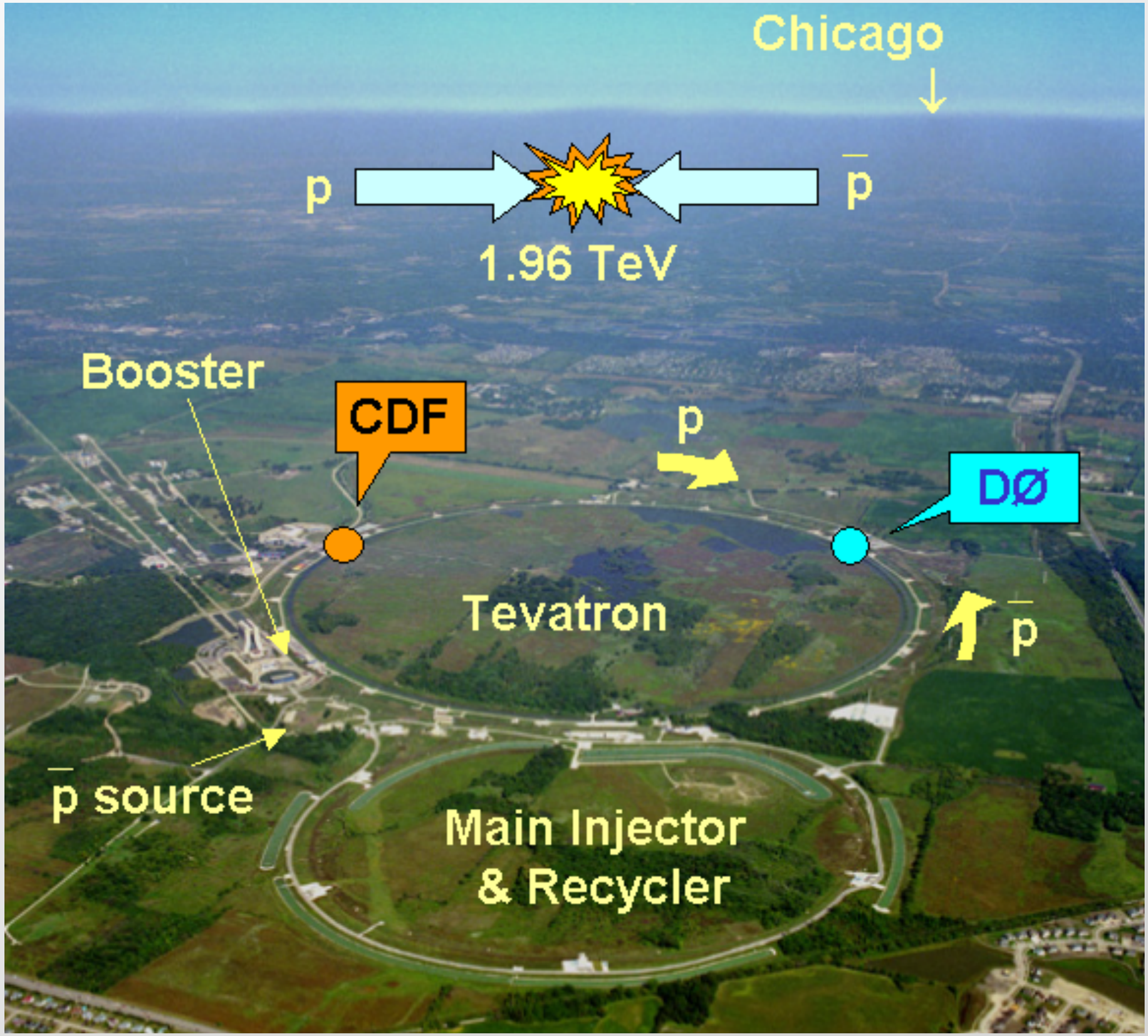

Richard E. Hughes
The Ohio State University
for
The CDF and DO Collaborations

# Low Mass SM Higgs Search at the Tevatron

# Tevatron and Experiments



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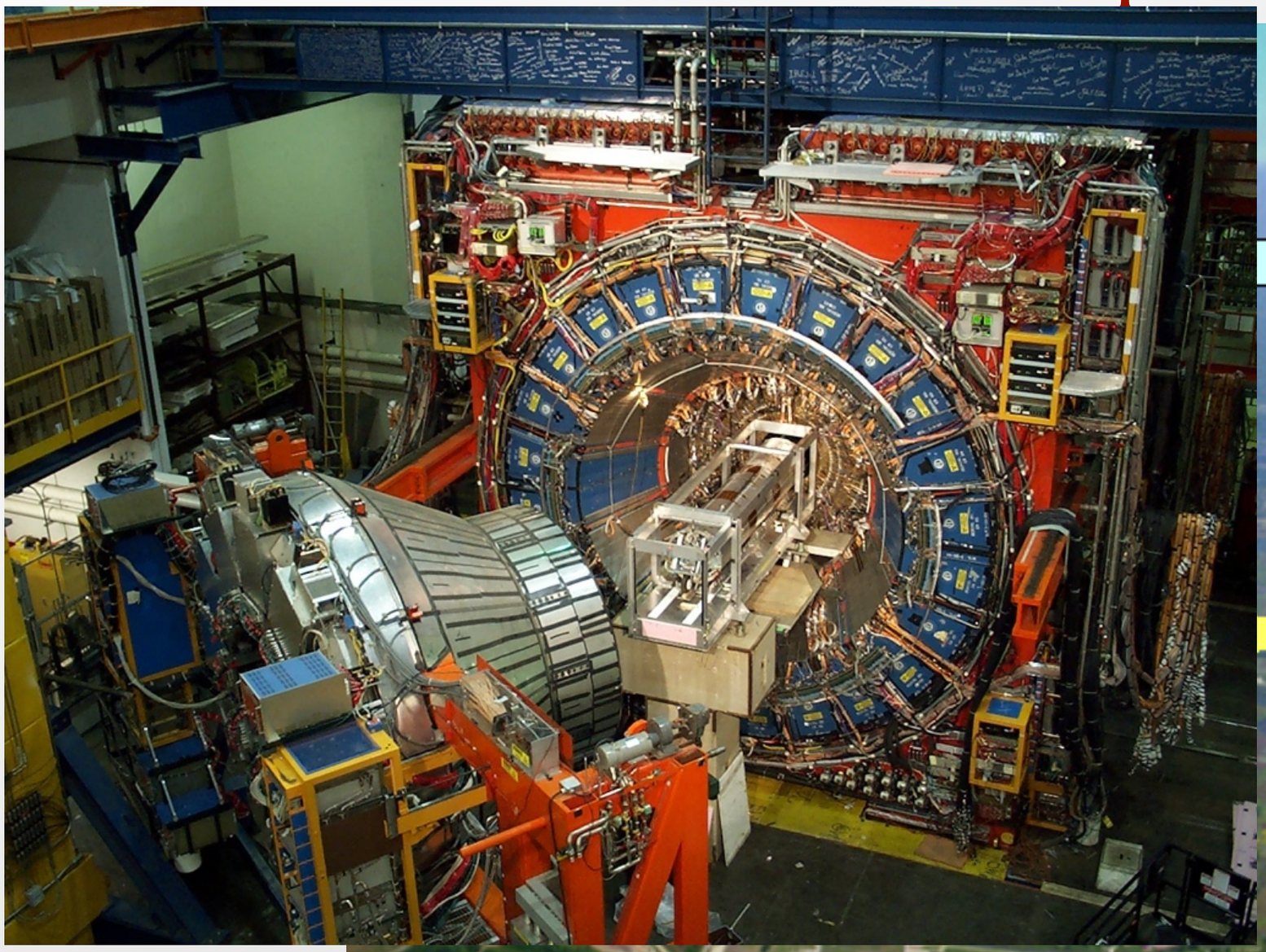

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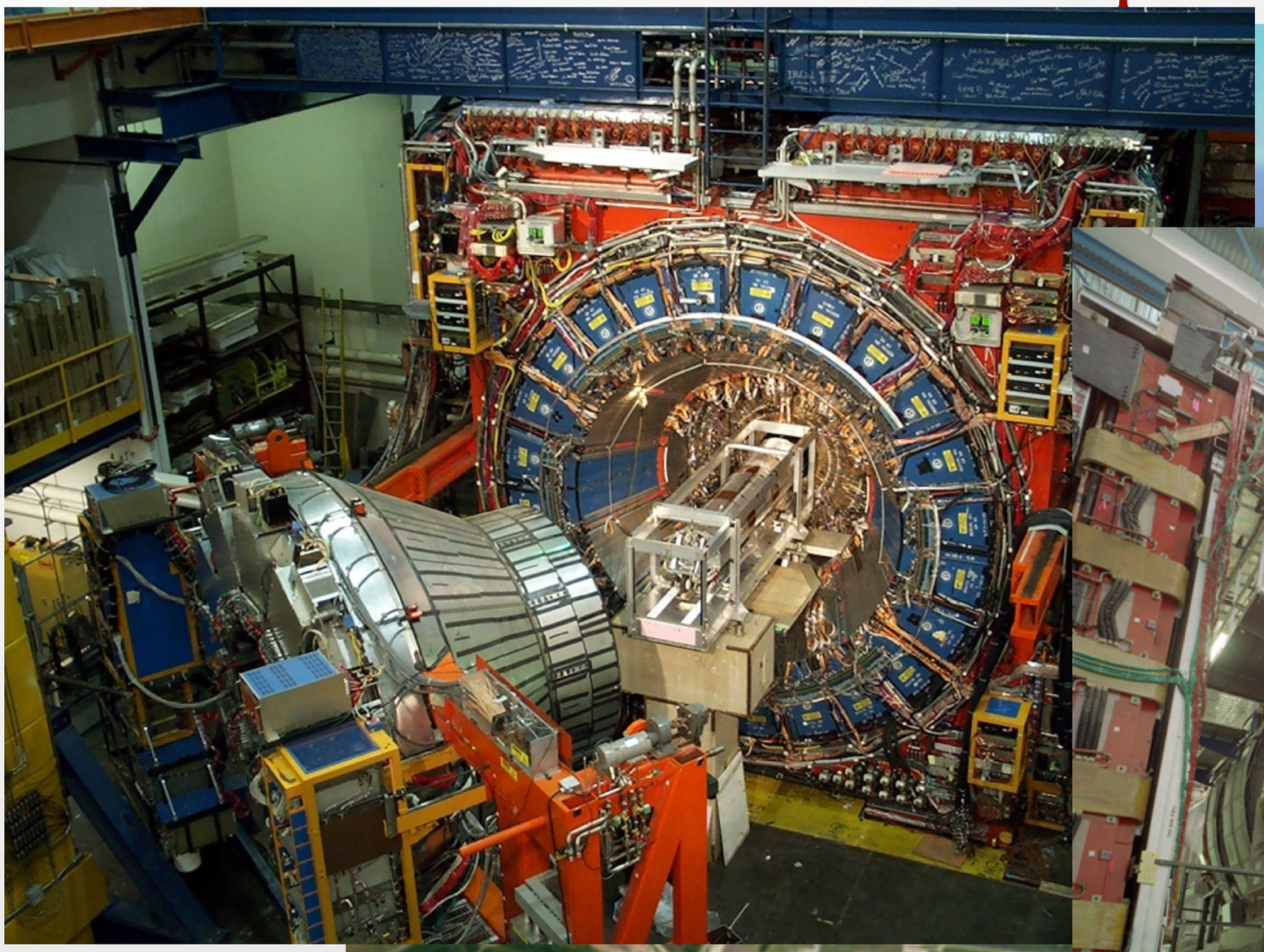

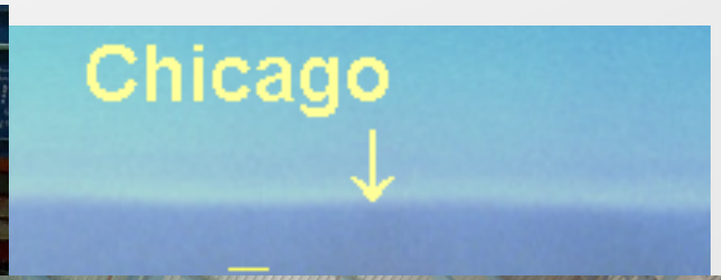


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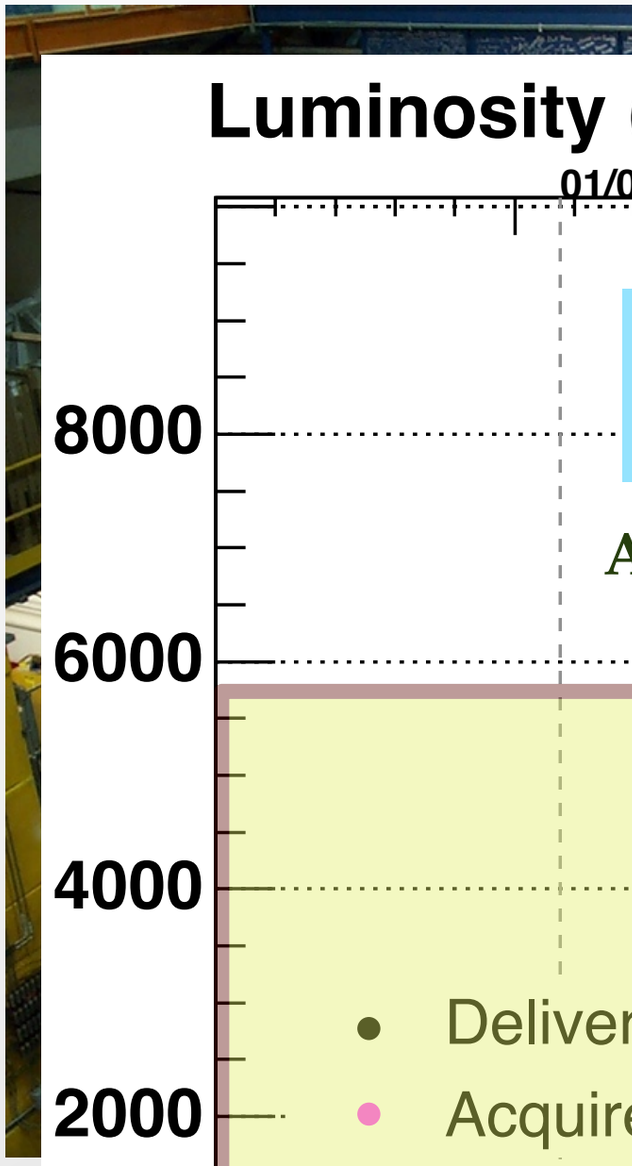
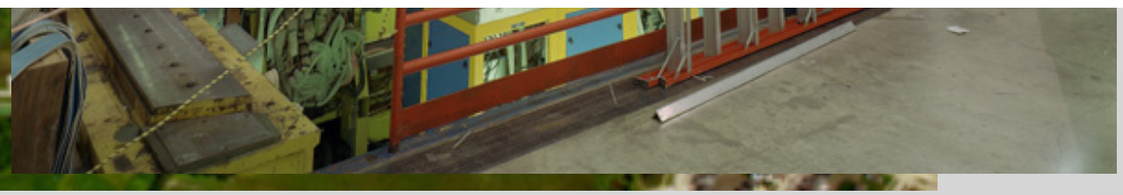




# *Constraints on the SM Higgs Boson*

**What we know:**

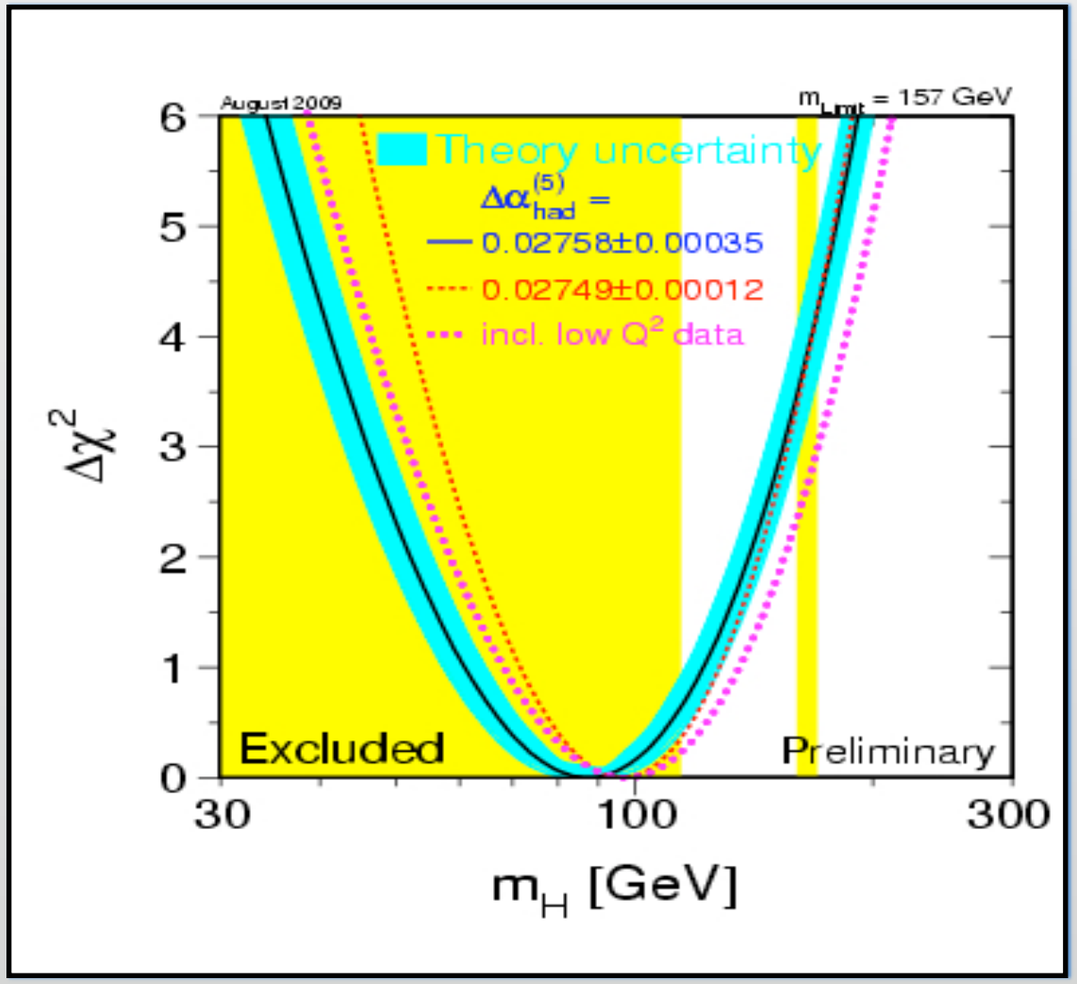
- **Direct search at LEPII:**

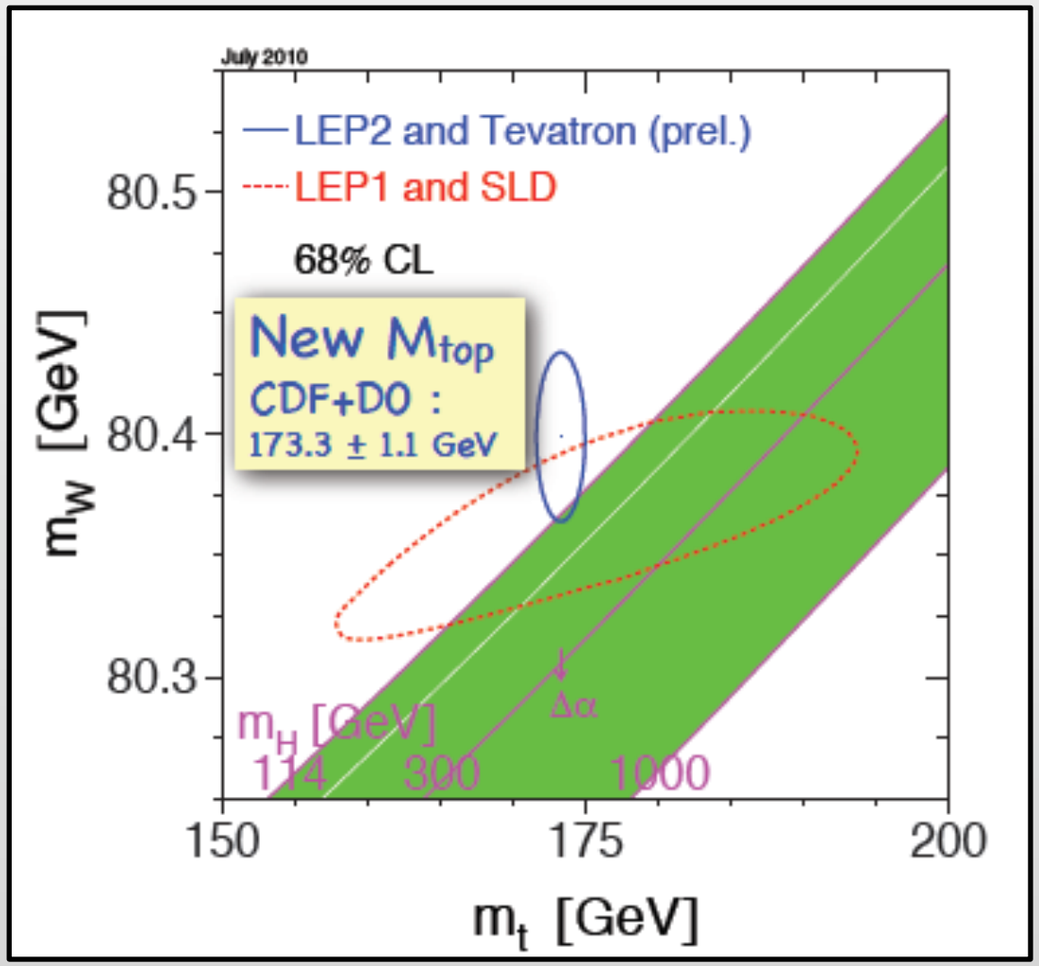
  **Mh > 114 GeV/c2 @95% CL**

- **Precision EWK meaurements (top mass, W mass, etc):**

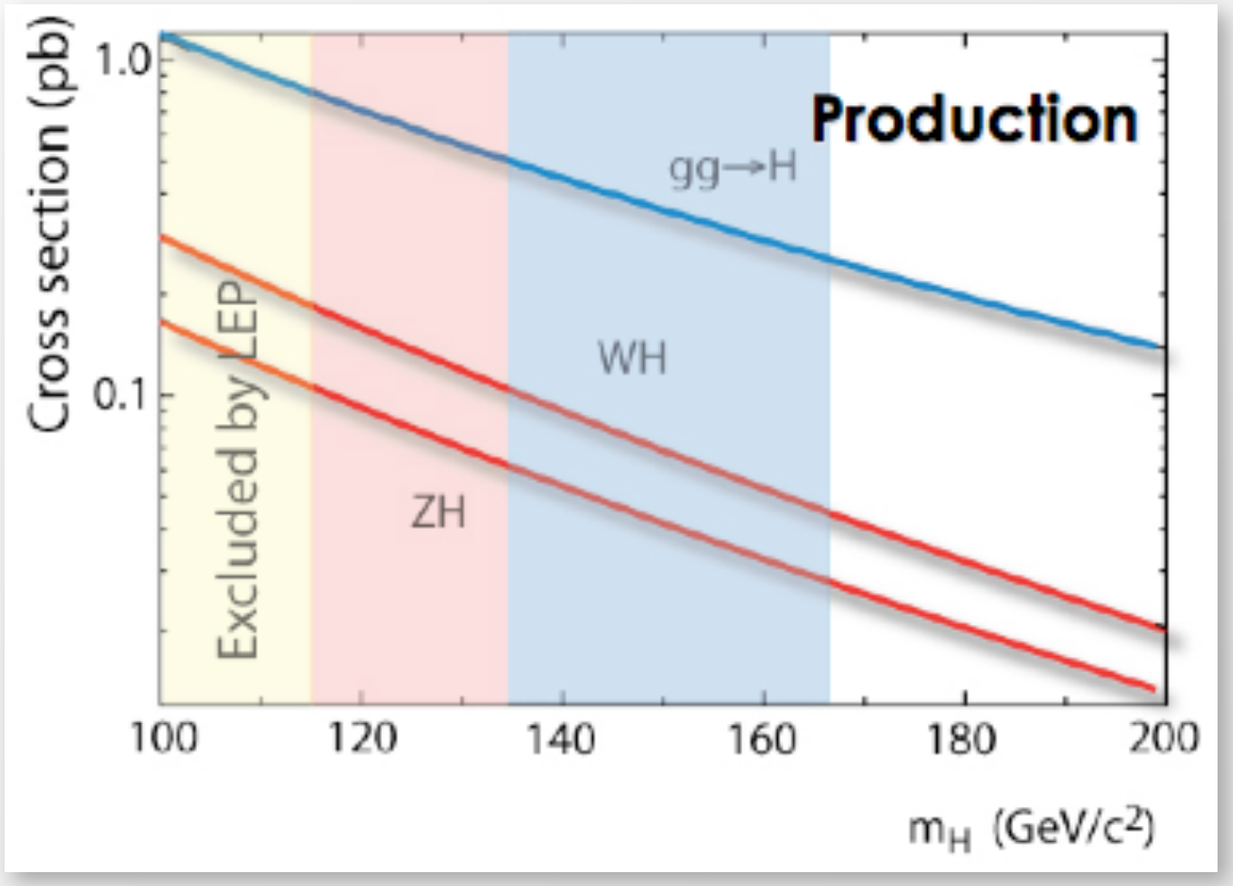
  **$M_h = 89.0^{+35}_{-26}$ GeV/$c^2$**

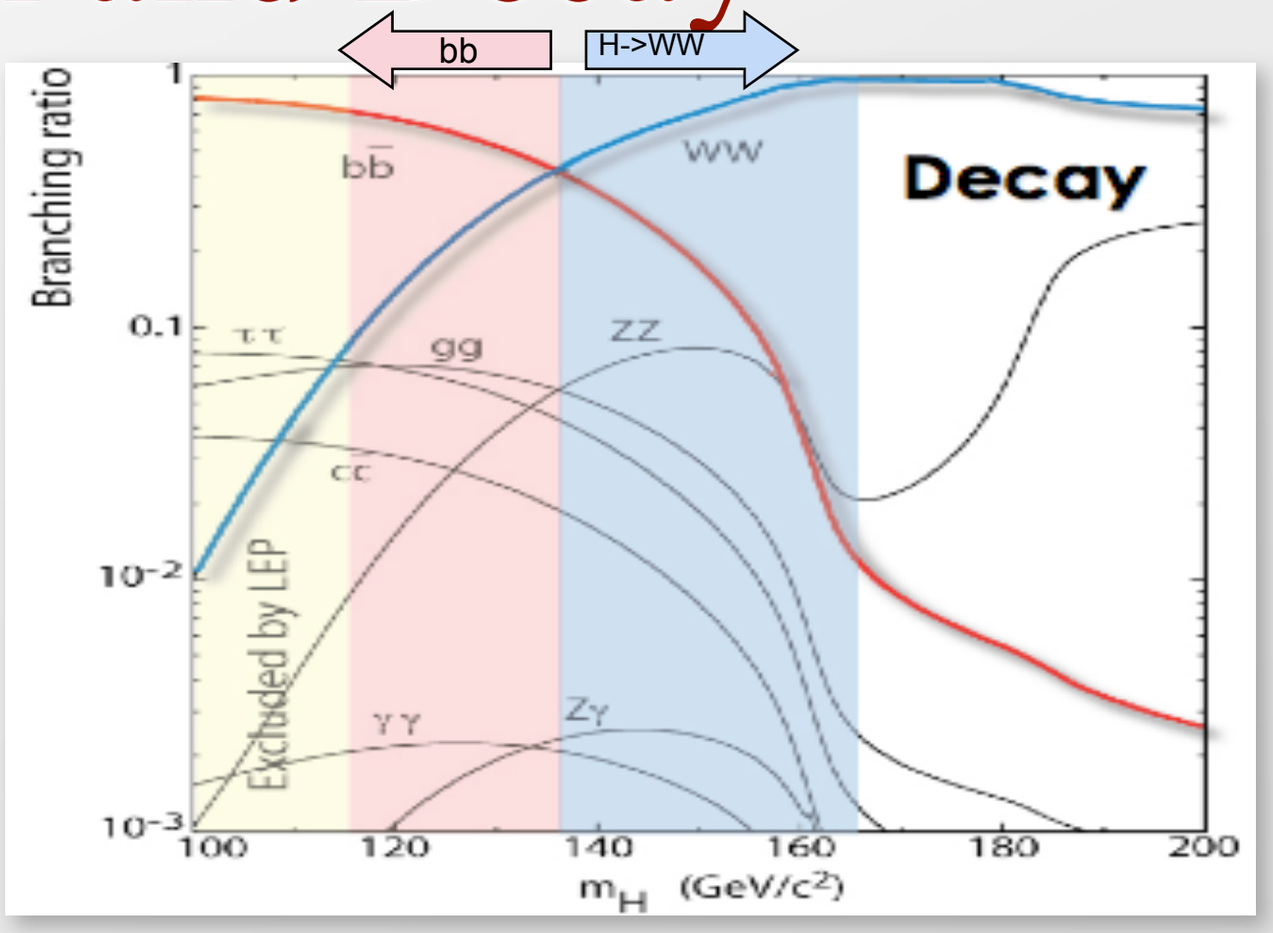
  **$M_h < 158$ GeV/$c^2$ @95% CL**



# Production and Decay




## Low Mass Final States

$$WH \to \ell\nu b\bar{b}$$
$$ZH \to \ell\ell b\bar{b}$$

$$ZH \to \nu\nu b\bar{b}$$
$$WH \to (\ell)\nu b\bar{b}$$

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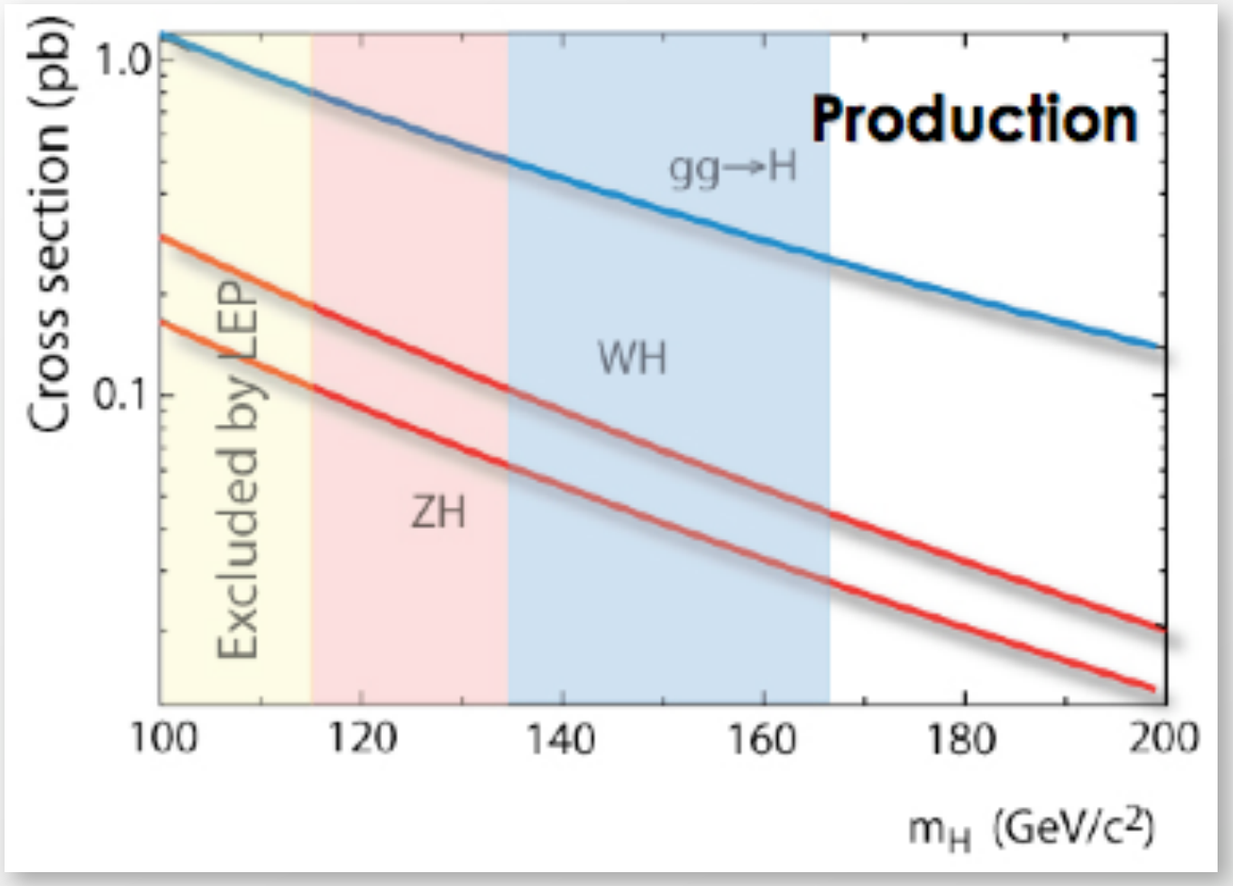


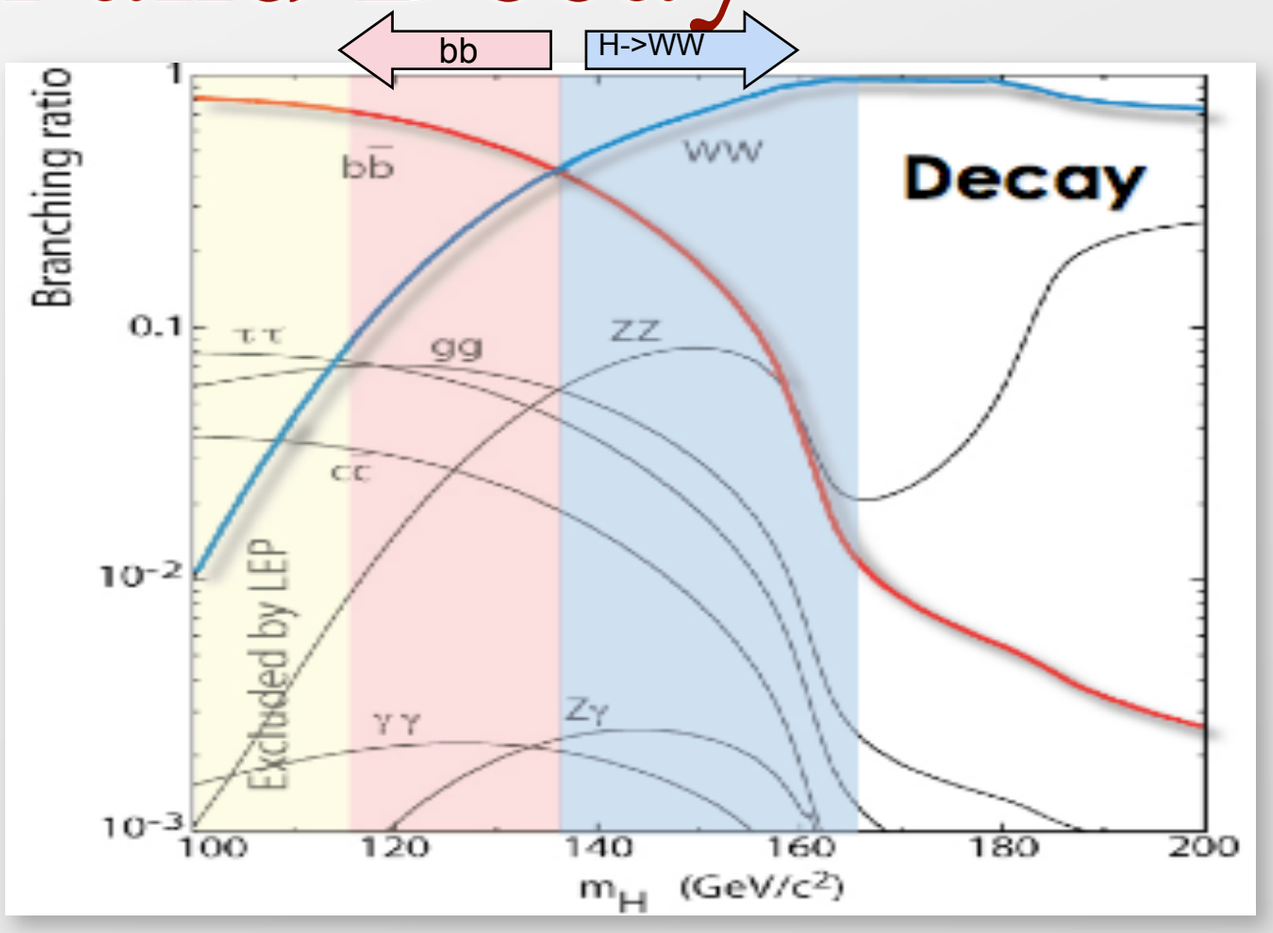


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→ 1 High $P_T$ Lepton + $\not{E}_T$ + b jets

