CDF's SM and MSSM Higgs Search Sensitivity

Tom Junk
University of Illinois at Urbana-Champaign

SM Higgs Searches

$W^{\pm}H \rightarrow \ell^{\pm}\nu b\bar{b}$

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

$ZH \rightarrow \ell^{+}\ell^{-}b\bar{b}$

$gg \rightarrow H \rightarrow W^{+}W^{-}$

$W^{\pm}H \rightarrow W^{\pm}W^{+}W^{-}$

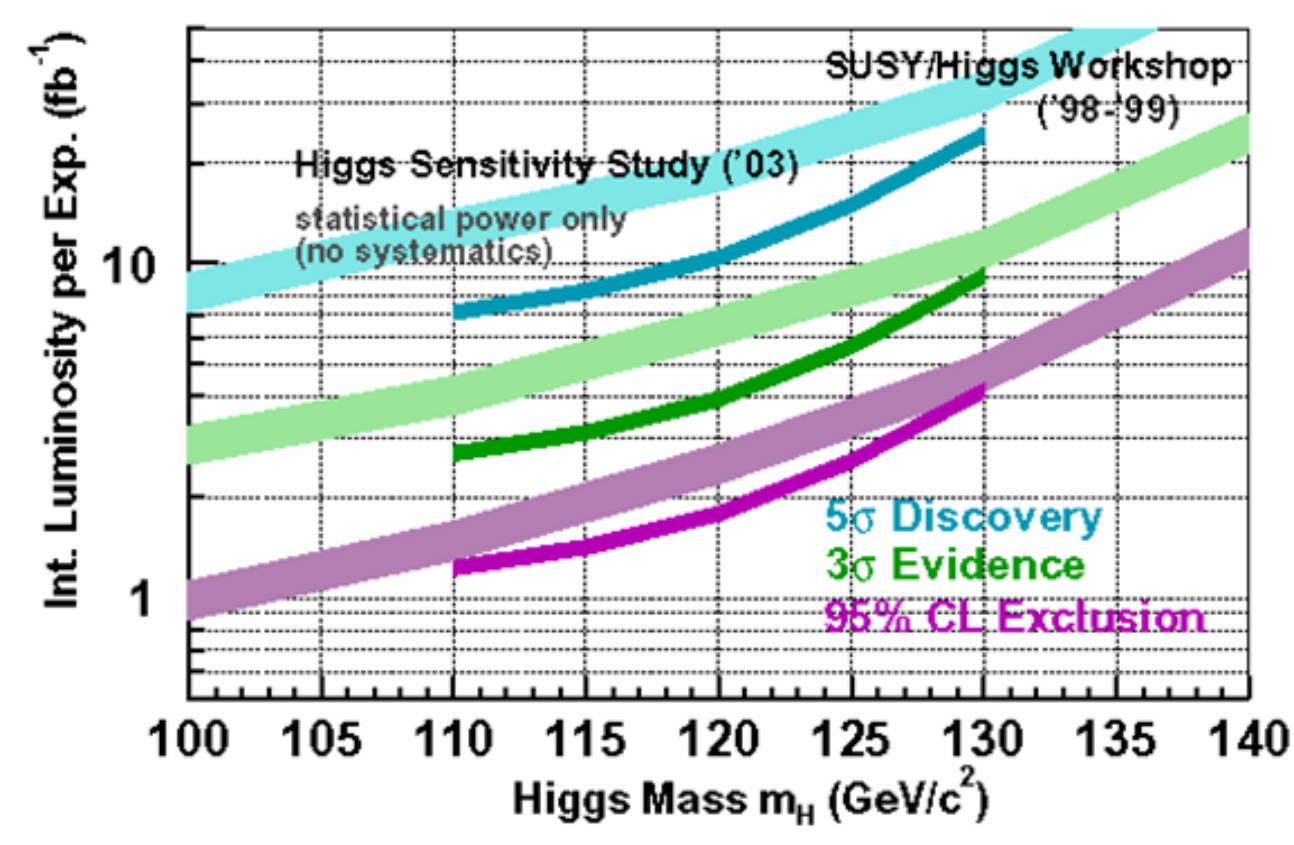
MSSM Higgs Search

$H \rightarrow \tau^{+}\tau^{-}$

Sensitivity of Combined Channels
Projections for the Future

21 Oct, 2005

SM Higgs Sensitivity Projections (2003)



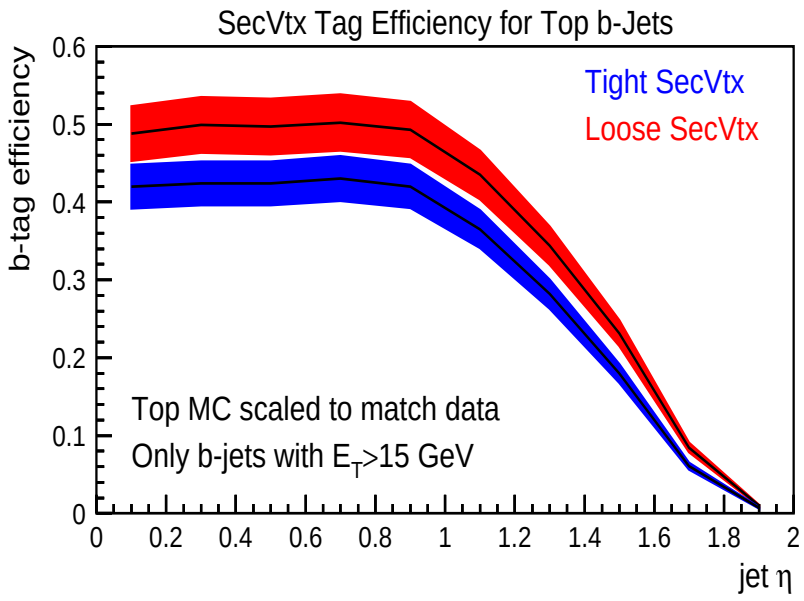
Run II Detectors
Realistic MC
Some data for calibrating bg
No Systematic Errors!

2003 Predictions:

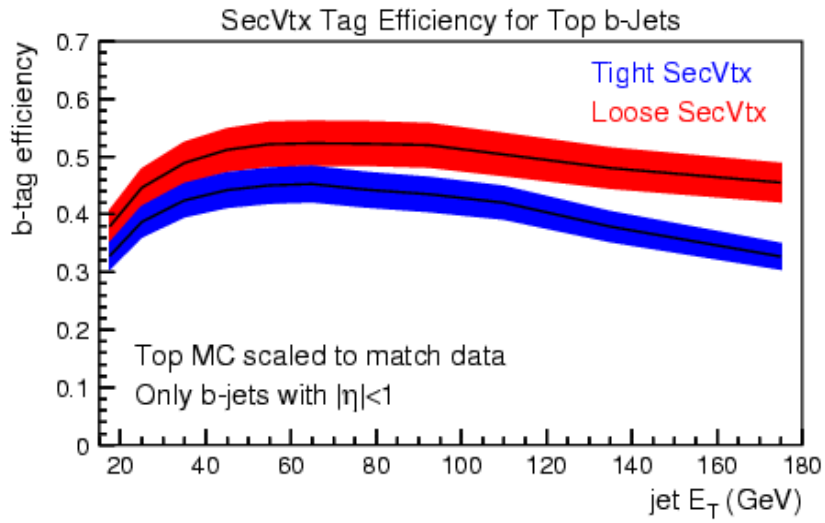
- 1.5 – 2.5 fb^{-1}/Exp. to exclude m_H=115 GeV (if it's not there!)
- 3 - 5 fb^{-1}/Exp. to get 3σ Evidence in a median experiment if m_H=115 GeV

SECVTX B-tag efficiency

- s/b tradeoff: Leptons & Missing E_T are distinctive; real backgrounds have two b quarks. Single-tag is enough.
  Future: Combine single and double-tag analyses, do a tight-loose tag, or better yet, use a continuous tagging variable.
- Jet-probability tags are available but not yet used in Higgs analyses -- more complication for estimating mistags



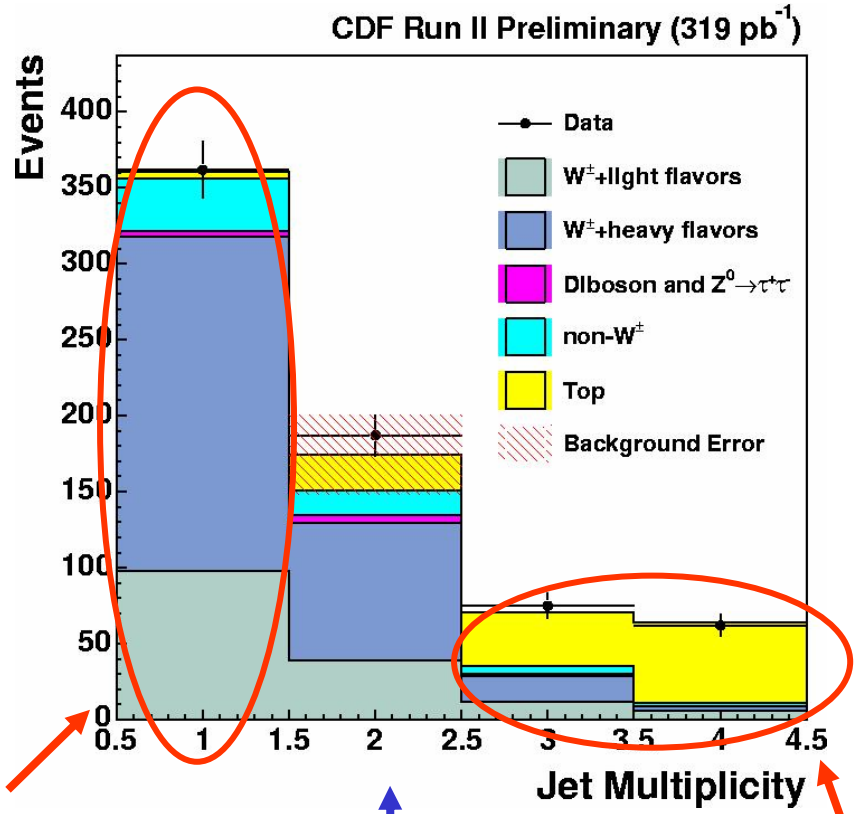
Mistag rates typically ~0.5% for displaced vertex tags



WH→lνbb

Select events with

- Identified electron or muon E_T>20 GeV, isolated
- Missing E_T > 20 GeV
- Two jets with $|\eta| < 2.0$, E_T>15 GeV.
- Veto extra jets, Z^0, cosmics, conversions, extra isolated tracks
- At least one b-tag

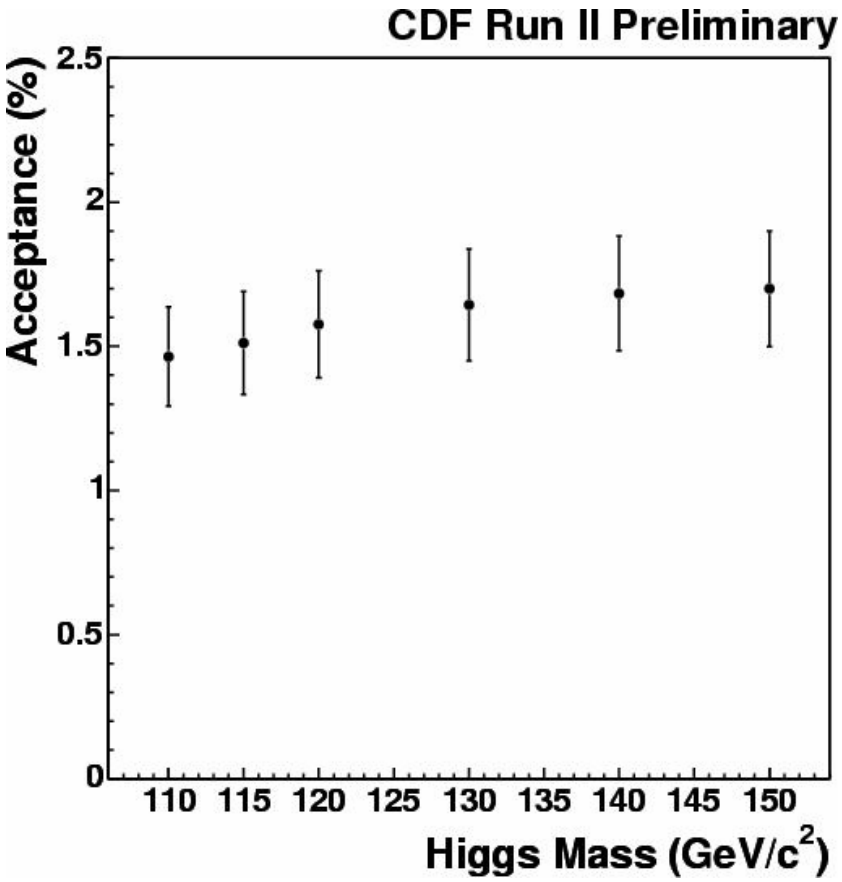


1-jet bin: Used to normalize Wbb & W2p ALPGEN predictions. HF fraction measured here.

2-jet bin: signal region

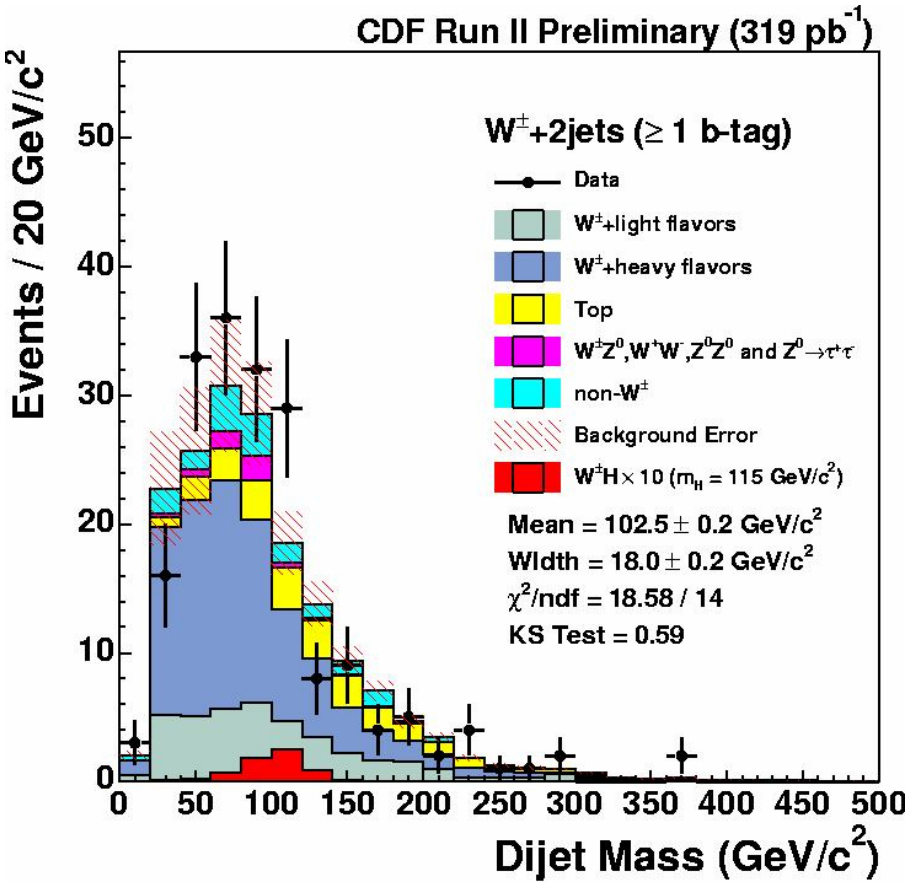
3 & 4-jet bins used to normalize t-tbar background rate.

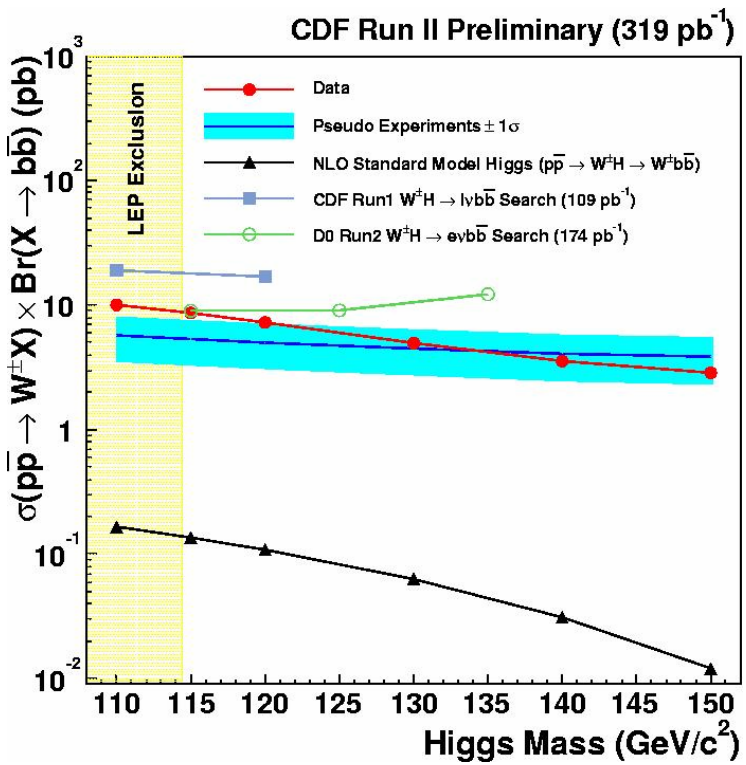
WH→lνbb Signal Acceptance



Source of Uncertainty	Syst (%)
Lepton ID	5
Trigger	<0.1
PDF	1
ISR	3
FSR	7
Jet Energy Scale	3
B-tag	5
Jet Energy Resolution	1
Soft Jet Modeling	1
Total	11

WH→lνbb Channel: m_{jj} Distribution and Limits

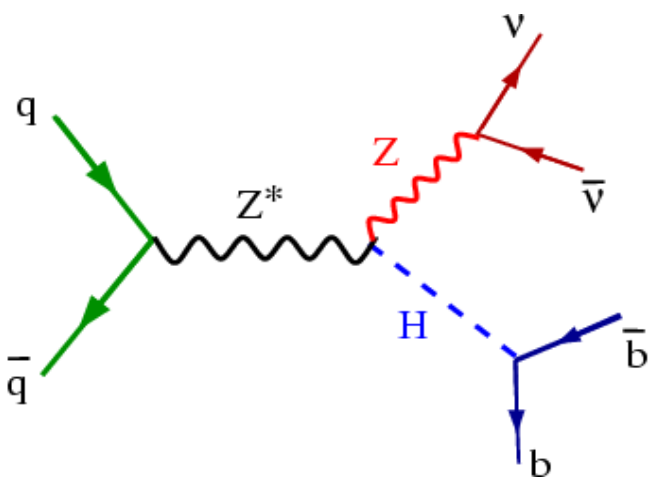


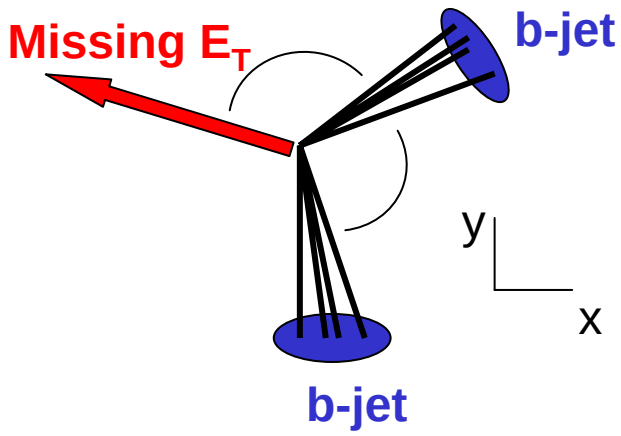


Background = 174.7 ± 26.3
Data = 187 Events

The Search for $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

- This signature proved to be the very sensitive in Run I





Event Selection:

- At Least 2 jets
  - 1st Jet E_T > 40 GeV
  - 2nd Jet E_T > 20 GeV
- $\not{E}_T$ > 70 GeV
- At Least 1 b-tag

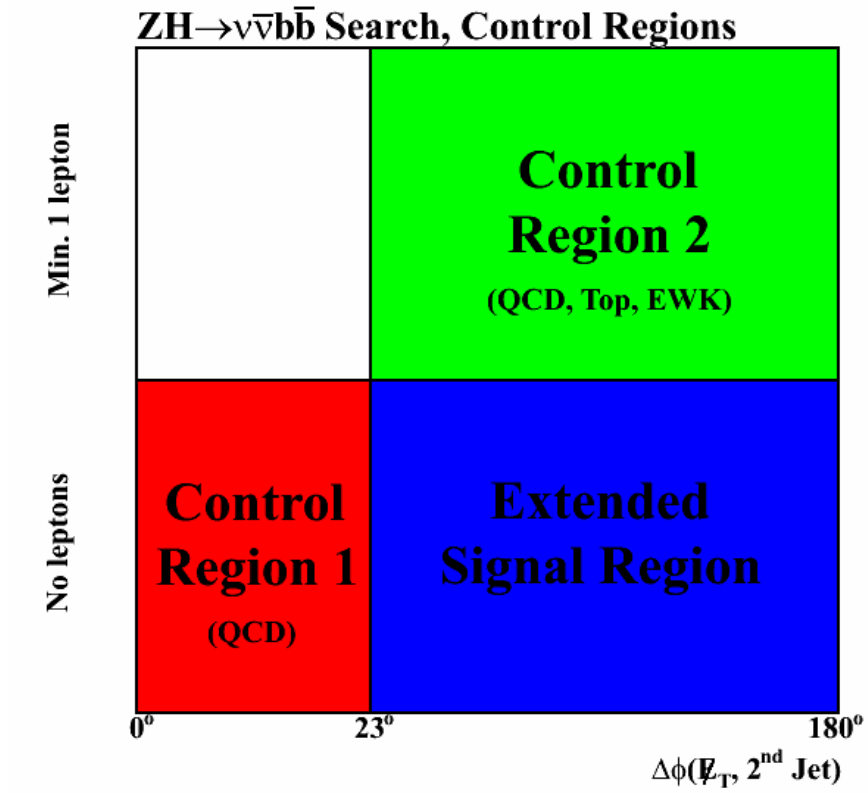
- Signal has a distinctive topology
  - Large missing transverse energy
  - two jets (one is b-tagged)

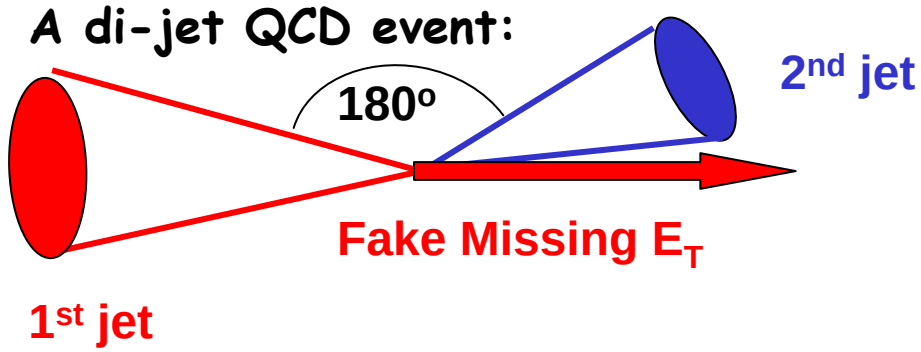
ZH→ννbb Channel: Selection and Control Samples

Veto events with isolated leptons (W+jets bg).

