



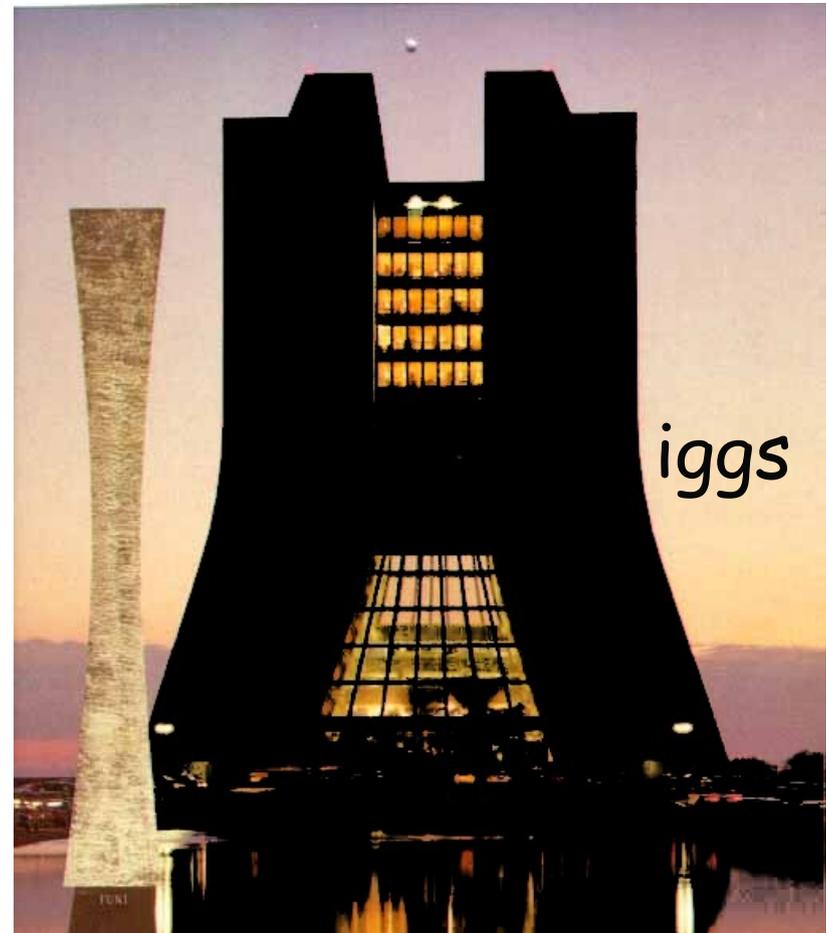
# Latest Results and Prospects for Higgs Searches at the Tevatron



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DØ / ATLAS  
Columbia University

*with results from the  
DØ and CDF Collaborations\**

Saclay/Orsay Seminars  
March 10-11, 2008



*\*Mostly from Moriond EW 2008  
(last week)*

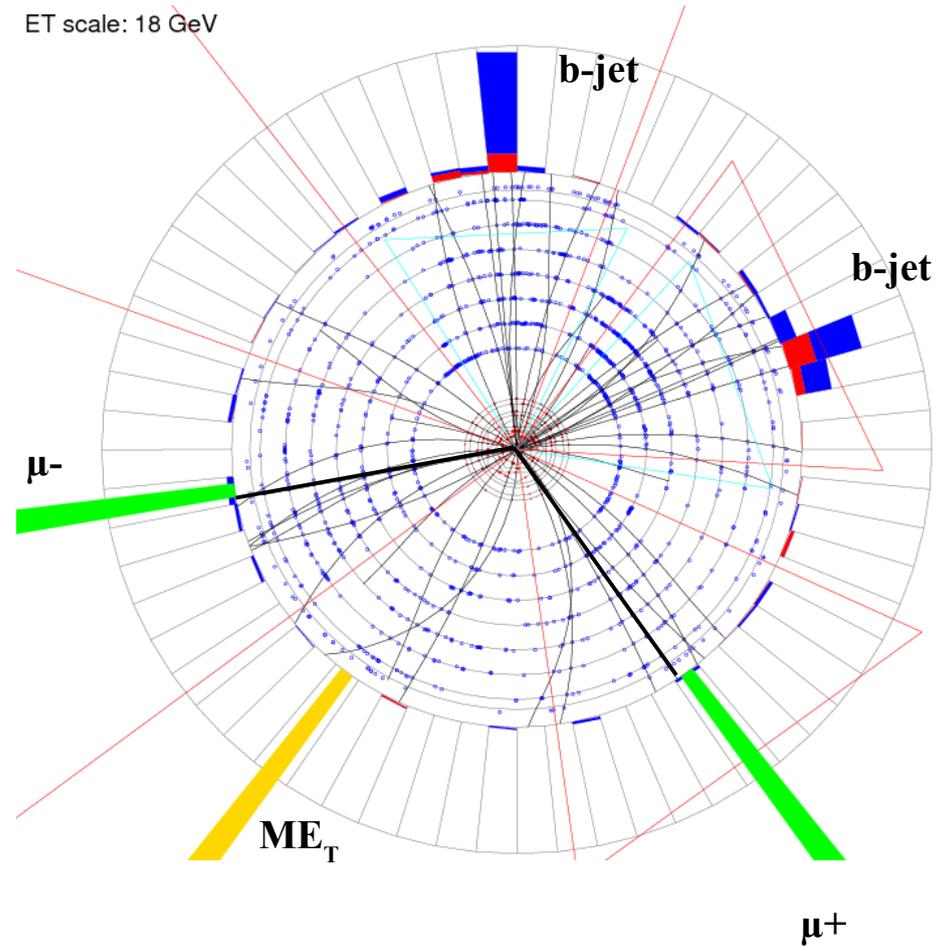
# Outline

## Standard Model Higgs searches

- Low mass
- High mass
- Improvements
- Prospects

## MSSM Higgs searches

## Other Higgs searches



# The Standard Model

3 families of matter

3 forces

- “gauge symmetries”:  
 $U(1)_Y \times SU(2)_L \times SU(3)_C$

*Massive W,Z gauge bosons*

Scalar Higgs field, non-zero VEV

- W,Z get masses through “Higgs mechanism”
- Fermions can get Yukawa masses:

$$-\frac{1}{v} m_f \bar{\Psi}_f \phi_h \Psi_f$$

Higgs boson: excitation of the Higgs field

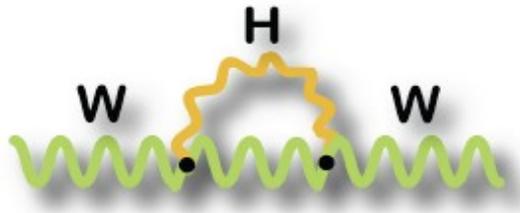
- Scalar boson
- Couplings specified
- Unknown mass:  $m_H$

Leptons	$\nu_e$ e- Neutrino	$\nu_\mu$ μ- Neutrino	$\nu_\tau$ τ- Neutrino
	$e$ electron	$\mu$ muon	$\tau$ tau
Quarks	$d$ down	$s$ strange	$b$ bottom
	$u$ up	$c$ charm	$t$ top
	I	II	III

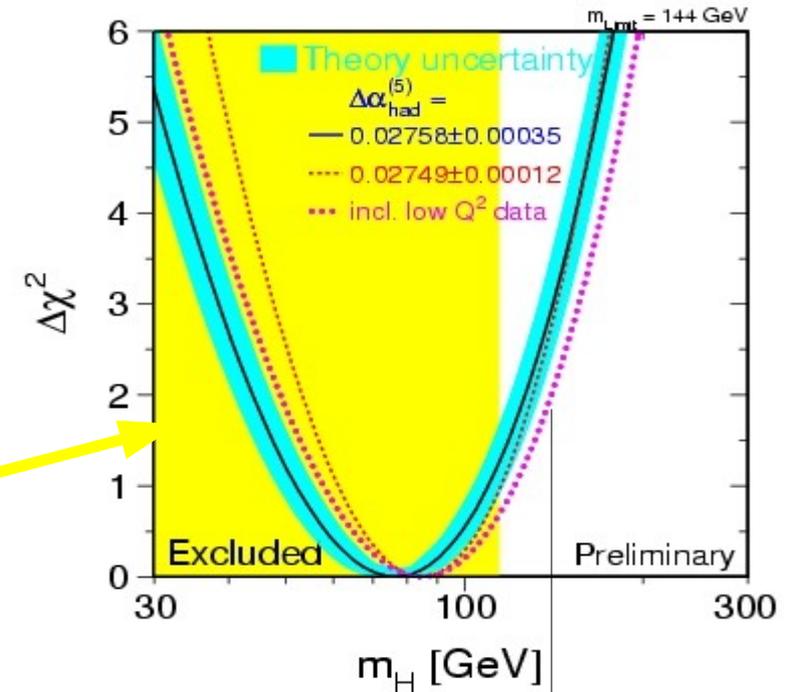
The Generations of Matter

# Higgs Mass Constraints

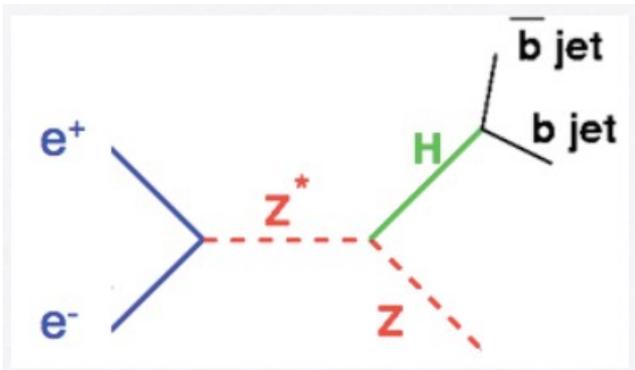
EW variables sensitive to  $m_H$   
via radiative corrections:



$$\log \frac{m_H}{m_Z} \rightarrow \Delta\chi^2$$



LEP II direct:  $m_H > 114.4$  GeV

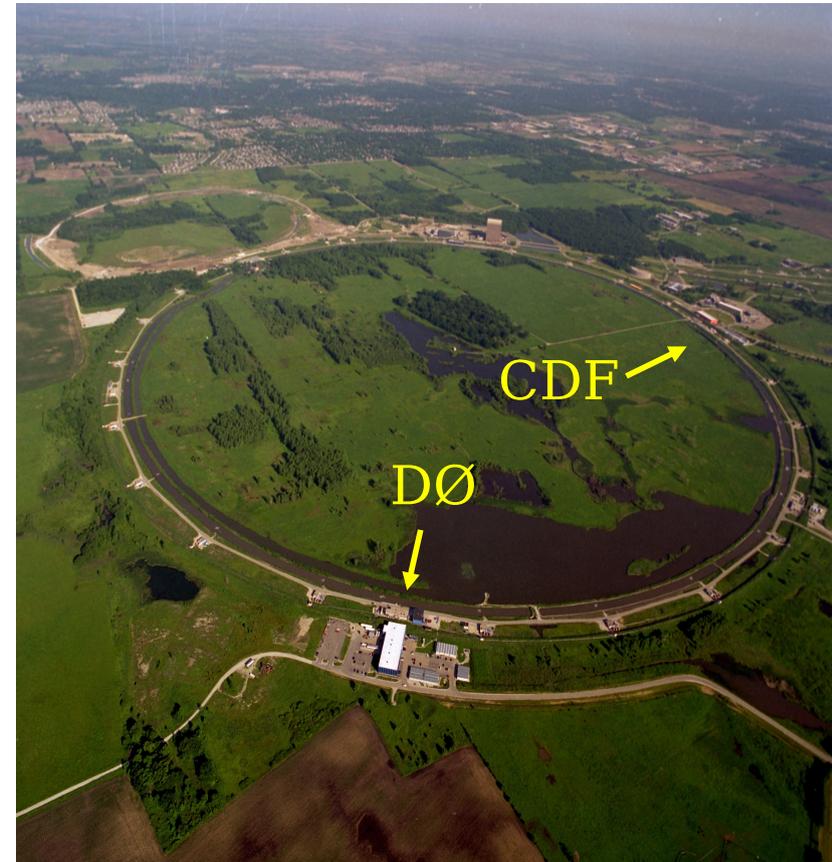
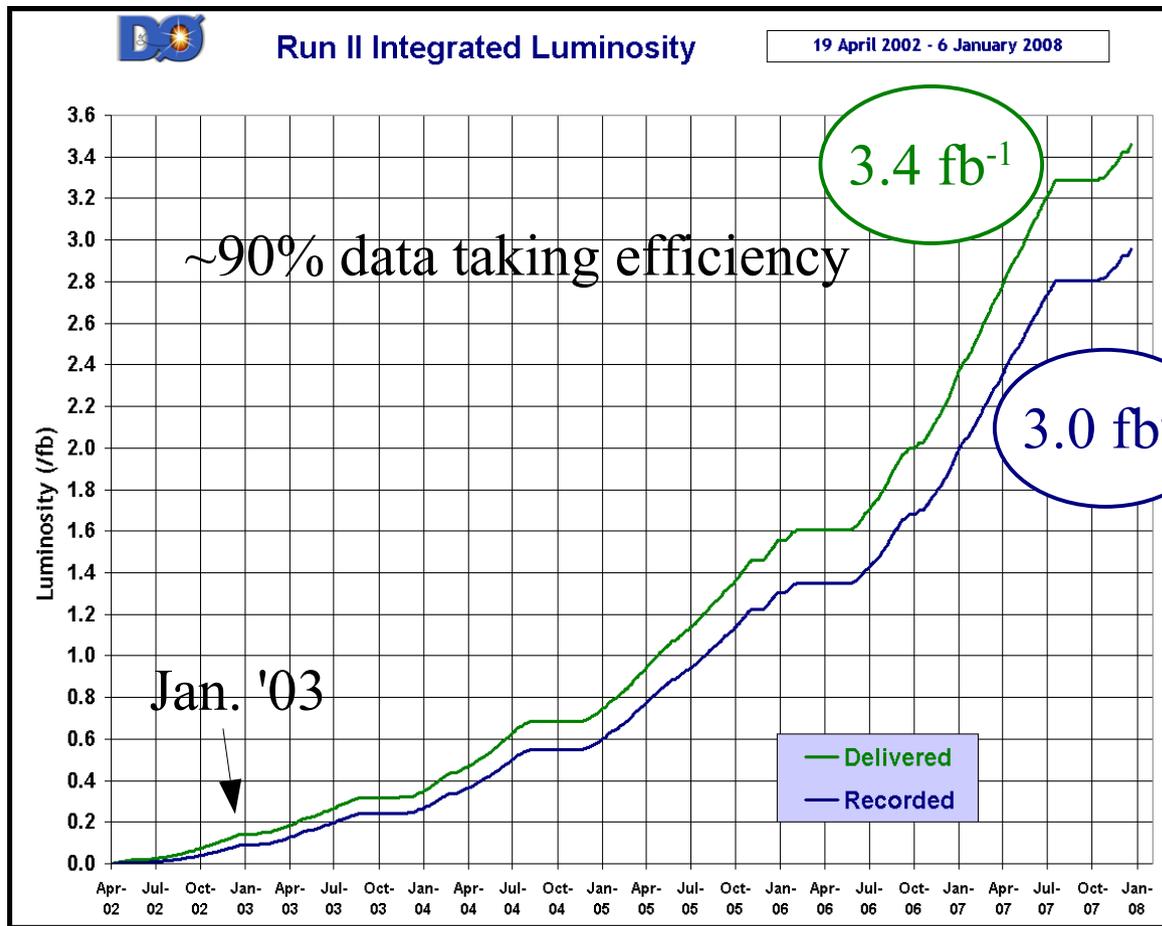


$m_H < 144$  GeV  
(at 95% CL)

$m_H < 182$  GeV (including direct limit)

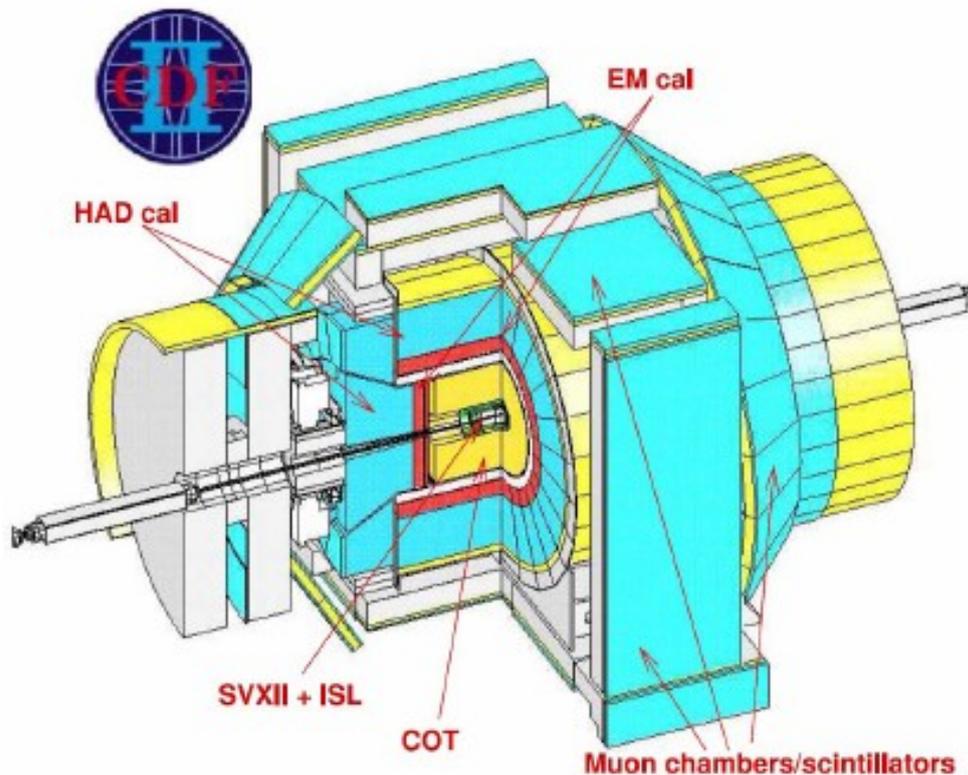
# The Tevatron at Fermilab

Running (again) since ~2003  
p-pbar,  $\sqrt{s}=1.96$  TeV  
Record luminosity:  $2.9 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  !  
Expect  $6 \text{ fb}^{-1}$  by '09 (*maybe*  $8 \text{ fb}^{-1}$  by '10)

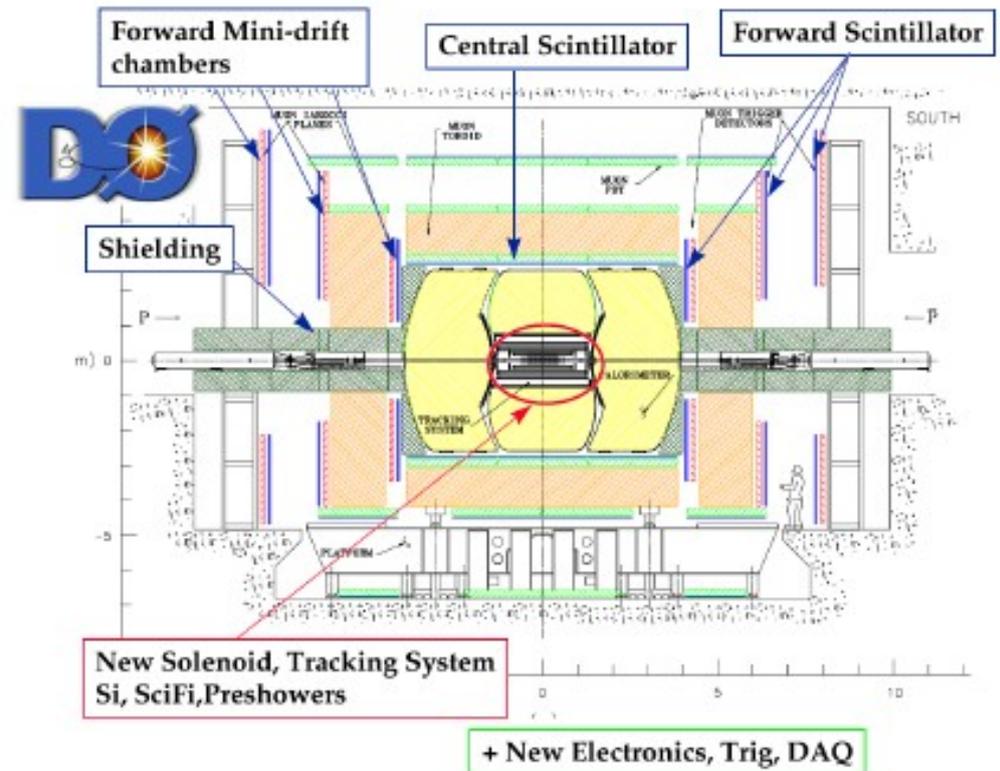


# CDF and DØ experiments in RunII

- ▶ Both detectors are highly upgraded in RunII
  - ▶ New silicon micro-vertex tracker
  - ▶ New tracking system
  - ▶ Upgraded muon chambers



- ▶ CDF: new Plug Calorimeters, new TOF



- ▶ DØ: new solenoid, new pre-showers, LØ for SMT in RunIIb, new L1Cal trigger

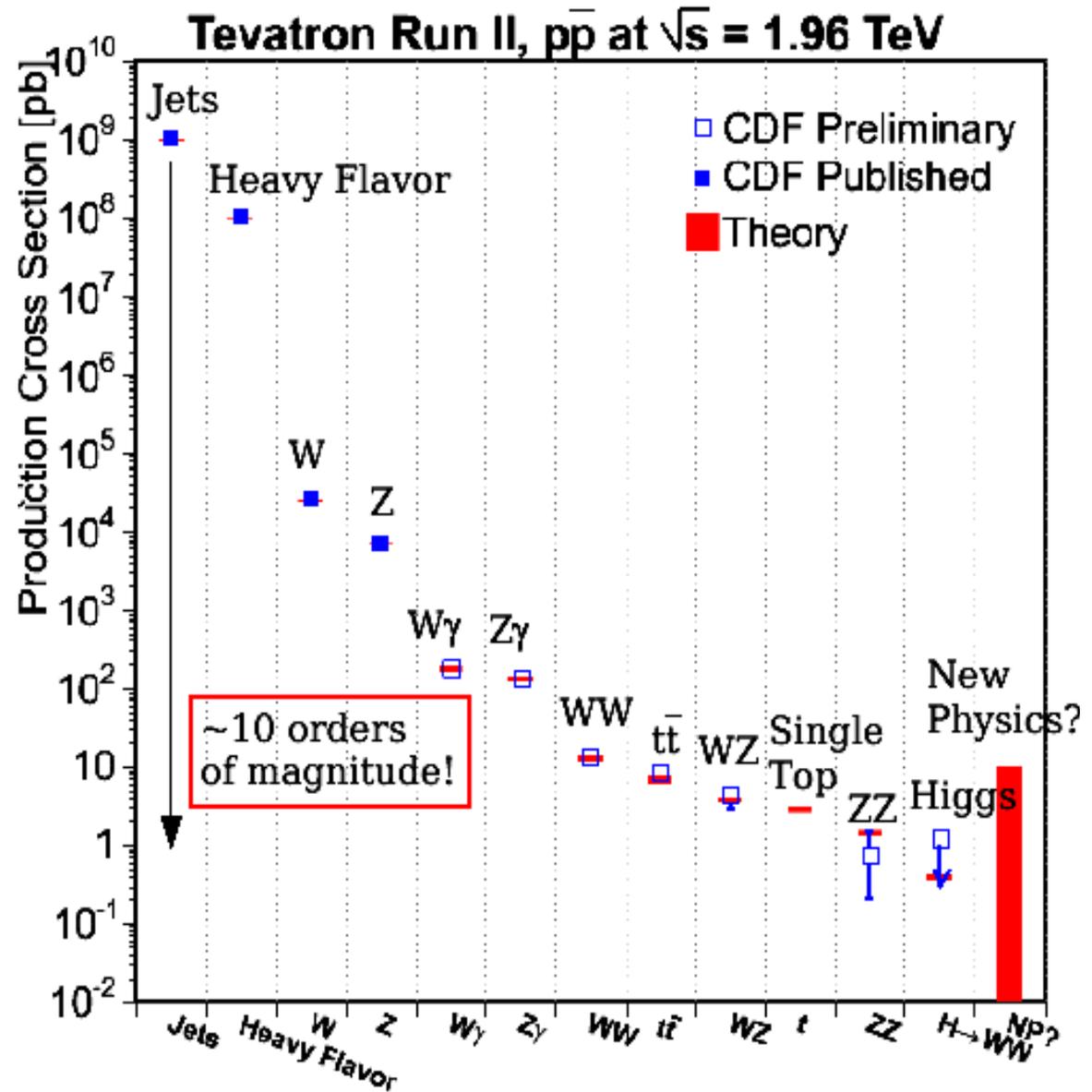
# Needle in a Haystack

Higgs has small cross-section at the Tevatron

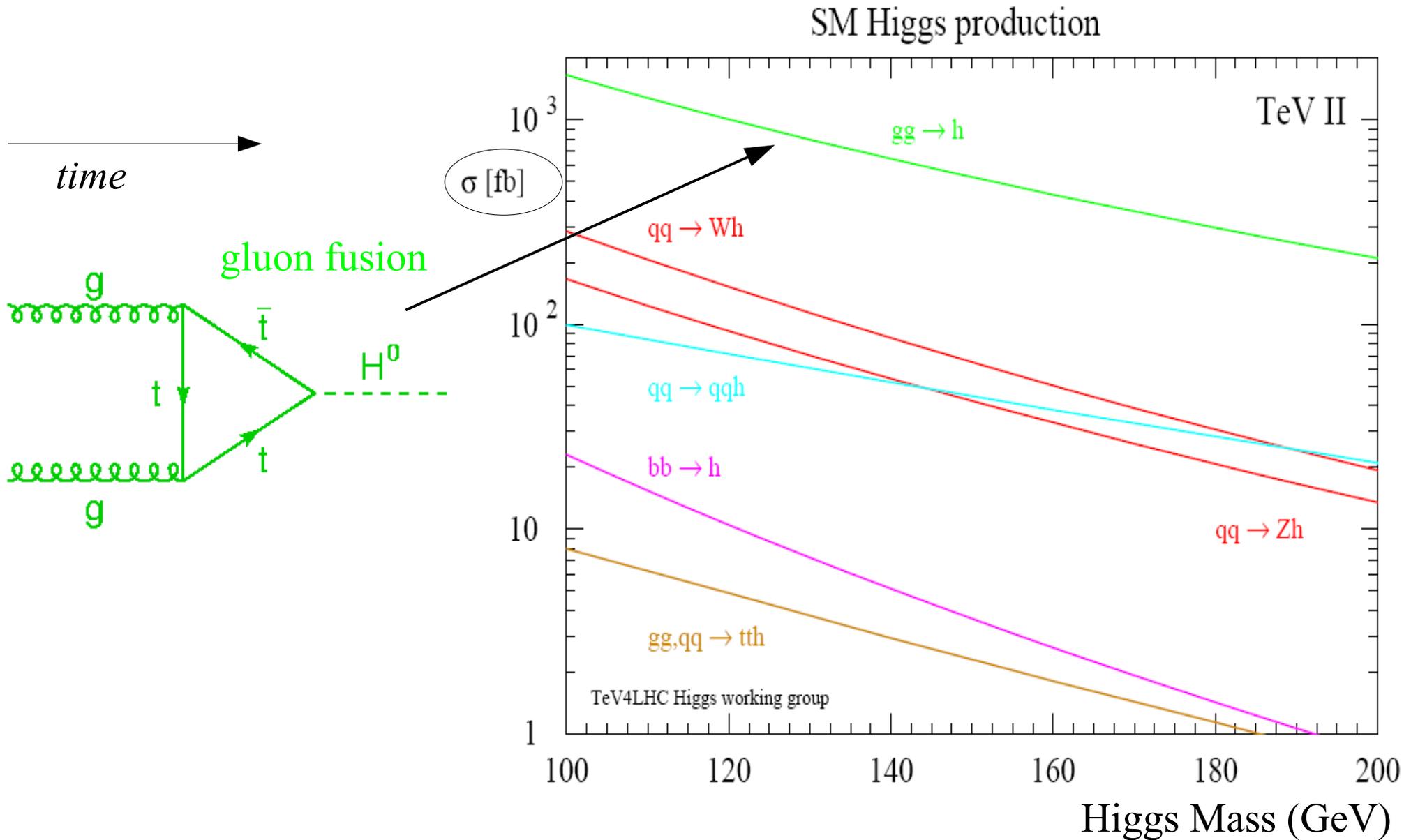
- Couples weakly to light quarks in the proton!

Large backgrounds from

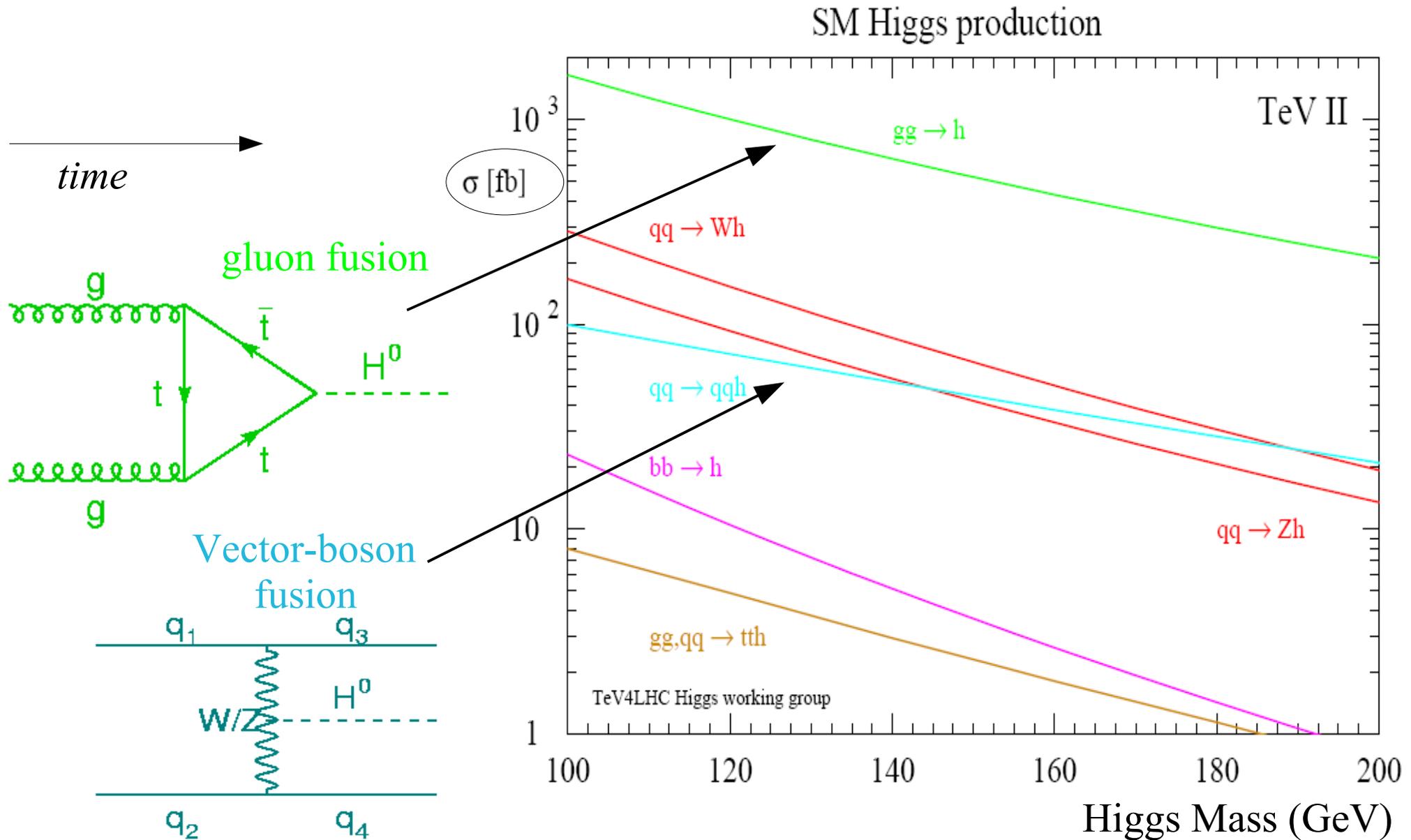
- Jets
- W,Z + jets
- ttbar
- WW, WZ, ZZ



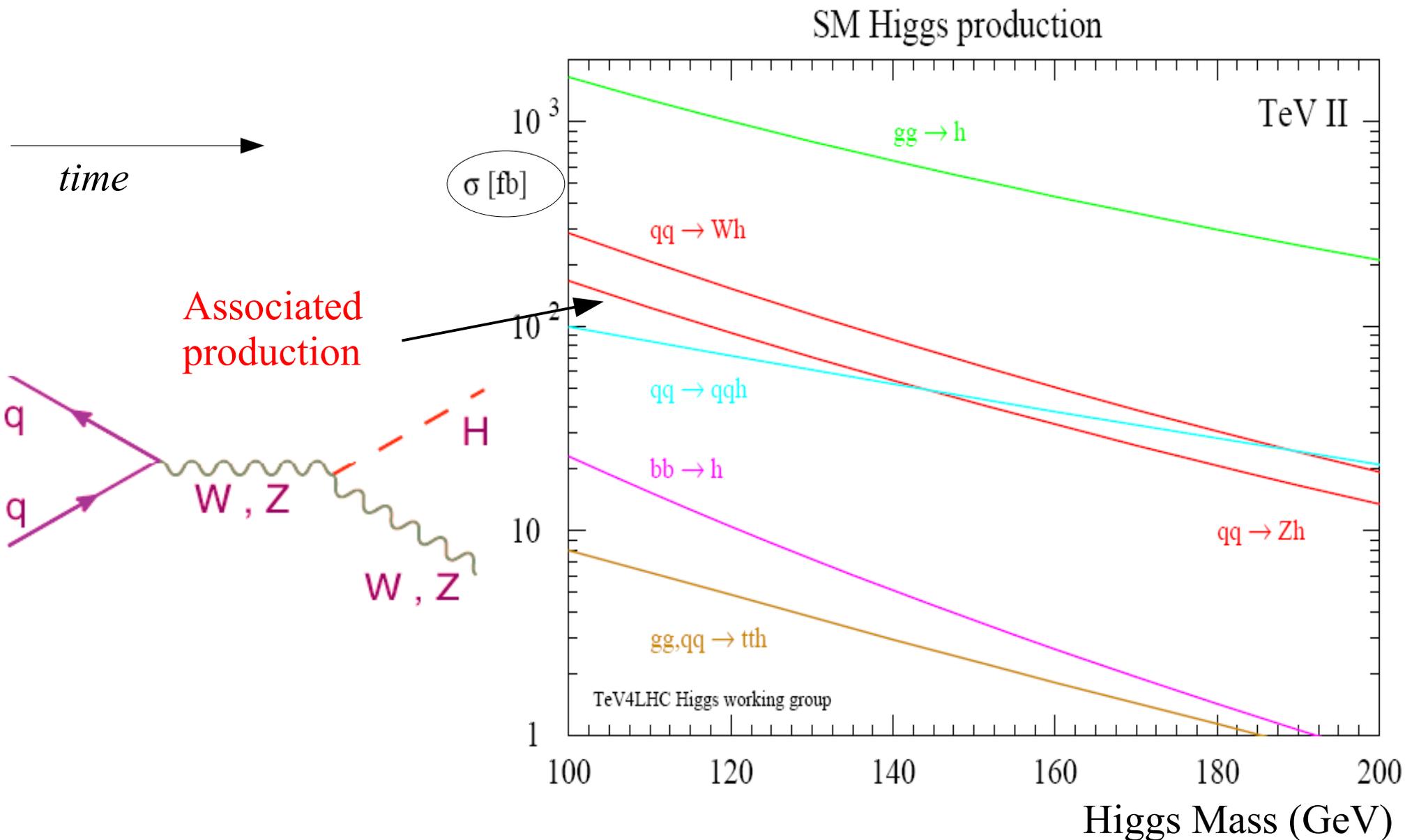
# Higgs Production at the Tevatron



# Higgs Production at the Tevatron



# Higgs Production at the Tevatron



# Higgs Decays

Coupling  $\propto$  fermion mass

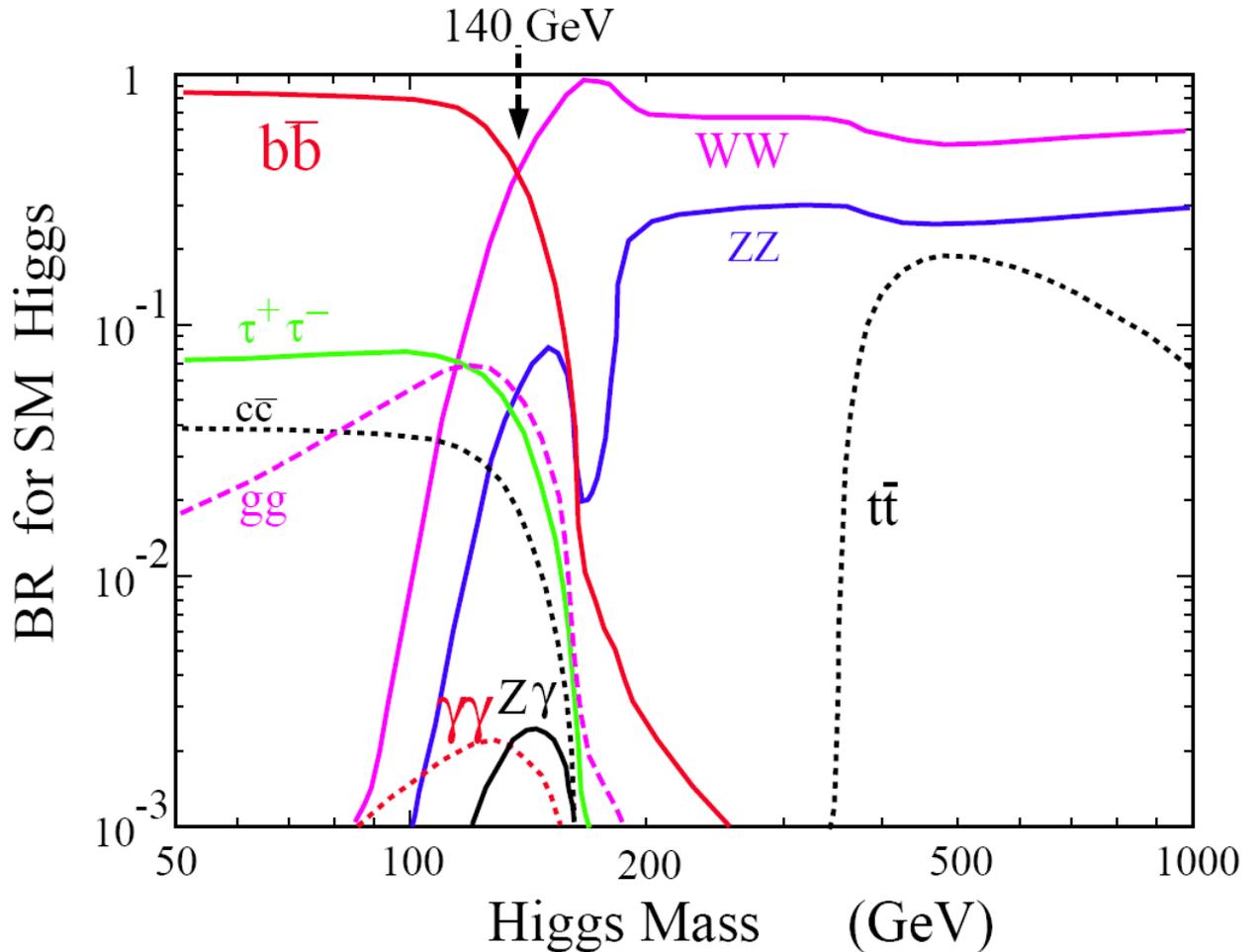
$$-\frac{1}{v} m_f \bar{\psi}_f \phi_h \psi_f$$

