Higgs Searches at Tevatron/CDF

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Introduction
SM Higgs at Tevatron/CDF
MSSM Higgs at Tevatron/CDF
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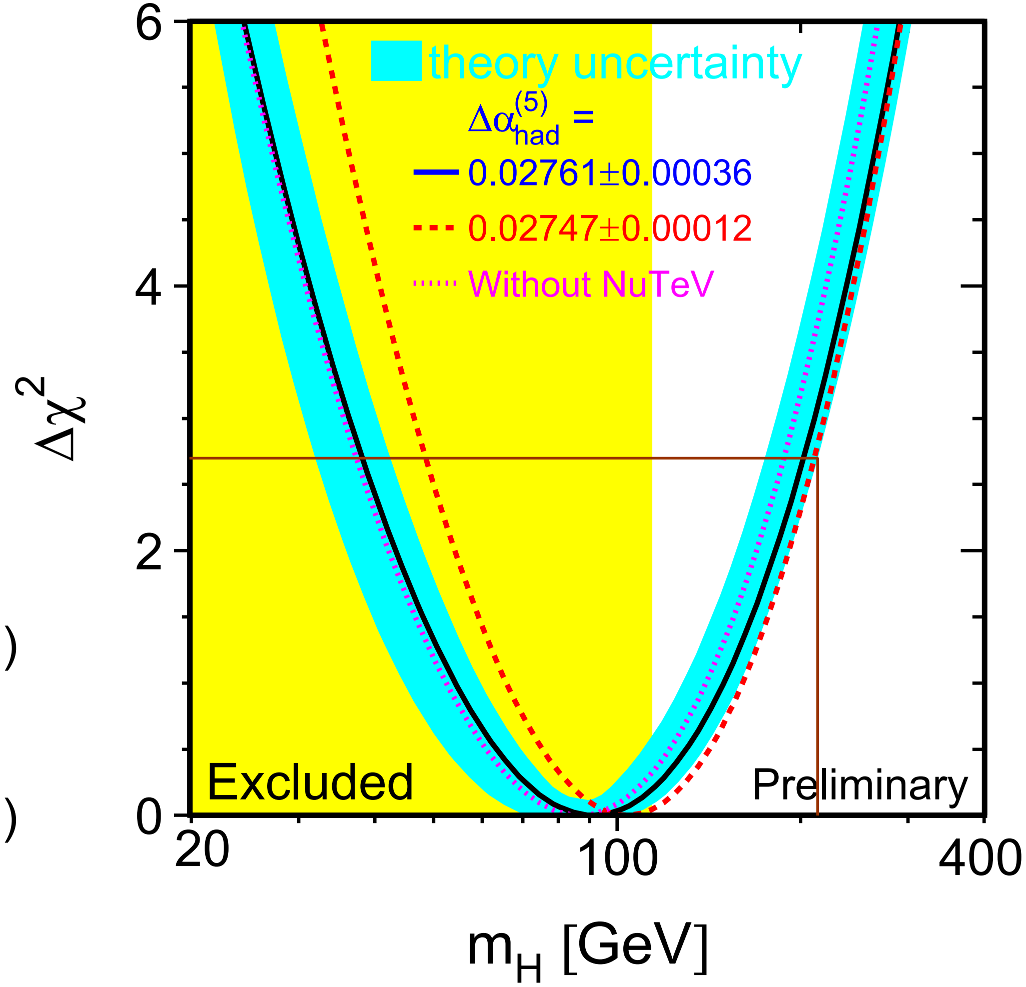
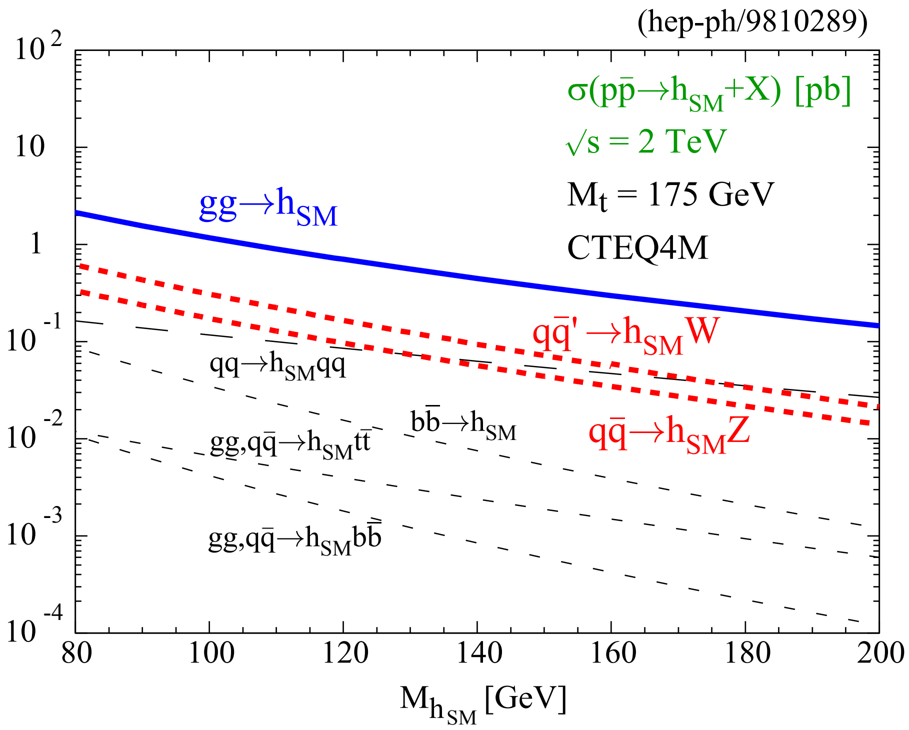
Summary

The Standard Model and the Higgs Boson

- Extreme success of SM
  - consistent with all the data
- Higgs boson
  - last missing brick in the SM
  - indispensable for
    - generating masses of particles
    - keeping the theory renormalizable at EW scale
- Direct searches for the SM Higgs
  $M_h > 114.4$ GeV/c² (95% C.L.)
  (LEP HiggsWG, Jul. 2002)
- EW global fit
  $M_h < 211$ GeV/c² (95% C.L.)
  (LEP EWWG, Mar. 2003)
  Tevatron contributed to M_t and M_W

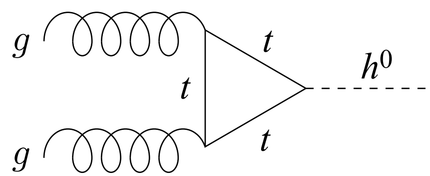


SM Higgs Production at Tevatron



- $p\bar{p}$ collision, $\sqrt{s}$ = 2TeV
- Gluon fusion

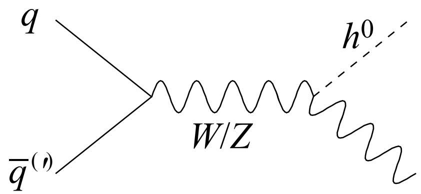
  $gg \to h$: 0.7 pb (M_h = 120 GeV/c^2)



- Vector-boson associated production

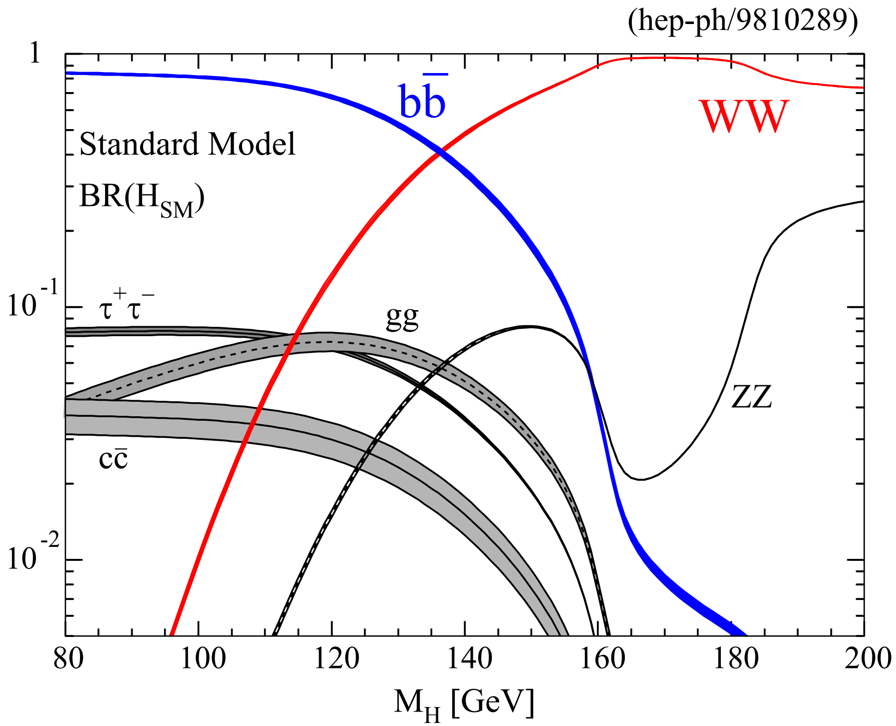
  $q\bar{q}' \to Wh$: 0.16 pb (M_h = 120 GeV/c^2)

  $q\bar{q} \to Zh$: 0.10 pb (M_h = 120 GeV/c^2)