Veto Cosmics, Z^0 Candidates

Select events where missing-E_T points away from jets. (rejects QCD dijets)

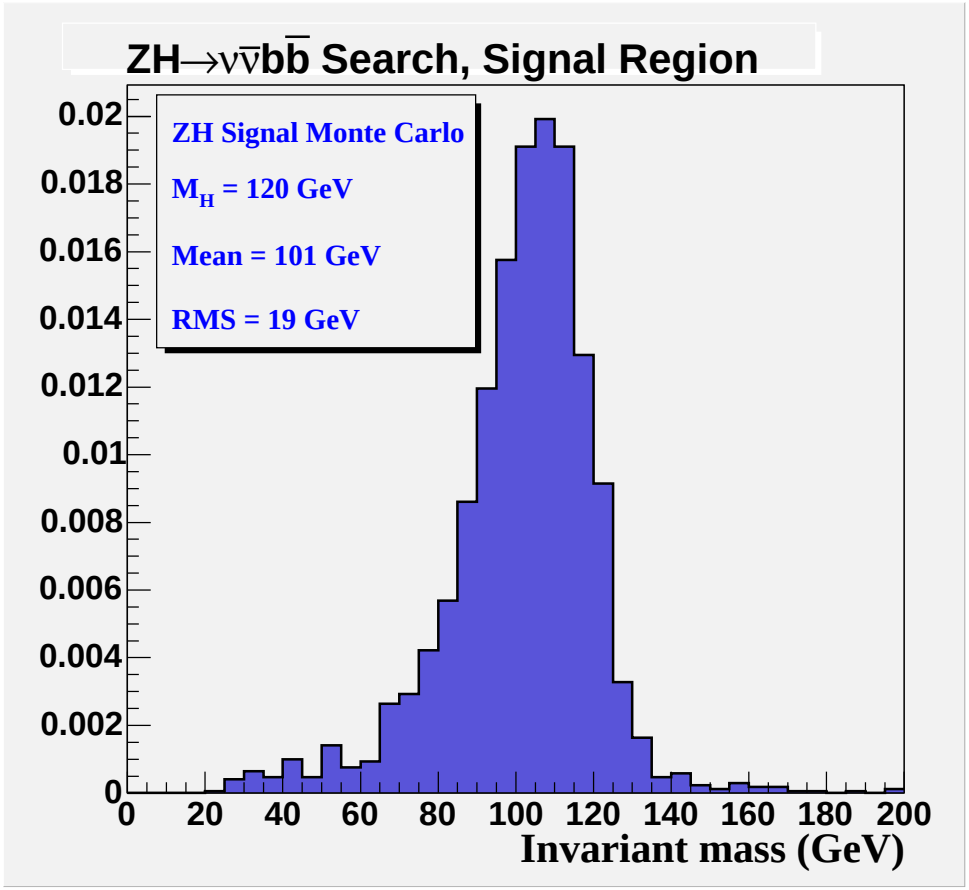




Choosing ZH→ννbb Mass Windows

- Last cut is on the dijet invariant mass

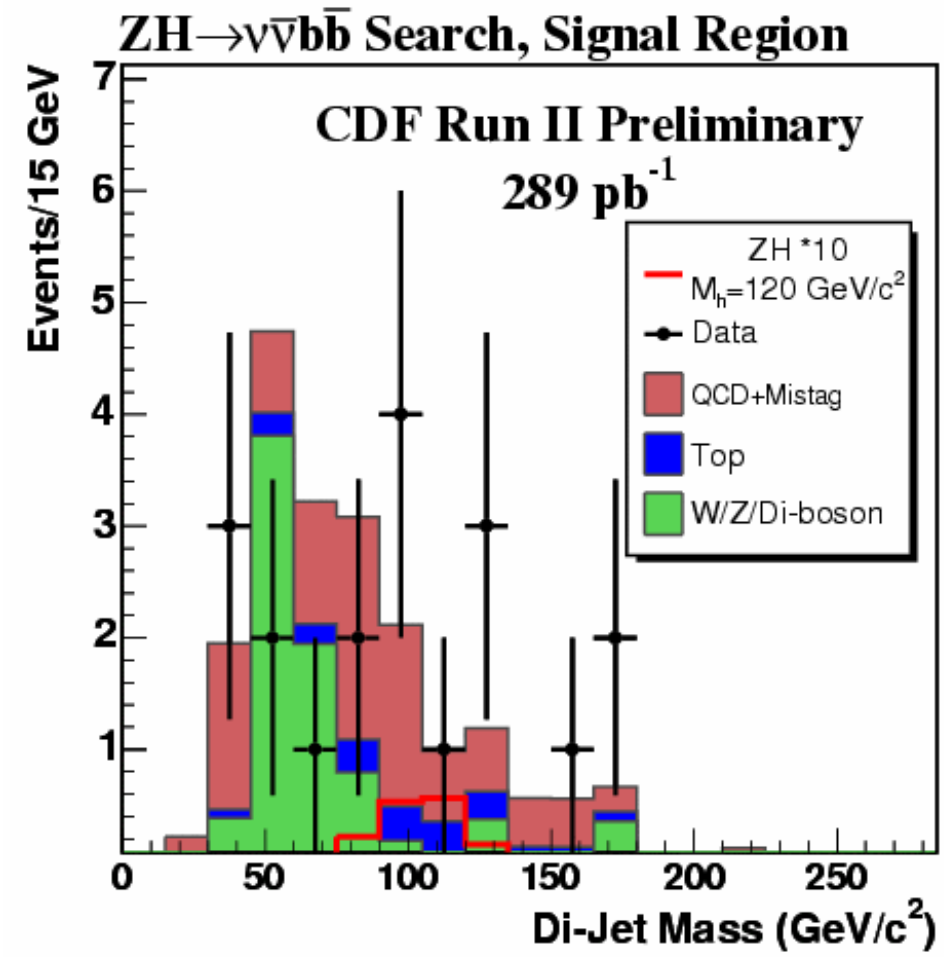
- A window of +20 GeV and –20 GeV is set around each of the mean of the mass peaks



Invariant Mass (GeV)		$s / \sqrt{b}$
min.	max.	
60	140	0.043
70	130	0.047
80	**120**	**0.060**
90	110	0.056

The ZH→ννbb Signal Region

(Still has low s/b)
Last cut: m_{bb} mass window cut: ±20 GeV around test-mass m_H



ZH→ννbb Systematic Uncertainties

Source	Signal Rel err (%)	Background Rel err (%)
Luminosity	6	6
B-tag eff	6	2
Trigger eff	3	2
Lepton Veto	2	2
Jet Energy	8	4
Uncorrel signal	2	0
Uncorrel bg	0	22

Totals: 12% for signal, 23% for background

Setting Limits: $ZH \rightarrow \nu\nu bb$

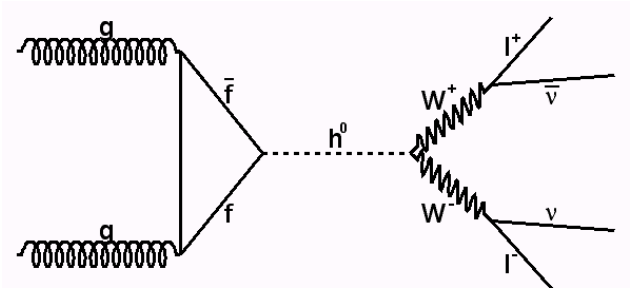
Mass (GeV)	Observed events	SM prediction	Higgs signal acceptance	Expected Limit (pb)	Observed Limit (pb)
90	6	7.18	0.45%	6.3 ± 1.2	5.4
100	7	7.07	0.55%	5.1 ± 1.0	5.0
110	7	5.9	0.64%	4.6 ± 1.4	5.2
115	7	5.9	0.67%	4.3 ± 1.4	4.8
120	6	4.36	0.73%	3.6 ± 1.4	4.5
130	8	4.11	0.77%	3.2 ± 1.0	5.2

Mass window cuts applied, but just a counting experiment

Expected Limits assume a Higgs boson is not present

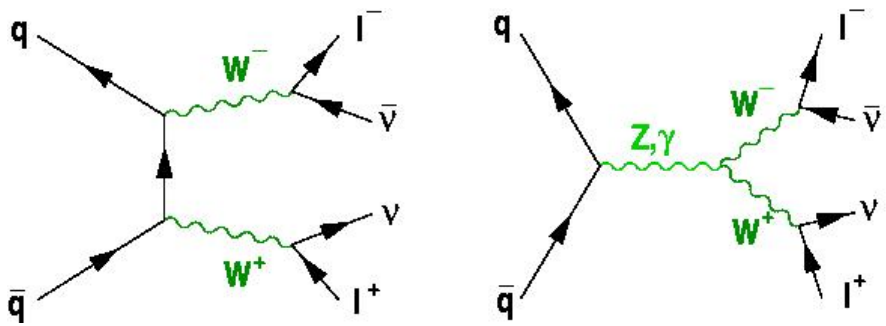
The $gg \rightarrow H \rightarrow W^+W^-$ Channel

Signal Process:



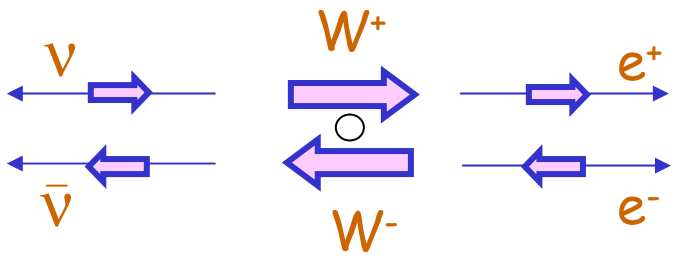
Dominant background:

$q\bar{q} \rightarrow W^+W^-$



- Interesting Angular Correlation due to Scalar nature of Higgs Boson

- Different from SM W^+W^- bg decay angular correlation!



Newly Updated $gg \rightarrow H \rightarrow W^+W^-$ Search

- Re-optimized selection requirements
- 360 pb^{-1} of data now used

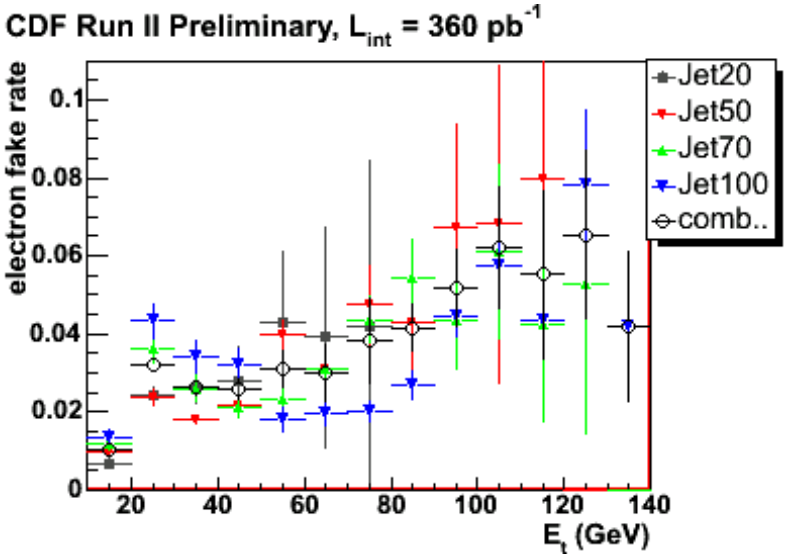
- Two opposite-sign, isolated leptons, with E_T>20 (10) GeV
  - Conversion, cosmic vetoes
- Missing $E_T > M_H/4$
- Missing E_T>60 GeV **OR** $\Delta\Phi_{MET,lep/jet}$>20°
- 16 GeV < m_{ll}< $M_H/2$ – 5 GeV
- p_{lept1} +p_{lept2} + Missing $E_T < M_H$
- Sophisticated jet requirements
  - No jets **OR**
  - 15 < E_T< 55 GeV with one jet (|η|<2.5) **OR**
  - 15 < E_T < 40 GeV with two jets (|η|<2.5)

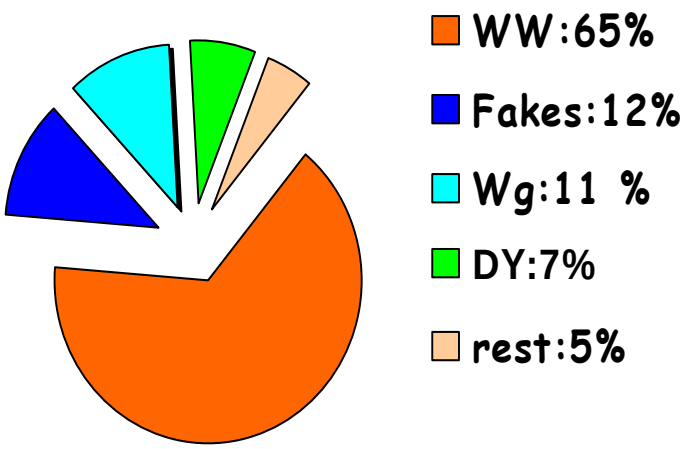
This search has explicit test-mass dependence. The background depends on the signal hypothesis

Acceptance is ~0.4% [including $Br^2(W \rightarrow l\nu)$] for m_H>160 GeV

Backgrounds in the $gg \rightarrow H \rightarrow W^+W^-$ Channel

- Mostly WW
- Lepton Fake Rates are calibrated with jet data

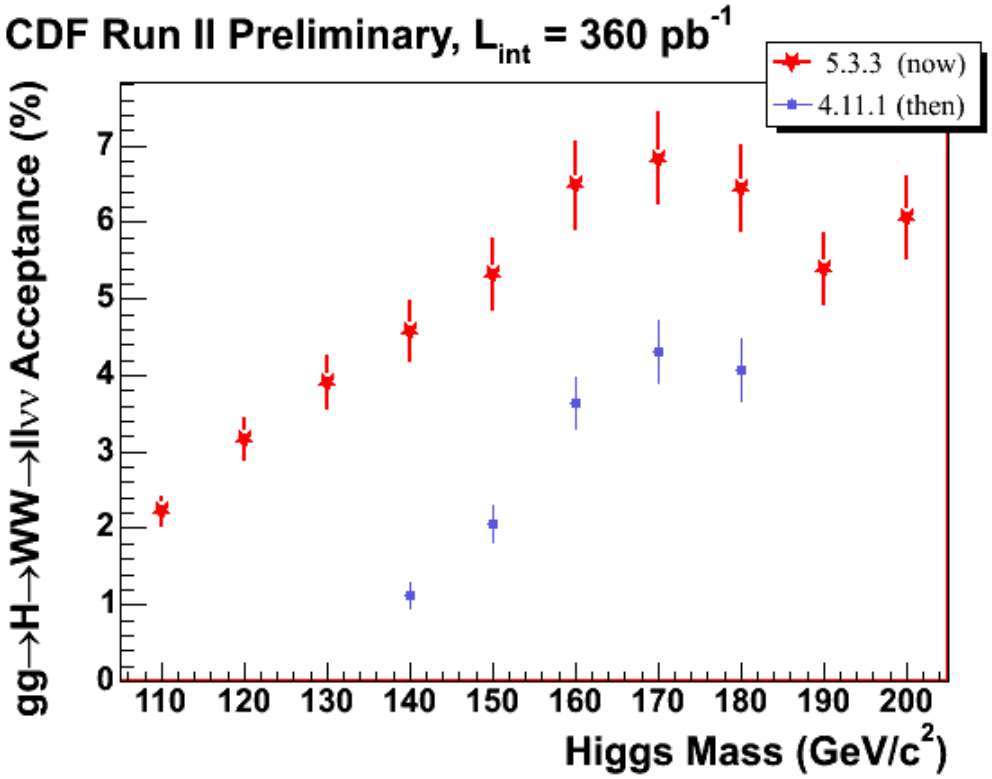




$$m_H = 160 \text{ GeV}, \quad \int \mathcal{L} dt = 360 \text{ pb}^{-1}$$

Category	Events
WW	9.79 ± 1.03
Drell-Yan+WZ+Wγ+ZZ+top	2.65 ± 0.22
Misid'd Leptons	1.33 ± 0.67
Total BG	13.78 ± 1.24
Observed	16
$H \rightarrow W^+W^-$	0.58 ± 0.04

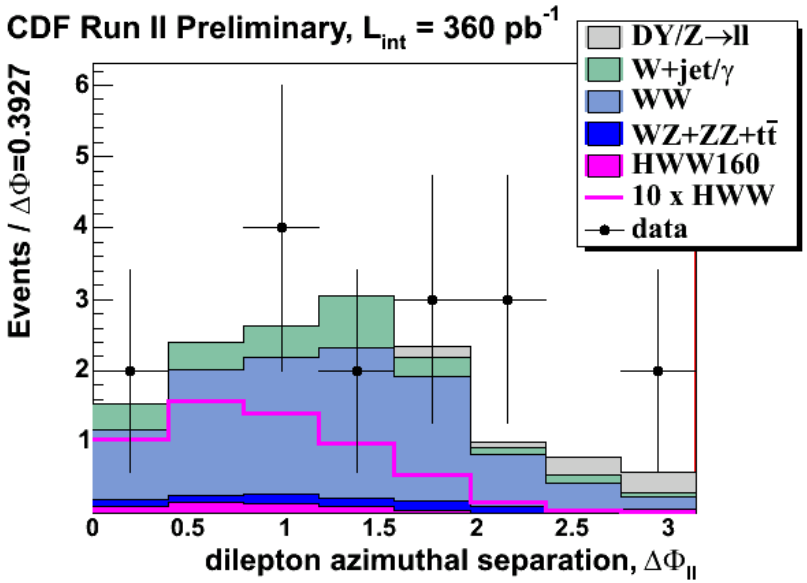
$gg \rightarrow H \rightarrow W^+W^-$ Acceptance

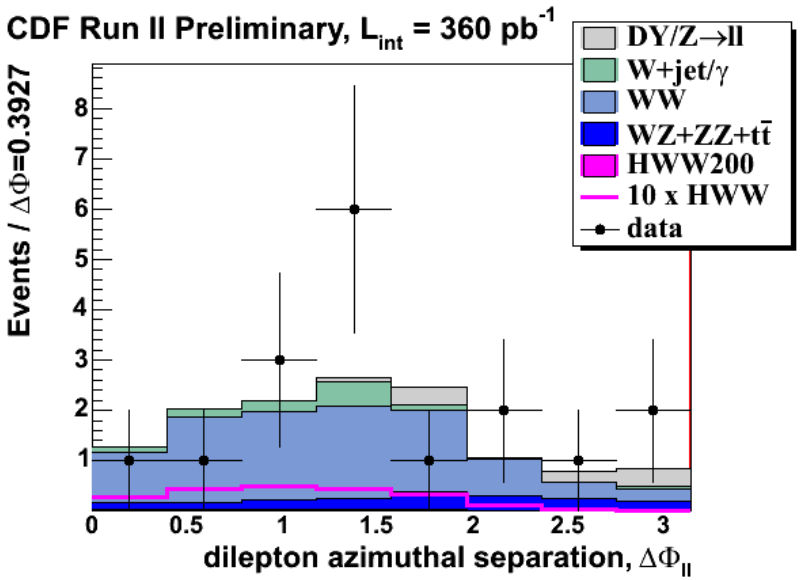


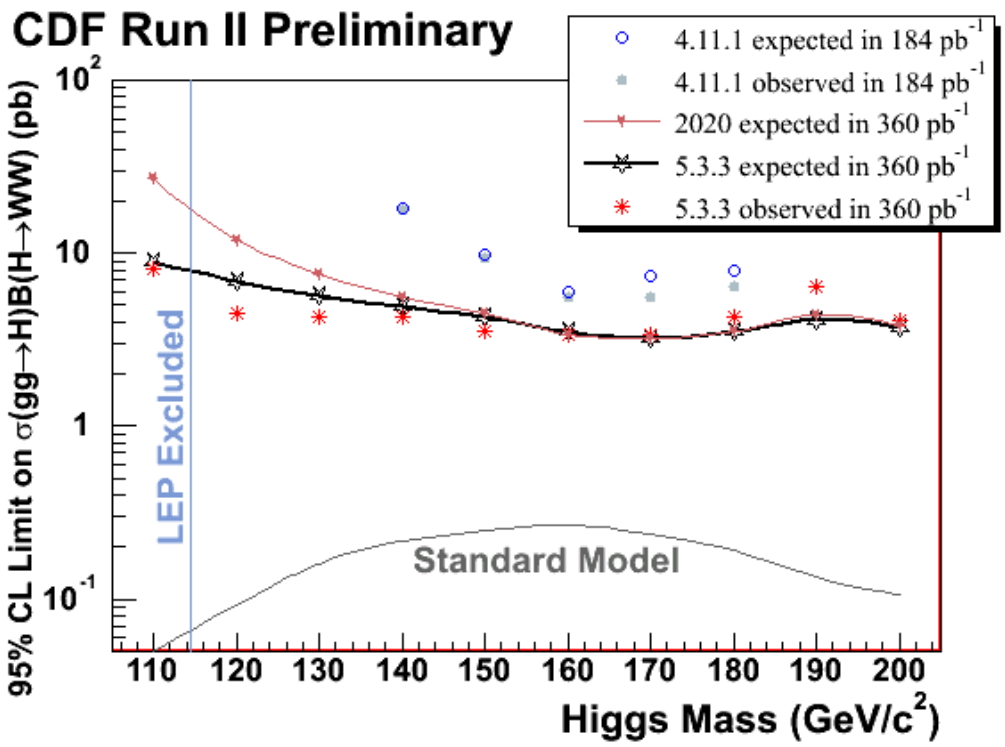
	Systematic Error (%)
ISR	3
α_s	3.3
PDF Acceptance	3
Jet Energy Scale	1
Lepton ID	2
Track Isolation	2
Trigger Efficiency	1
Combined	6