Main channels:

$WW^*$  (high mass)

$bb, \tau\tau$  (low mass)

*Need good b-jet tagging!*



# Main Higgs Analyses

$H \rightarrow bb, \tau\tau$   
(low mass)

$H \rightarrow WW^*$   
(high mass)

$p\bar{p} \rightarrow H$

~~$H \rightarrow bb$~~

$H \rightarrow WW^* \rightarrow$   
 $ee/e\mu/\mu\mu + MET$

$p\bar{p} \rightarrow WH$

$WH \rightarrow Wbb \rightarrow$   
 $e/\mu + bb$

$W/Z + H \rightarrow W/Z + WW^* \rightarrow$   
 $l^+l^- l^+ / l^+l^+jj + MET$

$p\bar{p} \rightarrow ZH$

$ZH \rightarrow Zbb \rightarrow$   
 $ee/\mu\mu + bb$   
 $MET + bb$

# Main Higgs Analyses

$H \rightarrow bb, \tau\tau$   
(low mass)

$H \rightarrow WW^*$   
(high mass)

$p\bar{p} \rightarrow H$

~~$H \rightarrow bb$~~

$H \rightarrow WW^* \rightarrow$   
 $ee/e\mu/\mu\mu + MET$

$p\bar{p} \rightarrow WH$

$WH \rightarrow Wbb \rightarrow$   
 $e/\mu + bb$

$W/Z + H \rightarrow W/Z + WW^* \rightarrow$   
 $l^+l^- l^+ / l^+l^+jj + MET$

$p\bar{p} \rightarrow ZH$

$ZH \rightarrow Zbb \rightarrow$   
 $ee/\mu\mu + bb$   
 $MET + bb$

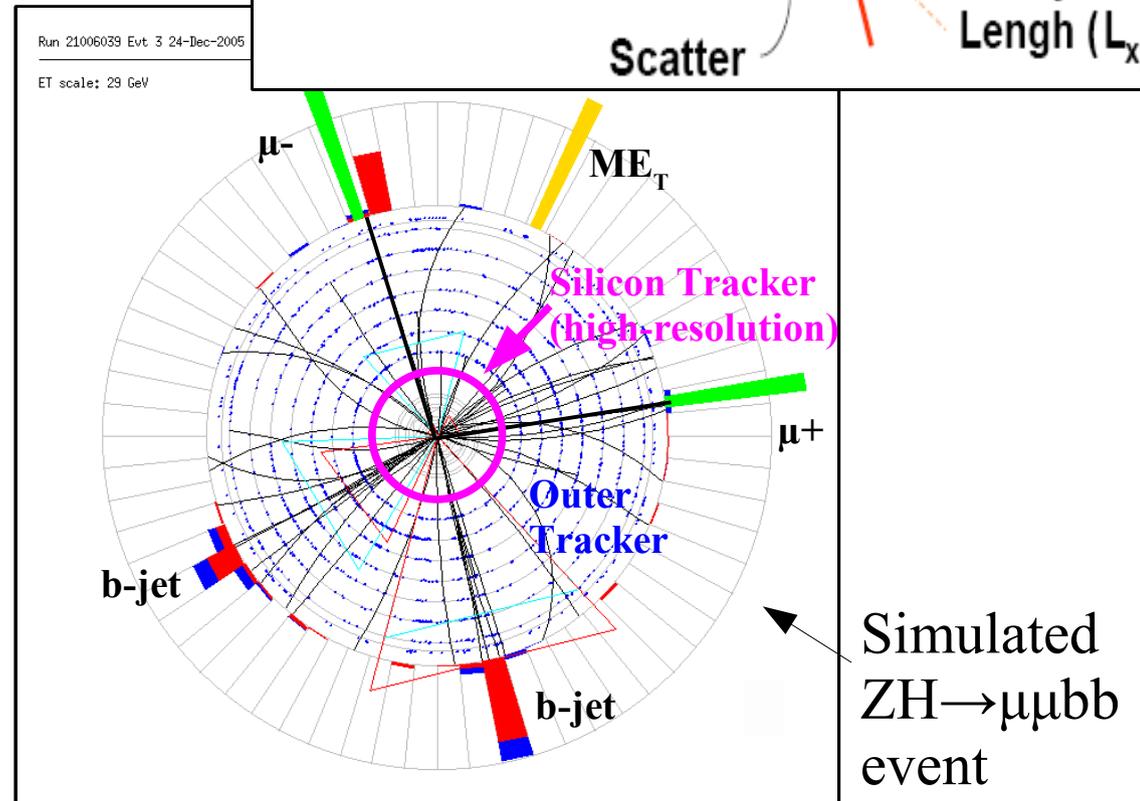
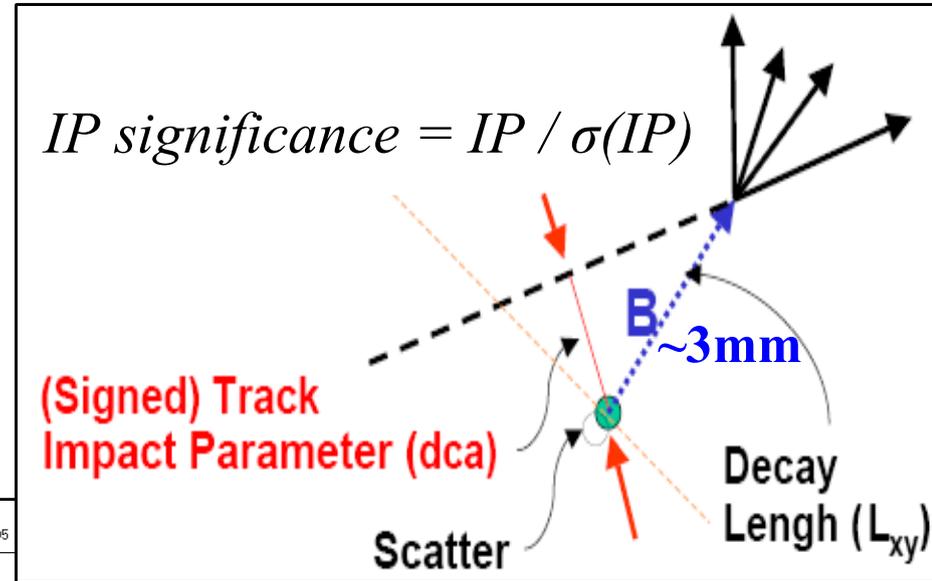
# b-Jet Tagging

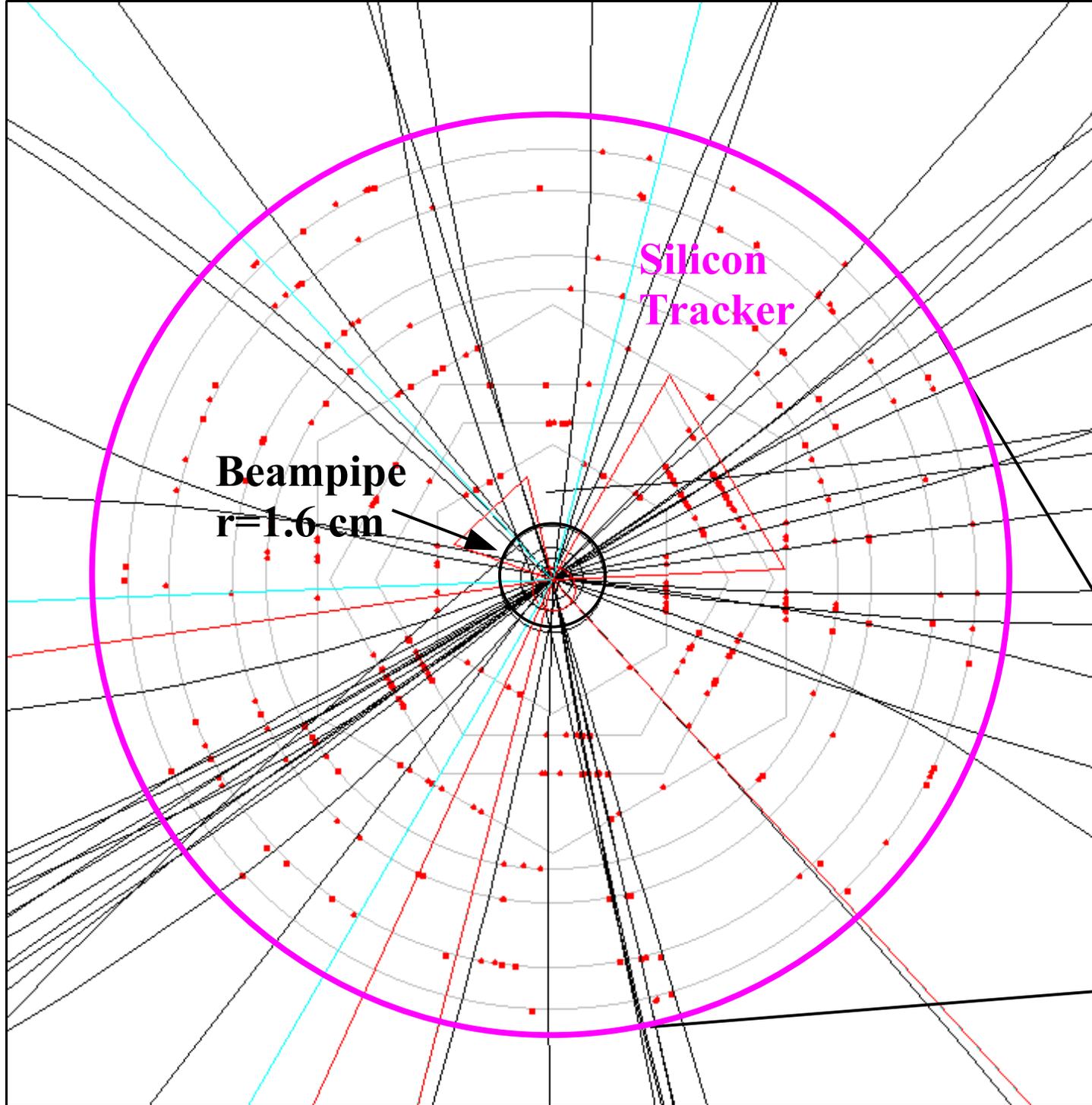
B hadrons are “long”-lived

- Reconstruct charged particles tracks
- Reconstruct “vertices” where tracks overlap

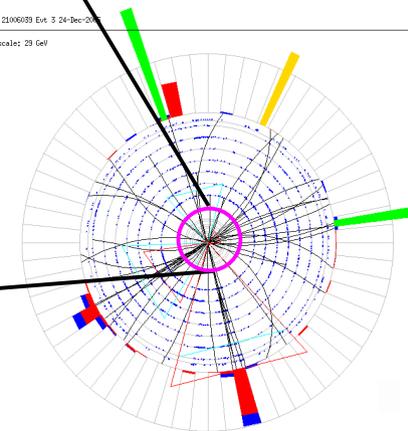
Identify jets with:

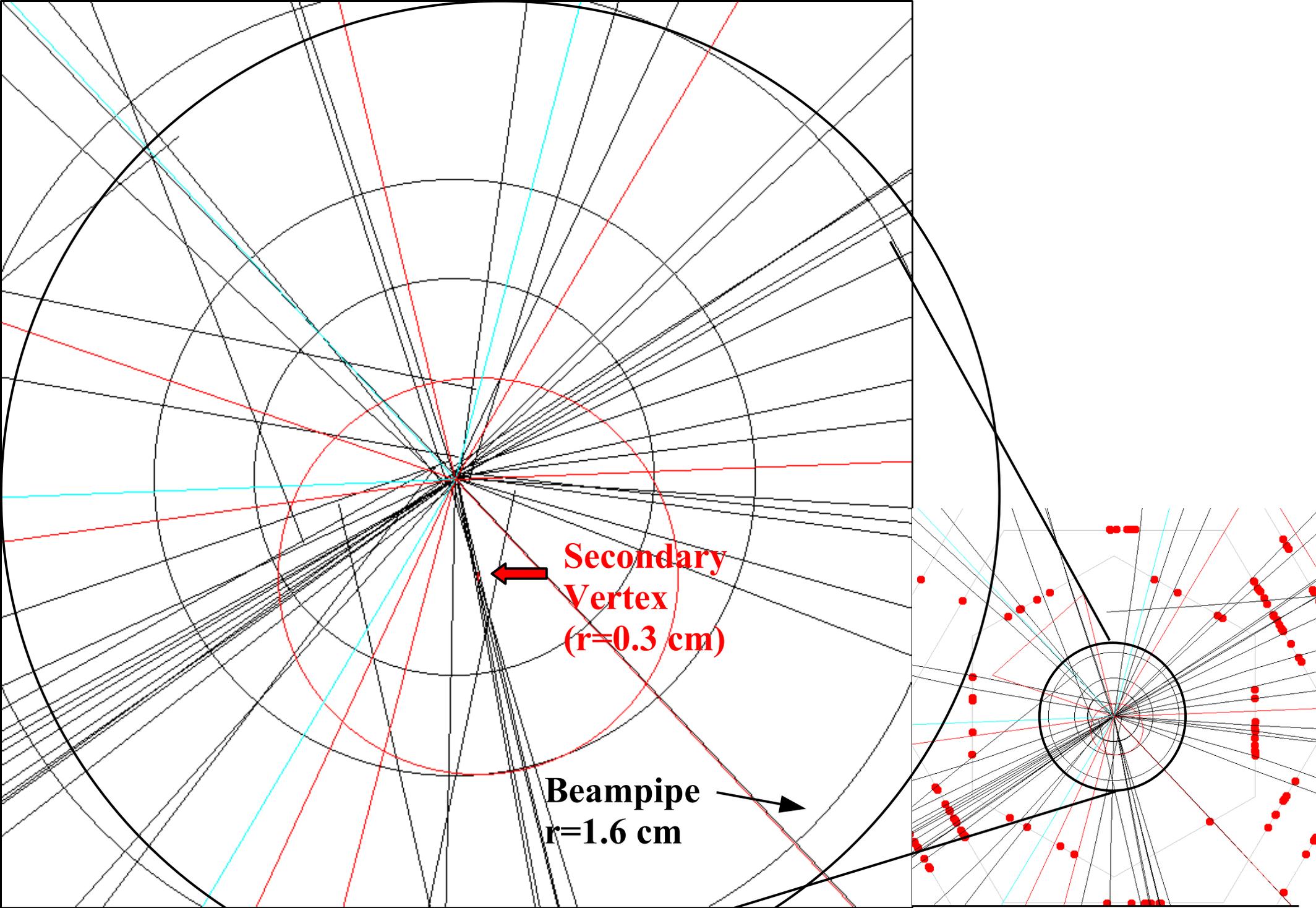
- large impact parameter significance tracks
- large decay length significance vertices





Run 2100693 Ev4.3 24-Dec-07  
 ET scale: 29 GeV





# b-Jet Tagging

Many variables with separation power:

- Secondary vertex:

*Decay-length significance*

*# tracks on vertex*

*# vertices*

*mass*

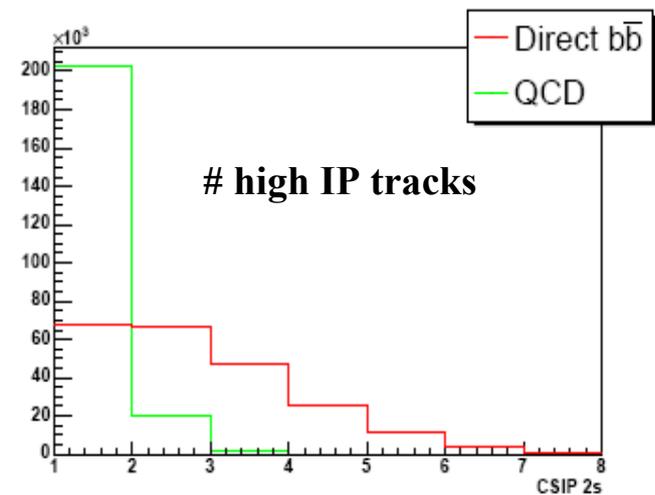
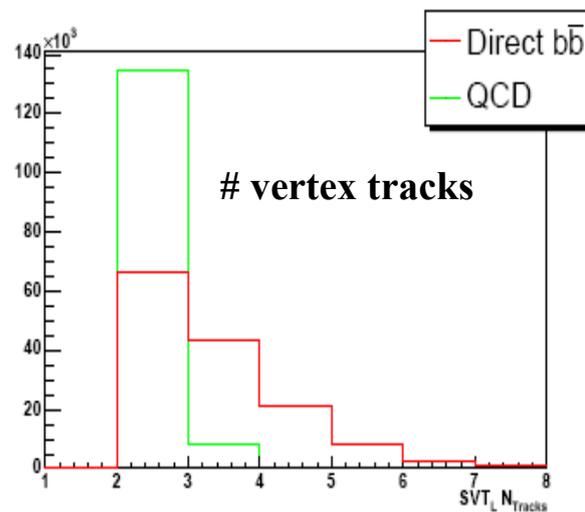
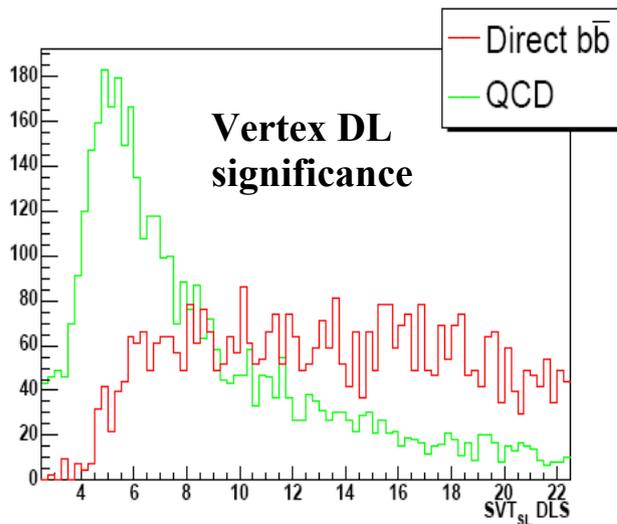
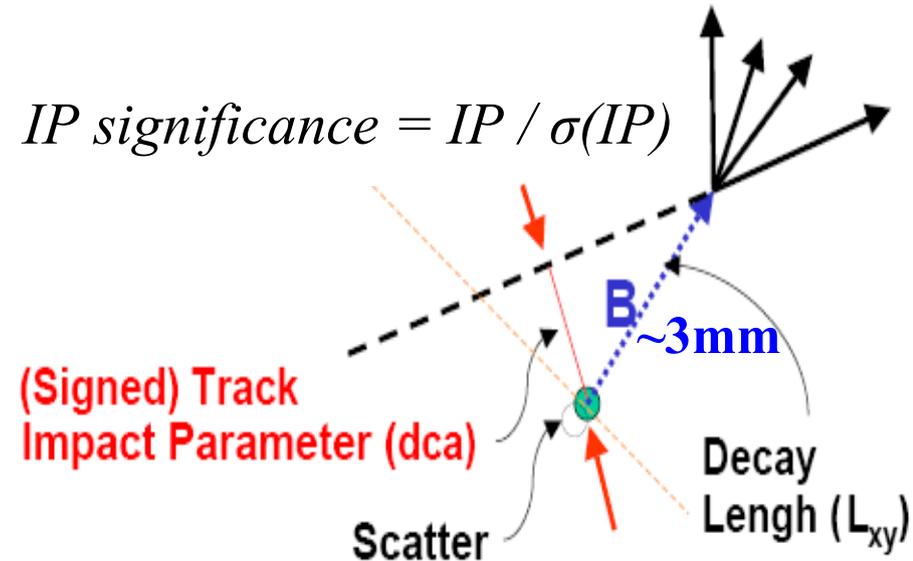
*chi<sup>2</sup>/dof*

- Jet:

*# high IP sig. tracks*

*combined light-jet probability*

$$IP\ significance = IP / \sigma(IP)$$



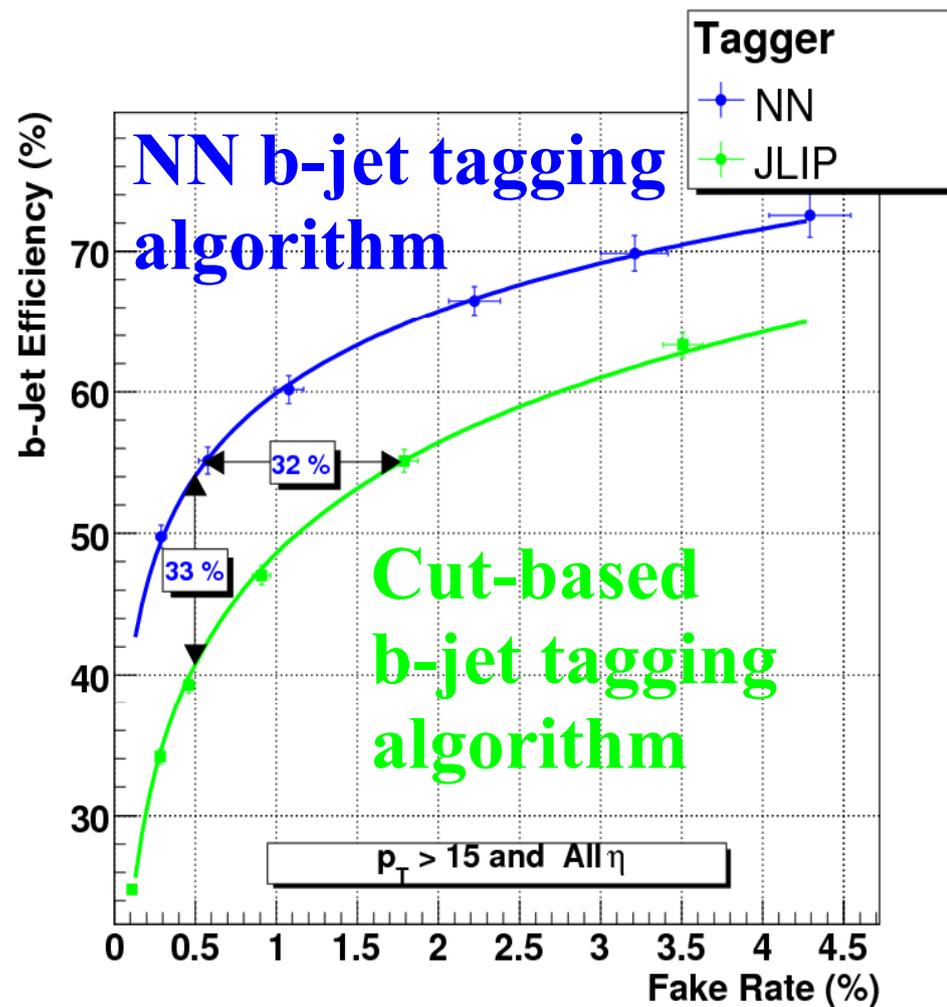
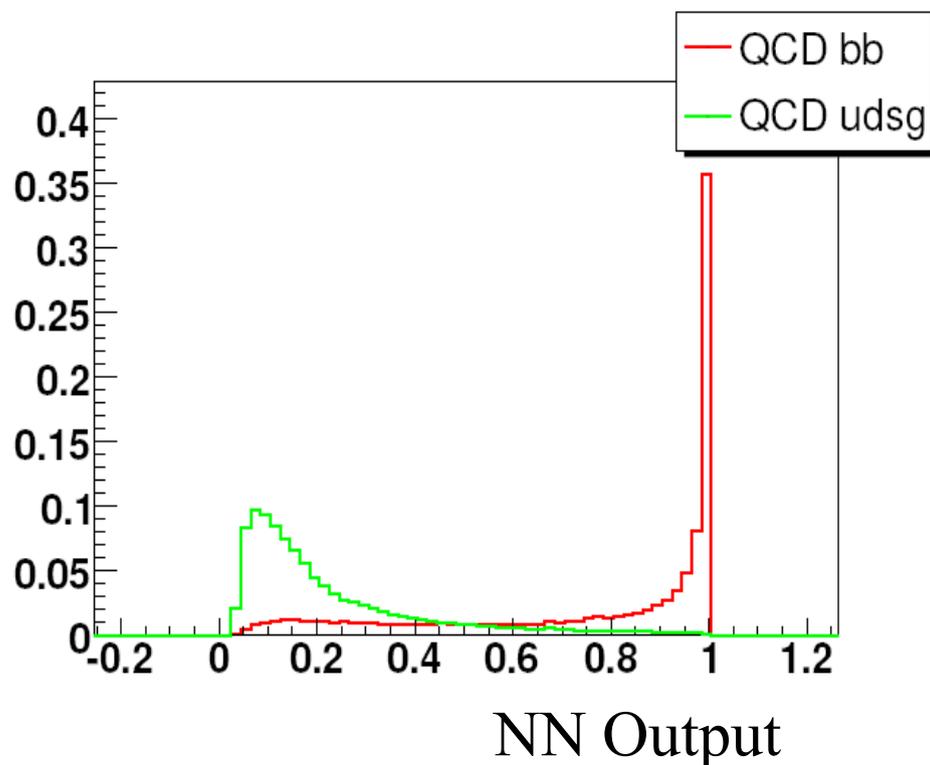
...

# Neural Network b-Jet Tagging

Train NN on simulated events

- Optimized inputs, training method, network topology

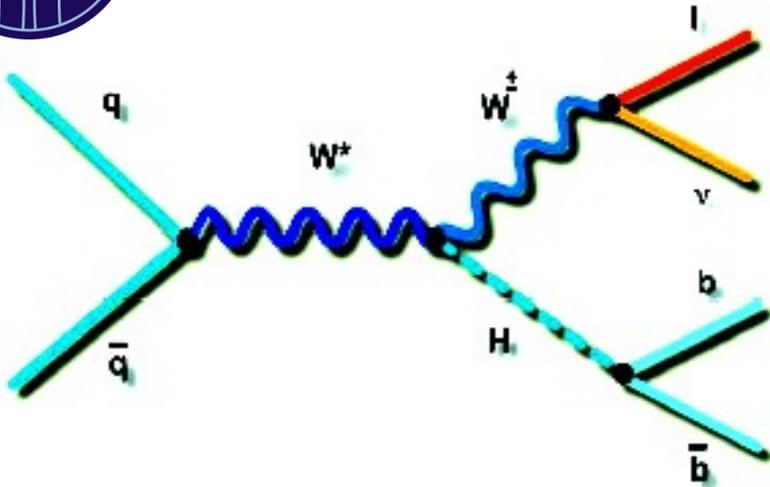
Test NN eff. and fake rate using data



*Equivalent to 2.5x as much data for a double-b-tag analysis!*



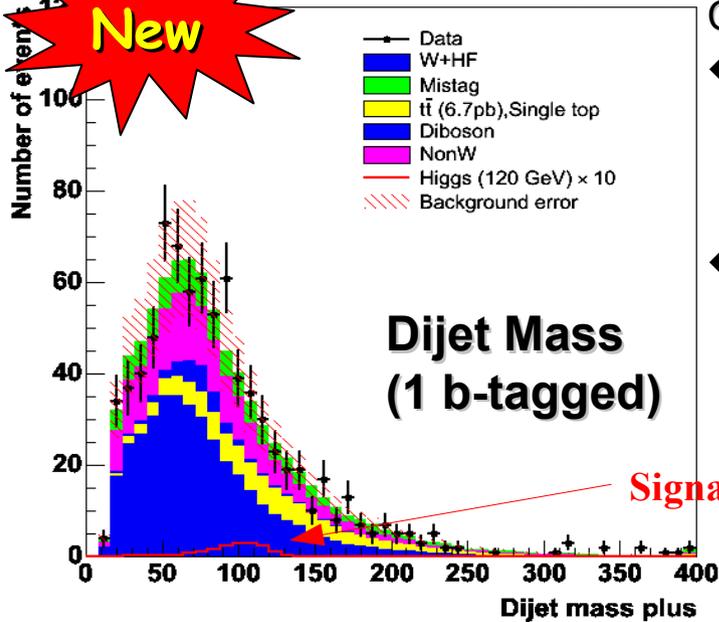
# WH-> l nu b b (l=e,mu)



- ◆ e or  $\mu$   $P_T > 20$  GeV
- ◆  $ME_T > 20$  GeV
- ◆ 2 jets, with 1 or 2 b-tagged
- ◆ Main backgrounds: W+bb, QCD, ttbar

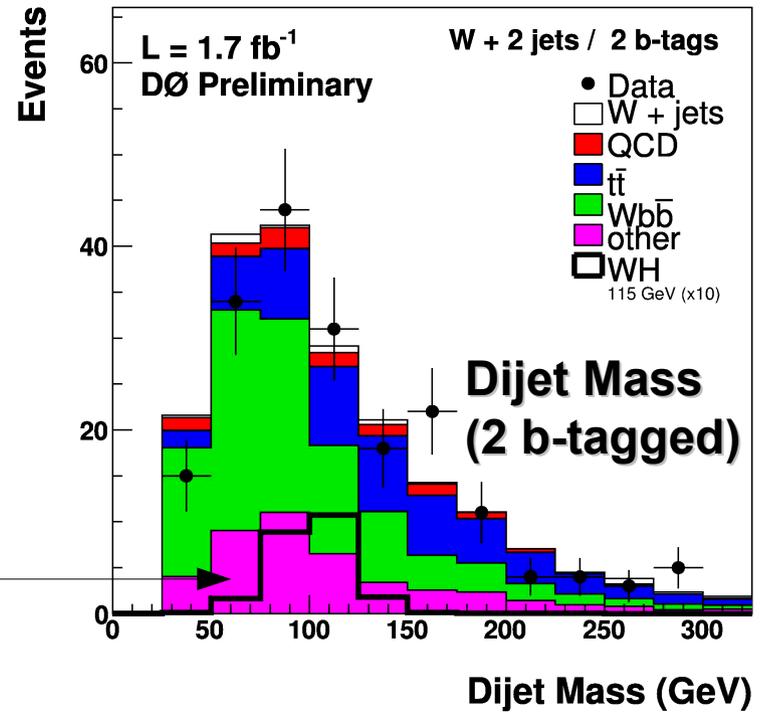


CDF Run II Preliminary (1.9 fb<sup>-1</sup>)



CDF updates:

- ◆ Added 1 b-tagged events with NN flavor separation
- ◆ Included forward electrons



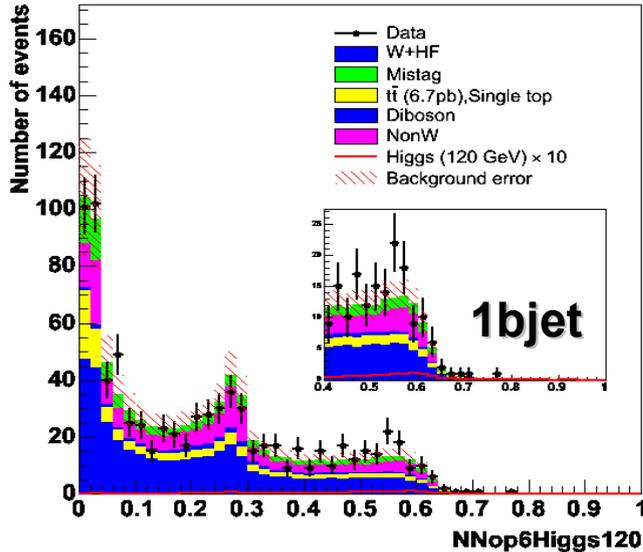
Dijete mass+: Inv. mass plus an extra loose jet ( $E_T > 12, |\eta| < 2.4$ ) if within  $\Delta R < 0.9$  of one of the tight jets



# WH-> l nu b b (l=e,mu)



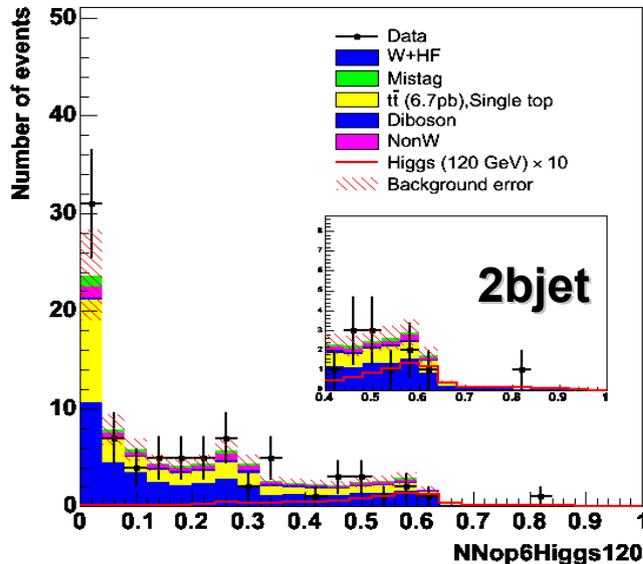
CDF Run II Preliminary (1.9 fb<sup>-1</sup>)