- Huge QCD background
  - need triggering on high-p_T leptons from W/Z's or h's

SM Higgs Decay Branching Fraction



- Low mass Higgs ($\lesssim$ 130GeV/c^2)
  - $b\bar{b}$ is dominant $\Rightarrow$ reconstruction of 2b jets
  - $gg \to h \to b\bar{b}$ swamps in QCD background
  - Vh production is promising

$$q\bar{q}' \to Wh \to \ell\nu b\bar{b}$$
$$q\bar{q} \to Zh \to \ell^+\ell^- b\bar{b},\ \nu\bar{\nu}b\bar{b}$$

- High mass Higgs (130GeV/c^2 ~ 190GeV/c^2)
  - WW is dominant $\Rightarrow$ multi-lepton signature

$$gg \to h \to W^*W^* \to \ell^+\ell^-\nu\bar{\nu}$$
$$q\bar{q}' \to Wh \to \ell^\pm\nu W^*W^* \to \ell^\pm\nu\ell^\pm\nu jj$$
$$q\bar{q} \to Zh \to \ell^\pm\ell^\mp W^*W^* \to \ell^\pm\ell^\mp\ell^\pm\nu jj$$

Overview of Run I Searches for SM Higgs

- SM Higgs was searched for in $p\bar{p} \to Vh$ followed by $h \to b\bar{b}$

$Wh \to \ell\nu b\bar{b}$

Expect :

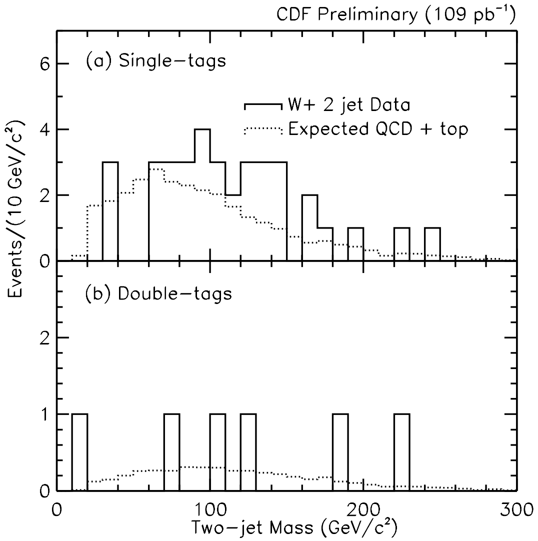
34 ± 5 (single tag)

3.8 ± 0.7 (double tag)

Observe :

36 (single tag)

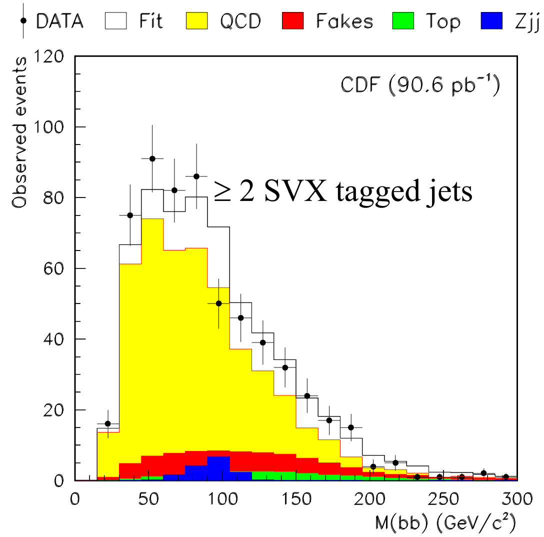
6 (double tag)



$Vh \to q\bar{q}^{(\prime)}b\bar{b}$

Expect : 594 ± 30

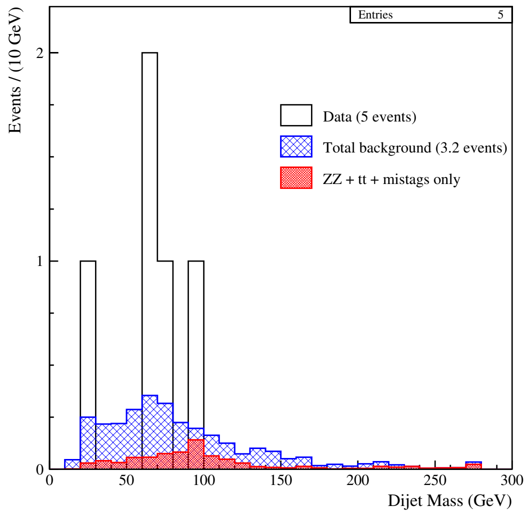
Observe : 589



$Zh \to \ell^+\ell^- b\bar{b}$

Expect : 4.0 ± 1.0

Observe : 5



$Zh \to \nu\bar{\nu}b\bar{b}$

Expect :

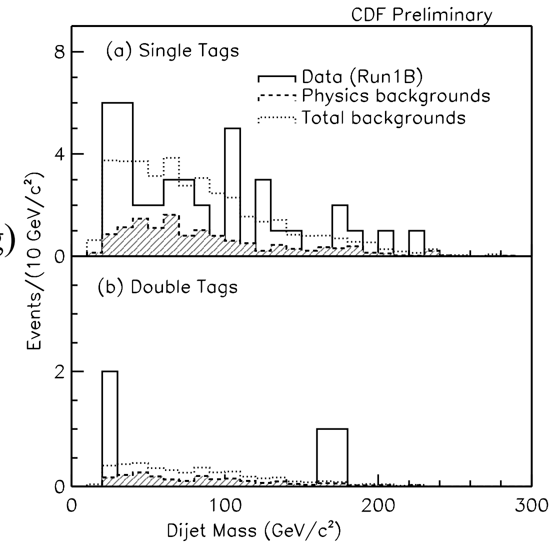
43 ± 5 (single tag)

4.9 ± 0.6 (double tag)

Observe :

40 (single tag)

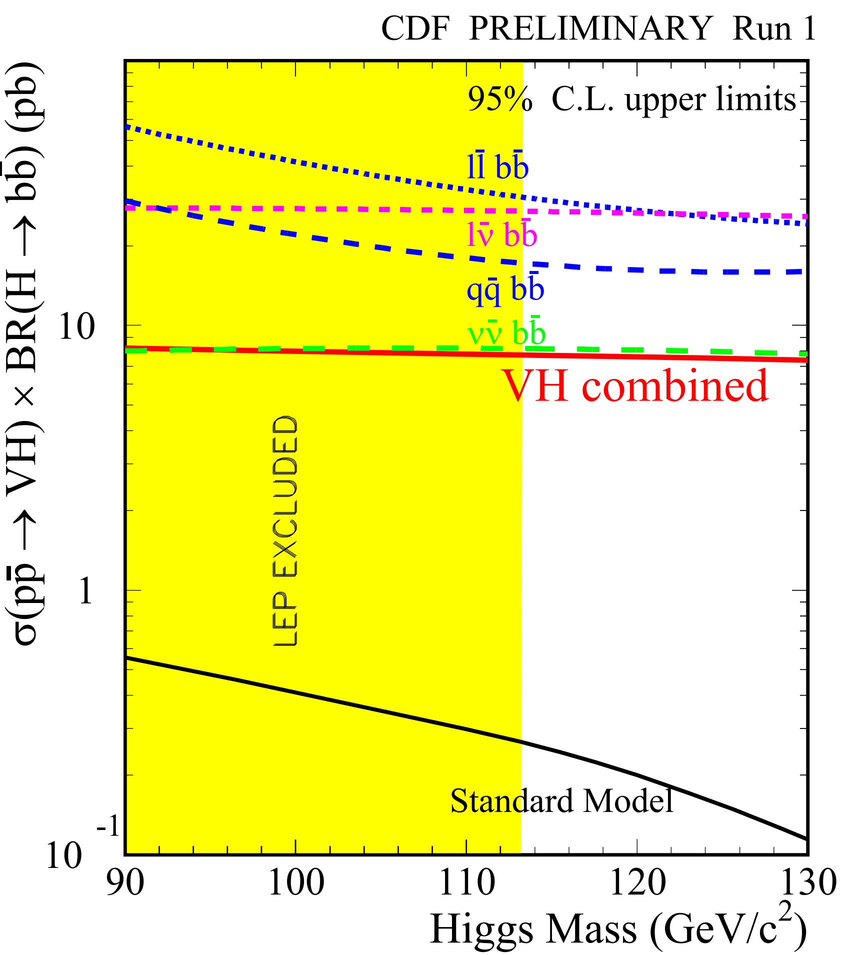
4 (double tag)



Overview of Run I searches for SM Higgs (2)

- No significant excess was observed

channel	$\int Ldt$ (pb^{-1})	b-tag	Observed	Background
$\ell^+\ell^- b\bar{b}$	106 ± 4	single	5	4.0 ± 1.0
$\nu\bar{\nu} b\bar{b}$	87 ± 4	single	40	43 ± 5
		double	4	4.9 ± 0.6
$\ell\nu b\bar{b}$	106 ± 4	single	36	34 ± 5
		double	6	3.8 ± 0.7
$q\bar{q}^{(\prime)} b\bar{b}$	87 ± 4	double	589	594 ± 30