!BR(W→lν)^2 not included

Extracting Limits with the ΔΦ Distribution

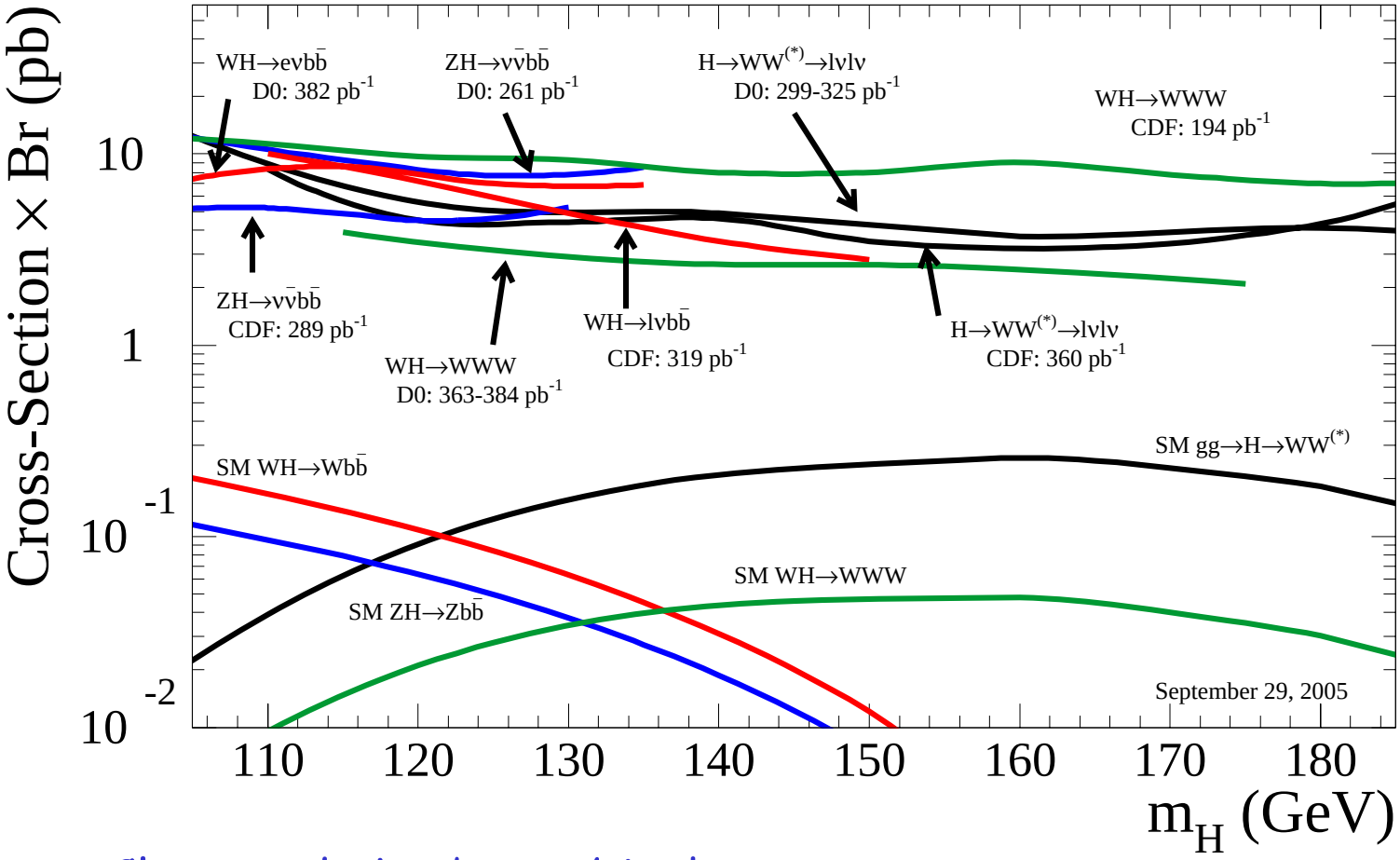






Collected CDF+DØ SM Higgs Limits

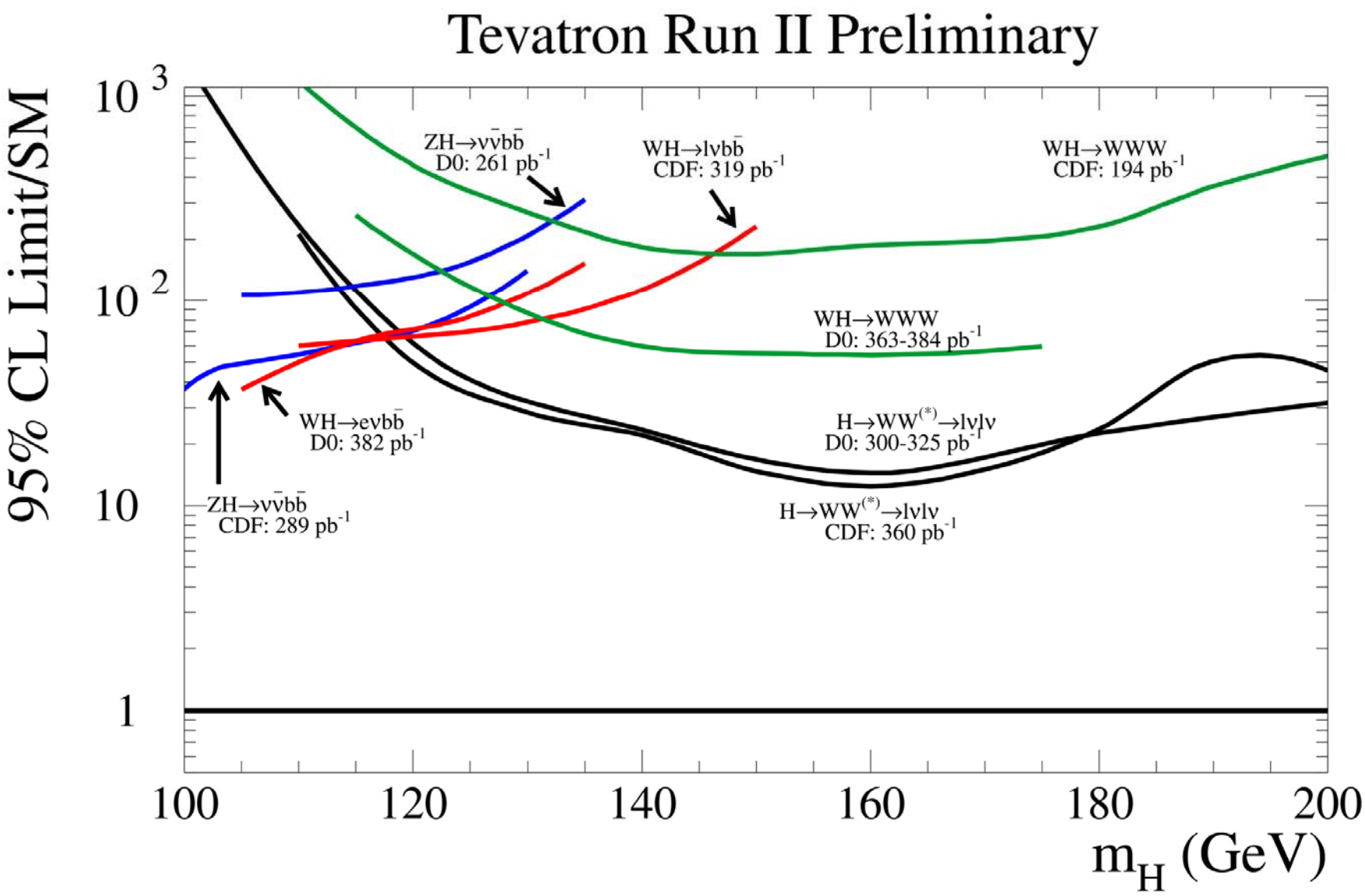
Tevatron Run II Preliminary



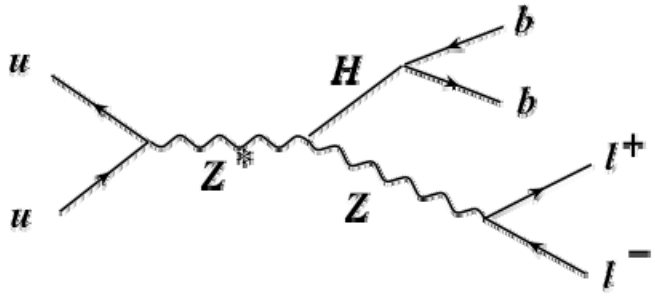
- A lot of work has been done!
- Latest version: Includes DØ's new WW search hep-ex/0508054 and CDF's latest WW search.

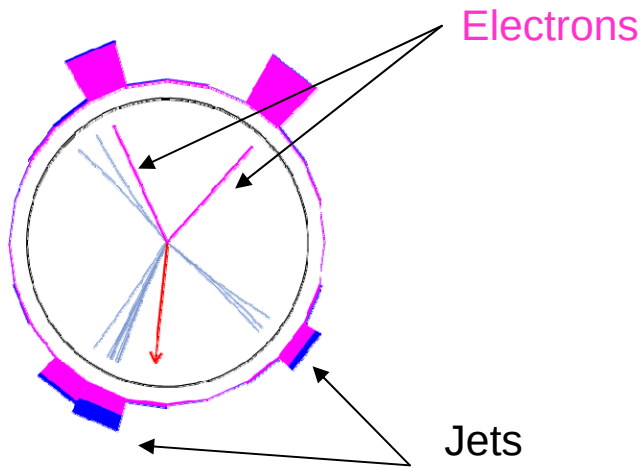
- Cluttered: Let's combine!
- Doesn't show expected limits: can be more important!
- Problem including WH signal in ZH search channel – what's the "SM prediction?" -- new plot: fractional rate limit

Another Representation – Ratios of Limits to SM



Getting Started with $ZH \rightarrow l^+l^-bb$

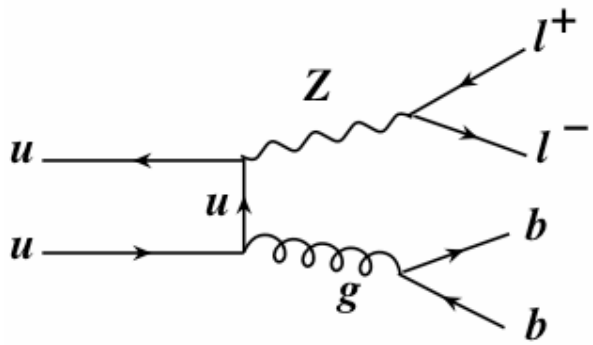




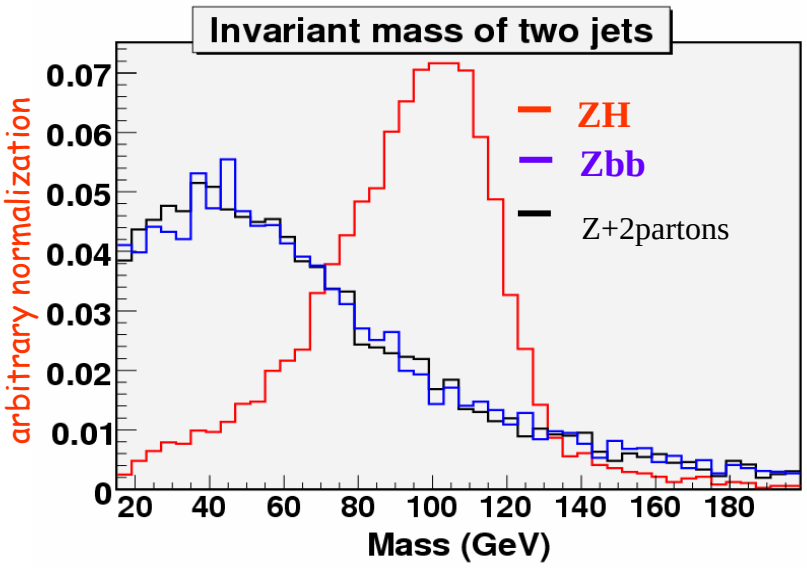
- Selection:
  - $Z^0 \rightarrow e^+e^-$ or $\mu^+\mu^-$
  - 2 or 3 jets, at least one b-tag
  - Low Missing E_T

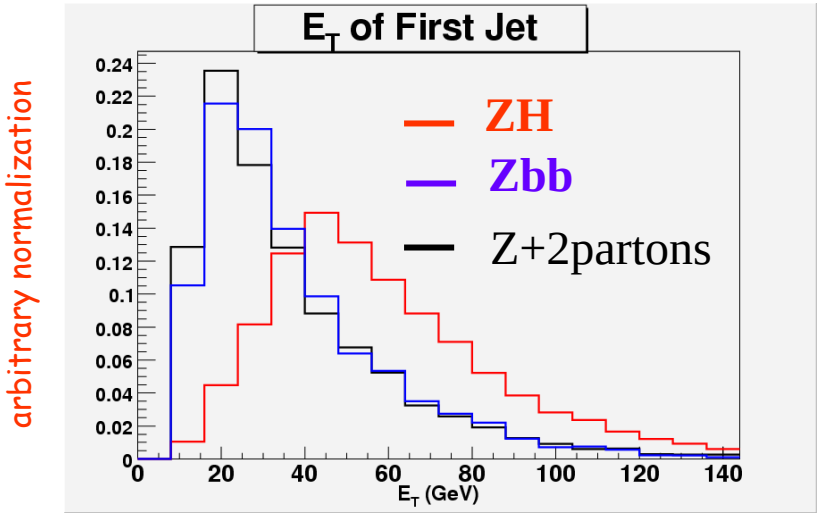
Most of Background: Z^0bb
(Zcc and Zc and Z+LF also there)

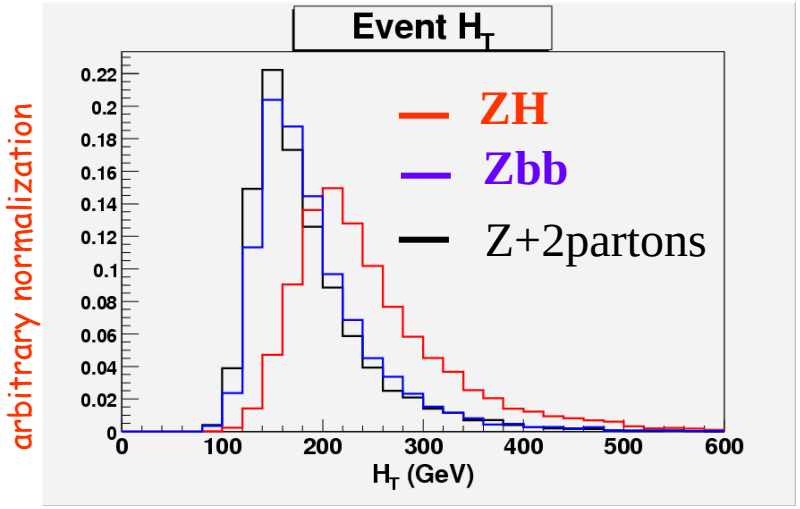
Background: 3 events/100 pb^{-1}
Signal: 0.03 events/100 pb^{-1}

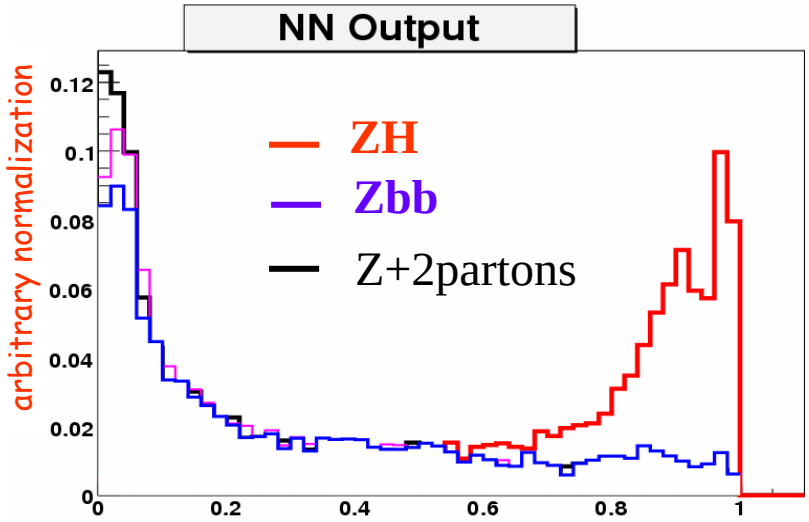


Additional Discrimination Power in the $ZH \rightarrow l^+l^-bb$ Channel







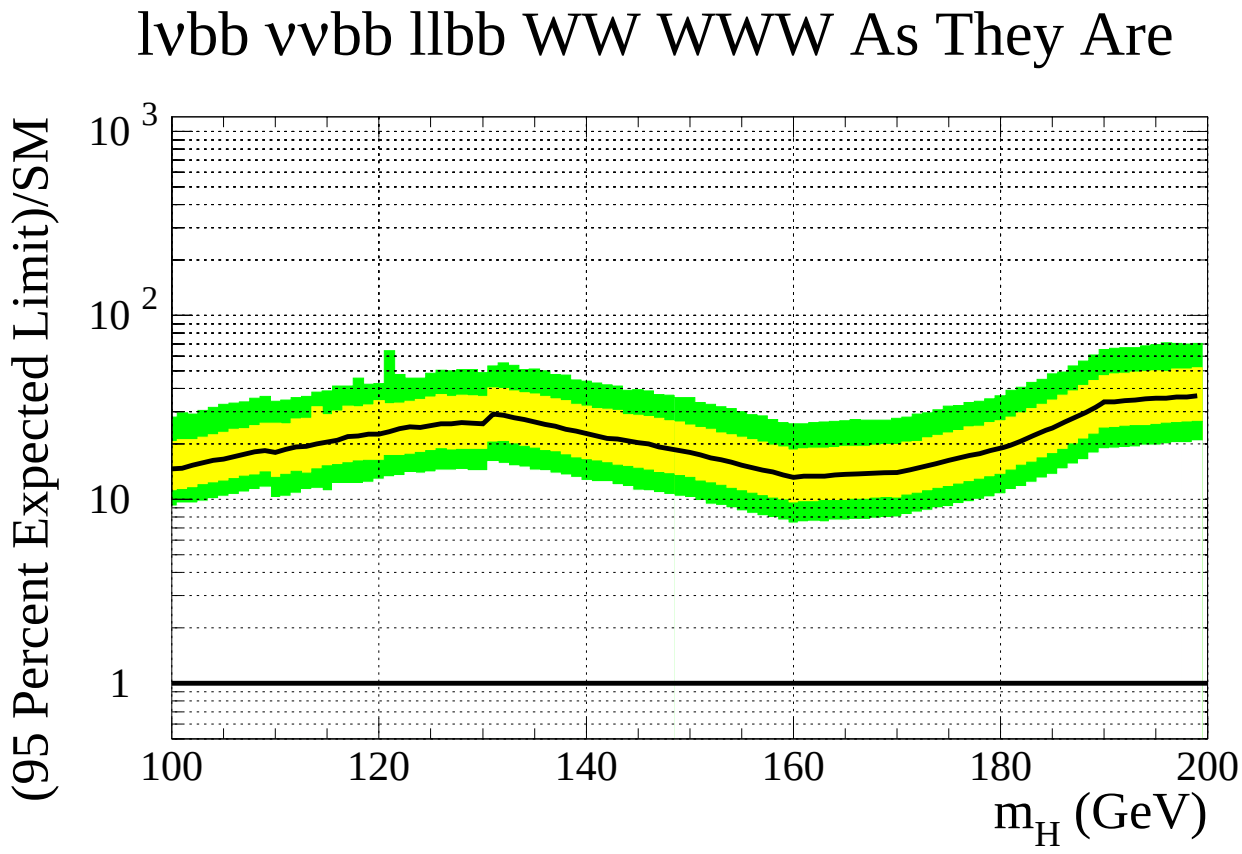


Encouraging feature: Predicted Zbb and Z+2p shapes are similar

Sensitivity with Existing CDF Analyses

New 360 pb^{-1} $h \rightarrow WW$ analysis used

Cross-Section times branching fraction limit as a multiple of the SM rate



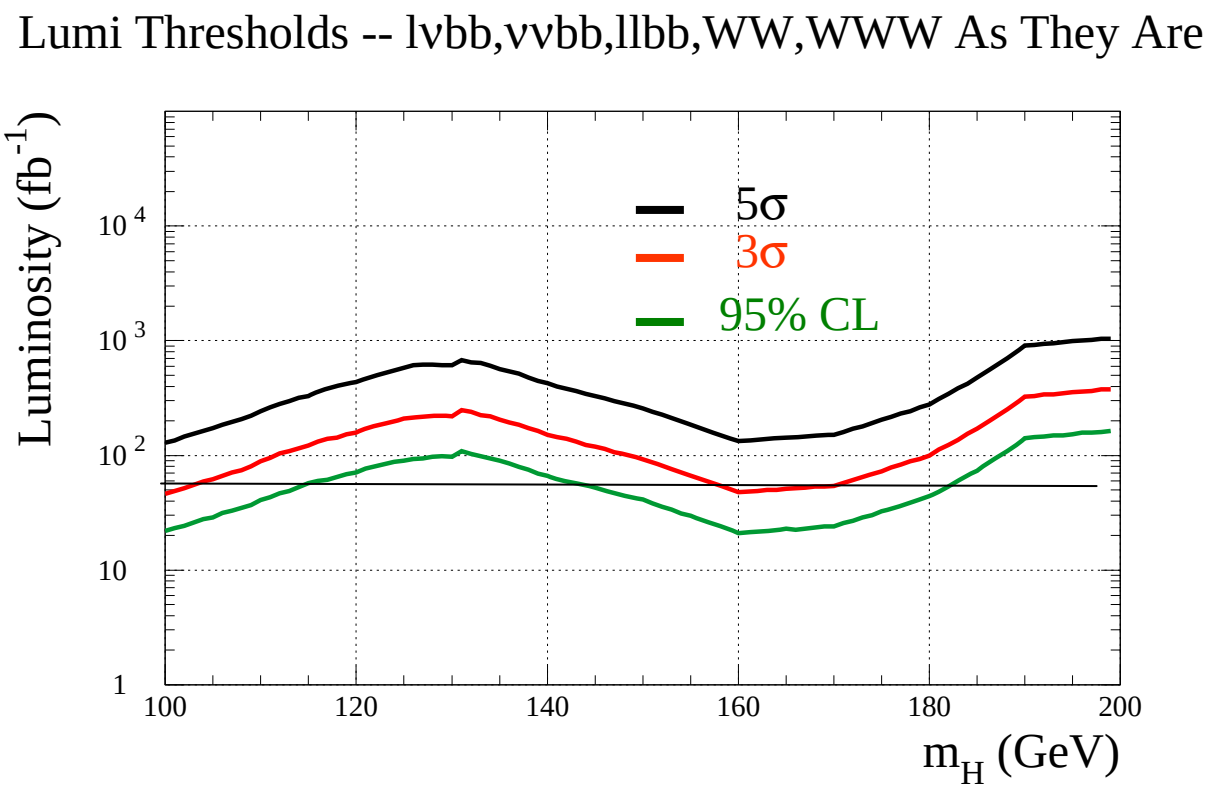
No Lumi Scale Factors: analyses "as is"

Luminosity Thresholds for CDF's Channels Combined

Assumption: Systematic errors scale with $1/\sqrt{\int \mathcal{L} dt}$

All channel's luminosities scaled to 300 pb^{-1} and then scaled together

Width of bands given by systematic errors on/off



Would need 50 fb^{-1} to exclude m_H=115 GeV if:

1) DØ stops taking data
2) CDF never does any work on the channels

We hope to do much better!

So How Do We Get There??

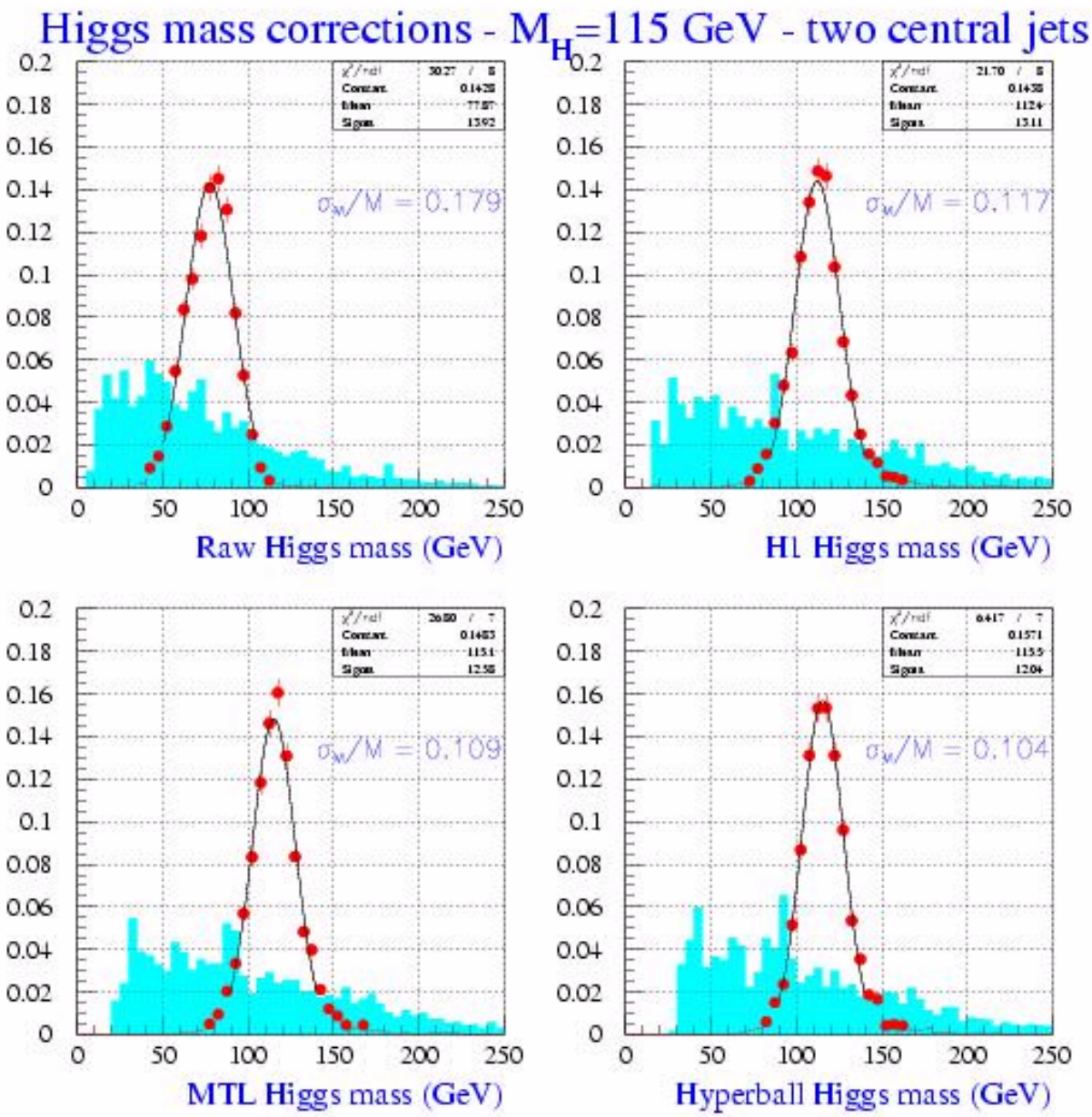
Luminosity Equivalent $(s/\sqrt{b})^2$

Start with existing channels, add in ideas with latest knowledge of how well they work.