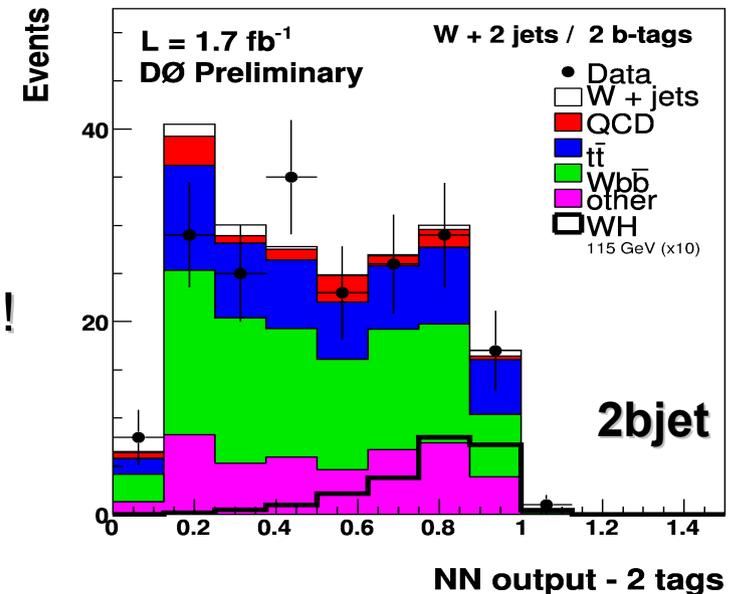
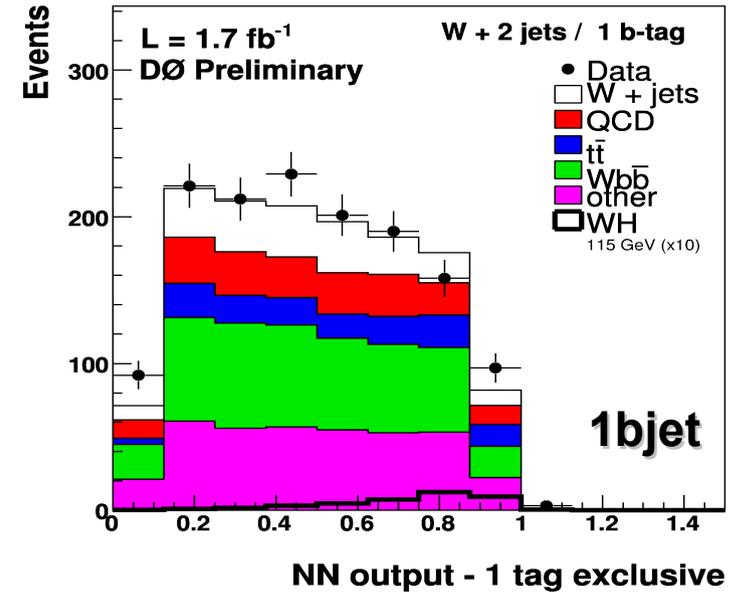
Use NN trained on MC to separate signal from background:

Signal → 1  
Background → 0

CDF Run II Preliminary (1.9 fb<sup>-1</sup>)

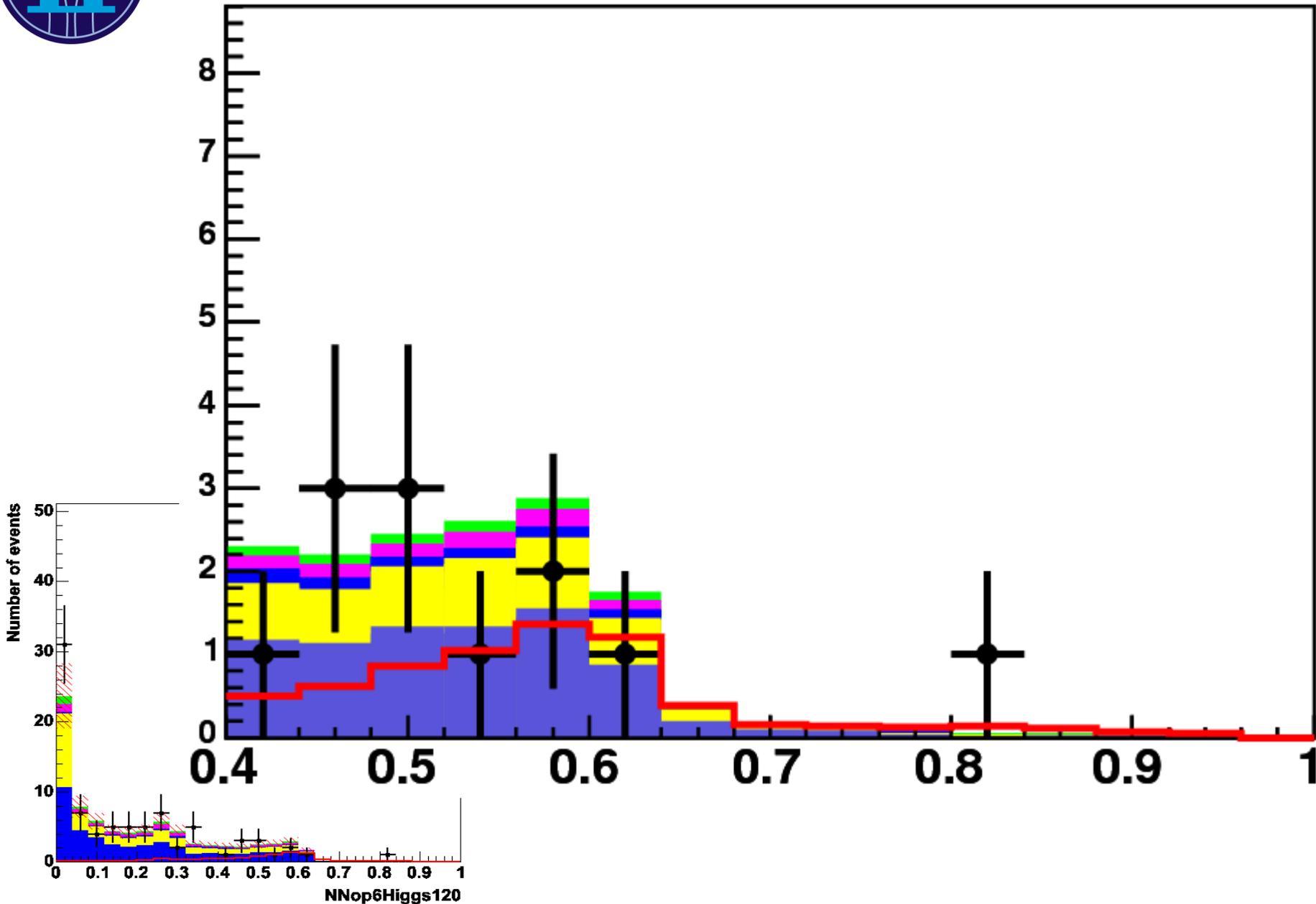


No significant excess in signal region for either CDF/DØ  
-> Set limits for exclusion!





# $WH \rightarrow l \nu b \bar{b}$ ( $l=e, \mu$ )

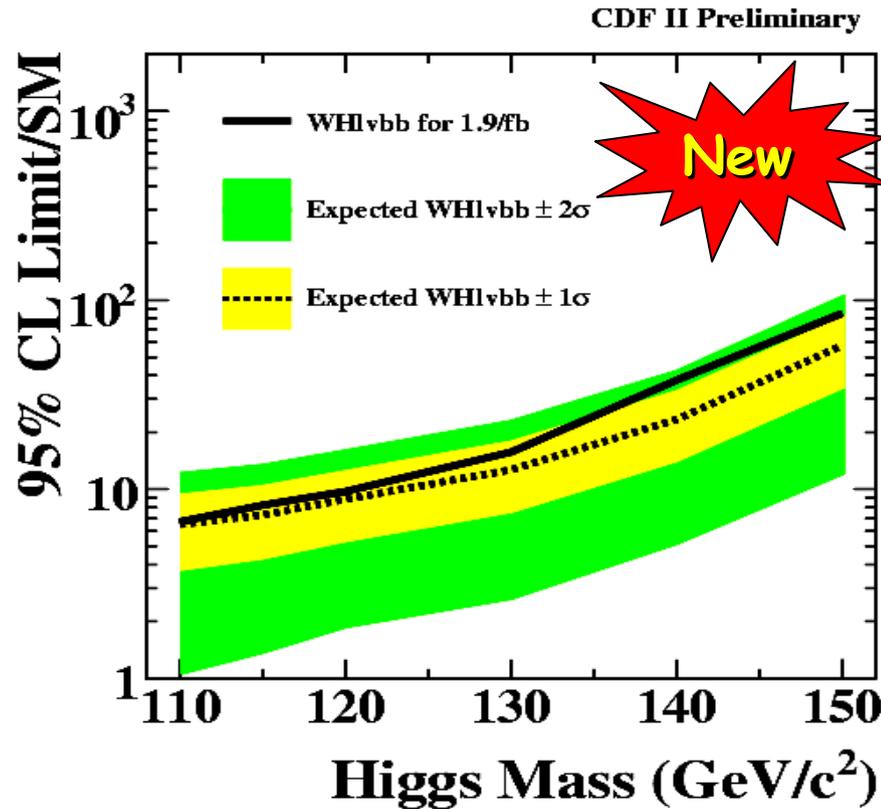




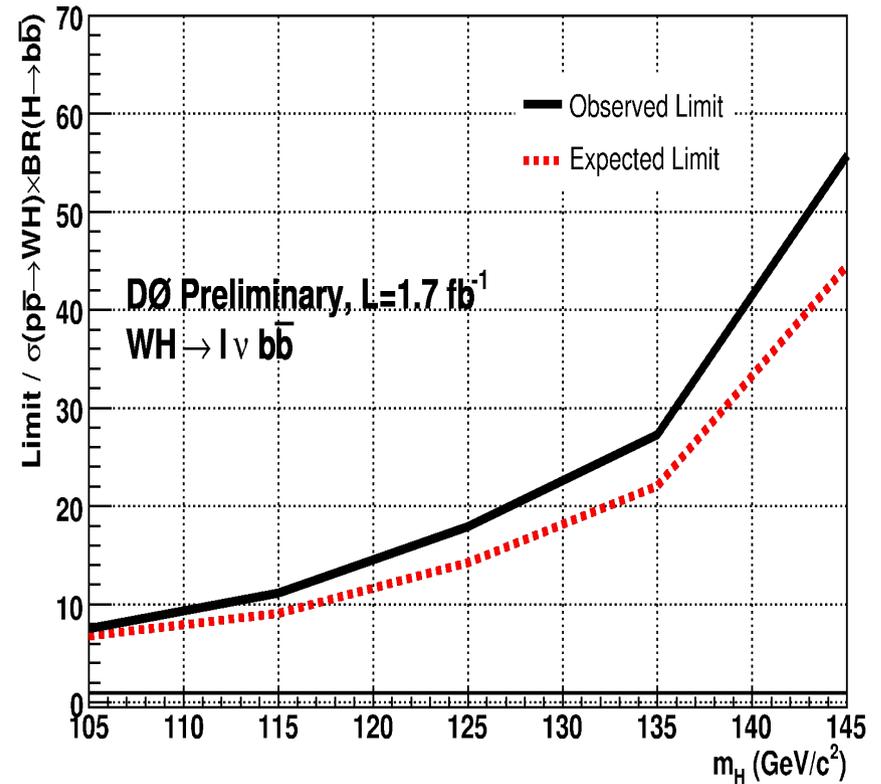
# WH- $\rightarrow$ l nu b b (l=e,mu)



- ◆ 95% Confidence Level Upper limit is set by binned likelihood method.  
-> Showing  $\sigma(\text{limit})/\sigma(\text{SM})$  Ratio (i.e. If reached 1, it is excluded)



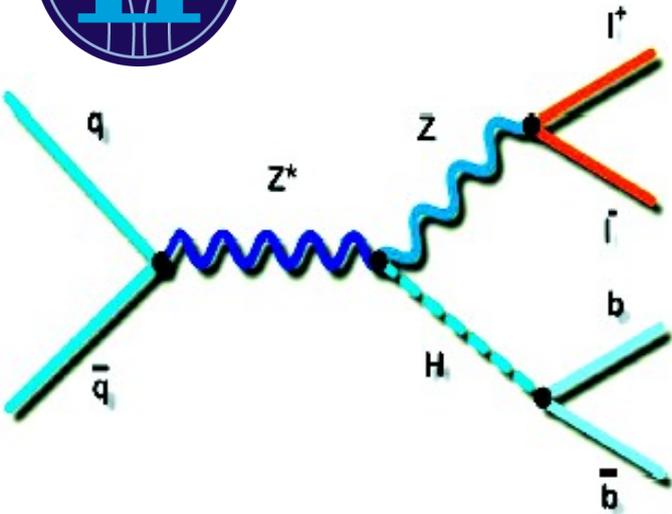
- ◆ CDF: (at  $M_H=115$  GeV)  
 $\sigma(\text{limit})/\sigma(\text{SM}) = 8.2/7.3$  (obs./exp.)



- ◆ DØ: (at  $M_H=115$  GeV)  
 $\sigma(\text{limit})/\sigma(\text{SM}) = 11/9$  (obs./exp.)



# ZH-> ll bb (l=e,mu)

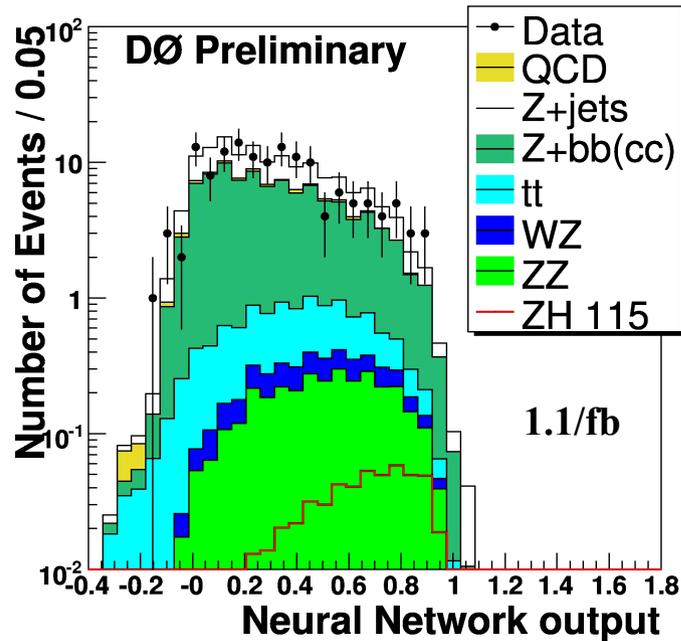
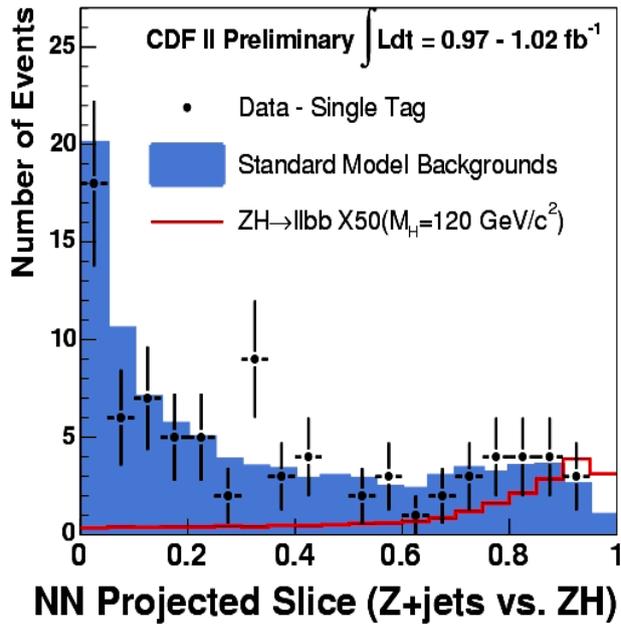
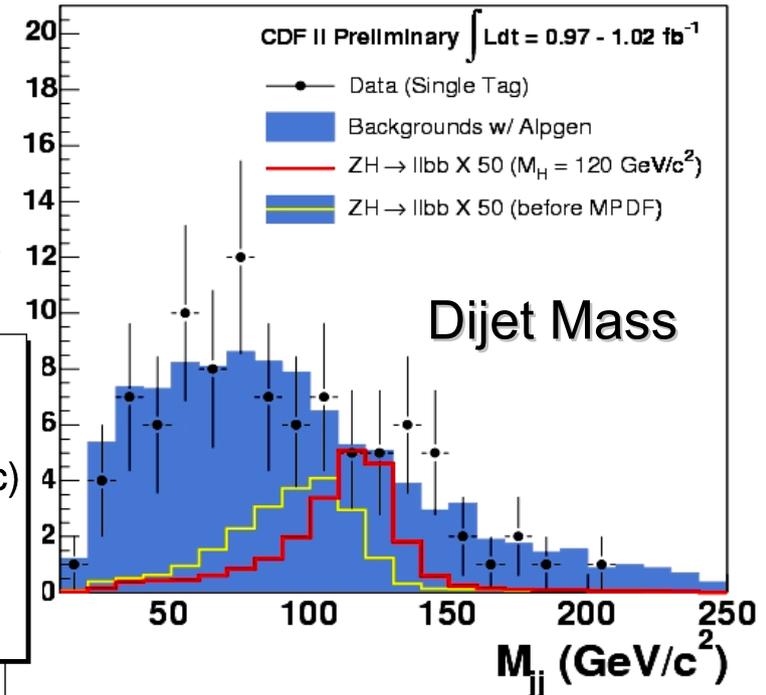


- ◆ 2 high  $P_T$  leptons from Z  
-> Clean signature !

**\*Summer 2007 results**

CDF: improve dijet mass resolution with  $ME_T$  projection

- ◆ Optimized by NN



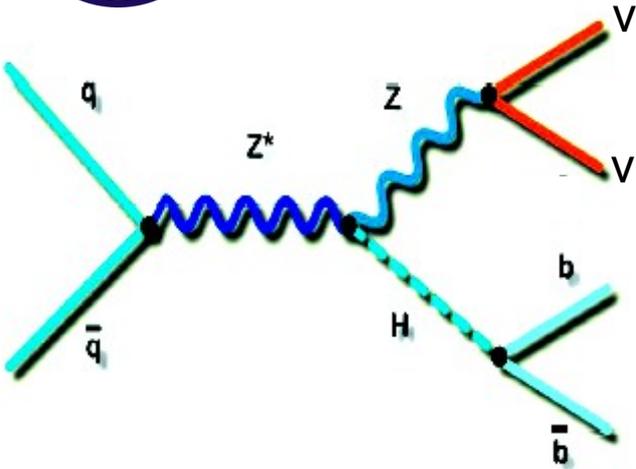
95% CL Limit (relative to SM)  
at  $M_H=115$  GeV:  
CDF: 16/16 (obs./expected)  
DØ: 18/20 (obs./expected)



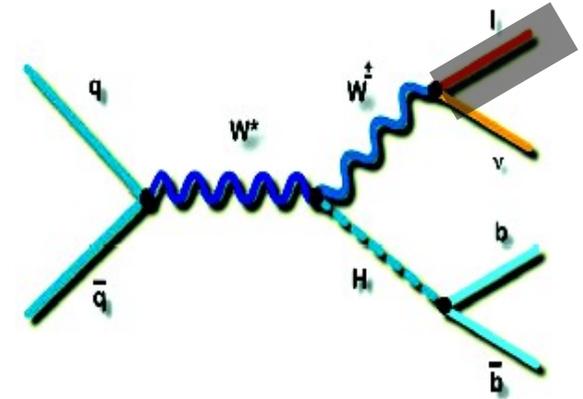
# ZH- $\rightarrow$ nu nu b b



Recovered WH $\rightarrow$ lvbb

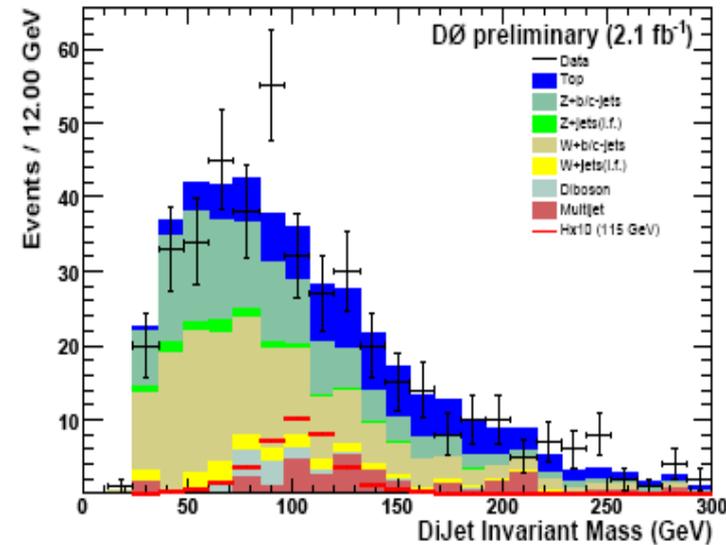
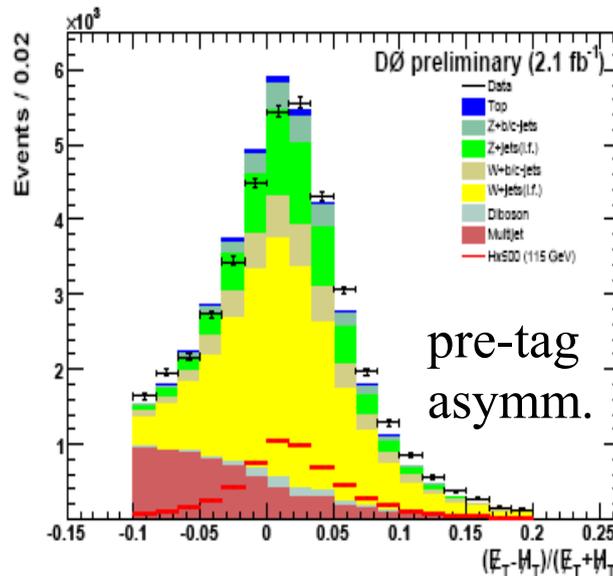
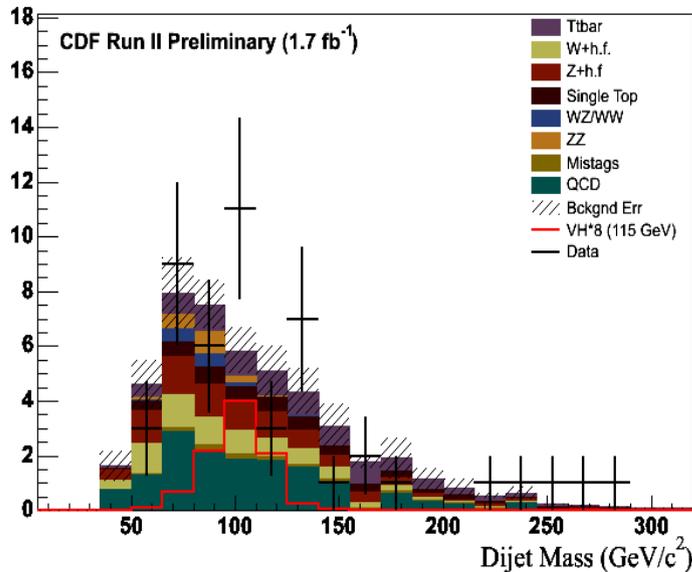


- ◆  $ME_T > 50$  GeV, 2 b-jets
- ◆ Data driven QCD estimate:  
CDF: NN with track-based  $ME_T$   
DØ: Asymmetry between  $ME_T$  and  $SumE_T$



- ◆ **New DØ result: Boosted Decision Tree, 2.1/fb**

Double Vertex Tag (Signal Region)

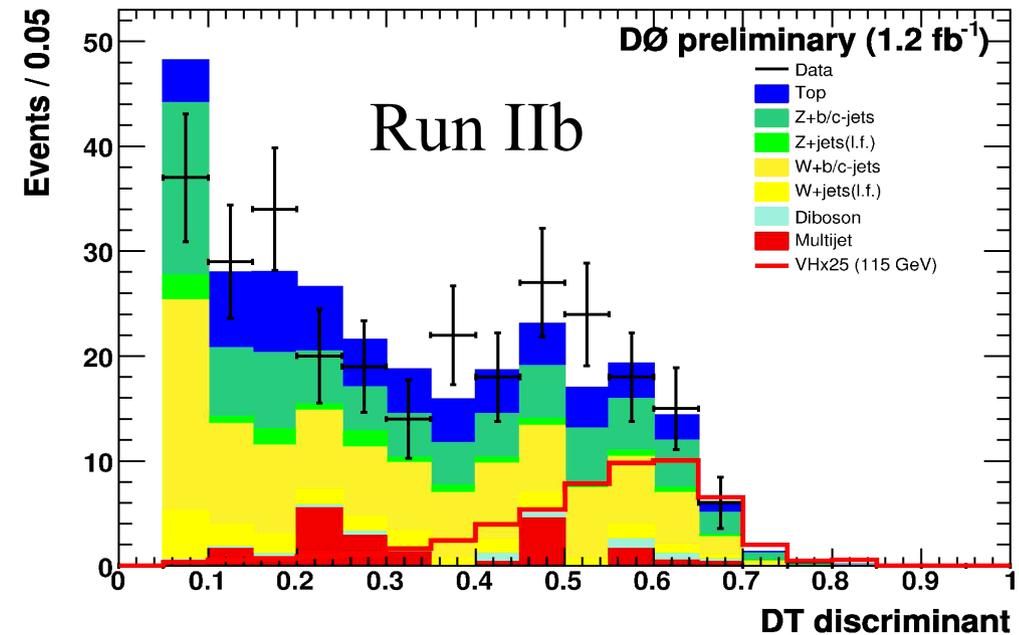
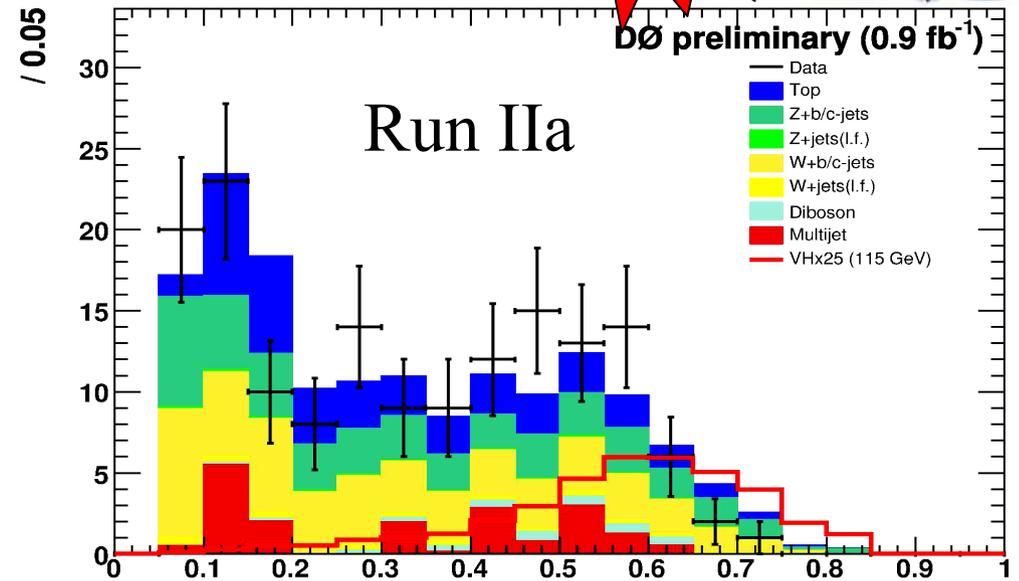
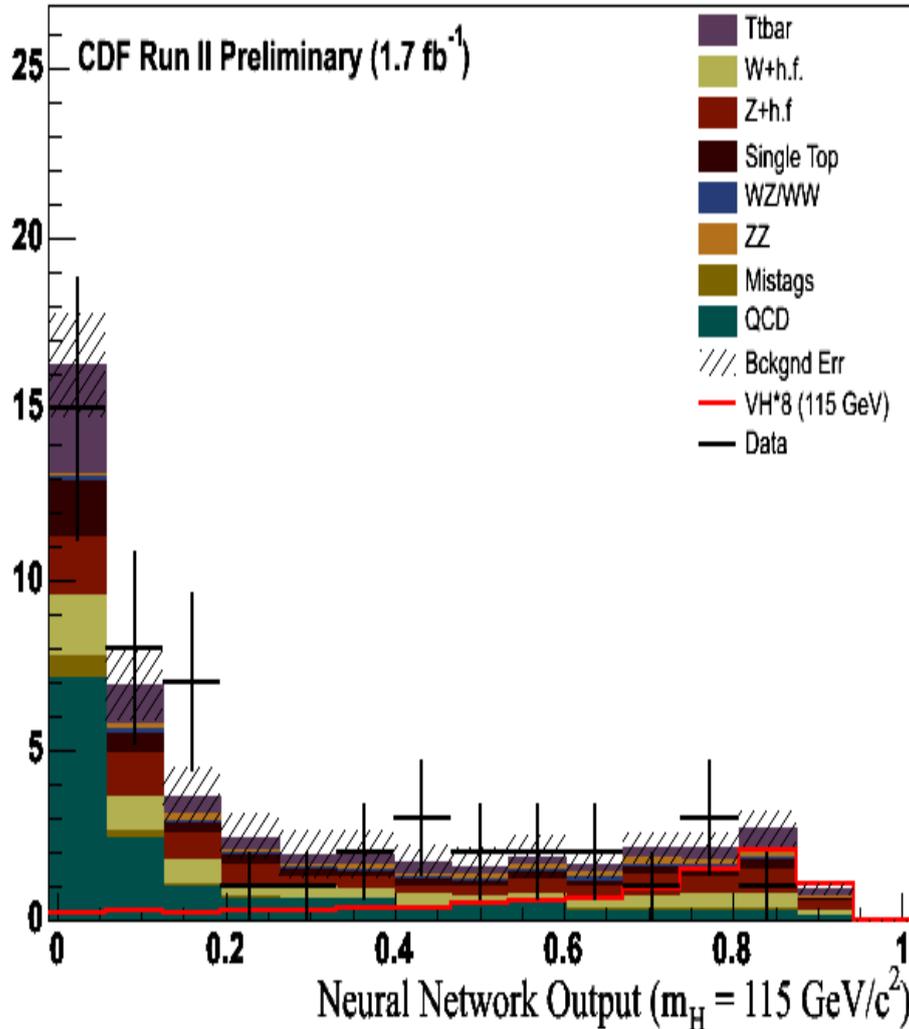




# ZH- $\rightarrow$ nu nu b b



## Double Vertex Tag (Signal Region)

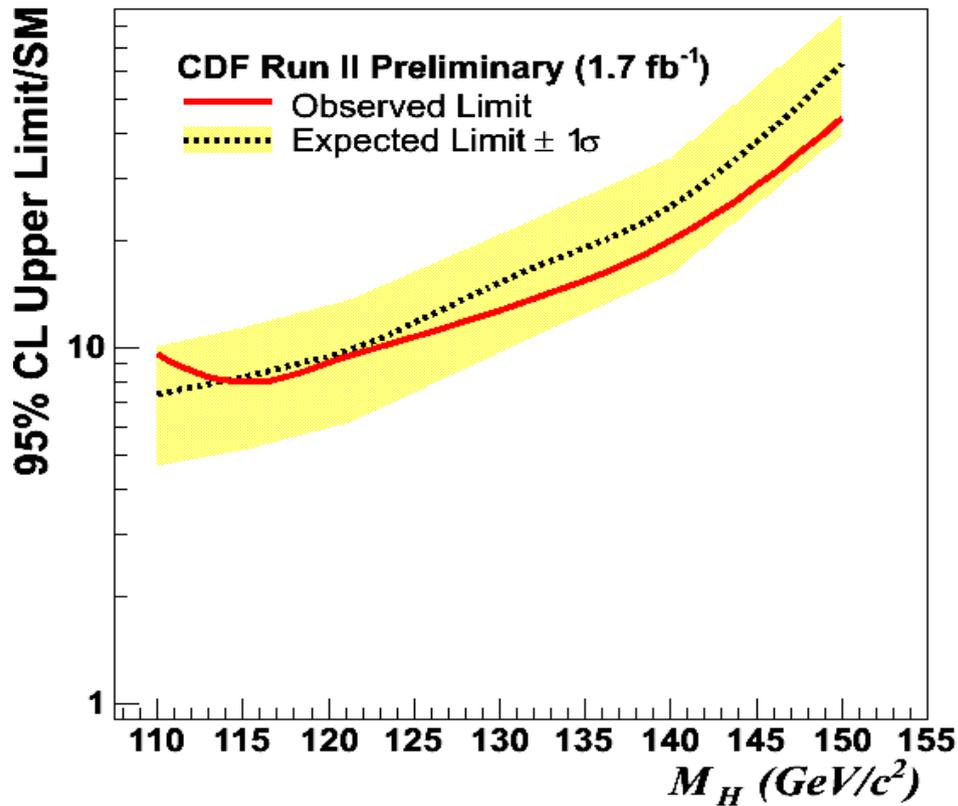




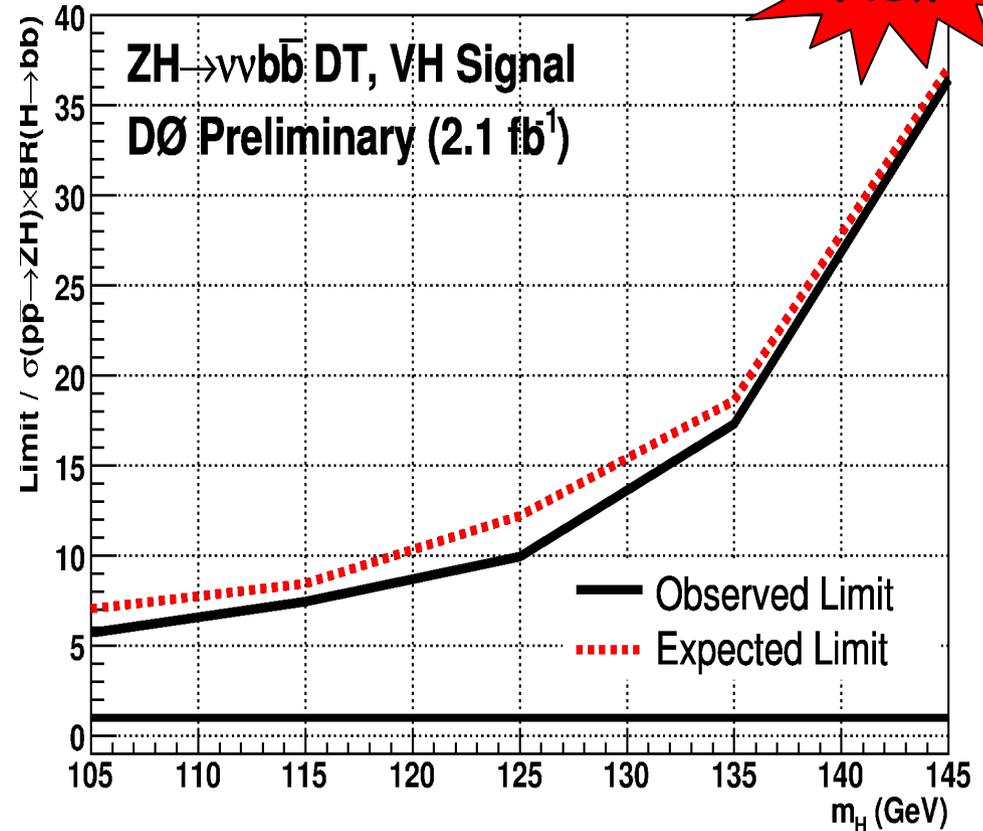
# ZH-> nu nu b b



## Met+Jets Search for ZH/WH



- ◆ CDF: (at  $M_H=115$  GeV)  
 $\sigma(\text{limit})/\sigma(\text{SM}) = 8/8.3$  (obs./exp.)



