

# Higgs Searches at Tevatron

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On behalf of the DØ & CDF Collaborations

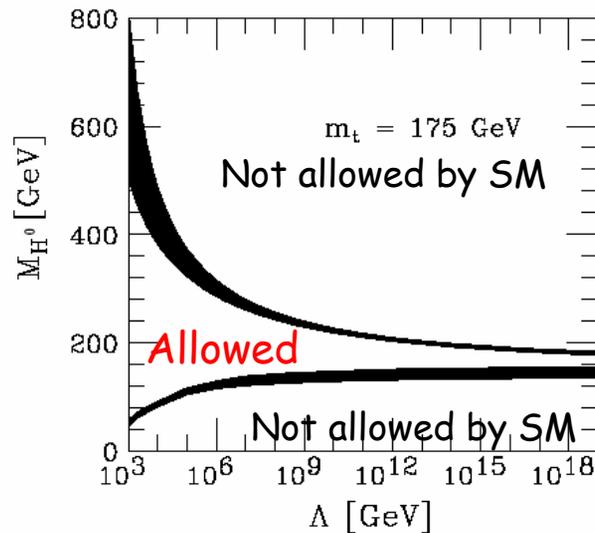
DIS2006 @ Tsukuba , April 21<sup>st</sup>, 2006

# Higgs boson searches

- Mass of fundamental particles are given by Higgs boson
  - Only particle predicted by SM and NOT discovered yet.
  - SM cannot predict the exact mass of Higgs boson, but....

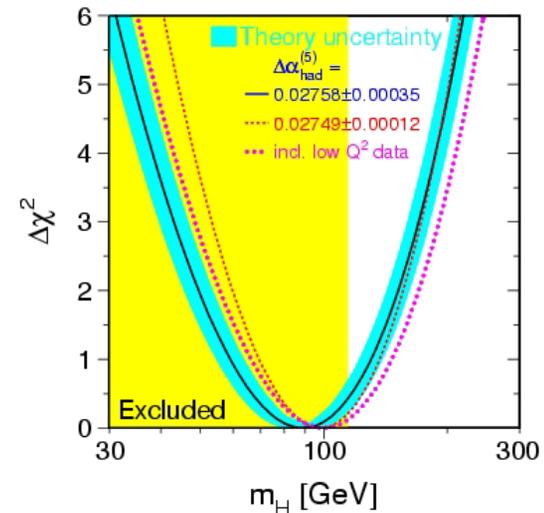
Theory predict

- SM Higgs mass is light
- New physics at  $\sim 1$  TeV



Experiments tell us:

- $M_H > 114$  GeV (95% CL) by LEP
- $M_H < 175$  GeV (95% CL) by global fit (center value =  $89 + 45 - 30$  GeV)



- Higgs bosons with extension models have been also looked for
  - 2HDM  $\rightarrow$  5 physical Higgs bosons,  $m_H(\text{lightest}) < 135$  GeV

Tevatron has capability to search for Higgs bosons in this mass region

# Outline

## 0. Tevatron/Tools

### 1. SM Higgs boson

$H \rightarrow bb$

- $WH \rightarrow l\nu bb$
- $ZH \rightarrow \nu\nu bb$

$H \rightarrow WW \rightarrow \text{leptonic}$

- $WH \rightarrow WW \rightarrow l\nu l\nu X$
- $H \rightarrow WW \rightarrow l\nu l\nu$

Combination

Many updates and new analysis  
→ Started combination of the Higgs search

Important signature of Higgs searches is leptons, b-jets, tau, and  $\cancel{E}_T$