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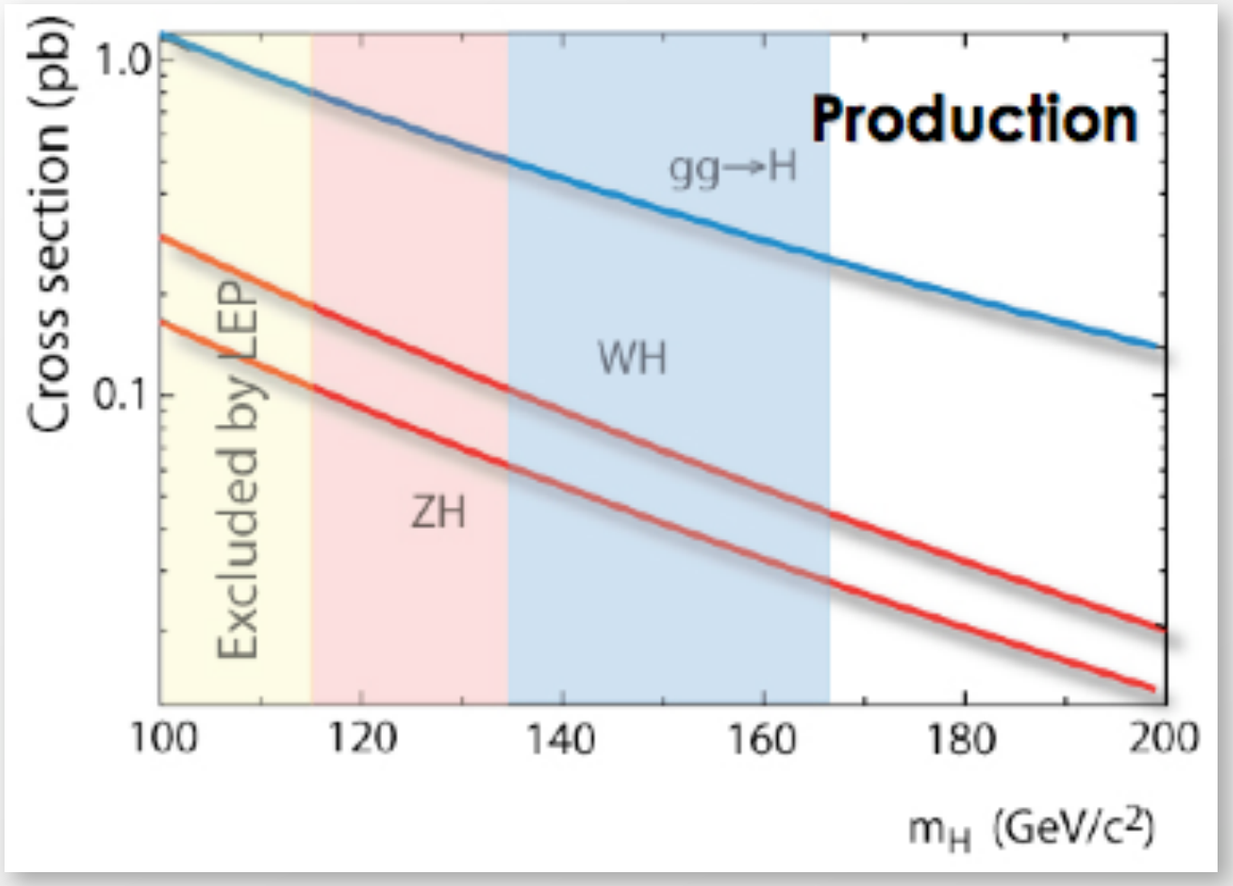


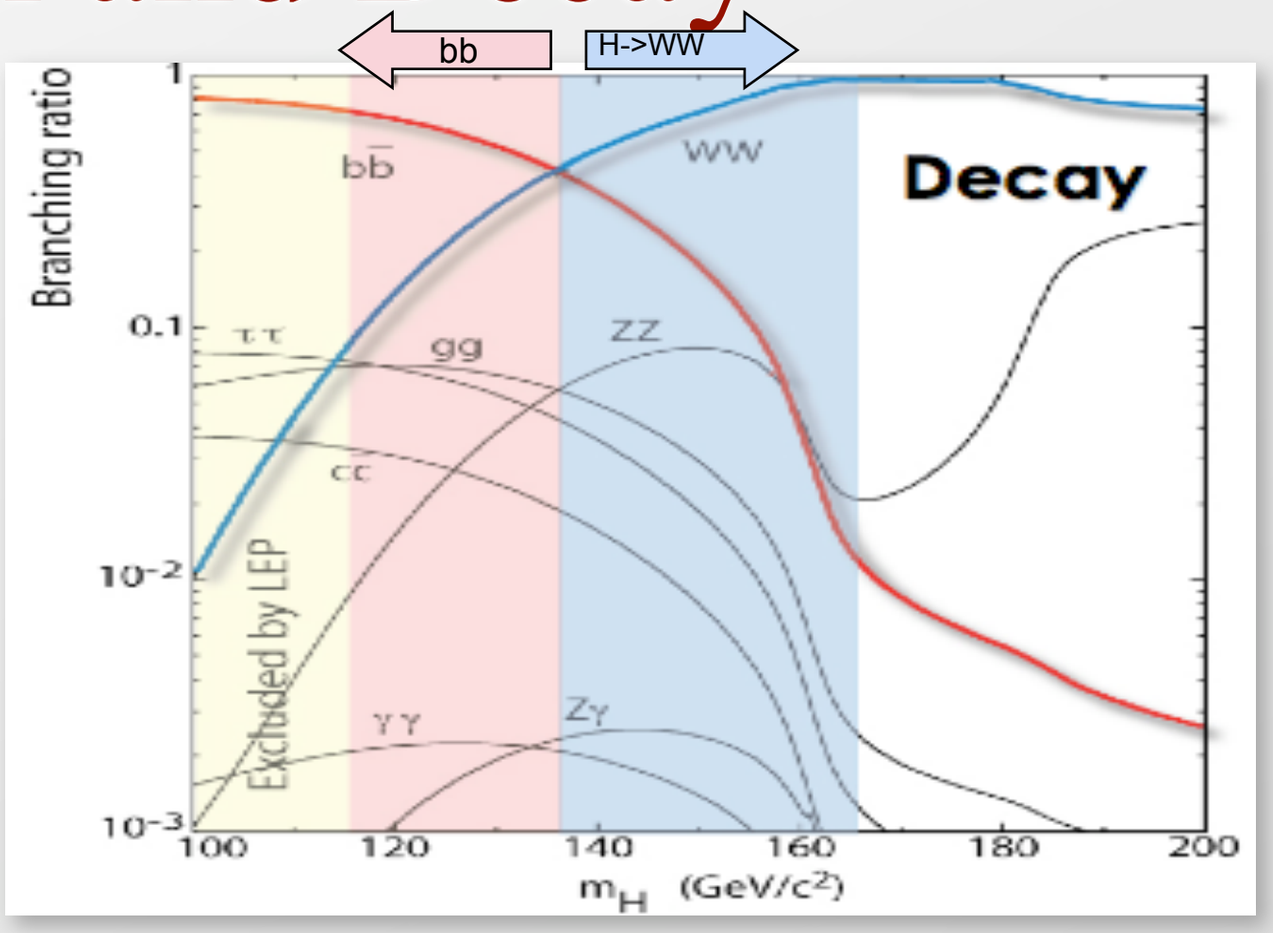


## Low Mass Final States

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$ZH \to \ell\ell b\bar{b}$ → 2 High $P_T$ Leptons + b jets

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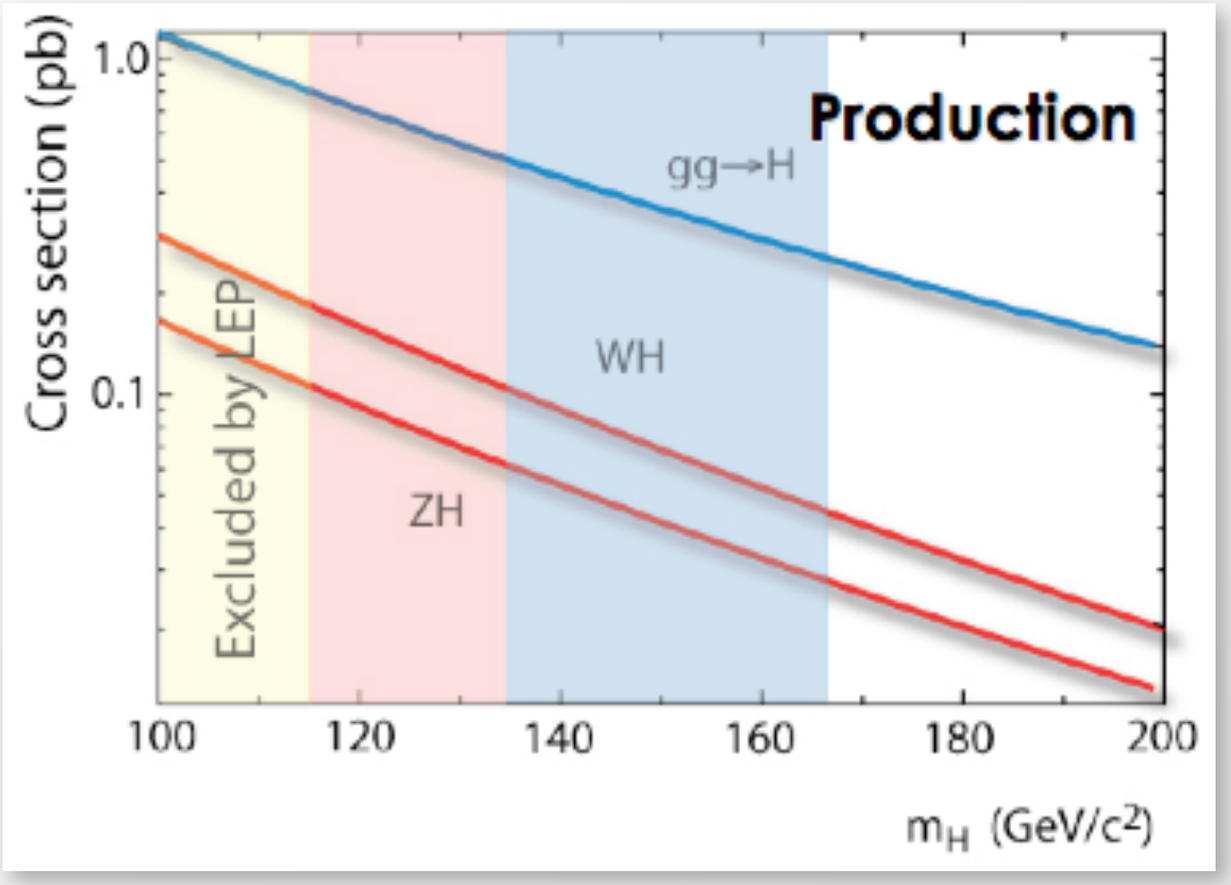
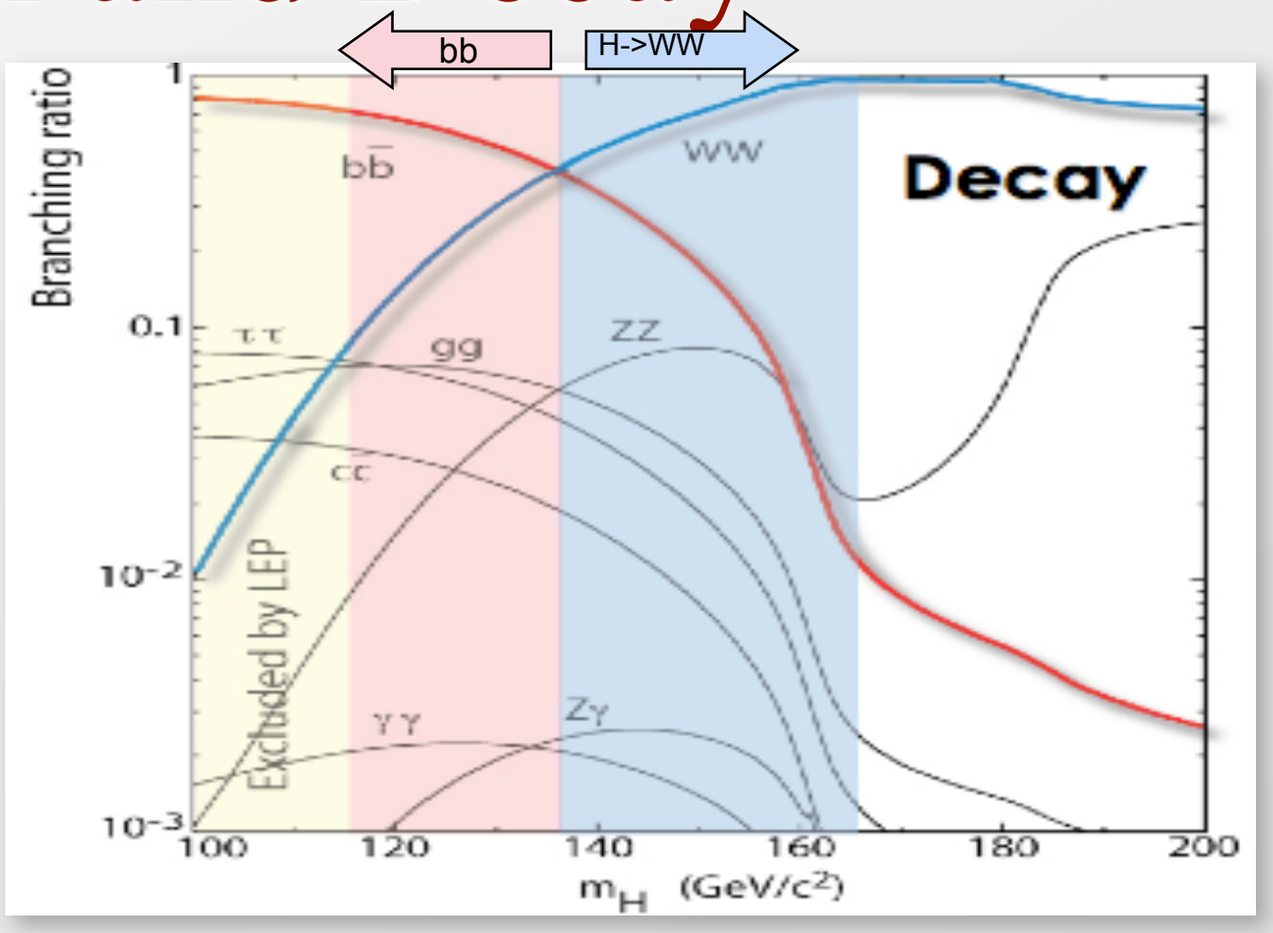
# Production and Decay




## Low Mass Final States

$WH \to \ell\nu b\bar{b}$ → 1 High $P_T$ Lepton + $\not{E}_T$ + b jets

$ZH \to \ell\ell b\bar{b}$ → 2 High $P_T$ Leptons + b jets

$ZH \to \nu\nu b\bar{b}$

$WH \to (\ell)\nu b\bar{b}$

→ 0 High $P_T$ Leptons + $\not{E}_T$ + b jets

# Events produced per Experiment in $1fb^{-1}$

Requires approximately 6 months to acquire

Events

70
60
50
40
30
20
10
0

Total

$H \rightarrow WW \rightarrow l\nu l\nu$

$WH \rightarrow l\nu bb$

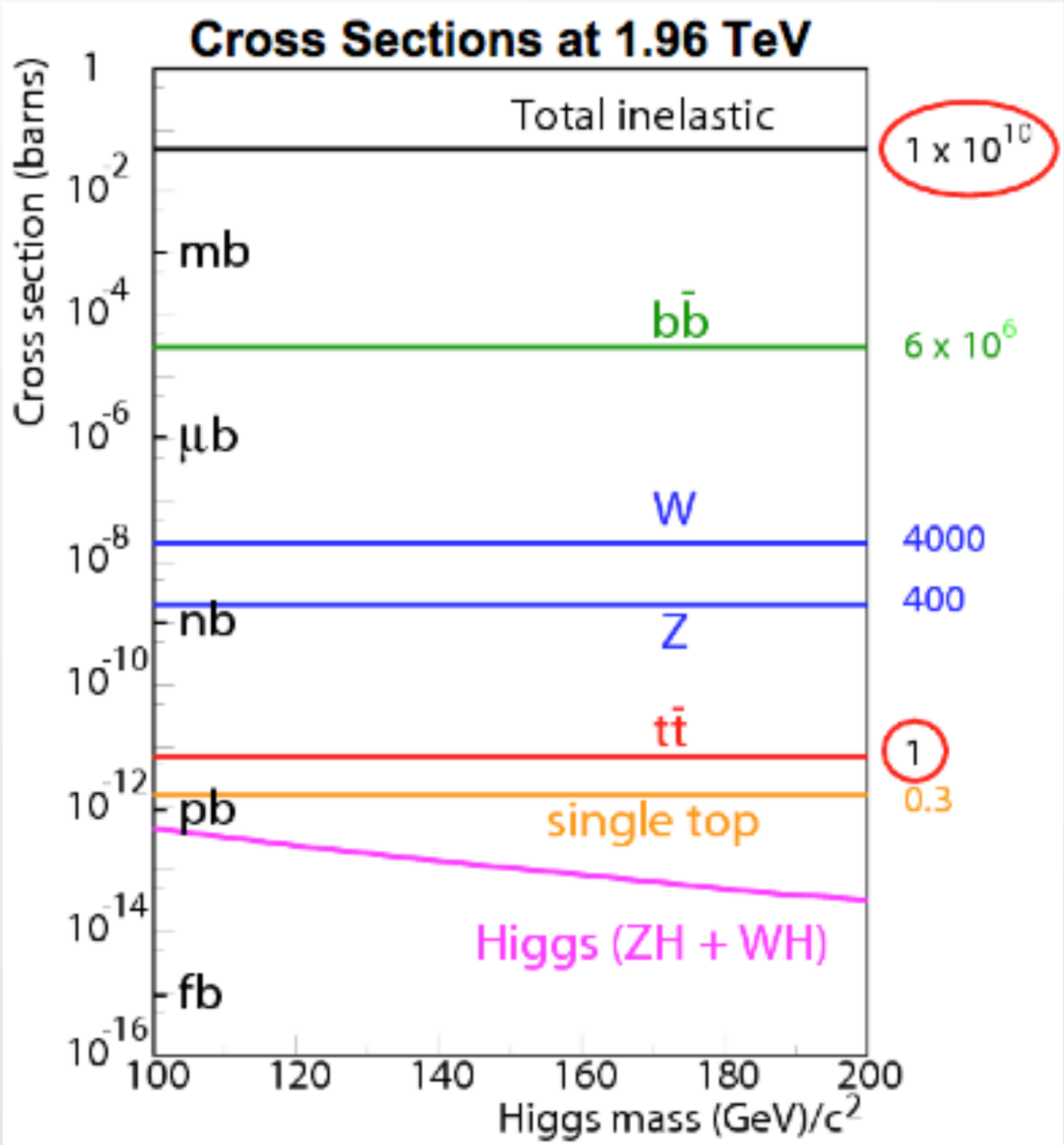
$ZH \rightarrow \nu\nu bb$

$ZH \rightarrow llbb$

110 120 130 140 150 160 170 180

Higgs mass (GeV)

# The Challenge...




- Higgs Production is a low rate process at the Tevatron.
- Backgrounds are many orders of magnitude larger.
- Challenge: Separate Signal from Background

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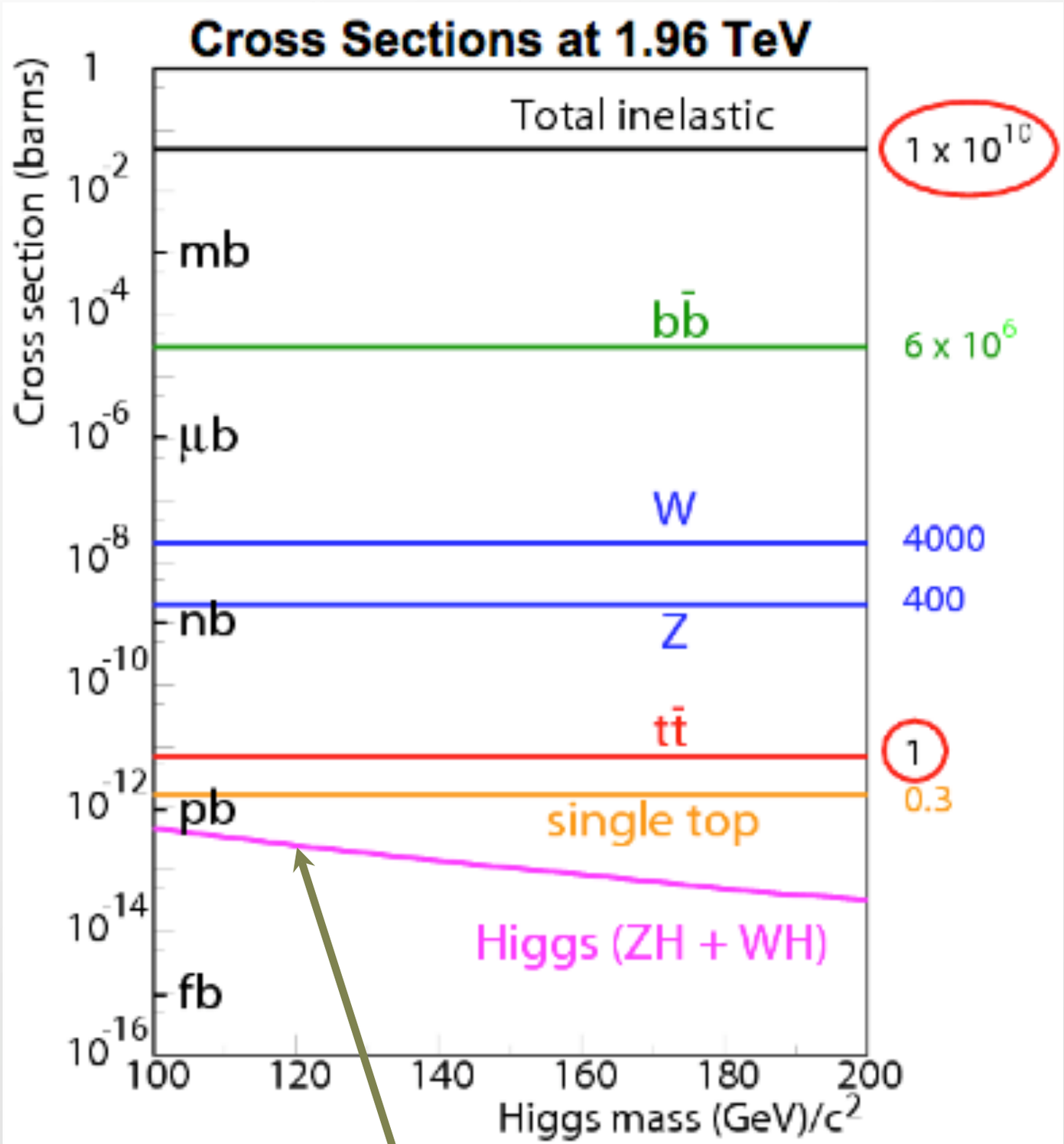


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Before Anything
S:B ~ $1:10^{11}$

# The Strategy

**Attack at every opportunity!**

**1) Maximize acceptance**

**"Tight"cuts on final state objects (leptons,jets, etc.) are too costly - valuable signal efficiency is available at the cost of additional hard work! Includes triggers as well.**

**2) Minimize backgrounds**

- **Often a good model of the backgrounds are needed to do this - some may come from the data itself**

**3) Maximize measurement resolution**

- **Improvements in jet energy resolution directly impact acceptance, backgrounds, and many other aspects of the analyses**

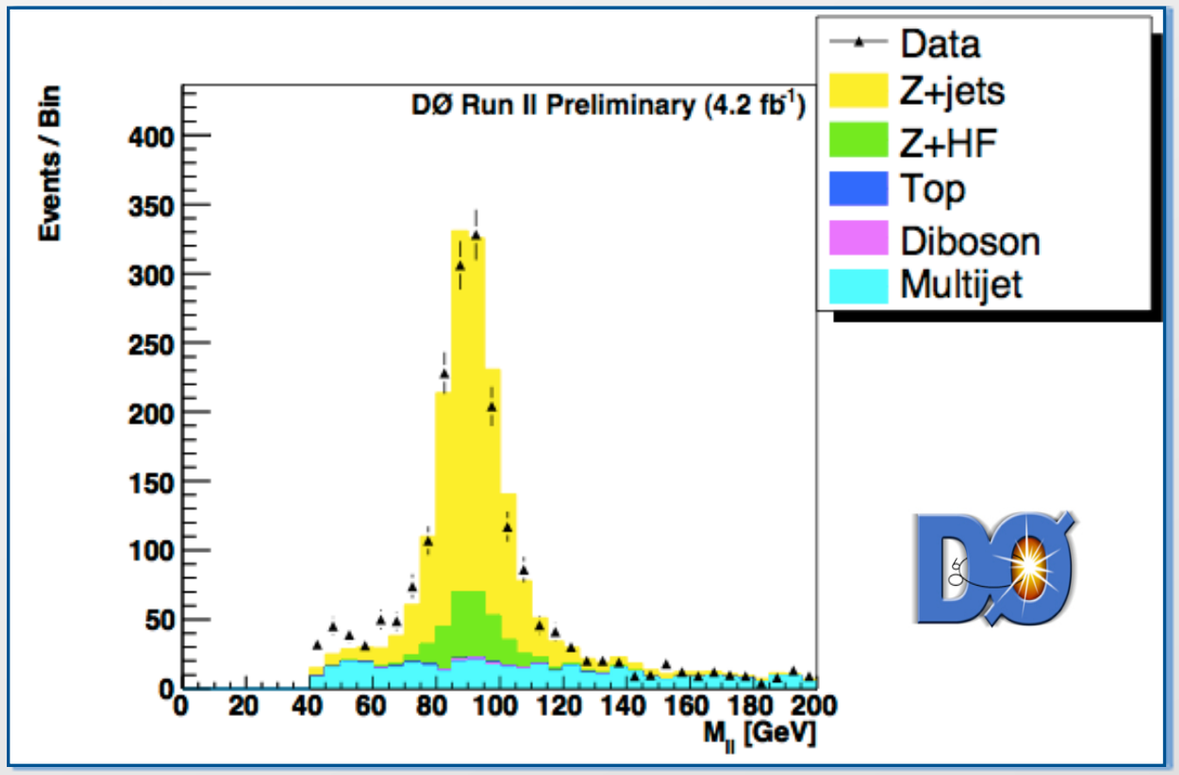
**4) Extract the most from the resulting events**

- **Use advanced algorithms like decision tree, neural networks, matrix elements, etc**

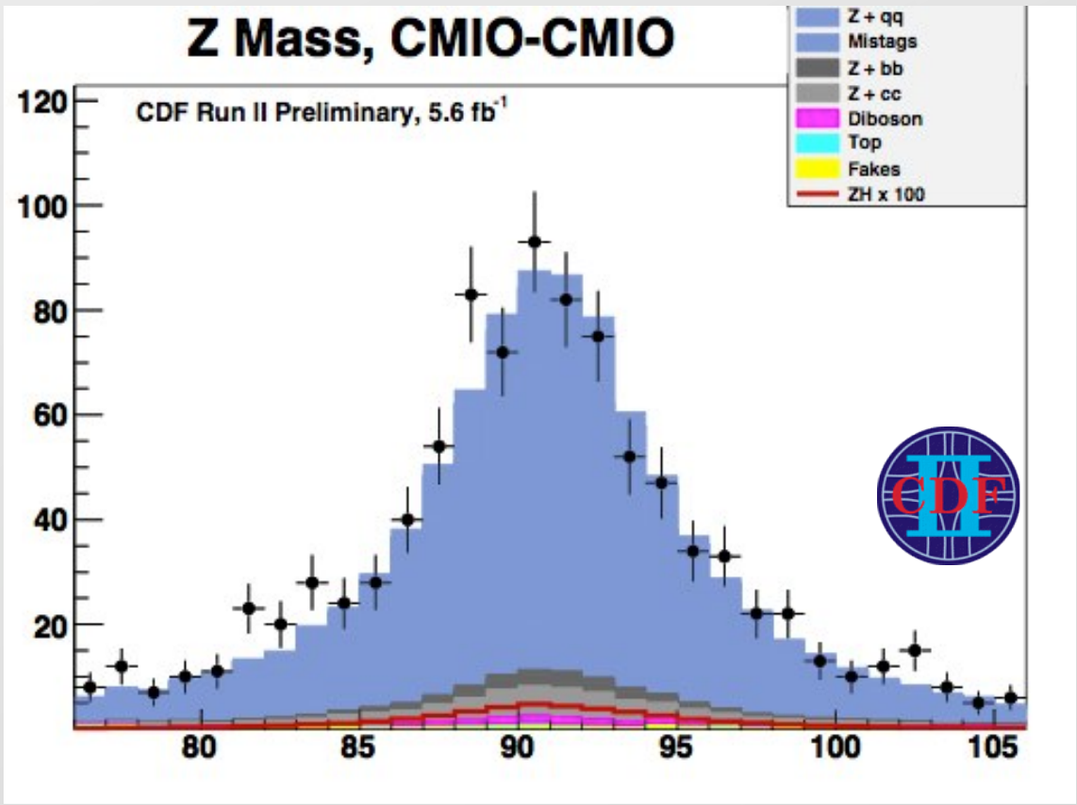
# Maximizing Acceptance

Example: $ZH \rightarrow \ell\ell b\bar{b}$

**Reconstruct Z candidate using a μ and an isolated track**




**Reconstruct Z candidate using two loose muons AND non-muon trigger!**



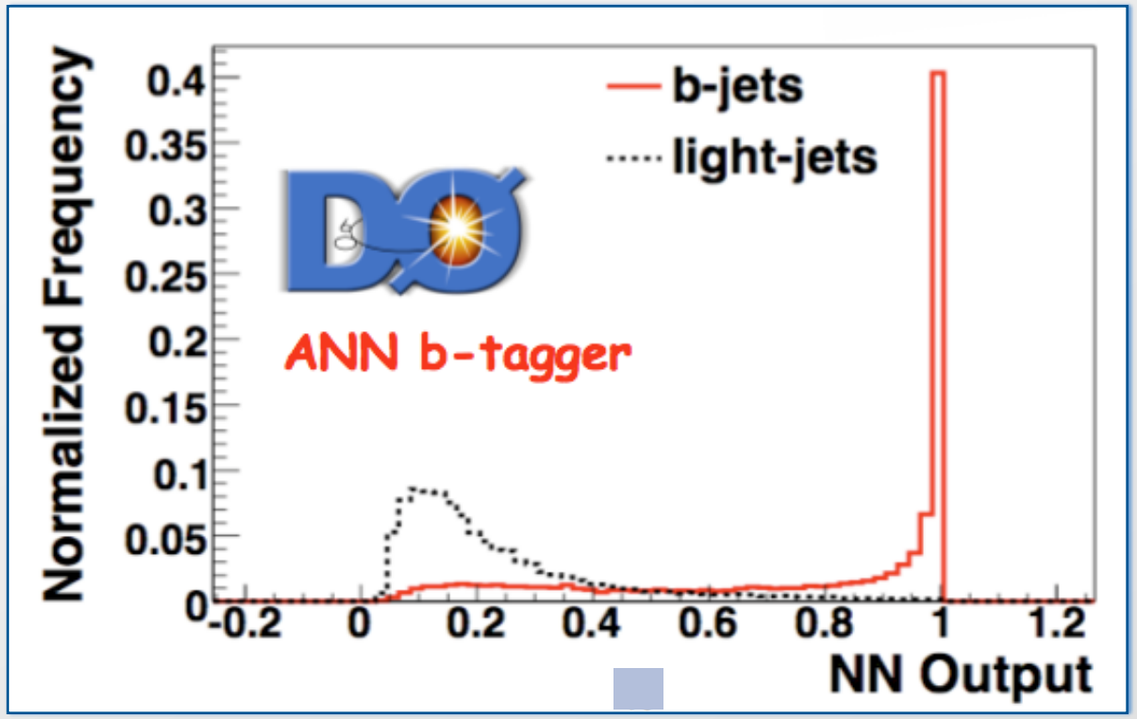

**Typical gain from increased lepton ID ~15%**

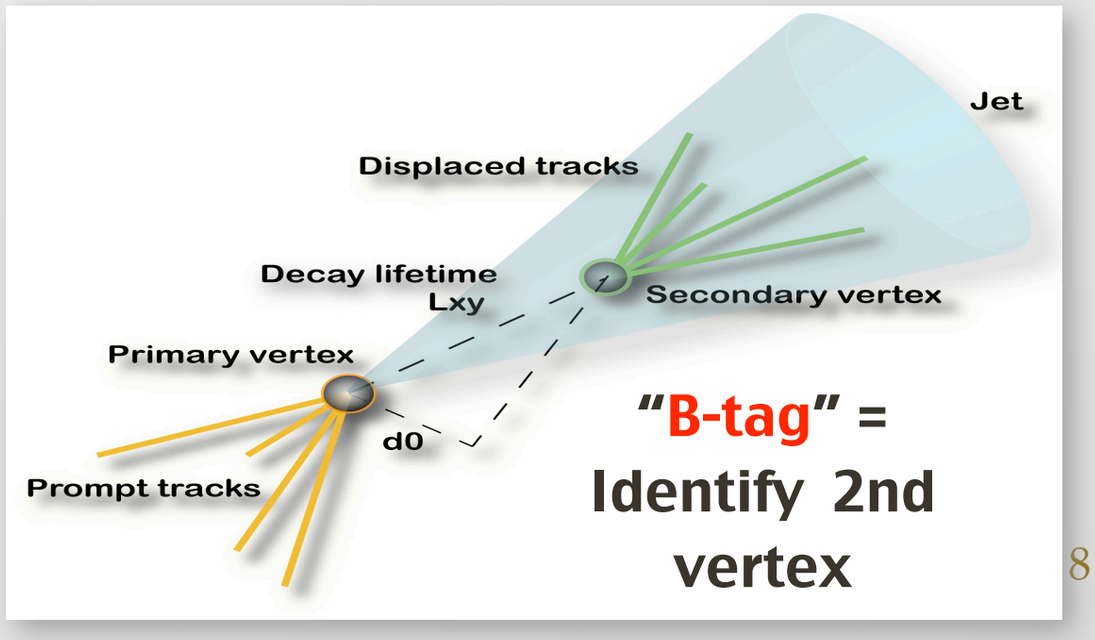
**See Justin Pilot's talk this afternoon**

