# Tevatron Higgs Searches in Run II

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## Overview

- Overview of Higgs signatures
- Higgs Production and Decay
- Tevatron and CDF/DØ upgrades
- B Tagging Capabilities and Jet Resolution
- Sensitivity for a Standard Model Higgs
- SUSY Higgs detection
- Summary

# The Standard Model

The ingredients of the SM are

- 12 fermions
  - 6 quarks (u, d, s, c, b, t)
  - 6 leptons ($e^-$, $\nu_e$, $\mu$, $\nu_\mu$, $\tau$, $\nu_\tau$)
- 3 electroweak bosons ($W^+$, $W^-$, $Z^\circ$, $\gamma$)
- 8 gluons to describe the strong force
- ?? to describe gravity

Enormously successful paradigm since $\sim 1975$

- Predicted rich phenomenology
- Accurate! (eg. $\delta_{M_z}/M_z \sim 8 \times 10^{-5}$)
- Successfully predicted existence of charm and top quark

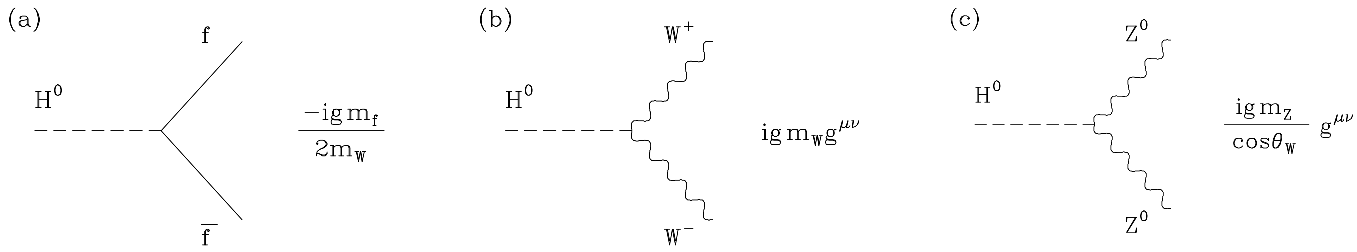
Higgs boson the only "essential" missing element

- Represents a significant "vacuum" of knowledge
- Its discovery has the highest scientific urgency

# Brief Overview of Higgs Phenomenology

## Higgs allows "spontaneous symmetry breaking" in SM

- Sets the EWK mass scale
- Yukawa interactions with fermions generates mass



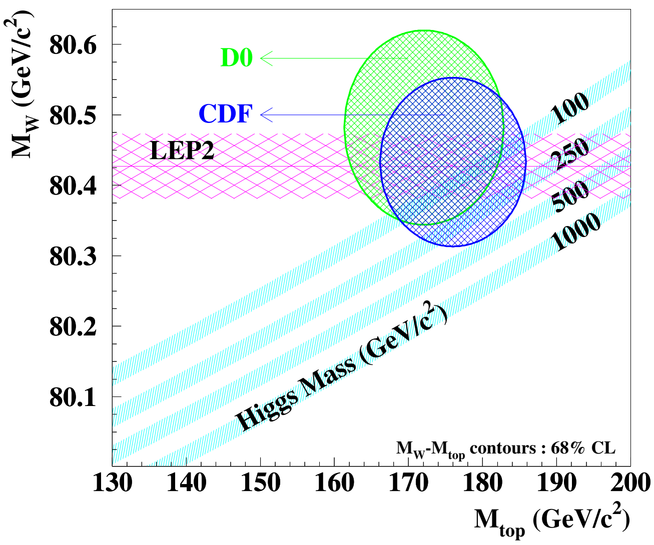

## It couples to quarks, leptons and EWK gauge bosons

- Production rate set by mass & couplings to "beam"
- Decays are mediated by same couplings
- In $p\bar{p}$ collisions, produced
  - via $q\bar{q}$ annihilations through
    * virtual $W/Z$ for light quark initial states
    * directly via $b\bar{b}$ initial states
  - indirectly in $gg$ interactions through $gg \to t\bar{t} \to H$

# Current Limits on the Higgs

Data point to a low mass Higgs

- LEP II data excludes $M_H < 113$ GeV/c$^2$
  - suggests an effect around 115 GeV/c$^2$
- Tevatron & LEP II data imply $M_H \lesssim 200$ GeV/c$^2$



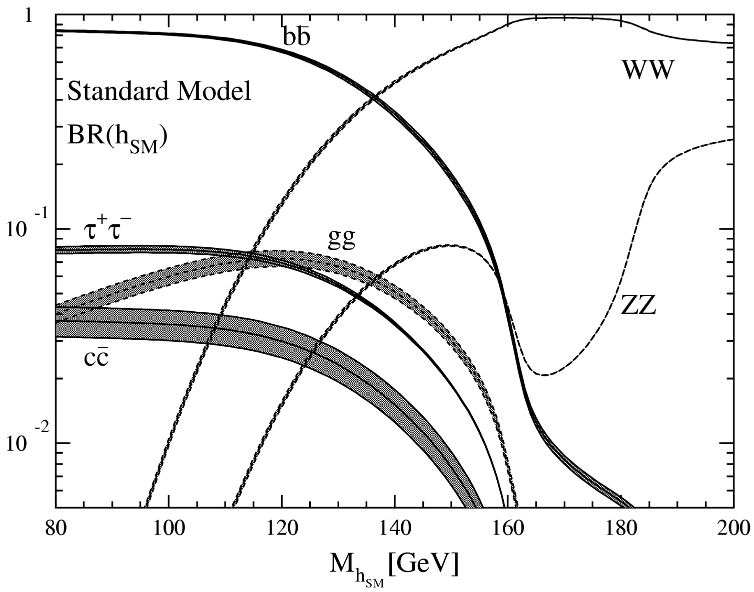

The Higgs sector is already constrained

- LEP II limit of 113 and $\sim 200$ GeV/c$^2$
- A Higgs discovery could be just around the "corner"

# Features of a Light SM Higgs

Higgs couplings to fermions & EWK bosons specify BR

- In region $M_H < 130$ GeV/c$^2$, $H \to b\bar{b}$ dominates
- For $M_H > 130$ GeV/c$^2$, $H \to WW^*$ takes over
- Cross over is $\sim 135$ GeV/c$^2$
- Other decay modes important, but are not relevant to a Tevatron search

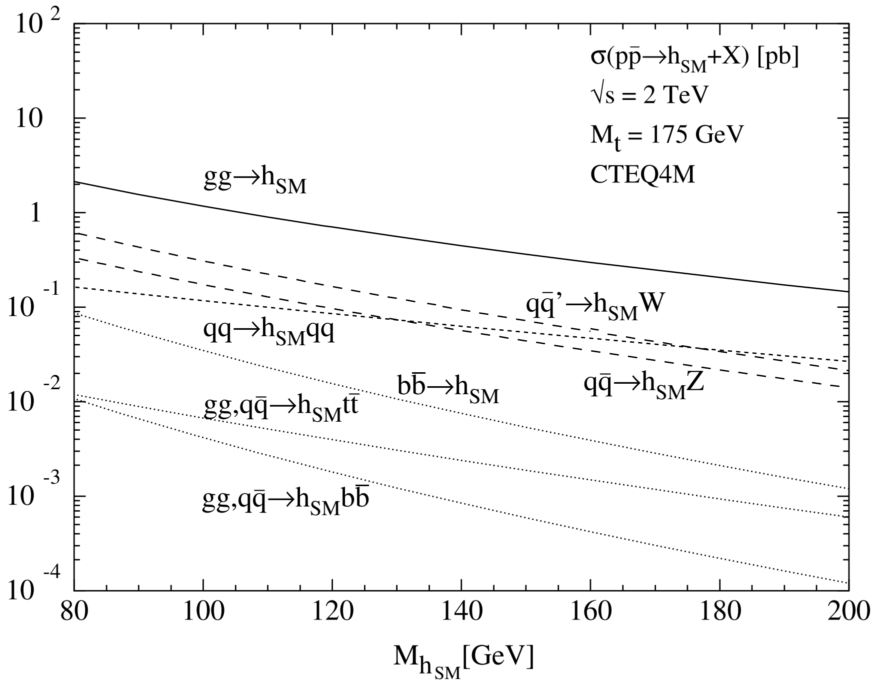



Dicus, Steltzer, Sullivan & Willenbrock, PRD D59 (1999)
Spira, private comm.

