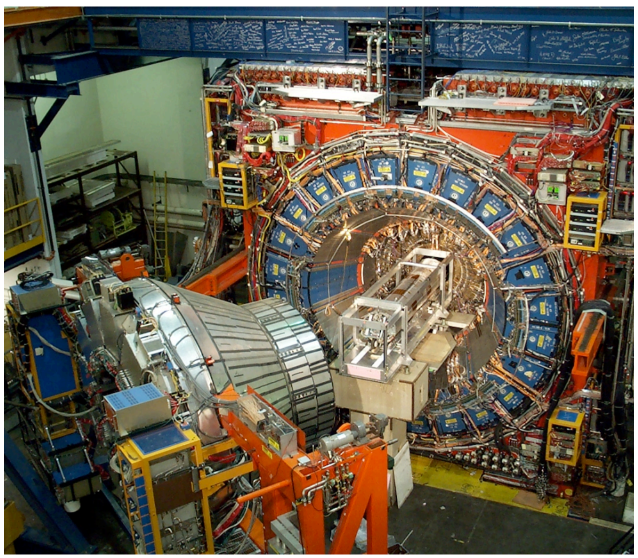
# High Mass SM Higgs Searches at the Tevatron



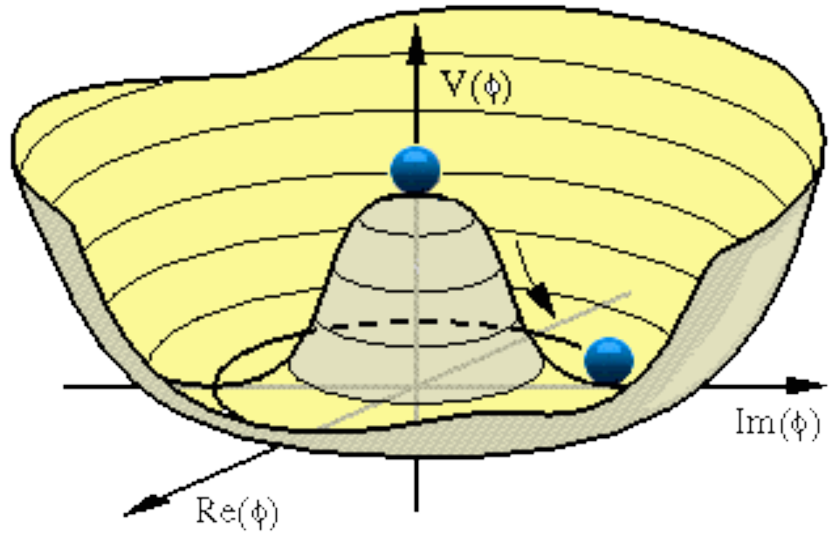

Michael Kirby

Northwestern University


Higgs Hunting Workshop

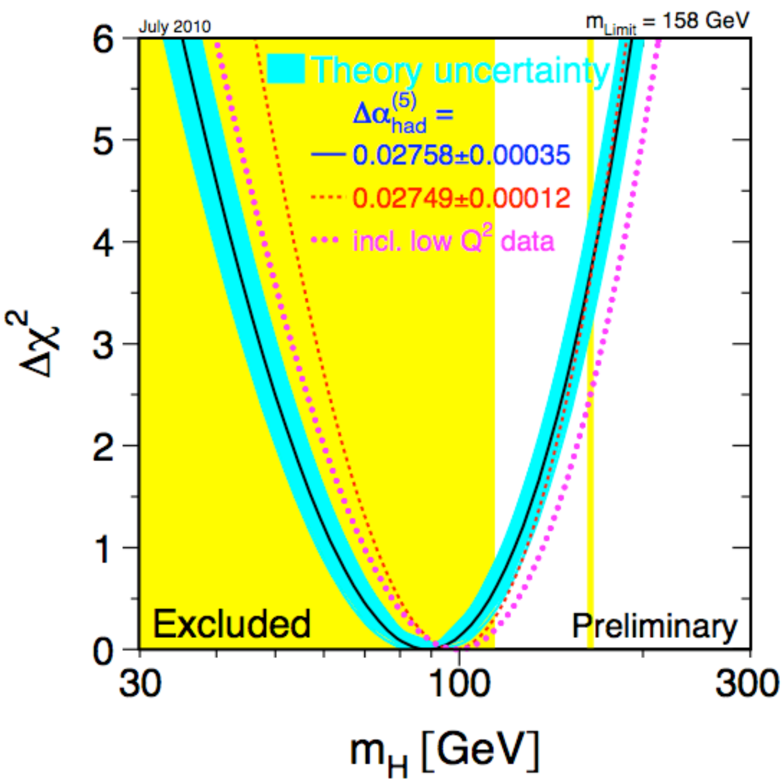
# Outline

- SM Higgs constraints
- Tevatron and luminosity
- high mass Higgs strategy
  - search channels
  - backgrounds
  - cross checks
  - systematic uncertainties
- CDF and D0 results
- combined Tevatron results
- sensitivity projections




# Where should we be looking?

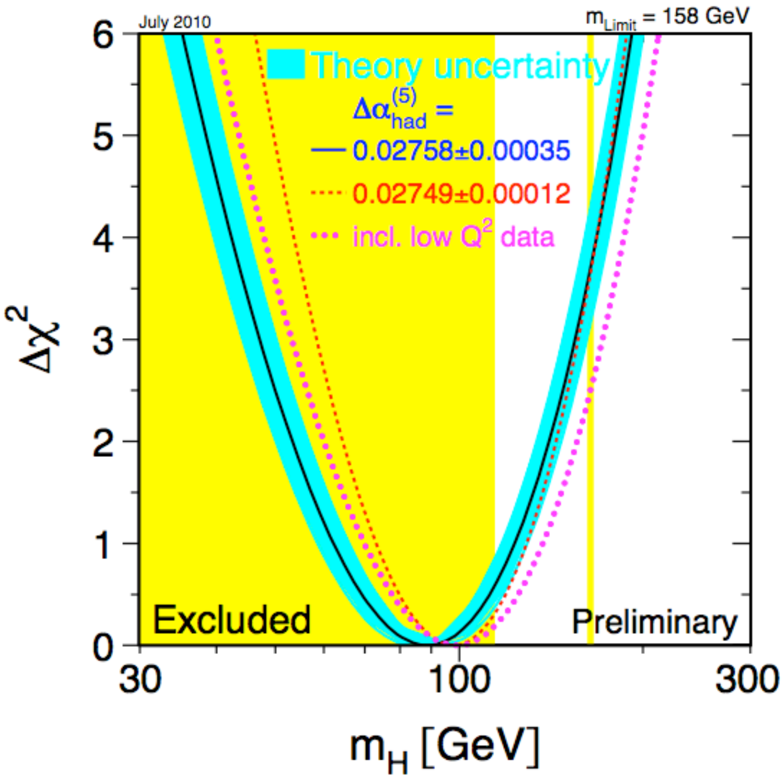
Precision EWK measurements at LEP, SLD, and Tevatron suggest the preferred SM region is accessible by the Tevatron




LEP Direct Search included
114 < $m_H$ < 186 GeV @95% C.L.

# Where should we be looking?

Precision EWK measurements at LEP, SLD, and Tevatron suggest the preferred SM region is accessible by the Tevatron



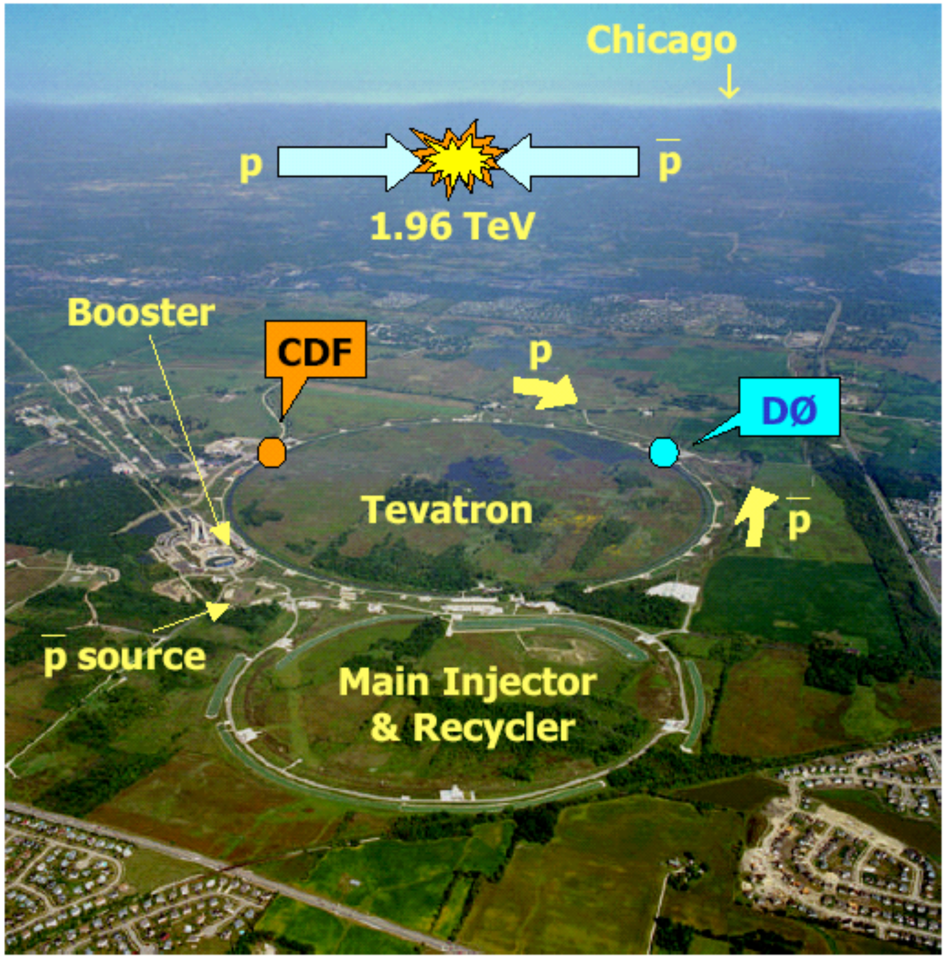

LEP Direct Search included
114 < $m_H$ < 186 GeV @95% C.L.

# Tevatron at Fermilab

- Tevatron proton-antiproton collider at Fermilab

$$\sqrt{s} = 1.96\text{TeV}$$

- EWK scale processes probe different PDF from LHC
- typical average initial: >300 x $10^{30}$ cm$^{-2}$ s$^{-1}$
- record:404 x $10^{30}$ cm$^{-2}$ s$^{-1}$
- ~ 50 pb$^{-1}$ per week
- long term goal is 10+ fb$^{-1}$
- optimistically planning for operation in 2012

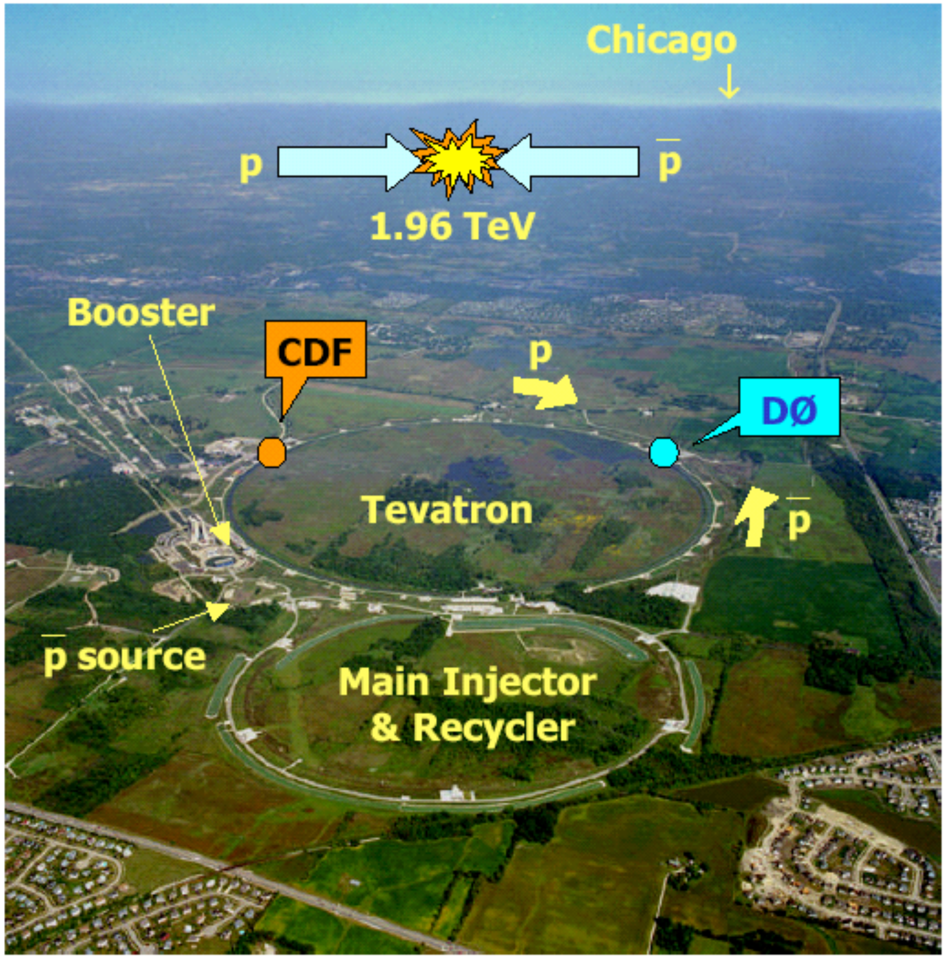


# Tevatron at Fermilab

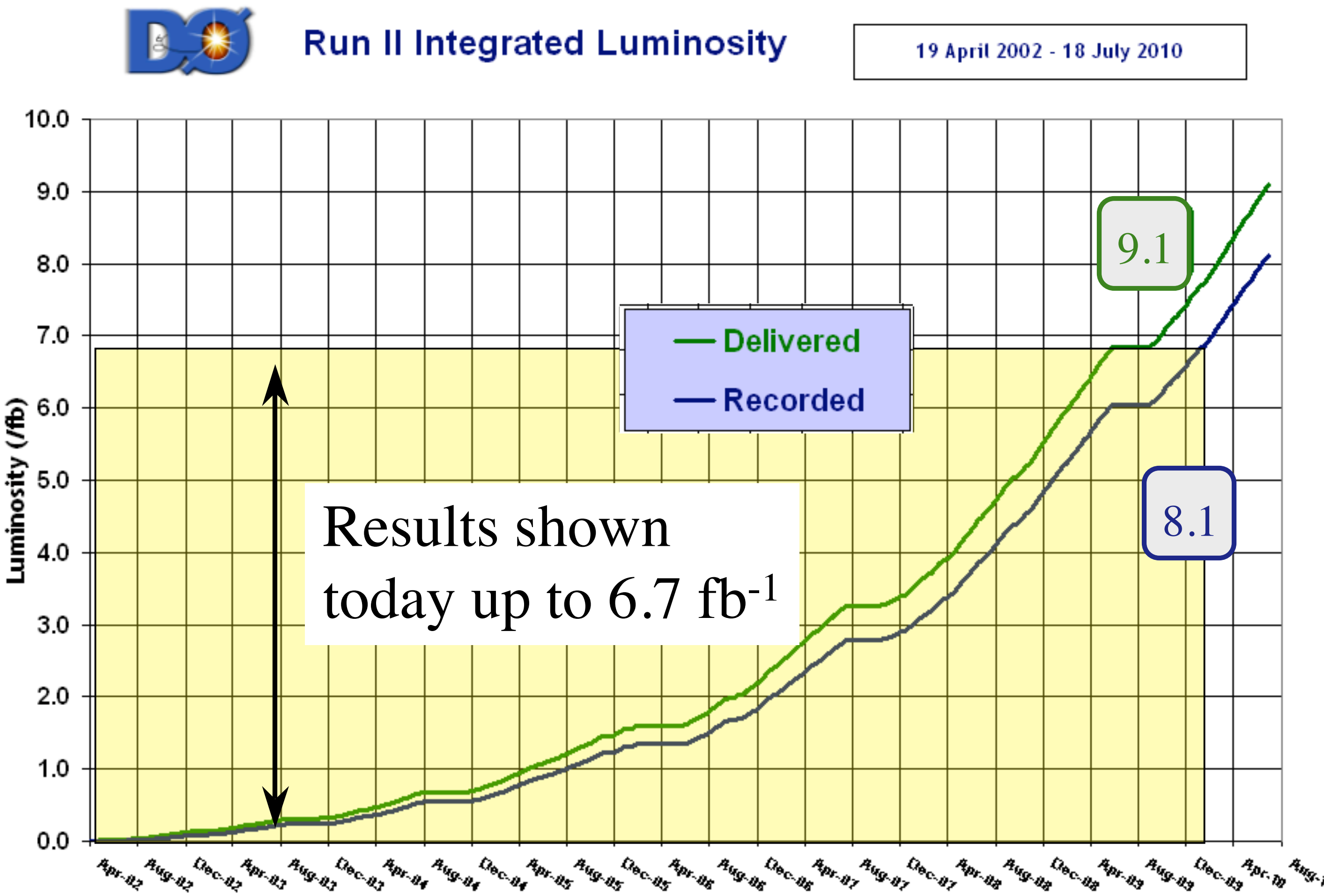
Immense thanks to the Fermilab Accelerator Division for all the collisions