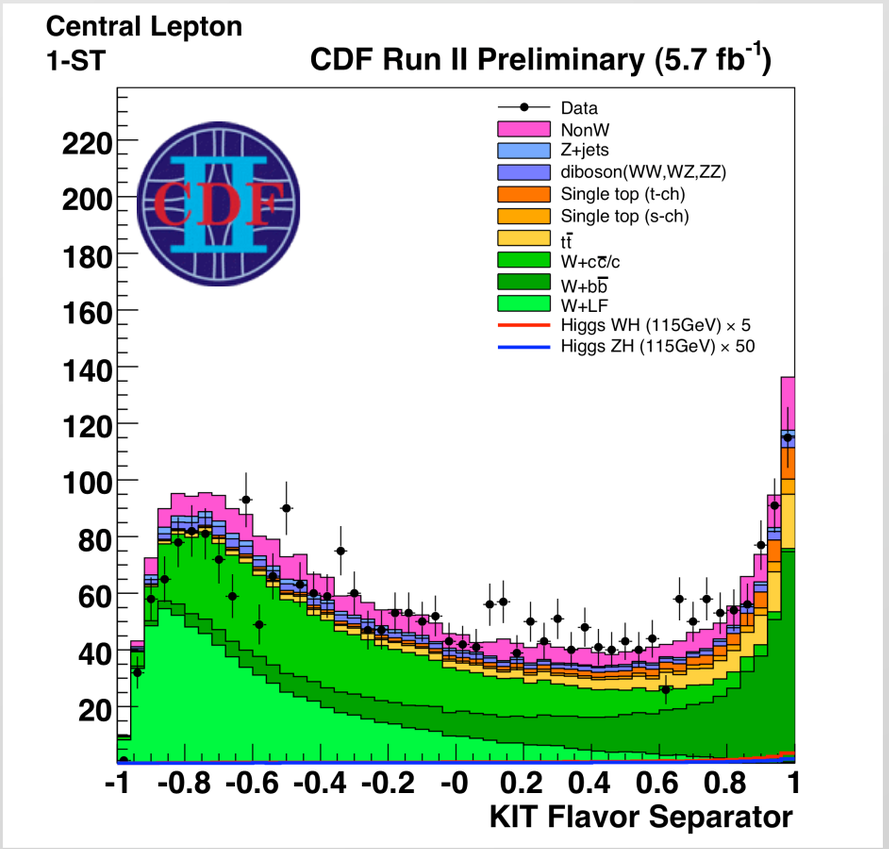
# Identification of B-jets

Btagging

- ~50-70%efficient
- Dependent on $E_T$ and η of jet.
- Mistag rates typically ~0.3 - 6.0%
- Loose tagging helpful in double tag situations
- D0 uses NN tagger based on 7 discriminating B-lifetime variables
- CDF uses a variety of secondary vertexing algorithms
  - ➡ New: a neural network Flavor Separator

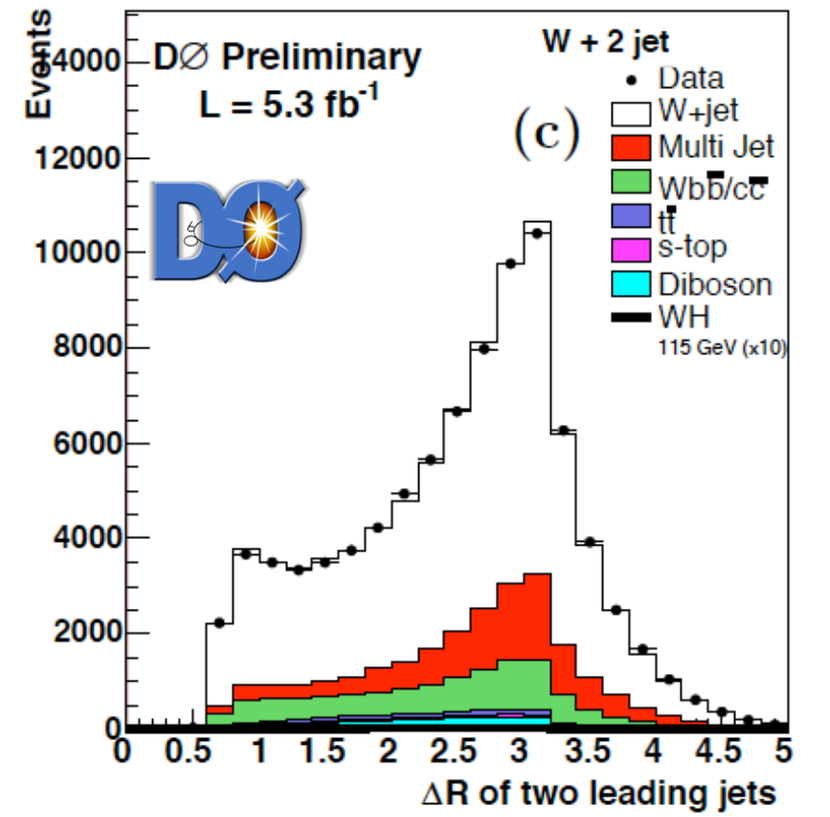


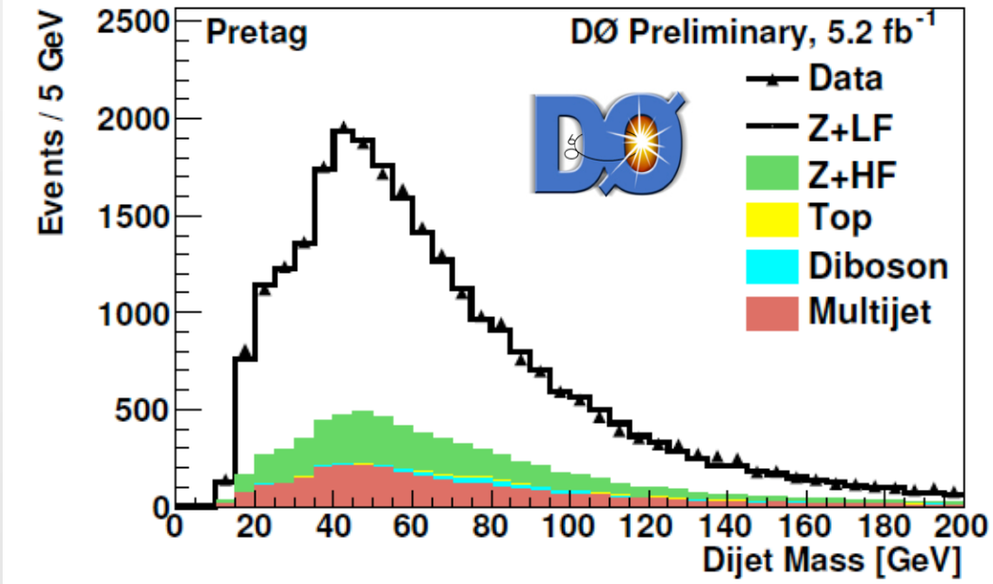



# Modeling of Backgrounds

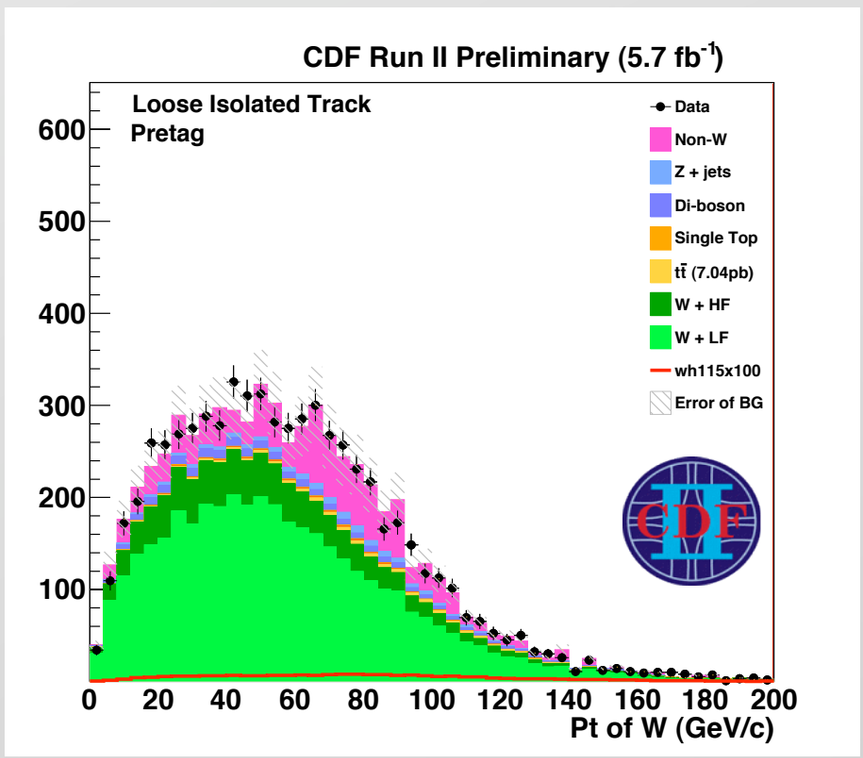
## Pre-tag W+jets




## Pre-tag Z+jets



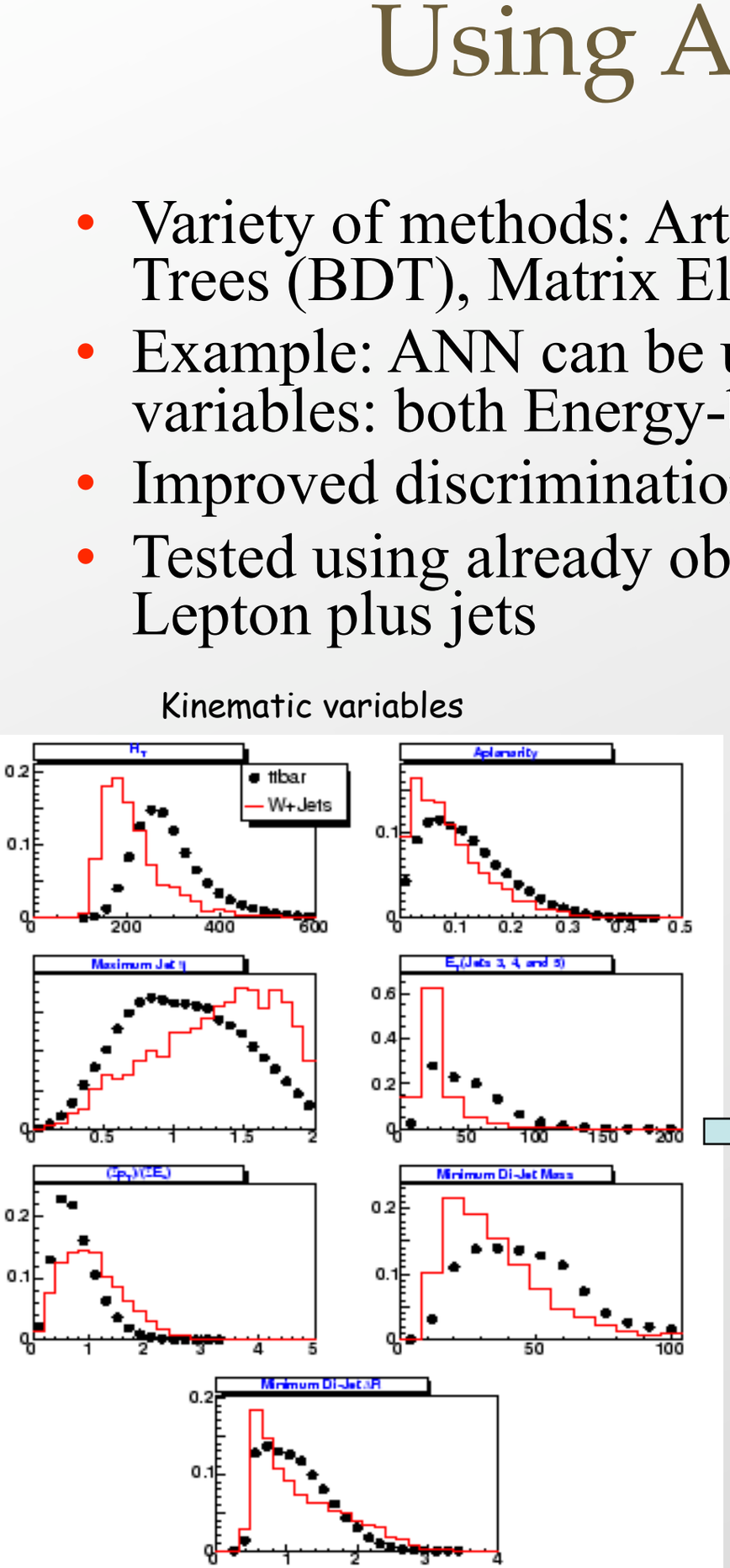

## Pre-tag W+jets loose isolated tracks (mostly electrons)



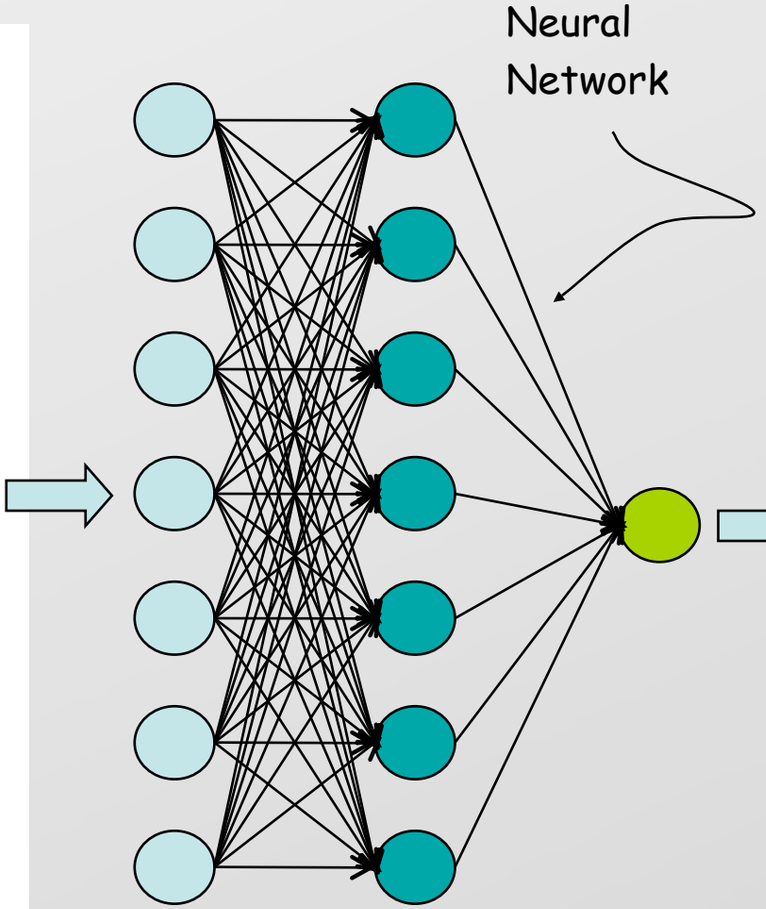
# Using Advanced Algorithms

- Variety of methods: Artificial Neural Networks (ANN), Boosted Decision Trees (BDT), Matrix Element (ME)
- Example: ANN can be used to combine information from different kinematic variables: both Energy-based and Shape-based
- Improved discrimination and less sensitive to systematic effects
- Tested using already observed physics processes: identification of top in Lepton plus jets

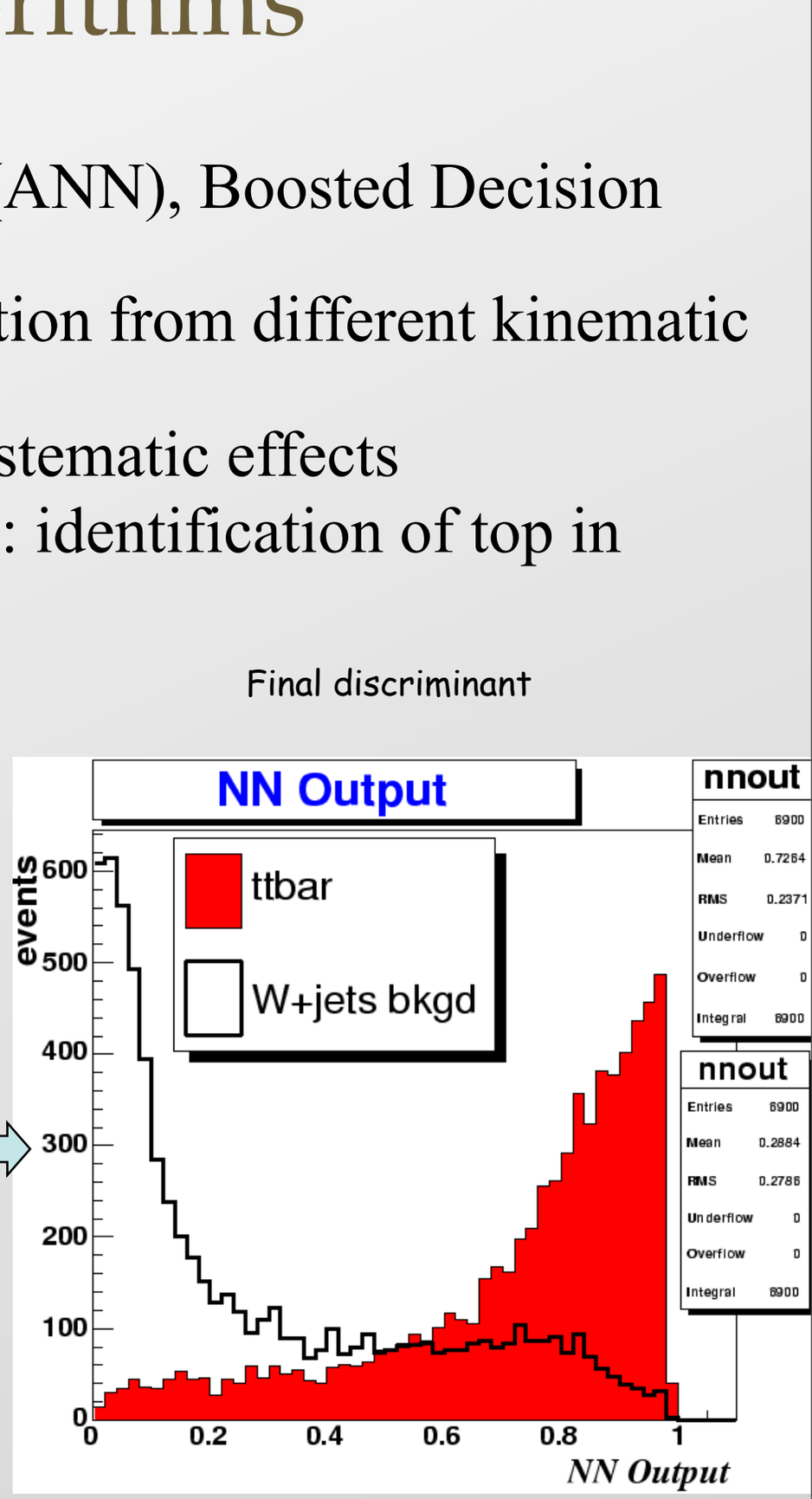
Kinematic variables




Neural Network



Final discriminant




**6.80 ± 0.38 (stat) ± 0.61 (syst) ± 0.39 (lumi) pb**

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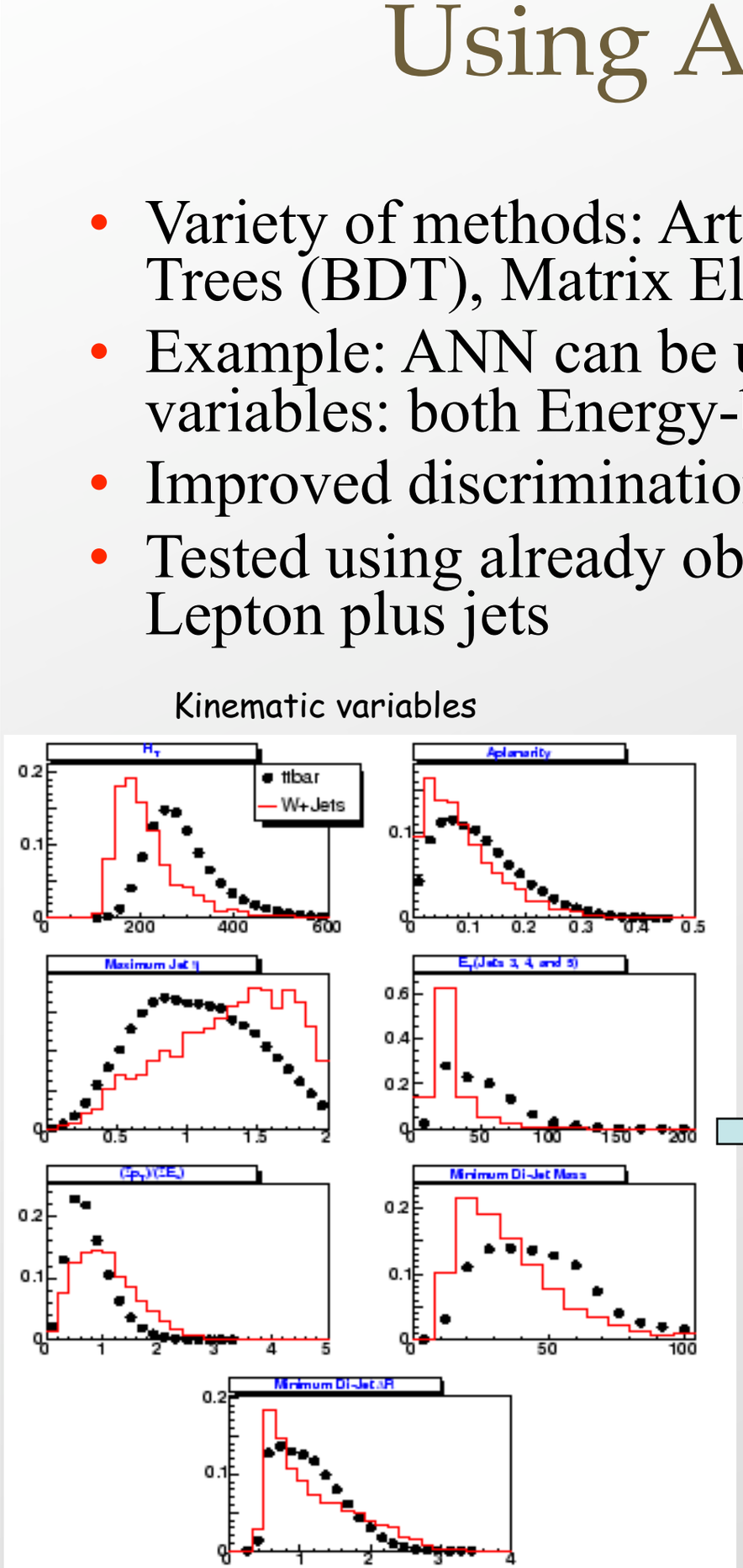
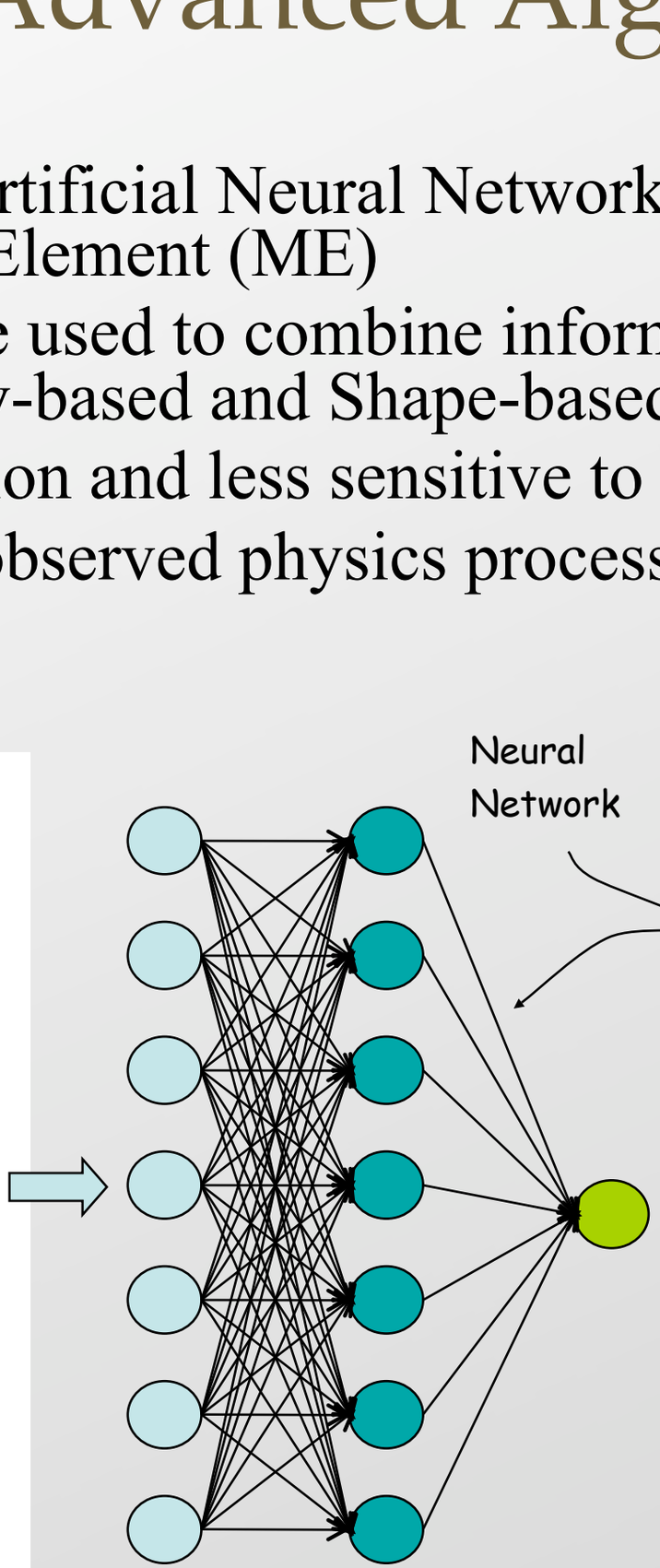



Neural Network



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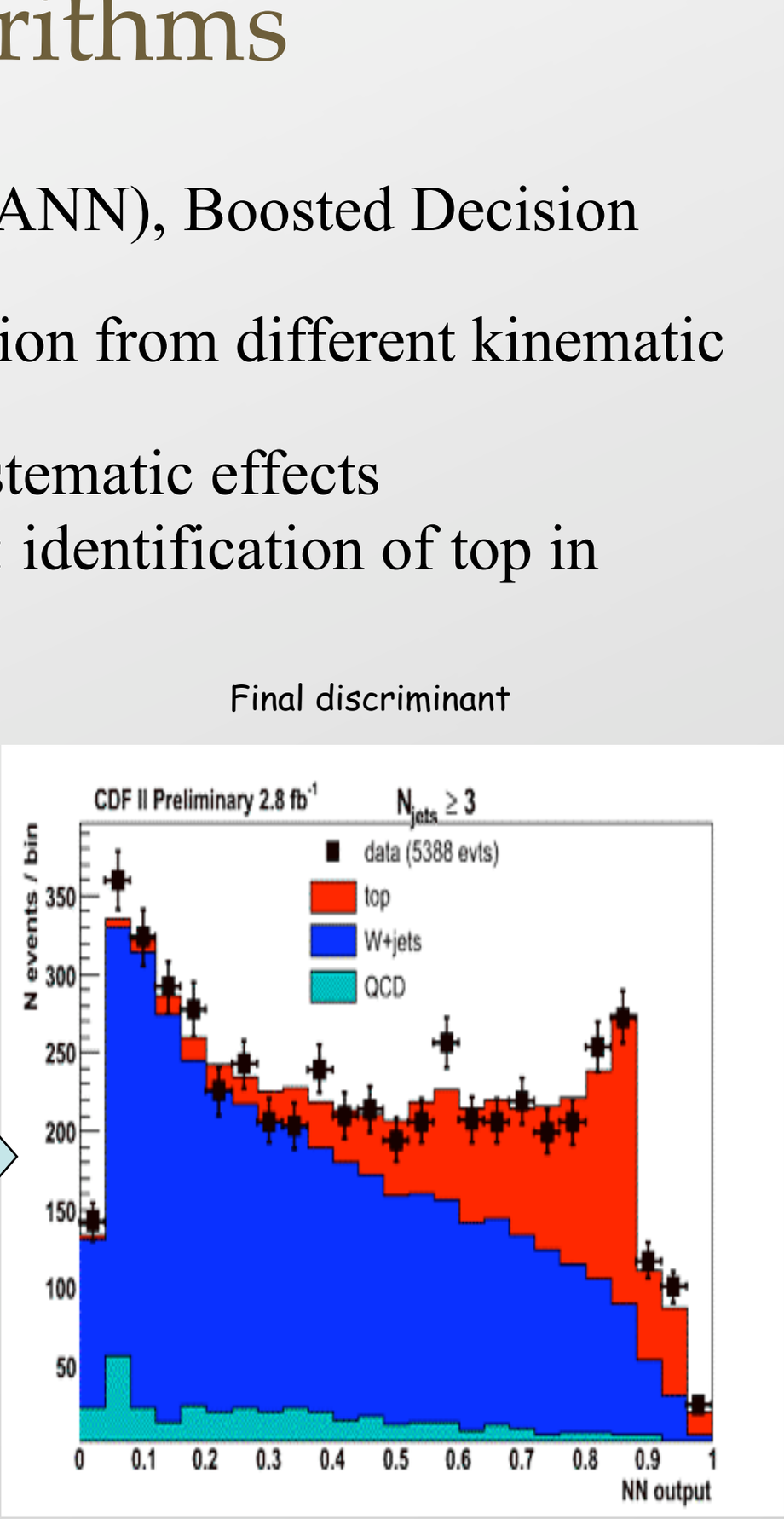




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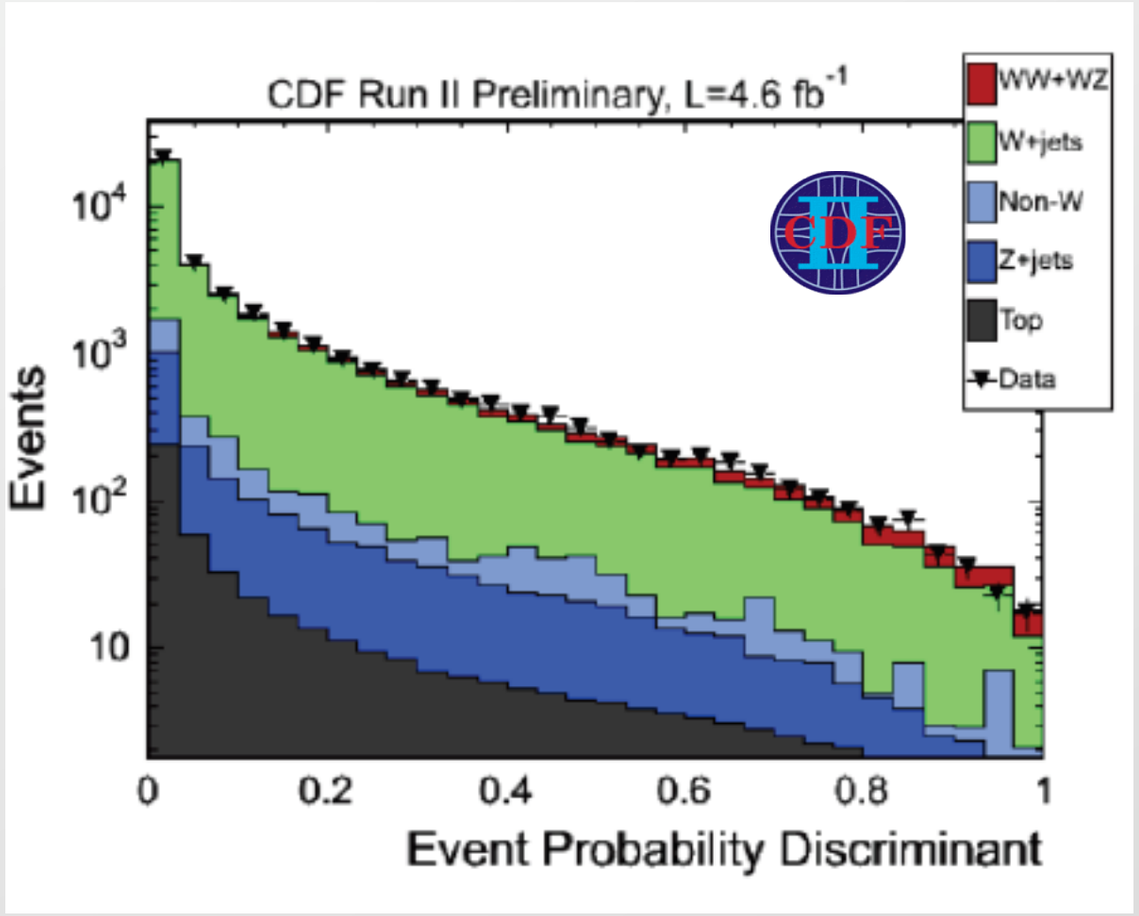
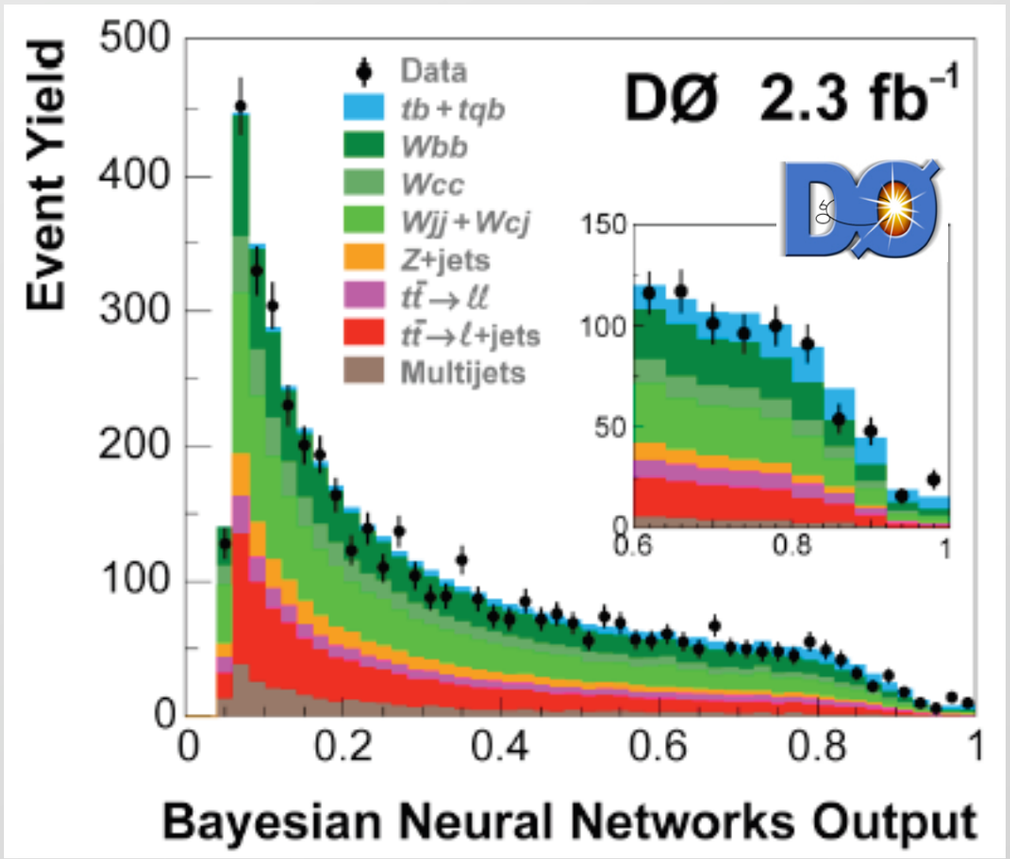
# Applications of Advanced Algorithms

Diboson observation :
WW + WZ → lνjj
Similar to WH → lνbb
Matrix Element :
Us: σ(WW+WZ) = 16.6+3.5-3.0 pb
SM : σ = 15.1 ± 0.8 pb

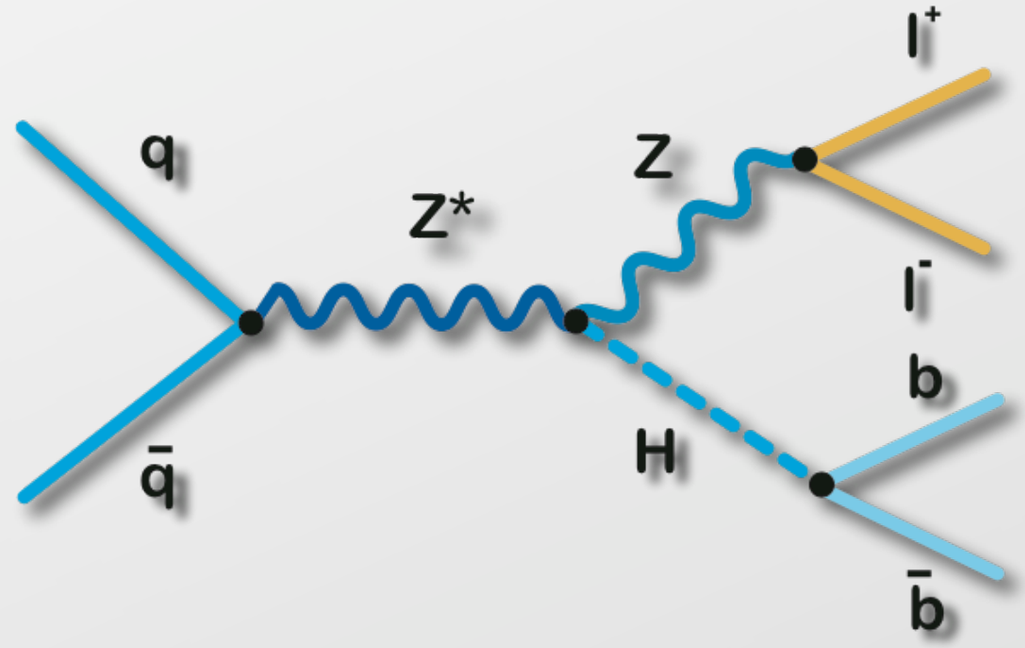
Single top observation
t+q → lνb+j (with b-tag)
Similar to WH → lνbb
Neural Network :
Us : σ(t) = 4.70 +1.18 -0.93 pb
SM : σ = 3.46 ± 1.8 pb



# $ZH \rightarrow \ell\ell b\bar{b}$

- Two High $P_T$ Leptons
- No (direct) Missing $E_T$
- >=2 jets
  - Split up 1 and 2 b-tags




## Features:

1. Small σ·BR
2. Several tight constraints

i. $M_{ll} \cong M_z$

ii. "$\not{E}_T$" → improve jet resol.

