Higgs Physics at Hadron Colliders: The Tevatron

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Higgs Physics at Hadron Colliders: The Tevatron

- Introduction: What do we know today?

▬ Precision data from LEP, SLC, Tevatron
$\Longrightarrow$ Standard Model (SM) provides an excellent fit to all observables
▬ There is one missing ingredient in the SM

The Higgs boson

$\Longrightarrow$ responsable for giving mass to all other particles
The mass of the SM Higgs is an unknown parameter

- How these issues may be connected?

▬ Precision data: M_t, M_W, $\sin^2\theta_W \to m_H$ (indirect)
▬ Direct m_H searches (LEP)

Standard Model Vs New Physics (NP)

What can we learn from RUN 2?

- Precision measurements:

  Top Physics (explore hints for NP)

  W Mass

$\rightarrow M_t$–M_W–M_H Correlation

  $A_{\rm FB} \leftrightarrow \sin^2\theta_W$

- B Physics

- Direct Standard Model Higgs Searches

Explore masses beyond LEP bound and probe the tantalizing hint from LEP?

- New Physics Searches *(see T. Kamon's talk)*

Explore some channels with excess over SM predictions at RUN 1 and search for:

  Supersymmetry $\longrightarrow$ MSSM Higgs Bosons

  New Exotic Quarks

  Strong Dynamics

- Explore new ideas : Extra Dimensions

Precision Measurements: Top Quark Mass, W Mass and $\sin^2\theta_W$

Run 1 measurements: CDF and DØ

$$M_t = 174.3 \pm 5.1 \text{ GeV}$$

$$M_W = 80.452 \pm 0.062 \text{ GeV}$$

$A_{\rm FB}$ measured at Z pole $\Longrightarrow$ meas. of $\sin^2\theta_W$.

$$u\bar{u} + d\bar{d} \to Z \to \ell^+\ell^-.$$

CDF Run 1: $\quad A_{\rm FB} = 0.070 \pm 0.015_{\rm stat} \pm 0.004_{\rm syst}$

Run 2 Expectations [per experiment]:

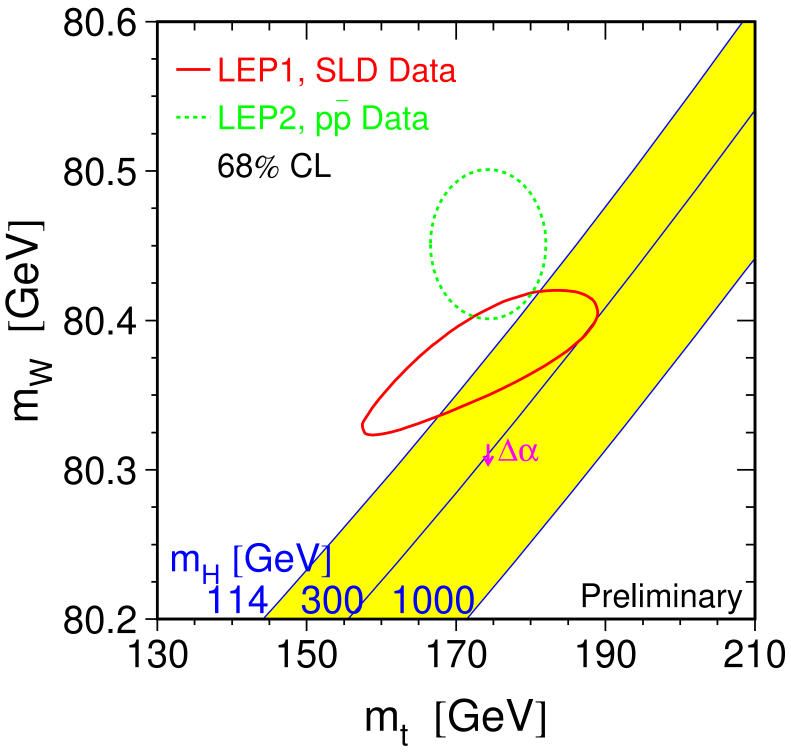
$\int \mathcal{L}$ [fb^{-1}]	2	10	15	30
δM_t [GeV]	≈ 3	≈ 2		≈ 1
δM_W [MeV]	30		20	15
$\delta A_{\rm FB}$ (stat.)		0.0016		0.0009
$\delta \sin^2\theta_W^*$		0.00028		0.00016

The current *world average* has $\delta\sin^2\theta_W^* = 0.00017$.
This would help to understand the discrepancy in $\sin^2\theta_W^*$ from A_ℓ(SLD) and A_{FB}^b.

M_t–M_W–M_H Correlation

- Direct M_t and M_W meas. from LEP and Tevatron
- Indirect M_t and M_W determination from SM fit to precision data (LEP, SLD, νN)
- SM relationship for M_t–M_W–M_H

$\Longrightarrow$ crucial information on M_H



Light SM Higgs Boson $\longrightarrow$ strongly favoured by data

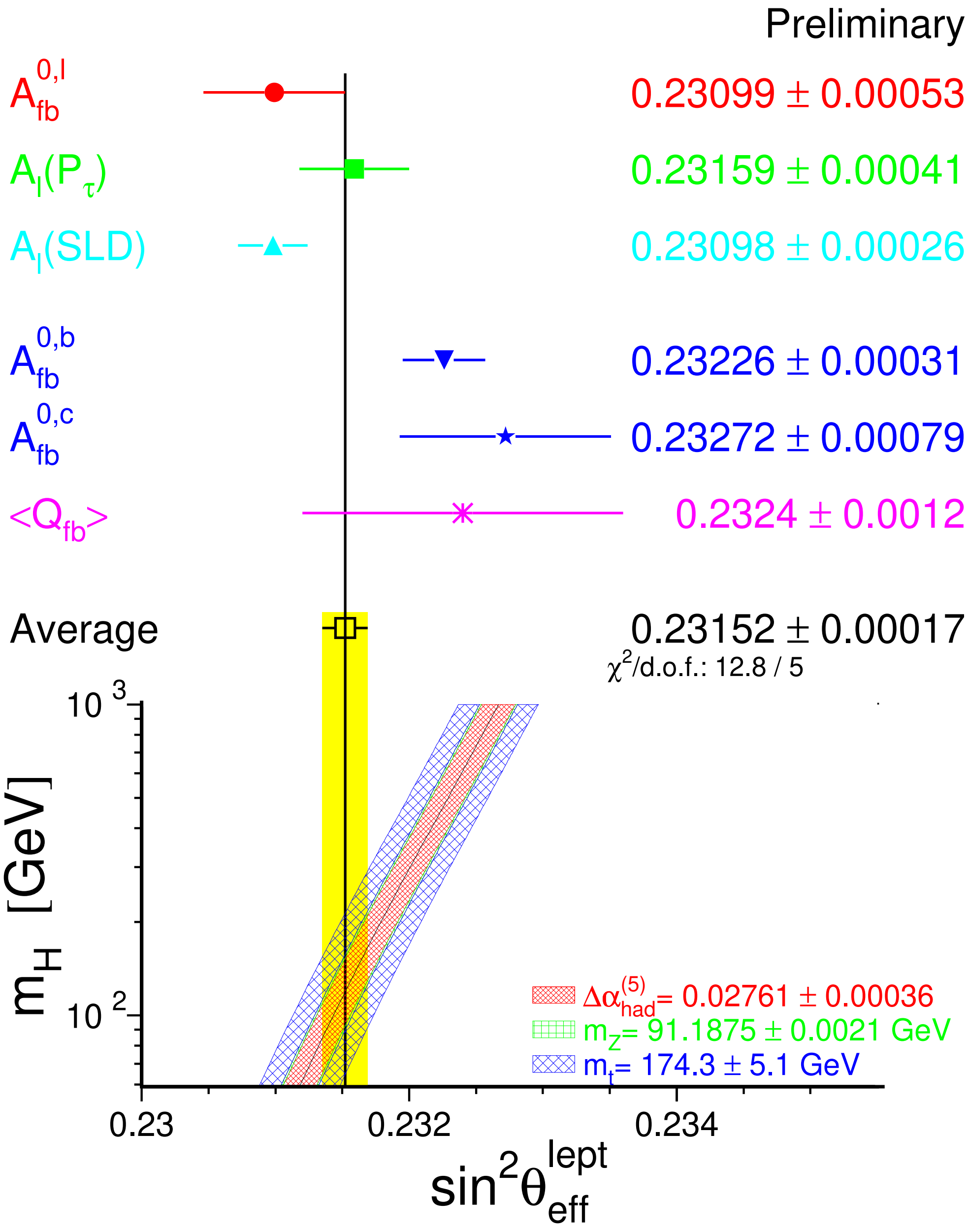
$\delta M_t \sim 3\ (2)$ GeV $\Longleftrightarrow$ $\delta M_W \sim 20\ (12)$ MeV

