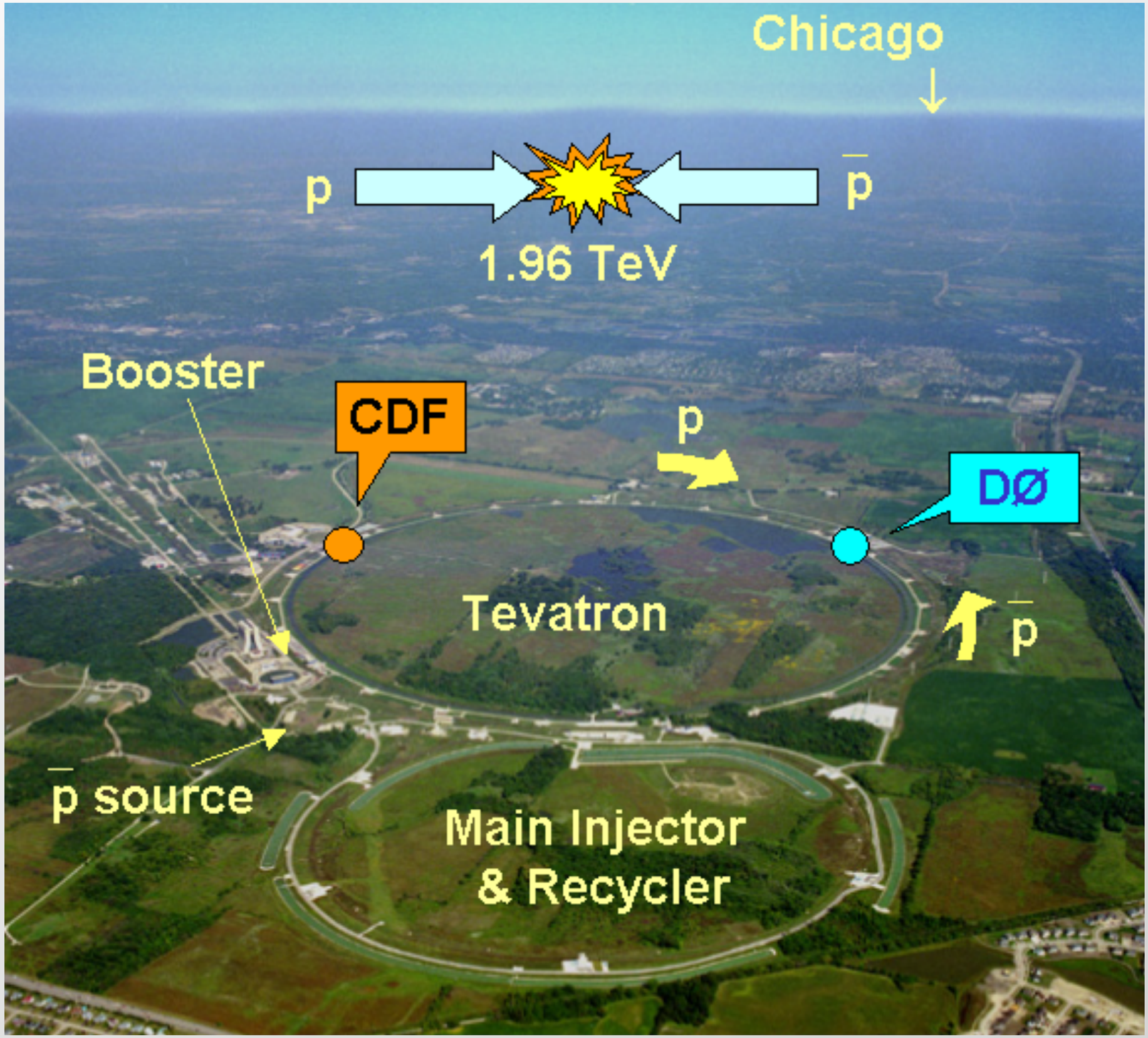
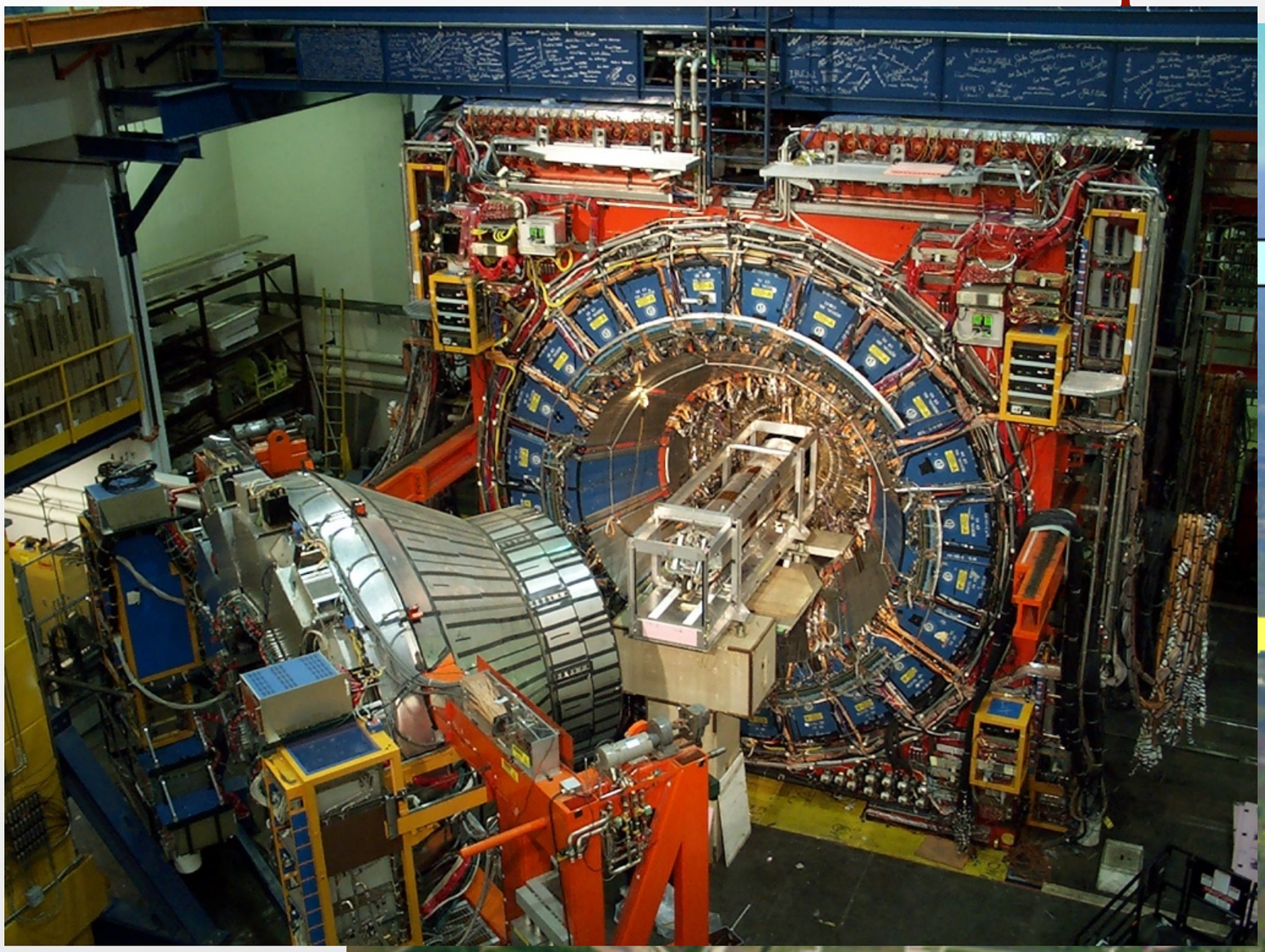
Richard E. Hughes
The Ohio State University
for
The CDF and DO Collaborations

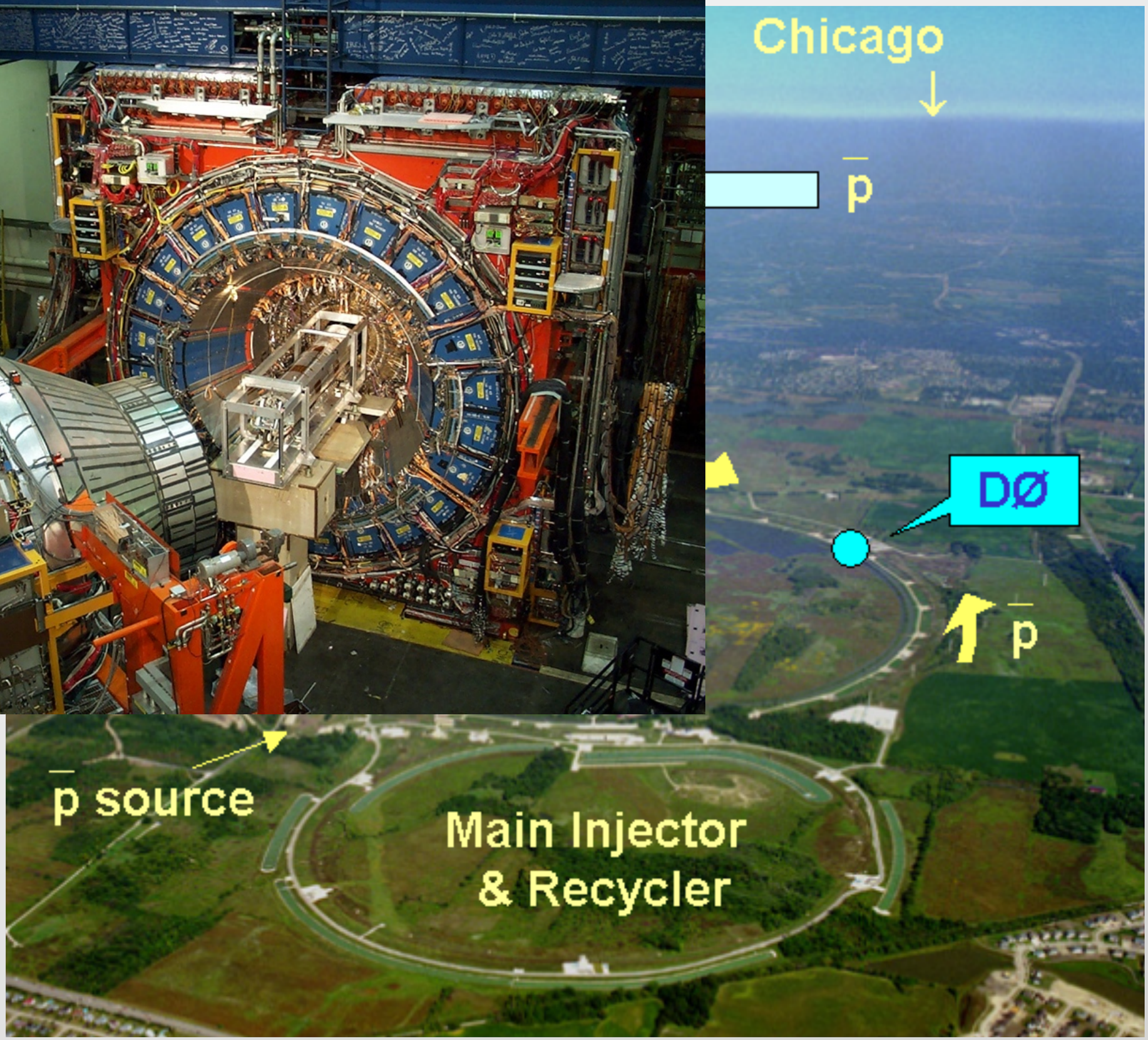
Low Mass SM Higgs Search at the Tevatron

