The search for $H \rightarrow WW$ at CDF

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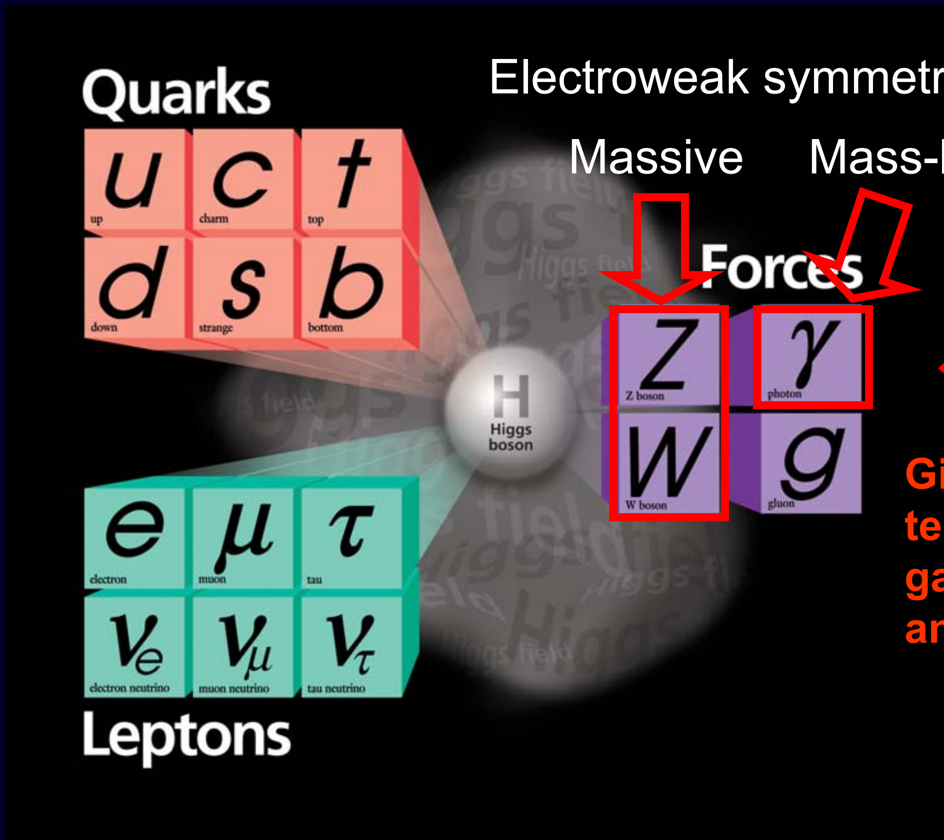
Outline

1. Brief introduction to the Higgs
   - Production and decays seen at the Tevatron
   - Final states and event selection
2. Analysis strategy and procedure
   - Improvements
   - Signal and background modeling
4. Results and systematics

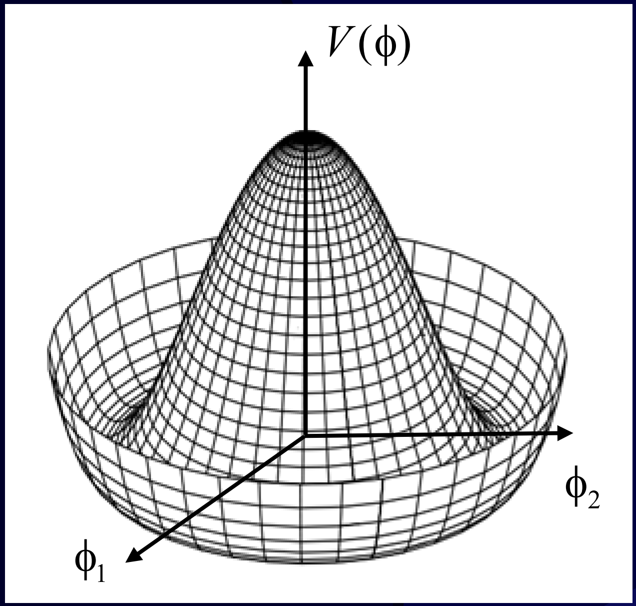
Higgs introduction

Electroweak symmetry broken

Massive Mass-less



Gives mass terms for gauge bosons and itself

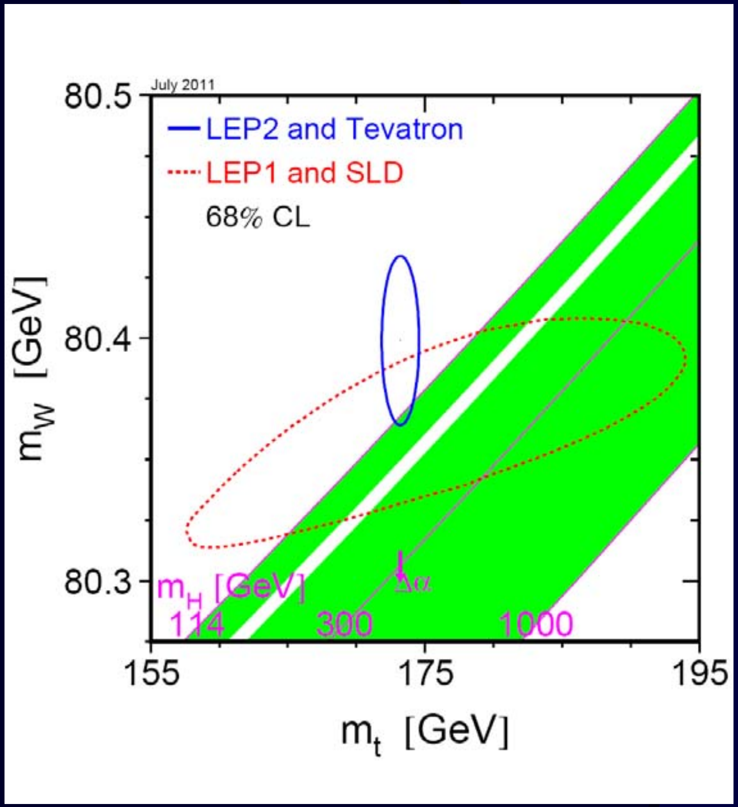


Where to look for the Higgs

Indirect constraints from precision electroweak measurements

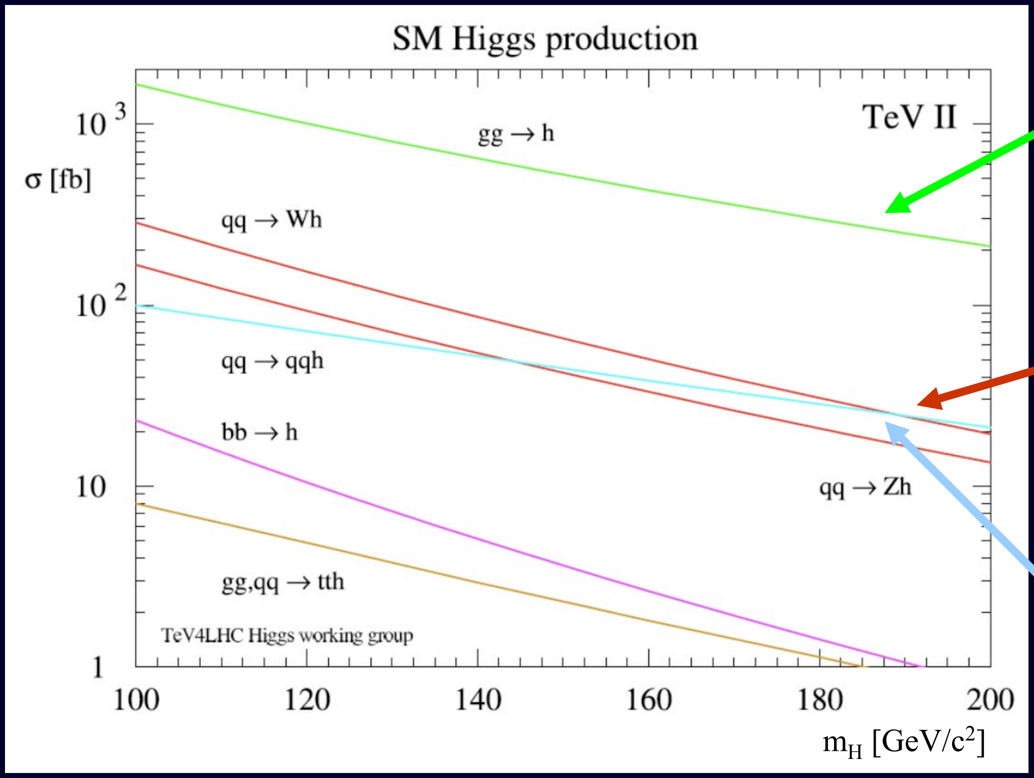
Top quark and Higgs boson contribute to W mass through self-interaction terms

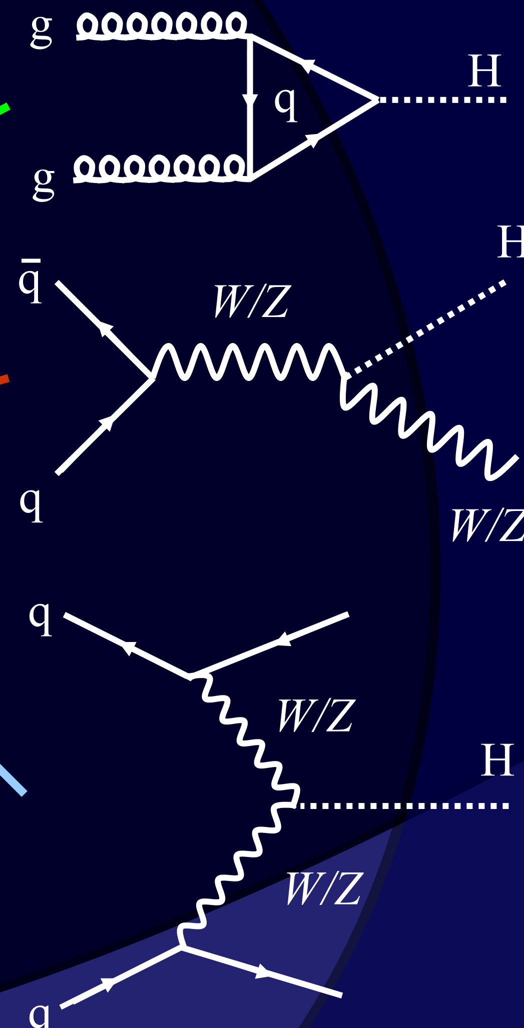
Central value of $m_H = 92\ \mathrm{GeV/c^2}$ and $m_H < 161\ \mathrm{GeV/c^2}$ at the 95% C.L.



LEP excluded masses less than $114.4\ \mathrm{GeV/c^2}$ at the 95% C.L.

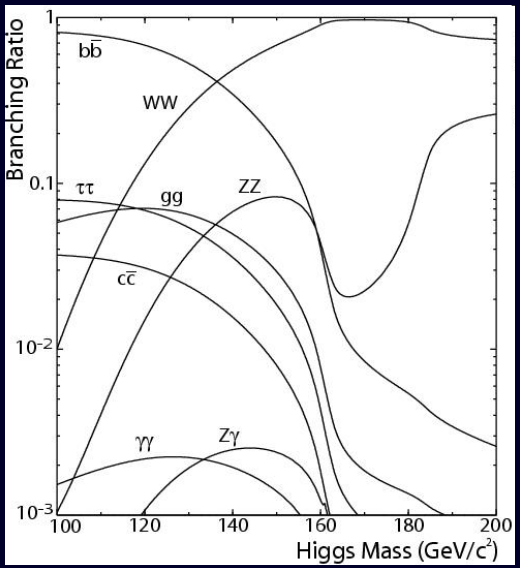
Higgs production at the Tevatron





Gluon fusion easily dominates
the other production mechanisms

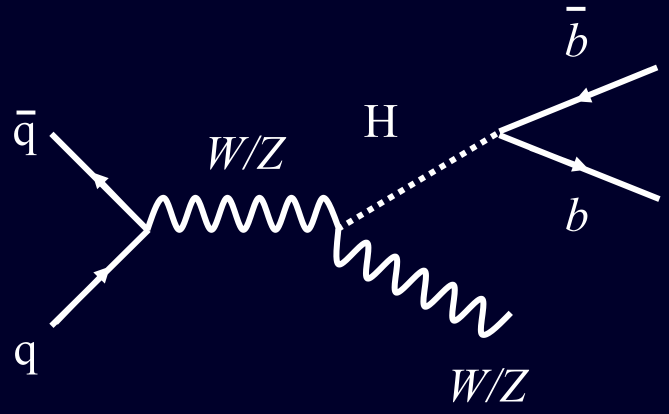
Higgs final states

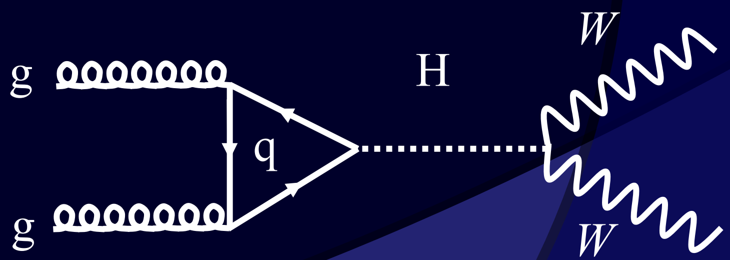


We concentrate on low and high mass separately at the Tevatron

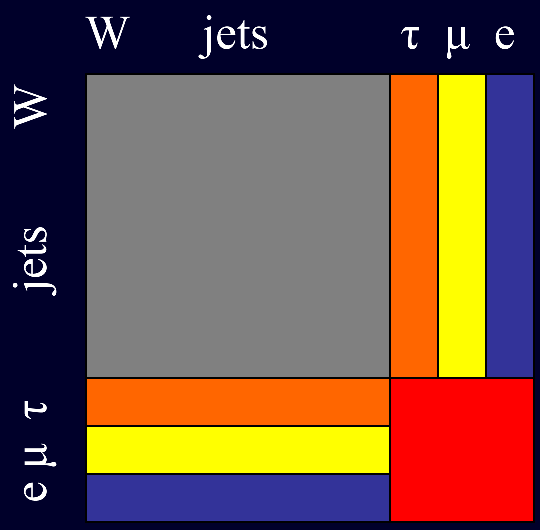
At $m_H < 135$ GeV/c^2, $H \to b\bar{b}$ dominates