1. ~1 evt/6 $fb^{-1}$ (dbl tags)

## Primary Backgrounds

$Zb\bar{b}$, $Zc\bar{c}$, $Zqq'$

$t\bar{t}$

$WW + jj$, $WZ$, $ZZ$

$Z \rightarrow \tau\tau$

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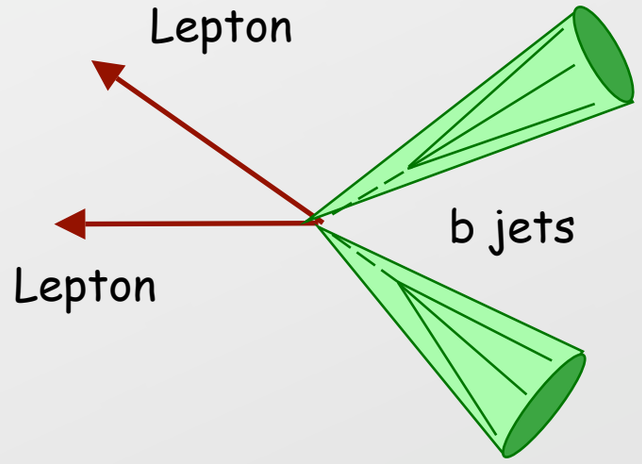


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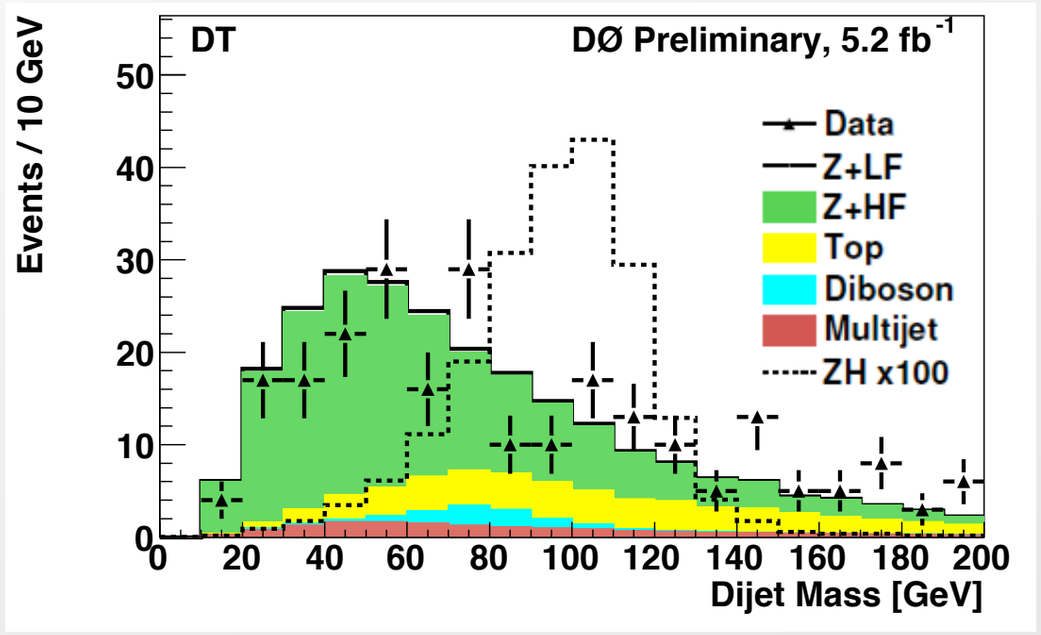
$t\bar{t}$

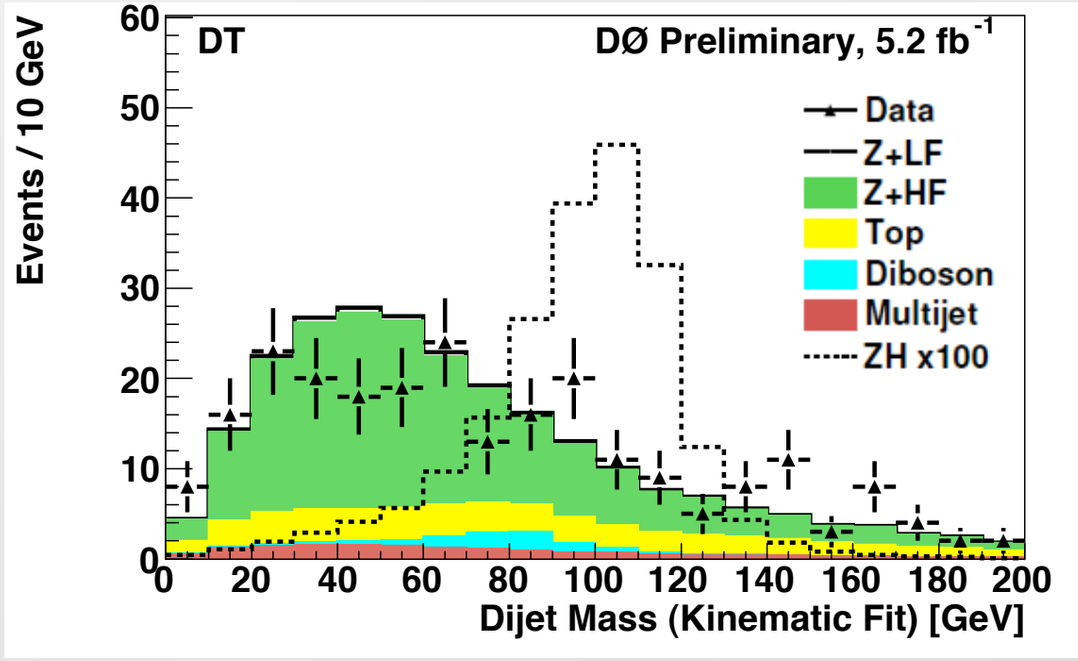
$WW + jj$, $WZ$, $ZZ$

$Z \to \tau\tau$

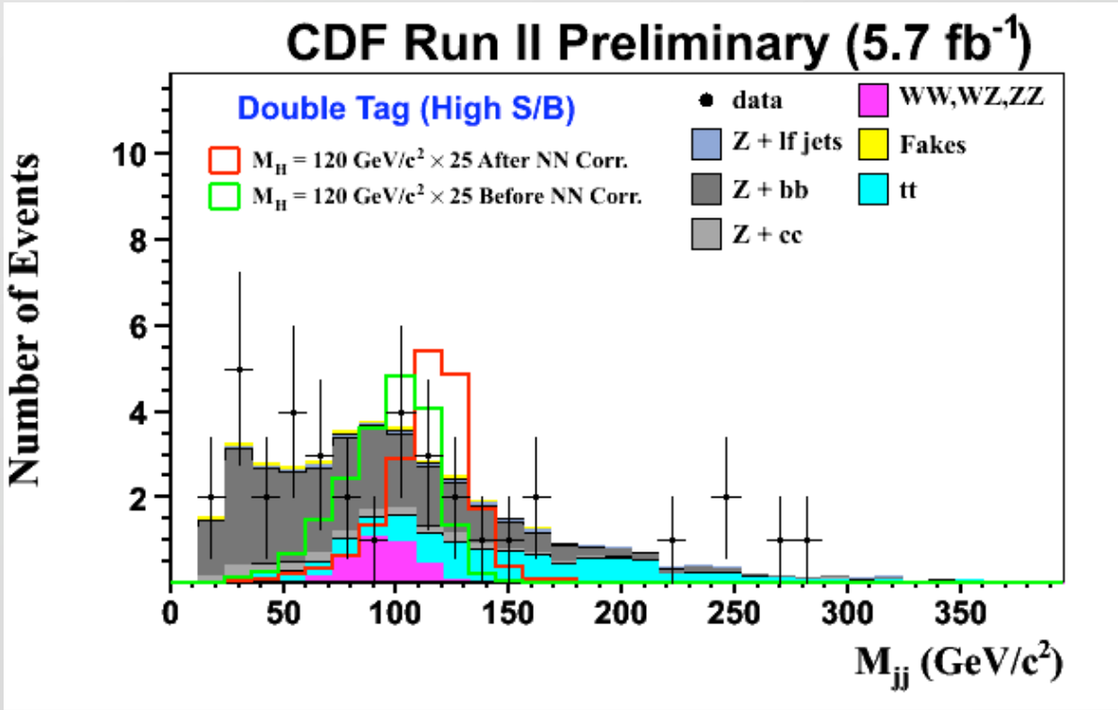
# $ZH \to \ell\ell b\bar{b}$ *Dijet Mass Improvements*

**D0 uses a kinematic fit, adjusting lepton and jet energies to obtain the correct $M_z$ and $P_t$ of the llbb system**



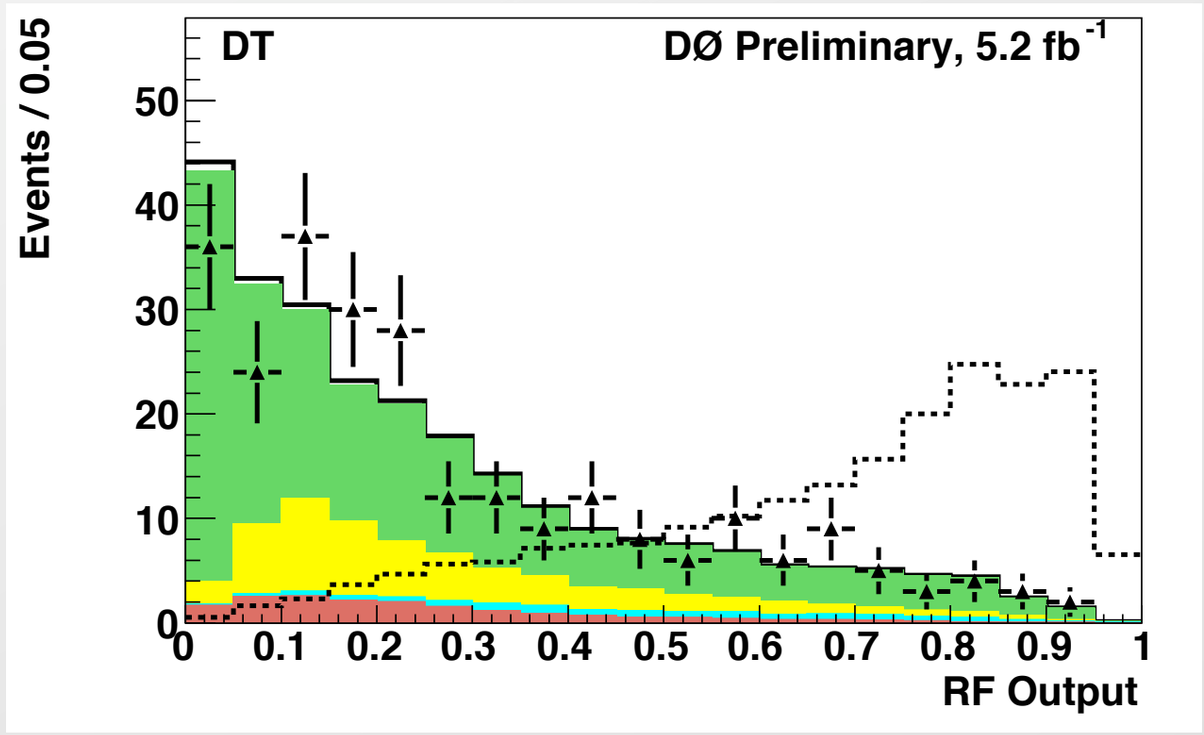

**CDF uses a NN, with inputs of observed jet energies and directions, MET magnitude and direction, to correct the two highest Et jets**



# $ZH \to \ell\ell b\bar{b}$ *Event Discriminants*

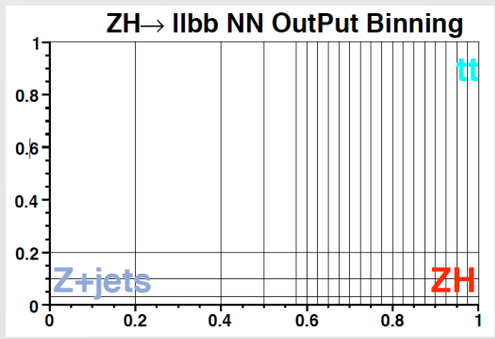
**D0 uses a Random Forest Decision Tree method:**

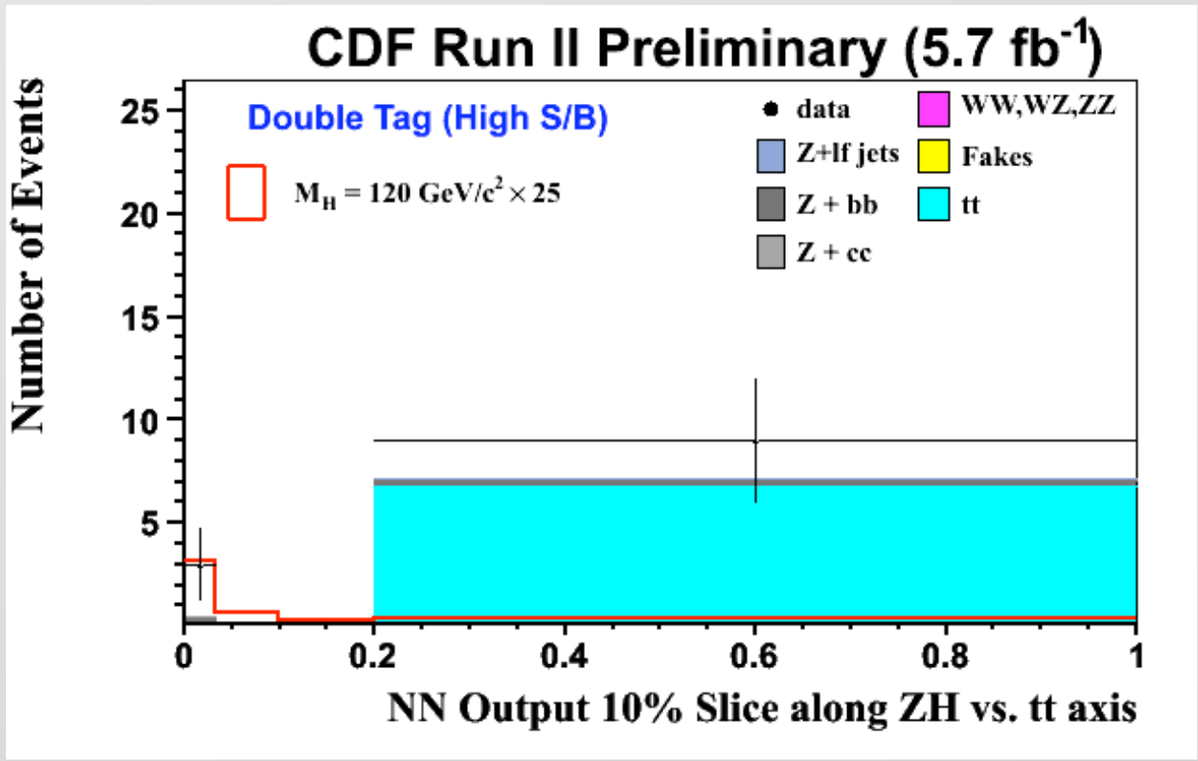
- **20 well modeled inputs chosed**
- **200 trees are trained, using a random subset of 10 inputs**
- **RF Output is the performance weighted result of all 200 trees**



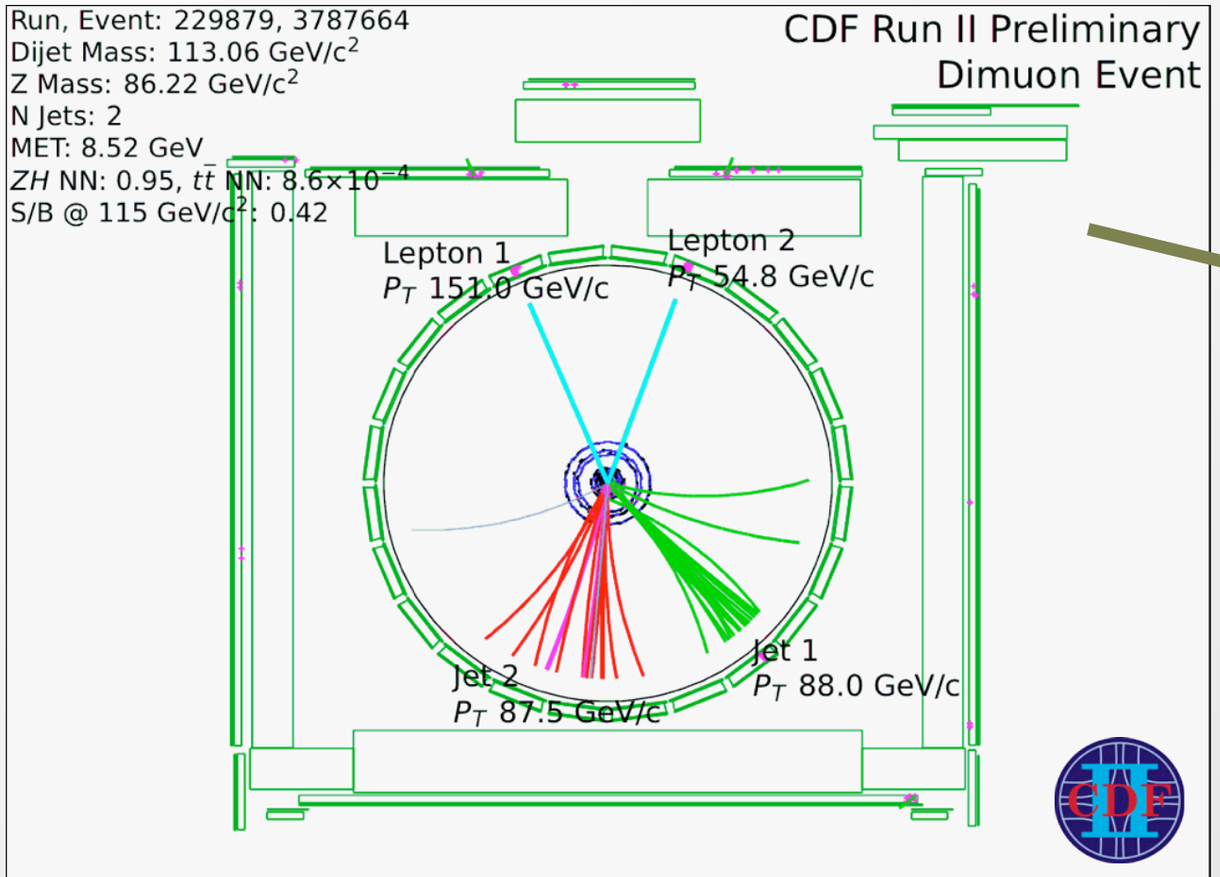

**CDF uses a 2D NN:**

- **one axis is ZH vs Z+jets**
- **one axis is ZH vs ttbar**
- **A 10% slice along the ZH vs ttbar is for display (full 2D is used in limit)**



# $ZH \to \ell\ell b\bar{b}$ *Event Displays*




Dijet Mass = 113 GeV / c²

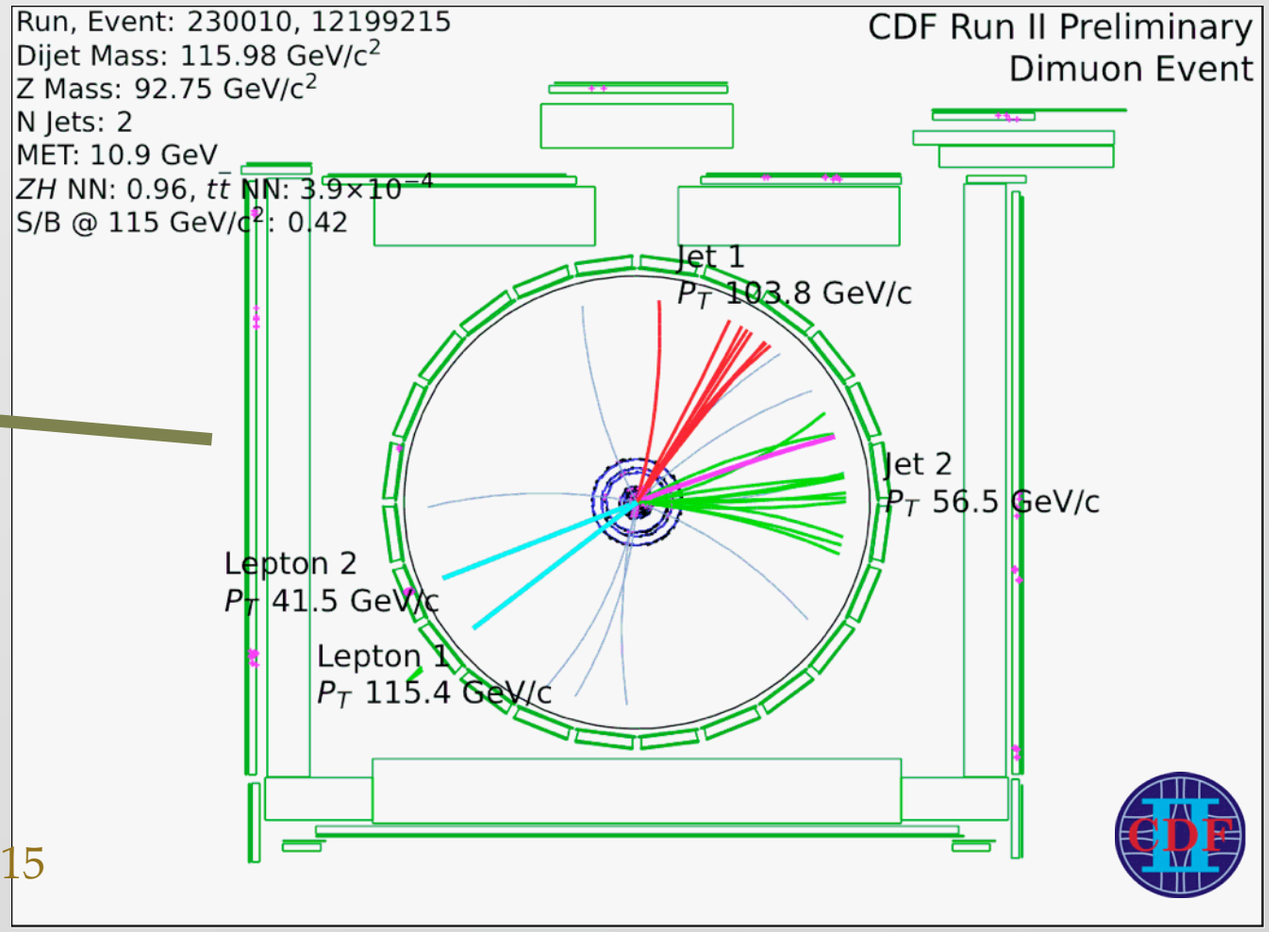
Z Mass = 86.2 GeV / c²

MET = 8.5 GeV

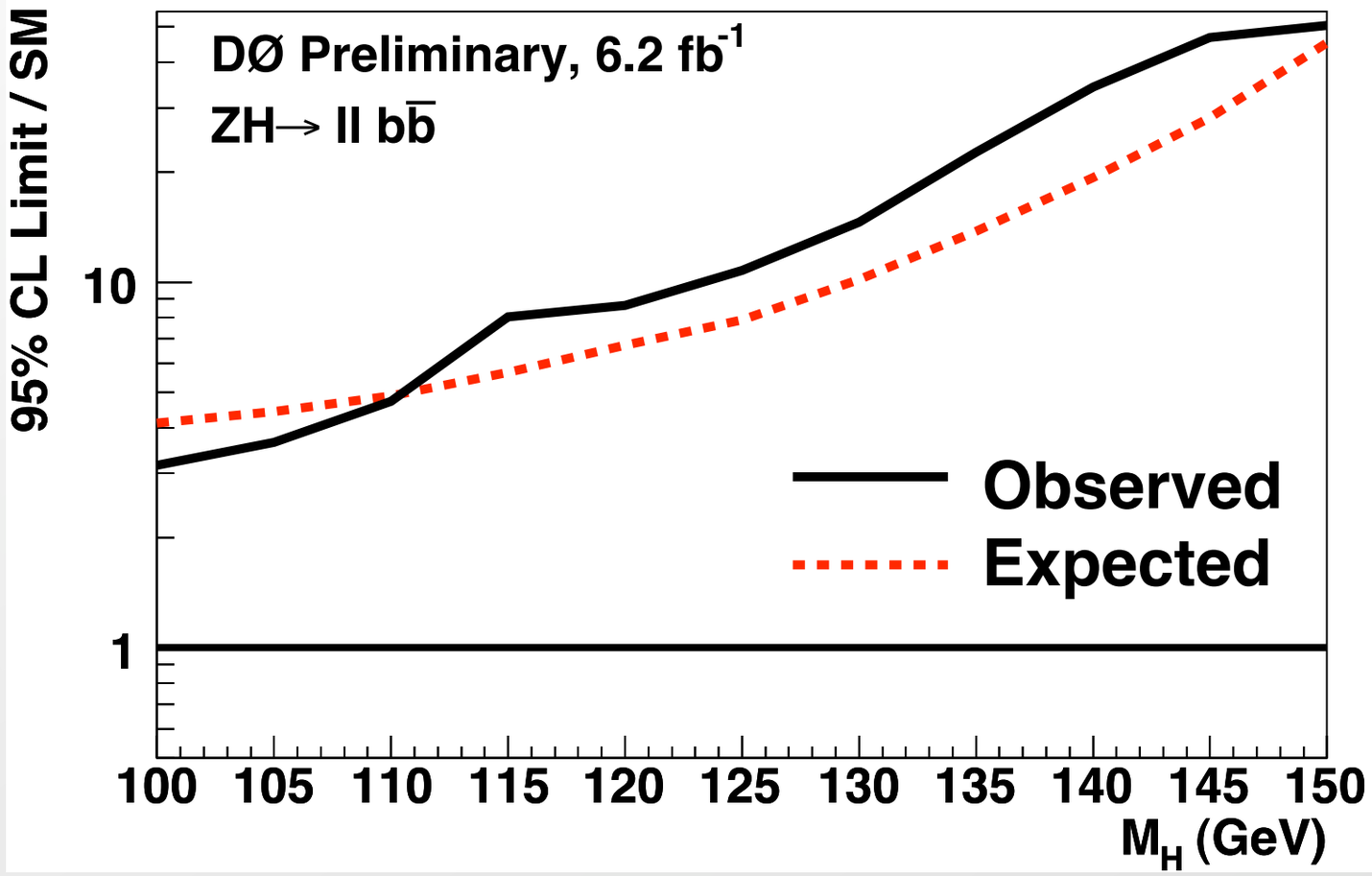
Dijet Mass = 116 GeV / c²

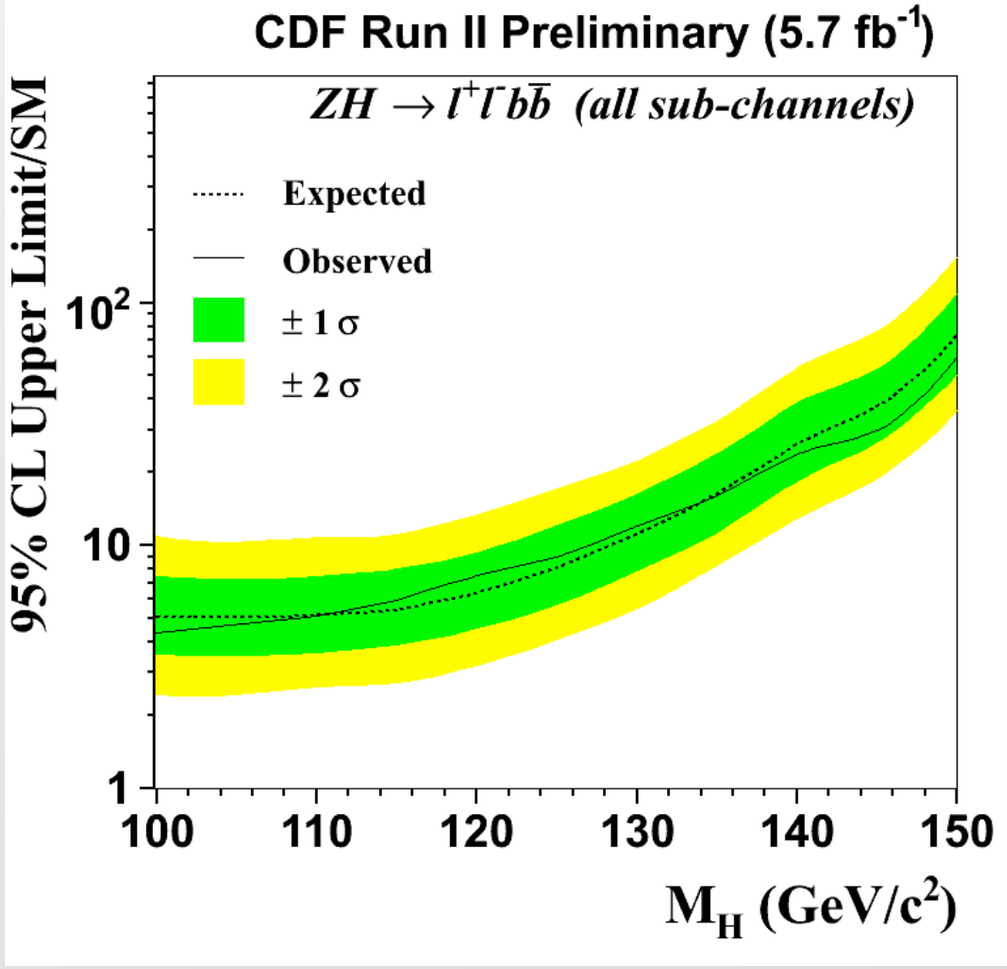
Z Mass = 92.8 GeV / c²

MET = 10.9 GeV



# $ZH \to \ell\ell b\bar{b}$ Results



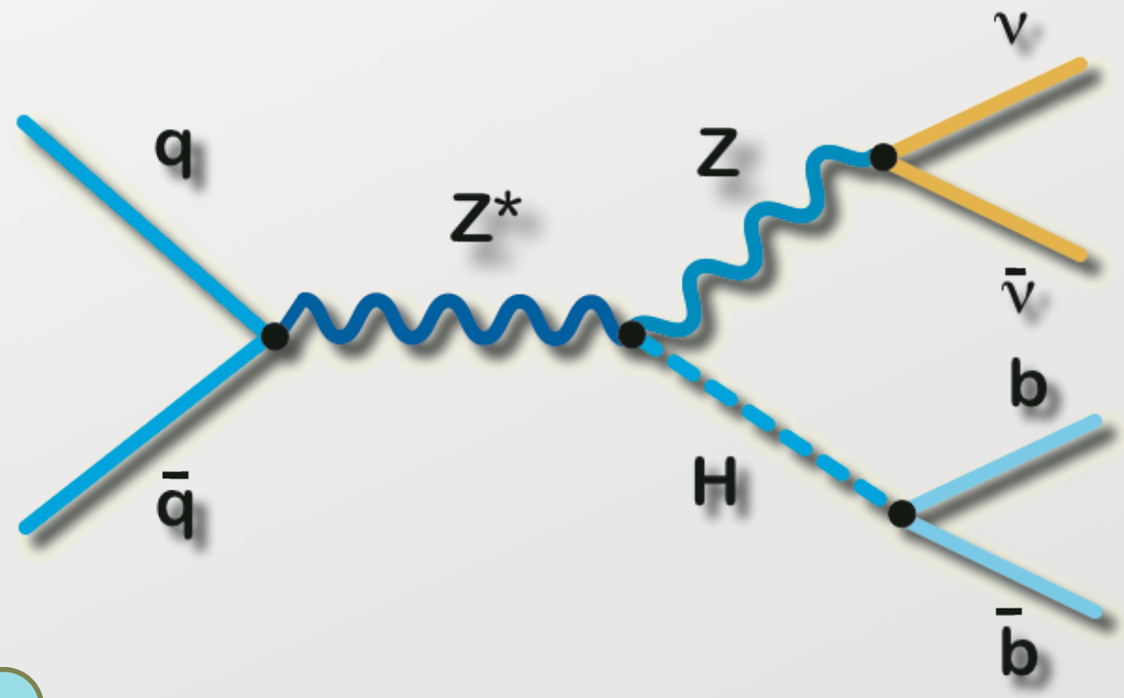

| Experiment | Lum | Obs/SM | Exp/SM |
|---|---|---|---|
| D0 | 6.2 $fb^{-1}$ | 8.0 | 5.7 |
| CDF | 5.7 $fb^{-1}$ | 6.0 | 5.5 |



$M_h = 115\ GeV/c^2$

# $ZH \to \nu\nu b\bar{b}$

- No High $P_T$ Leptons
- Large Missing $E_T$
- D0: 2 jets  2 b-tags
- CDF: 2/3 Jets, 1/2 b-tags




**Features**:

1. **Trigger is more challenging**
2. **Large QCD/Fake Bkg: Difficult to Simulate: *use data***
3. **Use tracks to help bkg identification.**
4. **Large contribution (~50%) from WH**
5. **~10 evts/ 6fb$^{-1}$ (double tags)**