- Combined results of all Vh ($h \to b\bar{b}$) channels

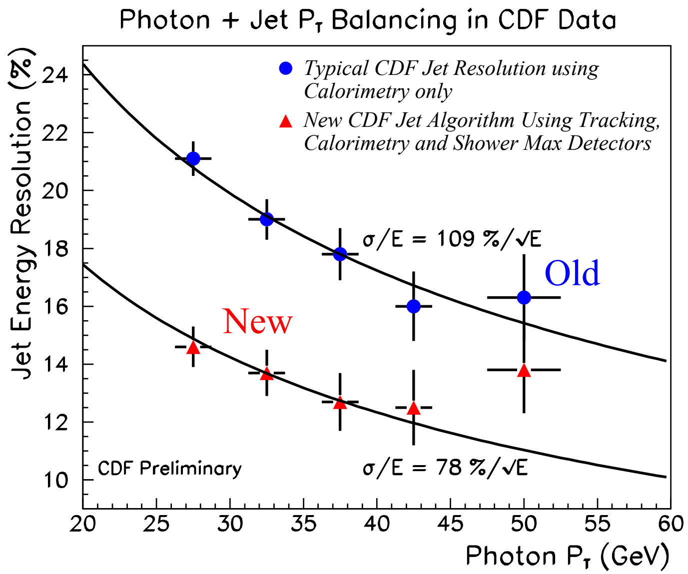
	SM pred	M_h
$\sigma_{Vh} \cdot B(h \to b\bar{b}) < 7.8$ pb	(0.30 pb)	110GeV/c^2
< 7.4 pb	(0.12 pb)	130GeV/c^2

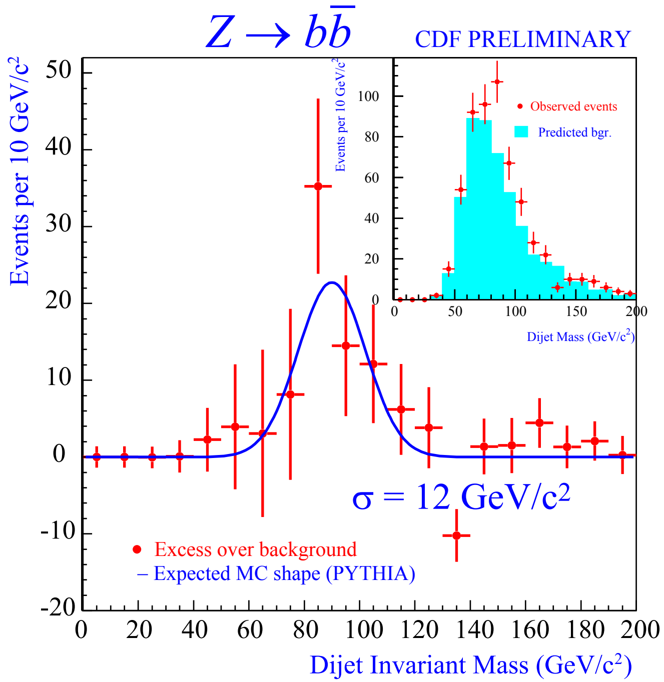
(95% C.L.)

Much more statistics in Run II : 2 fb^{-1} (Run IIa), ~10 fb^{-1} (Run IIb)

- Run II Studies - Jet Energy Resolution

- Crucial for M_{jj} reconstruction (M_{bb}, M_W)
- New algorithms to improve resolution in jet energy by using tracks and shower max detector information
- Jet energy resolution improves by ~30%
- σ_M/M_{bb} improves by ~40%





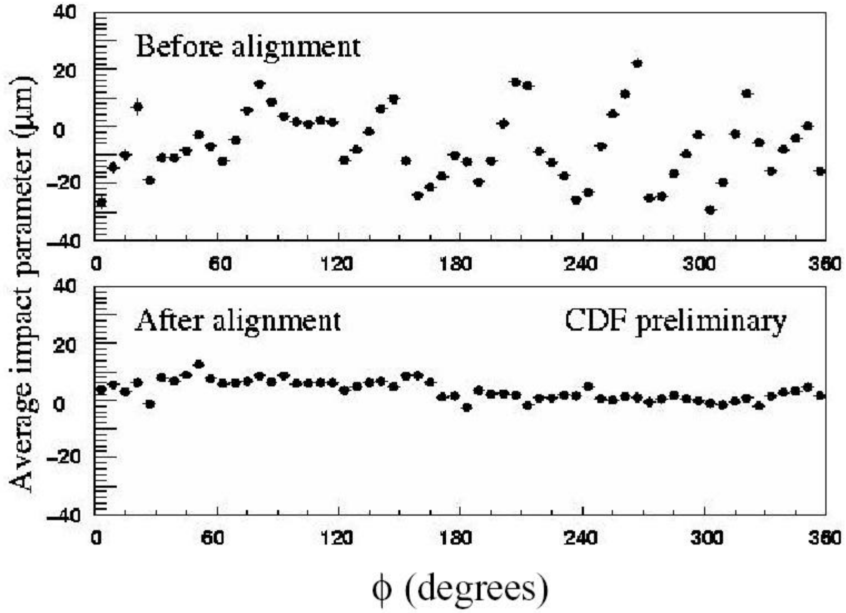
- Run II Studies - *b*-jet Identification

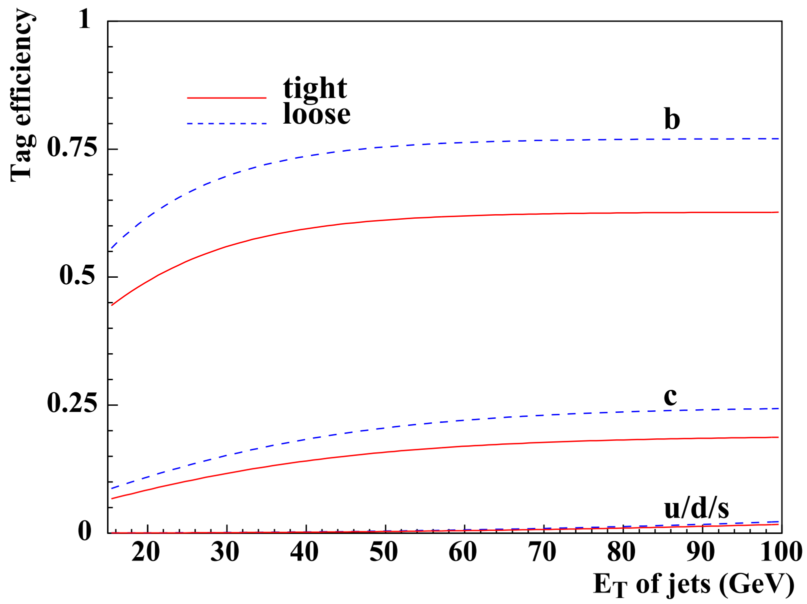
- Identification of b-jets (b-tagging) is indispensable for the Higgs search
  - b collection for $h \to b\bar{b}$
  - $t\bar{t}$ suppression for $h \to WW$

- Algorithms in CDF
  - Secondary vertex tagging
    ε(Run I) ~50%
  - Soft lepton tagging
    ε(Run I) ~20%
  - Jet probability tagging
    ε(Run I) ~45%

- New silicon detectors
  - b-tagging region $|\eta| < 2$
  - 3D tracking reduces mistags
  - need good alignment