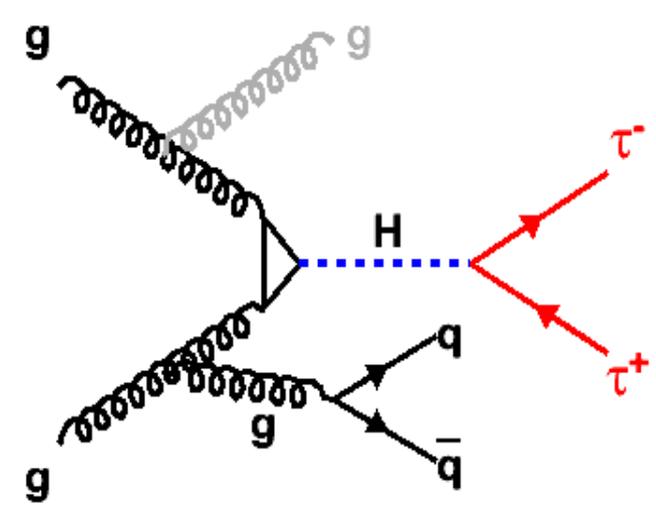
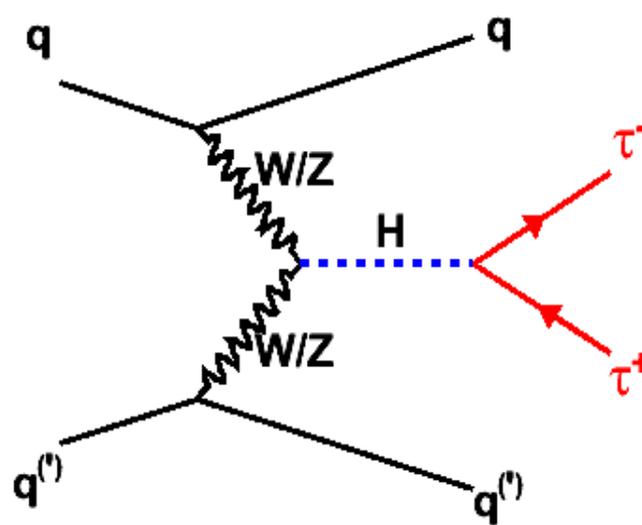
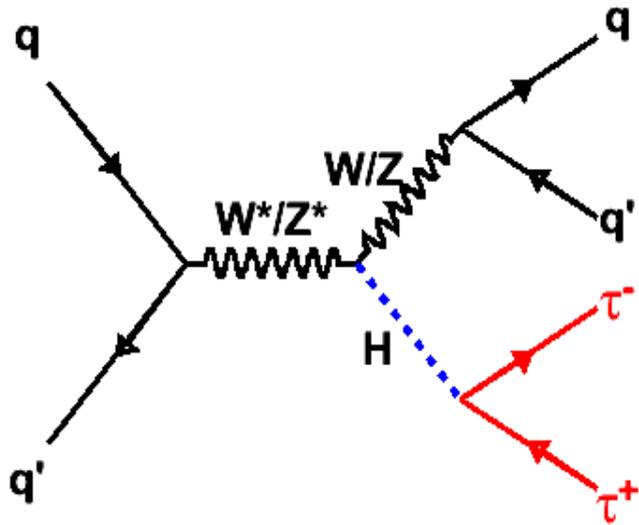
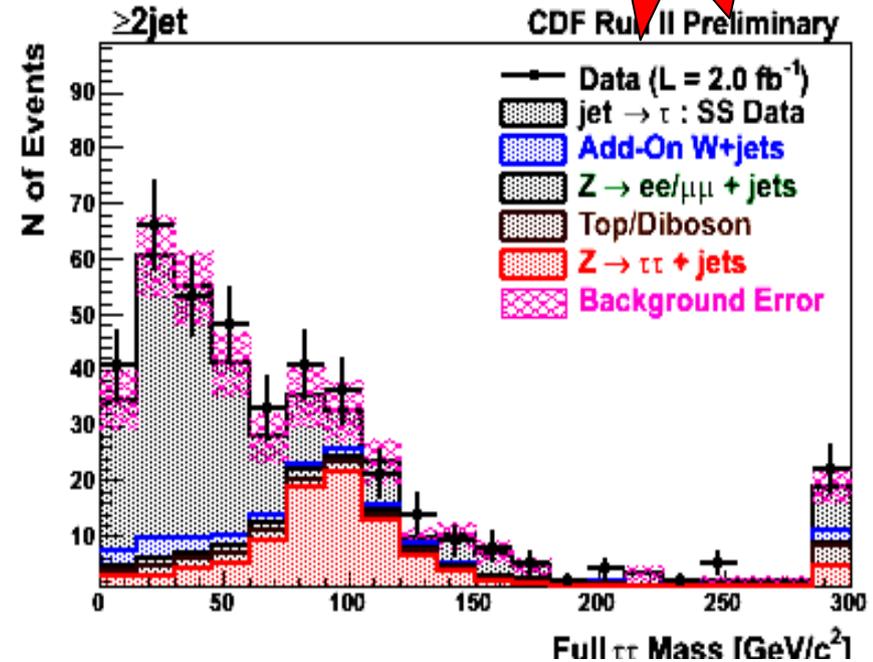
- ◆ DØ: (at  $M_H=115$  GeV)  
 $\sigma(\text{limit})/\sigma(\text{SM}) = 7.5/8.4$  (obs./exp.)



# WH/ZH/VBF/ggH -> $\tau\tau + 2$ jets

Brand New

- ◆  $H \rightarrow \tau\tau$  is hard due to small BR (10% of  $bb$ )
- ◆ But not impossible! Ideas are:
  1. Recover BR by looking at  $W/Z \rightarrow 2$  jets:
    - $W \rightarrow lv$  (22%),  $Z \rightarrow ll$  (6%),  $Z \rightarrow \nu\nu$  (20%)
    - $W \rightarrow jj$  (67%),  $Z \rightarrow jj$  (70%)
  2. Add all possible channels:
    - Simultaneous Search for  $WH+ZH+VBF+ggH$
  3. Many good kinematic variables to separate signal from backgrounds (dijet mass,  $d\eta(j,j)$  etc.)

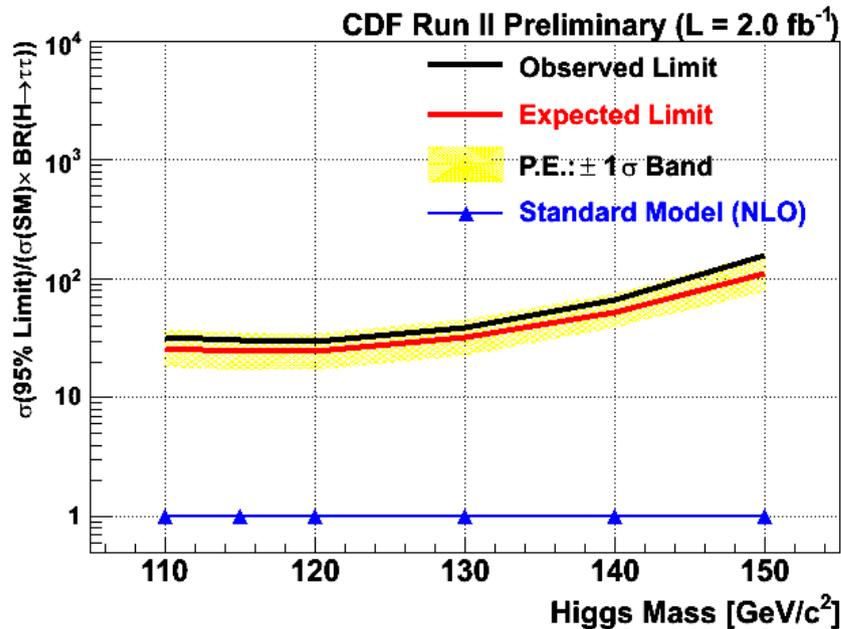
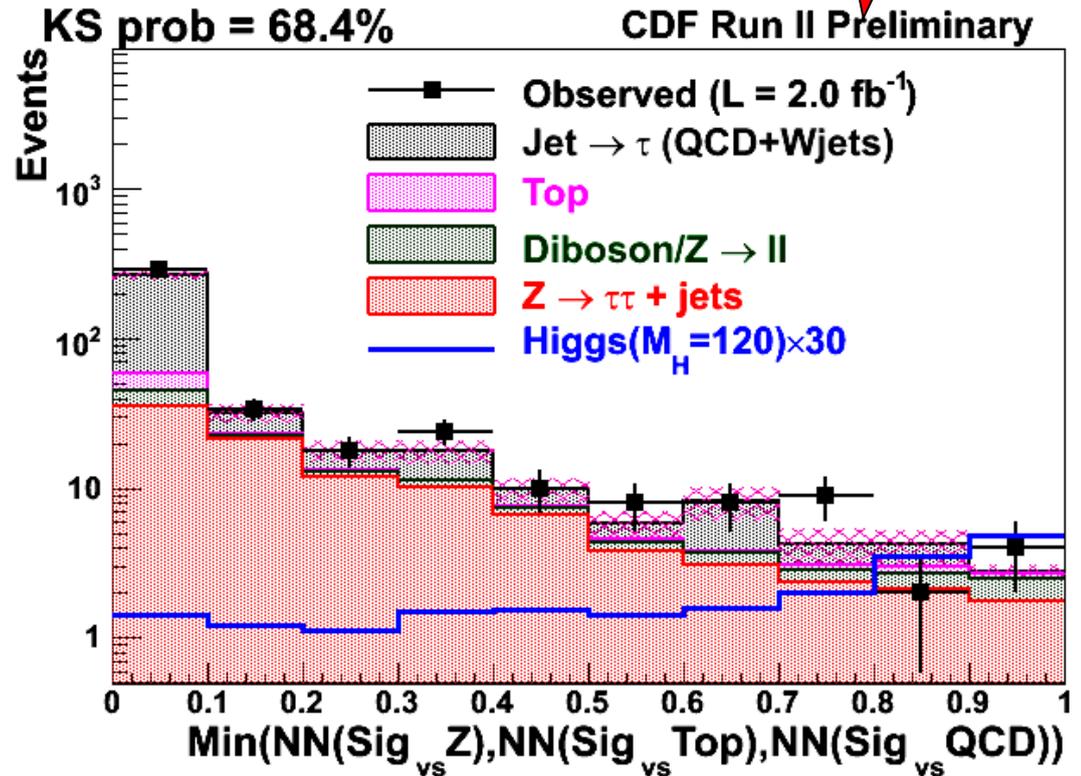




# WH/ZH/VBF/ggH -> $\tau\tau + 2$ jets

Brand New

- ◆ Use  $\tau_{lep}\tau_{had}$  mode.
  - Lepton  $P_T > 10$  GeV
  - Hadronic  $\tau P_T > 15$  GeV
- ◆ 3 Neural Nets are trained:
  - Signal vs Z->  $\tau\tau +$  jets
  - Signal vs ttbar
  - Signal vs QCD
- ◆ Select *minimum* of 3 NN scores



- ◆ CDF: (at  $M_H=120$  GeV)  
 $\sigma(\text{limit})/\sigma(\text{SM}) = 30/24$  (obs./exp.)

- \* Established background estimate & modeling
- \* Further improvement by adding 0j/1jet events
- \* Becomes more interesting at LHC

# Main Higgs Analyses

$H \rightarrow bb, \tau\tau$   
(low mass)

$H \rightarrow WW^*$   
(high mass)

$p\bar{p} \rightarrow H$

~~$H \rightarrow bb$~~

$H \rightarrow WW^* \rightarrow$   
 $ee/e\mu/\mu\mu + MET$

$p\bar{p} \rightarrow WH$

$WH \rightarrow Wbb \rightarrow$   
 $e/\mu + bb$

$W/Z + H \rightarrow W/Z + WW^* \rightarrow$   
 $l^+l^- l^+ / l^+l^+jj + MET$

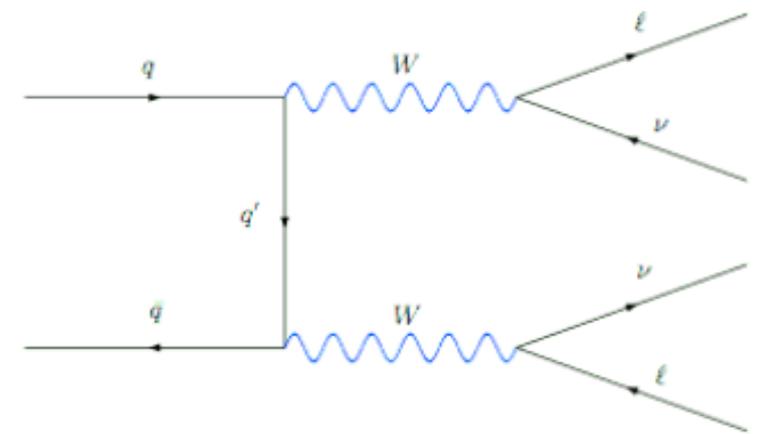
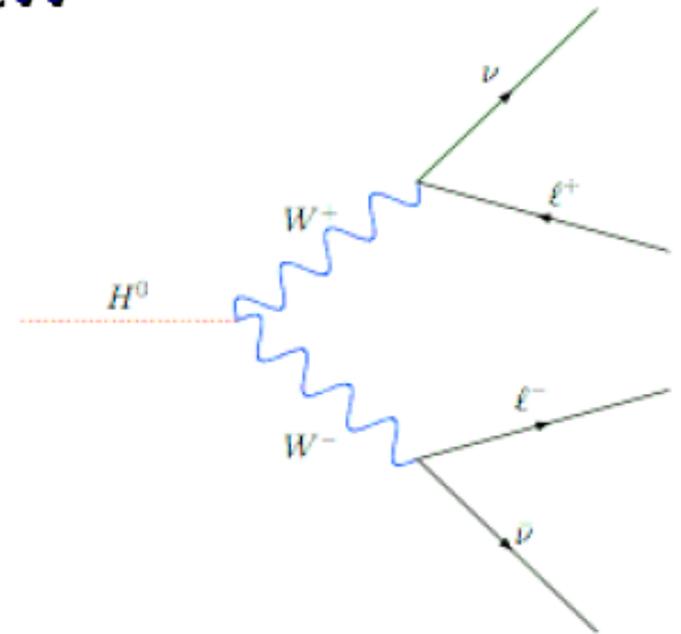
$p\bar{p} \rightarrow ZH$

$ZH \rightarrow Zbb \rightarrow$   
 $ee/\mu\mu + bb$   
 $MET + bb$

$$H \rightarrow WW^* \rightarrow \ell\ell \quad (\ell=e,\mu)$$

## Analysis overview

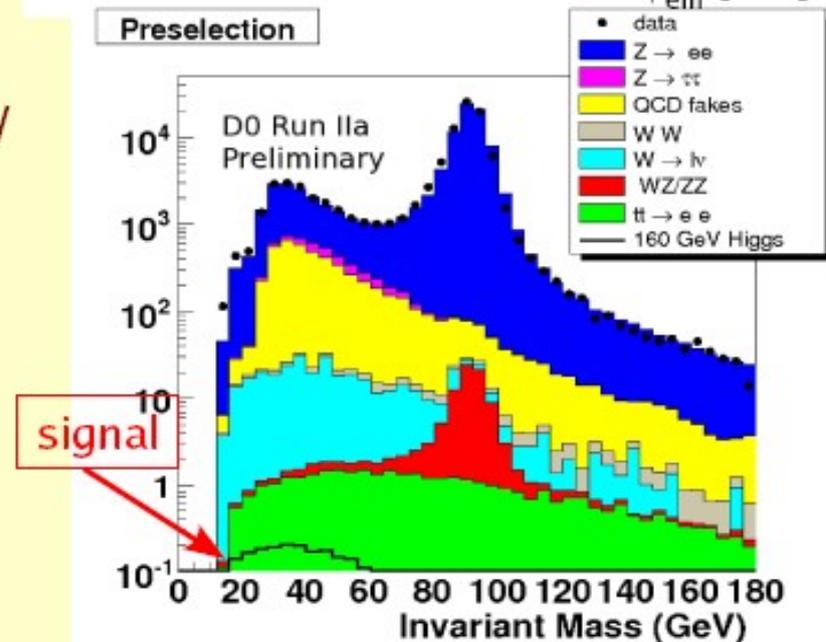
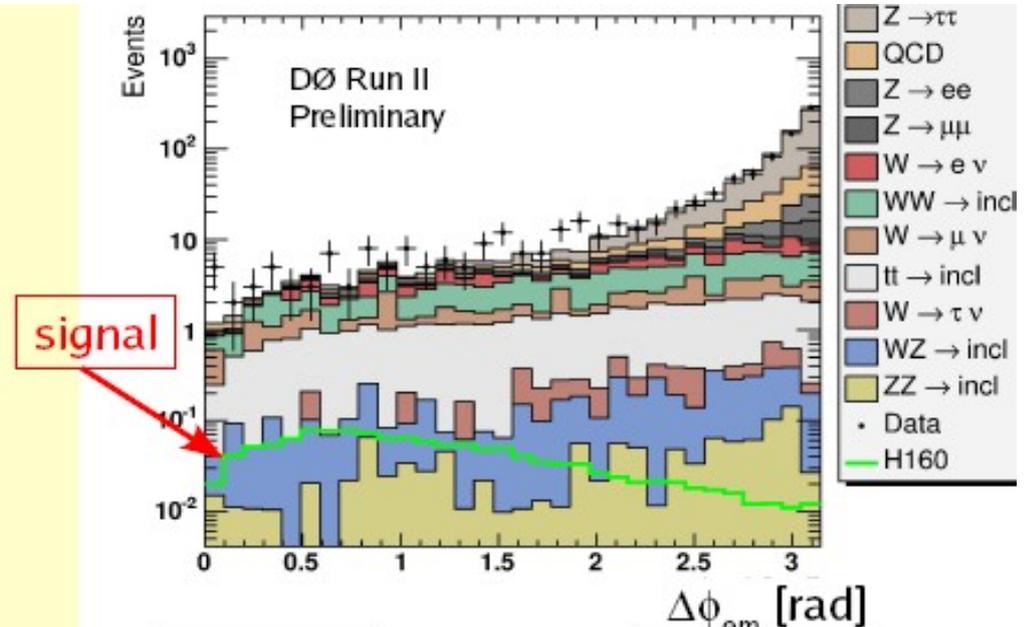
- To suppress hadron backgrounds we look into final states where both W decay to leptons, i.e.  $ee$ ,  $\mu\mu$  and  $e\mu$
- Major backgrounds: Diboson (mainly  $WW$ ), Drell-Yan, Multijets,  $t\bar{t}$ ,  $W$ +jets
- Signature:
  - Two energetic isolated leptons with opposite charge
  - Large missing transverse energy



# H $\rightarrow$ WW\* $\rightarrow$ ll (l=e,mu)

## Characteristics:

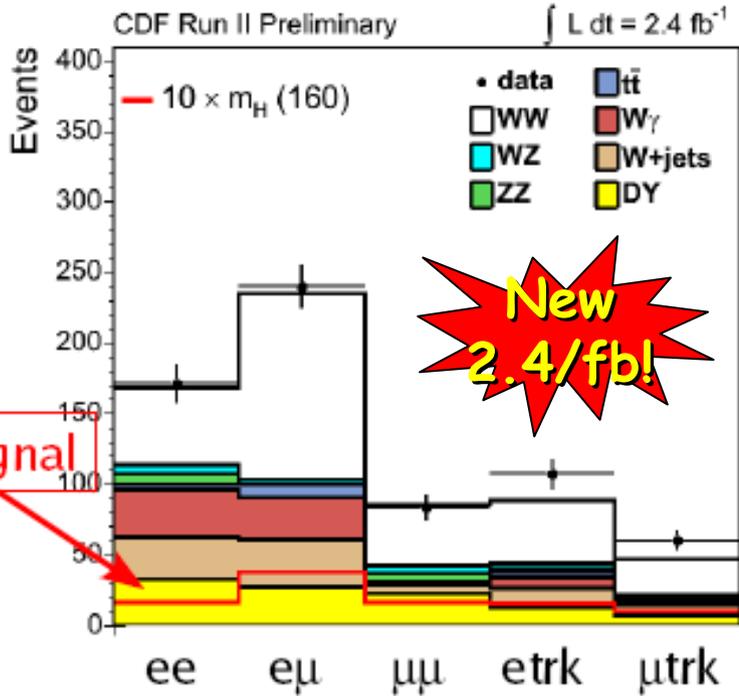
- In signal WW pair is coming from spin 0 Higgs boson
    - Leptons prefer to point in same direction
- 
- Di-lepton opening angle  $\Delta\phi_{ll}$  discriminates against dominant WW background.
- Dilepton mass is small and broad
    - Discriminates against Drell-Yan





$H \rightarrow WW^* \rightarrow \ell\ell$  ( $\ell=e,\mu$ )

Brand New  
2.3/fb!



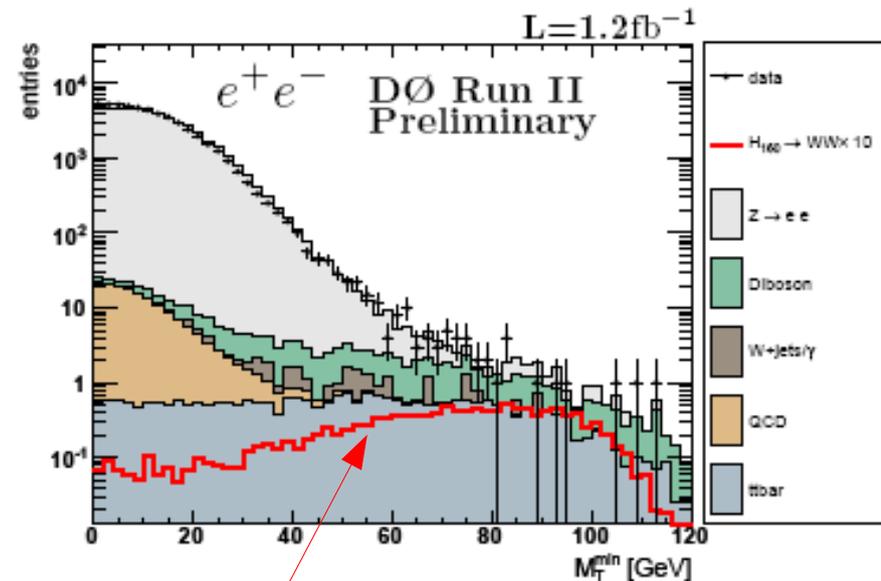
Selection criteria	$m_H = 115$ GeV	$m_H = 160$ GeV	$m_H = 200$ GeV
Cut 0 Pre-selection	lepton ID, leptons with opposite charge and $p_T^{e1} > 20$ GeV and $p_T^{e2} > 15$ GeV invariant mass $M_{ee} > 15$ GeV		
Cut 1 Missing Transverse Energy $\cancel{E}_T$ (GeV)	> 20	> 20	> 20
Cut 2 $\cancel{E}_T^{\text{scaled}}$	> 6	> 7	> 7
Cut 3 $M_T^{min}(\ell, \cancel{E}_T)$ (GeV)	> 35	> 50	> 50
Cut 4 Sum of $p_T^\ell + p_T^{\cancel{E}_T}$ (GeV)	80-120	90-160	120-200
Cut 5 Invariant mass $M_{ee}$ (GeV)	< 40	< 70	< 75
Cut 6 $H_T$ (GeV)	< 50	< 80	< 80
Cut 7 $\Delta\phi(e_1, e_2)$	< 2.5	< 2.0	< 2.0

### Lepton trigger selection

Several categories of lepton(track) pairs with opposite charge divided into two groups – high signal to background and low signal to background

Lepton and missing  $E_T$  cuts applied to reduce backgrounds:

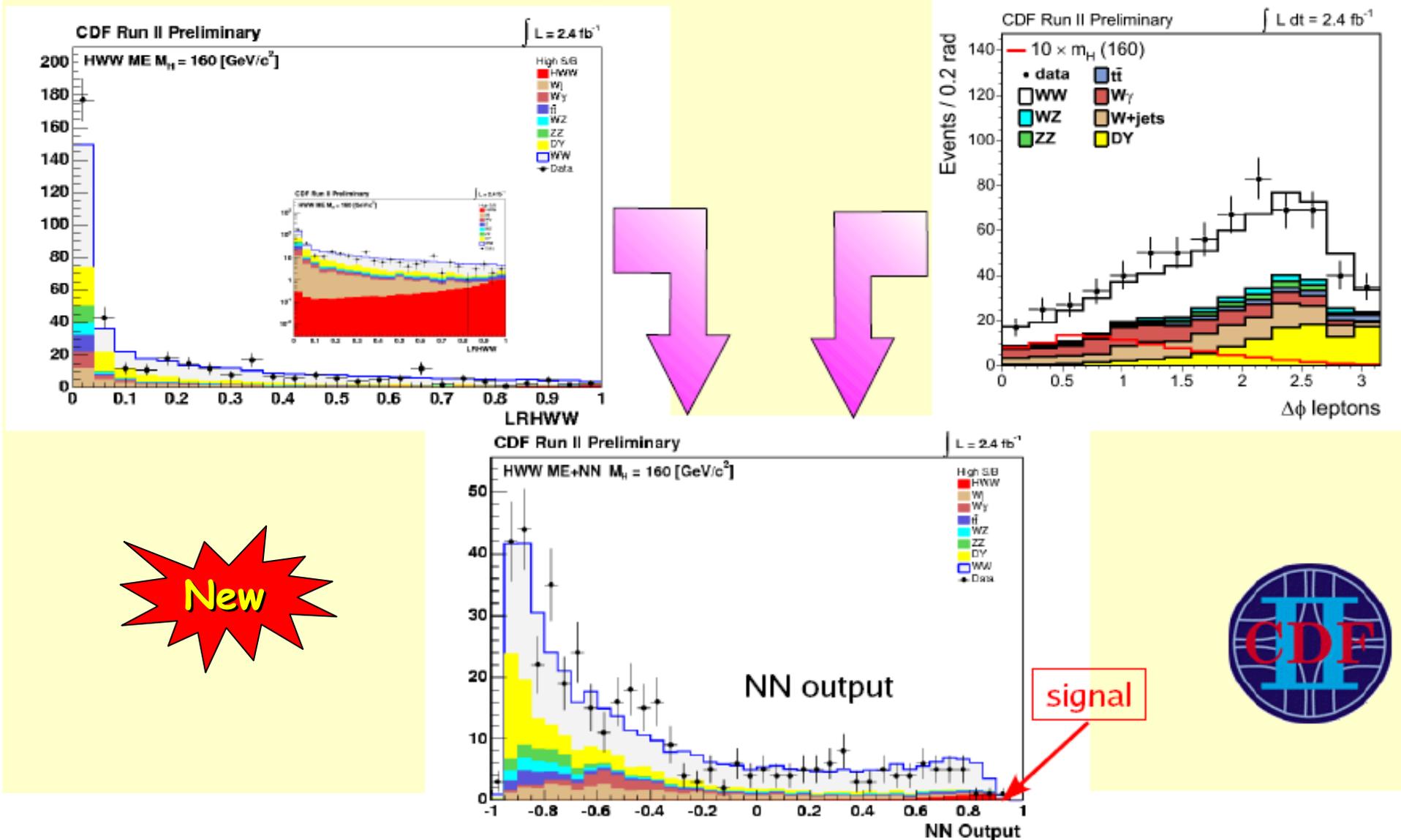
$p_T(l_1) > 20$  GeV,  $p_T(l_2) > 10$  GeV,  $\cancel{E}_T \cdot \sin(\min(\pi/2, \Delta\phi(\cancel{E}_T, l \text{ or jet})) > 25$  GeV,  $n_{jets} < 2$  ( $p_T(jet) > 15$  GeV,  $|\eta| < 2.5$ ),  $m_{ll} > 16$  GeV, tripleton veto



Signal (x10)

# H -> WW\* -> ll (l=e,mu)

- ME calculated from lepton 4-vectors and missing transverse energy is used as an input to NN together with several kinematic distributions



**New**





# H -> WW\* -> ll (l=e,mu)

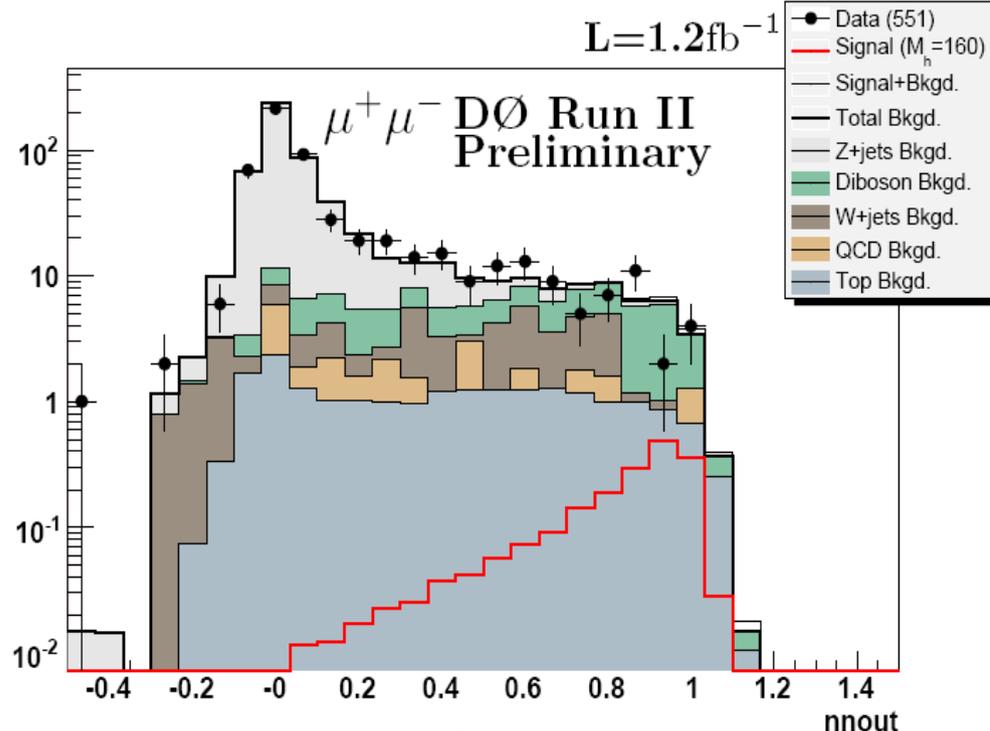
Brand New

Now also using H->WW vs. WW ME calculation as input to NN

NN trained for each Higgs mass in 5 GeV steps, for each channel

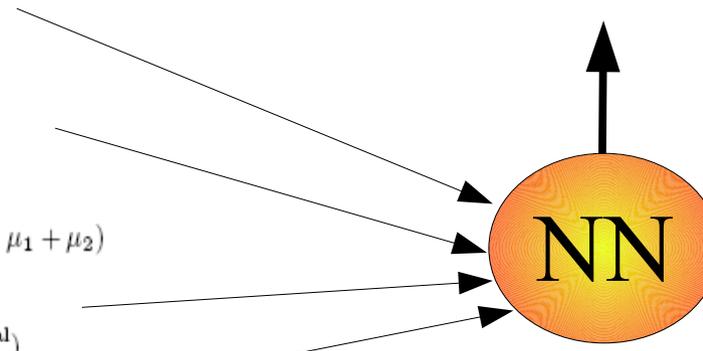
Full output used for setting limits

$L=1.2\text{fb}^{-1}$



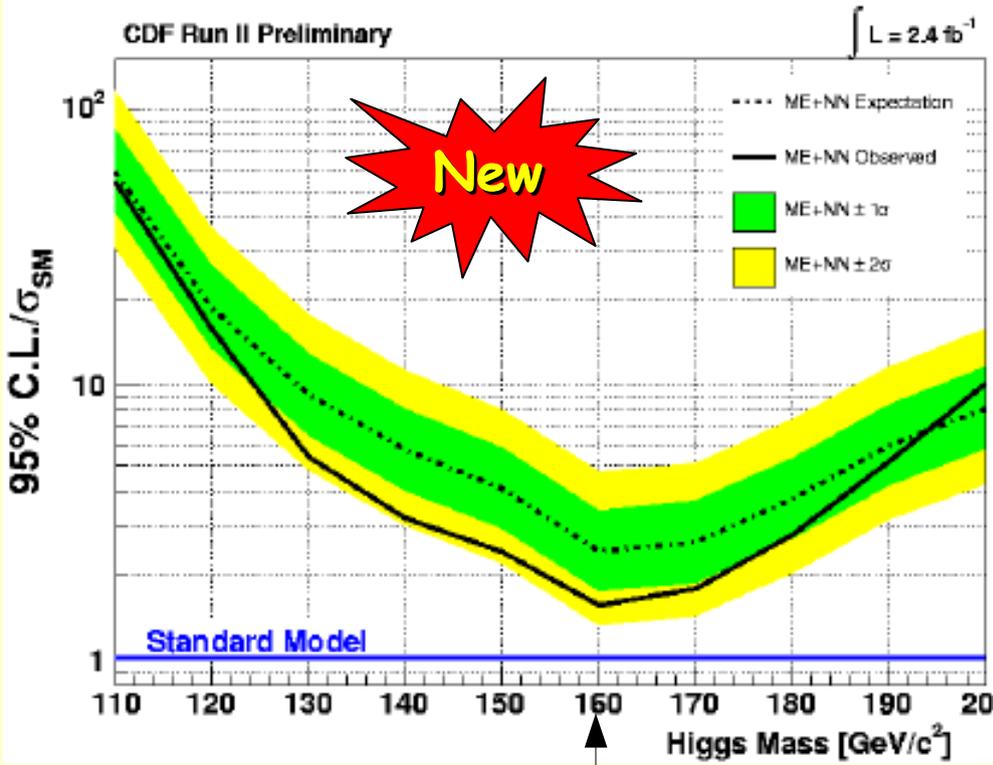
$\mu\mu$  NN Analysis Variables

Scaled $\cancel{E}_T$	$\cancel{E}_T^{\text{Scaled}}$
Invariant mass of the two muons	$M_{\mu\mu}$
Missing $E_T$	$\cancel{E}_T$
Sum of the $p_T$ 's of all 0.5 cone jets with $p_T > 6$ GeV	$H_T^{\text{all}}$
H -> WW vs. WW ME discriminant	$ME_{\text{disc}}$
$p_T$ of the $\mu\mu$ system	$p_T(\mu_1 + \mu_2)$
Smaller of the two muon- $\cancel{E}_T$ transverse masses	$M_T^{\text{min}}$
$p_T$ of the leading $p_T$ muon	$p_T(\mu_1)$
Azimuthal angle between the $\cancel{E}_T$ and the second-leading $p_T$ muon	$\Delta\phi(\mu_2, \cancel{E}_T)$
$\log_{10}$ of the sum of the muon scaled (track+cal) isolations	$\log_{10}(\text{scalediso } \mu_1 + \mu_2)$
Event scalar $E_T$	$SE_T$
Azimuthal angle between the two muons	$\Delta\phi(\mu_1, \mu_2)$
Worst of the two muon qualities (loose,medium,tight)	$\min(\mu_1^{\text{qual}}, \mu_2^{\text{qual}})$
Azimuthal angle between the $\cancel{E}_T$ and the leading $p_T$ muon	$\Delta\phi(\mu_1, \cancel{E}_T)$
$p_T$ of the second-leading $p_T$ muon	$p_T(\mu_2)$

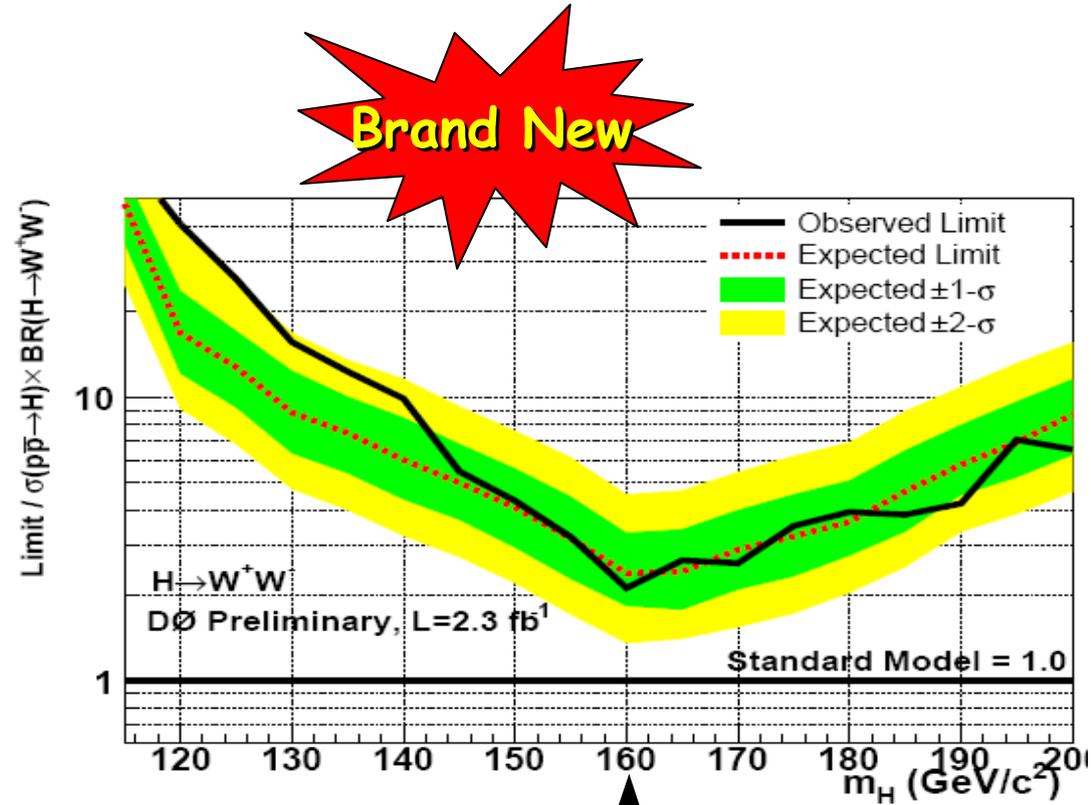




# H $\rightarrow$ WW\* $\rightarrow$ ll (l=e,mu)

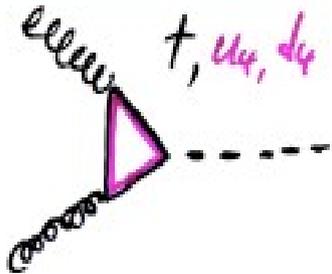


Observed Limit/ $\sigma_{SM}$  (NNLL)  $\sim 1.6$   
 Expected Limit/ $\sigma_{SM}$  (NNLL)  $\sim 2.4$



Observed Limit / SM  $\sim 2.1$   
 Expected Limit / SM  $\sim 2.4$

# 4<sup>th</sup> Generation



AMPLITUDE  $\times 3$   
OVER SM

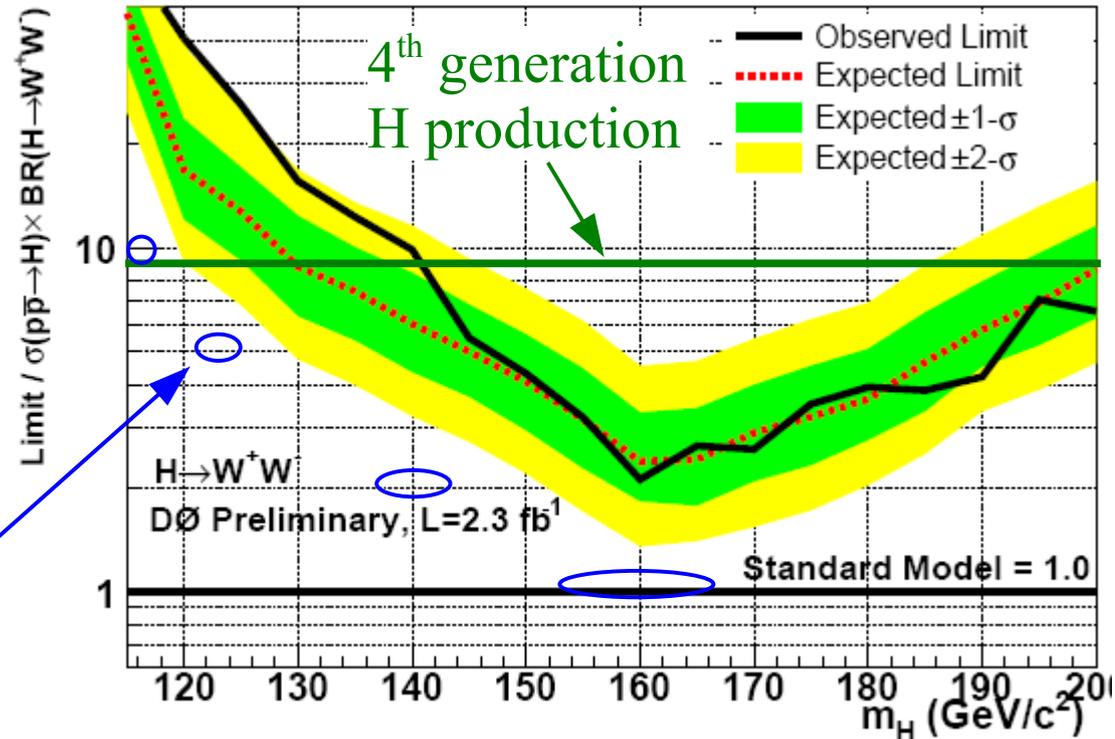
9x more gg  $\rightarrow$  H production!



