

# **Higgs Searches at the Tevatron**

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**for the CDF and DØ Collaborations**

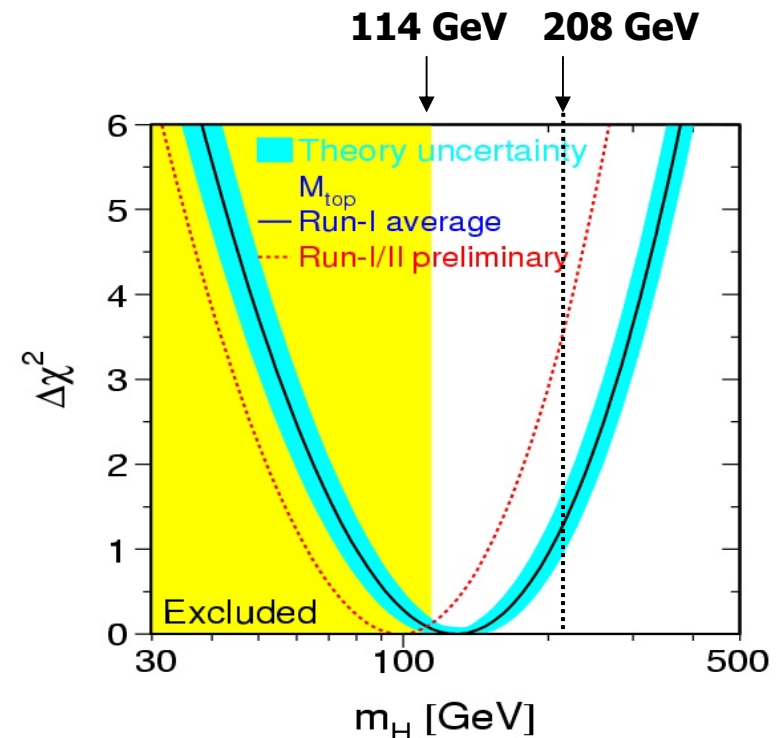
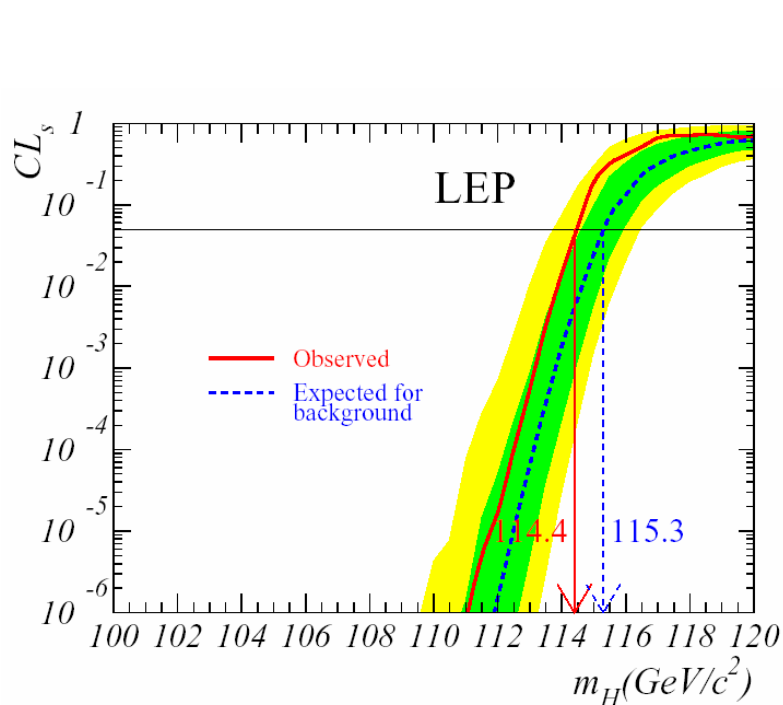
**Hadron Collider Physics Symposium  
Les Diablerets, Switzerland, July 2005**

# Outline

- **Higgs at the Tevatron: production, decay, expectations**
- **Search for SM Low Mass Higgs**
- **Search for SM High Mass Higgs**
- **Search for MSSM Higgs**
- **Summary**

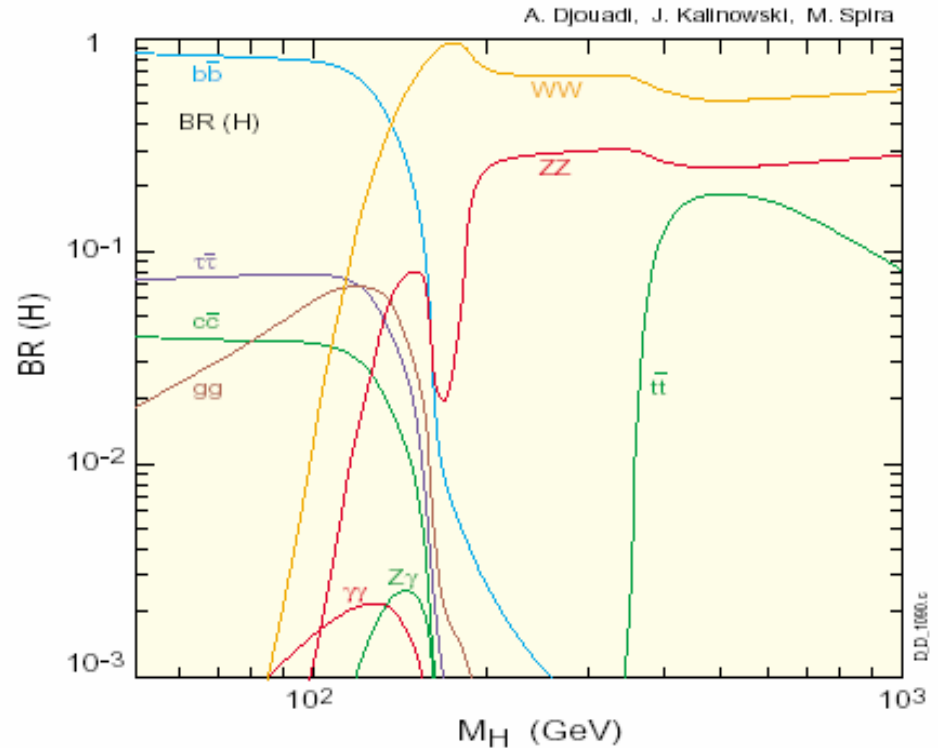
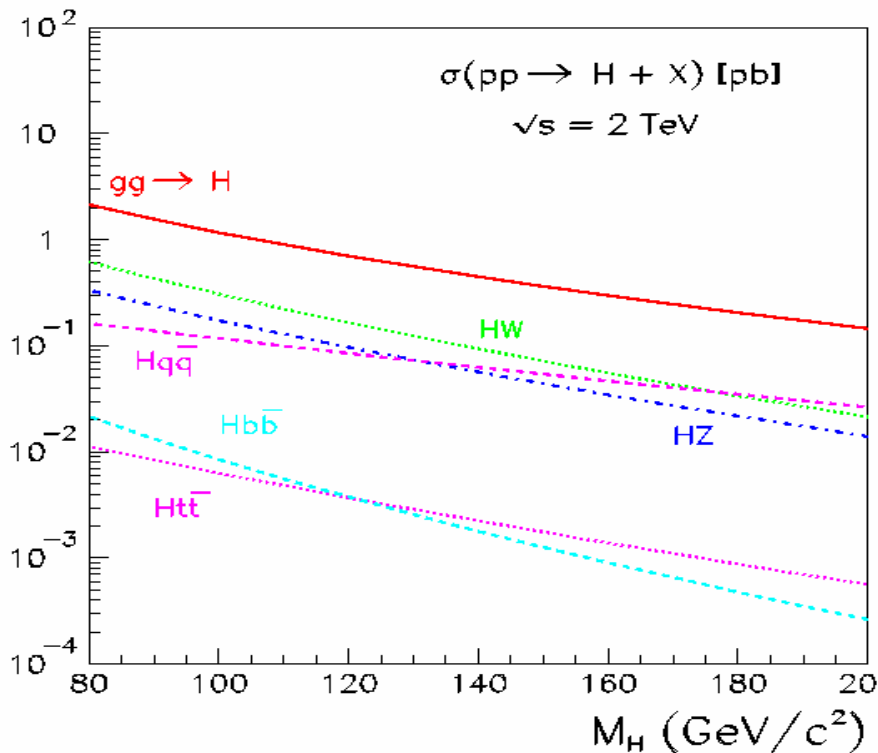
# Experimental Limits on the Higgs Mass

- direct searches at LEP:  $M_H > 114 \text{ GeV}$  (95% CL)
- precision EW fits:  $M_H = 98 \text{ GeV} \Rightarrow M_H < 208 \text{ GeV}$  (95% CL)



- Tevatron: both direct searches &  $(M_W, M_{\text{top}})$  precision measurements

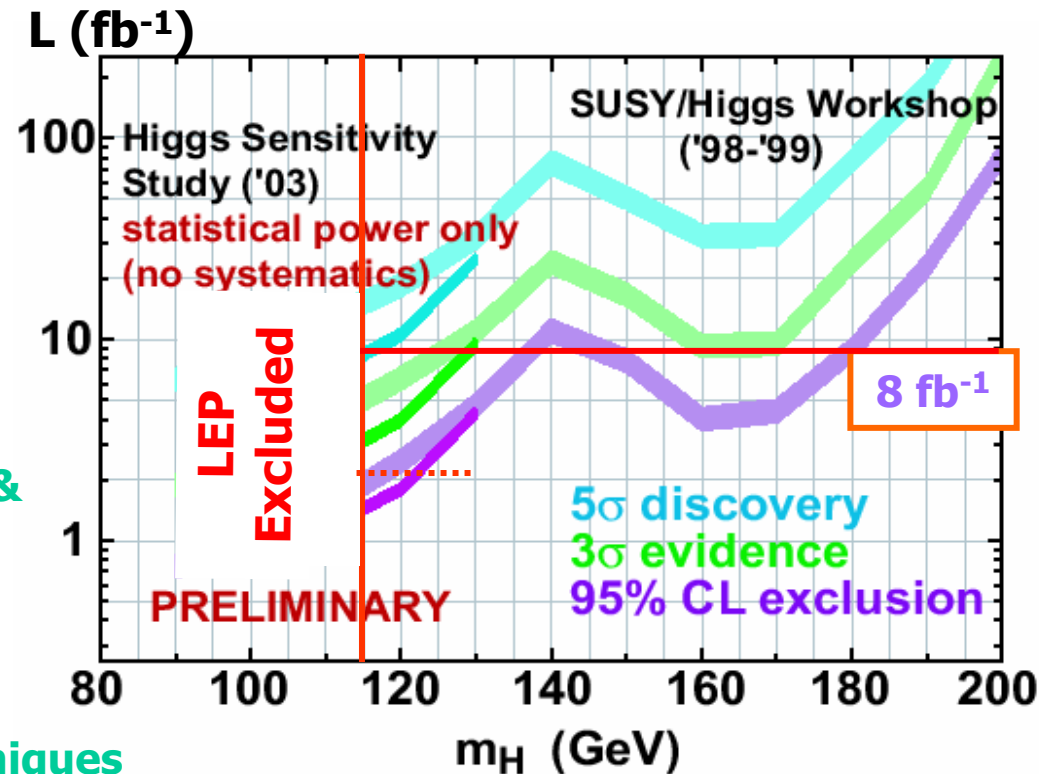
# SM Higgs production xsec & decays at TeV



- $M_H < 135 \text{ GeV}$ :  $H \rightarrow b\bar{b}$** 
  - gluon fusion production swamped by QCD background
  - need to search for (W/Z)H production (using leptonic decays of W/Z)
- $M_H > 135 \text{ GeV}$ :  $H \rightarrow W^+W^-$** 
  - can search both for gluon fusion & (W/Z)H production