At $m_H > 135$ GeV/c^2, $H \to WW$ dominates





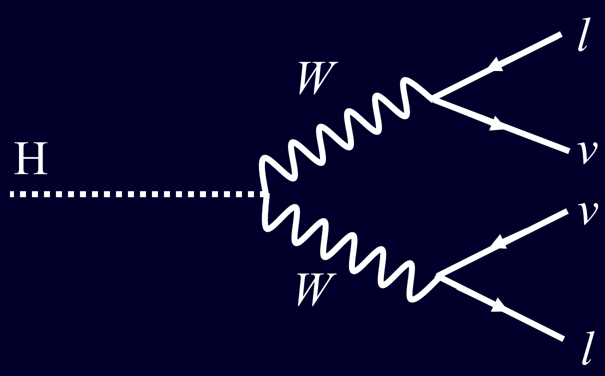
Higgs final states



Branching ratio of the *W*s

We focus on the decay modes of $W \to l\nu$ (about 10% for e, μ, and τ each)

The high p_T lepton from the W provides an excellent handle



Our event selection is simple: two high p_T leptons and missing E_T

CDF detector components

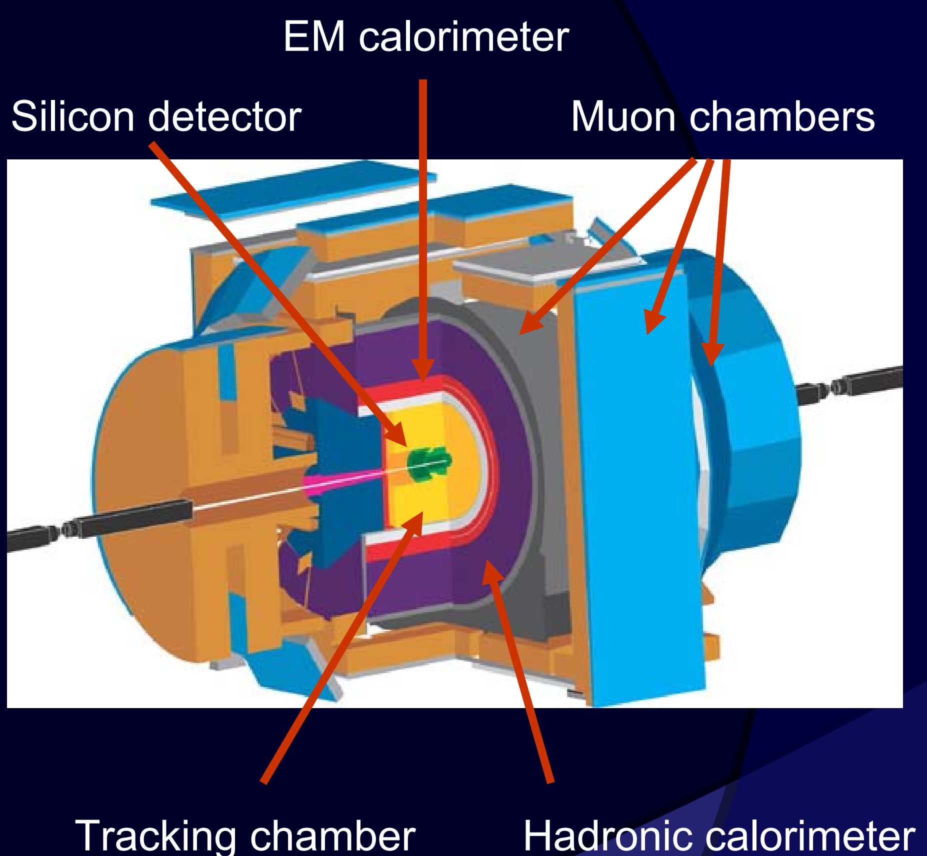
Higgs searches incorporate most detector components

- Tracking from silicon detector and drift chamber

- Central and forward muon chambers

- EM calorimeter for electron candidates

- Hadronic calorimeter to find jets



Challenging search at the Tevatron

Low cross-section at the Tevatron
- Less than 1 pb

Cover as many final states as possible
- Efficient triggers
- Efficient lepton identification

Event signature is background dominated
- Must model each background accurately

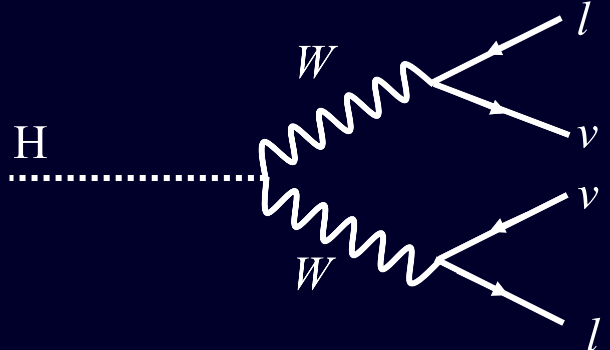
Simple counting is not sufficient
- Use kinematics to separate signal from background

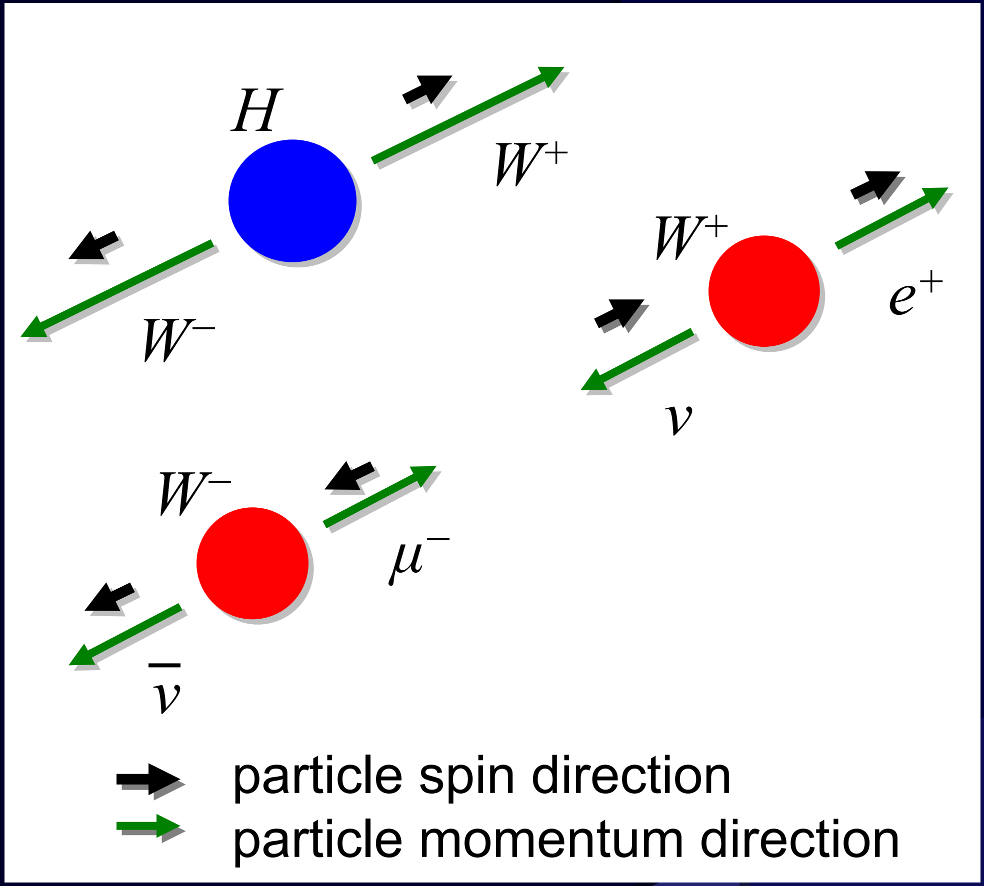
An example of kinematic separation

The Higgs is a spin 0 boson

- The *W* bosons must have 0 net spin

- The handedness of the weak interaction results in the charged leptons going off in same direction

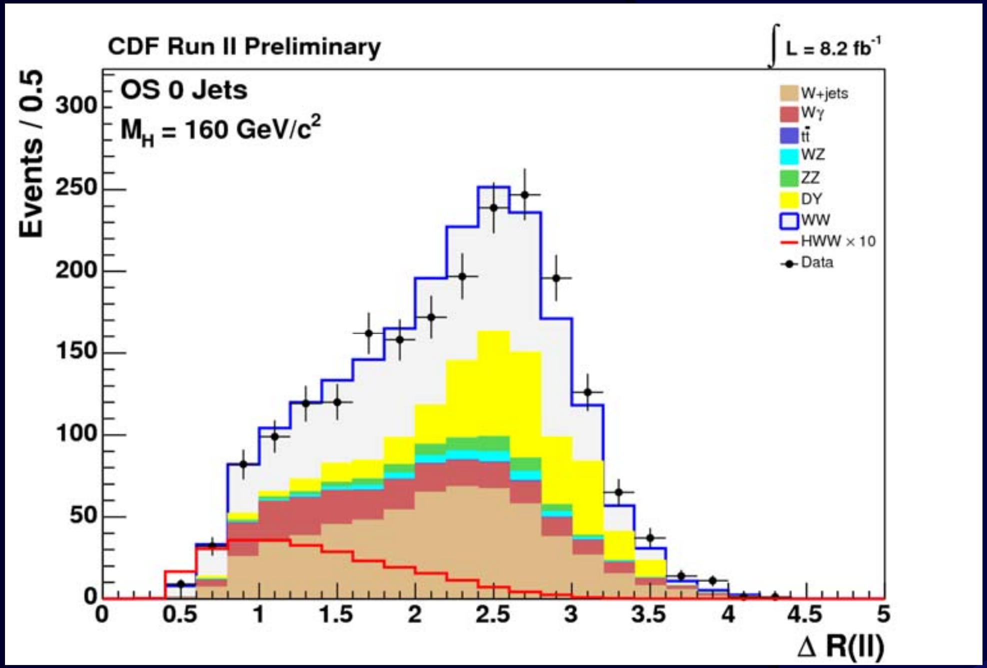


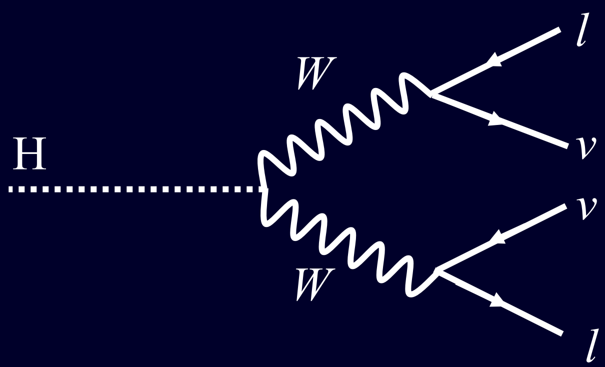


An example of kinematic separation

The small opening angle becomes one of our most powerful discriminants to separate out signal

In this instance, $\Delta R = \sqrt{(\Delta\varphi)^2+(\Delta\eta)^2}$ between leptons is a measure of spatial separation





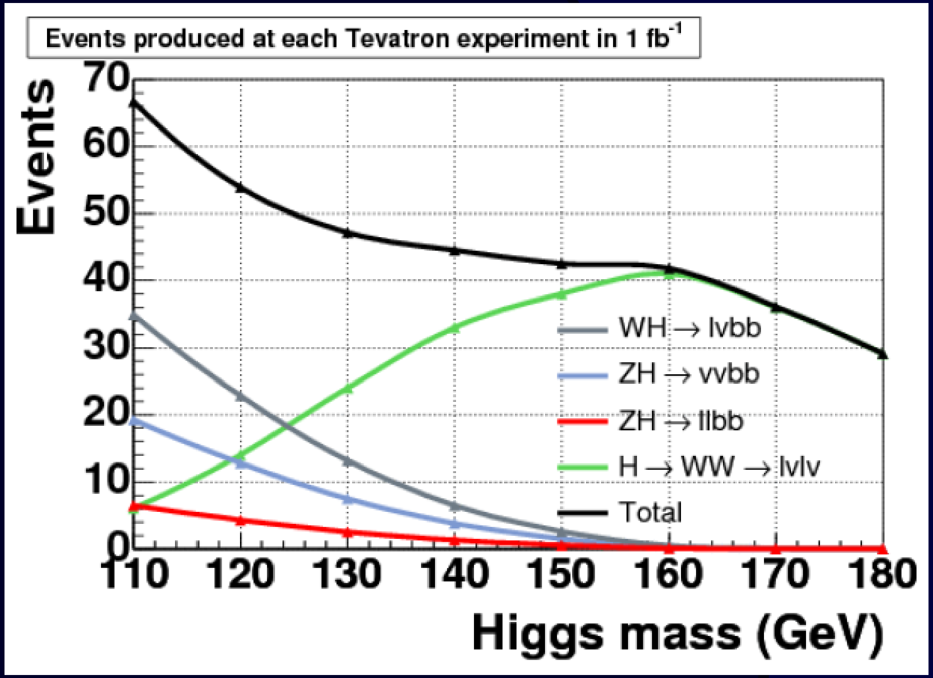
ΔR separates the red Higgs signal from the many backgrounds

The analysis roadmap

Start with high p_T e and μ triggered data, maximize acceptance

Model backgrounds accurately, check in control regions

Multivariate techniques separate signal from background (S/B~0.01)