DØ excluding from 140-200 GeV

Sensitive up to  $\sim 260$  GeV by 2010

(Also will be sensitive to fermiophobic Higgs...)



$$WH \rightarrow W WW^* \rightarrow l^\pm l^\pm + X \quad (l=e,\mu)$$

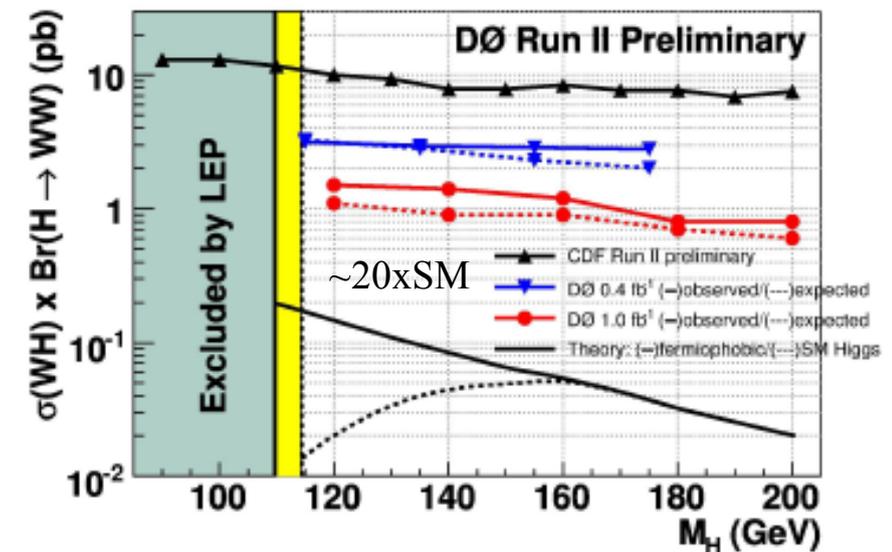
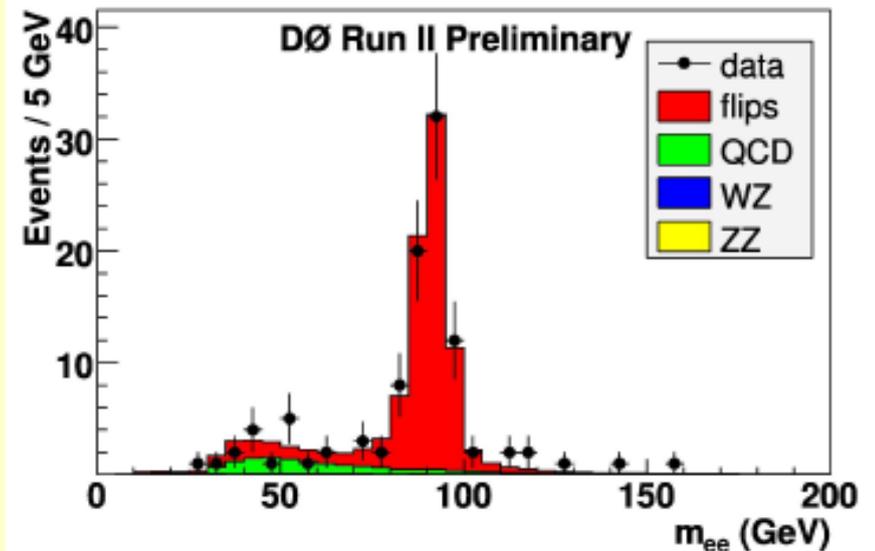
Basic selection requires two **same** charge leptons with  $p_T > 15$  GeV

Two main types of backgrounds:

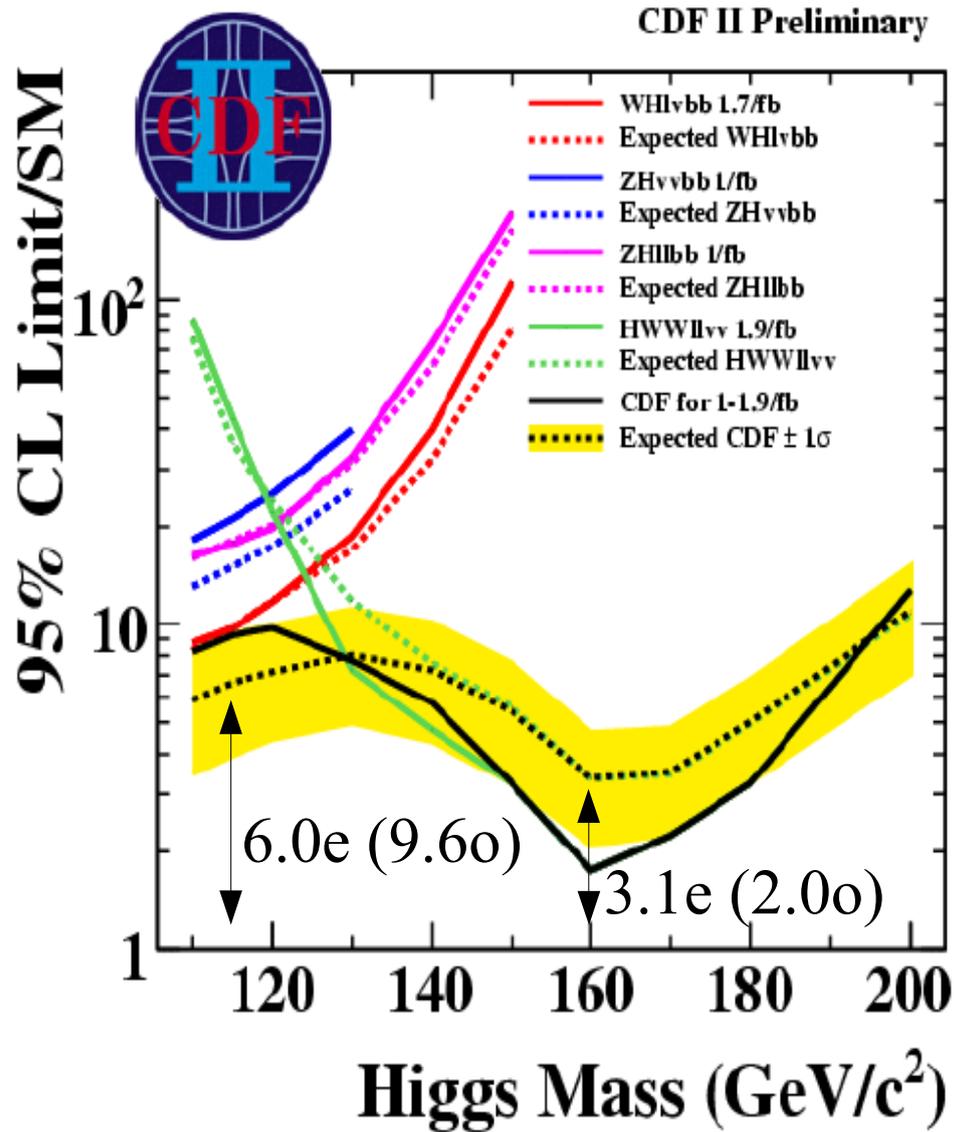
- With two real same charge leptons like  $WZ \rightarrow ll$
- Instrumental – measured from data:
  - “QCD” with misidentified lepton
  - “flip charge” when charge of the lepton is mismeasured

Main source of systematic uncertainty is coming from instrumental background (~30%)

Limit: 0.9 pb at 95% CL for  $m_H = 160$  GeV



# SM Higgs Combinations

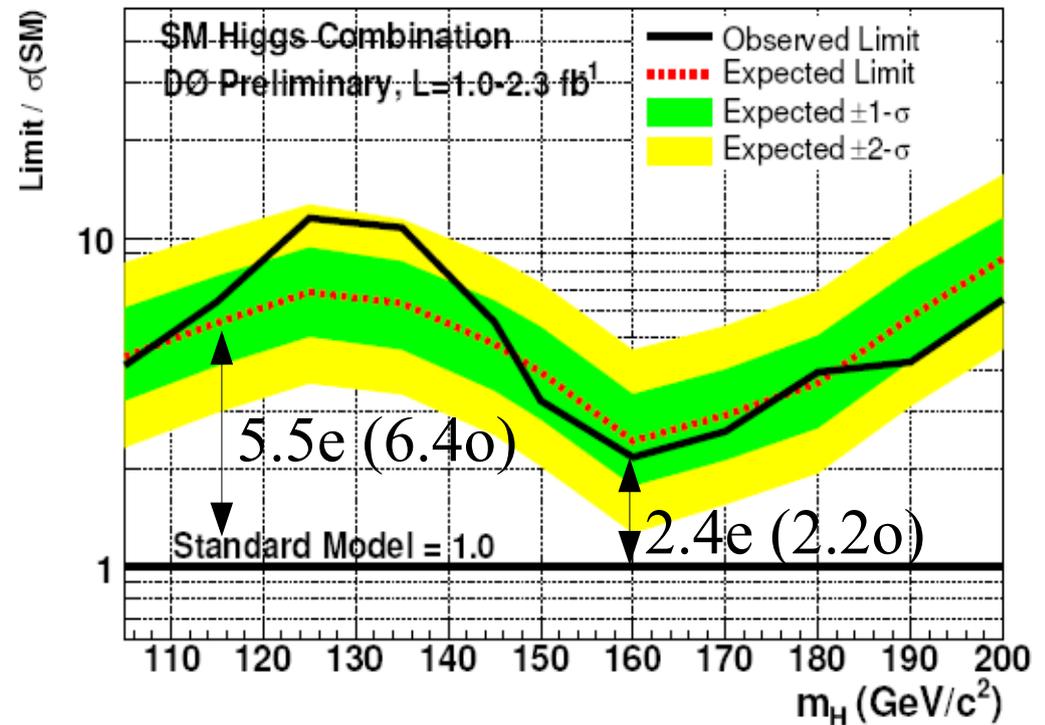


New things not in CDF combination yet:

WH  $\rightarrow$   $l\nu b\bar{b}$ : +200 $\text{pb}^{-1}$ ,  
1tag improvement,  
forward electrons

ZH  $\rightarrow$   $\nu b\bar{b}$ : data driven QCD

H  $\rightarrow$   $\tau\tau$ : 2.0 $\text{fb}^{-1}$

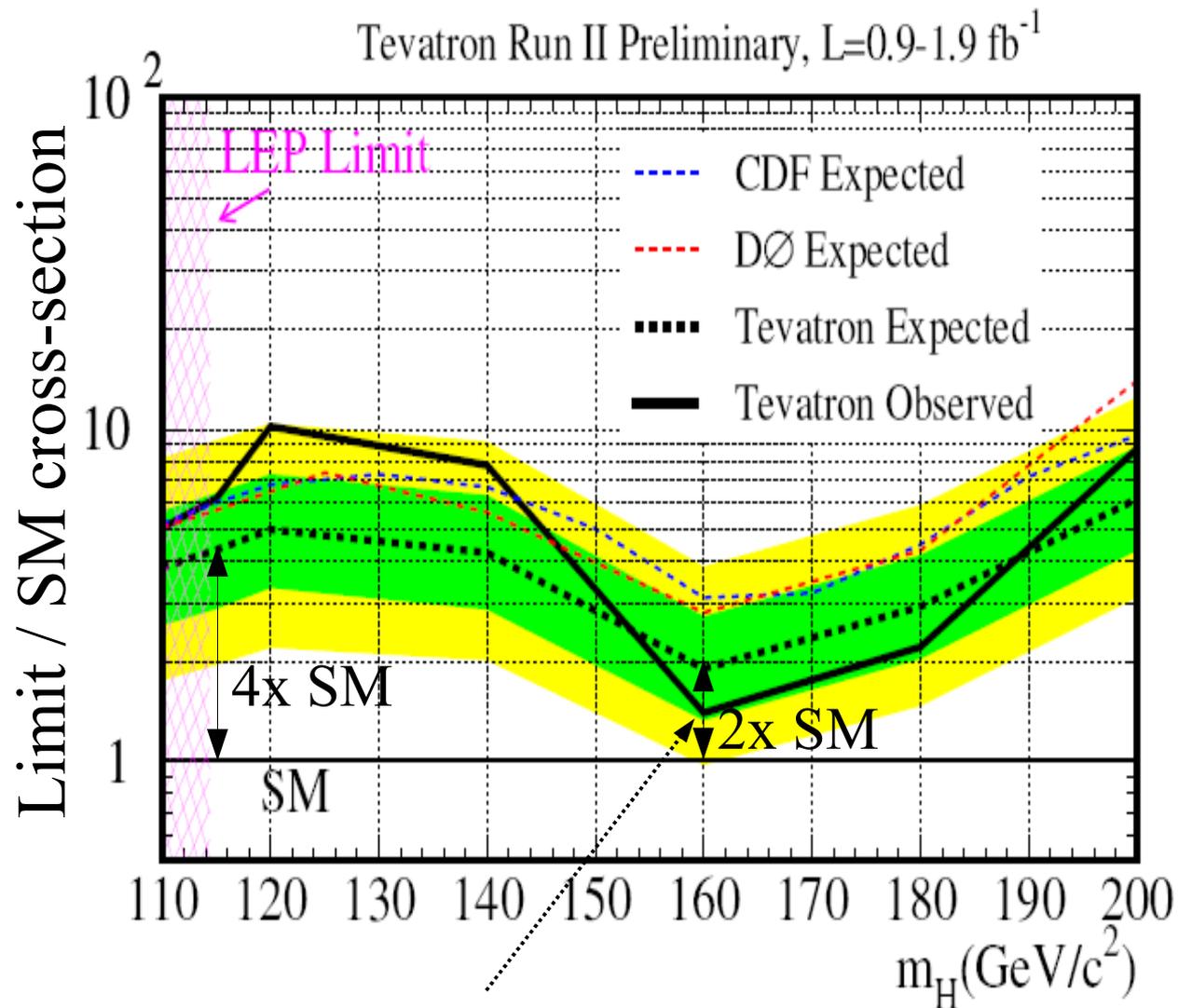


# D0/CDF SM Higgs Combination

New Tevatron combination coming very very soon!

Improvements underway:

- **Di-jet mass resolution**
- **Lepton efficiency**
- **Further improvements in analysis technique**
- **Better multivariate techniques**
- **Better b-tagging**



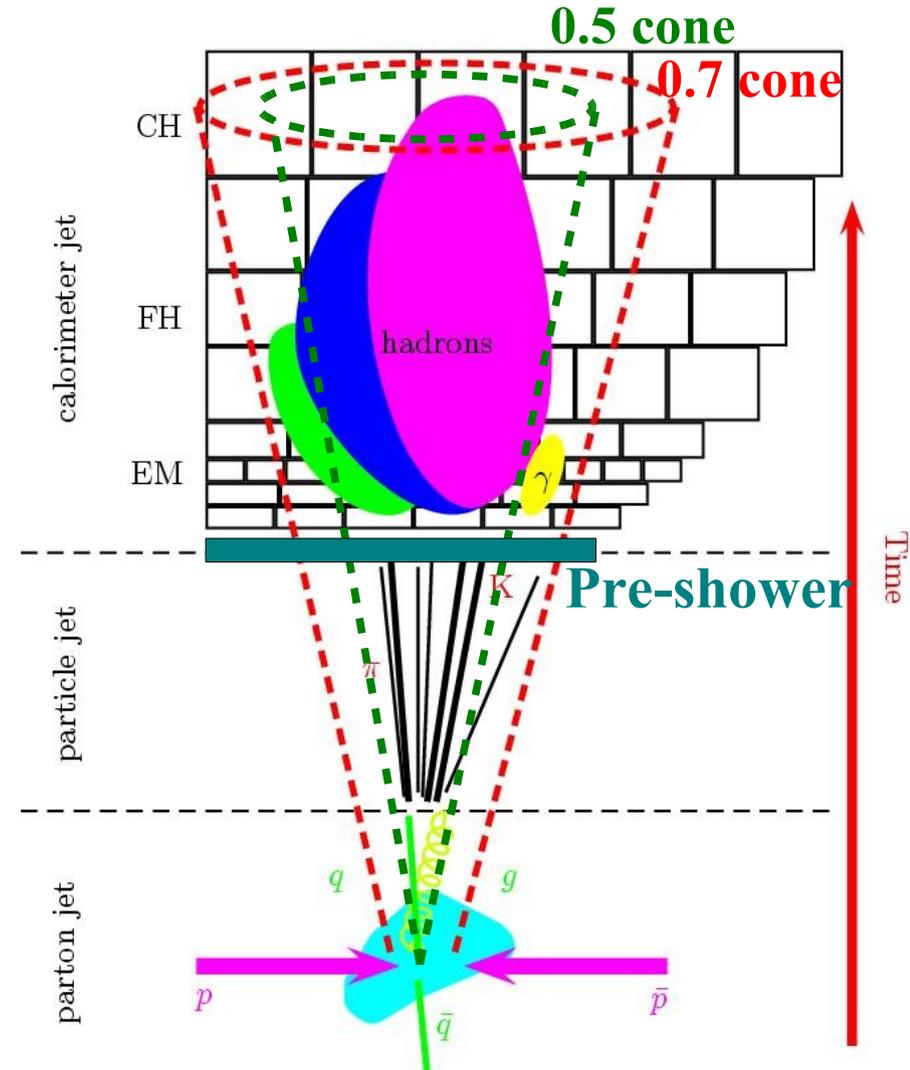
**Observed limit: 1.4x SM !**

# Di-jet Mass Resolution



Undertaking a major effort to improve jet energy resolution

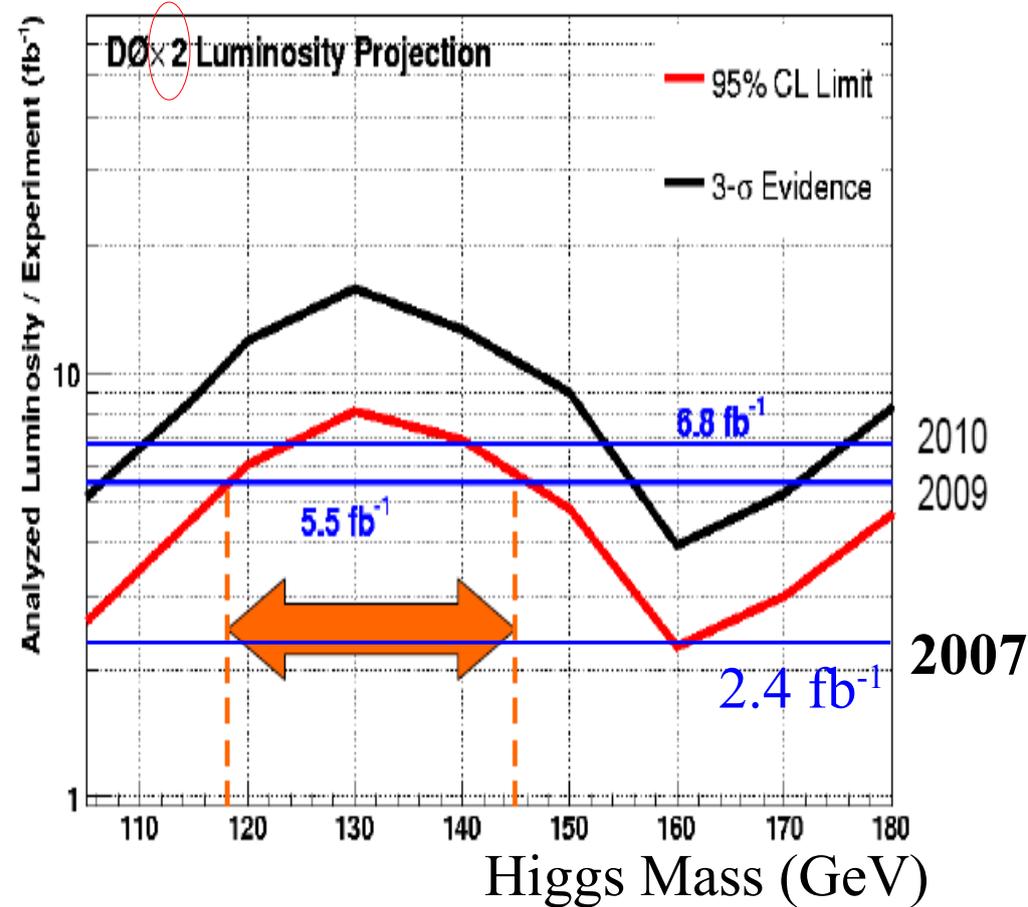
- Add “pre-shower” energy
- Correct for jet “width”
- Track-based corrections
- (H1-style) cell energy weighting
- Multiple jet-cone sizes
  - 0.5 less sensitive to noise, pileup, overlap
  - 0.7 captures more jet energy
  - *Jet-by-jet showering / FSR correction*



# Sensitivity Estimates

- Di-jet mass resolution (20%)
- Lepton efficiency (10% / lepton)
- Improved analyses (20%)
- Matrix Element (20%)
- Better b-tagging
  - Semi-leptonic tagging (5%)
  - Silicon Layer-0 (8%)

**Should be sensitive to  $m_H = 160$  GeV ~now**

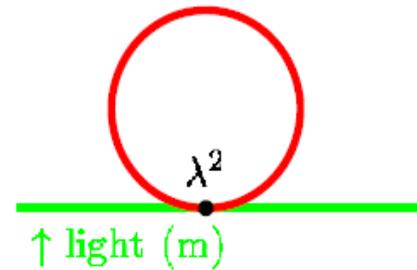


**Sensitive to SM Higgs up to 200 GeV by 2010**

# Why is the Higgs so Light?

The Higgs mass is *unstable*

- Large radiative corrections (it's a scalar)

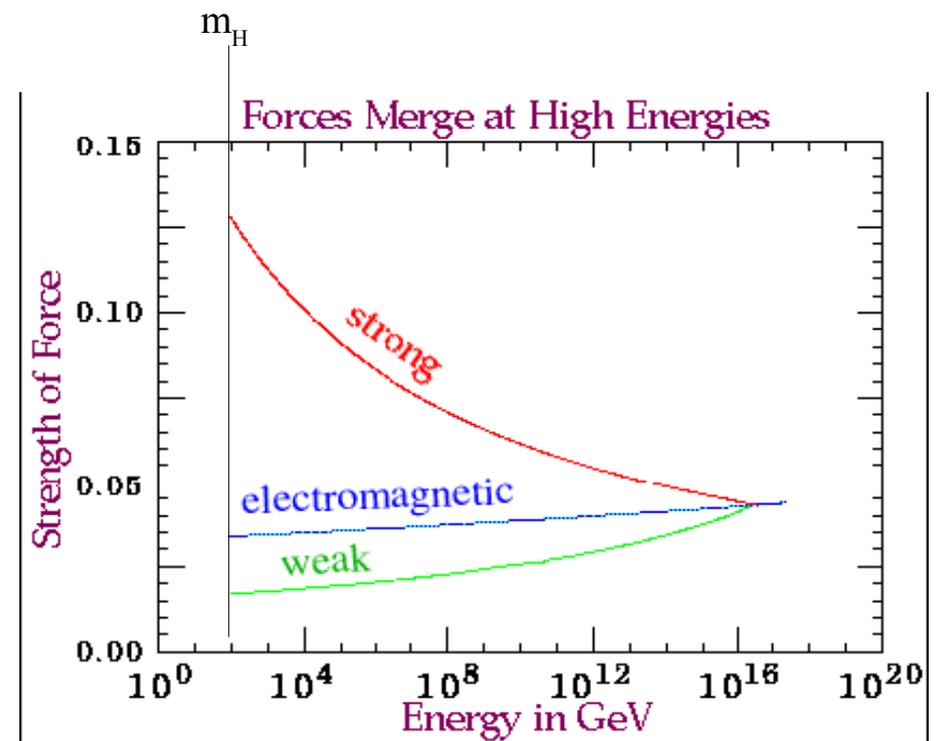


$$\Rightarrow \delta m^2 \sim \lambda^2 \cdot M^2$$

$$\begin{matrix} \lambda & \lambda & \lambda \\ 10^2 & 10^{-1} & 10^{16} \end{matrix}$$

Hierarchy problem:

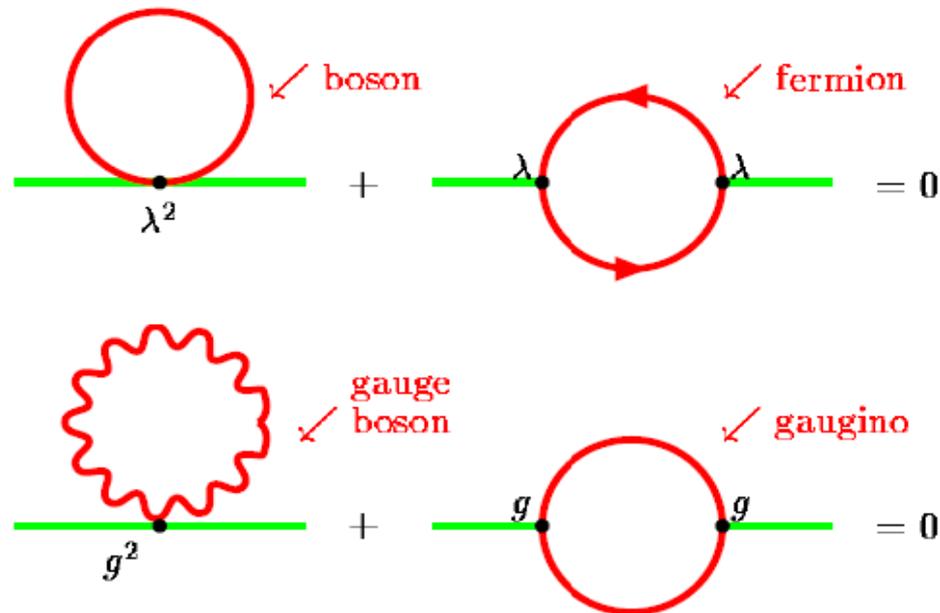
$$m_H \ll m_{\text{GUT}}$$



# Why is the Higgs so Light?

New physics: Supersymmetry !

- Particles come in fermion-boson pairs
- Corrections to Higgs mass nearly cancel, if boson and fermion masses are similar



# Higgs Bosons in the MSSM

Two Higgs doublet fields

- $H_u(H_d)$  couple to up(down)-type fermions
- $\tan\beta = \langle H_u \rangle / \langle H_d \rangle$
- 5 particles after EWSB
  - $h, H, A, H^+, H^-$
- $h$  must be light,  $< \sim 135$  GeV

At large  $\tan\beta$ , coupling of  $A, h/H$  to down-type fermions ( $b, \tau$ ) is enhanced

- *Cross-section proportional to  $\tan^2\beta$*
- *Branching ratio:  $bb \sim 90\%$ ,  $\tau\tau \sim 10\%$*

# Neutral MSSM Higgs $\rightarrow \tau_l \tau_{had}$

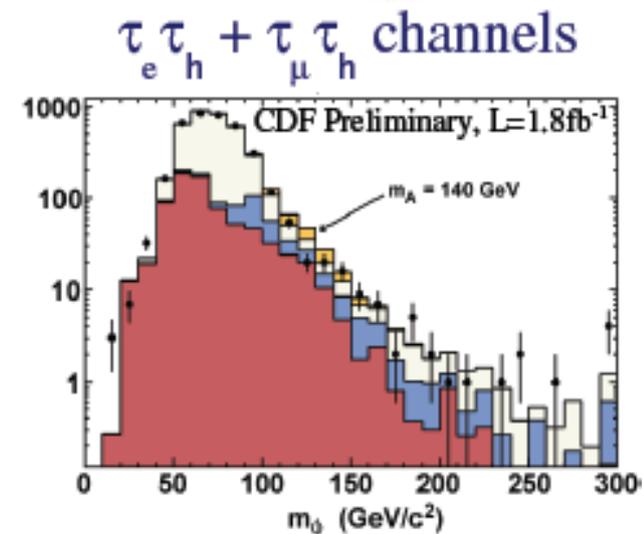
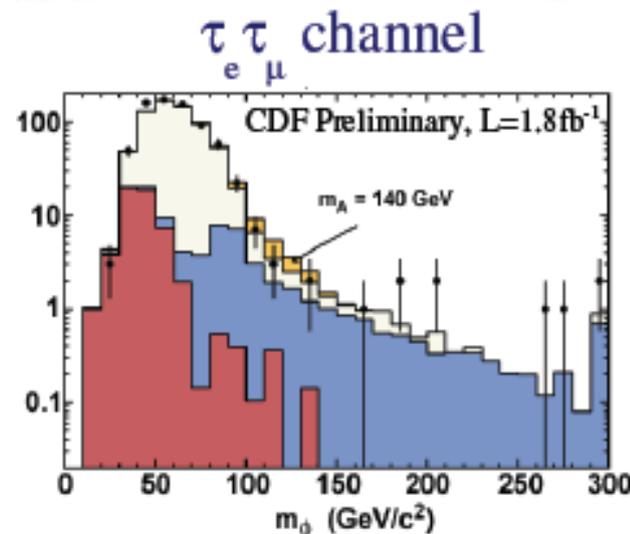
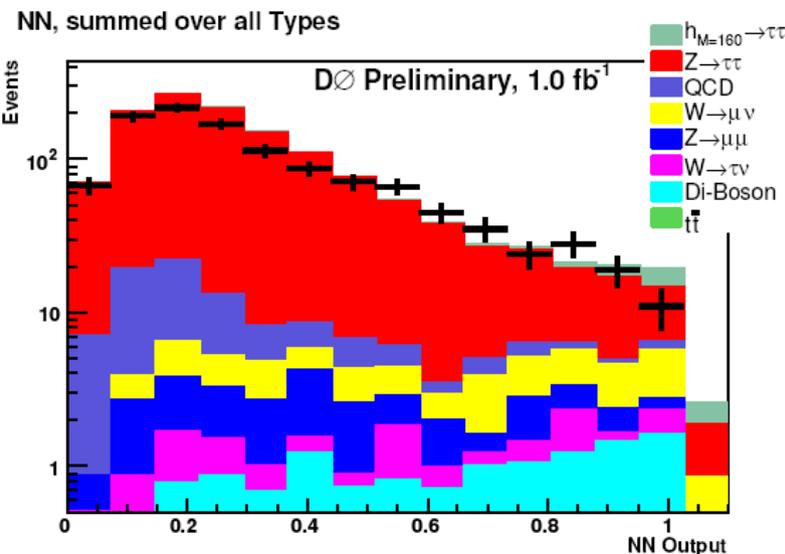


- ▶ Main backgrounds:  $Z \rightarrow \tau\tau$  (irreducible),  $W$ +jets,  $Z \rightarrow ee, \mu\mu$ , multijet, di-boson

- ▶  $D\phi$  ( $\mu$  channel only): Selection:
  - ▶ only one isolated  $\mu$  separated from the hadronic  $\tau$  with opposite sign
  - ▶ set of NNs to discriminate  $\tau$  from jets
  - ▶ cut on  $M_{W(\text{visible})} < 20$  GeV removes most of the remaining  $W$  boson backgr.

