Searching for the Higgs at the Tevatron

John Conway
Rutgers University

LHCC Meeting
7 July 2000

- Run 1 SM Higgs searches
- Run 2 projections for SM Higgs
- Run 2 SUSY Higgs reach from SM Higgs searches
- Enhanced SUSY Higgs production at large $\tan\beta$

The CDF Collaboration

Academia Sinica (Taipei), Argonne, INFN Bologna, Brandeis, Cantabria, Chicago, Davis, JINR Dubna, Duke, FNAL, Florida, INFN Frascati, Geneva, Glasgow, Harvard, Hiroshima, Illinois, Toronto, ITEP Moscow, Johns Hopkins, Karlsruhe, KEK, KHCL Kyungpook, Seoul/SungKyunKwan Univ., LBNL, Liverpool, MIT, Michigan State, Michigan, New Mexico, Ohio State, Osaka, Oxford, Padova, Pennsylvania, INFN Pisa, Pittsburgh, Purdue, Rochester, Rome, Rockefeller, Rutgers, Texas A&M, Texas Tech., INFN Trieste, Tufts, Tsukuba, University College London, UCLA, Waseda, Wisconsin, Yale

11 countries

51 institutions

526 collaborators

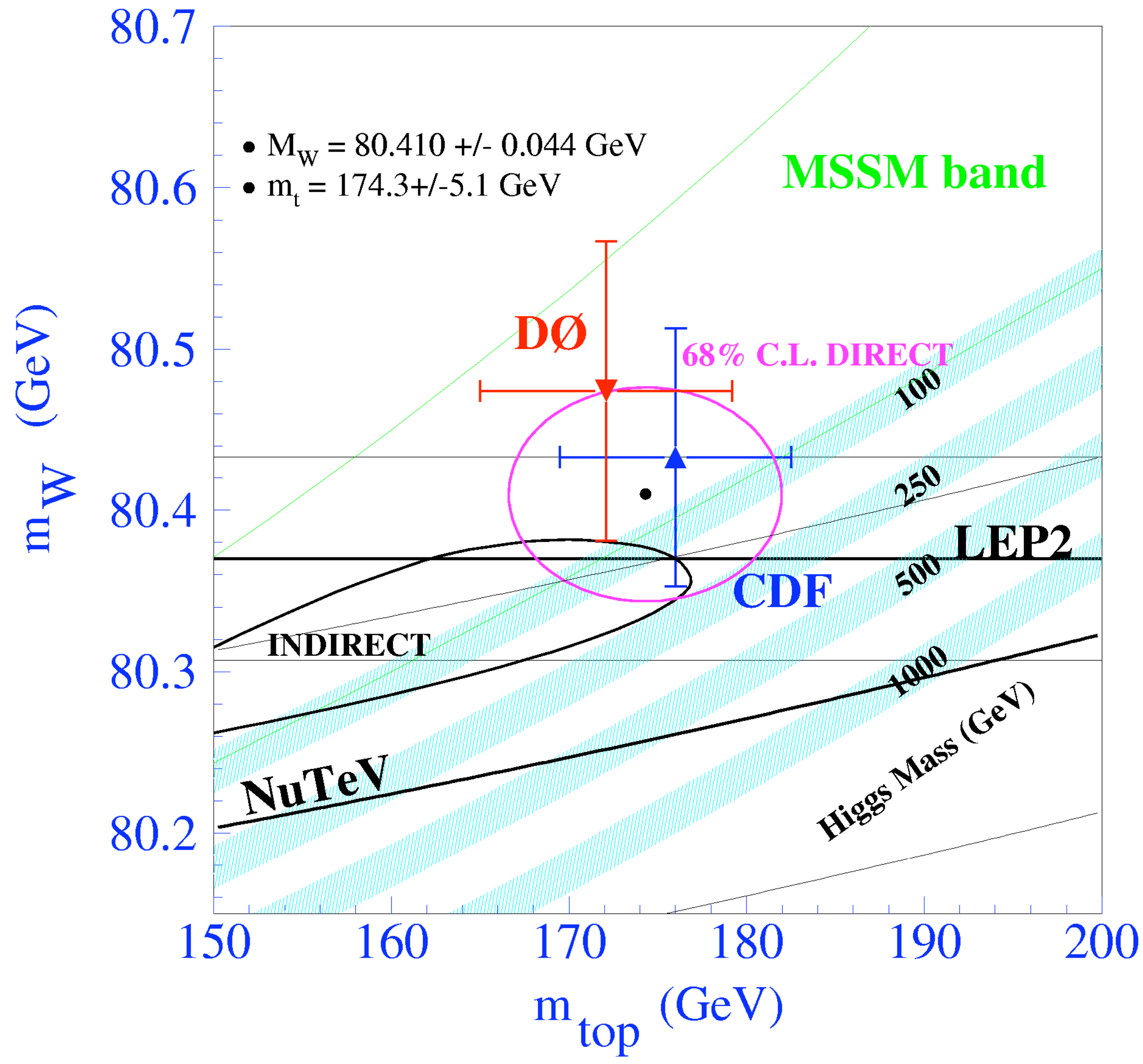
The DØ Collaboration

Arizona, Buenos Aires, LAFEX/Rio de Janeiro, Sao Paulo, Beijing, Bogota, Boston, Brookhaven, Brown, California State Fresno, Charles Univ. Prague, CINVESTAV Mexico City, Columbia, Czech Tech, Davis, Delhi, FNAL, Florida State, Grenoble, NIKHEF, Krakow, Imperial College London, Irvine, JINR Dubna, LAL Orsay, Lancaster, Langston Oklahoma, LBNL, LPNHE Paris, Manchester, Marseille, ITEP Moscow, Moscow State Univ., Tata Institute Mumbai, IHEP Protvino, PNPI Petersburg, Kansas, Kansas State, Louisiana Tech, Lund/Royal Institute/Stockholm/Uppsala, Univ. of Illinois at Chicago, Northern Illinois, Michigan, Michigan State, Nebraska, Northeastern, Indiana, Iowa State, Lyon, Mainz, Maryland, Munich, Northwestern, Notre Dame, Oklahoma, Panjab, Acad. Sci. Prague, Univ. San Francisco de Quito, Riverside, Rochester, Saclay, Stony Brook, Texas, Texas A&M, Rice, Washington

16 countries

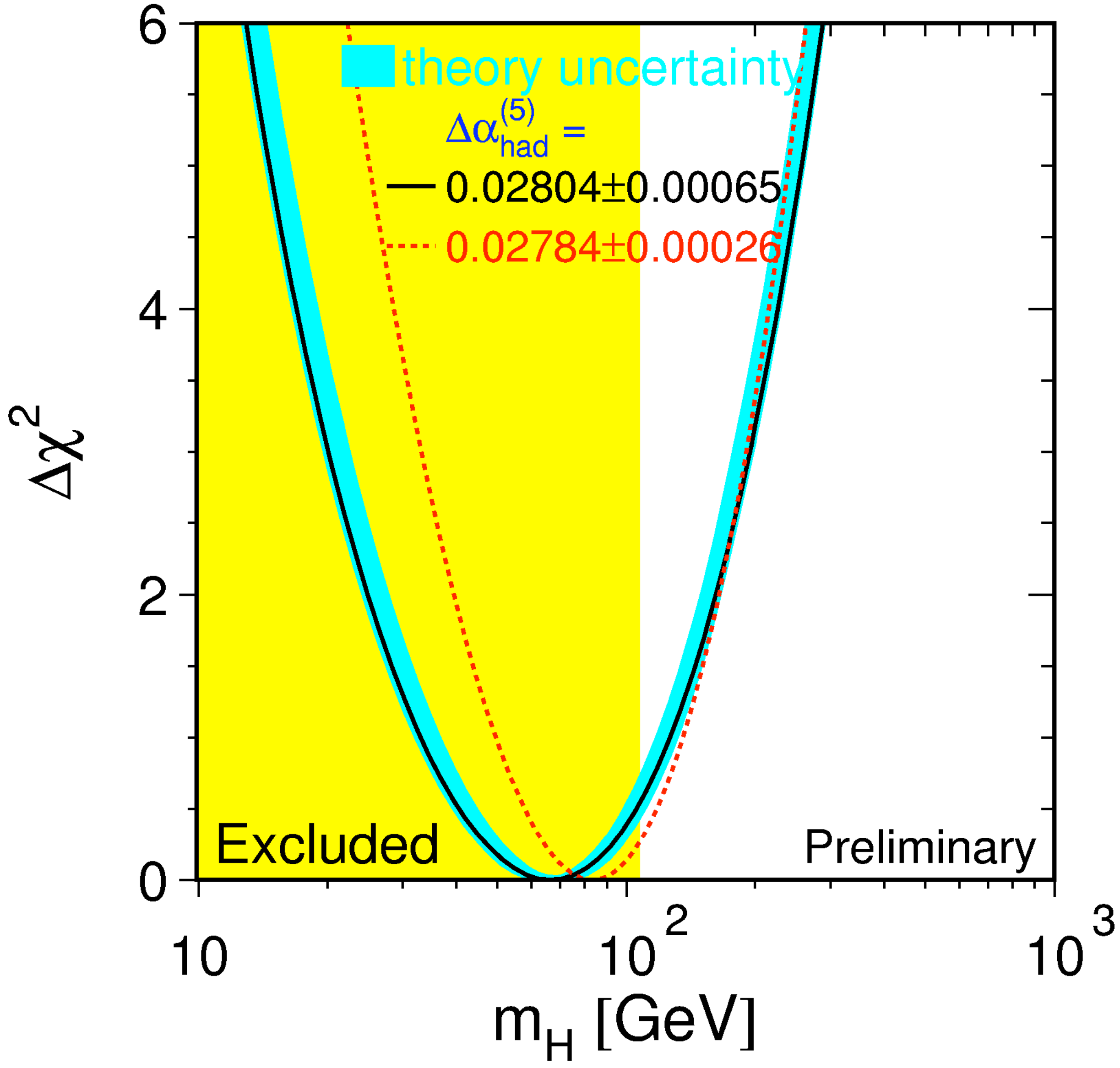
66 institutions

CDF/DØ Run 1 top and W mass



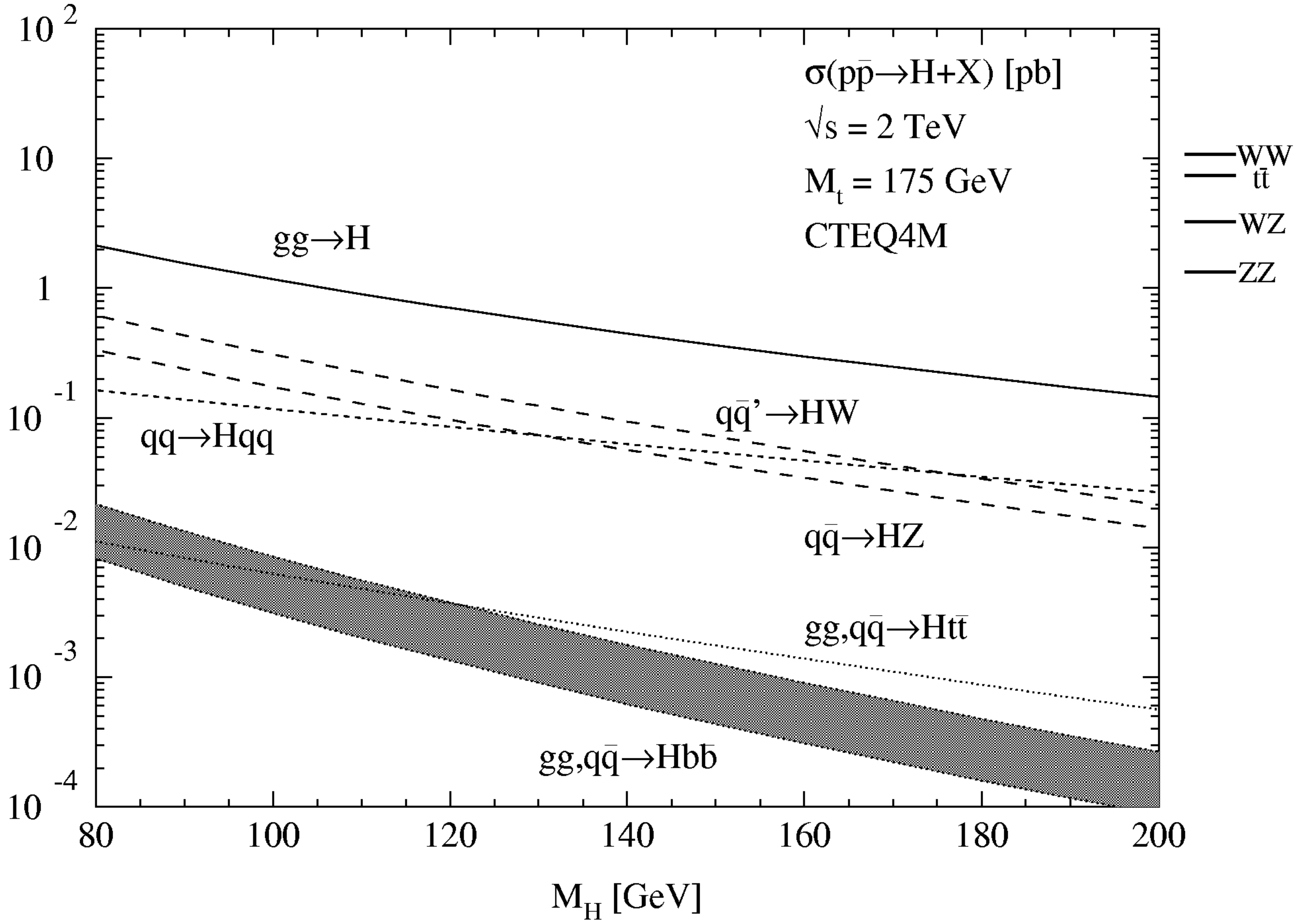
World’s combined electroweak measurements

March 2000:



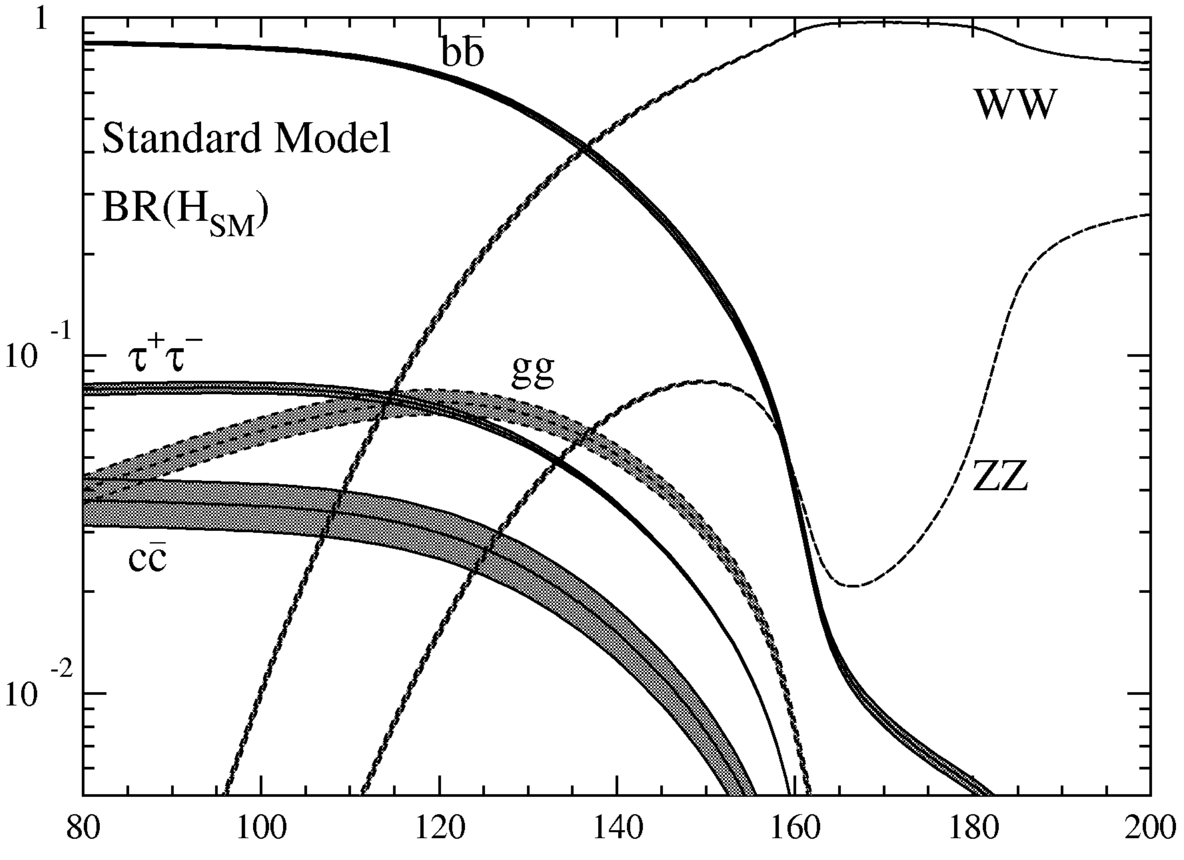
Standard Model Neutral Higgs searches

Higgs production rates at the Tevatron:



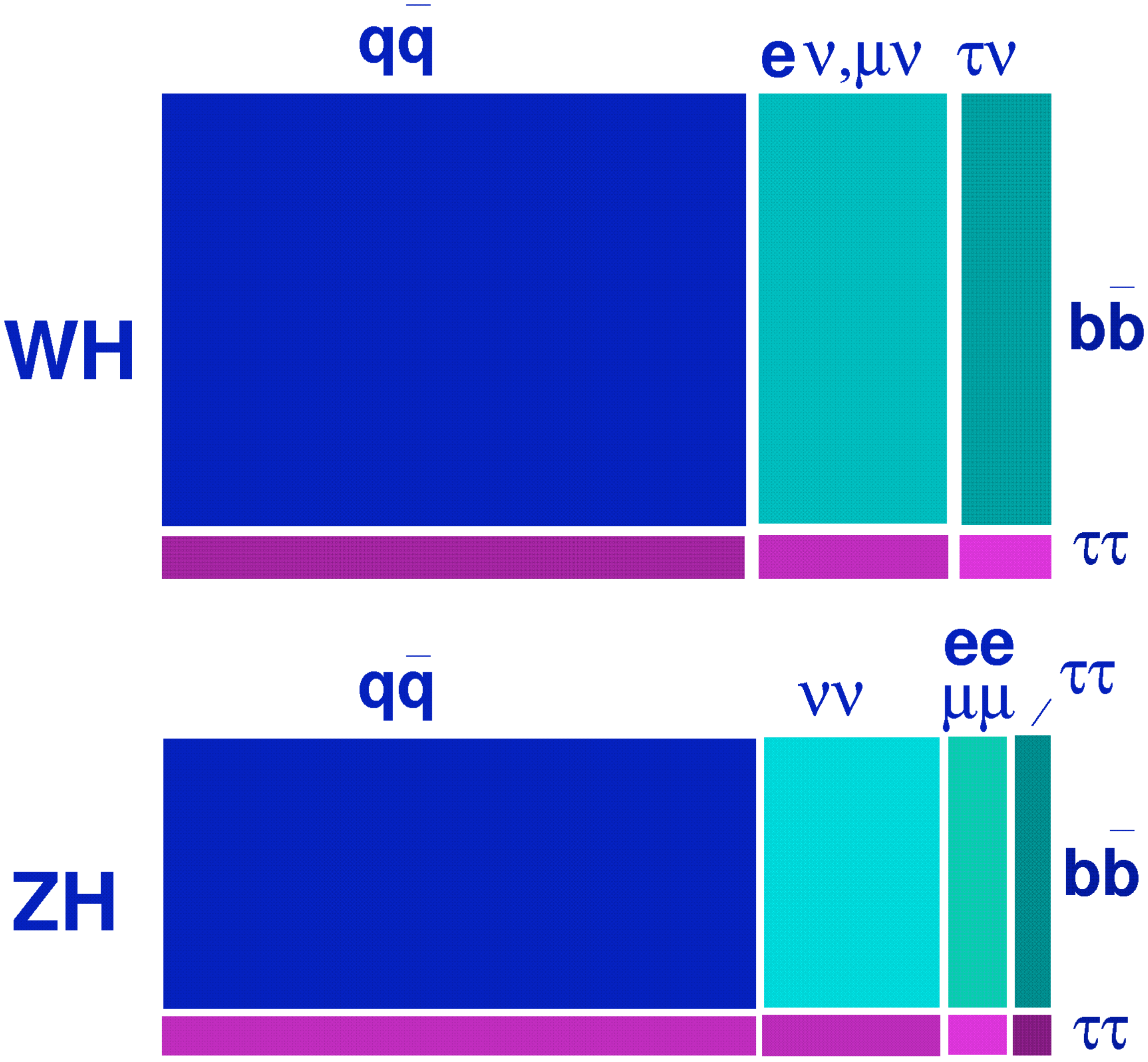
- gg→H dominates, but very difficult to see
- WH, ZH are most accessible
- SUSY enhances some cross sections!