# Higgs Production Cross Section

Cross section at Tevatron energies miniscule

- Arises from small couplings to light fermions
- Makes "associated" production quite important




Some relevant points of reference:

- Total cross section $\sim 7 \times 10^{10}$ pb
- Smallest measured total cross section $\sim 5$ pb
- Lowest upper limits $\sim 0.1 - 0.2$ pb ($W'$)

# Tevatron Upgrades for Run II

Tevatron has been significantly improved for Run II

- Main Injector replaces Tevatron for injection
  - Better $\bar{p}$ transfer efficiency
  - Emittance better-matched at injection

- Antiproton Recycler – effective doubling in $\bar{p}$ production rate

- Increase in $\sqrt{s}$ from 1.8 to 2.0 TeV

  $\Rightarrow$ 30-40% increase in production $\sigma$

- Go from $6 \times 6 \rightarrow 36 \times 36$ operation
  - Reduces interactions per crossing

Performance goals for collider are

- Increase typical $L_{max}$ from $1.6 \times 10^{31}$ to $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$

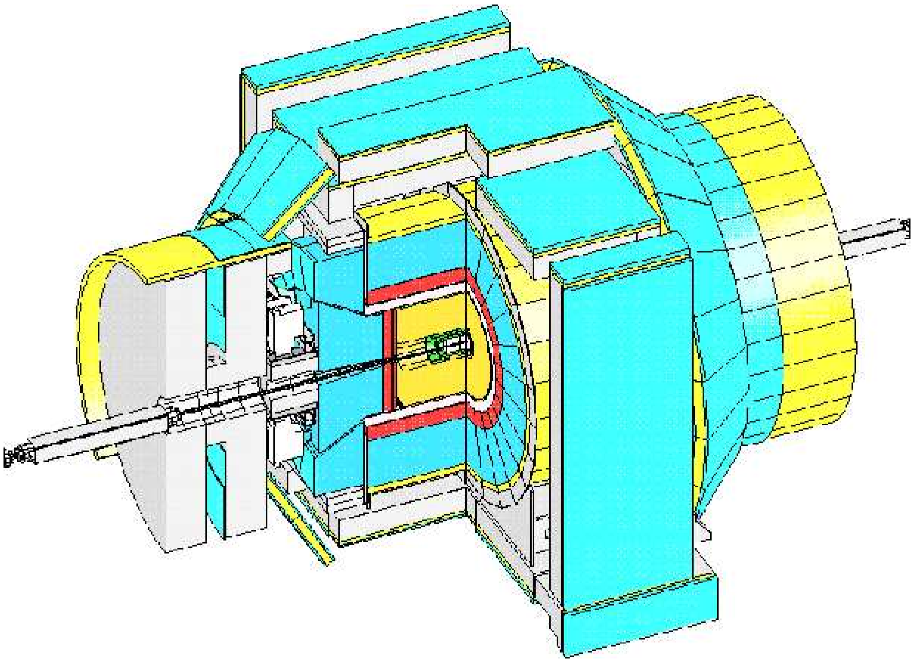
- Deliver $\sim 2$ fb$^{-1}$ by 2002 (Run IIa)

- If successful in increasing $\bar{p}$ availability
  - Go to $108 \times 108$ operation
  - Increase $L_{max}$ to $5 \times 10^{32}$ cm$^{-2}$s$^{-1}$
  - Deliver $\sim 15$ fb$^{-1}$ by end of 2007 (Run IIb)

# CDF Upgrades for Run II

CDF has undergone major upgrades for Run II

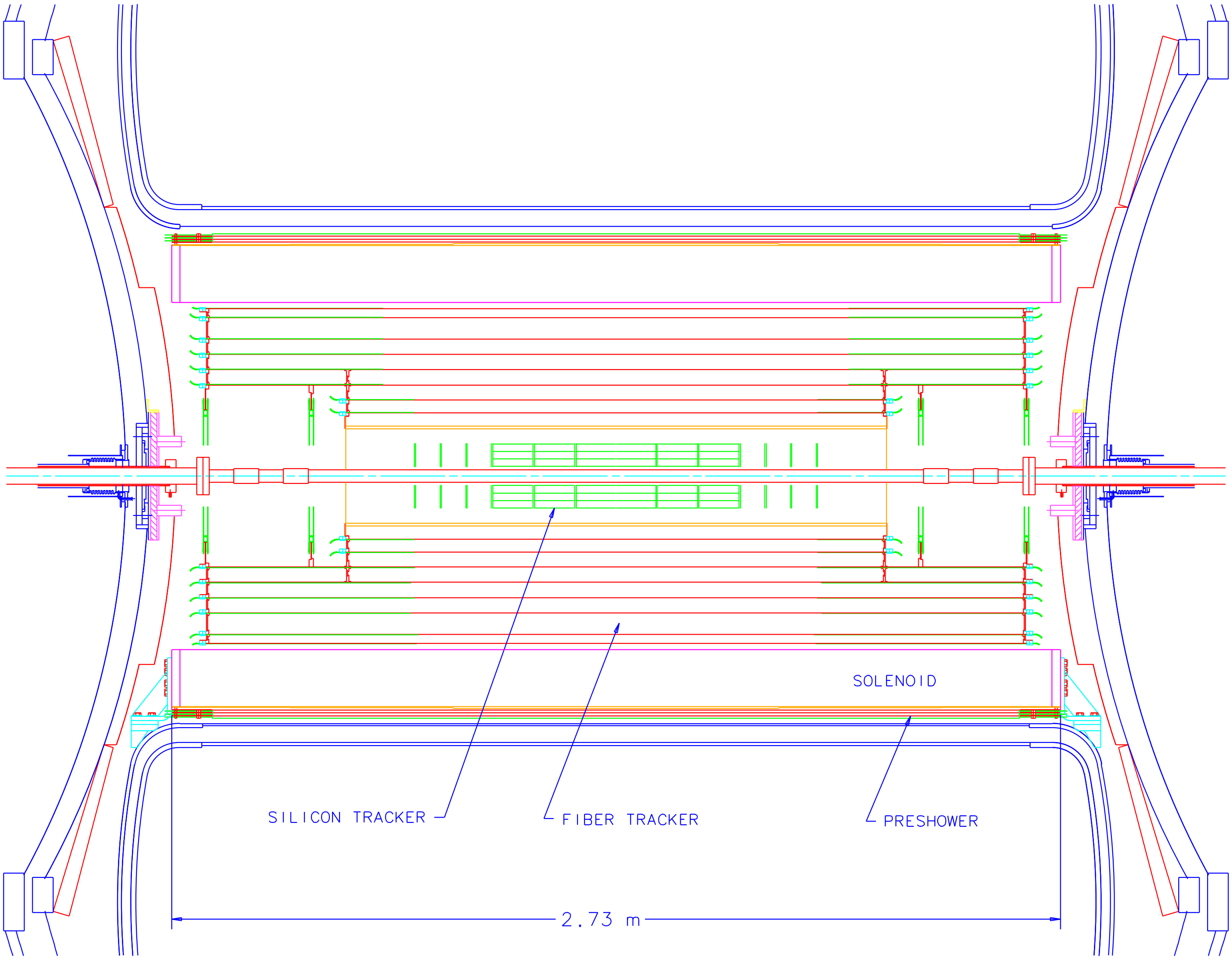
- Tile-scintillating fibre calorimeters in $1.0 < |\eta| < 3.6$
- Central outer tracker (COT)
- SVX II and ISL silicon tracking systems
- Fully pipelined electronics and new L1/L2/L3 triggers
- Upgraded muon systems in $0.8 \leq |\eta| \leq 1.2$
- C++ offline reconstruction and new processing farm