Tevatron and Experiments

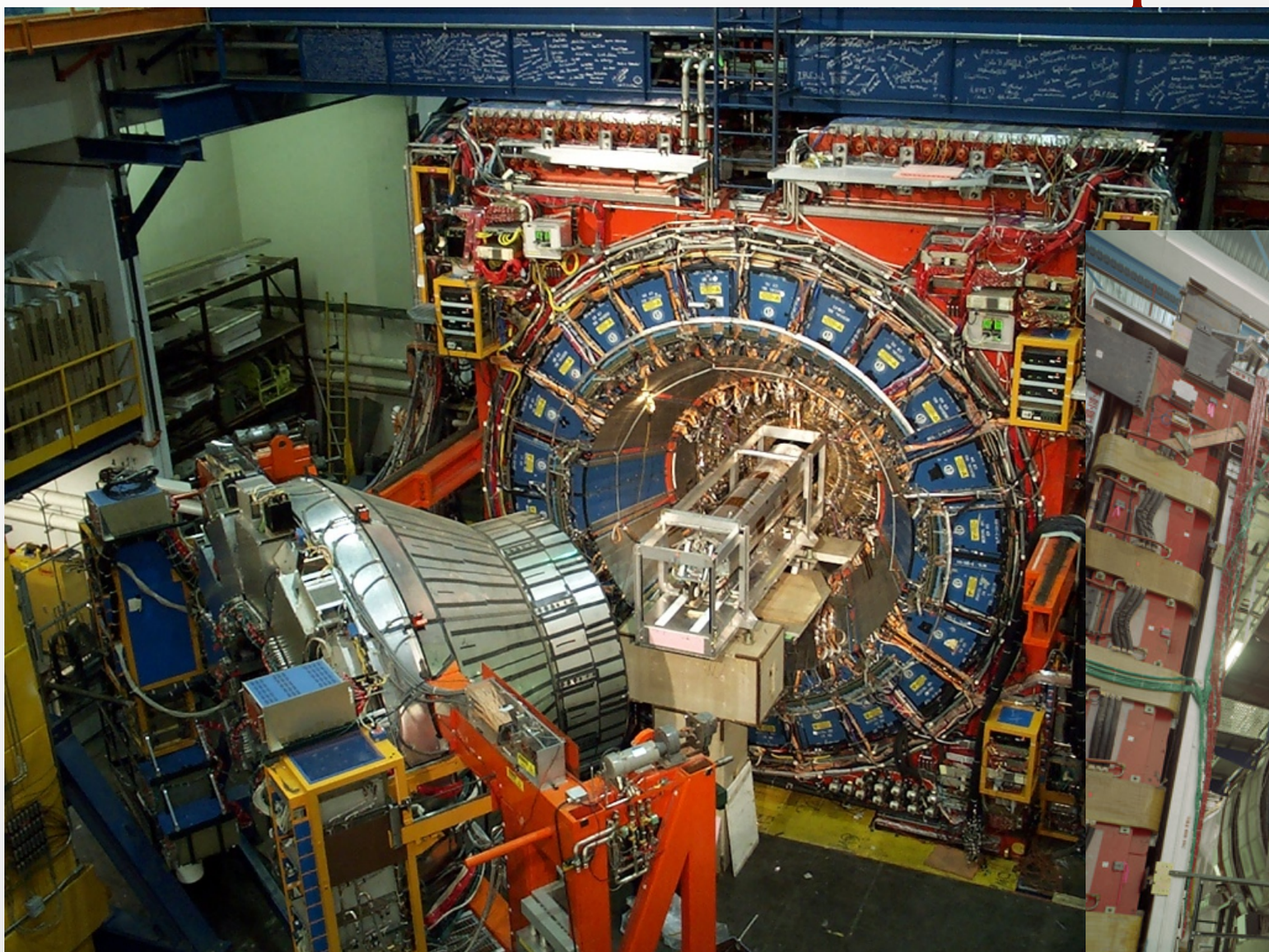


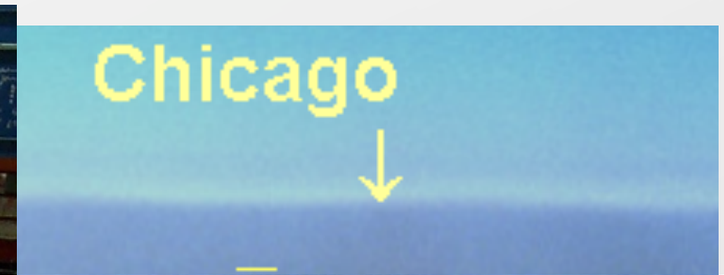
Tevatron and Experiments



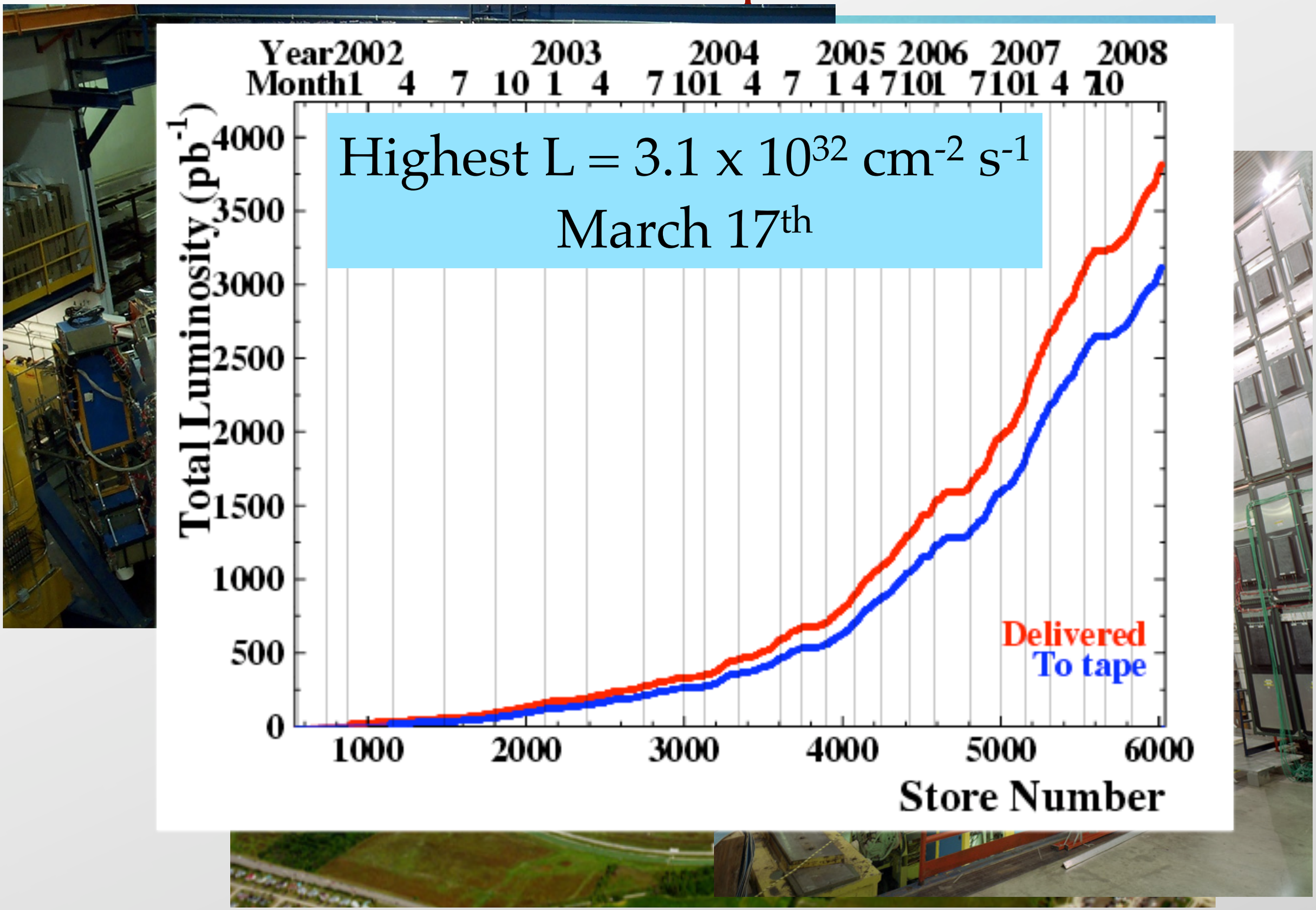


Tevatron and Experiments



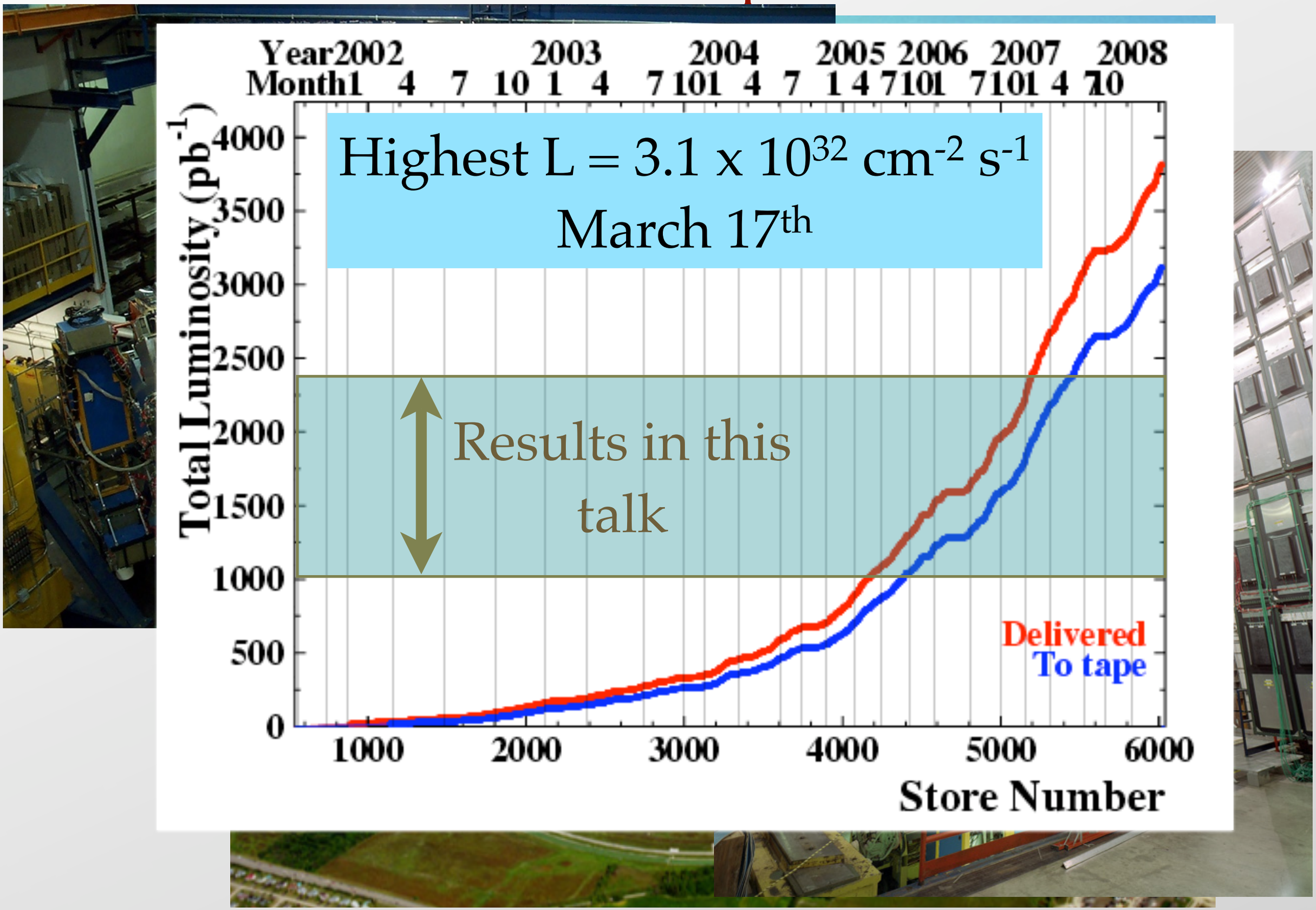


Tevatron and Experiments

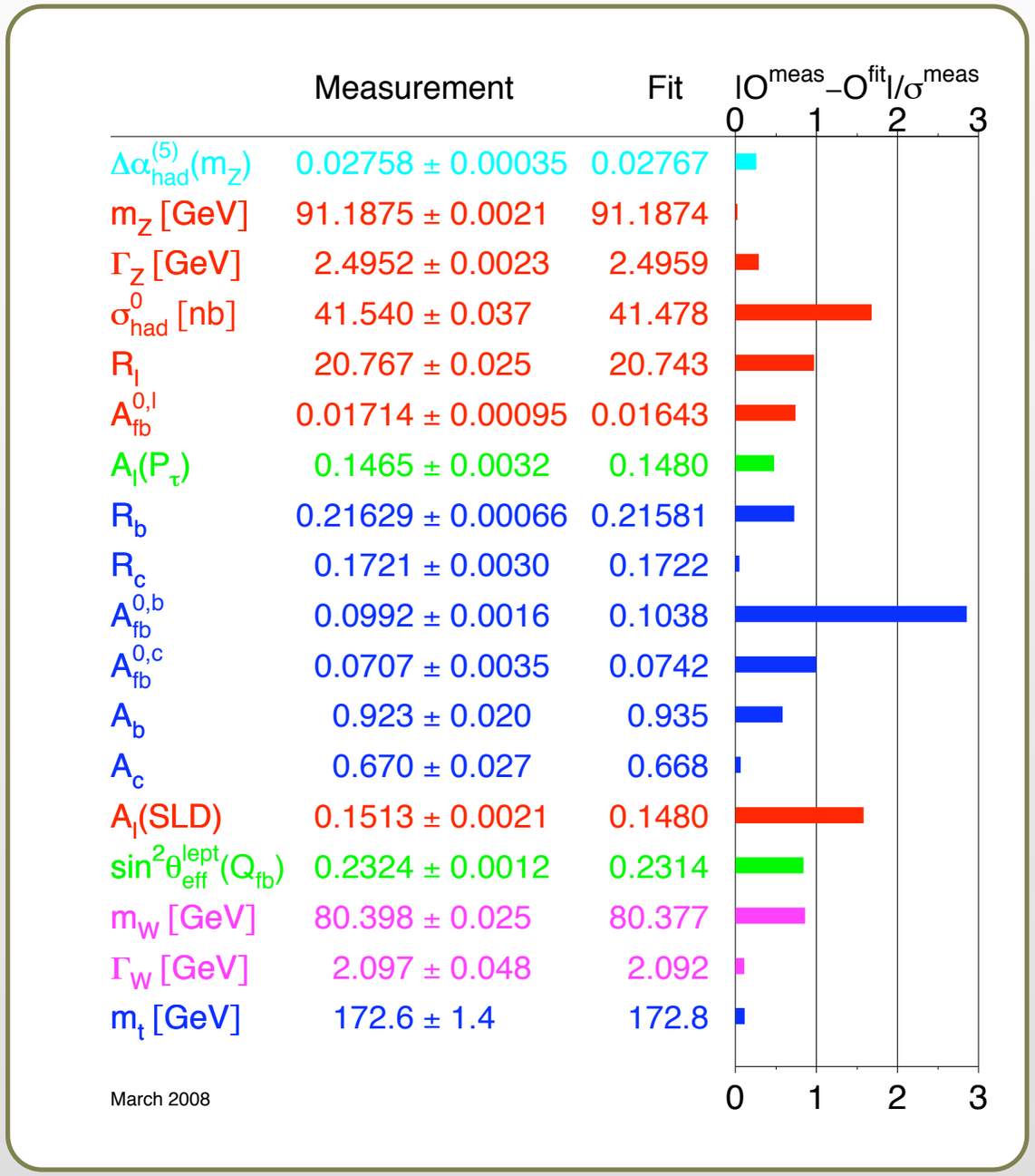


Highest L = 3.1 x 10^{32} cm^{-2} s^{-1}
March 17th

Tevatron and Experiments



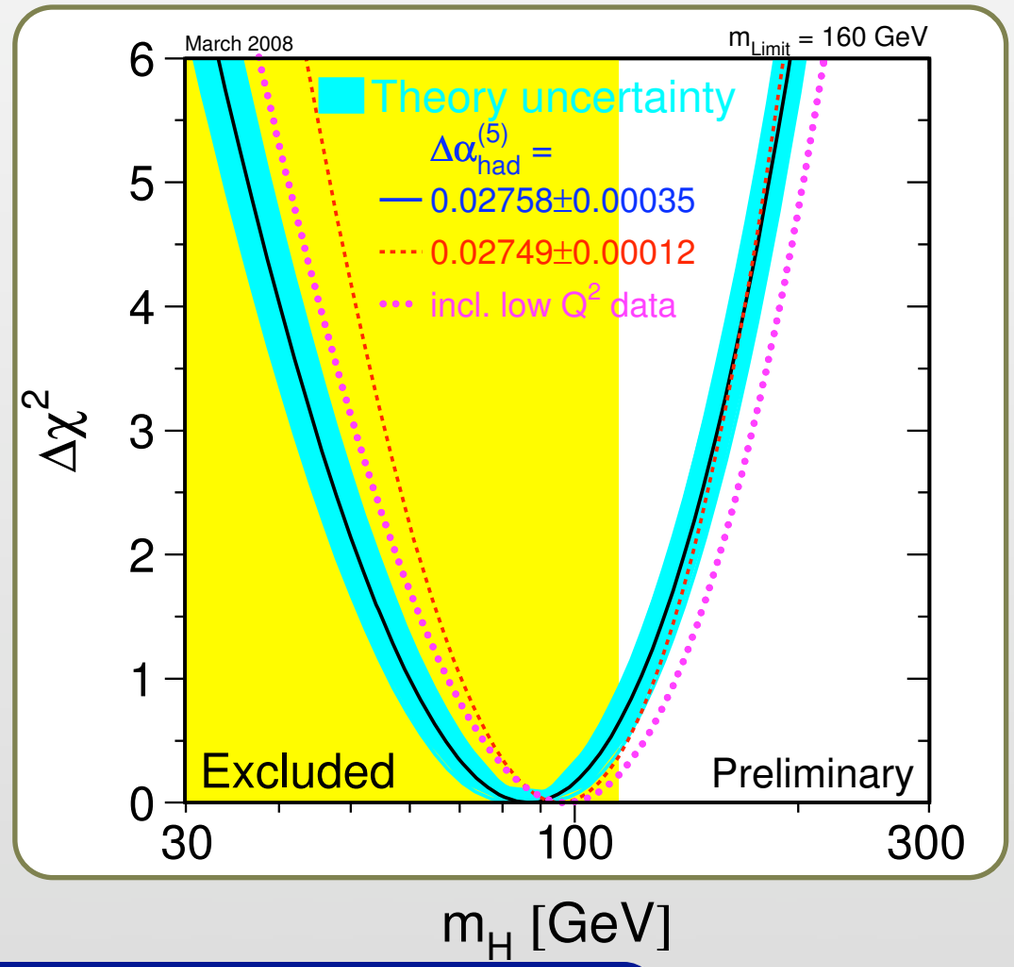
Constraints on the SM Higgs



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8

$m_H = 87^{+36}_{-27}$ GeV/c^2

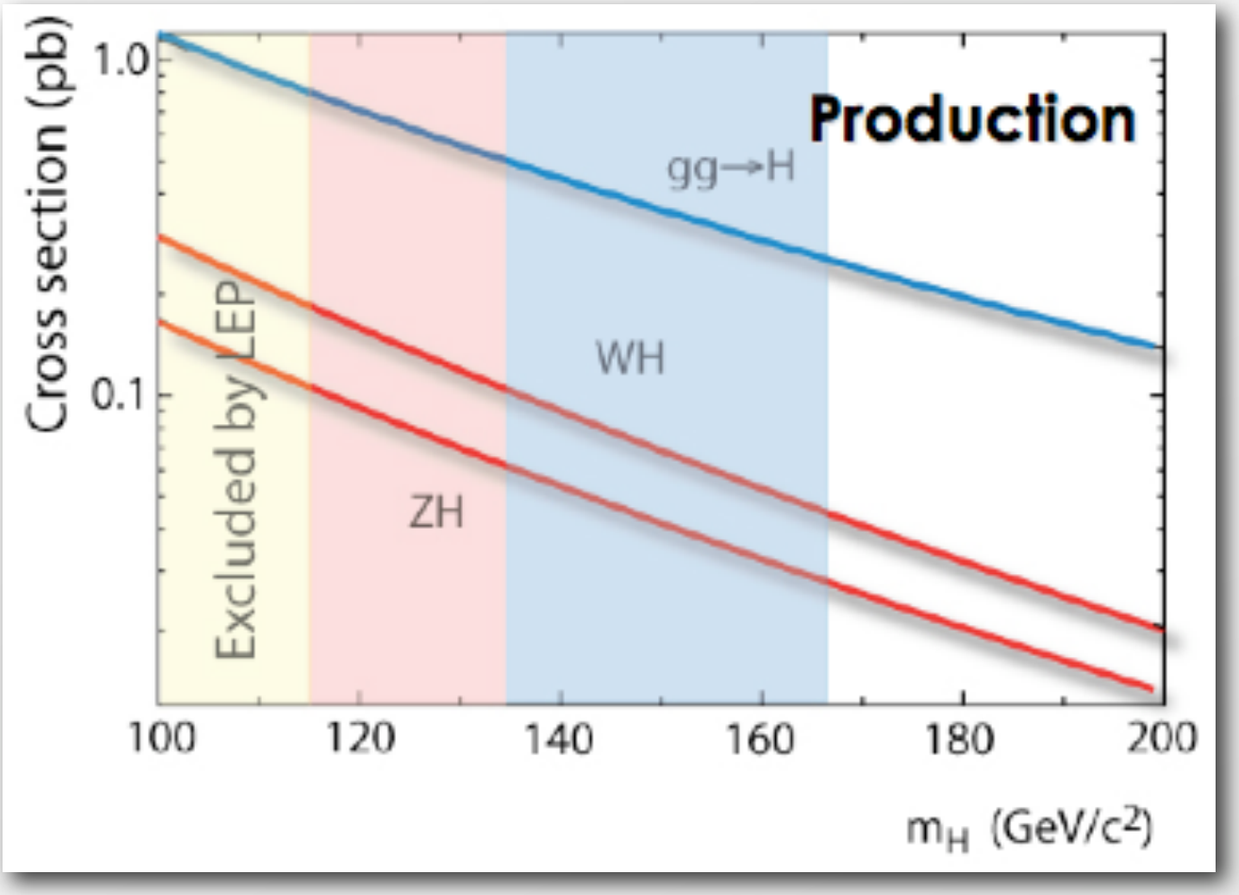
m_H < 160 GeV/c^2 @ 95 % CL

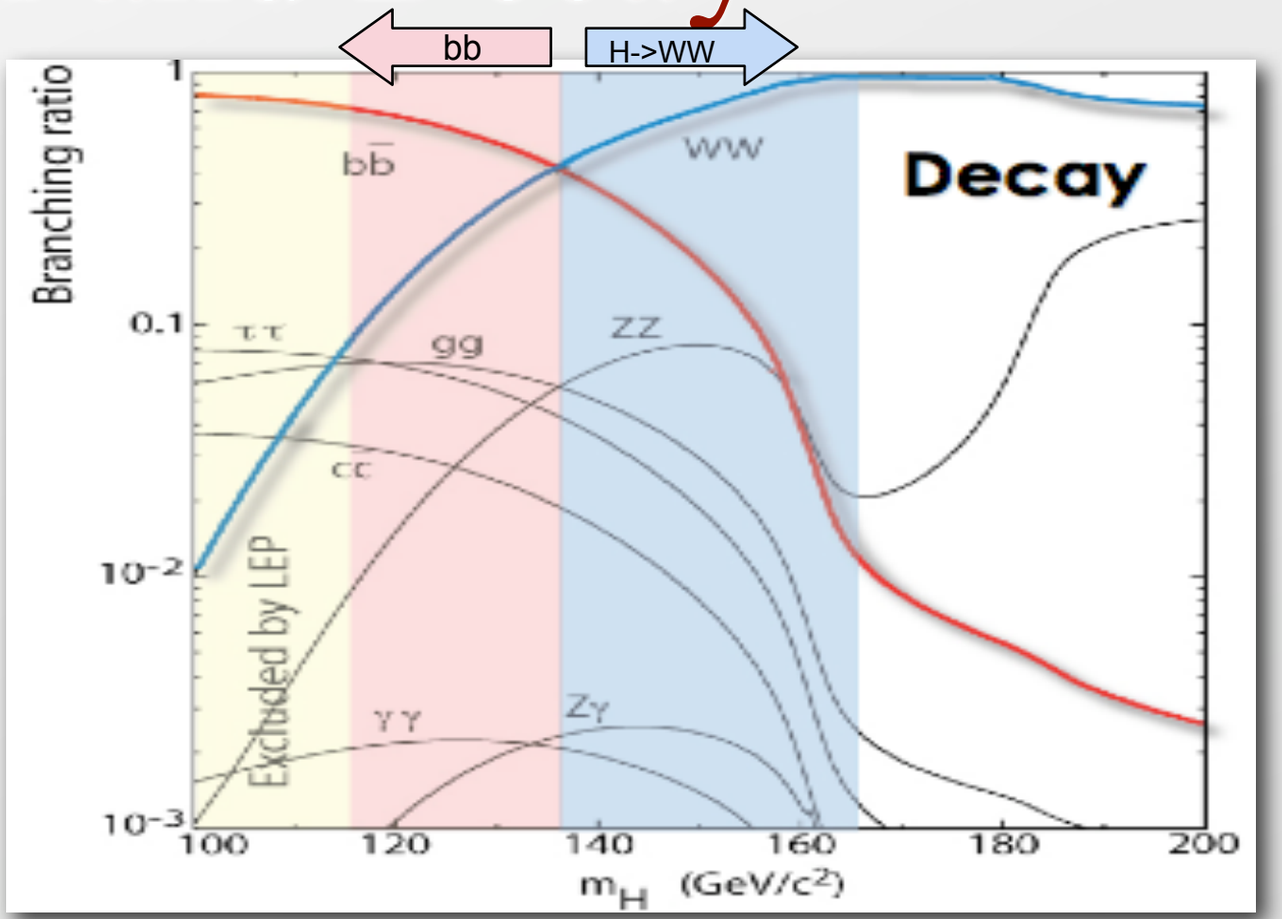


Direct searches at LEP II: M_h>114.4 GeV @ 95% CL

Indirect Constraints: Top, W-boson masses, EW meas.

Production and Decay



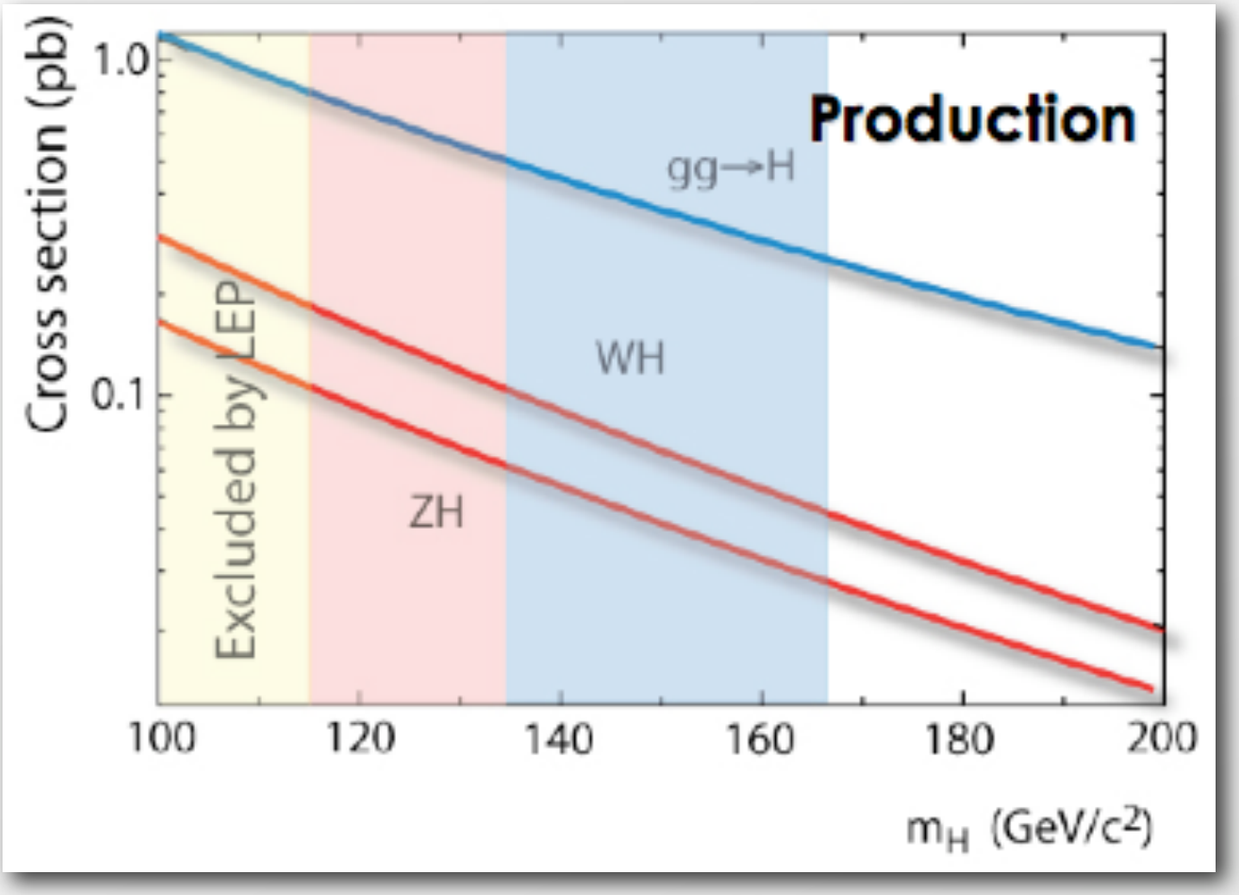


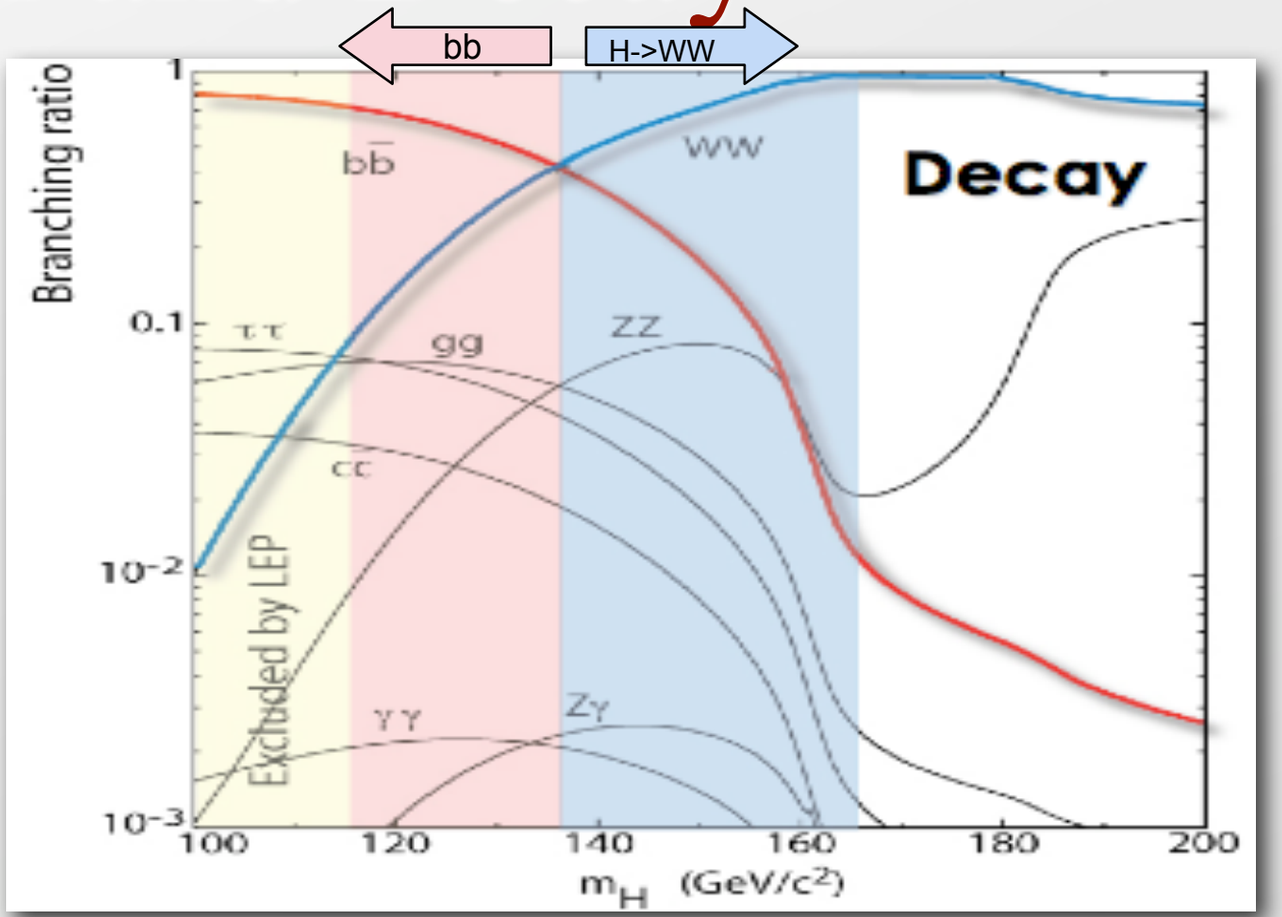
Low Mass Final States

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

$$VH,\ VBF, H \to \tau\tau + 2j$$

Production and Decay





Low Mass Final States

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

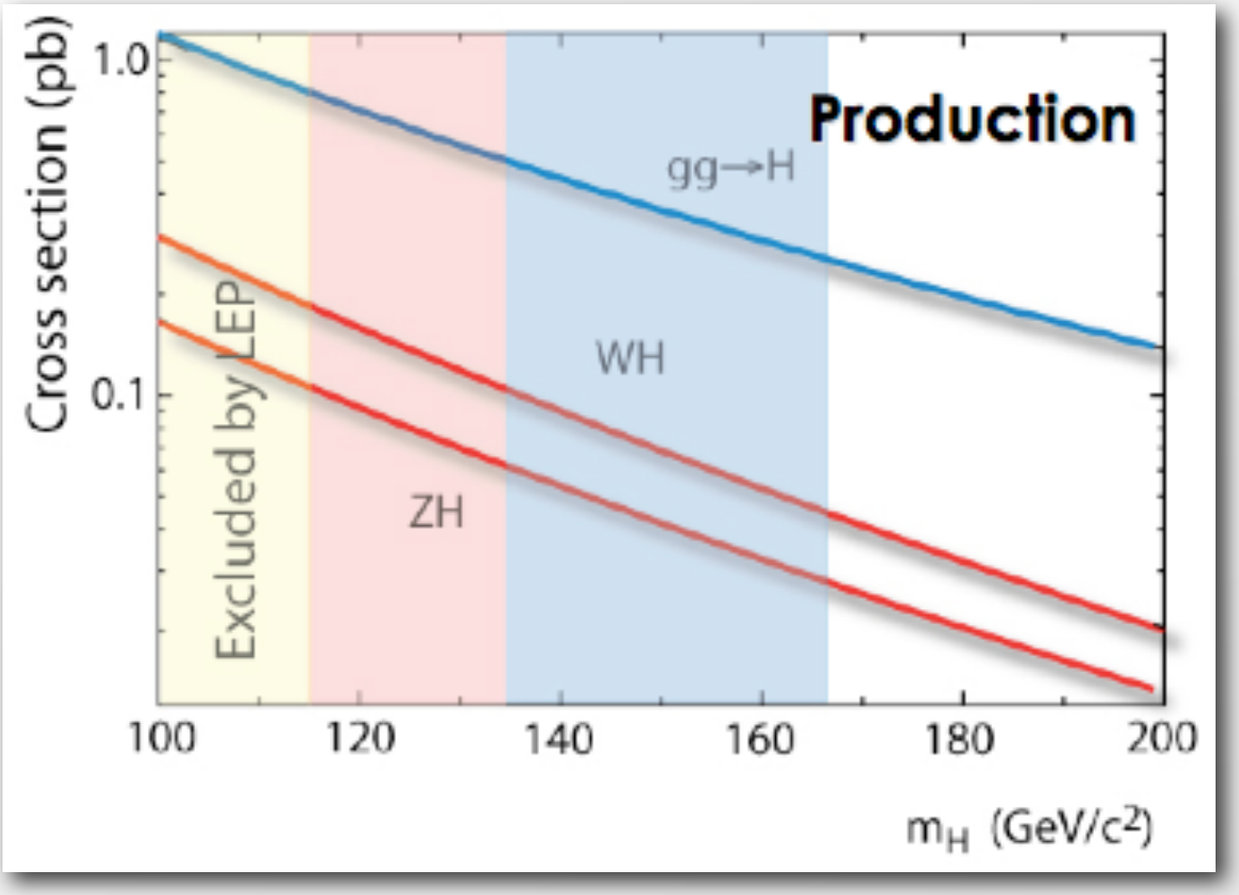
$ZH \to \ell\ell b\bar{b}$

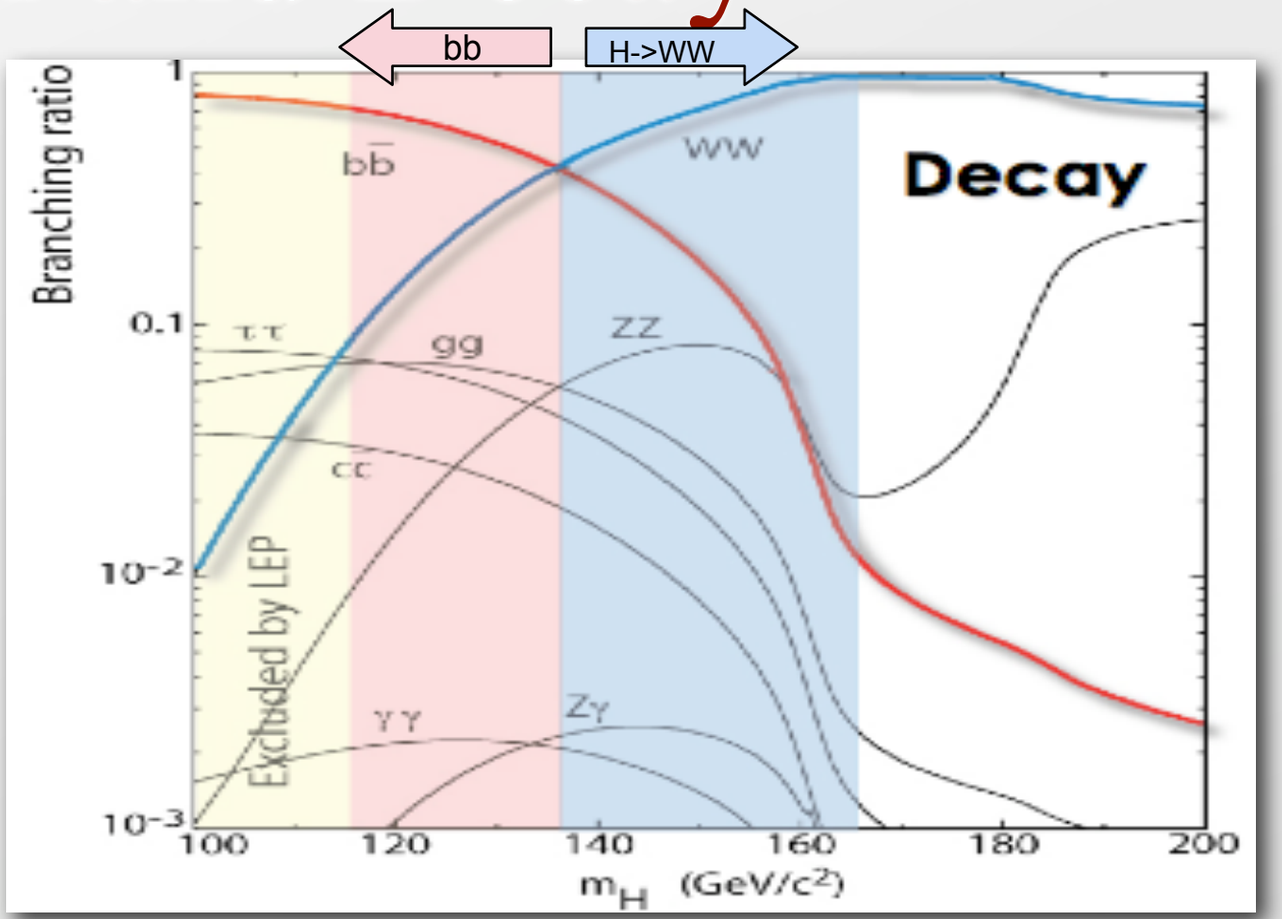
$ZH \to \nu\nu b\bar{b}$

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

$VH,\ VBF, H \to \tau\tau + 2j$

Production and Decay





Low Mass Final States

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

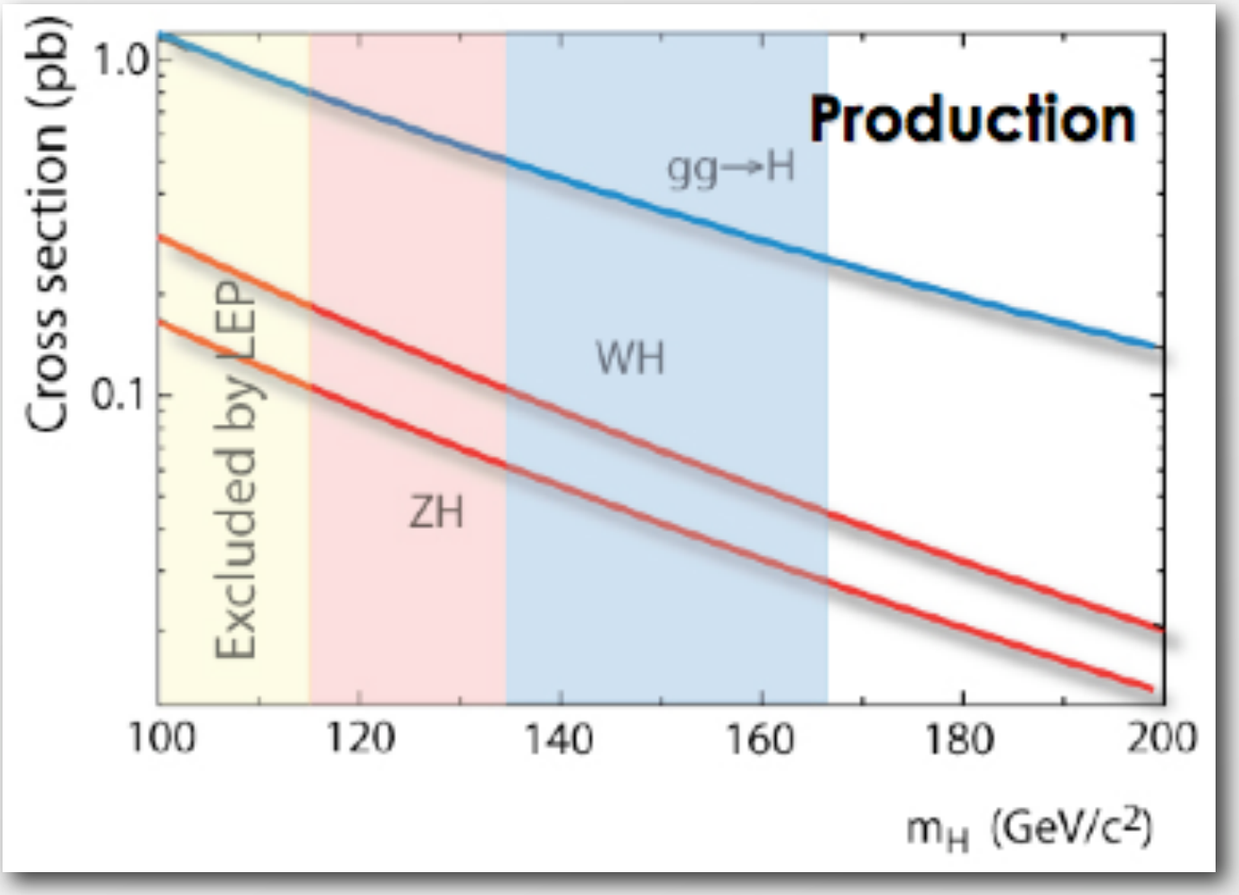
$ZH \to \ell\ell b\bar{b}$ → 2 High P_T Leptons + b jets

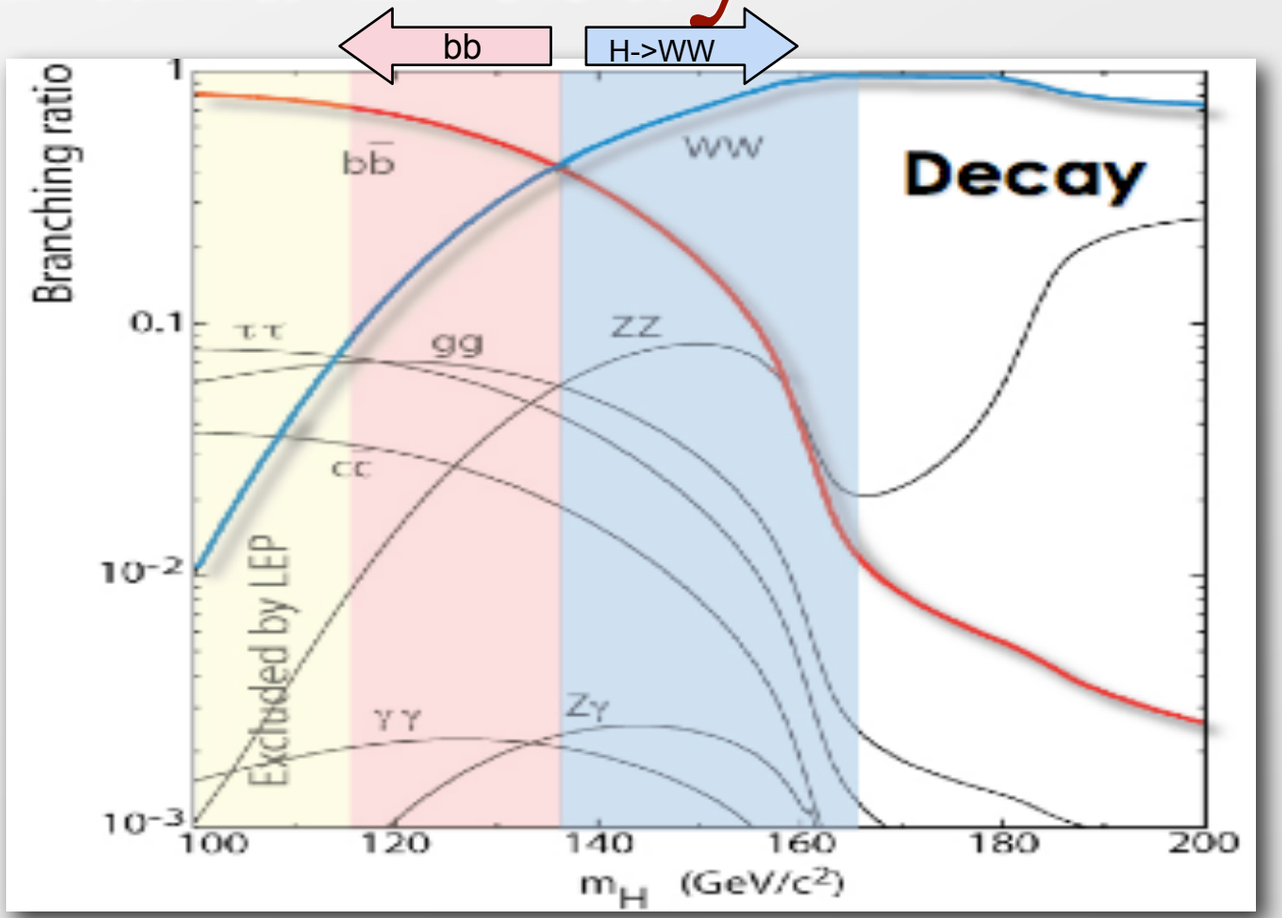
$ZH \to \nu\nu b\bar{b}$

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

$VH,\ VBF, H \to \tau\tau + 2j$

Production and Decay





Low Mass Final States

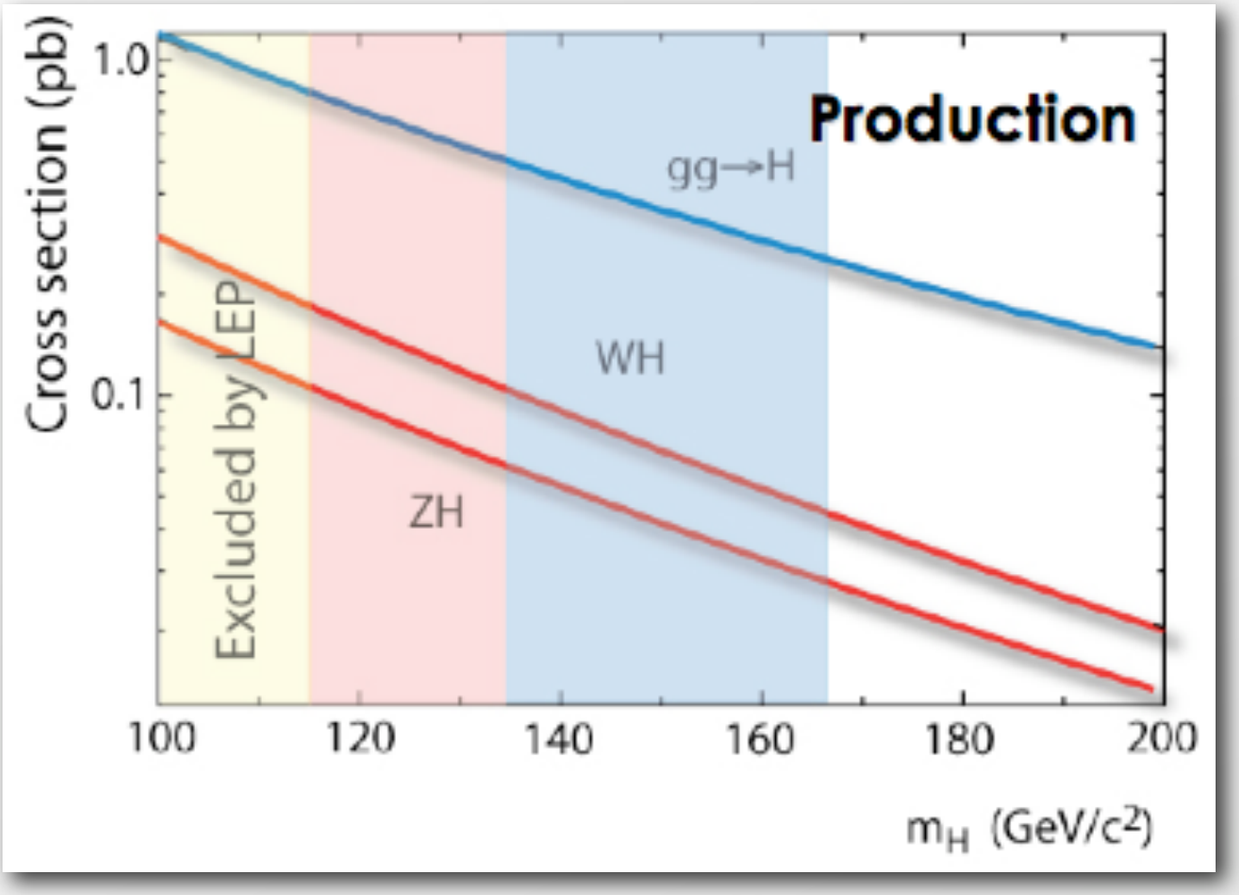
$WH \to \ell\nu b\bar{b}$ → 1 High P_T Lepton + $\not{E}_T$ + b jets