SM Higgs branching ratios:



Difficult crossover region near 135 GeV mass!

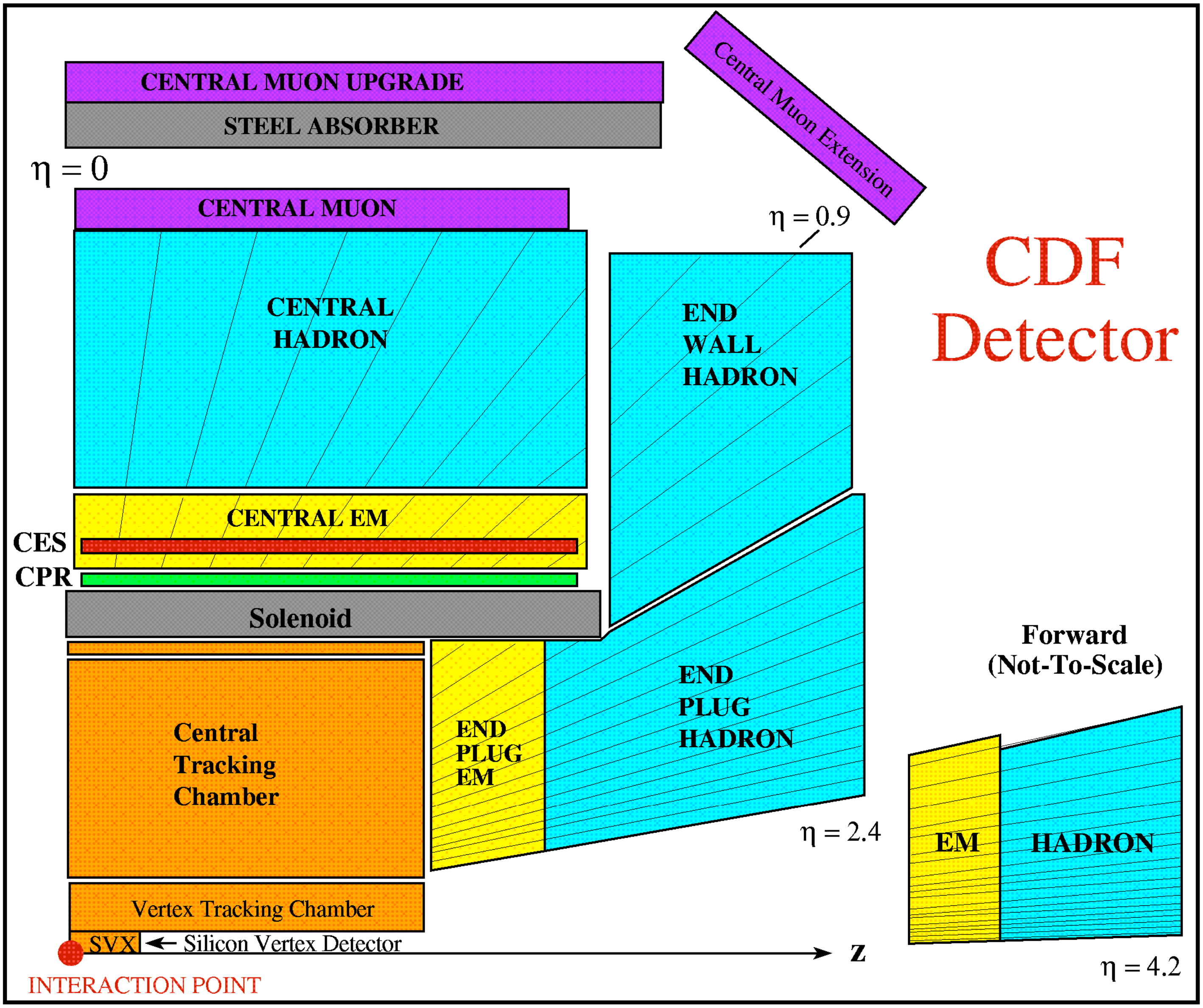
WH/ZH final states, $m(H) \sim 110$ GeV/c^2:



main channels: $\ell\nu b\bar{b}$, $\nu\bar{\nu}b\bar{b}$, $\ell^+\ell^- b\bar{b}$, $q\bar{q}b\bar{b}$

→ leptons, b-tagging, missing E_T

CDF in Run 1:


CENTRAL MUON UPGRADE
STEEL ABSORBER
Central Muon Extension
η = 0
CENTRAL MUON
η = 0.9
CDF
Detector
CENTRAL
HADRON
END
WALL
HADRON
CENTRAL EM
CES
CPR
Solenoid
Forward
(Not-To-Scale)
END
PLUG
HADRON
Central
Tracking
Chamber
END
PLUG
EM
η = 2.4
EM
HADRON
Vertex Tracking Chamber
SVX
Silicon Vertex Detector
z
η = 4.2
INTERACTION POINT

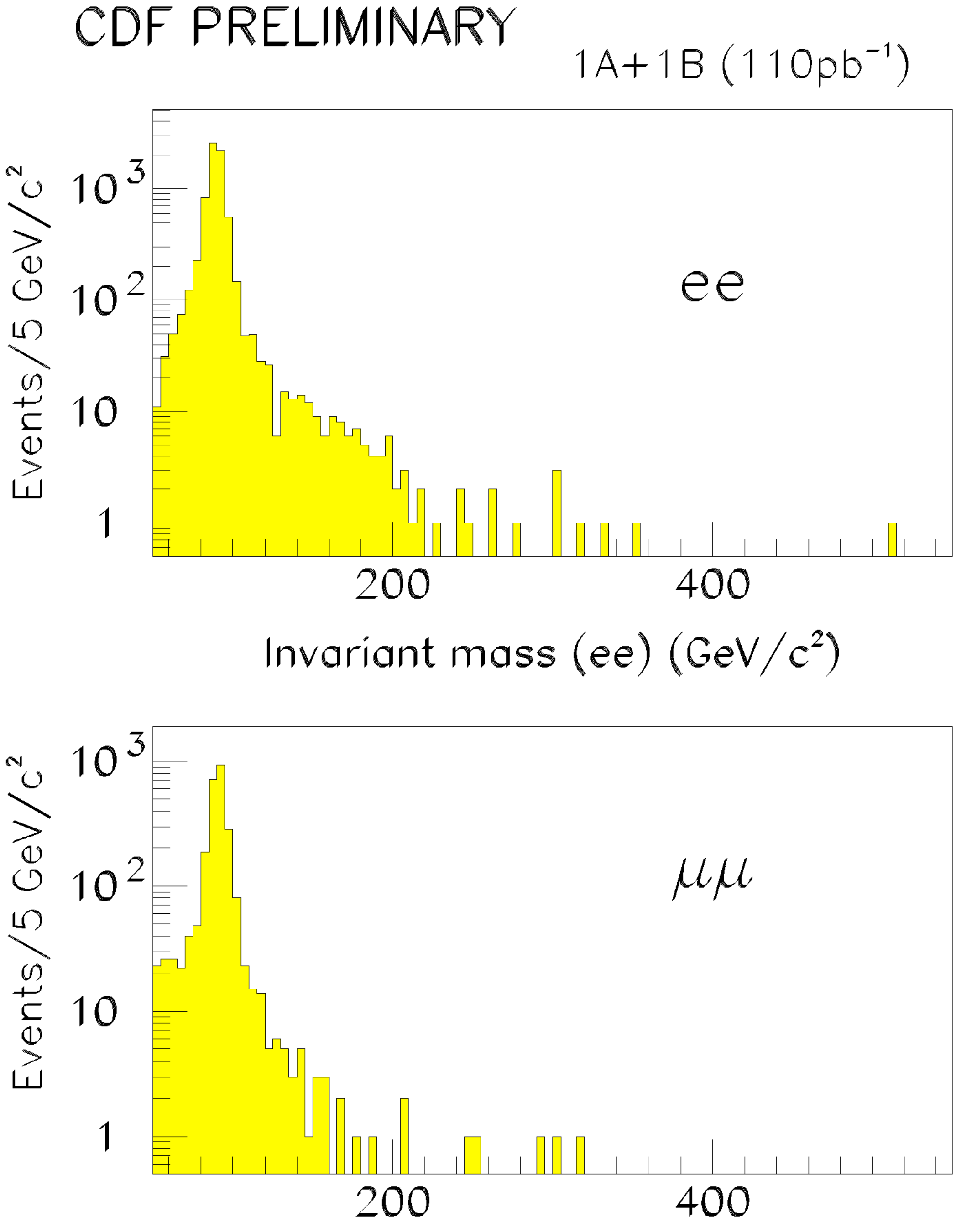
Run 1 CDF in a nutshell

---

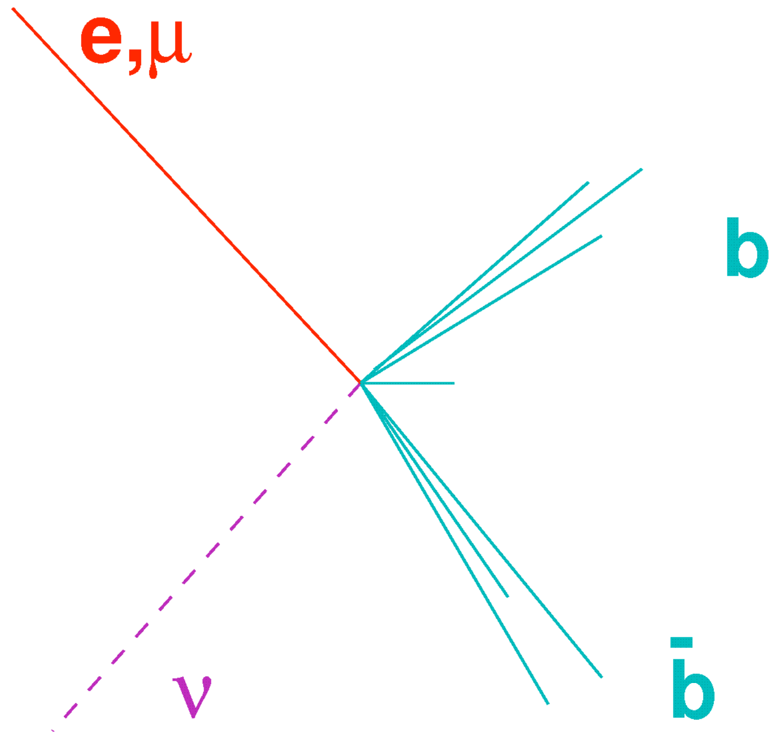
luminous region	$\sigma_z \sim$30 cm
beam size	$\sigma_r \sim$30 μm
silicon layers	4 single-sided
COT superlayers	8 axial, 4 stereo
track resolution	$\sigma_{r\phi} \sim$ 20 μm $\sigma_z \sim$ 1 cm
B field	1.4 T
momentum resolution	0.1%$\times p_T$
CEM calorimeter	lead/scintillator
CES shower max.	axial wires, strips
CHA calorimeter	iron/scintillator
forward cal.	gas sampling
μ detection	multilayer drift tubes, scintillator

Lepton pairs at high mass

CDF e and μ pair spectra:



SM Higgs in $\ell\nu b\bar{b}$ (WH) Channel



selection:

- high-p_T lepton triggers
- central e, or μ with E$_T$(p$_T$) $>$ 20 GeV
- $\not{E}_T$ $>$15 GeV
- no Z's: $m_{\ell\ell}$ not 75-105 GeV/c^2
- two jets (E$_T$ $>$ 15 GeV, $|\eta| < 2$), b-tagged

backgrounds:

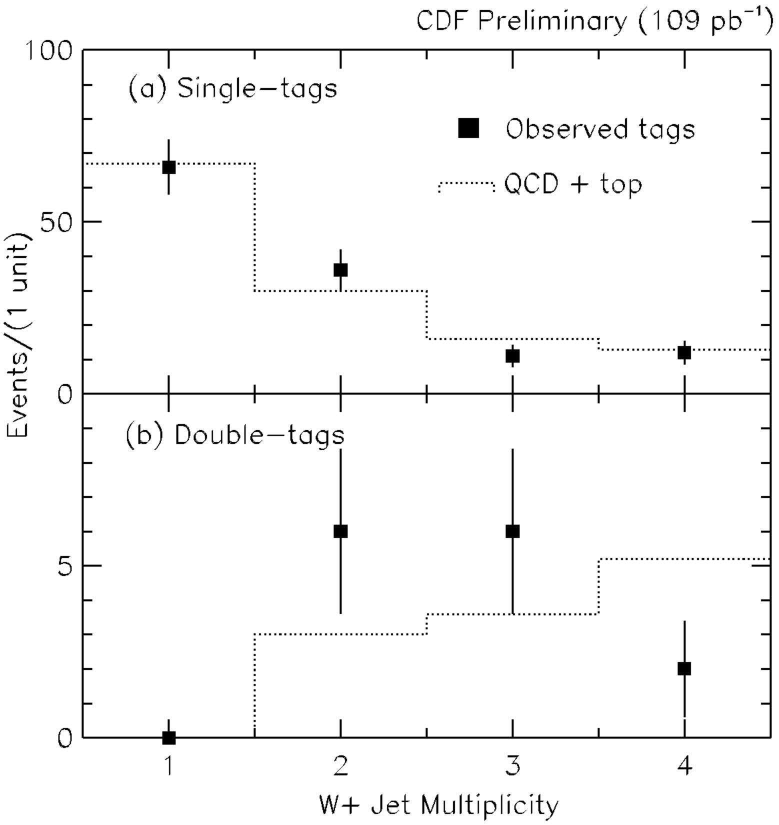
- $Wb\bar{b}$, $Wc\bar{c}$, Wc
- W+jet with mistags

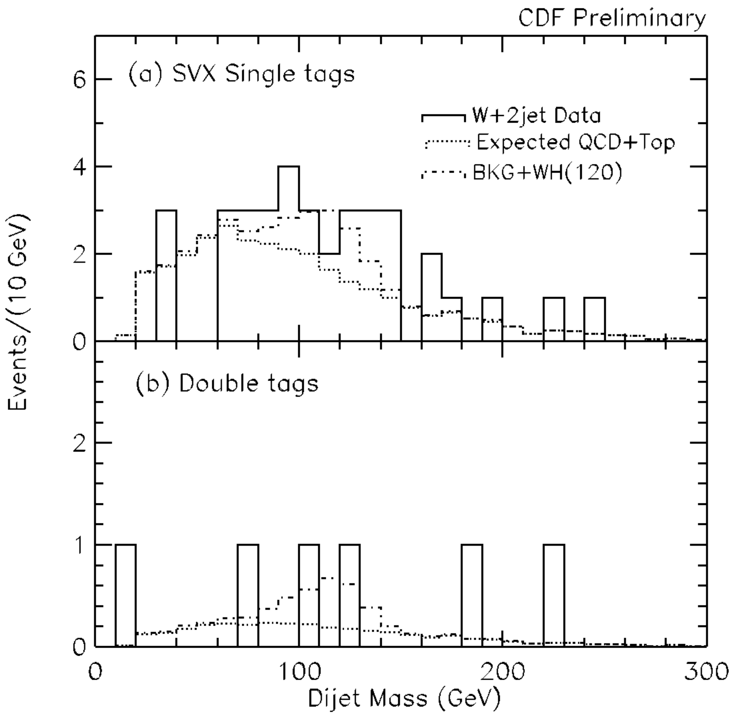
- single tags:

  expect 30±5
  see 36

- double tags:

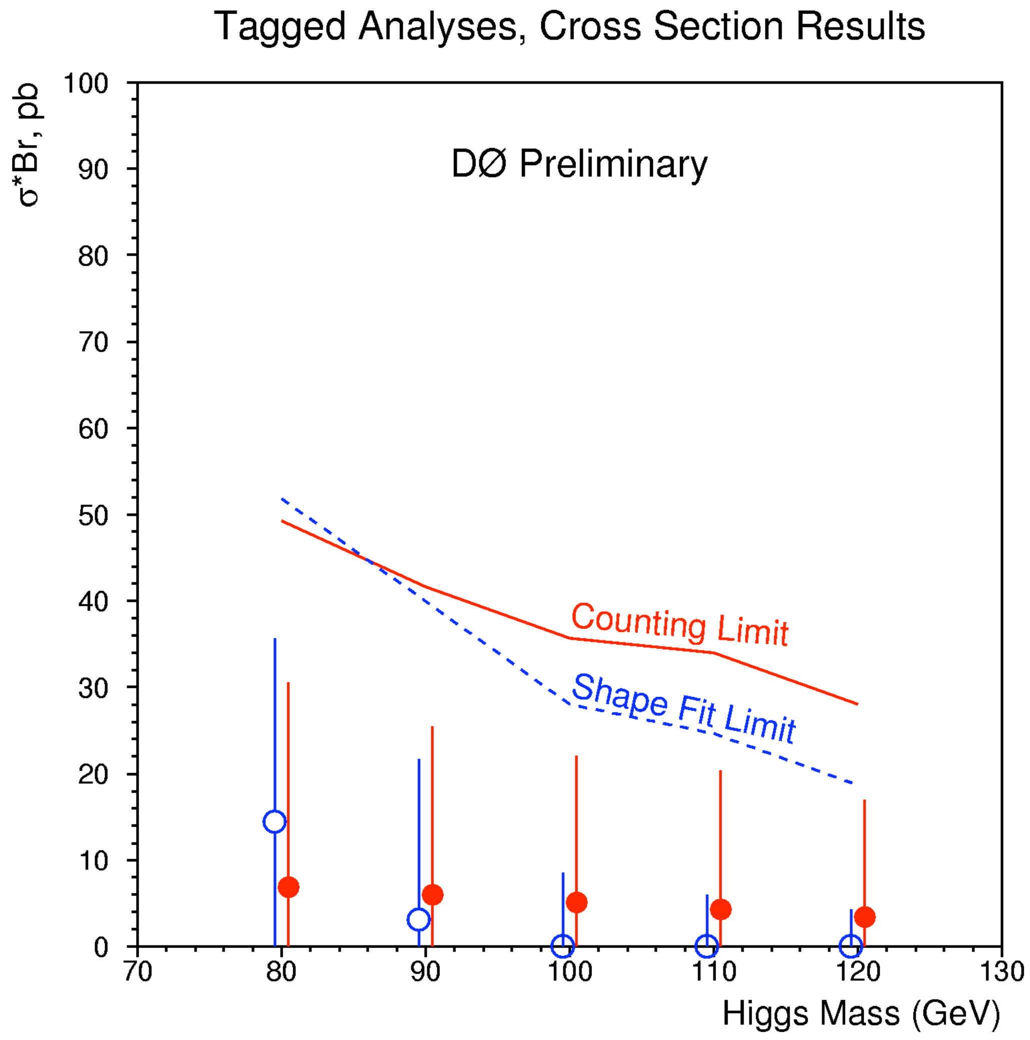
  expect 3.0±0.6
  see 6



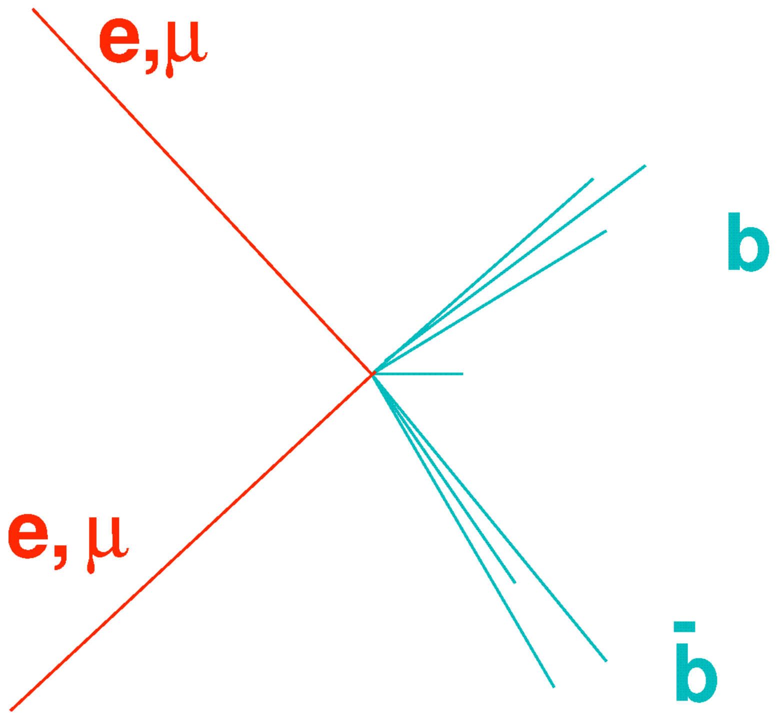


slight excess
in mass plot

DØ Run 1 limit: $WH \to \ell\nu b\bar{b}$



SM Higgs in $\ell^+\ell^- b\bar{b}$ (ZH) Channel

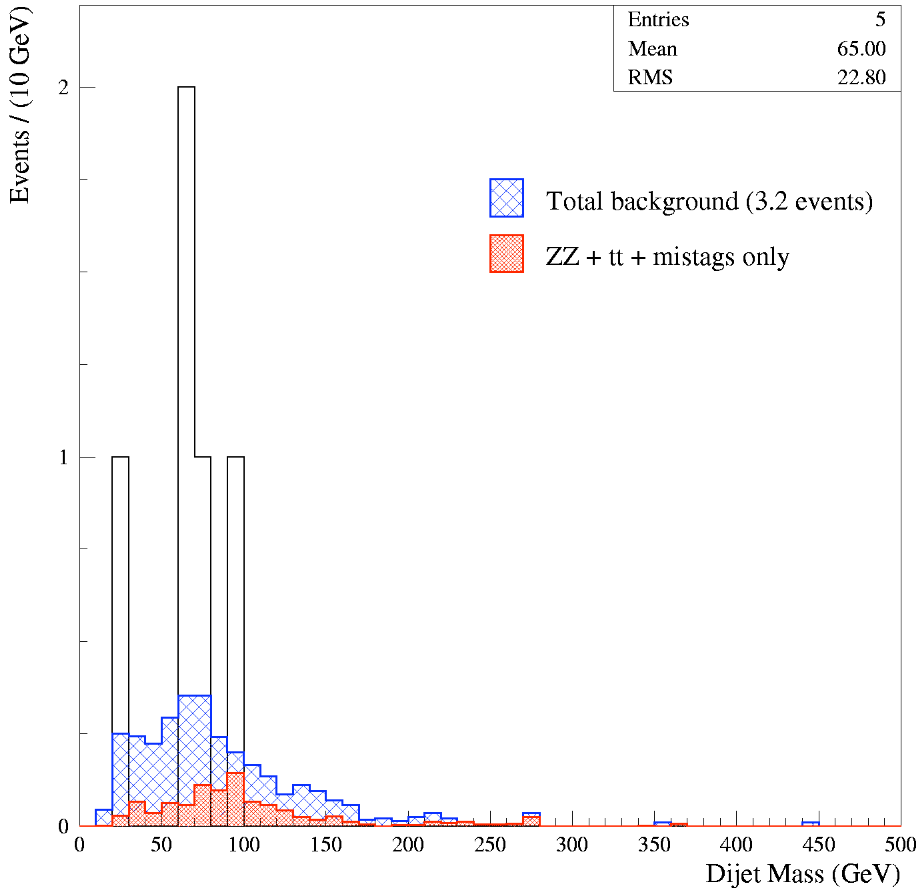


$\ell^+\ell^- b\bar{b}$ selection:

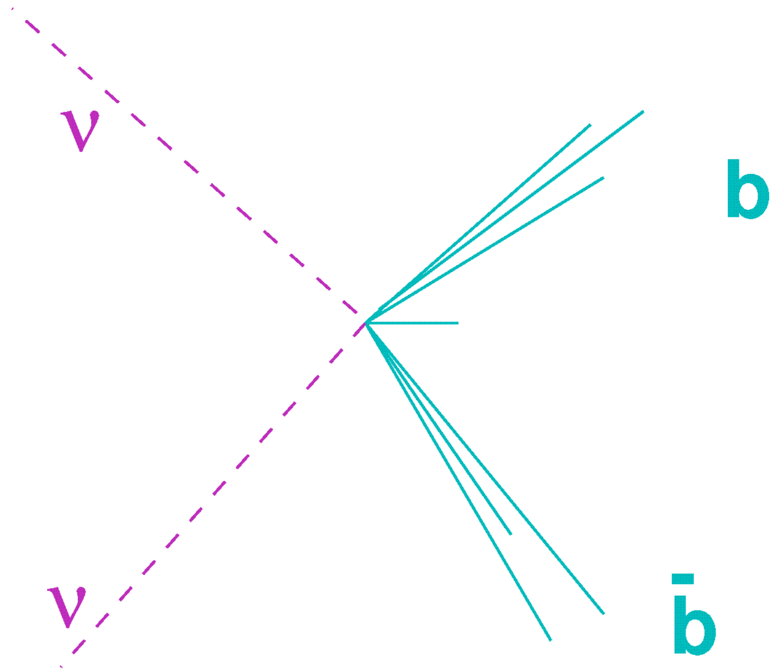
- high-p_T lepton triggers
- two central e or μ with $E_T(p_T) > 20/10$ GeV
- $\not{E}_T < 50$ GeV
- Z: $m_{\ell\ell}$ in range 75-105 GeV/c^2
- two or three jets ($E_T > 15$ GeV, $|\eta| < 2$)
- one (or more) b-tagged jets (sec. vertex tagger)

$\ell^+\ell^- b\bar{b}$ backgrounds and result:

$Zb\bar{b}$	1.7±0.7
mistags	0.65±0.13
$Zc\bar{c}$	0.32±0.15
WZ, ZZ	0.19±0.06
$t\bar{t}$	0.13±0.04
total	3.2±0.7
observed	5



SM Higgs in $\nu\bar{\nu}b\bar{b}$ (ZH) Channel

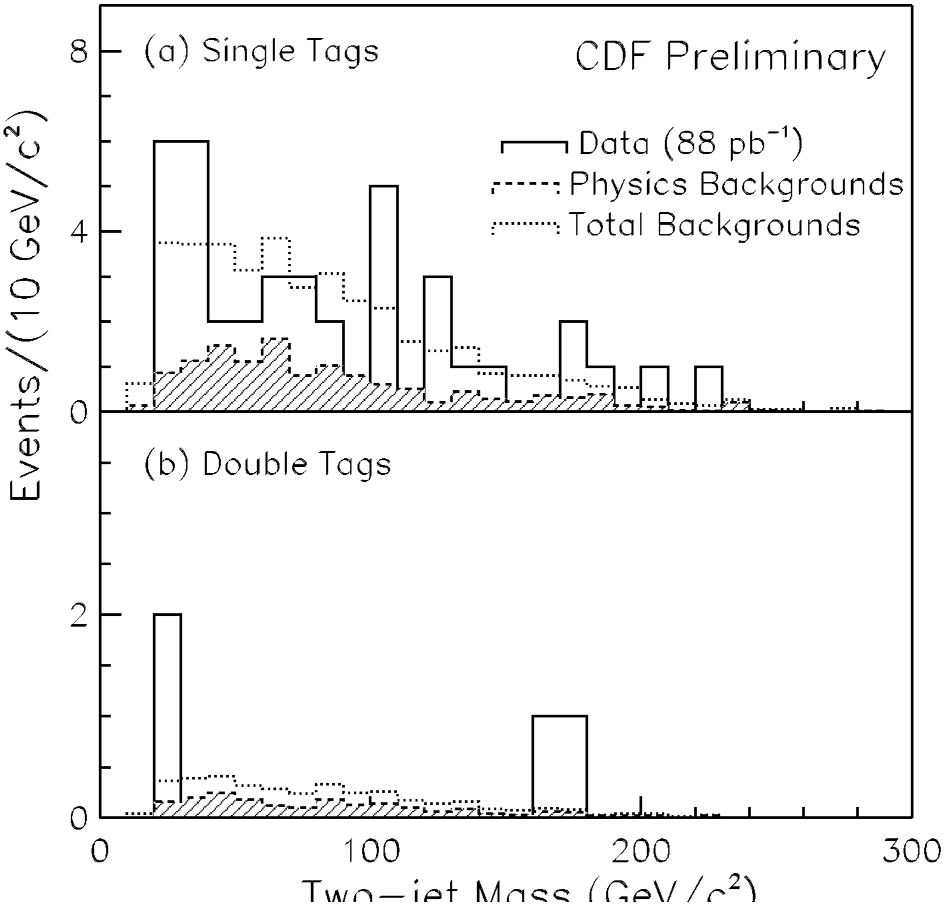


$\nu\bar{\nu}b\bar{b}$ selection:

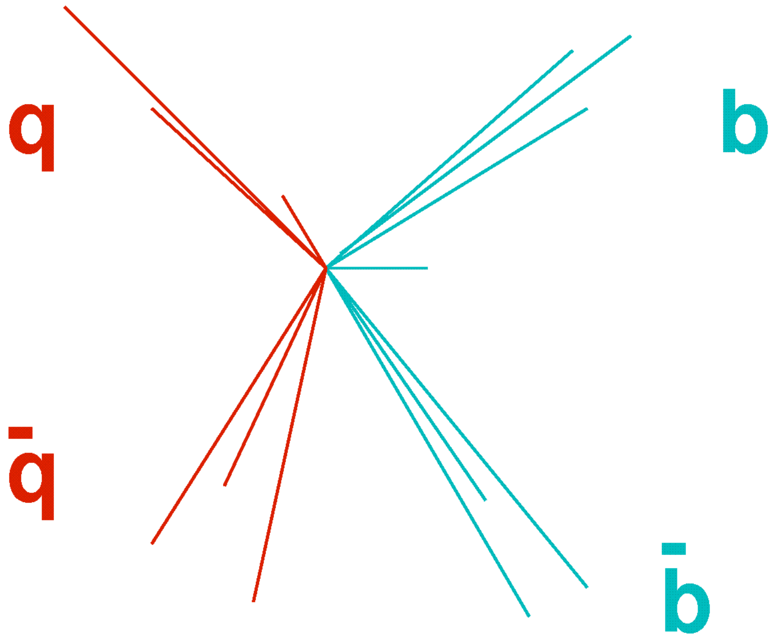
- $\not{E}_T > 35$ GeV trigger and cleanup
- no isolated leptons or tracks
- $\not{E}_T >$40 GeV
- two or three jets ($E_T > 15$ GeV, $|\eta| < 2$)
- $\Delta\phi(\not{E}_T$,jet$) > 1$ rad
- $\Delta\phi(jet, jet) < 2.6$ rad
- one (or more) b-tagged jets
- two sec. vert. tags *or*
  one sec. vert. and one jet prob. tag

$\nu\bar{\nu}b\bar{b}$ backgrounds and result:

	single tag	double tag
QCD dijet	26±3	1.9±0.4
$Zb\bar{b}, Zc\bar{c}$	10±2.5	1.0±0.2
top	2.4±0.6	0.8±0.2
WZ, ZZ	0.45±0.11	0.17±0.04
total	39±4	3.9±0.6
observed	40	4



SM Higgs in $q\bar{q}b\bar{b}$ (WH, ZH) Channel

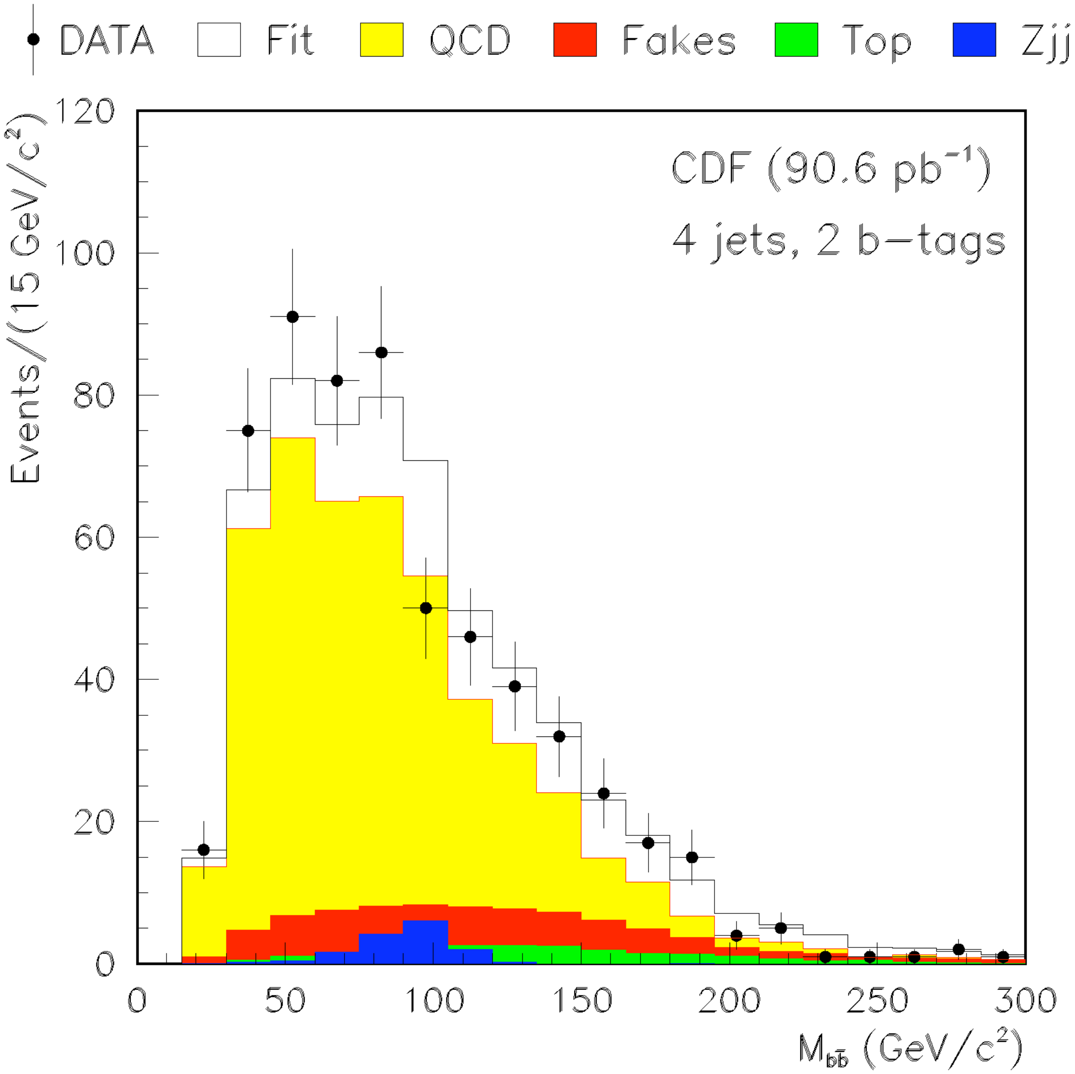


$q\bar{q}b\bar{b}$ selection:

- four-jet ($E_T > 15$ GeV) trigger ($\epsilon = 16 - 30\%$)
- four or more jets, $E_T > 15$ GeV, $|\eta| <$2.1
- at least two b tags (sec. vert.)
- $p_T(b\bar{b})$ >50 GeV

→ 589 events selected

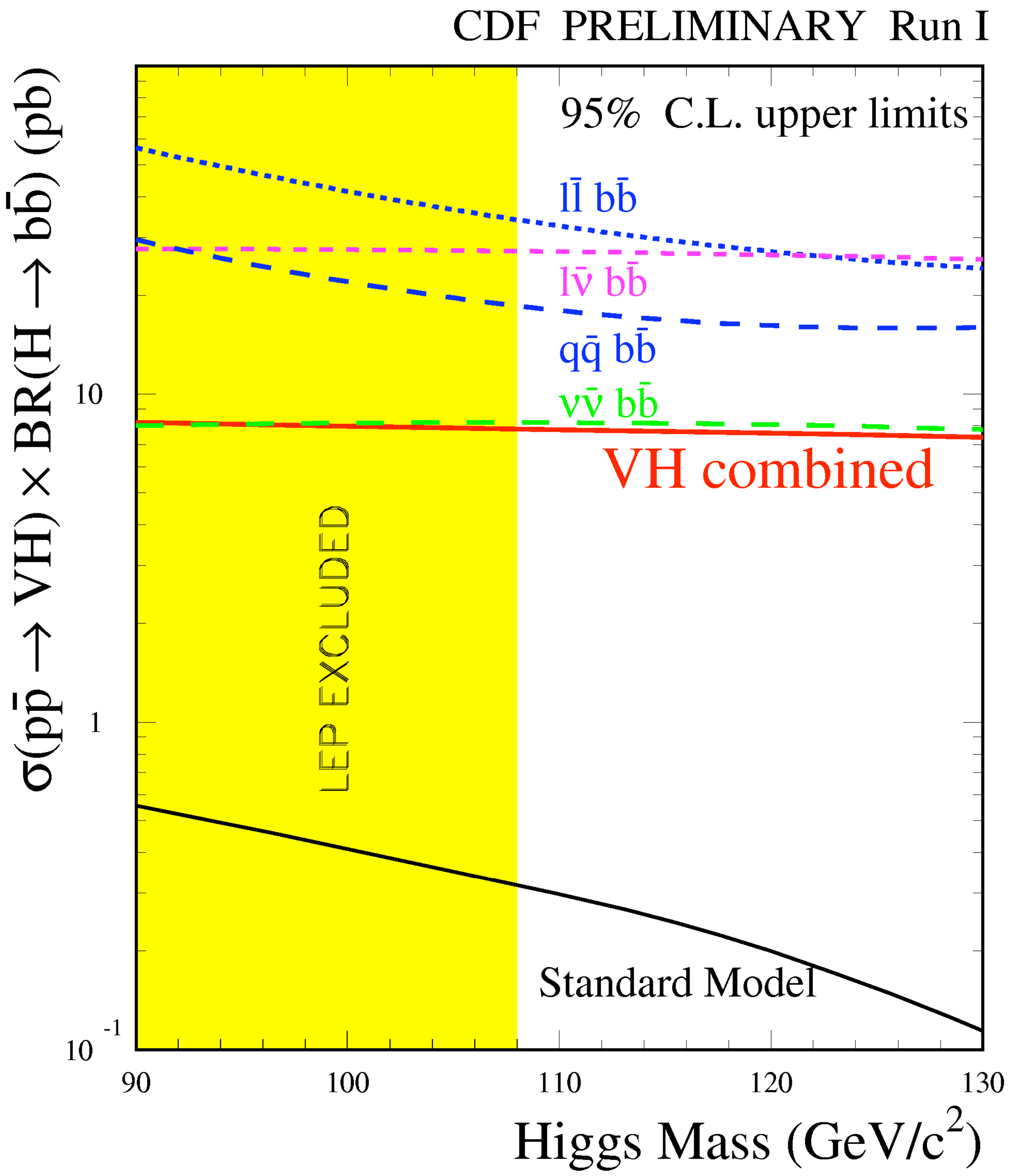
$q\bar{q}b\bar{b}$ backgrounds and result:



→ fit for Higgs of varying mass

→ published in Phys. Rev. Lett. 81, 5748 (1998)