- Expected Run II ε ~ 60 - 65%

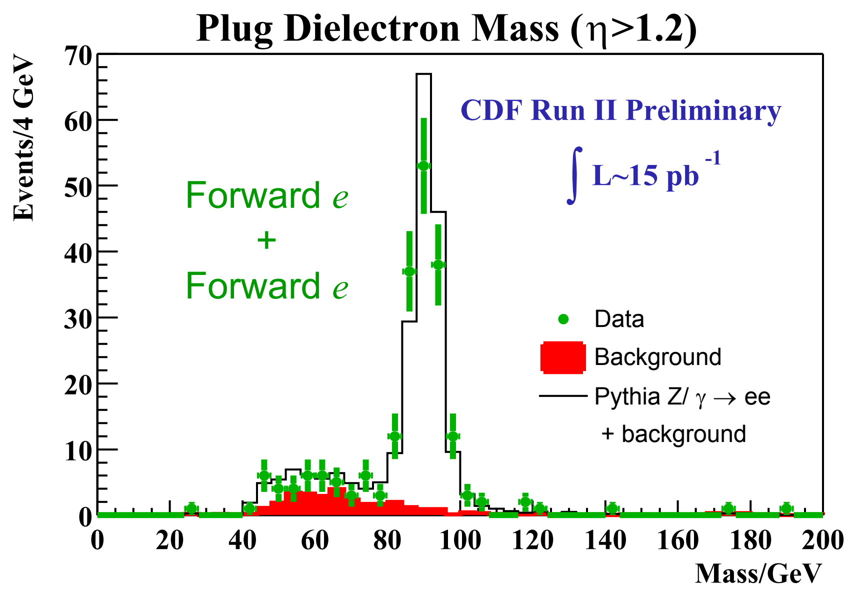


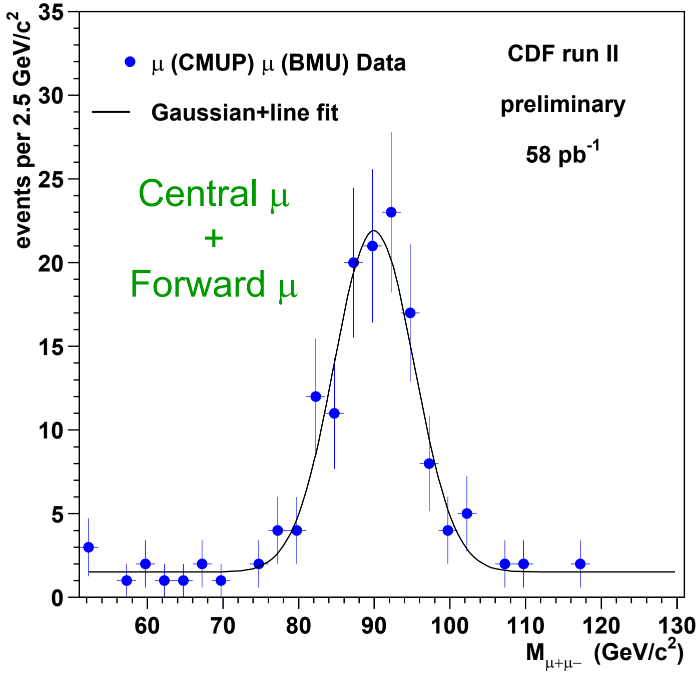


- Run II Studies -
Lepton Acceptance

- Leptons in Run I
  electrons : $|\eta| < 1.35$, muons : $|\eta| < 1.0$

- Leptons in Run II
  - New { silicon detectors, plug calorimeters, forward muon detectors
    electrons : $|\eta| < 2.0$, muons : $|\eta| < 1.5$
  - Increased coverage by 40~50%
  - Quality of forward electrons and muons is being improved





Run II Searches for SM Higgs

- Same search modes as Run I in the low-mass region
- Run II sensitivity reaches the high-mass region

- M_h < 130 GeV/c^2

  $Wh \to \ell\nu b\bar{b}$
  BKG : WZ, $Wb\bar{b}$, $t\bar{t}$, single t, QCD

  $Zh \to \nu\bar{\nu}b\bar{b}$
  Most sensitive in Run I
  BKG : ZZ, WZ, $Zb\bar{b}$, $Wb\bar{b}$, single t, QCD

  $Zh \to \ell^+\ell^- b\bar{b}$
  BKG : ZZ, $Zb\bar{b}$, $t\bar{t}$, single t

  $Vh \to q\bar{q}^{(\prime)}b\bar{b}$
  Largest branching ratio
  Huge QCD BKG

- M_h > 130 GeV/c^2

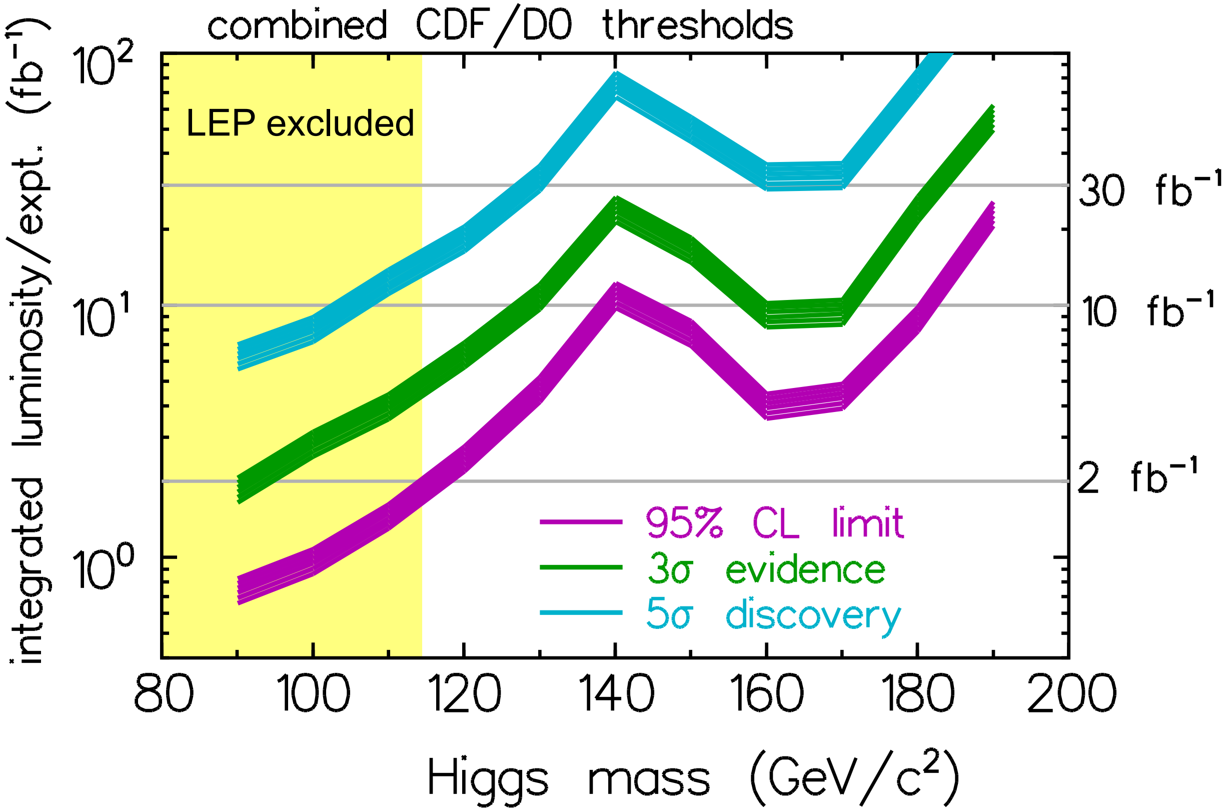
  $gg \to h \to W^*W^* \to \ell^+\ell^-\nu\bar{\nu}$
  BKG : WW, WZ, ZZ, $t\bar{t}$, $\tau^+\tau^-$

  $Wh \to WW^*W^* \to \ell^\pm\nu\ell^\pm\nu jj$
  $Zh \to ZW^*W^* \to \ell^\pm\ell^\mp\ell^\pm\nu jj$
  Like-sign dilepton
  BKG : WZ, ZZ, WW, $t\bar{t}$, VVV, $Vt\bar{t}$, W/Z + jets

- Every leading BKG has >10 times larger $\sigma \cdot Br$ than the Higgs signal

  Need careful optimization
  $\Rightarrow$ $S/\sqrt{B} \sim 0.5$ (Run II studies)

Run II Searches for SM Higgs (2)



2 fb^{-1} :

exclude M_h = 115 GeV/c^2, if not there

5 fb^{-1} :

3σ signal for M_h = 115 GeV/c^2

10 fb^{-1} :

3σ signal for M_h = 115 ~ 125, 155 ~ 175 GeV/c^2

- Sensitivity reevaluation in progress using fine-tuned full detector simulation

Run II Searches for SM Higgs (3)

- $\sqrt{s}$ = 1.96TeV

  $\sigma(W)$, $\sigma(Z)$ ~ 10% higher

  $\sigma(t\bar{t})$ ~ 30% higher

- With 2 fb^{-1} (Run 2a)

  ΔM_W ~ 30 MeV/c^2

  $\Delta M_t \lesssim$ 3 GeV/c^2

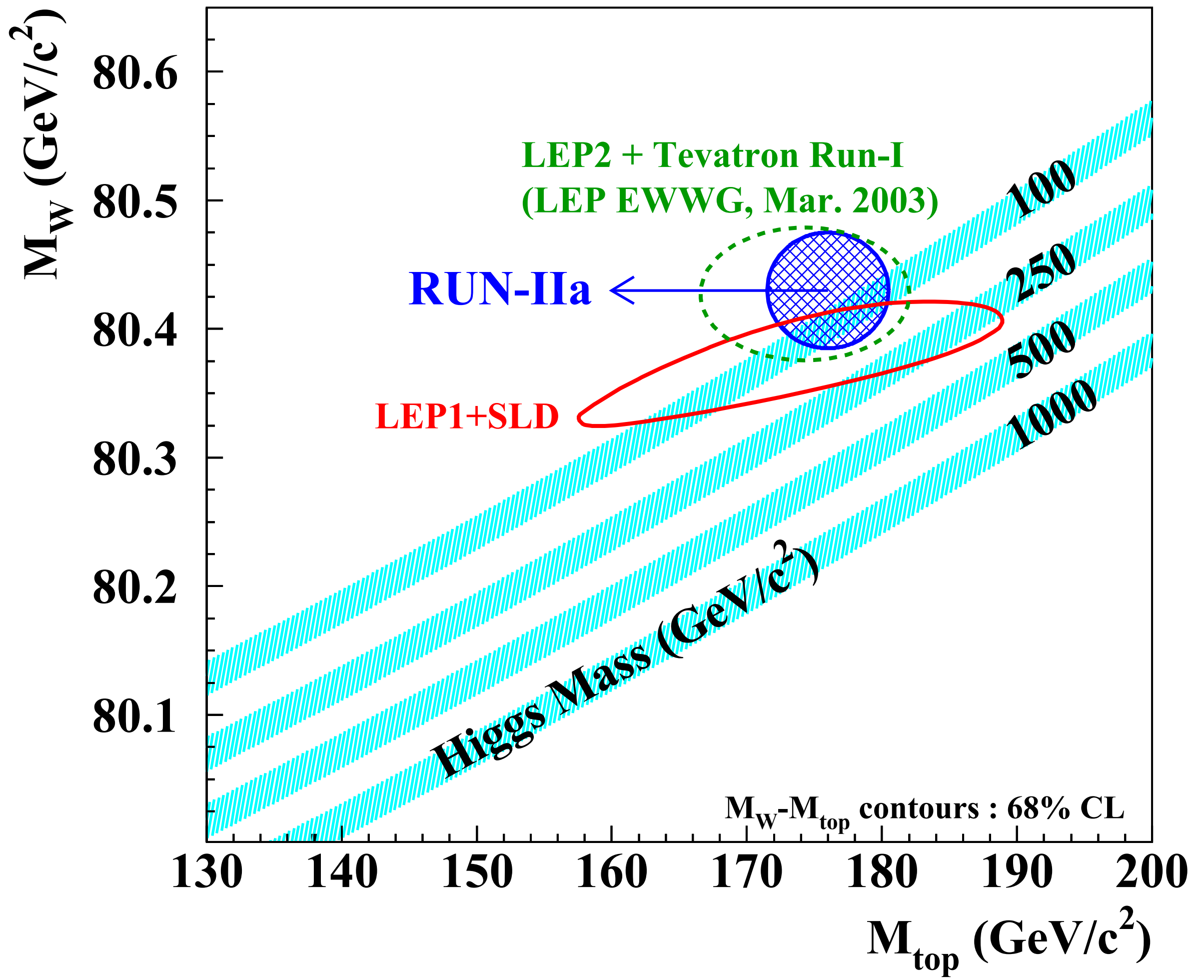
  $\Rightarrow \Delta(\log M_h) \sim \log 2$
  $(1/2\, M_h < M_h < 2\, M_h)$