# Tevatron SM Higgs Search Prospects

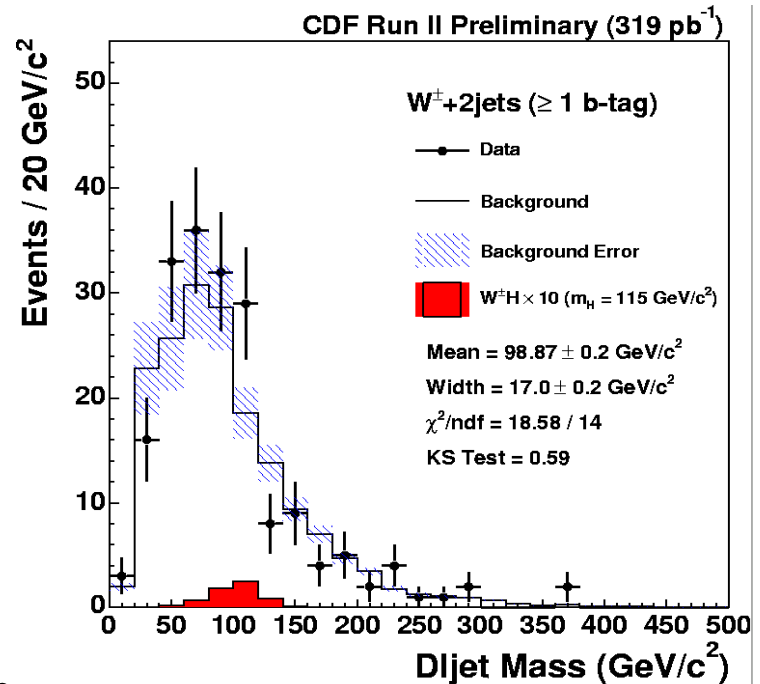
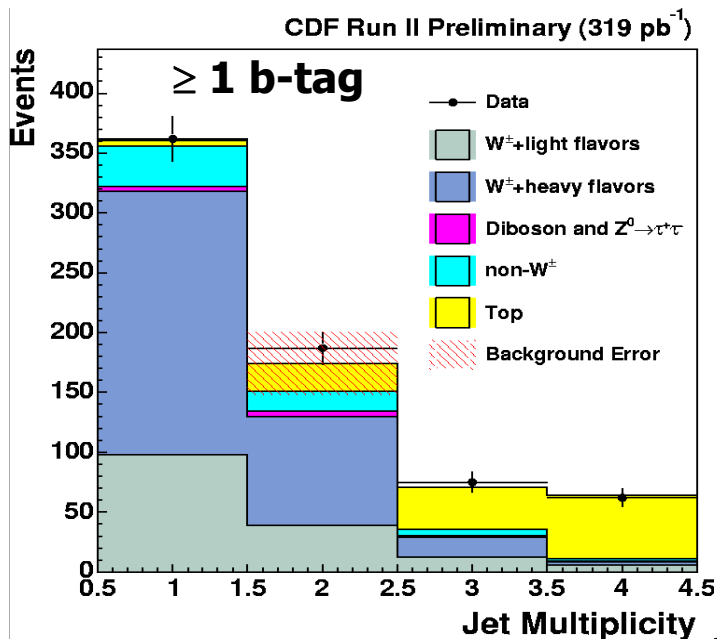
- **Higgs Sensitivity Study:**  
**WH $\rightarrow$ e $\nu$ bb, ZH $\rightarrow$  $\nu$  $\nu$ bb**
- Better detector understanding
- Updated x-sections
- Optimized analyses
- Sensitivity at 114 GeV starts with  $\sim 2 \text{ fb}^{-1}$
- With  $8 \text{ fb}^{-1}$ 
  - Exclusion up to 135 GeV & 150-180 GeV
  - $3\sigma$  up to 130 GeV
  - $5\sigma$  up to 115 GeV
- Meanwhile:
  - Optimizing analysis techniques
  - Understanding detectors better
  - Measuring SM backgrounds
  - Placing first Higgs limits



# Low Mass: $WH \rightarrow (e/\mu)\nu bb$ (CDF)

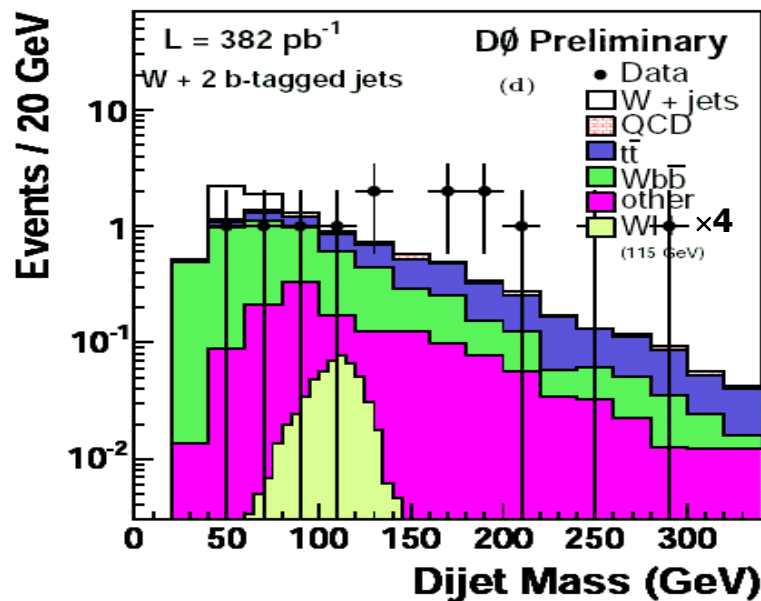
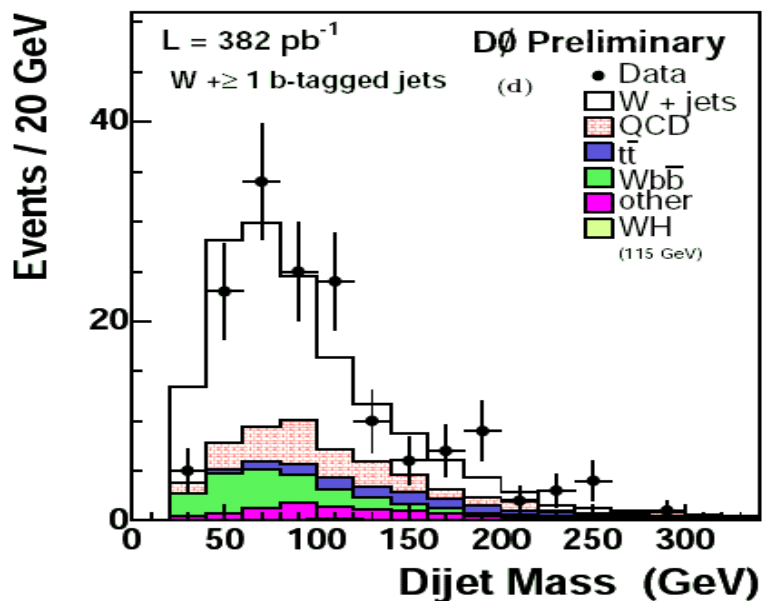
- **Sample**
  - 319 pb<sup>-1</sup>
- **Selection**
  - One high p<sub>T</sub> central e or μ
  - Missing E<sub>T</sub> > 20 GeV
  - 2 jets, at least one b-tagged
  - Veto events w/ >1 lepton

- **Backgrounds**
  - Wbb, Wcc
  - Wjj (mistags)
  - Diboson, Z→ττ
  - tt, single top
  - QCD multijet



# Low Mass: $WH \rightarrow e\nu bb$ ( $D\emptyset$ )

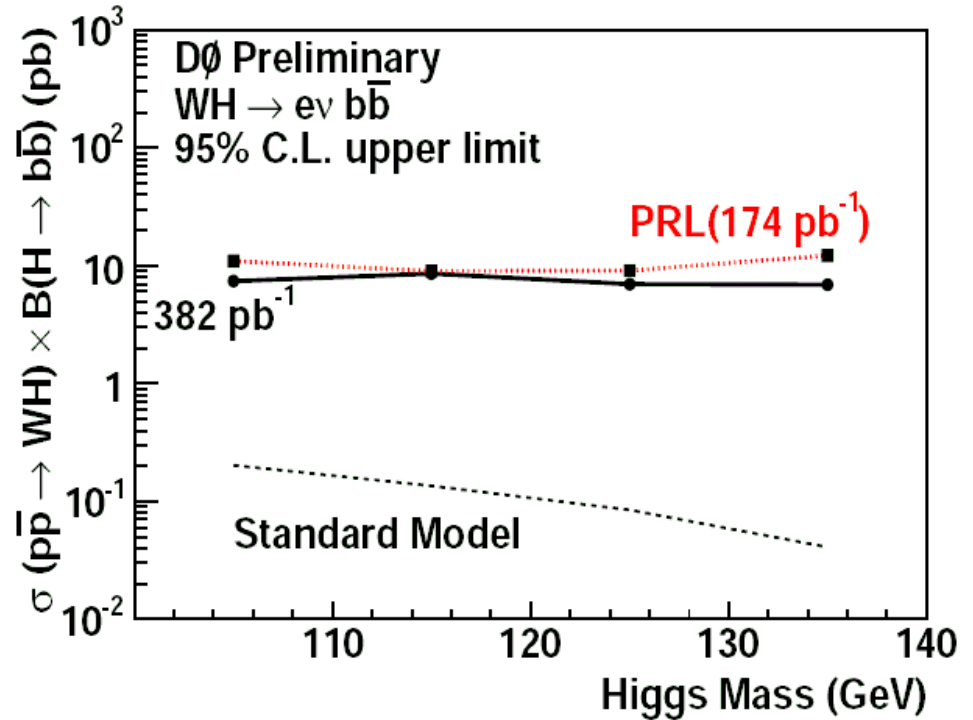
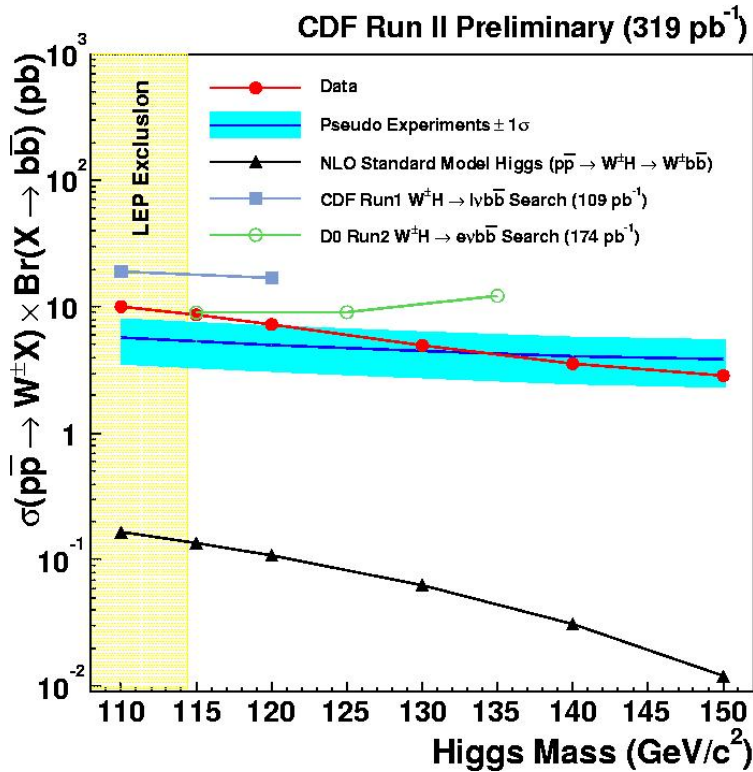
- 382 pb<sup>-1</sup>; One central e, p<sub>T</sub>>20 GeV; E<sub>T</sub> > 25 GeV; 2 jets, E<sub>T</sub>>20 GeV
- Then add b-tags