Detector Operations groups for high efficiency

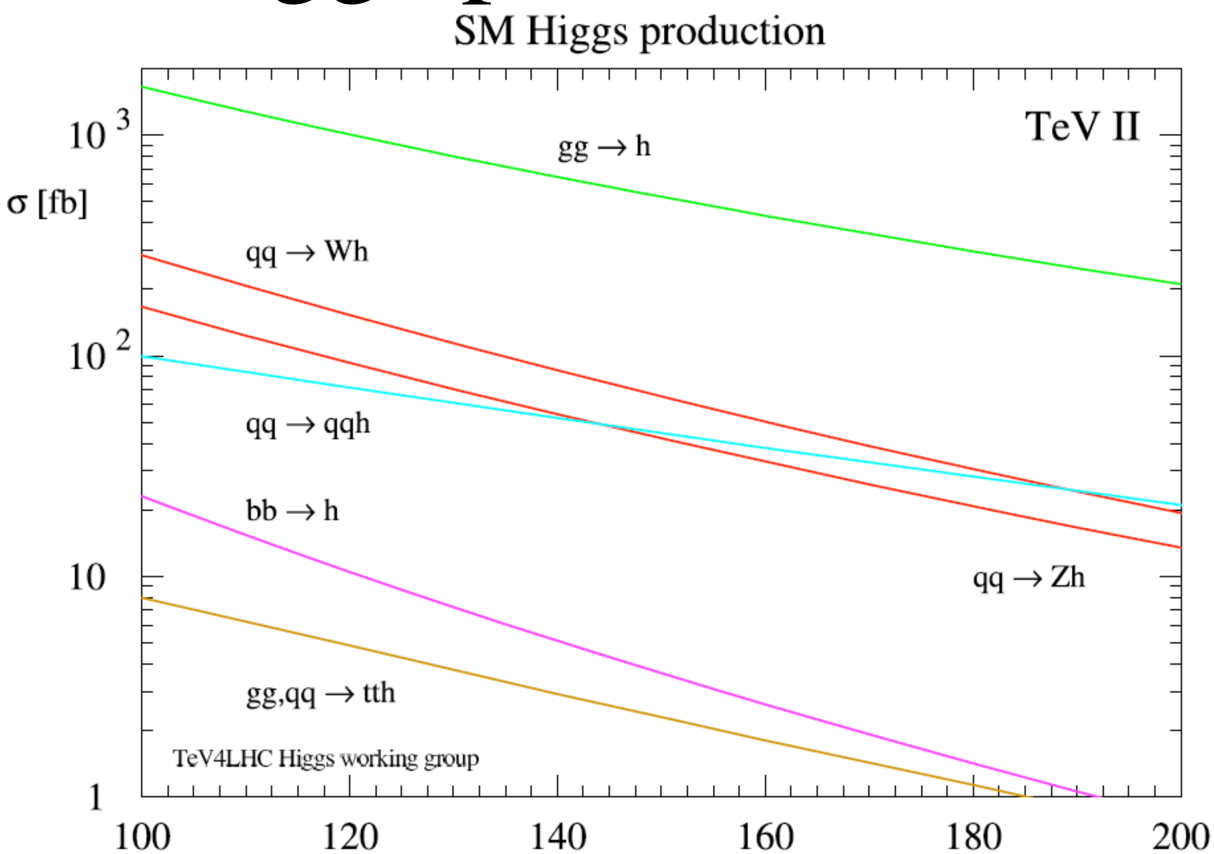
Computing Division for processing data

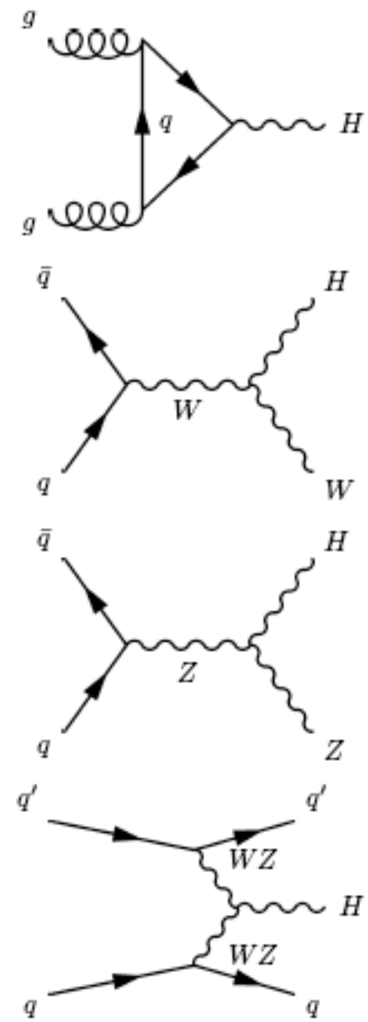


# integrated luminosity



# Higgs production at the Tevatron

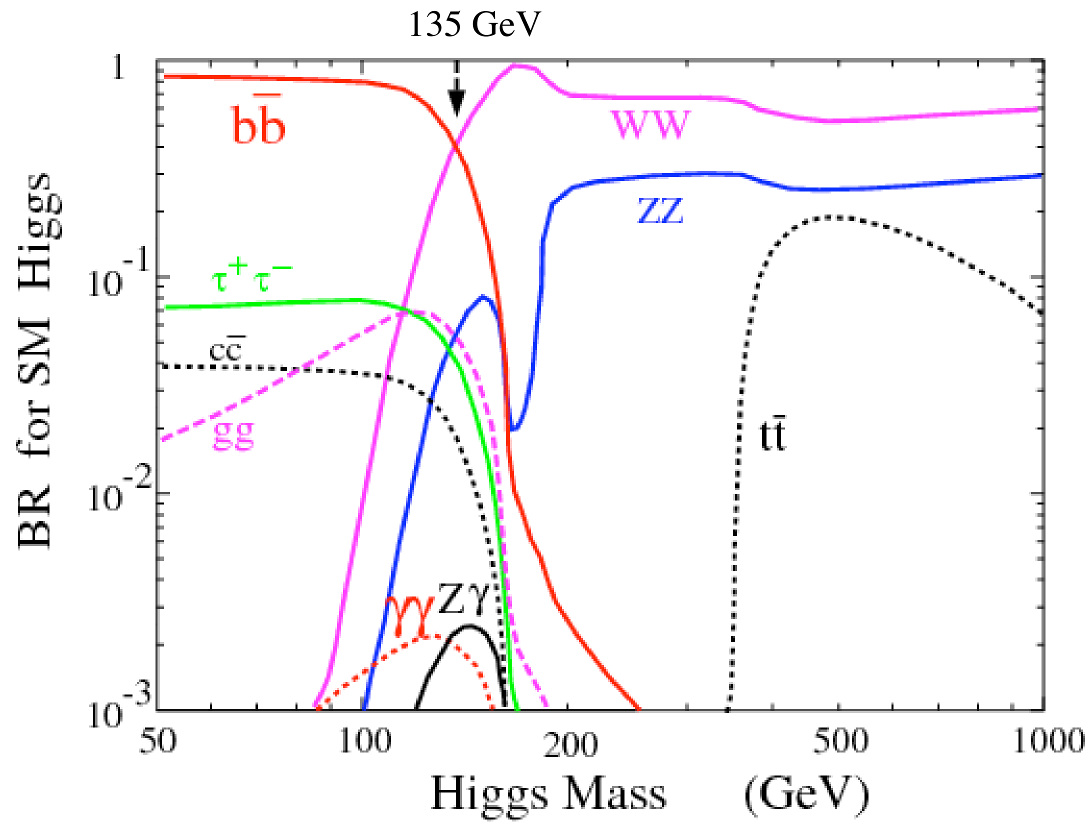



N(gg→H) ≈ (6.7/fb)x(1000fb) = 6,700 evts

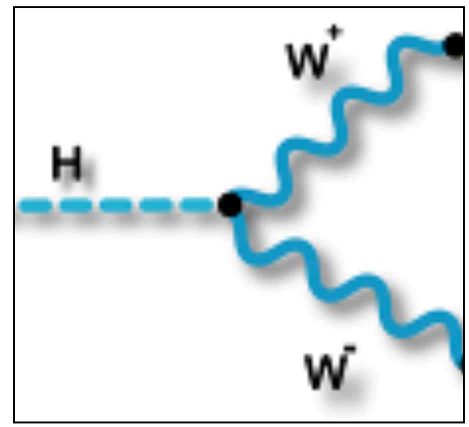
N(gg→bb) ≈ (6.7/fb)x($10^9$ fb) = 6,700,000,000 evts

# Higgs production at the Tevatron




$M_H$>135 GeV

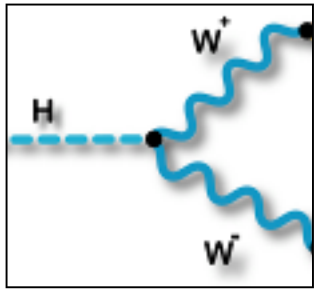
H→WW dominates

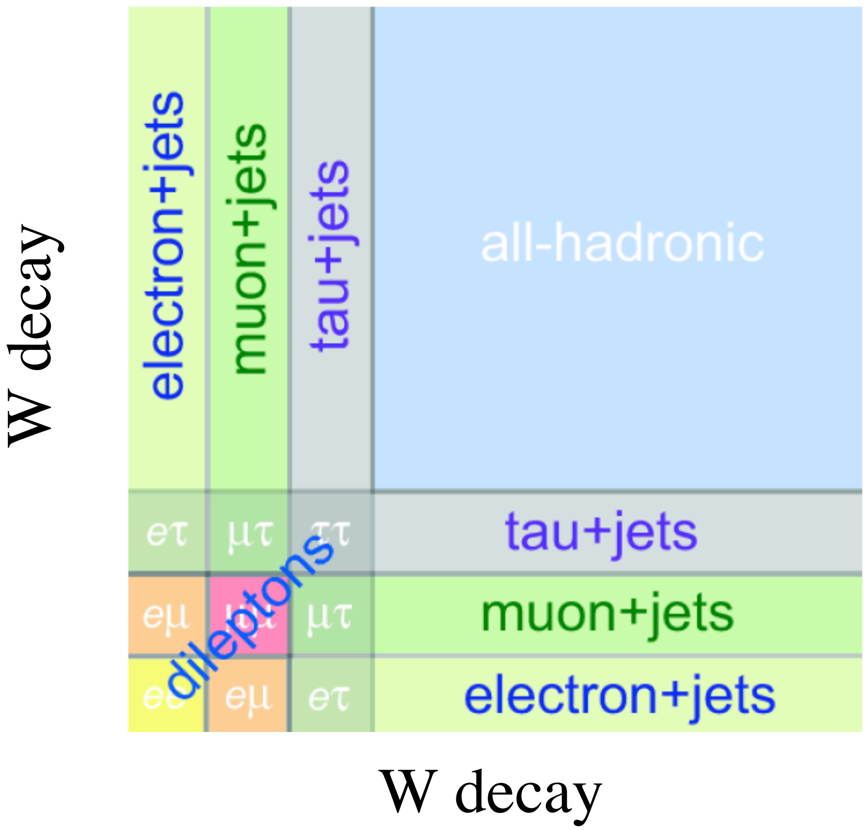



H→WW most sensitivity $M_H$ = [125 - 200]

Additionally, H→ZZ above $M_H$ = 180 GeV

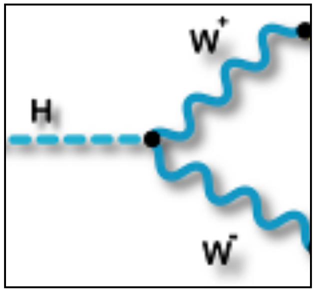
# Higgs final state signatures



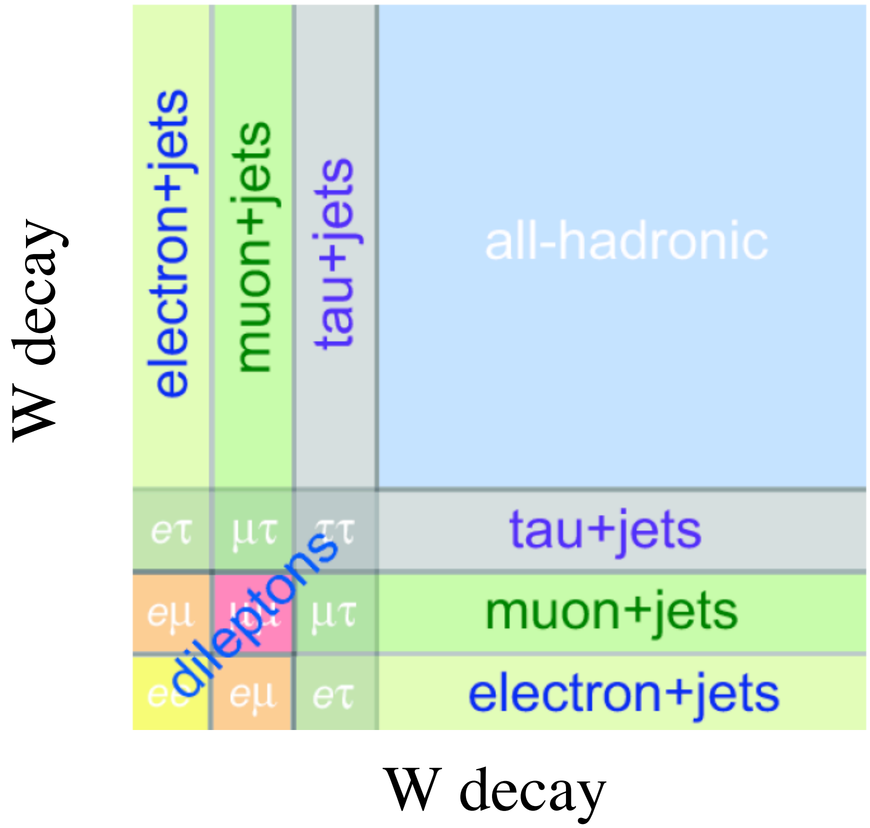



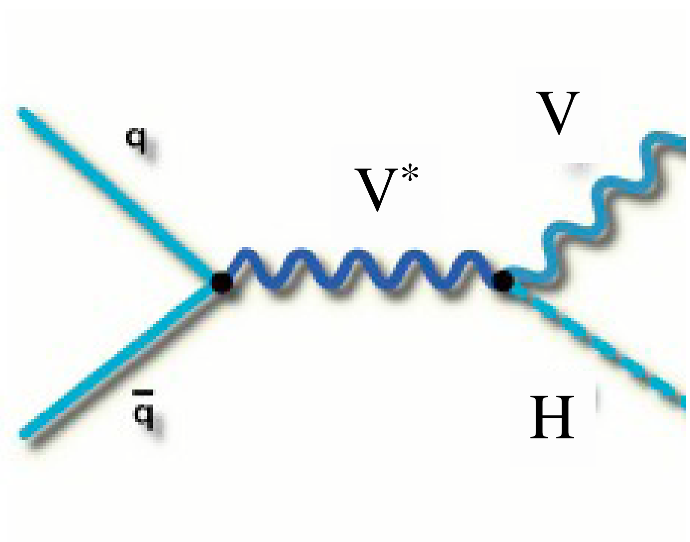

- H→WW→*l*ν*l*ν (*l*=e,μ) BR(*l*ν*l*ν)~6%
  - easy to trigger
  - well modeled bkg
  - τ →(e,μ) contributes
- H→WW→*l*ν*jj* (*l*=e,μ) BR(W→hadrons) ~30%
  - large QCD backgrounds
  - new D0 result
- H→WW→τνμν
  - hadronic τ decay
  - new CDF measurement

# Higgs final state signatures



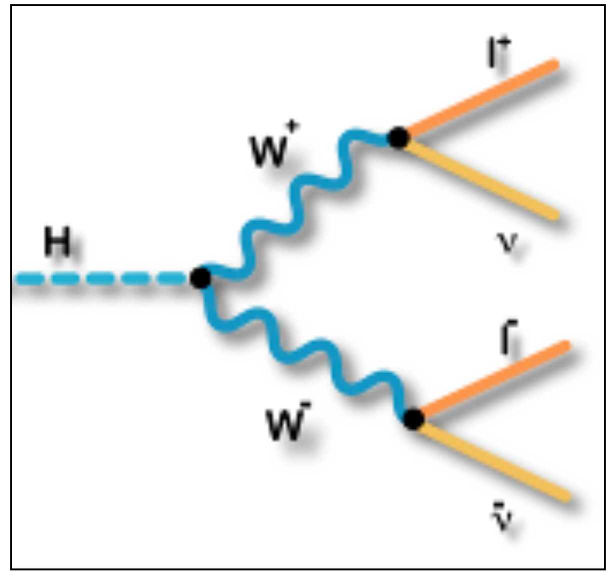

- *VH→VWW→l*±*νl*±*ν+X* (*l*=e,μ)
  - same charge dileptons
  - change in backgrounds



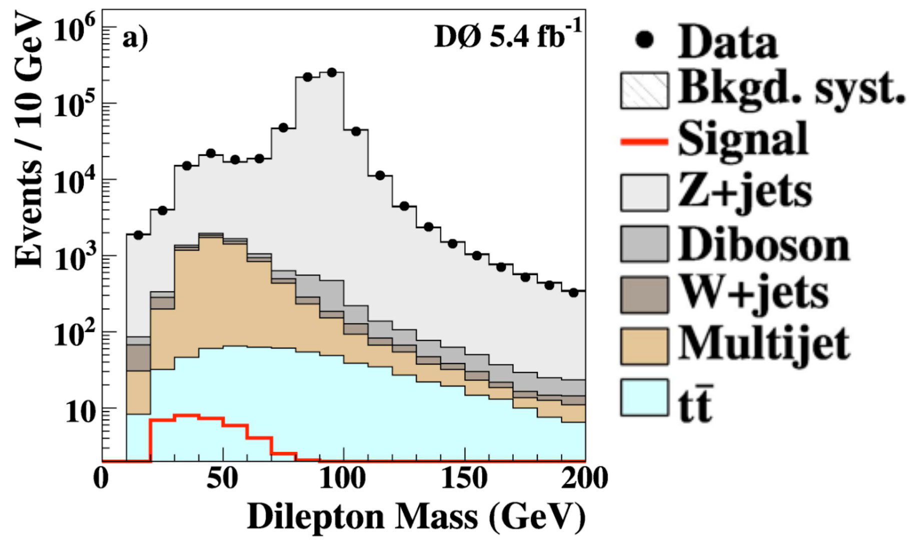
# high mass Higgs strategy

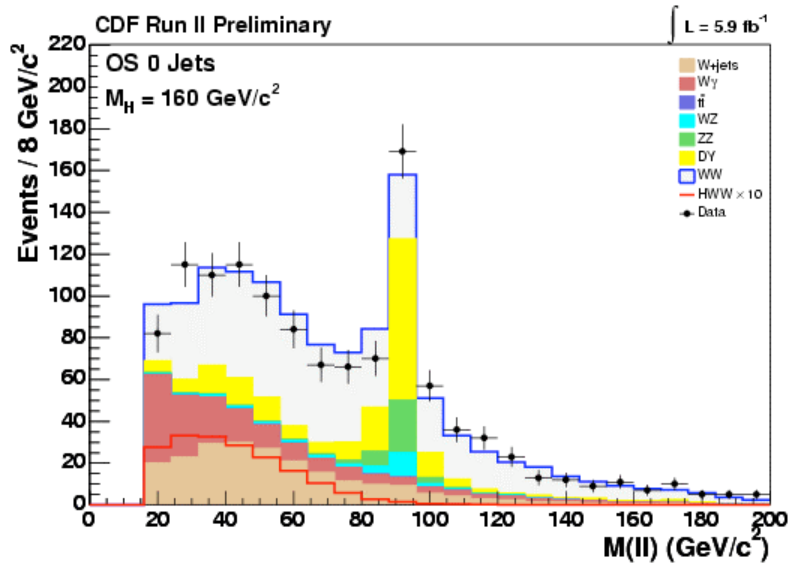
- leptonic W decays
  - provides efficient trigger
  - multijet bkg rejection
- missing transverse energy
- x-check bkg modeling
- improved signal modeling
- maximally separate signal from background
- minimize impact of systematic uncertainties



# lepton identification

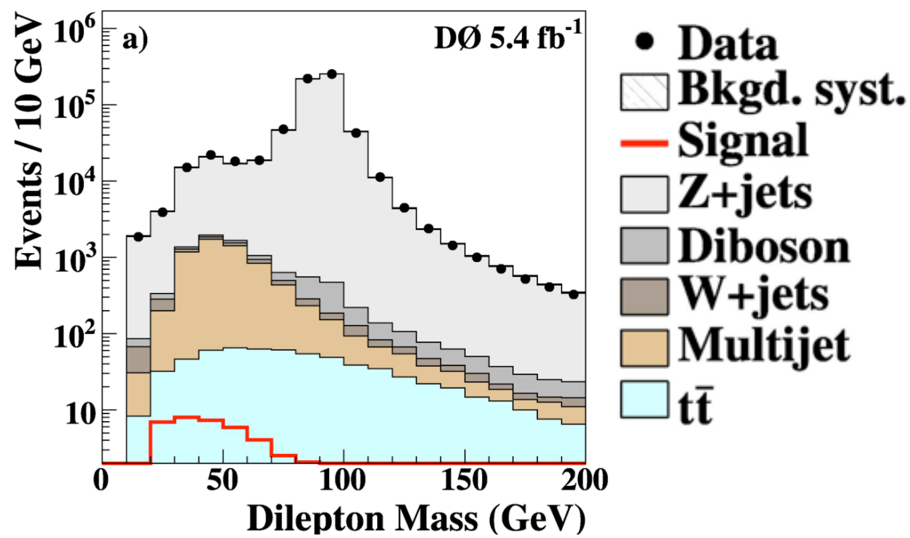
- large transverse momentum ($p_T$>15 GeV)
- isolated from other calorimeter or track activity
- electron
  - EM Cal cluster
  - matched track
- muon
  - muon chamber hits
  - matched track or MIP signal
- CDF also considers track-based electrons and muons

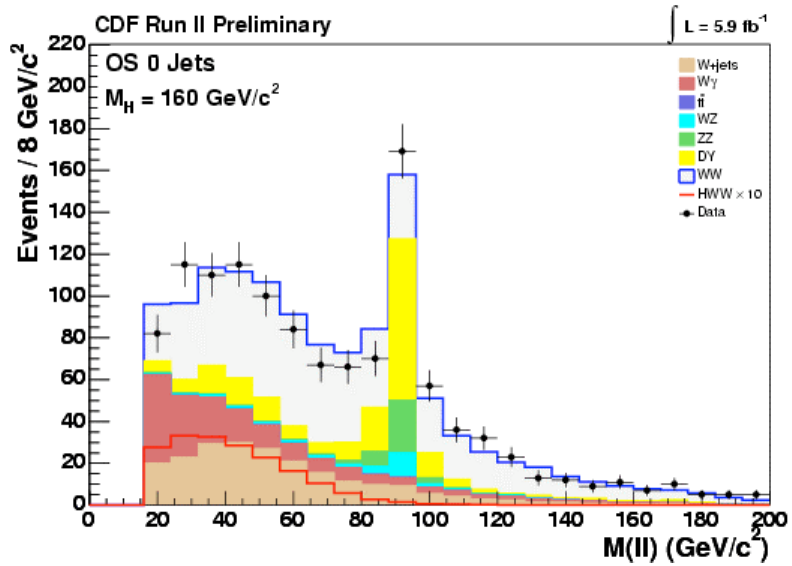


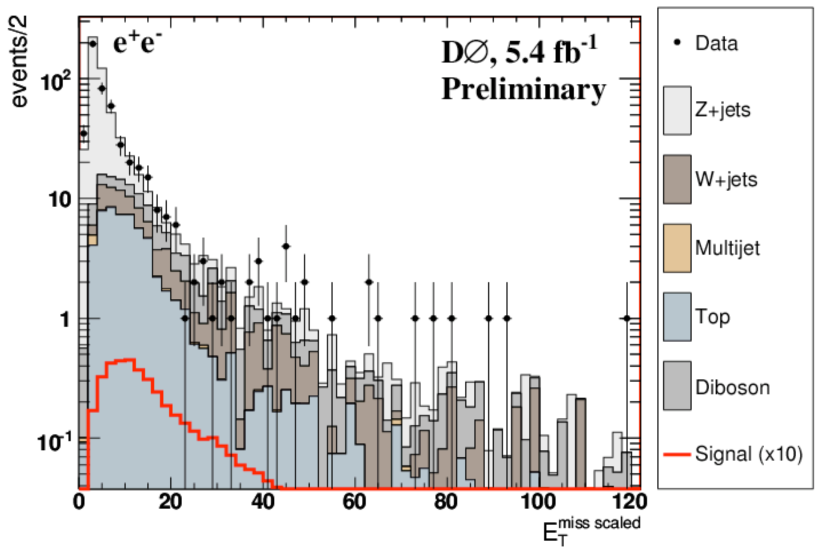
# missing transverse energy

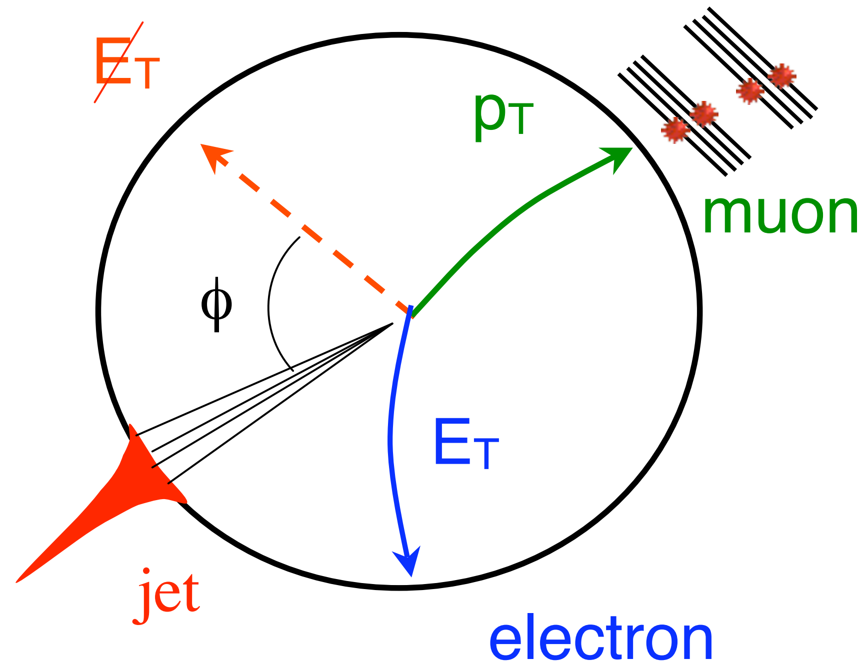
- neutrinos not reconstructed in detector
- need to reject mis-measurement
  - jet energy fluctuations
  - tracking resolution for high $p_T$ muons
  - underlying event
- suppress large Drell-Yan background