## D∅ Upgrades for Run II

D∅ has undergone a similar transformation

- New charged particle tracking system
  - 2.0 T solenoid
  - Inner silicon microstrip tracker (SMT)
  - New scintillating fibre tracker (CFT)
- Preshower detectors to improve $e/\pi$ separation
- Forward muon system chambers & scintillators
- Restructured L1/L2/L3 trigger, electronics and DAQ


SOLENOID
SILICON TRACKER
FIBER TRACKER
PRESHOWER
2.73 m

# Higgs Detection during Run II

SM Higgs production is in principle detectable

- Search of Run I data is clear demonstration
  - see G. Watts' parallel talk
- For case of $M_H = 120$ GeV/c$^2$, cross section
  - for $gg \to H_{SM}$ is $\sim$ 0.9 pb
  - for $q\bar{q}' \to W\, H_{SM}$ is $\sim$ 0.2 pb
  - for $q\bar{q} \to Z\, H_{SM}$ is $\sim$ 0.1 pb
- Issues for detection are:
  - Reconstruction technique and signal efficiency
  - Background rejection

Run II SUSY/Higgs Workshop has focussed activity

- Summarizes multiple studies done on
  - SM Higgs production
  - MSSM Higgs scenarios
- Results provided in terms of $\int Ldt$
- Report from workshop now available (hep-ph/0010338)

# Workshop Tools

Participants explored complementary approaches

1. Used existing CDF results and extrapolated
   - Accounted for SVX improvements
   - Took into account new triggers
   - Extrapolated jet resolution improvements

2. Developed independent detector simulation (“SHW”)
   - Parametrized resolutions and acceptances
   - Took account of DØ and CDF upgrades
     - Provide model of “average” detector

3. Assessed neural-net and “advanced” analysis techniques

Results provided for many scenarios and channels

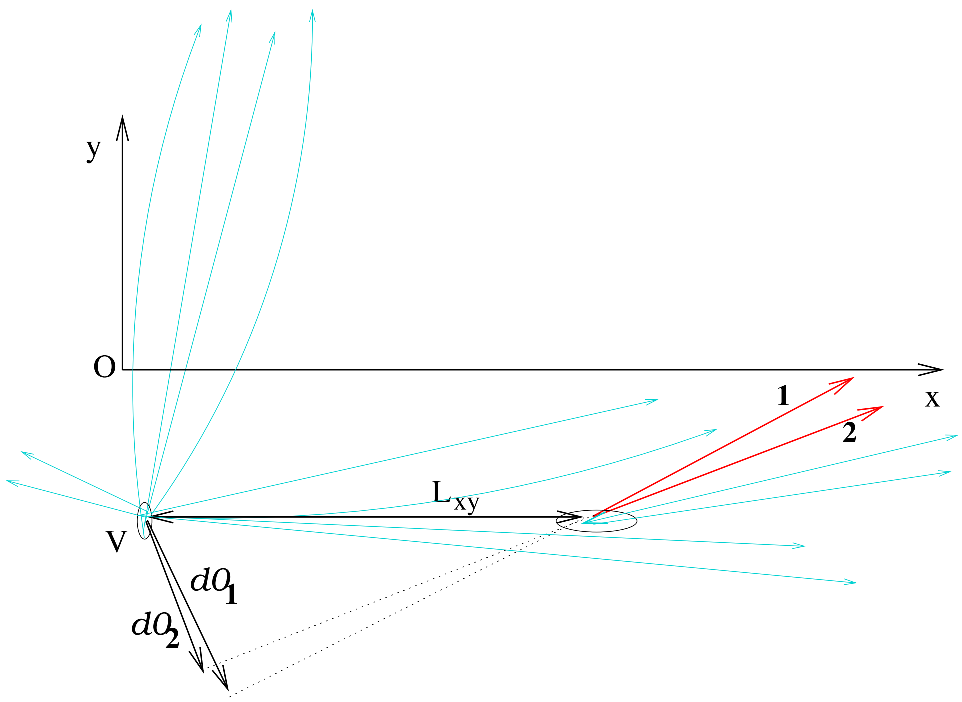
- Resulted in a fairly coherent set of predictions
  - Assessed impact of “combined” statistical power
  - Also noted some areas where uncertainties remain large

- Signal-to-noise issues are key to success

# B Tagging Issues

"B Tagging" an amalgam of various techniques

- Secondary vertex tagging primary technique (SECVTX)
  - Identify tracks with large impact parameter
  - Search for 2 or 3-track combinations with large $L_{xy}$




- Probability of tracks coming from primary vertex (JPB tag)
- Identify soft leptons in core of b-jet (SLT)

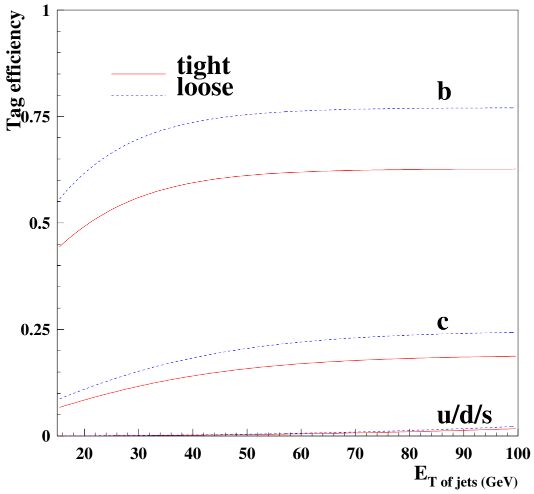
# Tight and Loose B Tags

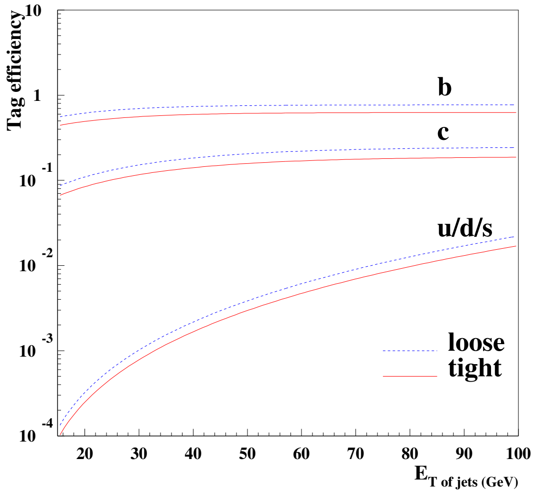
Employ concept of a "tight" and "loose" tag