Improvement	WH→lνbb	ZH→ννbb	ZH→llbb
Mass resolution	**1.7**	**1.7**	**1.7**
Continuous b-tag (NN)	1.5	1.5	1.5
Forward b-tag	1.1	1.1	1.1
Forward leptons	1.3	1.0	1.6
Track-only leptons	1.4	1.0	1.6
NN Selection	**1.75**	**1.75**	**1.0**
WH signal in ZH	**1.0**	**2.7**	**1.0**
Product of above	8.9	13.3	7.2
CDF+DØ combination	2.0	2.0	2.0
All combined	17.8	26.6	14.4

Expect a factor of ~10 luminosity improvement per channel, and a factor of 2 from CDF+DØ Combination

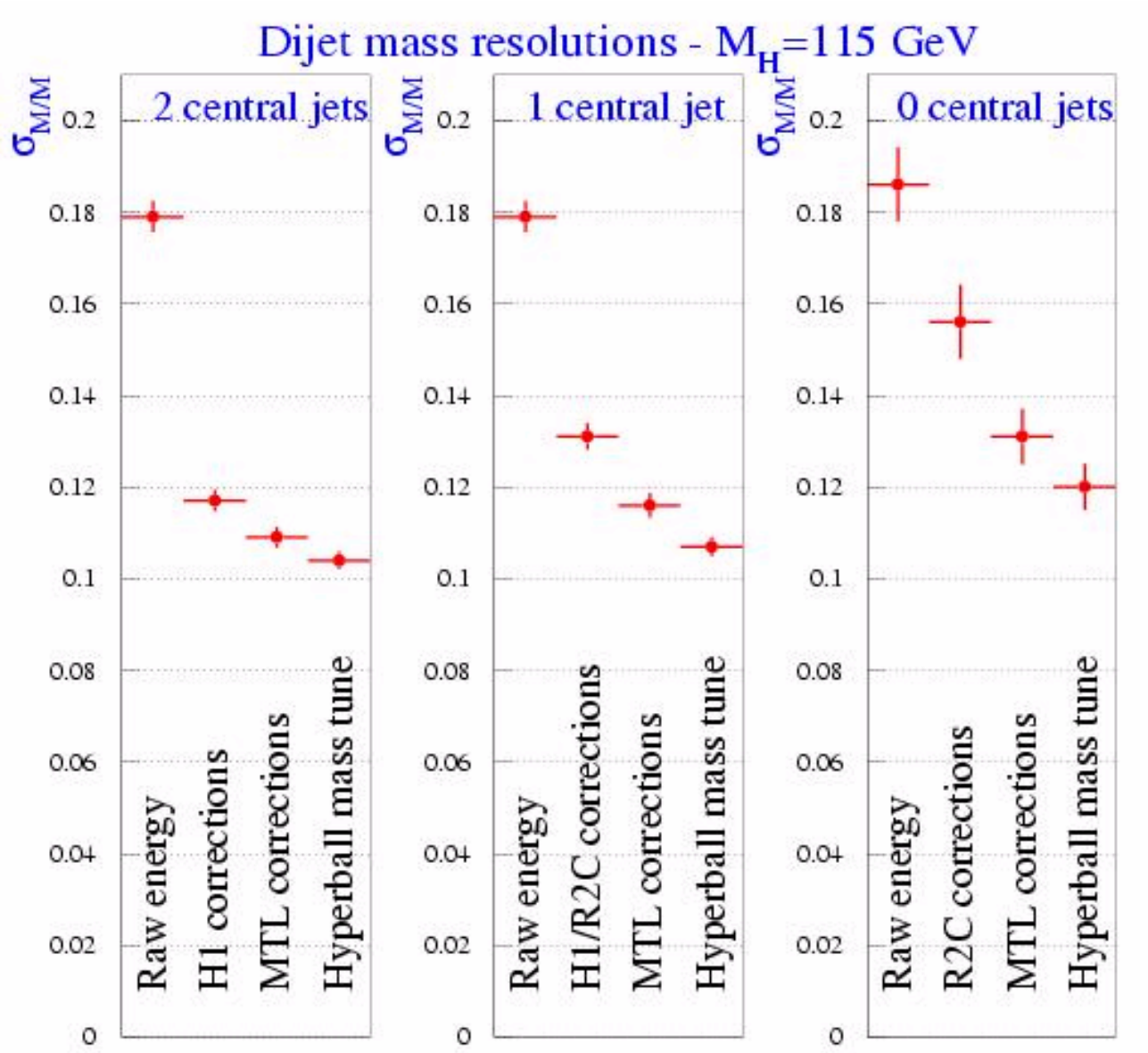
Dijet Mass Resolution Improvements



- Larger jet cones
- track-cluster association
- b-specific corrections
- Advanced techniques (NN, "hyperball")

Target: 10% resolution for two central jets

Effect of Forward Jets on Dijet Mass Resolution



NN Extension of SECVTX B-tag

non-top backgrounds (single-top) after SecVtx ¼ 50%

Approach:

- require SecVtx
- improve purity by including:
  - long lifetime (also by SecVtx)
    - decay length of SecVtx
    - D_0 of tracks
  - large mass
    - mass at SecVtx
    - p_T of tracks w.r.t jet axis
  - decay multiplicity
    - # of tracks
  - decay probability into leptons
    - # of leptons

Neural Network

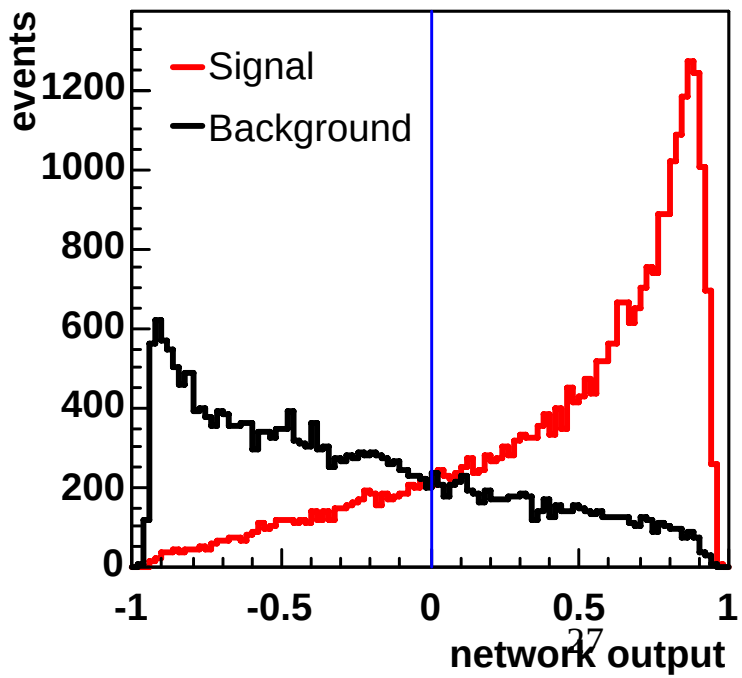
Signal:

single-top, $t\bar{t}$, $Wb\bar{b}$

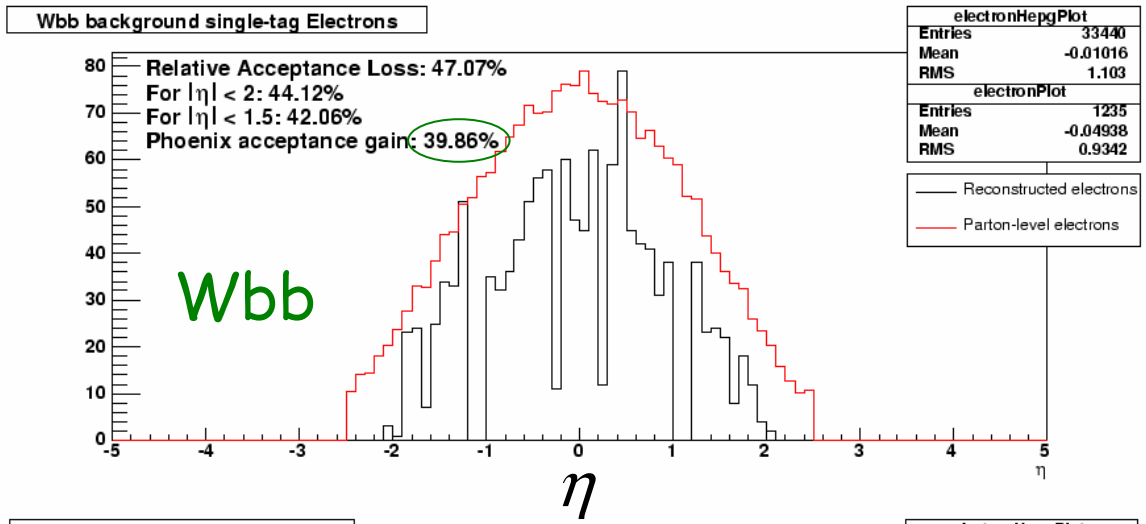
Background:

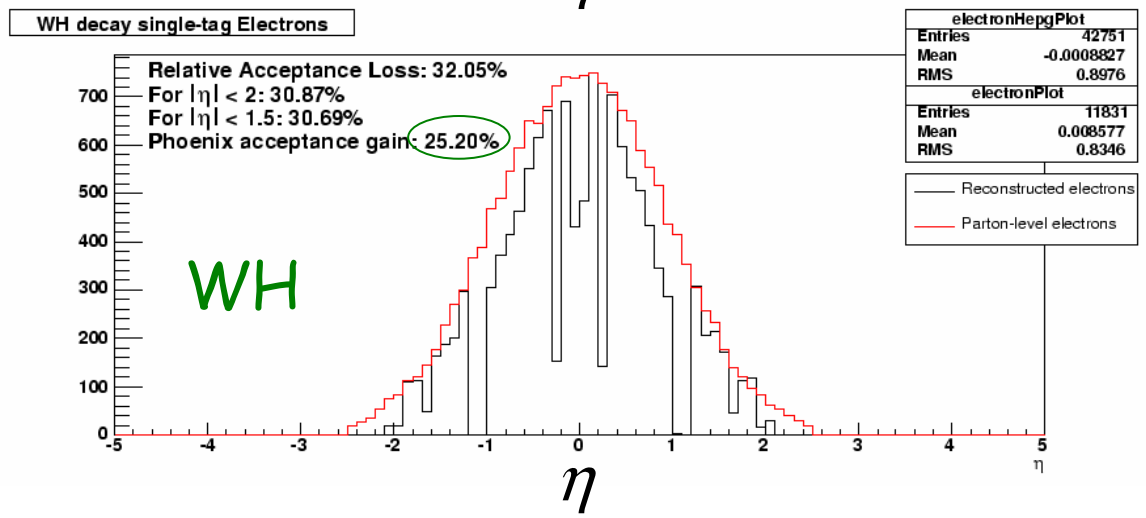
$Wc\bar{c}$, Wc, Mistags

(mixed acc. to background estimation)



Forward Electrons





Currently plug electrons only used as a Z^0 veto in the lvbb channel.

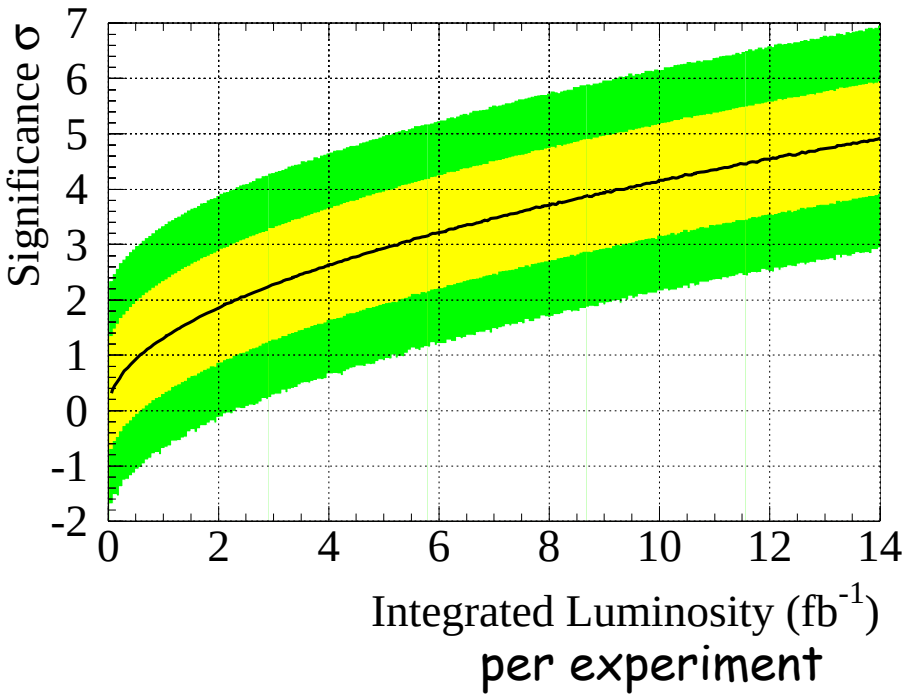
Phoenix electrons give
25% extra signal
40% extra background

$$s/\sqrt{b} \rightarrow 1.06 s/\sqrt{b}$$

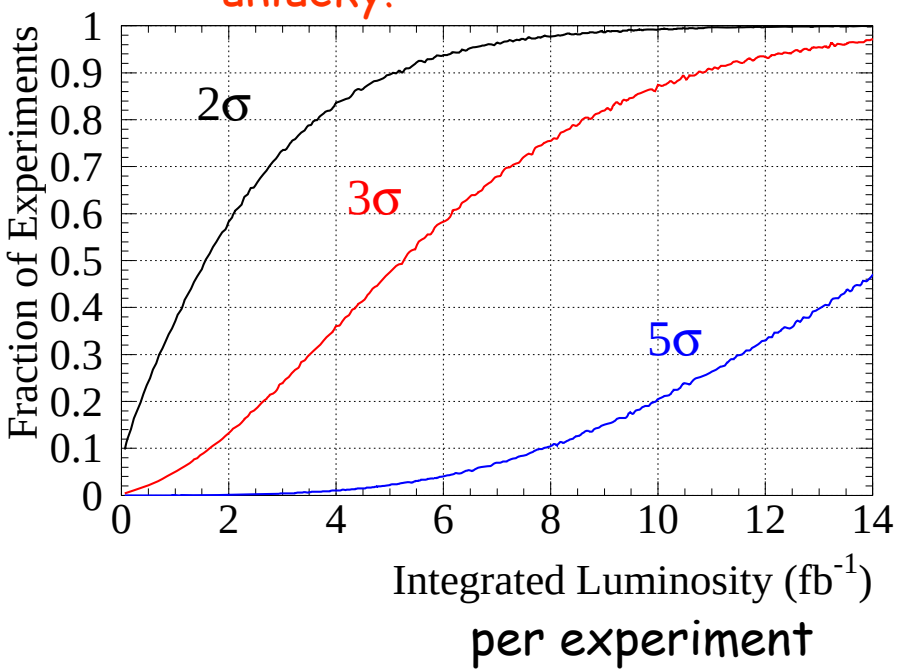
$(s/b)_{forw} = 0.6(s/b)_{central}$

Not optimal to add -- treat as separate channel!

Expected Signal Significance CDF+DØ vs Luminosity



It's possible to be lucky or unlucky!



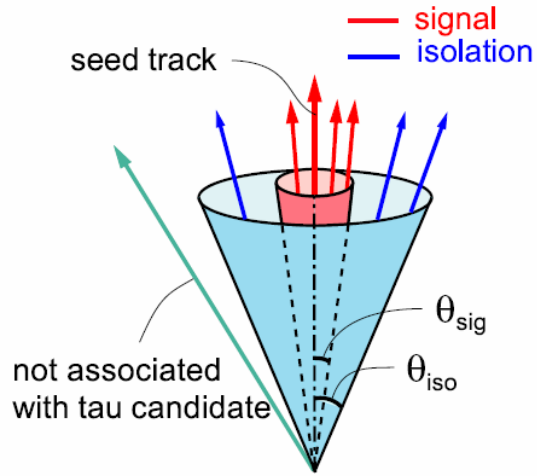
m_H=115 GeV assumed

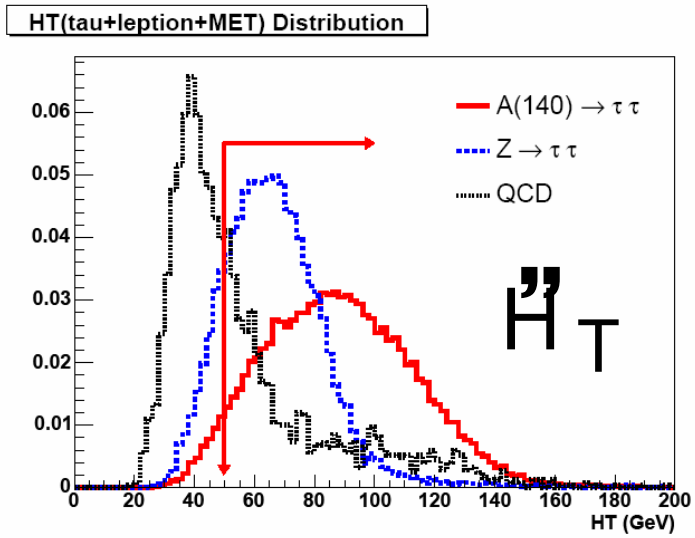
The $h^0, A^0 \rightarrow \tau^+\tau^-$ Channel: Selection

- Isolated e or μ, $E_T > 10$ GeV
- Hadronic tau:
  - 1 or 3 tracks. $\Sigma q = \pm 1$
  - $p_{T,had} > 15$ GeV
  - $m_{had} < 1.8$ GeV (incl. π^0's)
  - isolated (0.52 rad=θ_{iso})
  - charge opposite to leptonic tau
- Z^0 veto
- $\ddot{H}_T$ > [illegible]

  (sum of tau candidate E_T plus Missing E_T)

- ζ cut





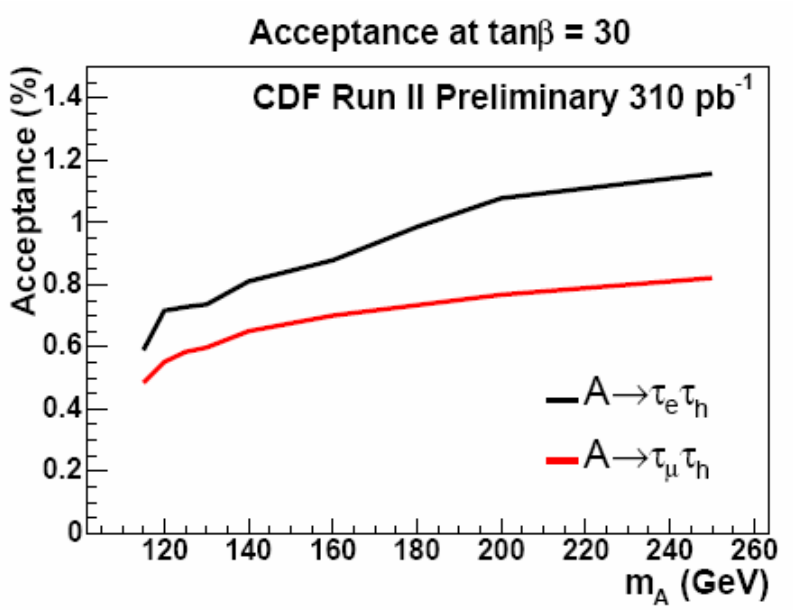
The $h^0, A^0 \rightarrow \tau^+\tau^-$ Channel: Backgrounds

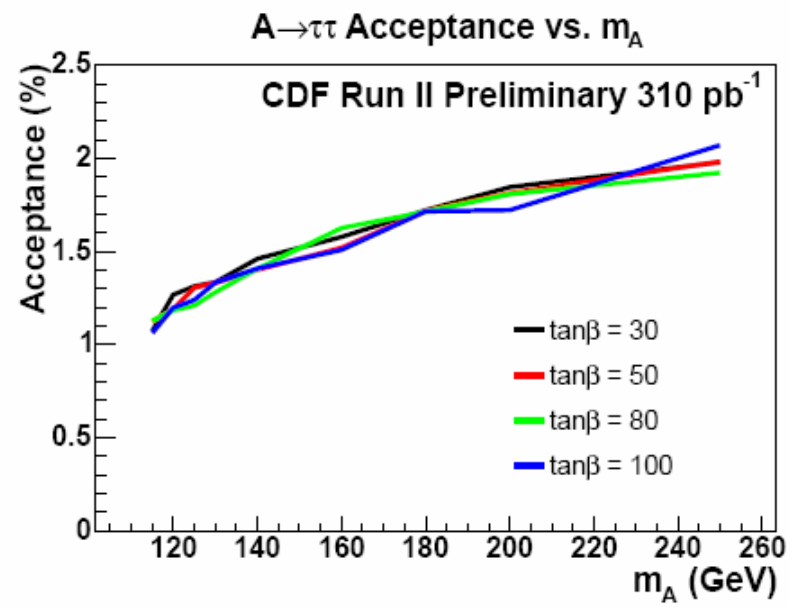
- $Z/\gamma^* \rightarrow \tau^+\tau^-$: irreducible
- $W \rightarrow l\nu$ + jet $\rightarrow$ fake τ: estimated with data
- dijets $\rightarrow$ fake lepton + fake τ_h: estimated with data
- Other backgrounds: $Z \rightarrow ll$, tt, diboson,... Use MC.

Fake rate: P(fake τ_h|jet) = 1.5% at E_T=20 GeV, drops to 0.1% at E_T=100 GeV

Source	Events in 310 pb^{-1}
$Z/\gamma^* \rightarrow \tau^+\tau^-$	405 ± 24
Fake τ_h + X	75 ±15
All other bg	16 ± 1
Total	496 ± 38
Observed	487

The $h^0, A^0 \rightarrow \tau^+\tau^-$ Channel: Signal Acceptance

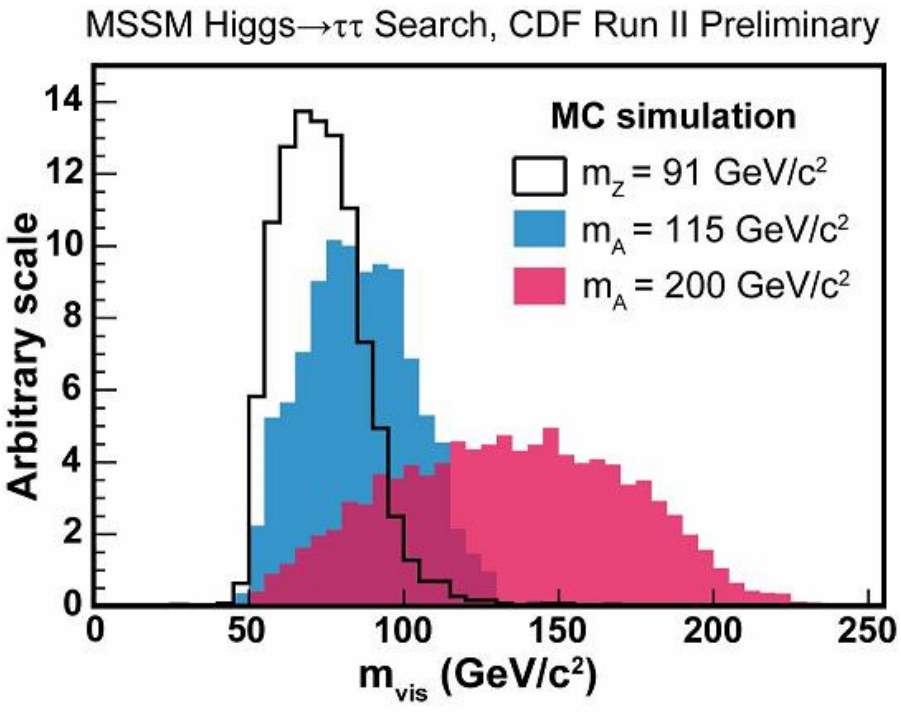


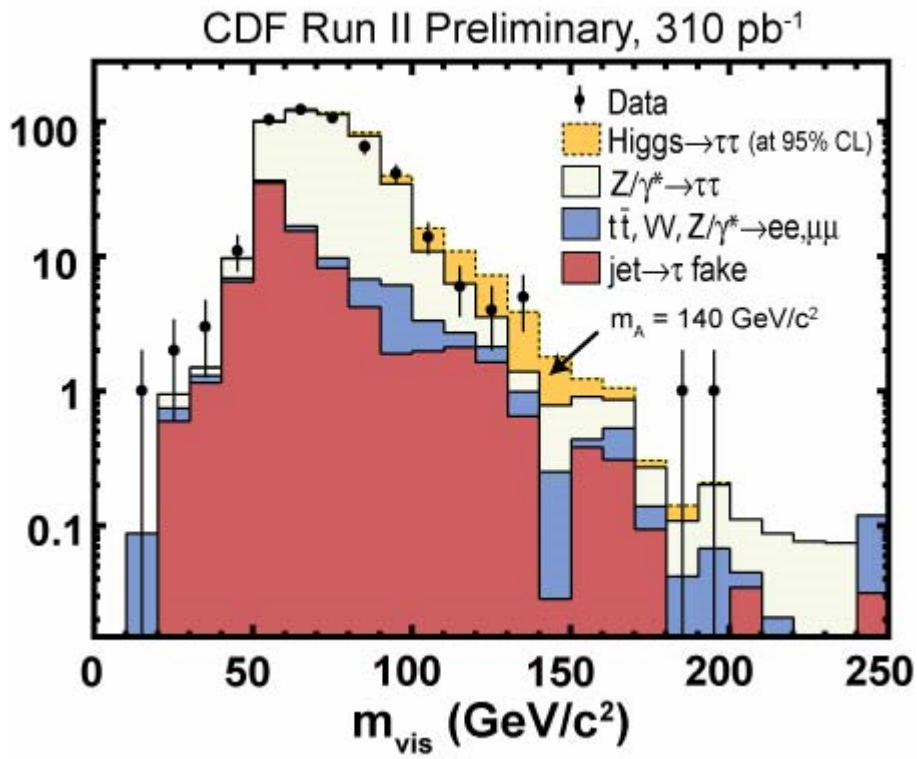


Systematic Uncertainties on Signal Estimation

Error Source	Error (%)	applies to
e ID	1.3	e
μ ID (CMUP)	**4.4**	μ
μ ID (CMX)	**4.6**	μ
τ ID	**3.5**	τ_h
Event Cuts	1.8	all
PDF	**5.7**	all signal
e trig	1.9	e
μ trig (CMU)	1	μ
μ trig (CMX)	1	μ
track τ trig	1	τ_h
Luminosity	**6**	all