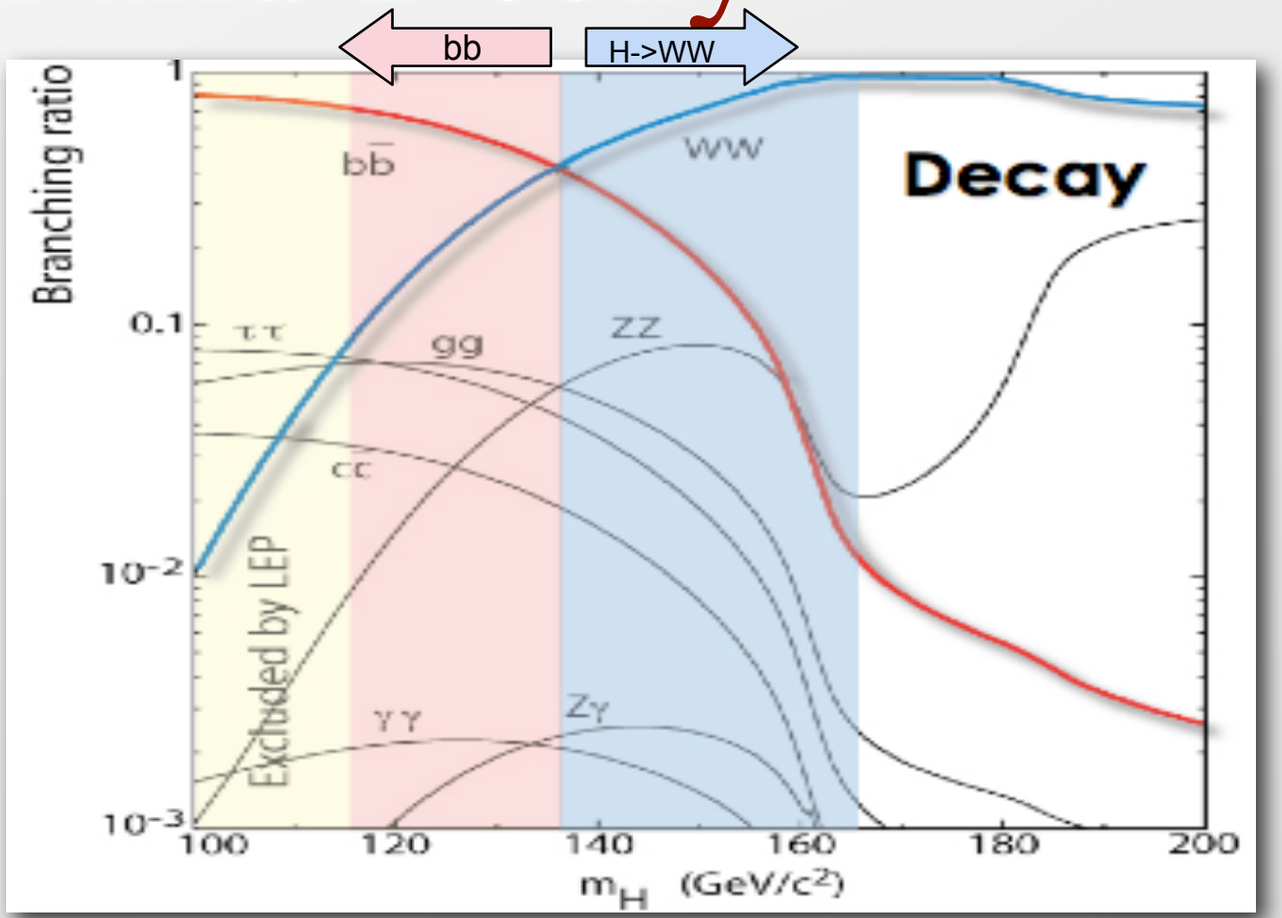
$ZH \to \ell\ell b\bar{b}$ → 2 High P_T Leptons + b jets

$ZH \to \nu\nu b\bar{b}$
$WH \to (\ell)\nu b\bar{b}$
→ 0 High P_T Leptons + $\not{E}_T$ + b jets

$VH,\ VBF, H \to \tau\tau + 2j$

Production and Decay





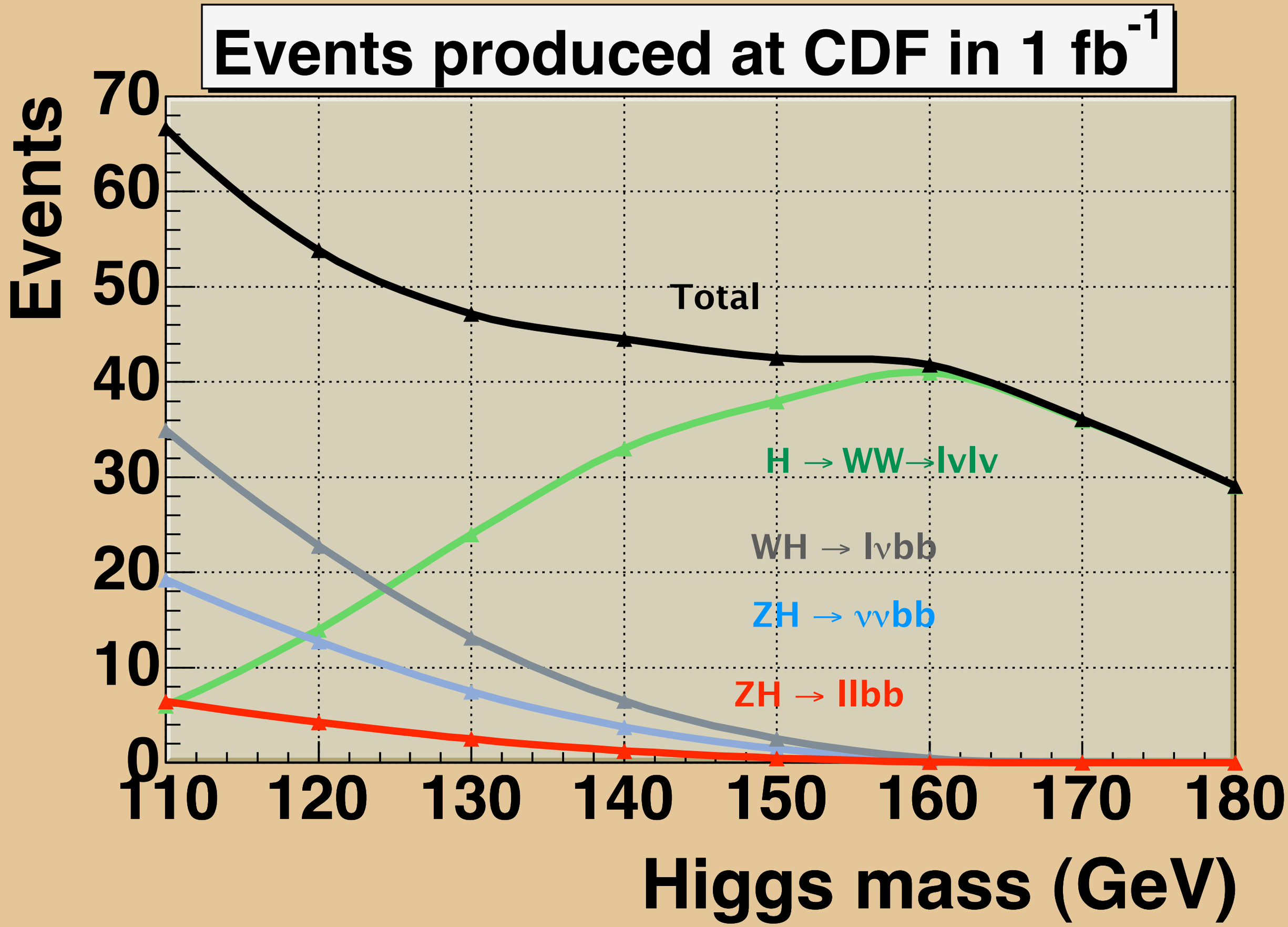
Low Mass Final States

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

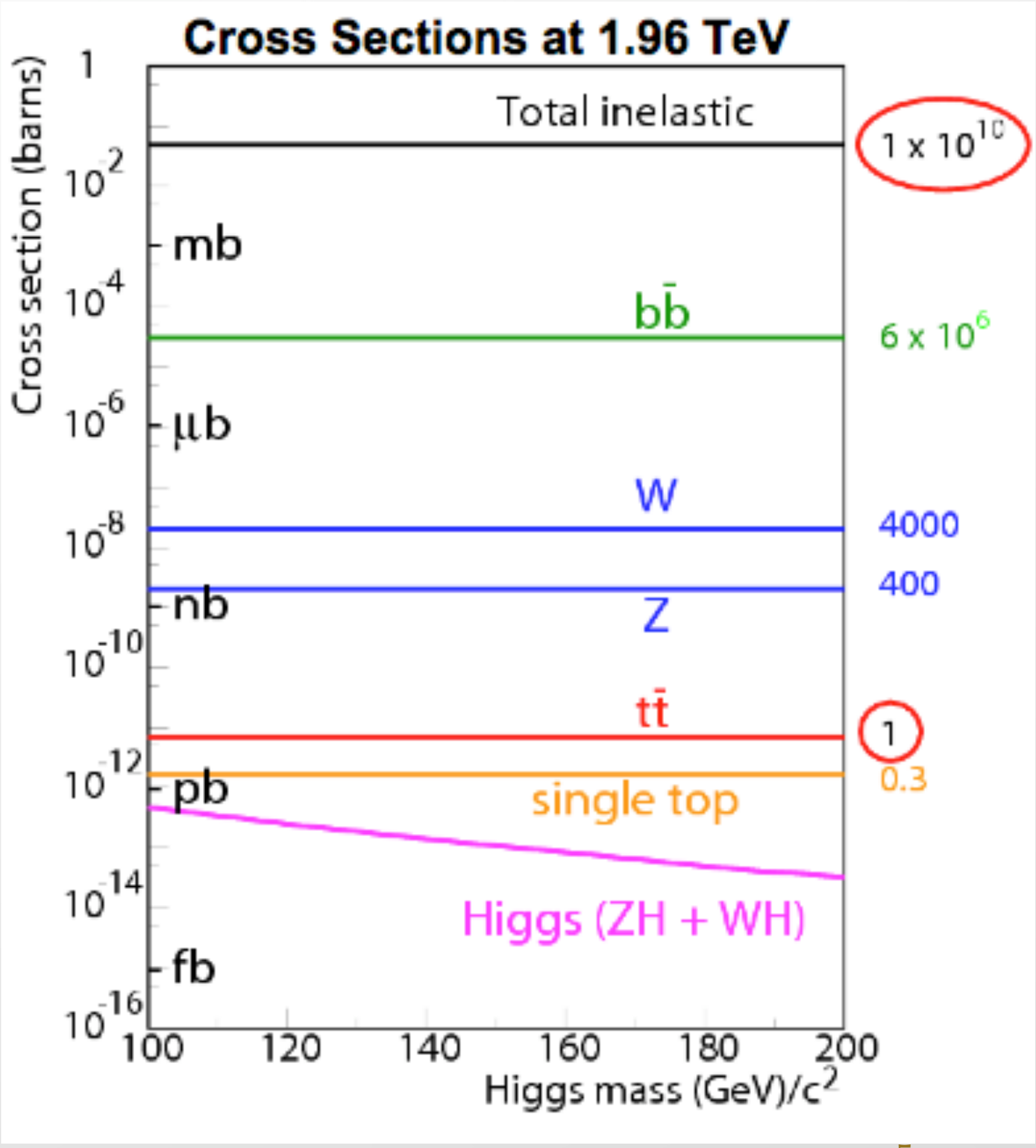
$ZH \to \ell\ell b\bar{b}$ → 2 High P_T Leptons + b jets

$ZH \to \nu\nu b\bar{b}$
$WH \to (\ell)\nu b\bar{b}$
→ 0 High P_T Leptons + $\not{E}_T$ + b jets

$VH,\ VBF, H \to \tau\tau + 2j$ → 1 Lepton + Trk(s)+ jets

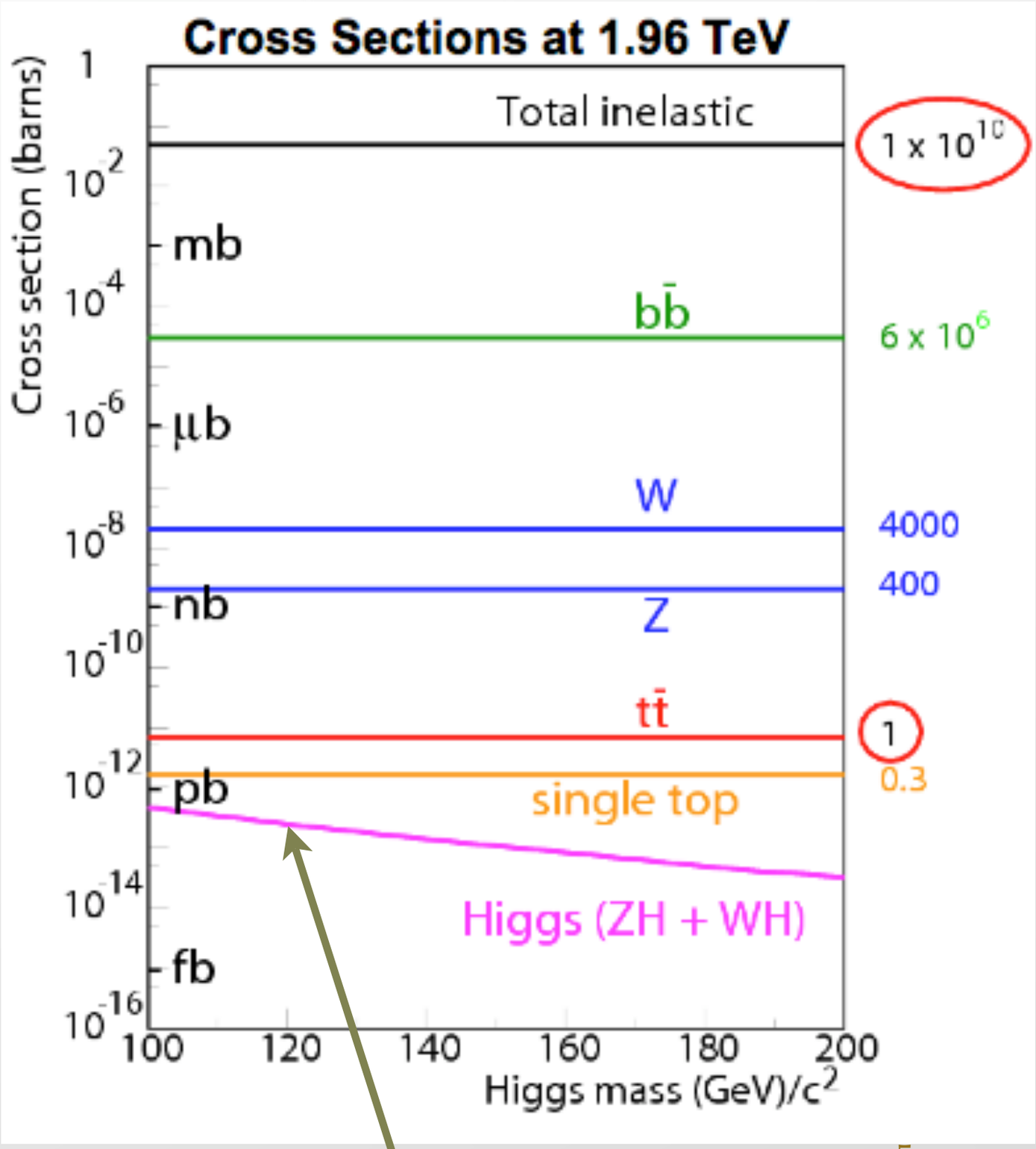

Events produced at CDF in 1 fb^{-1}
Events
70
60
50
40
30
20
10
0
110
120
130
140
150
160
170
180
Higgs mass (GeV)
Total
H → WW→lνlν
WH → lνbb
ZH → ννbb
ZH → llbb

The Challenge...



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

The Challenge...

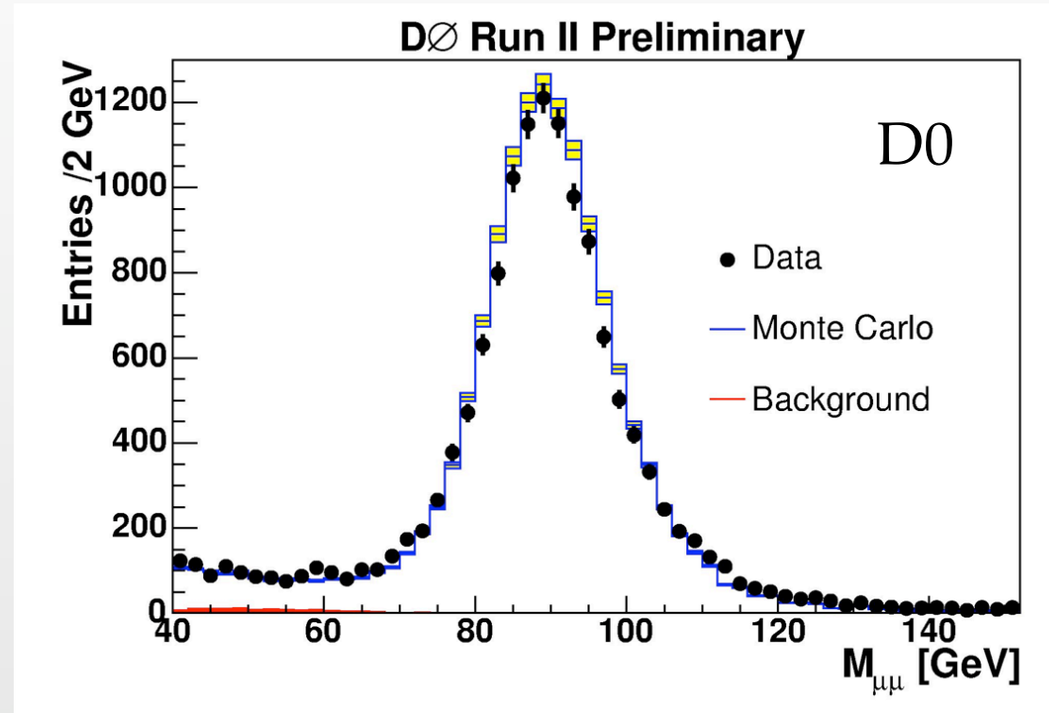


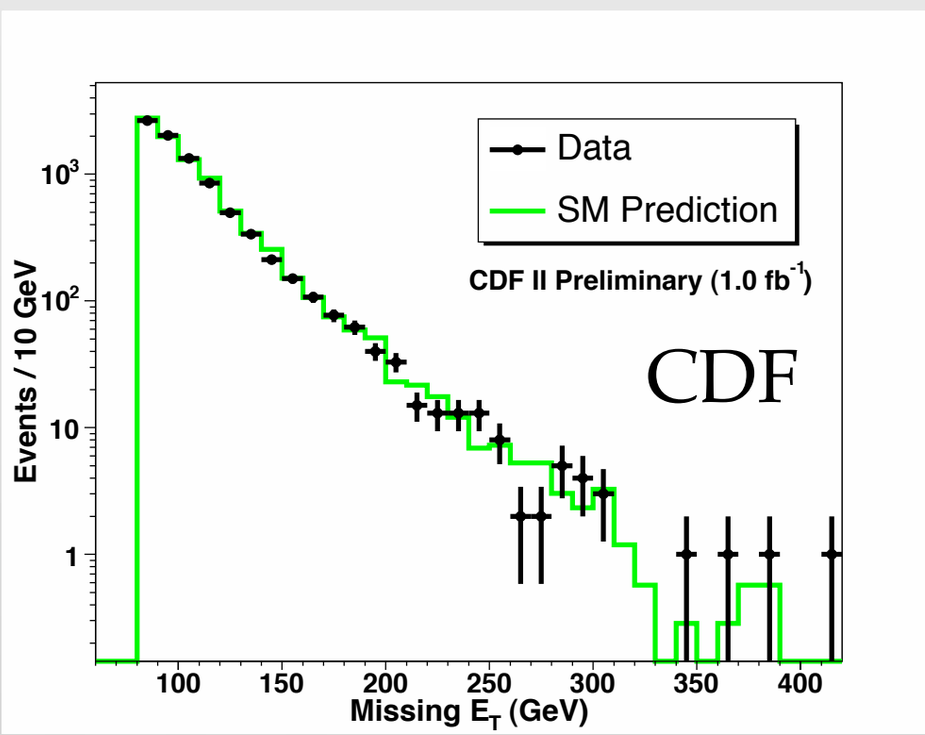
- Higgs Production is a low rate process at the Tevatron.
- Backgrounds are many orders of magnitude larger.
- Challenge: Separate Signal from Background

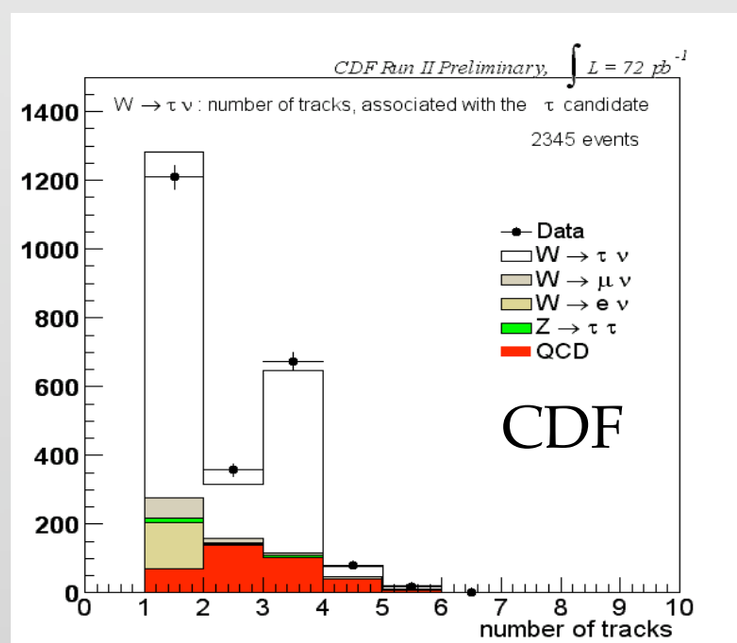
Before Anything
S:B ~ $1:10^{11}$

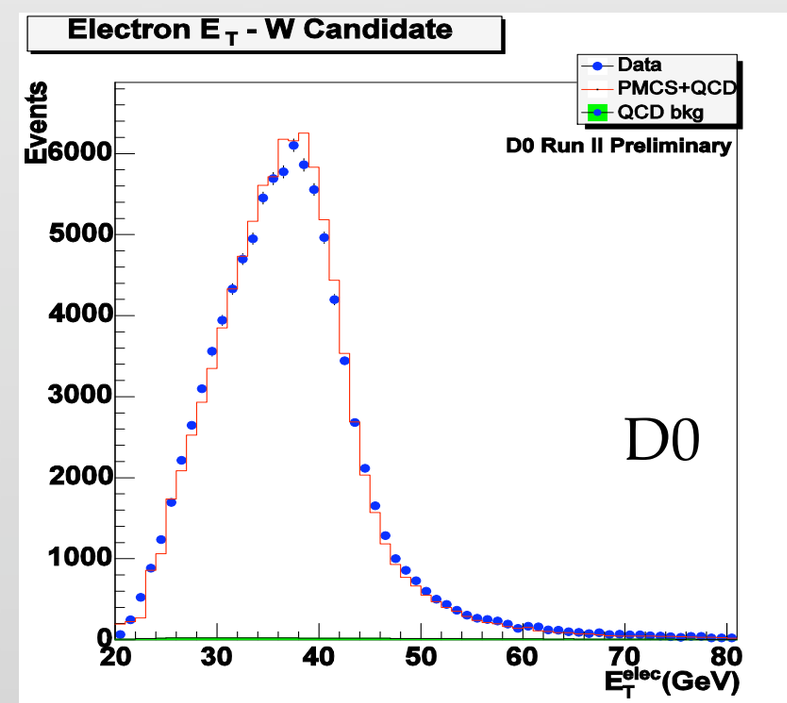
Identification of High Pt Leptons

- Most final states produced by Higgs decay involve high-Pt leptons.
- CDF and D0 have efficient lepton triggers and high purity ID selection
- Tau leptons are also starting to contribute





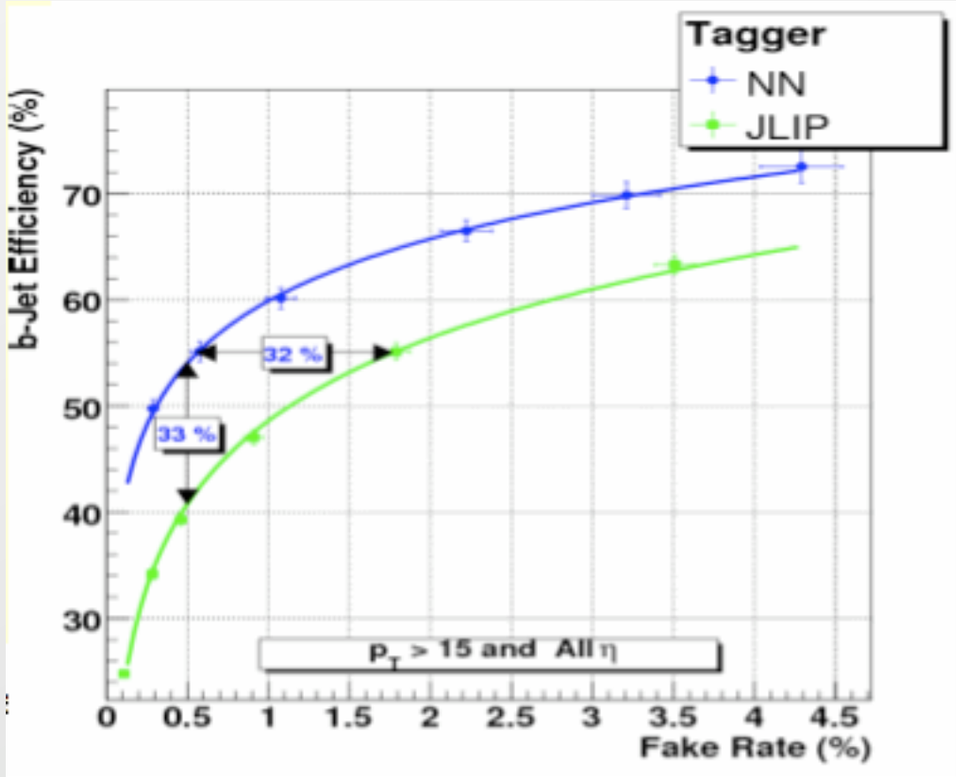


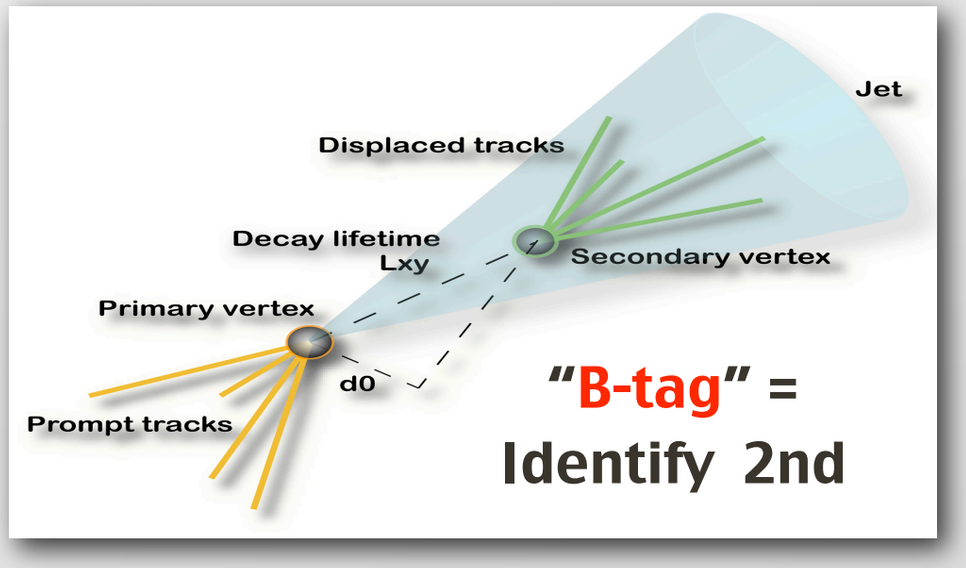


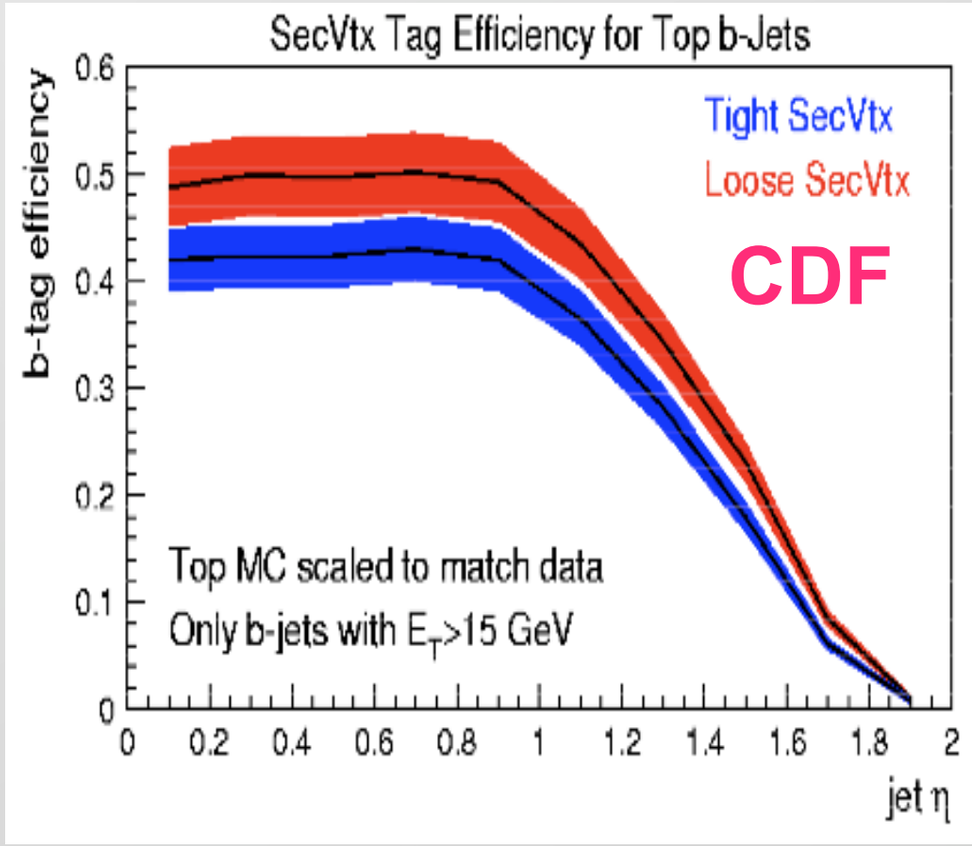
Identification of B-jets

Btagging

- ~ 50-70% efficient
- Dependent on E_T and η of jet.
- Mistag rates typically ~ 0.3 - 5%
- Loose tagging helpful in double tag situations
- D0 uses NN tagger based on 7 discriminating B-lifetime variables
- CDF uses secondary vertexing algorithm
- New tagging: Neural network using flavor separation