Maximal use of the obtained δM_t, δM_W accuracy

Compilation of $\sin^2\theta_W$ measurements

Compare the two most precise values:

they disagree at the 3σ level!



The χ^2/d.o.f is mediocre.

Higgs Physics

Within the Standard Model:

- LEP final results $\Longrightarrow m_{h_{\rm SM}} \geq 114.1$ GeV
  Hint of a Higgs at about 115 GeV ??

- Limit from precision electroweak data:
  $\Longrightarrow m_{h_{\rm SM}} \leq 196$ GeV at 95 % C.L.

$$\Downarrow$$

Upgraded Tevatron $\longrightarrow$ good sensitivity precisely in this mass region

$\downarrow$

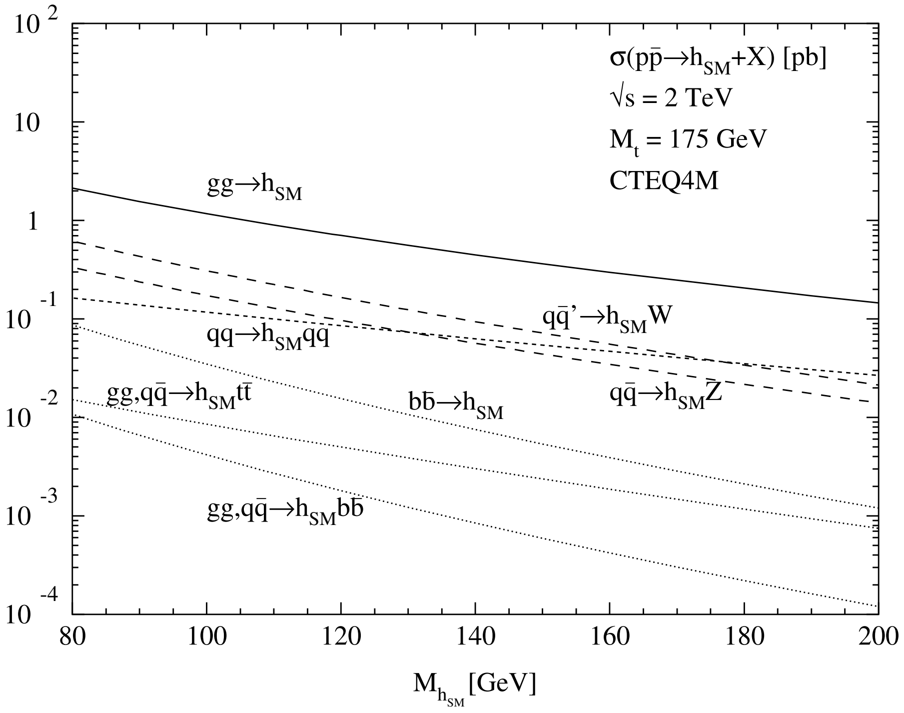
Next chance to reveal mechanism of Electroweak Symmetry Breaking

- from perturbativity and stability bounds:

• for 130 GeV $\lesssim m_{h_{\rm SM}} \lesssim$ 200 GeV
$\Longrightarrow$ SM description valid up to $\Lambda \sim 10^{13}$–10^{19} GeV

• for $m_{h_{\rm SM}} \lesssim$ 130 GeV
$\Longrightarrow$ New Physics expected to appear at $\Lambda \ll M_{\rm Pl}$
($\Lambda \sim 10^5$–10^9 GeV)

SM Higgs Production Cross Sections



- $gg \to h_{\rm SM} \longrightarrow$ largest cross section

NLO QCD corr. $\Longrightarrow$ *a factor 2 larger!*

NNLO $\Longrightarrow \sim 10$–30% increase

theoretical uncertainties:

scale dependence & h.o. effects $\sim 15\%$ PDF's $\approx 10\%$

- $q\bar{q} \to W^{\pm} h_{\rm SM} \longrightarrow 2^{\rm nd}$ largest if $m_h < 175$ GeV

$\to Z\, h_{\rm SM} \longrightarrow$ about factor 2 lower

QCD corrections about 30%

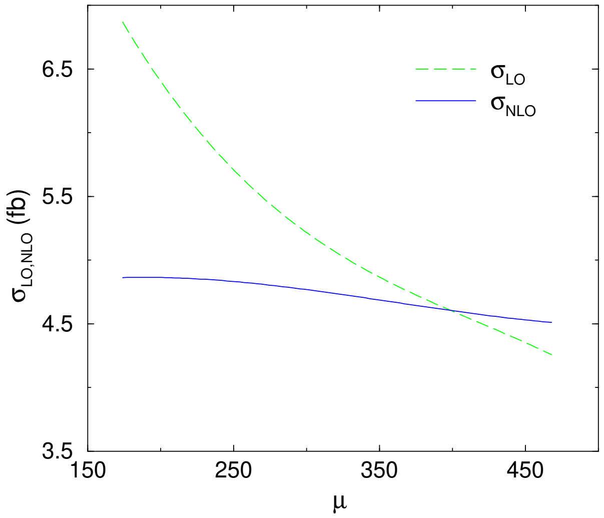
theoretical uncertainties:

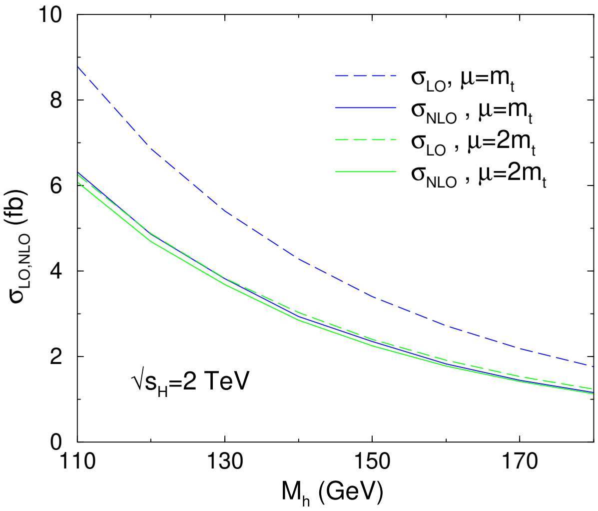
scale dependence & h.o. effects $\sim 15\%$ PDF's $\approx 15\%$

- $gg, q\bar{q} \rightarrow t\bar{t}\, h_{\text{SM}}$

  NLO QCD corrections recently completed

Size of corrections depends sensitively on the choice of normalization/factorization scale μ in α_S & PDF's at LO:





L.Reina, S.Dawson, D.Wackeroth

W.Beenakker, S.Dittmaier, M.Krämer, B.Plümper, M.Spira, P.M.Zerwas

NLO $\Longrightarrow$ cross section of order 1–5 fb

for $m_{h_{\text{SM}}}$ within the reach of the Tevatron

- Vector Boson Fusion: $q\bar{q} \longrightarrow q\bar{q}\, h_{\text{SM}}$

  (also, $ud \rightarrow du\, h_{\text{SM}}$ + c.c.)

QCD corrections $\sim 10\%$

- $gg, q\bar{q} \longrightarrow b\bar{b}\, h_{\rm SM}$

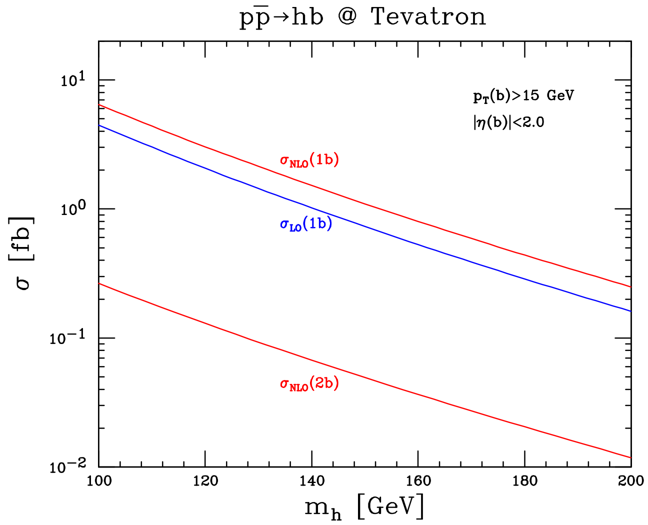
tree level, fixing α_S, PDF's and h_b at scale $m_{h_{\rm SM}}$
$\Longrightarrow$ implicitly includes part of QCD correc. to full inclusive cross section, but
$\longrightarrow$ significant QCD correc. from kinematic region where b's emitted in the forward direction $\Longrightarrow$
large collinear logs $\propto \alpha_S \ln(m^2_{h_{\rm SM}}/m_b^2) \sim \mathcal{O}(1)$ which must be resummed in generation of b-quark distrib. function

$\Longrightarrow$ fully inclusive QCD cross section well approx. by $b\bar{b} \rightarrow h_{\rm SM}$ + QCD correc. (one order of magnitude larger)

Realistic simulation: ultimately needs QCD corrected differential cross section for $b\bar{b}\, h_{\rm SM}$

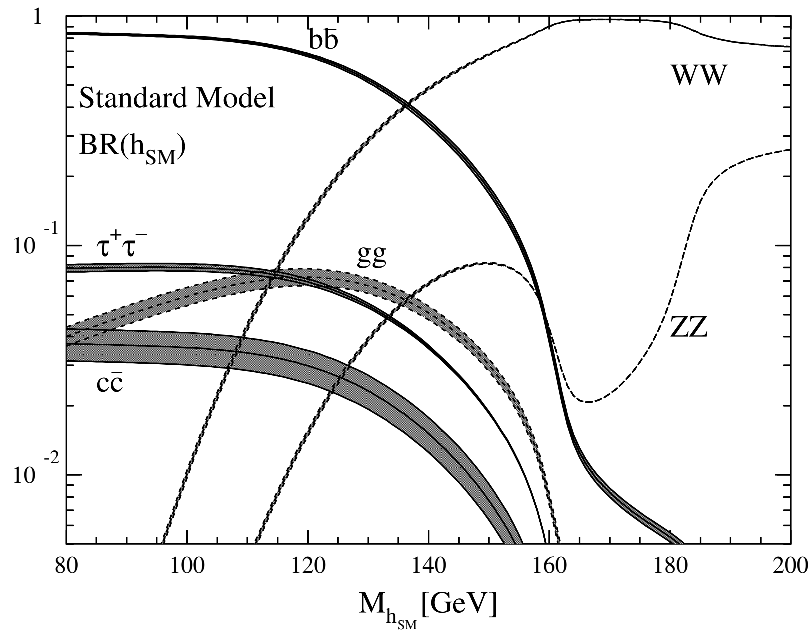
Studies for (i) $h_{\rm SM} + 2\, b$'s (ii) $h_{\rm SM} + 1\, b +$ jet

If only $1\, b$ tagged $\Longrightarrow$ sufficient to consider $bg \rightarrow b\, h_{\rm SM}$
$\Longrightarrow$ computed at NLO QCD
Campbell, Ellis, Maltoni, Willenbrock



$y_b = y_b(m_{h_{\rm SM}})$ $\alpha_S = \alpha_S(m_{h_{\rm SM}})$
at 1-loop (2-loop) for LO (NLO) curves
$\sigma(1b)$: $1\, b$ in tagging region
$\sigma^{\rm LO}(2b)$: $2\, b$'s in tagging region
$\sigma^{\rm NLO}(1b) \sim 2\, \sigma^{\rm LO}(1b)$

SM Higgs Decay Modes



uncertainties: $\alpha_s(M_Z) = 0.12 \pm 0.003 \quad M_t = 174 \pm 5$ GeV

$\bar{m}_b(M_b) = 4.22 \pm 0.05$ GeV $\quad \bar{m}_c(M_c) = 1.22 \pm 0.06$ GeV

- $m_{h_{\rm SM}} \lesssim 135$ GeV $\Longrightarrow h_{\rm SM} \to b\bar{b}$ dominant
- $m_{h_{\rm SM}} \gtrsim 135$ GeV $\Longrightarrow h_{\rm SM} \to WW^*$ dominant