# missing transverse energy




$$\not{E}_T^{\mathrm{Scaled}} = \frac{\not{E}_T}{\sqrt{\sum_{\mathrm{jets}} \left(\Delta E^{\mathrm{jet}} \cdot \sin\theta^{\mathrm{jet}} \cdot \cos\Delta\phi\left(\mathrm{jet}, \not{E}_T\right)\right)^2}}.$$

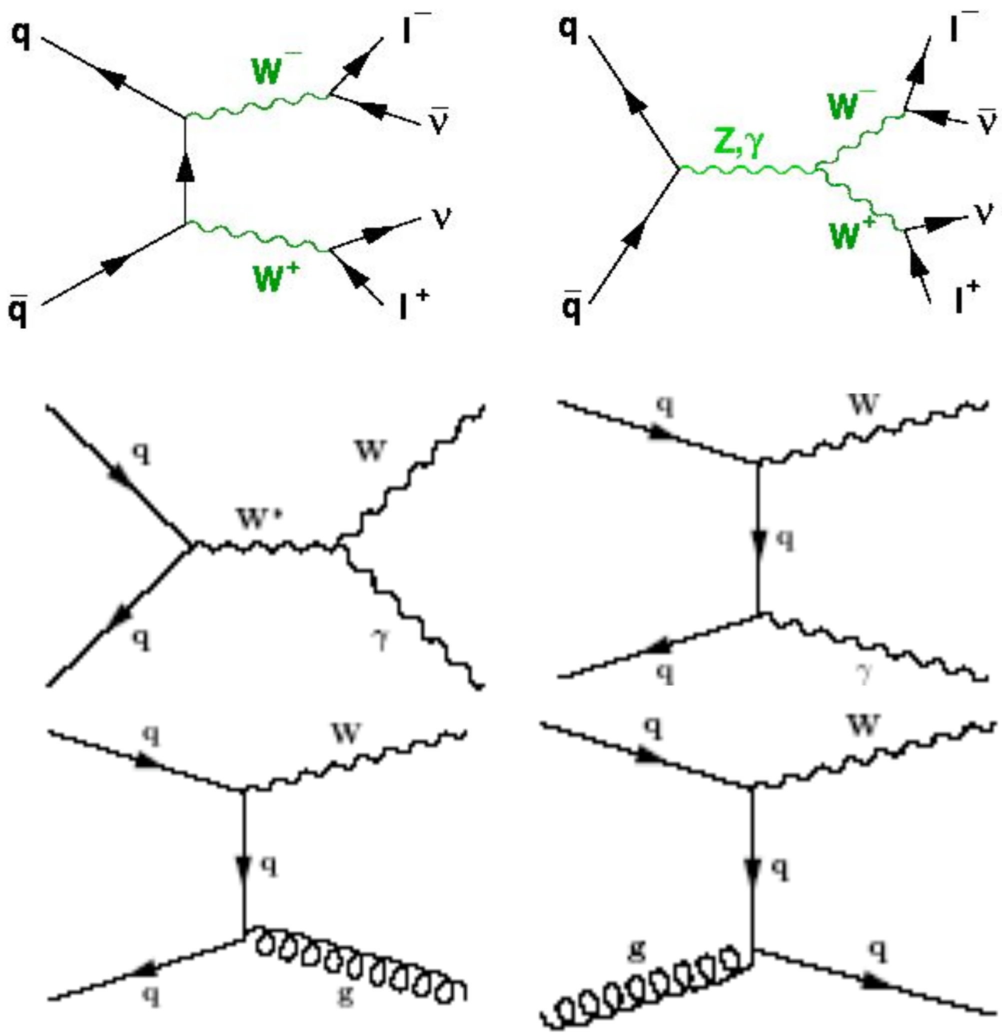
CDF

$$\not{E}_{T\mathrm{spec}} \equiv \begin{cases} \not{E}_T \\ \not{E}_T \sin(\Delta\phi(\not{E}_T, \mathrm{nearest-lepton-or-jet})) \end{cases}$$

CDF & D0 construct discriminant using resolutions

reject contribution from Z+jets

# H→WW Backgrounds

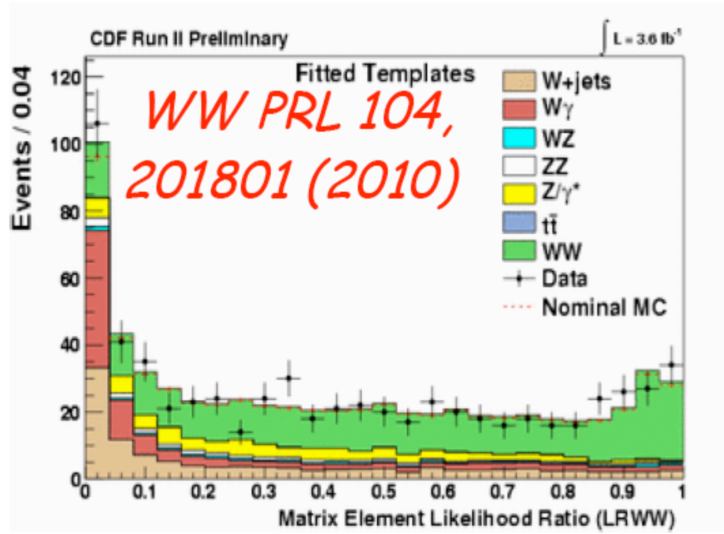


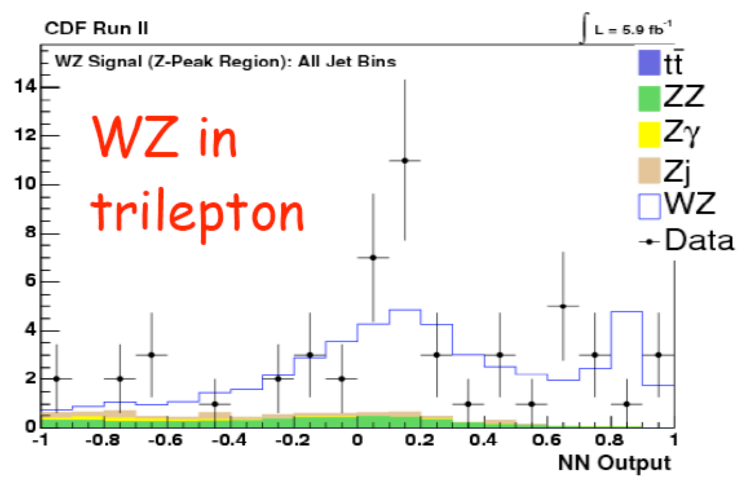

- WW/WZ
- W+Jets/γ
- Drell-Yan
- $t\bar{t}$, single top
- Multijet with jet faking lepton

All backgrounds have been measured

# H→WW background measurements

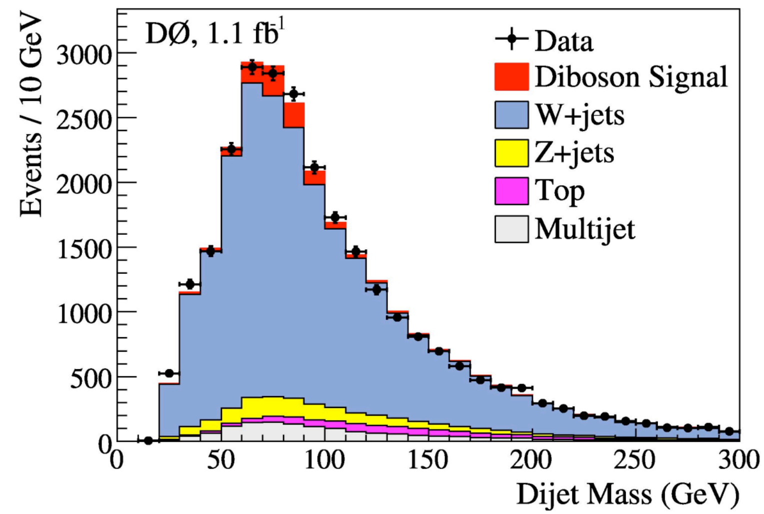
- Using same analysis frameworks, measure dominant backgrounds
- Provides confirmation of both sensitivity and MC modeling

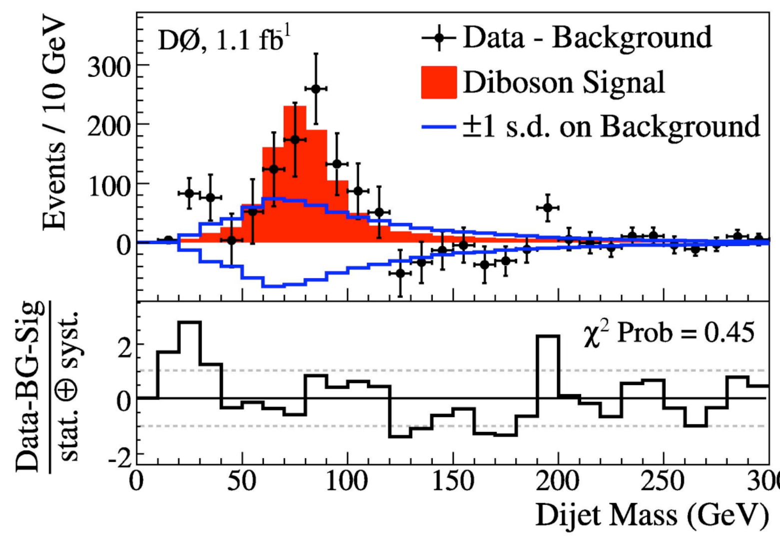


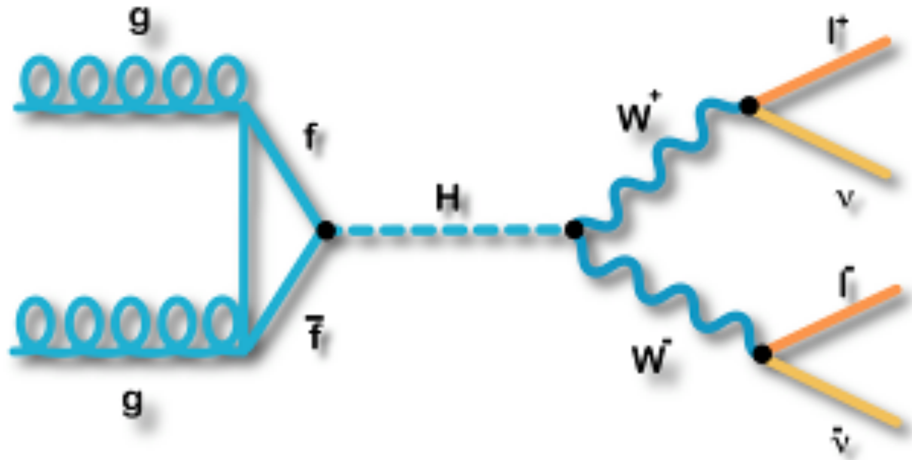
# H→WW background measurements

- Using same analysis frameworks, measure dominant backgrounds
- Provides confirmation of both sensitivity and MC modeling



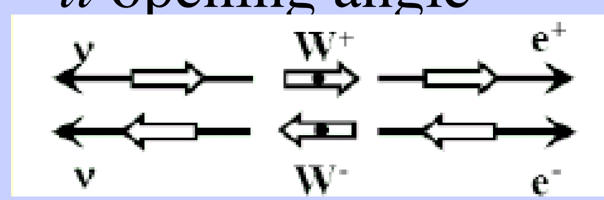



# H→WW→$l^+\nu l^-\nu$ Signature



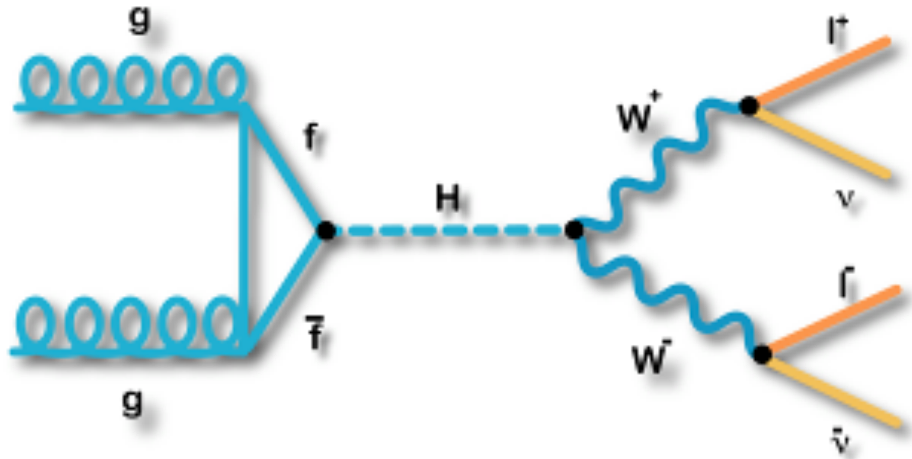

- leptonic W decays
- opposite charge
- large missing transverse energy

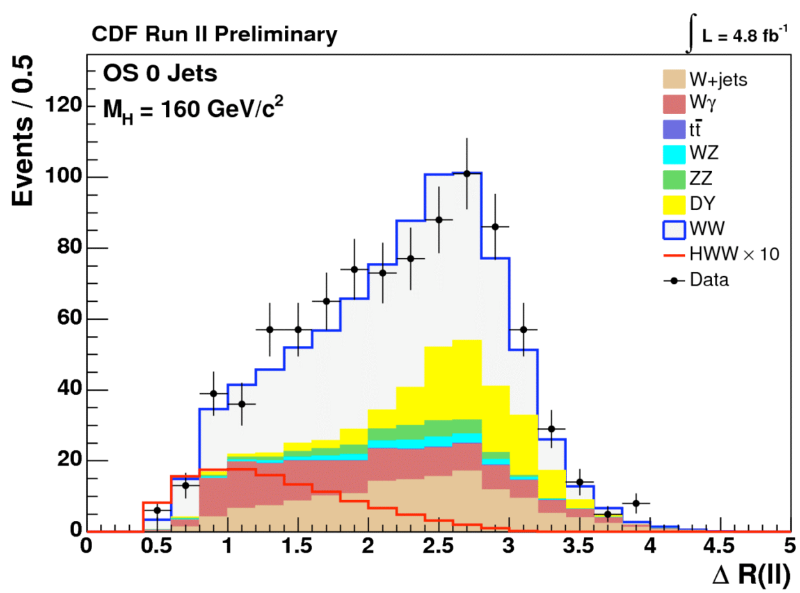
- Kinematic Discriminants
  - *ll* opening angle



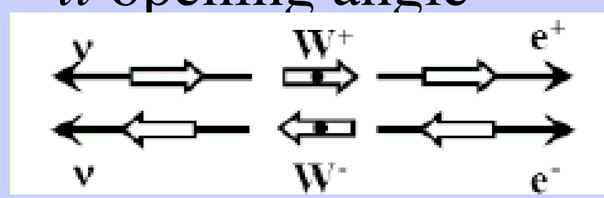

  - kinematics input MVA

# H→WW→$l^+ \nu l^- \nu$ Signature




- Kinematic Discriminants
  - *ll* opening angle



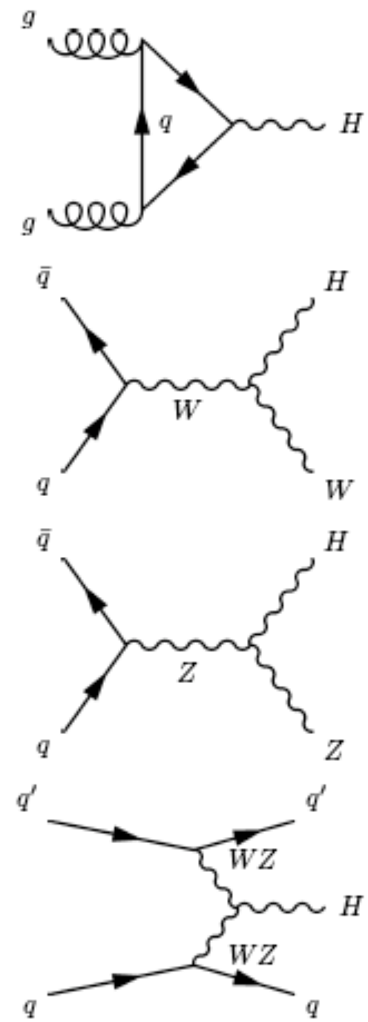

  - kinematics input MVA

# CDF Analysis Strategy

0 Jet Events

1 Jet Events

2+ Jet Events

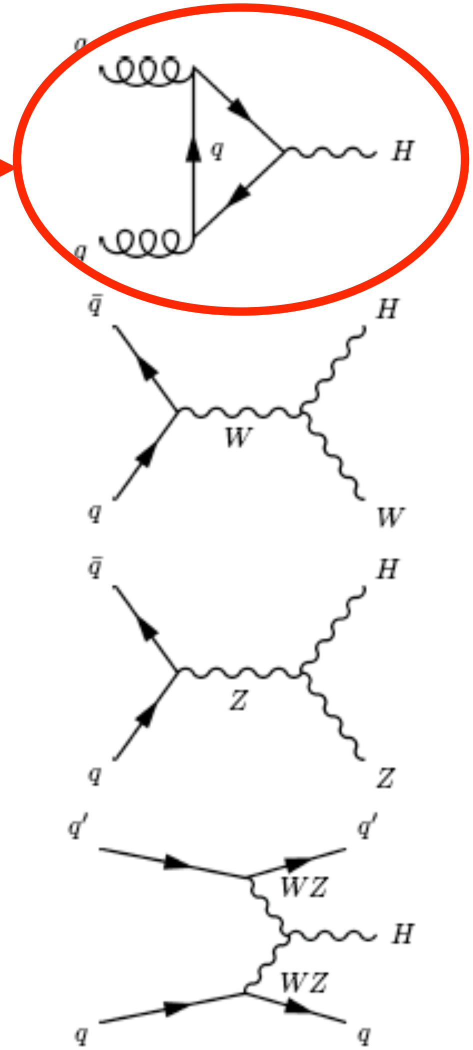


# 0 Jet Analysis Strategy

0 Jet Events

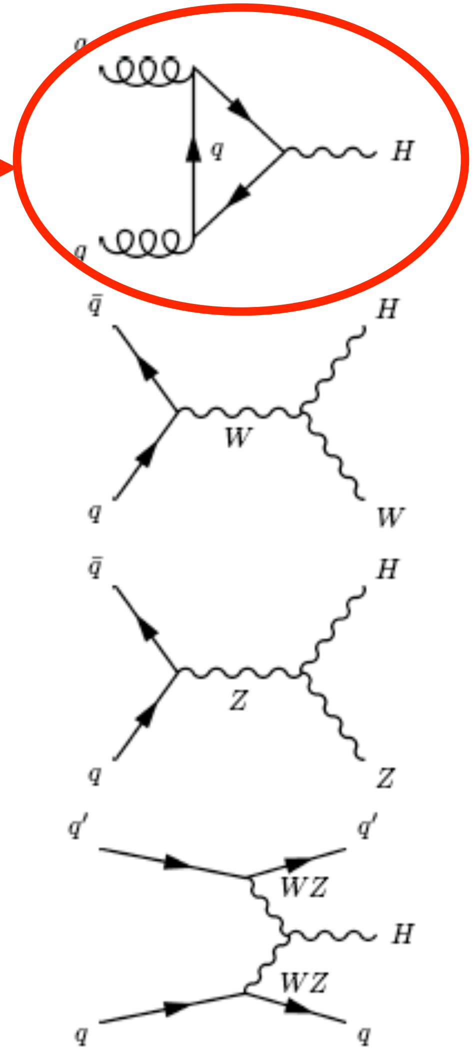
| CDF Run II Preliminary | $\int \mathcal{L} = 5.9\ \text{fb}^{-1}$ | | |
|---|---|---|---|
| $M_H = 165\ \text{GeV}/c^2$ | | | |
| $t\bar{t}$ | 2.23 | ± | 0.66 |
| $DY$ | 227 | ± | 62 |
| $WW$ | 563 | ± | 56 |
| $WZ$ | 25.5 | ± | 3.8 |
| $ZZ$ | 38.3 | ± | 5.4 |
| $W$+jets | 215 | ± | 51 |
| $W\gamma$ | 155 | ± | 22 |
| **Total Background** | 1226 | ± | 120 |
| $gg \to H$ | 16.9 | ± | 3.0 |
| $WH$ | 0.410 | ± | 0.070 |
| $ZH$ | 0.416 | ± | 0.059 |
| $VBF$ | 0.140 | ± | 0.028 |
| **Total Signal** | 17.8 | ± | 3.1 |
| **Data** | 1230 | | |

OS 0 Jets



# 0 Jet Analysis Strategy

0 Jet Events




Inputs into Neural Network

- $\Delta R(l,l)$, $\Delta\phi(l,l)$, $H_T$(all)

Matrix Element Likelihood Ratios

- $LR_{HWW}$, $LR_{WW}$

$$P_m(x_{obs}) = \frac{1}{<\sigma_m>}\int \frac{d\sigma_m^{th}(y)}{dy}\epsilon(y)G(x_{obs},y)$$

$$LR(x_{obs}) \equiv \frac{P_H(x_{obs})}{P_H(x_{obs}) + \Sigma_i k_i P_i(x_{obs})}$$