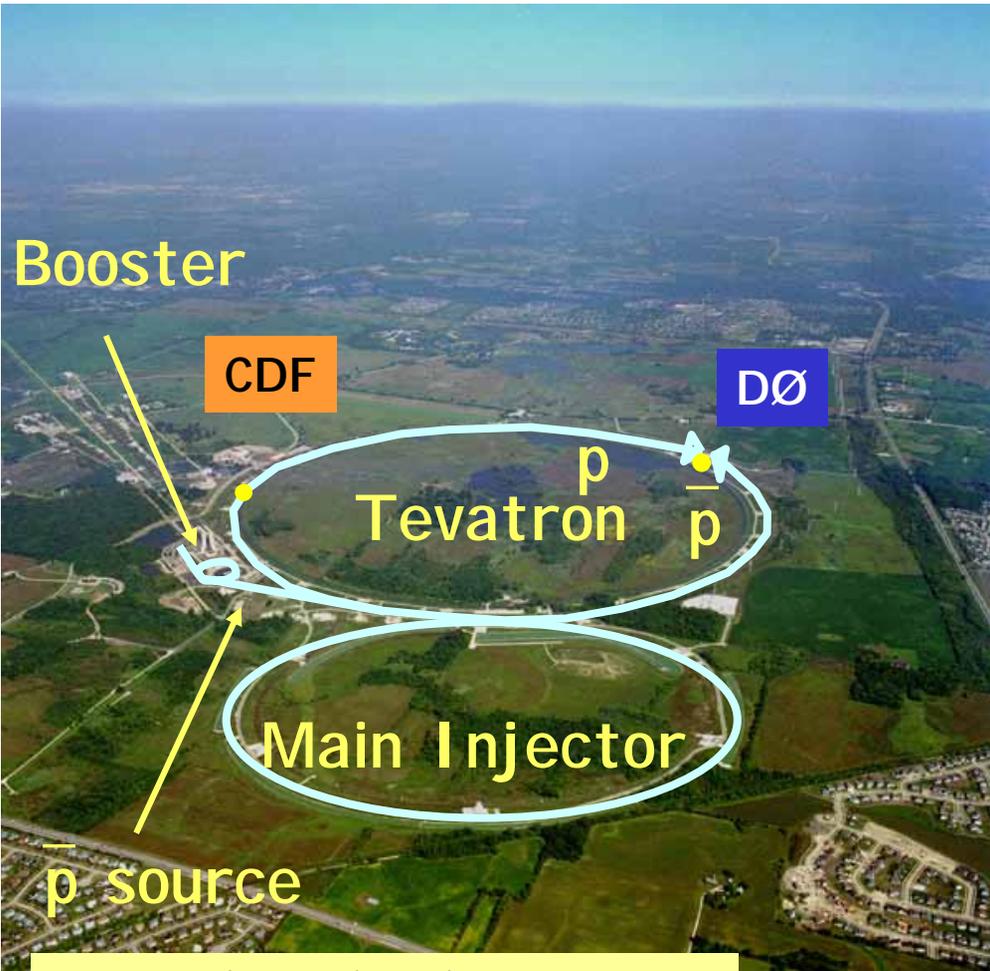
### 2. SUSY Higgs boson

1.  $pp \rightarrow hb(b)$

2.  $pp \rightarrow h \rightarrow \tau\tau$

3. Charged MSSM Higgs boson

# Tevatron Status



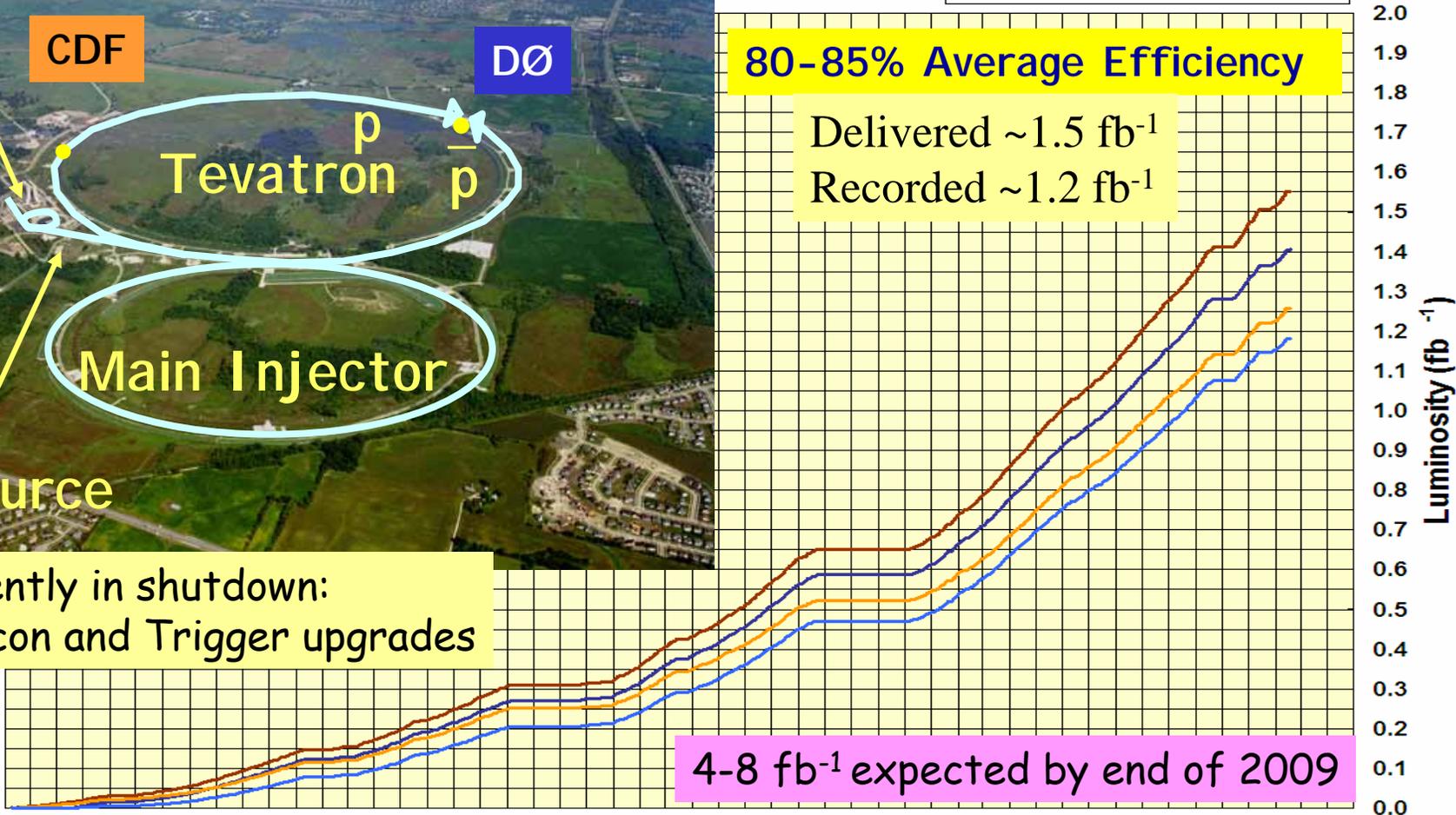
through 18 February 2006

80-85% Average Efficiency

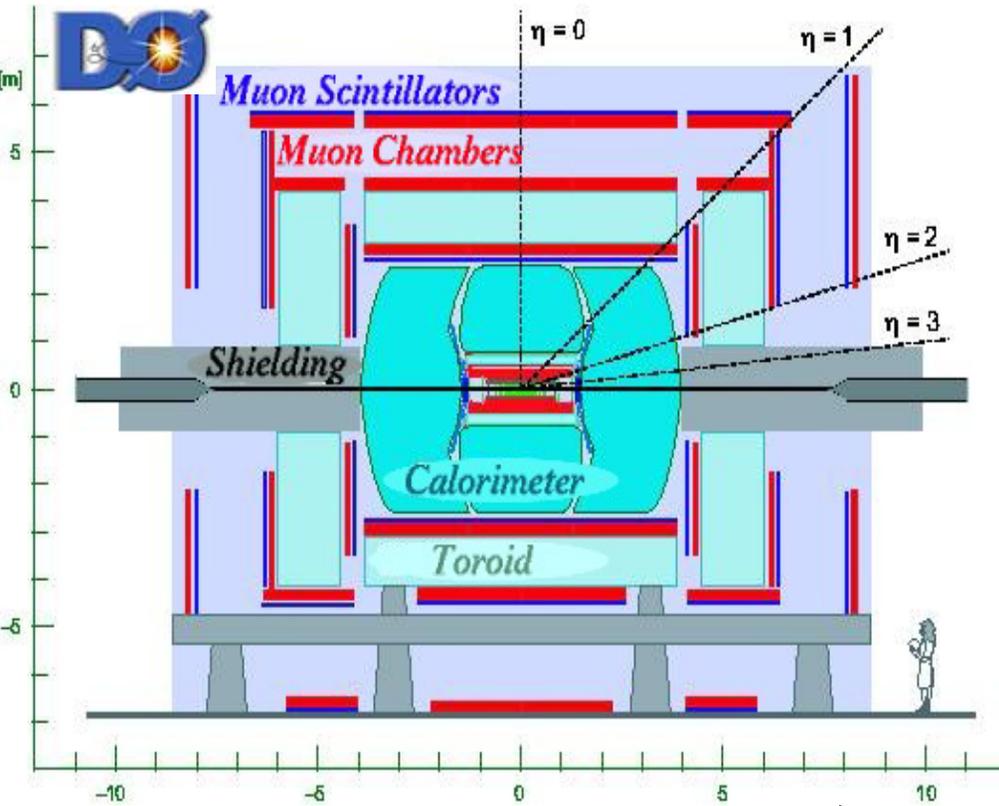
Delivered  $\sim 1.5 \text{ fb}^{-1}$   
Recorded  $\sim 1.2 \text{ fb}^{-1}$

Currently in shutdown:  
• Silicon and Trigger upgrades

4-8  $\text{fb}^{-1}$  expected by end of 2009

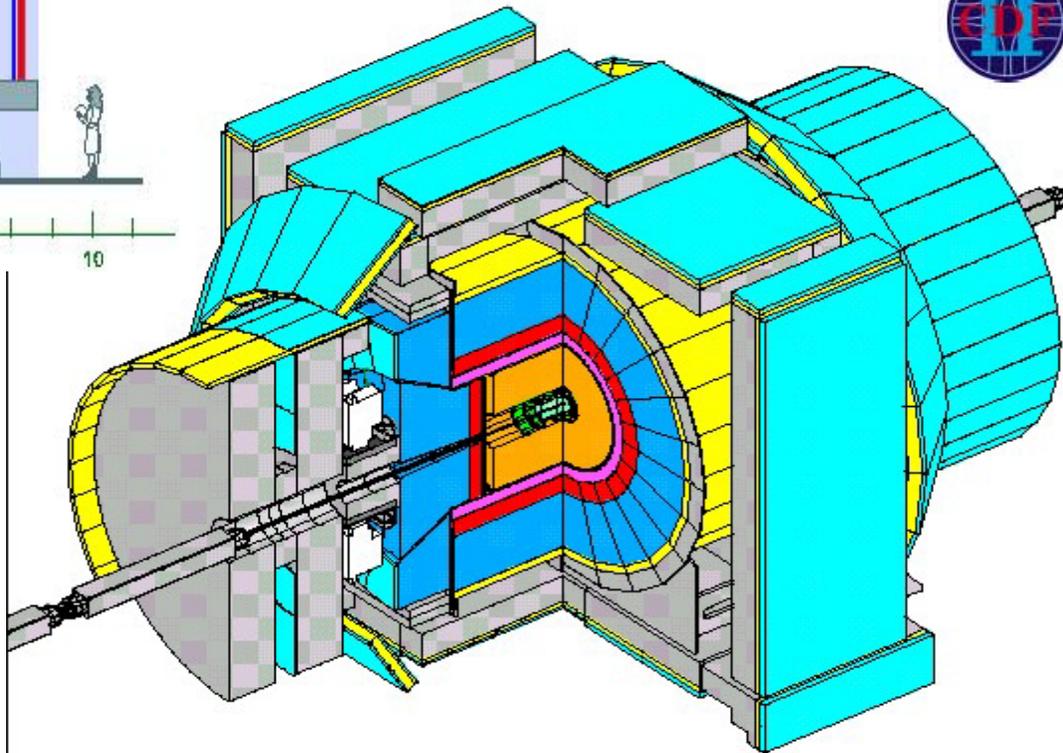


# DØ & CDF detectors



Higgs searches rely on

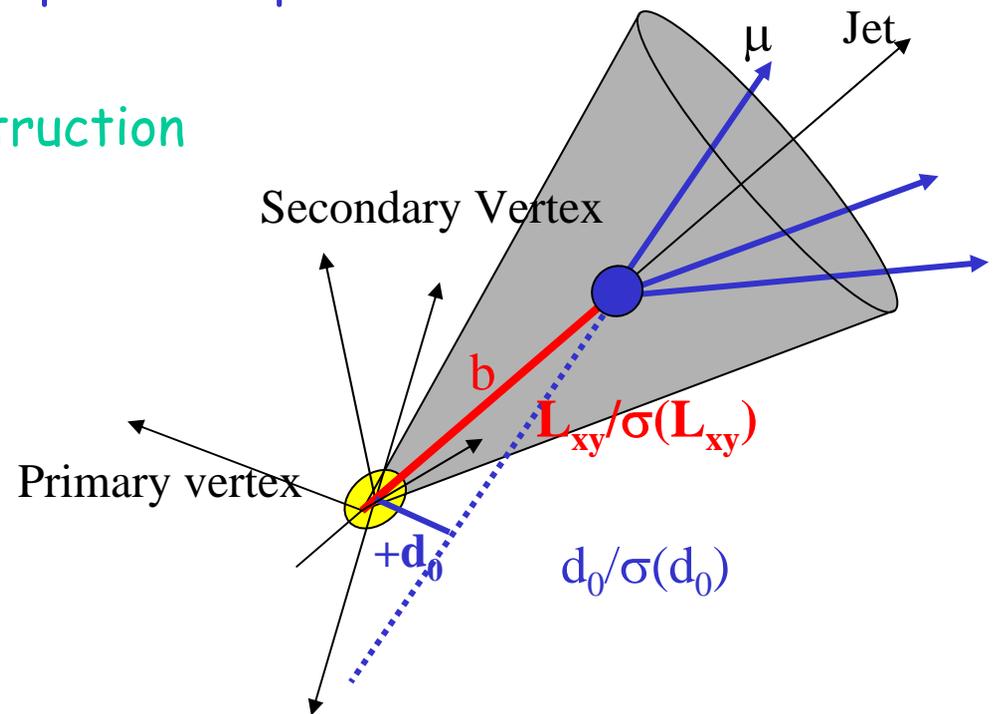
- Jets
- Lepton ID for W/Z
- b quark jets for  $H \rightarrow bb$  decay
- tau ID for  $h \rightarrow \tau\tau$
- missing  $E_T$  for  $W \rightarrow l\nu$  and  $Z \rightarrow \nu\nu$

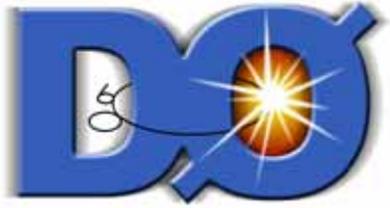


- e/jet ID by Calorimeter
- Good muon detector
- b-ID by inner tracking system
- muon/electron/jet triggers
- tau ID using Neural Network

# b tagging

- Characteristics of b-quarks
  - Leptons from semileptonic b decay ( $\text{Br}(b \rightarrow l\nu) \sim 10\%$ )
  - Travel some distance from the primary vertex before decaying
    - $\sim 1\text{mm}$
    - With charm cascade decay, about 4.2 charged tracks
- 3 main algorithms under development/improvement
  - Soft-lepton tagging
  - Secondary Vertex reconstruction
    - $L_{xy}/\sigma(L_{xy})$
  - Impact Parameter based
    - $d_0/\sigma(d_0)$