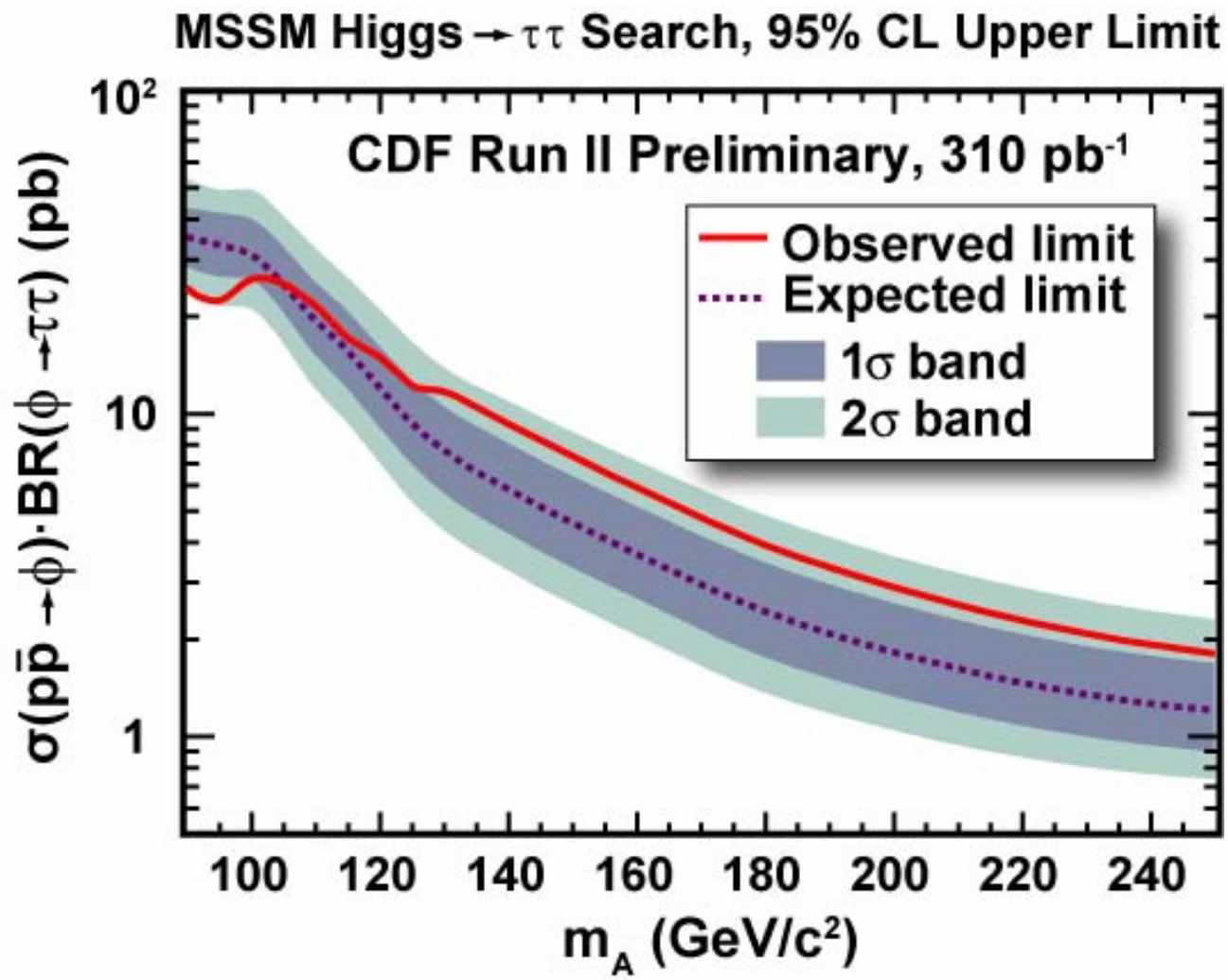
An Approximate Mass Reconstruction: m_{vis}





Invariant mass of visible $\tau^+\tau^-$ decay products plus Missing E_T

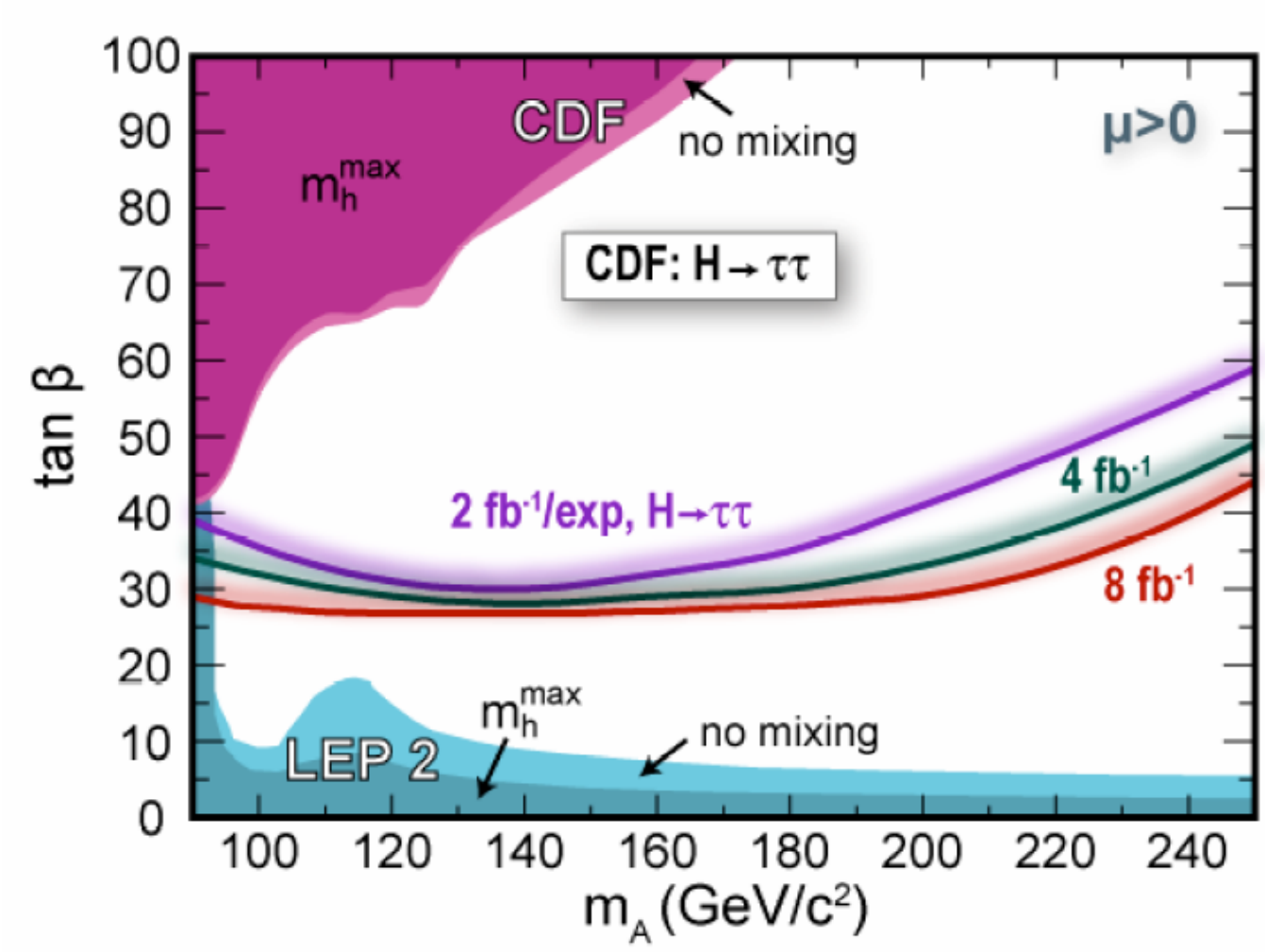
Limits on Cross-Section × Branching Ratio



$\phi = h^0$, A^0 or H^0 or a sum of states with similar masses

Tau Channel Prospects for the Future

We will soon test models with tanβ=40



Summary and Outlook

- We have preliminary searches in a great variety of channels, most with ~300 pb^{-1} of data analyzed for Summer 2005.

SM Higgs Searches

$$W^{\pm}H \to \ell^{\pm}\nu b\bar{b} \quad ZH \to \nu\bar{\nu}b\bar{b}$$
$$ZH \to \ell^{+}\ell^{-}b\bar{b} \quad gg \to H \to W^{+}W^{-}$$
$$W^{\pm}H \to W^{\pm}W^{+}W^{-}$$

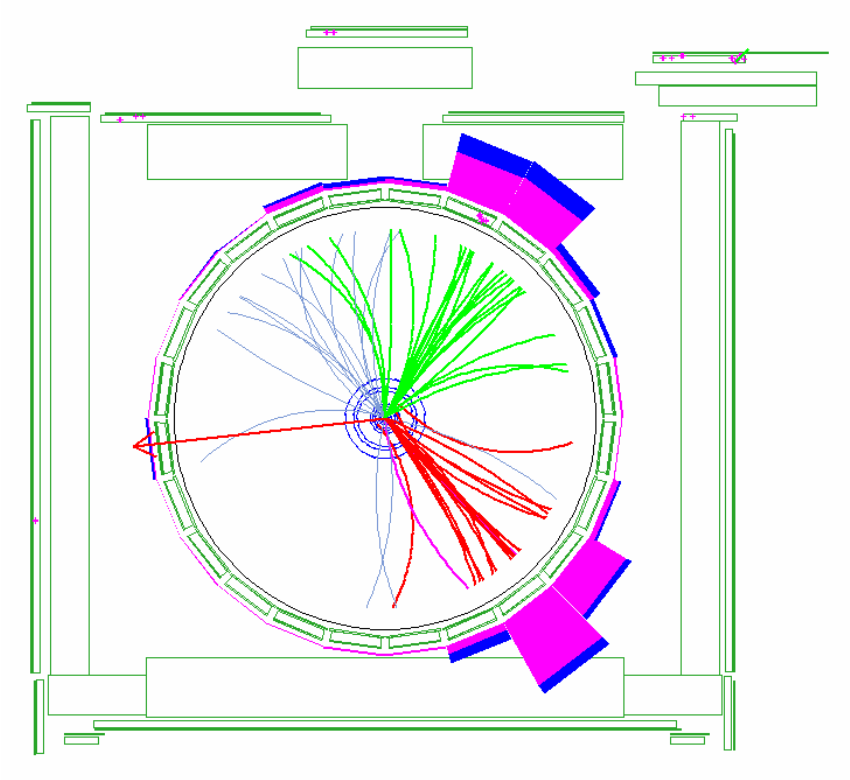
MSSM Higgs Search

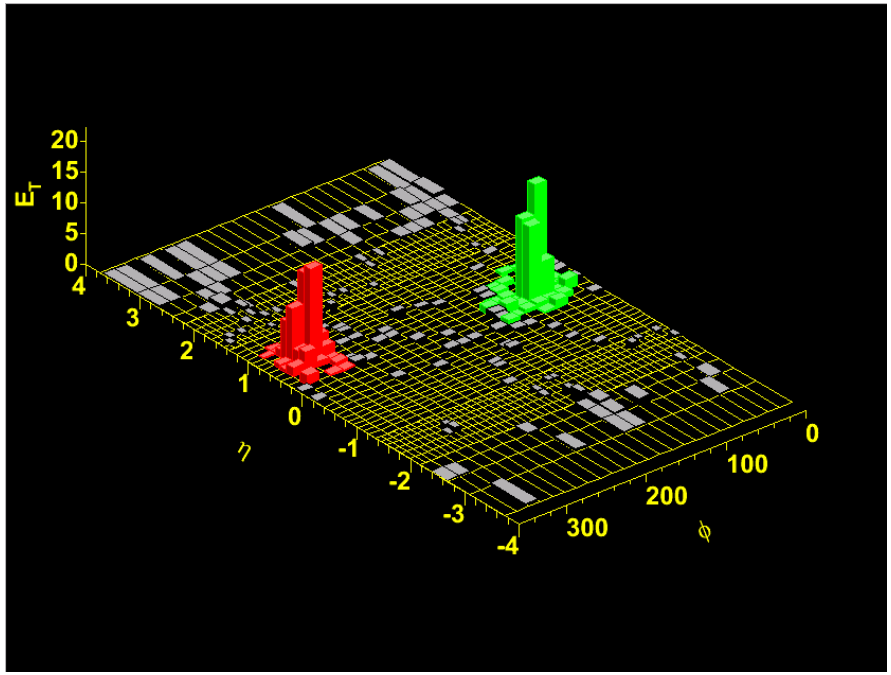
$$H \to \tau^{+}\tau^{-}$$

- We have tools to combine them together and estimate sensitivity
- The sensitivity is currently insufficient to test for presence or absence of a SM Higgs boson but we will get more data and improve our channels with well-understood techniques.
- MSSM Higgs searches are getting exciting.

Backup Slides Follow

Another Interesting Candidate Event



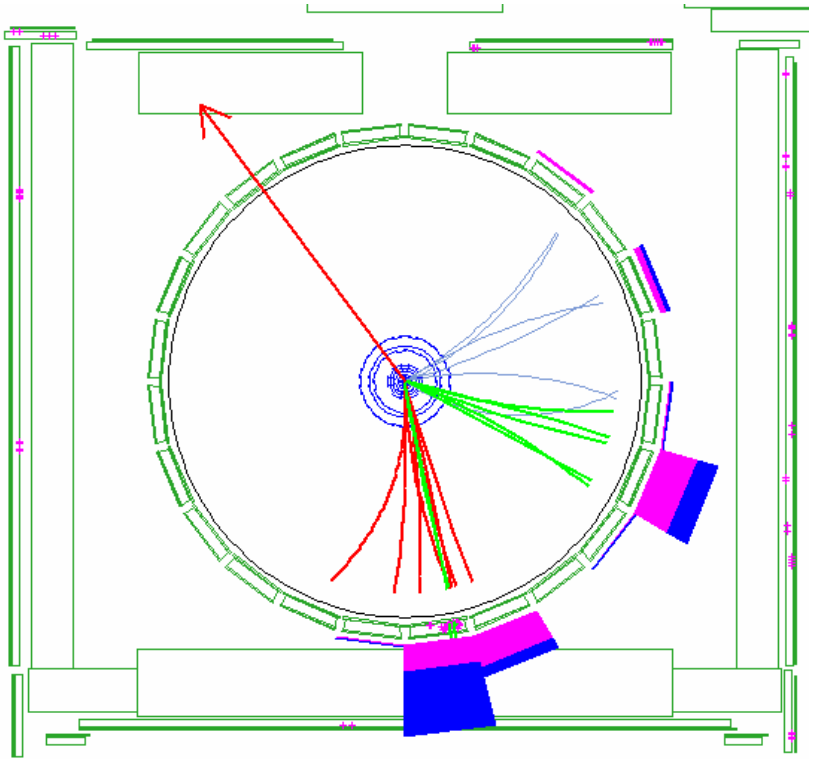


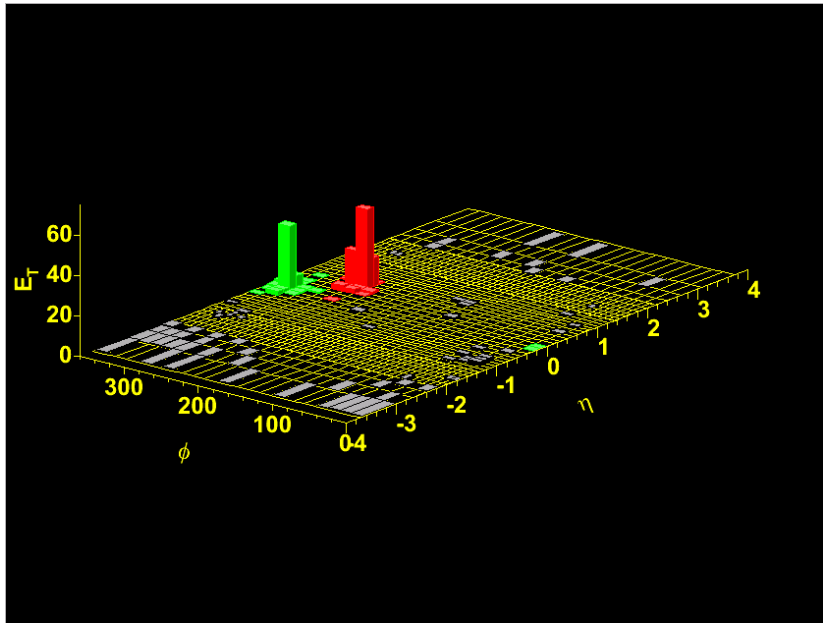
Jet_1 E_T=84.7 GeV
Jet_2 E_T=71.9 GeV -- Tagged

m_{jj} = 129 GeV

Missing E_T = 98 GeV

An Interesting Candidate Event





Two b-tagged jets

m_{jj}= 82 GeV

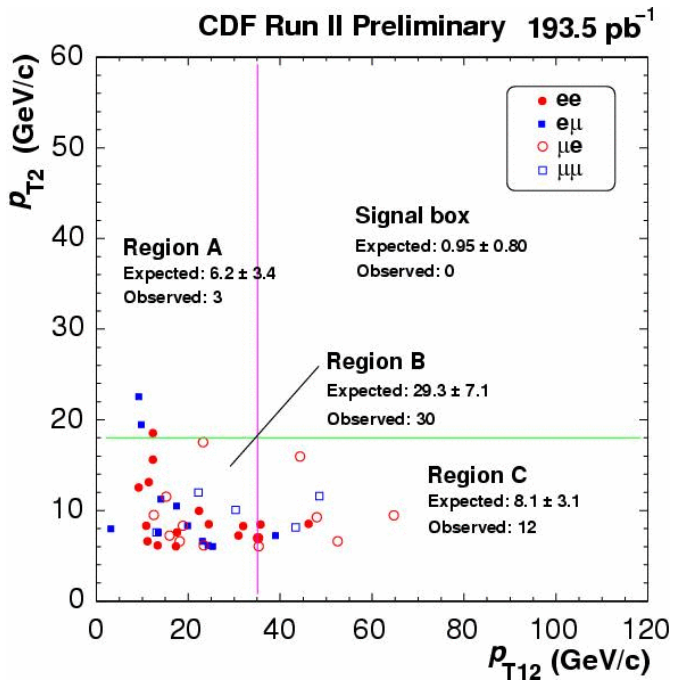
Missing E_T=145 GeV

Jet_1 E_T= 100.3 GeV
Jet_2 E_T= 54.7 GeV

Could be ZZ

Search For $W^{\pm}H^{0} \rightarrow W^{\pm}W^{+}W^{-}$

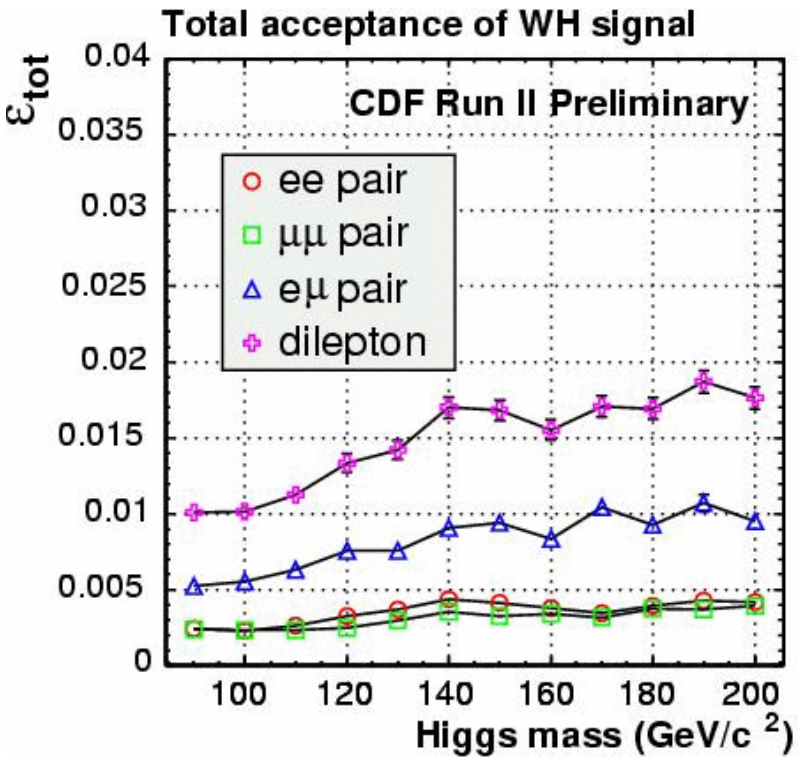
- Like-sign dilepton selection ("1"=more energetic lepton, "2"=less energetic)
  - $p_{T,1}$>20 GeV, $p_{T,2}$>6 GeV
  - reject conversions, cosmics, Z→leptons
  - Signal region: $p_{T,2}$>16 GeV, $p_{T,12} = |\vec{p}_{T,1} + \vec{p}_{T,2}| > 35$ GeV
    for m_H<160 GeV. Harden $p_{T,2}$ cut to 18 GeV for m_H>160 GeV



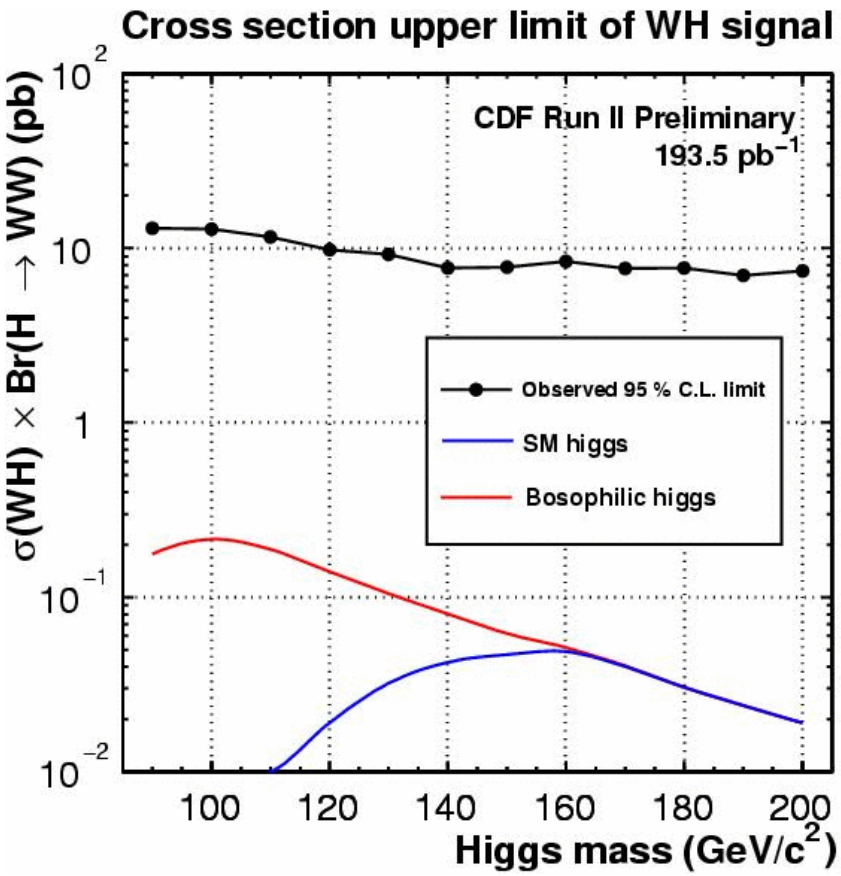
Category	Events in 193.5 pb^{-1}
Conversions	0.61 ± 0.61
Fake Leptons	0.12 ± 0.01
Other sources*	0.22 ± 0.10
Total background	0.95 ± 0.64
Observed	0

*Other backgrounds: Diboson, top, Wqq
SM WH signal: 0.03 events (m_H=160 GeV)

$W^{\pm}H^{0} \rightarrow W^{\pm}W^{+}W^{-}$ Signal Acceptance and Limits



Acceptance includes W branching fractions



Acceptance Systematic Error: 11%

ISR, FSR, PDF, Lepton ID, MC Stat., Mass dependence

CDF sees Z→bb decays in Run 2

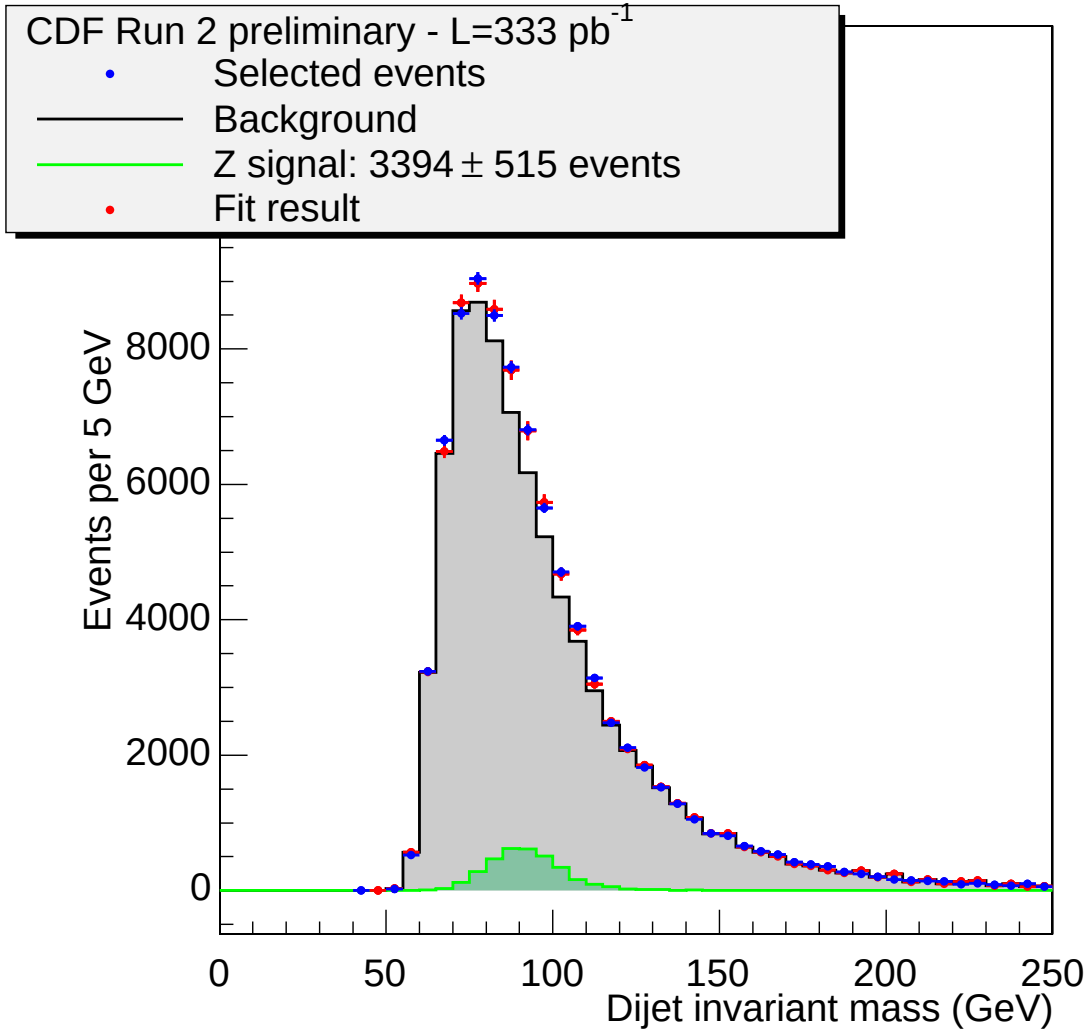
Double b-tagged events with no extra jets and a back-to-back topology are the signal-enriched sample: E_t^3<10 GeV, $\Delta\Phi_{12}$>3

Among 85,784 selected events CDF finds 3400±500 Z→bb decays

- signal size ok
- resolution as expected
- jet energy scale ok!