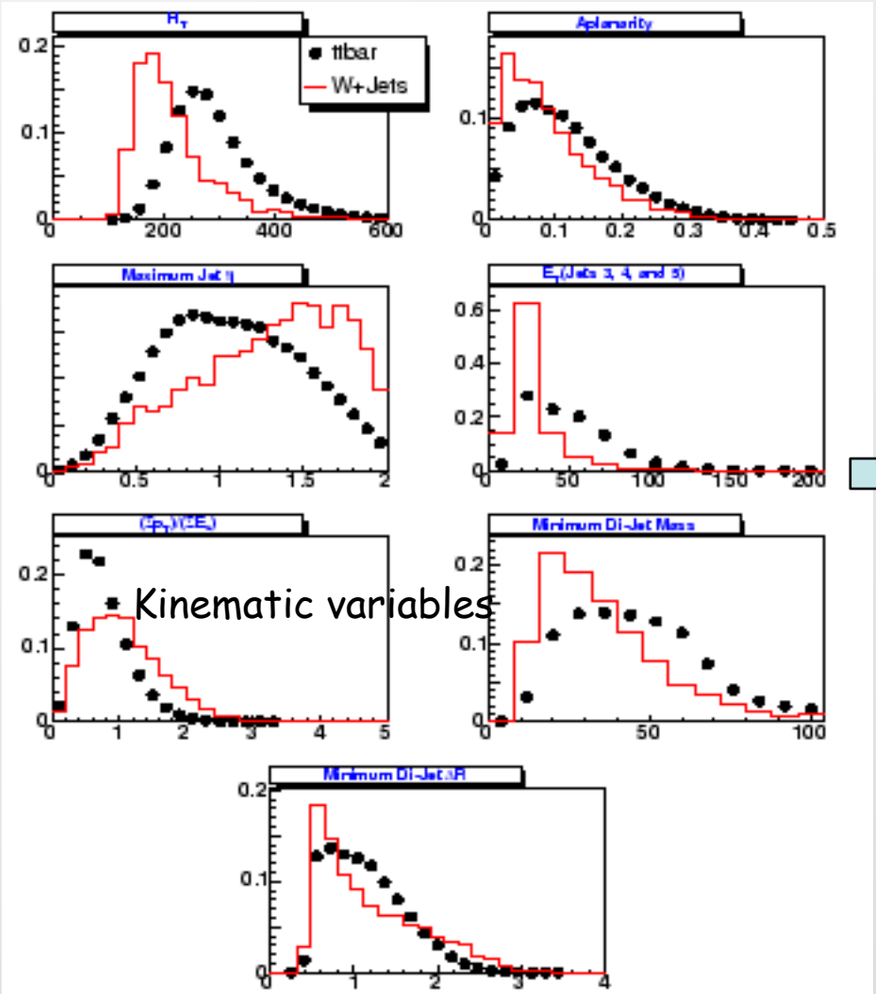


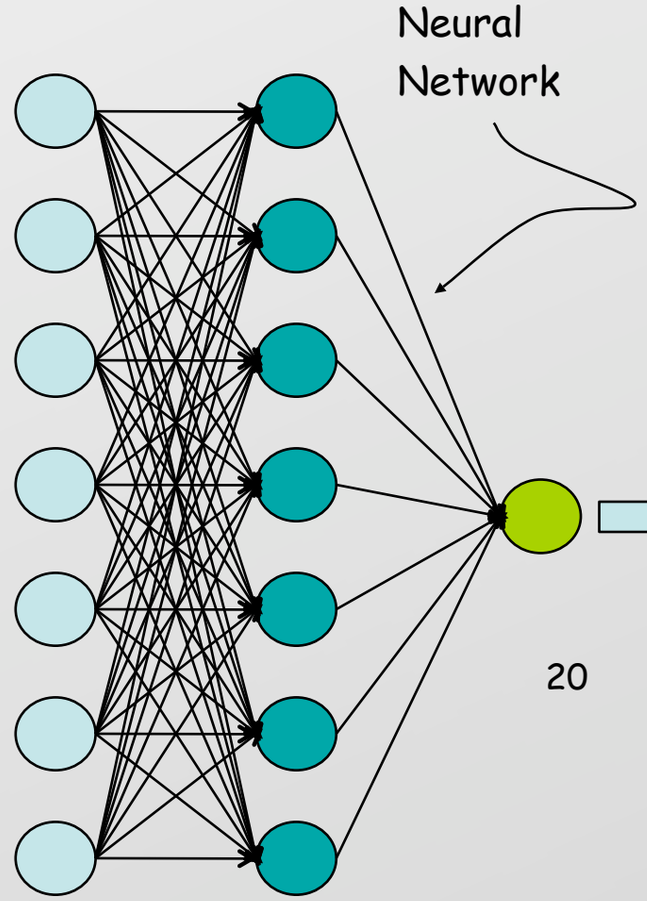




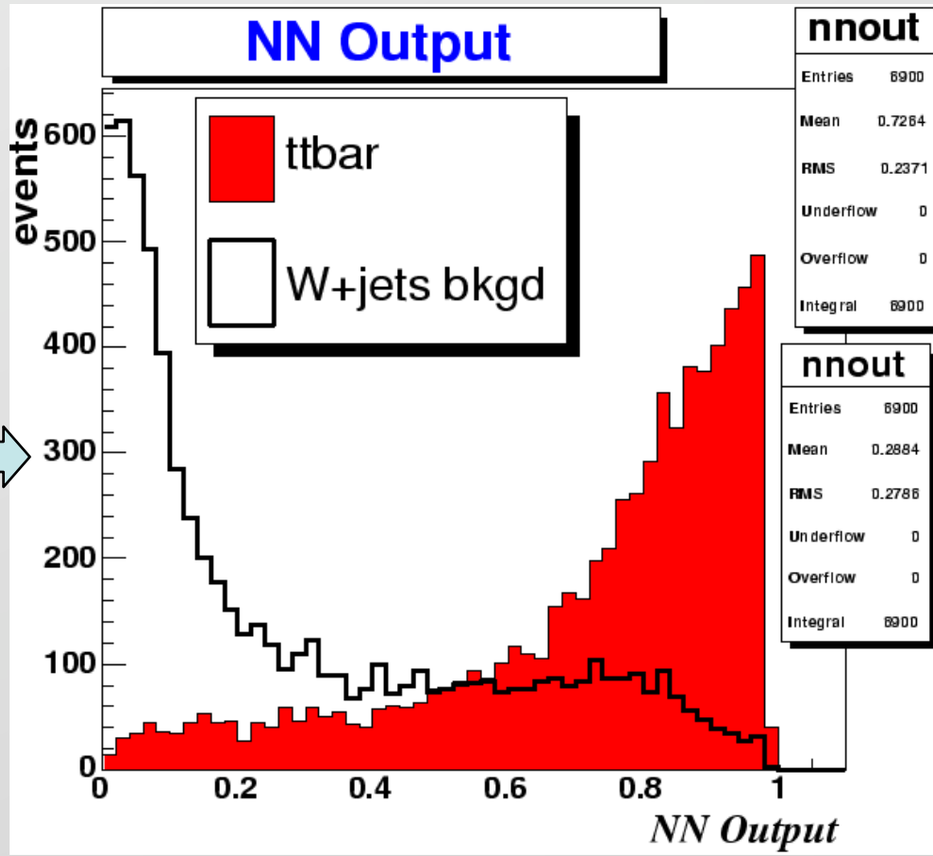
Using Advanced Algorithms

- 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



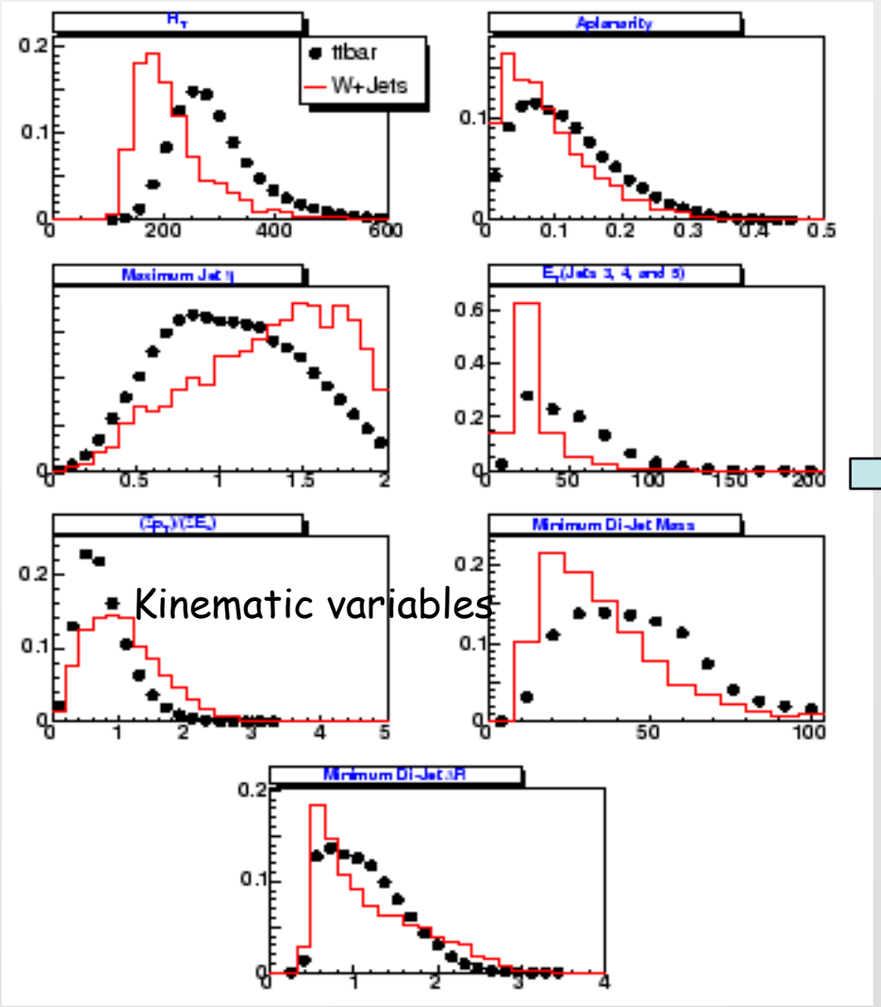


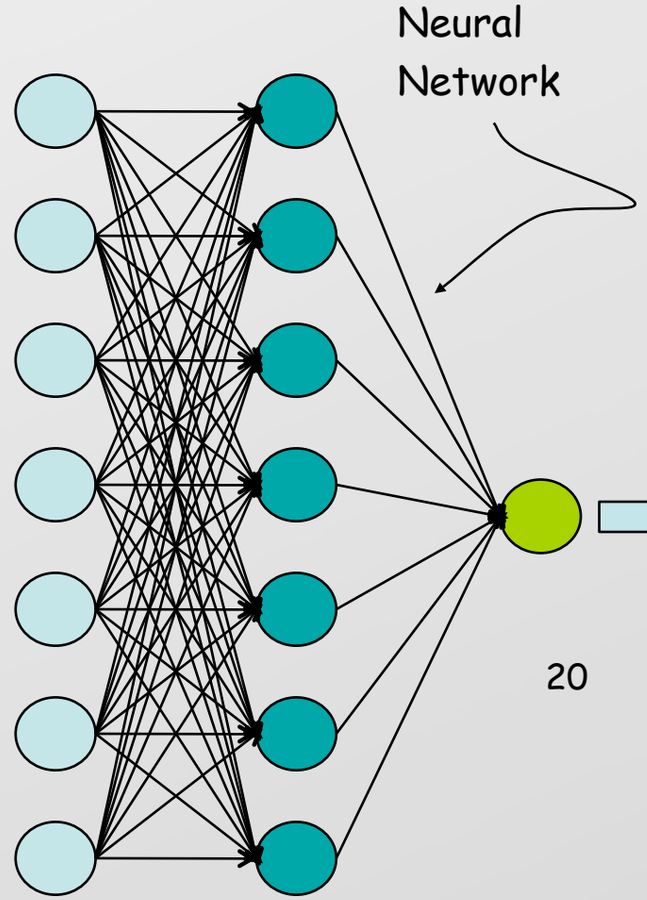
Final discriminant



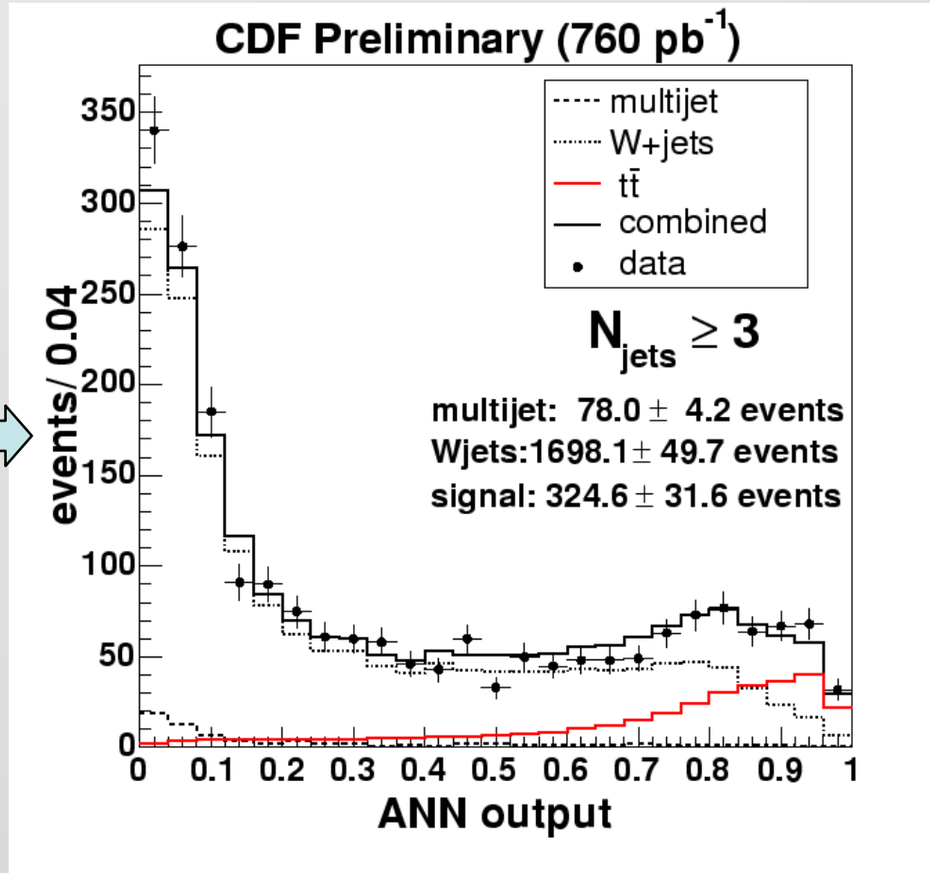
Using Advanced Algorithms

- 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



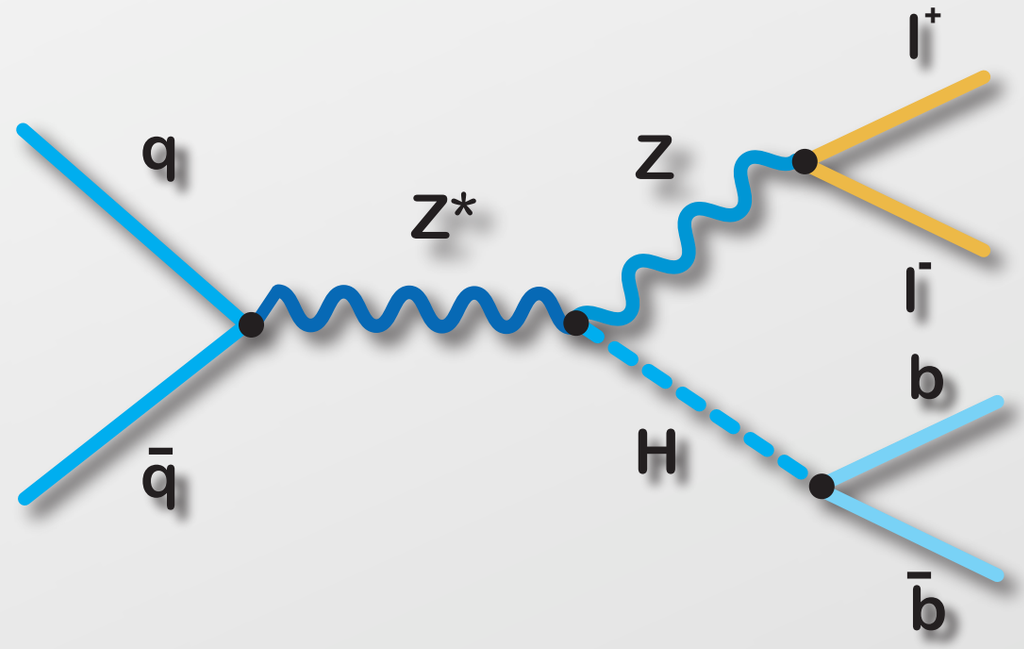


Final discriminant



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

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



Features:

1. Small $\sigma \cdot BR$
2. Several tight constraints
   i. $M_{ll} \cong M_z$
   ii. "$\not{E}_T$" $\rightarrow$ improve jet resol.
3. ~1 evt/fb^{-1}

Primary Backgrounds

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

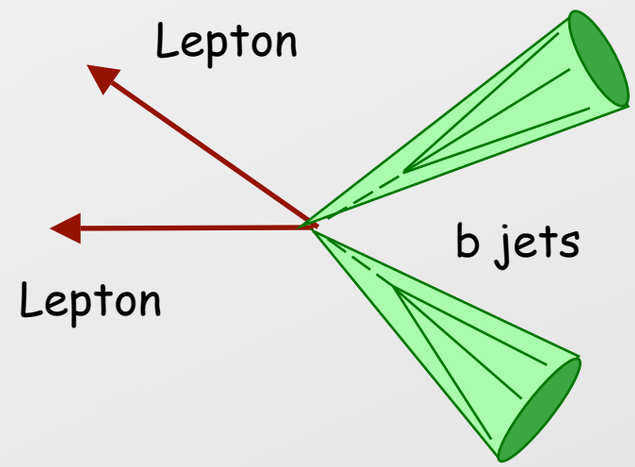
$t\bar{t}$

$WW + jj$, WZ, ZZ

$Z \rightarrow \tau\tau$

$ZH \longrightarrow \ell\ell b\bar{b}$ Channel

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



Features:

1. Small $\sigma \cdot BR$
2. Several tight constraints
   i. $M_{ll} \cong M_z$
   ii. "$\not{E}_T$" $\rightarrow$ improve jet resol.
3. ~1 evt/fb^{-1}

Primary Backgrounds

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

$t\bar{t}$

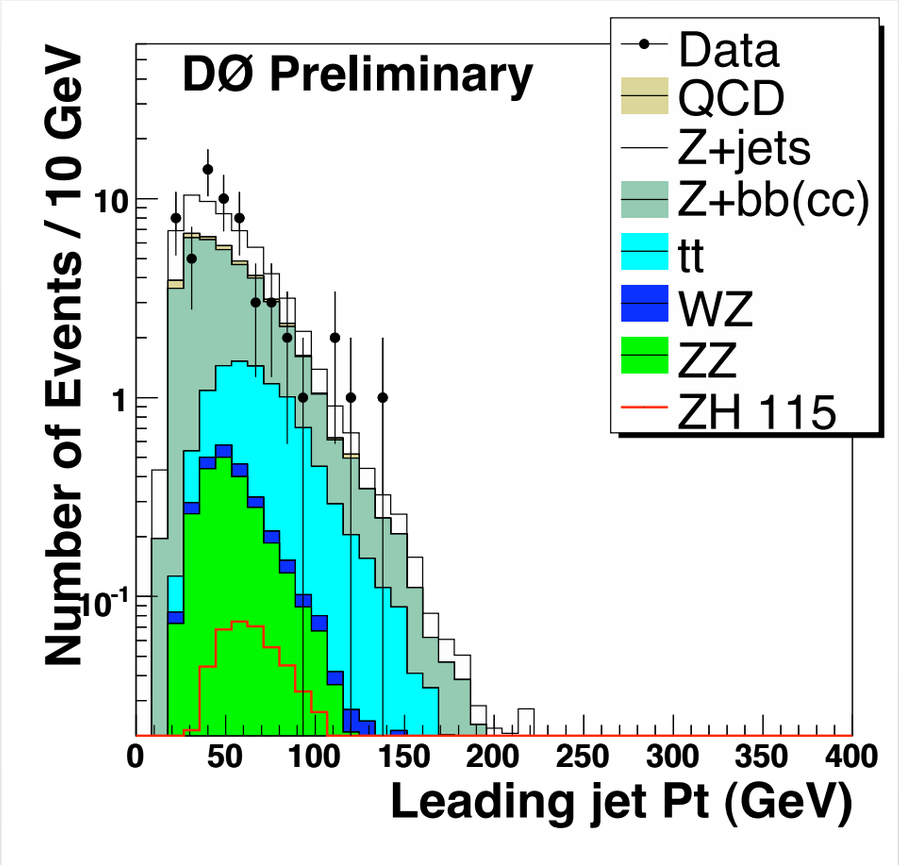
$WW + jj$, WZ, ZZ

$Z \rightarrow \tau\tau$

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

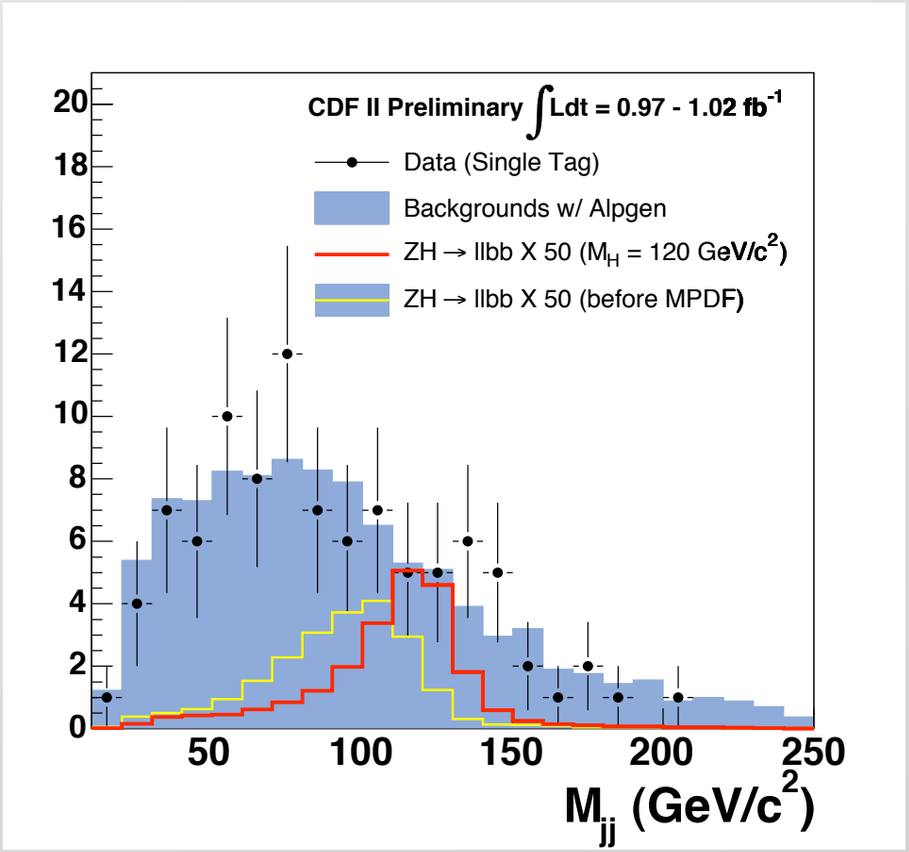
Lepton types: ee and μμ
b-Tagging: 1Tight tag
2Loose Tag

ANN Inputs M_{bb}, $P_T^{j_1}$, $P_T^{j_2}$, $\Delta R_{\ell\ell}$, $|\Delta\eta_{jj}|$, $|\Delta\phi_{jj}|$, ΔR_{Z-j_1}, $|\eta_Z|$, MET, ΣE_T^i



Tagging split into double tag and single Tag

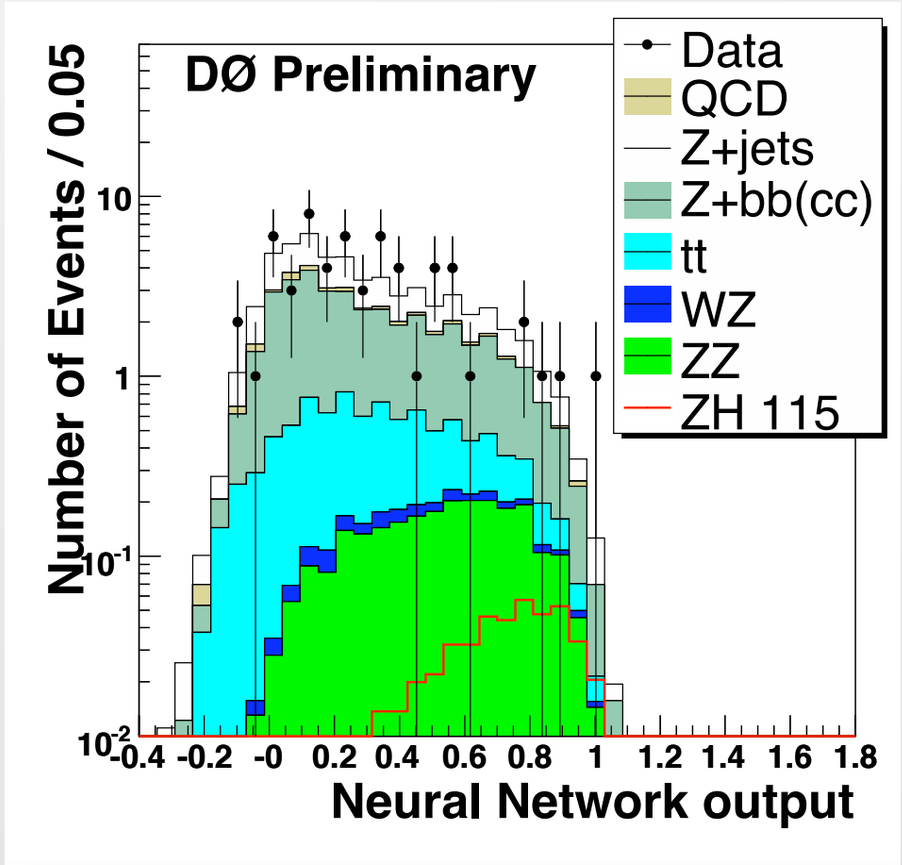
2D ANN Inputs $\not{E}_T$, H_T, M_{jj}, Sph, η_{j_2}, $\Delta R_{j_1,Z}$, $\Delta R_{j_2,Z}$, $\Delta R_{j_1,j_2}$



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

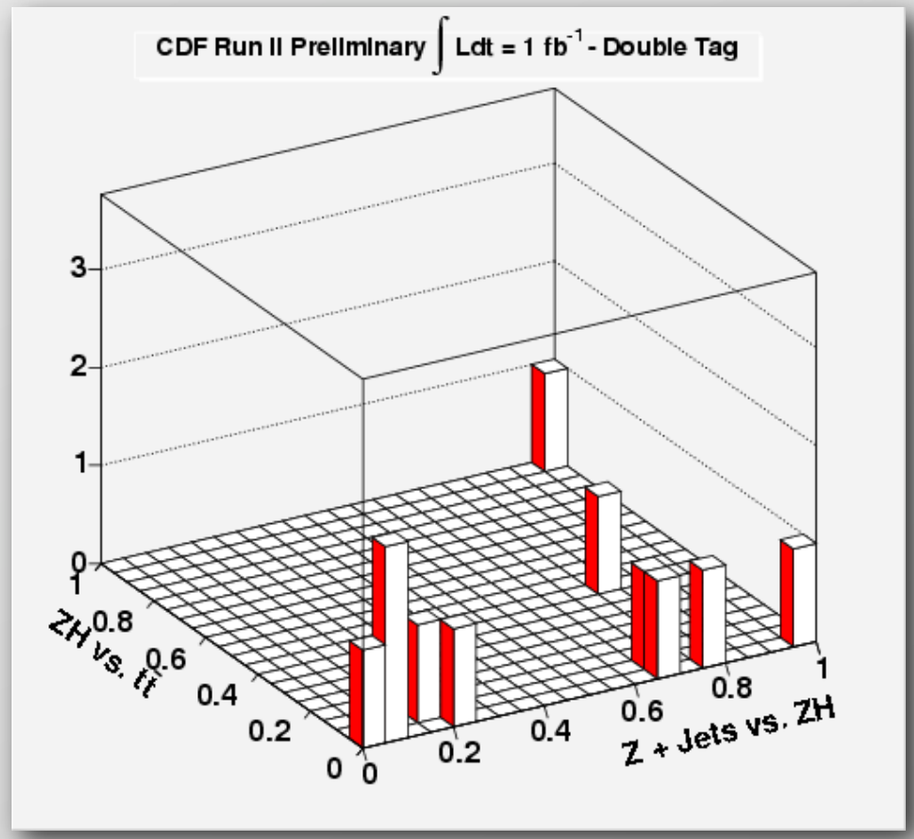
Lepton types: ee and μμ
b-Tagging: 1Tight tag
2Loose Tag

ANN Inputs M_{bb}, $P_T^{j_1}$, $P_T^{j_2}$, $\Delta R_{\ell\ell}$, $|\Delta\eta_{jj}|$, $|\Delta\phi_{jj}|$, ΔR_{Z-j_1}, $|\eta_Z|$, MET, ΣE_T^i