# 0 Jet Analysis NN Output

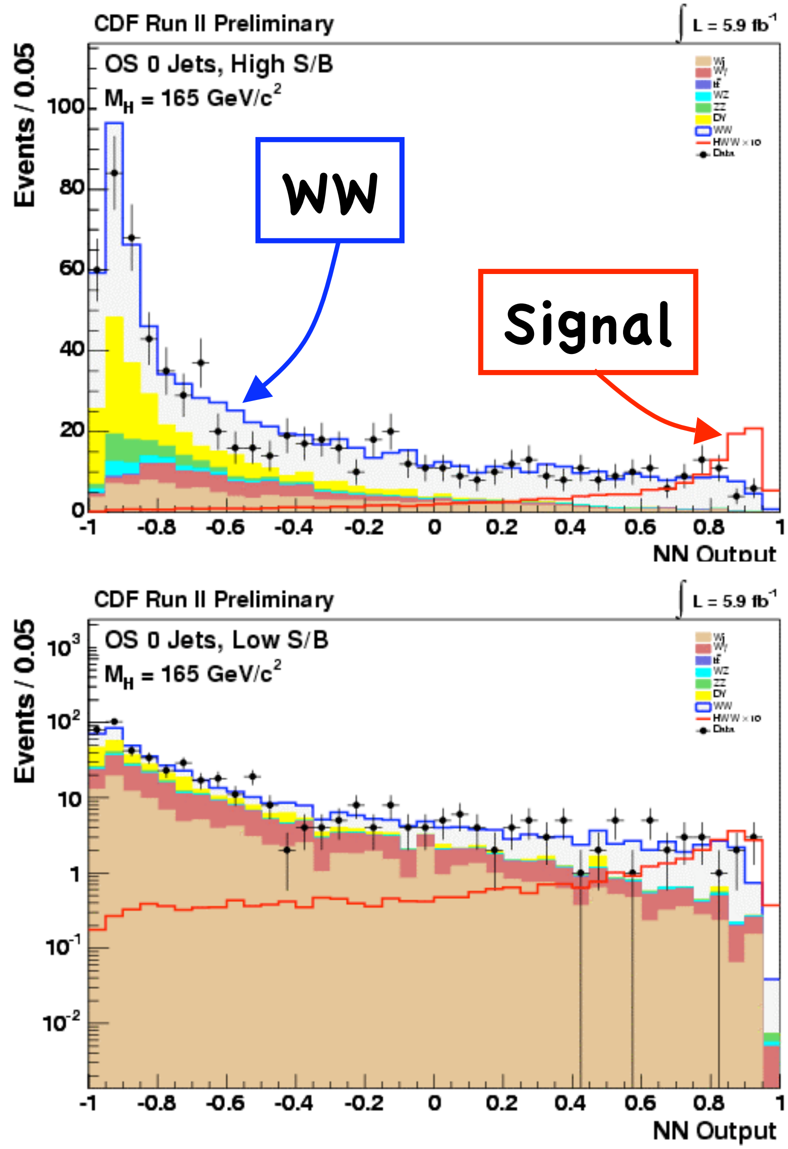
Separate high and low S/B samples

Kinematic inputs into NN

- $\Delta R(l,l)$, $\Delta\phi(l,l)$, $H_T$(all)

Matrix Element Likelihood Ratios

- $LR_{HWW}$, $LR_{WW}$

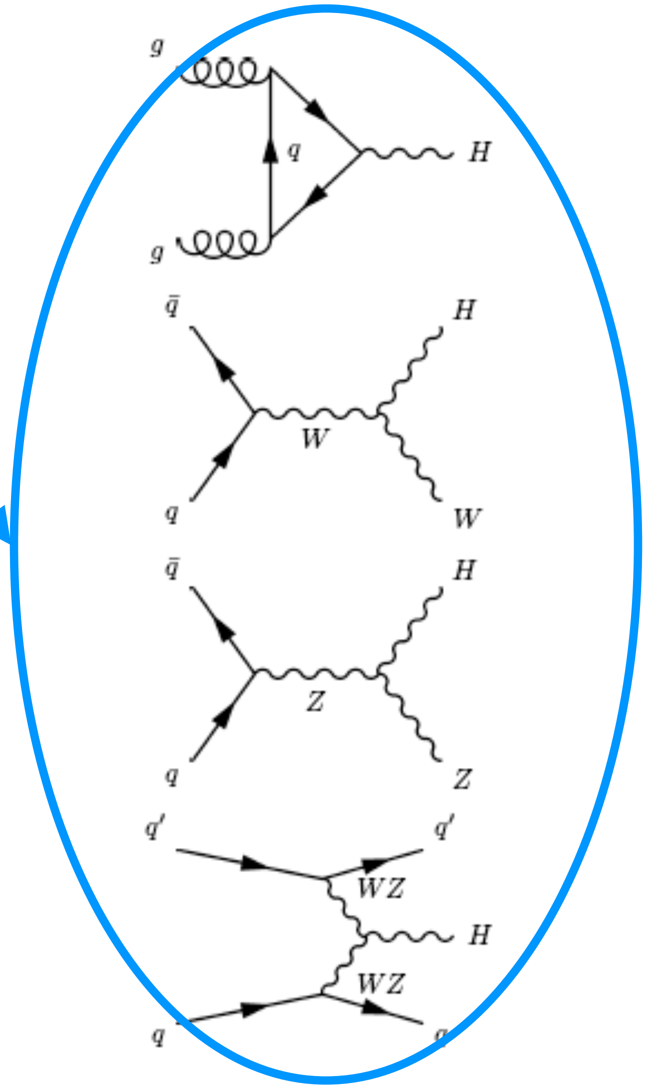


# 1 Jet Analysis Strategy

1 Jet Events

| CDF Run II Preliminary | $\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$ | | |
|---|---|---|---|
| $M_H = 165\ \mathrm{GeV}/c^2$ | | | |
| $t\bar{t}$ | 56 | $\pm$ | 11 |
| $DY$ | 218 | $\pm$ | 49 |
| $WW$ | 151 | $\pm$ | 18 |
| $WZ$ | 25.4 | $\pm$ | 3.5 |
| $ZZ$ | 10.3 | $\pm$ | 1.5 |
| $W$+jets | 77 | $\pm$ | 20 |
| $W\gamma$ | 25.1 | $\pm$ | 4.3 |
| **Total Background** | 563 | $\pm$ | 69 |
| $gg \to H$ | 8.0 | $\pm$ | 2.4 |
| $WH$ | 1.13 | $\pm$ | 0.18 |
| $ZH$ | 0.439 | $\pm$ | 0.066 |
| $VBF$ | 0.74 | $\pm$ | 0.13 |
| **Total Signal** | 10.3 | $\pm$ | 2.5 |
| **Data** | | 533 | |

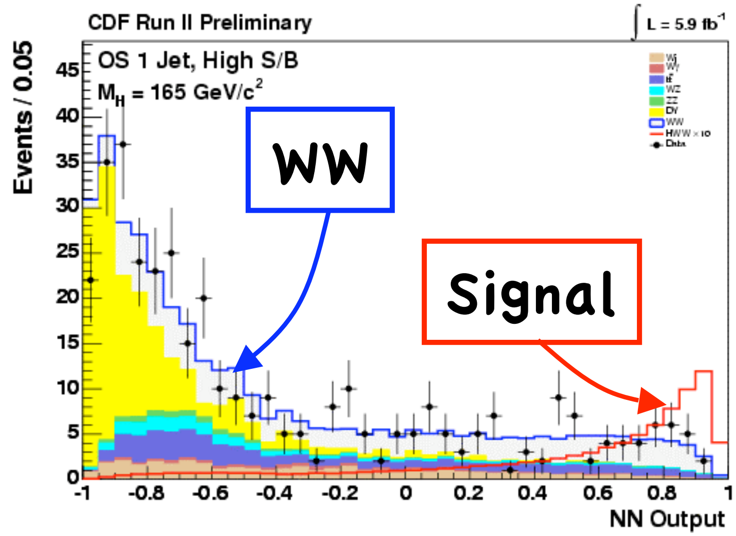
OS 1 Jet

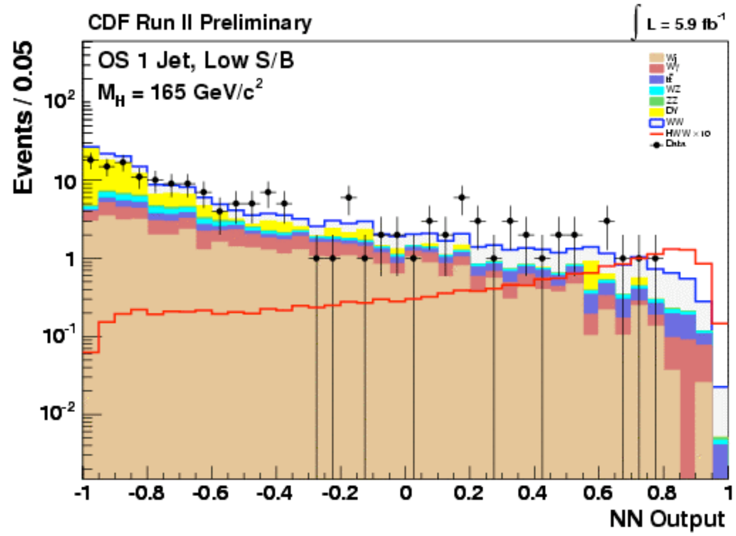


# 1 Jet Analysis NN Output

| CDF Run II Preliminary | $\int \mathcal{L} = 5.9$ fb$^{-1}$ | | |
|---|---|---|---|
| $M_H = 165$ GeV$/c^2$ | | | |
| $t\bar{t}$ | 56 | $\pm$ | 11 |
| $DY$ | 218 | $\pm$ | 49 |
| $WW$ | 151 | $\pm$ | 18 |
| $WZ$ | 25.4 | $\pm$ | 3.5 |
| $ZZ$ | 10.3 | $\pm$ | 1.5 |
| $W$+jets | 77 | $\pm$ | 20 |
| $W\gamma$ | 25.1 | $\pm$ | 4.3 |
| **Total Background** | 563 | $\pm$ | 69 |
| $gg \rightarrow H$ | 8.0 | $\pm$ | 2.4 |
| $WH$ | 1.13 | $\pm$ | 0.18 |
| $ZH$ | 0.439 | $\pm$ | 0.066 |
| $VBF$ | 0.74 | $\pm$ | 0.13 |
| **Total Signal** | 10.3 | $\pm$ | 2.5 |
| **Data** | 533 | | |

OS 1 Jet




**Neural Net Inputs**

$\Delta R(l,l)$, $M_T(ll,\not{E}_T)$, $M_{ll}$, $\not{E}_t^{spec}$

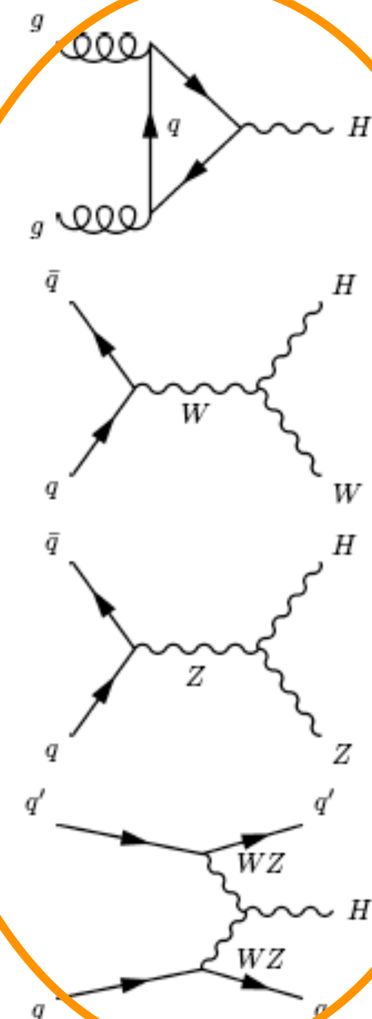
$E(l_1)$, $P_T(l_1)$, $P_T(l_2)$, $H_T$

# 2 Jet Analysis Strategy

2+ Jet Events

| CDF Run II Preliminary | $\int \mathcal{L} = 5.9\ \mathrm{fb}^{-1}$ | | |
|---|---|---|---|
| $M_H = 165\ \mathrm{GeV}/c^2$ | | | |
| $t\bar{t}$ | 169 | $\pm$ | 24 |
| $DY$ | 80 | $\pm$ | 31 |
| $WW$ | 33.6 | $\pm$ | 6.1 |
| $WZ$ | 6.8 | $\pm$ | 1.3 |
| $ZZ$ | 3.10 | $\pm$ | 0.57 |
| $W$+jets | 26.7 | $\pm$ | 7.5 |
| $W\gamma$ | 4.4 | $\pm$ | 1.2 |
| **Total Background** | 324 | $\pm$ | 50 |
| $gg \rightarrow H$ | 2.6 | $\pm$ | 1.8 |
| $WH$ | 2.50 | $\pm$ | 0.35 |
| $ZH$ | 1.28 | $\pm$ | 0.17 |
| $VBF$ | 1.37 | $\pm$ | 0.23 |
| **Total Signal** | 7.8 | $\pm$ | 2.0 |
| **Data** | 307 | | |

A11SB-2JOS




VH and VBF dominant

# 2 Jet Analysis NN Output

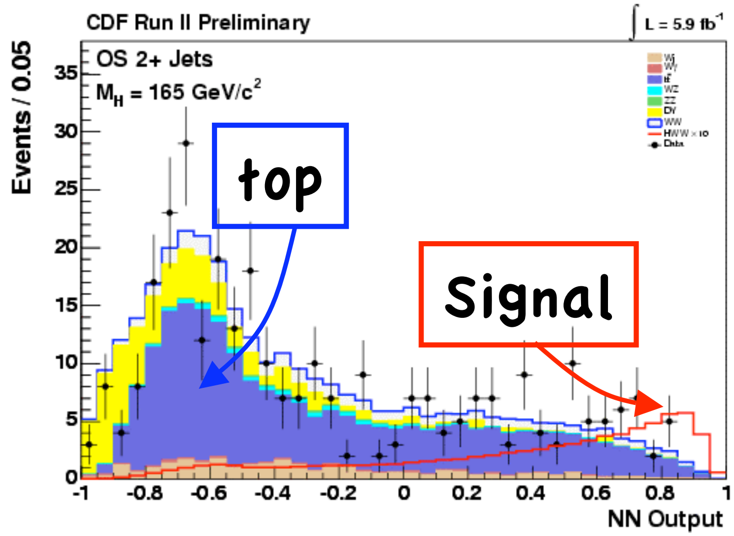
Anti-b-tag cut suppresses $t\bar{t}$

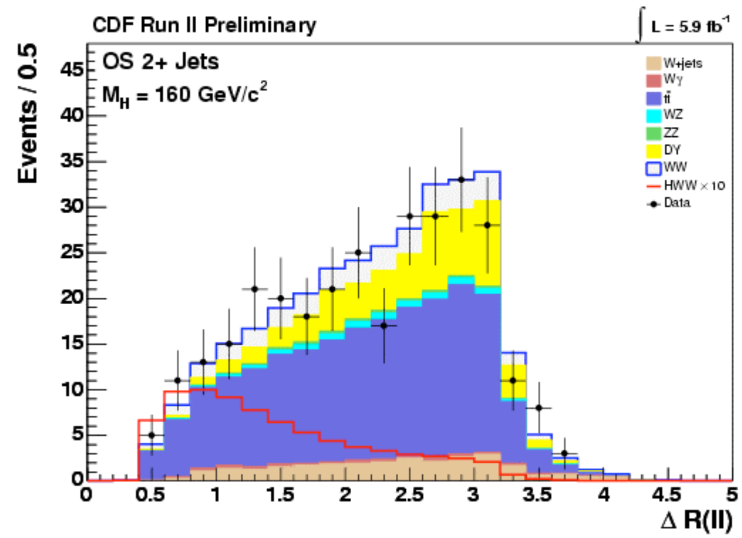
Neural Net Inputs

$\Delta R(l,l)$, $\Delta\phi(l,l)$, $M_{ll}$,$\Sigma P_T^{jets}$

$\Delta\phi(E_T^{ll},E_T)$, $E_T(l_1)$, $E_T(l_2)$, $H_T$

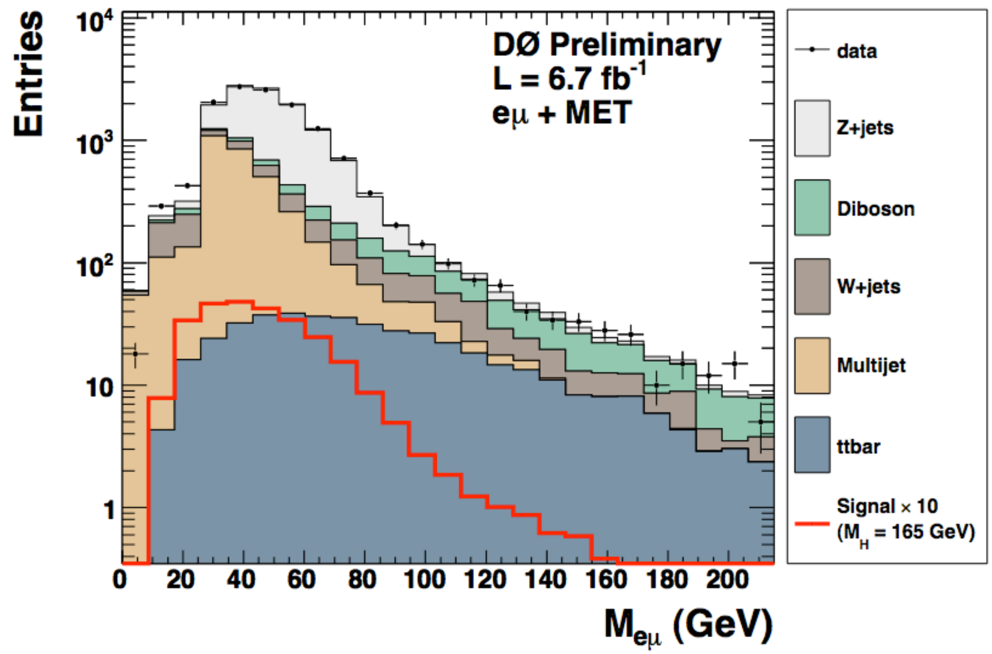
VH and VBF contribution dominant 60% (~3.5 evts)



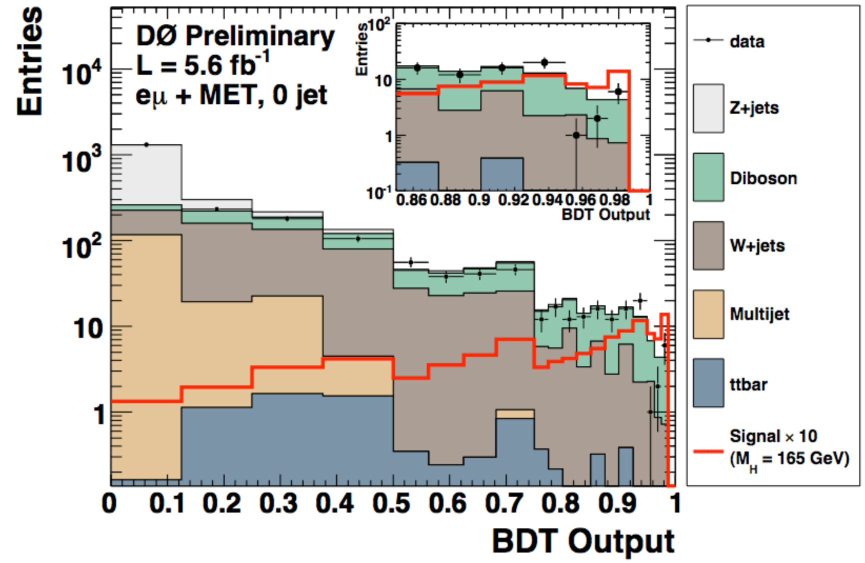
# H→WW→$e^{\pm}\nu\mu^{\pm}\nu$ Signature

- updated to largest dataset in a Higgs search
  - $\int L = 6.7\ fb^{-1}$
- incorporate jet selection
- train Decision Tree for each jet sample
  - 15+ input variables based on event kinematics and topology