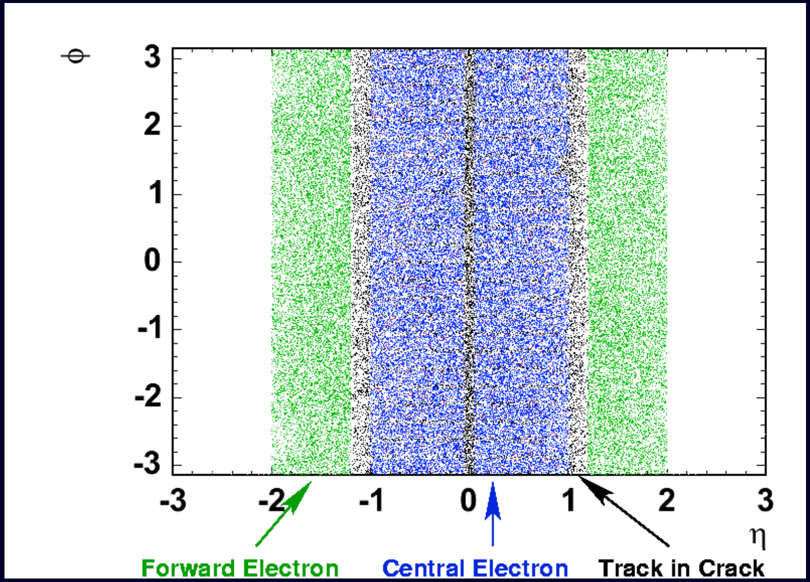


Expect only about 10 events per experiment at 165 GeV/c^2 after trigger, reconstruction, and event selection

The first step is maximizing the $H \rightarrow WW$ acceptance

Identifying electrons and muons

Electron ID

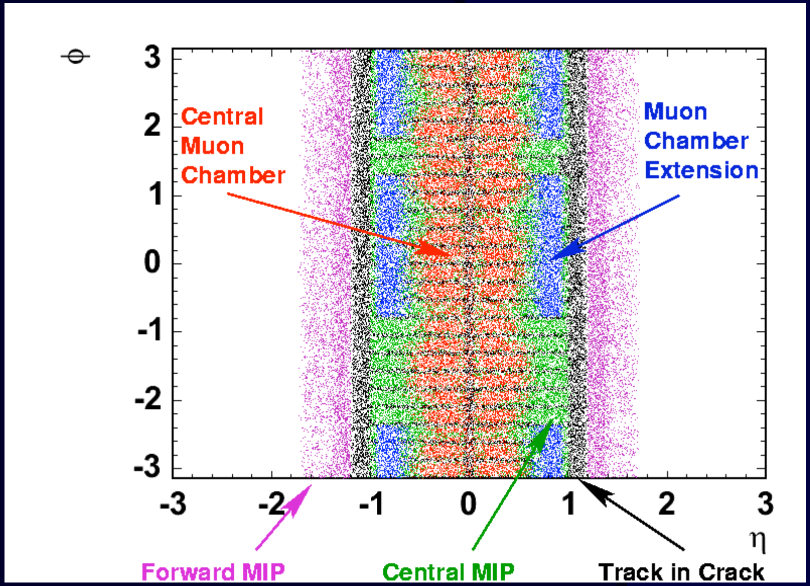


Central electrons (cut and likelihood based)

Forward electrons (cut and likelihood based)

Isolated tracks

Muon ID



Standard muons (red and blue)

Minimum ionizing tracks (central and forward)

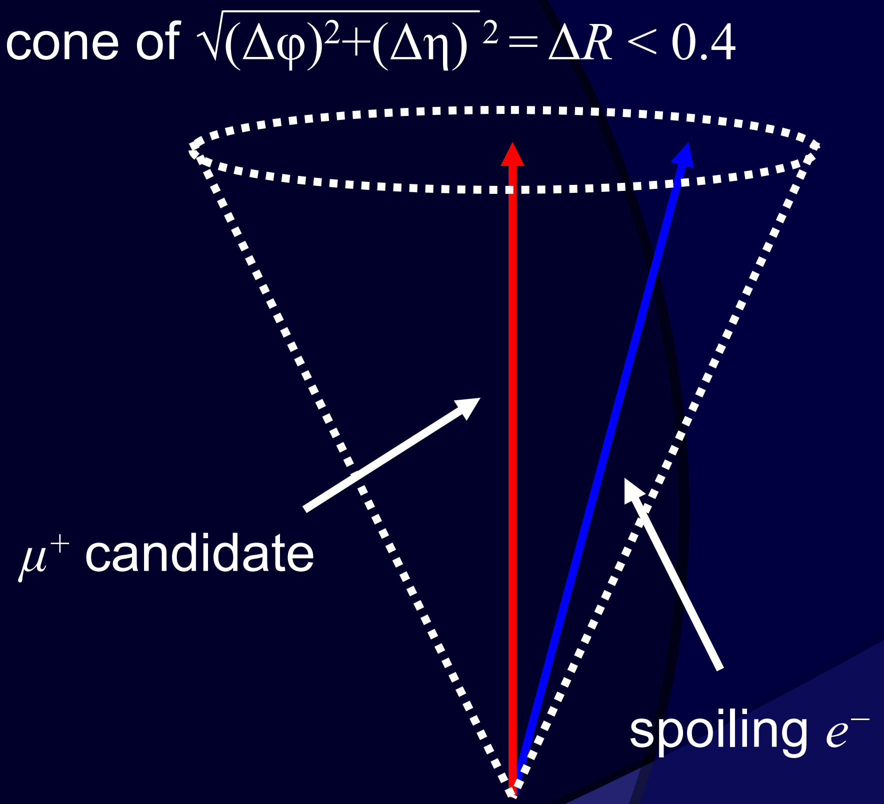
Isolated tracks

Improvements from CDF

Maximizing acceptance is the goal, motivates the improvements

Largest improvement from changing isolation calculation to prevent mutual spoilage from nearby candidates

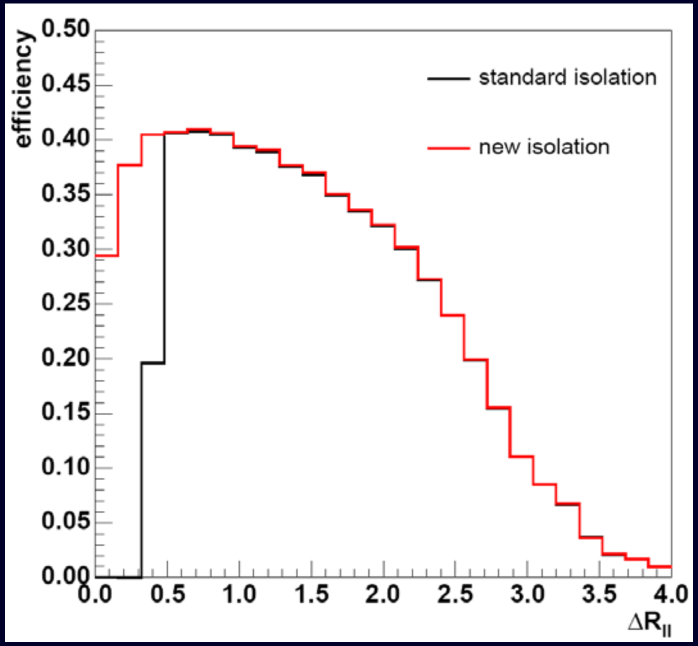
CDF also adds in likelihood based forward electrons and an improved isolated track



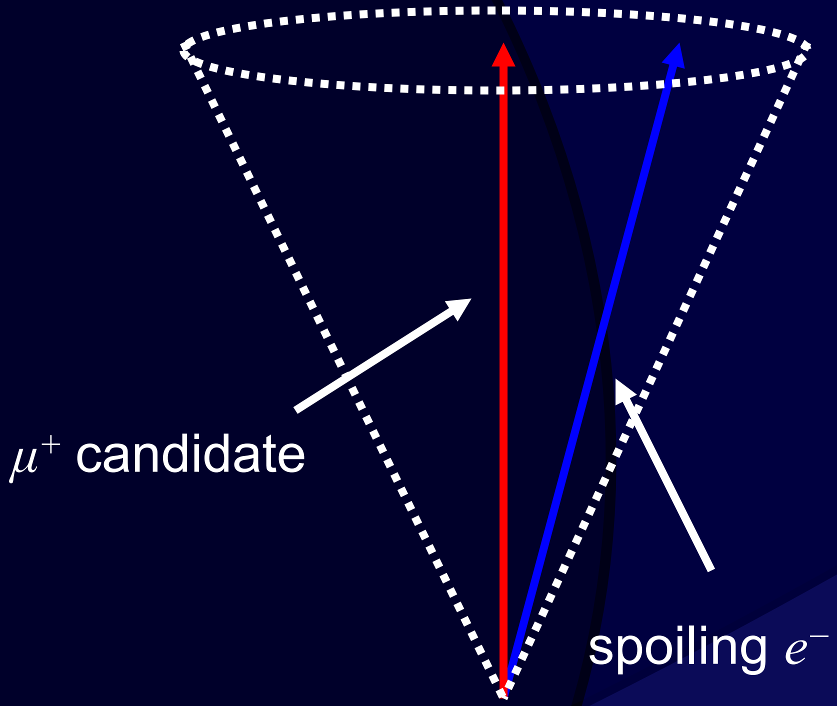
The new isolation

When the leptons are close enough in ΔR, they can spoil each others isolation requirements

CDF re-evaluates the isolation criteria, removing likely electron or muons from the cone