## Primary Backgrounds

QCD Heavy Flavor,

$t\bar{t}$, $W/Z + b\bar{b}/c\bar{c}$,

Single Top,

$ZZ$, $WZ$, $WW$

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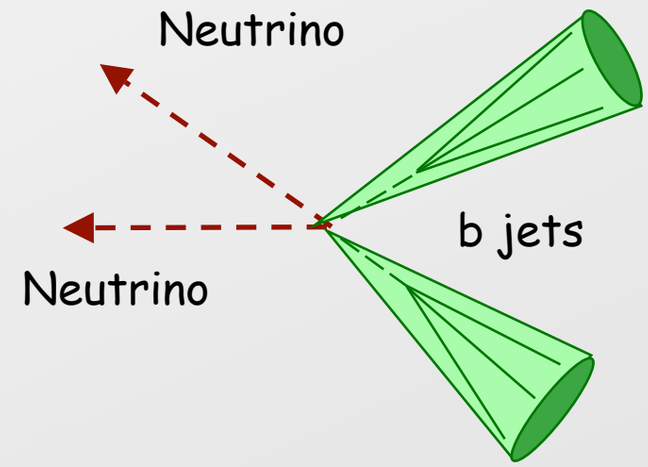


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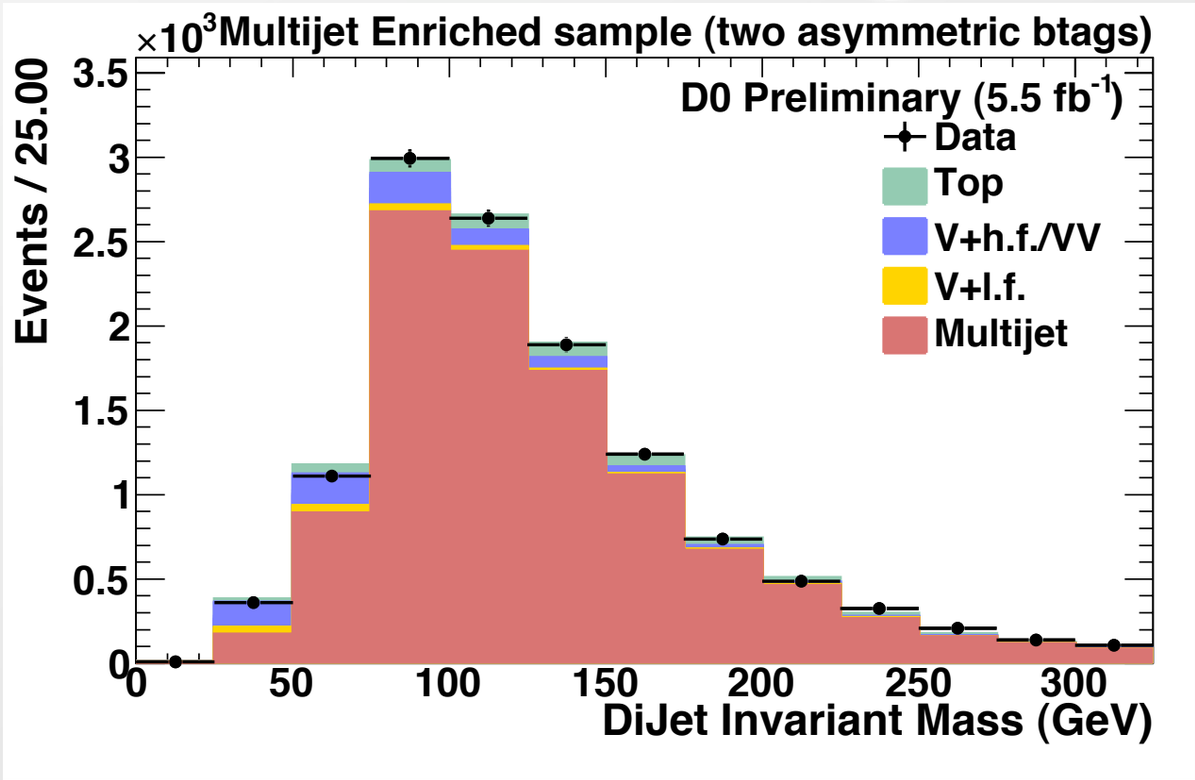
# $ZH \to \nu\nu b\bar{b}$ Background Modeling

D0 divides data into 4 subsamples:

- Signal used to search for Higgs
- MJ-model for modeling MJ background in signal sampl
- MJ-control to validate MJ-modeling
- EWK control, enhanced in W->μν




CDF divides data into 5 subsamples:

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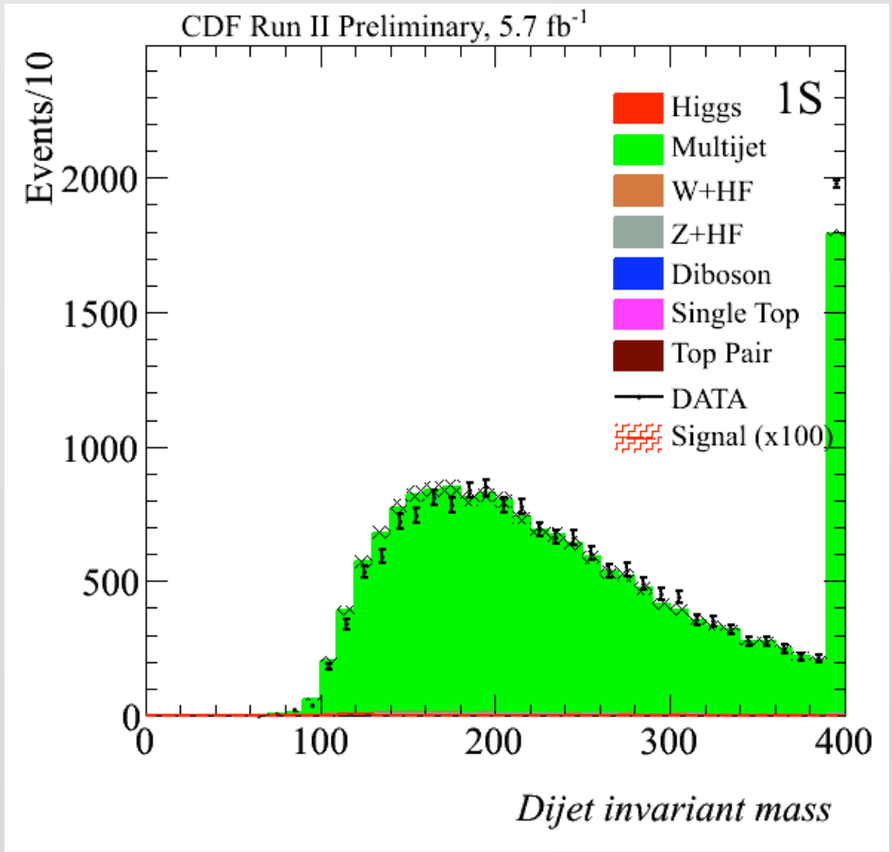
- QCD Region for systematic studies
- EWK region for modeling ewk processes
- QCD Regions (2) to check normalization of MJ



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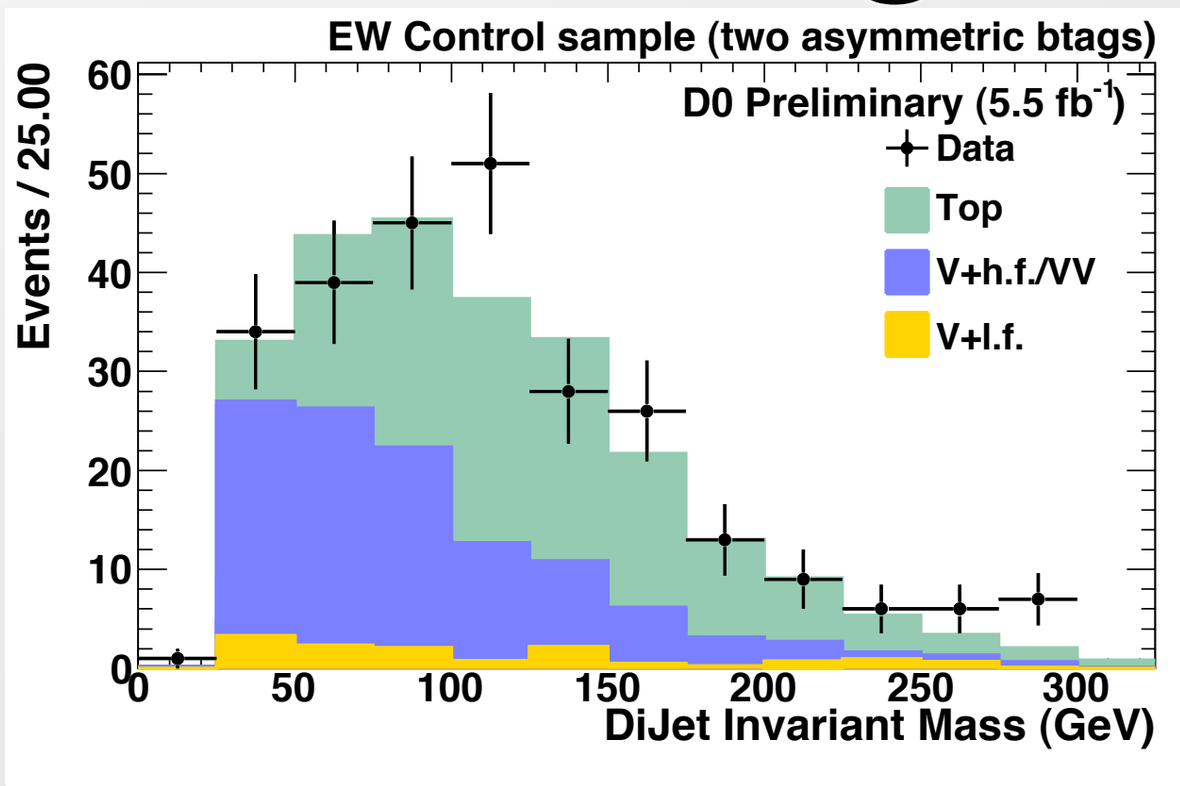


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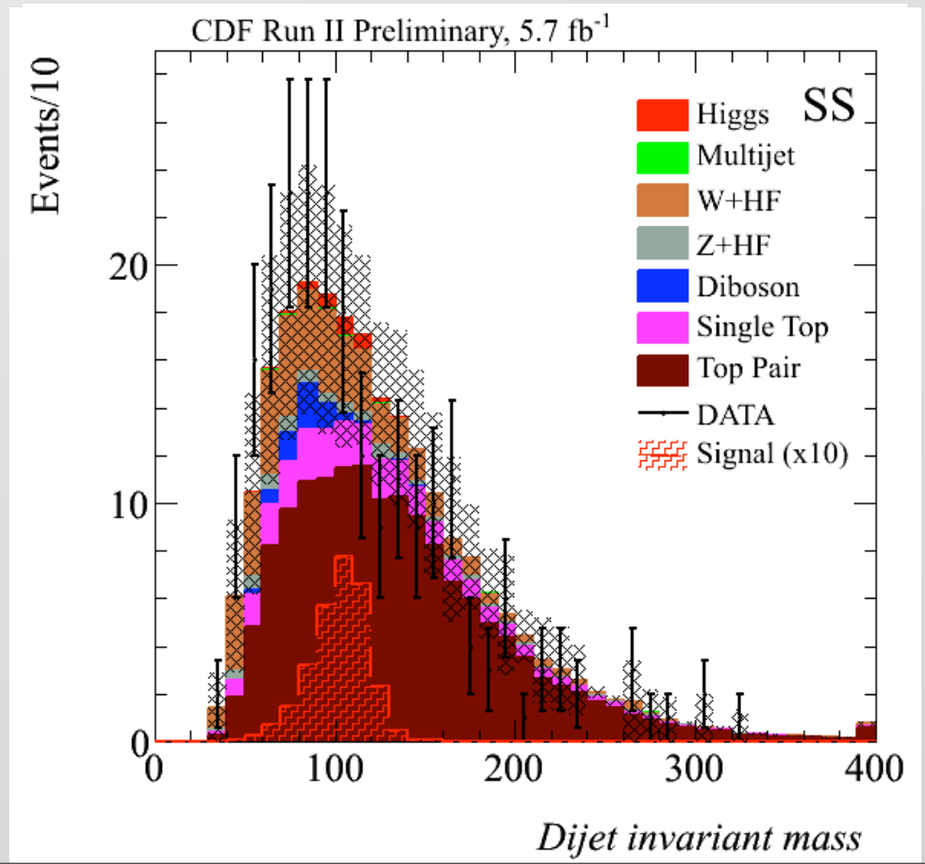
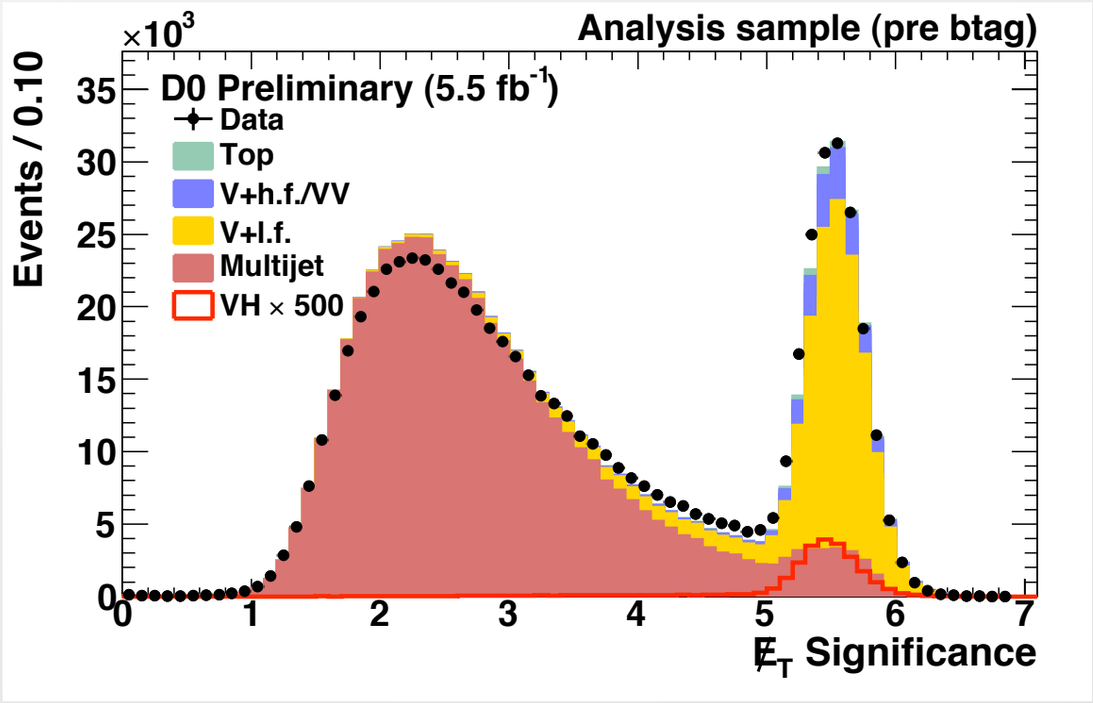


# $ZH \to \nu\nu b\bar{b}$ MultiJet (QCD) Removal

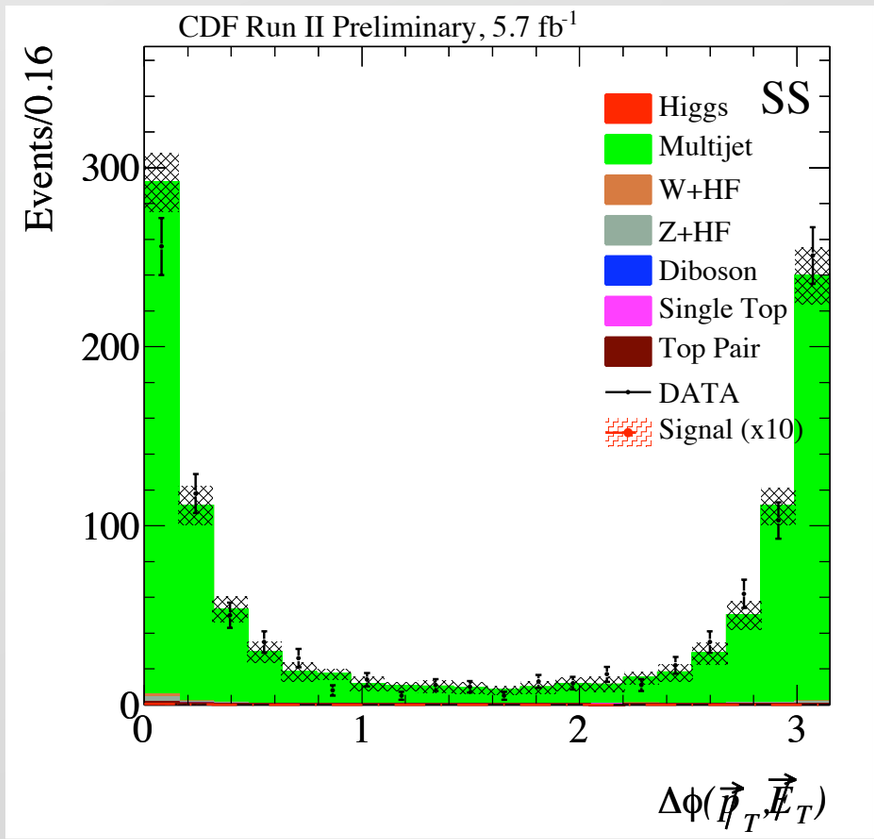
D0 employs a Multijet Discriminant:

- Based on jet kinematics (but after a cut on "track-based missing transverse momentum")
- Removes 95% of MJ and 65% of non-MJ background
- Preserves 70% of signal




CDF uses a QCD NN:

- Based on Jet kinematics as well as "track missing transverse momentum"
- Removes 87% of MJ, 50-70% of non-MJ background
- Preserves 90-95% of signal



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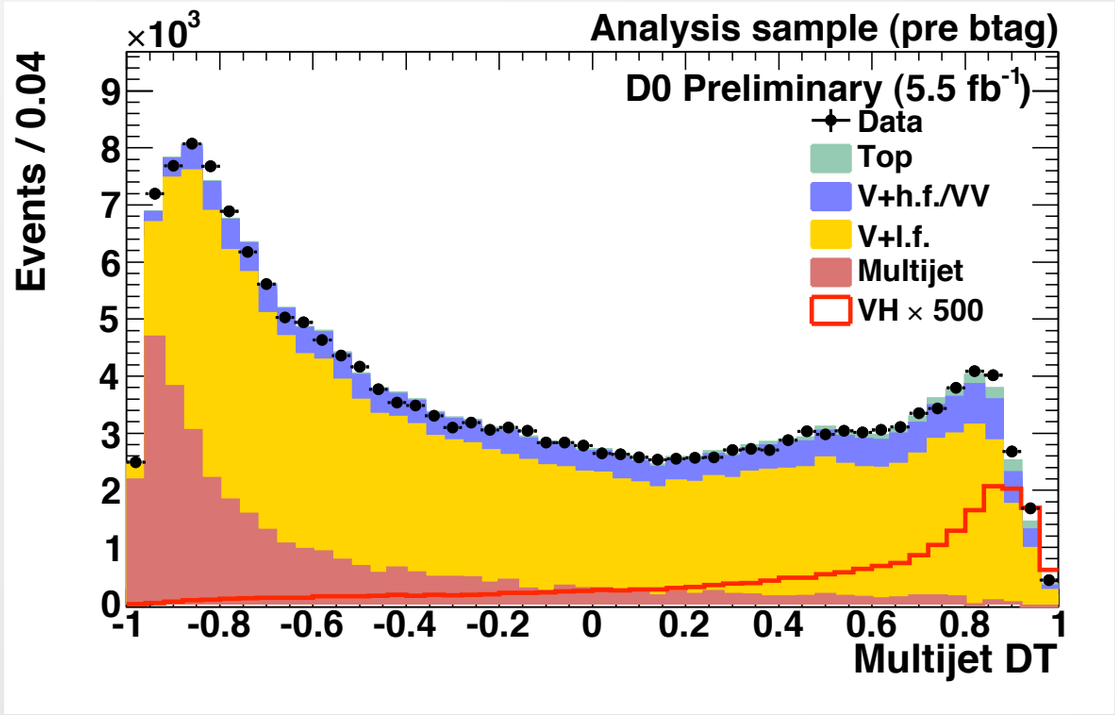


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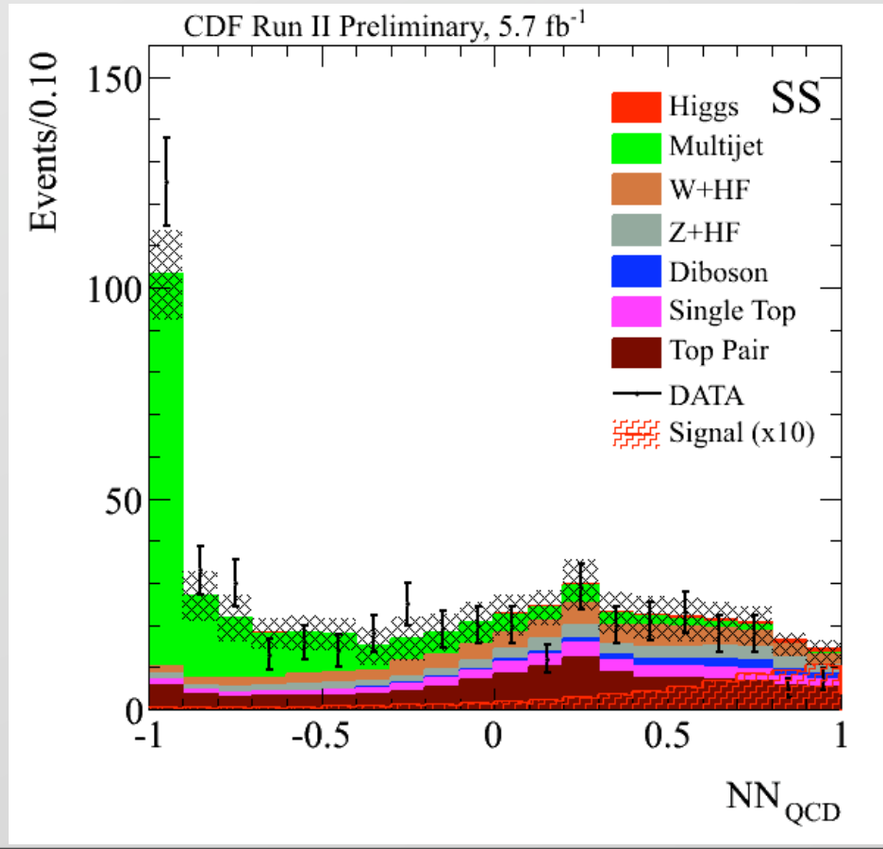
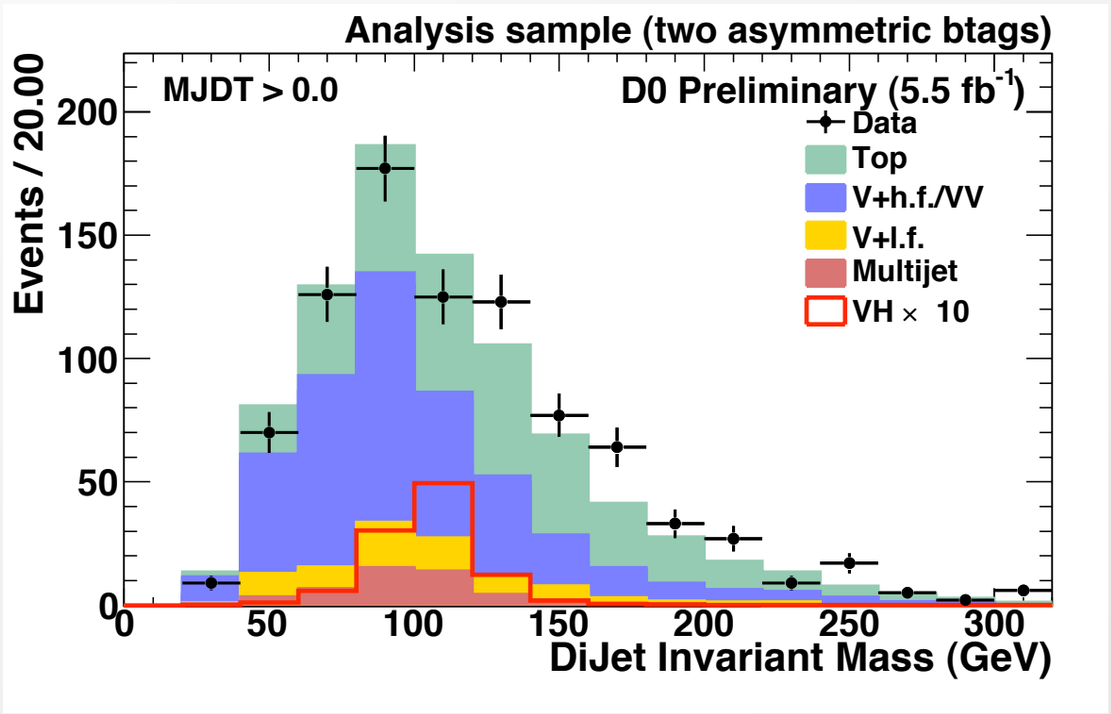
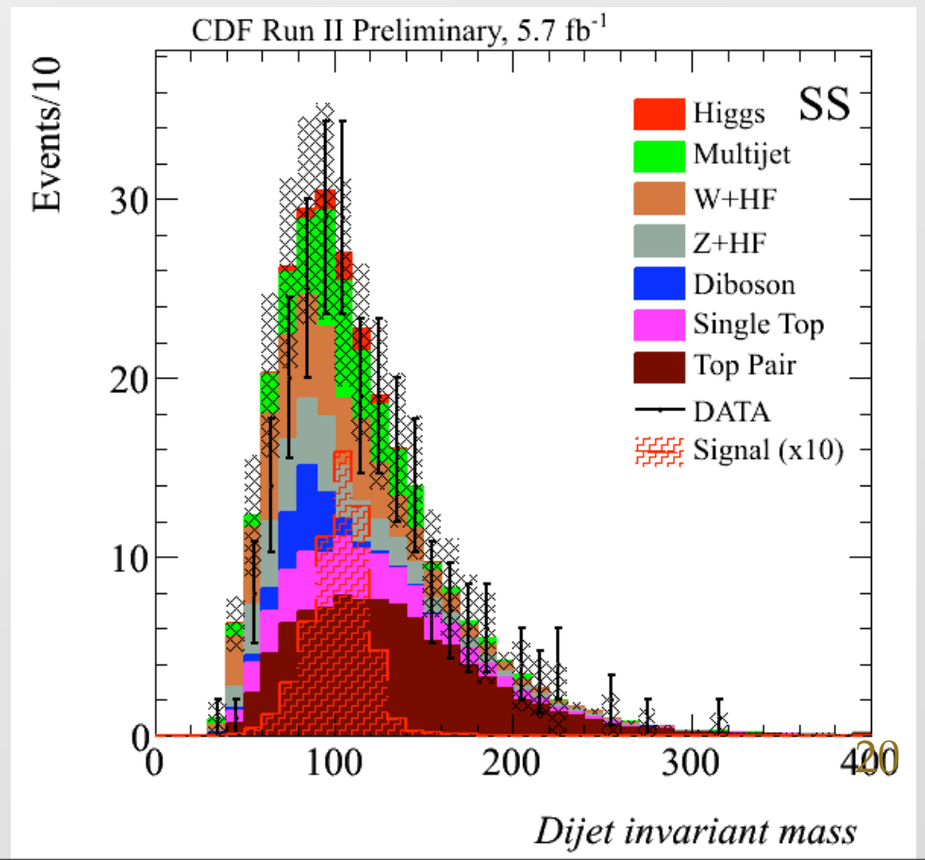
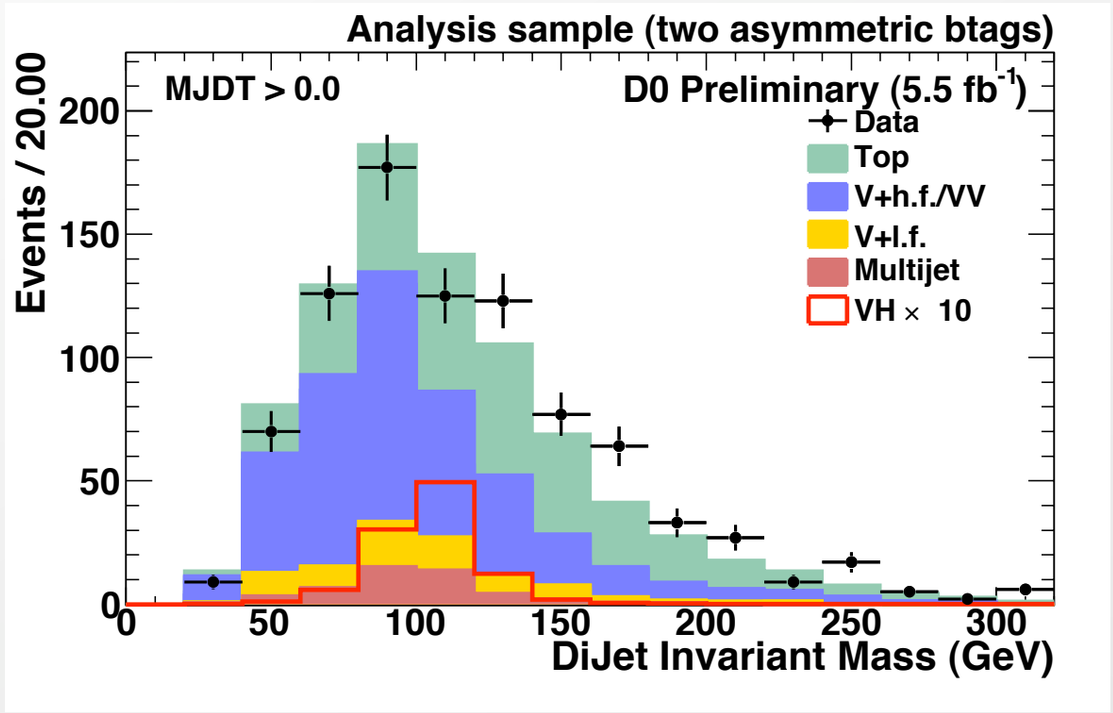


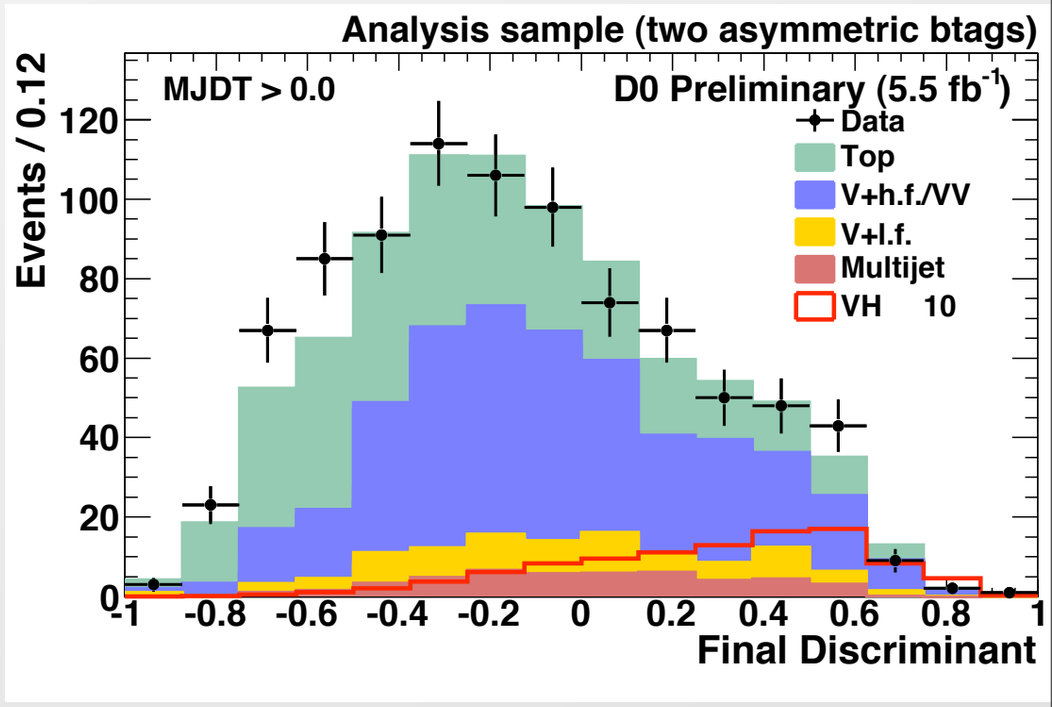
# $ZH \to \nu\nu b\bar{b}$ Event Discriminants