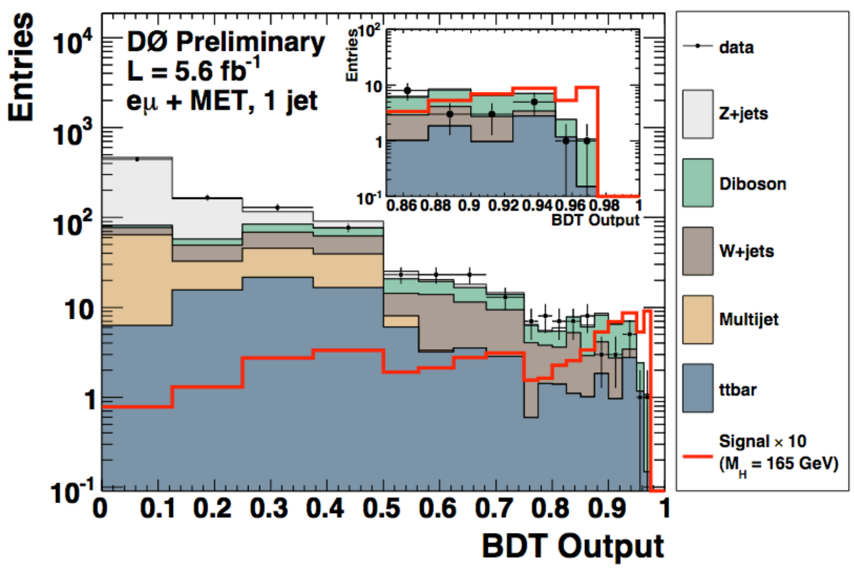


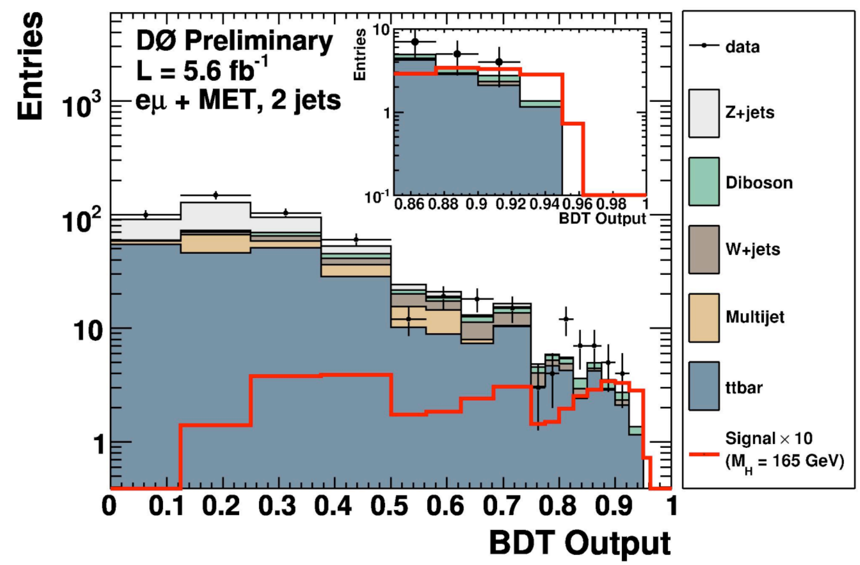

| | Data | Signal | Total Background | $Z\to ee$ | $Z\to\mu\mu$ | $Z\to\tau\tau$ | $t\bar{t}$ | $W+jets$ | $WW$ | $WZ$ | $ZZ$ | Multi-jet |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 jets | 2662 | 13.2 | 2838±224 | 8.9 | 172.2 | 1318 | 10.8 | 684.2 | 447.0 | 16.5 | 2.2 | 177.8 |
| 1 jet | 1164 | 7.9 | 1132±91 | 4.8 | 40.6 | 585.5 | 107.6 | 147.6 | 99.0 | 6.5 | 1.6 | 138.4 |
| ≥ 2 jets | 636 | 4.8 | 594±58 | 2.3 | 14.4 | 162.8 | 300.6 | 38.1 | 21.9 | 2.7 | 1.4 | 49.2 |

# $H \rightarrow WW \rightarrow e^{\pm}\nu\mu^{\pm}\nu$ Signature




- train Decision Tree for each jet sample
- important background for each discriminant changes
  - Diboson, W+jets, top

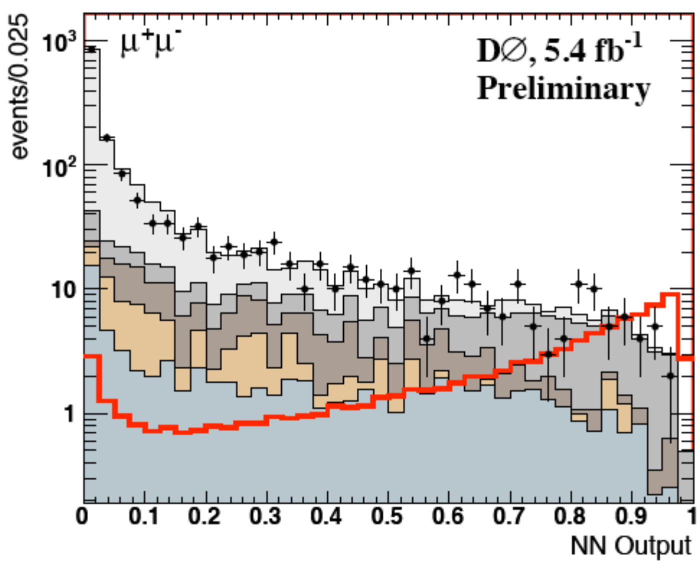


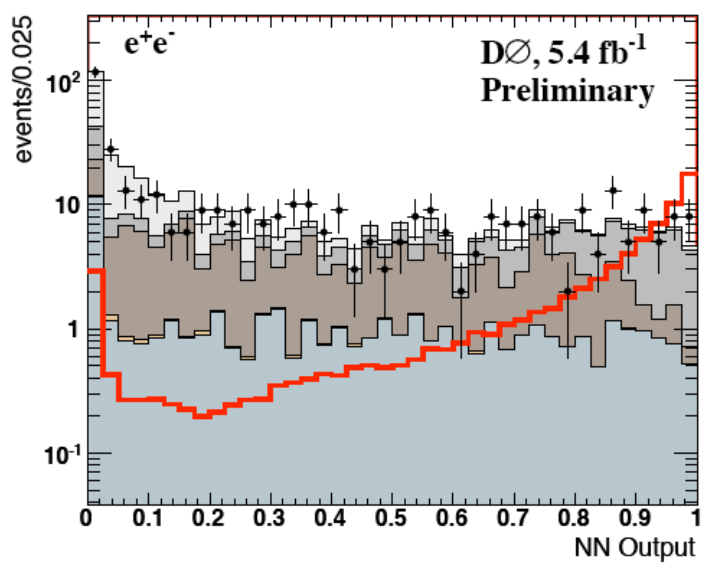



# $H \rightarrow WW \rightarrow l^{+}\nu l^{-}\nu$

- published 5.4 $fb^{-1}$ dielectron and dimuon analysis combined with updated eμ
- artificial Neural Network final discriminant

| Object Variables | Event Var | Topo Var |
|---|---|---|
| $P_T^{l1}$ & $P_T^{l2}$ | $M_{inv}(l,l)$ | N Jets |
| $\Sigma$ lepton $P_T$ | $M_t^{min}(1,\not{E}_T)$ | $\Delta\phi(l,l)$ |
| $\Sigma$ jet $P_T$ ($H_T$) | $\not{E}_T$ | $\Delta\phi(\not{E}_T,l_1)$ |
| Lepton Quality | $\not{E}_t^{scalar}$ | $\Delta\phi(\not{E}_T,l_2)$ |



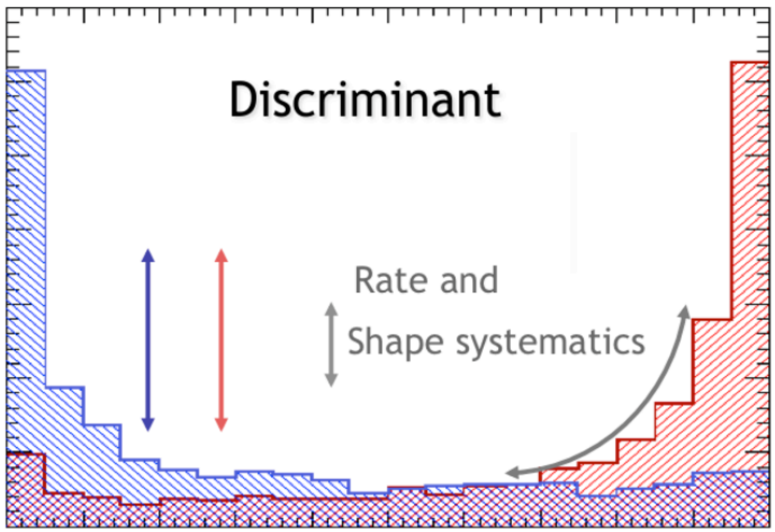



# H→WW→$l\nu l\nu$ Systematics

Shape systematics - modify the output of discriminant

Flat systematics - efficiencies, normalizations, etc

| Syst(%) | Signal | ∑Bkg |
|---|---|---|
| JES | 1.0 | 4.0 |
| Jet ID | 1.6 | 4.9 |
| PV Rew | 0.9 | 0.6 |
| V-$p_T$ Rew | 7.0 | 1.0 |
| WW NLO | 0.4 | 1.1 |
| σ | 22 | 6-10 |
| Multijet | 0 | 2 |
| PDF | 4 | 4 |
| Lepton ID | 2.5 | 2.5 |

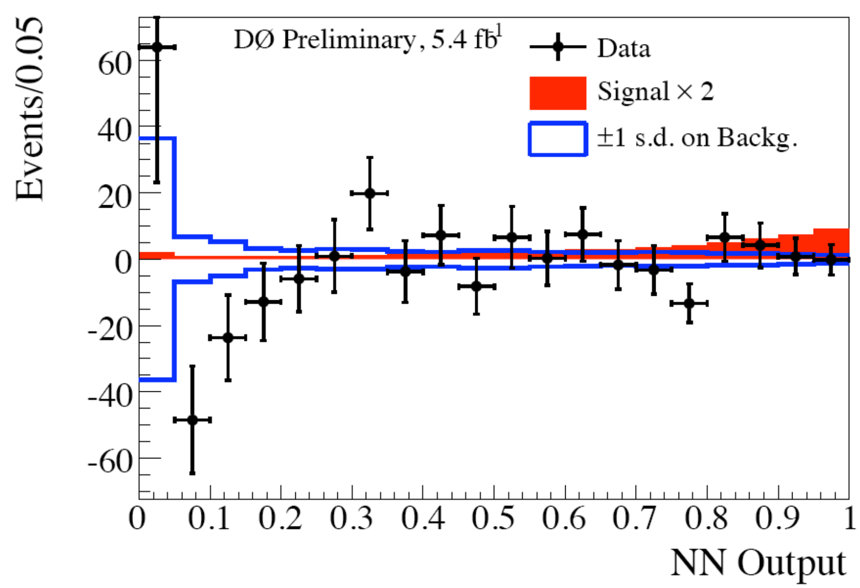


# H→WW→$l\nu l\nu$ Systematics

Shape systematics - modify the output of discriminant

Flat systematics - efficiencies, normalizations, etc

| Syst(%) | Signal | ΣBkg |
|---|---|---|
| JES | 1.0 | 4.0 |
| Jet ID | 1.6 | 4.9 |
| PV Rew | 0.9 | 0.6 |
| V-$p_T$ Rew | 7.0 | 1.0 |
| WW NLO | 0.4 | 1.1 |
| σ | 10 | 6-10 |
| Multijet | 0 | 2 |
| PDF | 4 | 4 |
| Lepton ID | 2.5 | 2.5 |

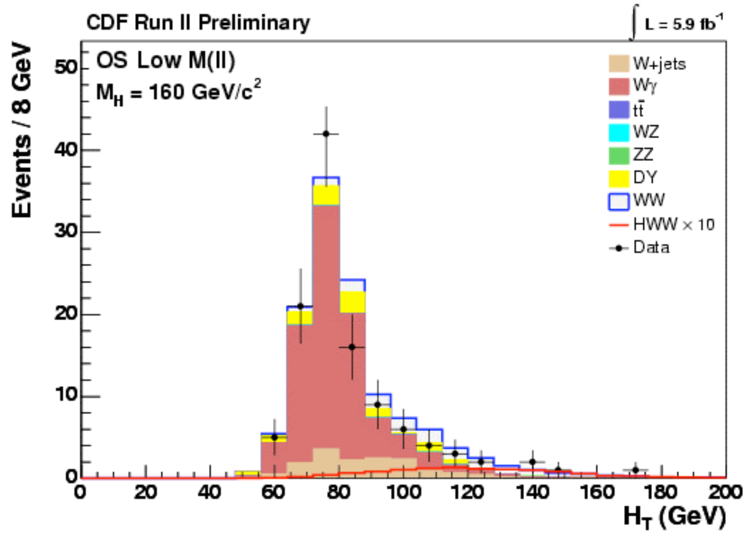


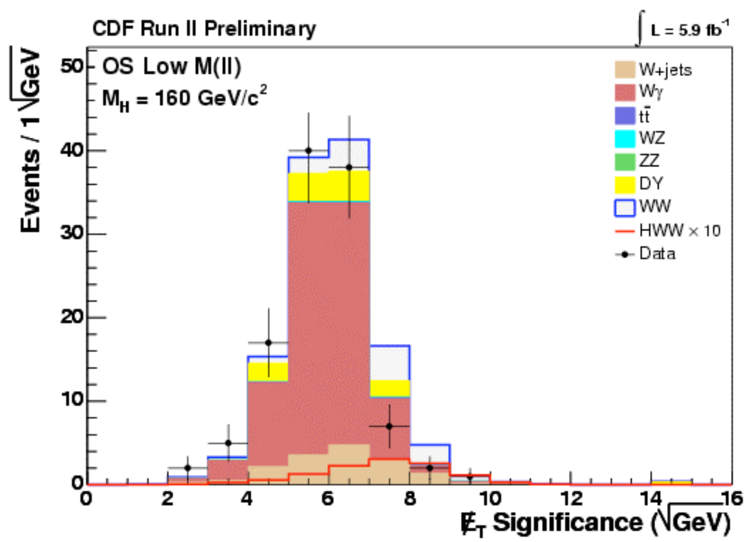
# CDF H→WW Low M(*ll*)

- extend the opposite sign analysis
- M(*ll*) < 15 GeV

| CDF Run II Preliminary | $\int \mathcal{L} = 5.9\ \text{fb}^{-1}$ | | |
|---|---|---|---|
| $M_H = 165\ \text{GeV}/c^2$ | | | |
| $t\bar{t}$ | 0.55 | ± | 0.10 |
| $DY$ | 4.35 | ± | 0.78 |
| $WW$ | 13.8 | ± | 1.3 |
| $WZ$ | 0.371 | ± | 0.052 |
| $ZZ$ | 0.139 | ± | 0.019 |
| $W$+jets | 16.2 | ± | 3.0 |
| $W\gamma$ | 76.8 | ± | 7.7 |
| **Total Background** | 112.2 | ± | 8.6 |
| $gg \to H$ | 1.00 | ± | 0.20 |
| **Total Signal** | 1.00 | ± | 0.20 |
| **Data** | 112 | | |

AllSB-lowMll



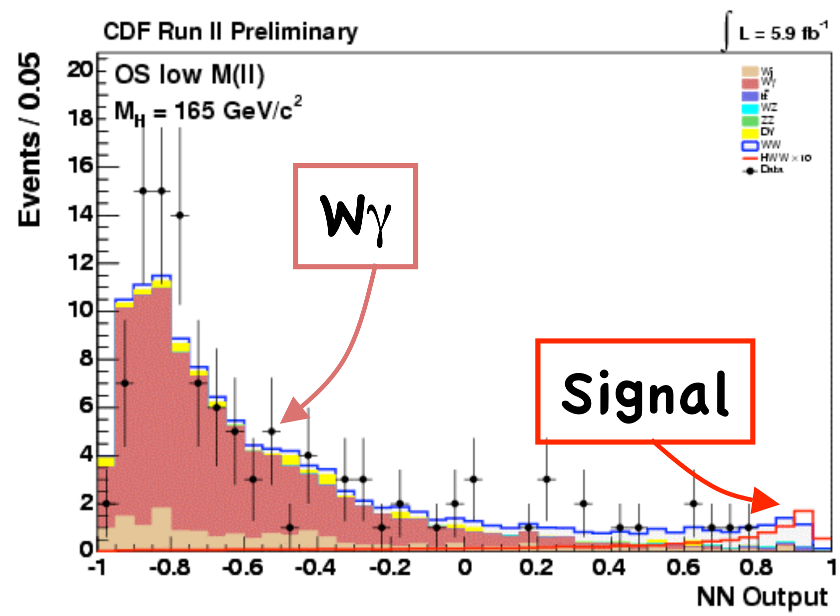



# CDF H→WW Low M($ll$)

- extend the opposite sign analysis
- M($ll$) < 15 GeV

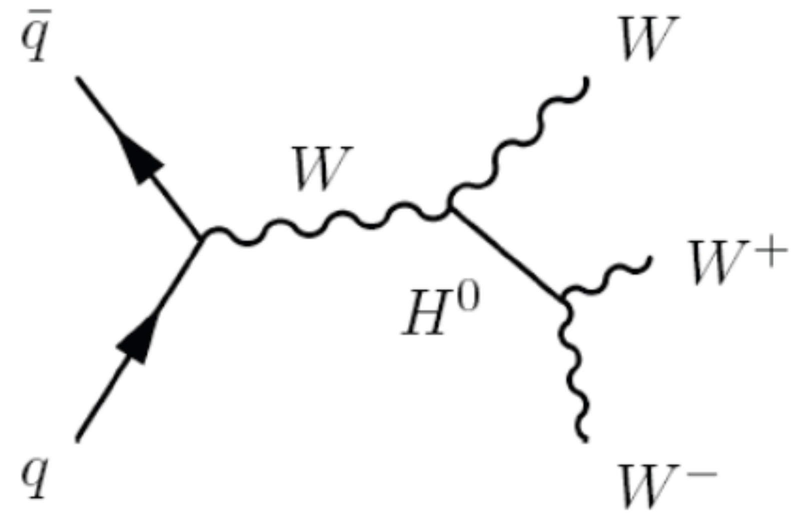
| CDF Run II Preliminary | $\int \mathcal{L} = 5.9$ fb$^{-1}$ | | |
|---|---|---|---|
| | $M_H = 165$ GeV/$c^2$ | | |
| $t\bar{t}$ | 0.55 | ± | 0.10 |
| $DY$ | 4.35 | ± | 0.78 |
| $WW$ | 13.8 | ± | 1.3 |
| $WZ$ | 0.371 | ± | 0.052 |
| $ZZ$ | 0.139 | ± | 0.019 |
| $W$+jets | 16.2 | ± | 3.0 |
| $W\gamma$ | 76.8 | ± | 7.7 |
| **Total Background** | 112.2 | ± | 8.6 |
| $gg \to H$ | 1.00 | ± | 0.20 |
| **Total Signal** | 1.00 | ± | 0.20 |
| **Data** | 112 | | |

AllSB-lowMll



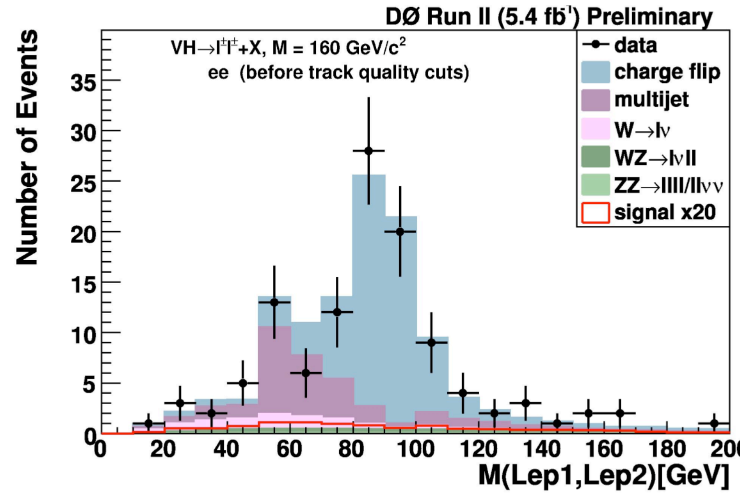
# $VH \rightarrow V(WW^*) \rightarrow l^{\pm}l^{\pm} + X$

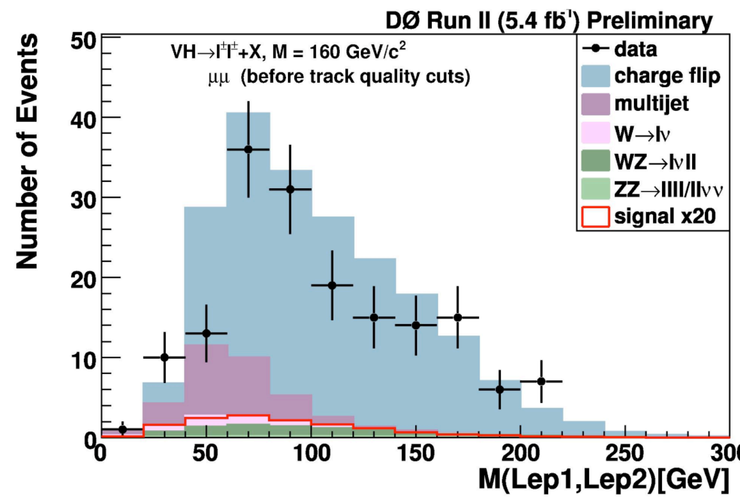
- leptonic decay of the vector boson
- one of Higgs Ws decay hadronically
- utilize same lepton selection from opposite charge analysis
- require two same charge leptons



# VH→V(WW*)→$l^{\pm}l^{\pm}$+X

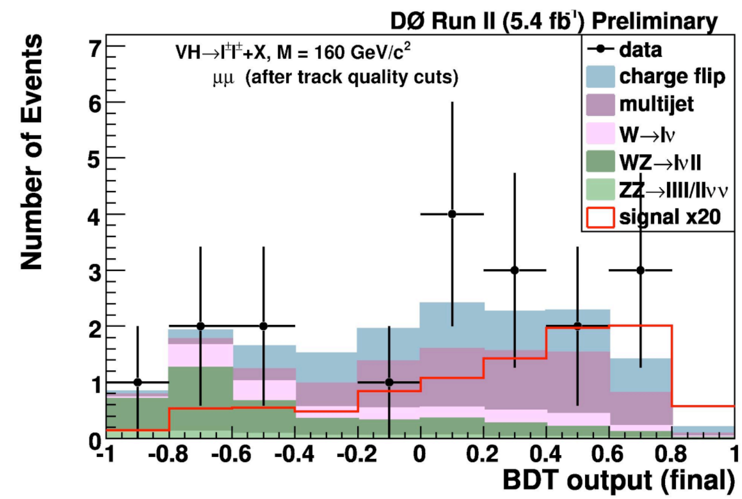
- Charge flip background
  - ee - like-sign in Z mass
  - μμ - use track vs muon system charge measurements
- Multijet background
  - measure from data
  - loose/tight sample estimate