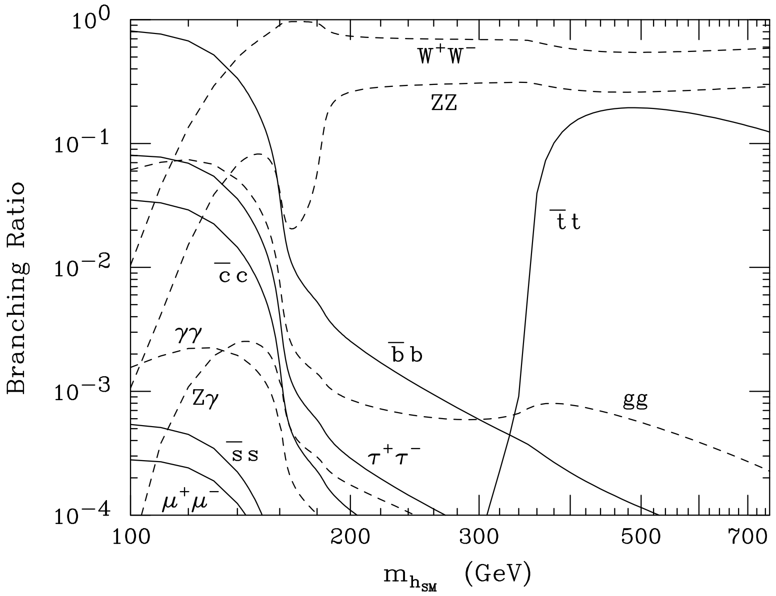
leading QCD corrections to decays into quark pairs

$\Longrightarrow m_f(m_{h_{\rm SM}})$ in tree level formula

IMPORTANT: expected hierarchy of Higgs decays:

$BR(\tau^+\tau^-) < 10^{-1}\, BR(b\bar{b}) \longrightarrow \mathcal{O}\,(m_b^2/m_\tau^2) \times 3_{\rm (color)}$

$BR(c\bar{c}) < BR(\tau^+\tau^-) \longrightarrow$ due to smallness of $\bar{m}_c(m_{h_{\rm SM}})$



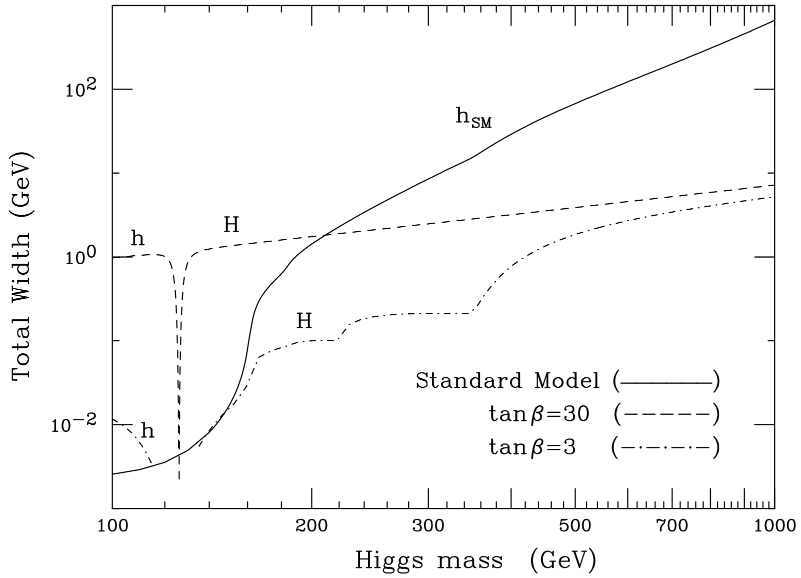
Above $t\bar{t}$ threshold $\longrightarrow$ decay into top pairs

increases rapidly to $\sim 20\%$ at $m_{h_{\rm SM}} = 450$ GeV

$h_{\rm SM} \to gg$, $\gamma\gamma$, $Z\gamma$ generated at one-loop

$\Gamma(h_{\rm SM} \to gg)$ interesting: it determines $\sigma(gg \to h_{\rm SM})$

Total SM Higgs Width:



compare $\Gamma_{\rm tot}(h_{\rm SM})$ to $\Gamma_{\rm tot}(h)$ and $\Gamma_{\rm tot}(H)$

in the MSSM for $\tan\beta = 3$, 30

SM Higgs Prospects at the Tevatron

$\bullet M_H \leq 130\text{GeV} \Longrightarrow p\bar{p} \to VH \to Vb\bar{b}$ (V = W,Z)

signal: leptonic decays of W,Z

$\ell\nu b\bar{b}$ and $\nu\bar{\nu}b\bar{b}$, $\ell^+\ell^- b\bar{b}$

main backgrounds:

for Wh_{SM}: $Wb\bar{b}$, $t\bar{t}$, WZ, single-t

for Zh_{SM}: $Zb\bar{b}$, ZZ, $t\bar{t}$, $W^* \to t\bar{b}$

$\bullet M_H \geq 130\text{GeV} \Longrightarrow p\bar{p} \to VH \to VWW^*$

$\Longrightarrow p\bar{p} \to H \to WW^*$

signal:

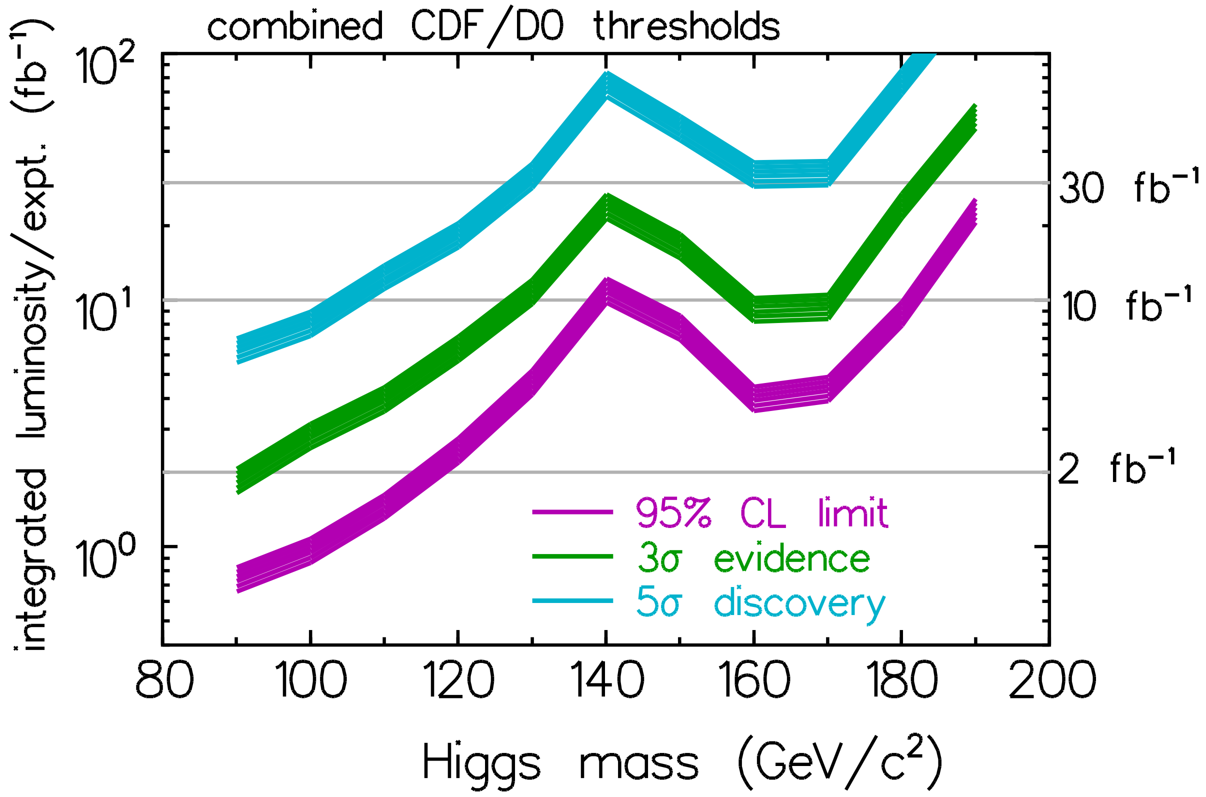
$\ell^+\ell^-$+jets, $\ell^\pm\ell^\pm$, 3ℓ

main backgrounds:

WW, WZ, ZZ, W+jets, Z+jets

Crucial Issues in the Analysis:

- b-tagging efficiency
- M_{bb} resolution
- background estimation
- mass window *vs.* spectrum fit



- $m_{h_{\rm SM}} \leq 180$ GeV $\Longrightarrow$ 95 % C.L. excl. $\rightarrow$ 10 fb^{-1}/*exp.*
3σ evidence $\rightarrow$ 20 fb^{-1}/*exp.* 5σ discovery $\rightarrow \approx$ 60 fb^{-1}/*exp.*

- $m_{h_{\rm SM}} \leq 130$ GeV $\Longrightarrow$ 95 % C.L. excl. $\rightarrow$ 5 fb^{-1}/*exp.*
3σ evidence $\rightarrow$ 10 fb^{-1}/*exp.* 5σ discovery $\rightarrow \approx$ 30 fb^{-1}/*exp.*

- $m_{h_{\rm SM}} \approx 115$ GeV (LEP Hint?) $\Longrightarrow$ 3σ with $\approx$ 5 fb^{-1}/*exp.*
$\Longrightarrow$ 5σ with $\approx$ 15 fb^{-1}/*exp.*

Crucial Issues with the Analysis

$\boxed{b\text{-tagging}}$ *note:* $\mathcal{L}$ scales with ϵ_b^2

HWG considered Run 1 efficiencies (ϵ_b)

$\longrightarrow$ probably conservative by 10–20%

$\boxed{b\bar{b}\text{ Mass Resolution}}$

assumed 10% (compare to 13.5% for $Z \rightarrow b\bar{b}$ in Run 1)

Run 2: hope to attain 10–12% for $h \rightarrow b\bar{b}$

$\boxed{\text{Background Estimation}}$

- assume QCD background in $\nu\bar{\nu}b\bar{b}$ channel equal to sum of all other backgrounds (based on Run 1 results)
- $W\,b\bar{b} \rightarrow$ Ellis *et al.* studies yet to be implemented

$\boxed{\text{Multivariate Methods}}$

assume 30% improvement from neural network

$\rightarrow$ investigate training with real data

$\boxed{\text{Mass Window } vs. \text{ Spectrum Fit}}$

- performed simple event counting within mass window
- studies by T.Kruse & J.Conway indicate $\sim$ 20% reduction in required $\mathcal{L}$ from fitting

$\boxed{\text{Systematic Uncertainties}}$

assumed 10% max uncertainty on background rate

$\longrightarrow$ tough to achieve

$\longrightarrow$ need to measure bg shape and normalization

New Studies

$\boxed{p\bar{p} \to t\bar{t}h}$ Goldstein et al. '00

- striking final states:

  $h \to b\bar{b} \Longrightarrow W^+W^-\, b\bar{b}\, b\bar{b}$

  $h \to WW^* \Longrightarrow W^+W^-\, b\bar{b}\, WW^*$

- backgrounds:
  - $t\bar{t}$+jets, $t\bar{t} + b\bar{b}$, $t\bar{t} + Z(\to b\bar{b})$, $WZ + jj$
  - $t\bar{t}$+jets, $t\bar{t} + W$, $t\bar{t} + Z(\to \ell^+\ell^-)$

$m_h < 140$ GeV: $\ell^\pm\, jj\, b\bar{b}b\bar{b}\not{E}_T$ (considered w/ 3b-tags)

(other options either too small or not studied)

Results before NLO cross sections available:

For $m_{h_{\rm SM}} = 120$ GeV $\Longrightarrow$

15 fb^{-1} gives 2.8σ (1 exp), 4.1σ (2 exp)

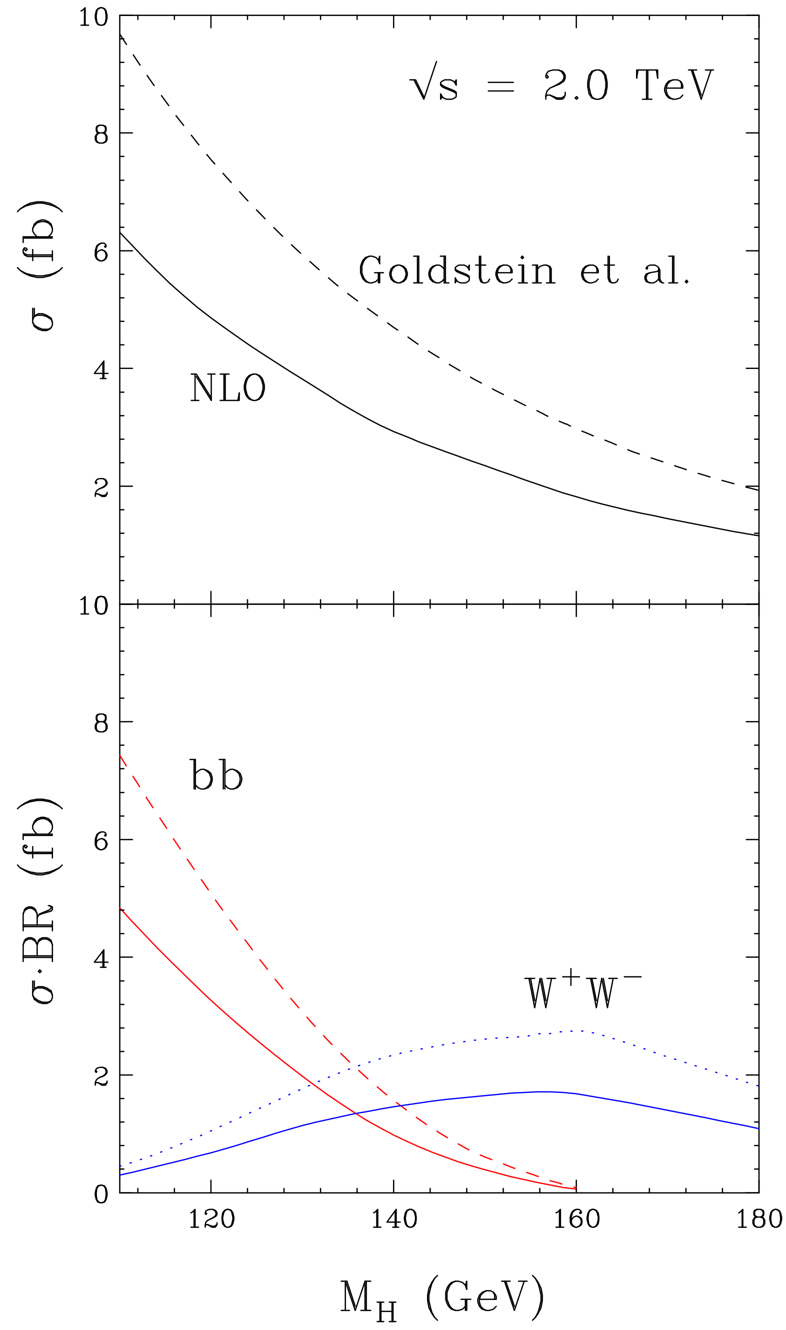
After NLO σ's considered:

$\longrightarrow$ signal is factor ~ 0.7 smaller

$\Longrightarrow$ factor 2 more luminosity needed

($h \to WW^*$ channel is more difficult)

NLO impact on σ's in Run II Analysis



$\boxed{gg \to h \to \tau^+\tau^-}$

(Belyaev, Han, Rosenfeld '02)

signal: consider leptonic and hadronic decays for efficiency

- good simulation tool for τ decays available
- better understanding of τ-ID efficiencies

backgrounds: $Z\,j \to \tau^+\tau^-\,j$ (irred.), $3j \to \tau^+\tau^-\,j$ (mis-ID)
$W^\pm jj$, $W^+W^-\,j$ ($W \to \tau$, j faking τ) smaller

m_h	120 GeV	130 GeV	140 GeV
95% CL exclusion $L(\mathrm{fb}^{-1})$	15	18	33
5σ discovery $L(\mathrm{fb}^{-1})$	94	110	210
κ for 95% CL (2 fb^{-1})	2.6	3.0	4.1
κ for 95% CL (15 fb^{-1})	0.97	1.1	1.4
κ for 5σ (2 fb^{-1})	6.7	7.5	10
κ for 5σ (15 fb^{-1})	2.5	2.7	3.7

K-factors over SM rate in new theories to achieve a 95% CL exclusion or 5σ discovery with given $\mathcal{L}$

Combining these with results from the Higgs report:
$\Longrightarrow$ 10–20% (up to 35%) improvement in required $\mathcal{L}$
$\Longrightarrow$ sensitivity in $m_{h_{\mathrm{SM}}} \sim$ 120–140 GeV range improved

MSSM Higgs sector at Tree-Level

H_1, H_2 doublets $\Longrightarrow$ 2 CP-even Higgs h, H

1 CP-odd state A   2 charged Higgs H$^\pm$

Higgs masses and couplings given in terms of two parameters: m_A and $\tan\beta \equiv v_2/v_1$

mixing angle $\alpha \Longrightarrow \cos^2(\beta-\alpha) = \frac{m_h^2(m_Z^2-m_h^2)}{m_A^2(m_H^2-m_h^2)}$

Couplings to gauge bosons and fermions (norm. to SM)

hZZ, hWW, ZhA, WH$^\pm$h $\longrightarrow \sin(\beta-\alpha)$

HZZ, HWW, ZHA, WH$^\pm$H $\longrightarrow \cos(\beta-\alpha)$

(h,H,A) $u\bar{u} \longrightarrow \cos\alpha/\sin\beta,\ \ \sin\alpha/\sin\beta,\ \ 1/\tan\beta$

(h,H,A) $b\bar{b} \longrightarrow -\sin\alpha/\cos\beta,\ \ \cos\alpha/\cos\beta,\ \ \tan\beta$

If $m_A \gg M_Z \rightarrow$ decoupling limit

- $\cos(\beta-\alpha)=0$ up to correc. $\mathcal{O}(m_Z^2/m_A^2)$
- lightest Higgs has SM-like couplings and mass $m_h^2 \simeq m_Z^2\cos^2 2\beta$
- other Higgs bosons: heavy and roughly degenerate $m_A \simeq m_H \simeq m_H^\pm$ up to correc. $\mathcal{O}(m_Z^2/m_A^2)$

Radiative Corrections to Higgs Masses

important quantum correc. due to loops of particles and their superpartners: incomplete cancellation due to SUSY breaking $\Longrightarrow$ main effects: top and stop loops; bottom and sbottom loops in large $\tan\beta$ regime

$$m_h^2 = M_Z^2 \cos^2 2\beta + \frac{2\, g_2^2\, m_t^4}{8\pi^2\, M_W^2} \left[\ln(M_S^2/m_t^2) + \frac{X_t^2}{M_S^2} \left(1 - \frac{X_t^2}{12\, M_S^2} \right) \right] + \text{h.o.}$$

$M_S^2 = \frac{1}{2}(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2)$ and $X_t = A_t - \mu/\tan\beta \longrightarrow$ stop mixing

- two-loop log. and non-log.effects are numerically important $\rightarrow$ computed by different methods:
  - diagrammatic
  - effective potential
  - RG-improved effective potential (see Haber's talk)
- upper limit on Higgs mass: $m_h \lesssim 135$ GeV

$$M_S = 1 \rightarrow 2 \text{ TeV} \Longrightarrow \Delta\, m_h \simeq 2 - 5 \text{ GeV}$$
$$\Delta\, m_t = 1 \text{ GeV} \Longrightarrow \Delta\, m_h \sim 1 \text{ GeV}$$

- main effects already present in one-loop formulae
  - m_t^4 enhancement
  - depend. on $\tilde{t}$-mixing X_t
    $\Longrightarrow$ max. value $X_t \sim \sqrt{6} M_S$ (scheme depend.) small asym. at h.o.
  - logarithmic sensitivity to $m_{\tilde{t}_i}$

Radiative Corrections to Higgs Boson Couplings

$\boxed{1}$ Through rad. correc. to the CP-even Higgs mass matrix, $\delta\mathcal{M}^2_{ij}$, which defines the mixing angle α

$$\sin\alpha\cos\alpha = \mathcal{M}^2_{12} \,/\, \sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\,\det\mathcal{M}^2}$$

important effects of rad. correc. on $\sin\alpha$ or $\cos\alpha$ depending on sign of $\mu\, A_t$ and magnitude of A_t/M_S.