CDF Run 1 Higgs limits



Tevatron in Run 2

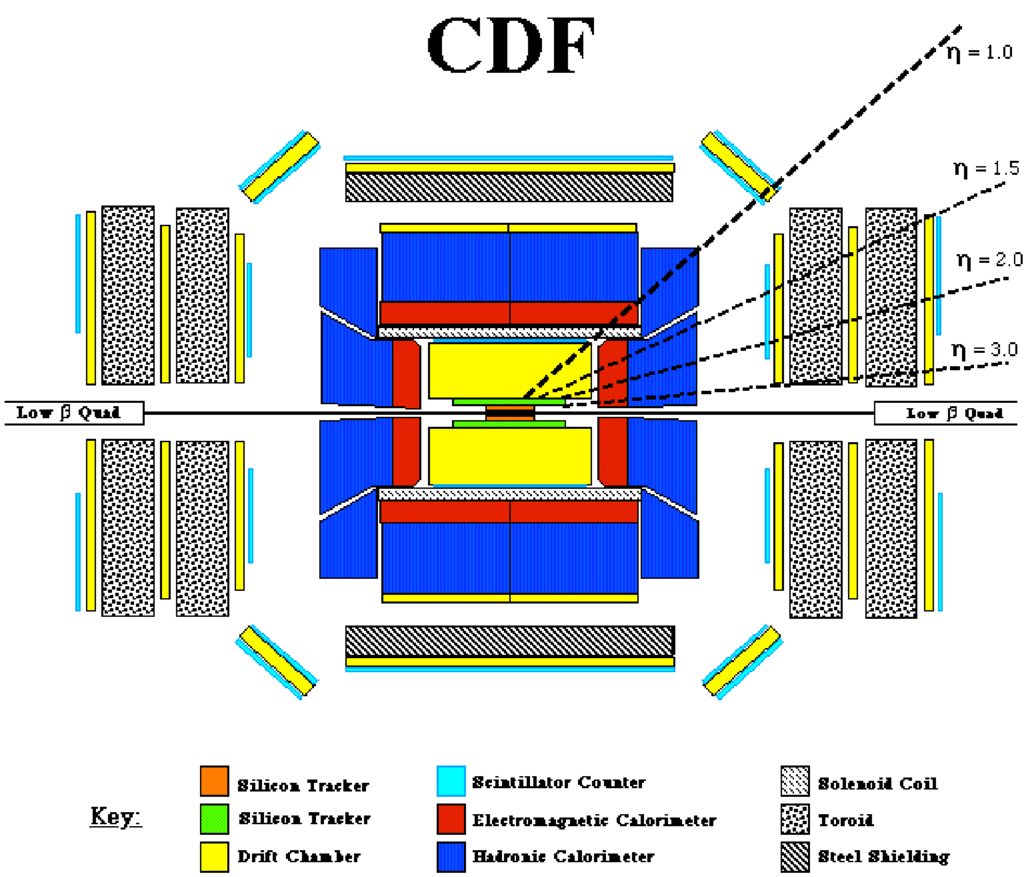
- new 120-GeV Main Injector
- Recycler Ring: more $\bar{p}$'s

goals:
2×10^{32} $\text{cm}^{-2}\text{sec}^{-1}$ at
396 nsec (36×36) bunch crossing
→ 2 fb^{-1} by end of 2002

5×10^{32} $\text{cm}^{-2}\text{sec}^{-1}$ at 132 nsec ($\sim$ 140 × 103) bunch crossing
→ 15 fb^{-1} by end of 2007

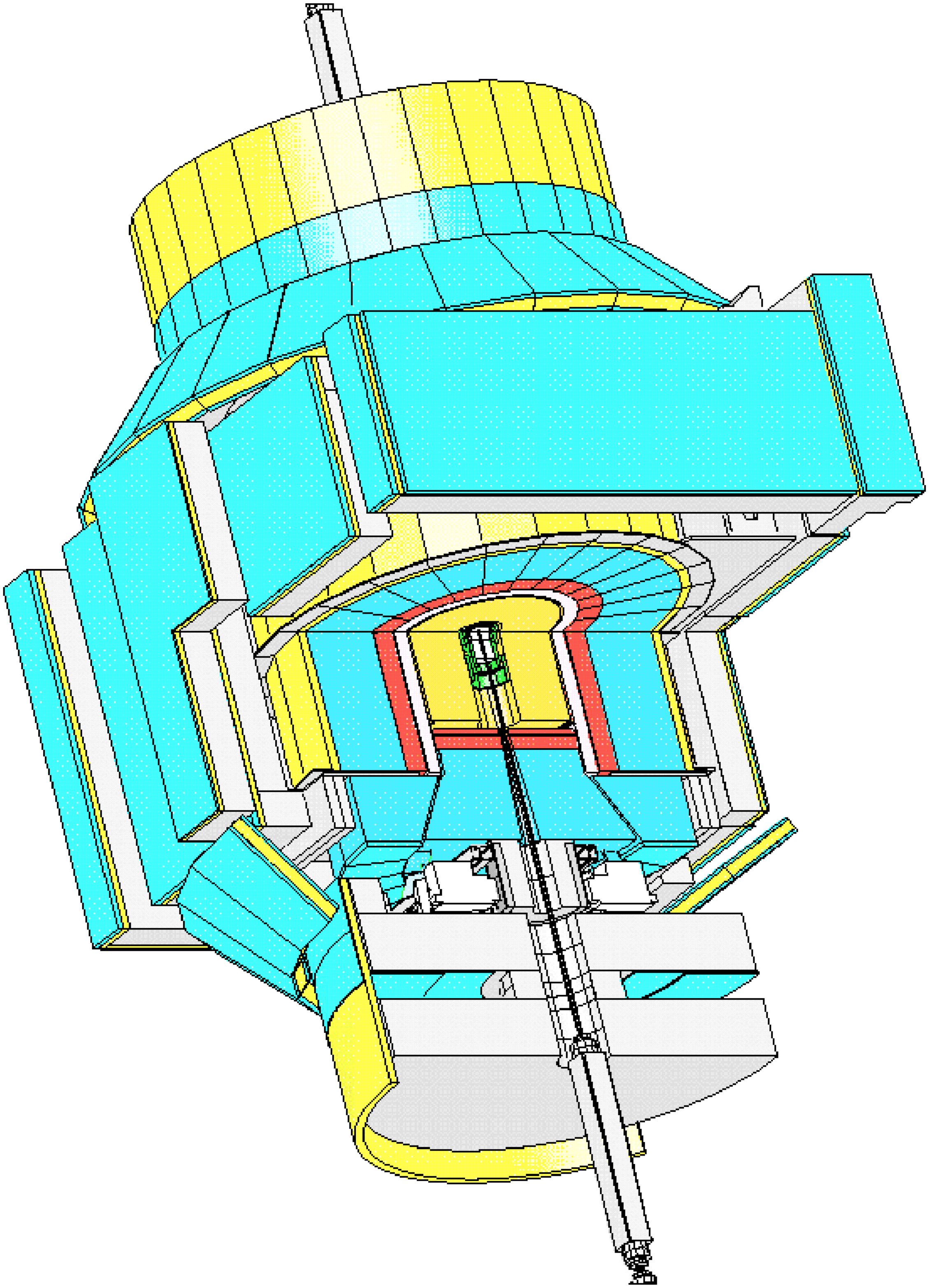
→ commissioning run Aug-Sep 2000

→ full detectors, begin physics Mar 2001

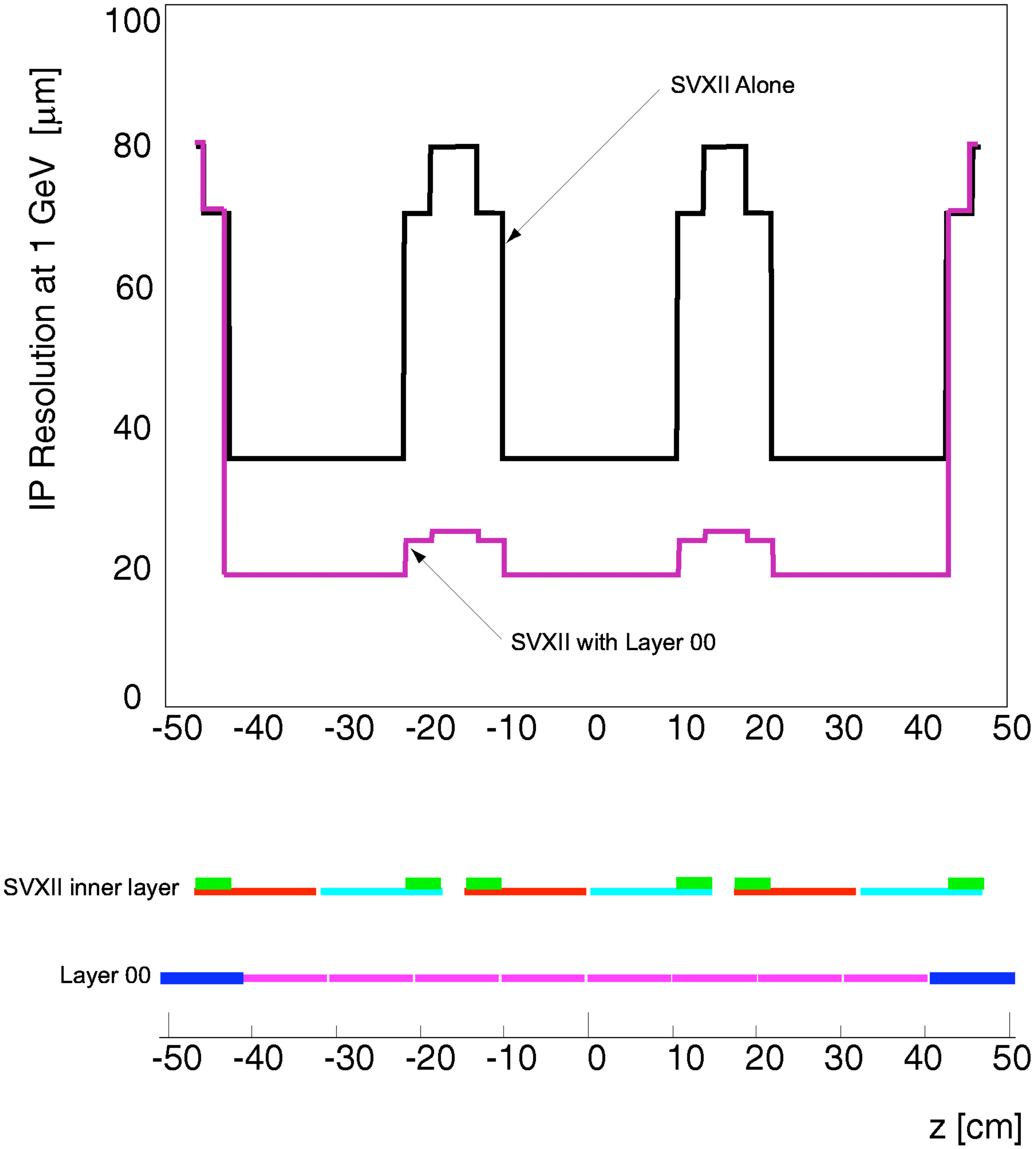


CDF Run 2 Upgrade

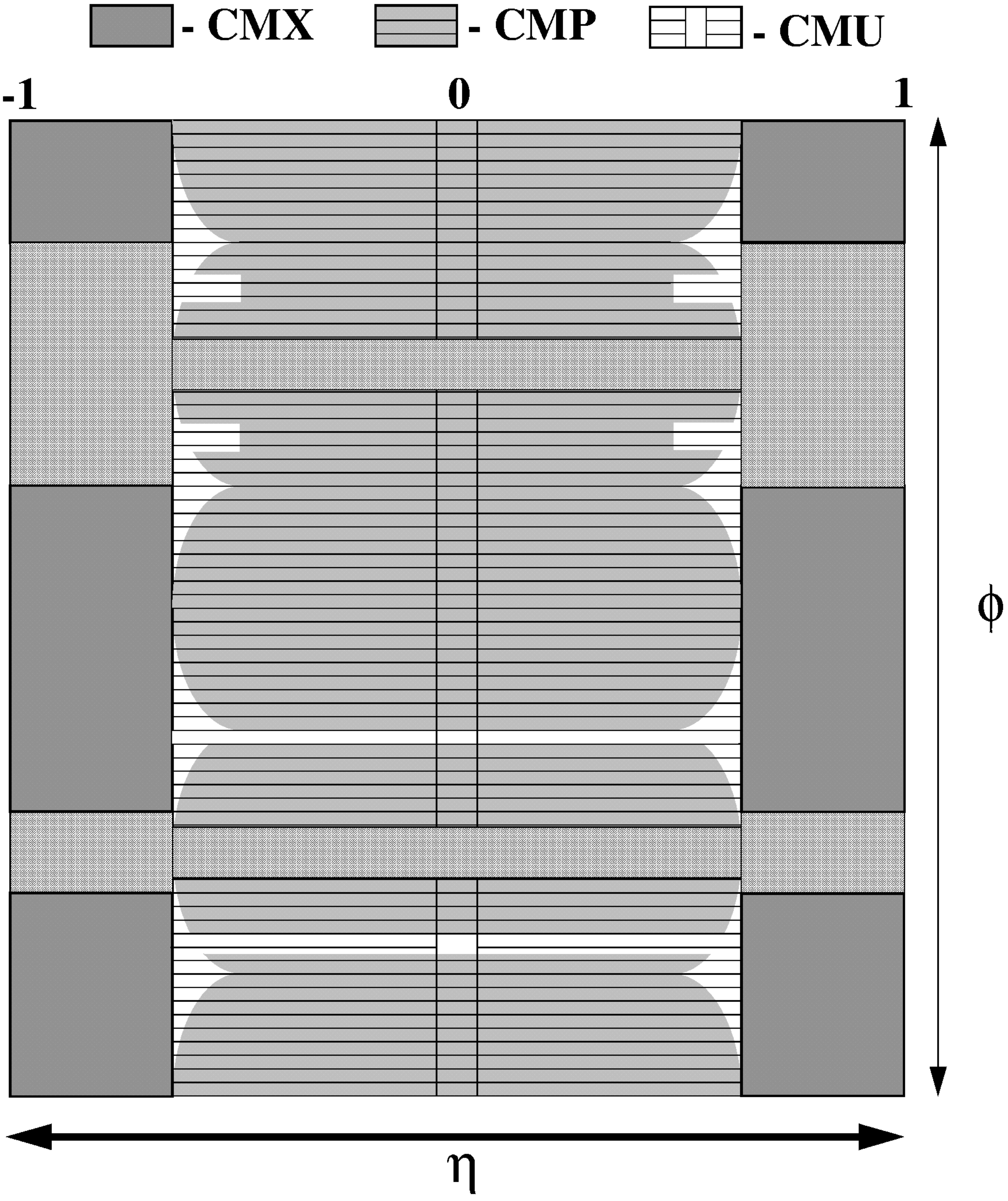
- all-new inner tracking:
  - L00 single sided Si mounted on beam pipe
  - 5-layer SVX-II double-sided Si
  - 2-layer ISL, double-sided Si
  - COT axial/stereo wire drift chamber
- new scintillating tile endplug calorimeter
- more muon coverage
- new DAQ/trigger electronics
  - new front-end digitizers
  - all-new digital trigger electronics
  - new VME-based DAQ
  - scaled-up Level 3 trigger

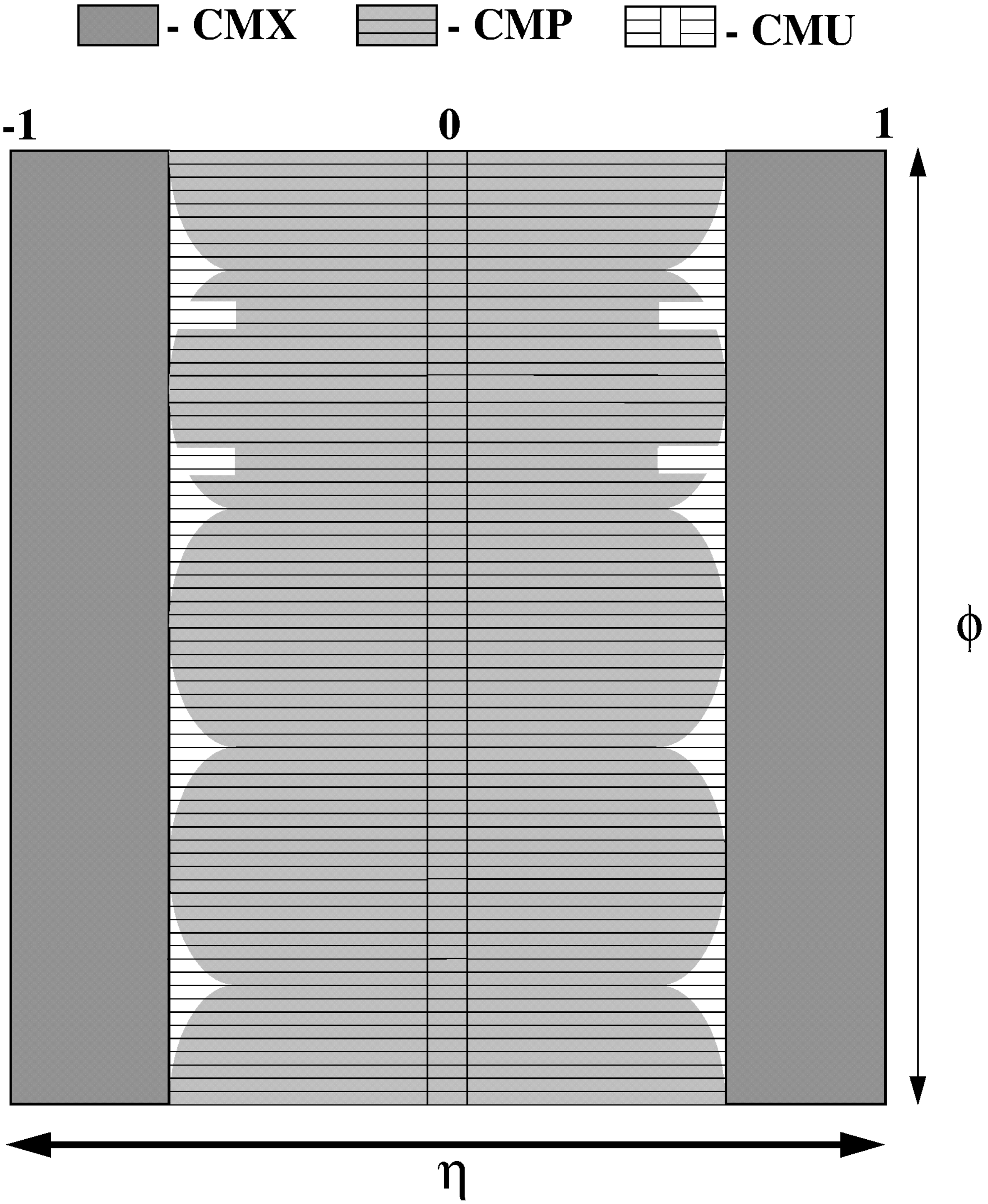


Effect of Layer 00 on impact parameter:



→ get ~20-25 μm resolution everywhere


- CMX
- CMP
- CMU
-1
0
1
φ
η


- CMX
- CMP
- CMU
-1
0
1
φ
η

DØ Run 2 Upgrade

- all-new tracking:
  - 4–layer double–sided silicon vertex detector, barrel and disk geometry
  - 16–layer axial+stereo scintillating fiber tracker
  - hermetic scintallating strip pre–shower detectors
  - 2T solenoidal magentic field
- updgraded muon system
  - replace forward ($1.0 \leq |\eta| \leq 2$) system with streamer tubes and scintillator pixels
  - improved scintillator coverage for central region
- new DAQ/trigger electronics
  - standalone track trigger; uses all tracking detectors
  - upgraded, higher speed calorimeter electronics
  - include new muon scintillator detectors in trigger
  - new trigger control framework
  - additional hardware trigger level for all subdetector systems
- new online/offline C++ software

Tevatron Run 2 Workshop

- repeat and extend the previous studies
- combine all possible channels
- simulate "average" of CDF and DØ
- establish SM Higgs discovery thresholds
- interpret SM Higgs results in MSSM
- explore new SUSY Higgs possibilities

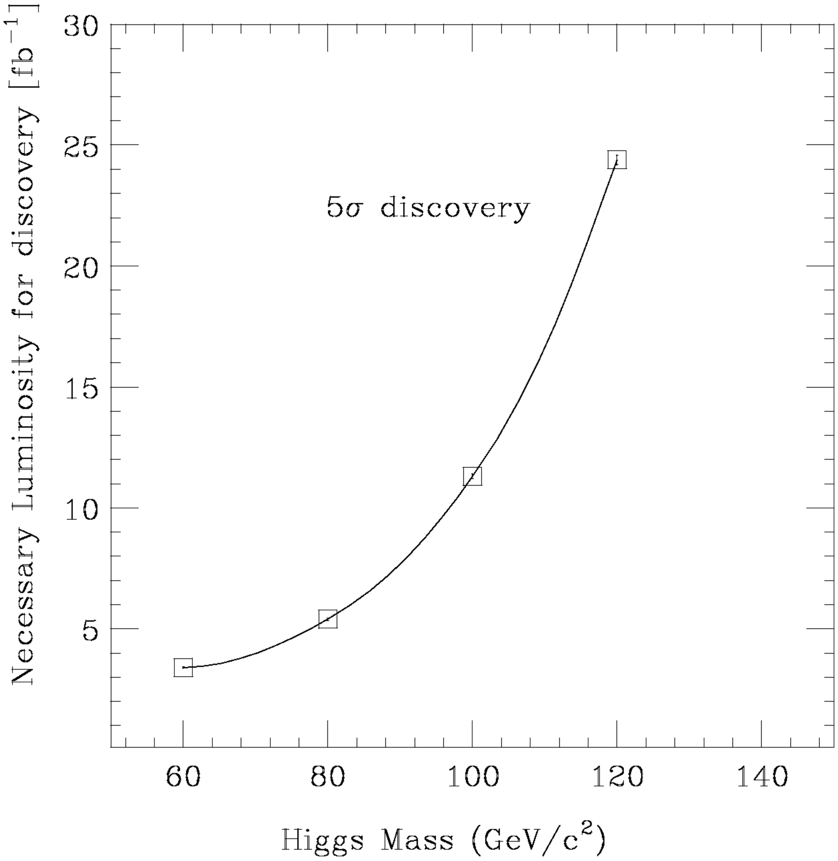
SHW - simple CDF/DØ simulation

→ go beyond "parton-level" studies
→ simulate "average" CDF/DØ response

1. generate event (PYTHIA, ISAJET,...)
2. create list of tracks
3. create calorimeter tower energies
4. find calorimeter clusters
5. make list of trigger objects
6. make list of physics objects (γ, e, μ, τ, jets ...)