Expect 18.1 ± 4.3 Wbb  
 0.4 ± 0.1 WH  
 153.7 ± 37 W/Z+jets  
 Total 172 ± 41 events  
 Observe 153

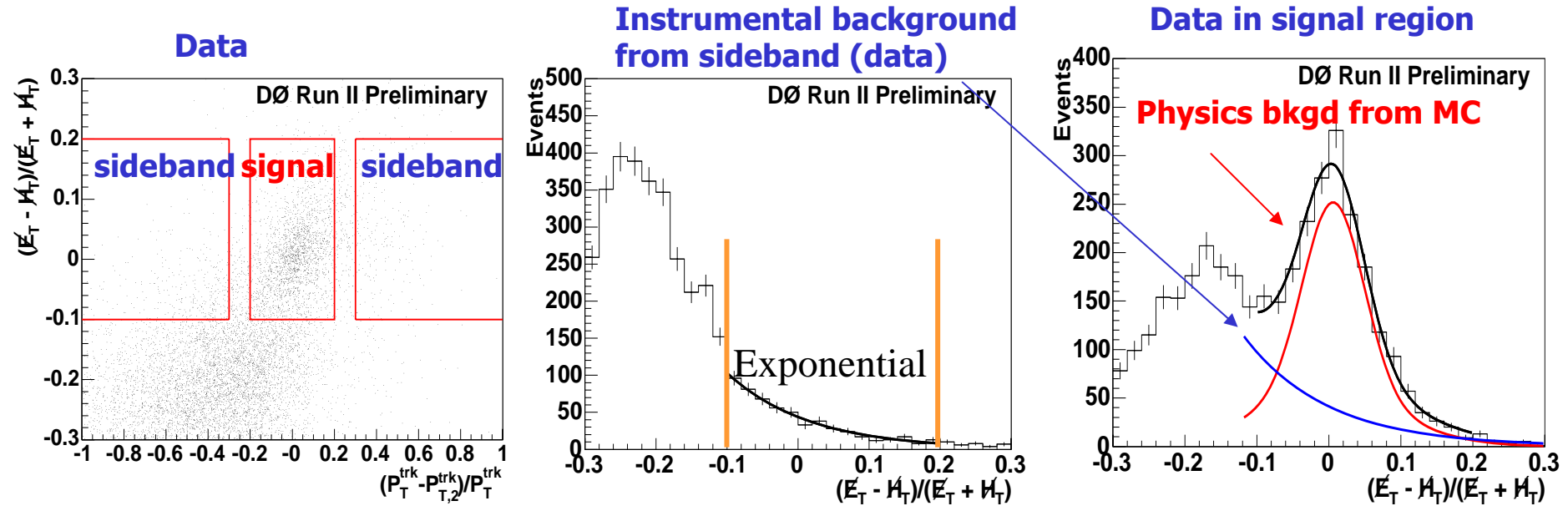
Expect 4.29 ± 1.03 Wbb  
 0.14 ± 0.03 WH  
 5.73 ± 1.45 tt,W/Z+b-jets,single top  
 Total 10.2 ± 2.4 events  
 Observe 13

# Low Mass: $WH \rightarrow (e/\mu)\nu bb$ Limits



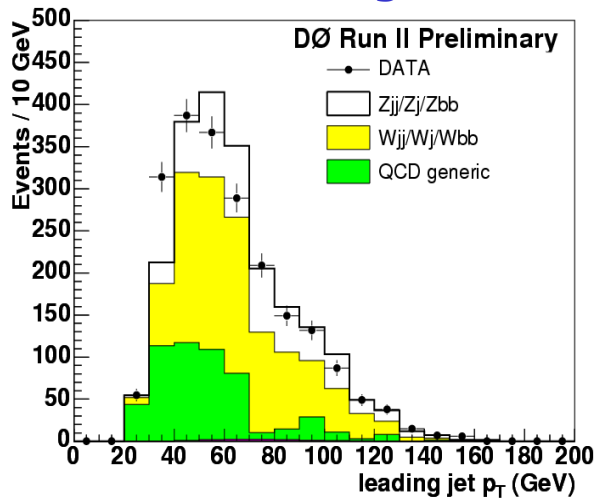
# Low Mass: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

- Trigger on events w/ large  $\cancel{E}_T$  & acoplanar jets
- Offline:  $\cancel{E}_T > 25$  GeV & 2 acoplanar b-jets w/  $E_T > 20$  GeV
- Physics bkgd: W+jets, Z+jets, top, WW, ZZ
  - Veto events with isolated tracks
  - $H_T = \sum |\mathbf{p}_T(\text{jets})| < 200$  GeV
- Instrumental bkgd: QCD multijet events w/ mismeasured or mistagged jets
  - Jet acoplanarity
  - Various asymmetries

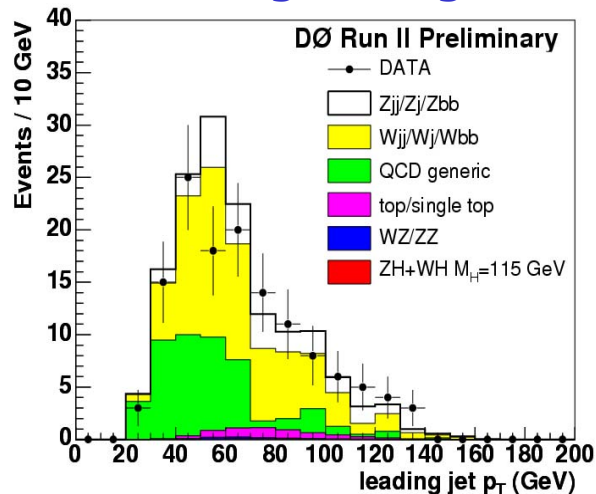


# Low Mass: $ZH \rightarrow \nu\bar{\nu}bb$

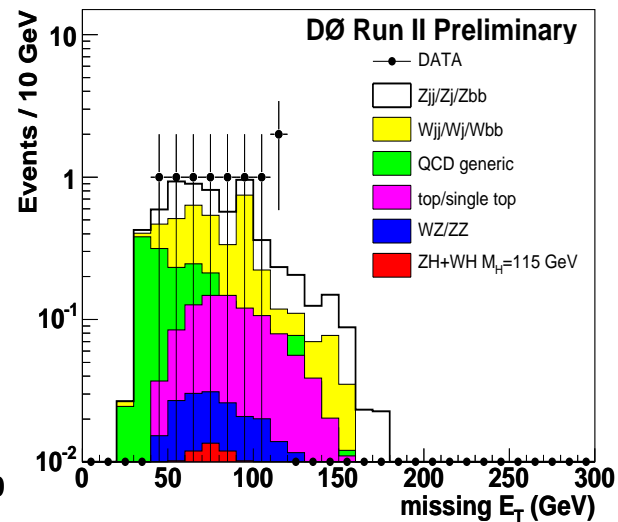
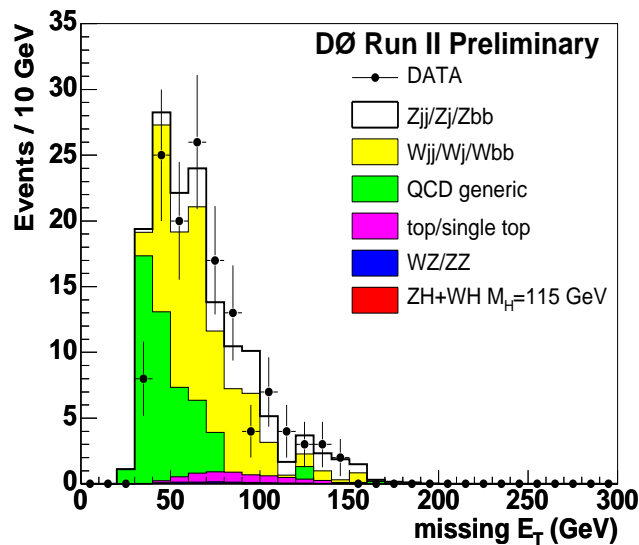
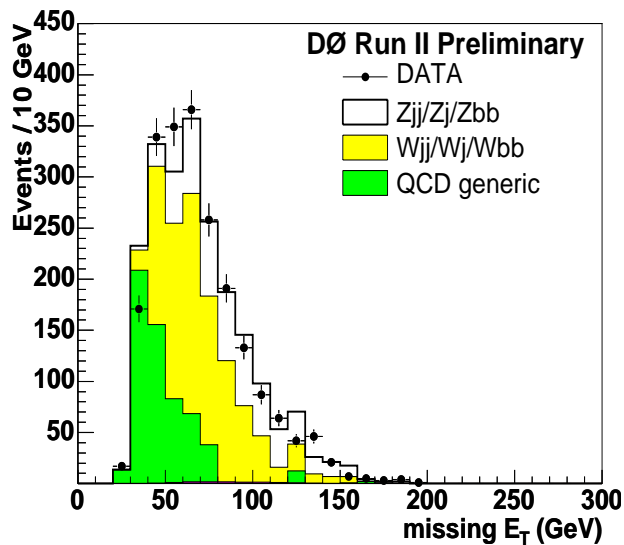
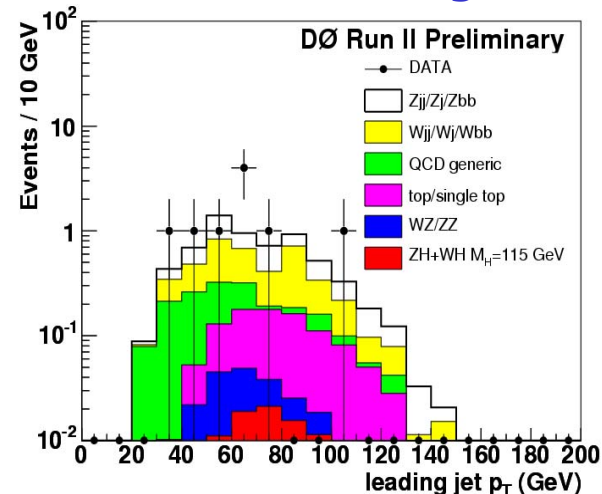
No b-tag