- Tight $\Rightarrow$ SECVTX tag
- Loose $\Rightarrow$ Either SECVTX, JPB or SLT
- Allows trade-off between efficiency & bkg rejection

Use CDF Run I tagging efficiency

- Account for increase in SVX acceptance
- Use Run I mistag rates

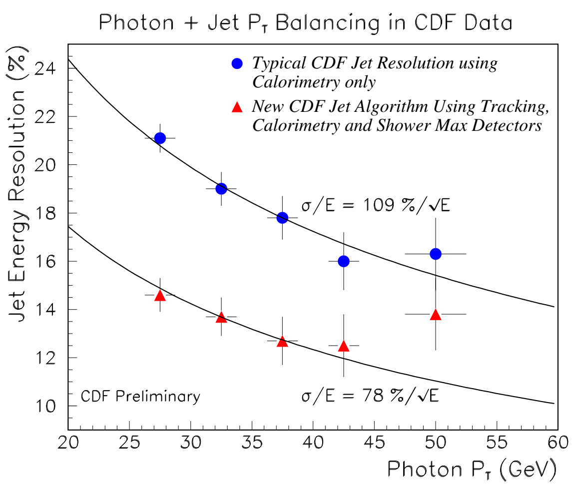


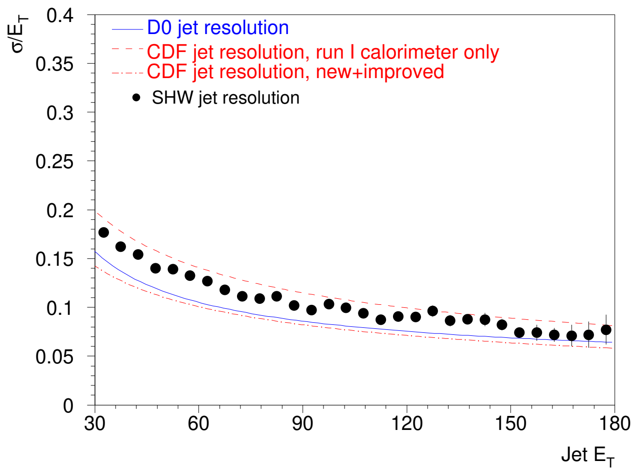



# Higgs Mass Resolution

Higgs mass resolution relies on jet reconstruction

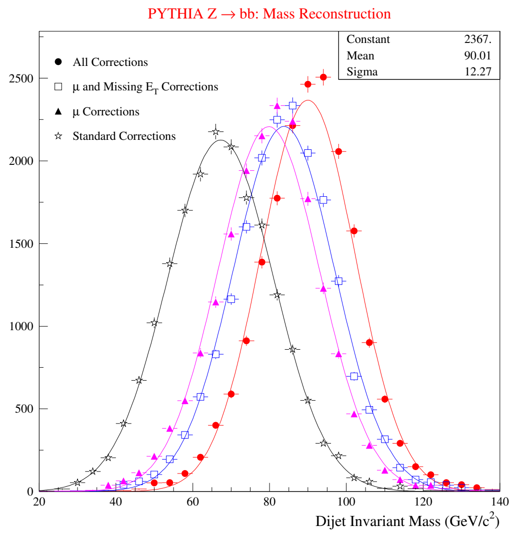
- "Standard" CDF jet algorithm
  - gives $M_H$ resolution $\sim 16$ GeV/c$^2$ at $M_H = 110$ GeV/c$^2$
- Track & shower-max data provides $\sim 20-30\%$ improvement
  - Measured using photon-jet balancing

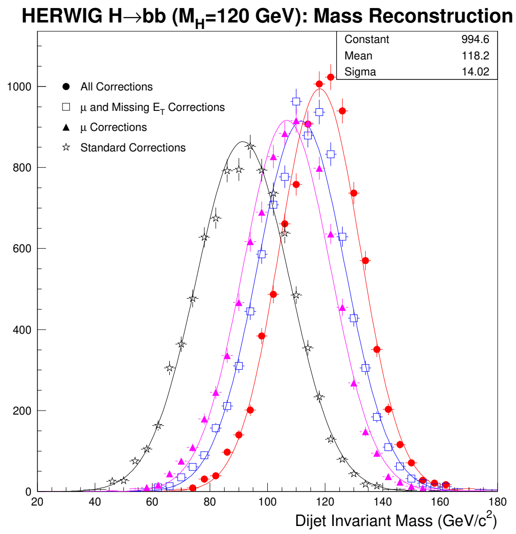


# Assumed Improvement in Mass Resolution

Provides $10 - 20\%$ improvement in $H \to b\bar{b}$ mass




This still requires work

- Topology dependence needs to be understood
  - Overlap with other objects in event
  - Combinatorial confusion
- Take into account other calorimetry effects
- Overall, promising development for Run II

## Detection Strategy for Light SM Higgs

The most promising channels for a light SM Higgs are

$$
\begin{aligned}
p\,\overline{p} &\rightarrow W^+\,H \rightarrow l^+\nu_l\;b\overline{b}\\
p\,\overline{p} &\rightarrow Z^0\,H \rightarrow l^+l^-\;b\overline{b}
\end{aligned}
$$

- Identify $e^+$ or $\mu^+$ with $p_T > 20$ GeV/c
- Require $\not\!\!E_T > 20$ GeV and reject dilepton events
- Only two jets with $E_T > 25$ GeV and $> 10$ GeV with $|\eta| < 2$
  - Both b-tagged (one tight and one loose)
  - Impose $M_{bb}$ mass window $\sim \pm 15\%$
  - No extra jets with $E_T > 20$ GeV and $|\eta| < 2.4$

Results in $\epsilon \times \mathcal{B}(H \rightarrow b\overline{b}) \sim 2\%$

- Expected 8 fb observed for $M_H = 90$ GeV/c$^2$
  - Falls to 2 fb for $M_H = 130$ GeV/c$^2$

# Background Rates for $WH$

All of the above come down to control of backgrounds

- Non-physical backgrounds estimated to be small
- Largest physical backgrounds are
  - QCD production of $Wb\bar{b}$
  - Production of $t\bar{t}$ where two jets are missed
  - Di-vector boson production
  - Single top production ($tb$ and $tqb$)
- Use HERWIG and PYTHIA, checked against Run I data

Observed Cross Section (fb)

| Process | $M_H = 90$ | $M_H = 110$ | $M_H = 130$ |
|---|---|---|---|
| Signal | 8.4 | 5.0 | 2.2 |
| $Wb\bar{b}$ | 21.5 | 18.9 | 15.4 |
| $t\bar{t}$ | 9.6 | 12.2 | 13.0 |
| $VV$ | 7.7 | 4.9 | 0.6 |
| $tb$ and $tqb$ | 9.4 | 11.8 | 12.7 |

# Uncertainties in Signals and Backgrounds

Signal estimates suffer mostly from

- Uncertainties on b-tagging estimates
- Jet resolution estimates
- Uncertainties in production rates
- How large? SHW estimates are about 10-20% higher

What should you worry most about backgrounds?