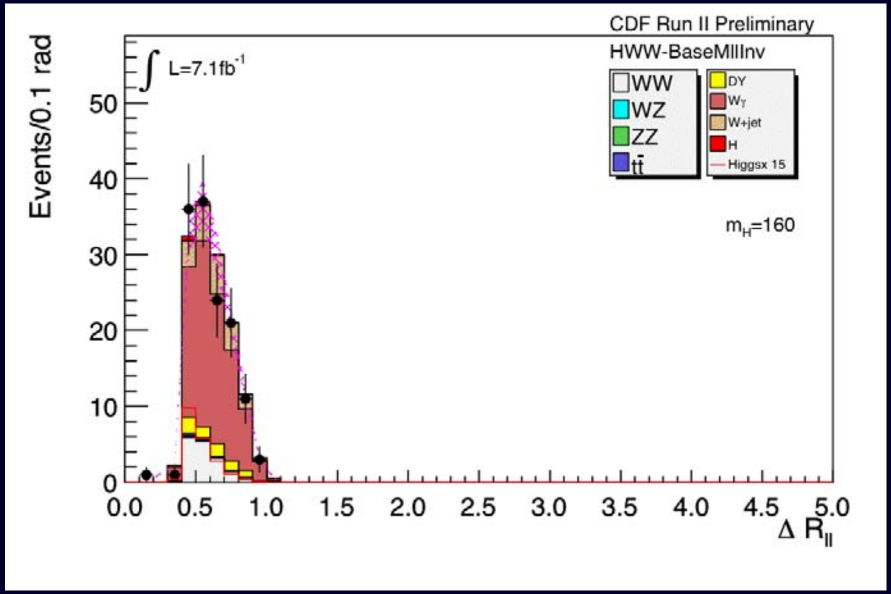


cone of $\sqrt{(\Delta\varphi)^2+(\Delta\eta)^2} = \Delta R < 0.4$

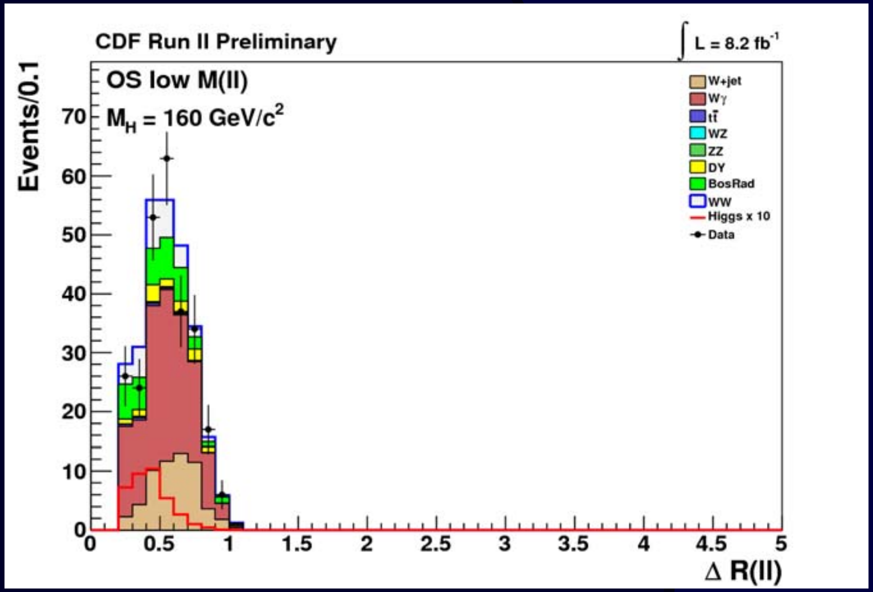


$$Isolation = \frac{E_T^{cone} - E_T^{from\ muon}}{E_T^{muon}}$$

The new isolation's impact



Before



After

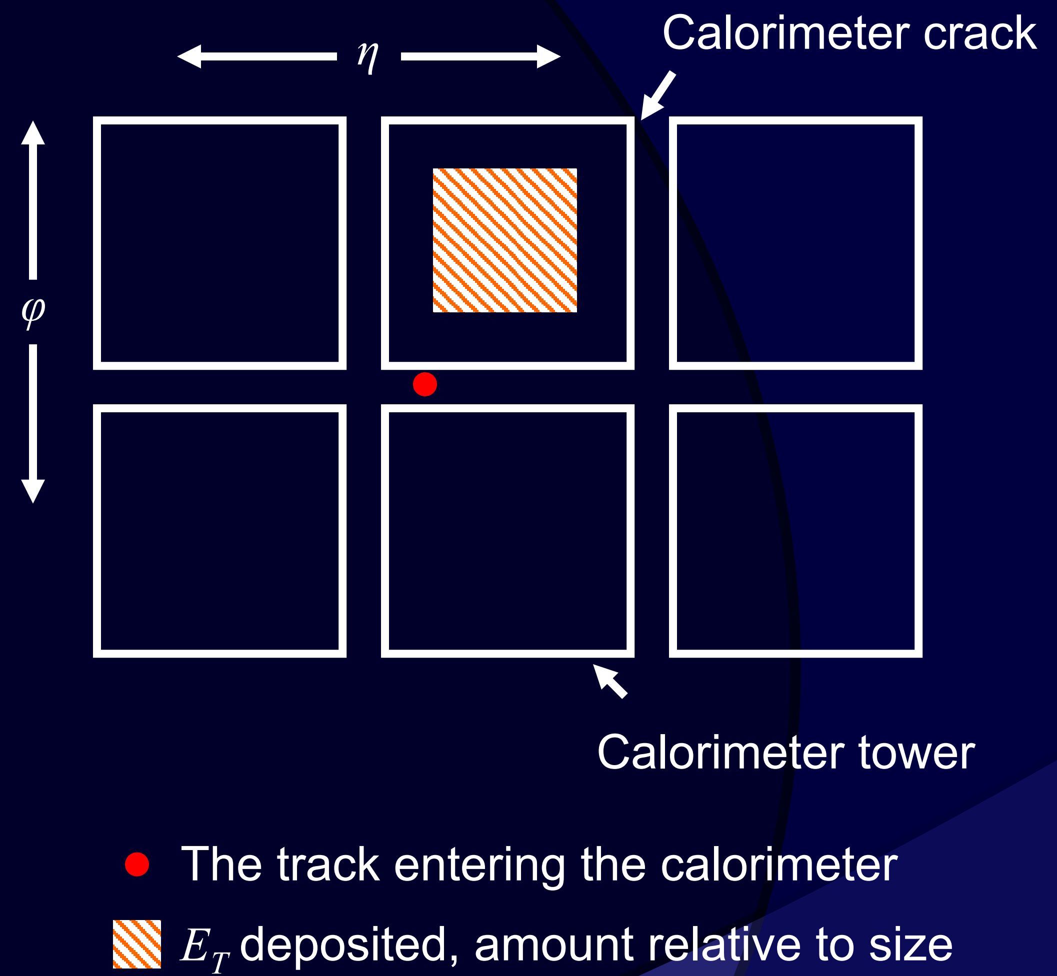
This improved our sensitivity in our low M_{ll} channel by a factor of 3!

New IsoCrkTrk category

Already take lepton tracks incident in calorimeter cracks without energy deposition or muon stubs

Electrons can radiate a photon, leaving EM energy in nearby towers

Accepted these candidates by relaxing EM isolation requirement



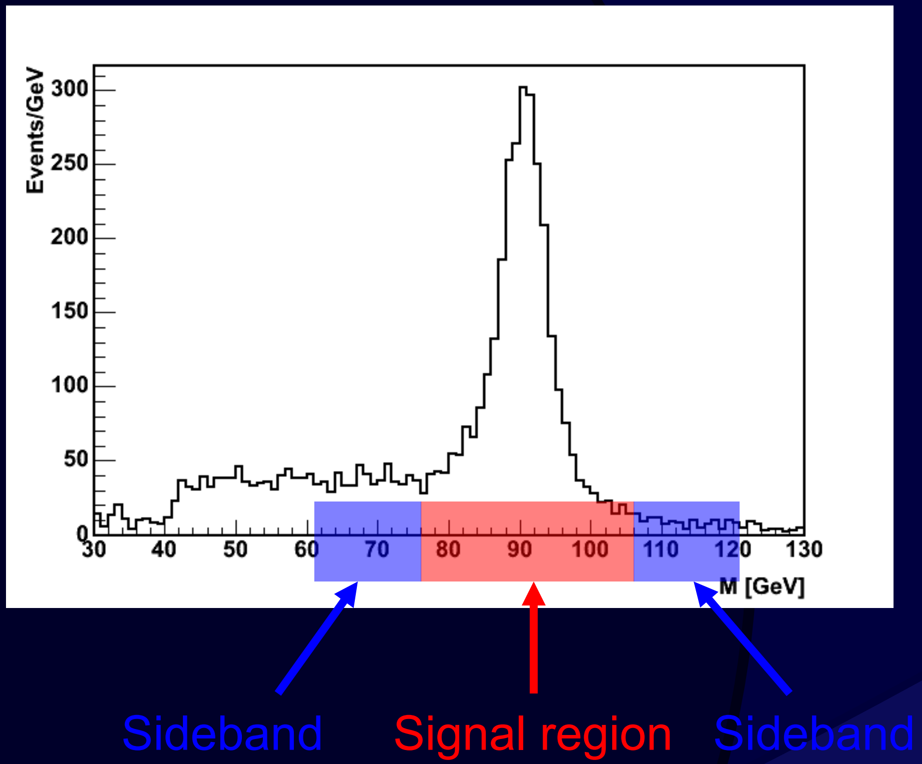
Challenges of adding new leptons

Lepton ID efficiencies are different between data and MC

We use $Z \rightarrow ll$ decays to measure efficiencies and correct for it

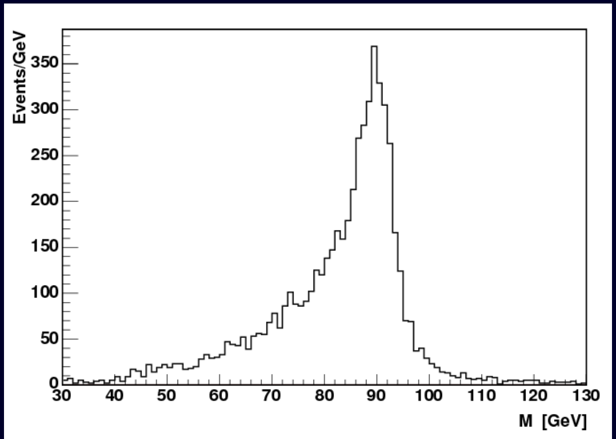
$$SF = \varepsilon_{data}/\varepsilon_{MC}$$

To determine Z signal events, normally use sideband subtraction

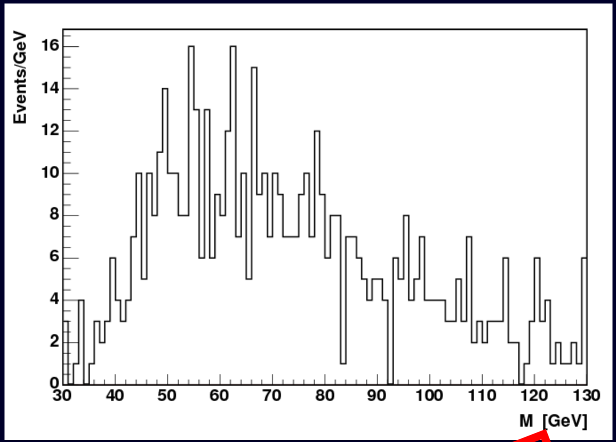


Challenges of adding new leptons

Sideband subtraction inadequate for IsoCrkTrk

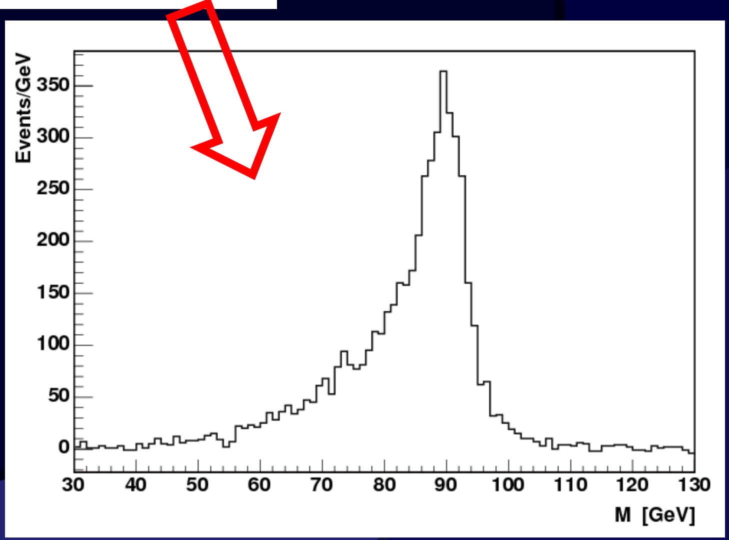


$Z \to ll$ (has tail)



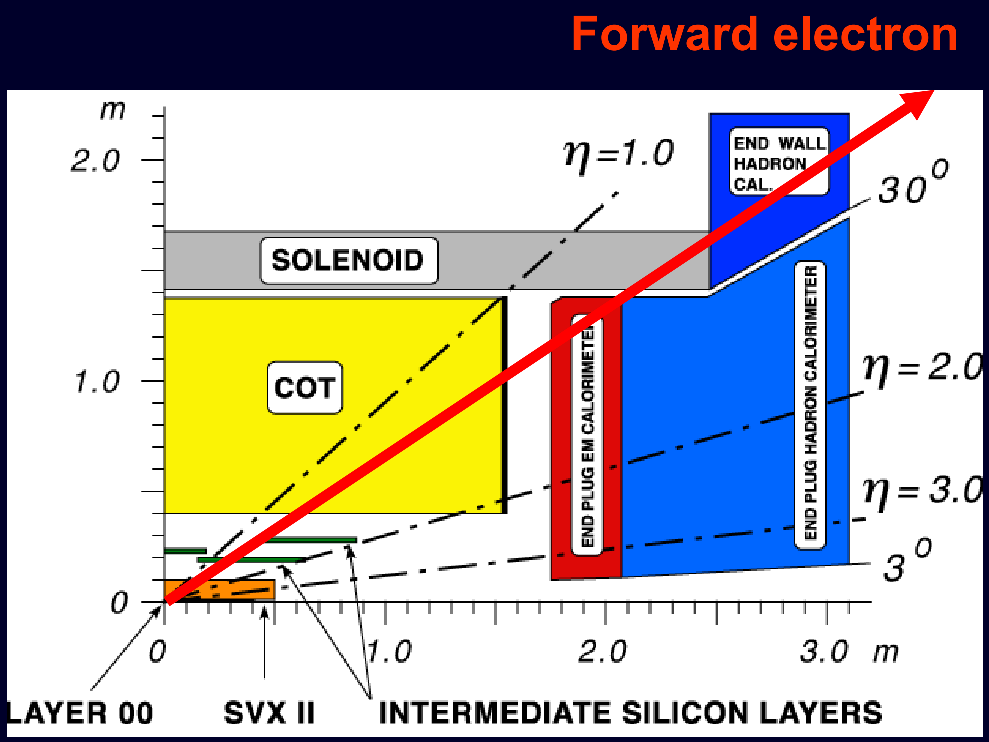
Same-sign

$Z \to ll$, SS subtracted



Normal plot showed large radiation tail, subtract out same-sign

Likelihood based forward electrons



Aimed to recover candidates that failed our normal forward electron criteria

Signal templates created from $Z \rightarrow ee$ events; background events from dijet data

Used variables such as E_{had}/E_{em}, E_T/p_T, and track η

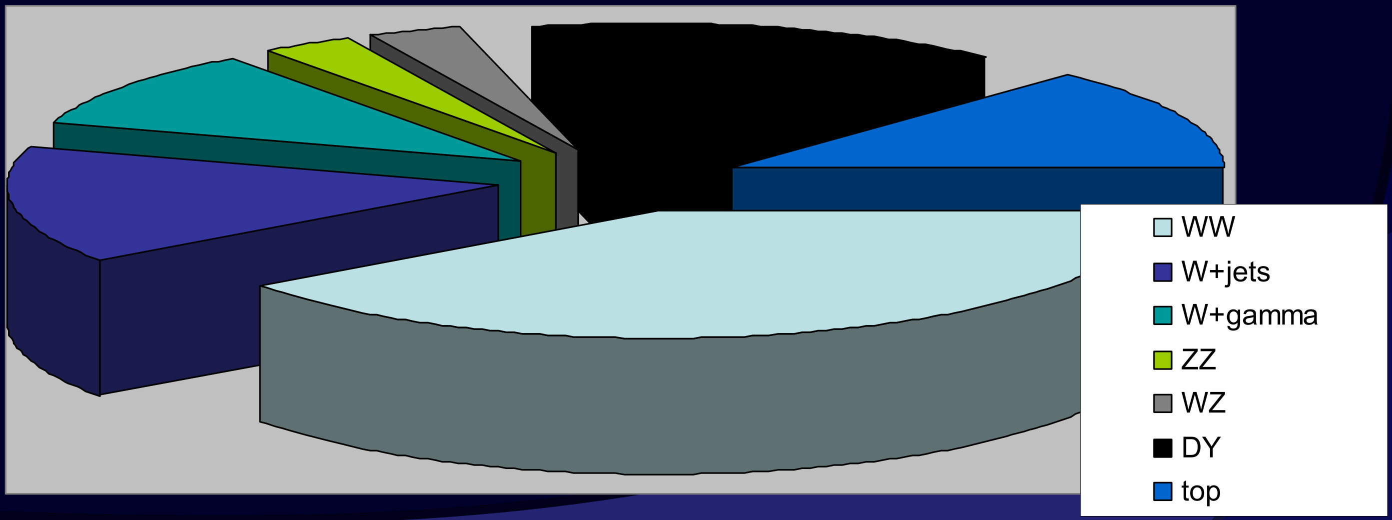
The Standard Model backgrounds in the $H \rightarrow WW$ channel