Single b-tag



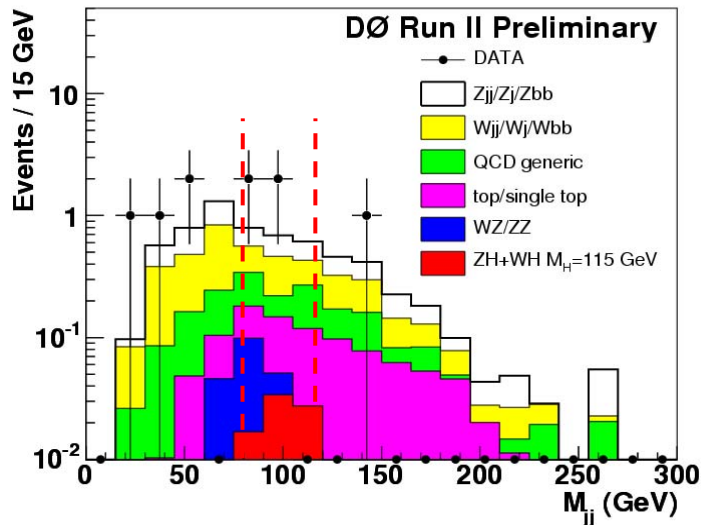
Double b-tag



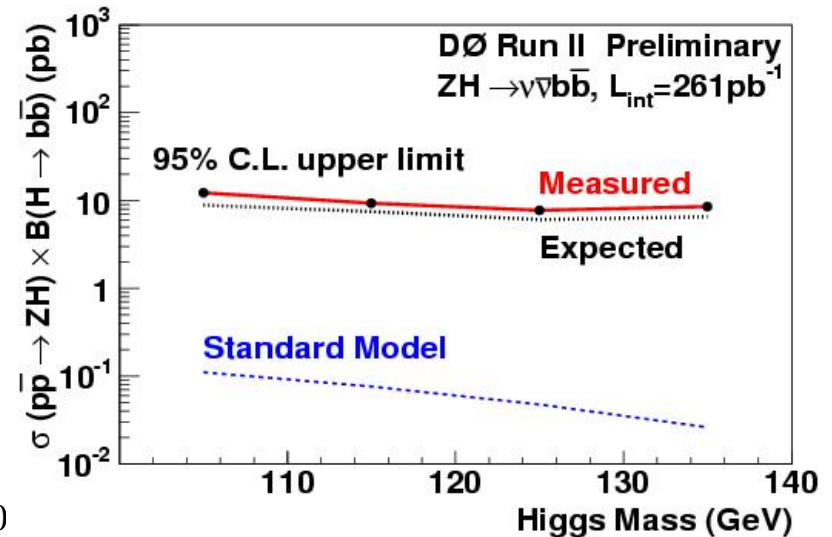
# Low Mass: $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

Search for an excess in the di-b-jet mass distribution

| Mass (GeV)                  | 105             | 115             | 125             | 135             |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|
| Window                      | [70,120]        | [80,130]        | [90,140]        | [100,150]       |
| Data                        | 4               | 3               | 2               | 2               |
| ZH/WH                       | 0.11            | 0.082           | 0.060           | 0.034           |
| Total bkgd.                 | $2.75 \pm 0.88$ | $2.19 \pm 0.72$ | $1.93 \pm 0.66$ | $1.71 \pm 0.57$ |
| Expected limit (pb)         | 8.8             | 7.5             | 6.0             | 6.5             |
| <b>Limit @95% C.L. (pb)</b> | <b>12.2</b>     | <b>9.3</b>      | <b>7.7</b>      | <b>8.5</b>      |

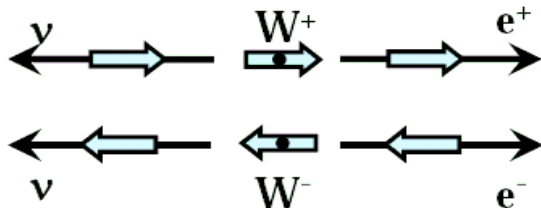


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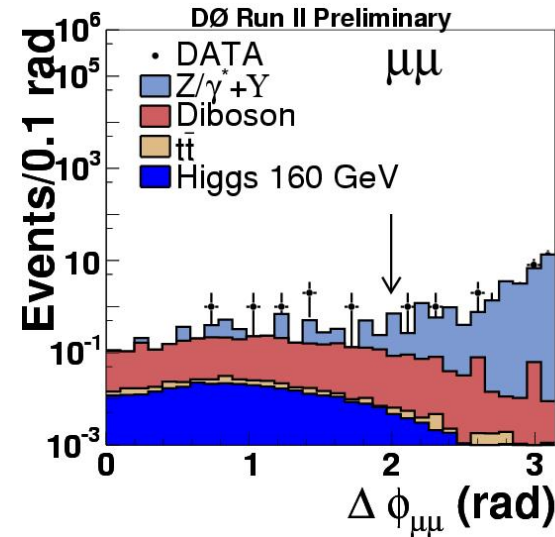


# High Mass: $gg \rightarrow H \rightarrow WW(*)$

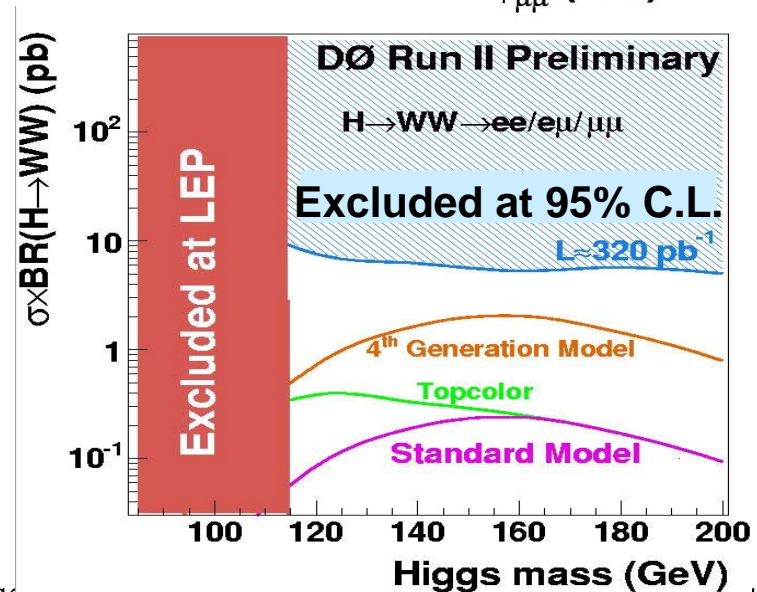
- 299-325  $\text{pb}^{-1}$  dilepton data
  - $ee, e\mu, \mu\mu$  w/  $p_T > 15/10$  GeV, opposite charge
  - Missing  $E_T > 20$  GeV
- Backgrounds
  - $Z/\gamma^*$
  - $WW, WZ, ZZ$
  - $W+\text{jet}/\gamma$
- Additional kinematic cuts (e.g.,  $m_{ll}, m_{Tll}, H_{Tl}$ , etc.)
- Exploit spin correlations in decay (leptons from H tend to point in the same direction)
  - $\Delta\phi_{ll} < 2$



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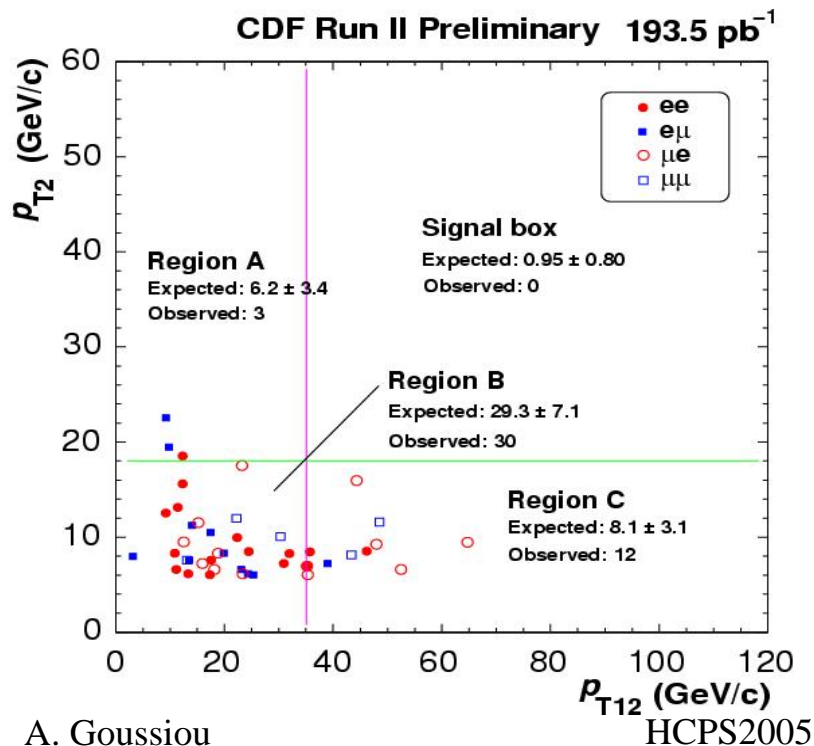
After final selection



HCPS2005

# High Mass: $WH \rightarrow WWW(*)$ (CDF)

- First, dataset w/ 1<sup>st</sup> lepton w/  $p_{T1} > 20$  GeV & 2<sup>nd</sup> lepton w/  $p_{T2} > 6$  GeV of same charge analyzed, found in agreement with expectations
- Then, optimized cuts applied to the 2<sup>nd</sup> lepton (e.g.,  $p_{T2} > 18$  GeV for  $M_H > 160$  GeV) & to the vector sum of the two lepton  $p_T$ 's ( $p_{T12} > 35$  GeV) to determine signal region



**Zero events**  
**observed**

**$0.95 \pm 0.61 \pm 0.18$**   
**expected bkgd**

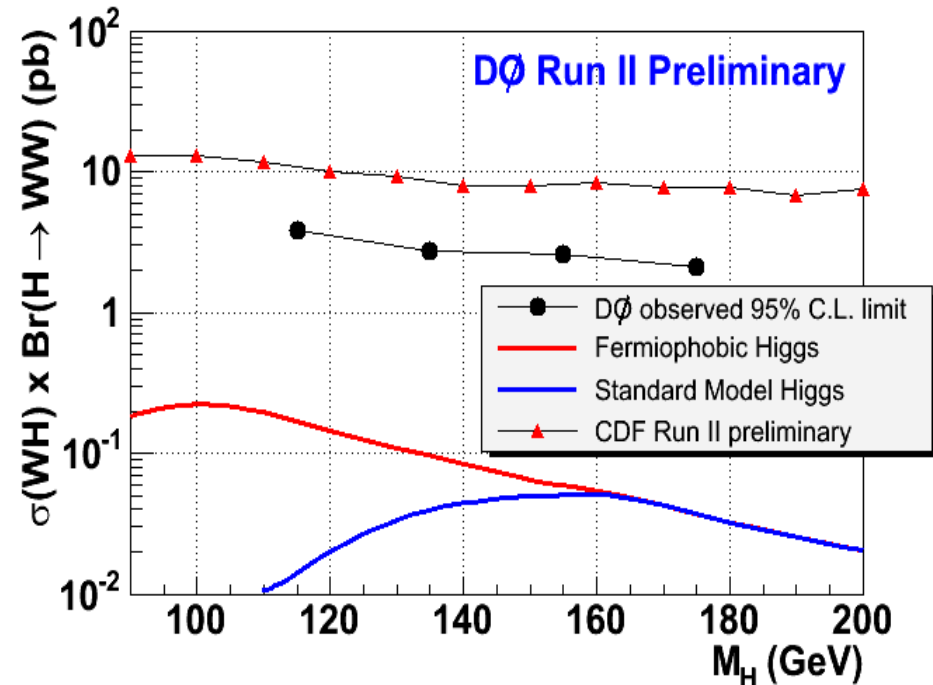
**0.03 expected**  
**SM Higgs 160 GeV**

**95% CL limits:**  
**12 (8) pb for**  
 **$M_H = 110$  (160) GeV**

# High Mass: $WH \rightarrow WWW(*)$ ( $D\emptyset$ )

- $ee/e\mu/\mu\mu$  data, 384-363  $\text{pb}^{-1}$
- Backgrounds
  - Physics
    - $WZ \rightarrow l\nu ll$ 
      - From theoretical xsec  $\otimes$  experimental eff
  - Instrumental
    - Charge flips ( $Z/\gamma^* \rightarrow ll$ )
      - From data
    - QCD or  $W$ +jets
      - From data
- Selection
  - 2 like-sign isolated leptons,  $p_T > 15$  GeV, veto 3<sup>rd</sup> lepton
  - track quality cuts
  - Missing  $E_T > 20$  GeV

|               | ee   | e $\mu$ | $\mu\mu$ |
|---------------|------|---------|----------|
| Observed data | 1    | 3       | 2        |
| Total bkgd    | 0.70 | 4.32    | 3.72     |