- Rate of $Wb\bar{b}$ remains uncertain
  - Other physical backgrounds reasonably well understood
- Could $Wb\bar{b}$ be $\times 2$ larger?
  - Probably not...CDF estimate constrained by the b-tagging rates and kinematic data
  - Also have other tools not used
    - NN approach gets 50% lower background
- Remains a challenge in this analysis

# Results for $ZH$ Channel

$ZH \to l^+l^- b\bar{b}$ is straightforward

- Suffer about $\times 5$ hit due to BR and lepton ID efficiency
- Expect about 1/6 of $WH$ observed rate
- Background rates are also approximately 1/6-1/7

$ZH \to \nu_l\bar{\nu}_l b\bar{b}$ presents challenge

- Only have $\not{E}_T$ signature from $Z \to \nu\bar{\nu}$
- Have two b-tagged jets reconstructing to $H$
- Creates a very "modest" signature
  - Issues with triggering
  - Issues with beating down the backgrounds

# Backgrounds to $\nu\bar{\nu}\, b\bar{b}$ Final State

Physical backgrounds reasonably well understood

- QCD production of $Zb\bar{b}$
- QCD production of $Wb\bar{b}$ (miss charged lepton)
- $WZ$ and $ZZ$
- $t\bar{t}$ and single top

Observed cross section (fb)

| Process | $M_H = 90$ | $M_H = 110$ | $M_H = 130$ |
|---|---|---|---|
| Signal | 3.6 | 2.7 | 0.9 |
| $Zb\bar{b}$ | 6.5 | 4.9 | 3.8 |
| $ZZ$ | 5.4 | 3.4 | 0.0 |
| $t\bar{t}$ | 1.6 | 2.2 | 2.2 |
| $q\bar{q} \to b\bar{b}$ | $\sim 7$ | $\sim 6$ | $\sim 3$ |

QCD $b\bar{b}$ background difficult to estimate

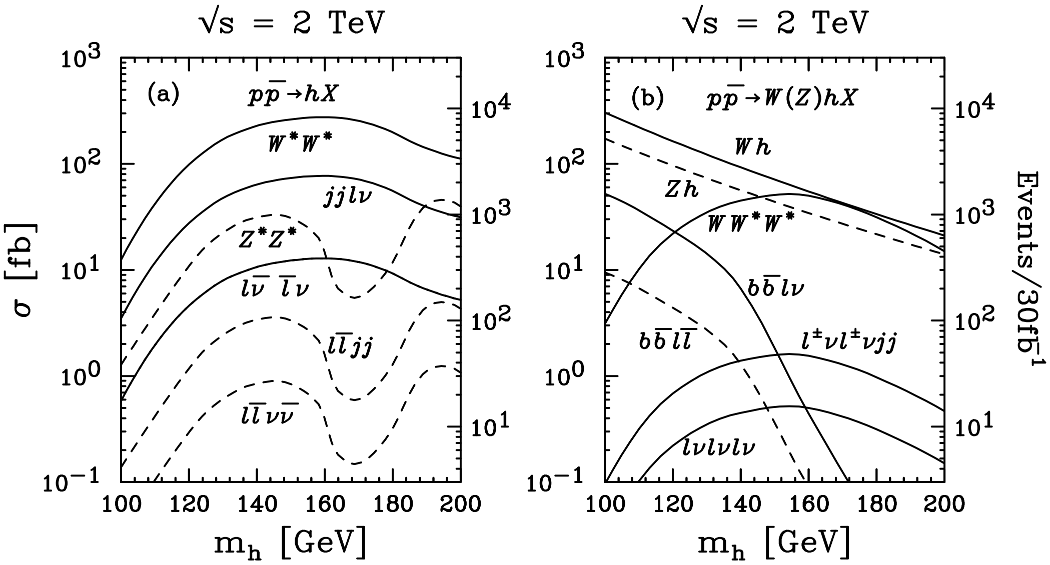
- Depends crucially on $\not{E}_T$ measurement
- Raw production cross section not well understood

$\Rightarrow$ Have to measure with data

# Higher Mass Higgs Searches

Heavier Higgs ($M_H \gtrsim 130$ GeV/c$^2$) rates lower

- $H \to WW^*$ becomes dominant decay mode
- Production via $gg \to HX$ and $q\bar{q}' \to WH$ are important
- Realistically, will require in excess of 15 fb$^{-1}$




This presents a number of decay channels

$$p\bar{p} \to H \to W^*W^* \to l\bar{l}\nu_l\bar{\nu}_l$$
$$p\bar{p} \to W^+H \to W^+W^*W^* \to l^+l^+q\bar{q}'X$$

- These two represent the highest rate topologies
- Same-sign dileptons very clean

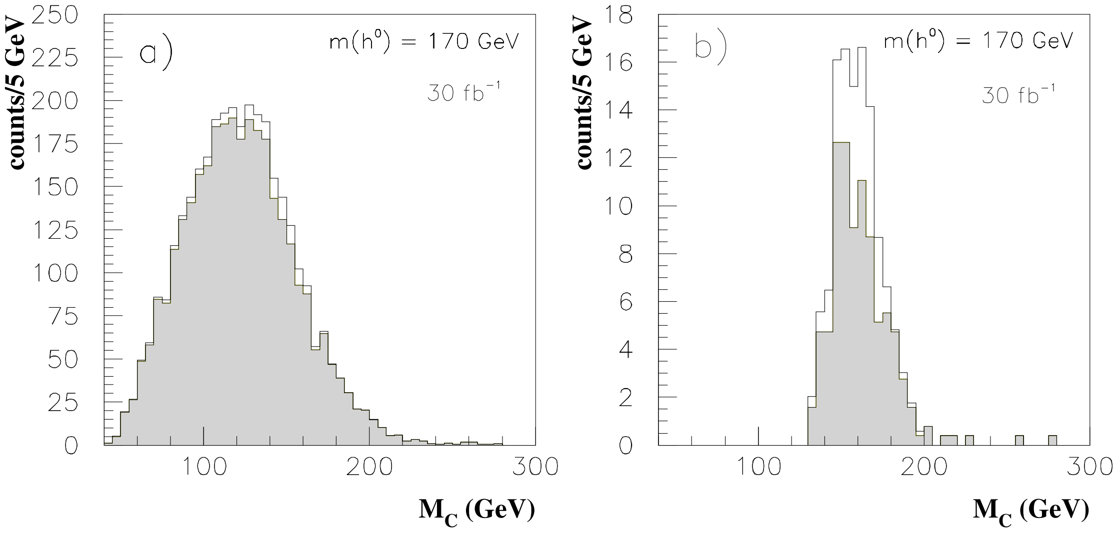
# Signal and Background Estimates

Signal requirements for $H \to l\bar{l}'\nu_l\bar{\nu}_l$ are:

- Isolated leptons with $p_T > 10$ GeV/c and $|\eta| < 1.5$
- Require $M_{ll'} < 78$ GeV/c$^2$ for $e^+e^-$ and $\mu^+\mu^-$
  - and $M_{ll'} < 110$ GeV/c$^2$ for $e^+\mu^-$
- Make decay angle cuts to reject $\tau^+\tau^-$ events
- Reject events with high energy jets (eg., $E_T > 95$)