Standard Model backgrounds

Our backgrounds are *WW*, *WZ*, *ZZ*, Drell-Yan, W+γ, *W*+jets, and top

We need to separate out a small signal from a large background

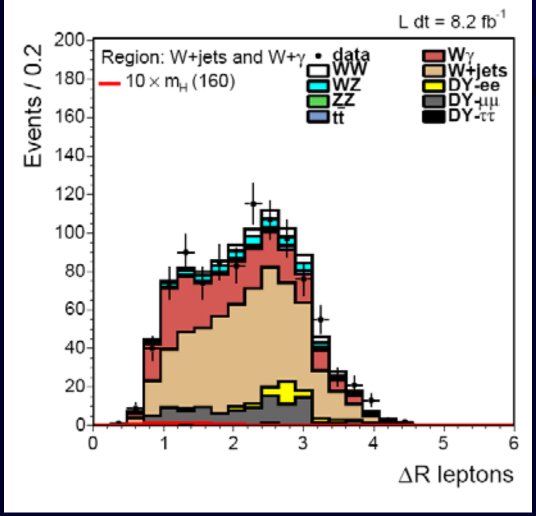
Remember, even in CDF's most sensitive channel, we still only have S/B~0.01 after preselection cuts



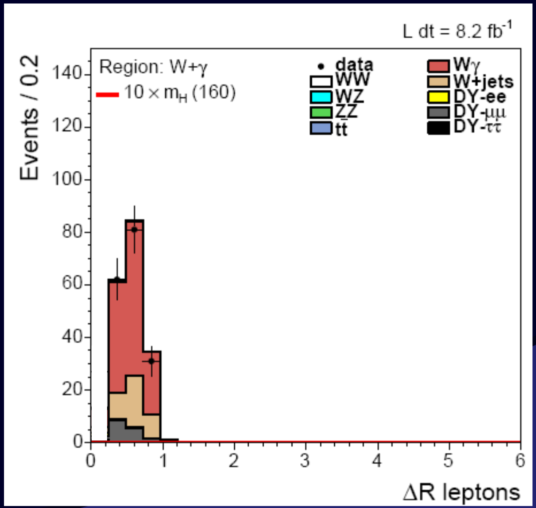
Cross-checking the background modeling

For each background, we preferably have a control region to validate our modeling of it

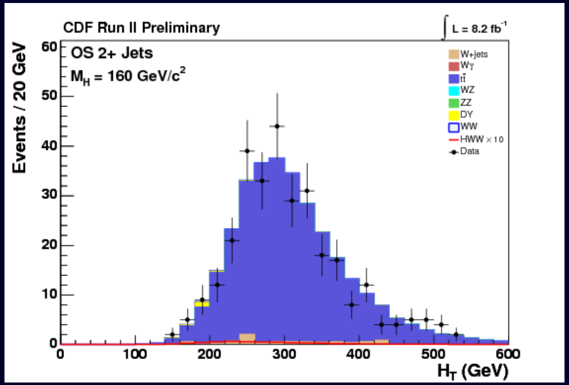
For WW, WZ, and ZZ though, we are not able to define a region, rely on cross-section measurement, will come back to this later



For W+jets, use same-sign dileptons



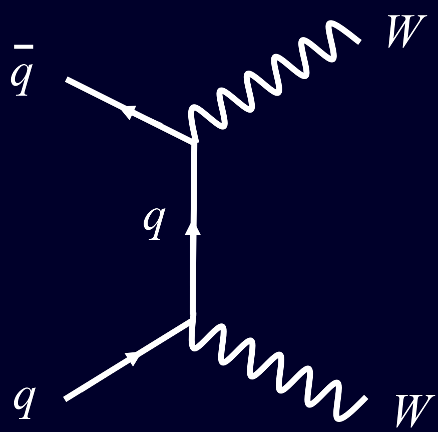
For W+γ, use same-sign dileptons for $M_{ll} < 16$ GeV/c^2

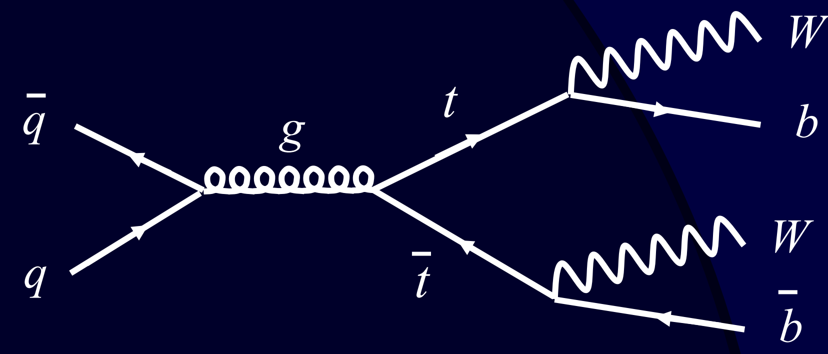


For top, use opposite-sign dileptons, 2+jets and a b-tag

What else does CDF do to maximize our sensitivity to $H \rightarrow WW$?

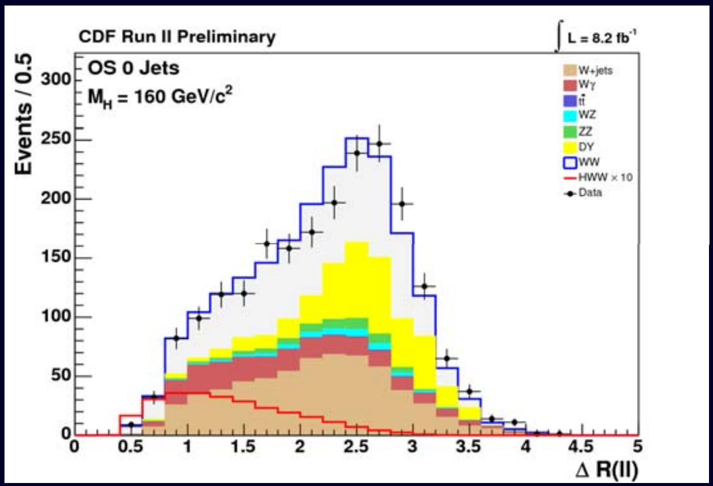
Know your signals and backgrounds

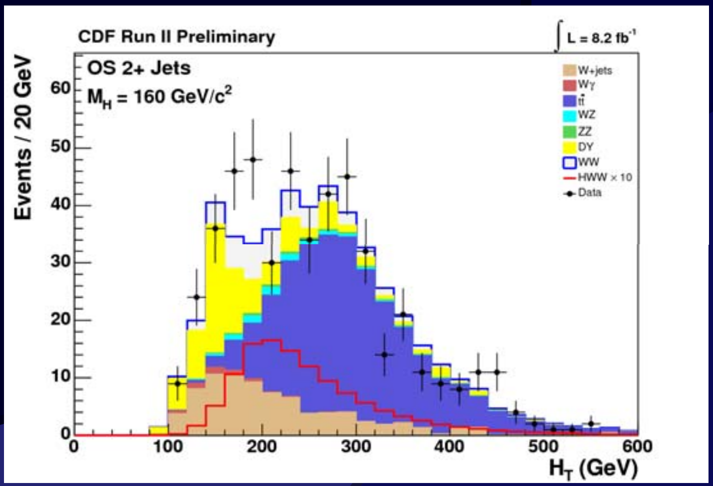




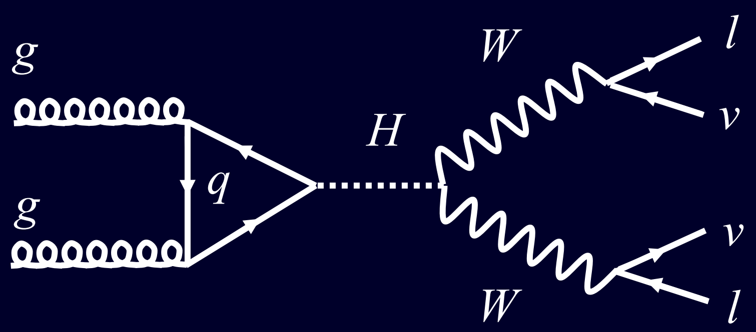
With no jets at LO, the *WW* background dominates in no jets bin

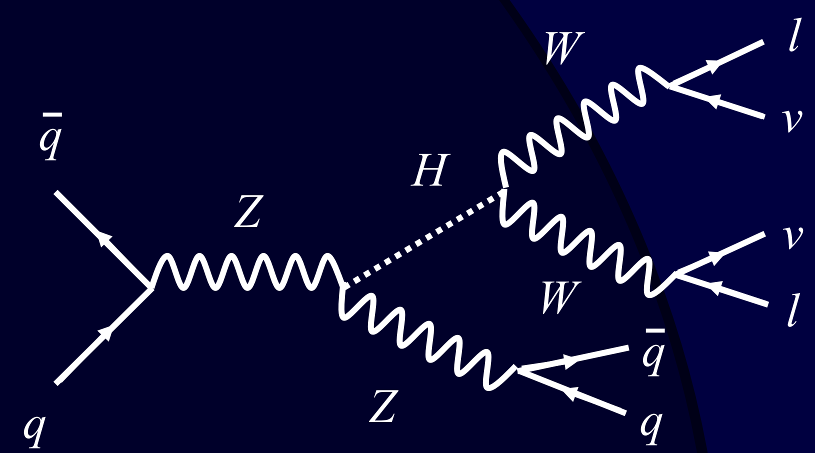
With two jets, the $t\bar{t}$ background dominates





Know your signals and backgrounds





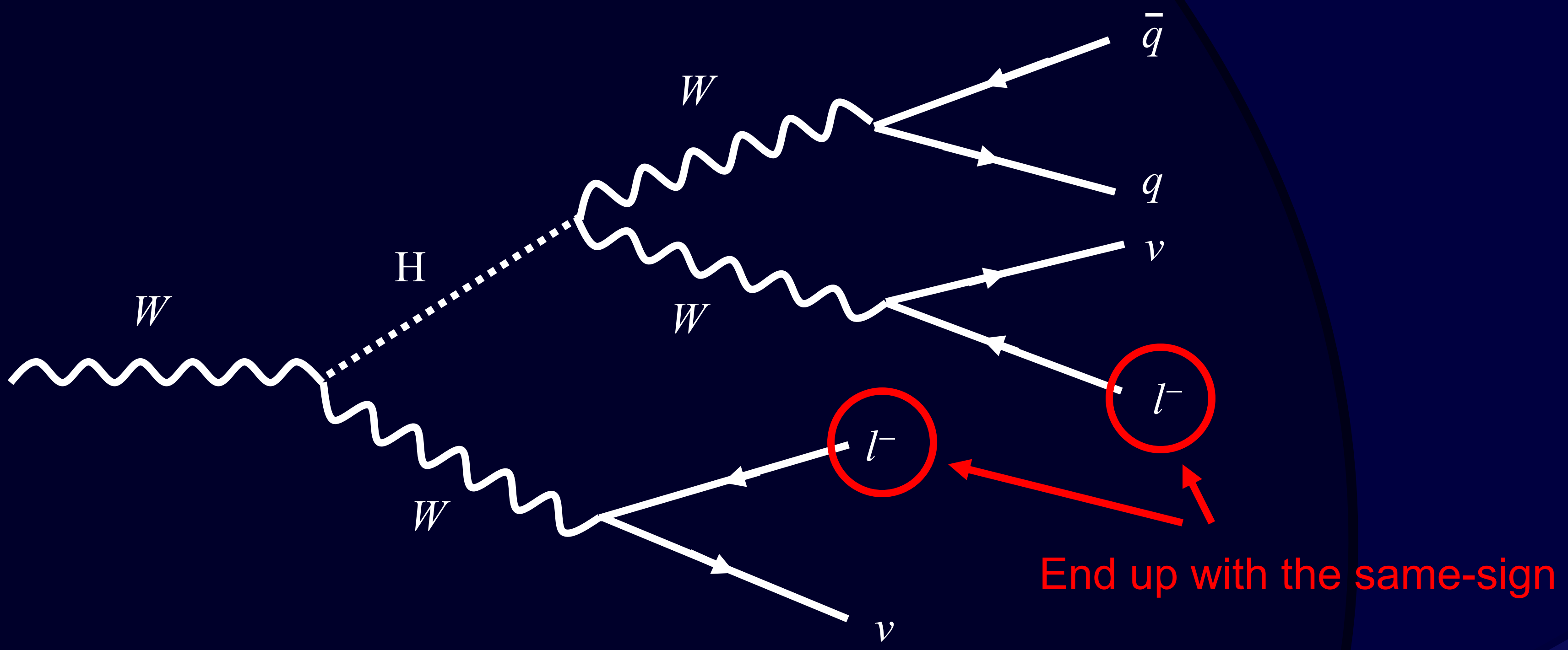
No jets at LO for $gg \to H$

Two jets at LO for $qq \to ZH$

Our signals and backgrounds vary by the number of jets!