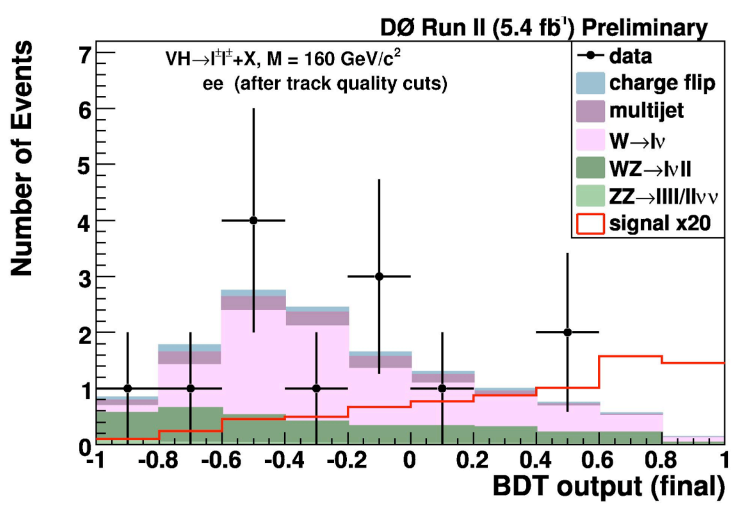


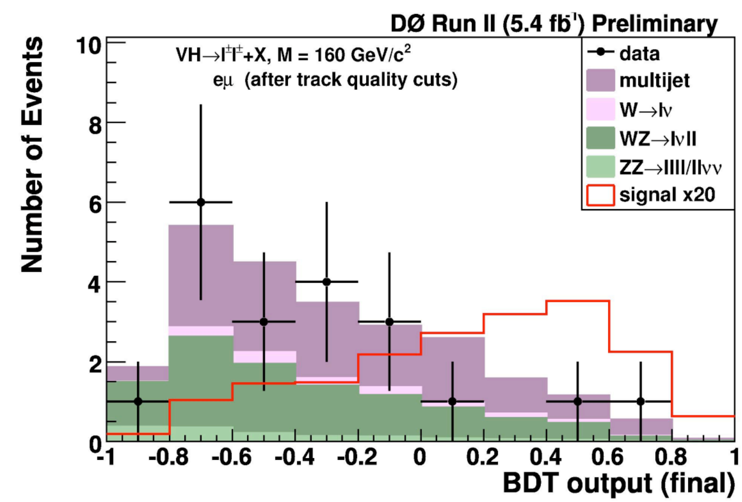



# VH→$l^{\pm}l^{\pm}+X$ Analysis

- Boosted Decision Tree Discriminants
  - instrumental background
  - physics background rejection final discriminant



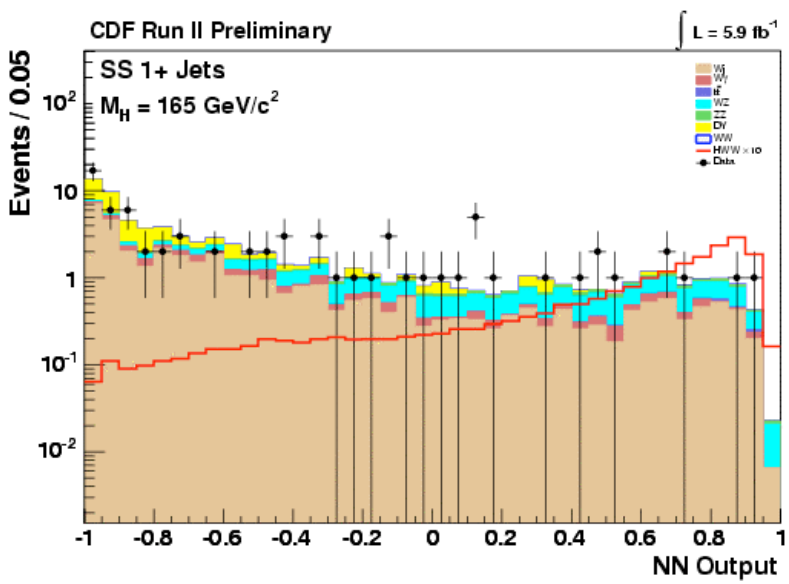



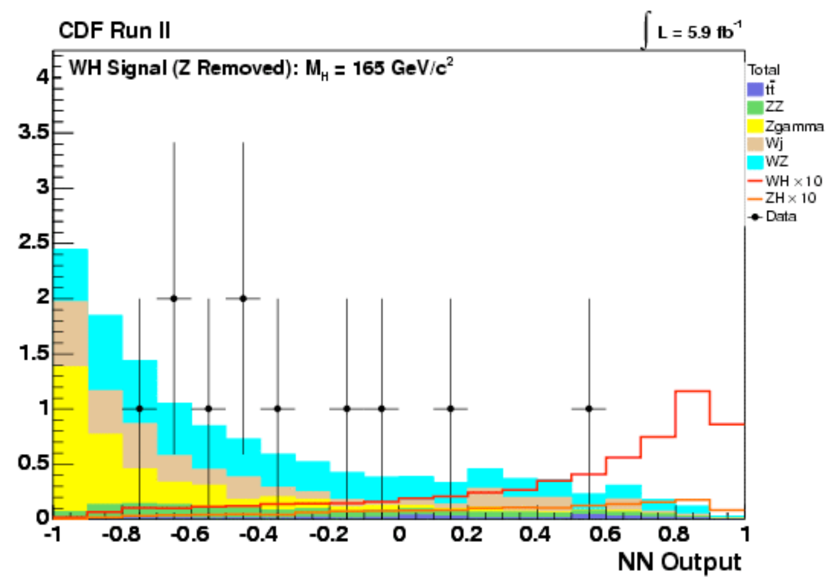



# $VH \rightarrow V(WW^*) \rightarrow l^{\pm}l^{\pm}+X$

- Opposite chage dilepton
- >=1 jet ($P_T$ > 15 GeV)
- W+jet dominant bkg
- Neural Network final discriminant

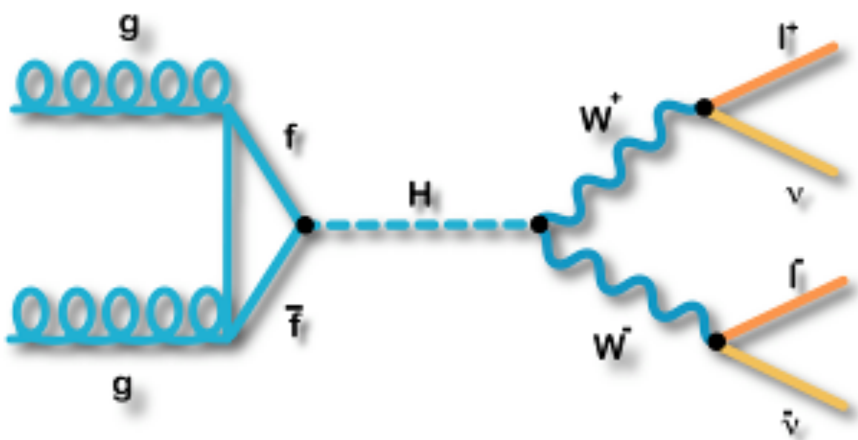
- Trilepton search
- Separate by presence of Z candidate and jet multiplicity
- Neural Network final discriminant

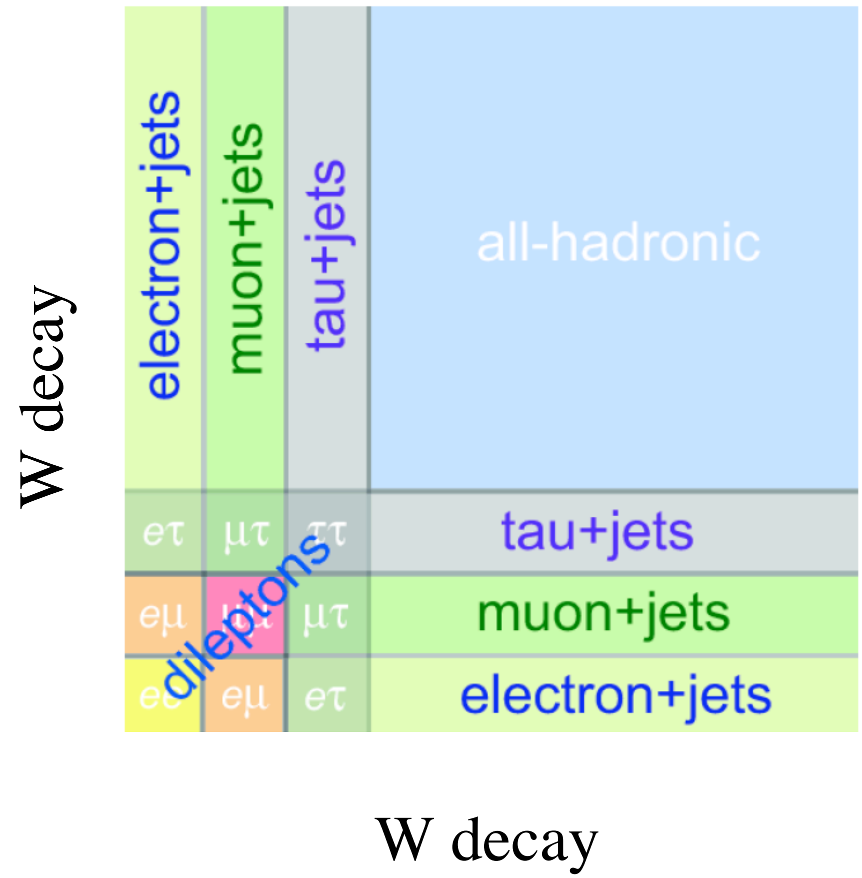


# new search channels

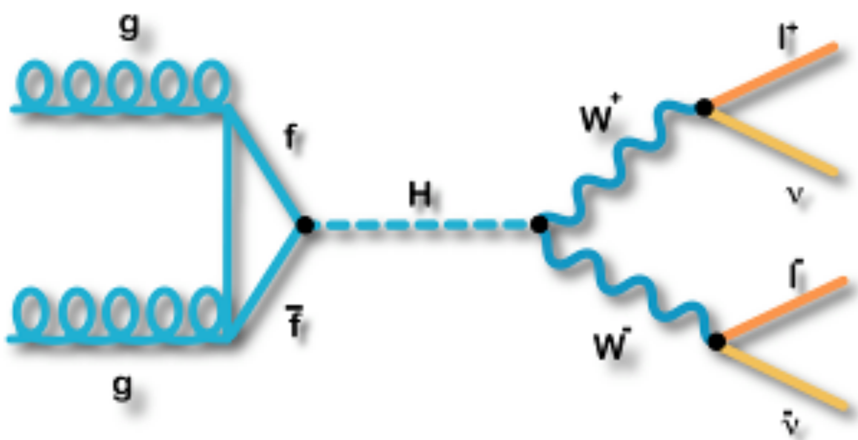
- $H \rightarrow WW^* \rightarrow l\nu jj$ - D0
- $H \rightarrow WW^* \rightarrow \mu\nu\tau\nu$- CDF

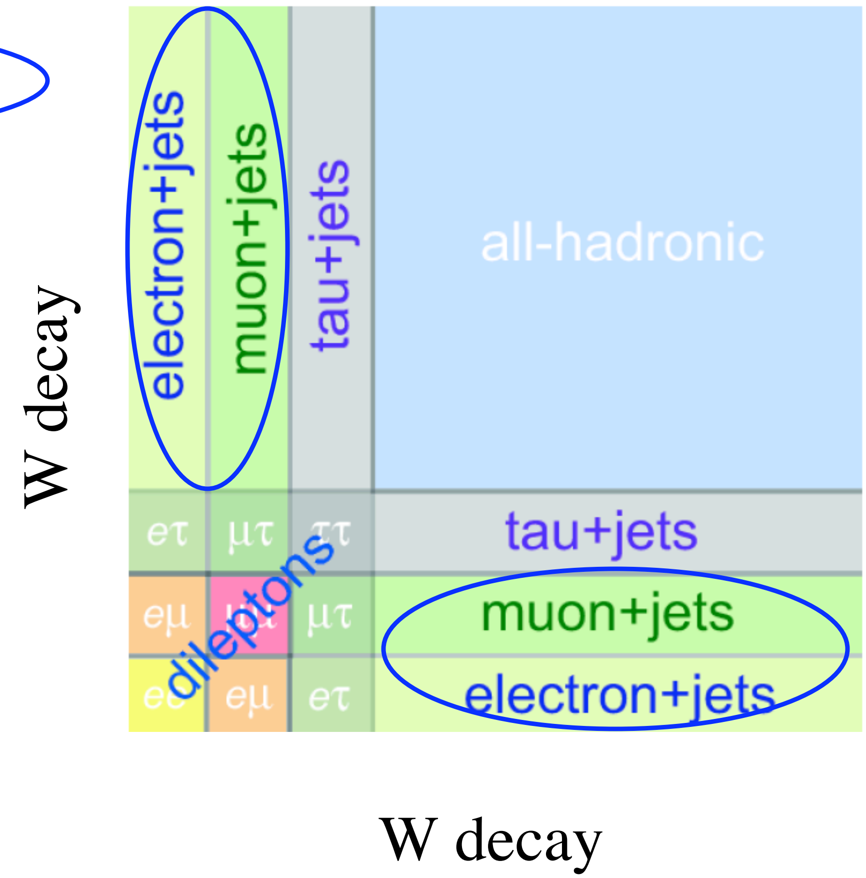


# new search channels

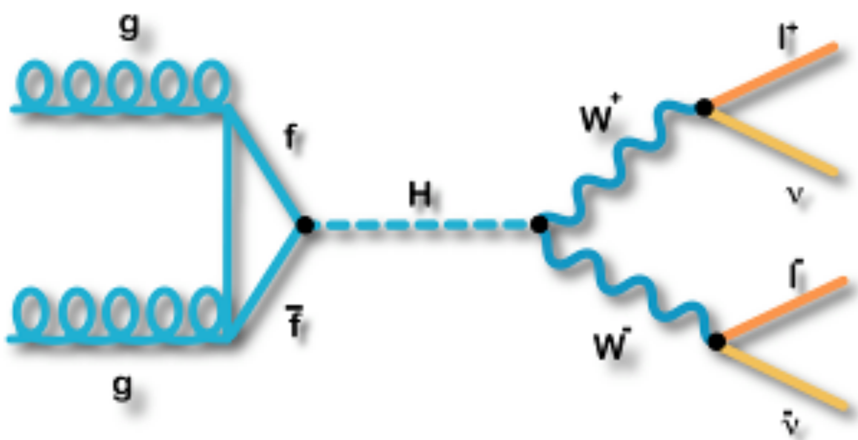
- $H \rightarrow WW^* \rightarrow l\nu jj$ - D0
- $H \rightarrow WW^* \rightarrow \mu\nu\tau\nu$- CDF

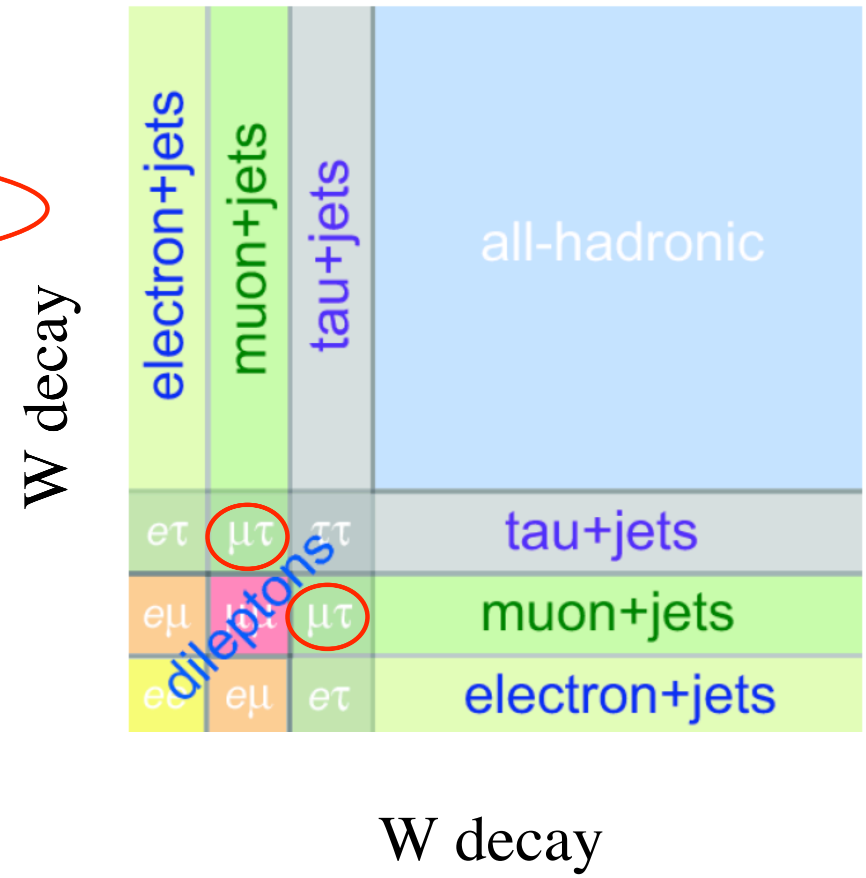


# new search channels

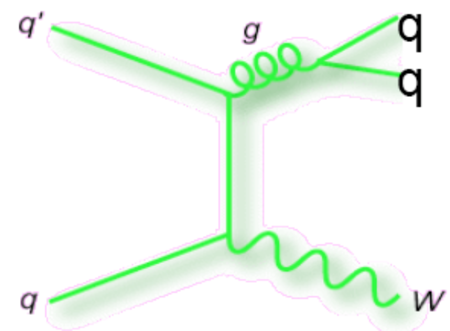
- $H \rightarrow WW^* \rightarrow l\nu jj$ - D0
- $H \rightarrow WW^* \rightarrow \mu\nu\tau\nu$ - CDF

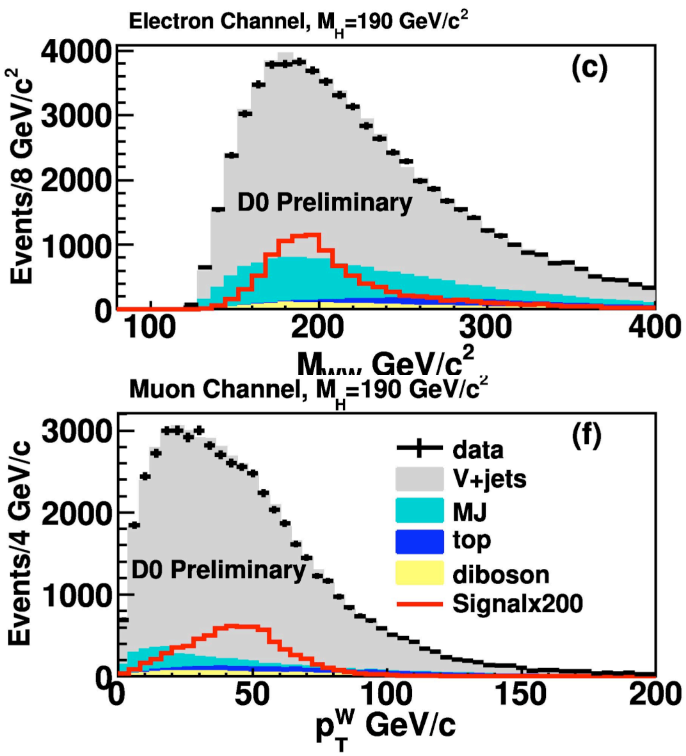


# H→WW→*lvjj*

- Event selection
  - high-$p_T$ lepton > 15 GeV
  - large missing $E_T$ > 15 GeV
  - 2 high-$p_T$ jets




•background composition

–W+2 jets

–top production

–Diboson - WW, WZ, ZZ

–QCD multijet events

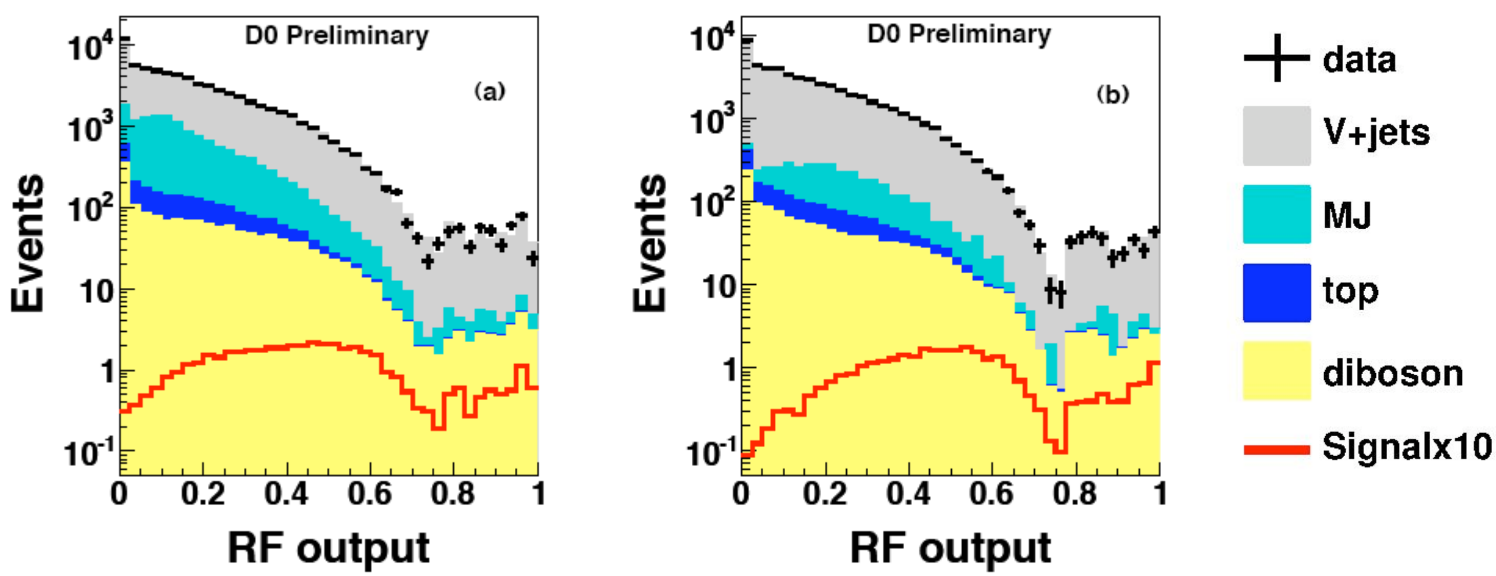
•utilize techniques from low mass analyses