TeV33

study result

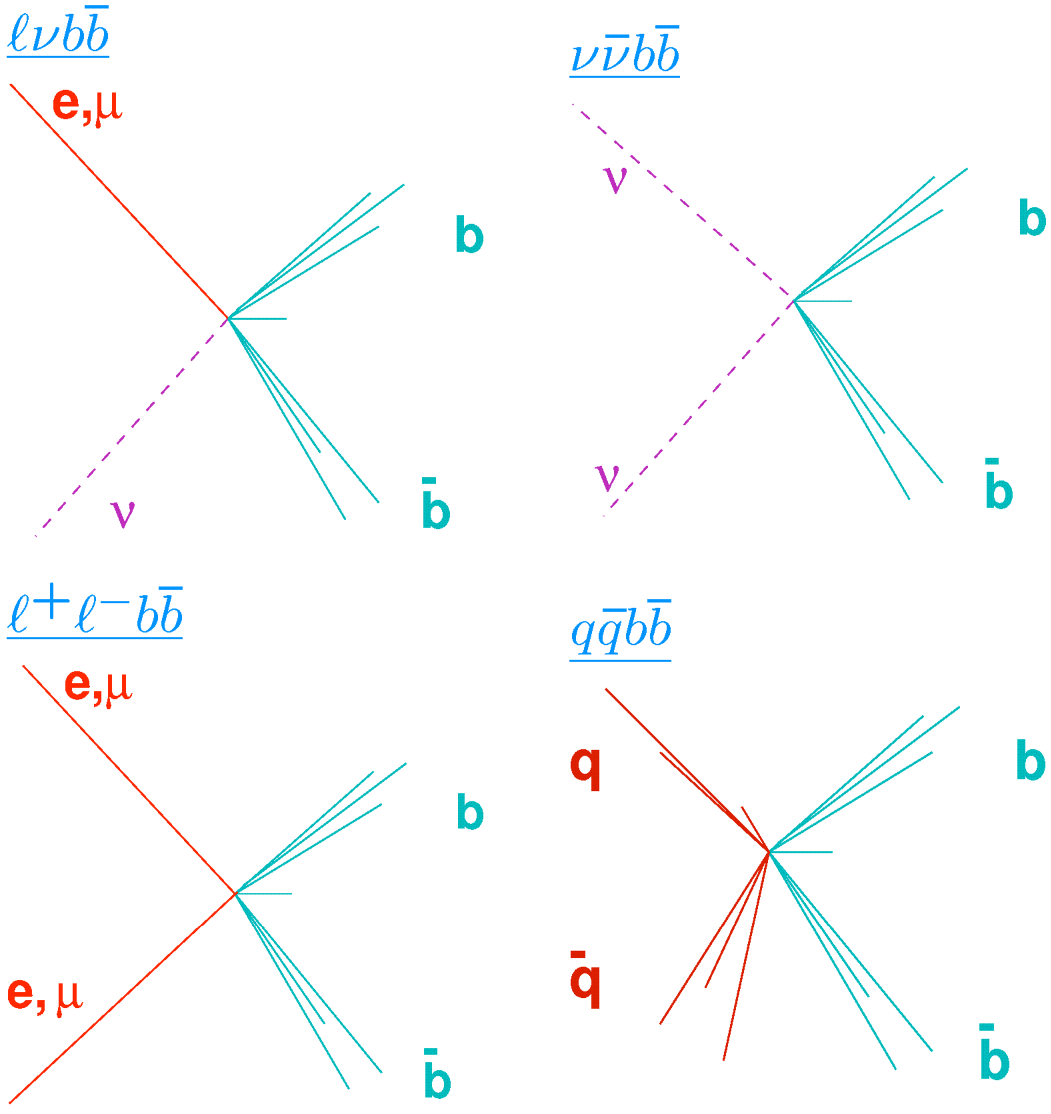


How do we improve upon previous studies?

- better $b\bar{b}$ mass resolution
- more efficient b tagging
- new triggers
- improved selection selection
- add new channels
- combine all channels

Low mass SM Higgs channels

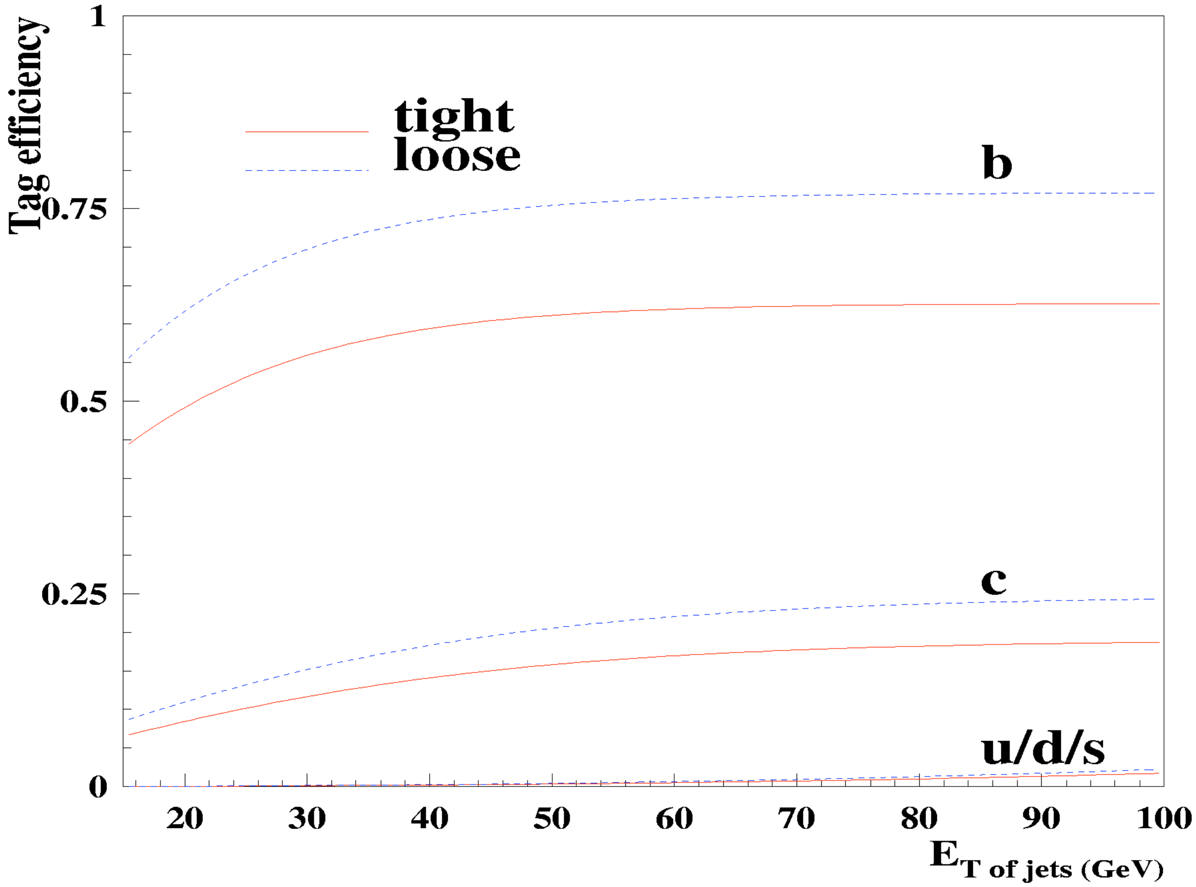
E. Barberis, W. Yao, P. Bhat, H. Prosper, W. Bokhari, R. Jesik, R. Gilmartin,
R. Demina, M. Kruse, D. Hedin



main backgrounds: $Wb\bar{b}$, $Zb\bar{b}$, $t\bar{t}$, WZ, single top, QCD

b tagging

tight/loose b tagging efficiency:

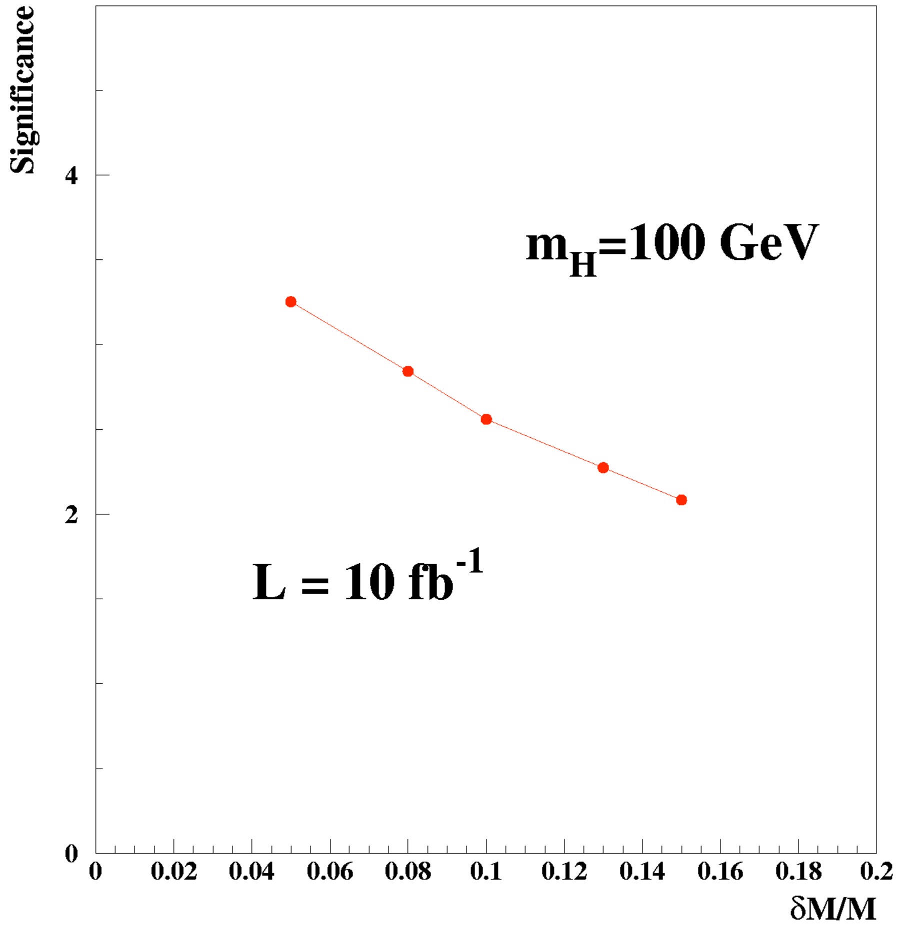


→ we assume CDF Run 1 efficiencies

→ we use Run 2 detector geometry

→ can very likely do better!

$\ell\nu b\bar{b}$ channel dependence on mass resolution

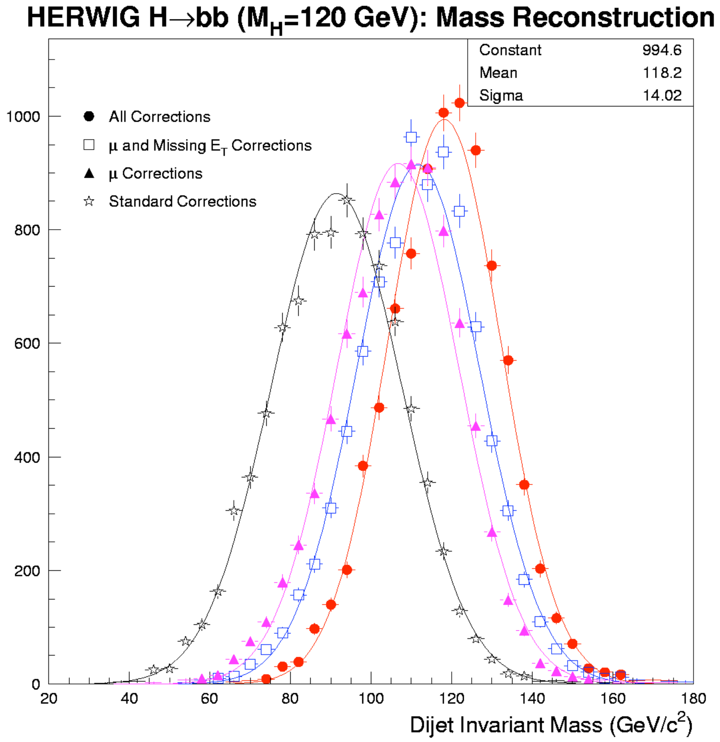


→ can reasonably hope for 10% mass resolution:

- use jet energy information from *all* subdetectors
- correct for $\not{E}_T$ in jet (leptons in jet)
- use $Z \to b\bar{b}$ as calibration

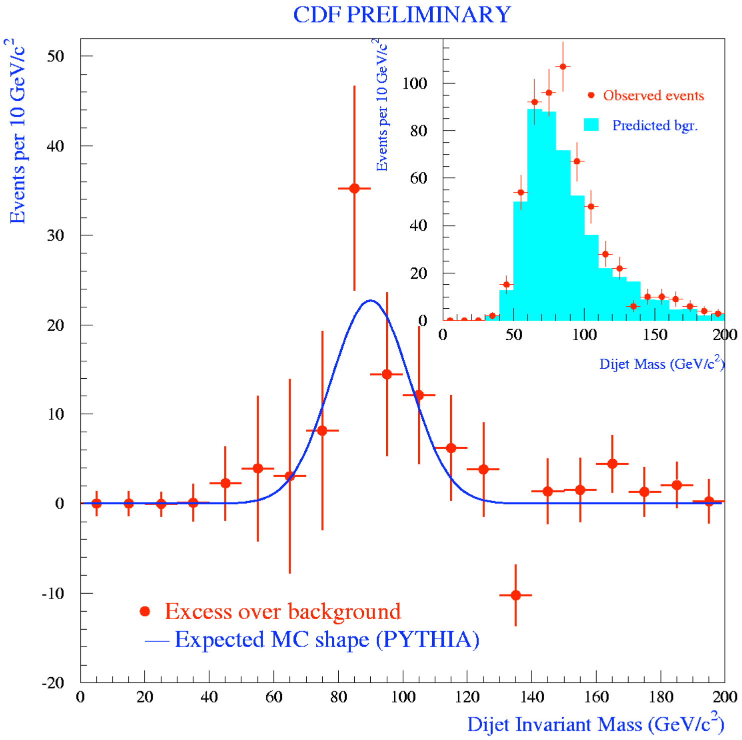
Studies of $b\bar{b}$ mass resolution

T. Dorigo, S. Kuhlmann, S. Lami, R. Snihur, A. Ribon

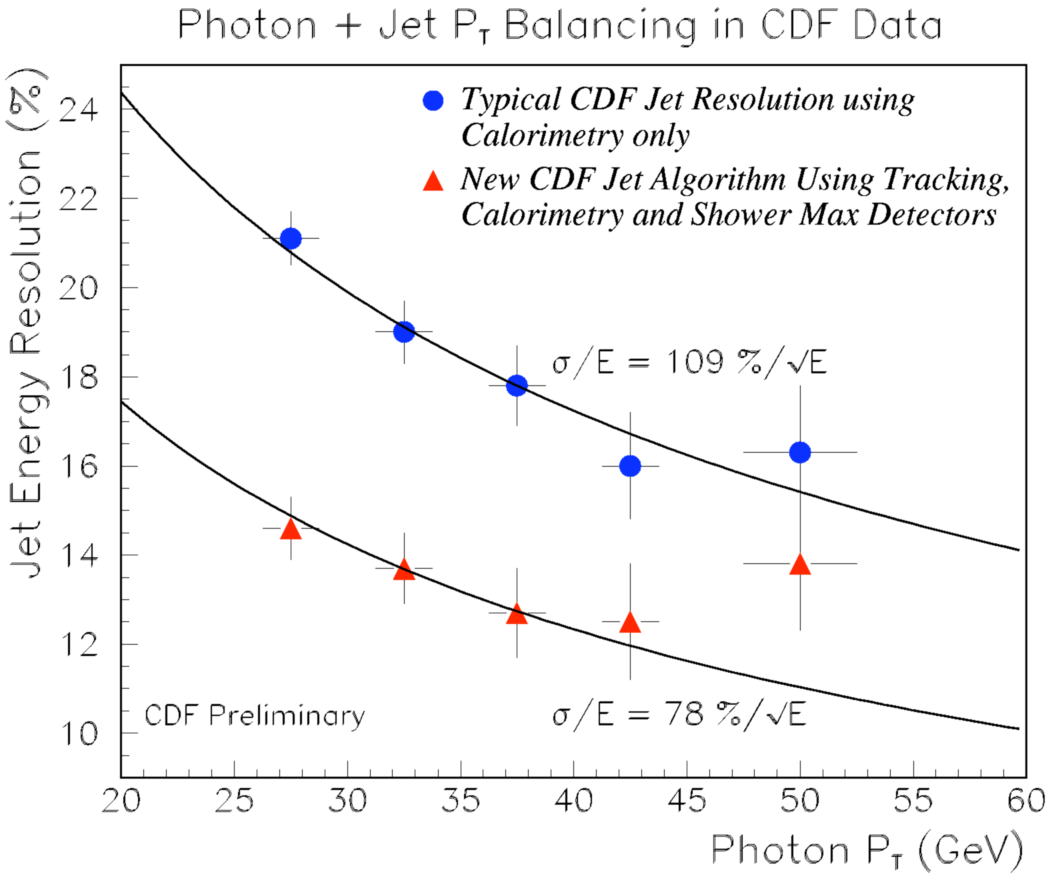


correct for missing E_T, lepton E_T...