# Comparison to prospects

|  |   |   |
|--|---|---|
| <b>WH<math>\rightarrow</math>e<math>\nu</math>bb</b><br><br><b>M<sub>H</sub> = 115 GeV</b> | <b>DØ RunII</b><br><b>382 pb<sup>-1</sup></b> | <b>HSS</b><br><b>scaled to</b><br><b>382 pb<sup>-1</sup></b><br><b>e-only</b> |
| <b>Dijet mass window</b>   | <b>[85,135]</b>                               | <b>[100,136]</b>  |
| <b>Dijet mass resolution</b>   | <b>14 ± 1 %</b>                               | <b>10 %</b>   |
| <b>Signal events (S)</b>   | <b>0.12 ± 0.03</b>                            | <b>0.48</b>   |
| <b>Background events (B)</b>   | <b>2.37 ± 0.59</b>                            | <b>5.79</b>   |
| <b>Significance (S/√B)</b>   | <b>0.08</b>                                   | <b>0.20</b>   |

- **HSS/DØ = 2.5**
- **HSS assumed**
  - **Larger ECAL coverage (+30%)**
  - **Better em-id (+30%)**
  - **Larger b-tagging eff (+40%)**
    - **Silicon Level 0**
    - **NN combination of b-taggers**
  - **Better mass resolution (+40%)**
    - **Calorimeter calibration**
    - **Energy Flow ideas**
  - **Factor of ~2 can be recovered from the above  $\Rightarrow 2.5/2=1.25$**
- **Furthermore:**
  - **Trigger upgrades**
  - **Advanced analysis techniques**
- **Missing factors can be recovered!**

# Higgs in the Minimal Supersymmetric SM

- EWSB via vacuum expectation values of 2 Higgs doublets resulting in five physical Higgs bosons:  $h^0, H^0, A^0, H^\pm$
- Two free parameters:  $M_A$  and  $\tan\beta = v_2/v_1$
- After radiative corrections:  $M_h$  or  $M_H \lesssim 135$  GeV
- In a large region of SUSY parameter space, one of the CP-even Higgs bosons ( $h^0$  or  $H^0$ ) is SM-like

## h/H/A Production at TeV

At small  $\tan\beta$  or high  $M_A$  or large  $\tan\beta$  & small  $M_A$ : h or H couplings to W/Z similar to SM

=> search for (W/Z)h or (W/Z)H

At large  $\tan\beta$ : (h/A) or (H/A) couplings to down-type fermions enhanced by  $\tan\beta$

=> complimentary search for  $b\bar{b}(h/A)$  or  $b\bar{b}(H/A)$

## h/H/A Decays

In most of parameter space:

$h/H \rightarrow b\bar{b}$  (90%)

$\rightarrow \tau^+\tau^-$  (10%)

$\rightarrow WW/ZZ$  suppressed

except for small  $\tan\beta$  &  $M_H > 160$  GeV

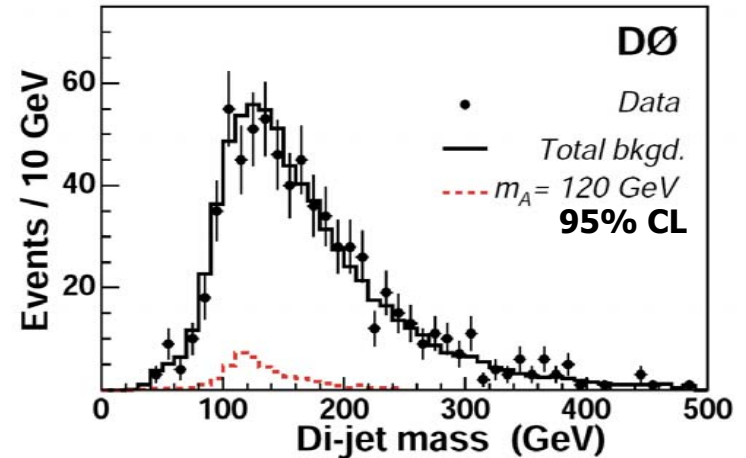
In all of parameter space:

$A \rightarrow b\bar{b}$  (90%)

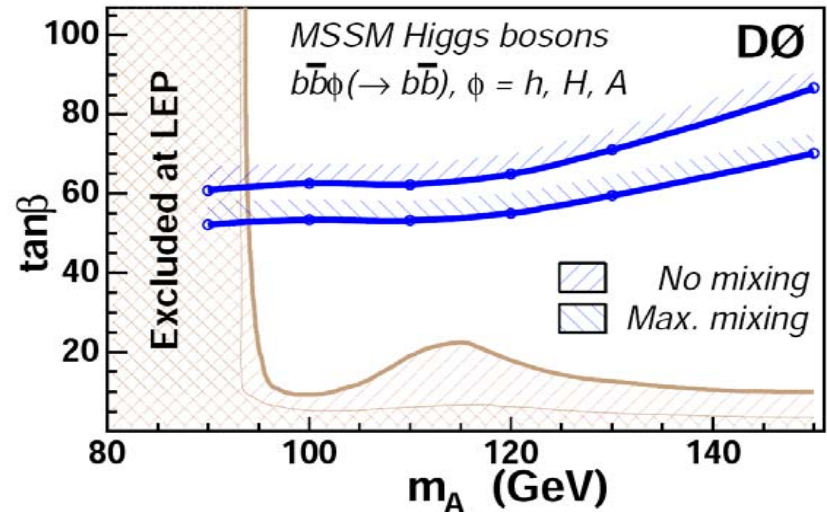
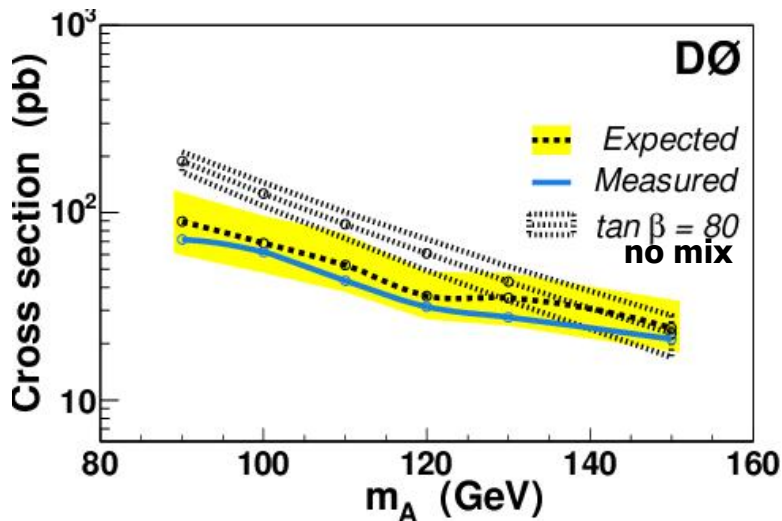
$\rightarrow \tau^+\tau^-$  (10%)

# $b(b)\phi \rightarrow b(b)bb, \phi = h/A \text{ or } H/A$

- $bb\phi$  coupling enhanced at large  $\tan\beta \Rightarrow$  large cross section for  $bb\phi$  production (at tree level,  $\sim \tan^2\beta$ )
- Selection: at least 3 b-tagged jets
- Backgrounds: multijet production, modelled using data
- Reconstruct Higgs boson mass in  $bb$  spectrum

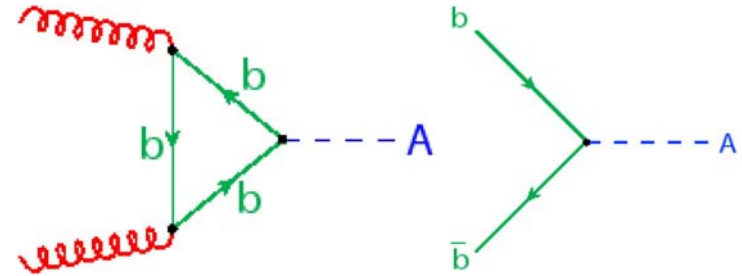
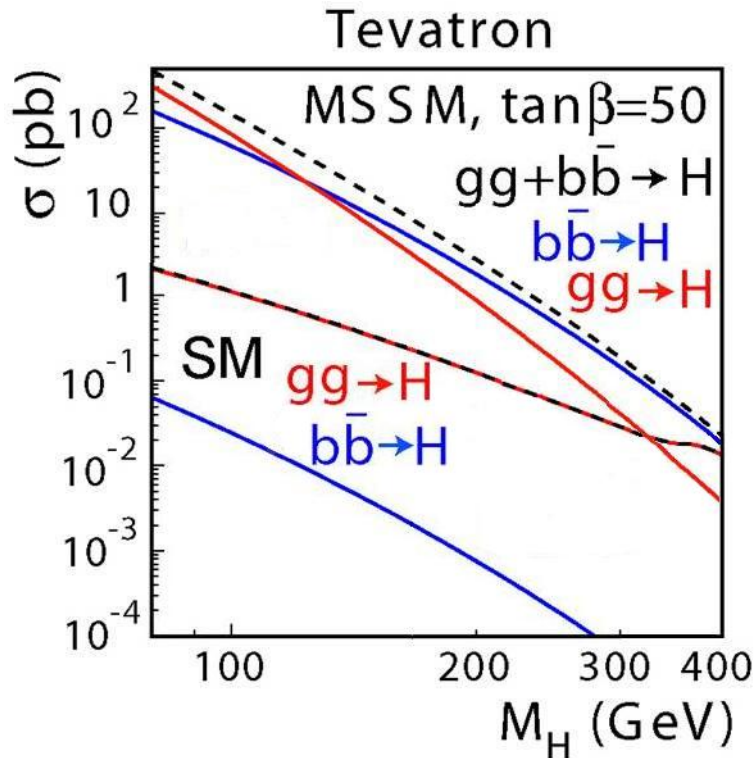


No hint for signal in  $260 \text{ pb}^{-1}$



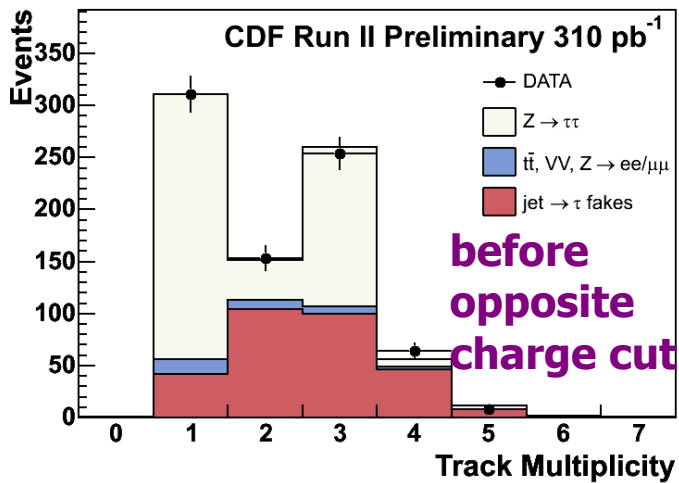
# $h/H/A \rightarrow \tau\tau$

$b(h/H/A)$  coupling  
enhanced by  $\tan\beta \Rightarrow$   
production rate in MSSM  
can be much larger than in  
SM at high  $\tan\beta$