This is a proof that we are in business with small S/N jet resonances!

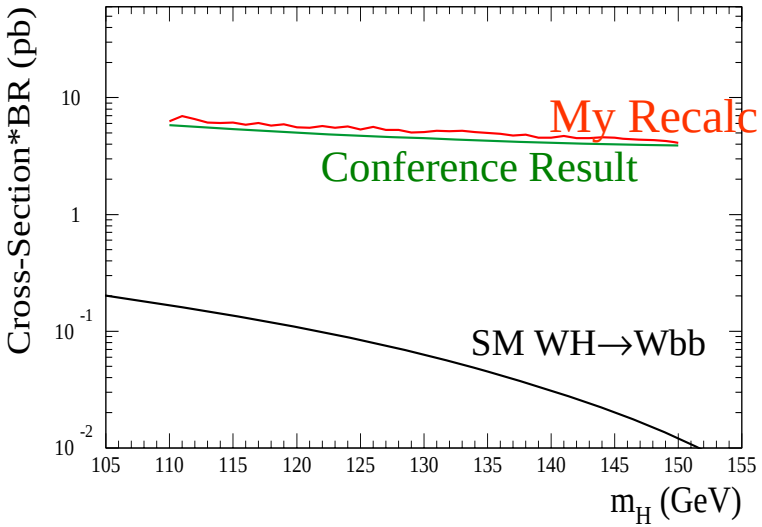
CDF expects to stringently constrain the b-jet energy scale with this dataset



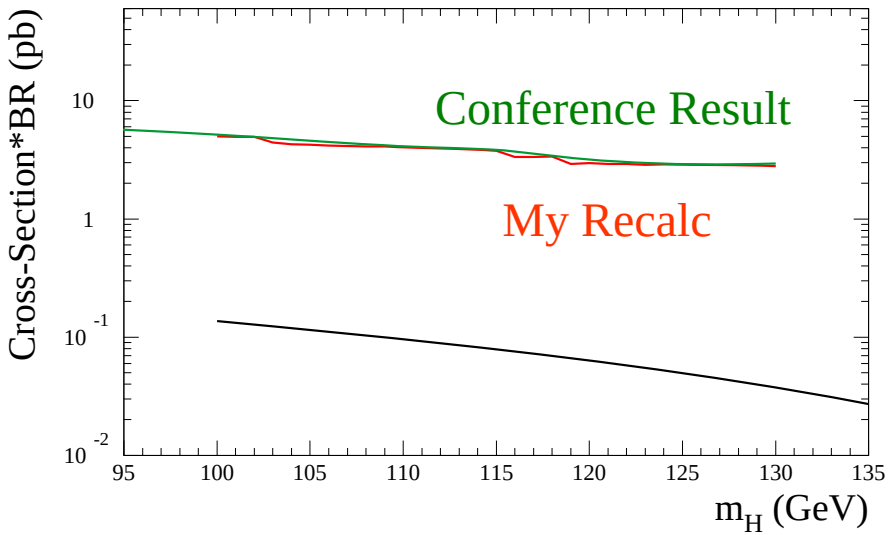
Check – Recalculate All Channels' Sensitivities with CL_s

(look for mistakes in preparation of results)

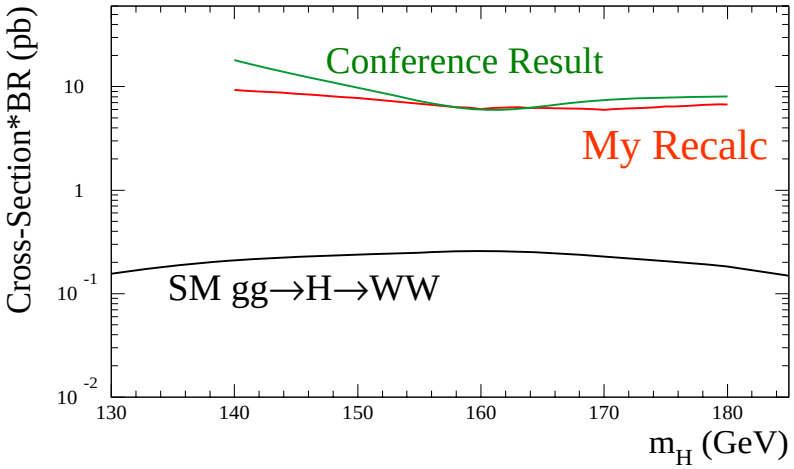
WH to lvbb Expected Limit



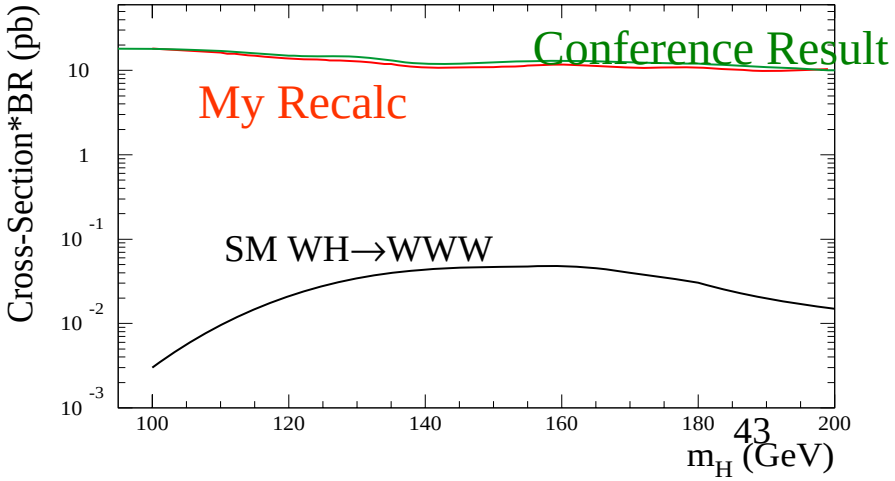
ZH to ννbb Expected Limit



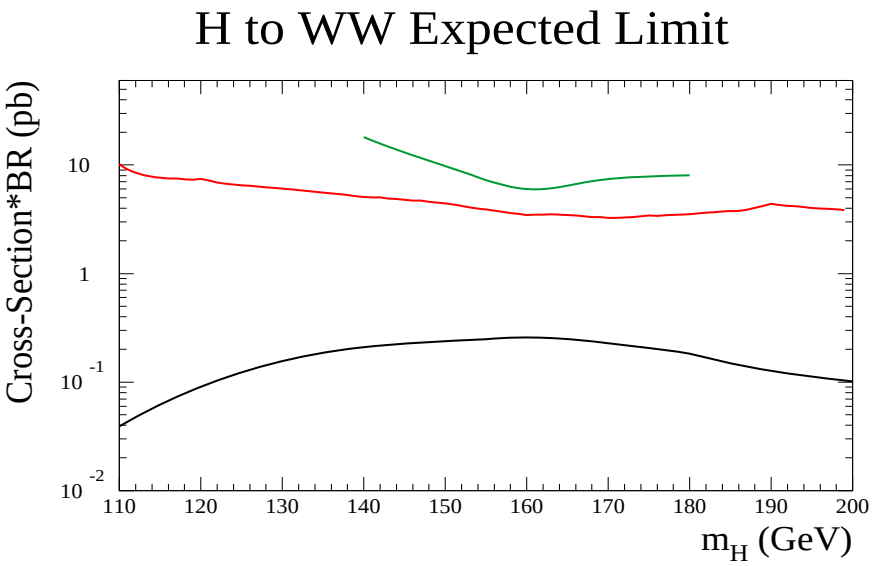
H to WW Expected Limit

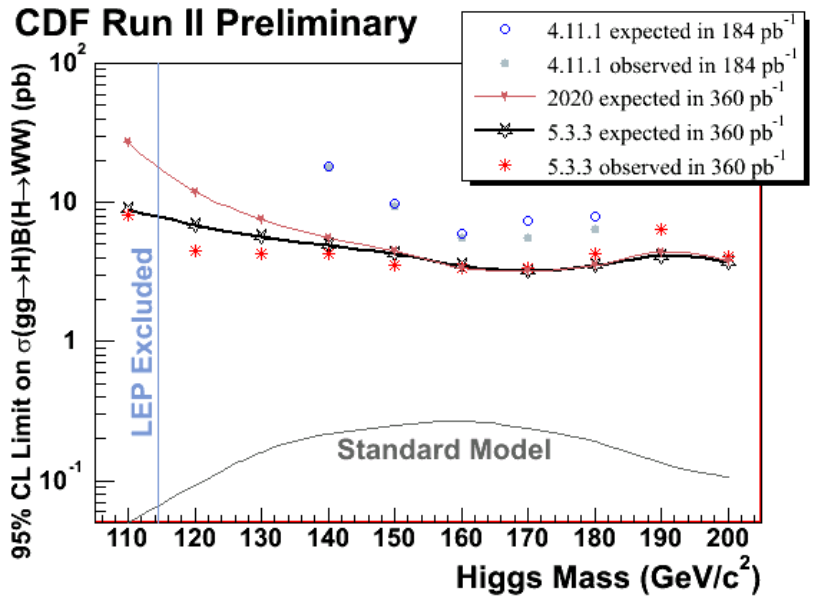


WH to WWW Expected Limit



Recomputing H to WW Expected limits





Green: Expected, old analysis.
Red: Expected, new analysis
Black: SM

Same limits computed by channel experts

Impact Parameter Resolution Performance

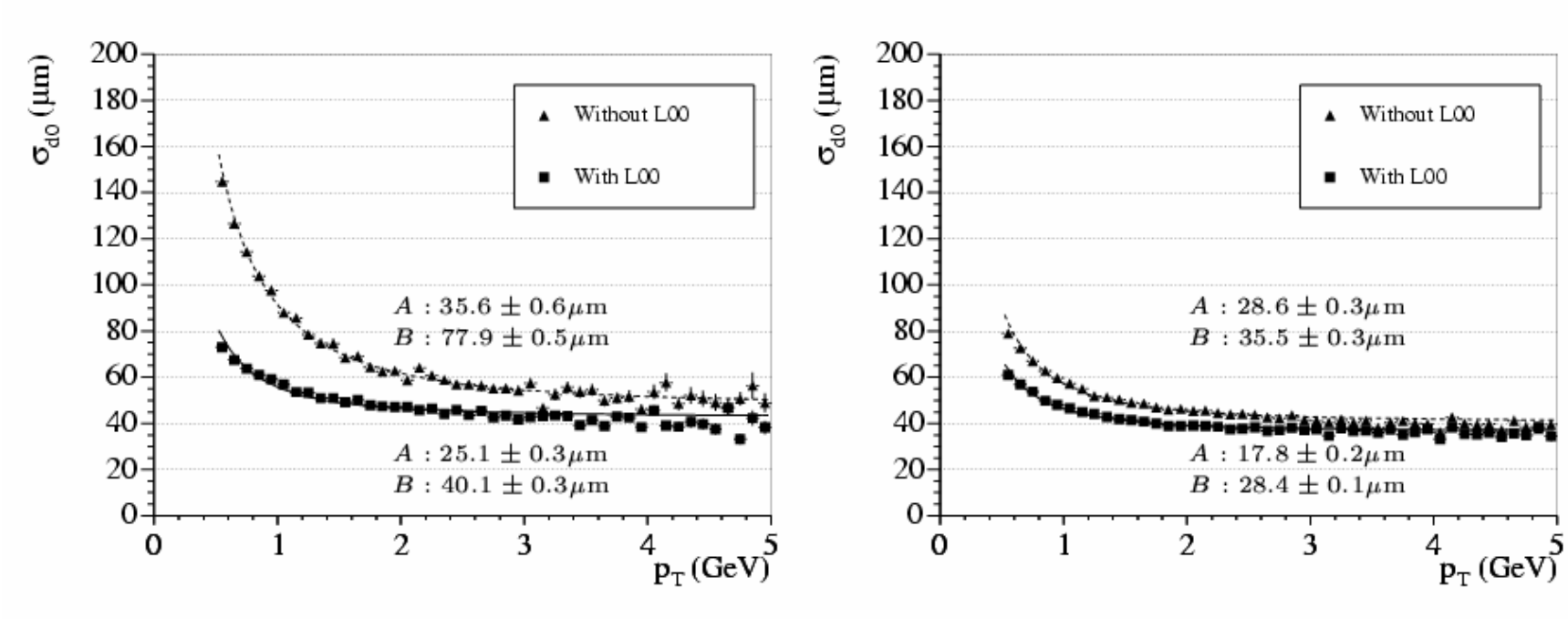


Fig. 2. σ_{d_0} vs. p_T for all tracks intersecting sensors located at $r = 1.6$ cm. Distributions for tracks intersecting regions of SVXII with (without) extra material are shown in the graph on the left (right). Fit results are shown overlaid.

$$\sigma_{d_0} = \sqrt{A^2 + (B/p_t)^2 + 32^2}$$

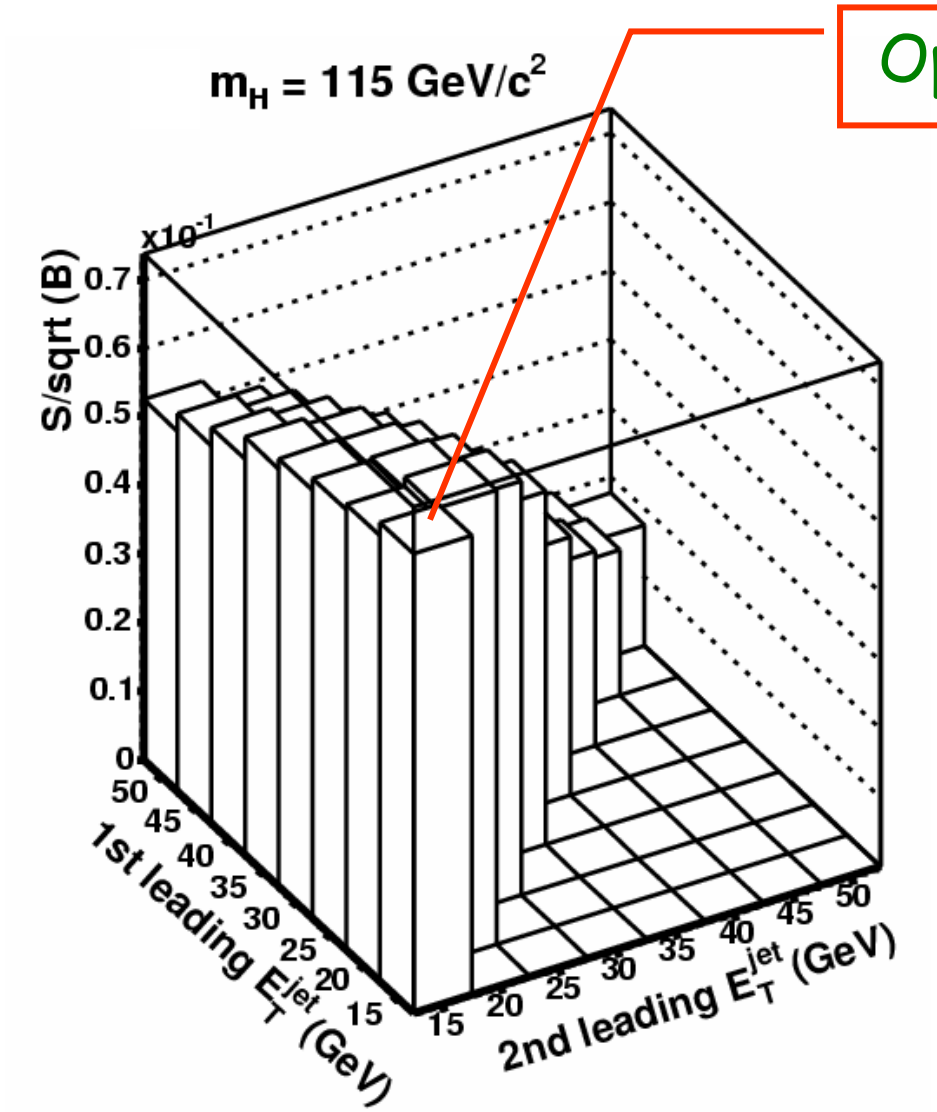
asymptotic resolution

multiple scattering

beam spot

Status as of Nov. 2004

WH→lνbb Cut Optimization: E_T Cuts on the two jets

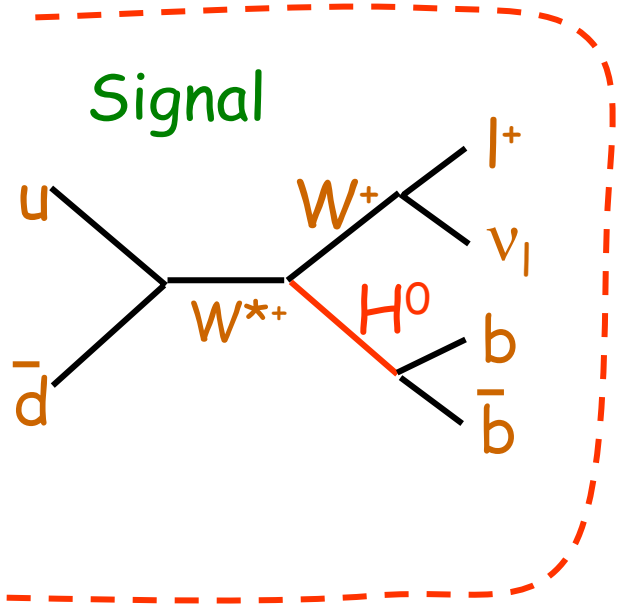


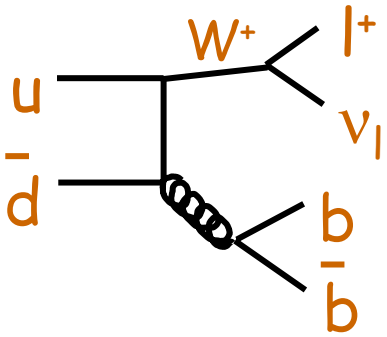
Operating point

s=ν b̄ is maximized with the lowest possible jet E_T cuts we can tolerate!

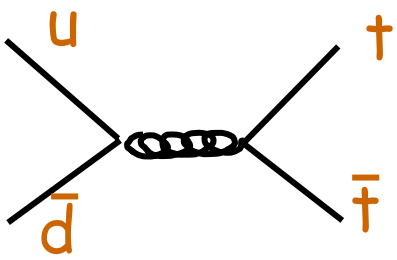
Further analysis optimization underway!

SM Higgs Searches at the Tevatron: WH→lνbb

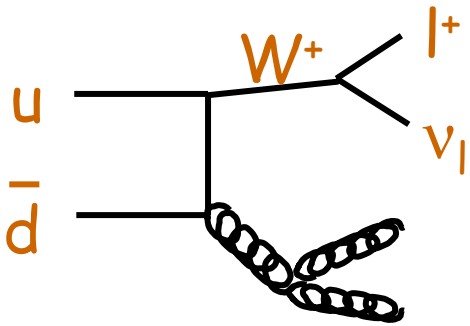




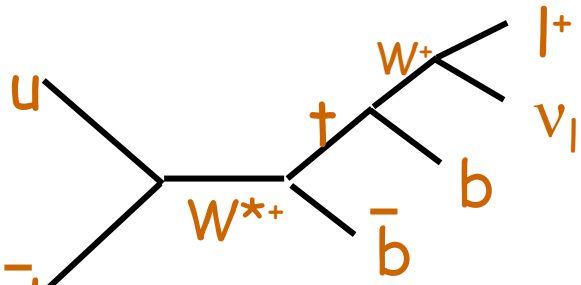
Large background (also $Wc\bar{c}$)



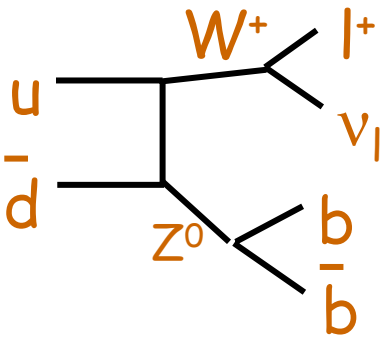
"ttbar": Jets+leptons from W decay



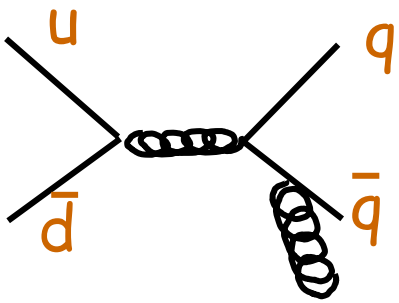
"W2p" Need one false b-tag



Single Top



"Diboson"



"Non-W"

ZH→ννbb Channel: Optimized Cuts

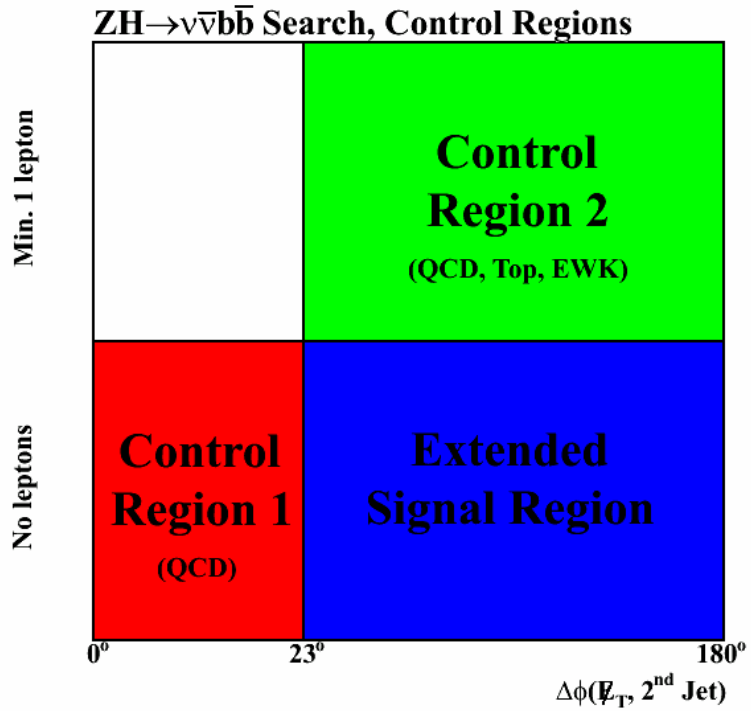
Benchmarked at M_h=120 GeV

Selection cut	ZH 120 288.9 pb^{-1}	Acceptance (%)	S/sqrt(B)
Basic Cuts	**0.205±0.004**	**5.92 ±0.1**	**0.03**
$\Delta\varphi(1^{st}\ Jet, \not{E}_T) > 0.8$	0.205 ±0.004	5.92±0.1	0.03
$\not{H}_T$ significance	0.183± 0.003	5.23±0.1	0.03
$1^{st}\ Jet E_T > 60 GeV$	0.161±0.003	4.68±0.09	0.04
Di-jet mass cut	**0.126±0.016**	**3.64±0.08**	**0.06**

