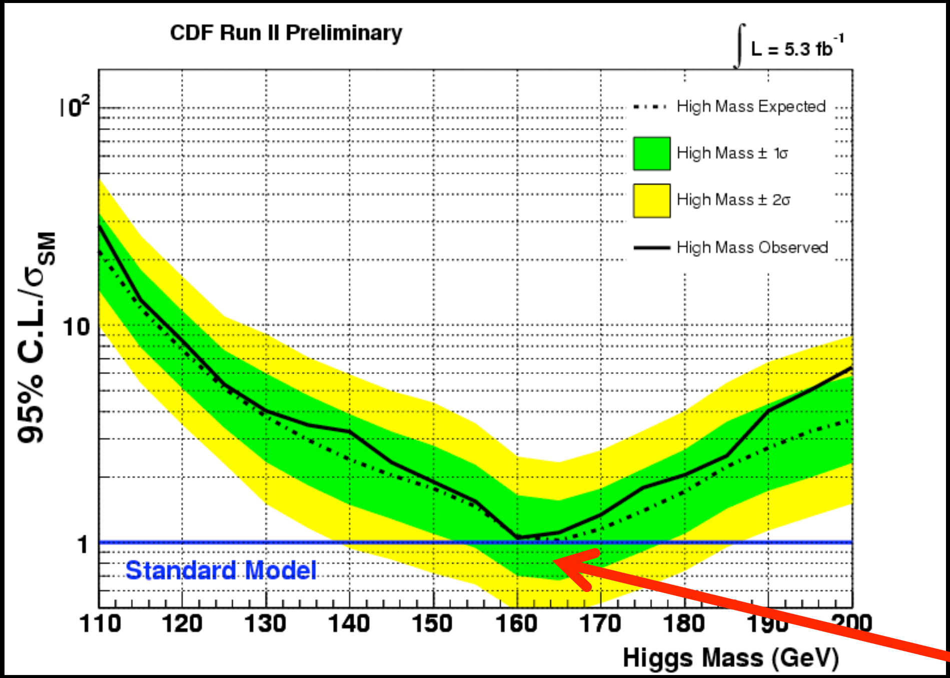




Updated CDF high mass combination:

With all channels and 5.3 fb^{-1} of data

Better analysis techniques contribute to more than 50% of the improvement

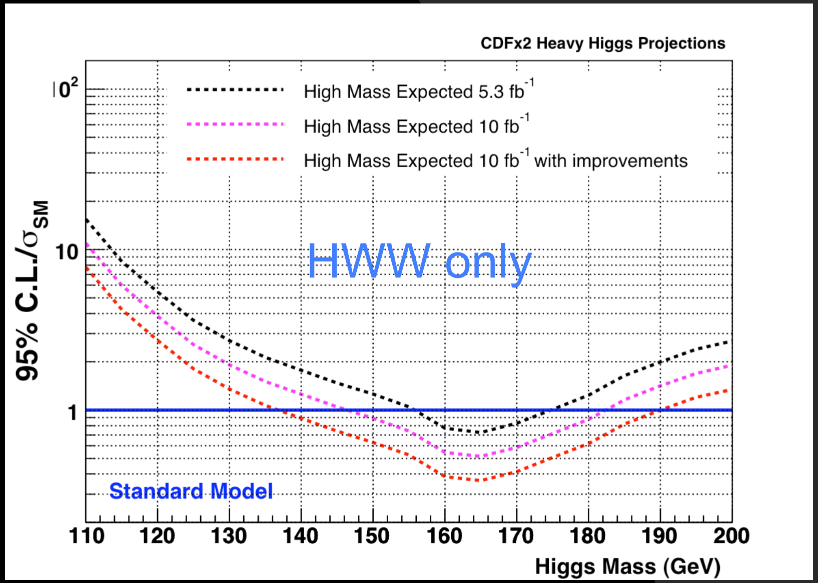


At m_H = 165 GeV,
1.02xSM expected
1.11xSM observed
(Spring 2010)