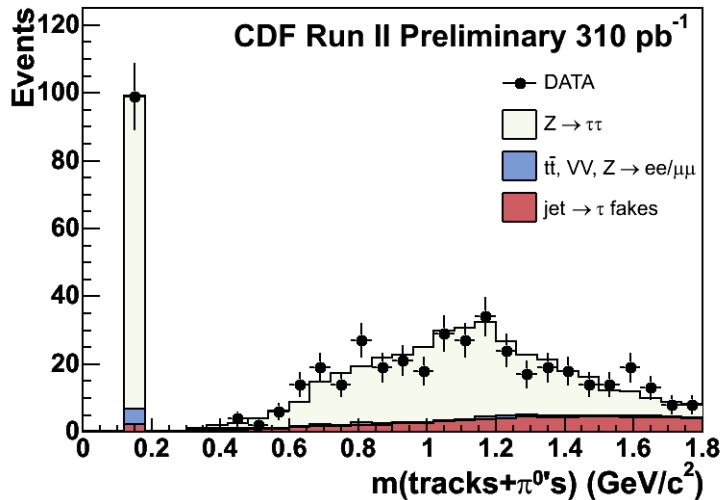


- $gg+bb \rightarrow \phi \rightarrow bb$ 
    - too large QCD background
  - $gg+bb \rightarrow \phi \rightarrow \tau\tau$ 
    - Sample
      - $310 \text{ pb}^{-1}$
    - Backgrounds
      - $Z \rightarrow \tau\tau$
      - $W + \text{jets}$ , QCD: jets faking  $\tau$
      - $t\bar{t}$ , diboson,  $Z \rightarrow ee/\mu\mu$
    - Selection
      - $e/\mu$  w/  $p_T > 10 \text{ GeV}$
      - $\tau_{\text{had}}$  w/  $p_T > 15 \text{ GeV}$
- opposite charge**
- $p_T(e/\mu) + p_T(\tau_{\text{had}}) + \cancel{E}_T > 50 \text{ GeV}$**
- Anti-W cut**

MSSM Higgs  $\rightarrow \tau\tau$  Search, Track Multiplicity



MSSM Higgs  $\rightarrow \tau\tau$  Search, Mass(tracks +  $\pi^0$ 's)

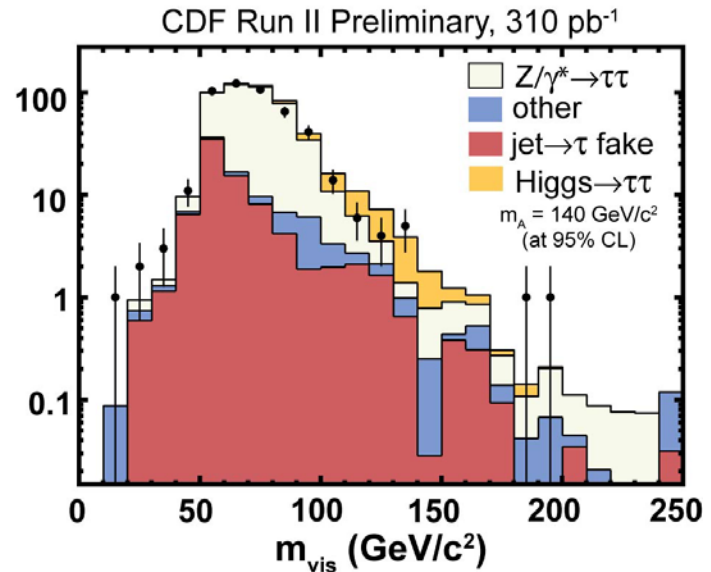


Total SM bkgd: 496  $\pm$  5  $\pm$  28  $\pm$  25  
 Observed: 487

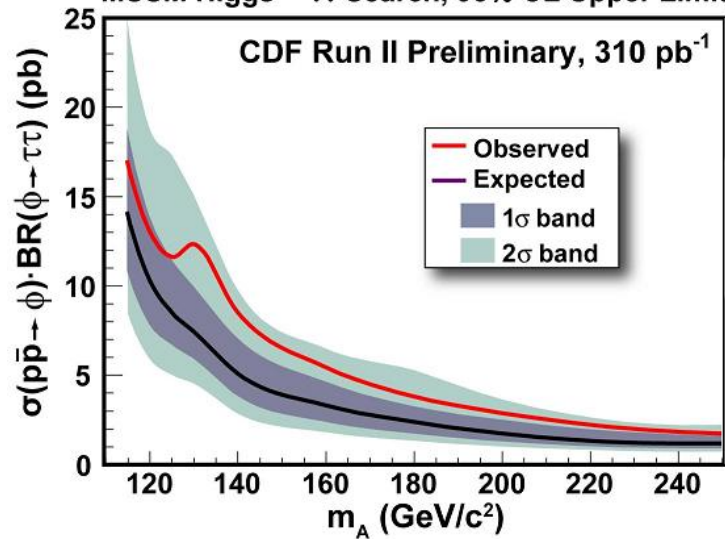
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**h/H/A  $\rightarrow \tau\tau$**

$$m_{vis}^2 = [p(e/\mu) + p(\tau_{had}) + p(E)]^2$$



MSSM Higgs  $\rightarrow \tau\tau$  Search, 95% CL Upper Limit



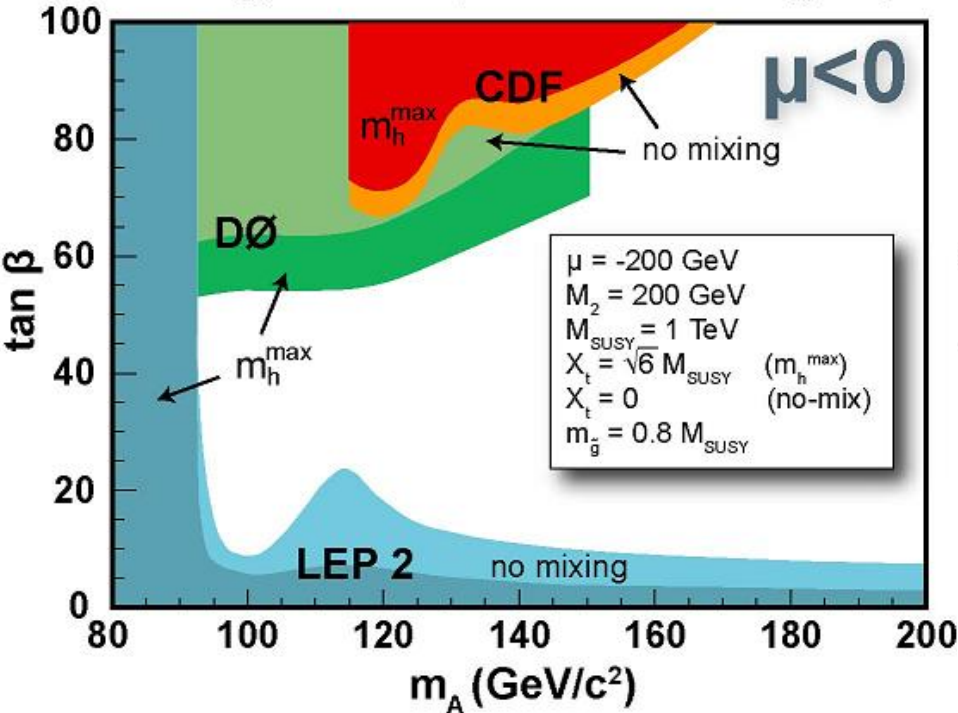
HCPS<sub>2003</sub>

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# $h/H/A \rightarrow \tau\tau$

**Interpret cross-section limit in terms of  $\tan\beta$  and  $m_A$ :**

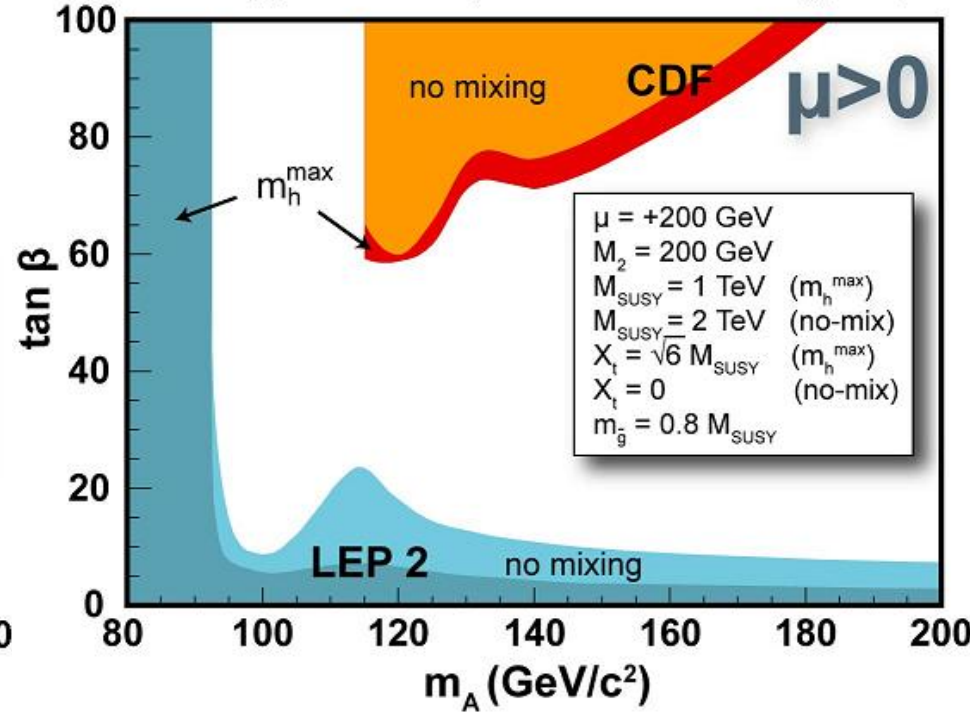
MSSM Higgs  $\rightarrow \tau\tau$  Search, CDF Run II Preliminary, 310 pb<sup>-1</sup>