# H→WW→$l\nu jj$

- Very large W+jets background after selection
  - $S/\sqrt{B} = 0.22$ ($m_H = 165$ GeV)

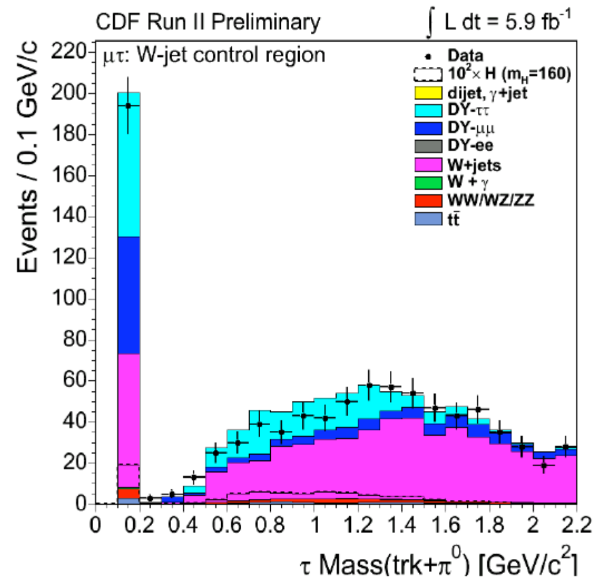
| Channel | $H \to WW$ | $V$+jets | Multijet | top | $VV$ | data |
|---|---|---|---|---|---|---|
| electron | 45.2 | 52156 | 11453 | 2433 | 1585 | 67627 |
| muon | 32.2 | 47201 | 2409 | 1598 | 1225 | 52433 |

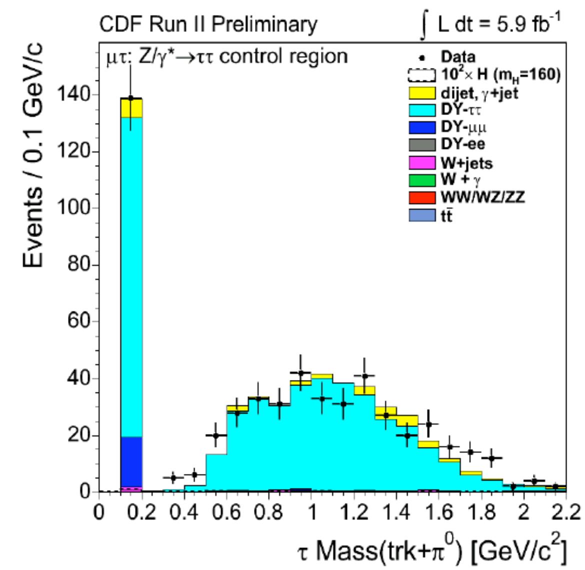
- Use W-Mass to constraint neutrino $P_Z$
- Combine kinematics into a Random Forest Decision Tree



# H→WW→$l\nu\tau\nu$

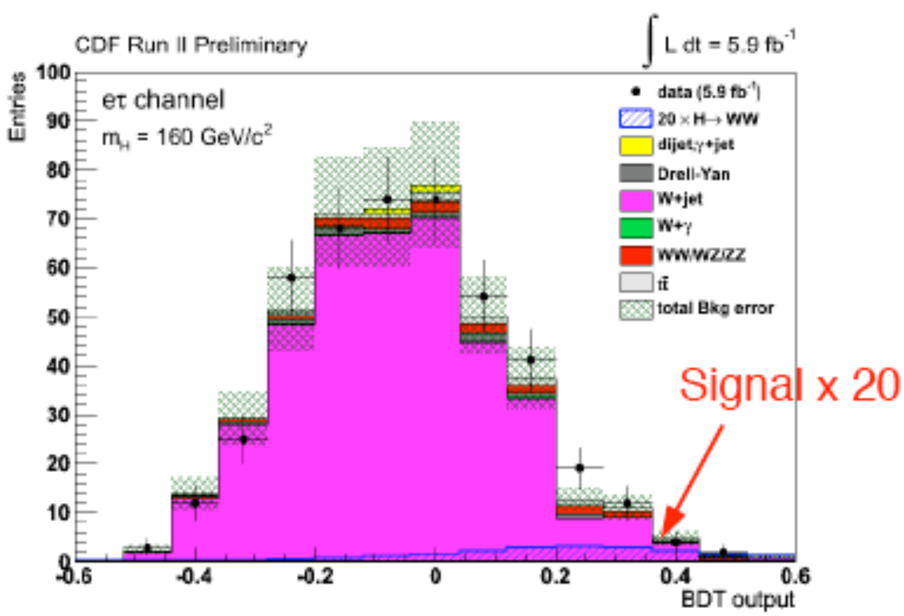
- backgrounds very different for $\tau$ samples
- Multijet and Z→$\tau\tau$ dominate
- Control samples allow for cross checks of $\tau$ kinematic and ID variables
  - W+jets (e$\tau$ & μ$\tau$)
  - Mulijet (e$\tau$)
  - Z→$\tau\tau$ (μ$\tau$)

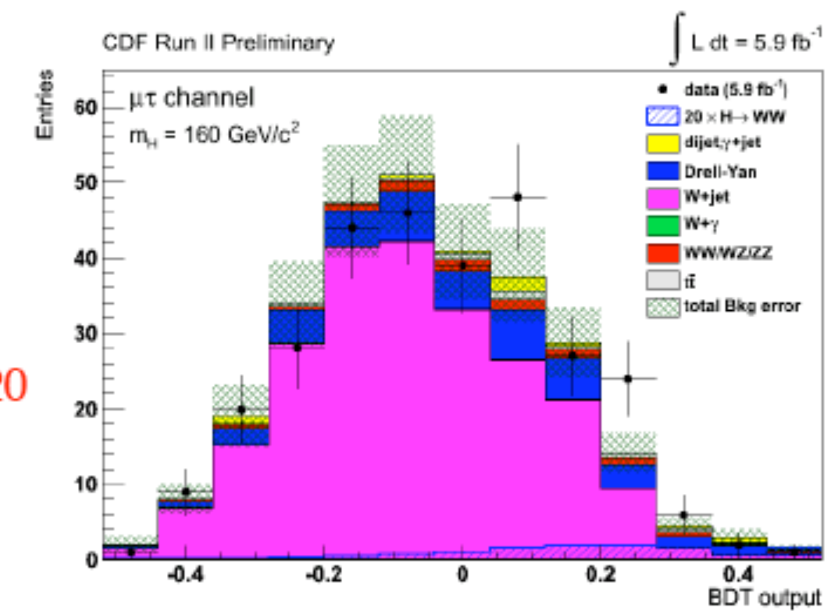


# H→WW→$\mu\nu\tau\nu$

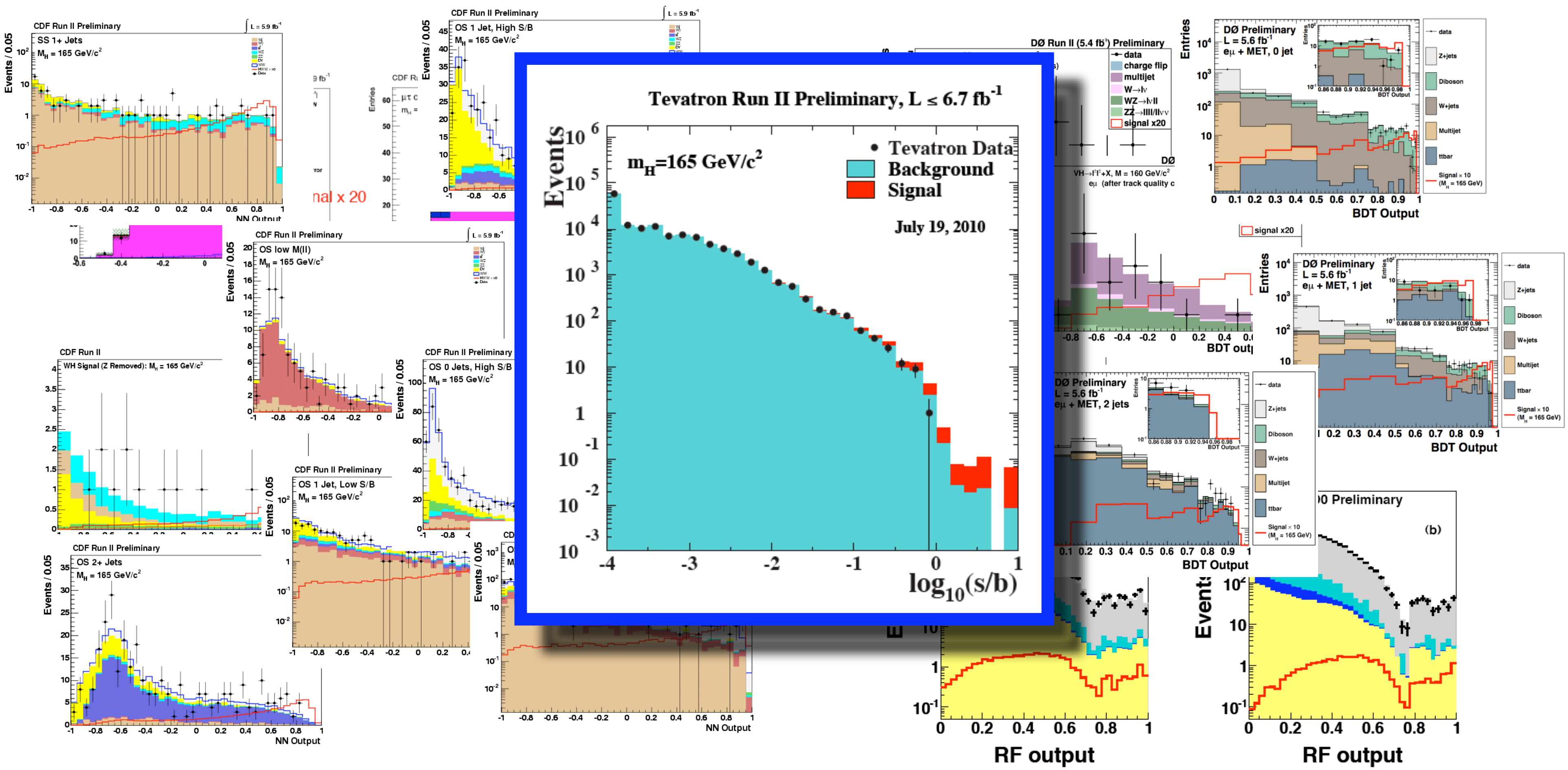
- Boosted Decision Tree discriminant
- W+jets modeled with ALPGEN
  - dominant background
- Expect 1.5 evts Higgs signal, ~700 background



# High Mass Higgs limits

both CDF and D0 see good agreement in all channels -- now combine!



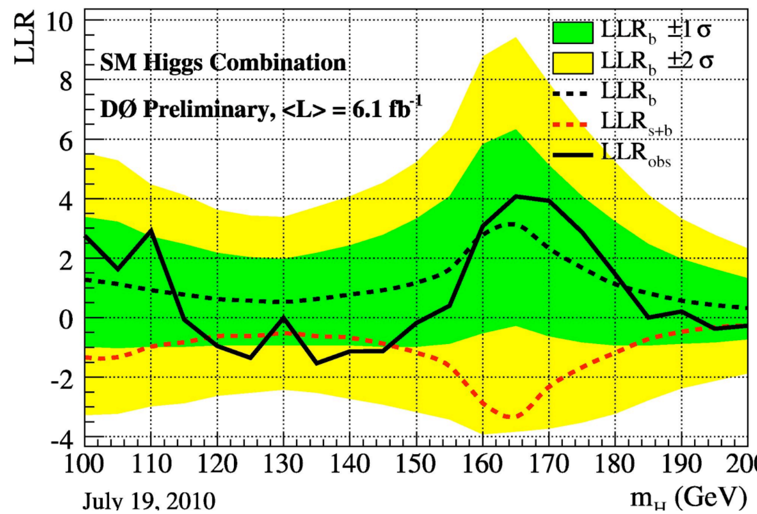
# DØ SM Higgs combination

•combine all 10 high mass channels

•modified frequentist approach with log likelihood ratio test statistic

•weighted by sensitivity, average integrated luminosity

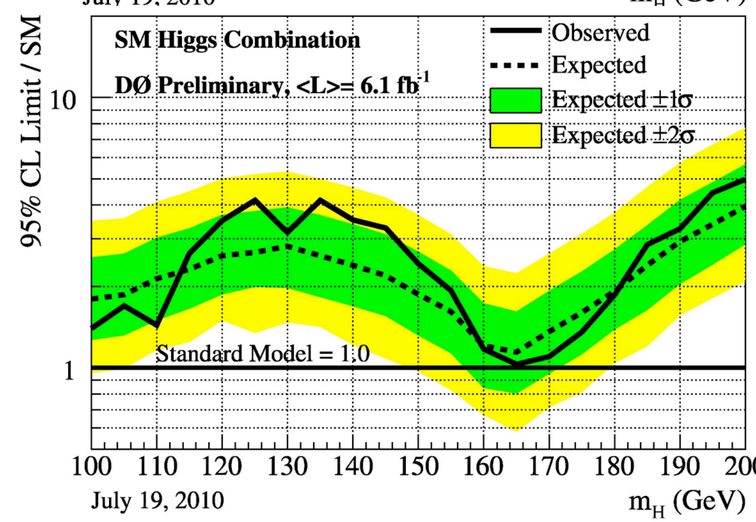
- •6.10 $fb^{-1}$ @ 165 GeV




D0 SM Higgs limit @165 GeV

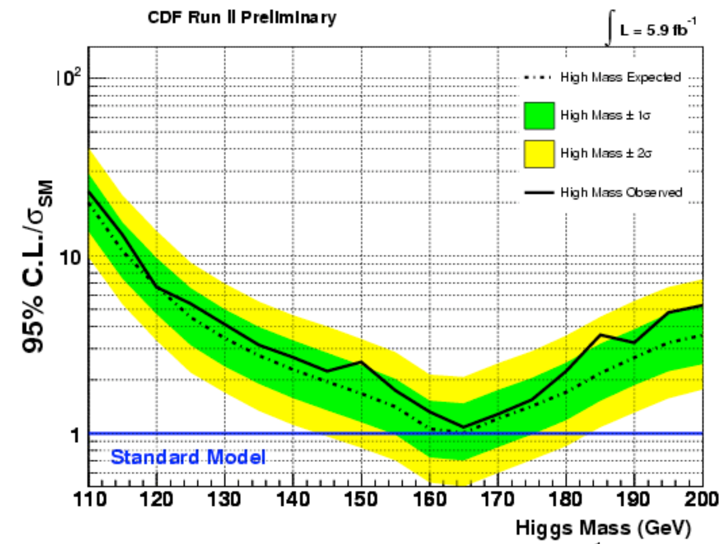
$\sigma/\sigma_{SM}$ (obs) = 1.03

$\sigma/\sigma_{SM}$ (exp) = 1.14



# CDF SM Higgs combination

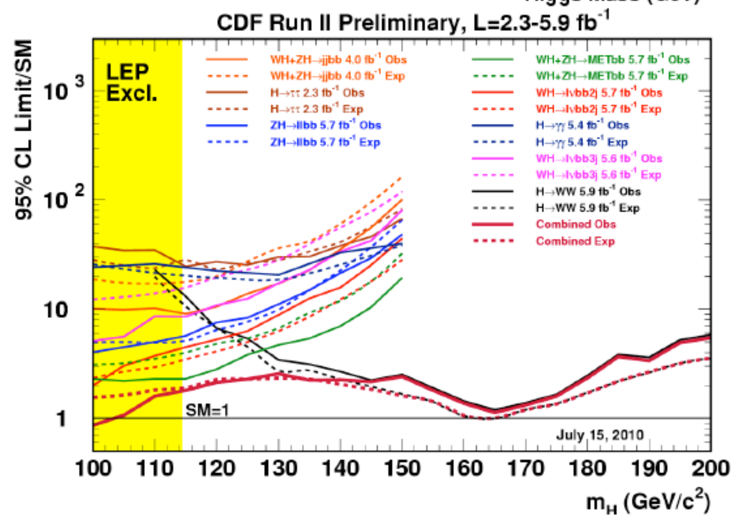
- combine all 18 high mass channels
- use bayesian approach
- weighted by sensitivity, average integrated luminosity
    - 5.90 $fb^{-1}$ @ 165 GeV