- With 10 fb^{-1}

  ΔM_W ~ 20 MeV/c^2

  $\Delta M_t \lesssim$ 2 GeV/c^2

  $\Rightarrow \Delta(\log M_h) \sim \log 1.3$



MSSM Higgs Searches

- Two Higgs doublets provide
  - Two neutral CP-even : h, H
  - One neutral CP-odd : A
  - Two charged : H^+, H^-

- Phenomenology as a function of tanβ ($= v_u/v_d$) and M_A

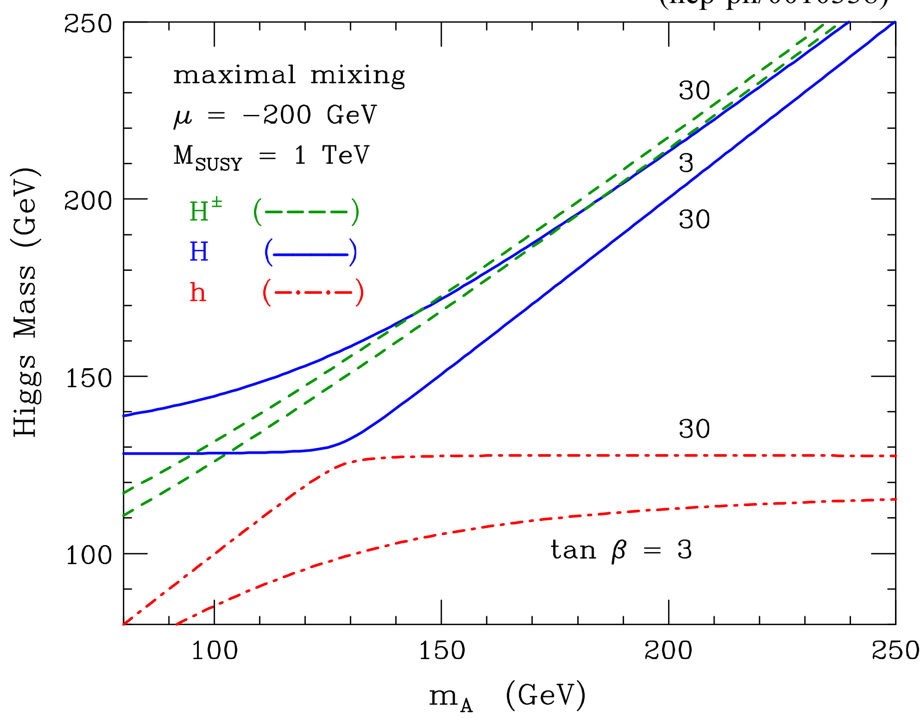
- Tree level mass relations

$$\begin{cases} M_h < M_A \\ M_h < M|\cos 2\beta| < M_Z < M_H \\ \qquad\qquad (M = \min(M_Z, M_A)) \\ M_{H^+} > M_W \end{cases}$$

  Radiative correction gives

  $M_h < 135$ GeV/c²

(hep-ph/0010338)



- Latest LEP limit (95% C.L.)

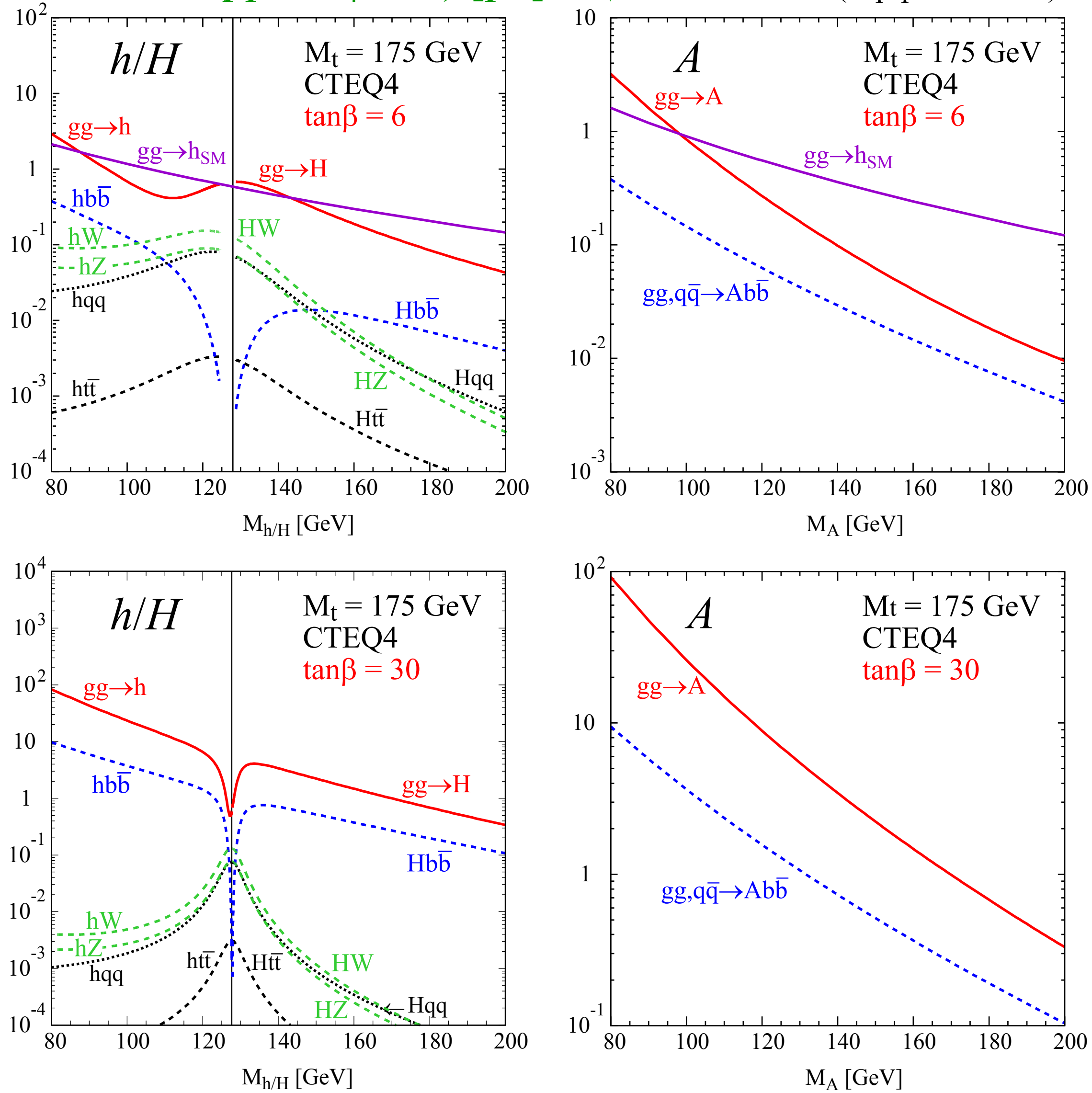
  $M_h > 91.0$ GeV/c², $M_A > 91.9$ GeV/c², $\tan\beta < 0.5$ or $\tan\beta > 2.4$ (hep-ex/0107030)

  $M_{H^+} > 78.6$ GeV/c² (hep-ex/0107031)