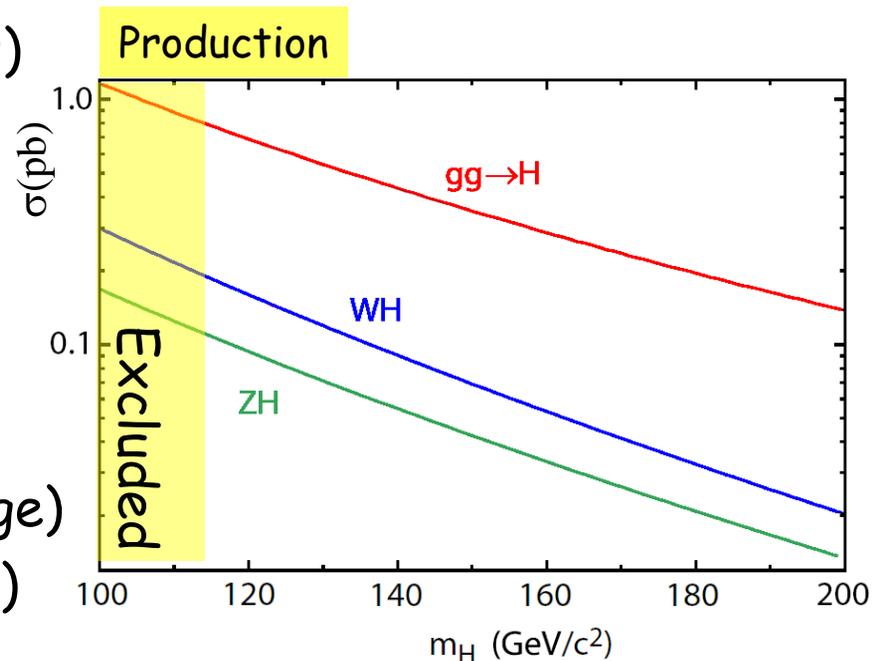




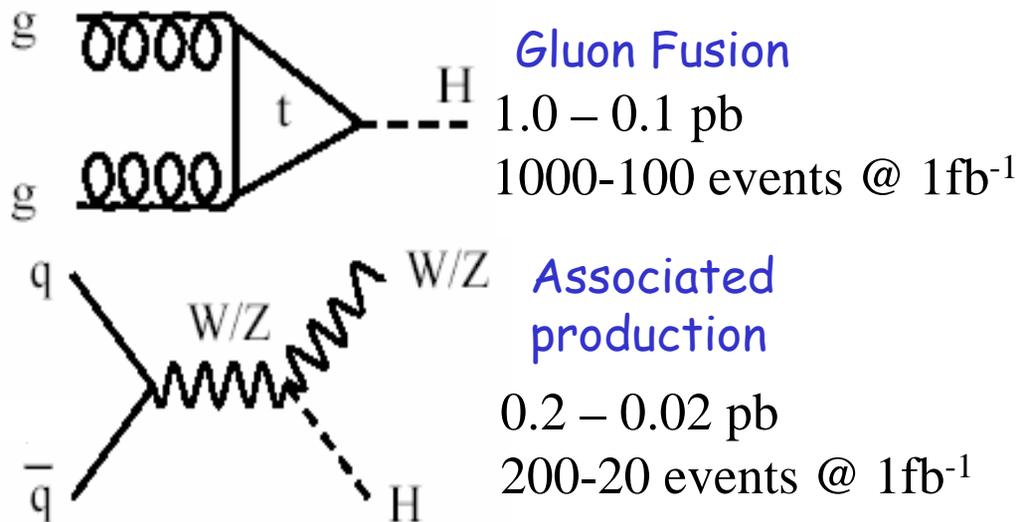
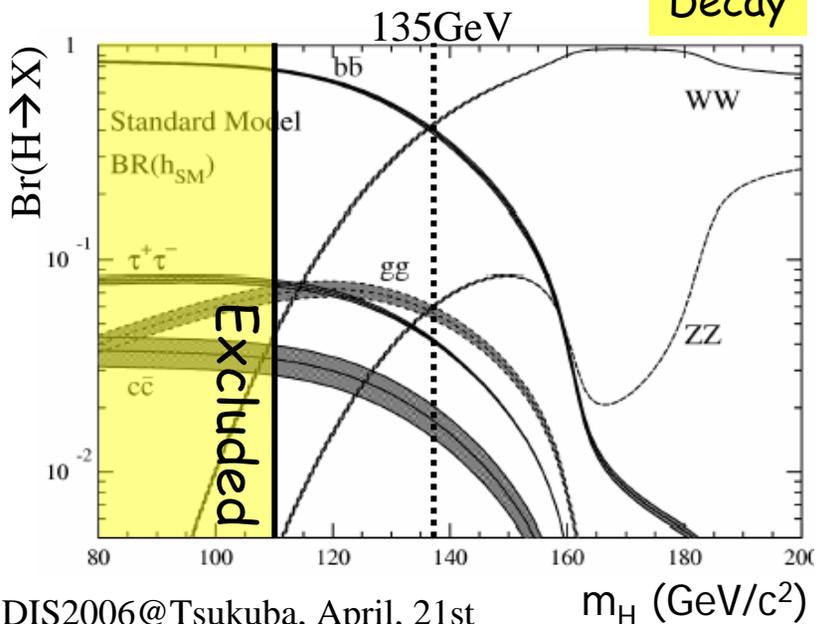
# 1. Standard Model Higgs boson searches

# SM Higgs searches at Tevatron

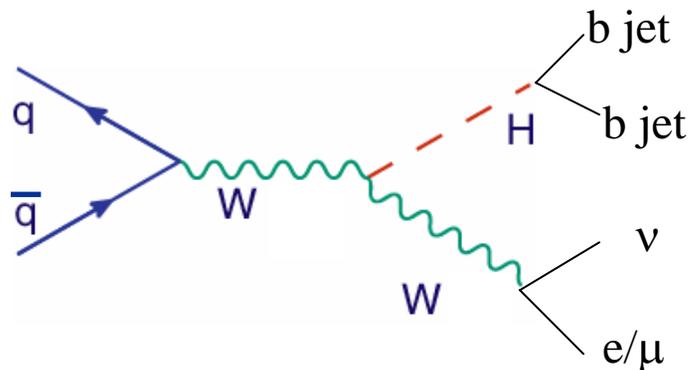
- $M_H < 135\text{GeV}$  :  $H \rightarrow bb$  (di b-jets mass)
  - $gg \rightarrow H \rightarrow bb$  sink down into deep QCD backgrounds
  - $WH \rightarrow l\nu bb$  (lepton +  $\cancel{E}_T$ )
  - $ZH \rightarrow \nu\nu bb, llbb$  ( $\cancel{E}_T$  or lepton(s))
- $M_H > 135\text{GeV}$  :  $H \rightarrow WW$  (di-lepton)
  - $gg \rightarrow H \rightarrow WW \rightarrow l\nu l\nu$  (opposite charge)
  - $WH \rightarrow WW \rightarrow l\nu l\nu X$  (same charge)



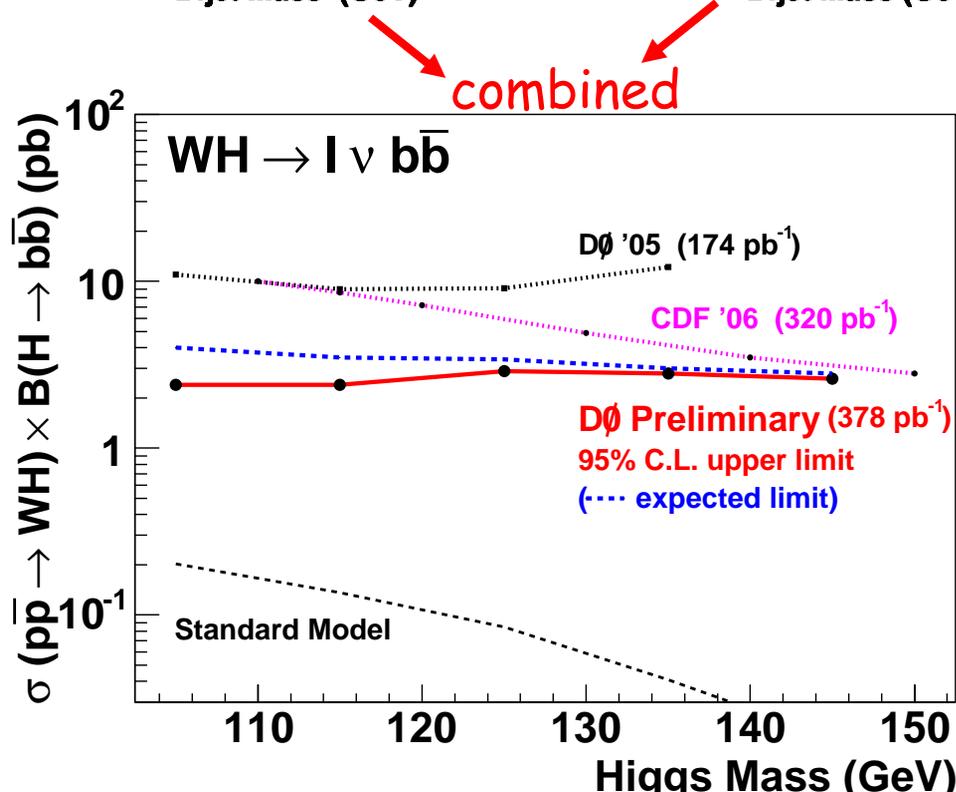
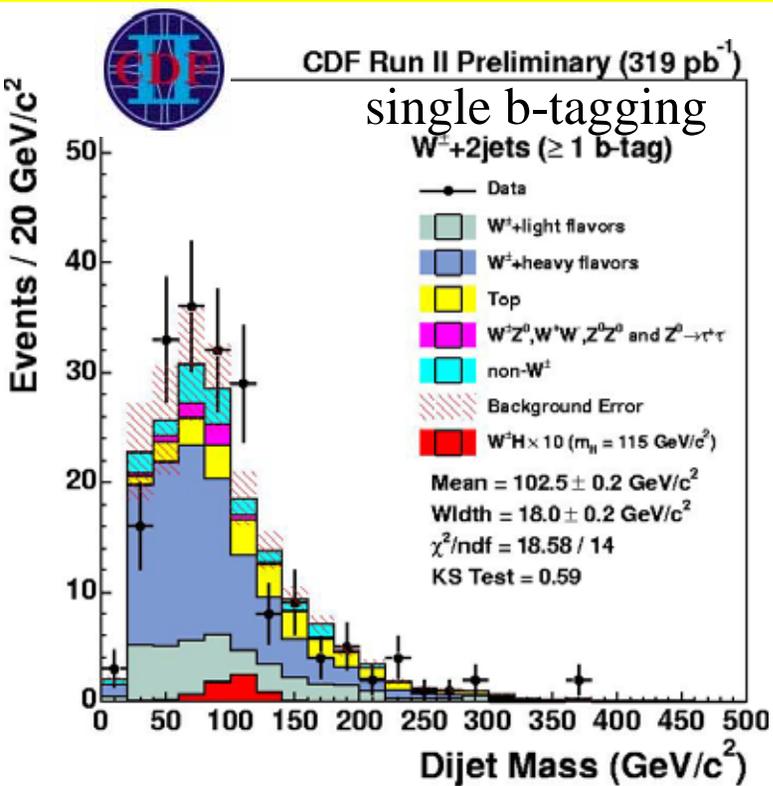
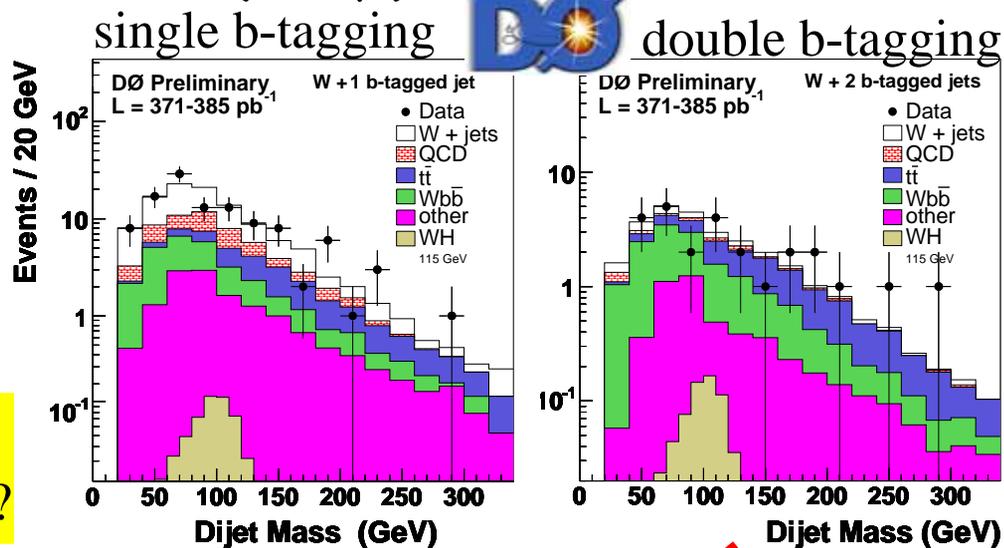
## Decay

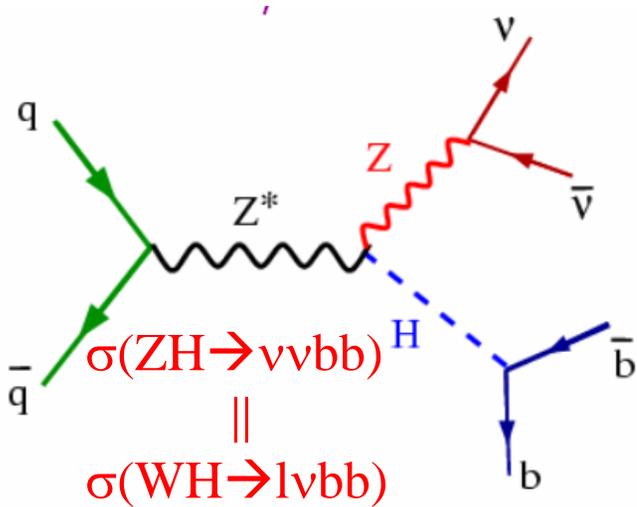


# WH → lνbb (l=e,μ)



- $e/\mu + \cancel{E}_T$  restricts QCD backgrounds
- Excess due to Higgs from dijet mass?