Looking into the future

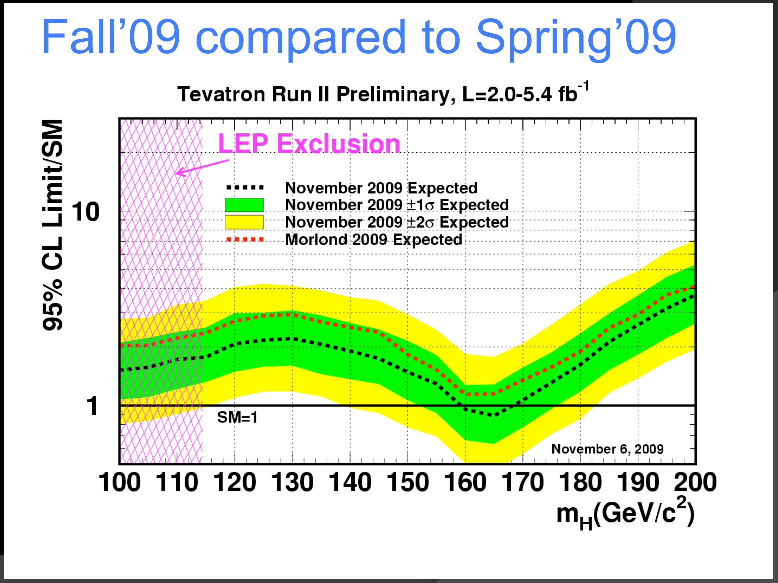
More data

• up to 10 fb-1 recorded data is expected per experiment by the end of run II (20 fb-1 combined!)



Many possible analysis improvements:

- Smarter lepton isolation
- H->WW->jjlν
- H->ZZ at higher Higgs masses
- new triggers
- ….

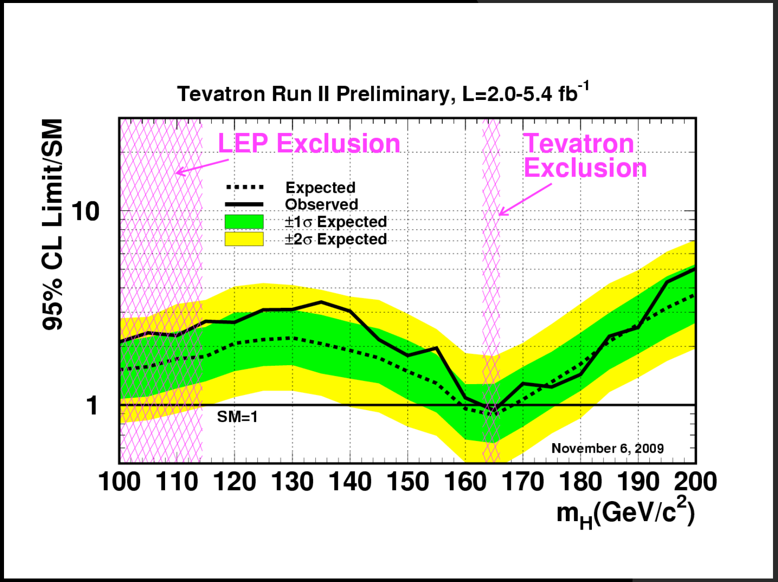


Outlook:

- We do better than just adding more data
- We have many cross-checks in place to ensure robustness of our techniques
- Improved precision of gluon fusion production cross section predictions and better understanding of the associated uncertainties is an important component in improving the sensitivity of these searches
- Excellent opportunity to either see first hints of a Higgs boson or exclude a significant range of mass values

Conclusions

- Great results from both experiments in both low and high mass sectors
- SM Higgs exclusion in the range 162-166 GeV/c2 @95% CL
- Expected exclusion range 159-168 GeV/c2