MSSM Higgs Production - Neutral Sector -

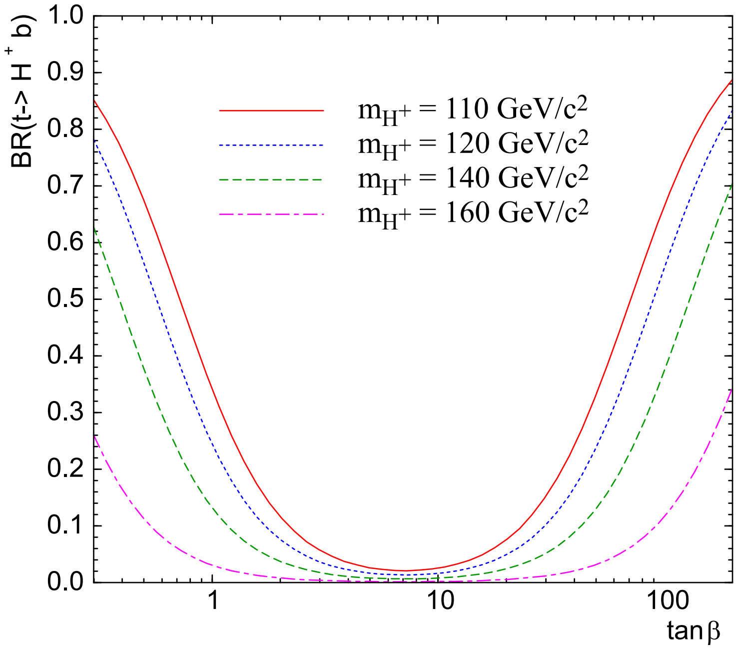
- Small $\tan\beta$:
  - ϕ 's (= $h/H/A$) have σ of the similar magnitude to the SM Higgs for
    $gg \to \phi$
    $q\bar{q}^{(\prime)} \to \phi W, \phi Z$
- Large $\tan\beta$:
  - ϕW and ϕZ are suppressed.
  - Some processes:
    $gg \to \phi$
    $gg, q\bar{q}^{(\prime)} \to \phi b\bar{b}$
    enhance σ by $\sim (1/\cos\beta)^2 \sim (\tan\beta)^2$

$\sigma(p\bar{p} \to \phi + X)$ [pb], $\sqrt{s} = 2\text{TeV}$ (hep-ph/0010338)



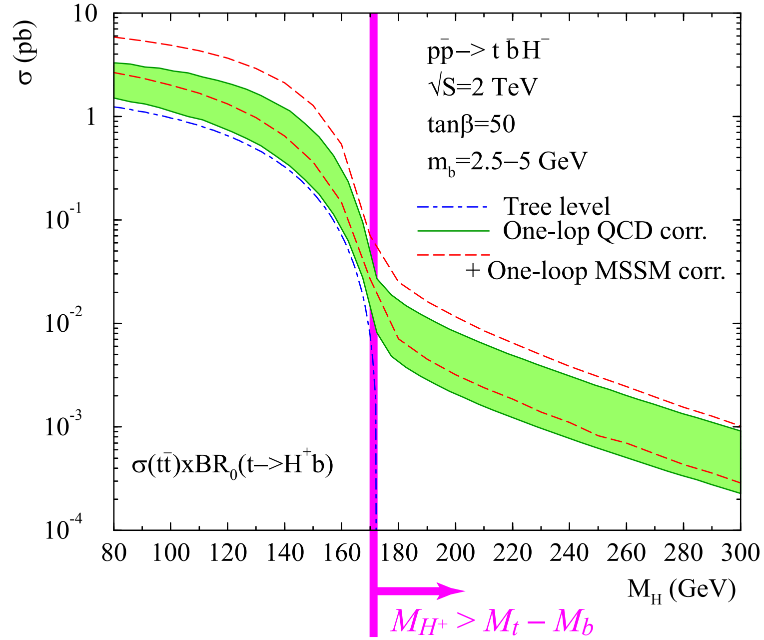
MSSM Higgs Production - Charged Sector -

- $M_{H^+} < M_t - M_b$
  - $t \to H^+ b$ dominates
  - compete with $t \to Wb$
  - large branching fraction at large $\tan\beta$ and very small $\tan\beta$



- $M_{H^+} > M_t - M_b$
  - radiation off a 3rd generation quark $p\bar{p} \to \bar{t}bH^+$
  - small cross section

(hep-ph/0010338)

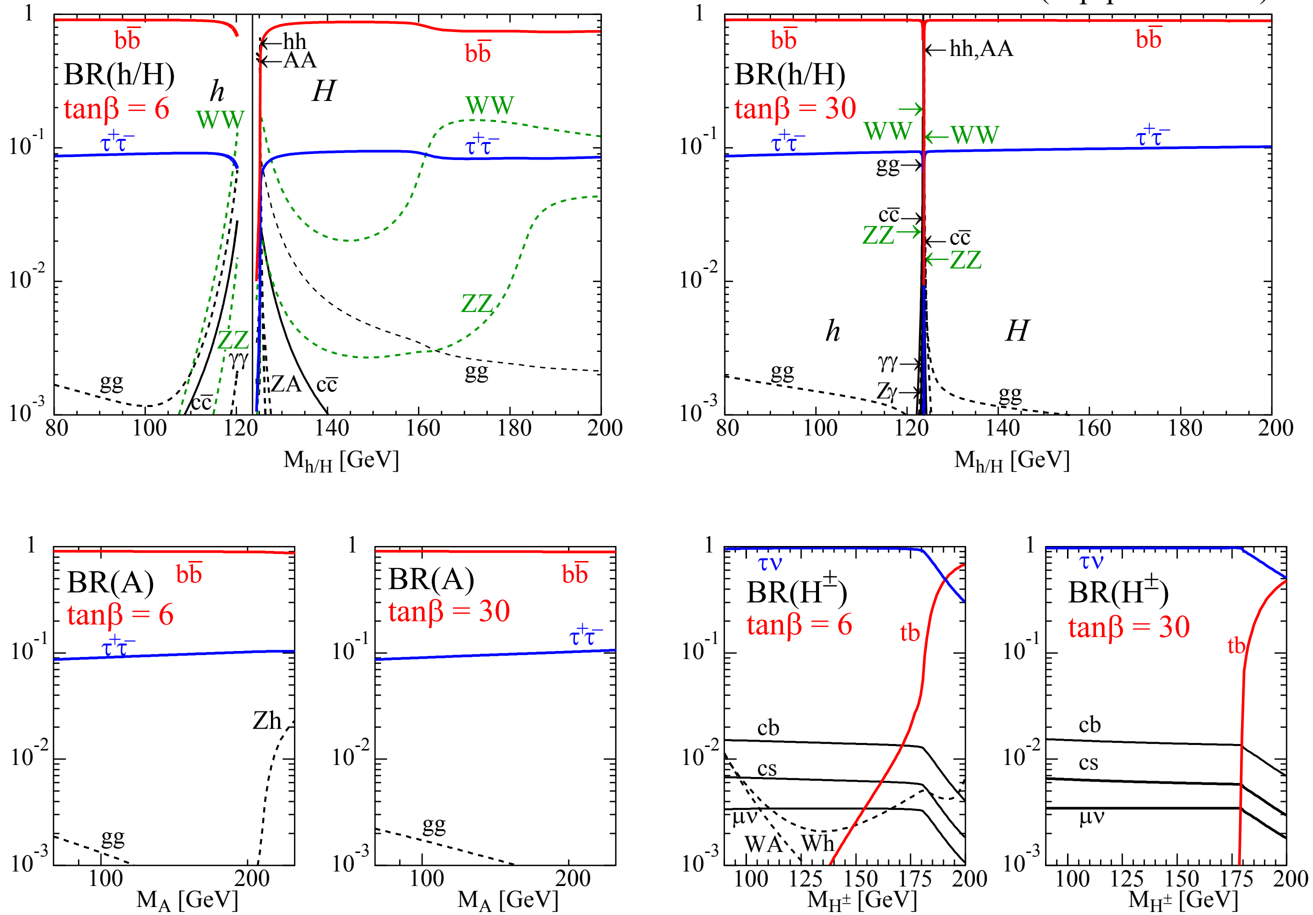


MSSM Higgs Decays

- Neutral sector ($h/H/A$)
  - $b\bar{b}$ and $\tau\tau$ are dominant in a wide mass range
    $\phi \rightarrow b\bar{b}$: 90%
    $\phi \rightarrow \tau\tau$: 10 %
- Charged sector ($H^{\pm}$)
  - $\tau\nu$ dominates for $M_{H^{\pm}}$ < 200 GeV/c^2
  - tb for $M_{H^{\pm}}$ > 200 GeV/c^2
- Run II search
  - $gg \rightarrow \phi \rightarrow \tau\tau$
  - $gg, q\bar{q} \rightarrow \phi b\bar{b} \rightarrow b\bar{b}b\bar{b}$
  - $t \rightarrow H^{+}b \rightarrow \tau\nu b$

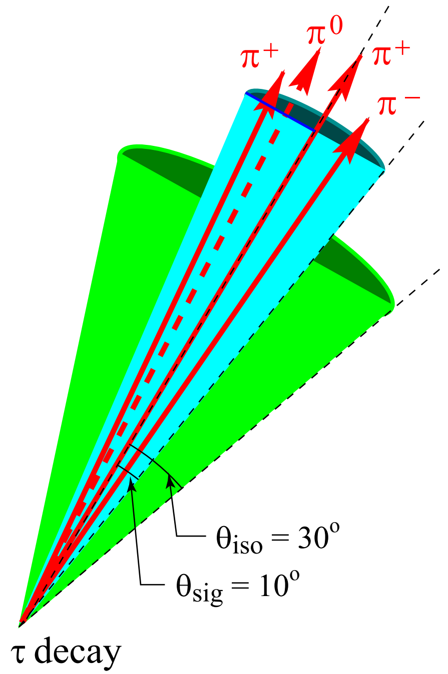
τ detection is important as well as b-tagging