• For  $\mu < 0$

**Complementary to SUSY Higgs  
bbb(b) mode**

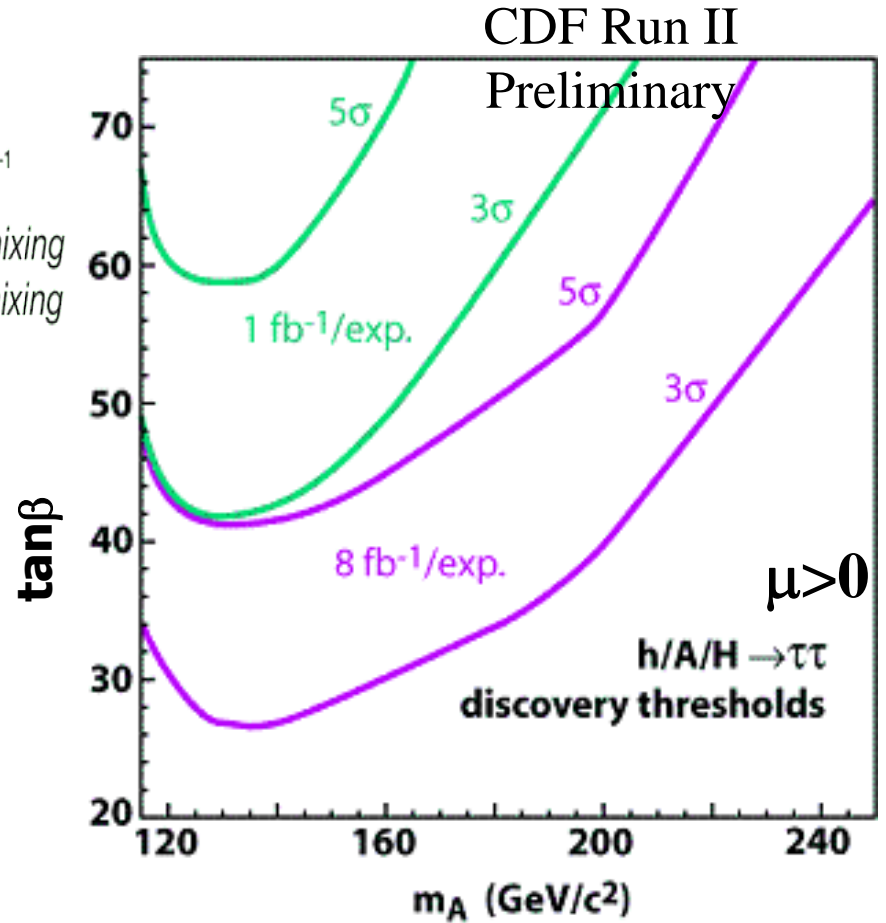
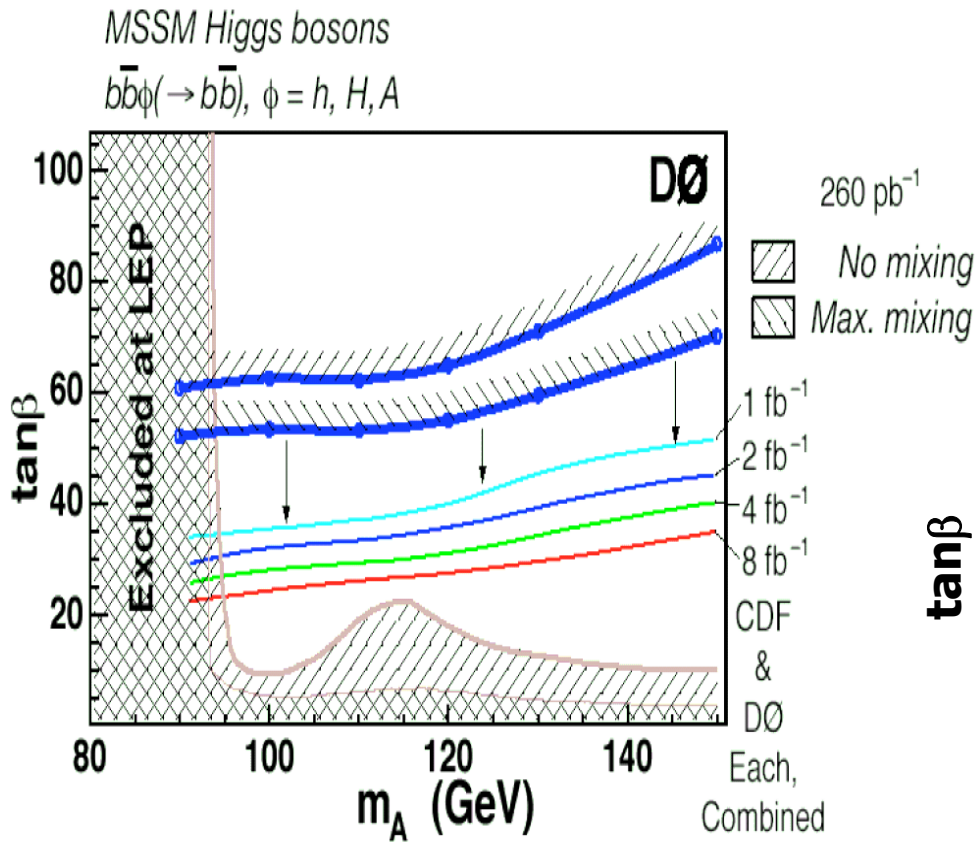
MSSM Higgs  $\rightarrow \tau\tau$  Search, CDF Run II Preliminary, 310 pb<sup>-1</sup>



• For  $\mu > 0$ :

**limits extended to higher higgs  
mass and lower  $\tan\beta$  region than  
for  $\mu < 0$**

# MSSM Higgs Prospects



# Other Higgs analyses we are pursuing...

- $ZH \rightarrow l^+ l^- bb$
- $bb(h/H/A) \rightarrow bb\tau\tau$
- **Charged Higgs**
- $H^{++}, H^{--}$
- $H \rightarrow \gamma\gamma$
- **W/Z + jets, W/Z + b-jets**
  - to understand backgrounds
- **Z  $\rightarrow$  bb**
  - proof of principle & di-b-jet mass resolution optimization

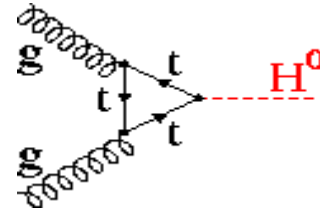
# Summary

- Tevatron is delivering design luminosity
- CDF and DØ experiments are running well (85-90% eff)
- Shown results based on  $\sim 0.4 \text{ fb}^{-1}$ ,  $0.8 \text{ fb}^{-1}$  on tape,  $1 \text{ fb}^{-1}$  by fall
- First limits placed on Higgs cross sections
- Expect improvements with
  - Improved b-tagging efficiencies
    - combination of b-taggers, silicon upgrade (DØ)
  - Improved  $M_{bb}$  resolution
    - better calorimeter calibrations, energy flow ideas
  - Optimization of object ID, optimization of selection, additional kinematic variables, advanced analysis techniques
  - More data
- Sensitivity at 114 GeV with  $2 \text{ fb}^{-1}$   
With  $8 \text{ fb}^{-1}$ : Exclusion up to 135 GeV & 150-180 GeV – or –  
signal up to 115-130 GeV

**backups**

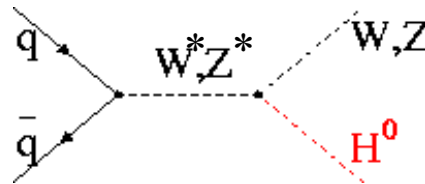
# SM Higgs production at the Tevatron

- Gluon fusion:  $gg \rightarrow H$



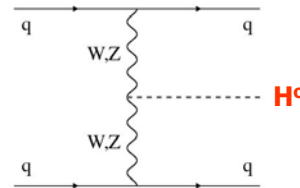
$\sigma = 0.70 \text{ pb}$   
for  $M(H) = 120 \text{ GeV}/c^2$   
with QCD NLO correction

- Higgsstrahlung:  $q\bar{q} \rightarrow VH$



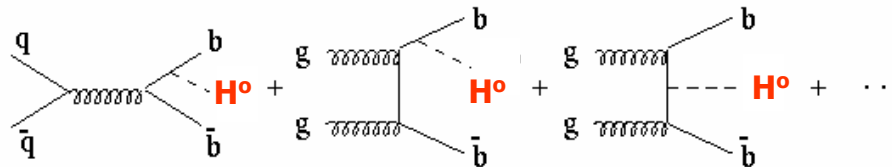
WH:  $\sigma = 0.16 \text{ pb}$   
ZH:  $\sigma = 0.10 \text{ pb}$

- Vector Boson fusion:  $q\bar{q} \rightarrow q\bar{q}H$



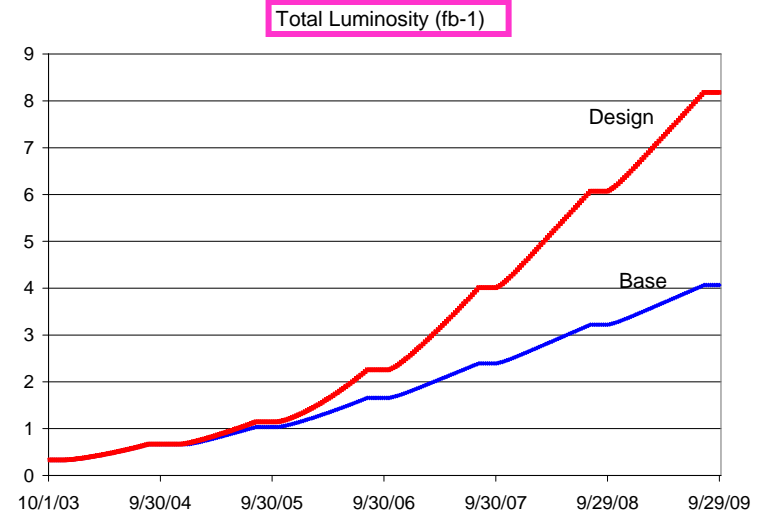
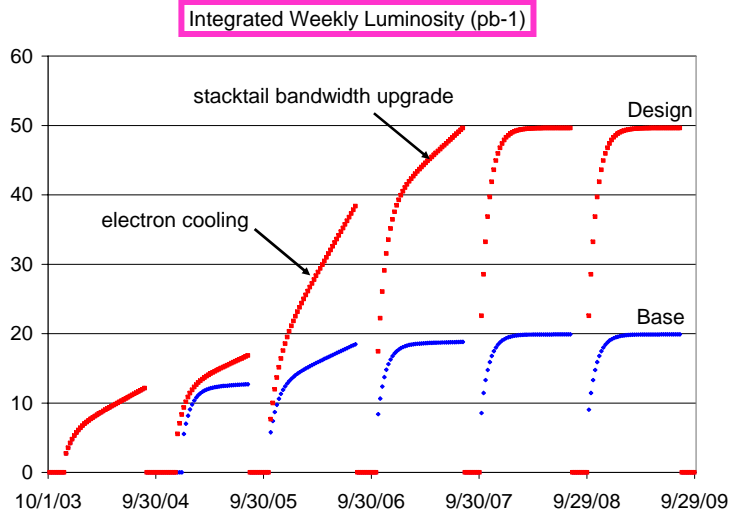
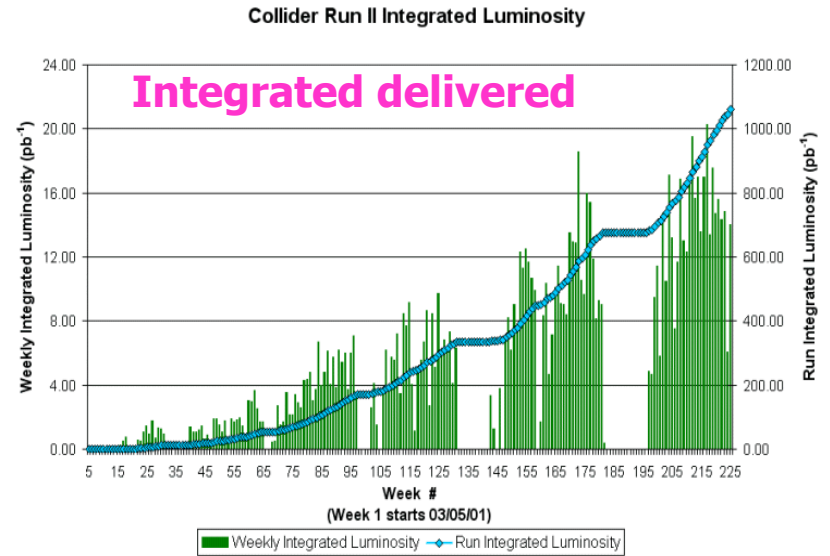
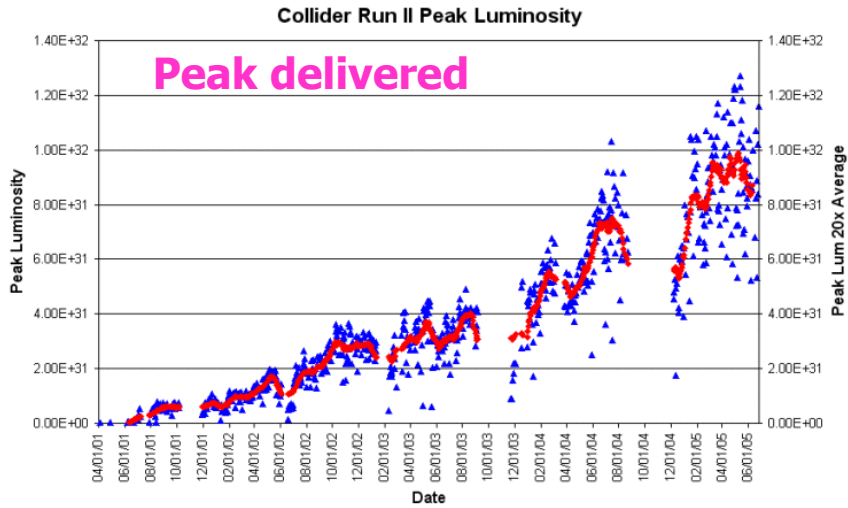
$\sigma = 0.10 \text{ pb}$