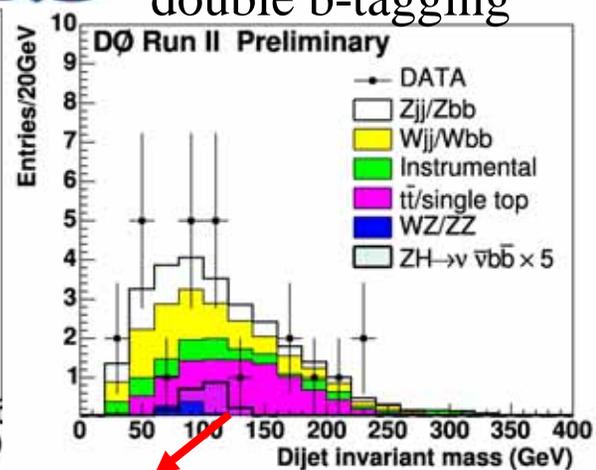
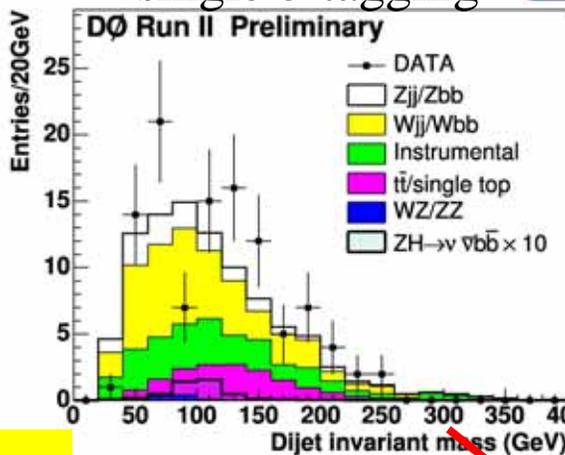


# ZH $\rightarrow$ $\nu\bar{\nu}bb$

single b-tagging



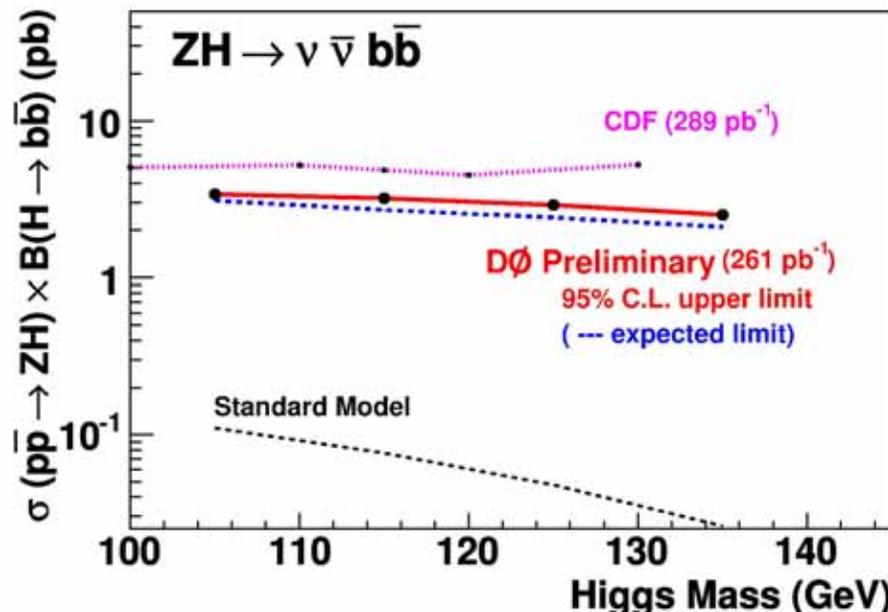
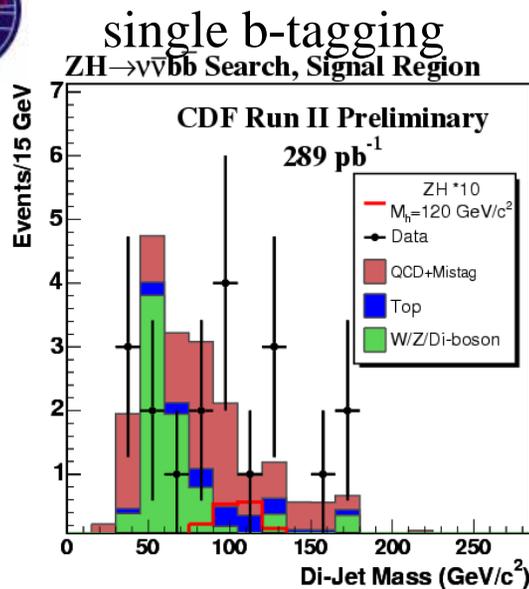
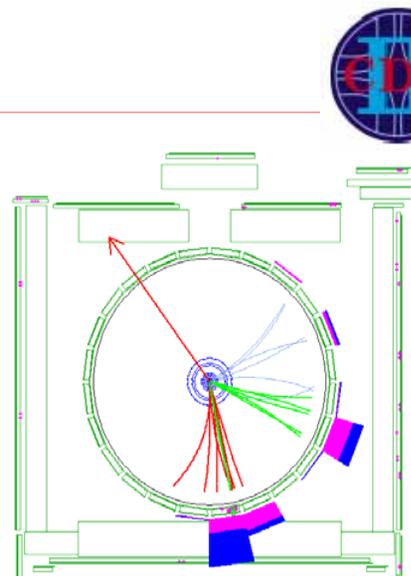
double b-tagging



combined

If lepton is missing  $\rightarrow$  WH  $\rightarrow$   $l\nu bb$  combined

- Large  $E_T$  rejects lots of QCD bkg  
 - QCD bkg estimated from sideband



$$WH \rightarrow WWW^* \rightarrow |vl'vX \quad (l, l' = e, \mu)$$

- Event Selection

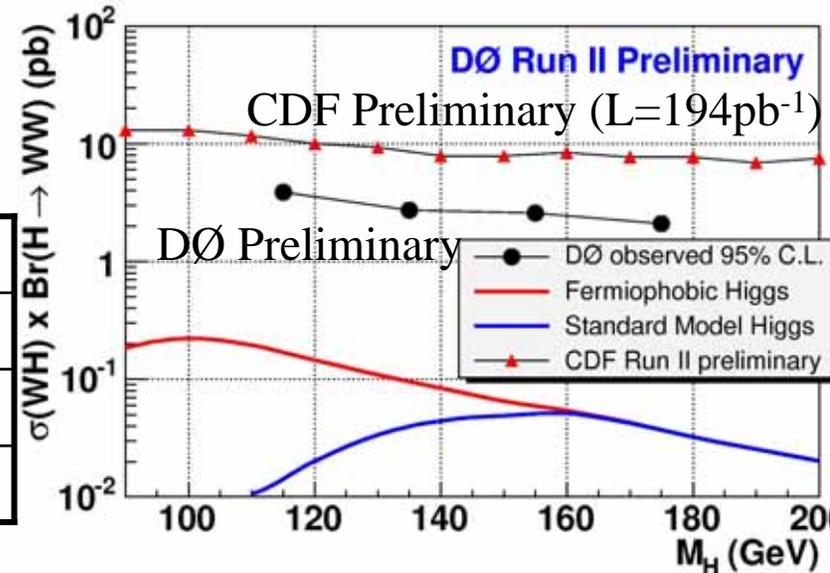
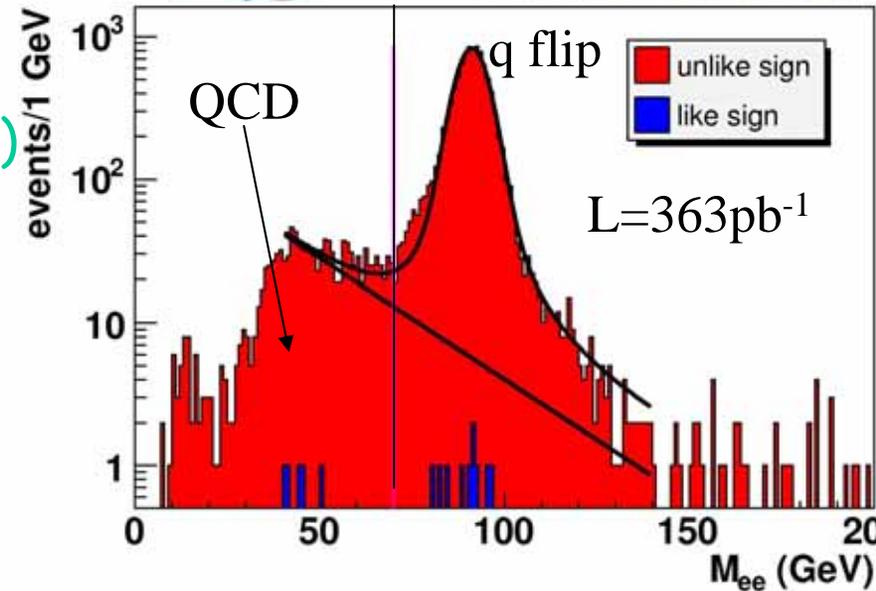
- Same charge di-lepton from W's (One from H, the other from WH) suppress SM backgrounds
- $p_T(\text{lepton}) > 15 \text{ GeV}$
- $E_T > 20 \text{ GeV}$

- Main backgrounds

- WZ production  $\rightarrow MC$
- Charge flip from  $Z/\gamma^* \rightarrow ll, WW,$  and  $tt \rightarrow llX \rightarrow \text{data}$
- QCD multijet,  $W+\text{jets} \rightarrow \text{data}$



DØ Run II Preliminary



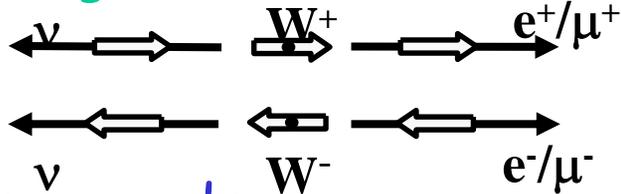
|          | observed | expected        | $\epsilon$ % ( $M_H=155\text{GeV}$ ) |
|----------|----------|-----------------|--------------------------------------|
| $ee$     | 1        | $0.70 \pm 0.08$ | $1.17 \pm 0.06$                      |
| $e\mu$   | 3        | $4.32 \pm 0.23$ | $2.81 \pm 0.19$                      |
| $\mu\mu$ | 2        | $3.72 \pm 0.75$ | $2.01 \pm 0.22$                      |