- Better than 2.2xSM sensitivity at all masses below 185 GeV

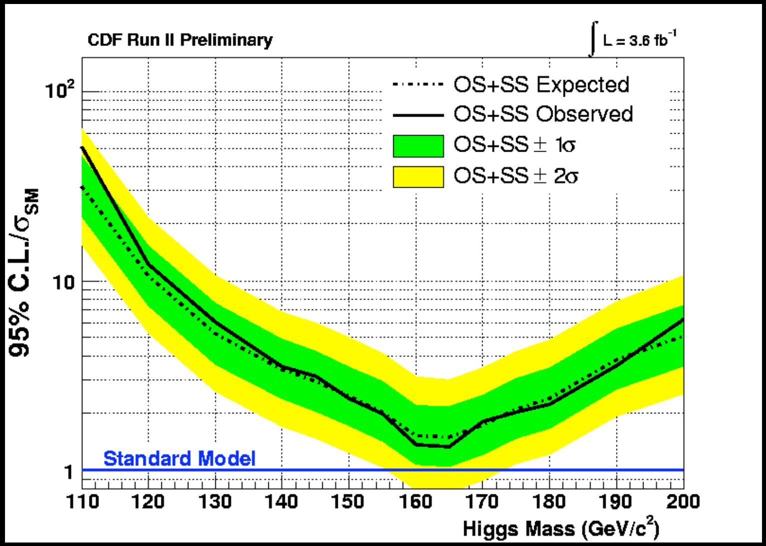
- Stay tuned for further Tevatron improvements in Higgs searches

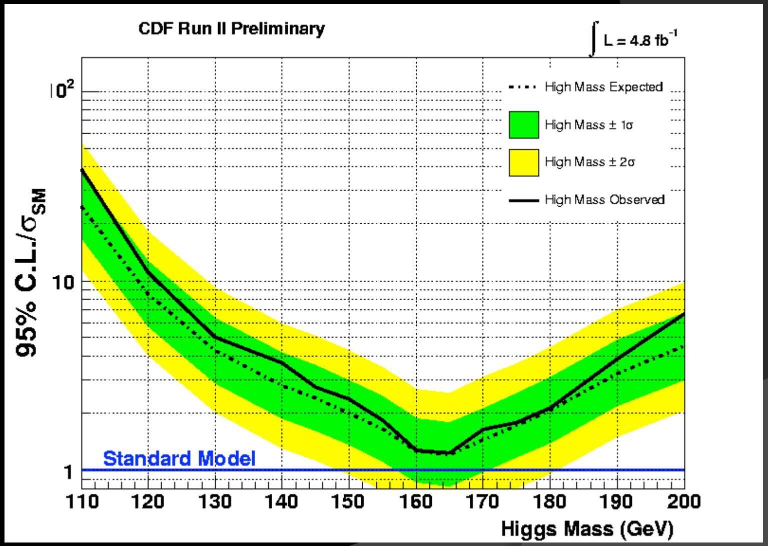
Backup

CDF old vs new results

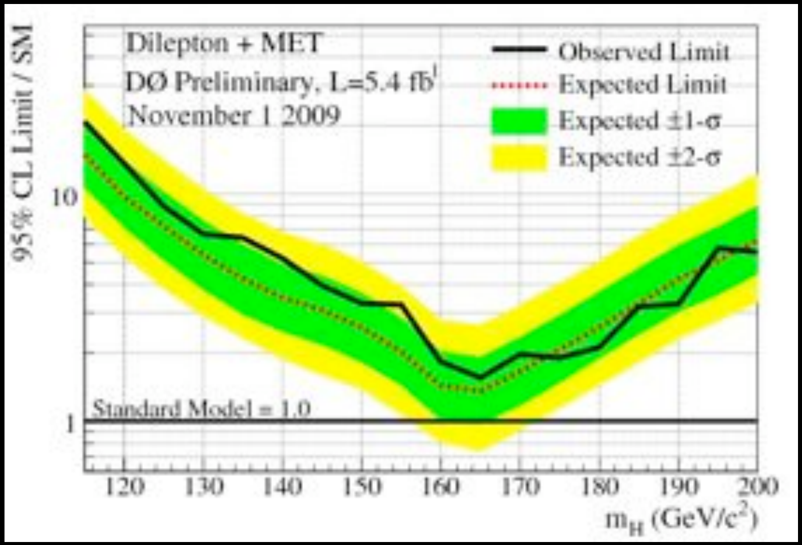
Spring 2009:
At Mh=165 GeV
Exp/σ_{SM}: 1.61
Obs/σ_{SM}: 1.46