- ▶ CDF ( $e, \mu, e+\mu$  channels): Selection:
  - ▶ isolated  $e$  or  $\mu$  separated from the hadronic  $\tau$  with opposite sign
  - ▶ variable-size cone algorithm for  $\tau$  discrimination
  - ▶ jet background suppressed by requiring:  $|p_T^l| + |p_T^{had}| + |\cancel{E}_T| > 55$  GeV
  - ▶ remove most of the  $W$  background by a requirement on the relative directions of the visible  $\tau$  decay products and  $\cancel{E}_T$

- ▶ Optimized NNs to separate signal from background





# $b(h/H,A) \rightarrow bbb$



$(h/H,A) \rightarrow bb$  swamped by QCD background

- Look for *associated* b production

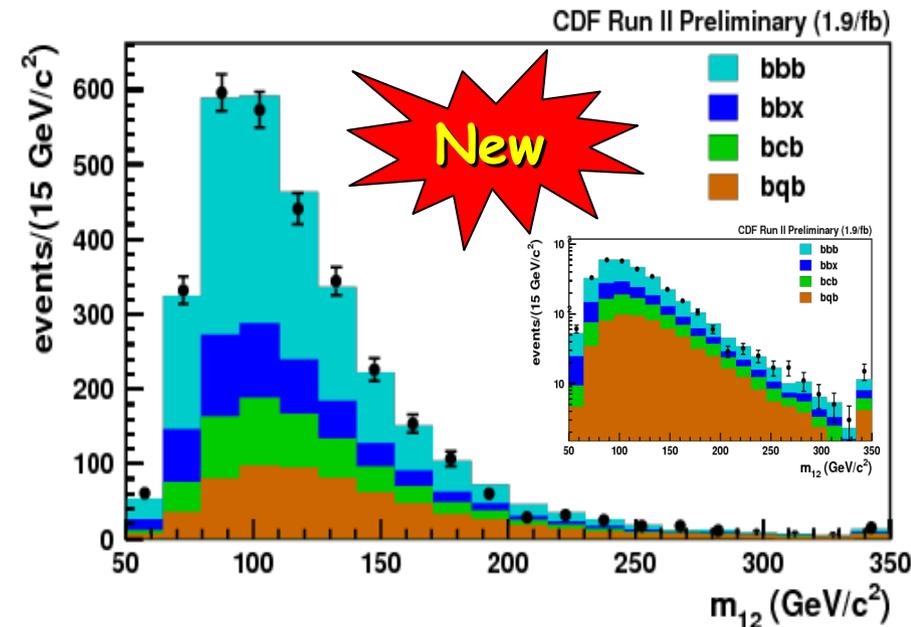
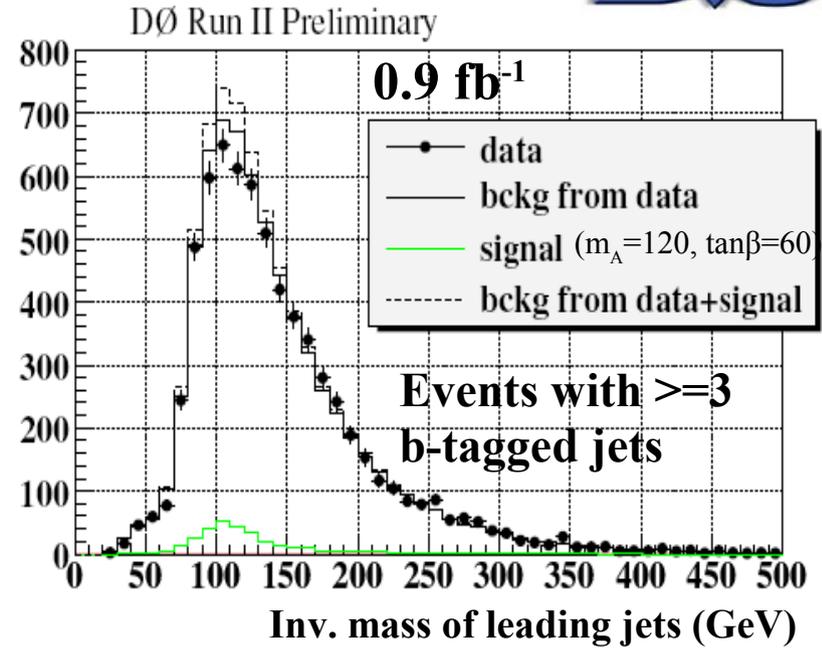
Require at least 3 *b-tagged* jets

Signal:

- Invariant mass of leading jets is peaked at  $m_A$

Backgrounds (determined from data):

- Shape based on the *double* b-tagged data sample
- Corrected for kinematic bias from the 3<sup>rd</sup> b-tag

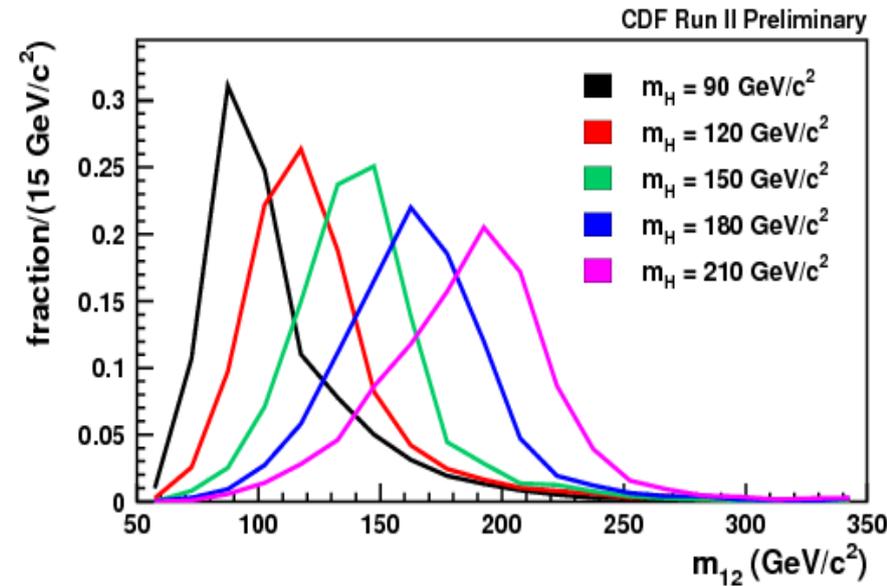
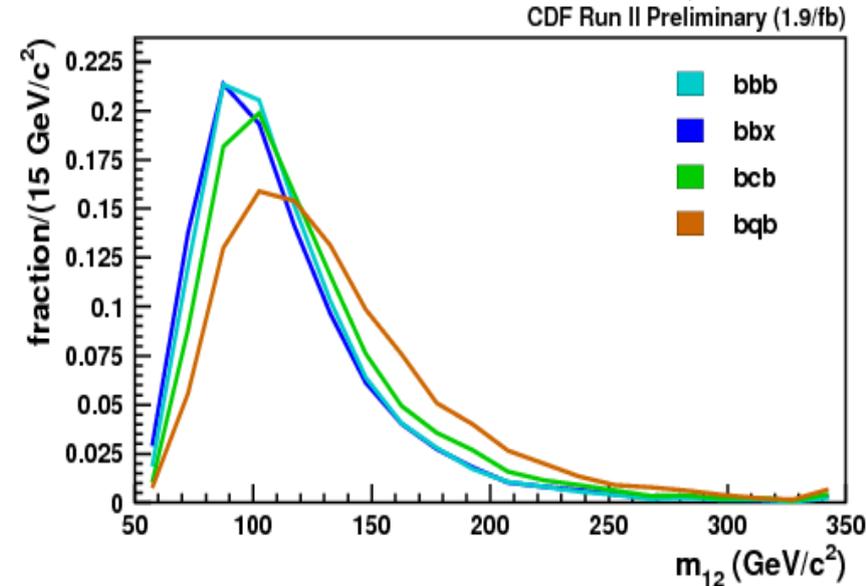




# $b(h/H,A) \rightarrow bbb$



- New result for Moriond QCD 08, using  $1.9 \text{ fb}^{-1}$
- Search in mass of two lead jets,  $m_{12}$
- Backgrounds are events with two true b-tags, and a b/c/fake tag
- Characteristic  $m_{12}$  spectra for each
- Start from bb+jet sample (corrected double-tags), weight events by flavor hypothesis
- Correct bbb and bcb shapes for double/triple-tag selection bias
  - Largest systematic error
- Fit the observed  $m_{12}$  spectrum with the backgrounds and a Higgs shape



$$b(h/H,A) \rightarrow b\tau\tau$$



344 pb<sup>-1</sup> (update in progress!)

Best S/B of all three MSSM analyses, but lowest cross-section x BR

Select  $\tau\tau(\rightarrow\mu)$  events, normalize to  $Z\rightarrow\tau\tau$  peak  
 Require  $\geq 1$  *b*-tagged jet, with  $p_T > 15$  GeV

Multijet (QCD) background measured using like-sign data

(for  $M_H = 120$  GeV and  $\tan\beta = 80$ )

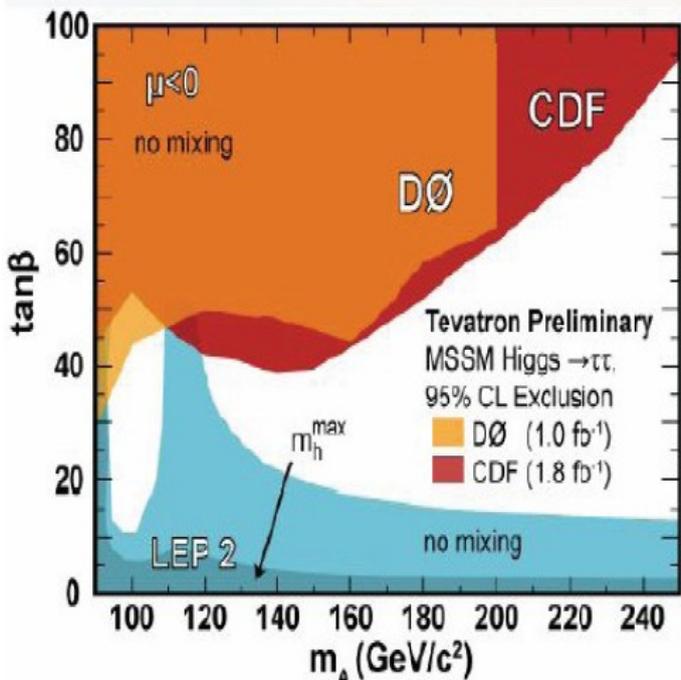
	single- $\pi$ -like $\tau$	rho-like $\tau$	3-prong $\tau$
Signal Accept. (%)	$0.15 \pm 0.03$	$0.87 \pm 0.11$	$0.30 \pm 0.04$
Expected Signal	$0.6 \pm 0.1$	$3.5 \pm 0.5$	$1.2 \pm 0.2$
QCD	$0.62 \pm 0.22$	$0.51 \pm 0.14$	$1.45 \pm 0.18$
Z+jet	$0.34 \pm 0.09$	$1.6 \pm 0.3$	$0.35 \pm 0.10$
$t\bar{t}$ (di- $l$ )	$0.18 \pm 0.03$	$0.50 \pm 0.11$	$0.007 \pm 0.0013$
$t\bar{t}$ ( $l$ +jet)	0	$0.008 \pm 0.008$	$0.15 \pm 0.04$
W+jj	$0.005 \pm 0.005$	$0.05 \pm 0.02$	$0.40 \pm 0.14$
Total Background	$1.2 \pm 0.2$	$2.6 \pm 0.3$	$2.5 \pm 0.2$
Observed	0	1	2



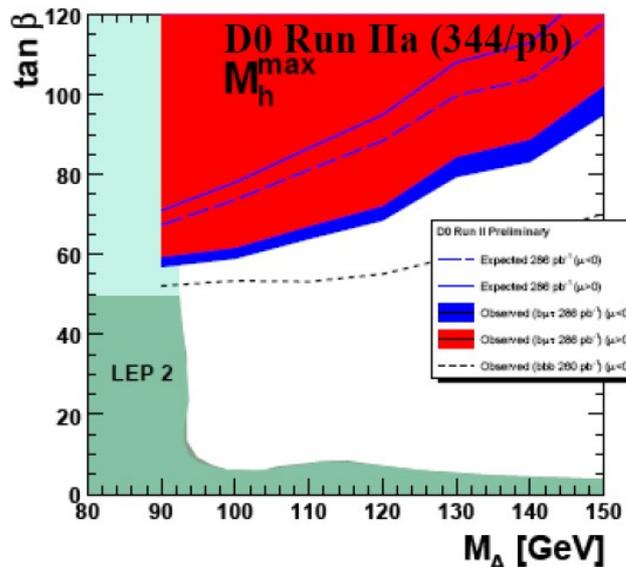
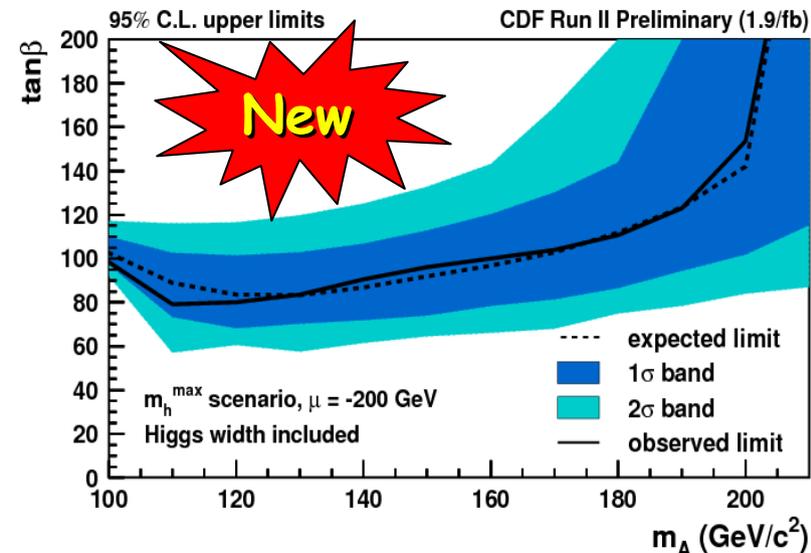
# MSSM Higgs Limits



$H \rightarrow \tau\tau$



$bH \rightarrow bbb$



$bH \rightarrow b\tau\tau$

*New DØ result soon!*

# MSSM Prospects

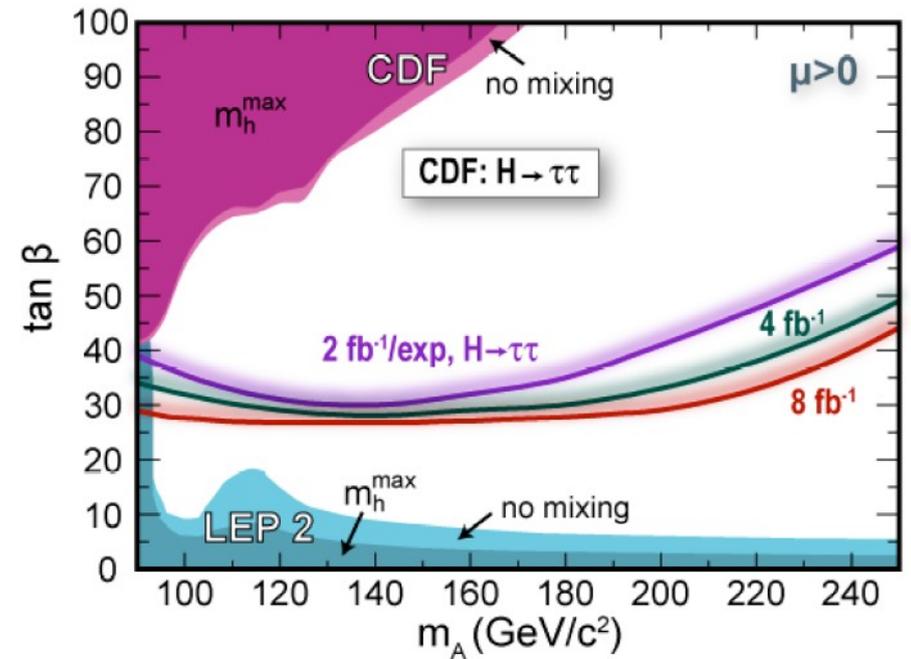
Results from the first 1-2/fb of data show very promising sensitivity

By 2010...

Exclude

- up to  $m_A \sim 300$  GeV for high  $\tan\beta$
- down to  $\tan\beta \sim 30$  for low  $m_A$

**Or make a discovery!**



New results on  $H^+$  coming soon!

# Other Higgs Searches

Showing results 1 through 47 (of 47 total)  
for ti:(Higgs AND Decay) and year 2008

4. arXiv:0801.4554 [ps, pdf, other]

Title: **Nonstandard Higgs Boson Decays**

5. arXiv:0801.3456 [ps, pdf, other]

Title: **Higgs boson decays to four fermions through an abelian hidden sector**

13. arXiv:0711.3361 [ps, pdf, other]

Title: **Higgs Boson Decays into Single Photon plus Unparticle**

18. arXiv:0710.5331 [ps, pdf, other]

Title: **Higgs boson decays in the Complex MSSM**

19. arXiv:0710.4923 [ps, pdf, other]

Title: **Di-photon Higgs Decay in SUSY with CP Violation**

21. arXiv:0710.4591 [ps, pdf, other]

Title: **Nonstandard Higgs Decays with Visible and Missing Energy**

24. arXiv:0710.0340 [ps, pdf, other]

Title: **Di-photon Higgs decay in the MSSM with explicit CP violation**

31. arXiv:0708.1939 [ps, pdf, other]

Title: **Effect of Charged Scalar Loops on Photonic Decays of a Fermiophobic Higgs**

34. arXiv:0708.0248 [ps, pdf, other]

Title: **Higgs decays in supersymmetric models with light neutralinos**

36. arXiv:0707.3152 [ps, pdf, other]

Title: **New Physics Effects in Higgs Decay to Tau Leptons**

37. arXiv:0707.1591 [ps, pdf, other]

Title: **Invisibly decaying Higgs boson in the Littlest Higgs model with T-parity**

39. arXiv:0706.1732 [ps, pdf, other]

Title: **GeV Seesaw, Accidentally Small Neutrino Masses, and Higgs Decays to Neutrinos**

# Other Higgs Searches

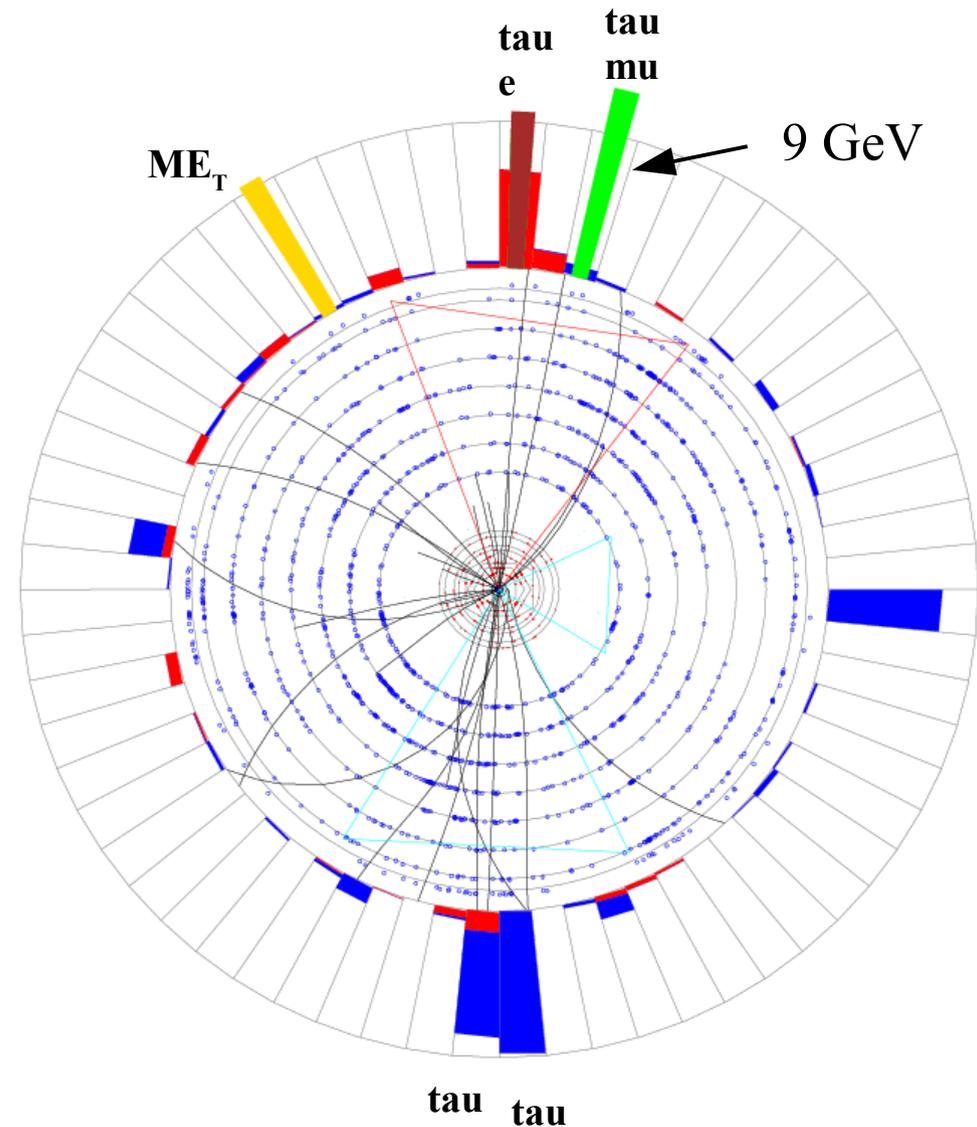
No shortage of new models!

Cover some general signatures we are sensitive to:

- Doubly charged Higgs
- Enhanced decays to photons

Others are harder, but on the way:

- Invisible Higgs
- CP-violating Higgs
- Higgs  $\rightarrow aa \rightarrow 4\tau$
- ...





# H<sup>++</sup>



## Models with H<sup>++</sup>

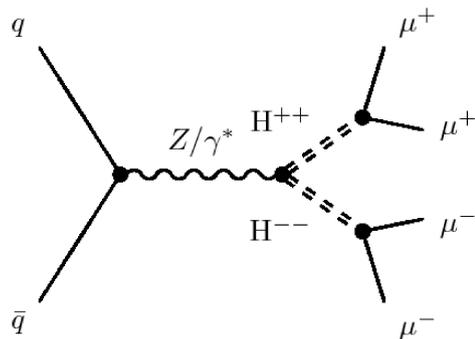
- Left-right symmetric models
- Higgs triplet
- Little Higgs

## Analysis Overview

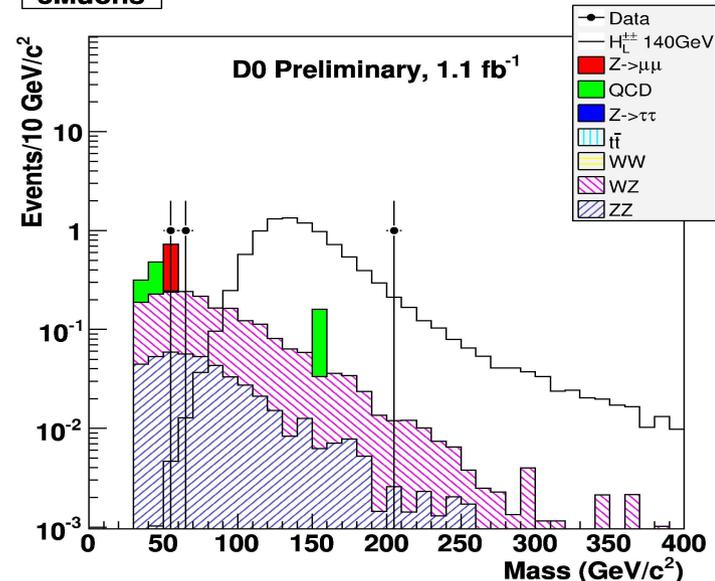
- 1.1 fb<sup>-1</sup>
- 3 μ's with:  
P<sub>T</sub> > 15 GeV  
|η| < 2.0
- ≥ 1 μμ pair with:  
M > 30 GeV/c<sup>2</sup>;  
Δφ < 2.5 rad

## Results

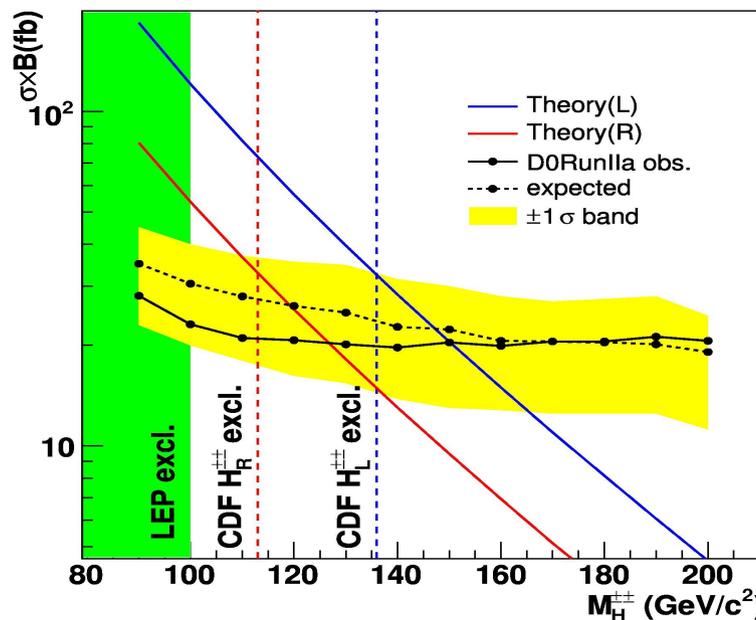
- Background: 3.1 ± 0.5
- Data: 3 events



3Muons



D0 RunII Preliminary, 1.1 fb<sup>-1</sup>



Result:

$H_R > 127 \text{ GeV}$

$H_L > 150 \text{ GeV}$

# H → γγ



Could be large H → γγ BR: “fermiophobic”

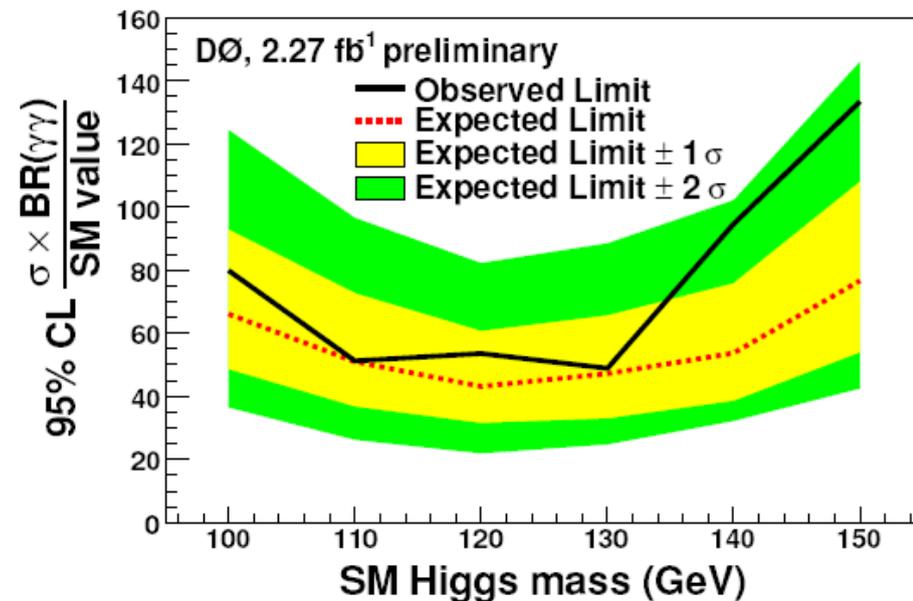
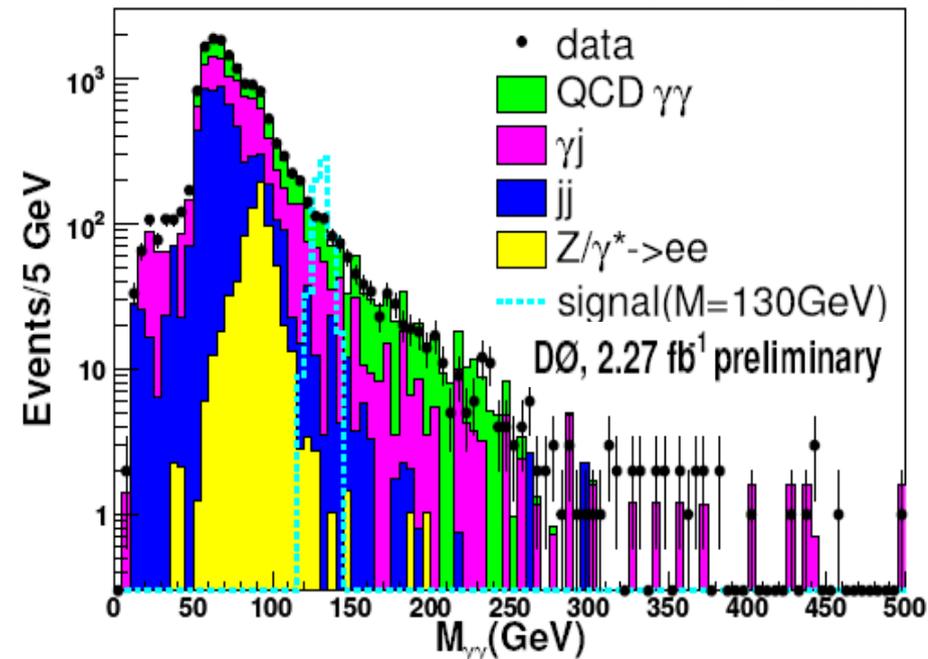
- Top-color models
- LED theories
- MSSM: H → bb suppressed by 1-loop corrections

Select 2 isolated photons,  $E_T > 25$  GeV

QCD jet fakes estimated using the shower-shape correlations between the 2 photons (“matrix method”)

Also contributes to SM Higgs search!

data	13827
Z/γ* → ee	740.9 ± 102.3
jet+jet	4778.6 ± 1264.6
γ+jet	4677.2 ± 1245.8
QCD γγ	3400.5 ± 711.0
total background	13597.2 ± 2548.5



# Conclusions

The Tevatron is closing in on the SM Higgs

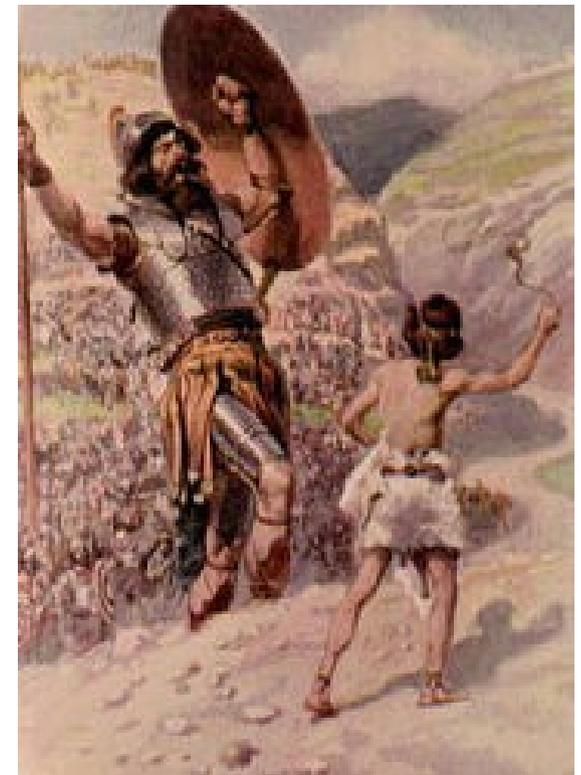
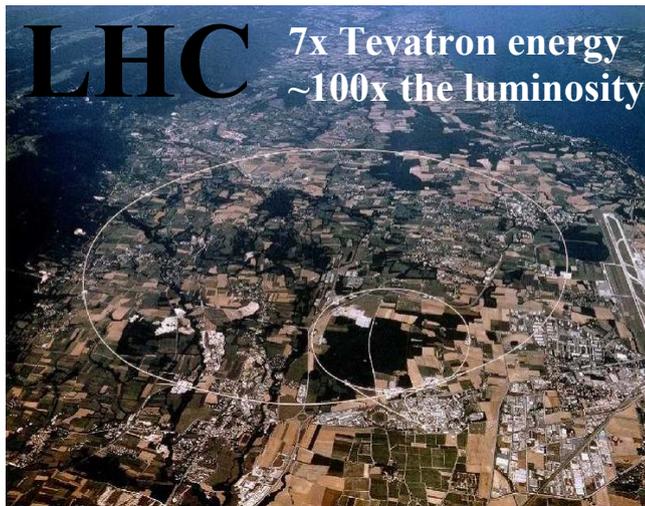
- **Sensitive at 160 GeV *this summer***
- **Sensitive to SM Higgs up to 200 GeV by 2010**

Also looking for Higgs in the MSSM and other plausible models

- **Already exploring new parameter space**

The LHC starts this year (!?)

- **SM Higgs boson by ~2011?**



# Backup

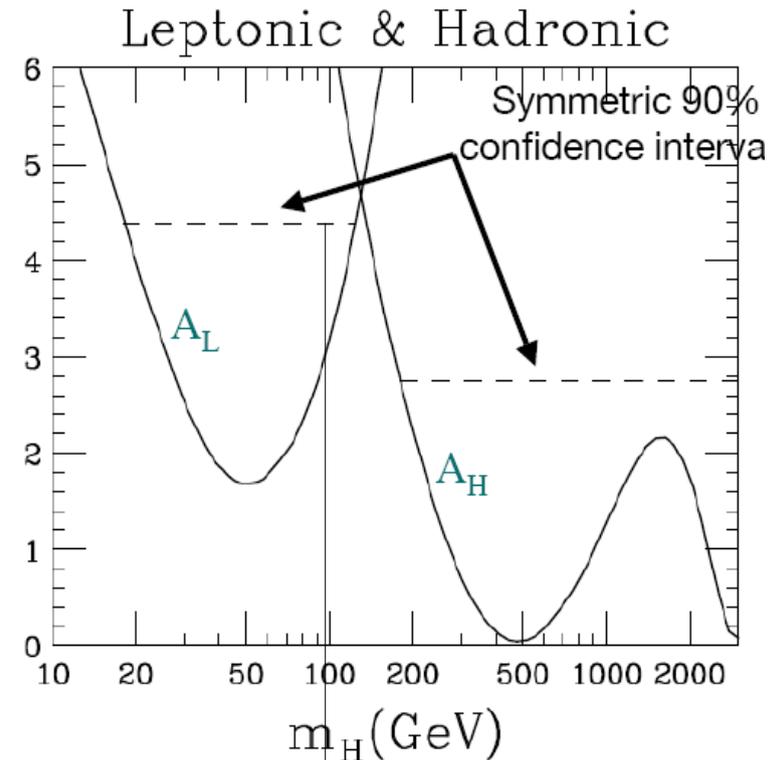
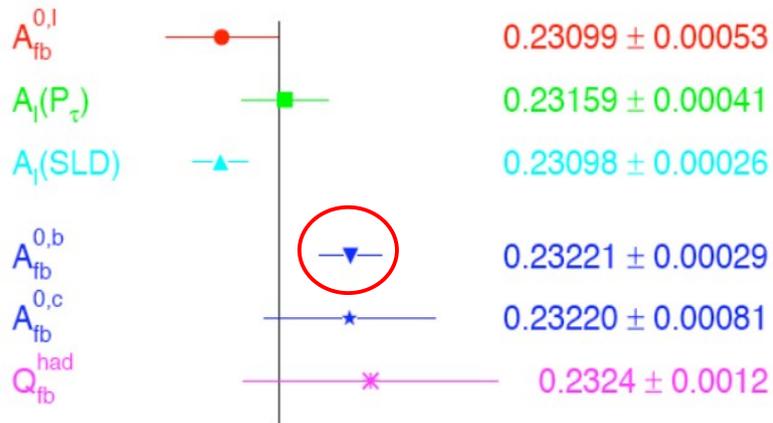
# Precision EW Constraints

EW variables sensitive to  $m_H$  via radiative corrections:

LEP II:  $m_H > 114.4$  GeV

$$\log \frac{m_H}{m_Z}$$

$\sin^2 \theta_{\text{eff}}^{\text{lept}}$  : most important observable for  $m_H$  fit



$m_H < 97$  GeV  
(at 95% CL)  
(leptonic only)

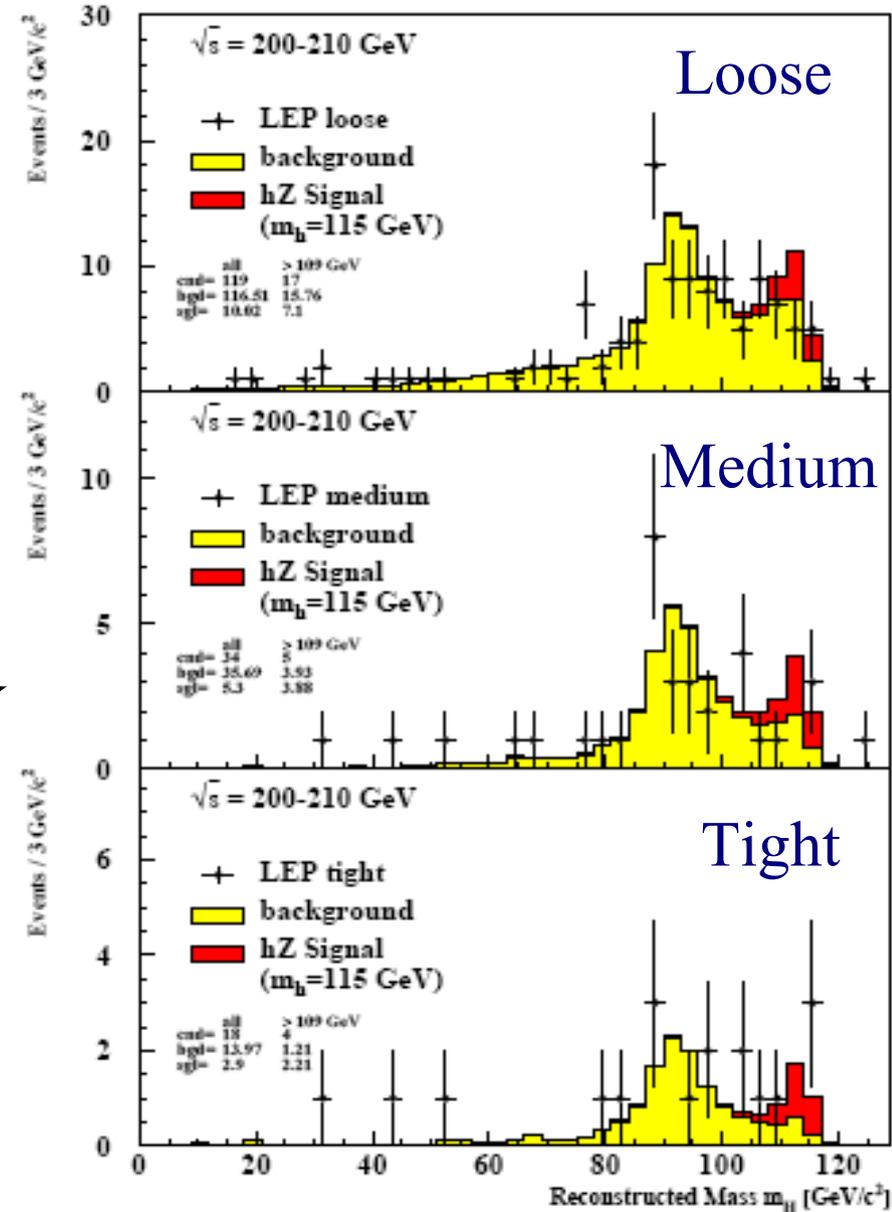
# LEP @ CERN in 2000

Circular  $e^+ e^-$  collider  
 Maximum E of 200-210 GeV



A good, but not the only variable...