$\not{H}_T$ significance = $\not{H}_T/H_T$

Background Contributions in Control Regions after Optimization Cuts

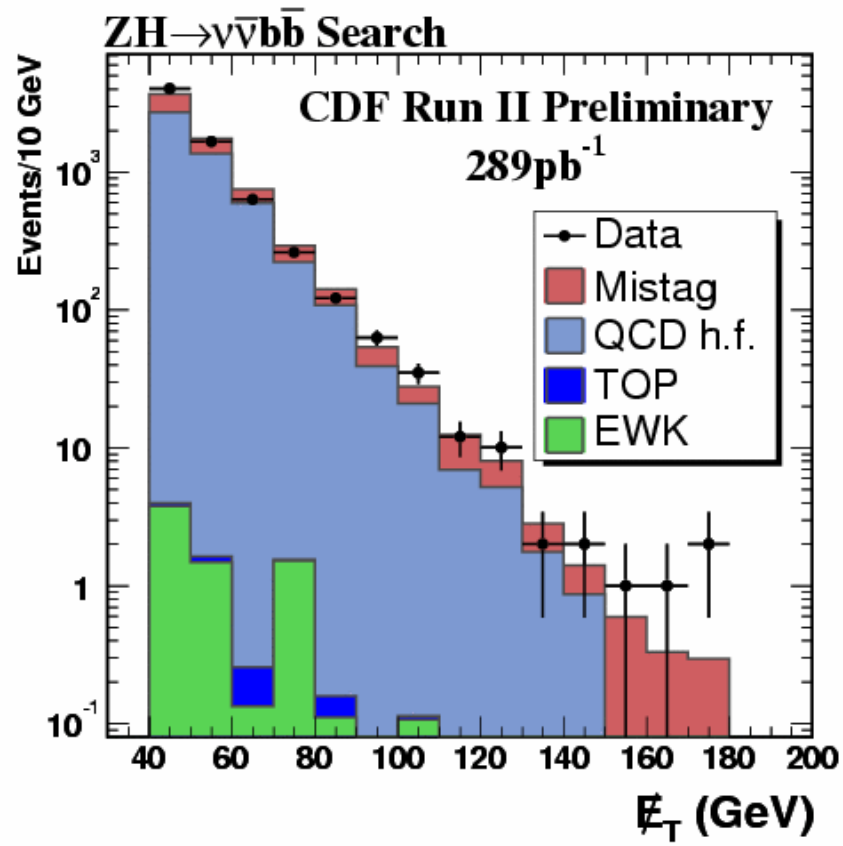
No mass window cut yet

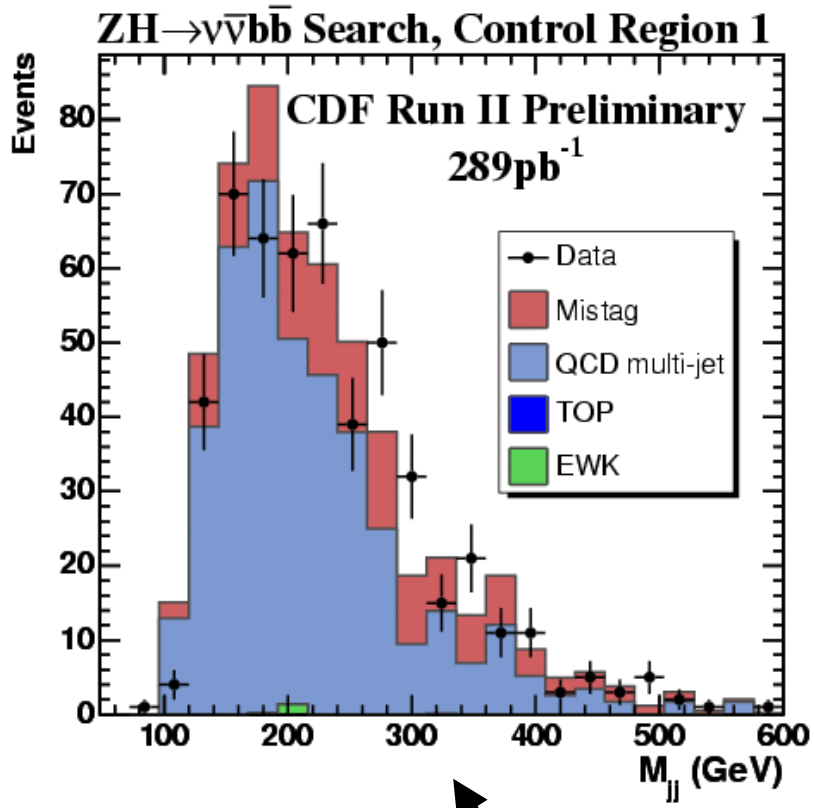


L=289 pb^{-1}

Process	Control Region 1	Control Region 2	Signal Region
QCD multi-jet	9.5 ± 4.3	5.2 ± 3	2.6 ± 1.7
TOP	0.01 ± 0.002	8.9 ± 2.3	2.1 ± 0.4
Di-boson	0 ± 1.2	1.5 ± 0.3	1.1 ± 0.2
W + h.f.	0 ± 1.2	9.7 ± 3.5	3.7 ± 2.6
Z + h.f.	0 ± 0.18	1.1 ± 0.3	3.2 ± 1.2
Mistag	2.9 ± 0.4	11.9 ± 2.3	7.0 ± 1.0
Total Expected BCK	12.4 ± 4.6	38.3 ± 5.7	19.7 ± 3.5
Observed	16	47	19

ZH→ννbb Control Samples – Constrain Background Levels

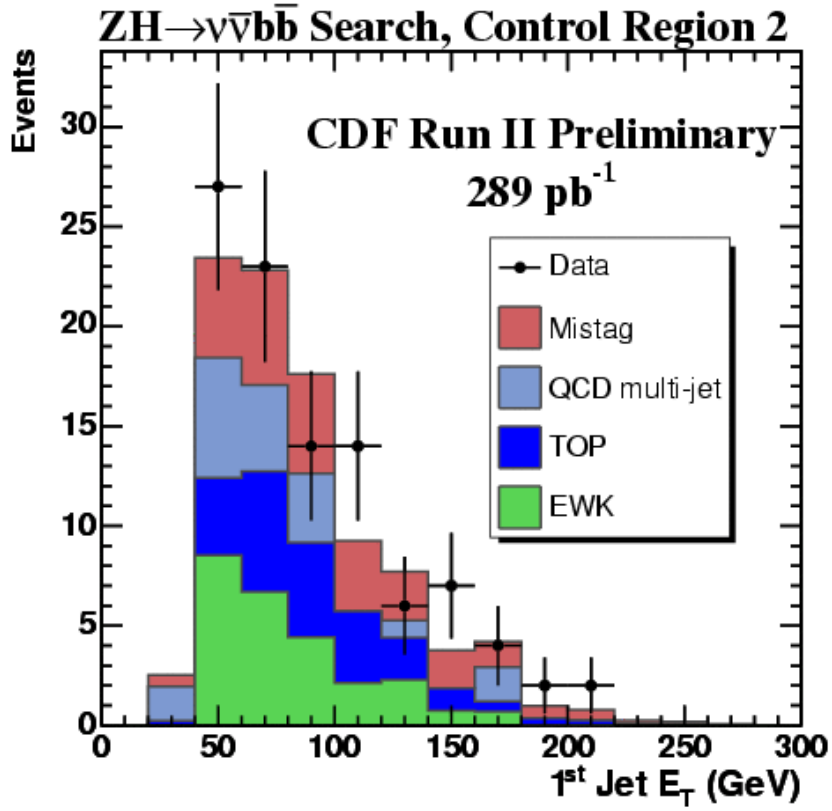


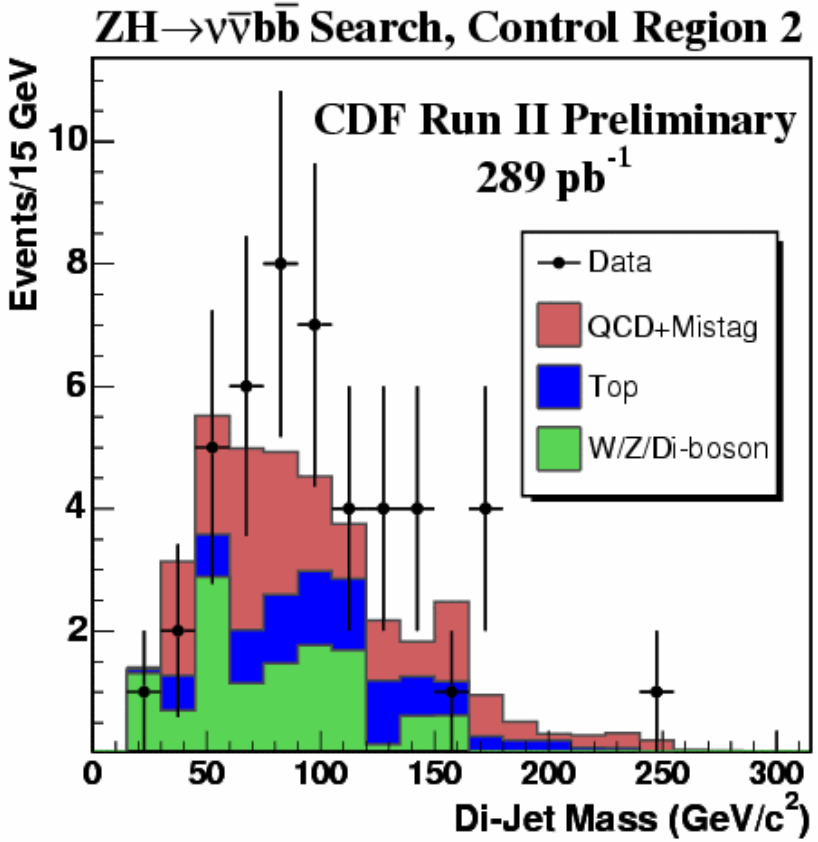


Region #1: QCD-dominated
Mistags from data, bb bg shape
from MC, scaled to fit data rate.

After "optimized cuts"

Control Region #2 – Requiring a Lepton

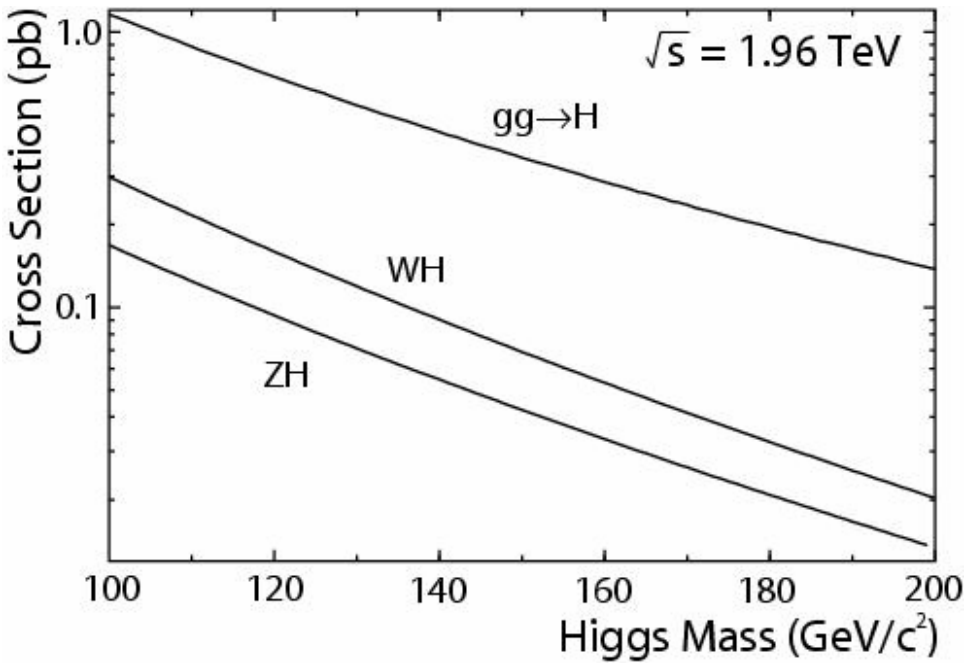




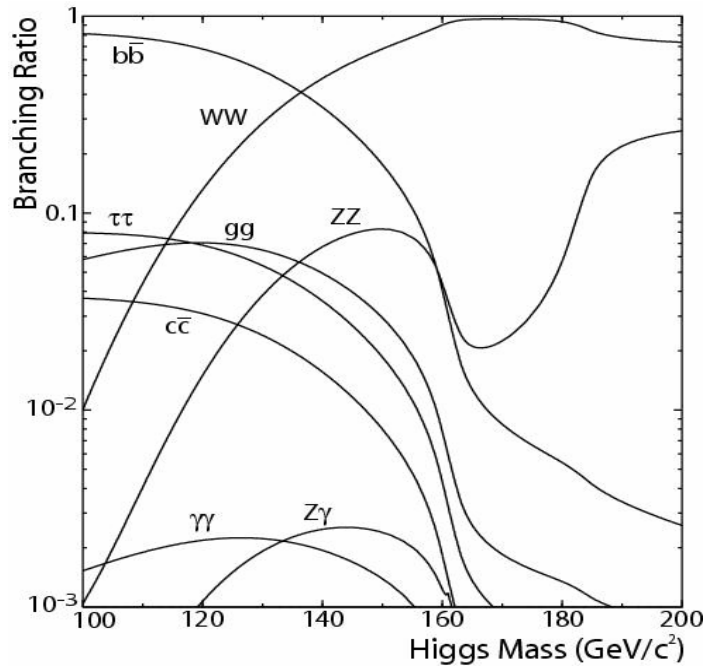
Optimized Cuts Applied

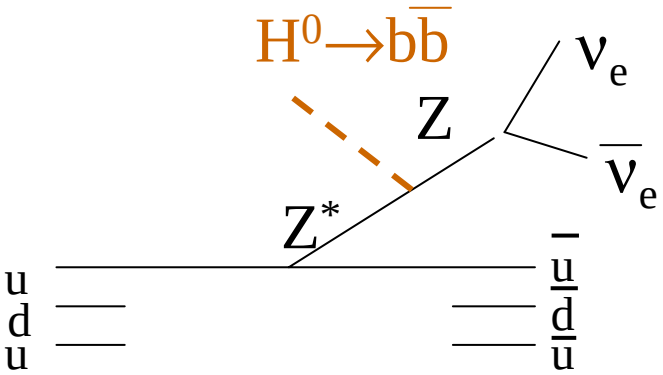
SM Higgs Boson Production and Decay

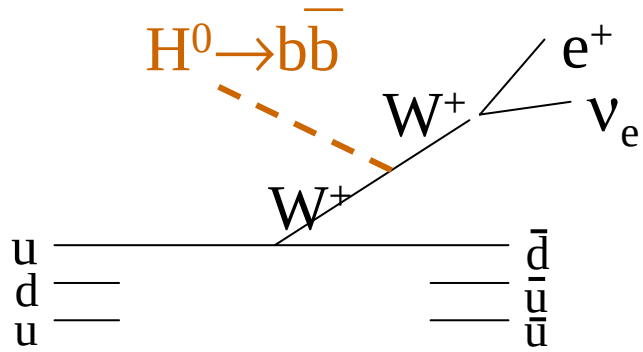
Production Cross-Sections



Decay Branching Ratios



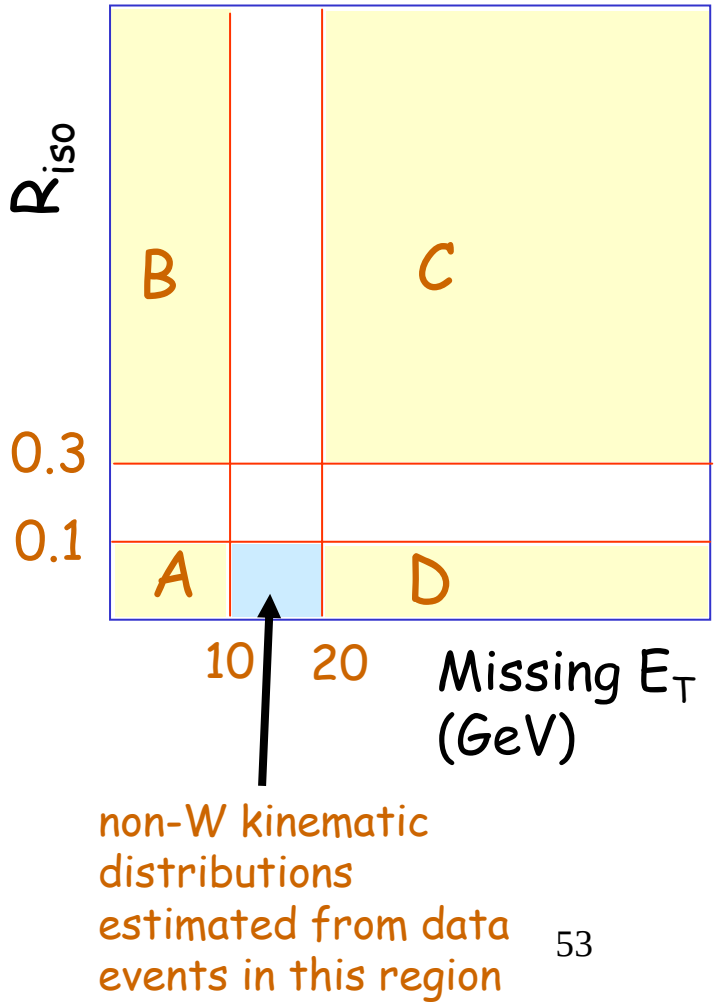




Non-W Backgrounds in WH→lνbb

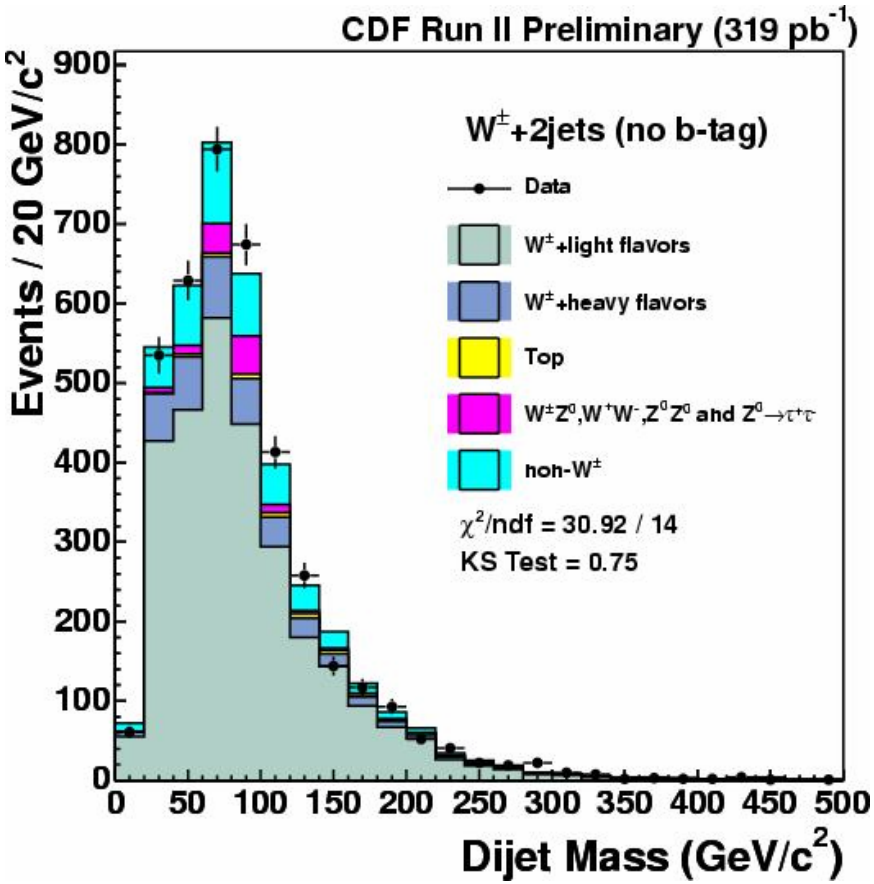
- Estimated with - Missing E_T vs. R_{iso}

R_{iso}=[Energy inside cone of size 0.4 around lepton] / [Energy of lepton]



Non-W background is assumed to have uncorrelated R_{iso} and $\not{E}_T$

Non-W: D= C*(A/B) (after correcting for signal in the background samples)


CDF Run II Preliminary (319 pb^{-1})
$W^{\pm}$+2jets (no b-tag)
Data
$W^{\pm}$+light flavors
$W^{\pm}$+heavy flavors
Top
$W^{\pm}Z^0$,W^+W^-,Z^0Z^0 and $Z^0 \to \tau^+\tau^-$
non-$W^{\pm}$
χ^2/ndf = 30.92 / 14
KS Test = 0.75
Events / 20 GeV/c^2
Dijet Mass (GeV/c^2)
0
100
200
300
400
500
600
700
800
900
0
50
100
150
200
250
300
350
400
450
500

$WH \rightarrow l\nu bb$ Background Summary

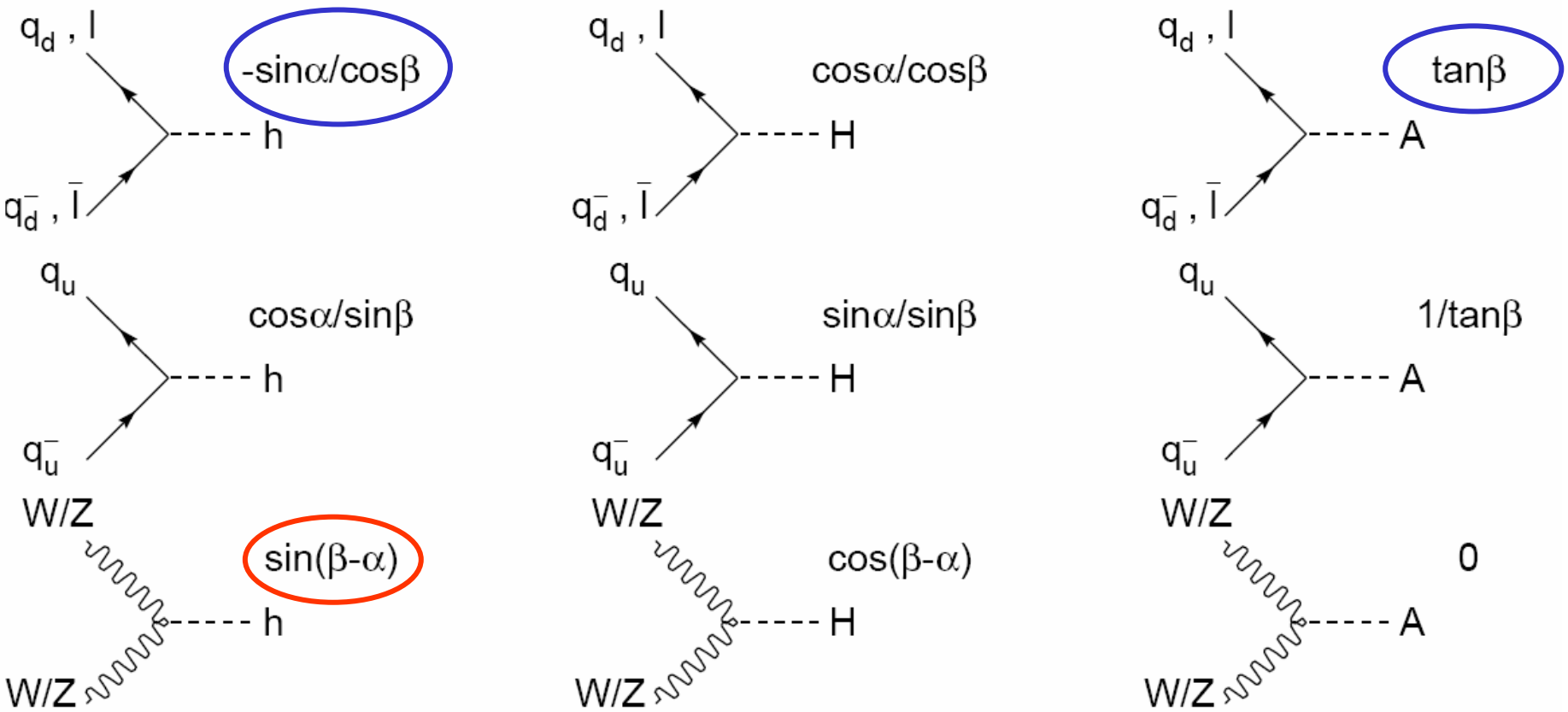
Background Source	Rate (events in 319 pb^{-1})	How Estimated
Mistags	39.9 ± 3.1	Neg. Tags in jet data
Wbb	54.0 ± 18.4	Data & MC
Wcc	19.5 ± 6.6	Data & MC
Wc	16.8 ± 4.3	Data & MC
Diboson+$Z \rightarrow \tau\tau$	5.0 ± 1.1	MC
non-W	16.5 ± 3.2	$\not{E}_T$ vs. isolation in data
tt	14.1 ± 2.5	MC
Single top	9.6 ± 2.0	MC
Total Background	174.7 ± 26.3	
Observed Data	187	

The Higgs Bosons of the MSSM

- Two Complex Higgs Doublets! Needed to avoid anomalies.
- Five Degrees of Freedom plus $W^{+,-}$, Z^0 longitudinal polarization states
- Five scalars predicted: h, H, A, H^+, H^-
- CP-conserving models: h, H are CP-even, A is CP-odd
- Independent Parameters:
  - m_A
  - $\tan\beta$ = ratio of VEV's
  - μ
  - M_{SUSY} (parameterizes squark, gaugino masses)
  - m_{gluino} (comes in via loops)
  - Trilinear couplings A (mostly through stop mixing)
- Map out Higgs sector phenomenology – variations of all other parameters correspond to a point in this space

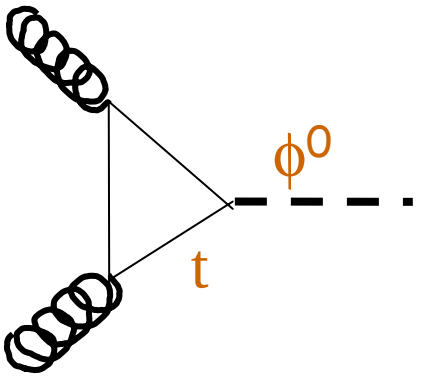
- And a real prediction: m_h < »  Let's test it!