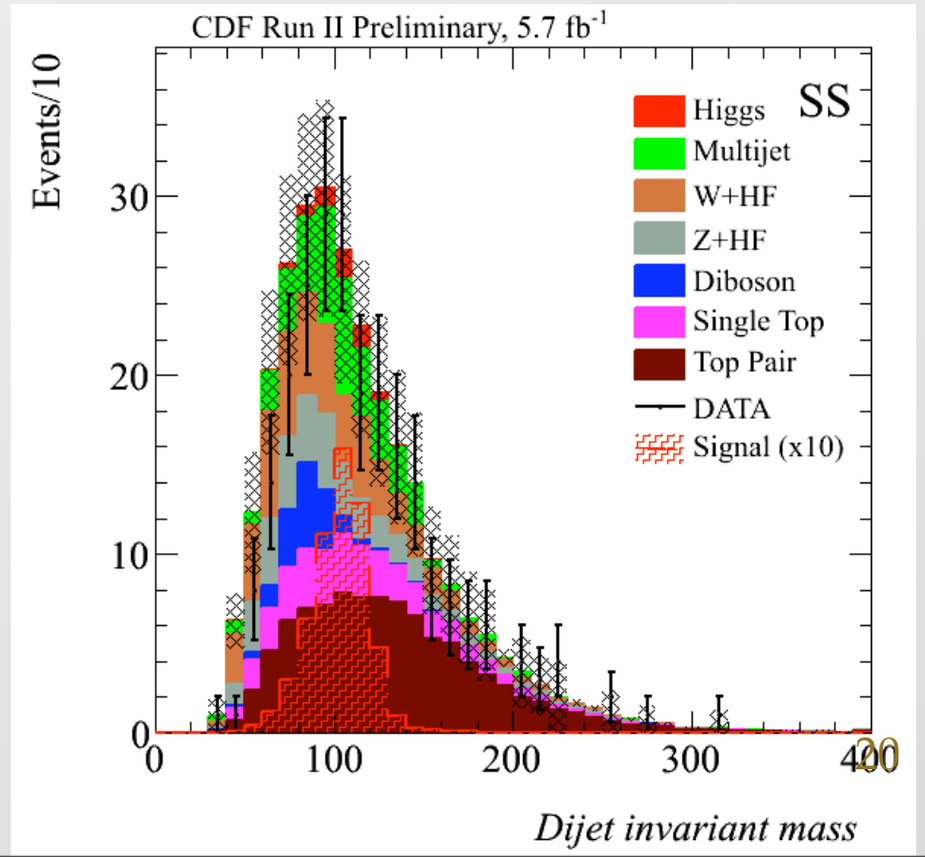


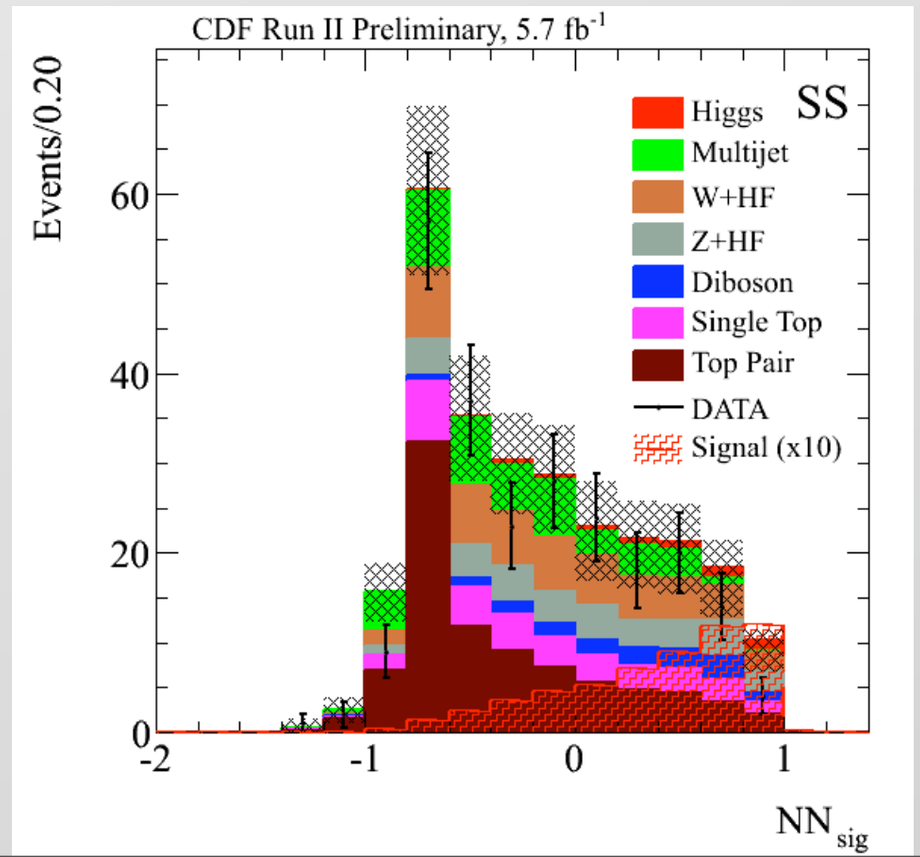



# $ZH \to \nu\nu b\bar{b}$ Event Discriminants

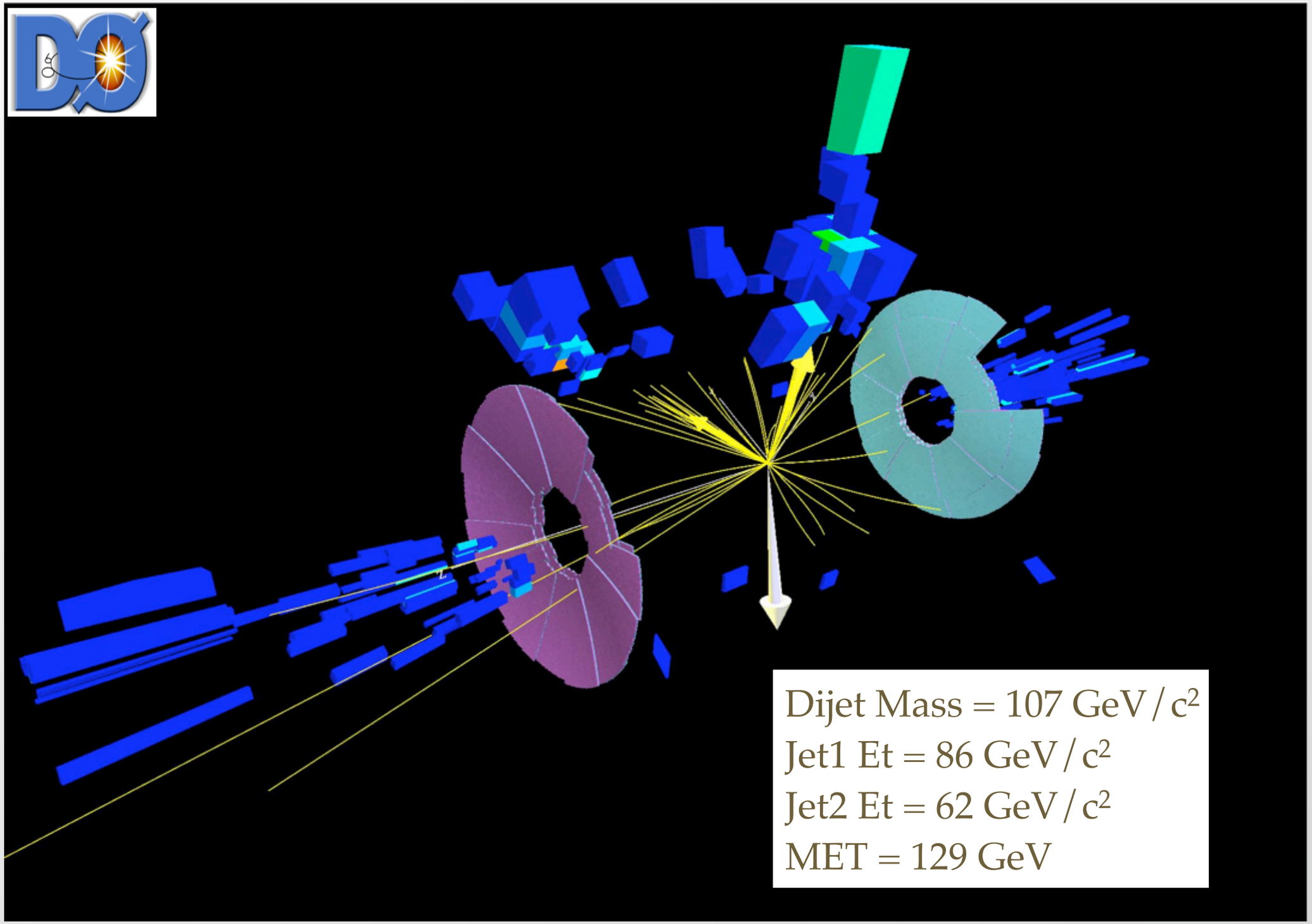


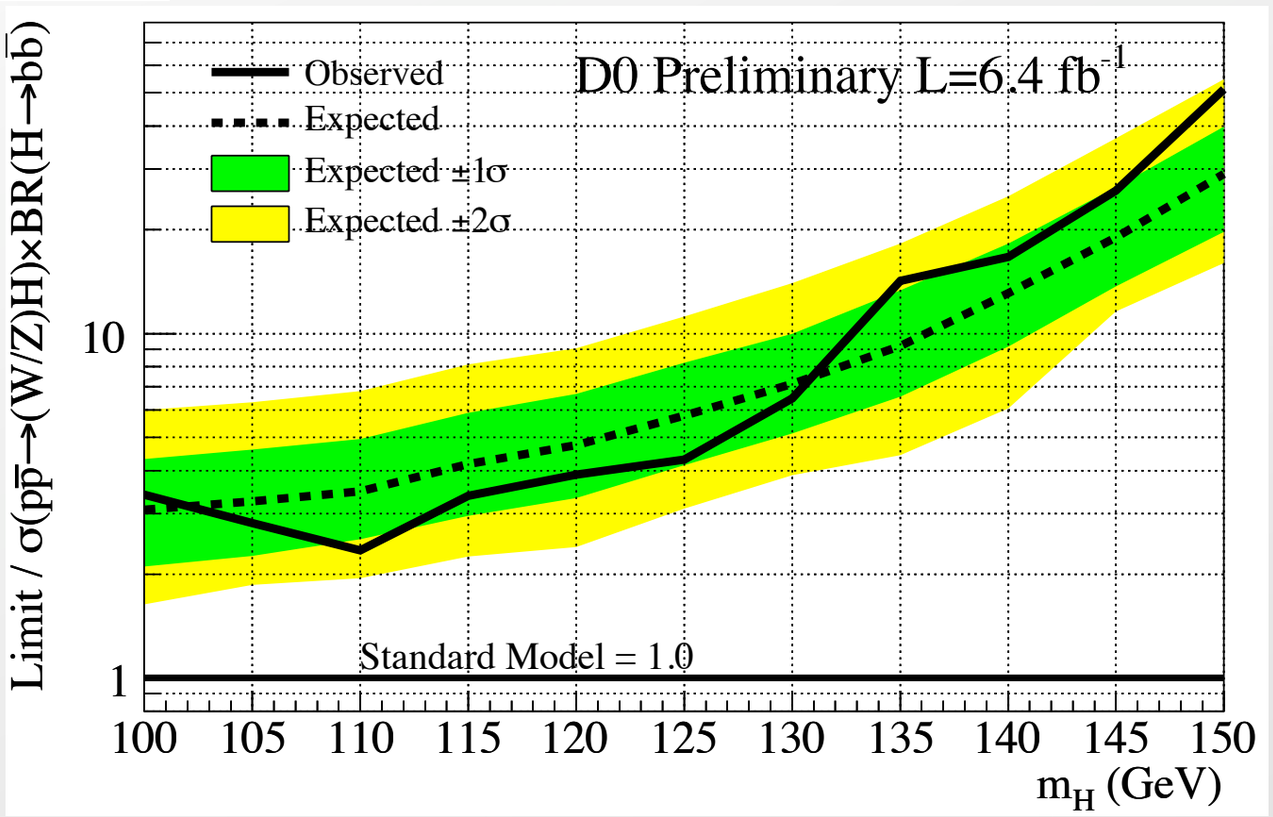



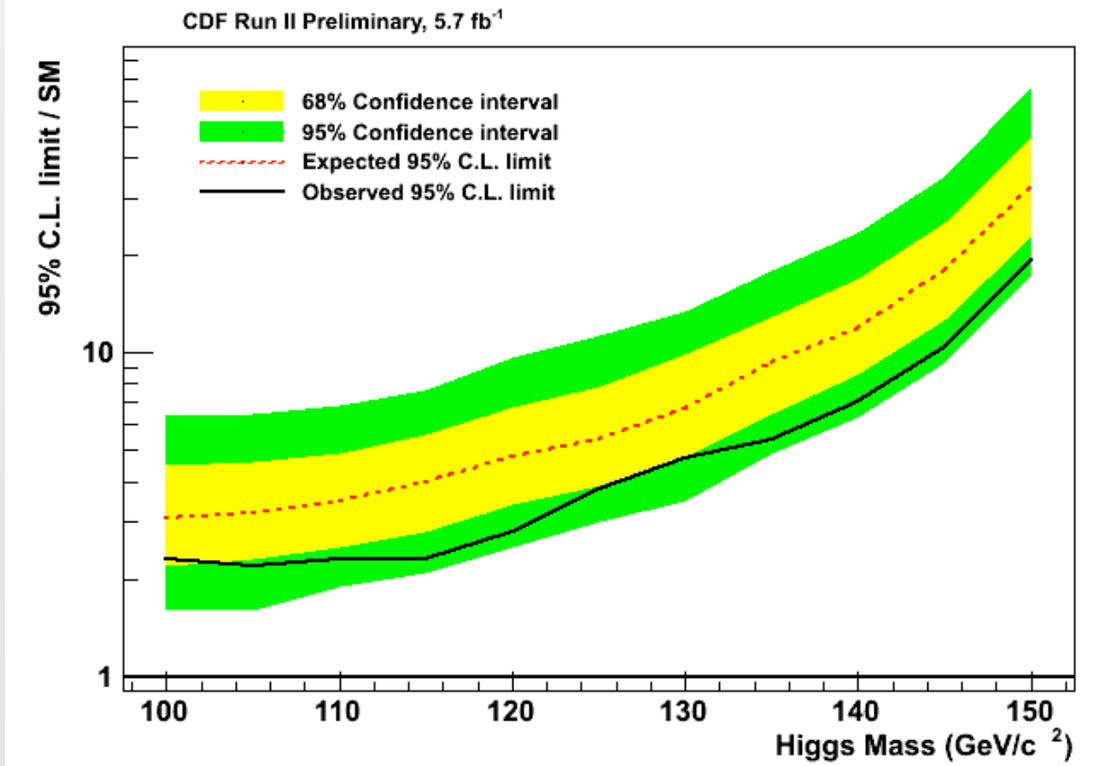



# $ZH \rightarrow \nu\nu b\bar{b}$ *Event Display*



# $ZH \to \nu\nu b\bar{b}$ *Results*



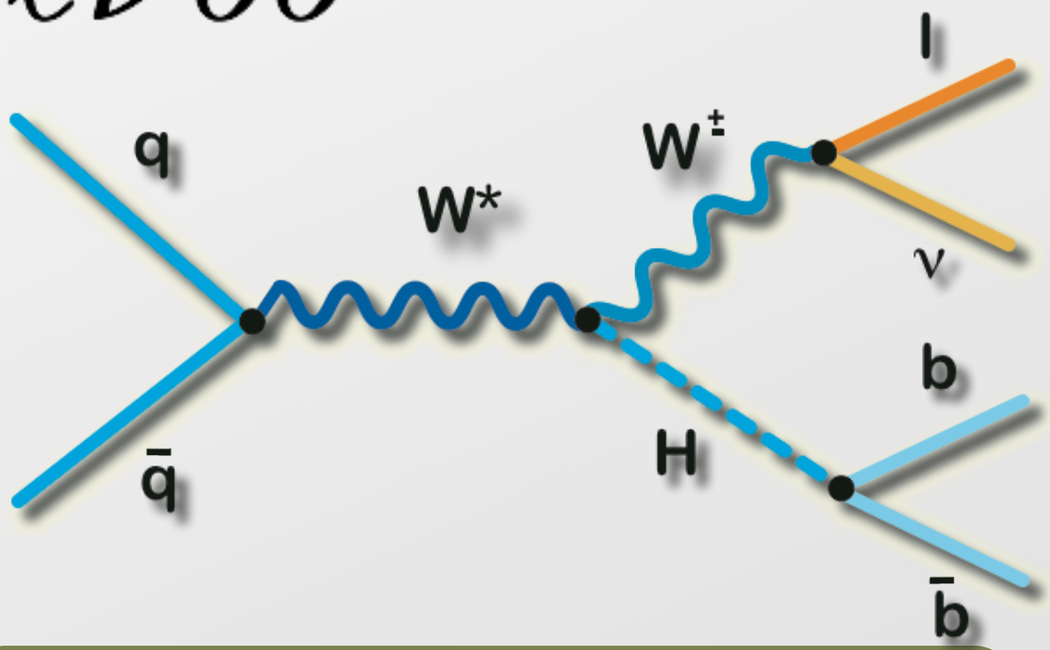

| Experiment | Lum | Obs/SM | Exp/SM |
|---|---|---|---|
| D0 | 6.4 $fb^{-1}$ | 3.4 | 4.2 |
| CDF | 5.7 $fb^{-1}$ | 2.3 | 4.0 |



$M_h = 115\ GeV/c^2$

# $WH \to \ell\nu b\bar{b}$

- **High $P_T$ Lepton**
- **Missing $E_T$**
- **2/3 Jets, 1/2 b-tags**




Features:

1. **Good Acceptance**
2. **Final state similar to single top prod.**
3. **~5 evts/ 6 fb$^{-1}$ (dbl tags)**

Primary Backgrounds

$W b\bar{b}$, $W c\bar{c}$, $W qq'$

$t\bar{t}$

Single top

non − W QCD

$WZ$, $WW$

$Z \to \tau\tau$

# $WH \to \ell\nu b\bar{b}$

- **High $P_T$ Lepton**
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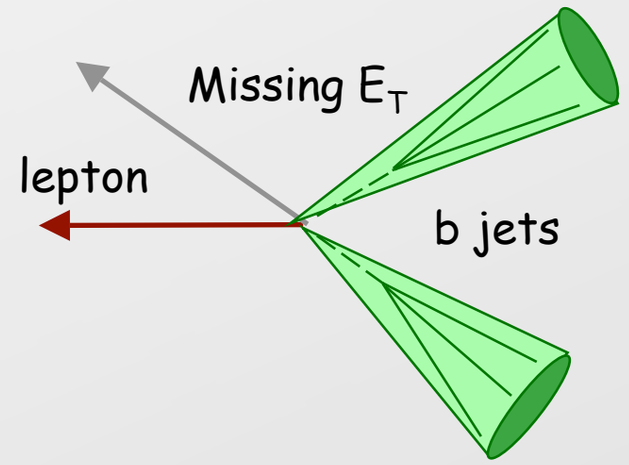


Features:

1. **Good Acceptance**
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3. **~5 evts/ 6 $fb^{-1}$ (dbl tags)**

Primary Backgrounds

$Wb\bar{b}$, $Wc\bar{c}$, $Wqq'$

$t\bar{t}$

Single top

non − W QCD

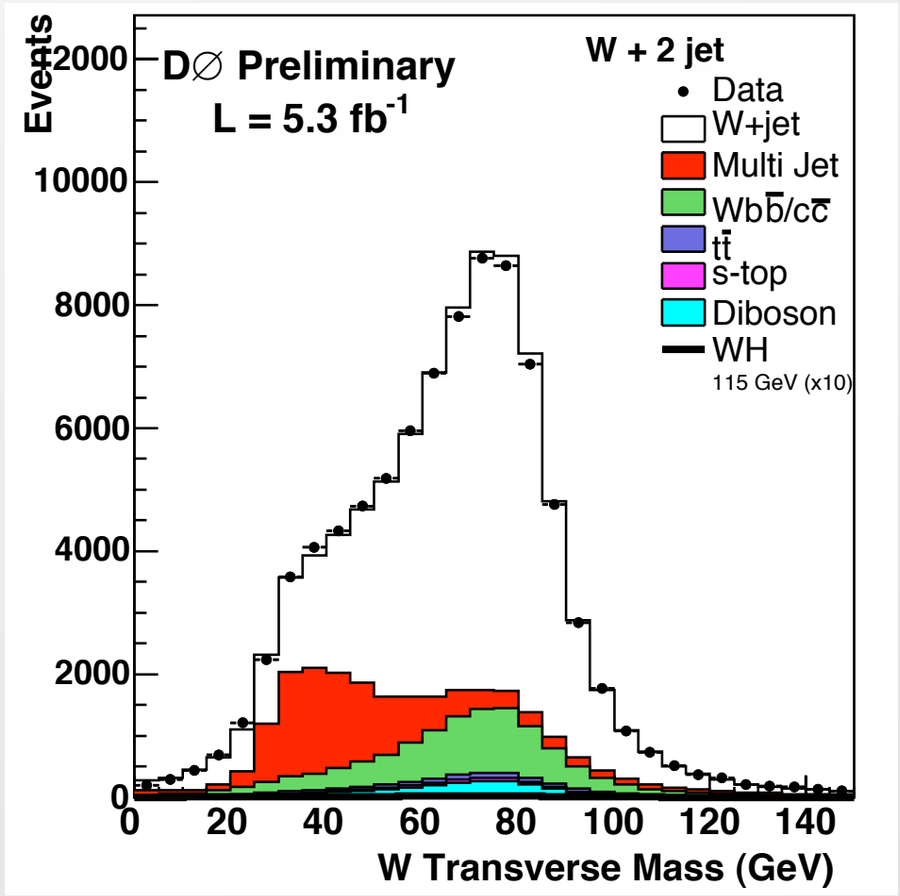
$WZ$, $WW$

$Z \to \tau\tau$

# $WH \to \ell\nu b\bar{b}$ Procedure

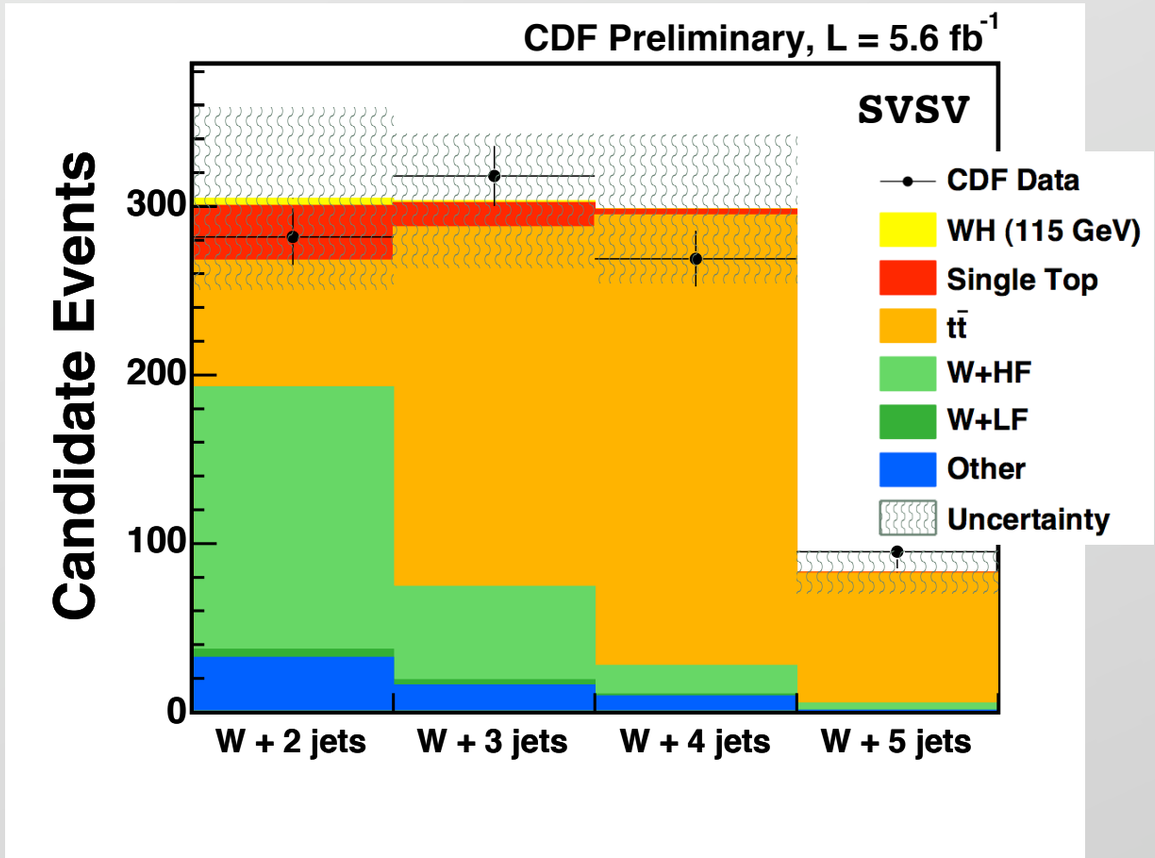
**D0 method:**

- **e/μ MET, 2/3 jets**
- **Double loose or single tight tagging**
- **Random forest discriminant**

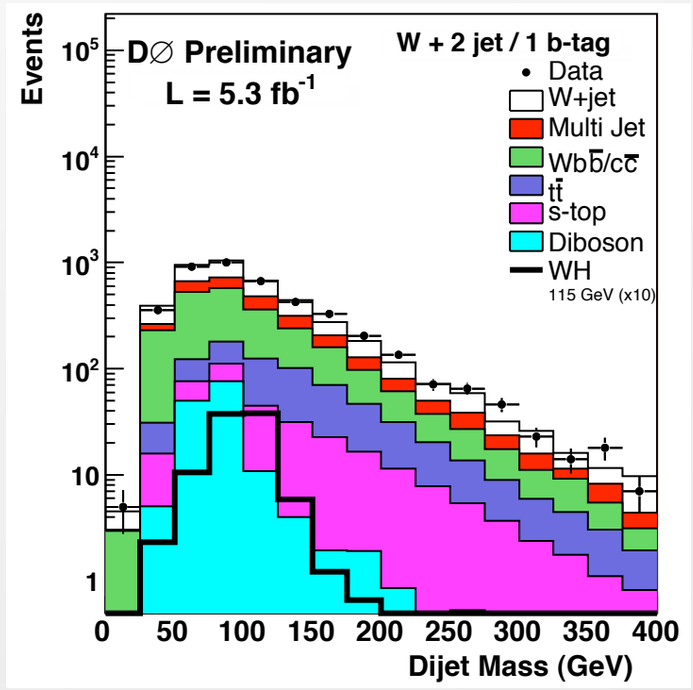


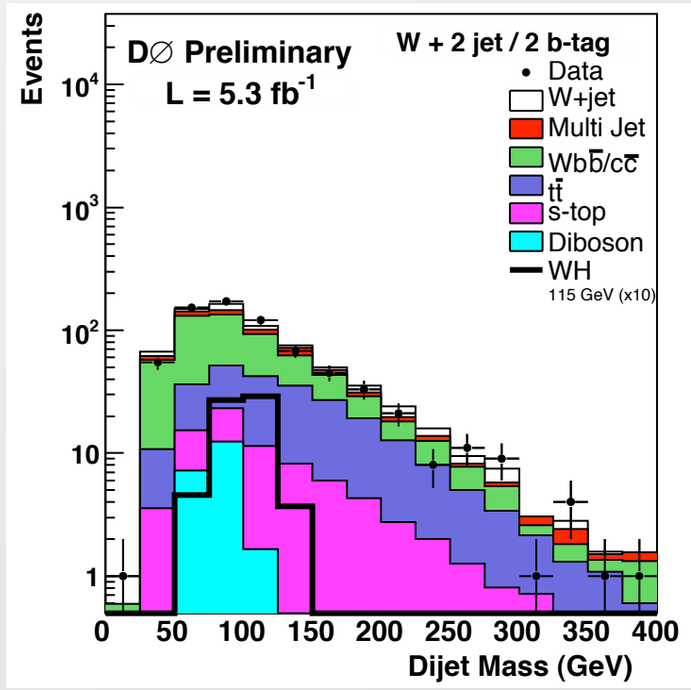

**CDF uses 2 methods:**

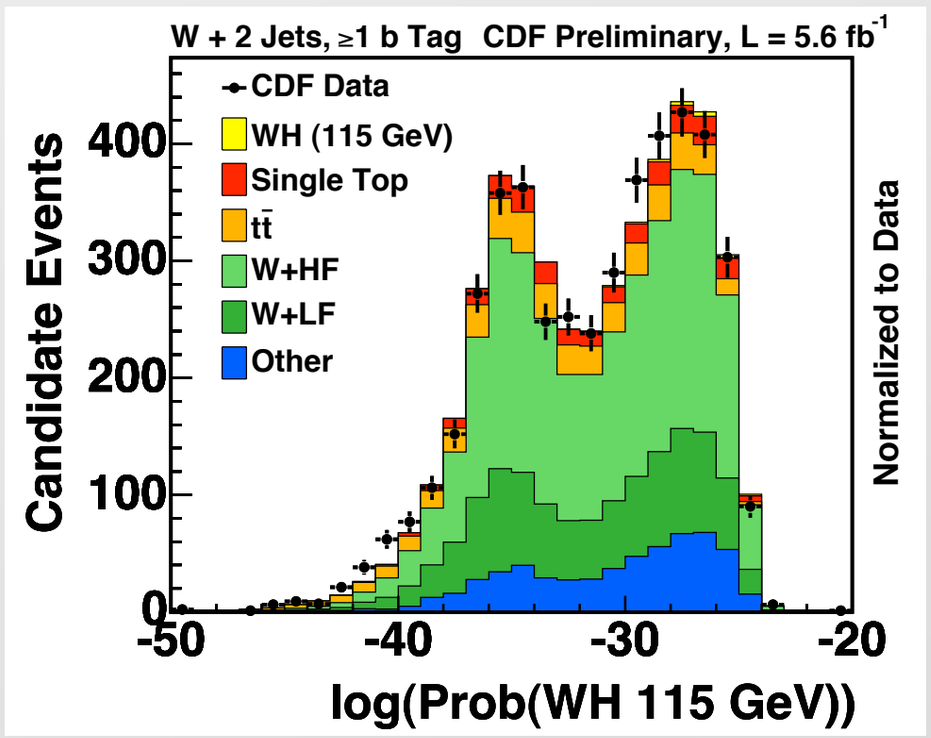
- **e/μ MET, 2/3 jets**
- **double loose or single tight tagging**
- **Flavor separator for single tags**
- **Two discriminants**
  - **1) Matrix Element**
  - **2) Bayesian Neural Network (adds in single isolated tracks as well)**