(hep-ph/0010338)



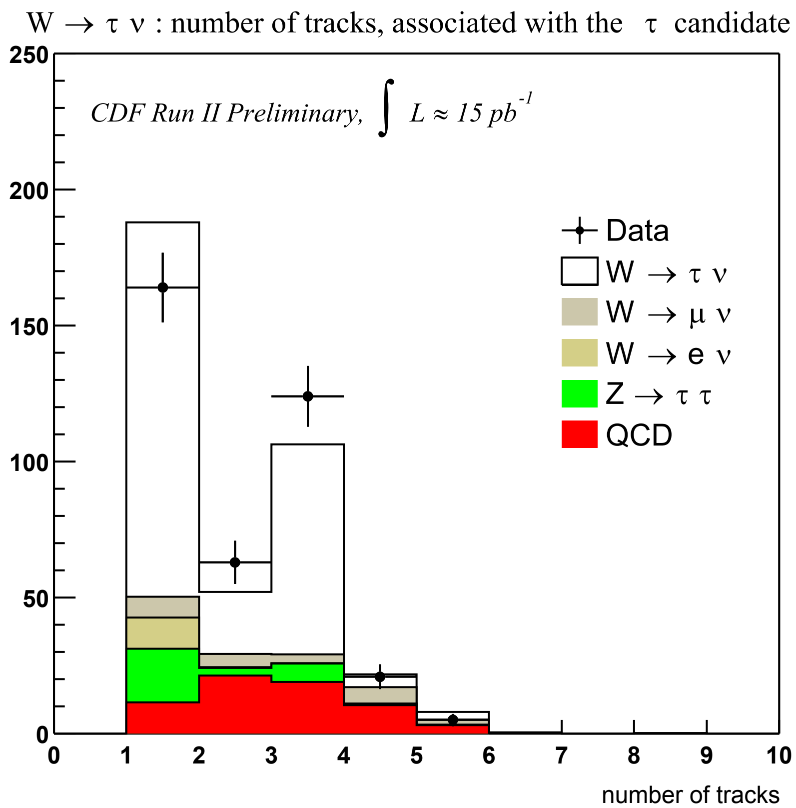
τ detection at CDF

- τ decay : collimated decay products



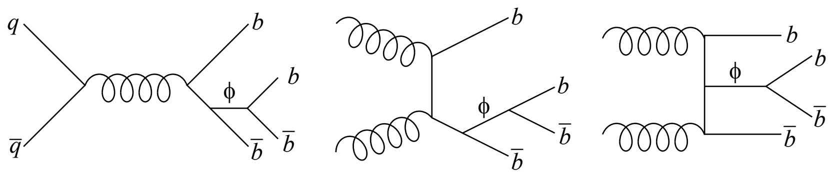
- τ triggers in CDF Run II
  - τ + missing E_T
  - lepton + track
  - di-τ

$W \to \tau\nu$ candidates in Run II

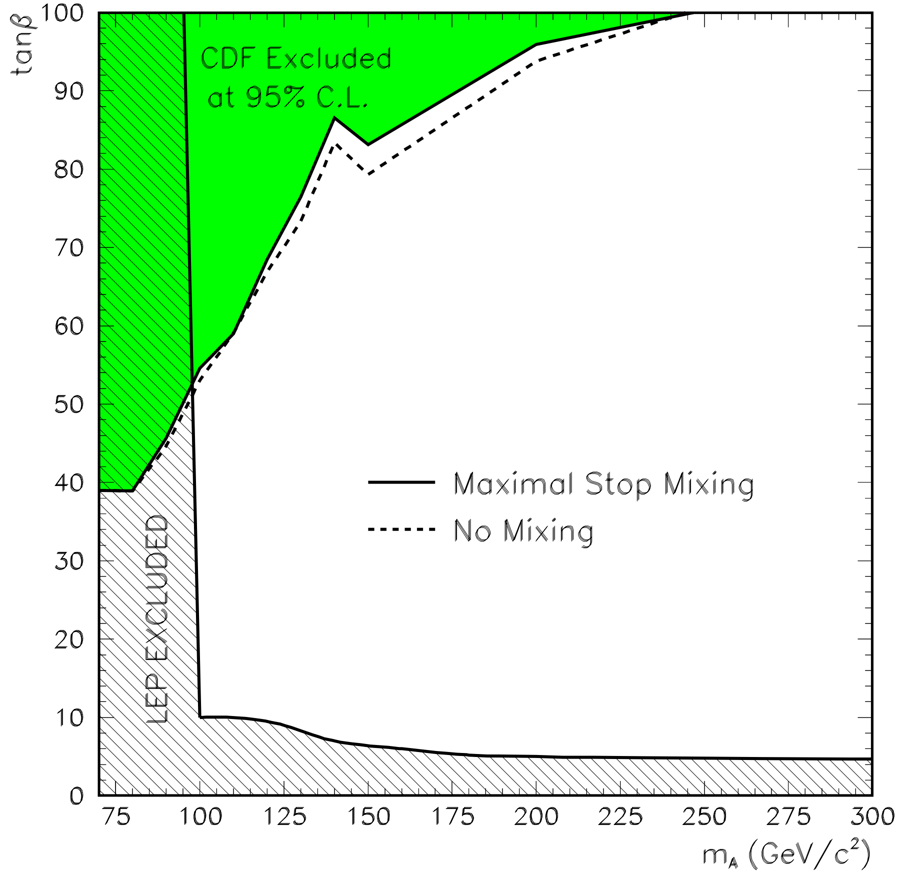


Run I Results - Neutral MSSM Higgs -

- $gg, q\bar{q} \rightarrow \phi b\bar{b} \rightarrow b\bar{b}b\bar{b}$



- 4 high-E_T jets required (E_T > 15 GeV)
- >=3 b-tagged jets required
- Backgrounds : QCD, $t\bar{t}$, W/Z + jets
- No excess was observed
  (Observed : 5, Expected : 4.6 ± 1.4
  for M_ϕ = 70 GeV/c^2)



Phys. Rev. Lett. 86 (2001) 4472.

Run I Results - Charged MSSM Higgs -

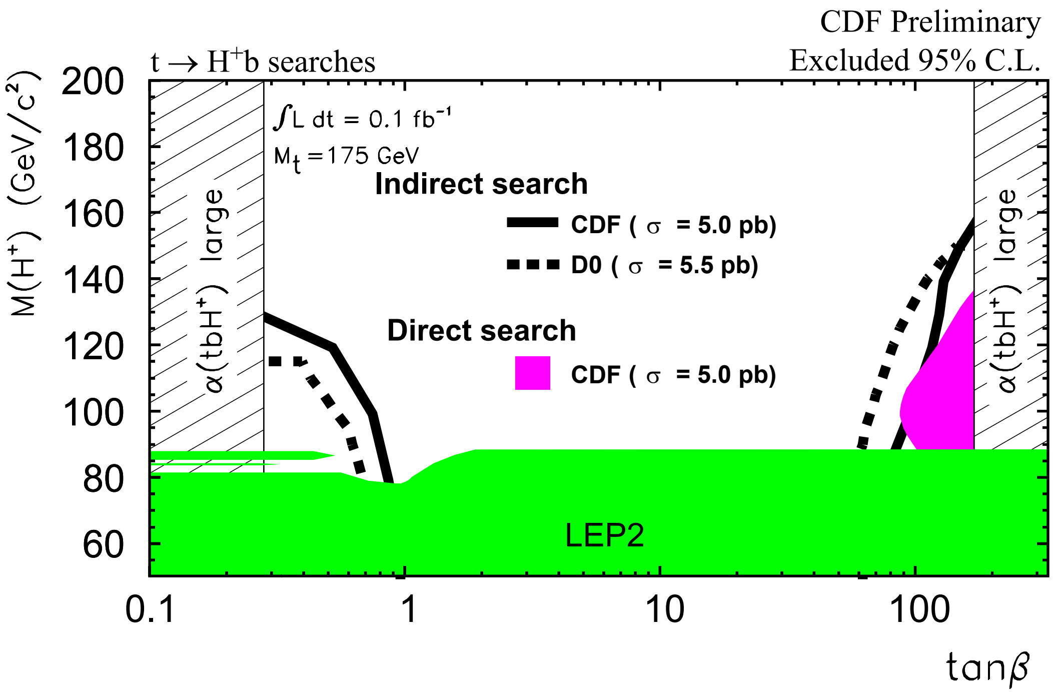
- $t \to H^+ b$

- Direct search

  $$p\bar{p} \to t\bar{t} \to H^+ b W^- \bar{b} \to (\tau\nu) b (\ell\nu/jj) \bar{b}$$
  $$\to H^+ b H^- \bar{b} \to (\tau\nu) b (\tau\nu) \bar{b}$$