A more sophisticated likelihood analysis defines

$$M_C \equiv \sqrt{p_T^2(ll) + M^2(ll)} + \not{E}_T$$



# Heavy Higgs Signal and Background Rates

Estimates of signal and background rates

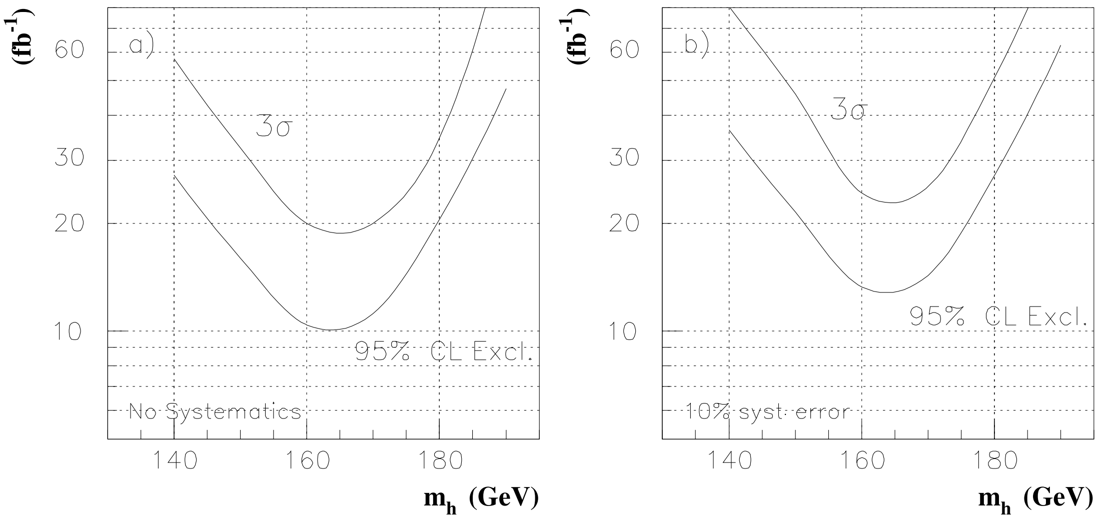
- Dominated by $W^+W^-$ and $t\bar{t}$

Observed Cross Section (fb)

| Process | $M_H = 140$ | $M_H = 160$ | $M_H = 180$ |
|---|---|---|---|
| Signal | 2.6 | 1.5 | 1.0 |
| Backgrounds | 4.4 | 4.4 | 3.8 |
| $S/\sqrt{B}$ | 2.1 | 3.9 | 2.7 |

Can estimate total integrated luminosity needed

- For either $3\sigma$ observation or 95% CL exclusion
- Include 10% systematic uncertainty



## Associated Production of $t\bar{t}H$

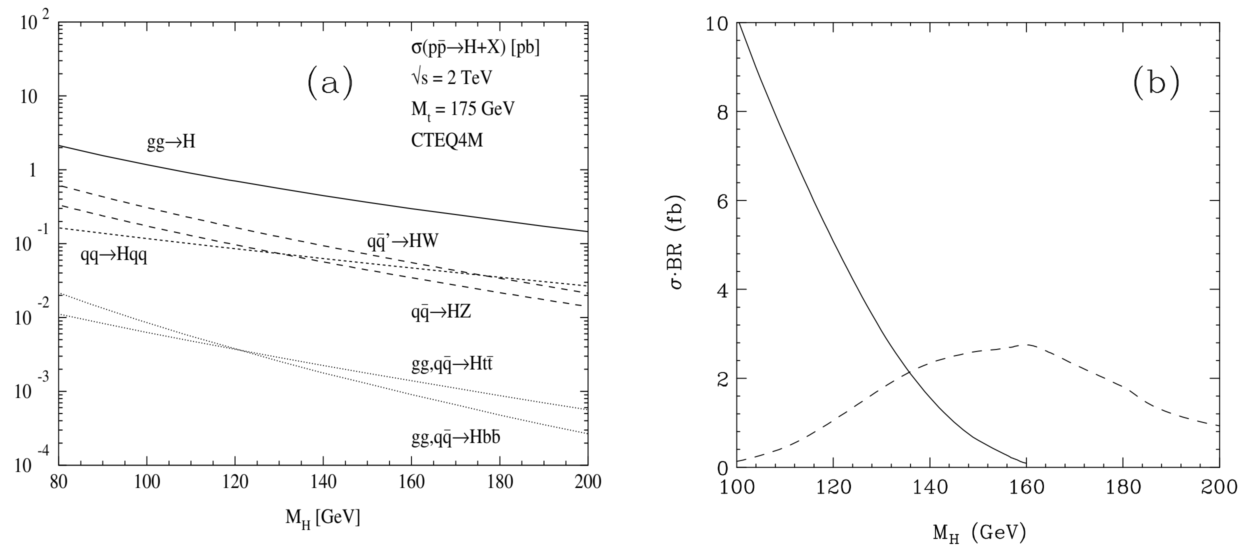
Recently, $t\bar{t}H$ has been reexamined at the Tevatron

Goldstein et al, hep-ph/0006311

- Analogous to $b\bar{b}H$ channel
- The $t\bar{t}$ gives efficient trigger and tag

Signal cross sections are small

- Estimate $\sigma \times \mathcal{B}$ of $t\bar{t}H$ few fb

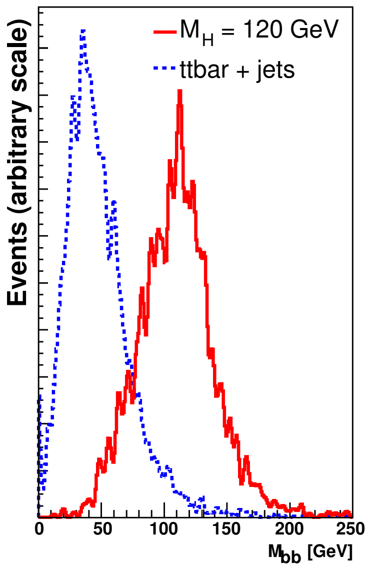


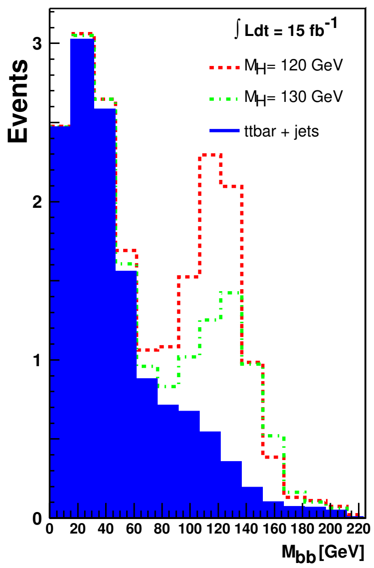
# $t\bar{t}H$ Rates

Have to deal with very large $t\bar{t}X$ background

- $t\bar{t} + jj$ has rate of $\sim 1,000$ fb
- B-tagging is crucial to pull out signal
  - Require 2 jets, at least one b-tagged
- For $M_H = 120$ GeV/c$^2$ and 15 fb$^{-1}$
  - 2-3 signal events and little background