We divide the data up into subsamples to capitalize

Not exclusively opposite-sign



We use a same-sign channel to take advantage of associated production

The channels used by CDF

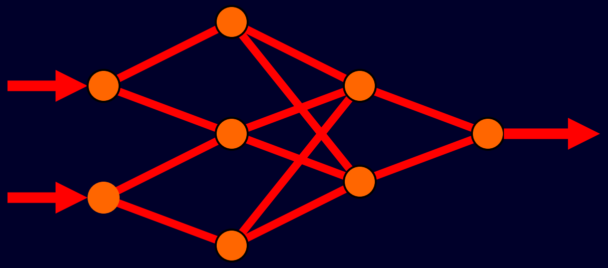
Channel	Main Signal	Main Background	Most Important kinematic variables
OS dileptons, 0 Jets	$gg \rightarrow H$	WW	LR_{HWW}, ΔR_{ll}, H_T
OS dileptons, 1 Jet	$gg \rightarrow H$	DY	ΔR_{ll}, $m_T(ll,E_T)$, E_T
OS dileptons, 2+ Jets	Mixture	t-tbar	H_T, ΔR_{ll}, M_{ll}
OS dileptons, low M_{ll}, 0 or 1 Jet	$gg \rightarrow H$	W+γ	$p_T(l2)$, $p_T(l1)$, $E(l1)$
SS dileptons, 1+ Jet	$WH \rightarrow WWW$	W+Jets	E_T, $\sum E_T^{jets}$, M_{ll}
Tri-leptons, no Z candidate	$WH \rightarrow WWW$	WZ	E_T, ΔR_{ll}^{close}, Type(lll)
Tri-leptons, Z candidate, 1 Jet	$ZH \rightarrow ZWW$	WZ	Jet E_T, ΔR_{lj}, E_T
Tri-leptons, Z candidate, 2+ Jets	$ZH \rightarrow ZWW$	Z+Jets	M_{jj}, M_T^H, ΔR_{WW}
OS dilepton, electron + hadronic tau	$gg \rightarrow H$	W+Jets	$\Delta R_{l\tau}$, τ id variables
OS dilepton, muon + hadronic tau	$gg \rightarrow H$	W+Jets	$\Delta R_{l\tau}$, τ id variables

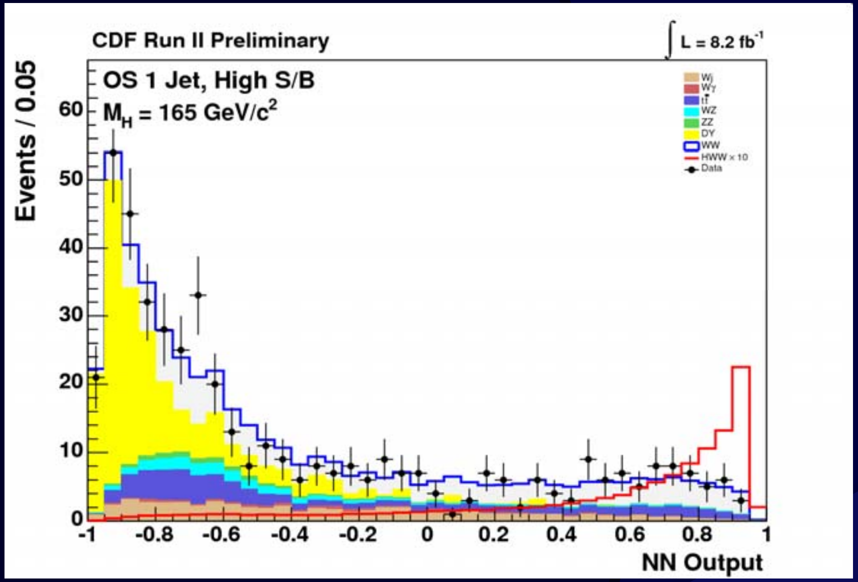
What I'm focusing on today

Neural network discriminant

Allows roughly a 10-20% improvement over a traditional cut based analysis

Event kinematics





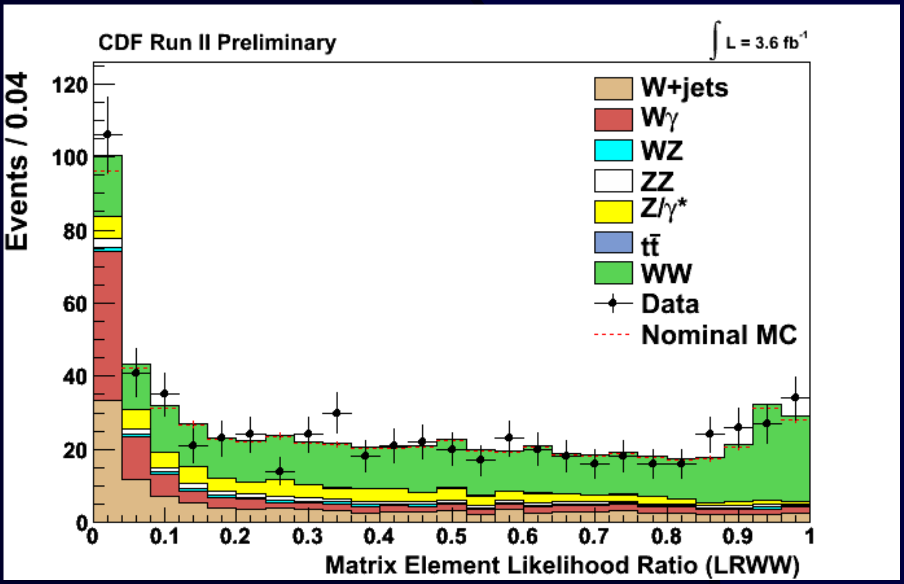
Produces final discriminant that we fit for final limits

The red Higgs signal gets separated from backgrounds

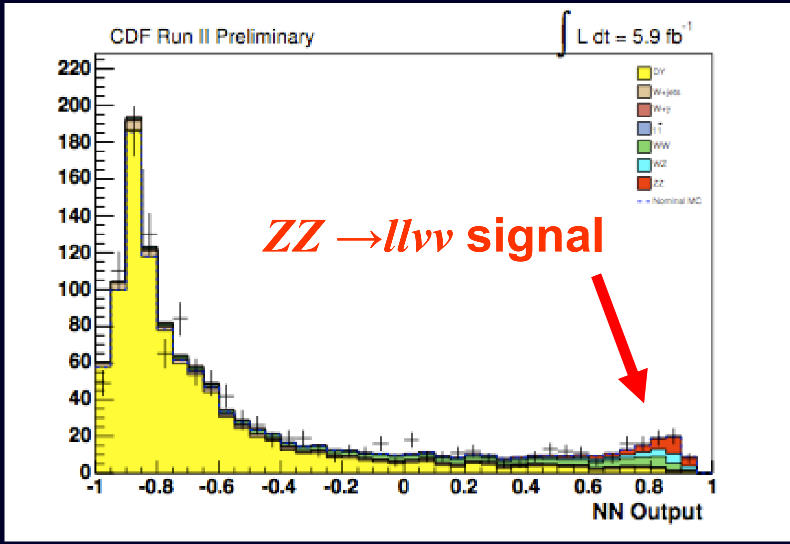
Diboson cross-sections

Measuring diboson cross-section in same final states provides a powerful cross-check of analysis techniques

Same analysis techniques are used as in the $H \rightarrow WW \rightarrow l\nu l\nu$ search



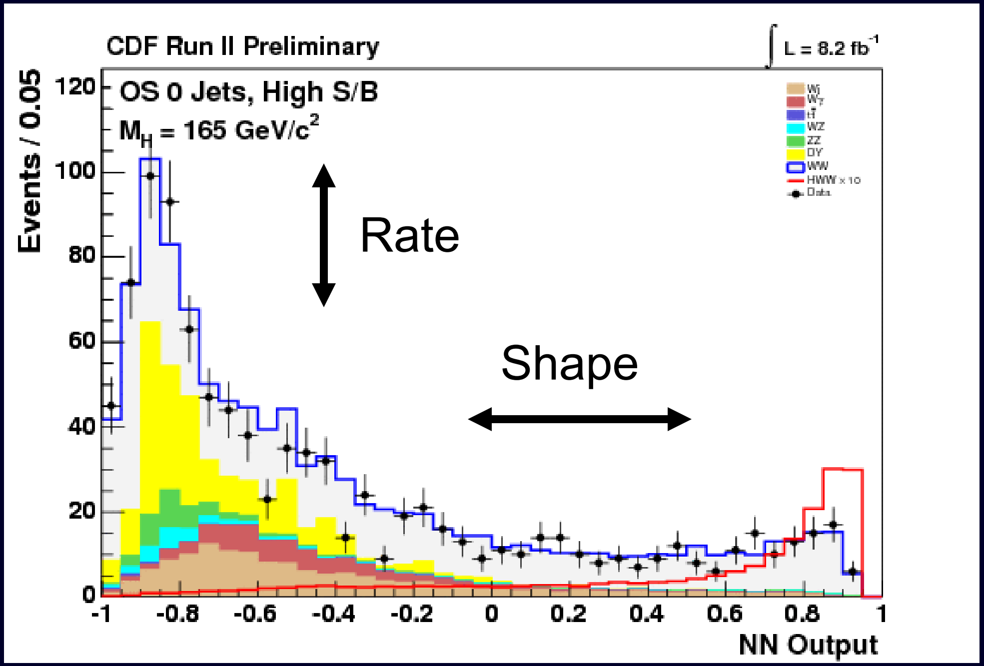
$$\sigma(pp \rightarrow WW) = 12.1 \pm 0.9\,(\text{stat.})\,^{+1.6}_{-1.4}\,(\text{syst.})\,[\text{pb}]$$



$$\sigma(pp \rightarrow ZZ) = 1.45 \pm\,^{+0.45}_{-0.42}\,(\text{stat.})\,^{+0.41}_{-0.30}\,(\text{syst.})\,[\text{pb}]$$

Both measurements agree very well with theory

Systematic uncertainties



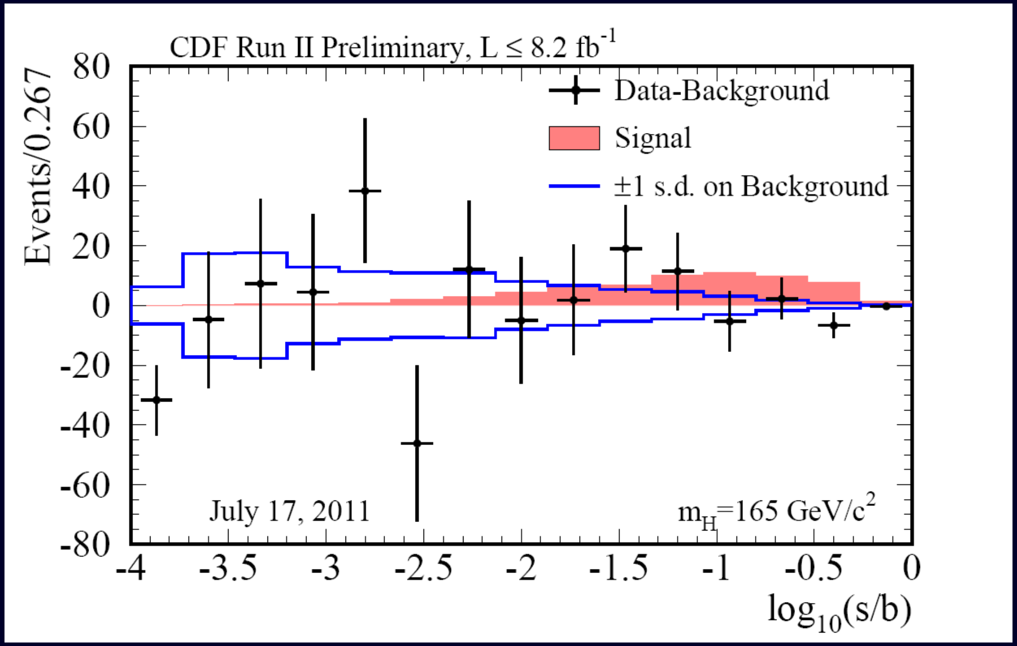
There are two categories of systematics impacting the final discriminant, shape and rate (normalization)

The uncertainties get accounted for as nuisance parameters in the final fit and limit calculations