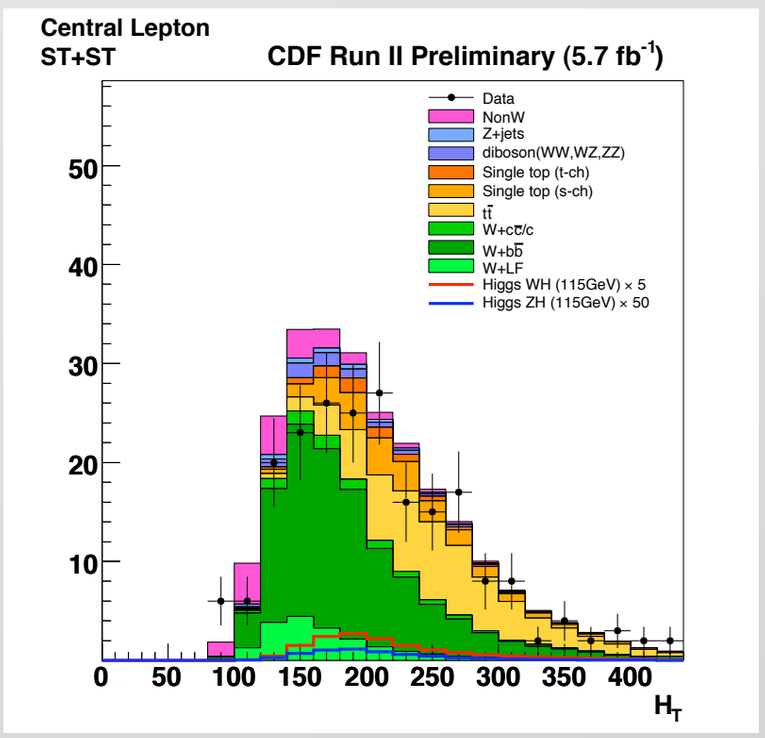


# $WH \to \ell\nu b\bar{b}$ *Discriminant Inputs*

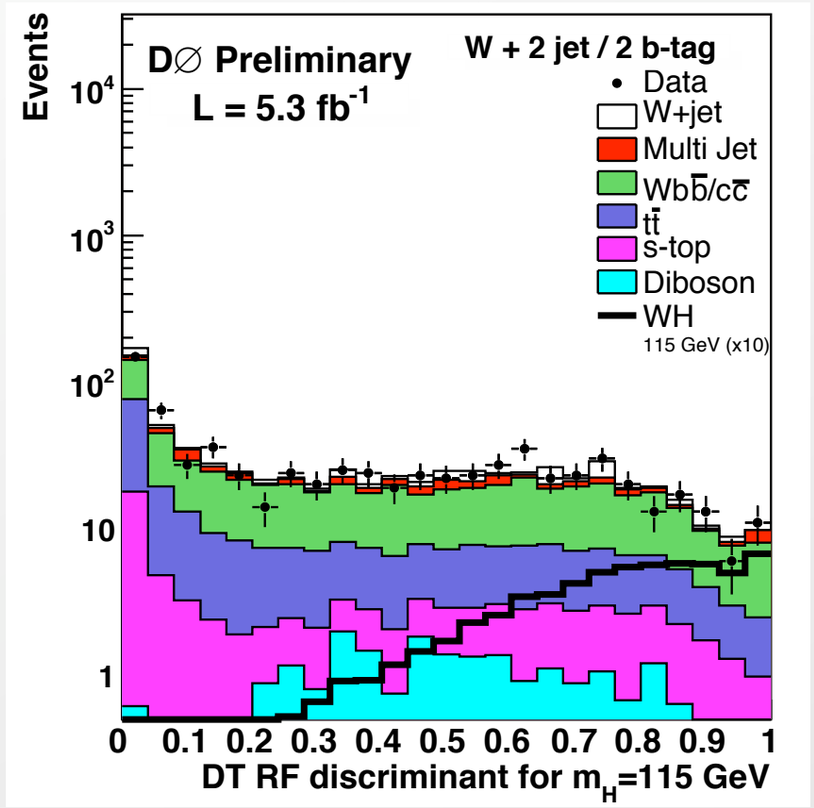


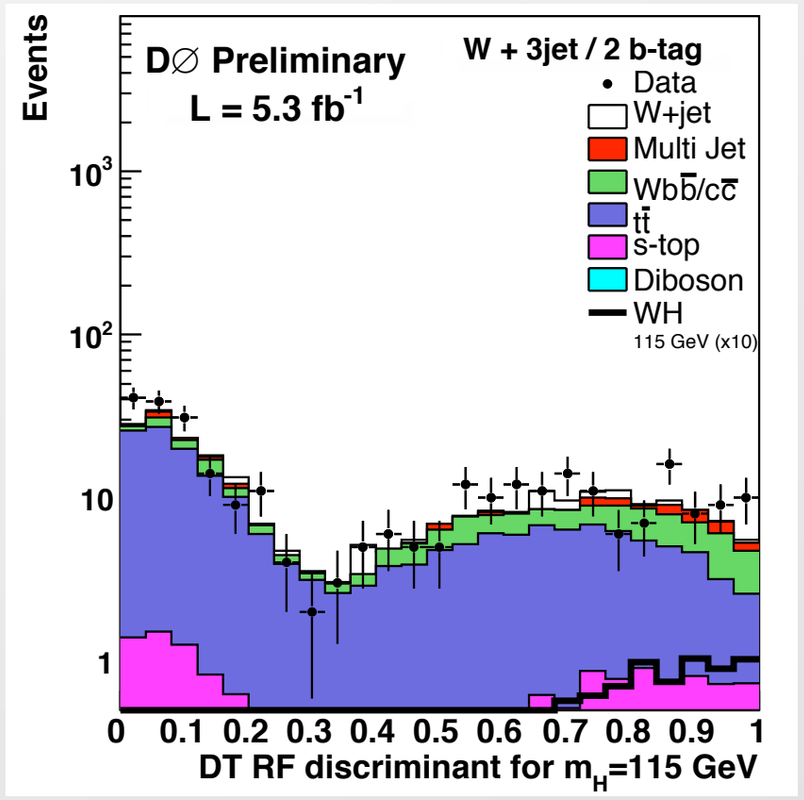



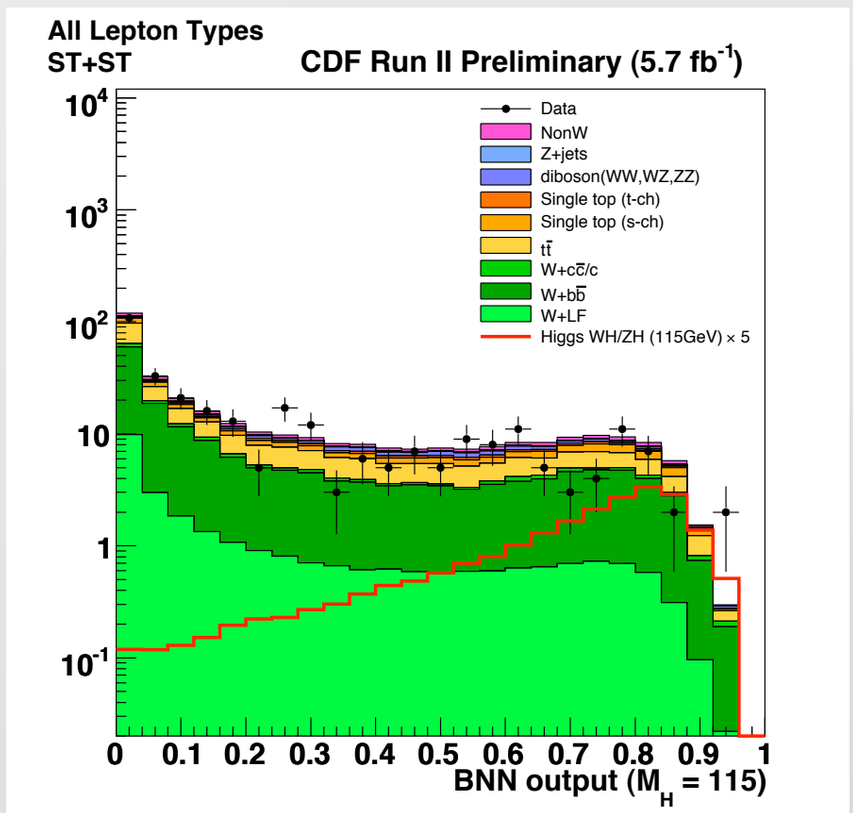



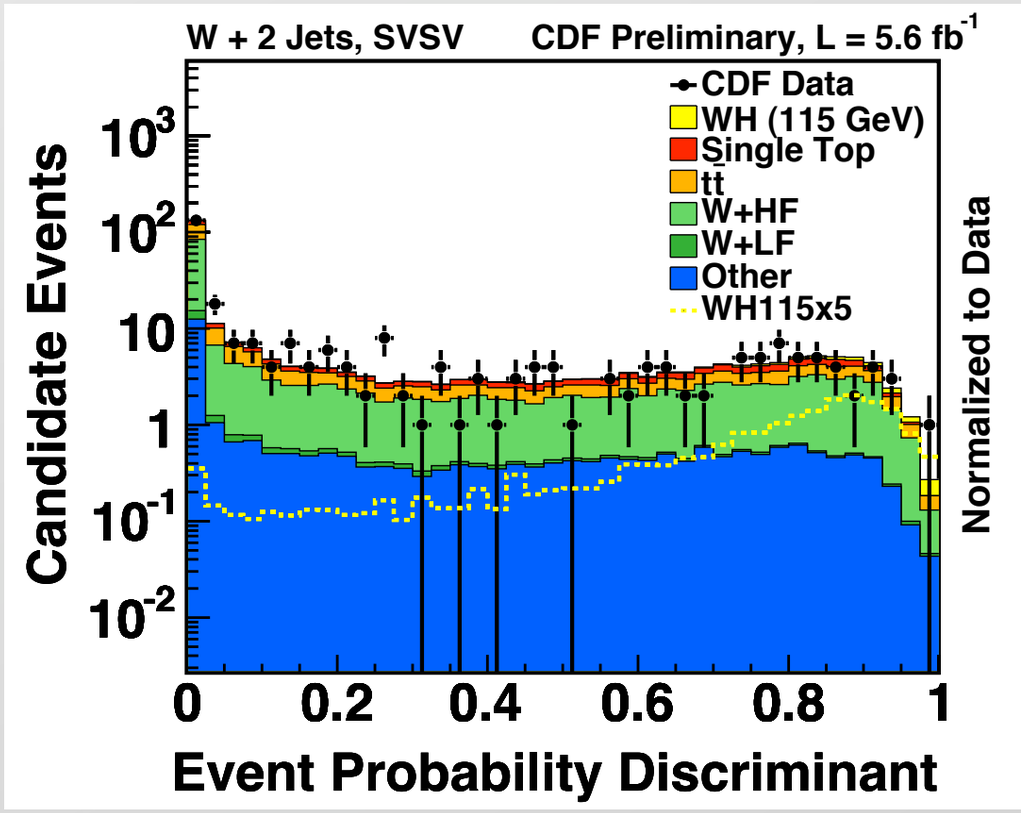



# $WH \to \ell\nu b\bar{b}$ *Final Discriminants*

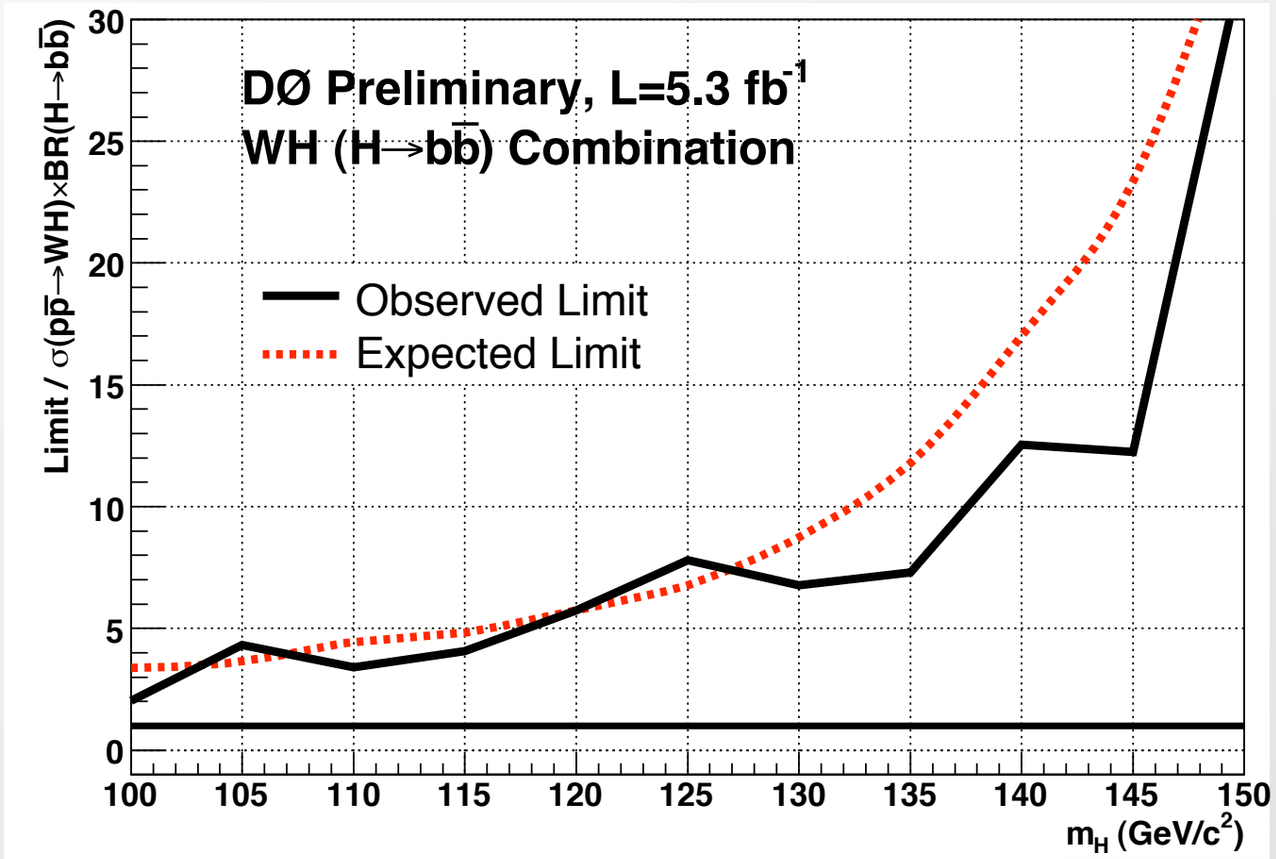


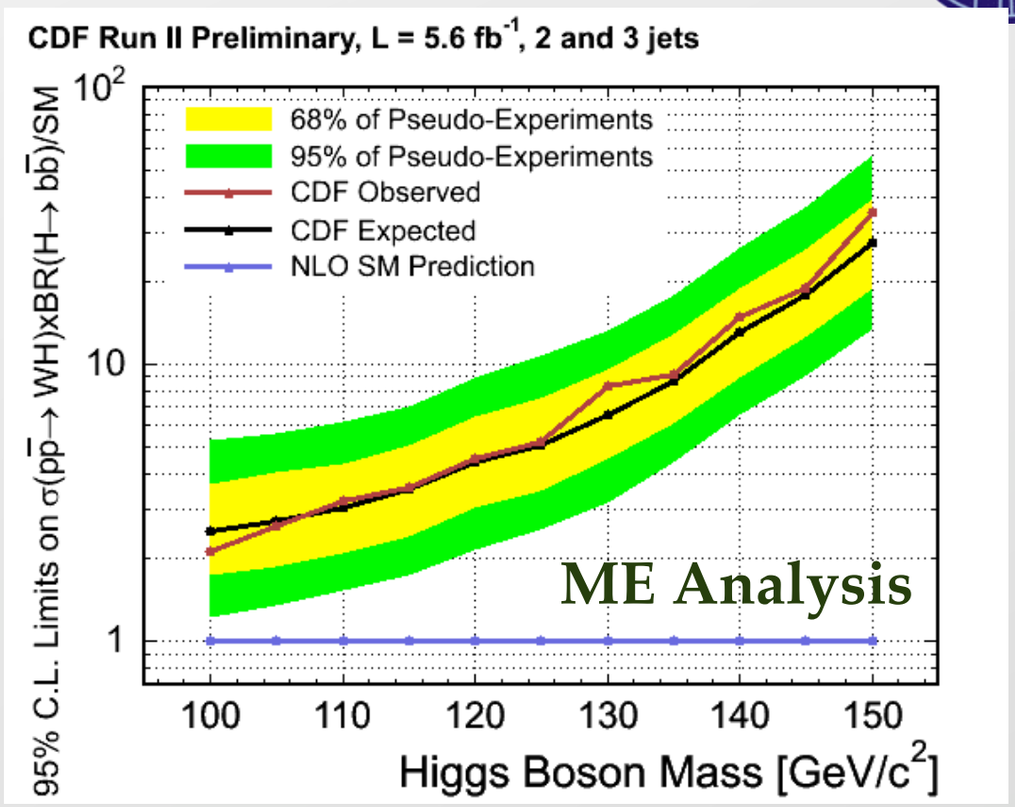



# $WH \to \ell\nu b\bar{b}$ Results



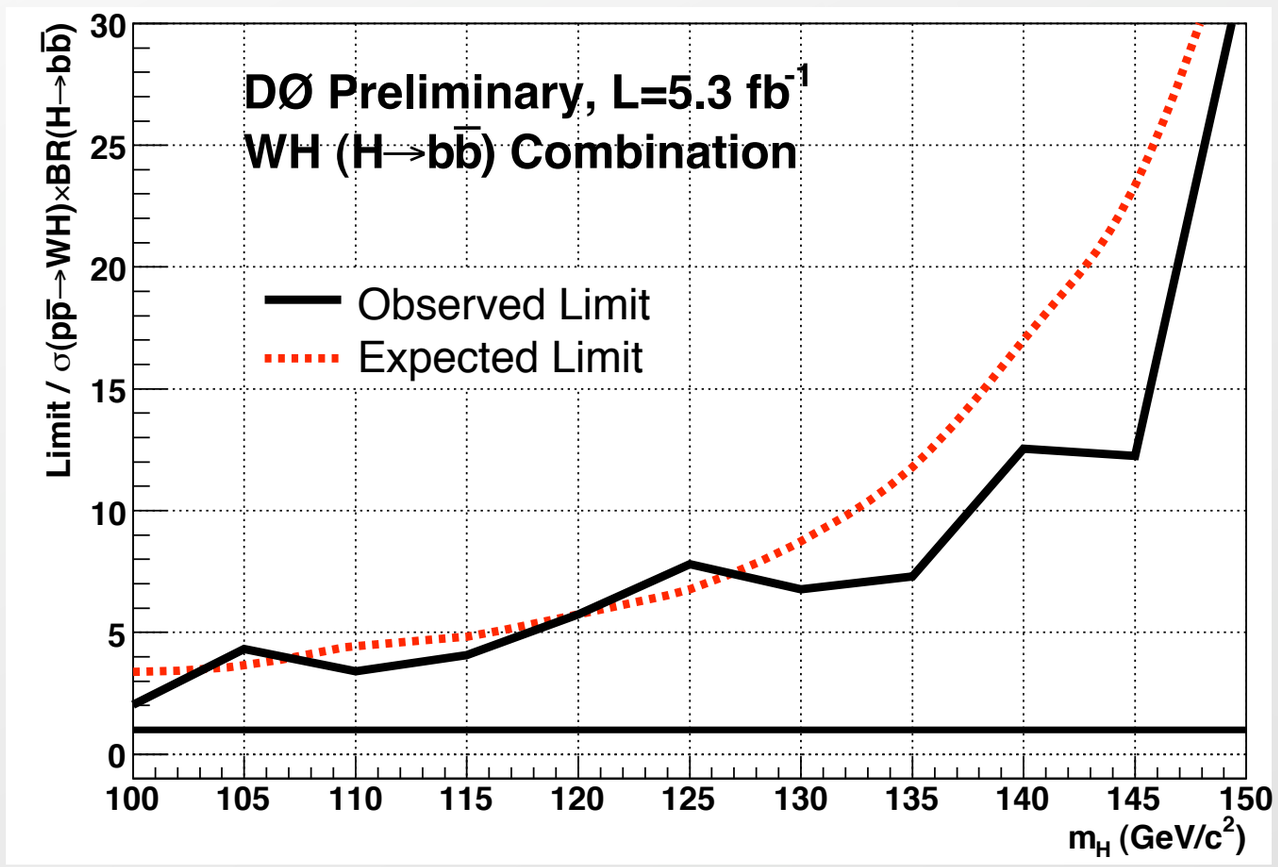



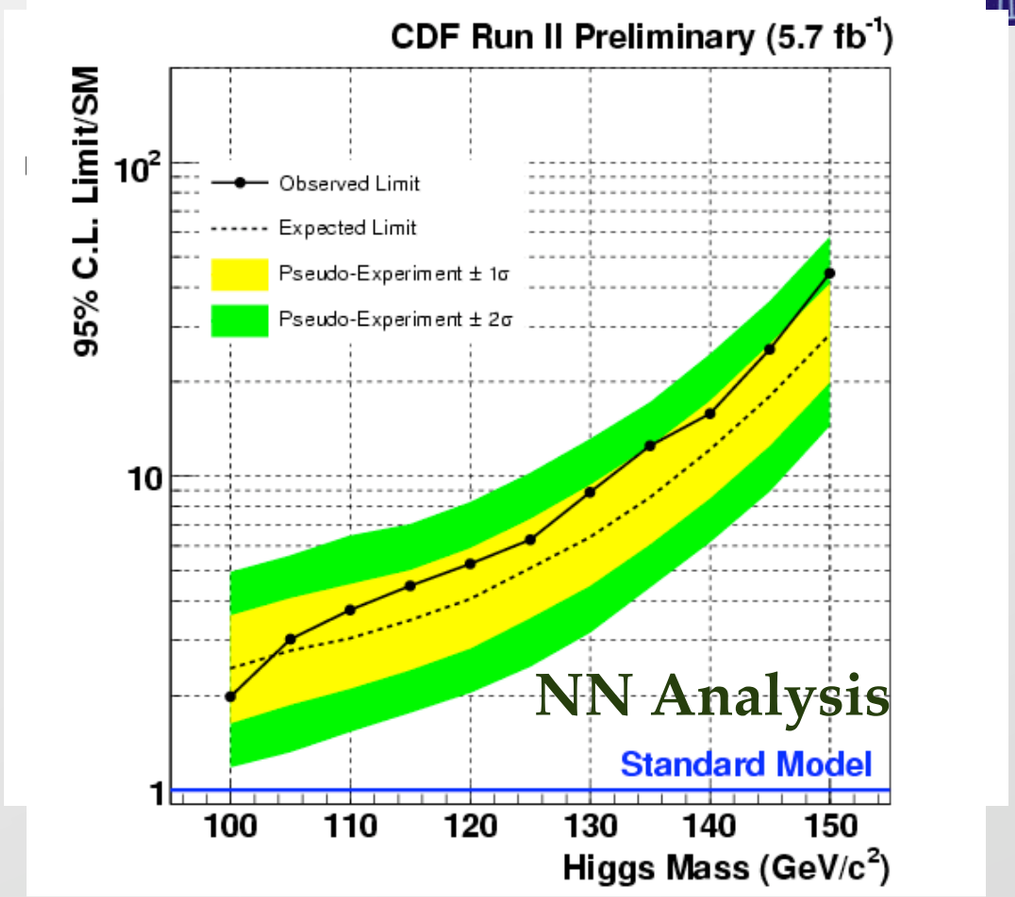

| Experiment | Lum | Obs/SM | Exp/SM |
|---|---|---|---|
| D0 | 5.3 $fb^{-1}$ | 3.7 | 4.7 |
| CDF | 5.7 $fb^{-1}$ | 3.6/4.5 | 3.5/3.4 |



$M_h = 115\ GeV/c^2$

# $WH \to \ell\nu b\bar{b}$ Results

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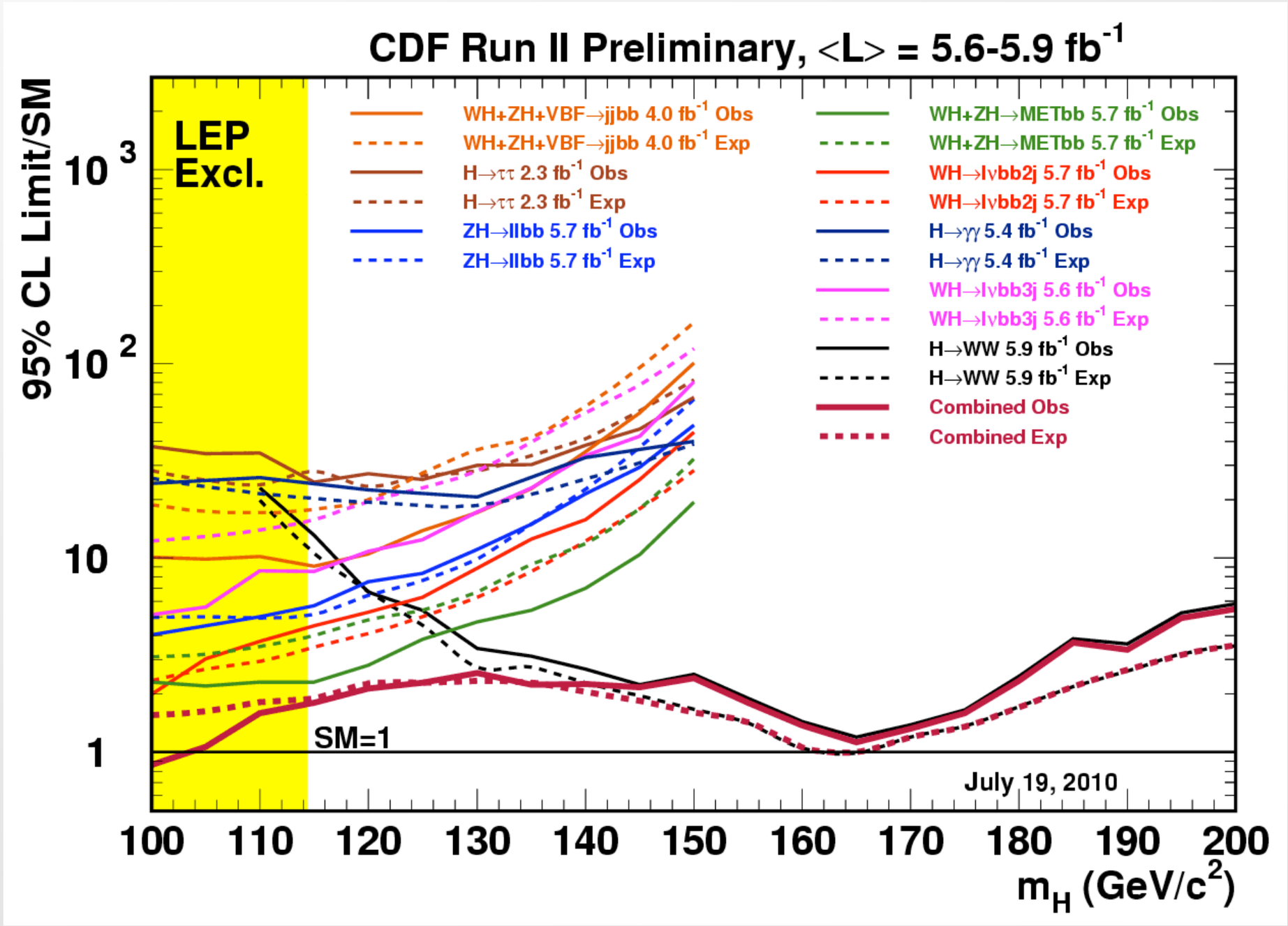
$M_h = 115\ GeV/c^2$

# CDF/D0 Combinations



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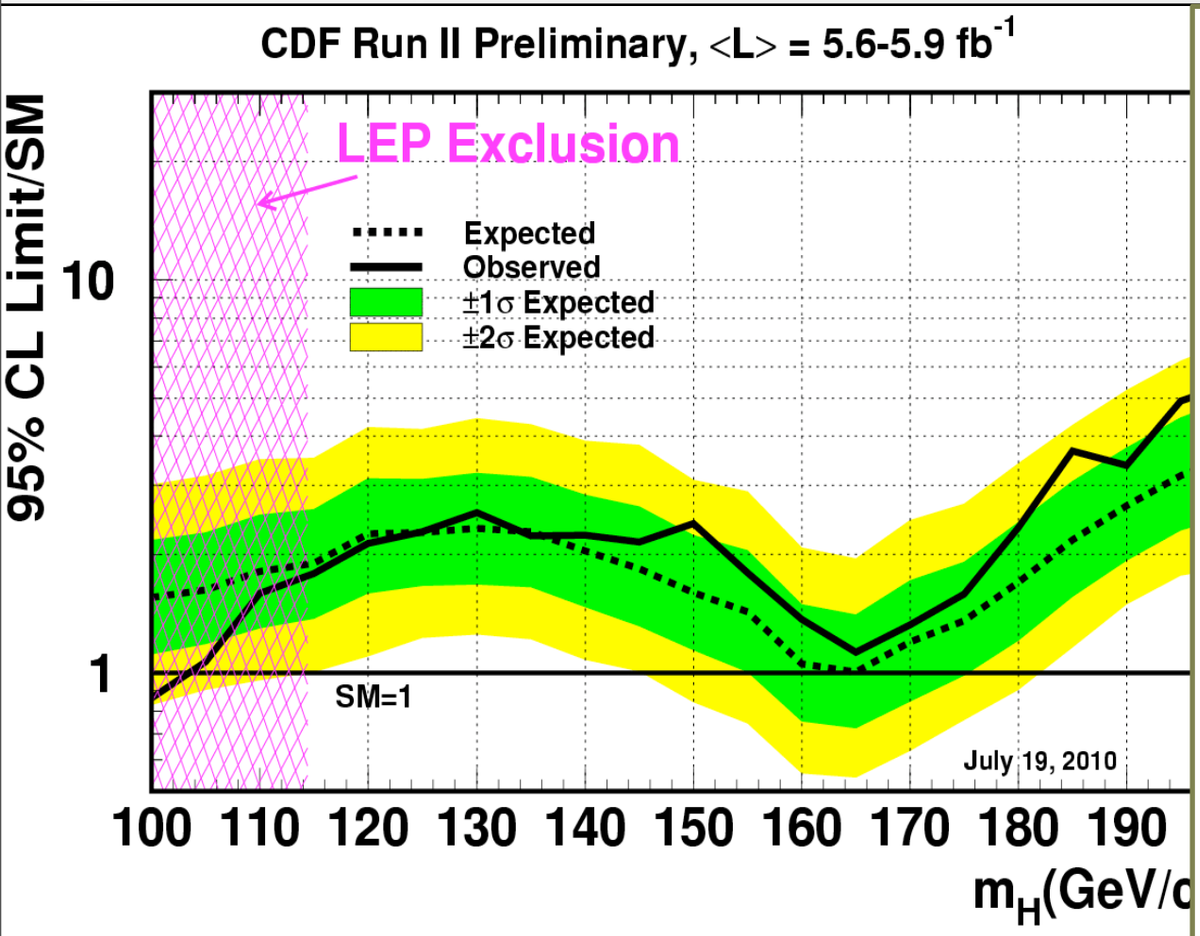
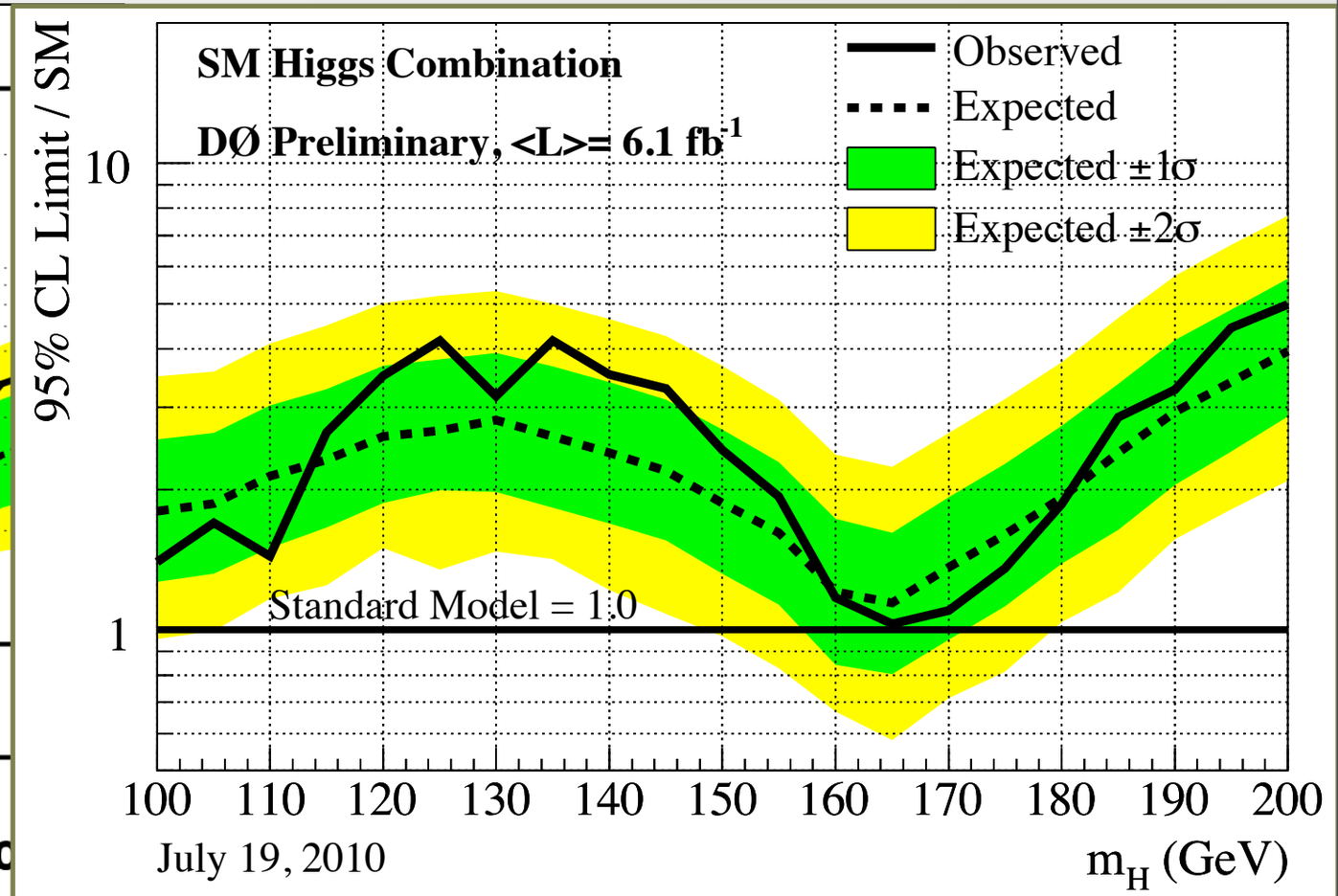
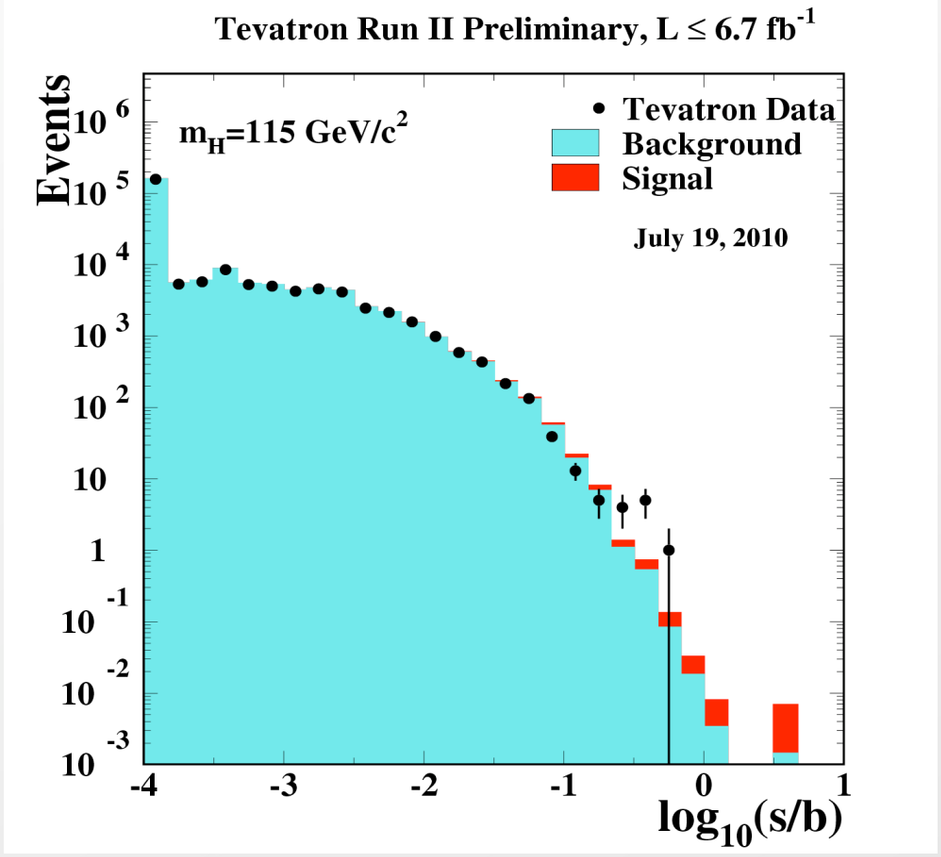
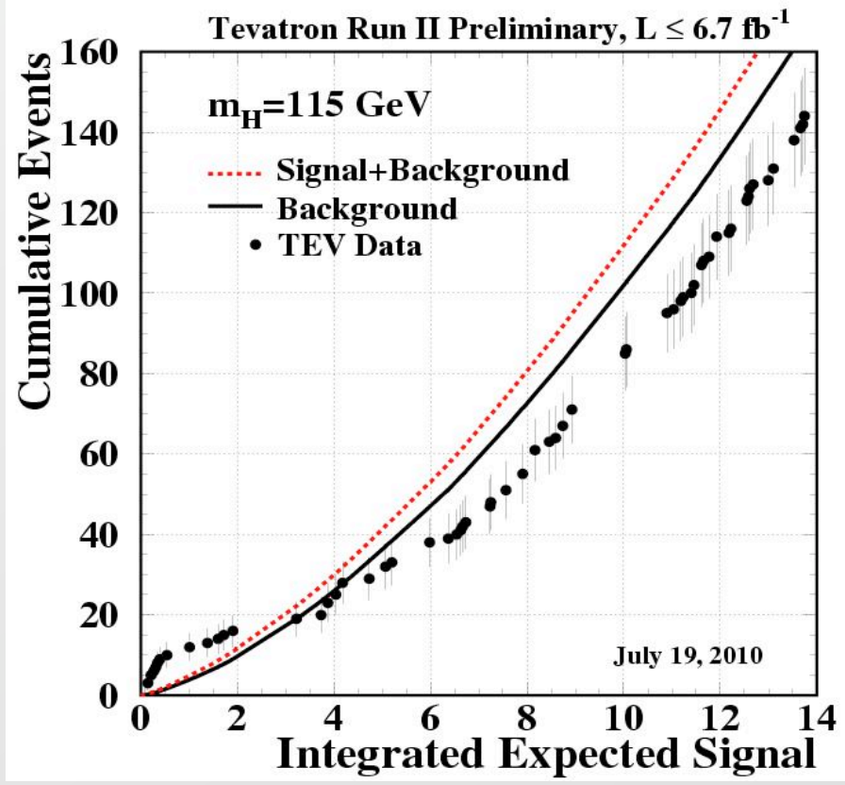
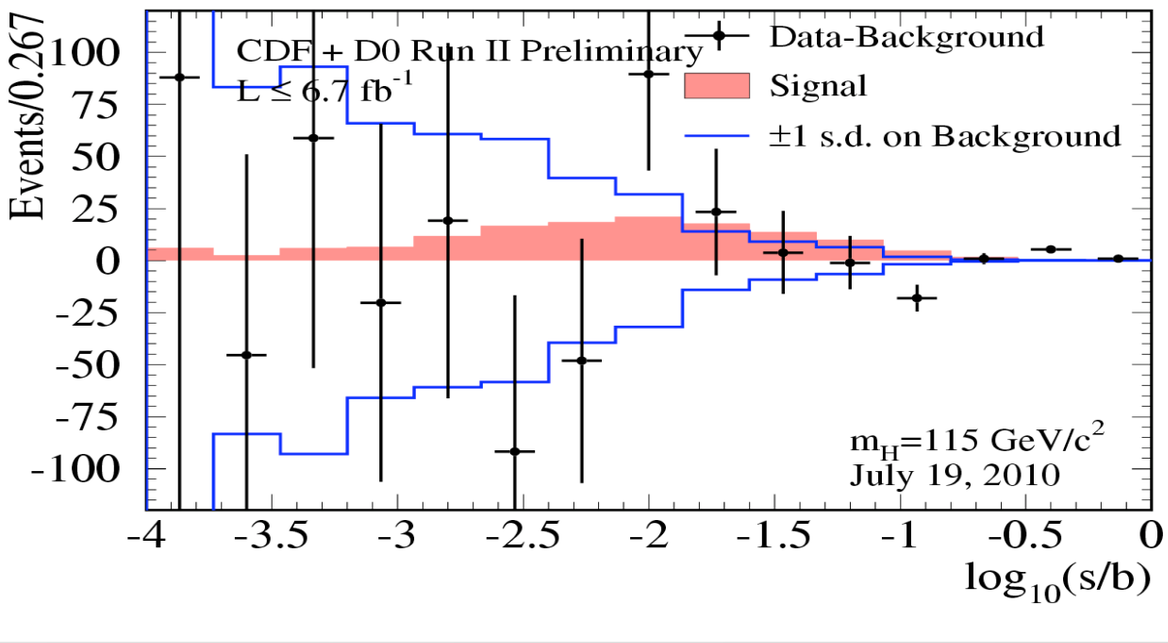