$\Longrightarrow$ govern couplings of Higgs to fermions

$\Longrightarrow$ via rad. correc. to $\underline{\cos(\beta-\alpha) \text{ and } \sin(\beta-\alpha)}$

governs Higgs couplings to vector bosons

$\boxed{2}$ SUSY vertex correc. to Yukawa couplings, which modify the effective Lagrangian, coupling Higgs to fermions

$$\mathcal{L}_{\mathrm{eff}} \longrightarrow h_b\, H_1^0\, b\bar{b} + \Delta h_b\, H_2^0\, b\bar{b}$$

Δh_b modifies the m_b–h_b relation

$$m_b \simeq h_b v_1 + \Delta h_b v_2 = h_b\, v\, \cos\beta \left(1 + \frac{\Delta h_b}{h_b} \tan\beta\right)$$

$$\Delta_b = \frac{\Delta h_b}{h_b} \tan\beta \sim \frac{2\alpha_S}{3\pi} \frac{\mu\, M_{\tilde{g}}}{\max(m^2_{\tilde{b}_1}, m^2_{\tilde{b}_2}, M^2_{\tilde{g}})} \tan\beta$$

$\Delta_b \sim \mathcal{O}(1)$ if $\tan\beta$ large

Modified Higgs Boson Couplings to b-quarks

$$g_{h\,b\bar{b}} \simeq \frac{-\sin\alpha\, m_b}{v\,\cos\beta(1+\Delta_b)}\,(1-\Delta_b/\tan\alpha\tan\beta)$$

$$g_{H\,b\bar{b}} \simeq \frac{\cos\alpha\, m_b}{v\,\cos\beta(1+\Delta_b)}\,(1-\Delta_b\tan\alpha/\tan\beta)$$

$$g_{A\,b\bar{b}} \simeq \frac{m_b}{v(1+\Delta_b)}\,\tan\beta$$

- similar effects on τ coupling but $|\Delta_\tau| \ll |\Delta_b|$

Important modifications of couplings occur for regions of MSSM parameter space

$\longrightarrow$ dep. on sign and values of μA_t, μA_b, $\mu M_{\tilde{g}}$
and magnitudes of $M_{\tilde{g}}/M_S$, μ/M_S

- destroy the basic relation: $g_{h\,b\bar{b}}/g_{h\,\tau\tau} \sim m_b/m_\tau$

- strong suppression of coupling of h (H) to bottoms
if $\tan\alpha \simeq \Delta_b/\tan\beta$ $\quad ((\tan\alpha)^{-1} \simeq -\Delta_b/\tan\beta)$

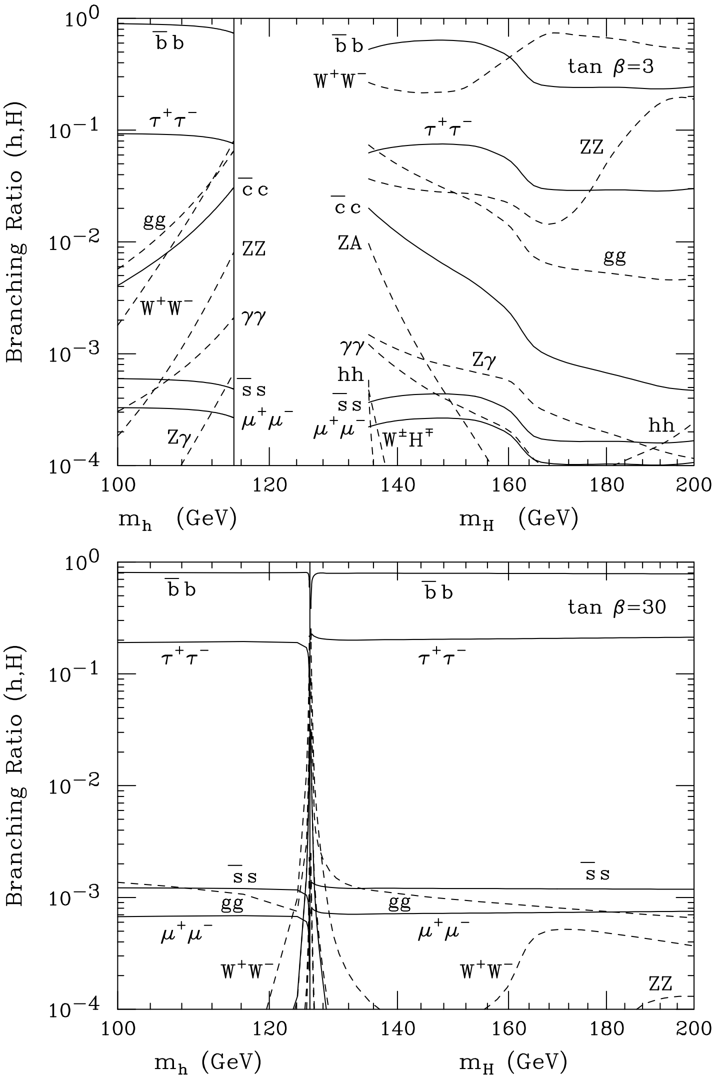
$\Longrightarrow$ main decay modes of SM-like MSSM Higgs
$b\bar{b} \sim 80\%$ $\qquad \tau^+\tau^- \sim 7-8\%$
drastically changed $\Longrightarrow$ other decay modes enhanced

$\Longrightarrow$ Higgs phenomenology at colliders revisited!!

Decay Patterns of MSSM Higgs Bosons

- large $\tan\beta$: h, H, A to $b\bar{b}$, $\tau^+\tau^-$ dominate
- low $\tan\beta$: richer pattern

  (still decays to $b\bar{b}$, $\tau^+\tau^-$ significant if $m_\phi \lesssim 2m_t$)



$M_S = 1$ TeV $\qquad X_t = \sqrt{6}\, M_S$

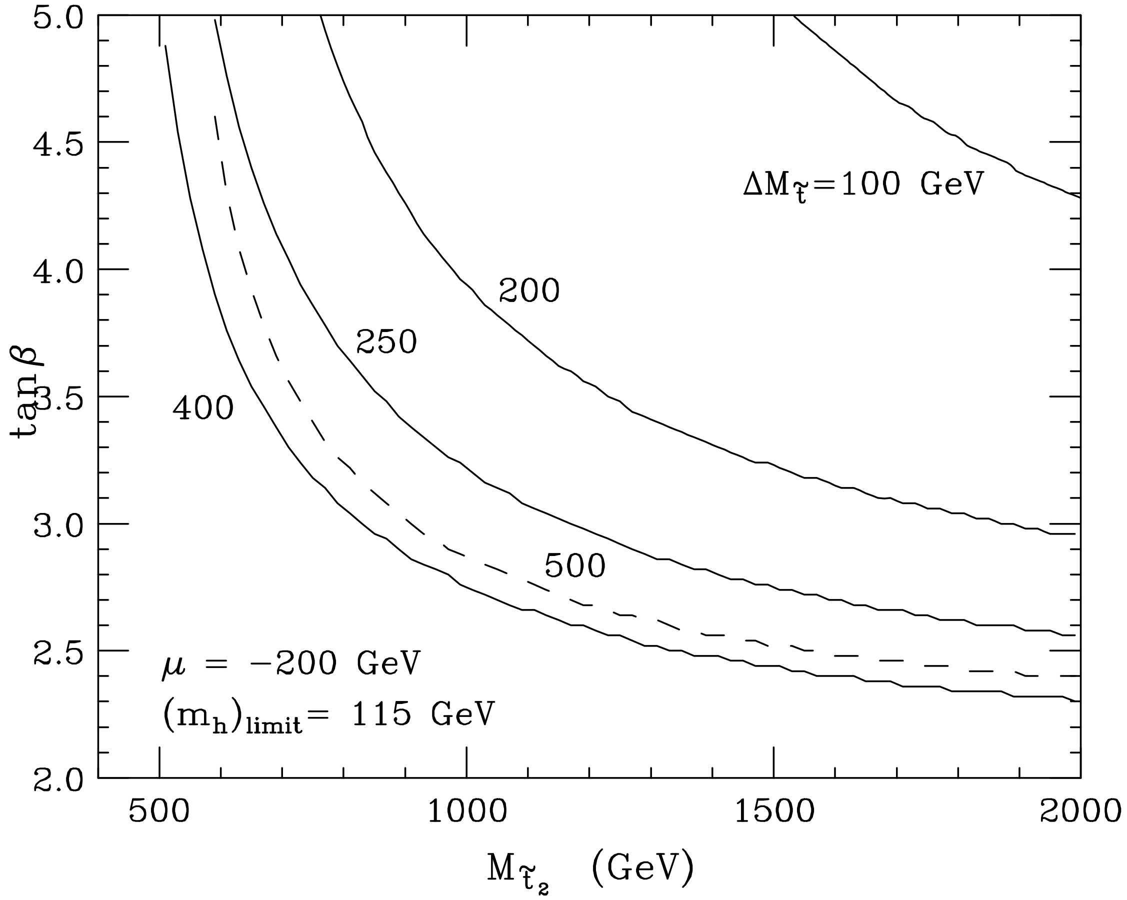
Decay to SUSY particles $\longrightarrow$ when open, very important