...can see $Z \rightarrow b\bar{b}$



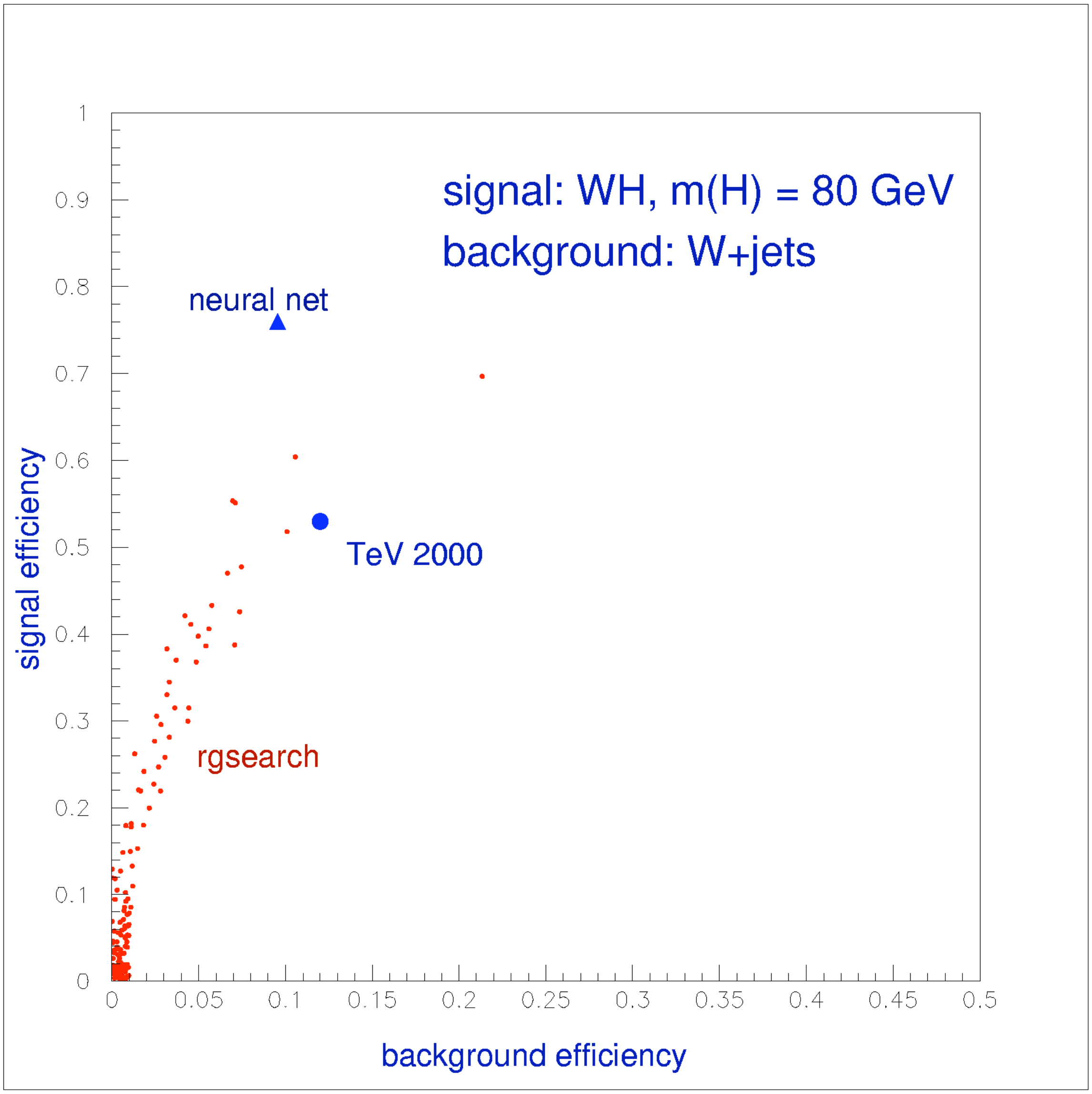
Jet resolution greatly improves with energy estimate based on linear combination of all detector elements:



CDF has not yet applied such techniques in physics analyses...

Studies of selection optimization

P. Bhat, R, Gilmartin, H. Prosper



→ significant improvement with these techniques

$S/\sqrt{B}$ with and without neural network:

channel	mass (GeV)	cuts	neural net
$\ell\nu b\bar{b}$	100 120 130	1.0 0.6 0.4	1.4 0.9 0.6
$\nu\bar{\nu}b\bar{b}$	100 120 130	1.0 0.6 0.4	1.3 0.8 0.6
$\ell^+\ell^-b\bar{b}$	100 120 130	0.2 0.13 0.06	0.5 0.33 0.22

Low-mass SM Higgs Channel Sensitivities

expected events and sensitivity in 1 fb^{-1}

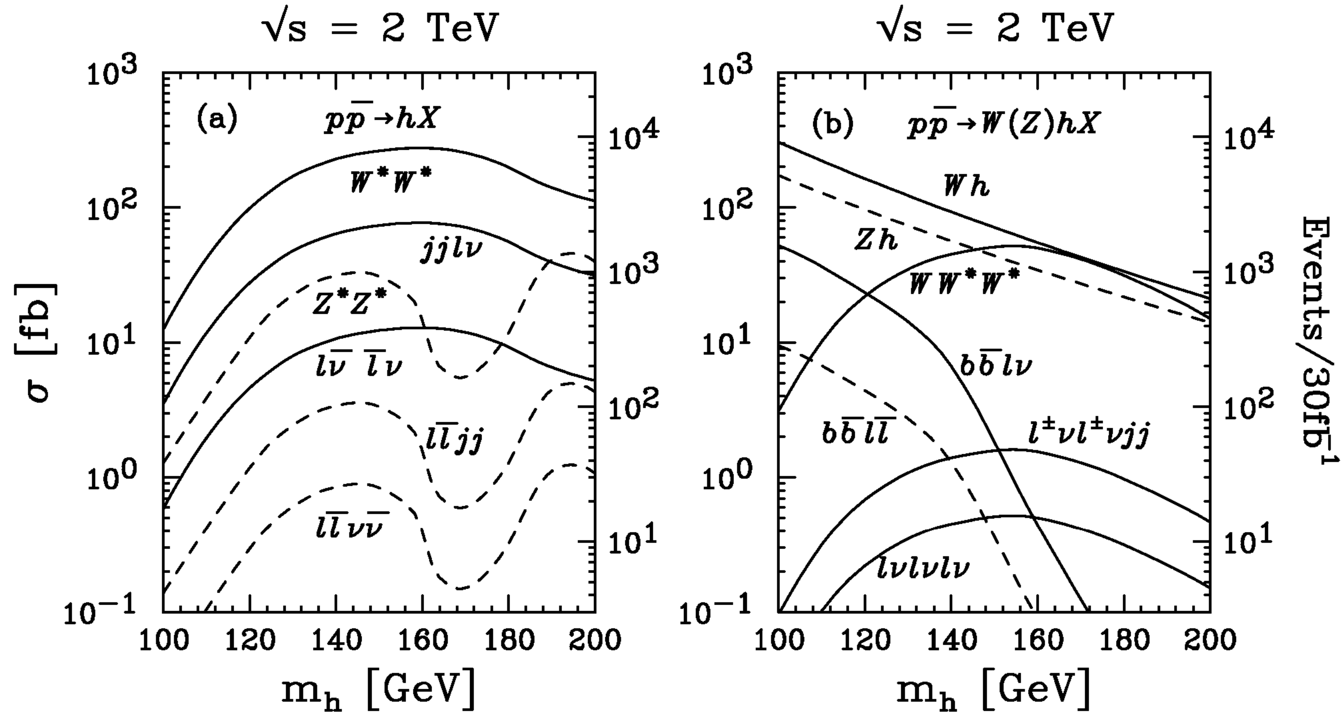
		Higgs mass (GeV/c^2)				
channel	rate	90	100	110	120	130
$\ell\nu b\bar{b}$ (CDF)	S	8.4	6.6	5.0	3.7	2.2
	B	48	52	48	49	42
	$S/\sqrt{B}$	1.2	0.9	0.7	0.5	0.3
$\ell\nu b\bar{b}$ (SHW)	S	10	8	5	4	3
	B	75	68	57	58	52
	$S/\sqrt{B}$	1.1	1.0	0.7	0.5	0.4
$\ell\nu b\bar{b}$ (NN)	S	8.7	9.0	4.8	4.4	3.7
	B	28	39	19	26	46
	$S/\sqrt{B}$	1.6	1.4	1.1	0.9	0.5
$\nu\bar{\nu}b\bar{b}$ (CDF)	S	2.5	2.2	1.9	1.2	0.6
	B	20.0	18.6	16.0	13.0	9.6
	$S/\sqrt{B}$	0.6	0.5	0.5	0.3	0.2
$\nu\bar{\nu}b\bar{b}$ (SHW)	S	8.9	6.7	4.6	3.2	2.1
	B	112	104	96	90	82
	$S/\sqrt{B}$	0.8	0.7	0.5	0.3	0.2
$\nu\bar{\nu}b\bar{b}$ (NN)	S	11	7	5.3	3.7	2.6
	B	108	60	48	40	42
	$S/\sqrt{B}$	1.1	0.9	0.8	0.6	0.4
$\ell^+\ell^-b\bar{b}$ (CDF)	S	1.0	0.9	0.8	0.5	0.3
	B	3.6	3.1	2.5	1.8	1.1
	$S/\sqrt{B}$	0.5	0.5	0.5	0.4	0.3
$\ell^+\ell^-b\bar{b}$ (SHW)	S	1.5	1.2	0.9	0.6	0.4
	B	4.9	4.3	3.2	2.3	1.9
	$S/\sqrt{B}$	0.7	0.6	0.5	0.4	0.3
$\ell^+\ell^-b\bar{b}$ (NN)	S	1.2	0.8	0.5	0.5	0.3
	B	4.2	2.7	2.3	2.0	1.9
	$S/\sqrt{B}$	0.6	0.5	0.3	0.3	0.2
	S	8.1	5.6	3.5	2.5	1.3

SM Higgs in WW^*, WWW^*, ZWW^* modes

T. Han, A. Lucotte, M. Schmitt, A. Turcot, R. Zhang

idea: exploit $H \rightarrow WW^*$ decays at higher masses

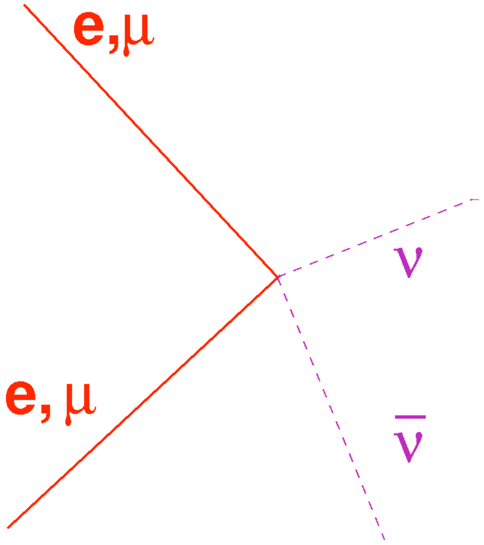
- $gg \rightarrow H \rightarrow WW^*$
- $ZH \rightarrow ZWW^*$
- $WH \rightarrow WWW^*$



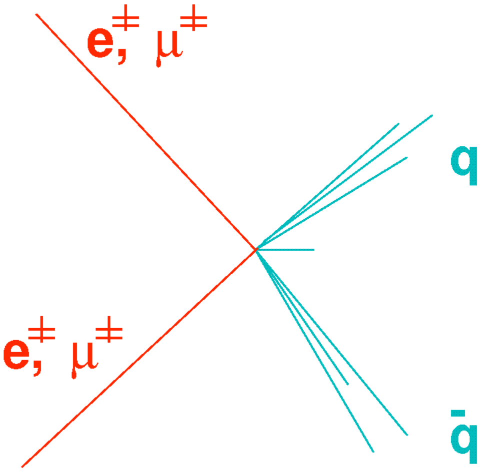
→ dilepton, trilepton, like-sign dilepton plus jets

High-mass SM Higgs channels

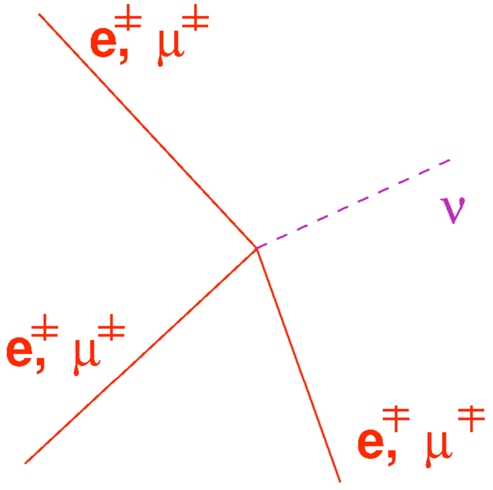
$\ell^+\ell^-\nu\bar{\nu}$



$\ell^\pm\ell^\pm jj$



$\ell^\pm\ell'^\pm\ell^\mp$



main backgrounds: WW, WZ, ZZ, $t\bar{t}$

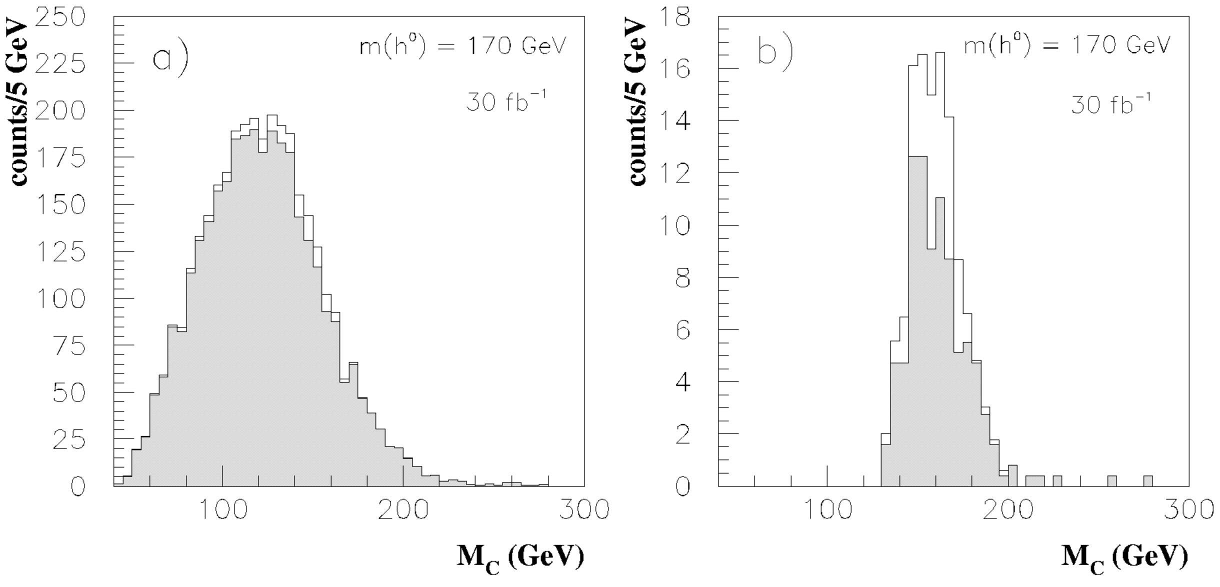
→ most powerful channel at high masses: $\ell^\pm\ell^\pm jj$

$\ell^+\ell^-\nu\bar{\nu}$ channel

→ lots of finely tuned kinematic cuts

→ use “cluster transverse mass” to sharpen mass

$$M_C \equiv \sqrt{p_T^2(\ell\ell)+m^2(\ell\ell)} + \not{E}_{\mathrm{T}}$$



(before cuts) (after cuts)

High-mass SM Higgs Channel Sensitivities

expected events and sensitivity in 1 fb^{-1}

channel	rate	Higgs mass (GeV/c^2) 130	140	150	160	170	180
$\ell^\pm \ell'^\pm \ell^\mp$	S	0.025	0.039	0.050	0.057	0.033	0.033
	B	0.025	0.025	0.025	0.025	0.025	0.025
	$S/\sqrt{B}$	0.16	0.25	0.32	0.36	0.21	0.21
$\ell^+ \ell^- \nu\bar{\nu}$	S	-	2.6	2.8	1.5	1.1	1.0
	B	-	44	30	4.4	2.4	3.8
	$S/\sqrt{B}$	-	0.39	0.51	0.71	0.71	0.51
$\ell^\pm \ell^\pm jj$	S	0.15	0.29	0.36	0.41	0.38	0.26
	B	0.58	0.58	0.58	0.58	0.58	0.58
	$S/\sqrt{B}$	0.20	0.38	0.47	0.54	0.50	0.34

- trileptons need very large data samples
- $gg \to H \to WW$ most sensitive!

Statistical method for combining channels

- Determine S and B for each channel (events expected in 1 fb^{-1}).
- For each channel, at some integrated luminosity, there is some outcome (n_{obs} in each channel.)
- Form joint likelihood of all channels (both experiments) as function of Higgs cross section.
- Convolute systematic errors into likehood.
- Exclusion: integrate likelihood as function of Higgs cross section to determine 95% CL limit.
- Discovery: use ratio of maximum likelihood to likelihood at zero Higgs cross section; equate to equivalent Gaussian ratio.
- Determine integrated luminosity at which 50% of future outcomes will meet desired threshold.

SM Higgs combined channel thresholds

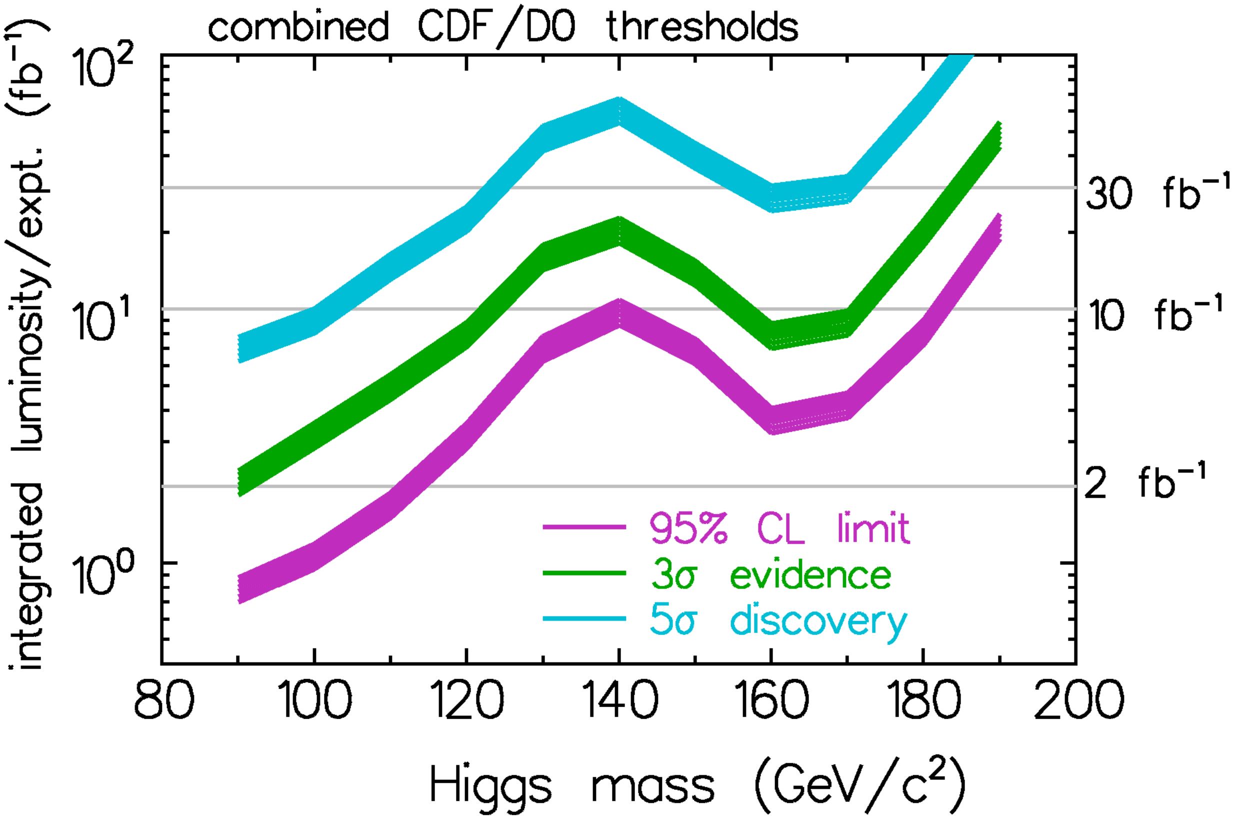
→ Bayesian combination method - two experiments

→ 30% better $m_{b\bar{b}}$ resolution than Run 1

→ SHW acceptance, neural network selection

→ double $\nu\bar{\nu}b\bar{b}$ background for QCD

→ nominal systematic errors: 10% or $1/\sqrt{LB}$



→ bands represent level of "uncertainty" in estimates

How reliable are these estimates?

b-tagging If efficiency goes up by 10%, required integrated luminosity drops by 20%

mass resolution Required integrated luminosity scales linearly with resolution.

backgrounds Required integrated luminosity scales linearly with background.

statistics Full spectral fits will be more sensitive than assumptions made here (single channel fits).

systematic errors Dominated by error on background; have not taken into account error on signal (compute time!)