$$H \rightarrow WW^* \rightarrow |v|v' (l, l' = e, \mu)$$



## Event Selection

- Cannot reconstruct H mass
- Angular correlation between  $e/\mu$

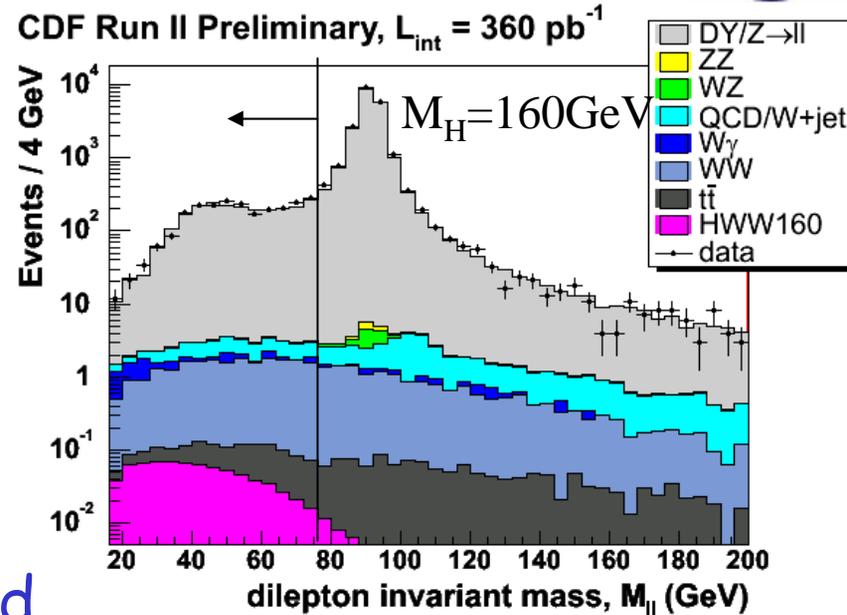
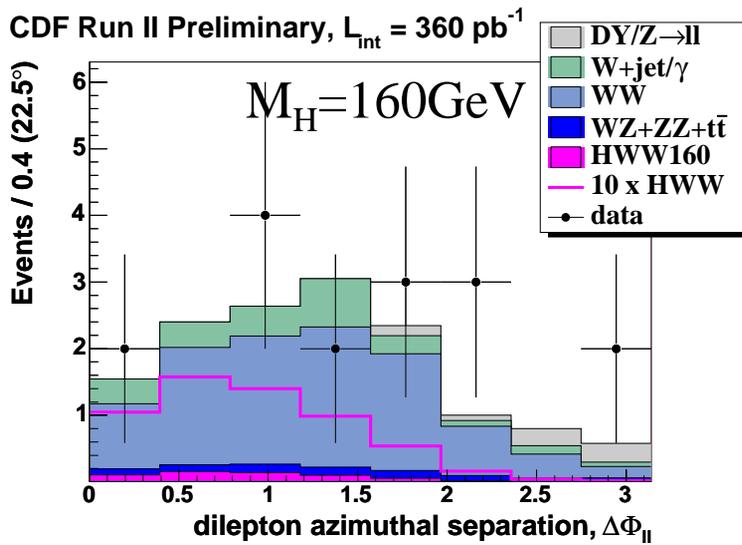


## Backgrounds

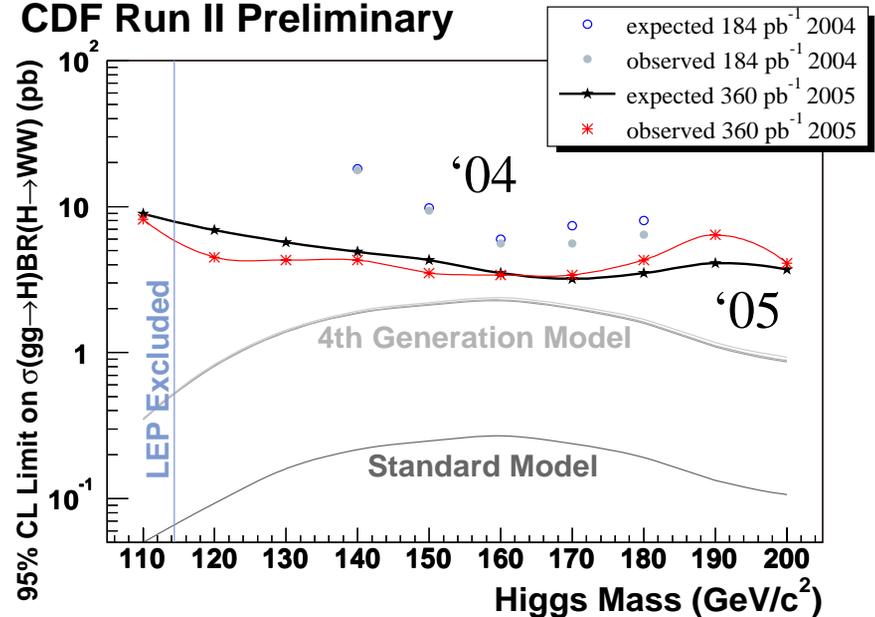
- $Z/\gamma^* \rightarrow ll$ ,  $WW$ ,  $W\gamma$ ,  $WZ$ ,  $ZZ$ ,  $t\bar{t}$ , and  $W$ +jets

## 95% limits from binned likelihood

- $\Delta\phi(ll)$  distribution



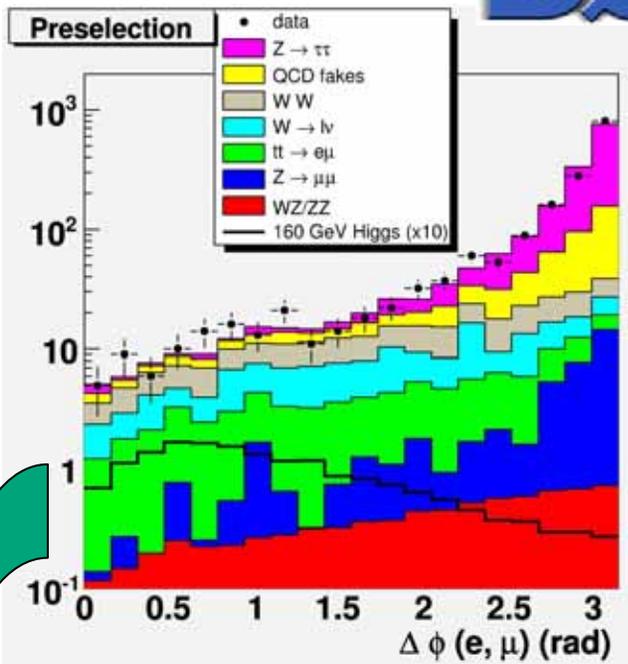
## CDF Run II Preliminary



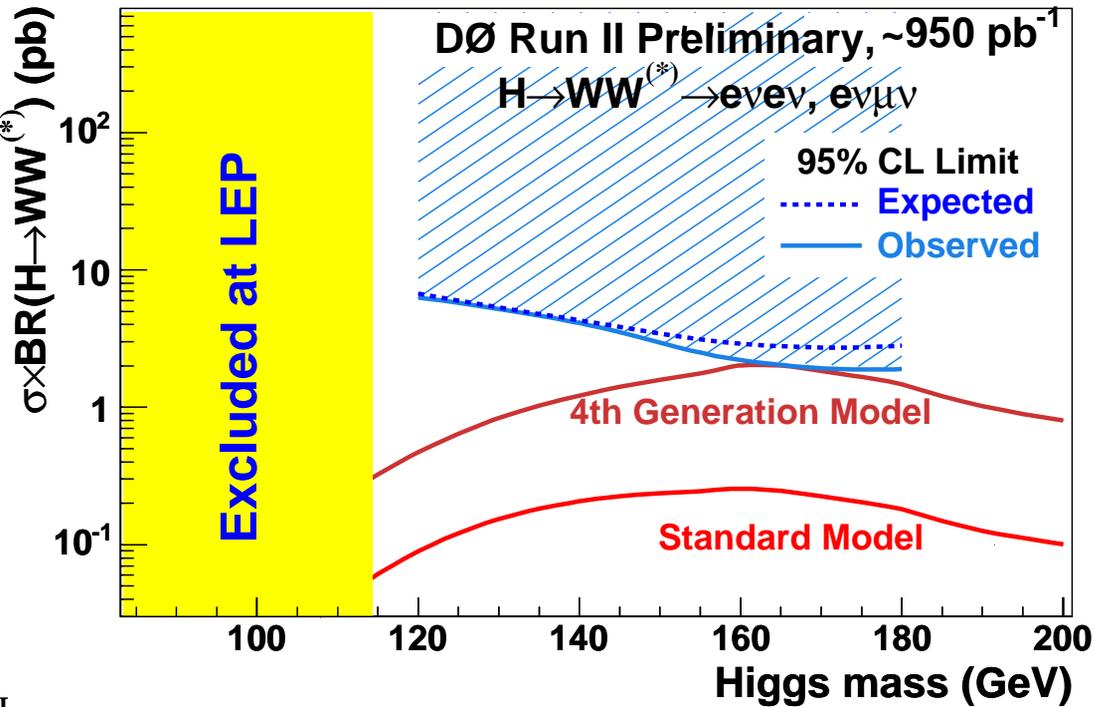
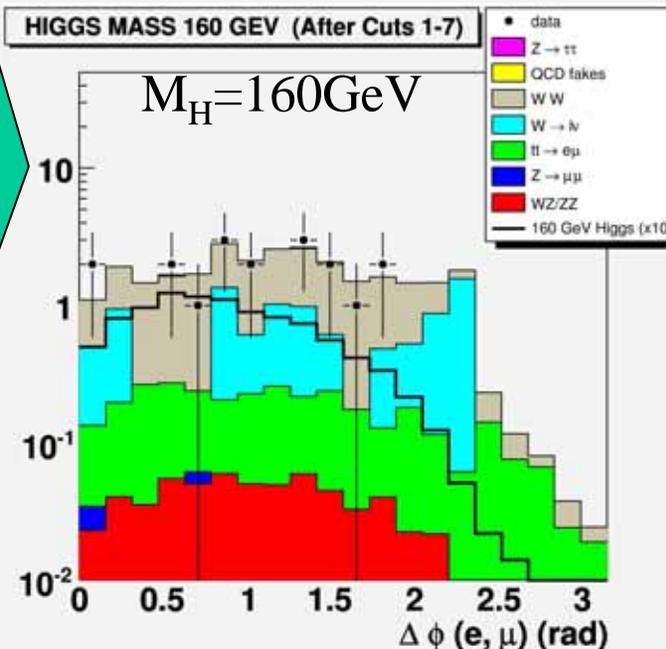


# $H \rightarrow WW^* \rightarrow l\nu l\nu$ (ee or $e\mu$ )

- Full data sets ( $L=950\text{pb}^{-1}$ )
  - ee and  $e\mu$  channel only
  - $p_T(1^{\text{st}}) > 15\text{GeV}$ ,  $p_T(2^{\text{nd}}) > 10\text{GeV}$
  - $Z/g^* \rightarrow ll$ , and energetic jets veto
- 95% C.L. limits from CLs method
  - 4<sup>th</sup> Generation Model starts to be excluded