Could yield a few "spectacular" events

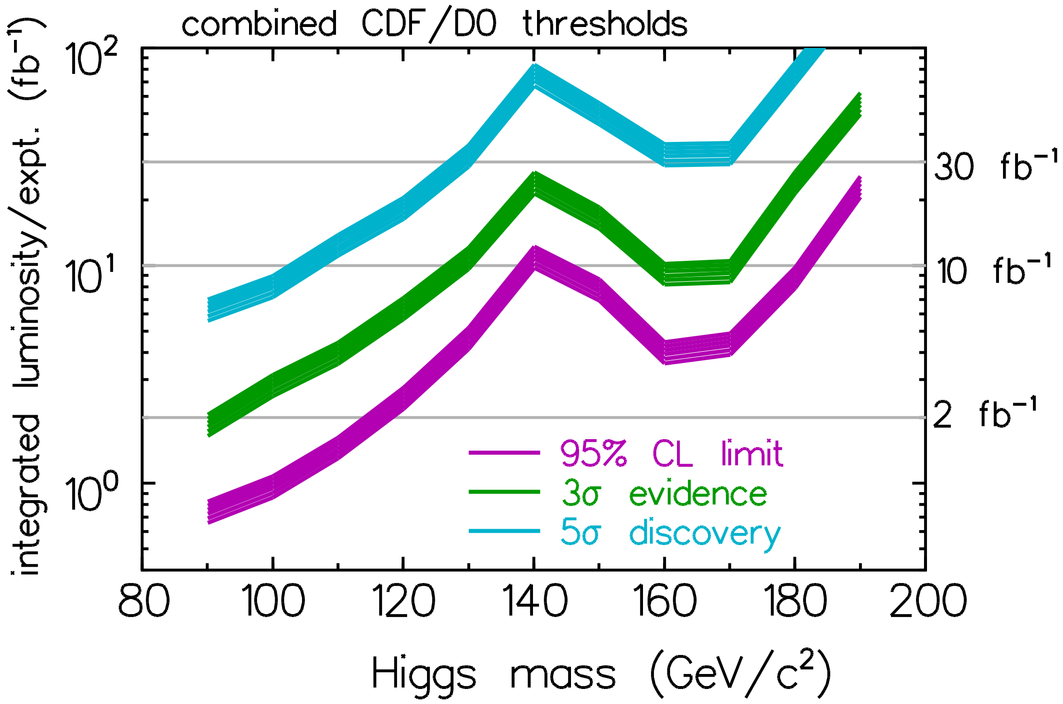


# Summary for SM Higgs Search

Results of the Workshop analysis can be combined:

- Use results of NN analysis
- Combine statistical power of both experiments
- Bands reflect 30% total additional “shift”



# MSSM Higgs Search

Search for MSSM Higgs has to grapple with

- 5 Higgs bosons in minimal model
  - two $CP$-even scalars $h$ and $H$
  - CP-odd scalar $A$
  - pair of charged states $H^{\pm}$
- A larger number of parameters
  - $\tan\beta = v_1/v_2$ and $M_A$

Sketch "benchmark" measure of Tevatron sensitivity

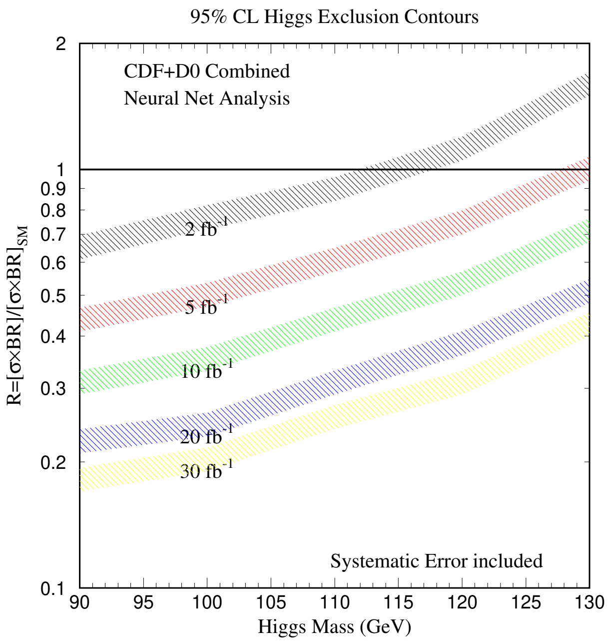
- Look at two production models
  - $q\bar{q} \to V\phi \to Vb\bar{b}$
  - $gg$ or $q\bar{q} \to b\bar{b}\phi \to b\bar{b}\,b\bar{b}$
- Reinterpret limits from earlier analyses

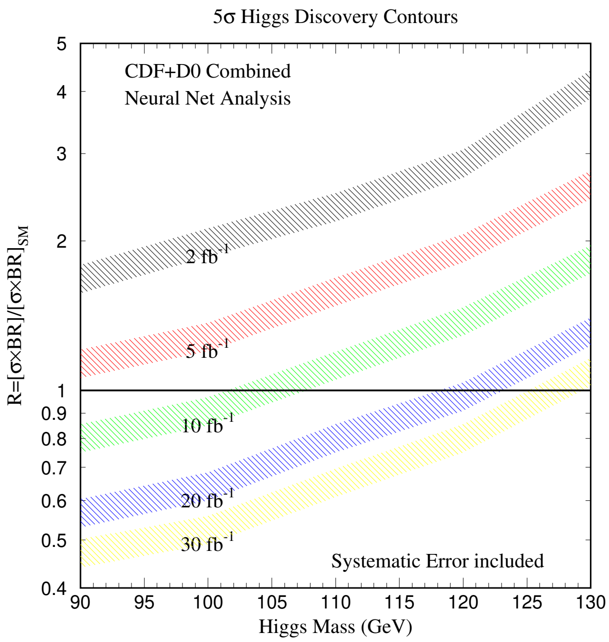
$$R_{th}(X,Y) \quad = \quad \frac{\sigma_X(\phi)\,\mathcal{B}(\phi \to Y)}{\sigma_X(h_{SM})\,\mathcal{B}(h_{SM} \to Y)}$$

# Reinterpreting SM Search Results

Take results from SM $WH \to Wb\bar{b}$ and $ZH \to Zb\bar{b}$

- Determine range of 95% exclusion and 5$\sigma$ sensitivity
- Add 10% systematic uncertainty




$$R_{\text{th}}(q\bar{q}' \to V\phi\,;\, b\bar{b}) \equiv \left(\frac{g^2_{VV\phi}}{g^2_{VVH_{SM}}}\right)\left[\frac{\text{BR}(\phi \to b\bar{b})}{\text{BR}(H_{SM} \to b\bar{b})}\right]$$