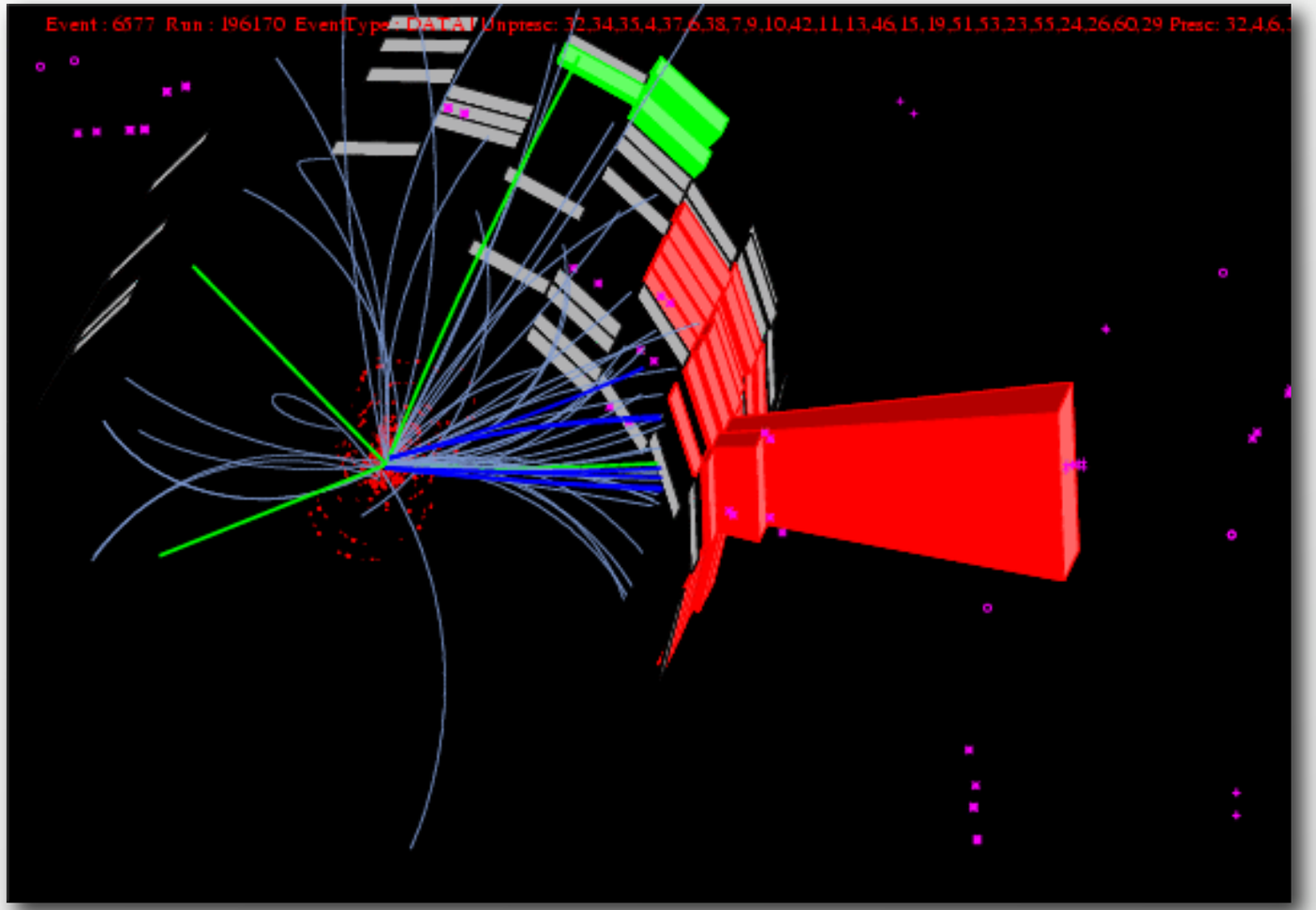
Tagging split into double tag and single Tag

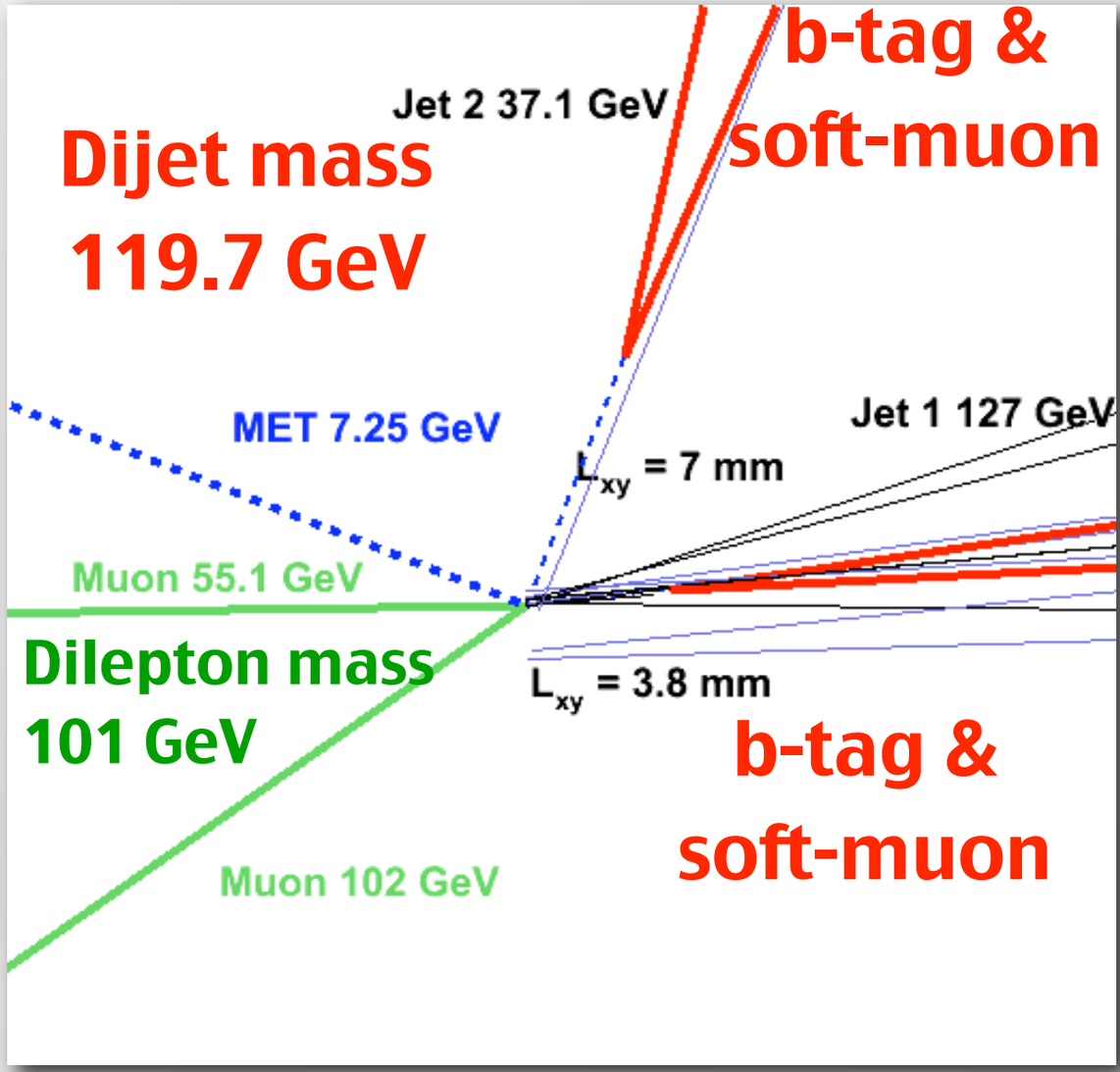
2D ANN Inputs $\cancel{E_T}$, H_T, M_{jj}, Sph, η_{j_2} $\Delta R_{j_1,Z}$, $\Delta R_{j_2,Z}$, $\Delta R_{j_1,j_2}$



Most Higgs-like Event

RUN 196170 EVENT 6577





Background in this bin

60% Z+bb

11% tt

9% Z+cc

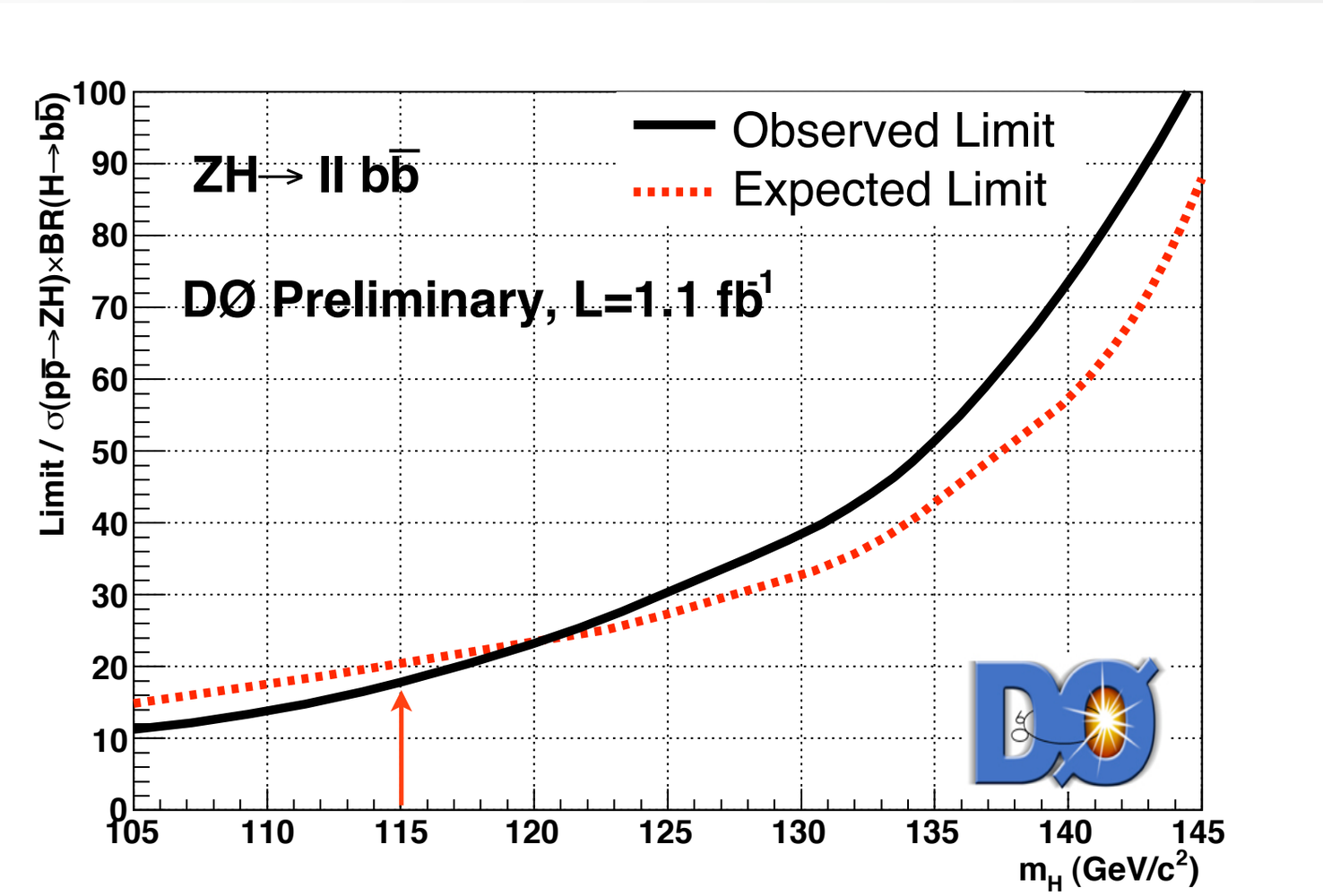
9% ZZ

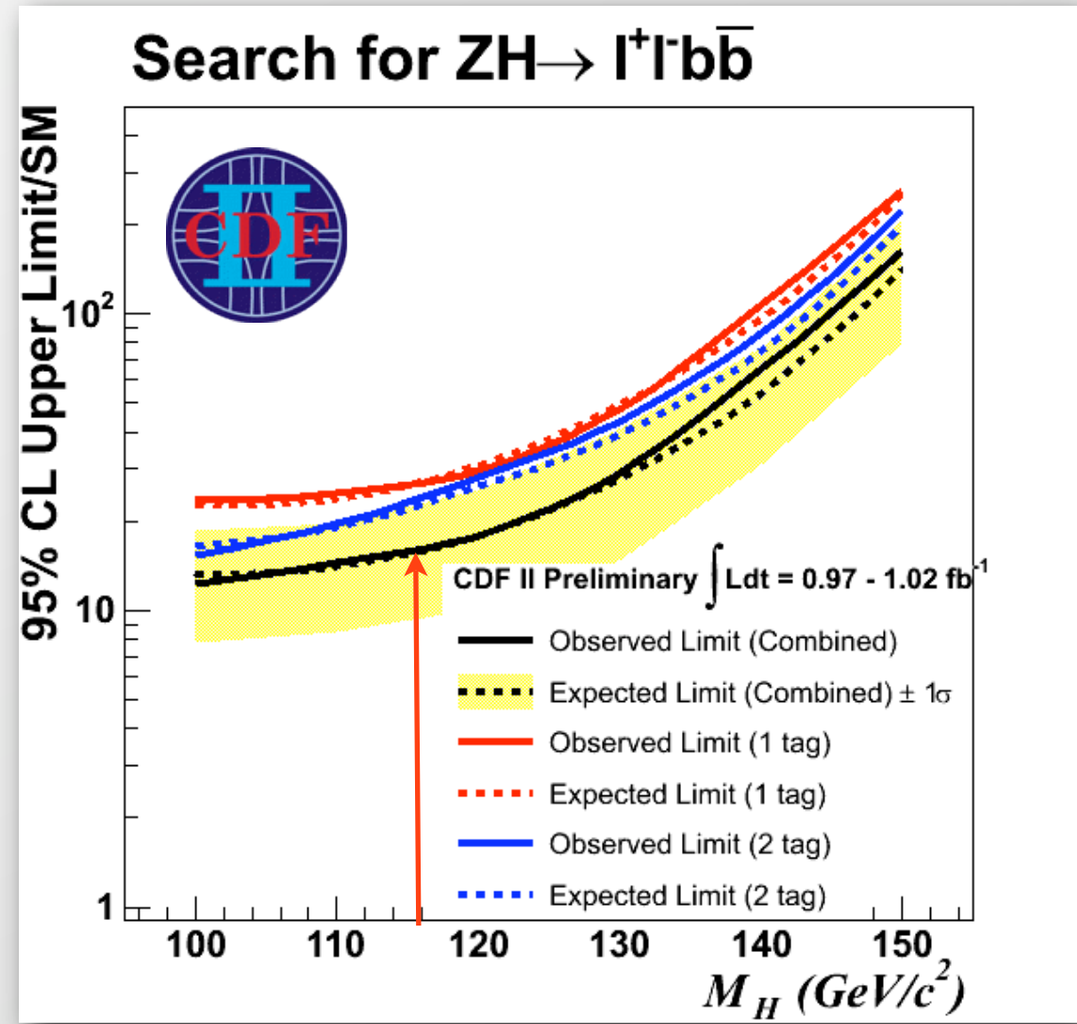
5% Z+qq (light)

Higgs ~ 2 times tt

S:B ~ 1:4

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



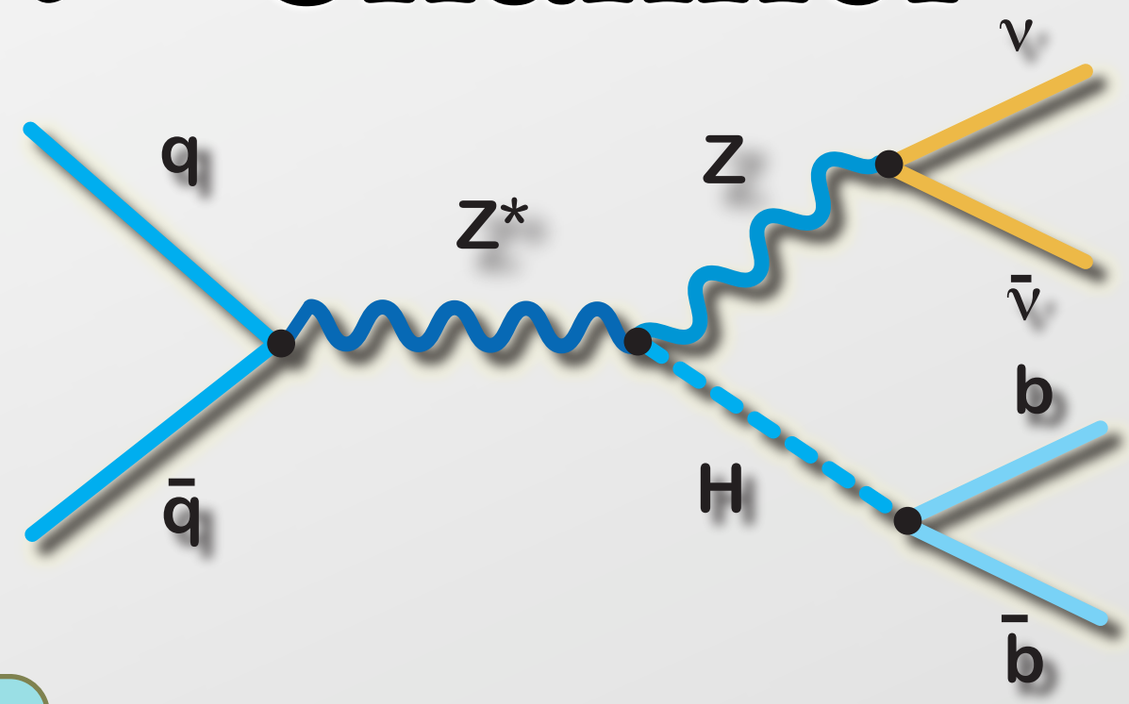


Experiment	Lum	Obs/SM	Exp/SM
D0	1.1 fb^{-1}	17.8	20.4
CDF	1.0 fb^{-1}	16	16

$M_h = 115\ GeV/c^2$

$ZH \rightarrow \nu\nu b\bar{b}$ Channel

- No High P_T Leptons
- Large Missing E_T
- 2 jets
  - Require 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 (~35%) from WH
5. ~2-3 evts/fb^{-1}

Primary Backgrounds

QCD Heavy Flavor,

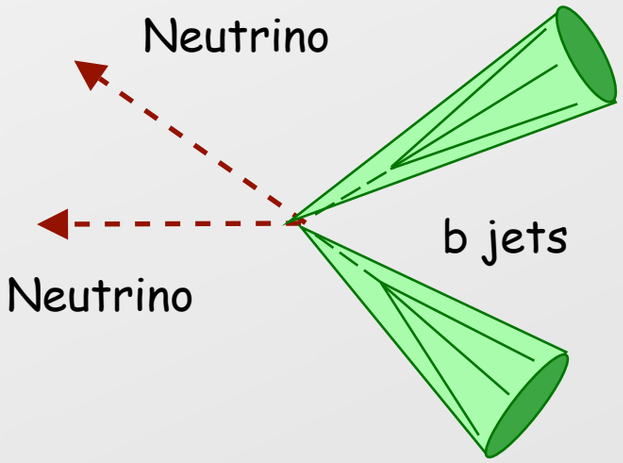
$t\bar{t}$, $W/Z + b\bar{b}/c\bar{c}$,

Single Top,

ZZ, WZ, WW

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

- No High P_T Leptons
- Large Missing E_T
- 2 jets
  - Require 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 (~35%) from WH
5. ~2-3 evts/fb^{-1}

Primary Backgrounds

QCD Heavy Flavor,

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

Single Top,

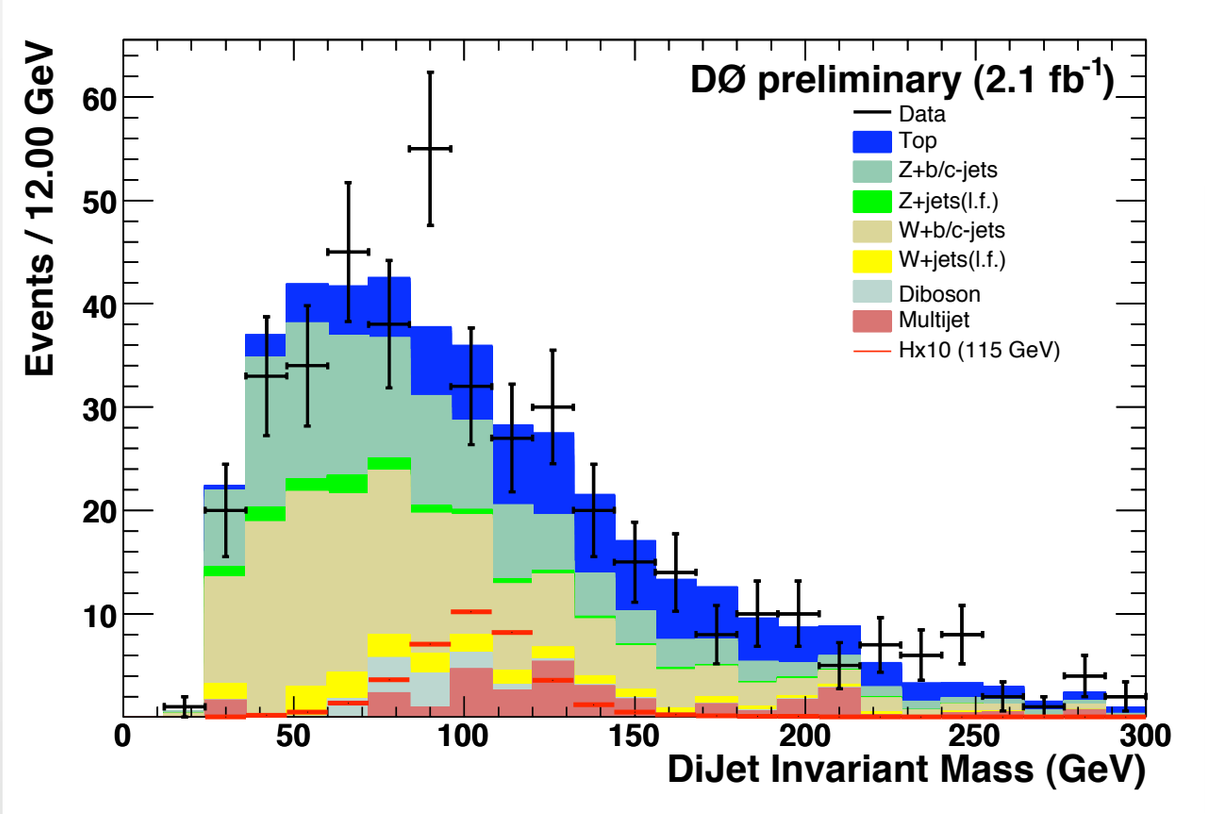
ZZ, WZ, WW

$ZH \rightarrow \nu\nu b\bar{b}$ Discriminants

Double b-tagging (loose +tight) required.

Boosted Decision Tree

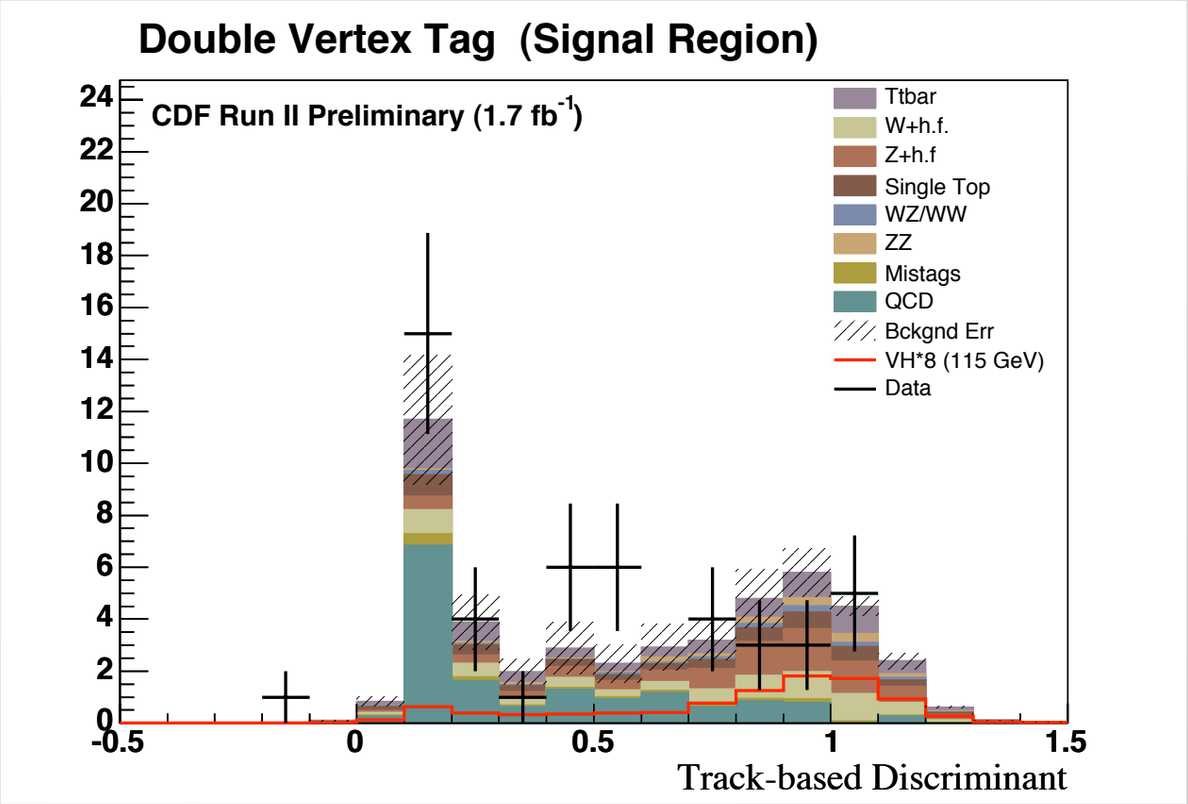
Inputs: 24 variables



double tight btag

1 tight + 1 loose btag

ANN Inputs $M_{bb},\ MET,\ \Delta R_{j_1-j_2},$ $MET_{cal} \cdot MET_{trk},\ Trk_{NN}$

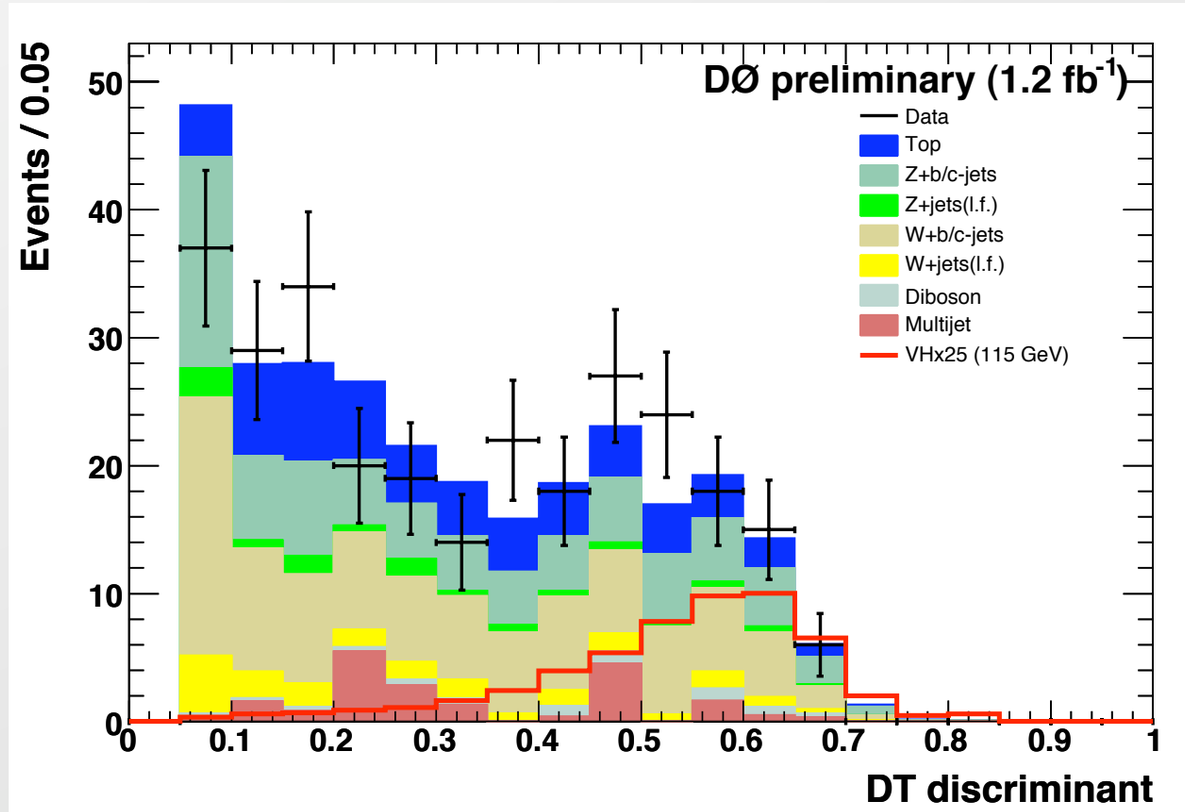


$ZH \rightarrow \nu\nu b\bar{b}$ Discriminants

Double b-tagging (loose +tight) required.