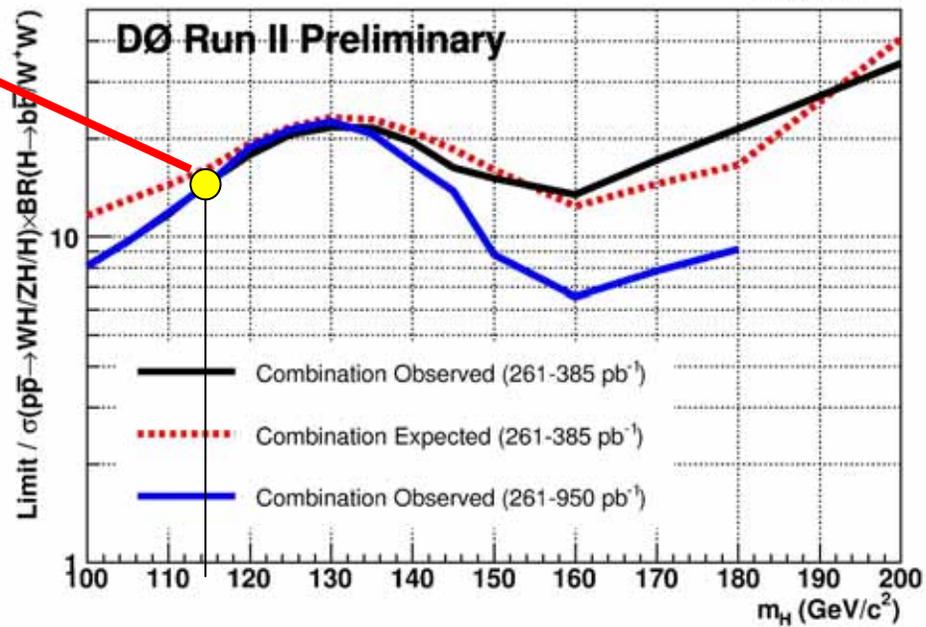
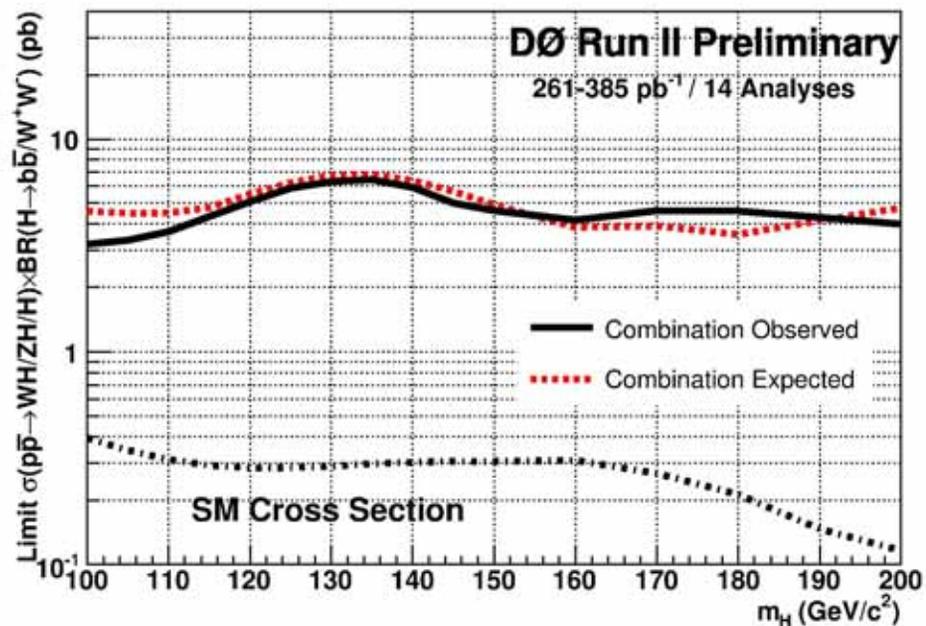
selections



# Combined Higgs boson search



- First attempt to see a combined result from DØ
  - 14 different analysis
    - decay mode, lepton flavor, b-tag conditions
  - Combination is done by modified frequentists method (CLs)
- So far, a factor of 15 away from SM prediction ( $M_H=115\text{GeV}$ )
  - with  $L=2\text{fb}^{-1}$ , CDF/DØ combined, NN b-tagging, NN selections, track-cal jets, increased acceptance, additionally new channels, cross efficiency, and reduced systematic
    - cross section factor  $\rightarrow 1$



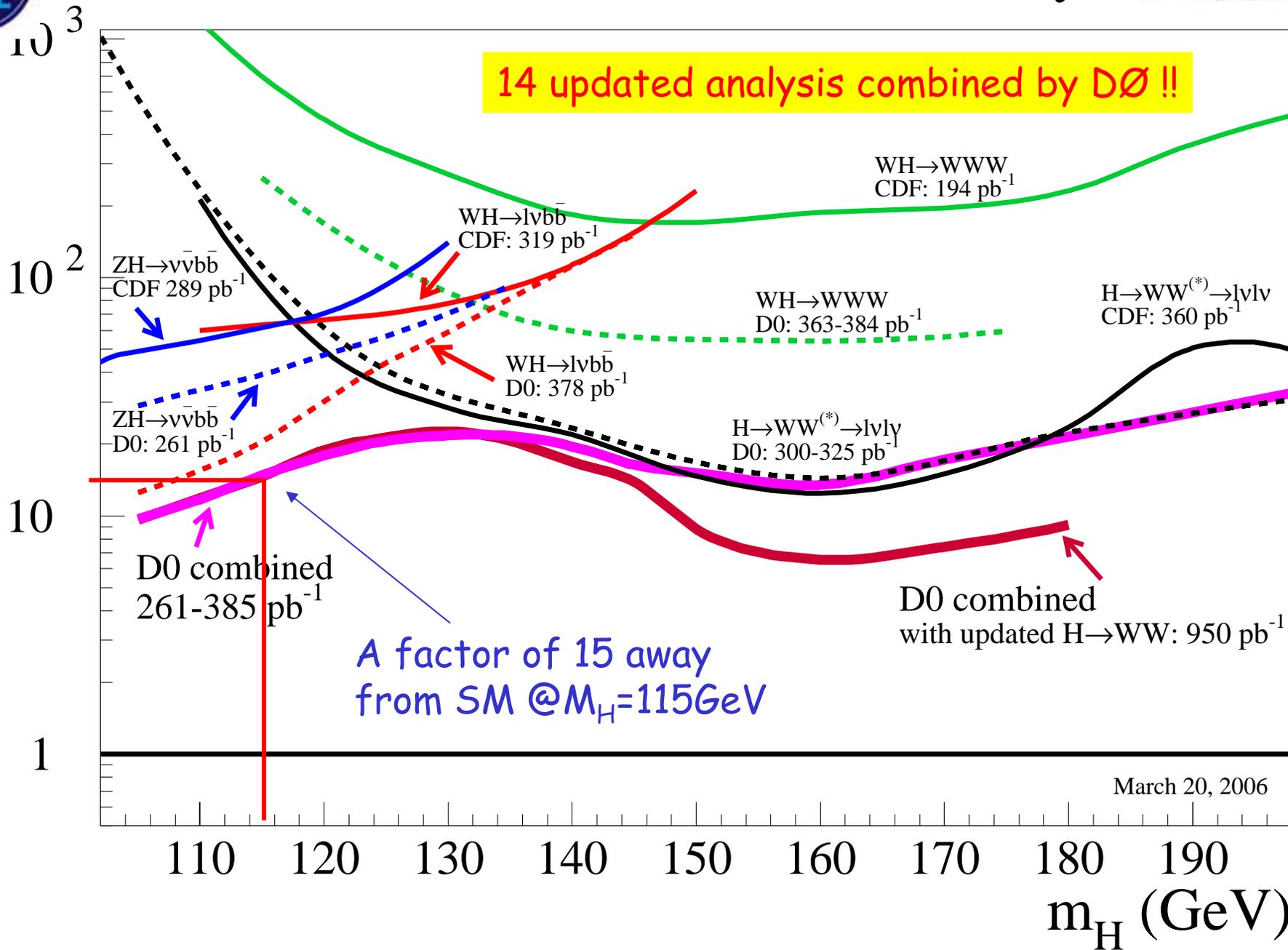


# Tevatron Run II Preliminary

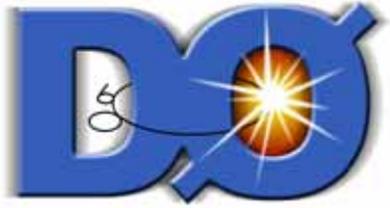


95% CL Limit/SM

14 updated analysis combined by DØ !!



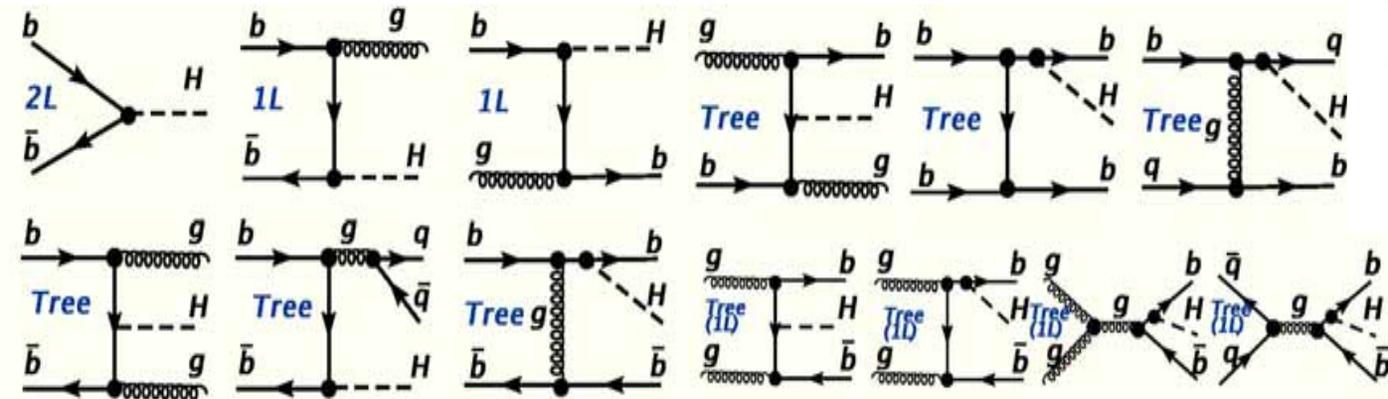
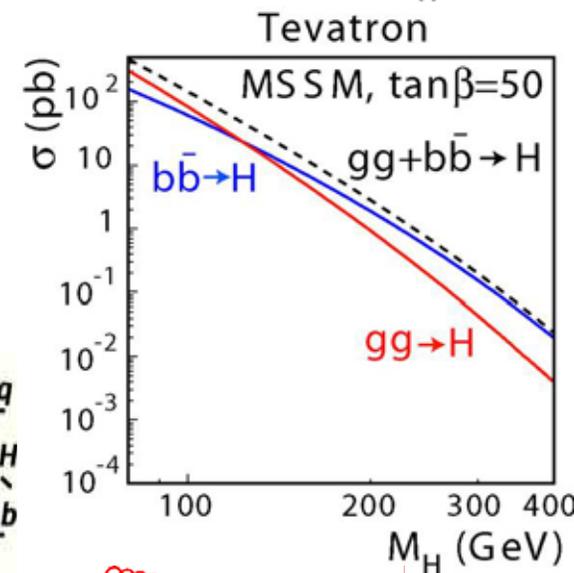
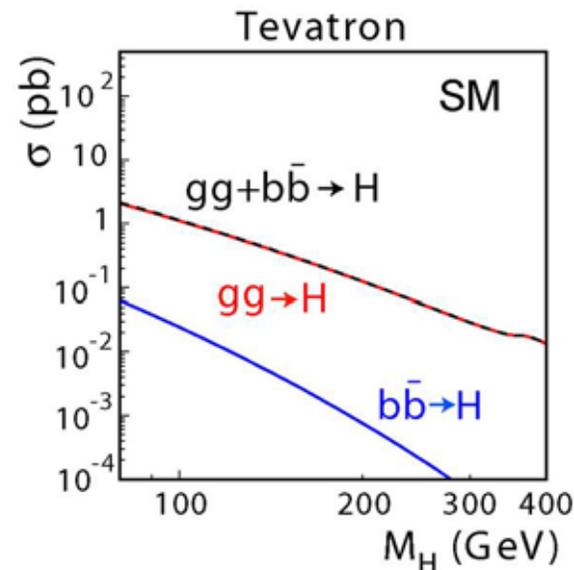
March 20, 2006