# *Tevatron Candidate Summary, $m_H$=115 GeV*

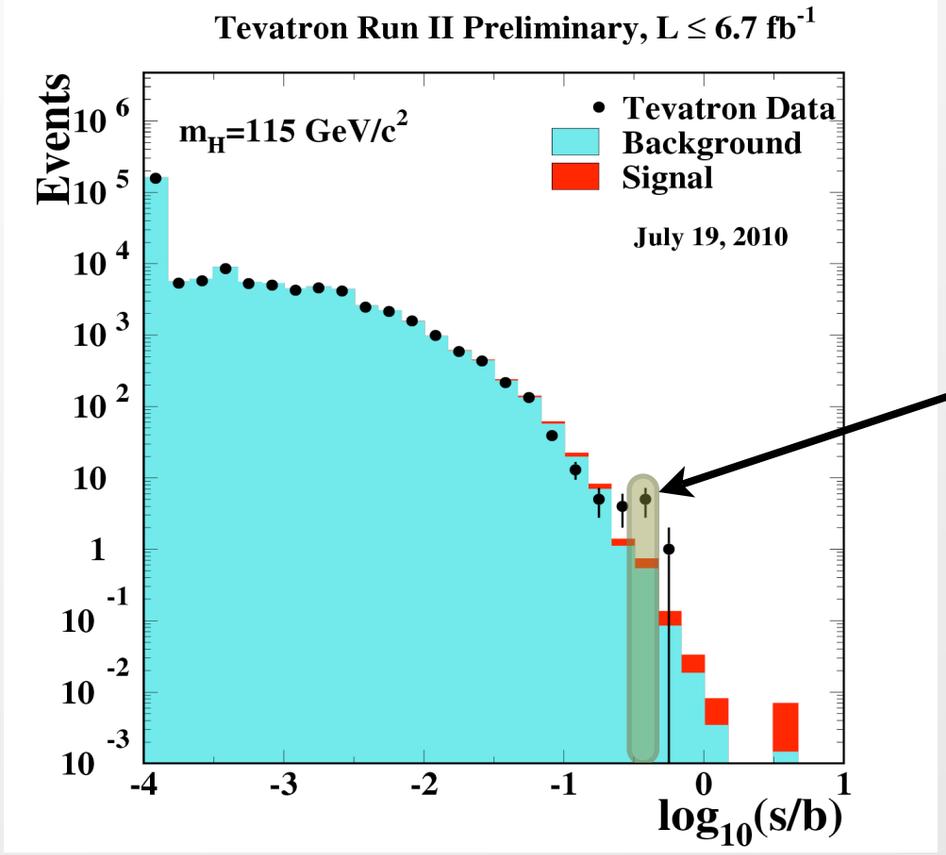


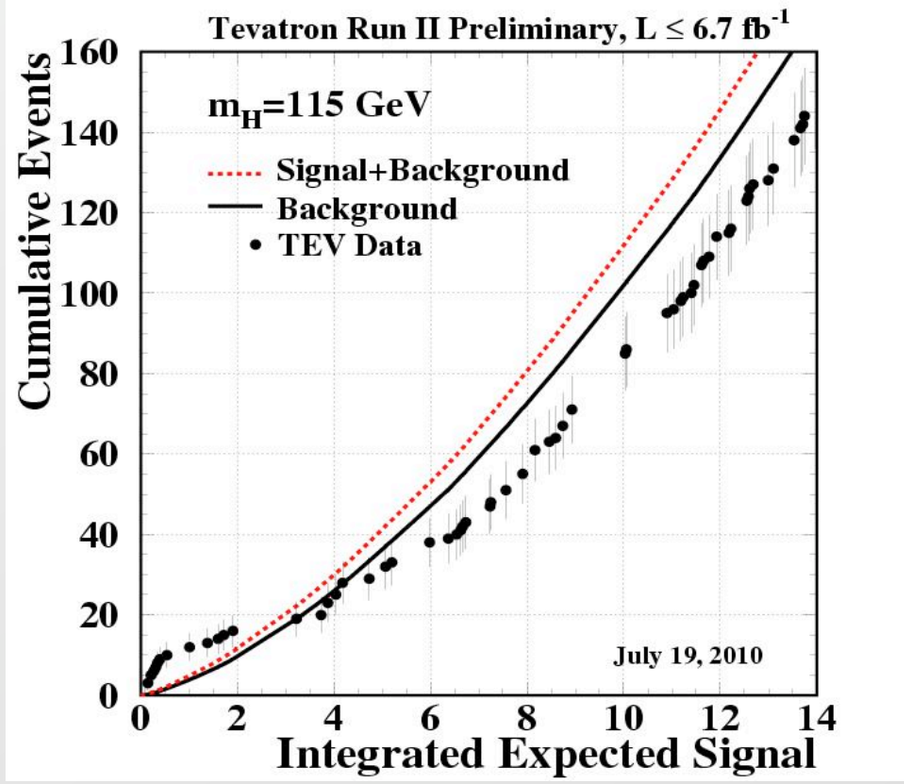



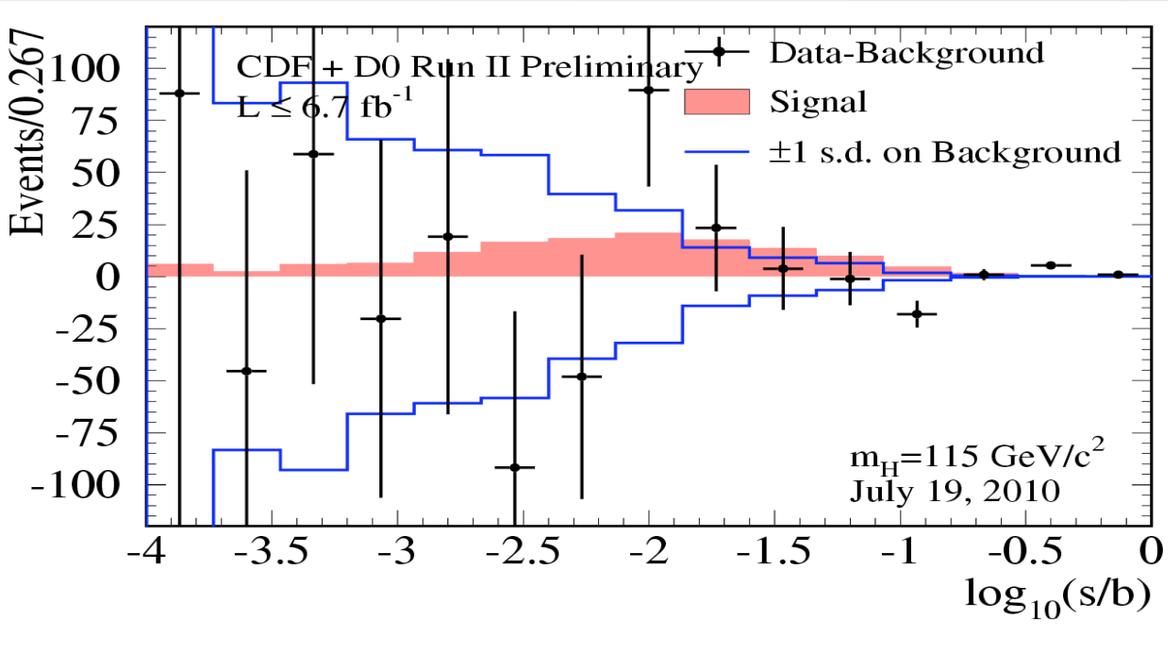

Fluctuations: Excess and deficit average out :
Expected limit 1.45*SM
Observed limit 1.56*SM

# *Tevatron Candidate Summary, $m_H$=115 GeV*




Data: 5 events
Backgnd: 0.8 events
S:B ~ 1:2

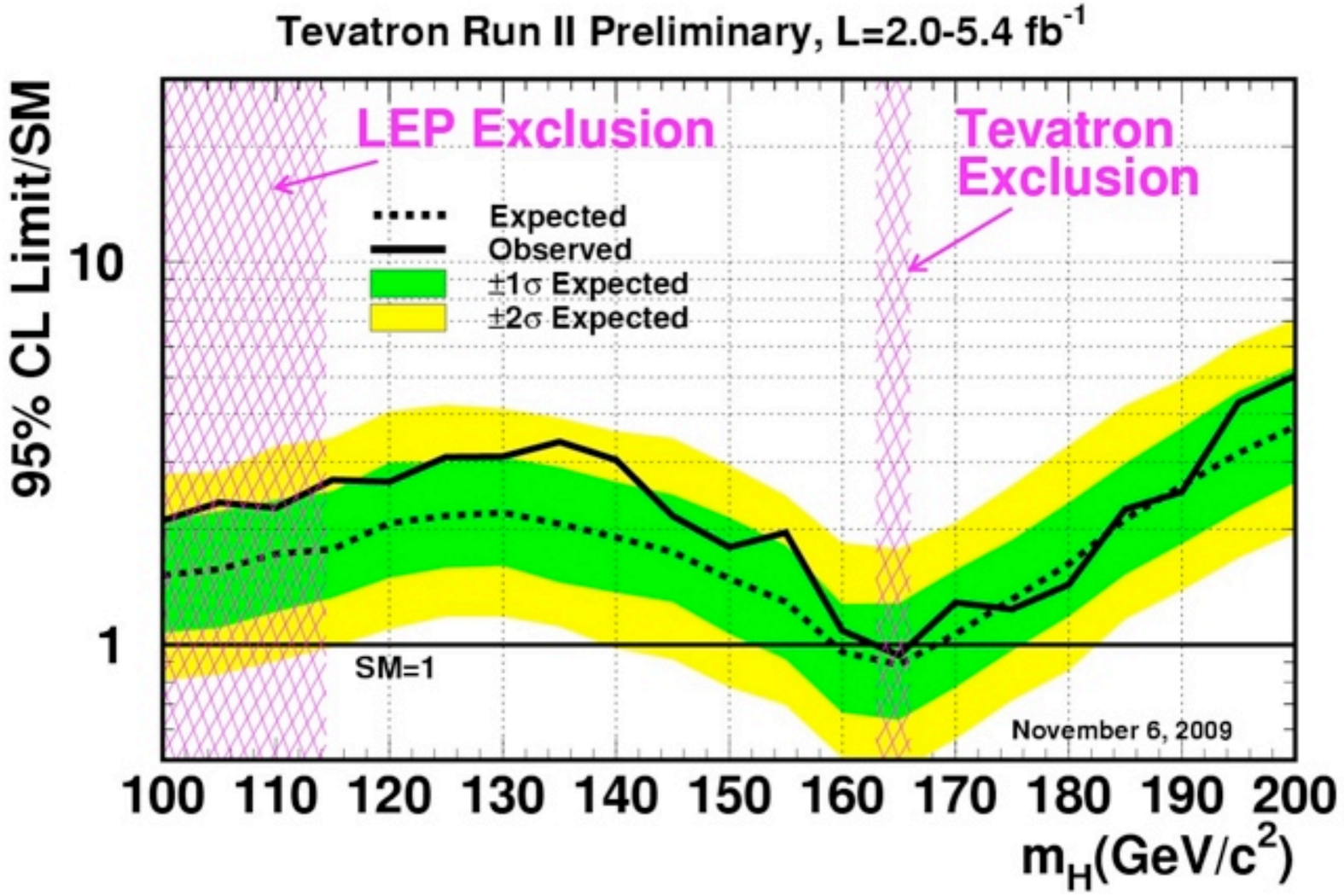



Fluctuations: Excess and deficit average out :
Expected limit 1.45*SM
Observed limit 1.56*SM

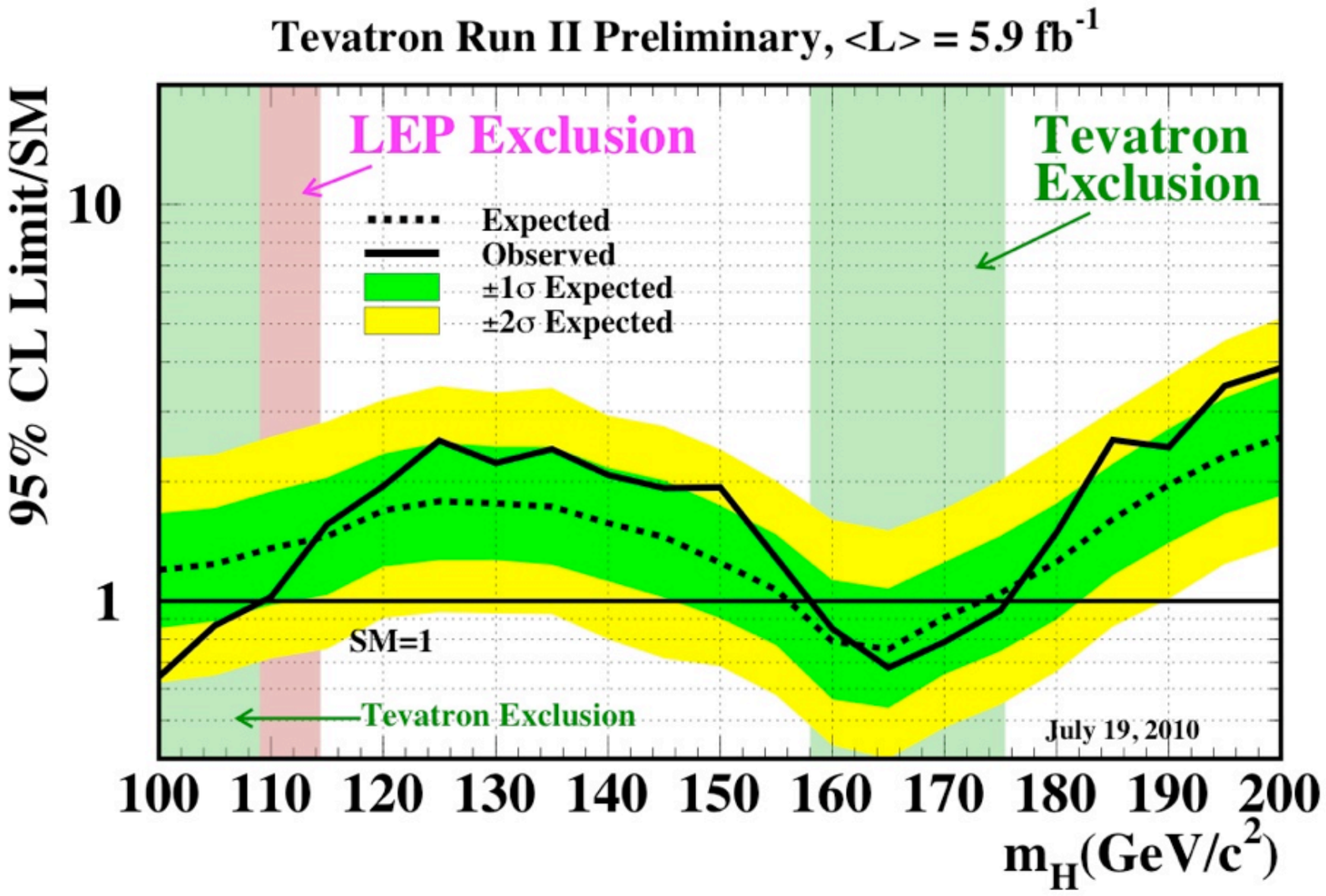
# *Conclusion: Tevatron Combination*

## *November 2009 Result*



# *Conclusion: Tevatron Combination*

## *New Result*




Low mass sensitivity approaching LEP exclusion :

At $M_H$ 105 GeV:

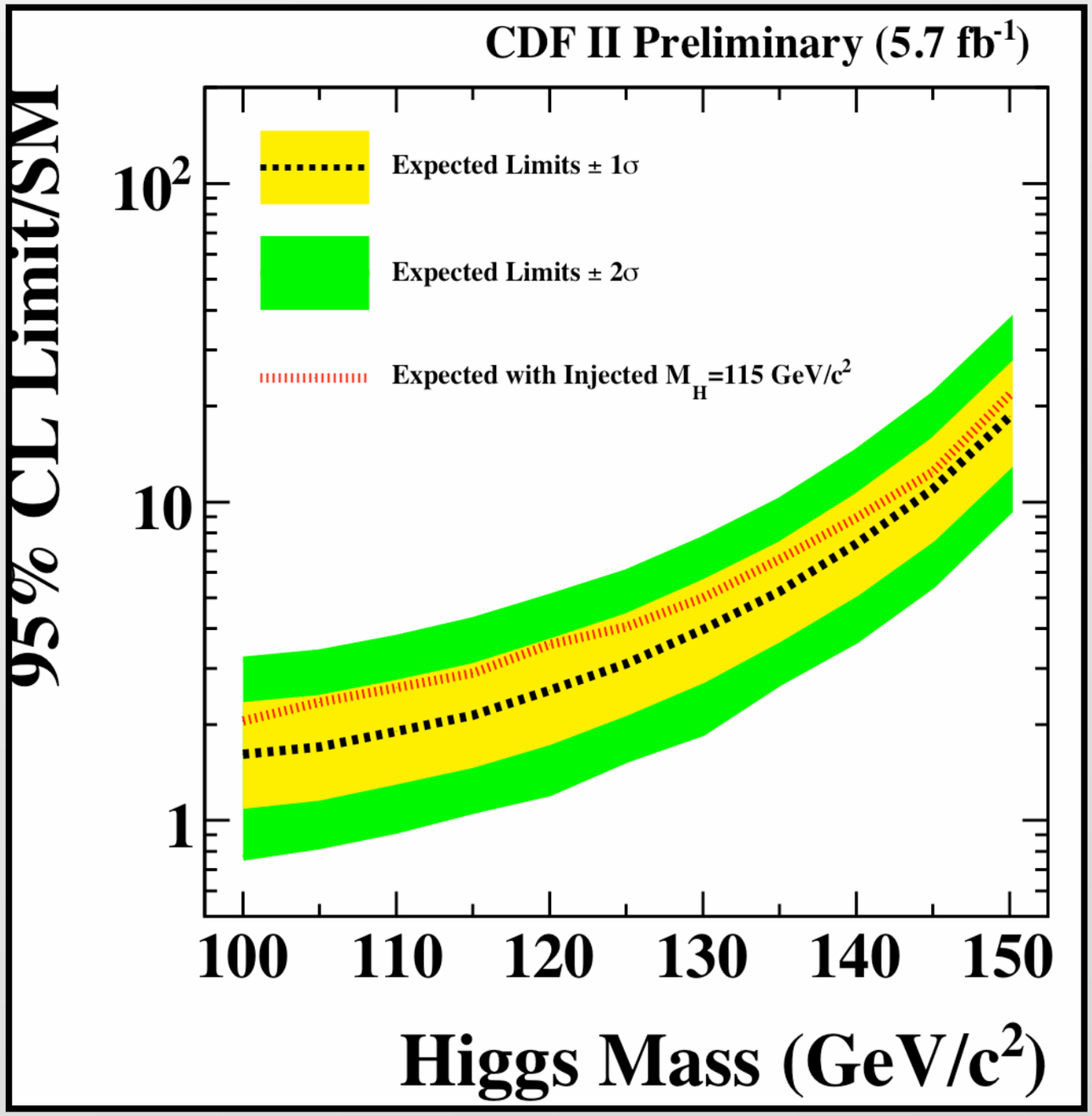
Expected Limit 1.24*SM

At $M_H$ 115 GeV:

Expected Limit 1.45*SM

# *Studies of Injecting a Signal at $m_H$=115 GeV*

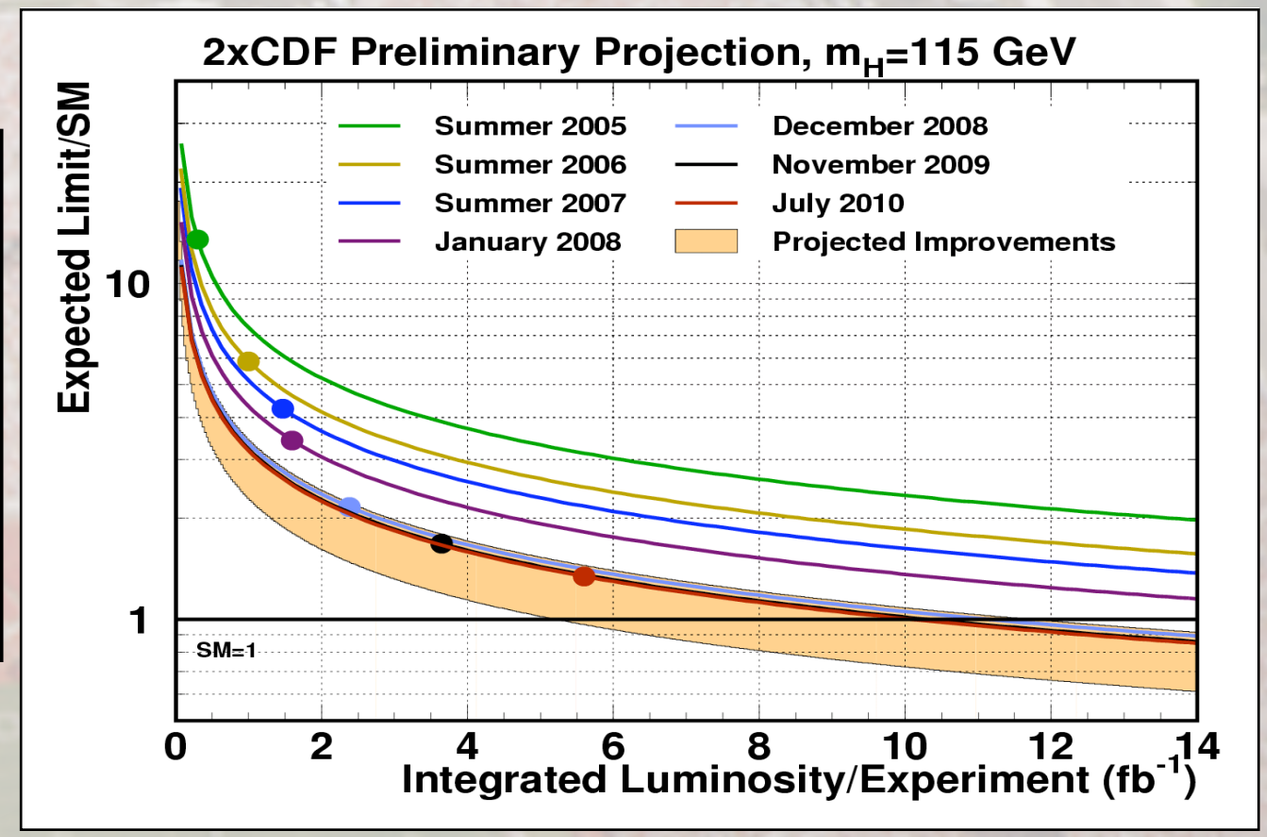
- lvbb, METbb, and llbb channels included
- Inject SM*1.0 signal at $m_H$=115 GeV on top of SM backgrounds, and generate pseudoexperiments with that.
- Analyze 115 signal+background pseudoexperiments at other test masses –100 GeV to 150 GeV
- Find the median expected limit with injected signal and compare with the distribution of limits when the signal is completely absent.

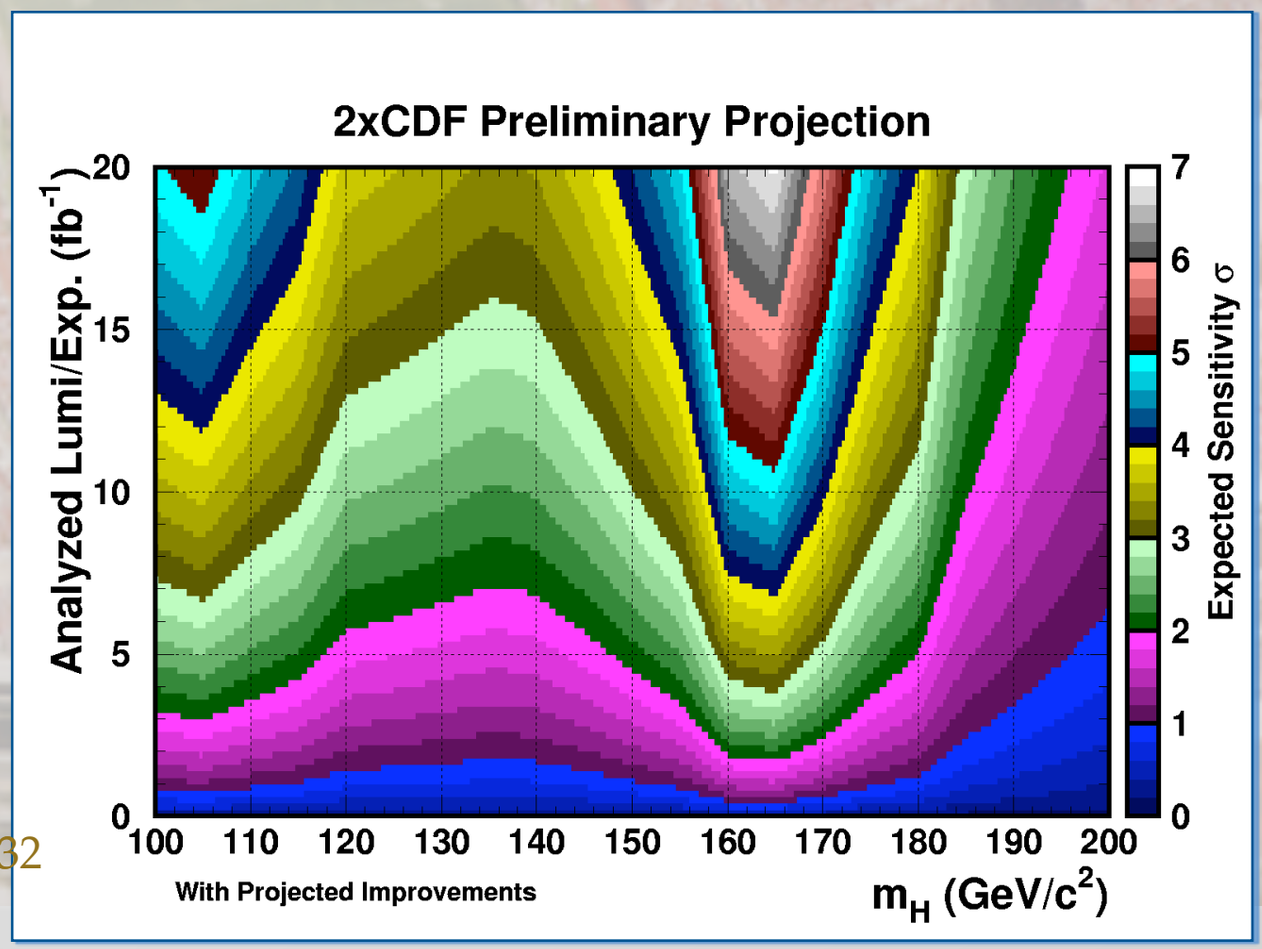


# *Future Expectations*

**Delivered luminosity now ~8.5 $fb^{-1}$ per experiment**

**Tevatron will deliver ~11 $fb^{-1}$ per experiment by end of 2011**



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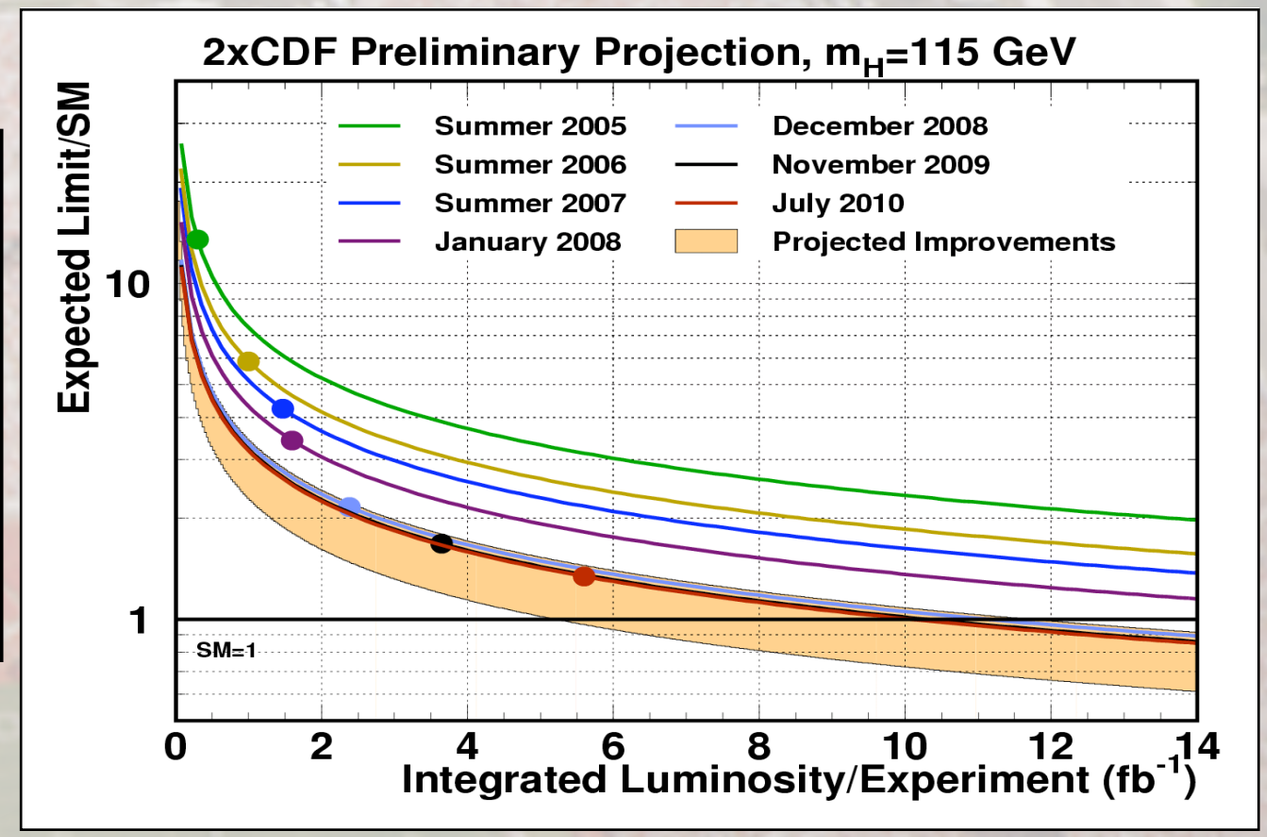
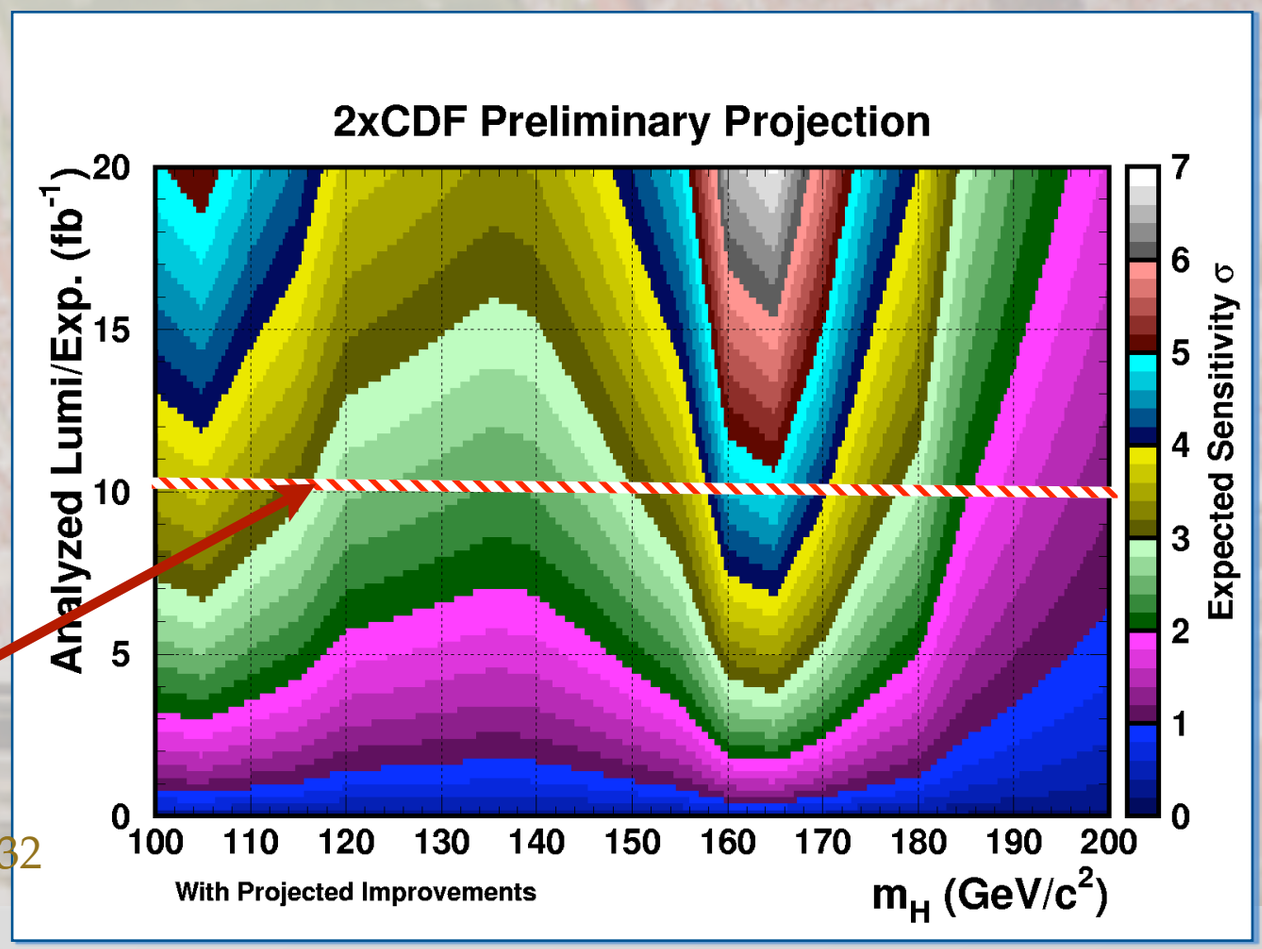



**Sensitivity to SM Higgs with 10 $fb^{-1}$ per experiment**

**➡Better than 2.4 σ expected sensitivity from 100 – 185 GeV**

**➡ 3 σ @ 115 GeV**



# *Future Expectations*

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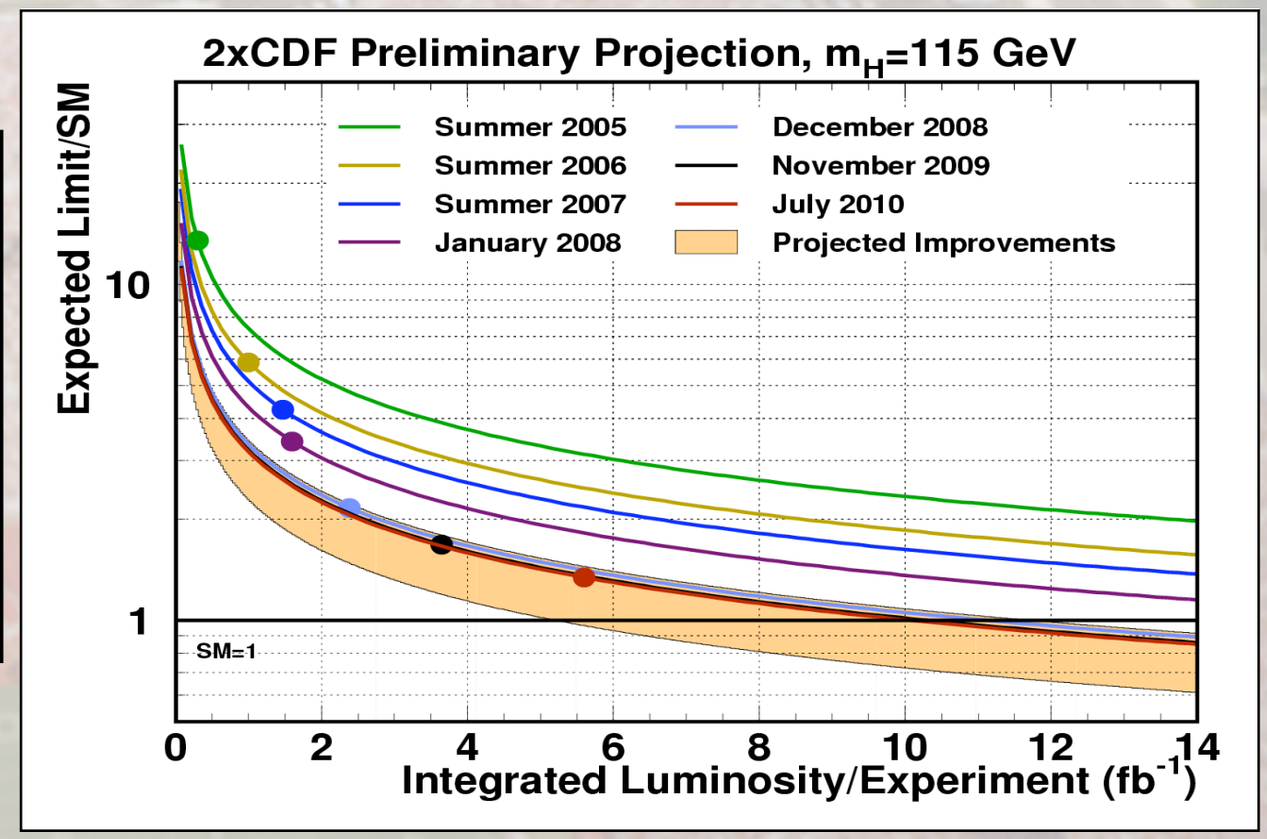


**Sensitivity to SM Higgs with 16 $fb^{-1}$ per experiment**

**➡Better than 3 σ expected sensitivity from 100 – 185 GeV**

**➡ 4 σ @ 115 GeV**

**Sensitivity to SM Higgs with 10 $fb^{-1}$ per experiment**

**➡Better than 2.4 σ expected sensitivity from 100 – 185 GeV**

**➡ 3 σ @ 115 GeV**