Largest systematics are

- Theoretical cross sections
- Missing E_T modeling in DY
- JES corrections

The analysis result



Combine information from final discriminant from all channels

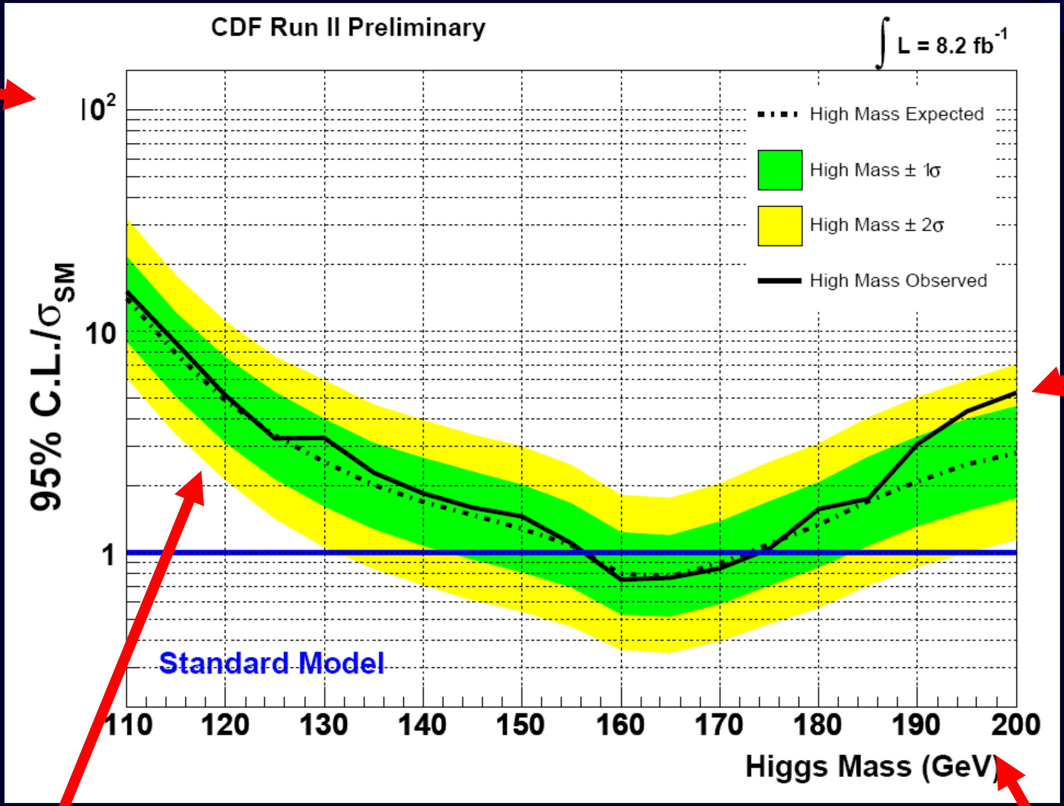
Discriminant bins sorted by *S*/*B*

Data has background subtracted, fitted uncertainty appears in blue

We see no evidence of a Higgs signal

The Final *H→WW* limit from CDF

Upper cross-section limit relative to SM prediction

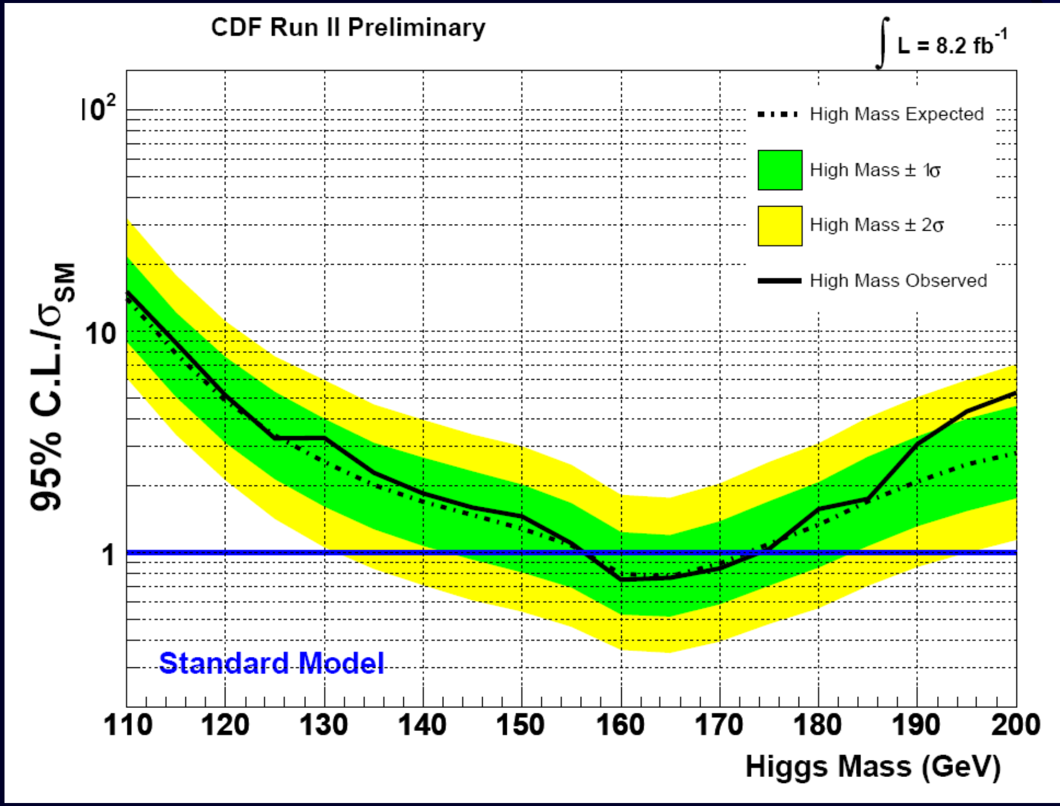


Solid line is observed limit

Dotted line is median expected limit, predicted exclusions 1σ/2σ (green/yellow bands) from background only pseudo-experiments

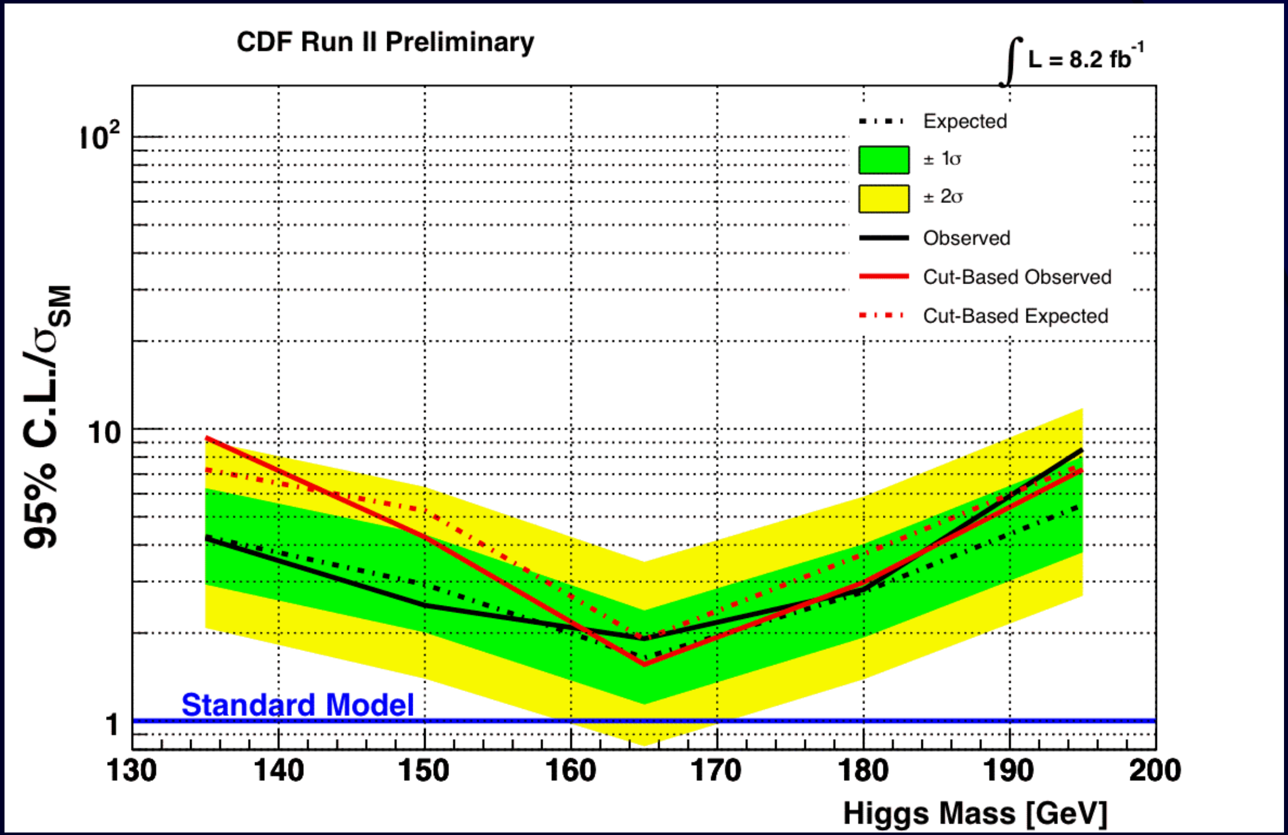
Repeat the analysis at 19 Higgs masses between 110 and 200 GeV/c^2 in 5 GeV/c^2 steps

The Final *H→WW* exclusion from CDF



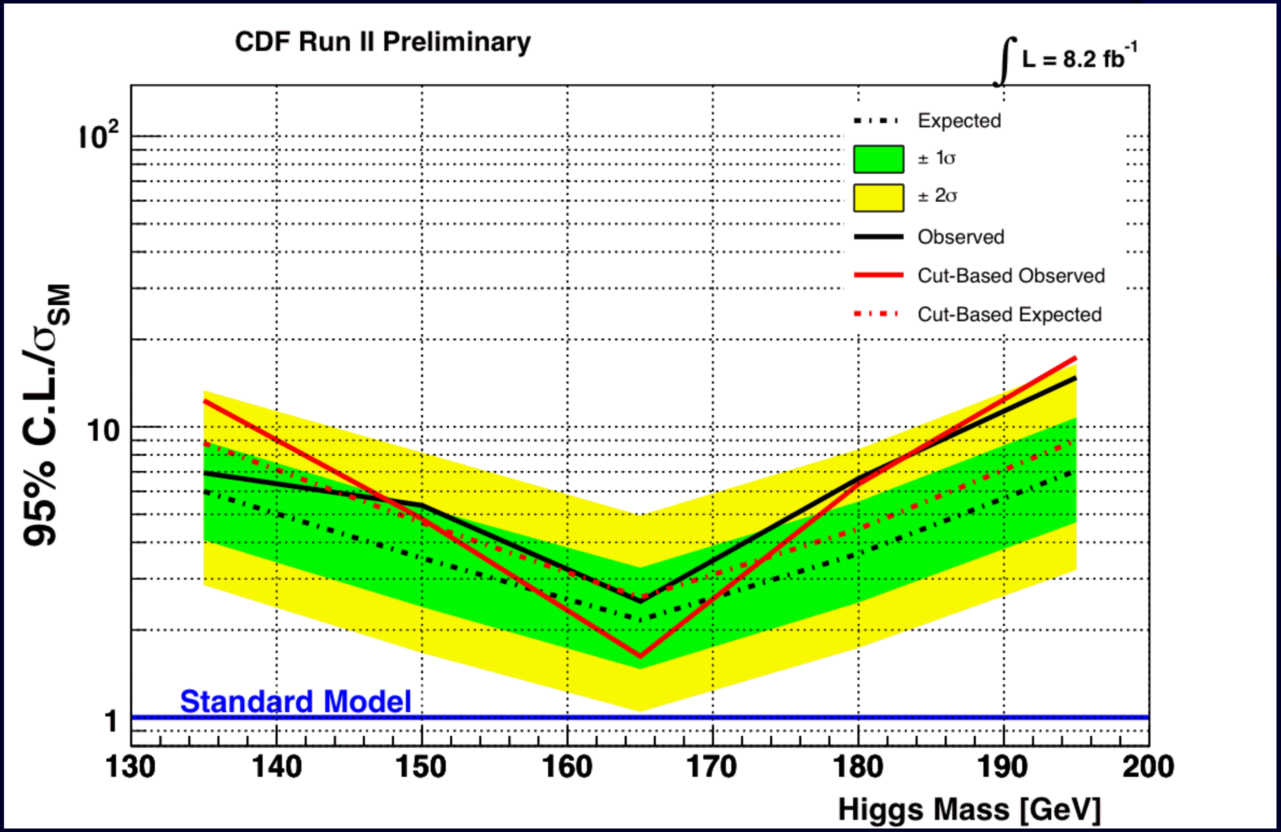
CDF sets a 95% CL exclusion from 156-175 GeV/c^2

What if we chose cut based?



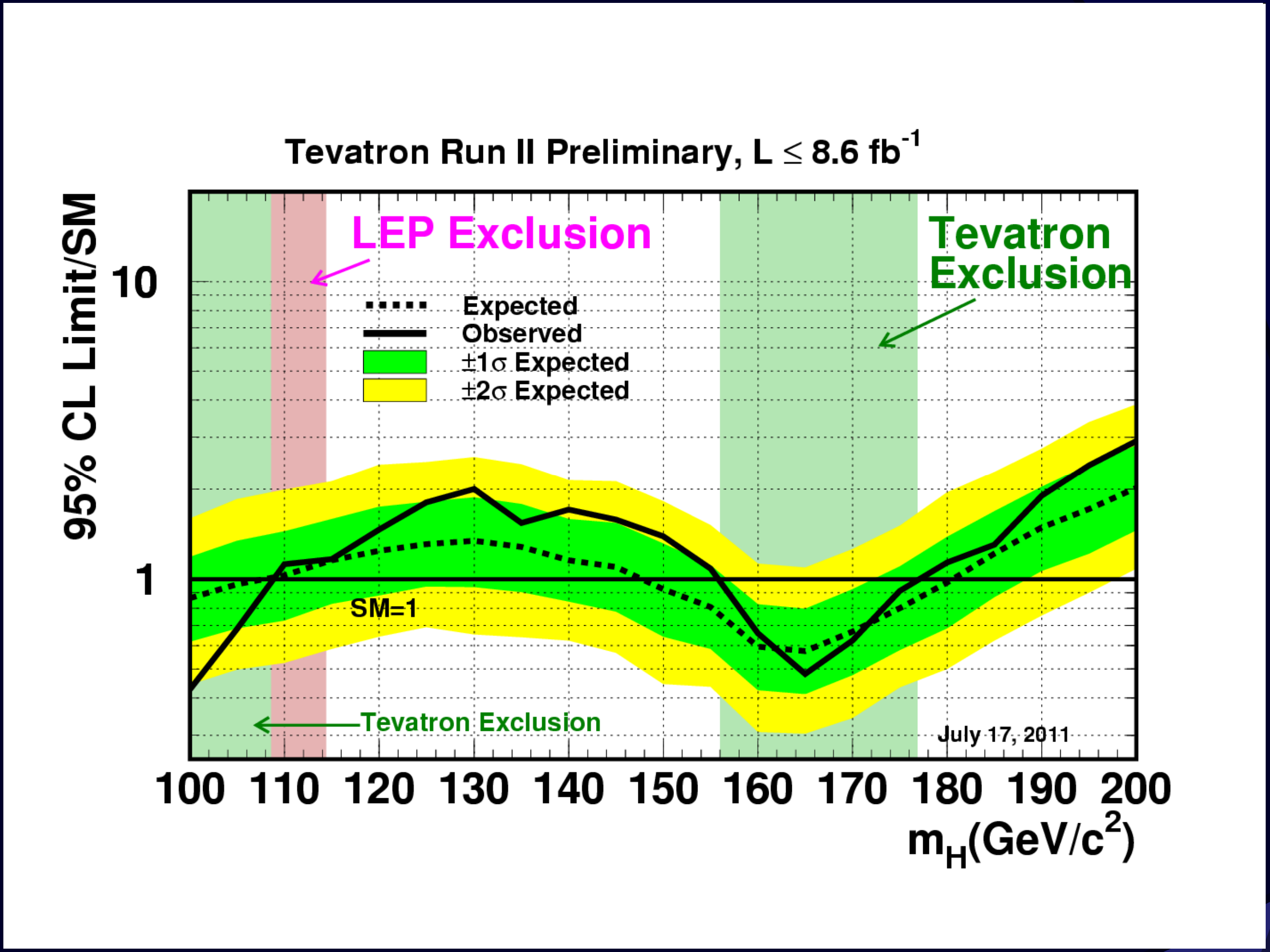
Cut based versus NN limits in 0 jets bin

What if we chose cut based?