Look for  $e^+ e^- \rightarrow Z+H(\rightarrow bb)$   
 Slight excess around 115 GeV  
 Higgs mass  $> 114.4$  GeV



# Limit Setting

- ◁ In the absence of signal, we set limits on Standard Model Higgs boson production

- × We calculate limits via the CLs prescription:

$$CL_s = \frac{CL_{s+b}}{CL_b}$$

- × Using a Log-Likelihood Ratio test statistic:

$$Q(\vec{s}, \vec{b}, \vec{d}) = \prod_{i=0}^{N_{Chan}} \prod_{j=0}^{N_{bins}} \frac{(s+b)_{ij}^{d_{ij}} e^{-(s+b)_{ij}}}{d_{ij}!} \bigg/ \frac{b_{ij}^{d_{ij}} e^{-b_{ij}}}{d_{ij}!} \quad LLR = -2 \times \text{Log}Q$$

$d_{ij}$  refers to “data” for model being tested: Observed events, or expected Background or Signal+Background

- ◁ Distributions of simulated outcomes are populated via Poisson trial with mean values given by B-only or S+B hypotheses
- × Systematics are folded in via Gaussian marginalization
- × Correlations held amongst signals and backgrounds

# Systematic Uncertainties

Luminosity, 6.1%

Lepton ID, 2%

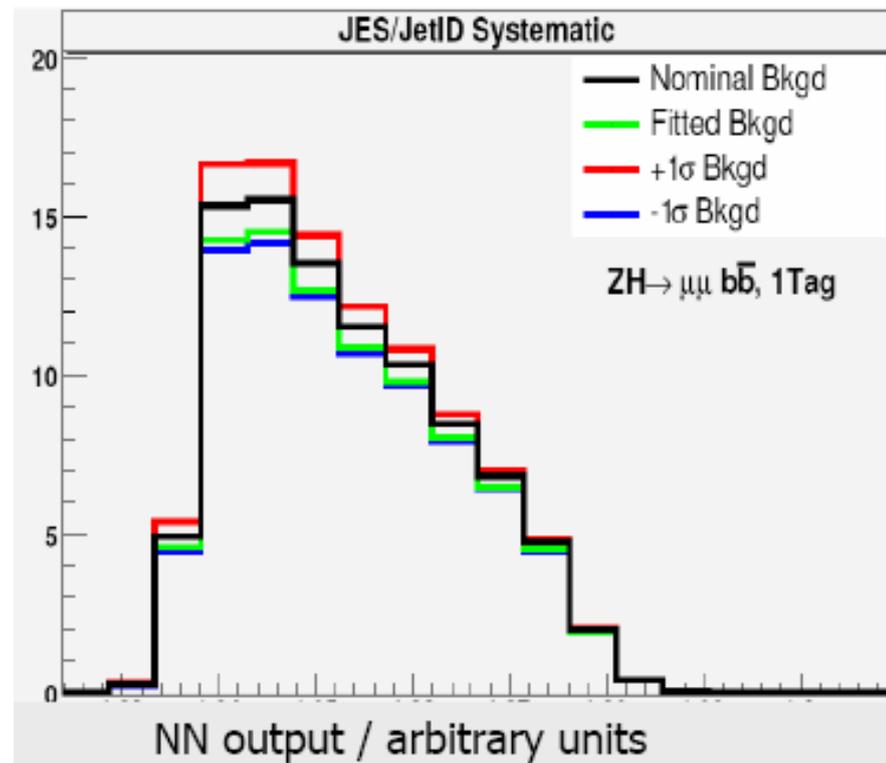
Background cross-sections, 5-30%

QCD estimation, 20%

Jet-energy scale\*

b-tagging\*

*\*Affects shape of NN output as well as normalization*



# Matrix Elements

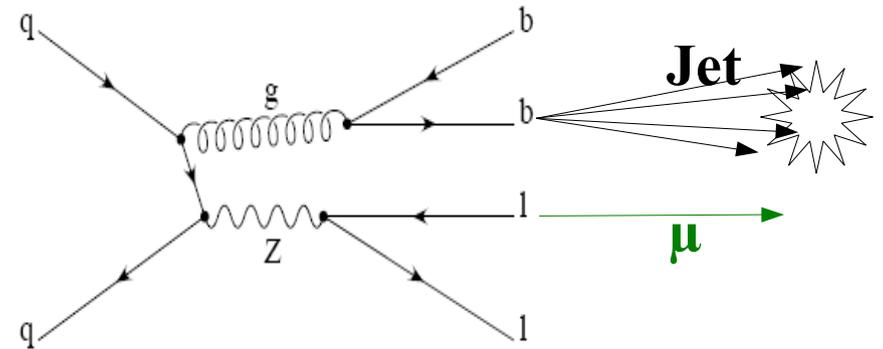
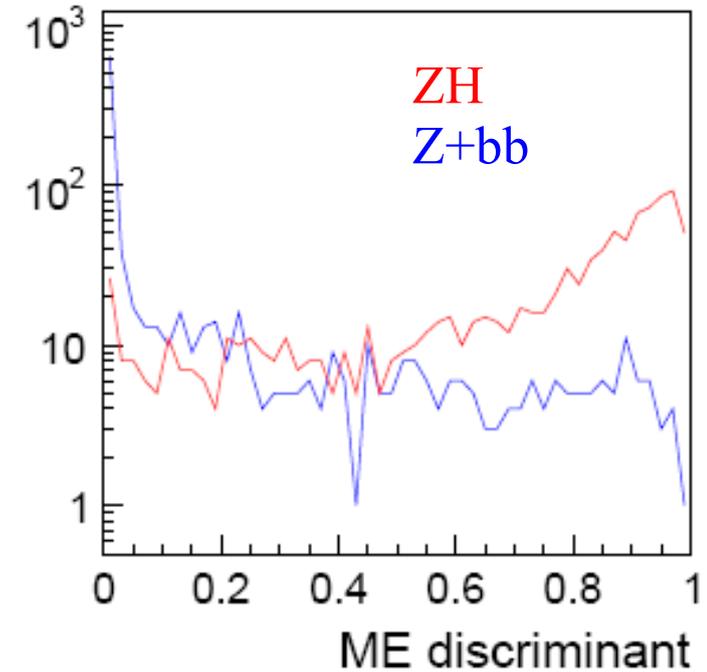
Calculate “cross-section” for an observed event to be from  $Z+bb$  or  $Z+(H \rightarrow bb)$

Use MC integration methods

Include as inputs to NN

$$p(m) = \int dx f_{\Phi} \cdot \sum_{a,b} f_a f_b |M_{ab}(k(m,x))|^2 \cdot T(k(m,x), m)$$

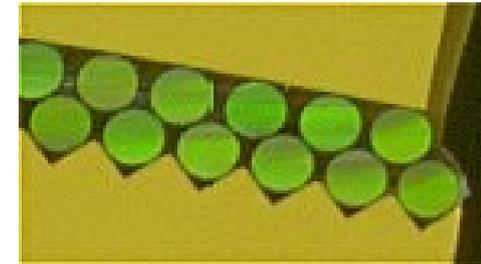
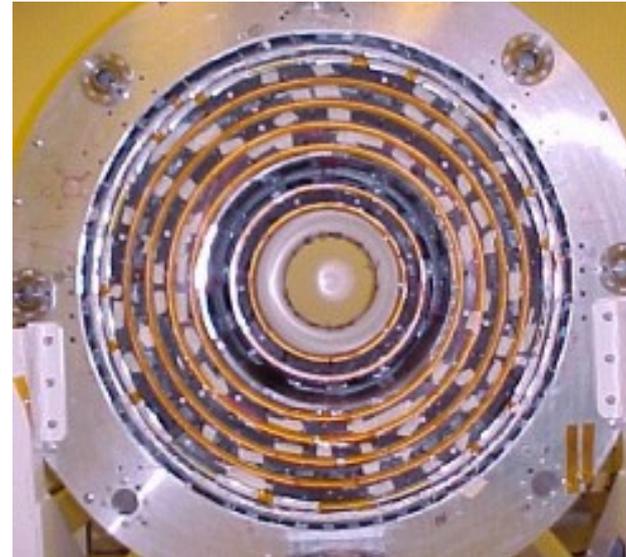
- ▷  $m$ : detector measurement of event.
- ▷  $x$ : integration parameters
- ▷  $k(x,m)$ : parton solution given  $m$  and  $x$ .
- ▷  $f_{\Phi}$ : phase-space factors.
- ▷  $f_a f_b$ : PDFs from MCFM.
- ▷  $M_{ab}$ : matrix element from MCFM.
- ▷  $T$ : transfer functions



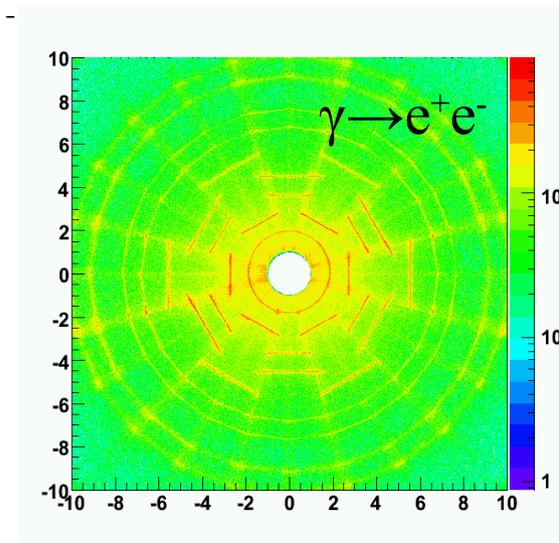
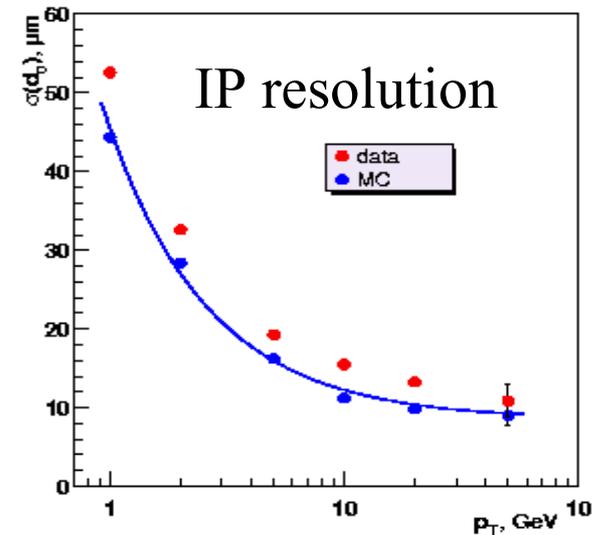
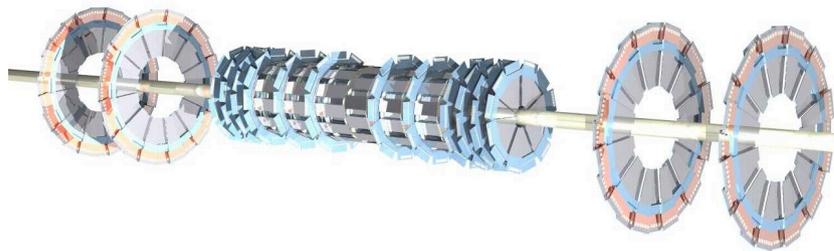
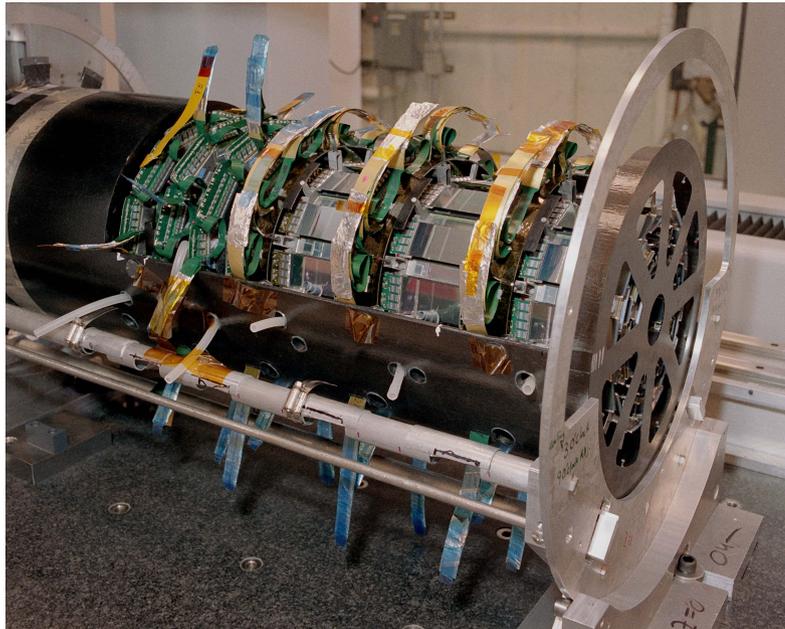
$$\text{MET} = \mu_1 + \mu_2 + j_1 + j_2 + \sigma(\text{MET})$$

# Tracking

## Central Fiber Tracker



## Silicon Microstrip Tracker



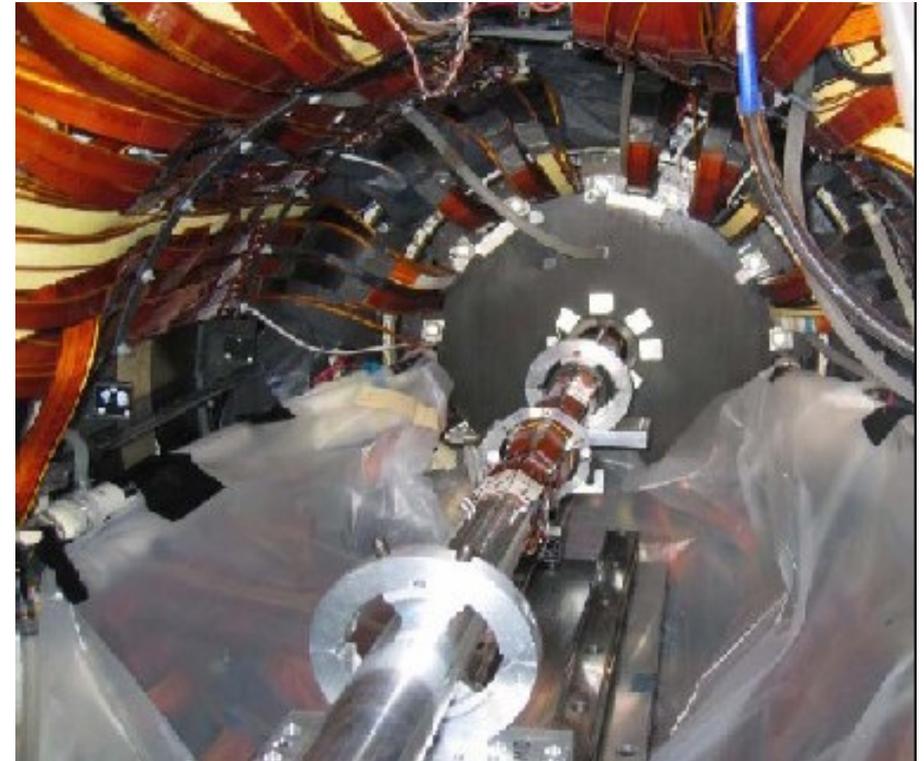
# Layer 0 of Silicon Tracker

Silicon detectors mounted just outside the beampipe

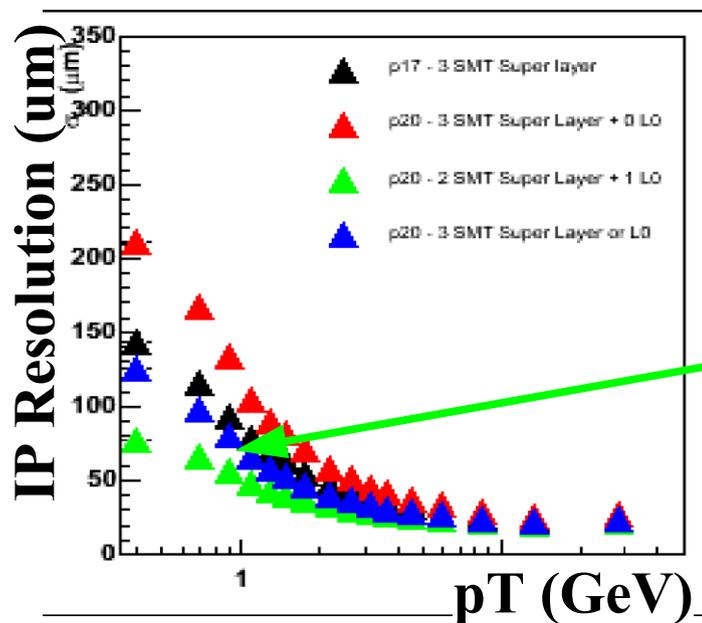
Installed fall '06

Better track impact-parameter resolution

-> Better b-jet tagging



*Layer 0 being inserted into the silicon tracker*



**Effect of Layer 0  
in recent data**

# b-Tagging Measurement

System 8 method:

$$\begin{aligned}n &= n_b + n_{uds} \\ p &= p_b + p_{uds} \\ n^{SLT} &= \varepsilon_b^{SLT} n_b + \varepsilon_{uds}^{SLT} n_{uds} \\ p^{SLT} &= \varepsilon_b^{SLT} p_b + \varepsilon_{uds}^{SLT} p_{uds} \\ n^{NN} &= \varepsilon_b^{NN} n_b + \varepsilon_{uds}^{NN} n_{uds} \\ p^{NN} &= \beta \varepsilon_b^{NN} p_b + \alpha \varepsilon_{uds}^{NN} p_{uds} \\ n^{SLT,NN} &= \kappa_b \varepsilon_b^{SLT} \varepsilon_b^{NN} n_b + \kappa_{uds} \varepsilon_{uds}^{SLT} \varepsilon_{uds}^{NN} n_{uds} \\ p^{SLT,NN} &= \kappa_b \beta \varepsilon_b^{SLT} \varepsilon_b^{NN} p_b + \kappa_{uds} \alpha \varepsilon_{uds}^{SLT} \varepsilon_{uds}^{NN} p_{uds}\end{aligned}$$

- Correlation coefficients, measured in MC:

$\alpha$  - Ratio of the *uds*-tagging efficiencies in the two samples.

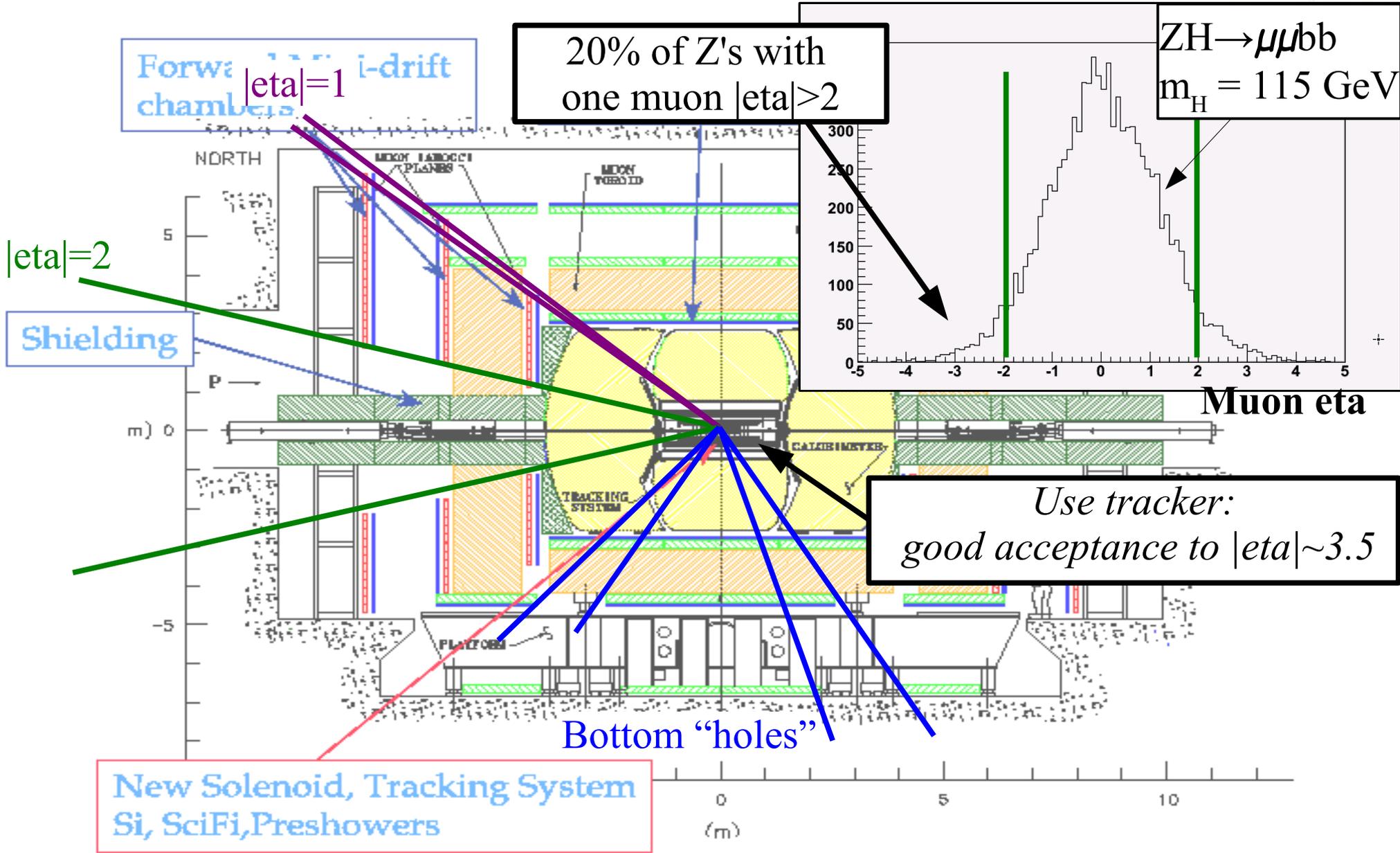
$\beta$  - Ratio of the *b*-tagging efficiencies in the two samples.

$\kappa_b$  - Correlations between the NN tagger and the SLT tagger on *b*-jets.

$\kappa_{uds}$  - Correlations between the NN tagger and the SLT tagger on *uds*-jets.

$p_{TRel}$  - Ratio of the SLT tagging efficiencies on *c* and *uds*-jets.

# Muon Acceptance

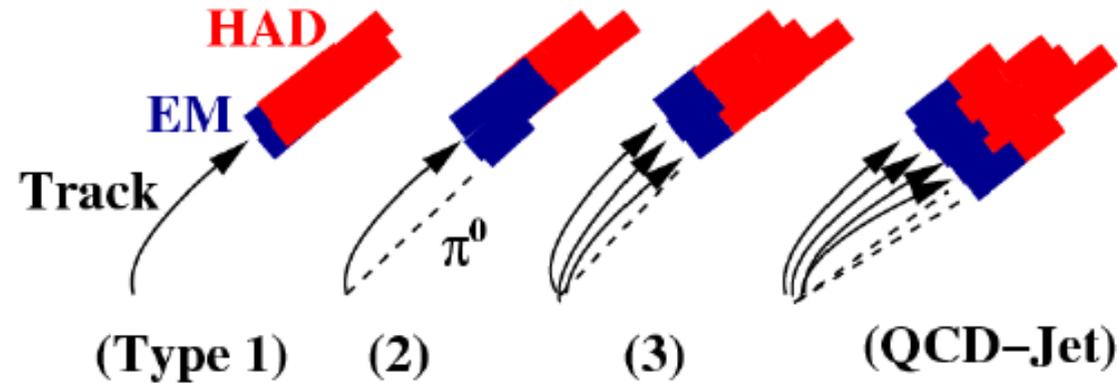


# Tau ID

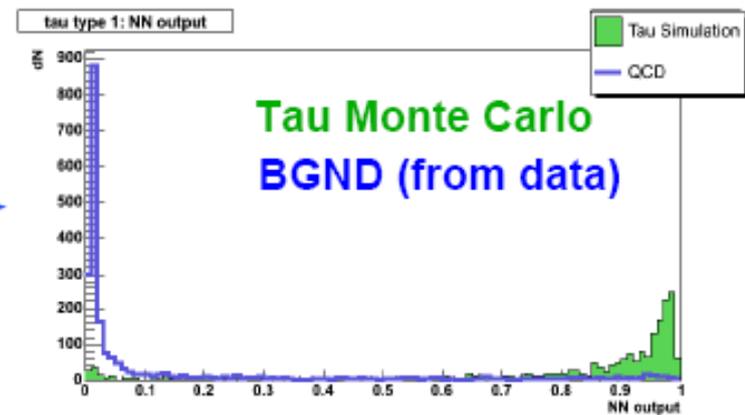
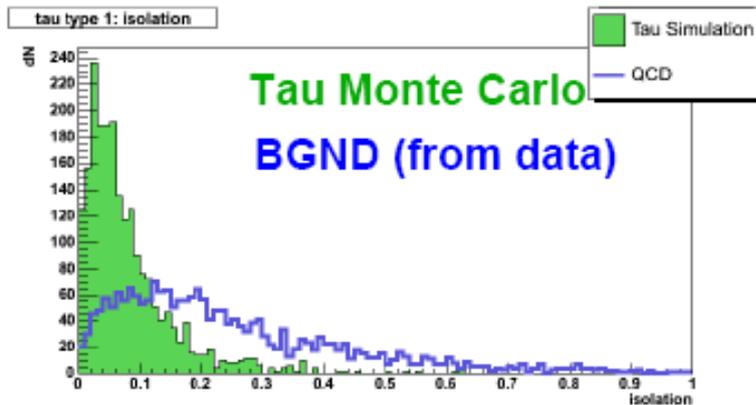


- Tau = narrow isolated jet with low track and  $\pi^0$  multiplicity

- Taus decay inside detector:
  - $BR(\tau \rightarrow e/\mu + w)$   $\sim 17\%$
  - $BR(\tau \rightarrow \text{hadrons} + \nu)$   $\sim 65\%$



- DØ uses one **Neural Network** per tau type to discriminate taus from jets



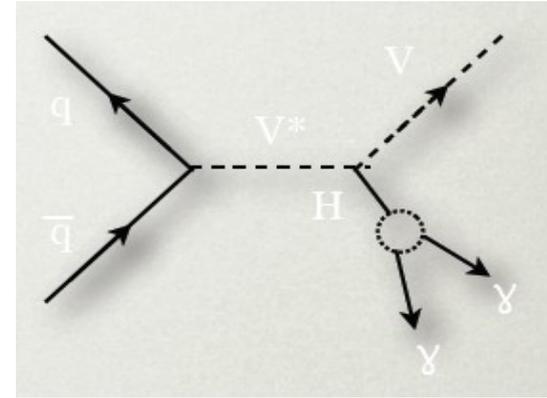
# H+V→γγ+X



- Associated Fermiophobic Higgs

$$p\bar{p} \rightarrow VV \rightarrow h_f \rightarrow \gamma\gamma + X$$

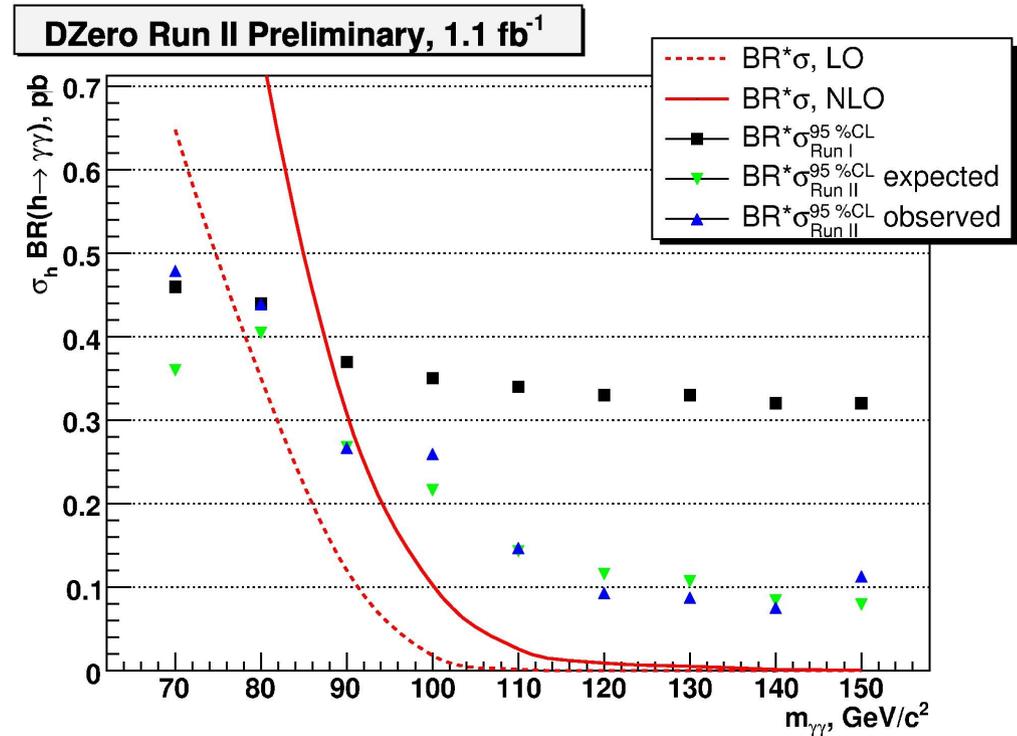
$$p\bar{p} \rightarrow h_f W^\pm(Z) \rightarrow \gamma\gamma + X$$



- Analysis overview

- 1.1 fb<sup>-1</sup>;
- 2 γ's with: E<sub>T</sub>>25 GeV, |η|<1.1, M<sub>γγ</sub>>65 GeV
- Two regions
  - Signal: q<sub>T</sub>>35 GeV
  - Control: q<sub>T</sub><35 GeV
- Backgrounds: γγ, γj, jj

- LEP: m<sub>H</sub>>109.7 GeV



# Fermiophobic Higgs $\rightarrow 3\gamma + X$



- ▶ In various extensions of the SM (also MSSM) the coupling of  $h$  might be suppressed to Fermions

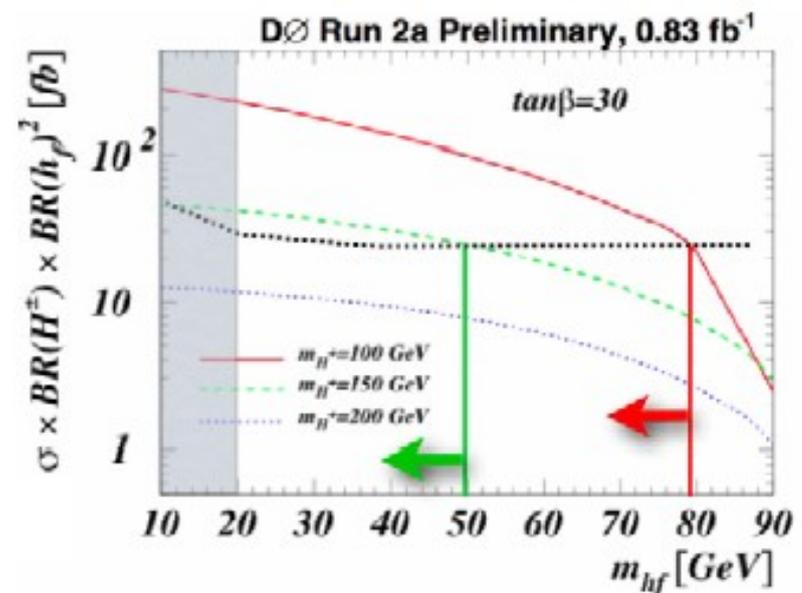
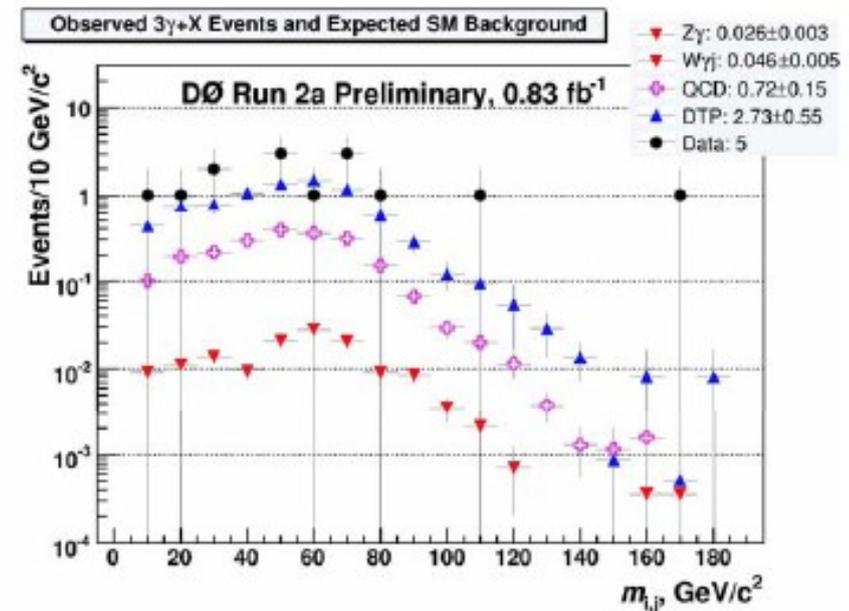
- ▶ Search for the channel:

$$p\bar{p} \rightarrow h_f H^\pm \rightarrow h_f h_f W^\pm \rightarrow \gamma\gamma(\gamma) + X$$

- ▶ Good photon identification is crucial
- ▶ Cuts:  $3\gamma$  within  $|\eta| < 1.1$   
 $E_T^{1,2,3} > 30, 20, 15$  GeV
- ▶ Backgrounds: Jets or electrons misidentified as  $\gamma$  and direct  $3\gamma$  prod.
- ▶ Background is estimated from data with efficiencies  $\varepsilon^\gamma$ ,  $P(j \rightarrow \gamma)$ ,  $P(e \rightarrow \gamma)$

$$3\gamma \text{ prod.: } N^{3\gamma} = \frac{N_{\gamma\gamma}(MC)}{N_{\gamma\gamma}(Data)} N_{\gamma\gamma}(Data) * \rho$$