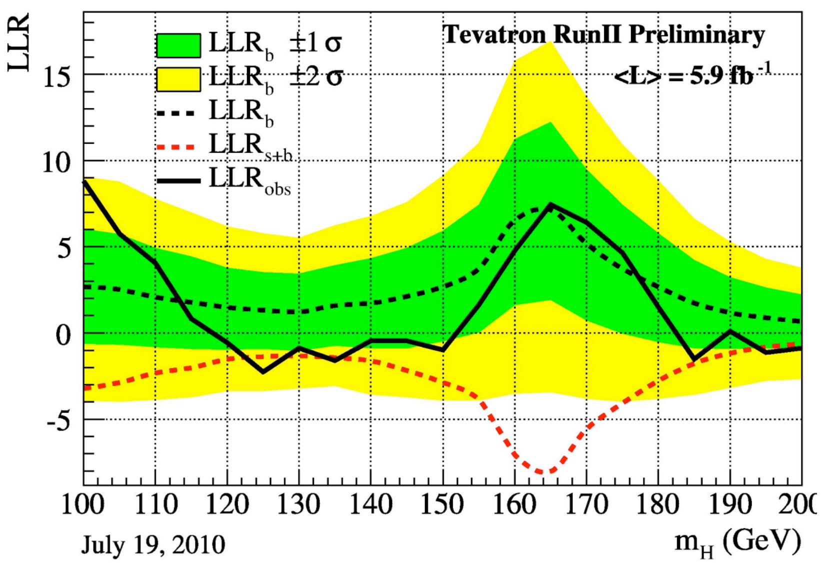

CDF SM Higgs limit @165 GeV

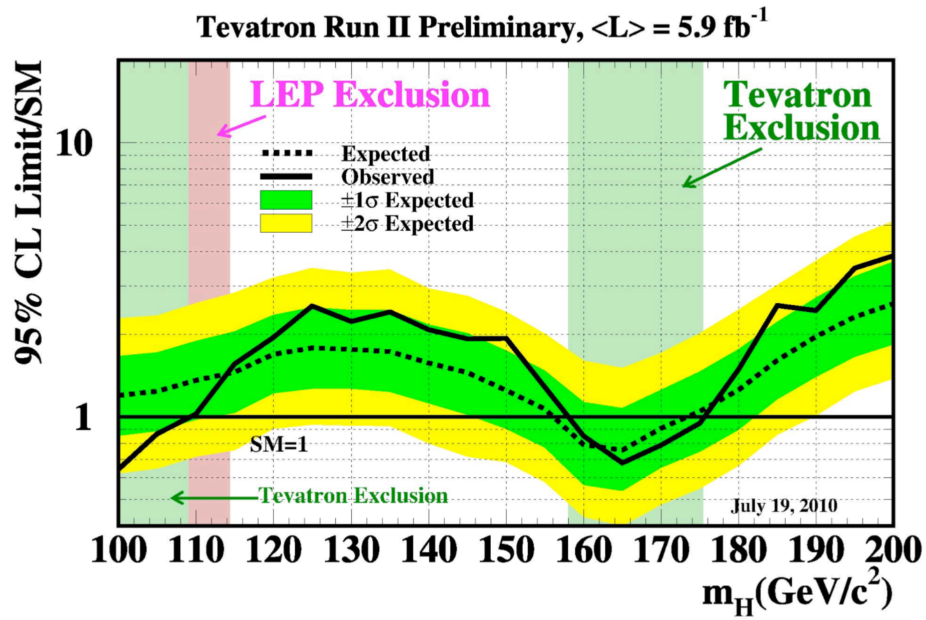
$\sigma/\sigma_{SM}$ (obs) = 1.13

$\sigma/\sigma_{SM}$ (exp) = 1.00



# Tevatron SM Higgs combination

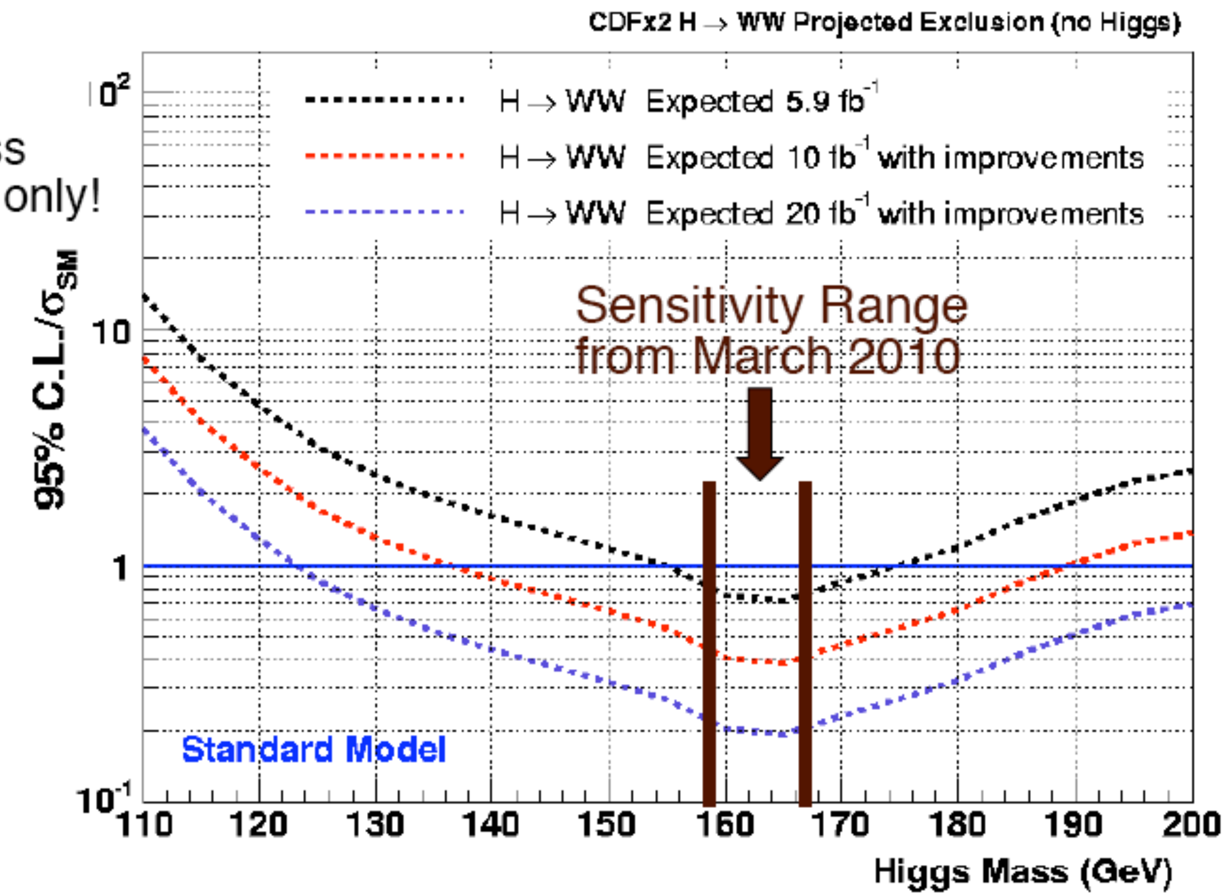



- Obs exclusion $M_H$ = [158-175] GeV
- Exp exclusion $M_H$ = [156-175] GeV

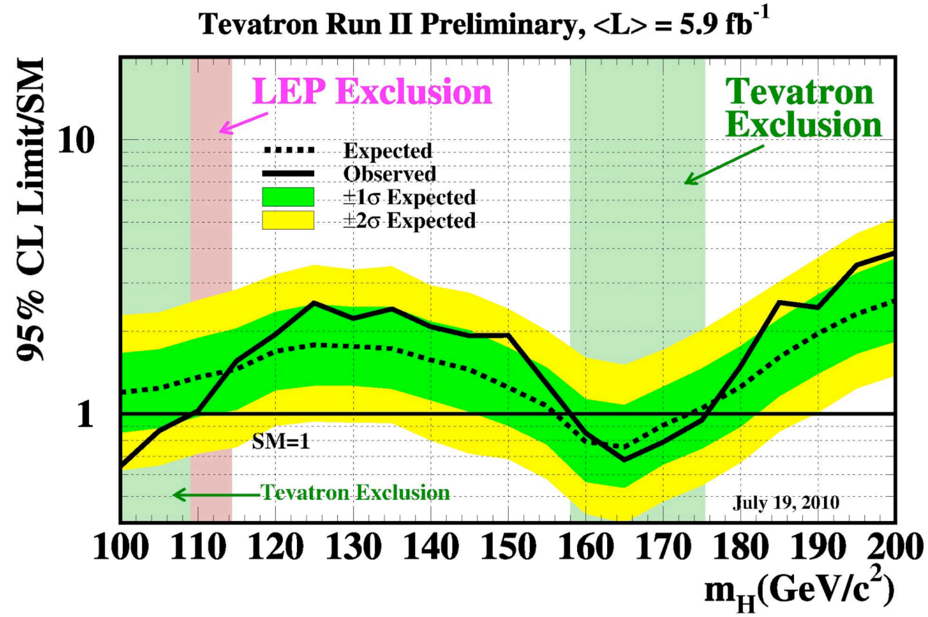
# Tevatron Projections

High Mass analyses only!




assumes two experiments with equal sensitivity

# Tevatron SM Higgs Summary

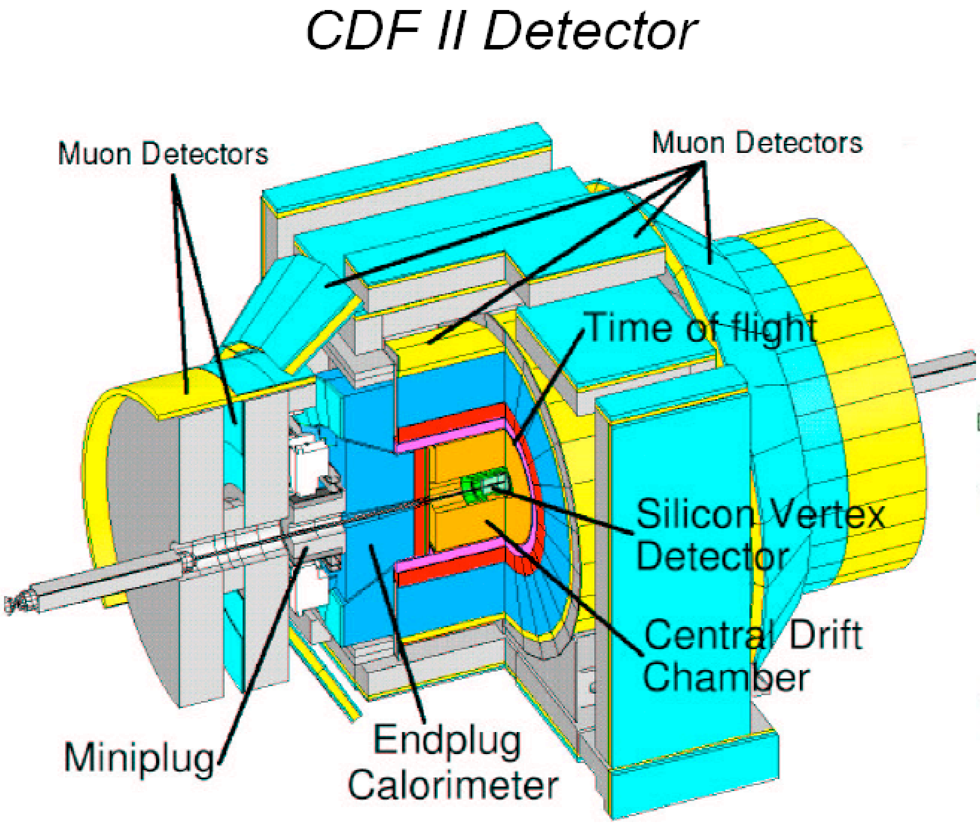



- SM Higgs searches are rapidly improving
- Inclusion of new channels and theory predictions is extending sensitivity
- Common tools and coherent treatment of systematics across numerous channels
- Validation of analytic tools with measurement of WW/WZ production in lνlν,lνjj signature
- Integrated luminosity increasing better than expected

- Tevatron will continue to expand the SM Higgs mass sensitivity regions
- extremely exciting time at the Tevatron

# Backup

# CDFII & DØ Detectors

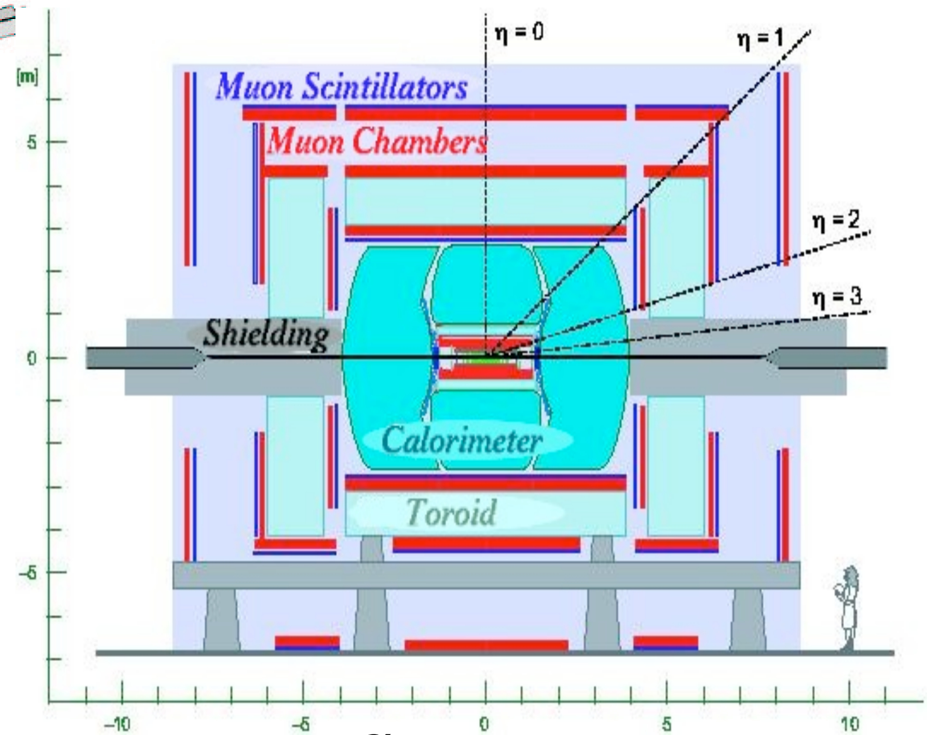



detector coverage |η|

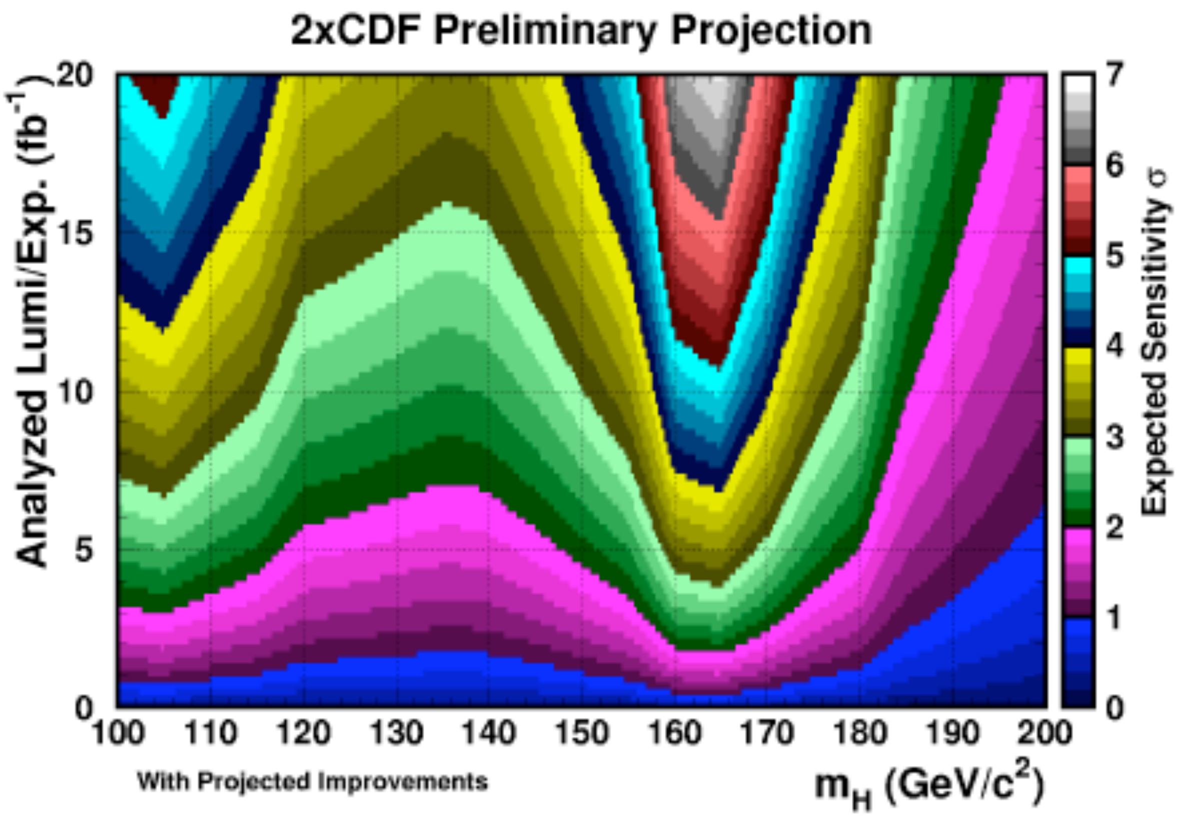
muons ~ 2

tracking ~ 2.5

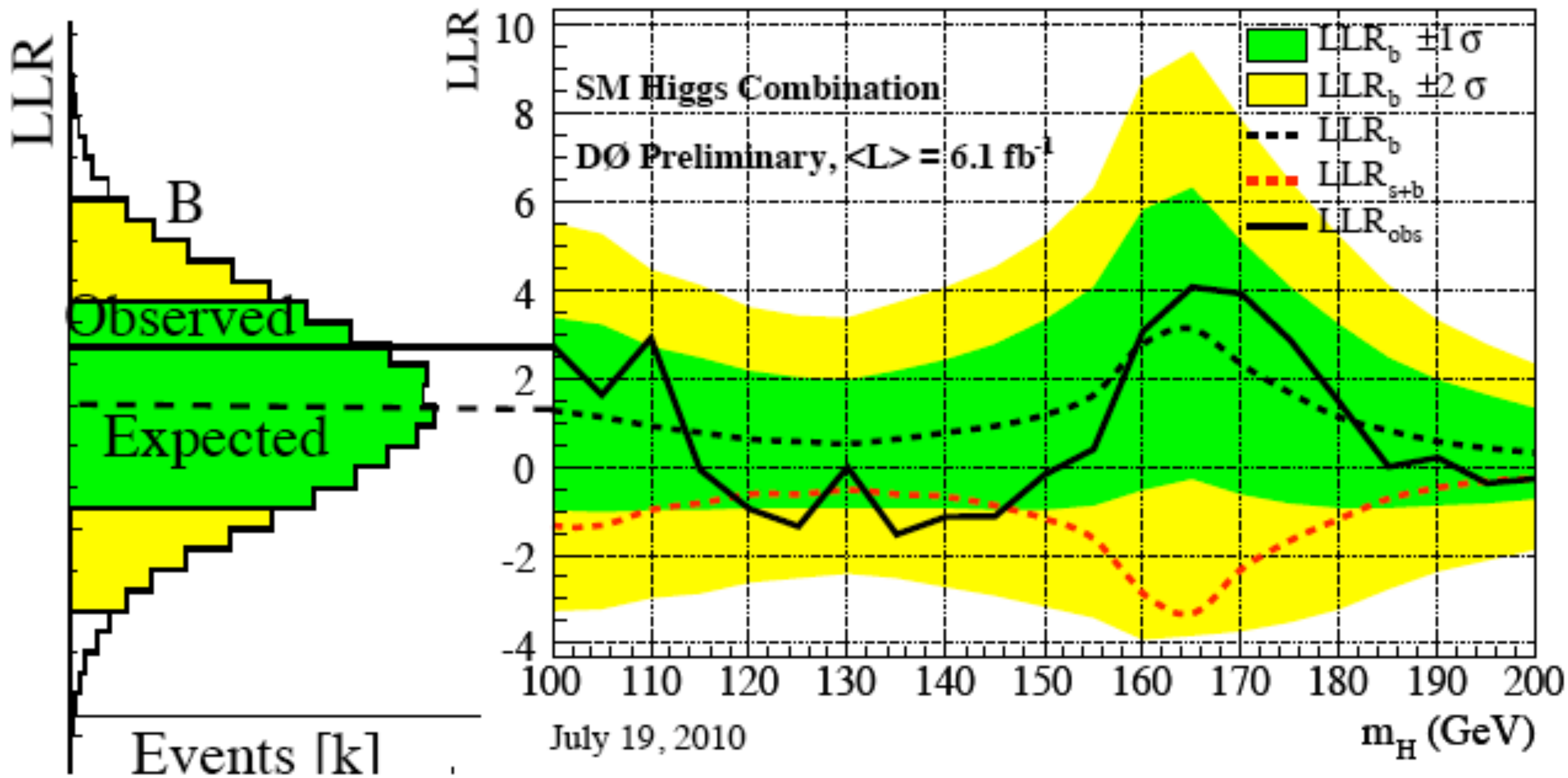
EM/Jet ~ 4



# Tevatron Projection

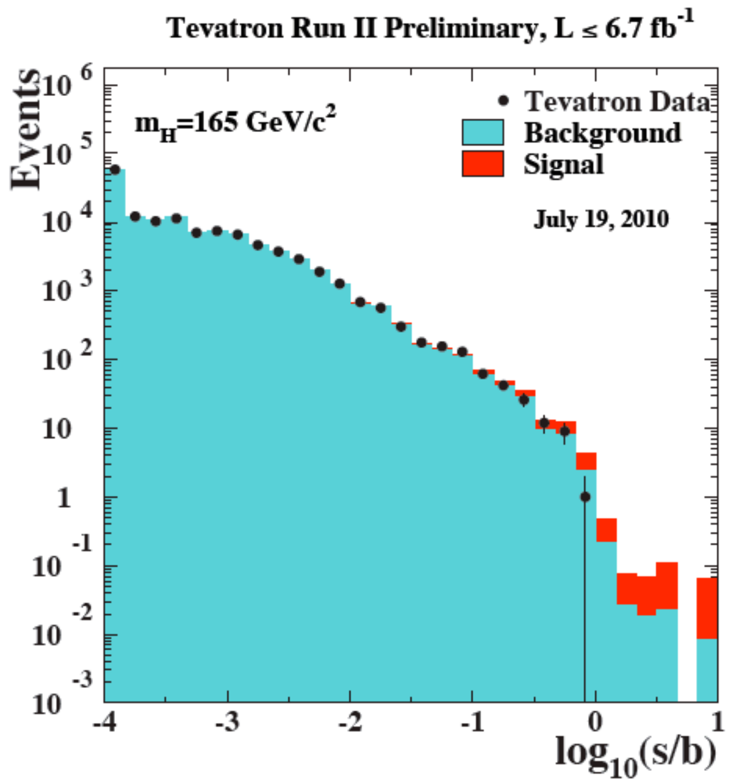


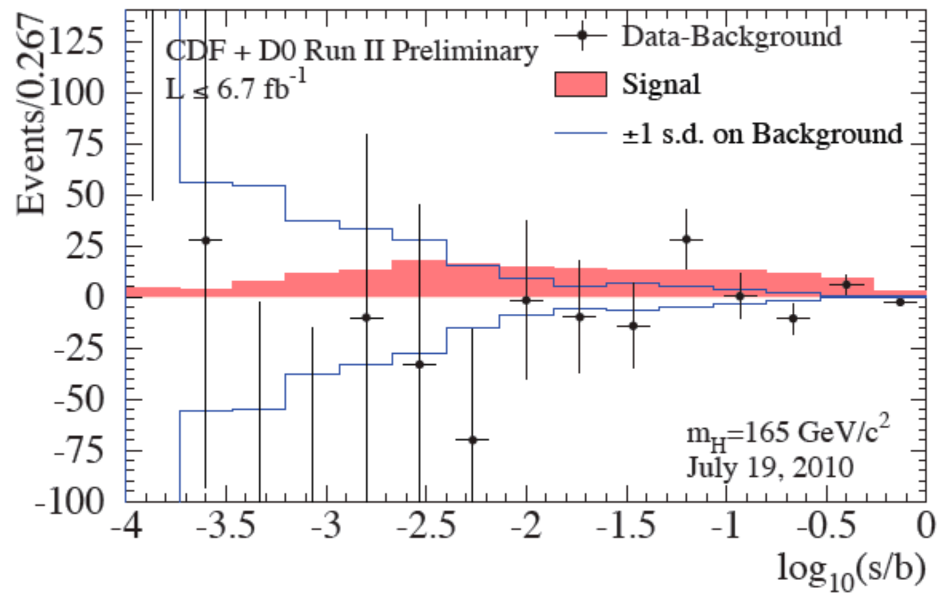
# LLR




- At each mass point, calculate observed LLR, generate pseudo-experiments to calculate expected LLR.

# combined CDF & D0 for $m_H$ = 165 GeV



# Gluon Fusion Production

- Use cross section calculations of de Florian and Grazzini (arXiv:0901.2427v2) to normalize MC
  - Soft-gluon resummation to NNLL
  - Proper treatment of b-quarks to NLO
  - Inclusion of two-loop electroweak effects
  - MSTW2008 Parton Density Functions
  - $\mu_F = \mu_R = m_H$
- In good agreement with calculations of Anastasiou, Boughezal, and Petriello (arXiv:0811.3458v2)
  - $\mu_F = \mu_R = m_H/2$


58

# Cross Section Uncertainties

- Higher-order QCD radiative corrections
  - Independently vary $\mu_F$ and $\mu_R$ between $0.5m_H$ and $2.0m_H$, within the constraint $0.5 < \mu_F/\mu_R < 2.0$
- PDF model
  - Use 40 alternative grids associated with MSTW2008 NNLO PDF to evaluate
- An additional complication at CDF is that cross section uncertainties coming from scale changes are topology dependent (e.g. dependent on number of jets criteria used to define channels) Anastasiou et al., arXiv:0905.3529v2


59