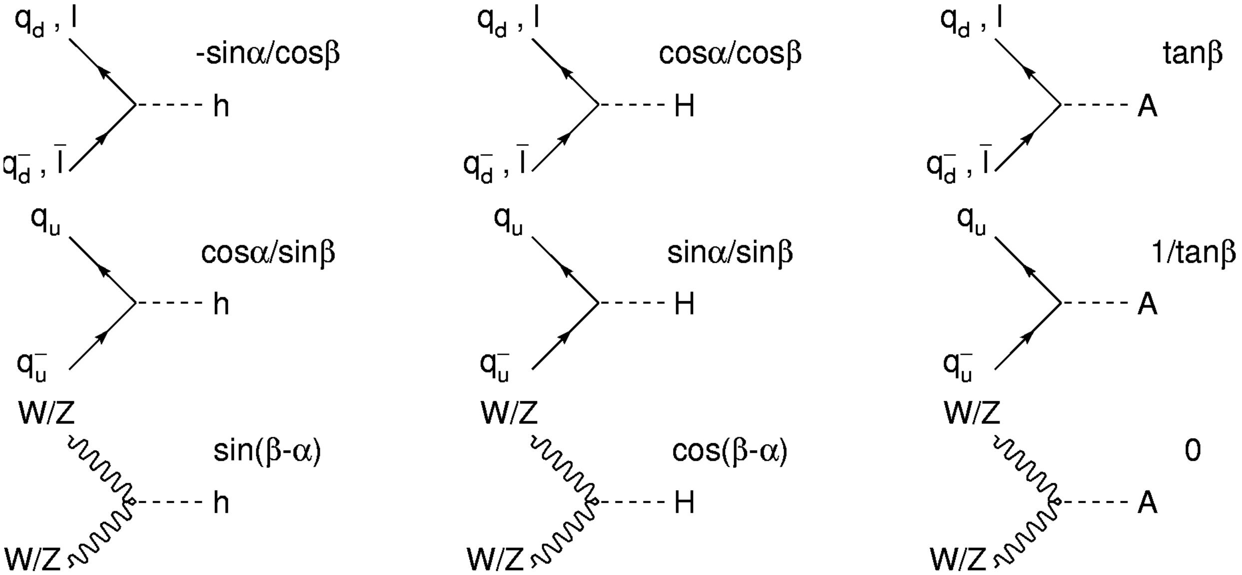
→ In $\nu\nu b\bar{b}$ channel, QCD $b\bar{b}$ dijet background difficult to estimate

→ CDF/DØ Run 1: dijet background was half of total

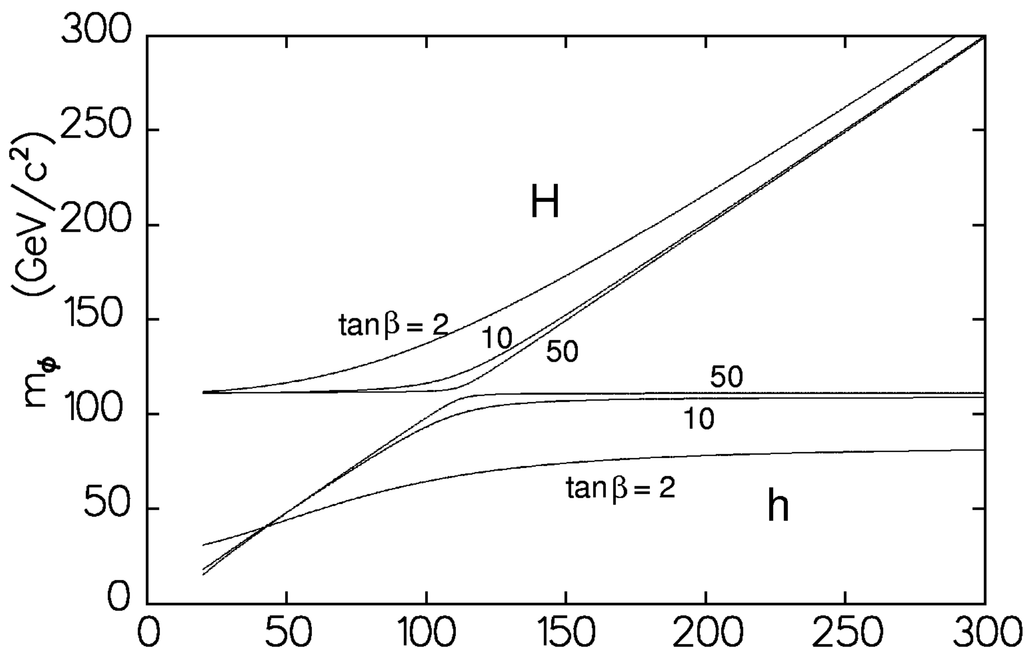
→ we conservatively assume this for Run 2...

SUSY Higgs (MSSM)

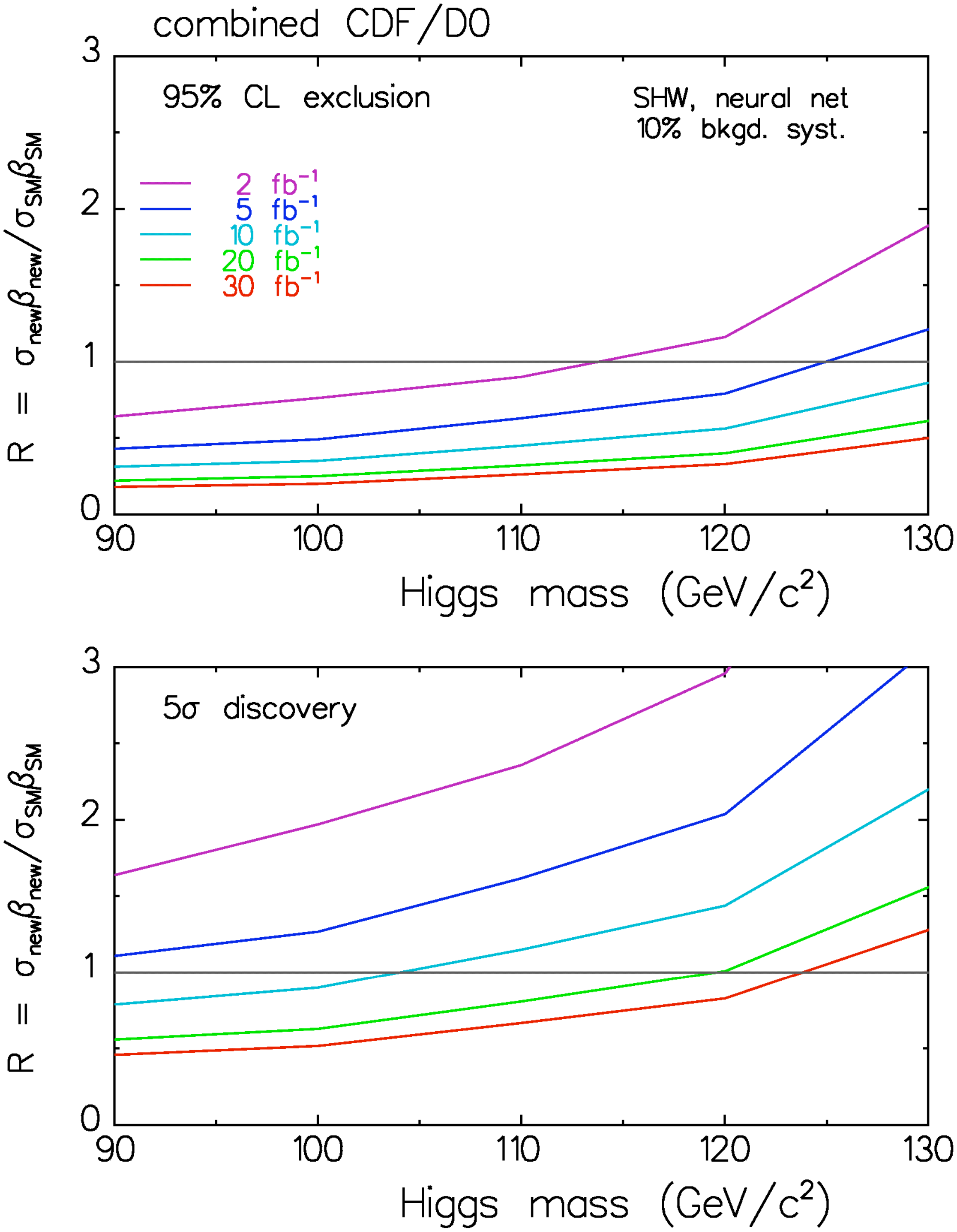
Have five Higgs bosons: h,A,H,$H^{\pm}$



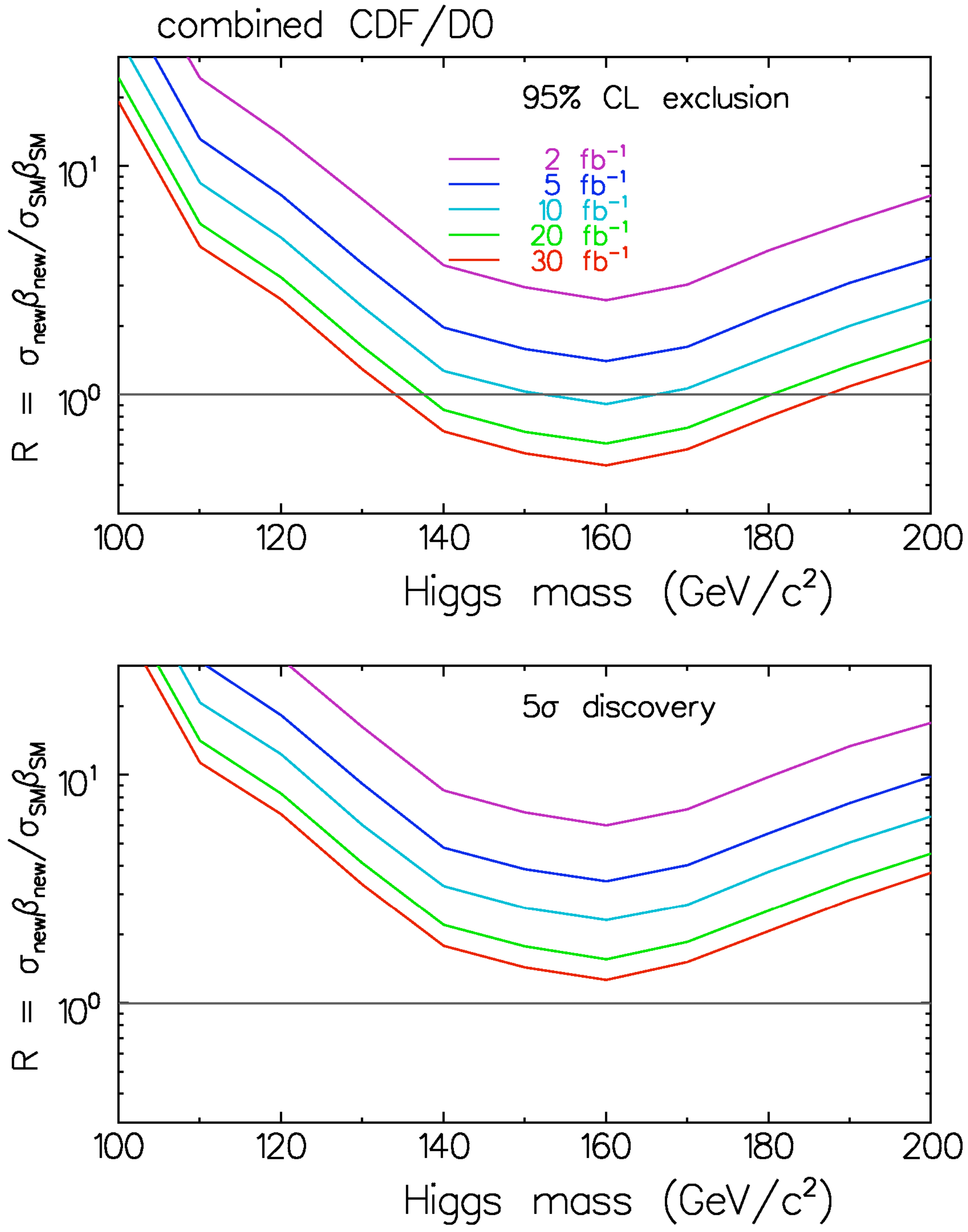
Masses governed by two parameters: m_A, tan β



Express SM contours in terms of ratio of new physics to Standard Model for low-mass channels:

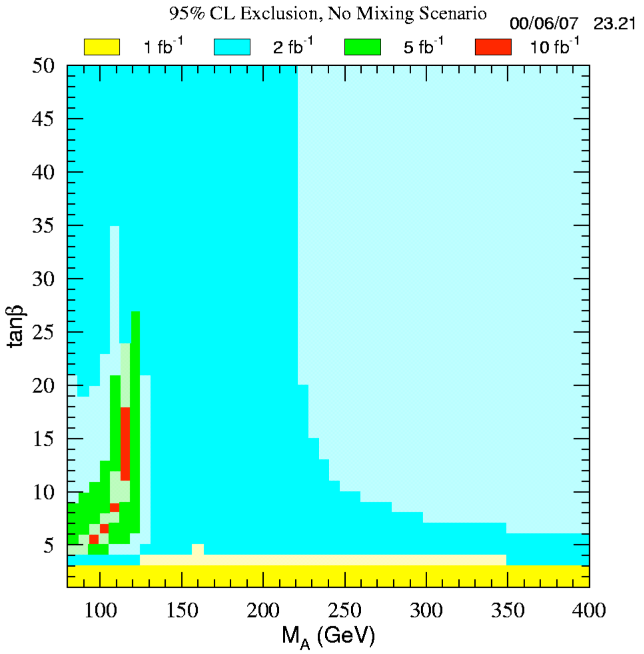


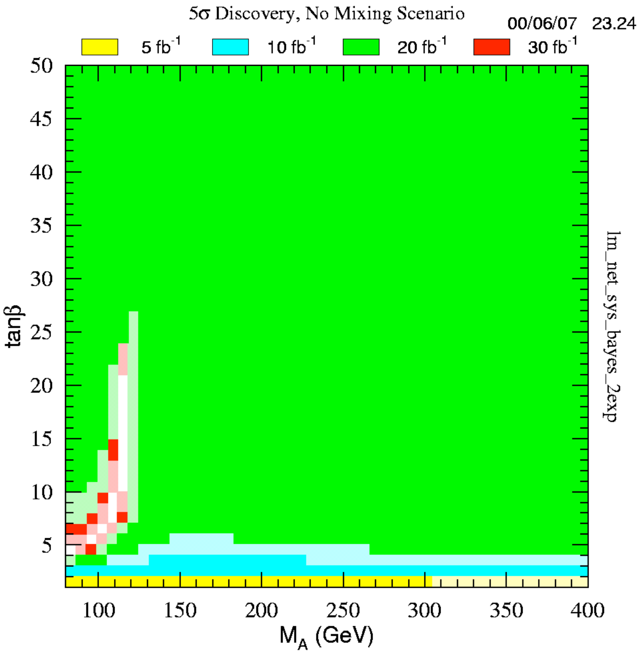
Express SM contours in terms of ratio of new physics to Standard Model for high-mass WH/ZH channels:



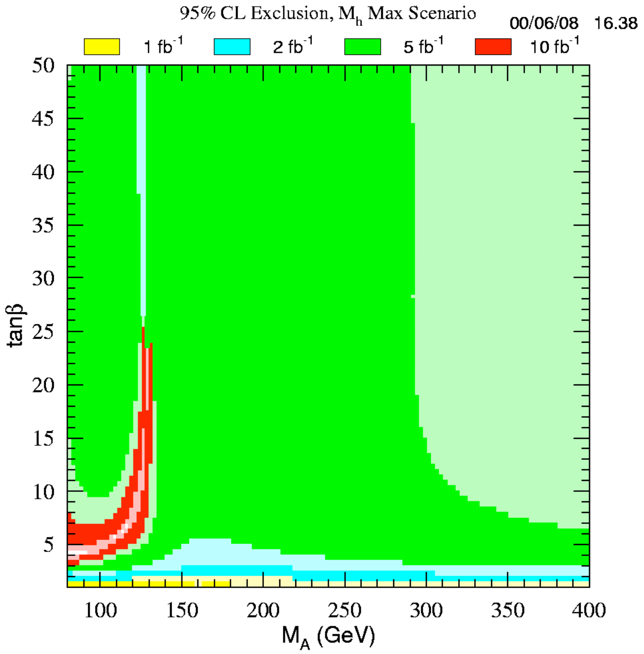
MSSM discovery/exclusion from SM Higgs channels