Cut based versus NN limits in 1 jet bin

The combined limits

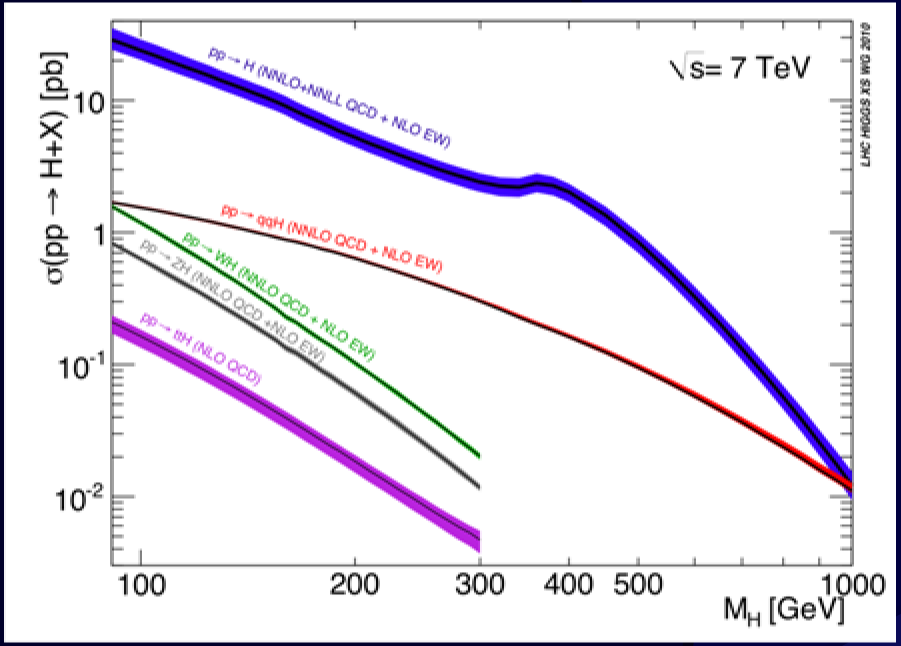


CDF and DØ exclude the masses between 156-177 GeV/c^2 at the 95% confidence level

What about the LHC?

Search at the LHC very similar to search at the Tevatron

LHC has a much larger production cross-section and higher S/B

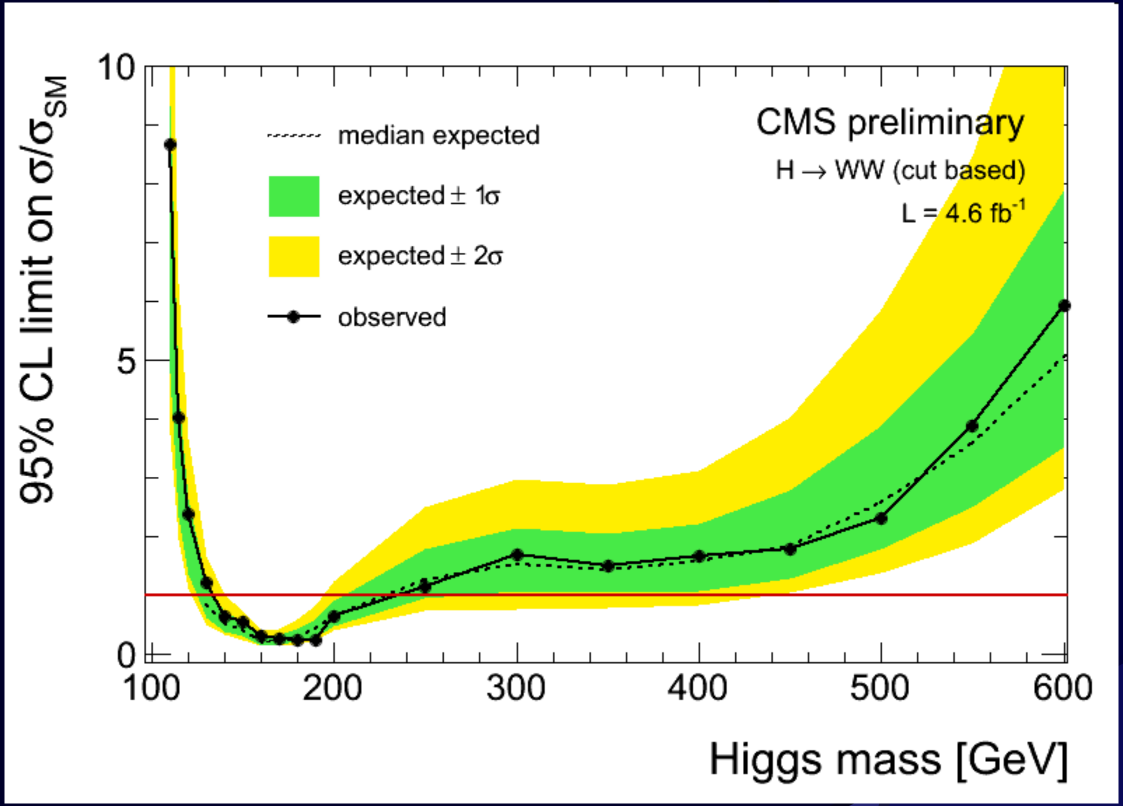


The $H \rightarrow WW$ result from CMS

Cut based analysis, cut on the NN variables used at Tevatron

Cuts used depend on Higgs mass

Result here based on $4.6\ \mathrm{fb}^{-1}$



CMS sets a 95% CL exclusion from 129-270 GeV/c^2

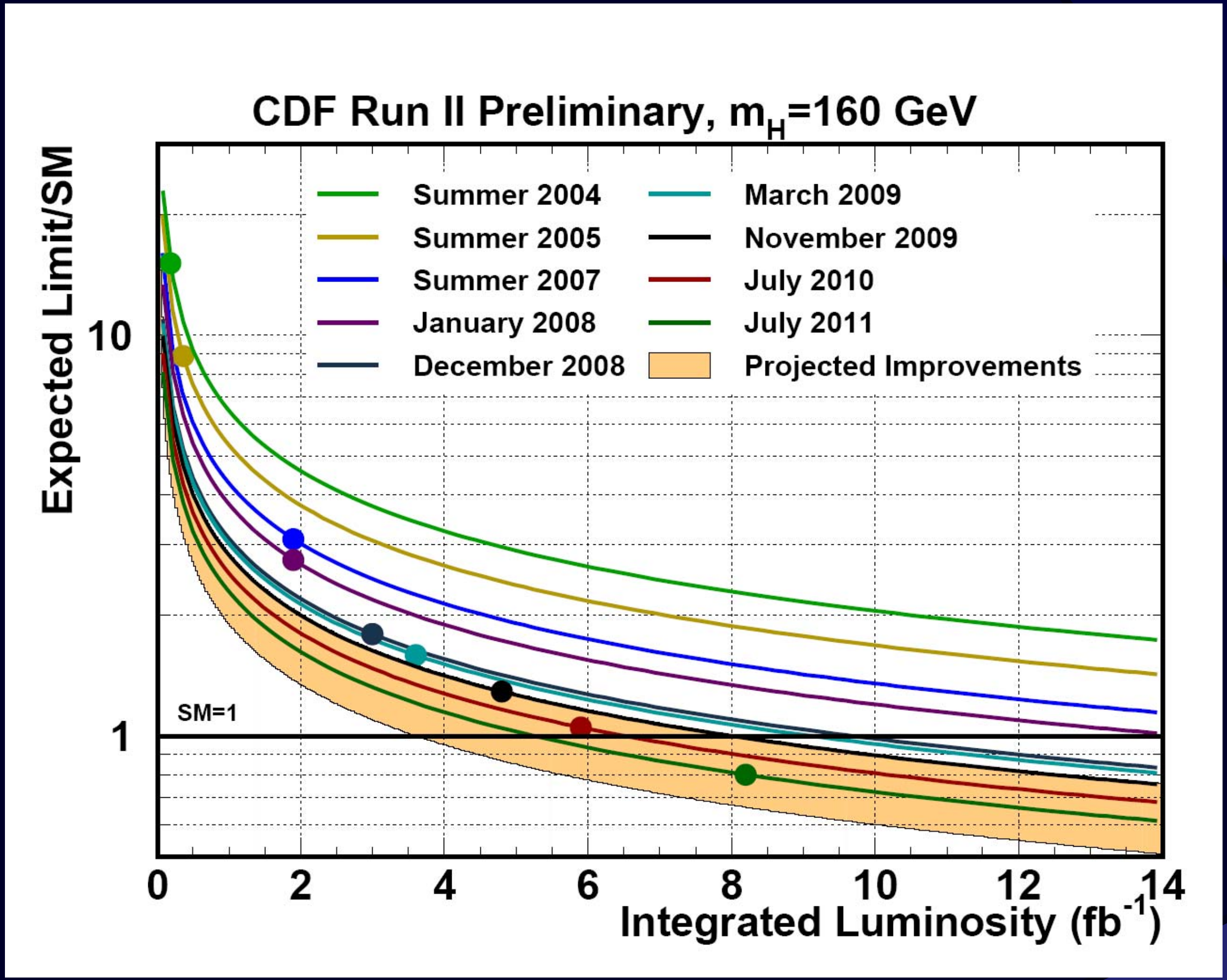
Conclusions and Outlook

Continuing improvements in Tevatron $H \rightarrow WW$ searches have led to first new Higgs mass exclusions since LEP

We now have welcome competition from ATLAS and CMS

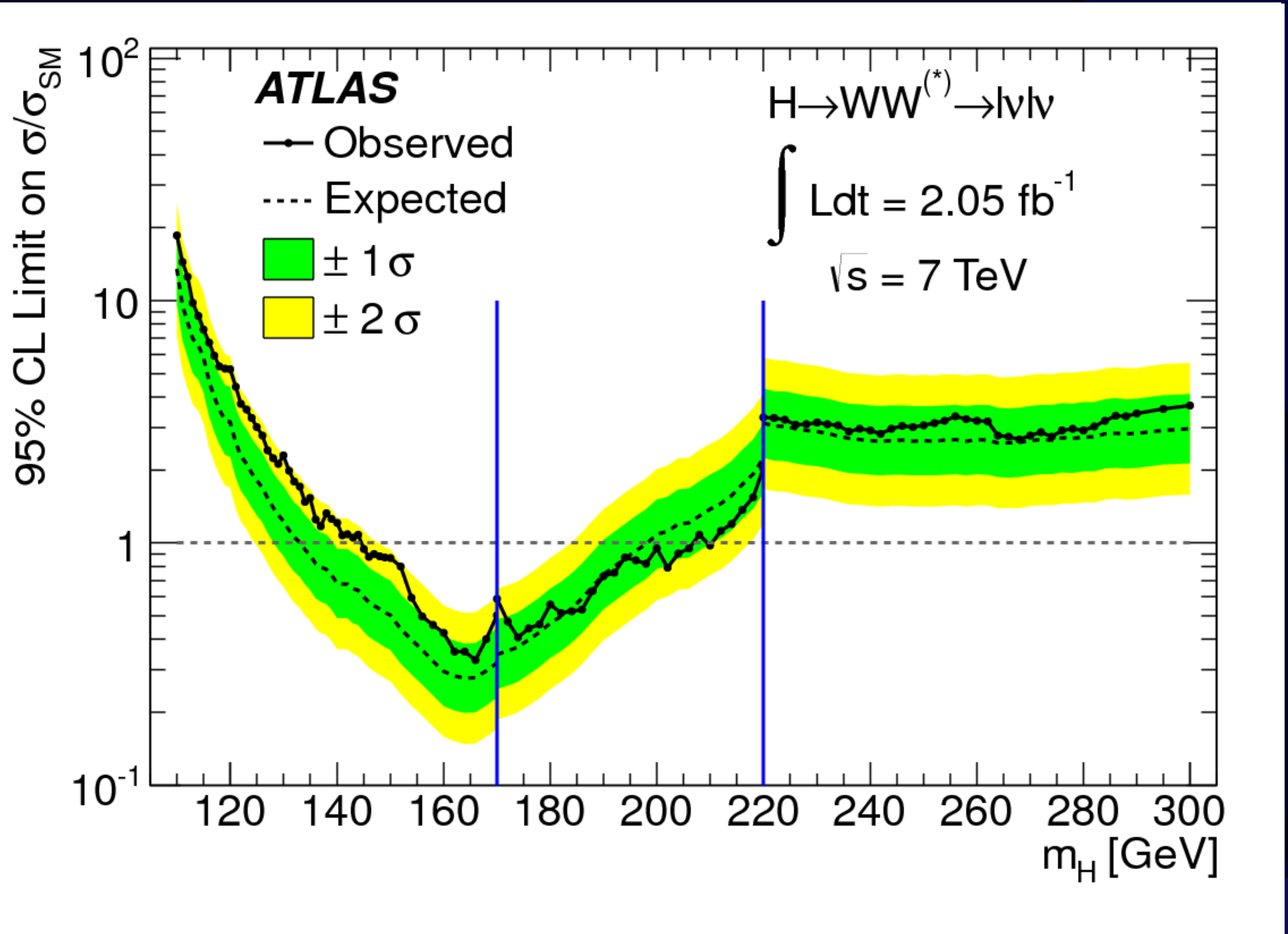
With final datasets, Tevatron expects to have sensitivity to exclude Higgs at 95% C.L. 100-185 GeV/c^2

Cataloging improvements



We continue to add analysis improvements which increase sensitivity faster than what would be obtained with data alone

The $H\to WW$ exclusion from ATLAS



ATLAS sets a 95% CL exclusion from 145-206 GeV/c^2