Boosted Decision Tree

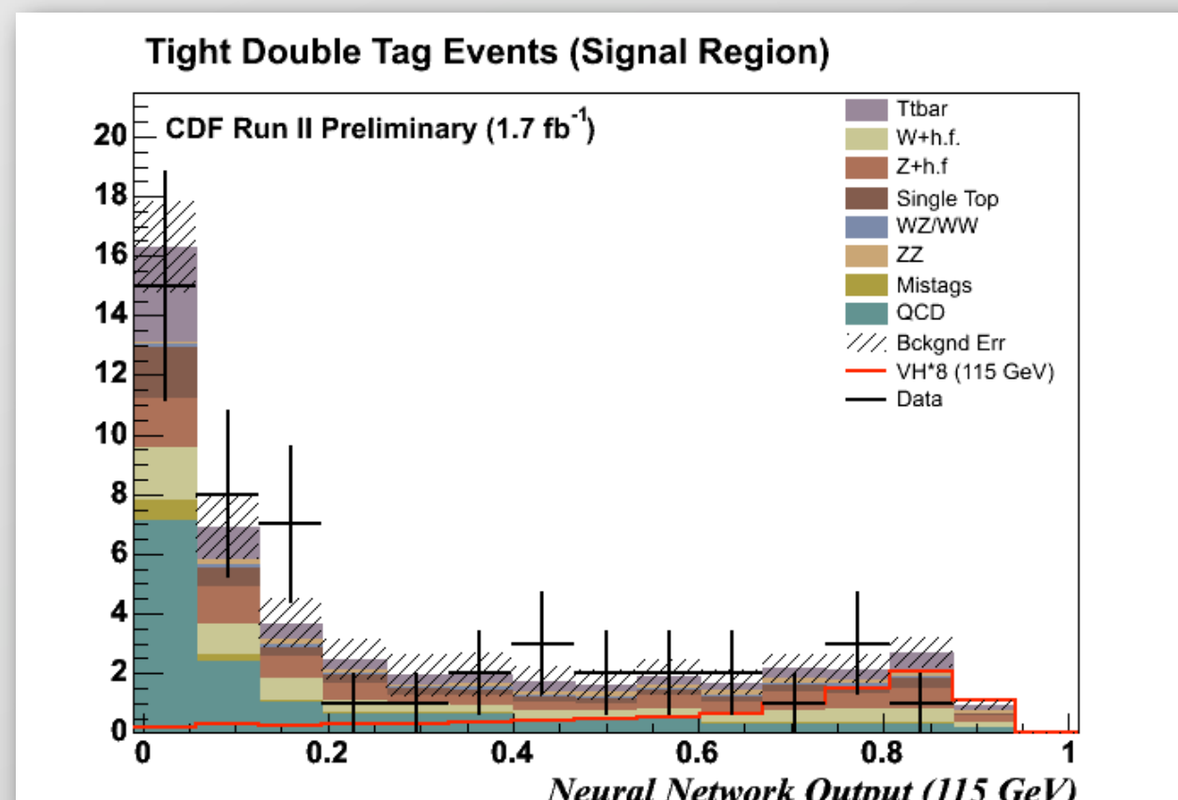
Inputs: 24 variables



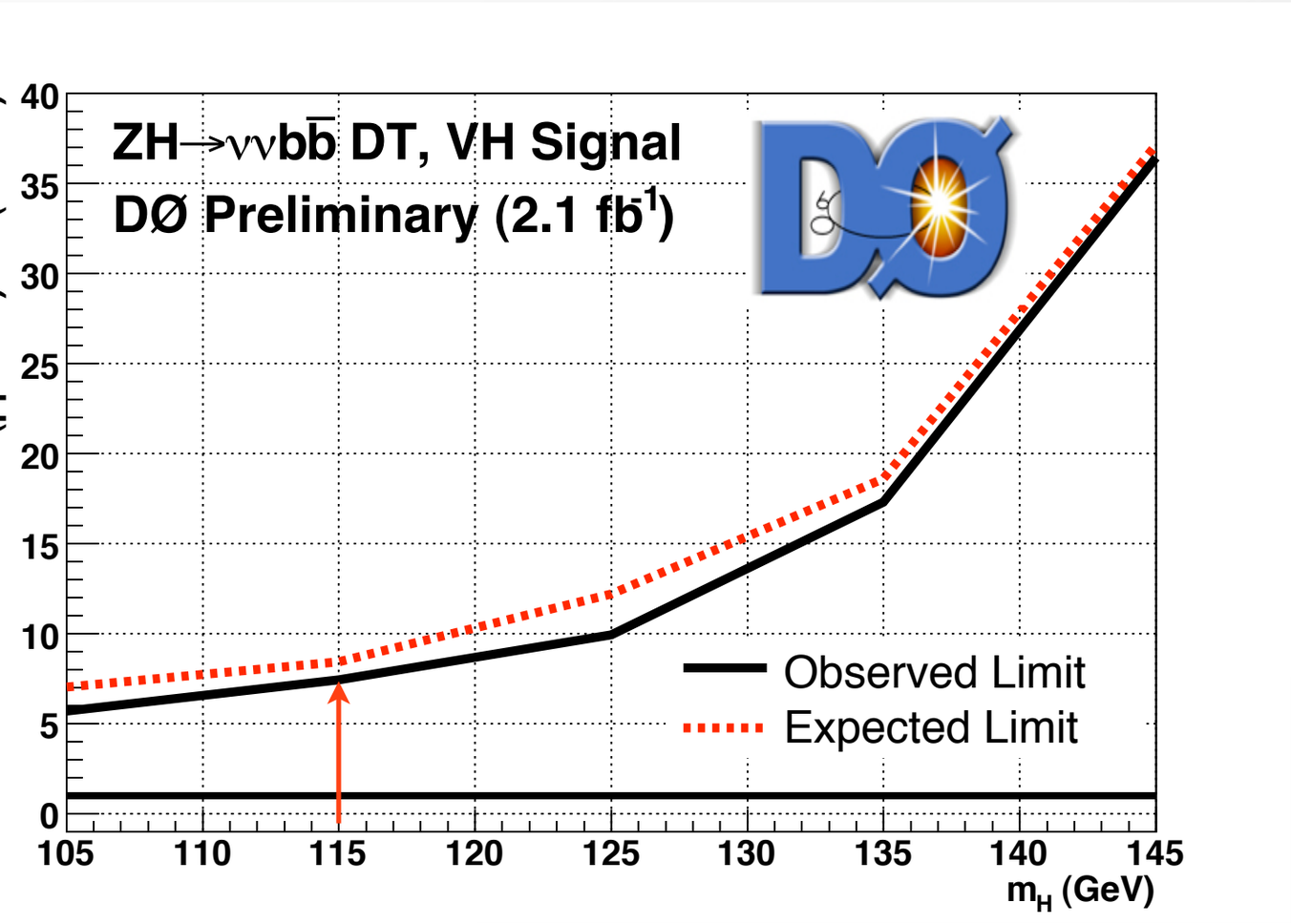
double tight btag

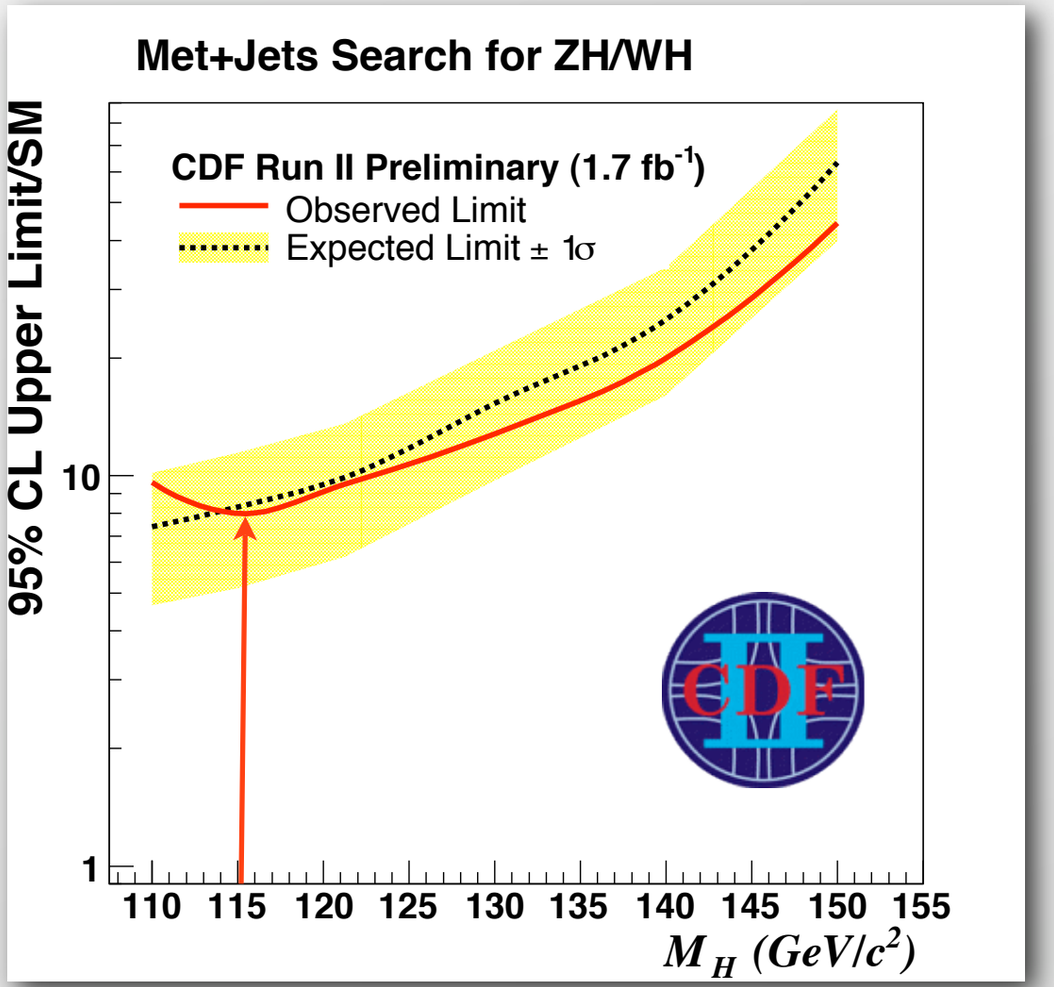
1 tight + 1 loose btag

ANN Inputs $M_{bb},\ MET,\ \Delta R_{j_1-j_2},$ $MET_{cal} \cdot MET_{trk},\ Trk_{NN}$



$ZH \rightarrow \nu\nu b\bar{b}$ Limits

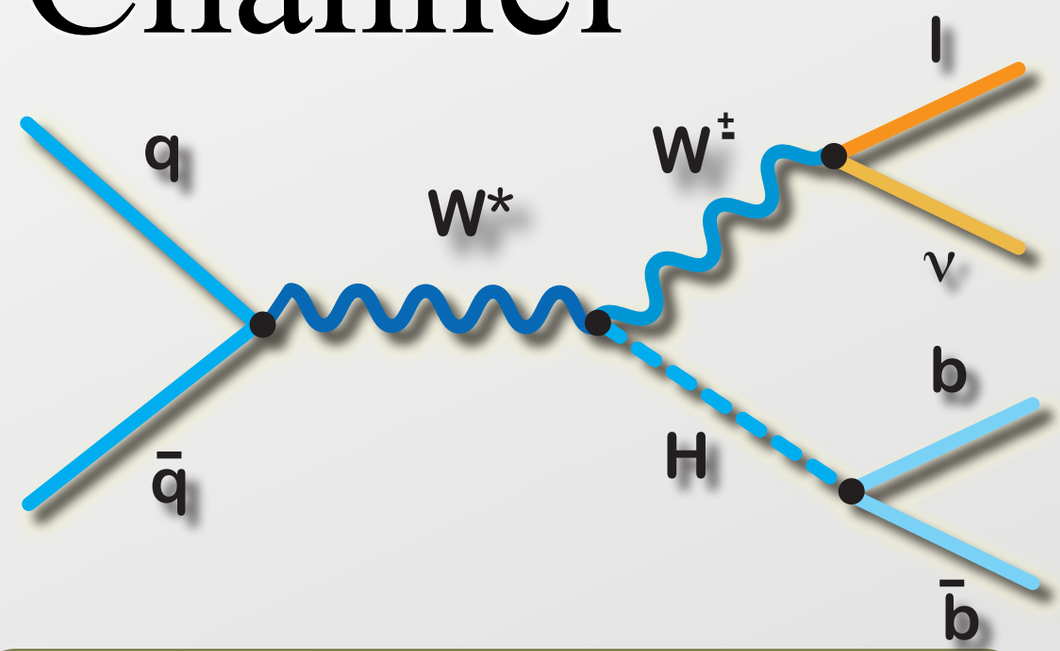




Experiment	Lum	Obs/SM	Exp/SM
D0	2.1 fb^{-1}	7.5	8.4
CDF	1.7 fb^{-1}	8.0	8.3

$M_h = 115\ GeV/c^2$

$WH \rightarrow \ell\nu b\bar{b}$ Channel



- High P_T Lepton
- Missing E_T
- 2 jets: Split up 1 and 2 b-tags

Features:

1. Good Acceptance
2. Final state similar to single top prod.
3. ~2-3 evts/fb^{-1}

Primary Backgrounds

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

$t\bar{t}$

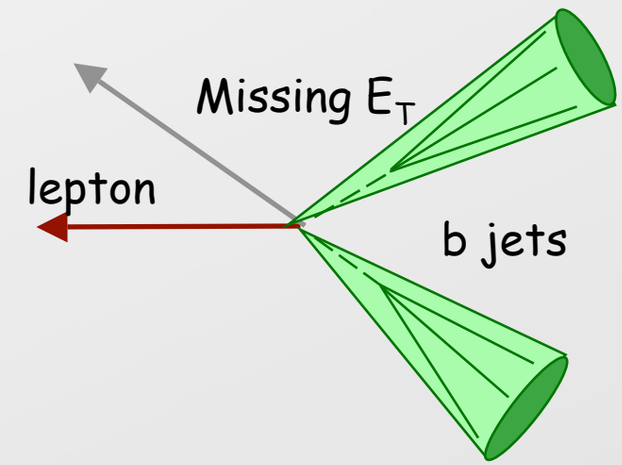
Single top

non − W QCD

WZ, WW

$Z \rightarrow \tau\tau$

$WH \rightarrow \ell\nu b\bar{b}$ Channel



- High P_T Lepton
- Missing E_T
- 2 jets: Split up 1 and 2 b-tags

Features:

1. Good Acceptance
2. Final state similar to single top prod.
3. ~2-3 evts/fb^{-1}

Primary Backgrounds

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

$t\bar{t}$

Single top

non − W QCD

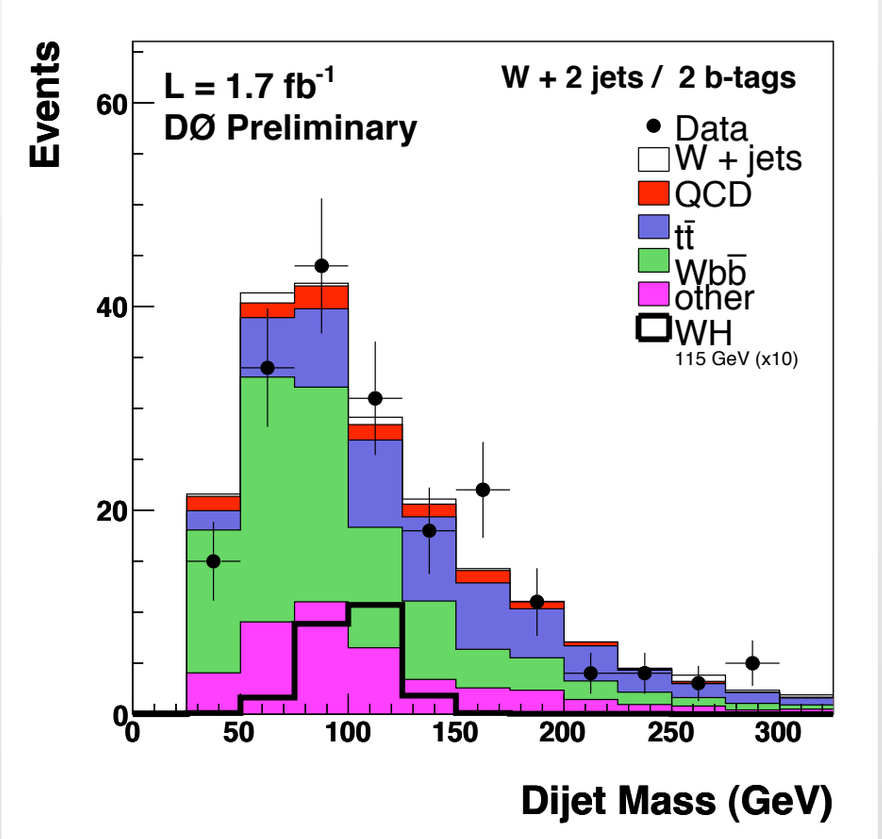
WZ, WW

$Z \rightarrow \tau\tau$

$WH \rightarrow \ell\nu b\bar{b}$ Discriminants

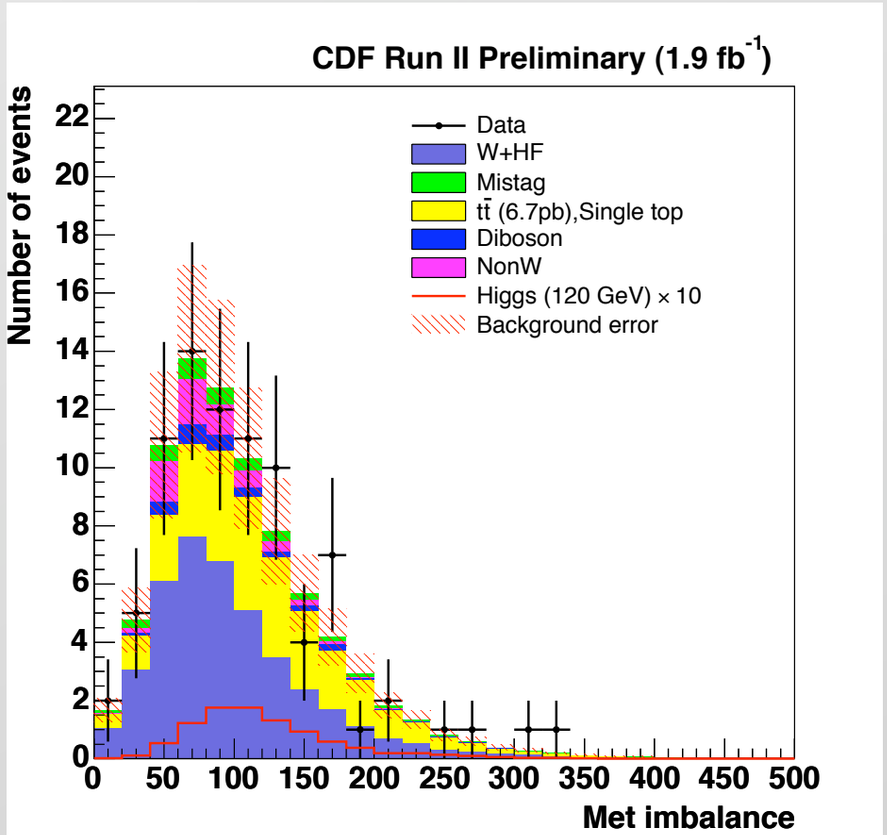
Lepton types: elec and muon
Two b-Tagging: 1 double tag
1 single Tag

ANN Inputs $P_T^{j_1},\ P_T^{j_2},\ \Delta R_{jj}, \Delta\phi_{jj},$
$P_T^{jj},\ M_{jj},\ P_T^{\ell-MET}$



Lepton types: Central and Forward
b-Tagging: 2 double tag
1 Single Tag using NN

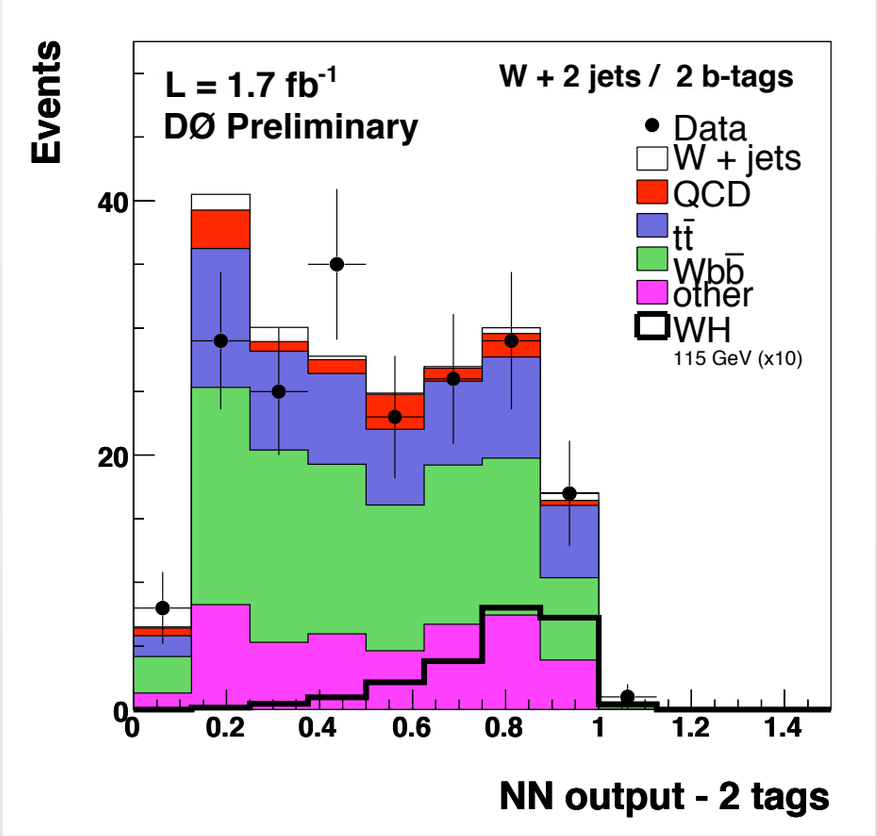
ANN Inputs $M_{jj}, P_T^{imb}, P_T^{sys},$
$M_{\ell\nu j}^{min}, \Delta R_{\ell\nu}, E_T^{jets}$



$WH \rightarrow \ell\nu b\bar{b}$ Discriminants

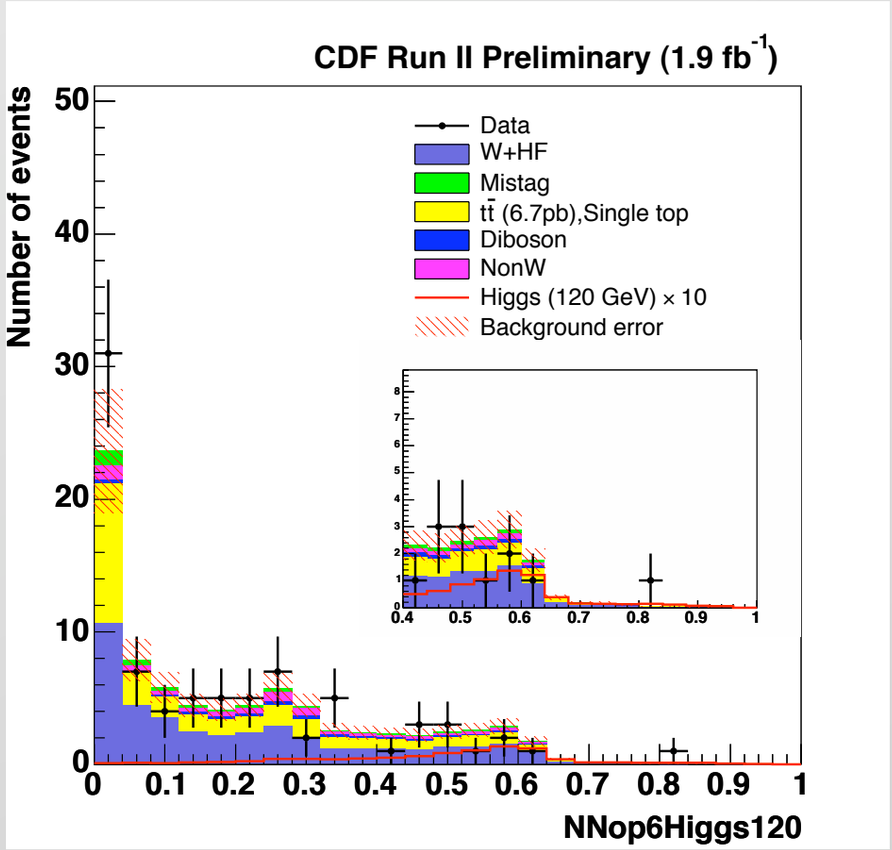
Lepton types: elec and muon
Two b-Tagging: 1 double tag
1 single Tag

ANN Inputs $P_T^{j_1},\ P_T^{j_2},\ \Delta R_{jj}, \Delta\phi_{jj},$
$P_T^{jj},\ M_{jj},\ P_T^{\ell-MET}$

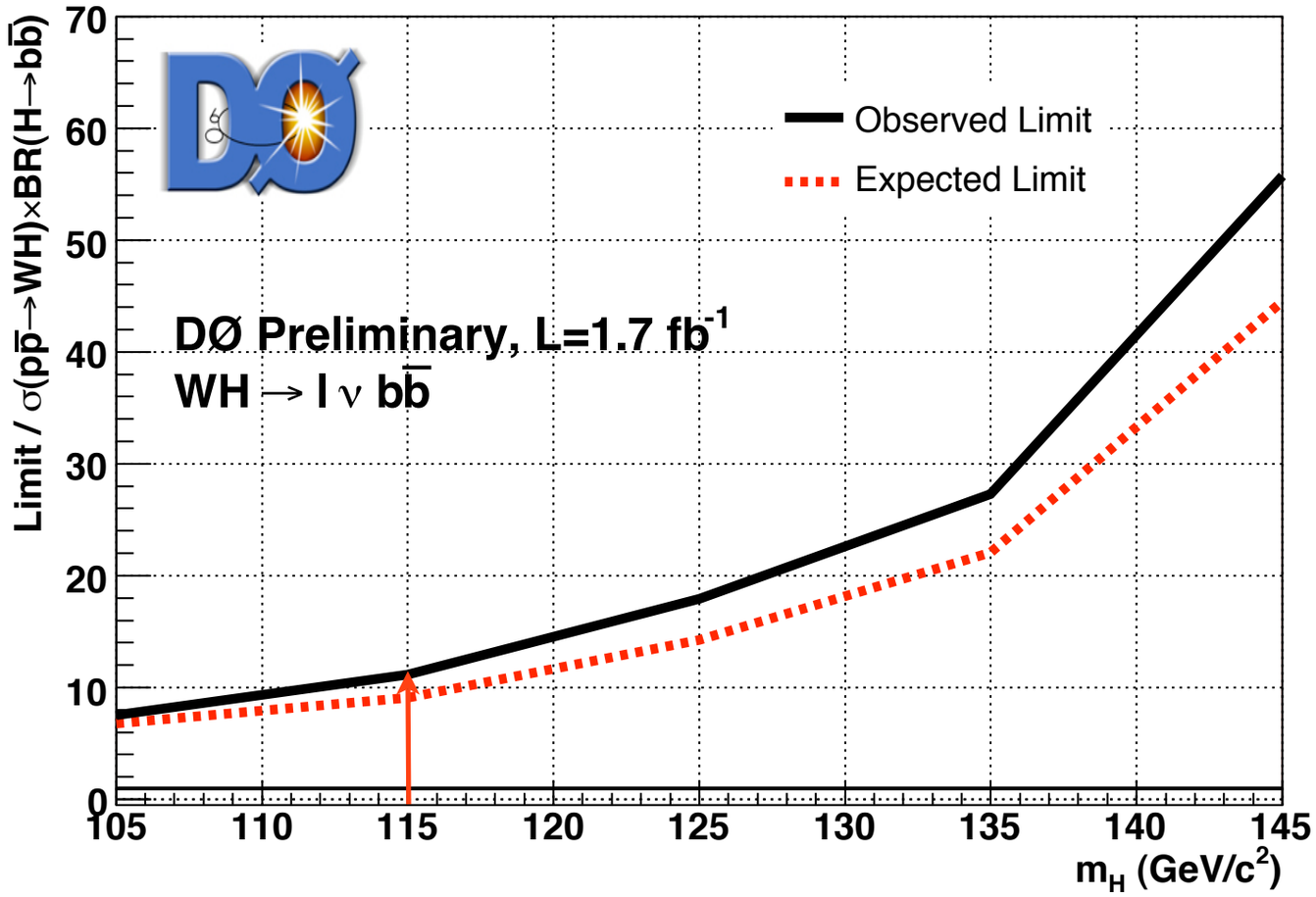


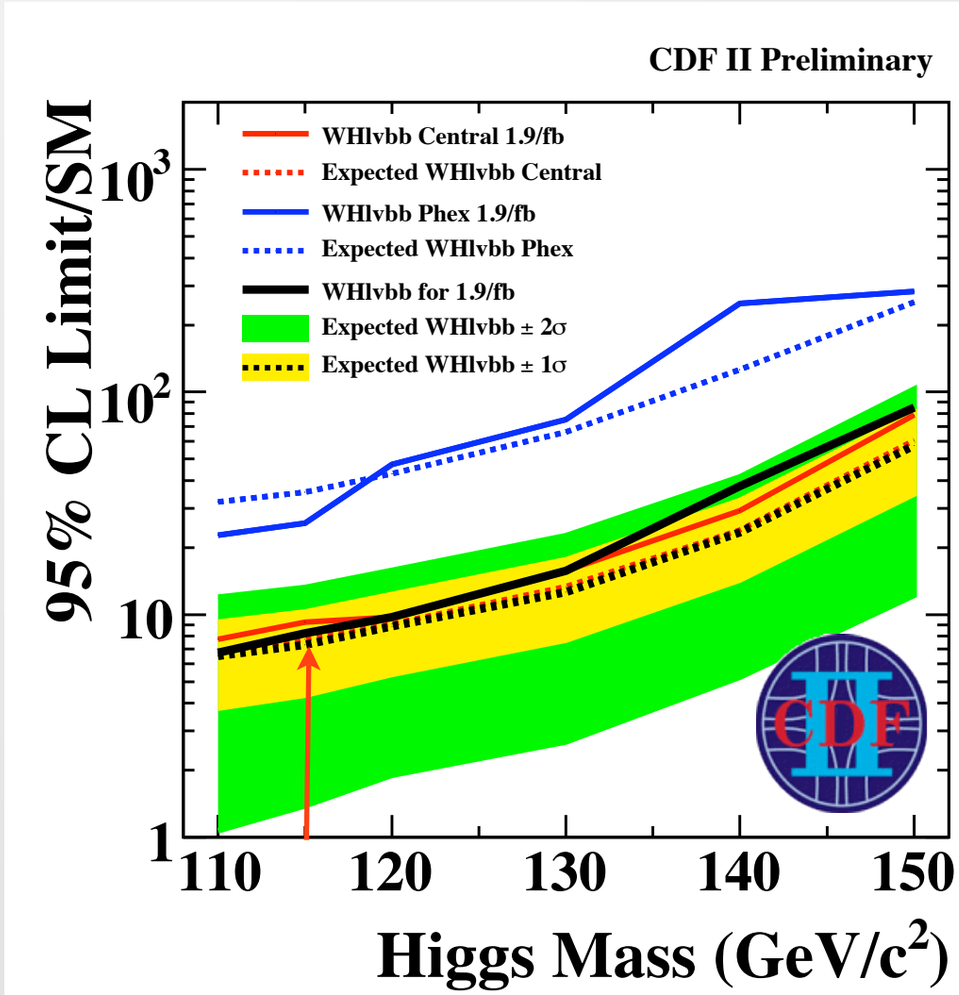
Lepton types: Central and Forward
b-Tagging: 2 double tag
1 Single Tag using NN

ANN Inputs $M_{jj}, P_T^{imb}, P_T^{sys},$
$M_{\ell\nu j}^{min}, \Delta R_{\ell\nu}, E_T^{jets}$