  signature : $\tau_h \, bjX + \not{E}_T$
  $\tau_h \tau_h + \not{E}_T$

  No excess was observed



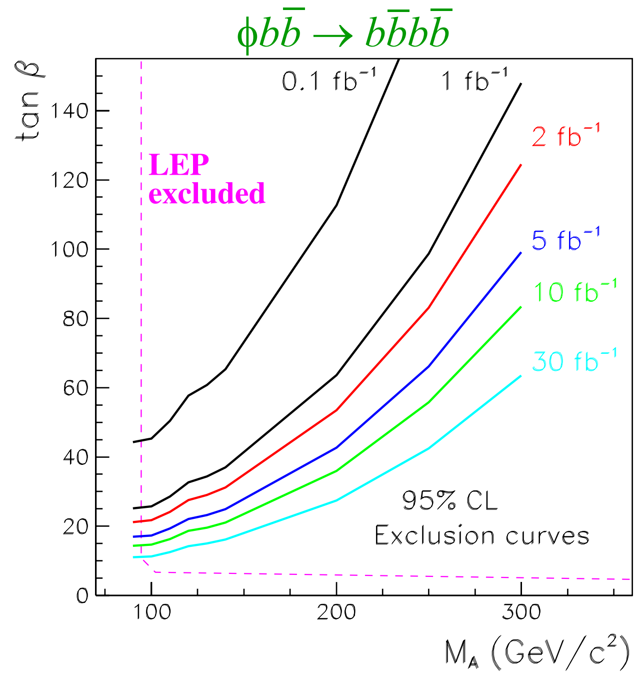
- Indirect search

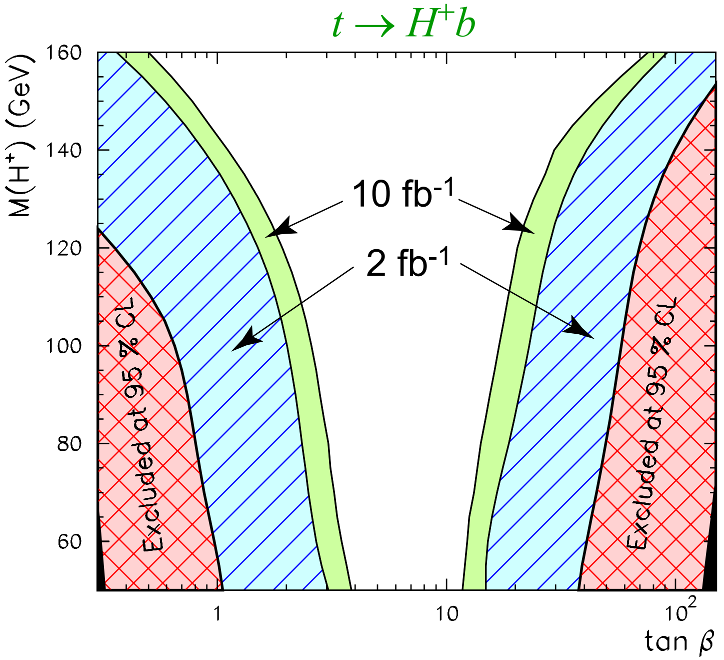
  $H^+ \to c\bar{s}$ $(\tan\beta < 1)$
  $H^+ \to \tau\nu$ $(\tan\beta > 50)$

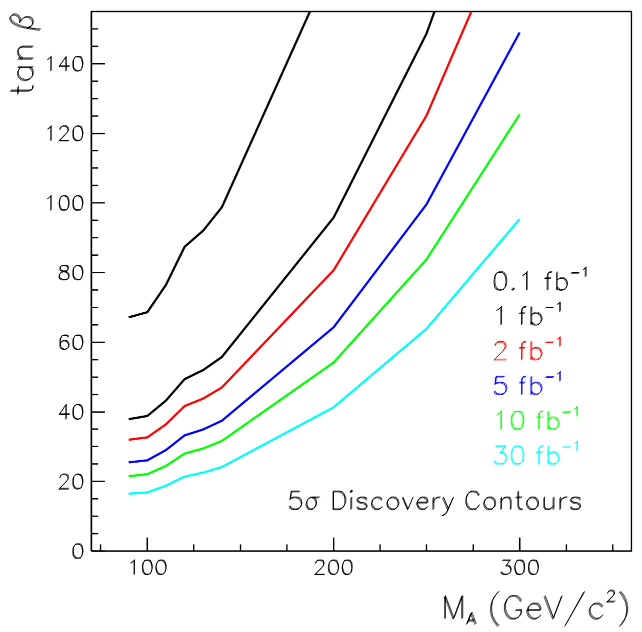
  Looked for deviation of *Br*(t) from the SM decay
  Br(t) was consistent with *Br*($t \to Wb$) = 1.0

MSSM Higgs Projections for Run II

- Studied the same search modes as Run I
  - neutral : $\phi b\bar{b} \to b\bar{b}b\bar{b}$
    10 fb^{-1} M_A < 175 GeV/c^2 (95% C.L.) [$\tan\beta = 30$]
    < 130 GeV/c^2 (5σ discovery) [$\tan\beta = 30$]
  - charged : $t \to H^+b \to (\tau\nu/c\bar{s}/Wb\bar{b})b$
    direct and indirect
    10 fb^{-1} M_{H^+} < 140 GeV/c^2 (95% C.L.) [$\tan\beta = 30$]

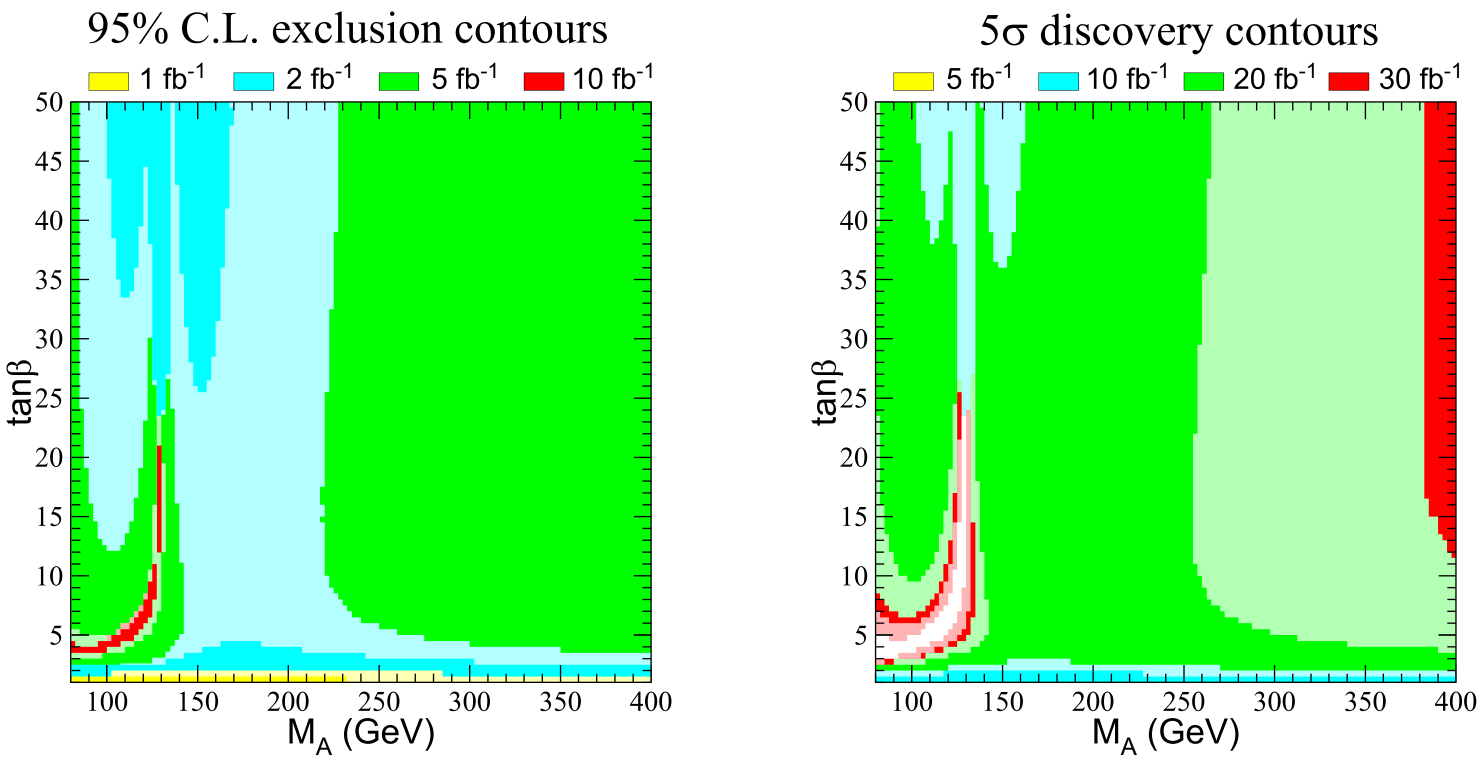






MSSM Higgs Projection for Run II (2)

- Applying the SM Higgs results to the MSSM
  $p\overline{p} \to V\phi \to Vb\overline{b}\ (V = W, Z)$
  Constraints on the MSSM parameter space



Maximal $\tilde{t}$-mixing case

Summary

- Tevatron Run I
  - We learned a lot to search for the Higgs at a hadron collider.
    Measures of analysis, backgrounds, . . .
    $\Rightarrow$ Constraints on the SM and MSSM Higgs bosons

- Tevatron Run II
  - Higgs search potential has significantly increased by both the accelerator upgrade and the detector upgrade.
  - We are accumulating $p\bar{p}$ collision data.
    Calibrations are ongoing, data quality is improving, analysis tools are being brushed up, . . .
  - We can explore the large space of the Higgs (SM and MSSM) with $2fb^{-1}$ in Run IIa and $\sim 10fb^{-1}$ in Run IIb.