Current:
At Mh=165 GeV
Exp/σ_{SM}: 1.19
Obs/σ_{SM}: 1.18



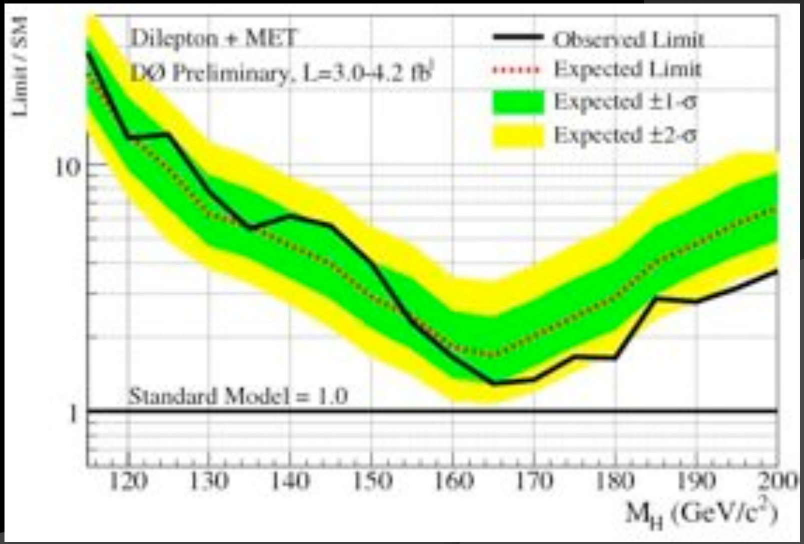


D0 old vs new results

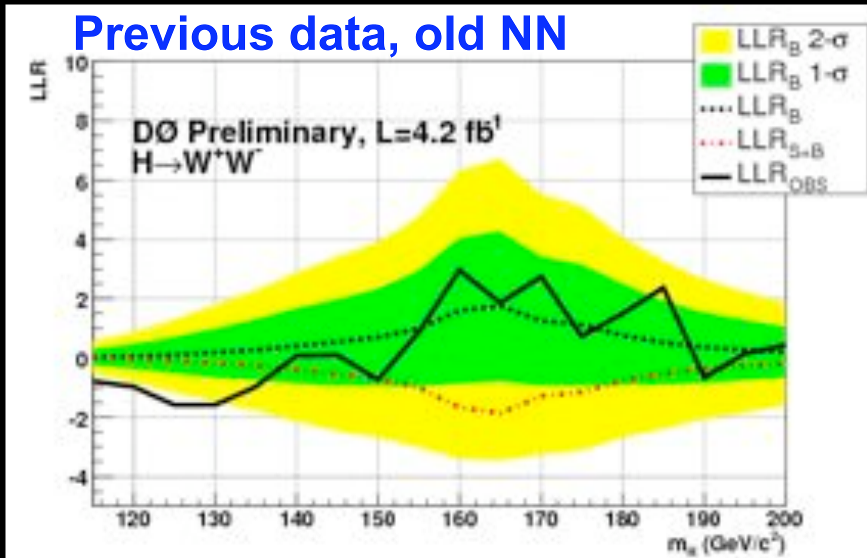


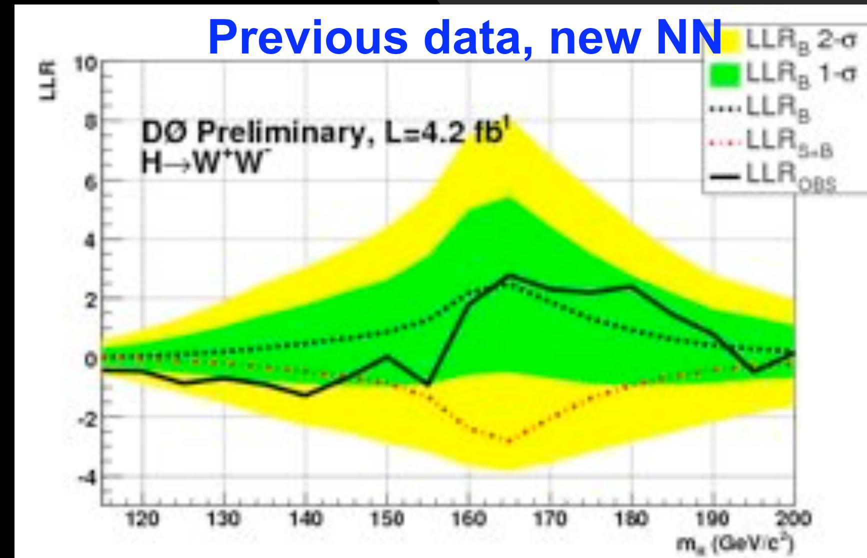
Current result at 165 GeV
1.36 (expected)
1.55 (observed)