- ▶ Cut on  $p_T^{3\gamma} > 25$  GeV gives 1.1 events in background and 0 in data
- ▶ Upper limit:  $\sigma = 25.3$  fb (95% CL)

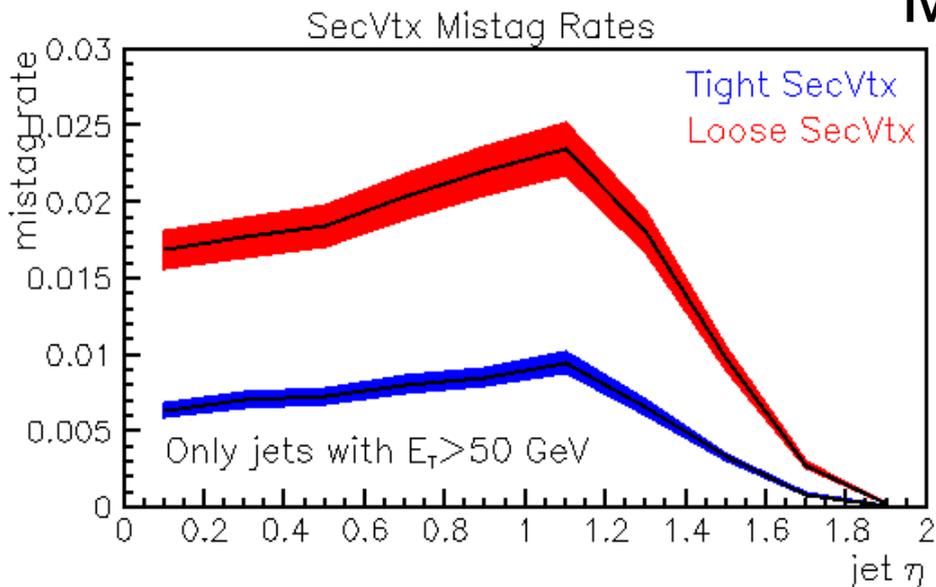
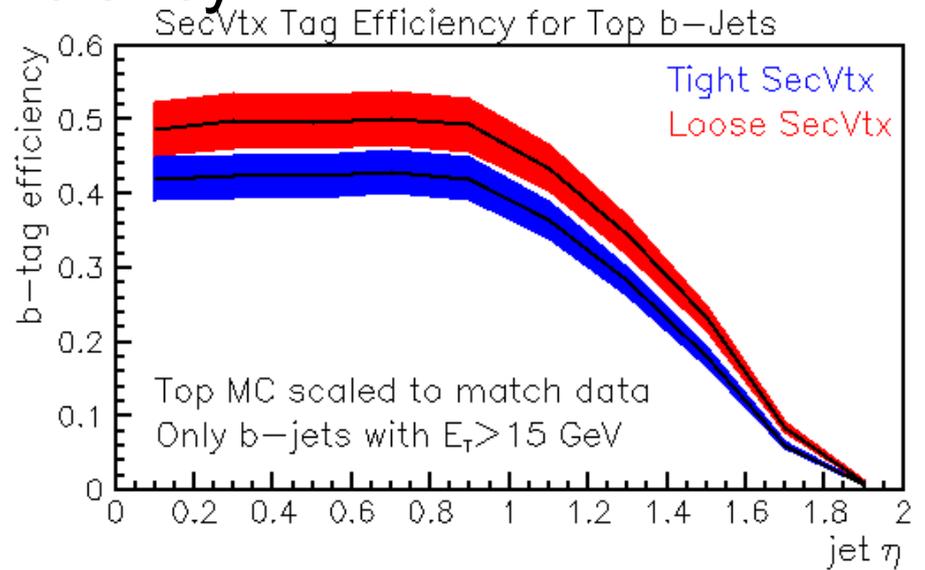
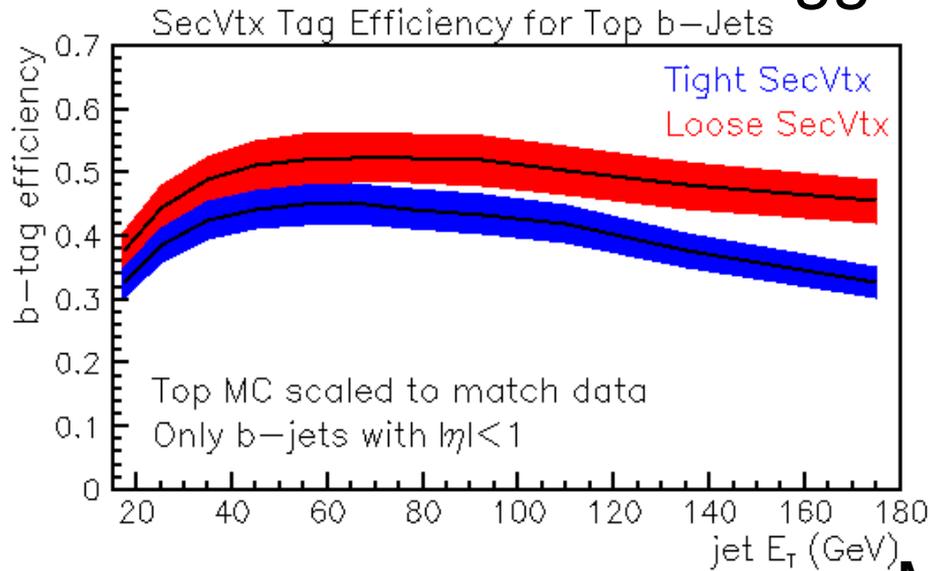




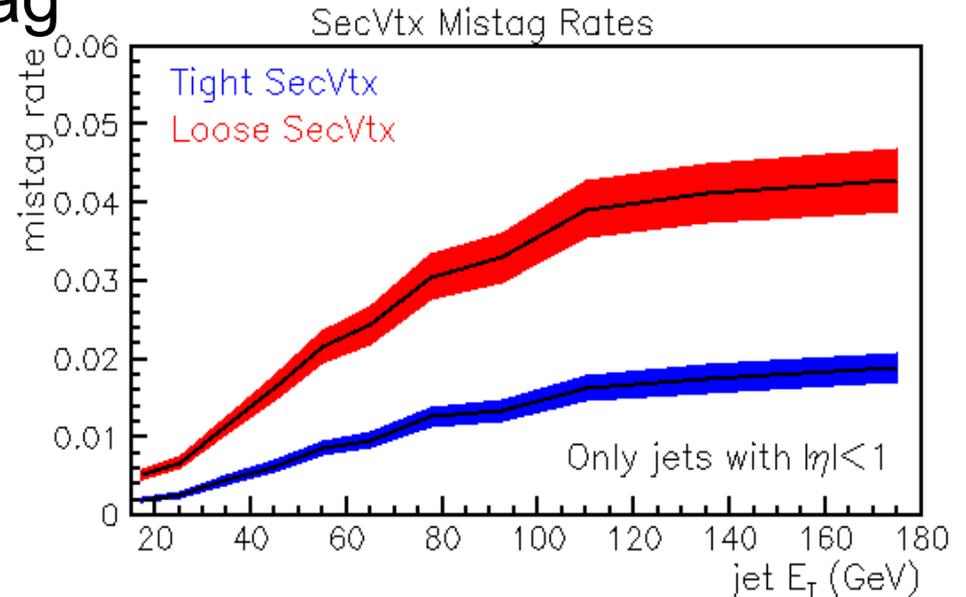
# Ref.) CDF SECVTX btag



## Tagging efficiency

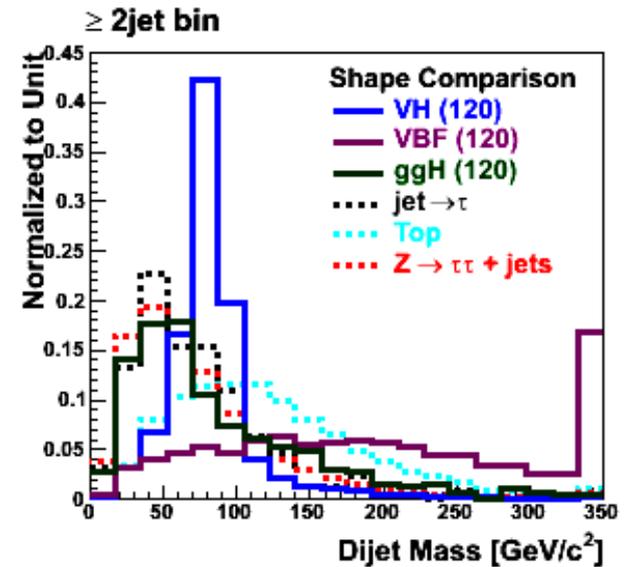
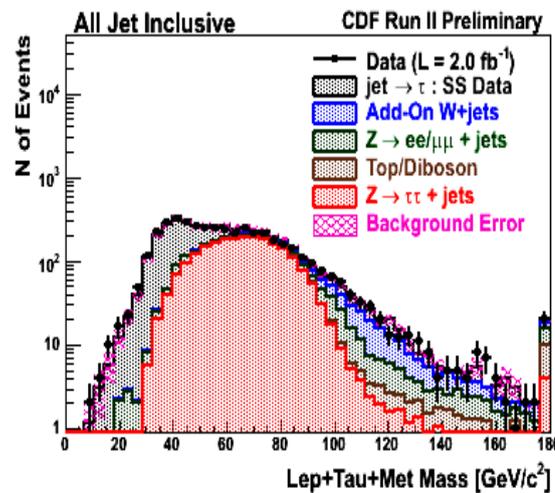
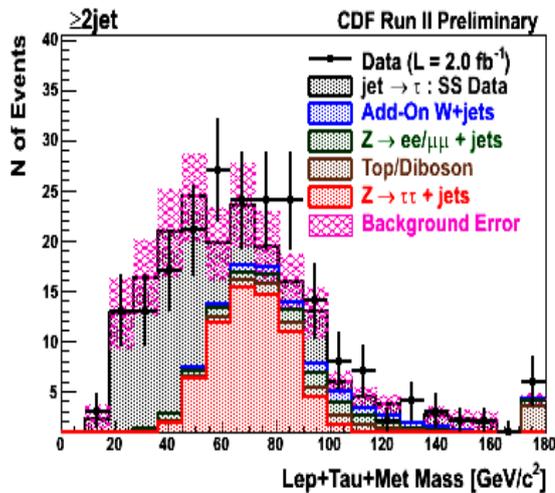
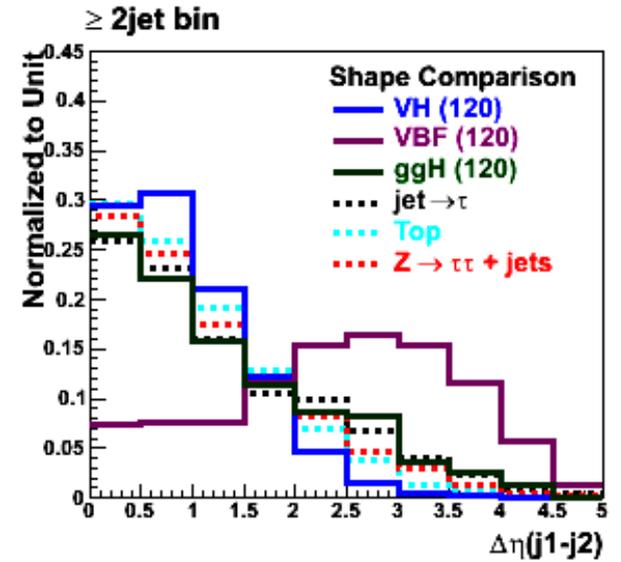
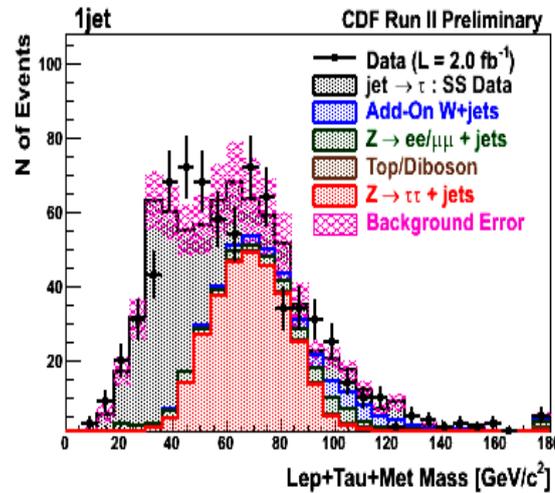
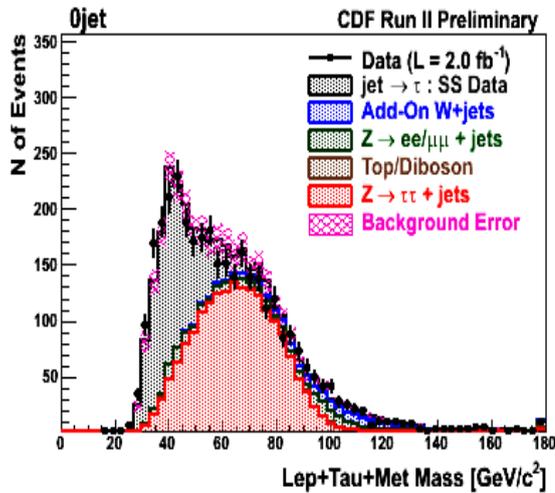


## Mistag



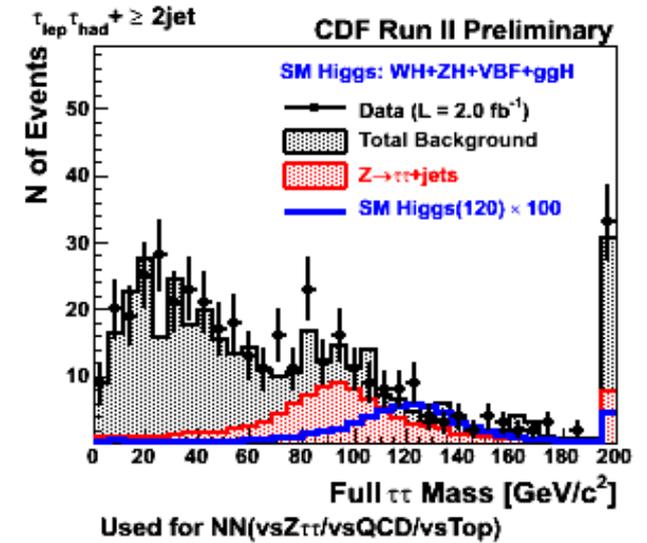
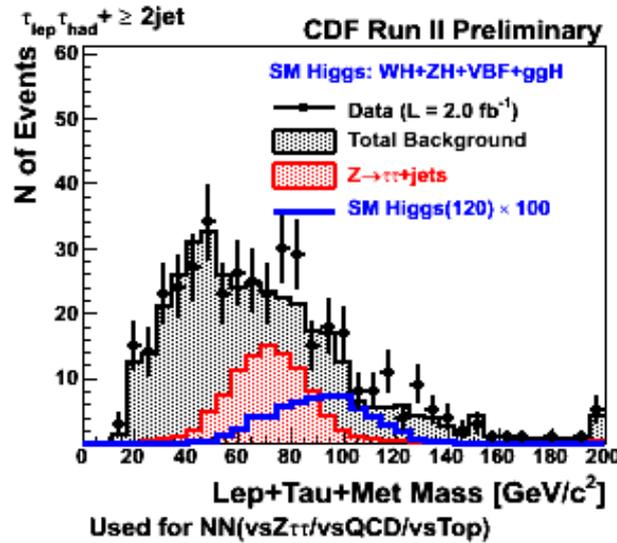
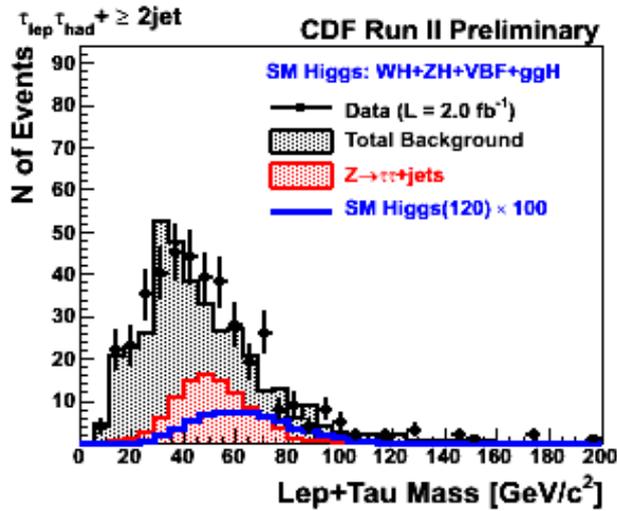


# More Plots : $H \rightarrow \tau\tau$ Channel

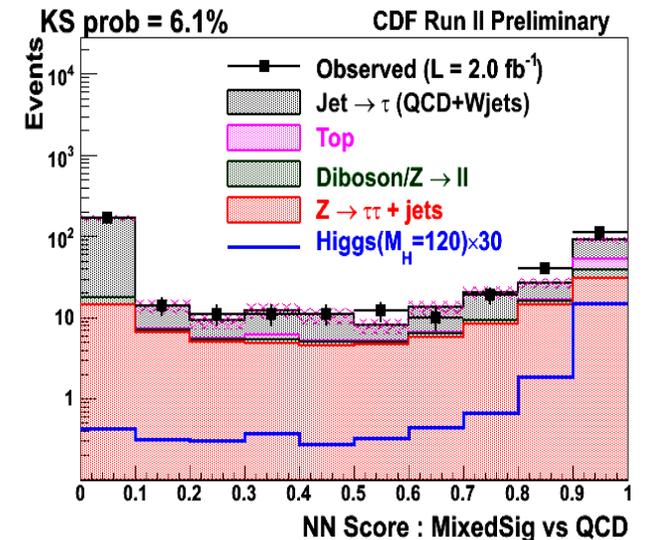
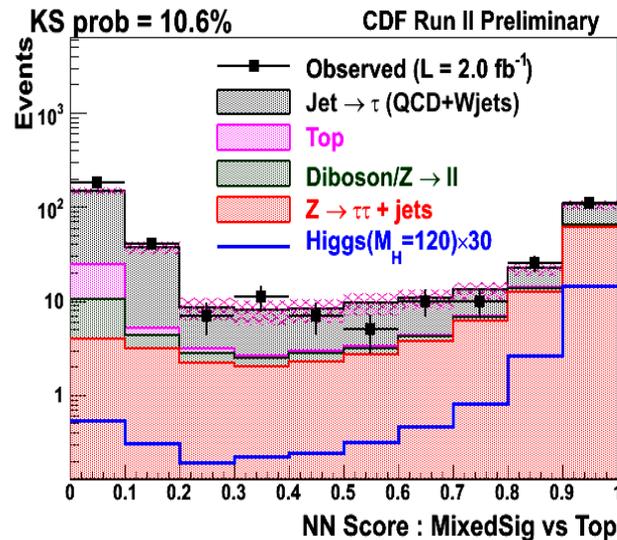
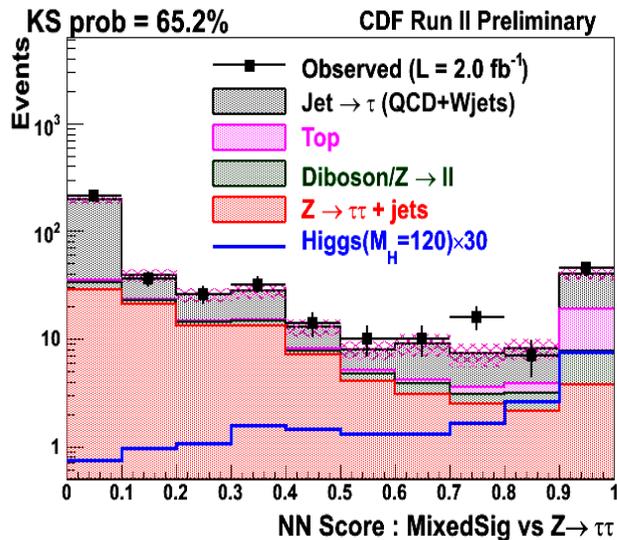




# More Plots : $H \rightarrow \tau\tau$ Channel

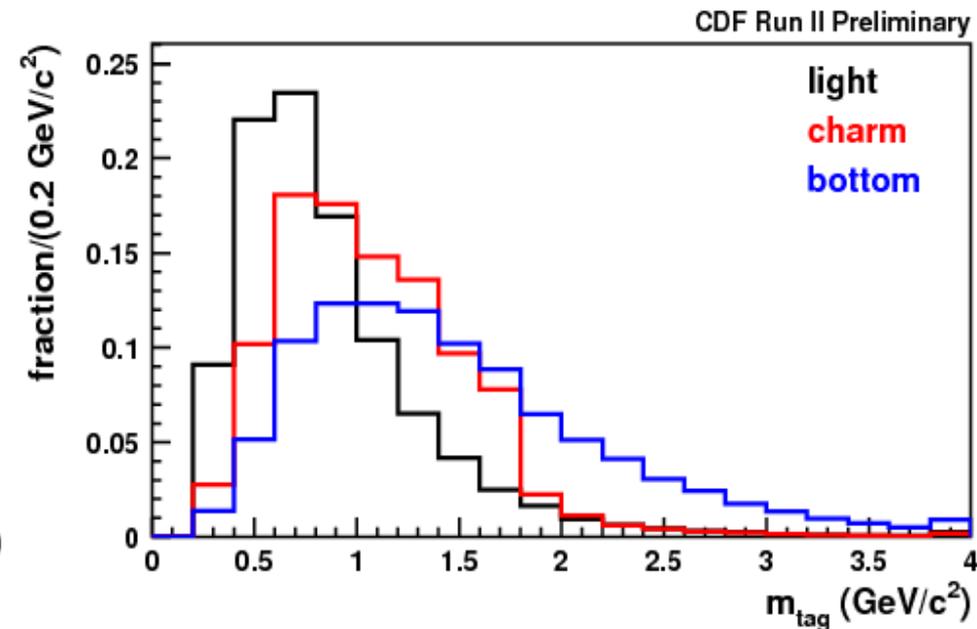
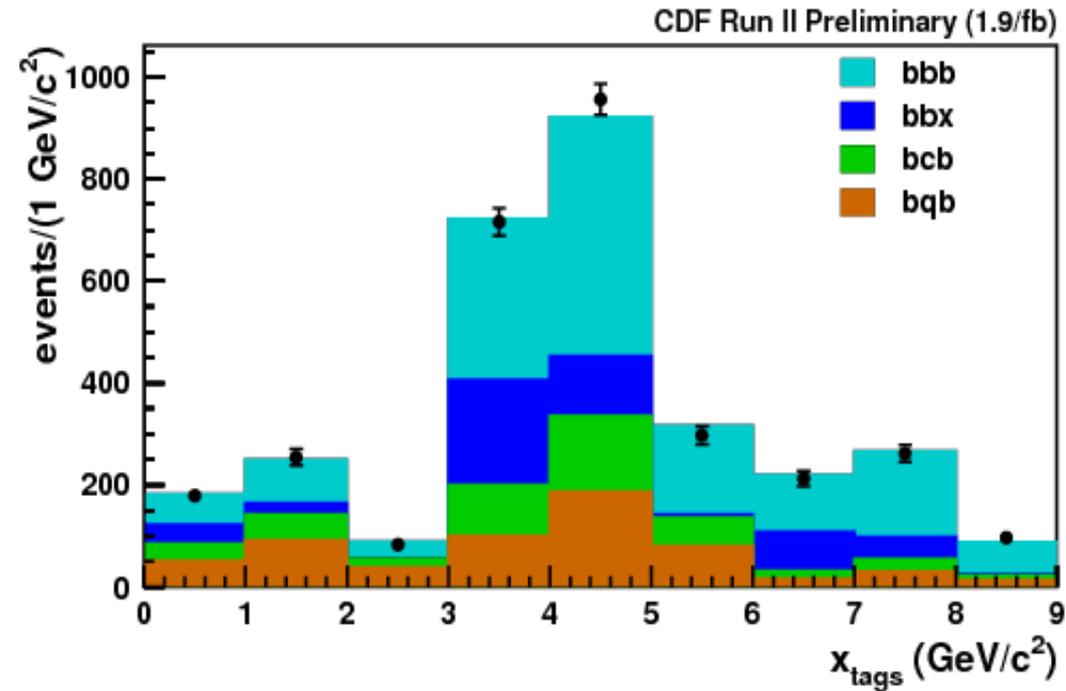
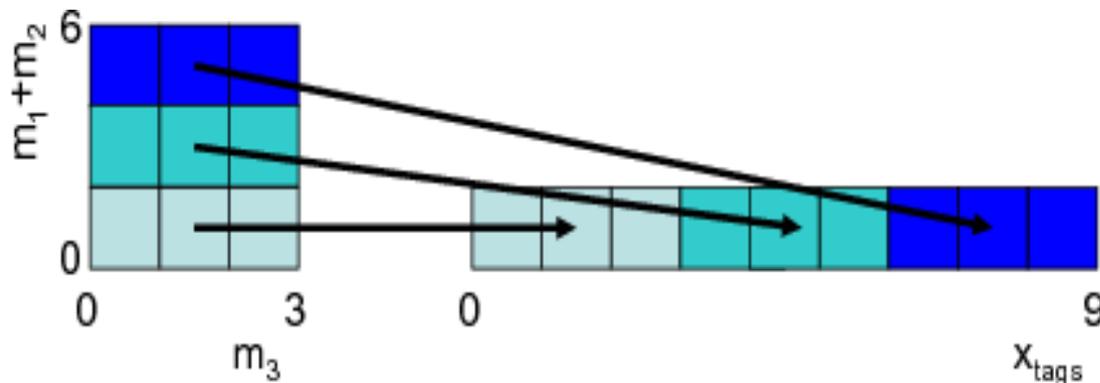


## > 3 Neural Nets Distributions:



# CDF 3b Channel

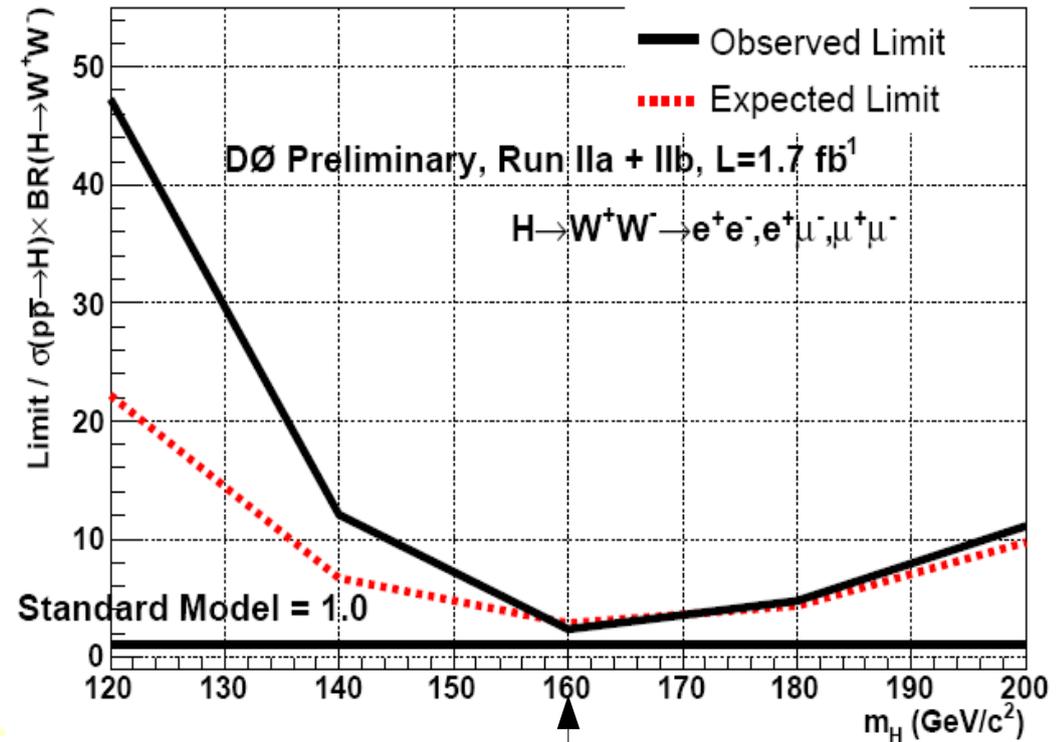
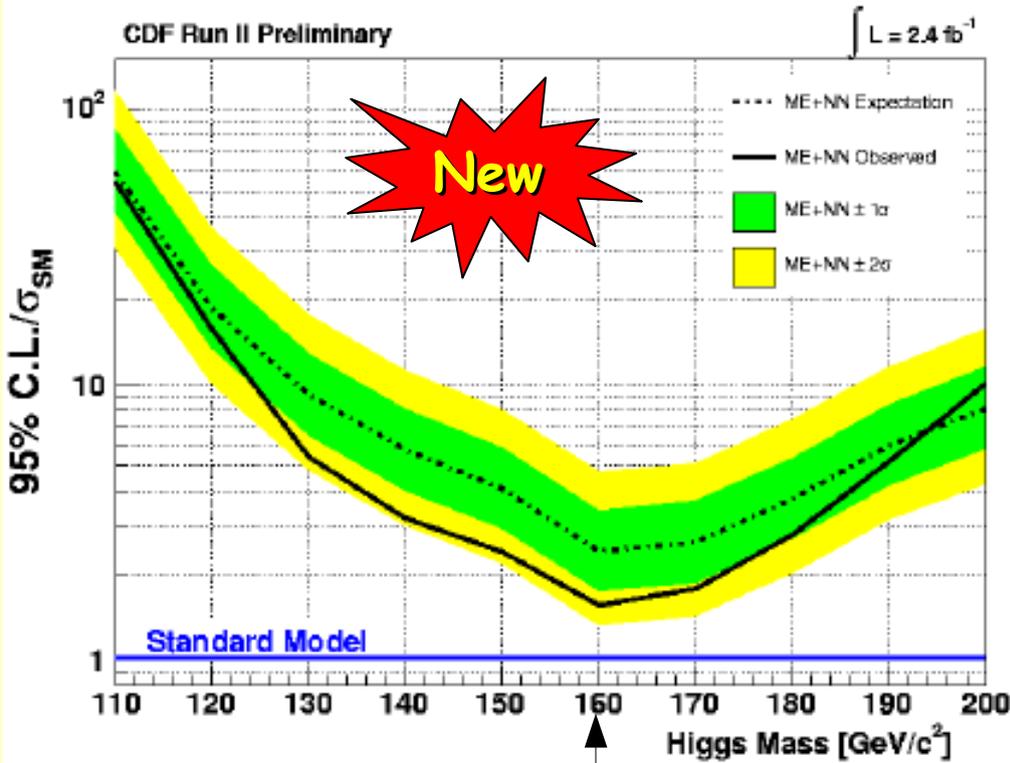
- Improve prediction of total background  $m_{12}$  using tag properties
  - Invariant mass of tracks in each vertex  $m_j$
- $m_1+m_2$  : bbb+bbx / bcb+bqb
- $m_3$  : bbx / bbb+bcb+bqb
- Unstack into 1D variable “ $x_{\text{tags}}$ ” for plotting/fitting
- Fits are 2D -  $m_{12}$  vs  $x_{\text{tags}}$ 
  - Four backgrounds
  - Higgs signal template



# Other Stuff



# $H \rightarrow WW^* \rightarrow ll$ ( $l=e, \mu$ )



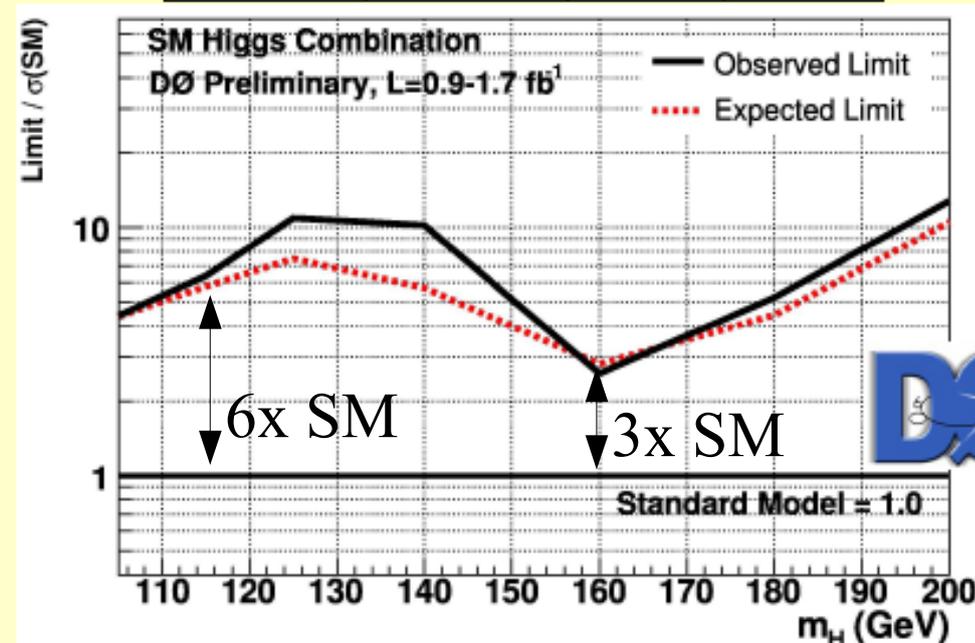
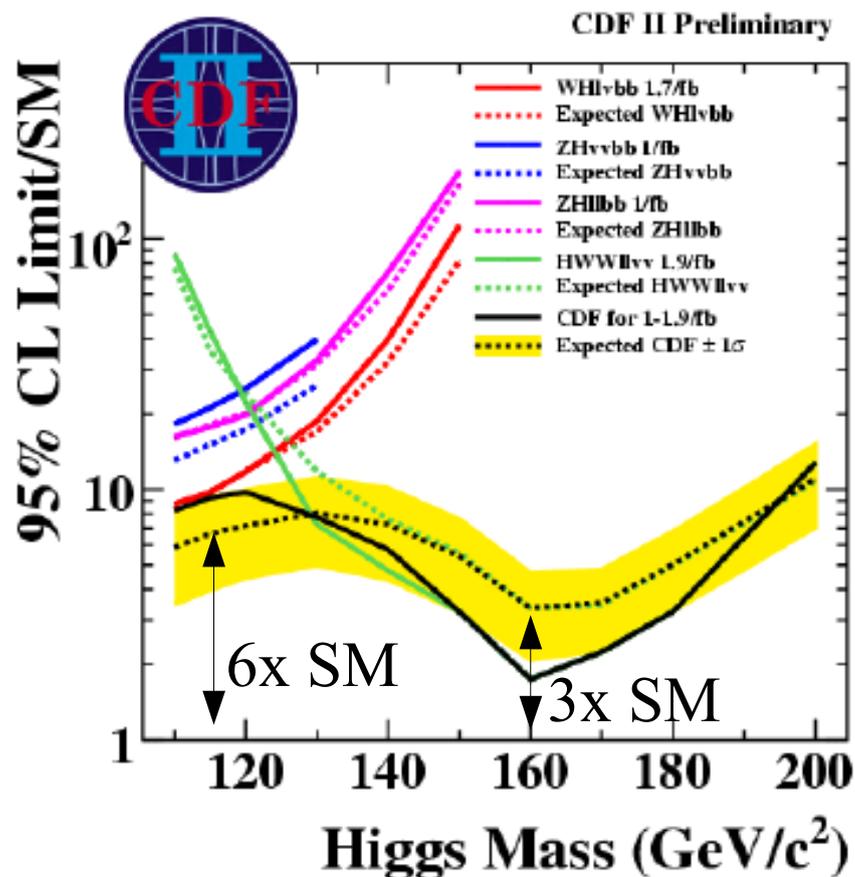
Observed Limit/ $\sigma_{SM}$  (NNLL)  $\sim 1.6$   
 Expected Limit/ $\sigma_{SM}$  (NNLL)  $\sim 2.4$

Observed Limit/ $\sigma_{SM}$  (NNLL)  $\sim 2.4$   
 Expected Limit/ $\sigma_{SM}$  (NNLL)  $\sim 2.8$

# SM Higgs Combinations

- Combined limits from December 2007
  - New results shown today not yet included!
- Expect both experiments to show improved limits next week

	$m_H$ [GeV]	CDF	DØ
expected	115	6	5.7
	160	3.1	2.8
observed	115	9.6	6.4
	160	2	2.5



# D0/CDF SM Higgs Combination



Improvements underway:

- **Di-jet mass resolution**
- **Lepton efficiency**
- **Further improvements in analysis technique**
- **Better multivariate techniques**
- **Better b-tagging**