## 2. SUSY Higgs boson searches

# SUSY Higgs bosons

- In two Higgs doublet model, such as MSSM
  - 5 physical Higgs bosons  $h, H, A, H^\pm (m_h < m_H)$
- $\tan\beta = v_u/v_d$ : ratio of VEV of 2 Higgs fields
  - Cross sections for  $bbh$  enhanced like  $\tan^2\beta$
- $h$  is predicted to be light ( $m_h < \sim 135 \text{ GeV}$ )
  - LEP limit is  $m_h > \sim 92 \text{ GeV @ 95 C.L.}$
  - Tevatron is sensitive to large  $\tan\beta$
- At high  $\tan\beta$ ,  $A$  is almost degenerate with  $h/H$ 
  - $\sigma(A) \sim \sigma(h/H), \Gamma(A) \sim \Gamma(h/H)$
  - $\text{Br}(A \rightarrow bb) \sim \text{Br}(h/H \rightarrow bb) \sim 90\% \dots hbb$
  - $\text{Br}(A \rightarrow \tau\tau) \sim \text{Br}(h/H \rightarrow \tau\tau) \sim 10\% \dots h \rightarrow \tau\tau$

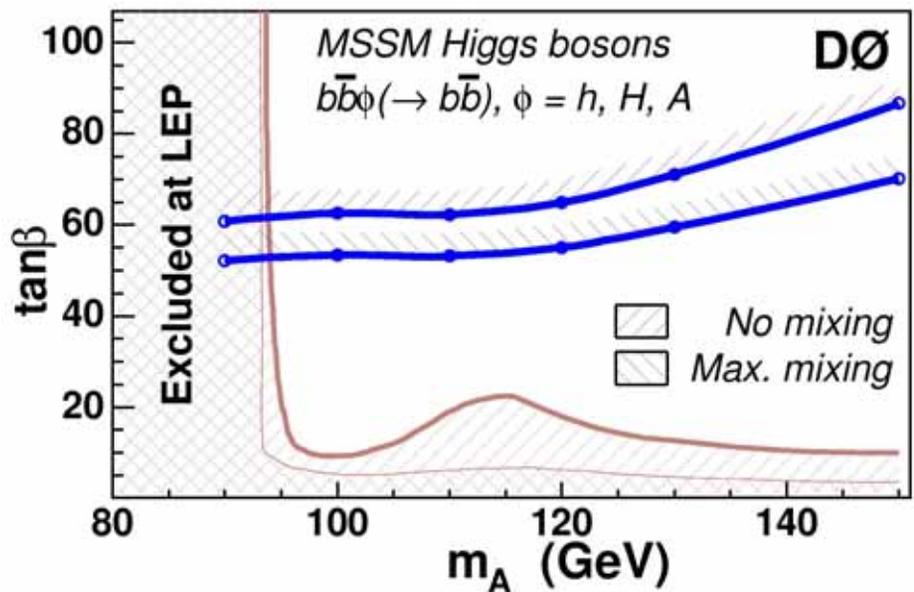
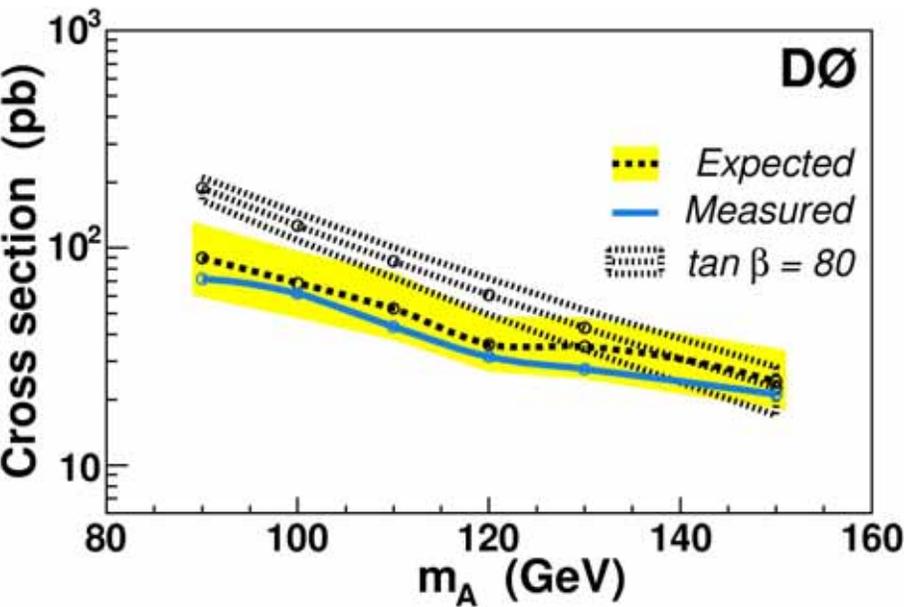
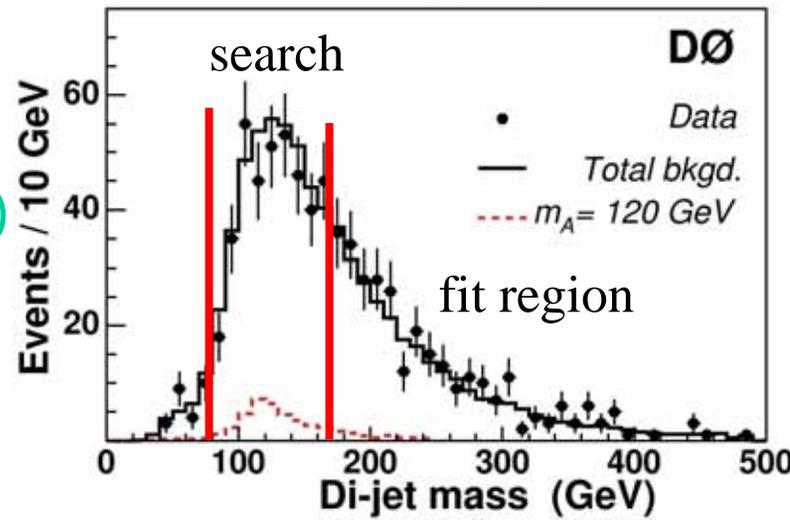


# hb(b)



- $L=260\text{pb}^{-1}$
- At least 3 b-tagged jets
  - $p_T$  cuts optimized
  - b-tag rate estimated from data ( $\sim 2\%$ )
    - 2 b-tagged sample  $\times$  b-tag rate
  - $Z(bb,cc)+\text{jets}, tt$  estimated from MC
- No Excess found
  - 95% C.L. from fit of dijet mass

at least 3 b-tagged jets





$$h \rightarrow \tau\tau$$



•  $L = 310(\text{CDF})/325(\text{DØ}) \text{ pb}^{-1}$

CDF:  $L=310\text{pb}^{-1}$ , DØ:  $348\text{pb}^{-1}$

• Sample

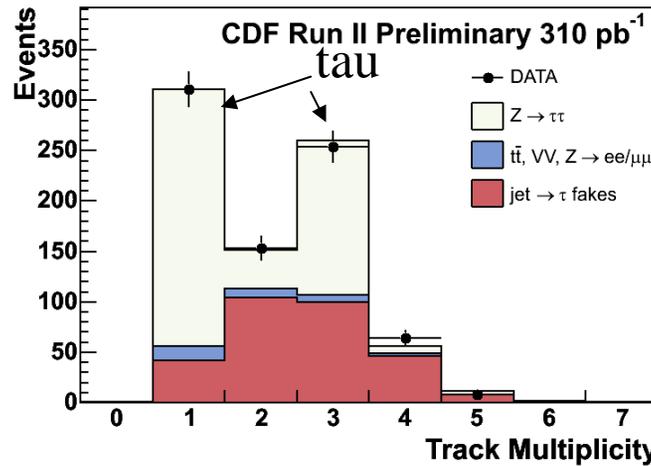
- $\tau_e/\tau_\mu + \tau_{\text{had}}$
- $\tau_e + \tau_\mu$  (DØ only)

• Selection

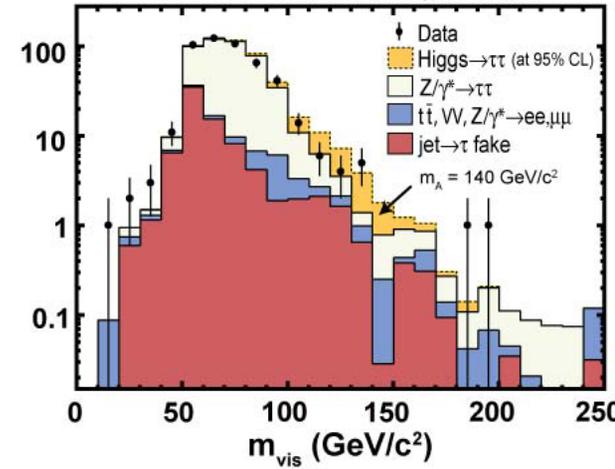
- NN for  $\tau$  ID
- visible mass

$p_T(e/\mu/\tau)$  and  $\cancel{E}_T$

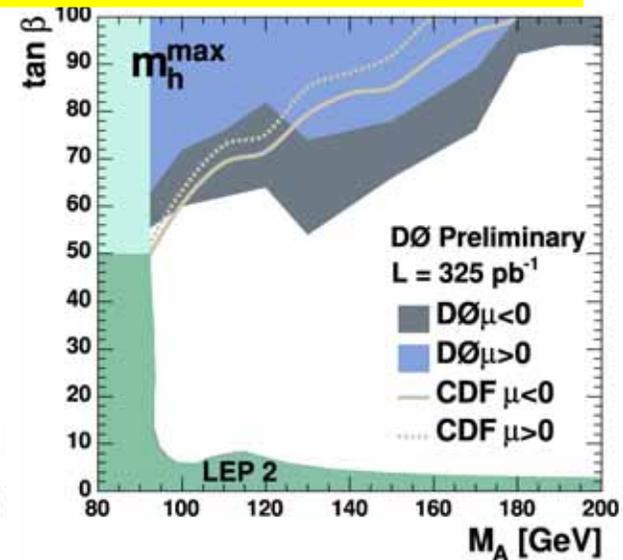
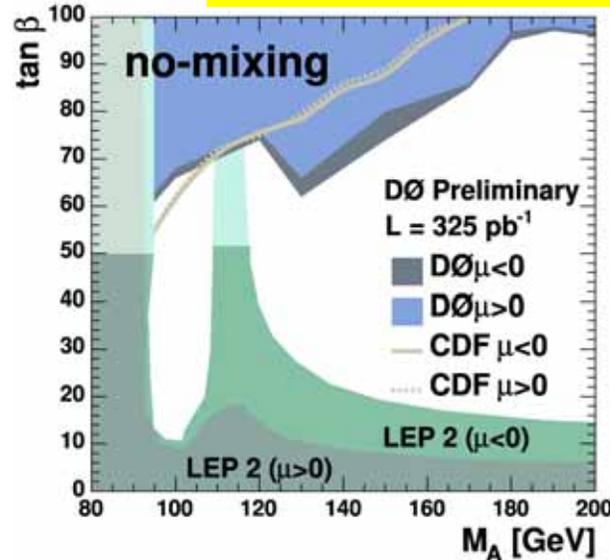
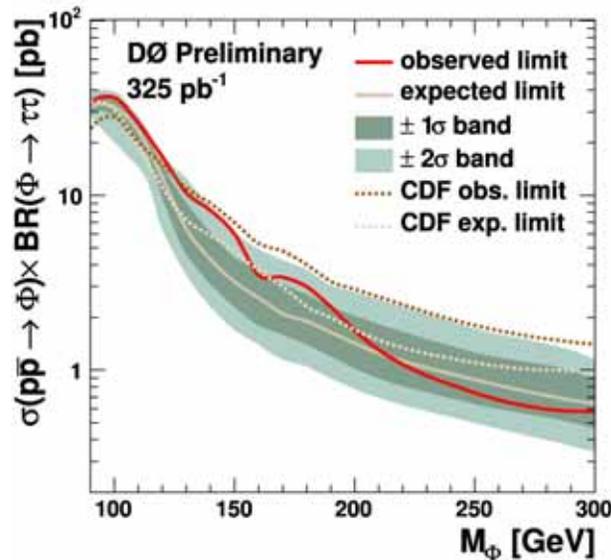
MSSM Higgs  $\rightarrow \tau\tau$  Search, Track Multiplicity