Previous result at 165 GeV
1.7 (expected)
1.3 (observed)

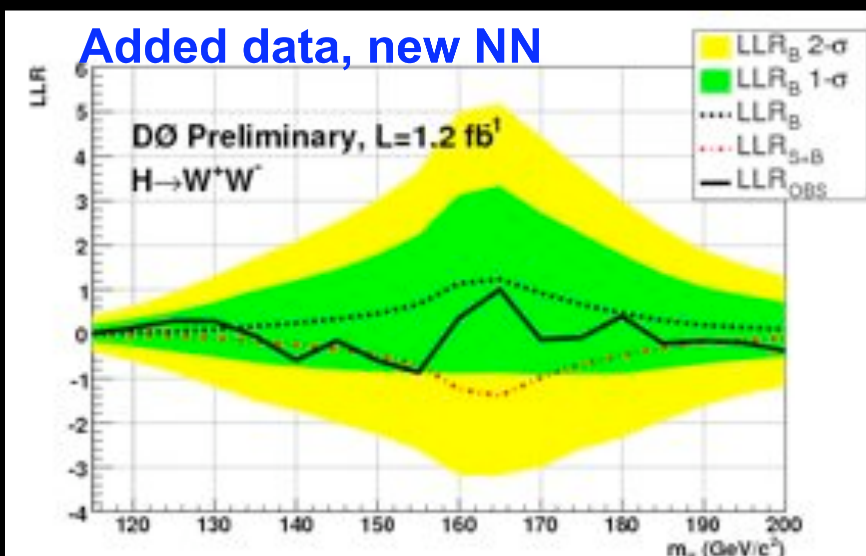


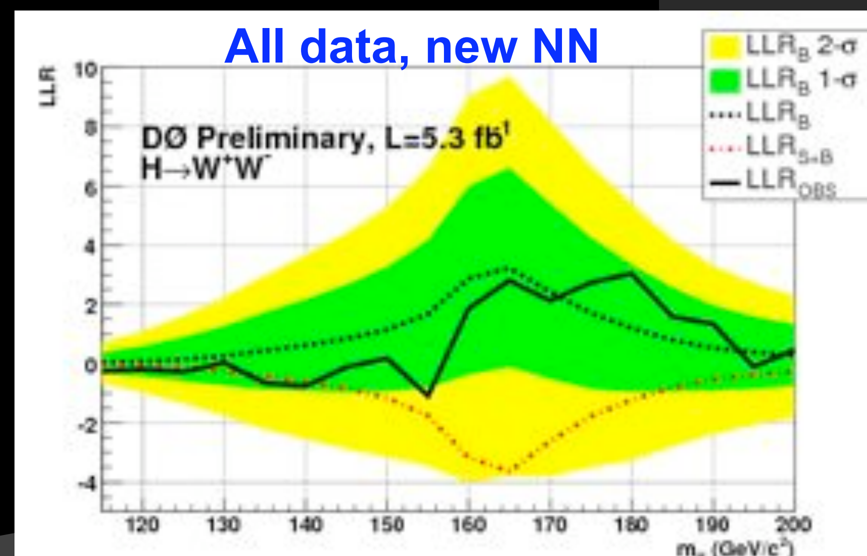
D0 Results comparison





NO SYSTEMATICS!





CDF Systematics

$H \rightarrow WW$ 0 Jet Systematics

0 Jet Uncertainties	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \rightarrow H$	WH	ZH	VBF
Cross Section											
Scale								10.9%			
PDF Model								5.1%			
Total	*10.0%*	*10.0%*	*10.0%*	15.0%	5.0%	10.0%		12.0%			
Acceptance											
Scale (leptons)								2.5%			
Scale (jets)								4.6%			
PDF Model (leptons)	1.9%	2.7%	2.7%	2.1%	4.1%	2.2%		1.5%			
PDF Model (jets)								0.9%			
Higher-order Diagrams	**5.5%**	**10.0%**	**10.0%**	10.0%	**5.0%**	**10.0%**					
Missing Et Modeling	1.0%	1.0%	1.0%	1.0%	20.0%	1.0%		1.0%			
Conversion Modeling						20.0%					
Jet Fake Rates											
(Low S/B)							21.5%				
(High S/B)							27.7%				
MC Run Dependence	3.9%			4.5%		4.5%		3.7%			
Lepton ID Efficiencies	2.0%	1.7%	2.0%	2.0%	1.9%	1.4%		1.9%			
Trigger Efficiencies	2.1%	2.1%	2.1%	2.0%	3.4%	7.0%		3.3%			
Luminosity	5.9%	5.9%	5.9%	5.9%	5.9%	5.9%		5.9%			