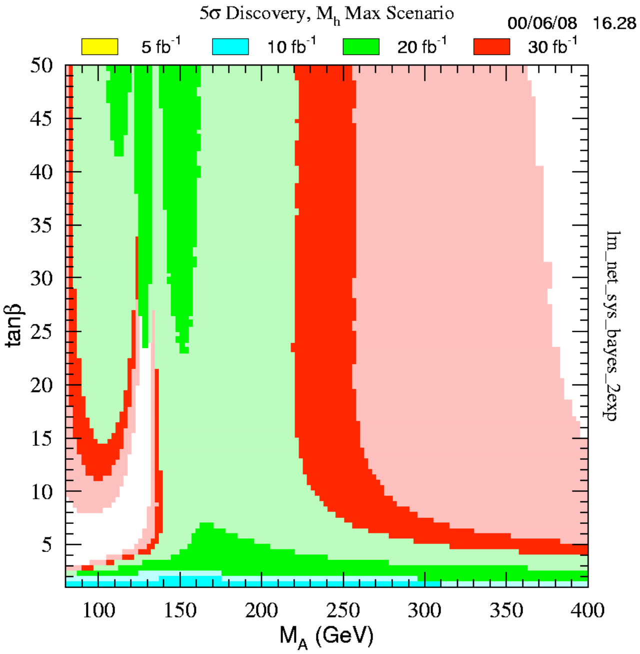
no mixing, $M_s = 1$ TeV



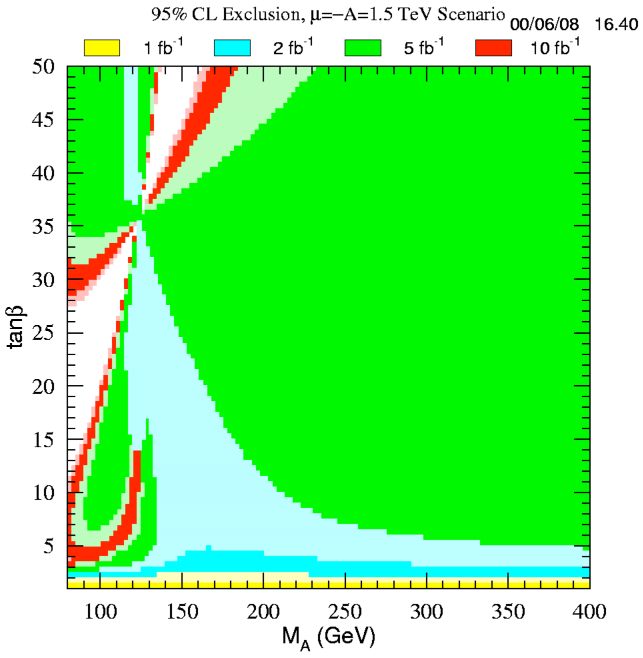


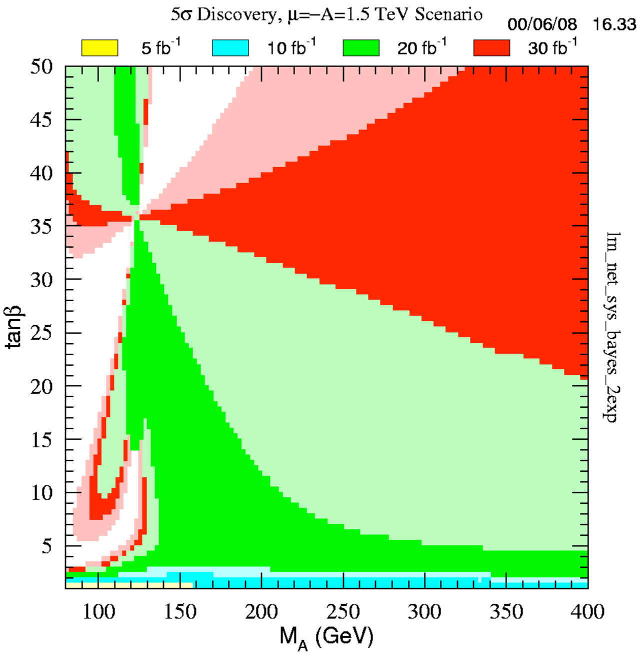
maximal mixing, $M_s = 1$ TeV





$-A = \mu = 1.5$ TeV

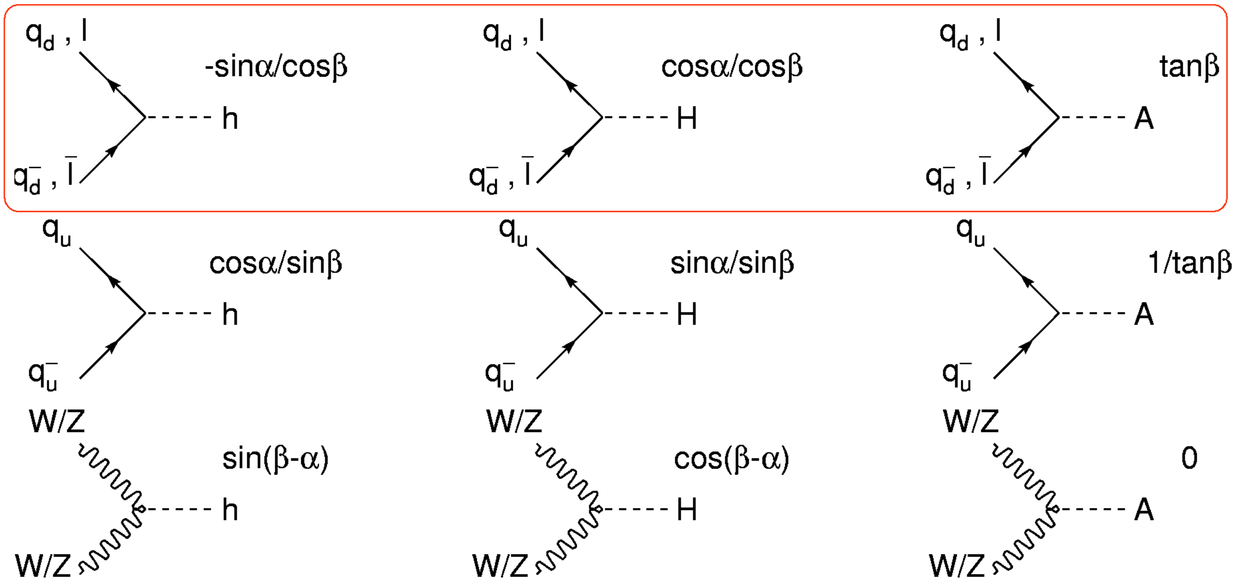




- MSSM coverage very parameter-dependent
- can exclude significant region with 2 fb^{-1}
- need large integrated luminosity for some regions

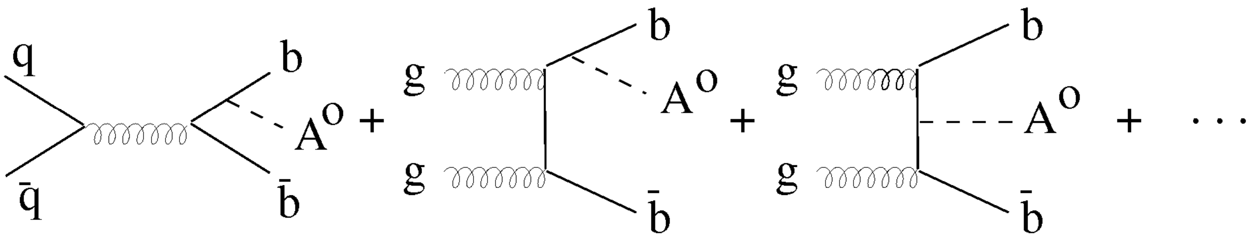
SUSY Higgs Production at large $\tan\beta$

Maria Roco, A. Belyaev, Juan Valls



$\rightarrow$ $b\bar{b}A/b\bar{b}h/b\bar{b}H$ enhanced at large $\tan\beta$

$\rightarrow$ cross sections $\propto \tan^2\beta$



possible search channels:

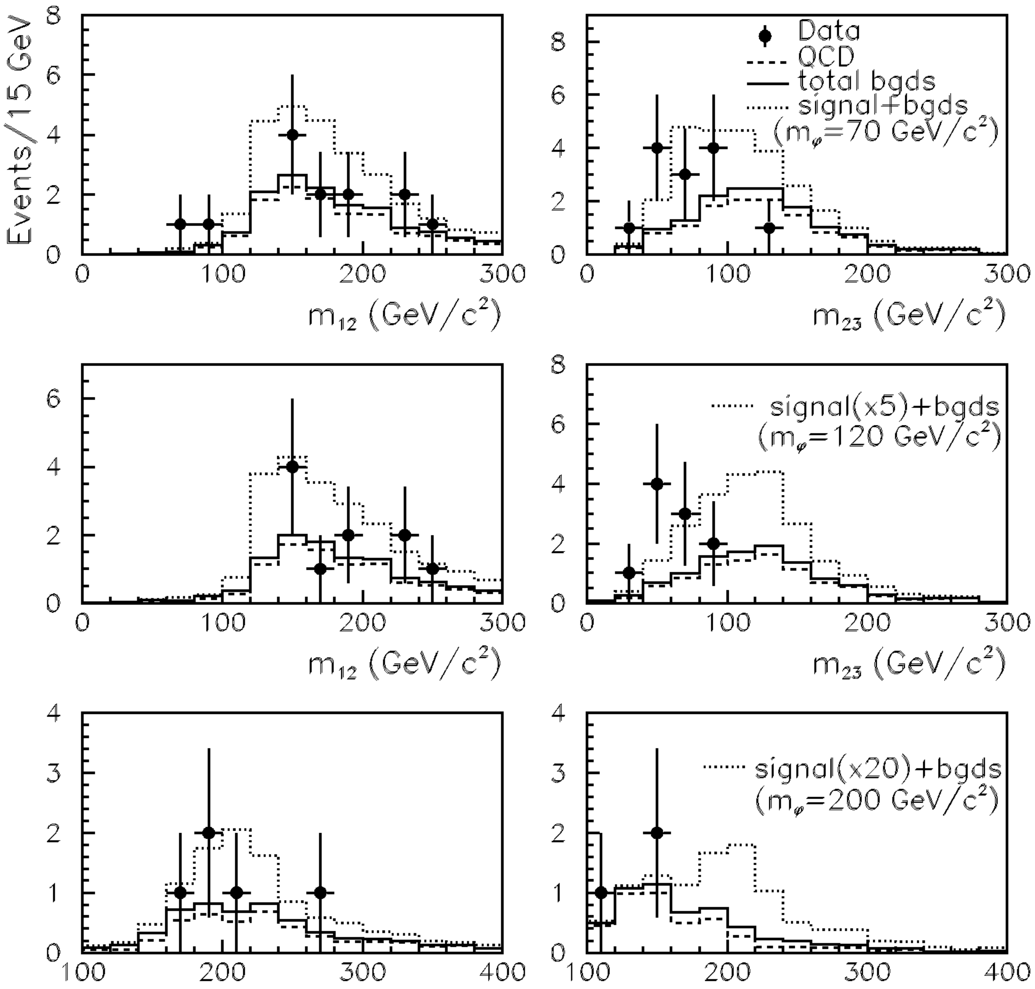
- $b\bar{b}b\bar{b}$
- $\tau\tau j\not{E}_T$
- $\tau b j\not{E}_T$

MSSM neutral Higgs in $b\bar{b}b\bar{b}$ Channel

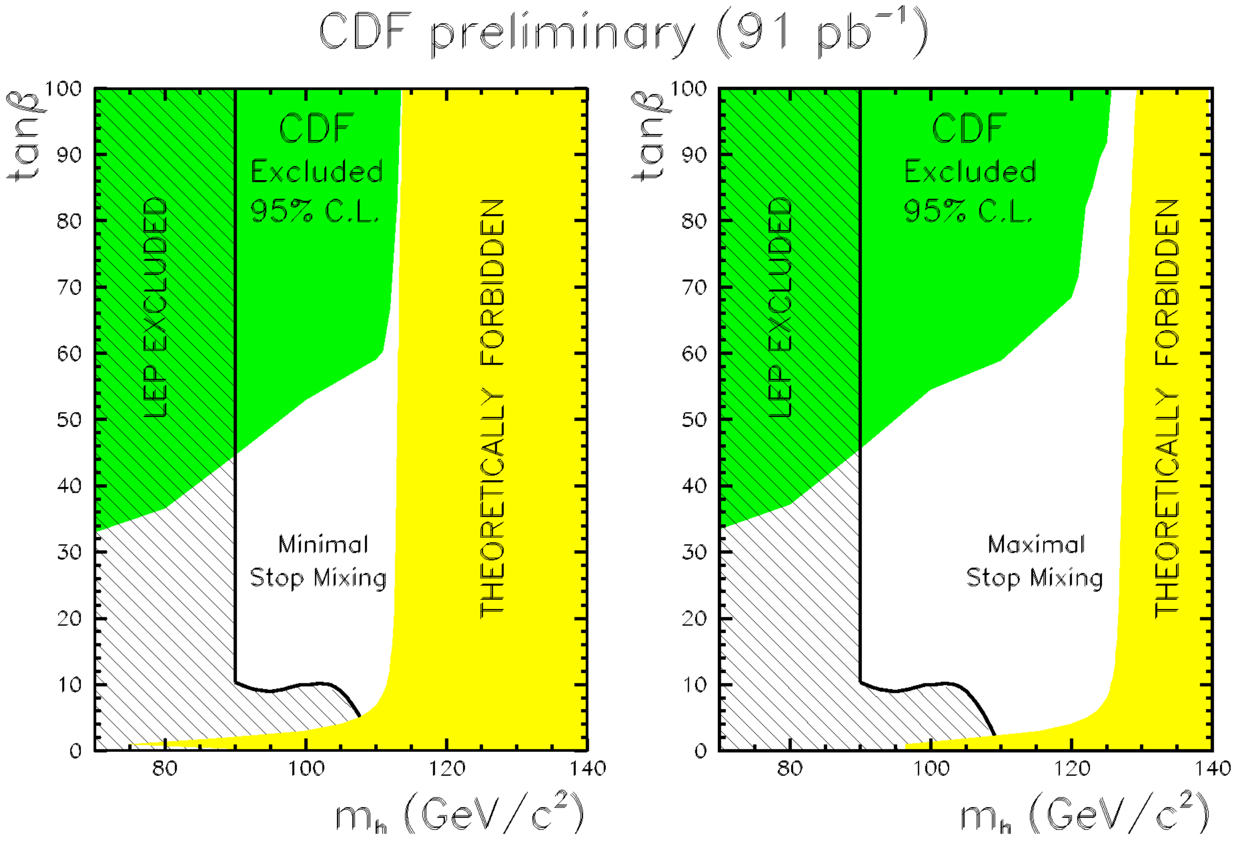
→ use same sample as SM Higgs $q\bar{q}b\bar{b}$ channel (589 events)

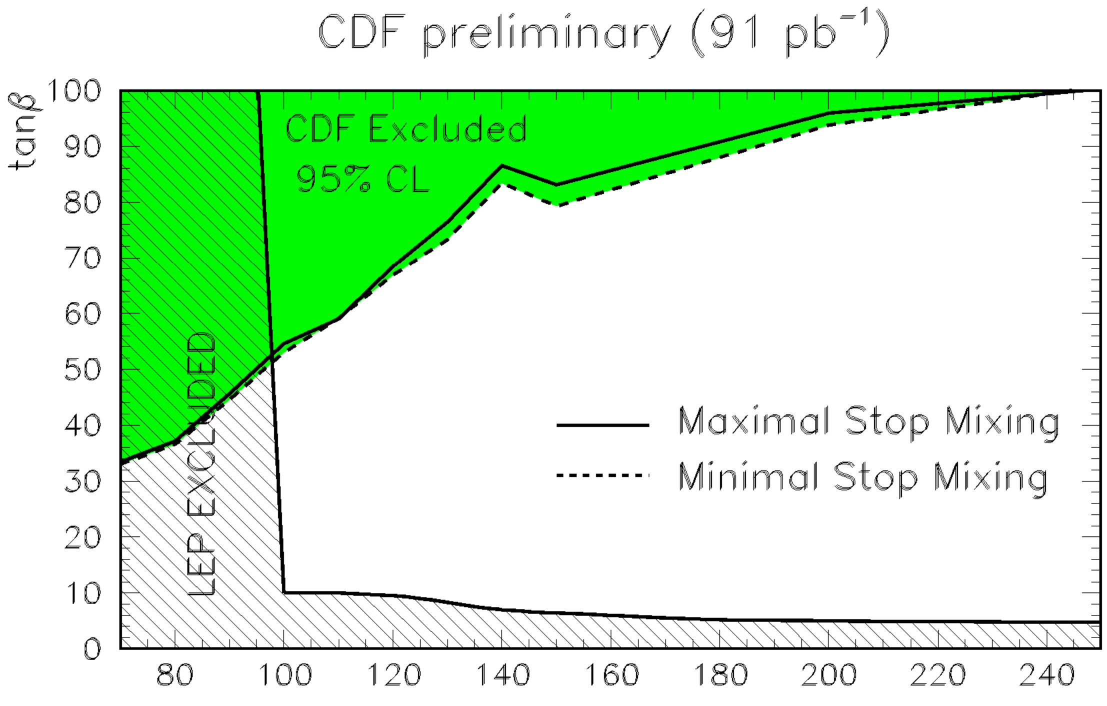
→ require additional b tag to kill QCD background

→ reconstruct mass using jets 1+2 ($m_H < 120$ GeV) or jets 2+3 ($m_H > 120$ GeV)

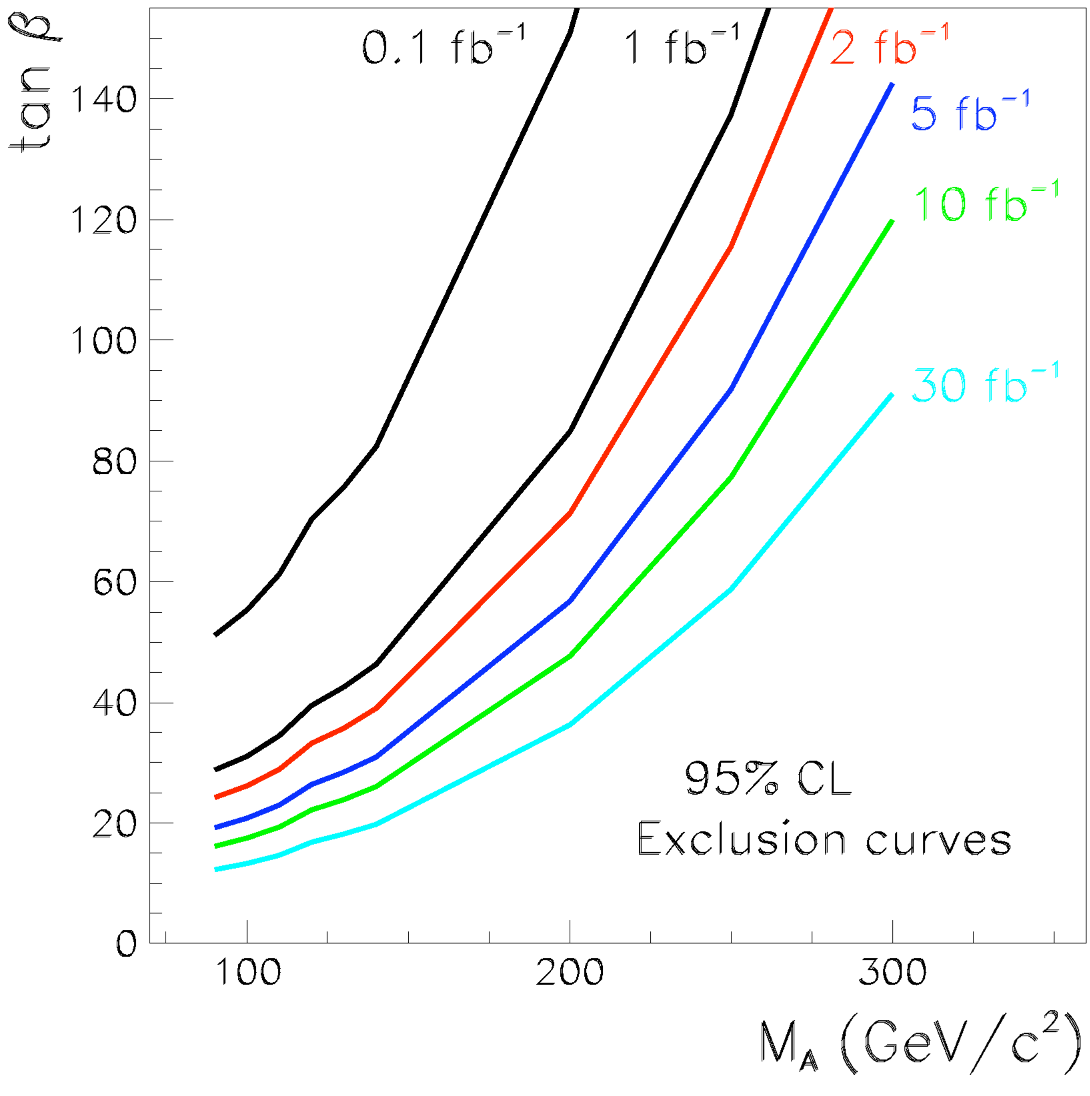


CDF Run 1 limits on MSSM Higgs in $b\bar{b}b\bar{b}$ channel





DØ projected reach in tan β versus m_A plane



(similar to CDF reach)

Summary

- In Run 1 we have established analysis techniques and obtained results for the four most important low-mass SM Higgs channels.
- We have greatly extended the depth and breadth of previous studies of Higgs reach at Run 2 and beyond.
- There is no single, golden discovery channel: combining all channels, and both experiments, is crucial!
- If there is no SM Higgs, we can exclude it at 95% CL up to 120 GeV mass in Run 2, and with 10 fb^{-1} can extend up to nearly 190 GeV mass.
- If there is a Higgs, we can discover it at the 3-5σ level with 10-30 fb^{-1} per experiment, up to 190 GeV mass.
- SUSY Higgs production enhanced at large tan β; CDF excludes large new region in Run 1, and will extend to lower tan β in Run 2 and beyond

We have a lot of work to do to!

- improve the $b\bar{b}$ mass resolution
- optimize the b tagging efficiency
- develop techniques for measuring backgrounds from data

We need to push the Tevatron to the highest possible integrated luminosity!

Commissioning run (CDF) starts in August

Collider physics run (CDF and DØ) begins March 2001