CDF Run II Preliminary, 310 pb<sup>-1</sup>

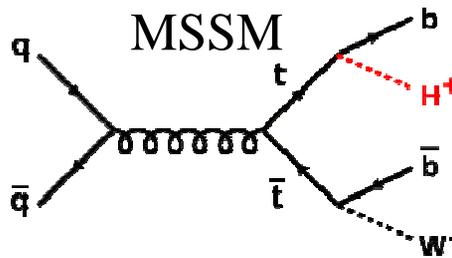
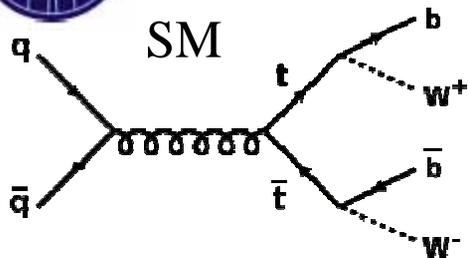


DØ:  $hbb+h \rightarrow \tau\tau$  combined, CDF:  $h \rightarrow \tau\tau$  only





# Charged MSSM Higgs boson search in $t\bar{t}$



Search for difference from SM  
Major decay modes:

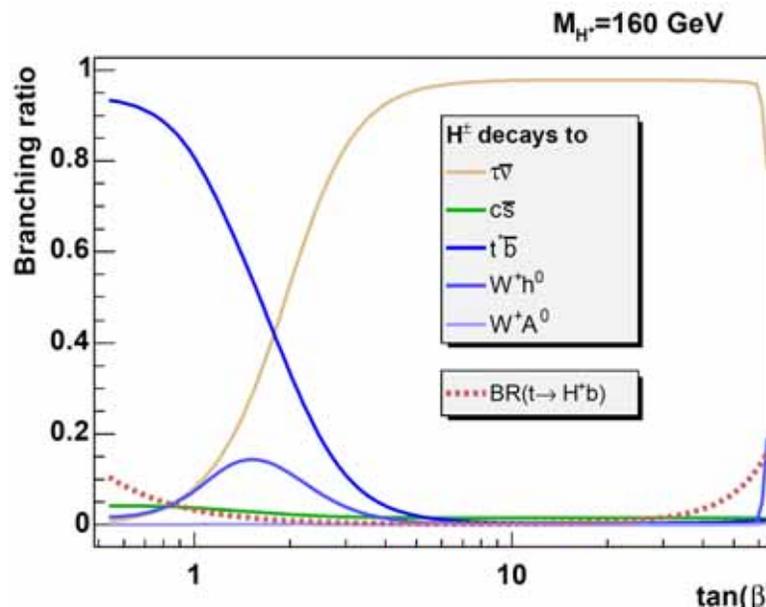
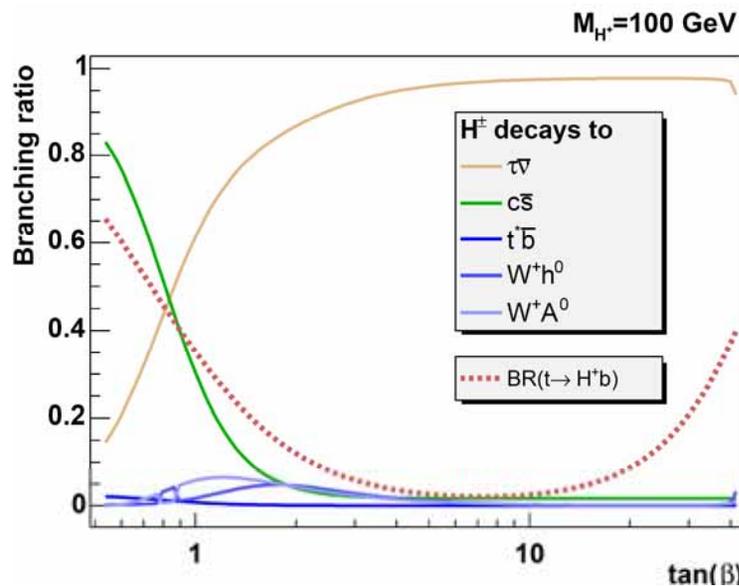
$$H^+ \rightarrow \tau \nu$$

$$H^+ \rightarrow c\bar{s}$$

$$H^+ \rightarrow t^* b \rightarrow W + bbb$$

$$H^+ \rightarrow W + h \rightarrow W + bb$$

- Look at four  $t\bar{t}$  final states:
  - di-lepton + jets
  - lepton + jets (=1 b-tag)
  - lepton + jets ( $\geq 2$  b-tags)
  - lepton + tau + jets
- Interpret for several MSSM scenarios,  $\tan \beta$ , and  $m_H$



# Charged MSSM Higgs search



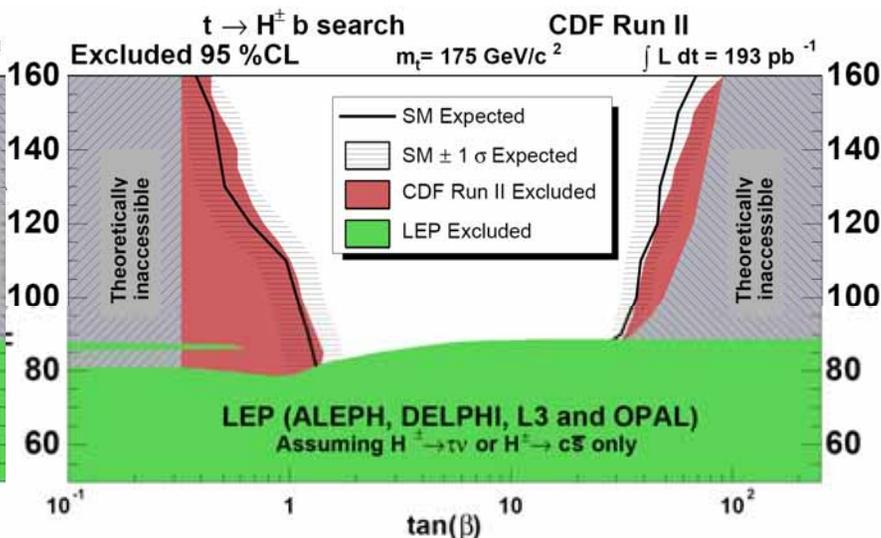
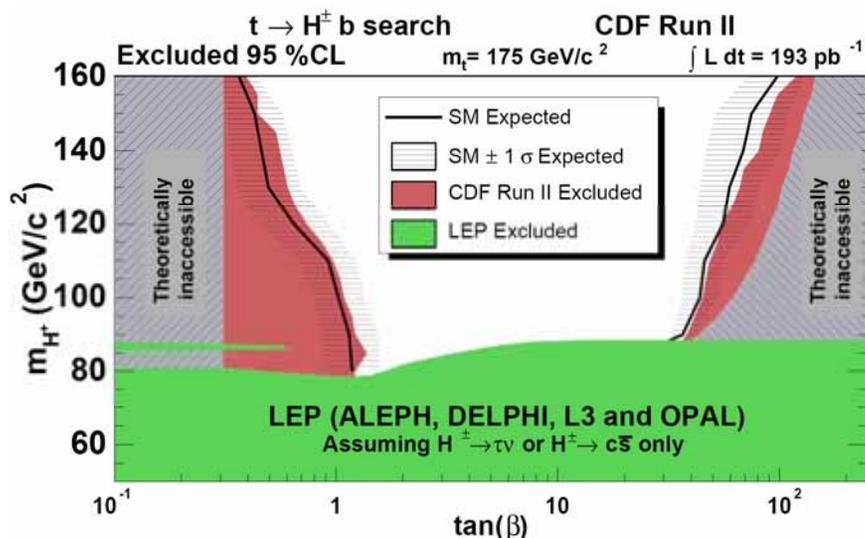
$L = 193 \text{ pb}^{-1}$

Consistent with SM prediction

| Final state                     | bg events       | SM exp | data |
|---------------------------------|-----------------|--------|------|
| $2\ell + \text{jets}$           | $2.7 \pm 0.7$   | 11     | 13   |
| $\ell + \text{jets (1b)}$       | $20.3 \pm 2.5$  | 54     | 49   |
| $\ell + \text{jets } (\geq 2b)$ | $0.94 \pm 0.17$ | 10     | 8    |
| $\ell + t + \text{jets}$        | $1.3 \pm 0.2$   | 2      | 2    |

No-mixing benchmark scenario

$m_h^{\max}$  benchmark scenario



$M_{\text{SUSY}}=1000 \text{ GeV}/c^2$ ,  $\mu=-200 \text{ GeV}/c^2$ ,  $A_t=A_b=\mu/\tan(\beta)$ ,  $A_\tau=500 \text{ GeV}/c^2$   
 $M_0=0.498 \cdot M_{\text{SUSY}}$ ,  $M_1=200 \text{ GeV}/c^2$ ,  $M_2=800 \text{ GeV}/c^2$ ,  $M_3=M_0$ ,  $M_H=M_A=M_{H^\pm}=M_{\text{SUSY}}$

$M_{\text{SUSY}}=1000 \text{ GeV}/c^2$ ,  $\mu=-200 \text{ GeV}/c^2$ ,  $A_t=A_b=\sqrt{6}M_{\text{SUSY}}+\mu/\tan(\beta)$ ,  $A_\tau=500 \text{ GeV}/c^2$   
 $M_0=0.498 \cdot M_{\text{SUSY}}$ ,  $M_1=200 \text{ GeV}/c^2$ ,  $M_2=800 \text{ GeV}/c^2$ ,  $M_3=M_0$ ,  $M_H=M_A=M_{H^\pm}=M_{\text{SUSY}}$

# Conclusion

- Tevatron is hunting Higgs bosons
  - SM Higgs boson
  - with extension like MSSM Higgs boson
- CDF and DØ competing and will perform combined result soon
  - First attempt of SM Higgs combination at DØ
- Current results encouraging us.
  - 3-4 times more data in tape
  - Learned improved analysis
  - Sensitivity to  $M_H > 114 \text{ GeV}$  starts at  $2 \text{ fb}^{-1}$
  - Exclusion up to  $180 \text{ GeV}$  possible with  $8 \text{ fb}^{-1}$