$WH \rightarrow \ell\nu b\bar{b}$ Limits



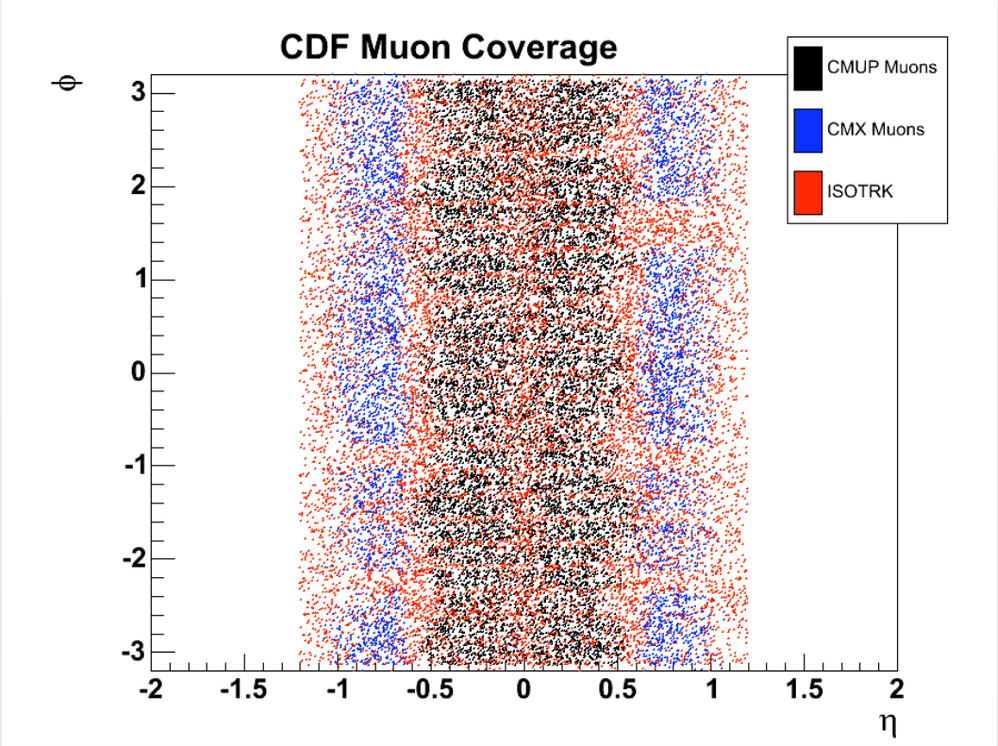


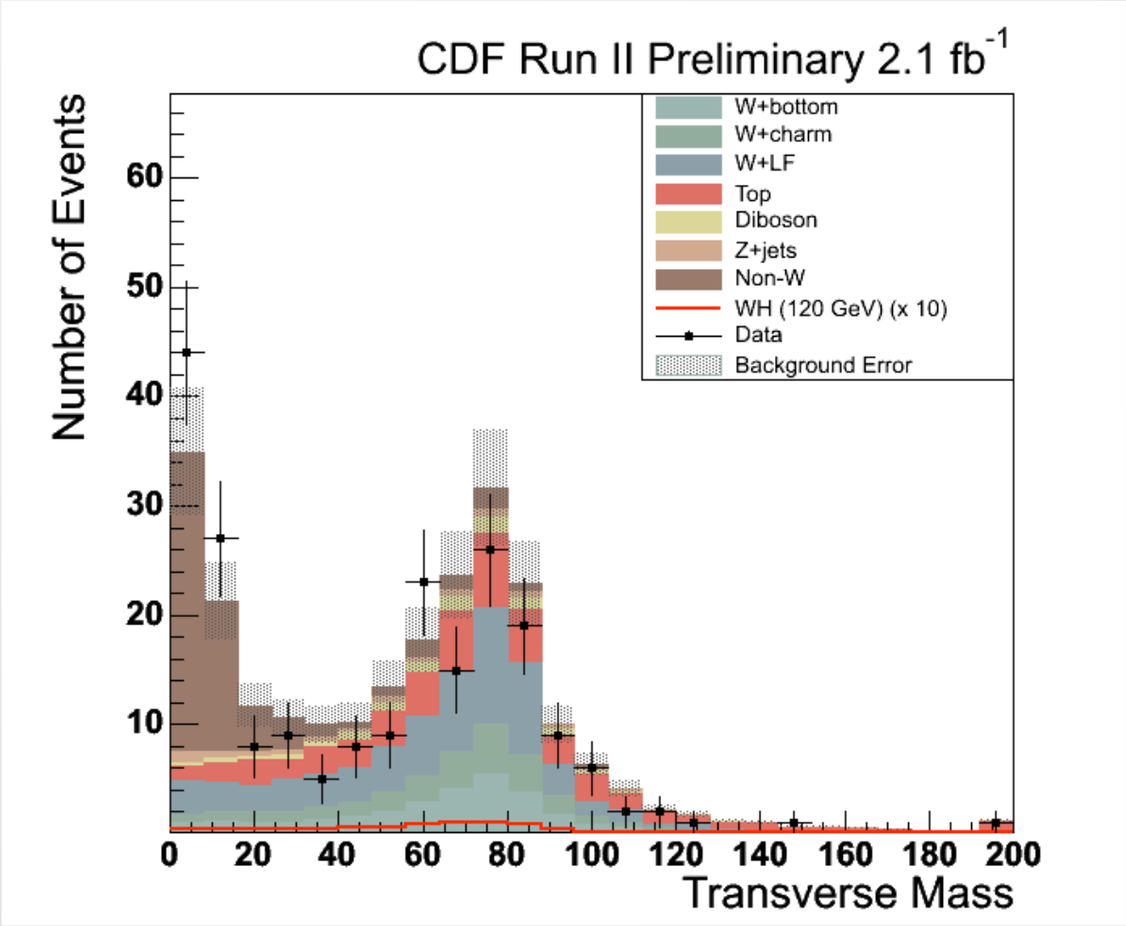
Experiment	Lum	Obs/SM	Exp/SM
D0	1.7 fb^{-1}	10.9	8.9
CDF	1.9 fb^{-1}	8.2	7.3

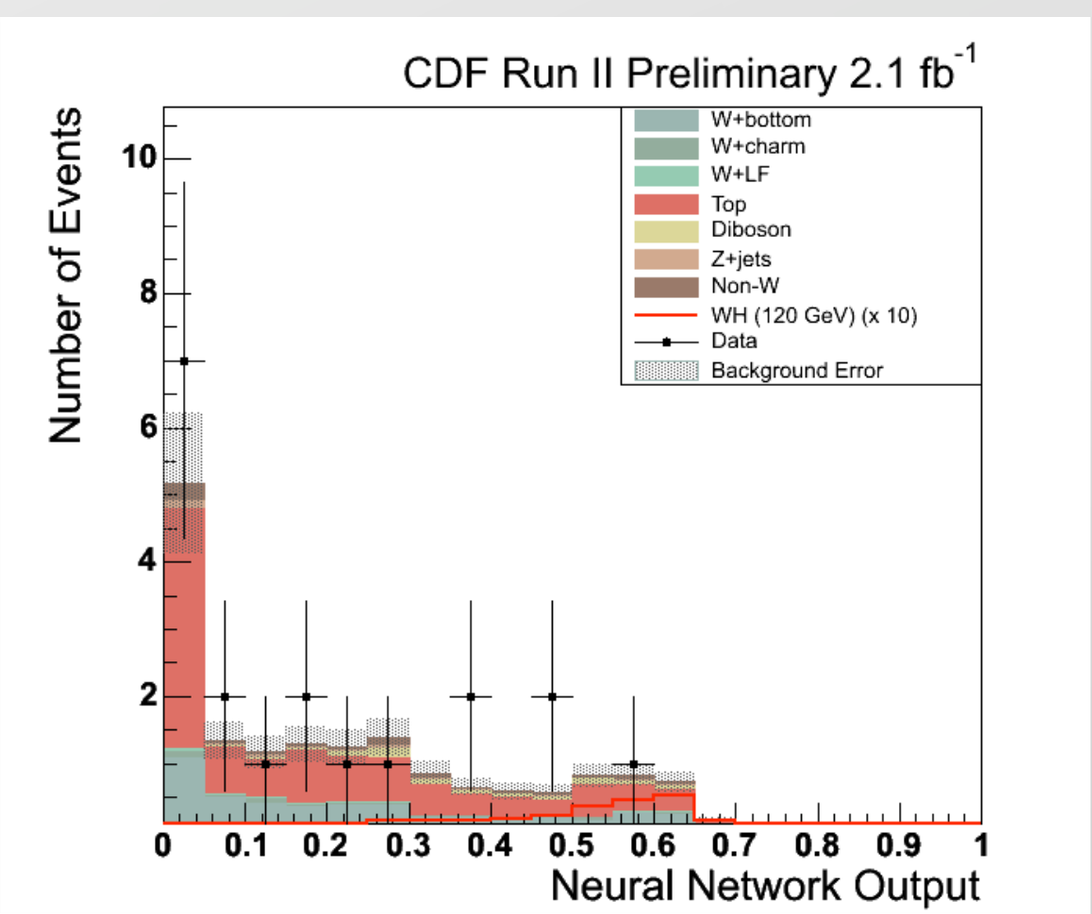
$M_h = 115\ \mathrm{GeV}/c^2$

Adding Acceptance to WH: ISOTrack

- Look for WH events which fail standard lepton selection
- Use MET + 2jet trigger
- Only use track info: no CAL or Muon chamber info
- Increases acceptance by 25%!

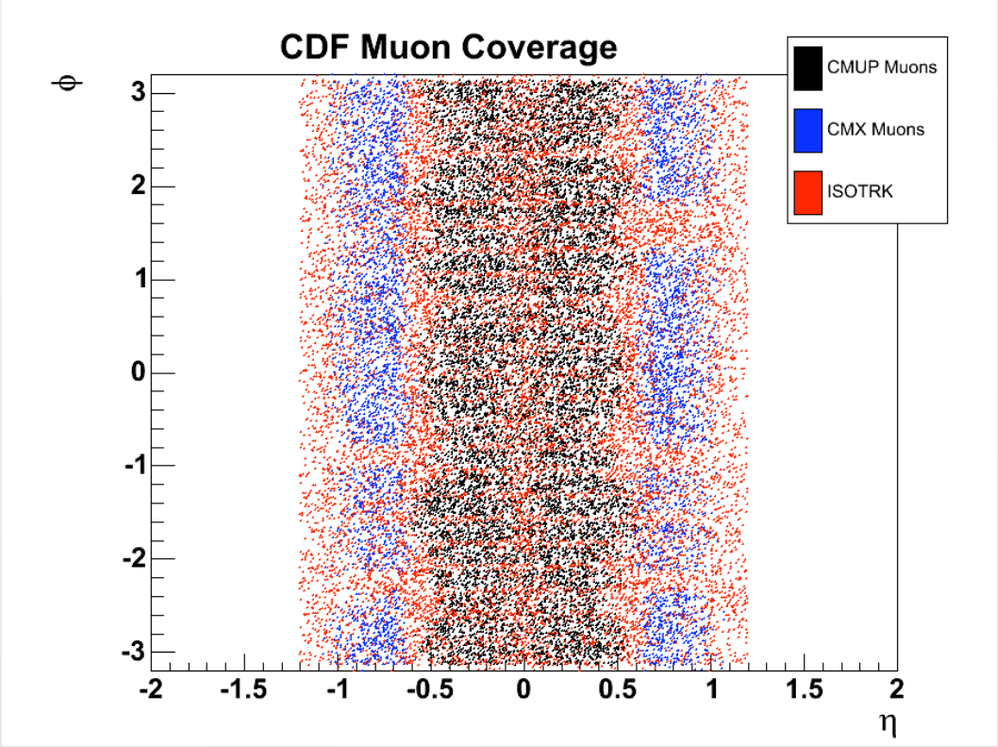


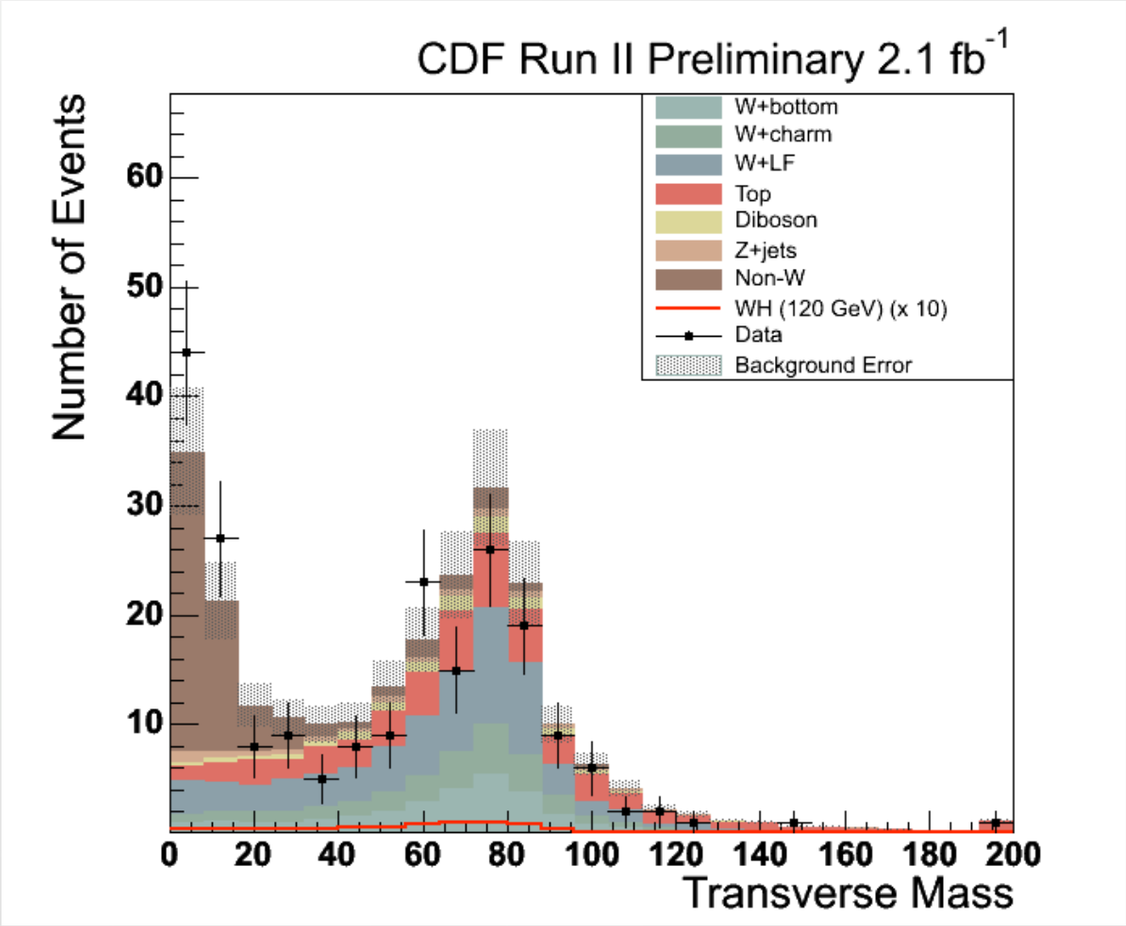


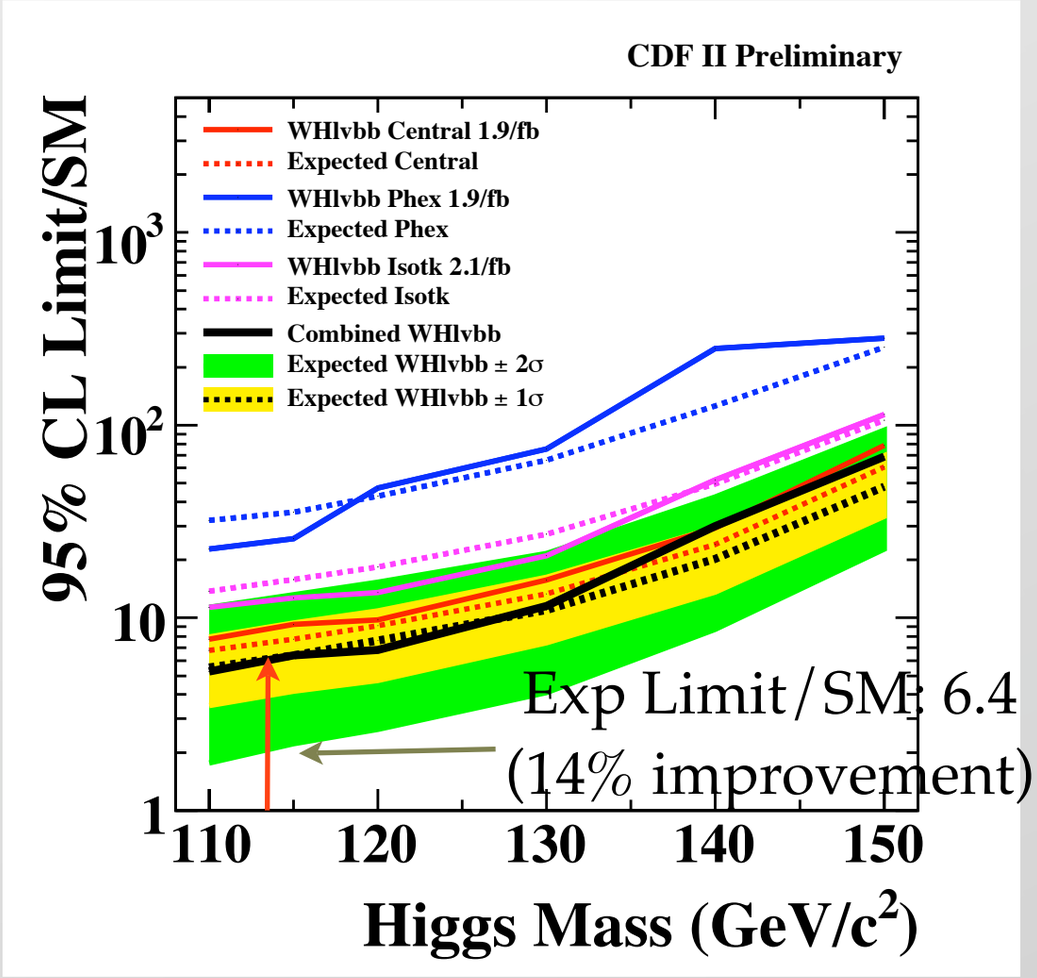


Adding Acceptance to WH: ISOTrack

- Look for WH events which fail standard lepton selection
- Use MET + 2jet trigger
- Only use track info: no CAL or Muon chamber info
- Increases acceptance by 25%!

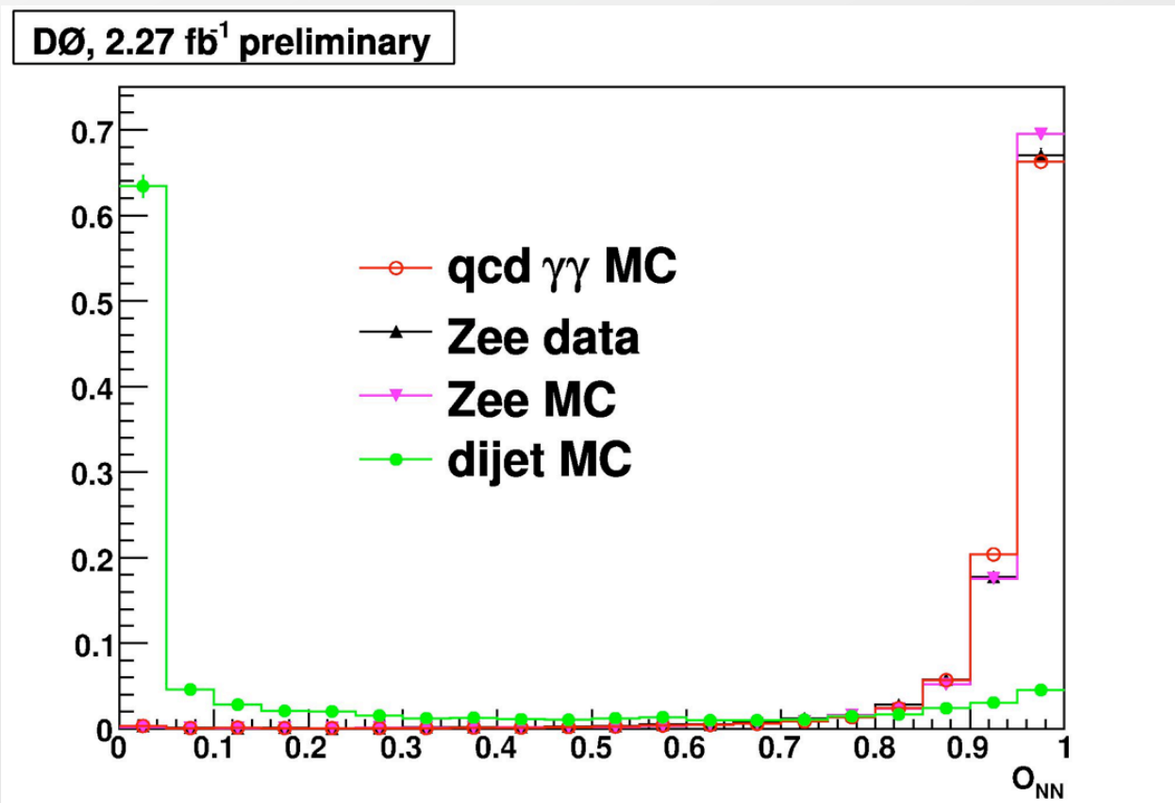






$\bar{p}p \rightarrow H \rightarrow \gamma\gamma$

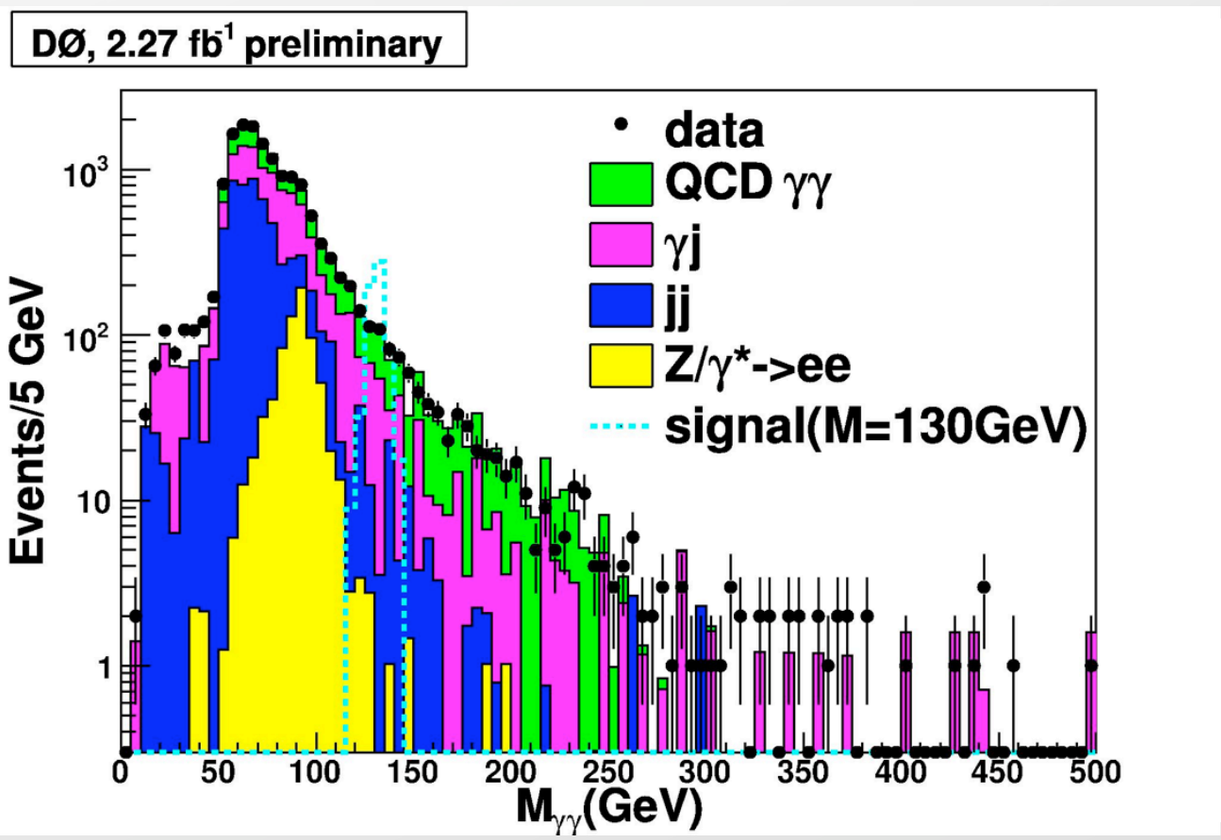
- Expected rate low (BR ~0.22% @ Mh=130 GeV)
- BUT, <u>every little bit helps</u> and <u>nature could be different</u>.



Observed	13827	----
Z->ee	741+/-102	MC
jet jet	4779+/-1265	data
gamma jet	4677+/-1246	data
QCD gamma	3400+/-711	MC

$\bar{p}p \rightarrow H \rightarrow \gamma\gamma$

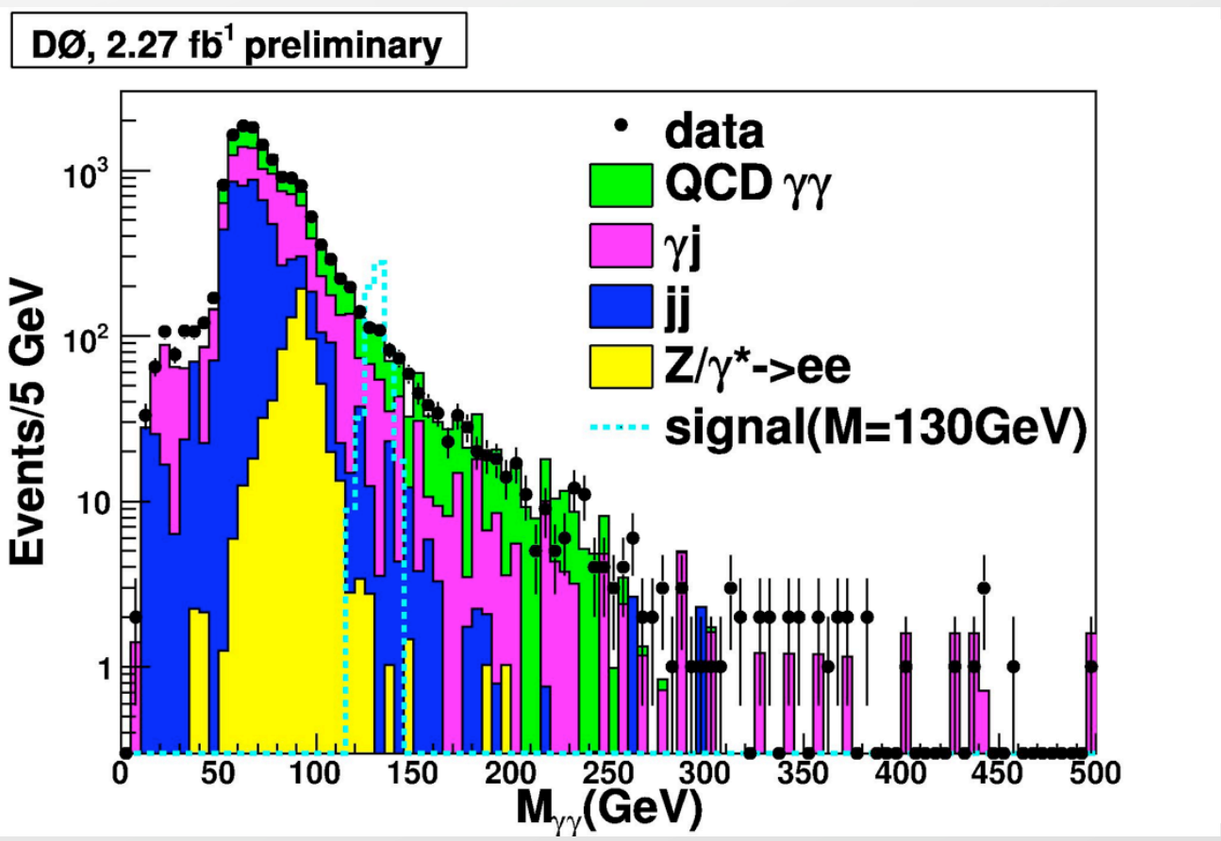
- Expected rate low (BR ~0.22% @ Mh=130 GeV)
- BUT, <u>every little bit helps</u> and <u>nature could be different</u>.

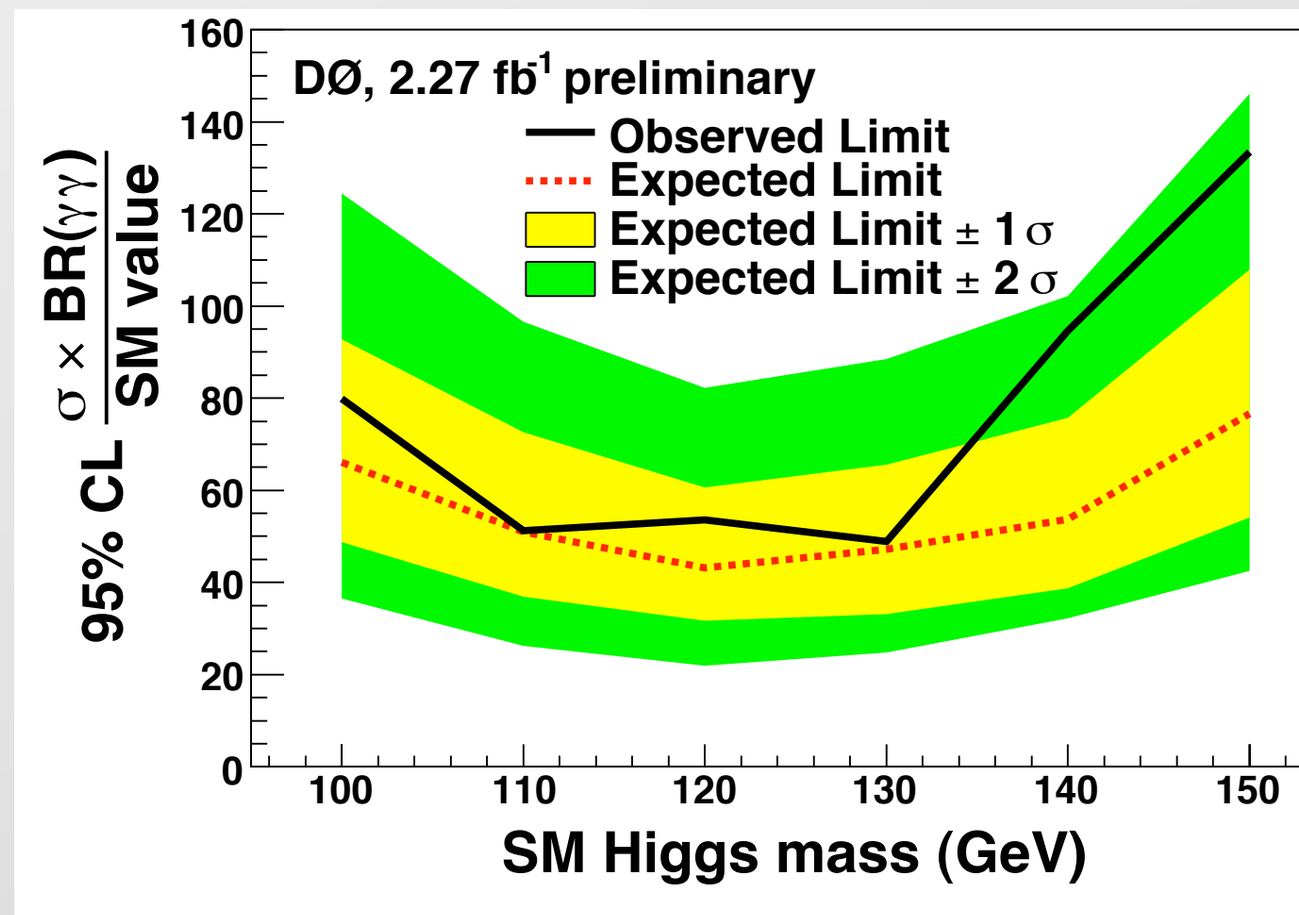


Observed	13827	----
Z->ee	741+/-102	MC
jet jet	4779+/-1265	data
gamma jet	4677+/-1246	data
QCD gamma	3400+/-711	MC

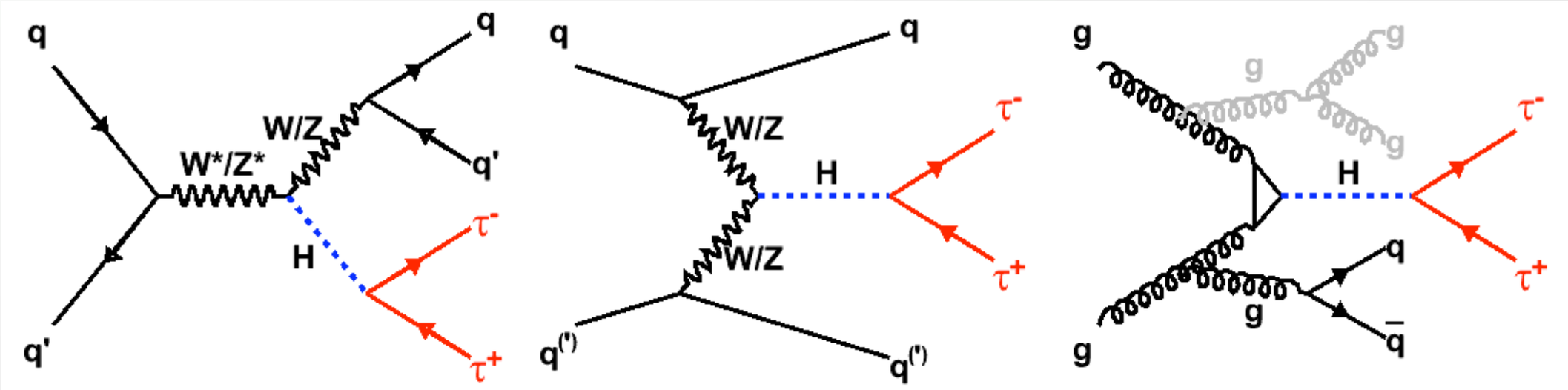
$\bar{p}p \rightarrow H \rightarrow \gamma\gamma$

- Expected rate low (BR ~0.22% @ Mh=130 GeV)
- BUT, <u>every little bit helps</u> and <u>nature could be different</u>.