Can map these limits onto specific MSSM models

# Looking at non-SM Channels

Final states that are unique to the MSSM Higgs

- SM production or decay rate is suppressed
- Results in a observable signature at Tevatron
- "Benchmark" example (for large $\tan\beta$) is

$$gg \text{ or } q\bar{q} \to b\bar{b}\phi \to b\bar{b}\,b\bar{b}$$

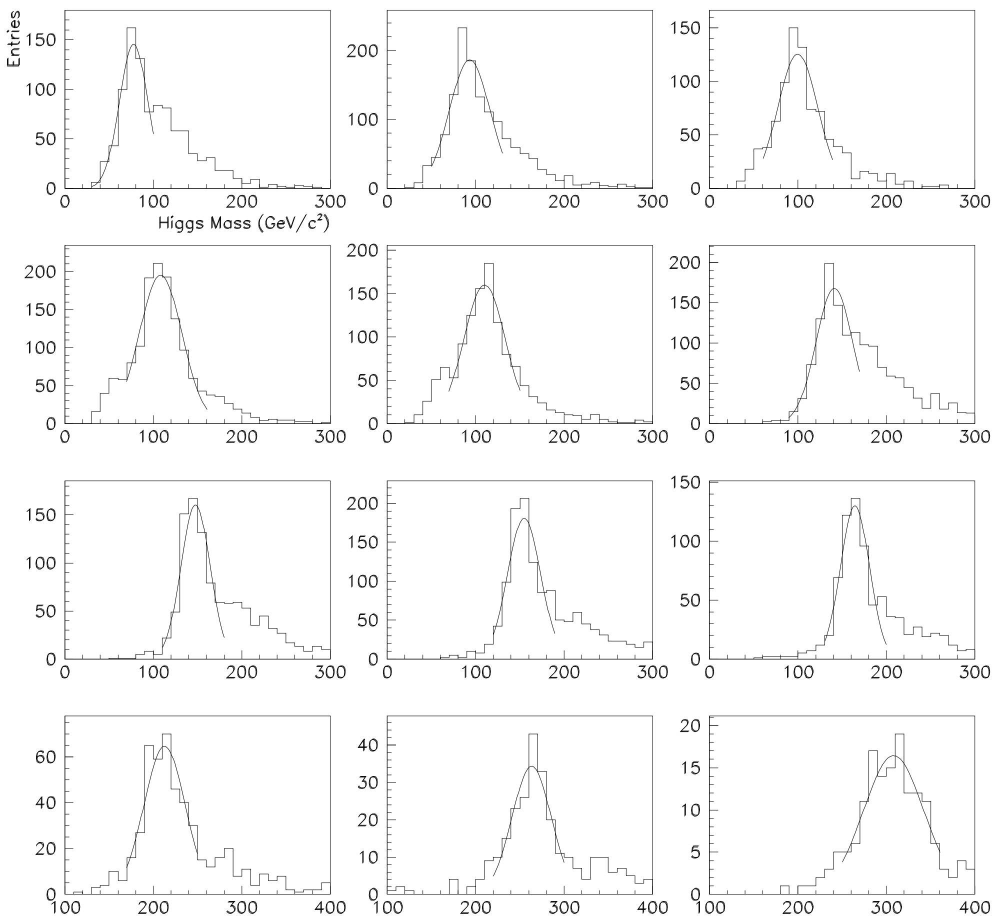
Search for $b\bar{b}\,b\bar{b}$ final states:

- Require 4 jets, $E_T > 15$ GeV and $|\eta| < 2.1$
- 1st and 2nd jet $E_T > 40 - 75$ GeV ($M_H = 70 - 200$ GeV/c$^2$)
- Require 3 $b$-tagged jets
- Reconstruct $\phi \to b\bar{b}$ signal

# Higgs Reconstruction $b\bar{b}$ Mode

Use a mass-dependent strategy to reconstruct $H$

- highest-$E_T$ pair of jets for $M_H > 120$ GeV/c$^2$
- 2nd and 3rd highest-$E_T$ jets for $M_H \leq 120$ GeV/c$^2$



# Estimated Signal and Background

Signal efficiency is relatively small

- Ranges from 0.4% to 0.5%
- Dominated by trigger requirements and $b$-tagging

Backgrounds are large (and somewhat uncertain)

- QCD background dominates (and largely irreducible)
- $t\bar{t}$ is next largest (about 1/5 of QCD)

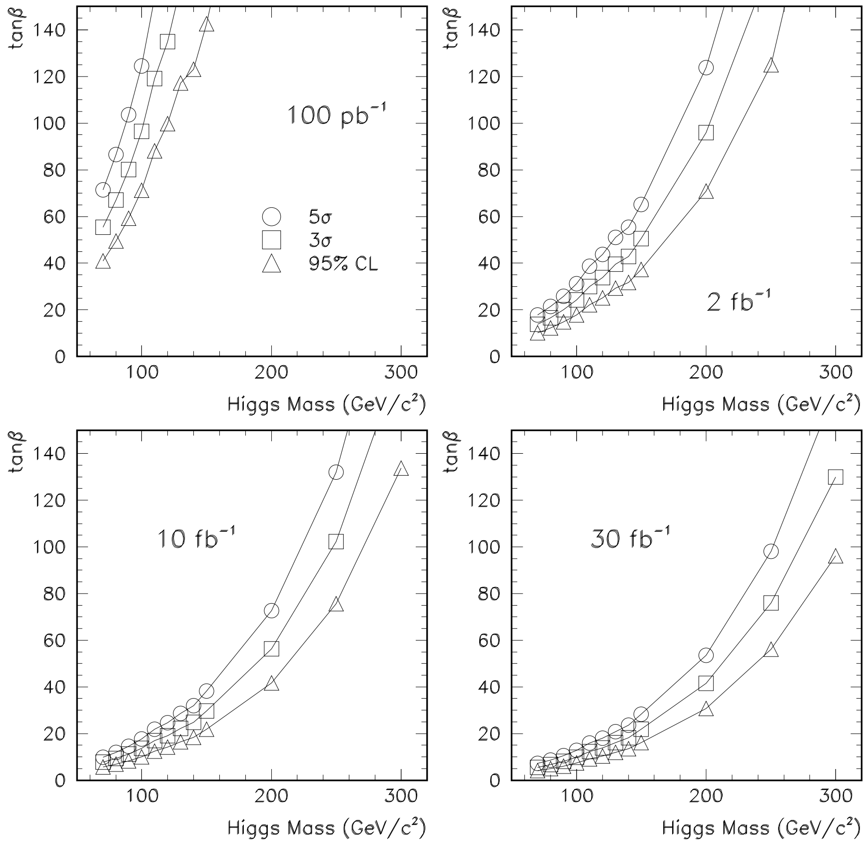
Observed Cross Section (fb)

| Process | $M_H = 120$ | $M_H = 140$ | $M_H = 200$ |
|---|---|---|---|
| Signal | 19 | 10 | 1.1 |
| QCD | $55 \pm 12$ | $34 \pm 9$ | $9 \pm 3$ |
| $t\bar{t}$ | $13 \pm 3$ | $11 \pm 3$ | $4 \pm 1$ |
| $S/\sqrt{B}$ | 2.2 | 1.4 | 0.3 |

# Summary of MSSM Higgs Mass Sensitivity

Can summarize these data

- 95% CL upper limits on $\tan\beta$ vs $M_H$
- Estimate $3\sigma$ and $5\sigma$ contours




Has extended reach for very large $\tan\beta$ values

- Large uncertainties in the QCD background
- $b$-tagging backgrounds are in "virgin" territory

# Summary

Higgs search at the Tevatron shows clear promise

- Limited reach with 2 fb$^{-1}$ (2002 goal)
- Data set of 15-20 fb$^{-1}$ does have sensitivity
  - Could discover SM Higgs up to 115-125 GeV/c$^2$
  - Sensitive to MSSM models over large parameter space

"Gold-plated" modes are

- $p\overline{p} \to VH \to Vb\bar{b}$ for $M_H \lesssim 130$ GeV/c$^2$
- $p\overline{p} \to H \to VV^*$ for $M_H \gtrsim 130$ GeV/c$^2$

Many uncertainties in these predictions

- Based on Run I flavour-tagging experience
- Requires optimal kinematic reconstruction tools
  - Promising results on dijet mass reconstruction
  - Have to be reproduced in Run II environment
  - Resolution in $\not{E}_T$ critical in some modes
- Will have to be resolved with the data