Couplings of MSSM Higgs Bosons Relative to SM

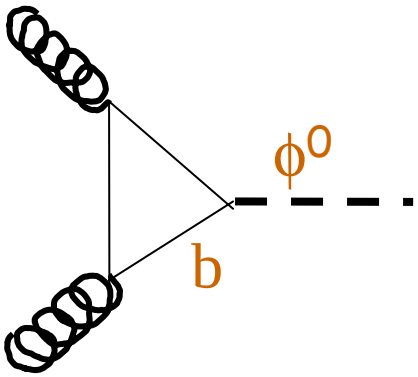


W and Z couplings to H, h are **suppressed** relative to SM (but the sum of squares of h^0, H^0 couplings are the SM coupling). Yukawa couplings (scalar-fermion) **can be enhanced**

Higgs Boson Production Mechanisms

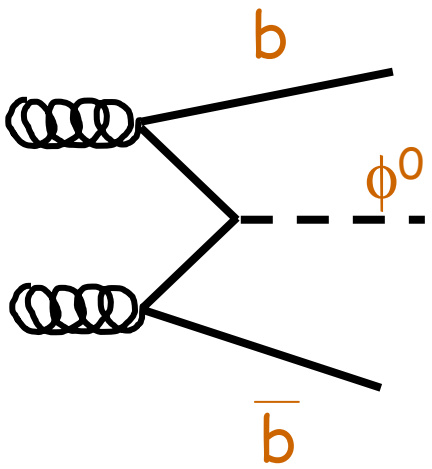


+



Amplitude $\propto 1/\tan\beta$
suppressed!

Amplitude $\propto \tan\beta$
enhanced!



Amplitude $\propto \tan\beta$
enhanced!

And many other diagrams

At high $\tan\beta$, $\sigma(h,A+X) \propto \tan^2\beta$

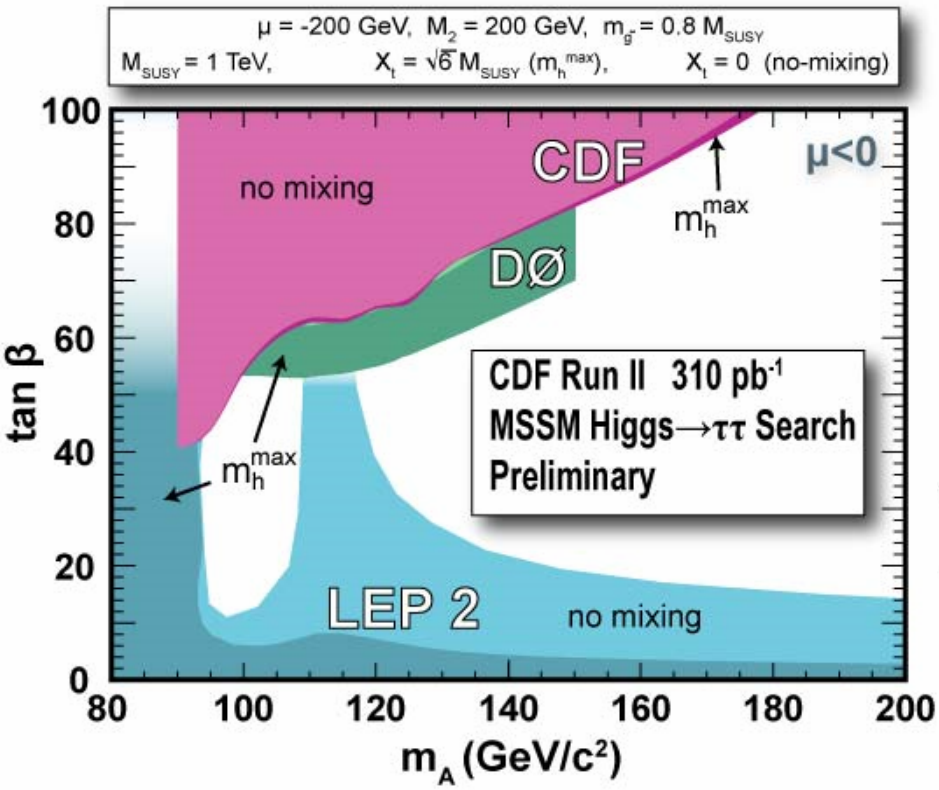
(low $\tan\beta$ and SM case: cross-sections too small to test with current data.)

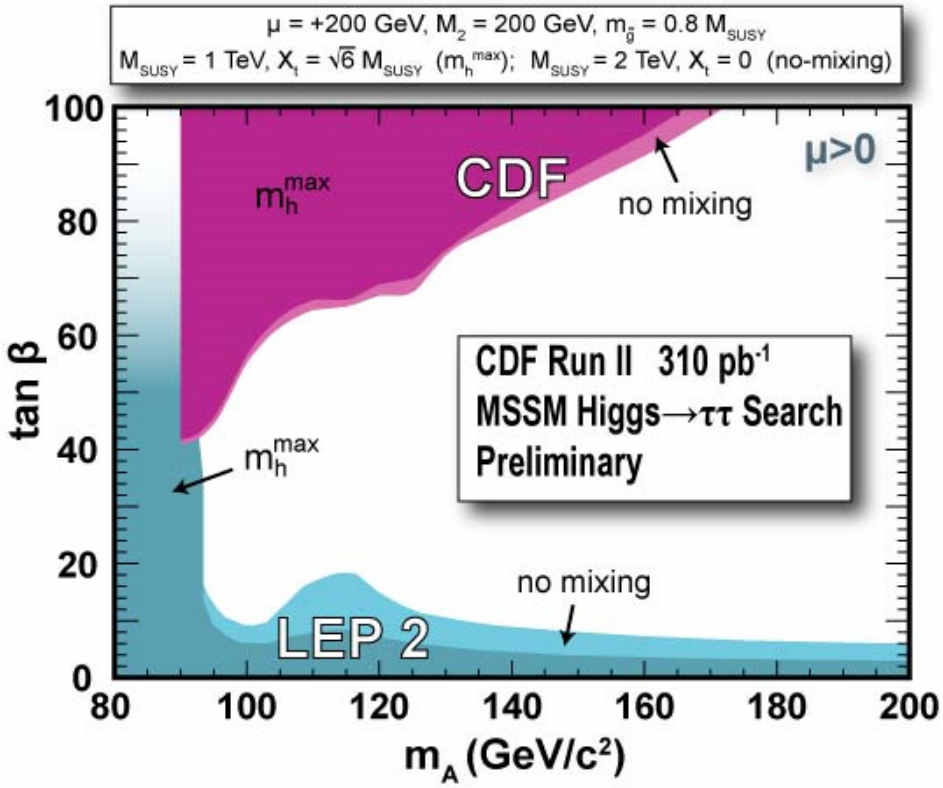
The $h^0, A^0 \rightarrow \tau^+\tau^-$ Channel

- Capitalize on large production cross-section
- Tau leptons are distinct from QCD background
- bbbb channel is possible too – we're working on it.
- Useful $\tau^+\tau^-$ decay modes – one hadronically decaying τ

Mode	Fraction (%)	Comments
$\tau_e\tau_e$	3	Large DY bg
$\tau_\mu\tau_\mu$	3	Large DY bg
$\tau_e\tau_\mu$	6	Small QCD bg
$\tau_e\tau_h$	23	Golden
$\tau_\mu\tau_h$	23	Golden
$\tau_h\tau_h$	41	Large QCD bg

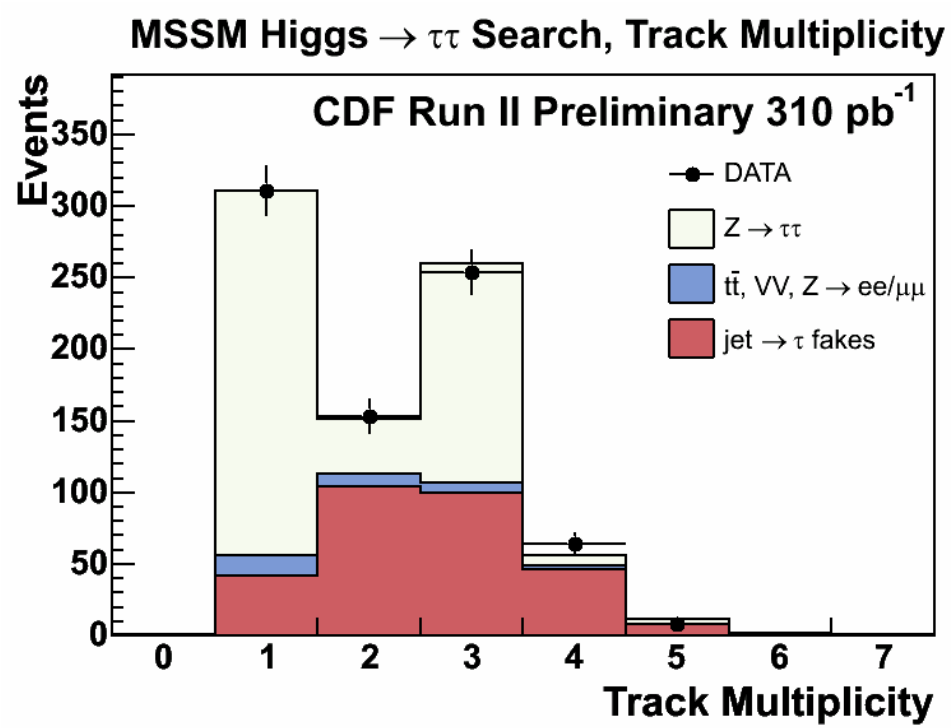
Interpretations in MSSM Benchmarks





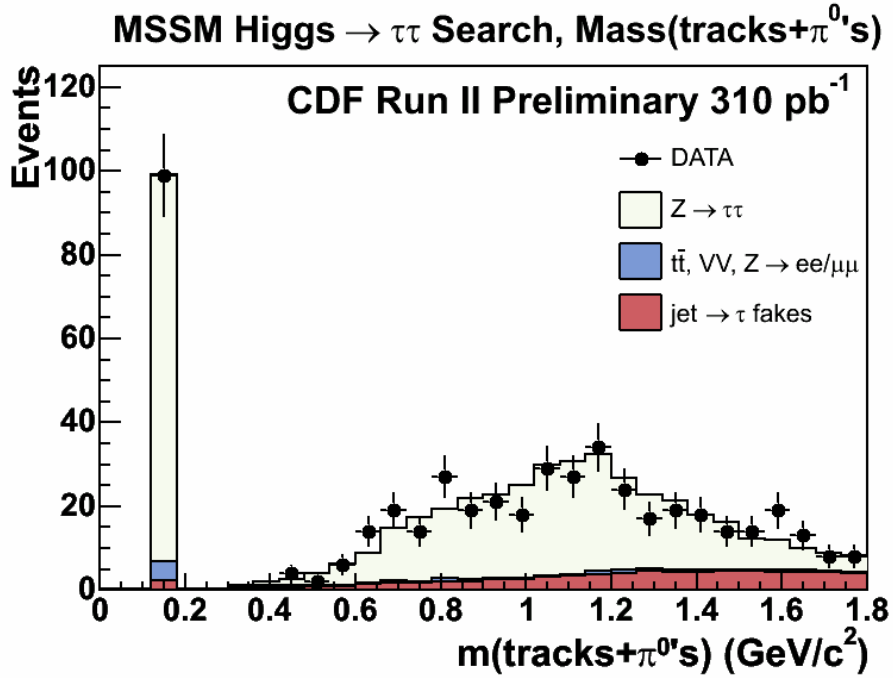
LEP Limits – m_{top}=174.3 GeV for historical reasons.

Hadronic Tau Candidates are Well Modeled



Before cuts on # tracks and opposite charge to other tau.

After n_{trk} and charge cuts.



Higgs Boson Production and Decay at High tanβ

- Interesting feature of many MSSM scenarios (but not all!):

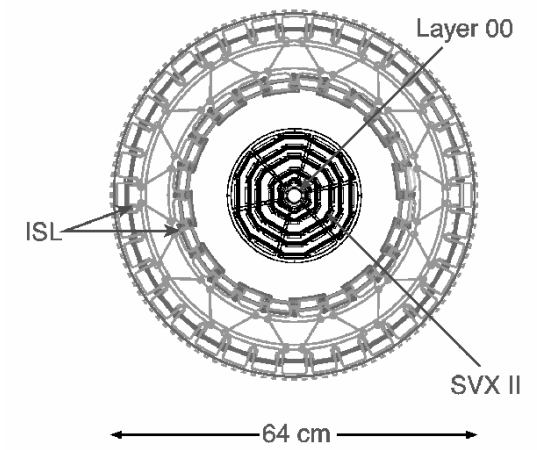
  $[m_h, m_H] \approx m_A$ at high tanβ (most benchmark scenarios..)

- At leading order, $\Gamma(A^0 \to bb)$ and $\Gamma(A^0 \to \tau^+\tau^-)$ are both proportional to $\tan^2\beta$.
- Decays to W, Z are not enhanced and so Br. falls with increasing tanβ (even at high m_A)

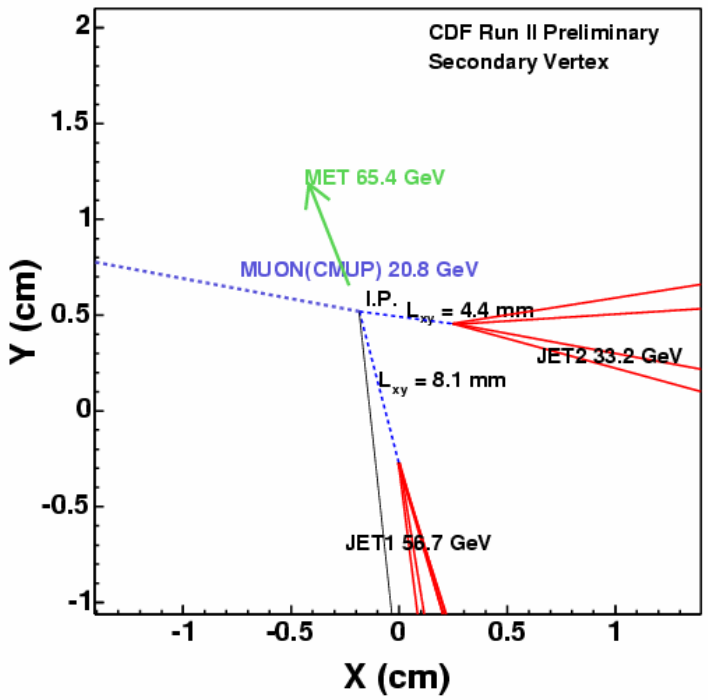
- $Br(A^0 \to bb) \sim 90\%$ and $Br(A^0 \to \tau^+\tau^-) \sim 10\%$ almost independent of tanβ (some gg too).

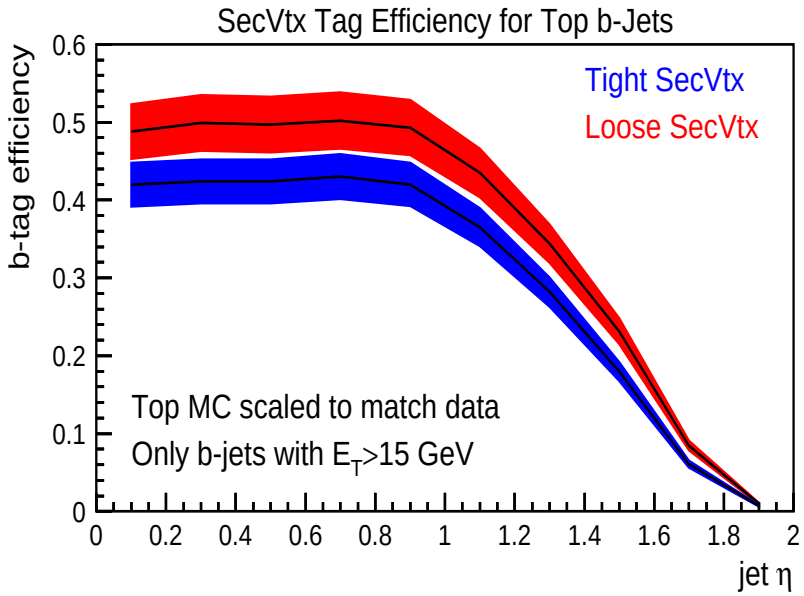
B-Tagging: A Tool Shared by the Low-Mass Analyses

L00 single-sided silicon +
5-layer double-sided silicon+
2-layer ISL



Impact parameter resolution for high-p_T tracks ~18μm





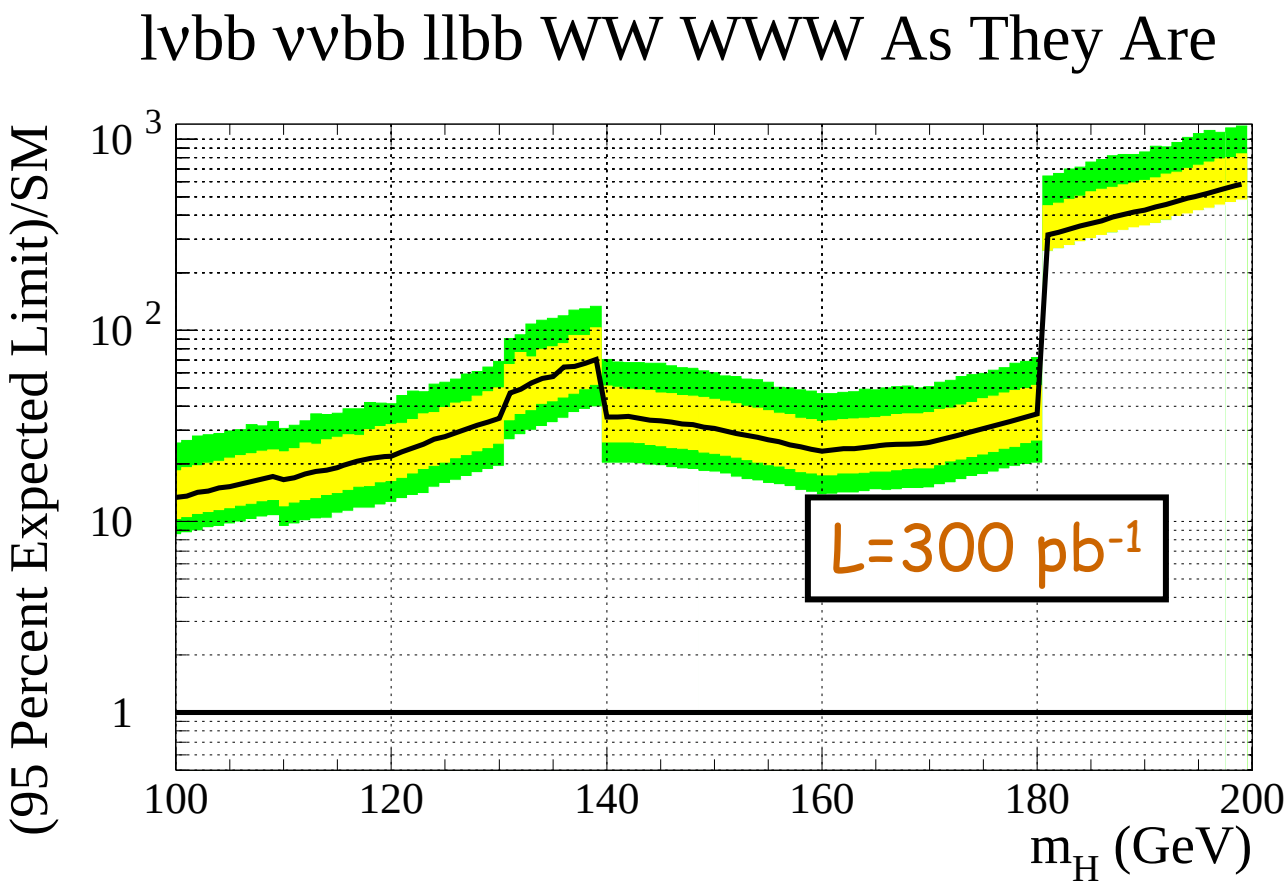
Mistag rates typically 0.5% for light-flavor jets

Example candidate event in lvbb search

Sensitivity with Existing CDF Analyses

old h→WW analysis used

Cross-Section times branching fraction limit as a multiple of the SM rate



Luminosity Thresholds for CDF's Channels Combined

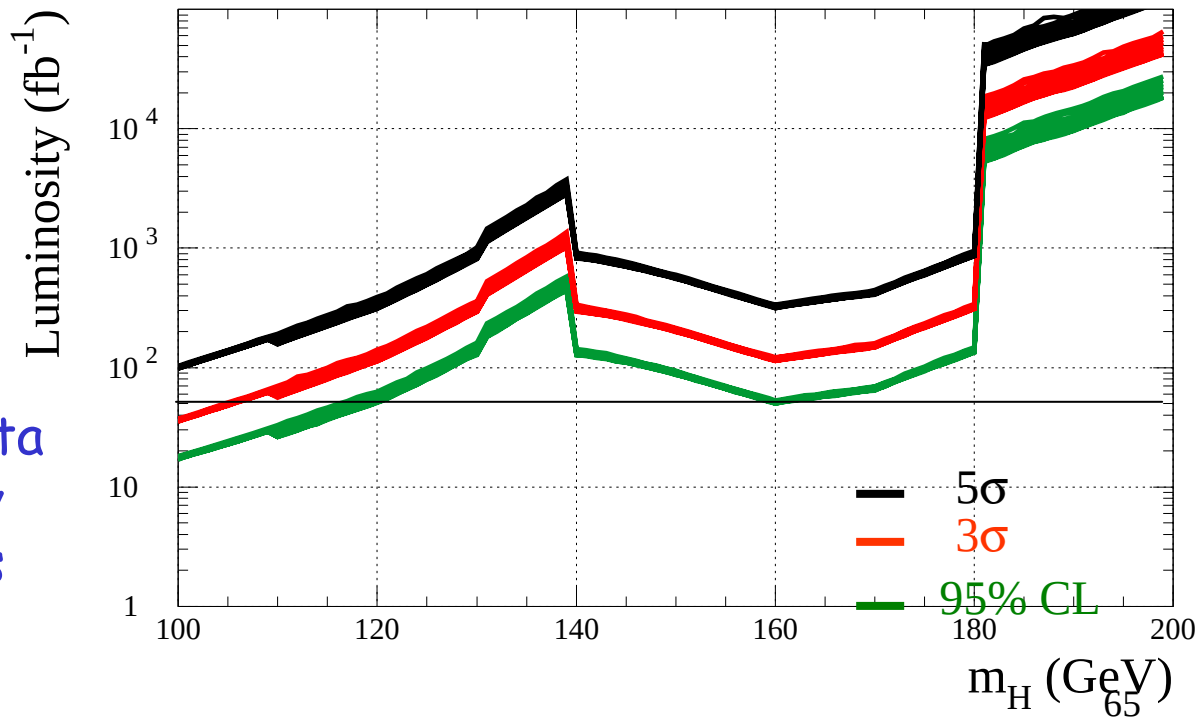
old h→WW analysis used

Assumption: Systematic errors scale with $1/\sqrt{\int \mathcal{L} dt}$

All channel's luminosities scaled to 300 pb^{-1} and then scaled together

Width of bands given by systematic errors on/off

Lumi Thresholds -- lνbb,ννbb,llbb,WW,WWW As They Are



Would need 50 fb^{-1} to exclude m_H=115 GeV if:

1) DØ stops taking data
2) CDF never does any work on the channels

Unlikely!!