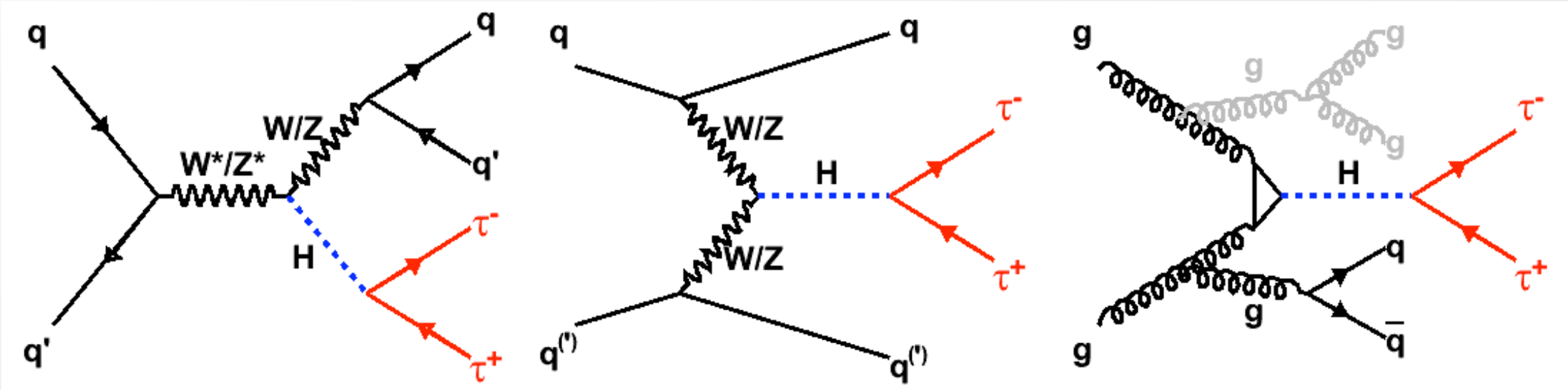
$H \rightarrow \tau\tau$ Plus 2 Jets

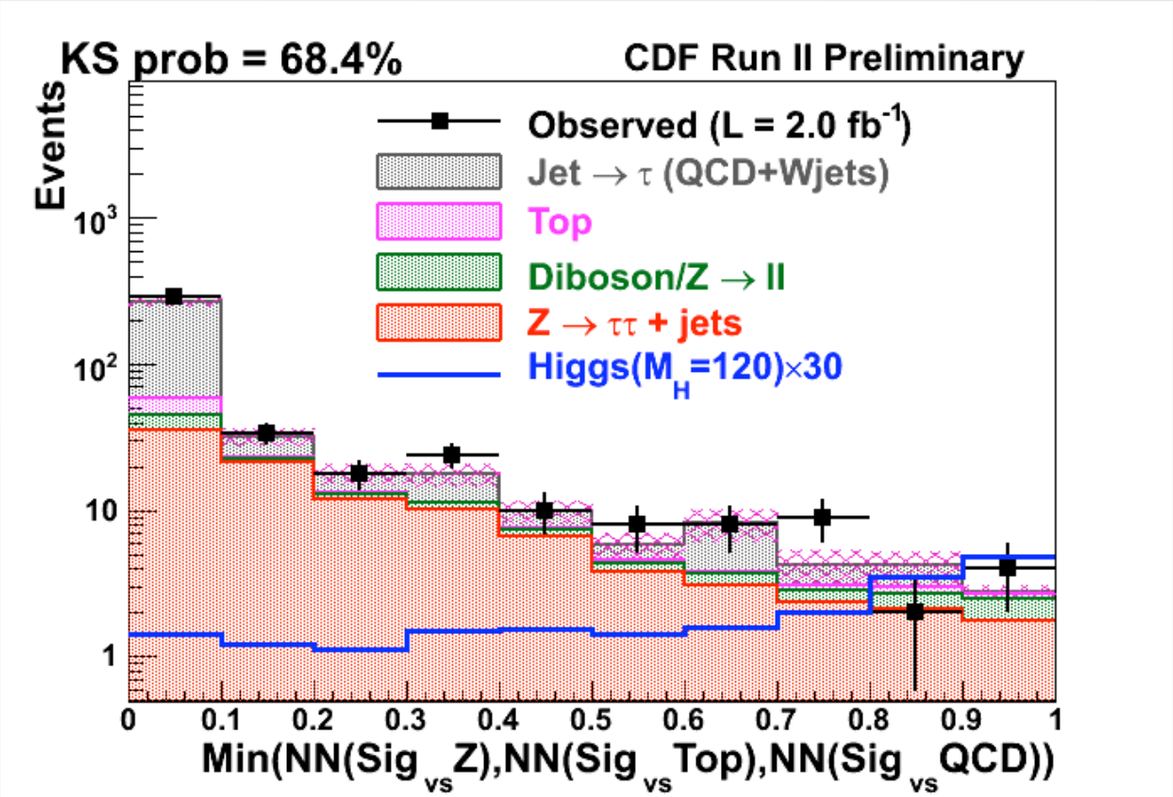


1. Require 1 hadronic tau and 1 opp sign Lepton (45%BR)
2. Uses lepton+track trigger
3. 1 and 3 prong taus
4. Two jets and Z veto

Process	Evt ($2fb^{-1}$)
WH	0.18
ZH	0.11
VBF	0.12
ggH	0.26
Total	0.67
Background	374

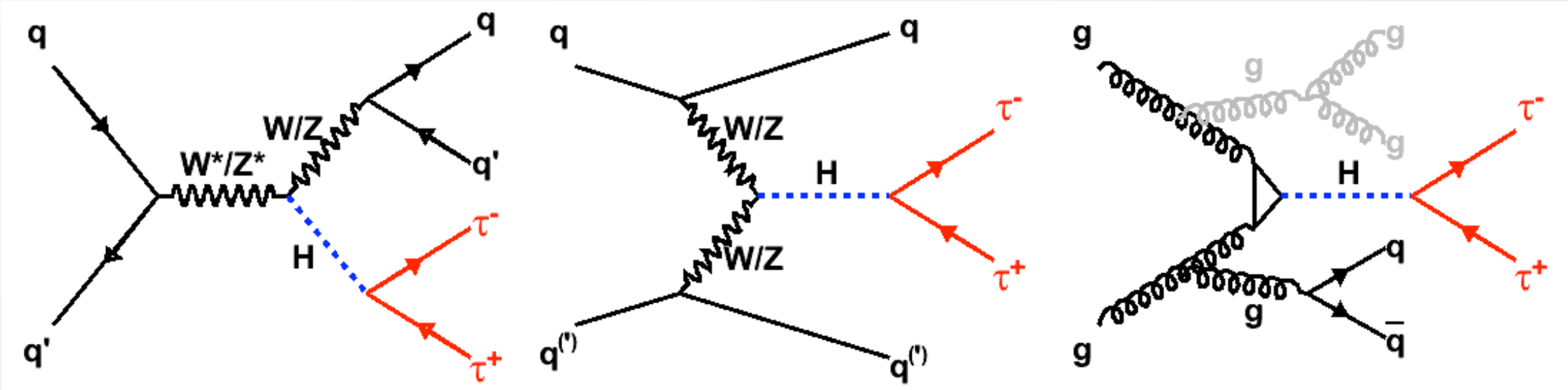
$H \rightarrow \tau\tau$ Plus 2 Jets

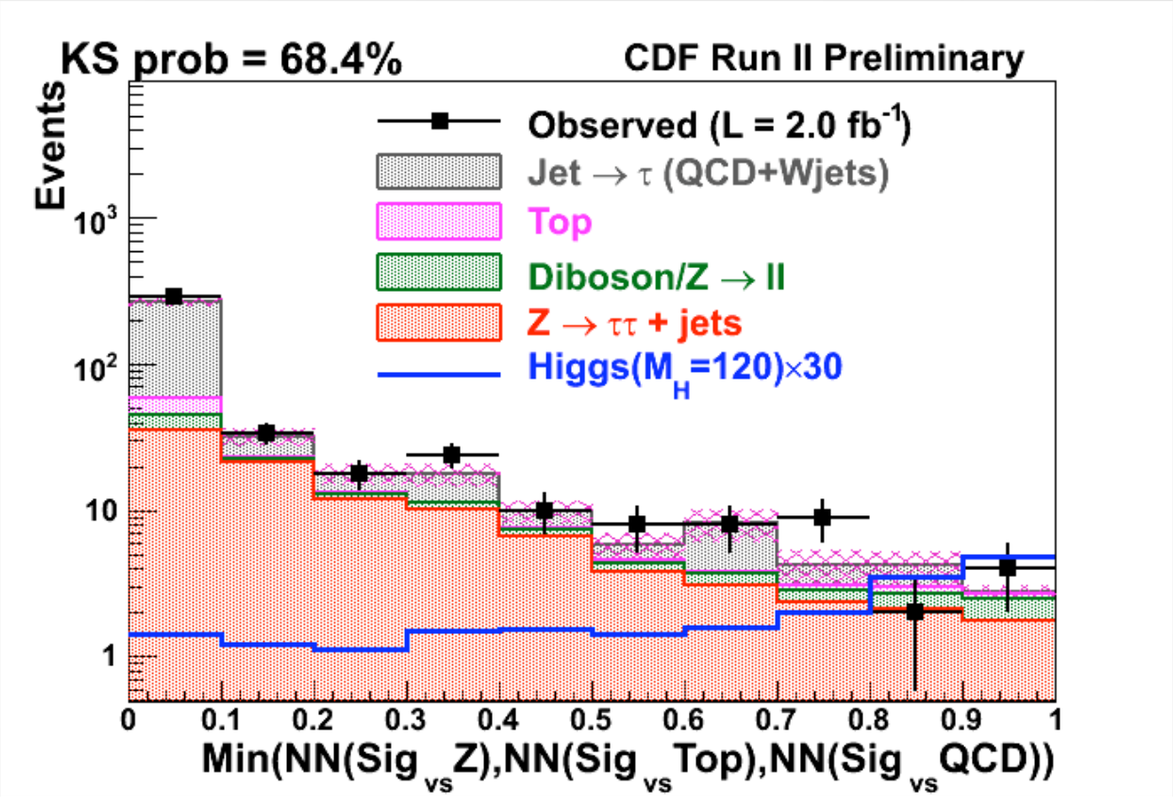


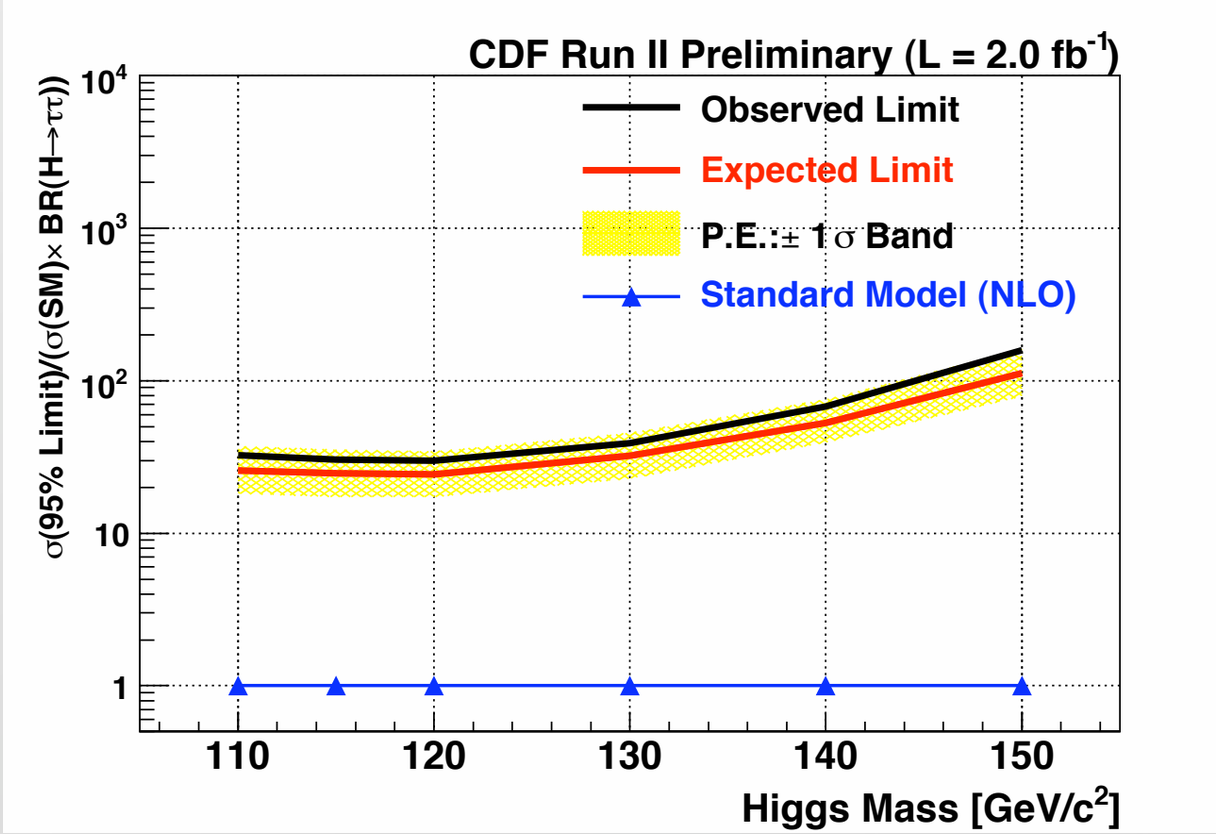


Minimum of 3 trained Networks:
NN(Signal vs Z→ττ)
NN(Signal vs tt)
NN(Signal vs QCD)

$H \rightarrow \tau\tau$ Plus 2 Jets





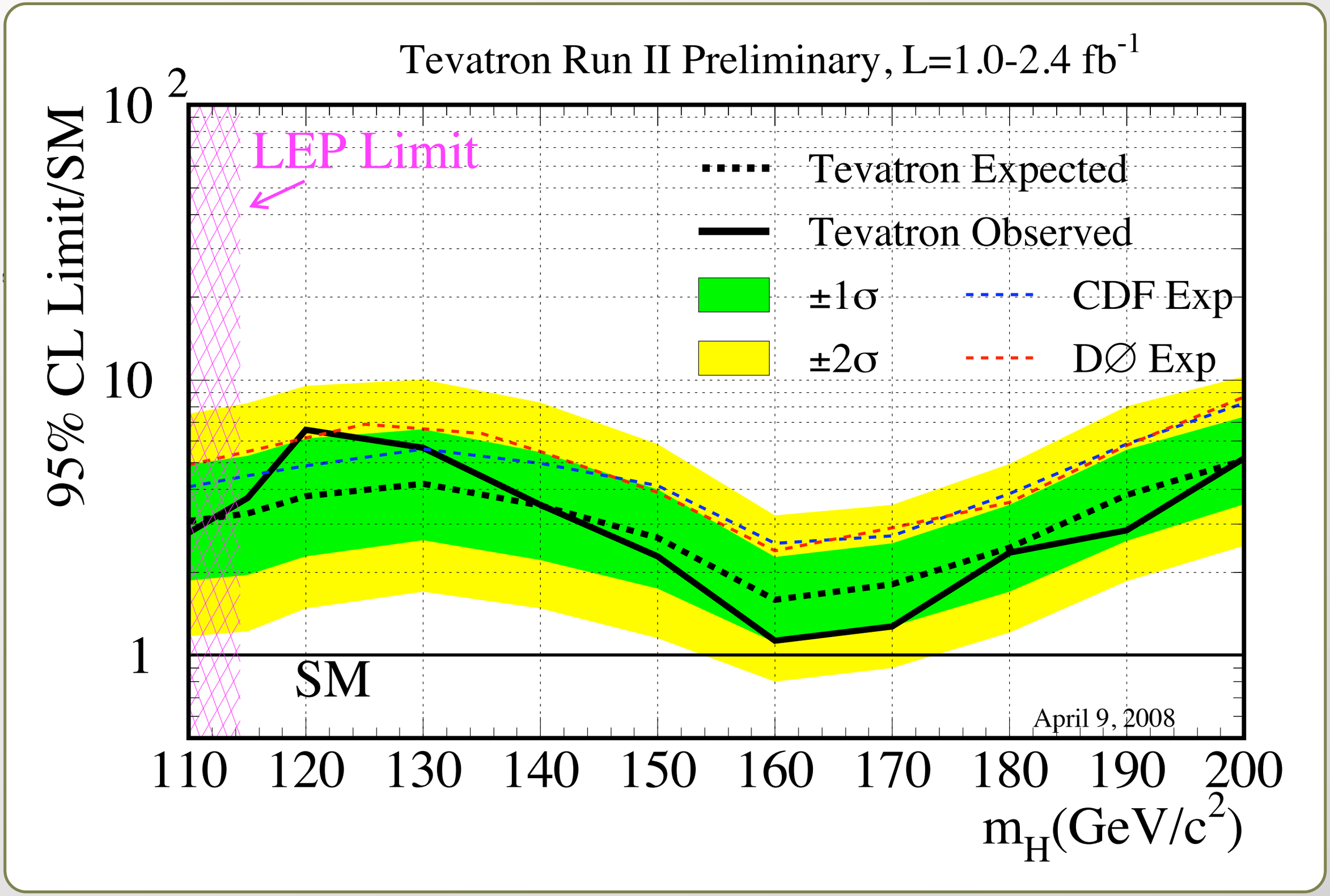


Conclusion: Tevatron Combination

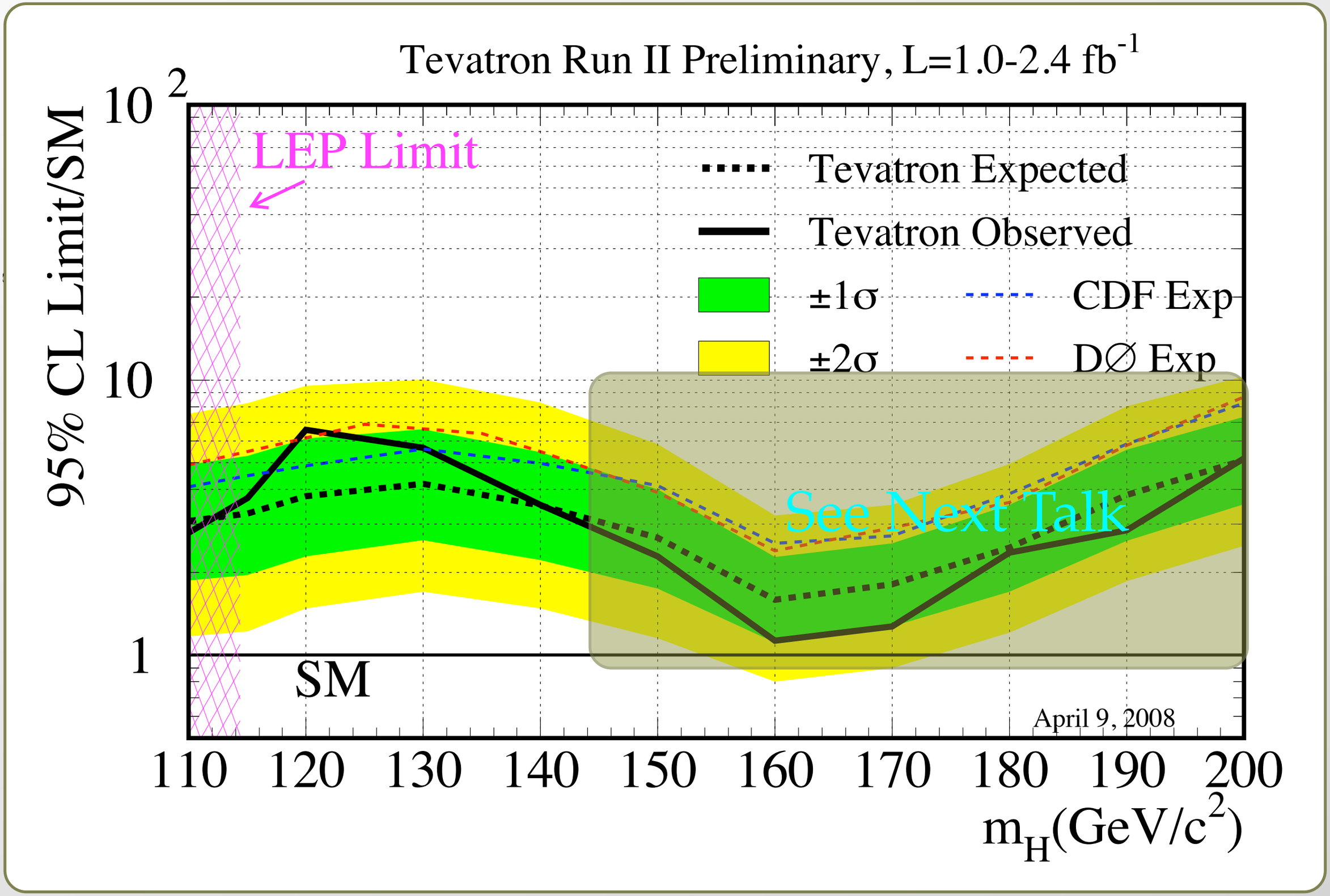
$M_H = 115$ GeV/c^2

Channel	CDF Limits: σxB/SM obs (exp)	DZero Limits σxB/SM obs (exp)
$WH \to \ell\nu b\bar{b}$	8.2 (7.3)	10.9 (8.9)
$ZH \to \ell\ell b\bar{b}$	16 (16)	17.8 (20.4)
$ZH \to \nu\nu b\bar{b}$	8.0 (8.3)	7.5 (8.4)
$H \to \tau\tau$ **adds 10%**	30.5 (24.8)	-
$\bar{p}p \to H \to \gamma\gamma$	-	~50
Combined	4.95 (4.6)	6.4 (5.5)
Tevatron Combined	**3.7 (3.3)**	

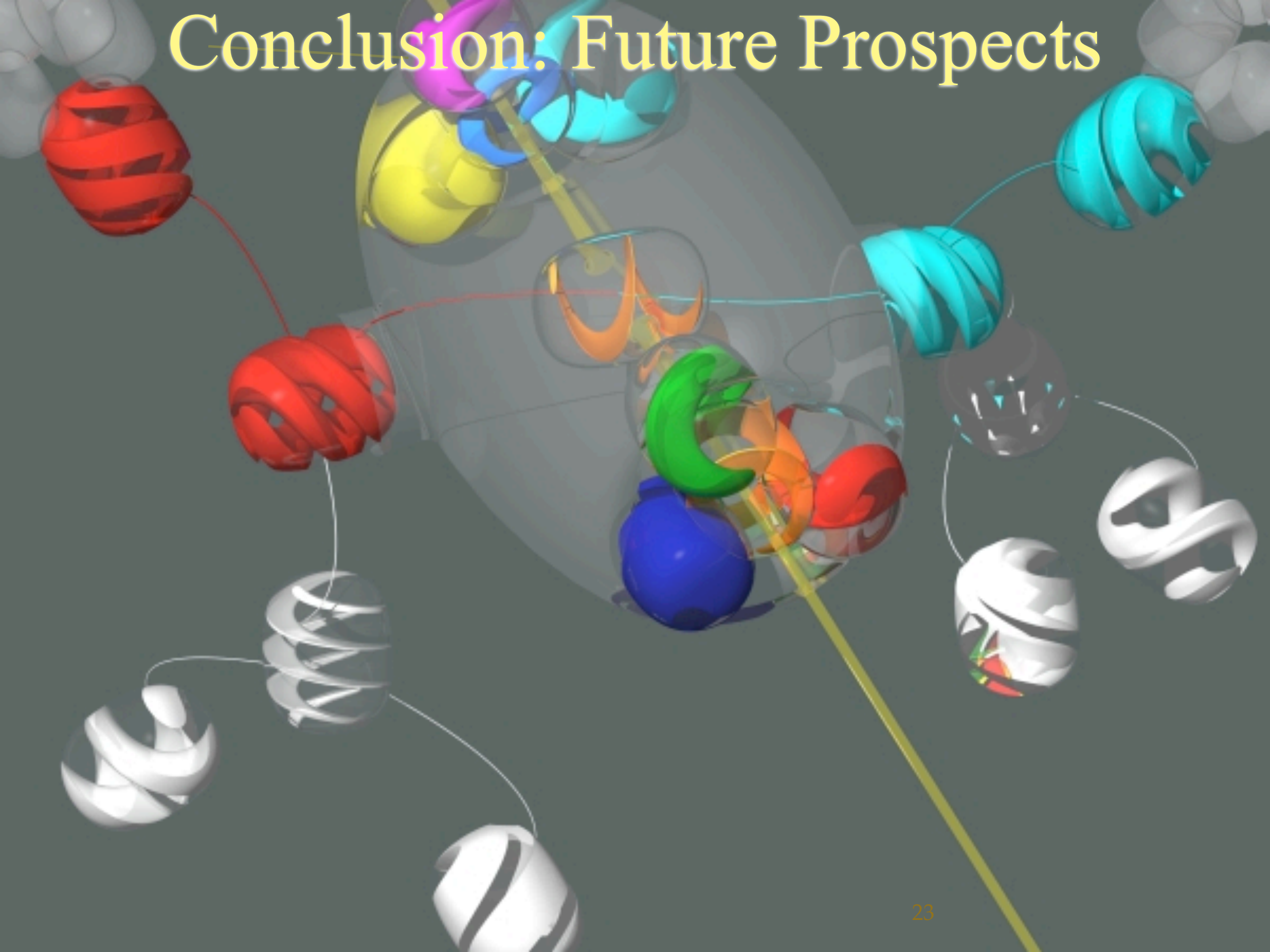
Conclusion: Tevatron Combination



Conclusion: Tevatron Combination



Conclusion: Future Prospects



Conclusion: Future Prospects

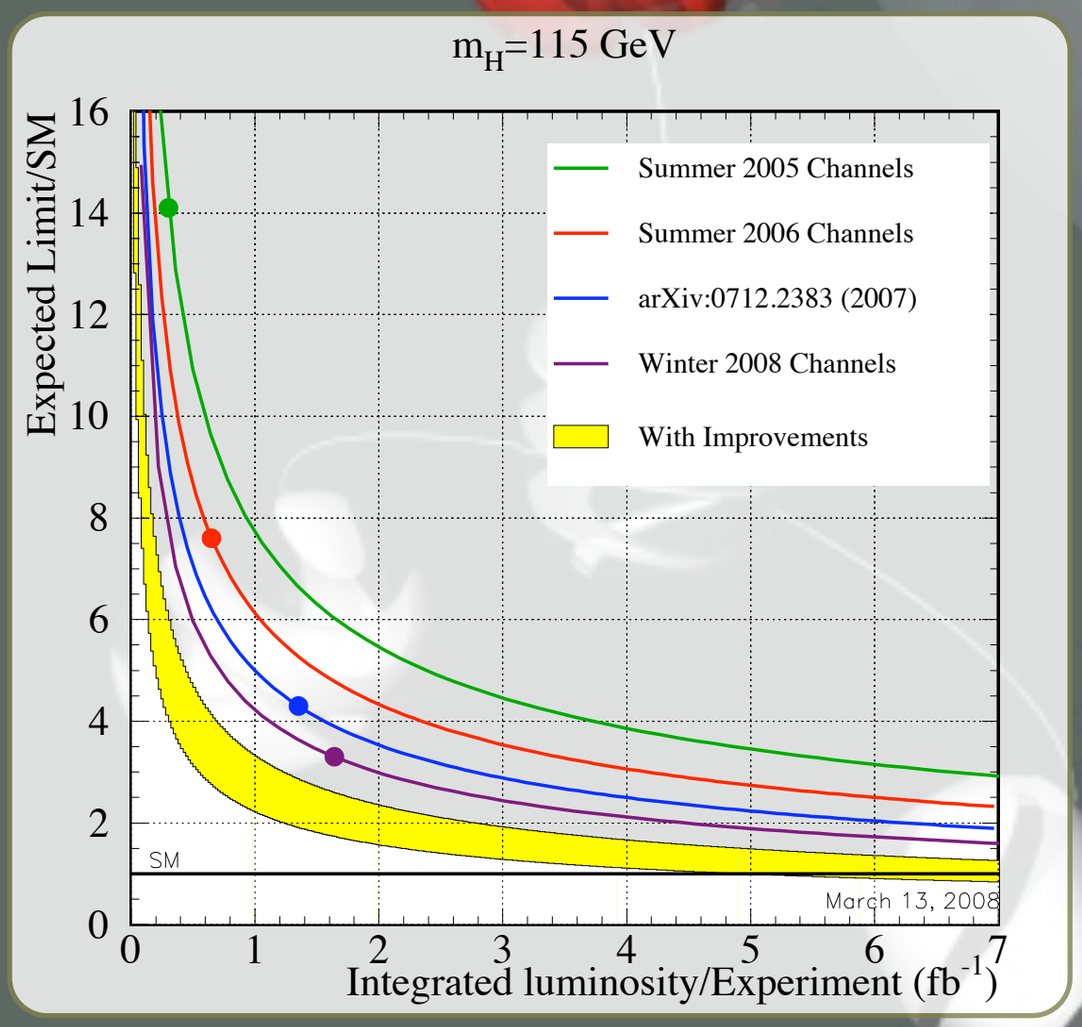
Improvements in the Higgs analyses have been exceeded that expected from more data

- Analyses can add ideas from other channels
  - e.g. Use of flavor separation NN for single tags
- Combination of techniques within channels
  - e.g. Combine ME plus NN
- Some new ideas still out there? (WH Isotrack added 25%!)

Conclusion: Future Prospects

Improvements in the Higgs analyses have been exceeded that expected from more data

- Analyses can add ideas from other channels
  - e.g. Use of flavor separation NN for single tags
- Combination of techniques within channels
  - e.g. Combine ME plus NN
- Some new ideas still out there? (WH Isotrack added 25%!)



Conclusion: Future Prospects

Improvements in the Higgs analyses have been exceeded that expected from more data

- Analyses can add ideas from other channels
  - e.g. Use of flavor separation NN for single tags
- Combination of techniques within channels
  - e.g. Combine ME plus NN
- Some new ideas still out there? (WH Isotrack added 25%!)