D0 Systematics

Sample of systematics considered

Systematic Uncertainty	Type	Value
Jet Energy Scale	Shape & Norm	3-17
Jet ID Efficiency	Shape & Norm	6-18
Jet Resolution	Shape & Norm	2
Cross Sections	Flat Norm	6-10
Multijet Background	Flat Norm	2-20
Parton Distribution Function	Flat Norm	8
Lepton ID	Flat Norm	2.5-4
Lepton Momentum Scale	Shape & Norm	2-8
p_T of WW/H/Z	Shape & Norm	1-5
Luminosity	Flat Norm	6.1

Relative uncertainty in %

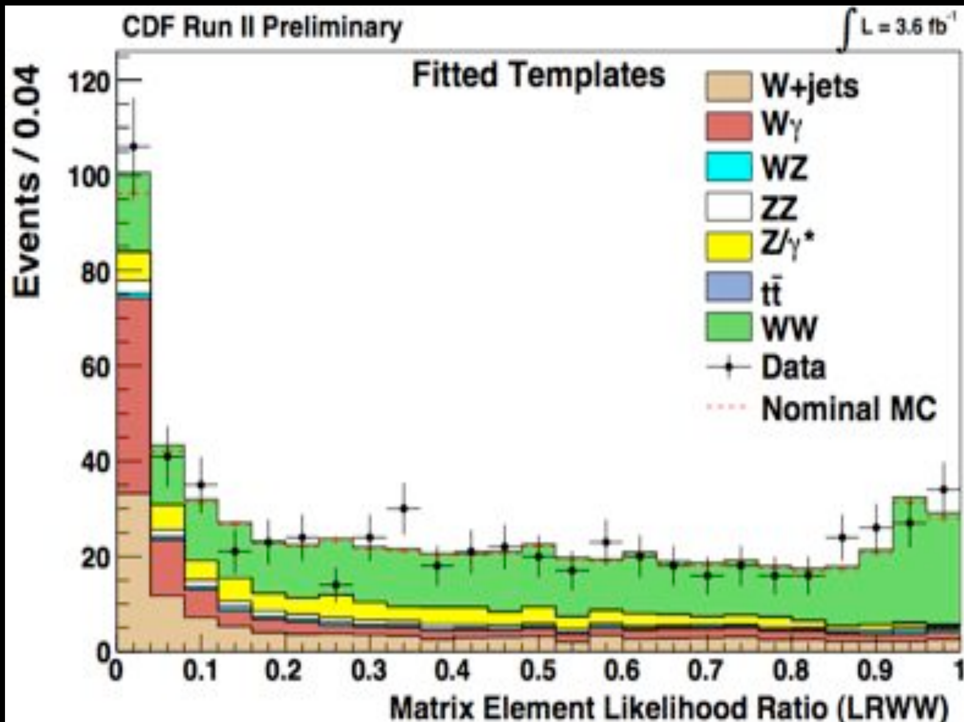
WW p_T – central value from MC@NLO, ±1☒ from MC@NLO studies

Higgs p_T – Central value from Sherpa, ±1☒ from Pythia

Z p_T – Central value from DØ measurement, ±1☒ from Alpgen

WW Cross Section

- Measure WW cross section in 0 jet signal region
- Maximum likelihood fit to WW likelihood ratio distribution
  - Systematic uncertainties included as Gaussian constraints in fit



- New world's best measurement!
  - Good agreement with theory (11.7 pb)

$$\sigma(p\bar{p} \to WW) = 12.1 \pm 0.9\ (\text{stat.})^{+1.6}_{-1.4}\ (\text{syst.})\ [\text{pb}]$$

Syst. **includes** 5.9% luminosity uncertainty