- Radiation off heavy quark:  $q\bar{q} \rightarrow t\bar{t}H, b\bar{b}H$

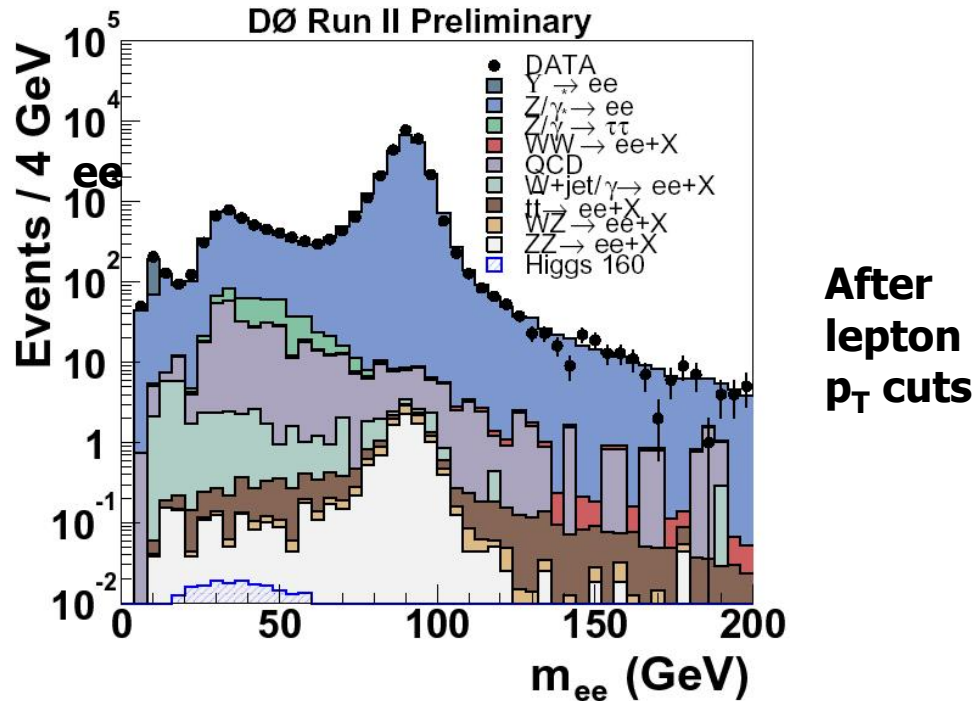


$\sigma = 0.004 \text{ pb}$

# Tevatron Luminosity



# High Mass: $gg \rightarrow H \rightarrow WW(*)$

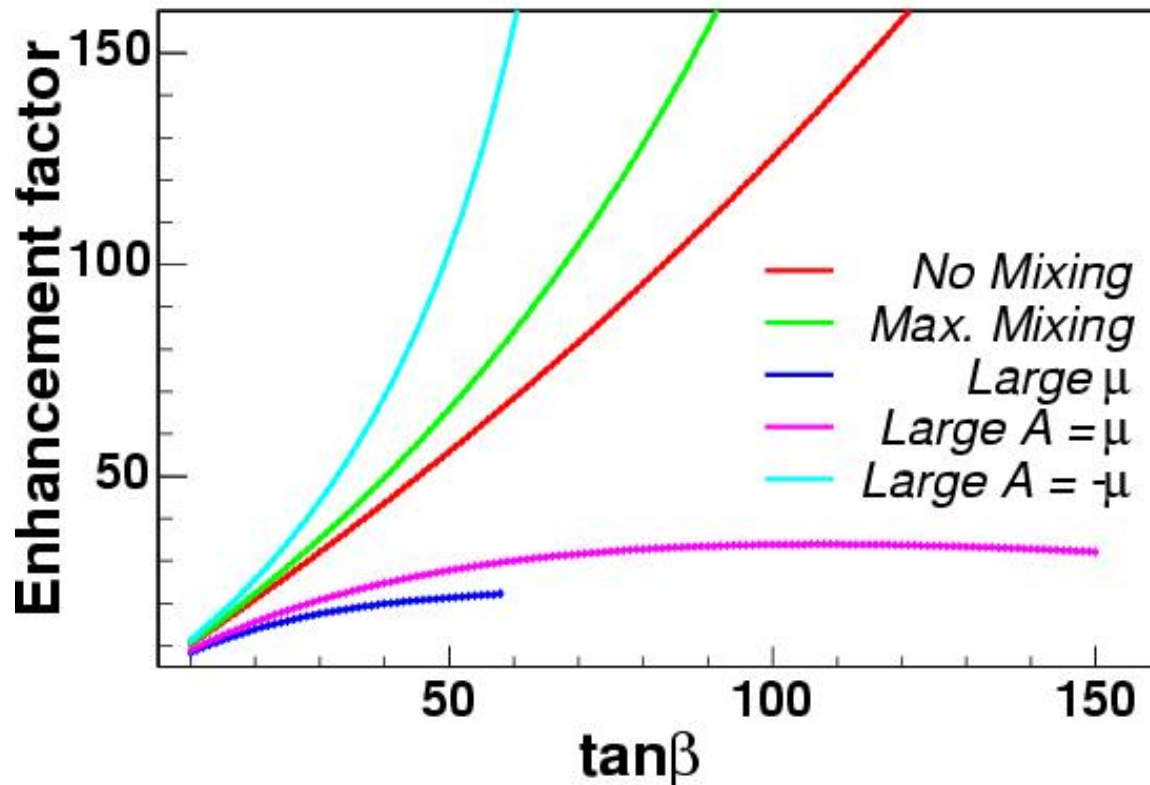


**Example:** expected and observed number of events for  $m_H = 160$  GeV

| Diboson        | Z/ $\gamma$   | W+jet/ $\gamma^*$ | tt+multijet   | Total                            | Data      |
|----------------|---------------|-------------------|---------------|----------------------------------|-----------|
| $11.7 \pm 0.2$ | $3.3 \pm 0.7$ | $2.1 \pm 0.7$     | $0.6 \pm 0.1$ | <b><math>17.6 \pm 1.0</math></b> | <b>20</b> |

# $b(b)\phi \rightarrow b(b)bb$ , $\phi = h/A$ or $H/A$

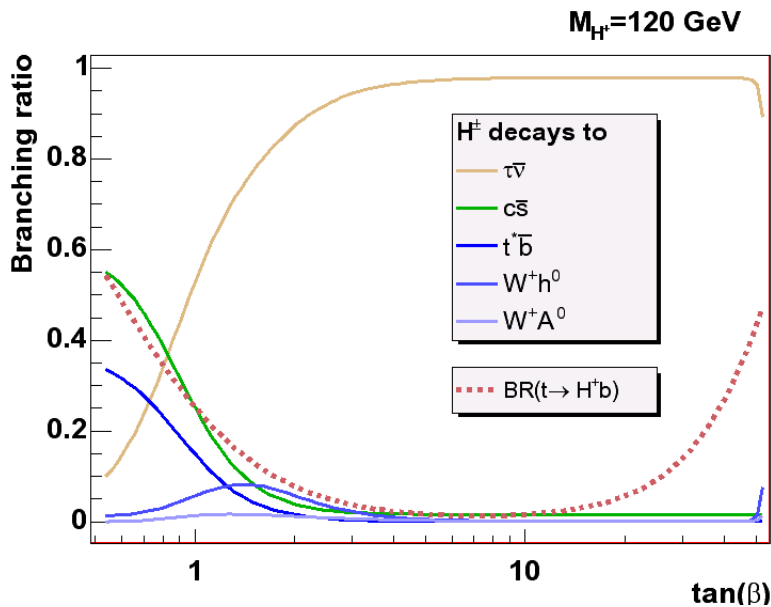
$$\sigma \times BR_{SUSY} = 2 \times \sigma_{SM} \times \frac{\tan^2 \beta}{(1 + \Delta_b)^2} \times \frac{9}{[9 + (1 + \Delta_b)^2]}$$



# Charged Higgs

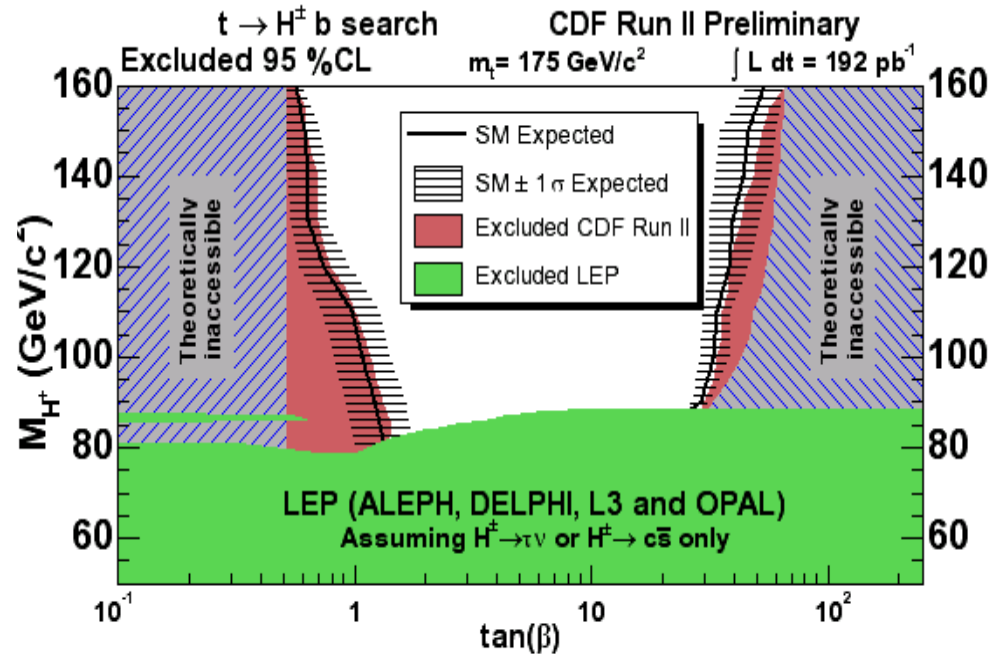
MSSM:  $t \rightarrow W^\pm b$  and  $H^\pm b \Rightarrow$  #events in each final state will change, depending on  $H^\pm$  decays

Compute expected #events in each final state for each  $M_{H^\pm}$  & compare to candidates in data



**$BR(t \rightarrow H^\pm b)$  enhanced at large  $\tan\beta$**

**At  $\tan\beta=1$  max stop mixing by maximizing  $m_h$**



$M_{\text{SUSY}} = 1000 \text{ GeV}/c^2, \mu = -500 \text{ GeV}/c^2, A_1 = A_b = 2000 \text{ GeV}/c^2, A_t = 500 \text{ GeV}/c^2$   
 $M_1 = 0.498 * M_2, M_2 = M_3 = M_0 = M_U = M_D = M_E = M_L = M_{\text{SUSY}}$

# Z → bb

- 333 pb<sup>-1</sup>
- Only 2 jets w/ E<sub>T</sub> > 10 GeV, back-to-back in  $\phi$
- Both jets b-tagged
- Bkgd: untagged data passing same kinematic selection
- Z → bb from Pythia
- Two shapes fit to data (blue points)
- Fit results in red (fit uncertainties stat-only)