Indirect Information on SUSY from Experiment

- Higgs mass constraints from LEP

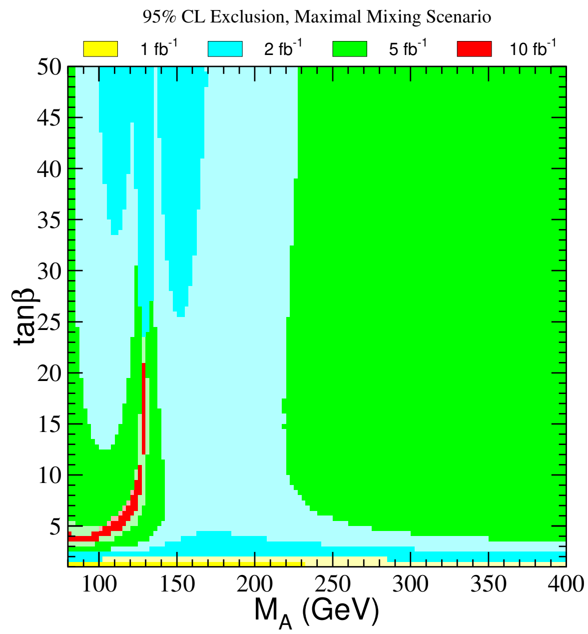
$\Longrightarrow$ impose important constraints on SUSY breaking models and 3rd gen. squark masses.

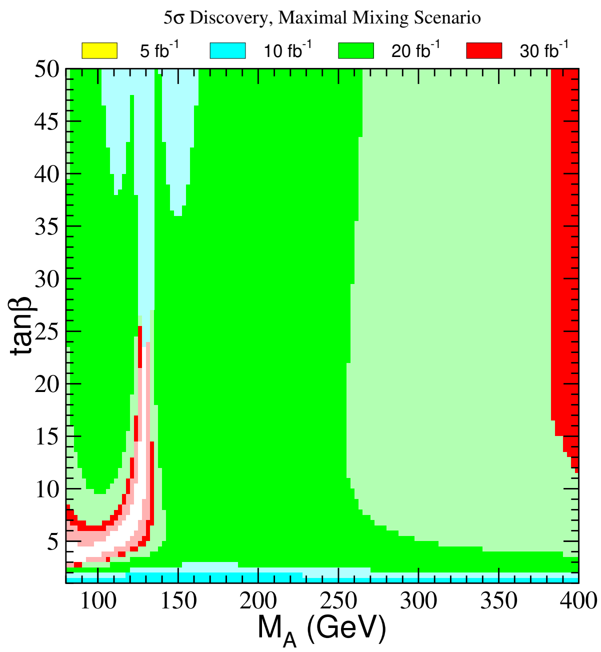
Model Independent bounds on $\tan\beta$ as a function of heaviest stop mass for different values of the stop mass splitting $\Delta M_{\tilde{t}} = m_{\tilde{t}_2} - m_{\tilde{t}_1}$, for $m_h = 115$ GeV



Maximal Mixing Scenario

$p\bar{p} \rightarrow Vh/H \rightarrow Vb\bar{b}$

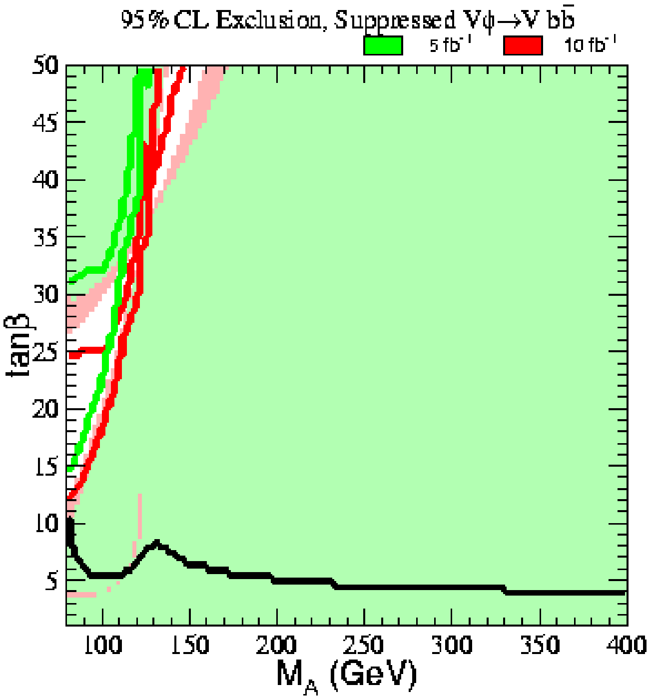




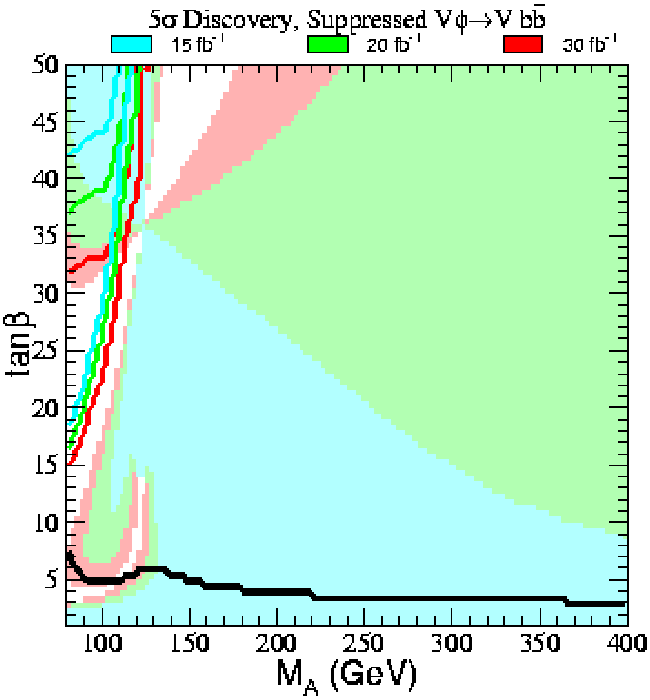
MSSM Higgs Sector Studies

Higgs/SUSY Workshop & Higgs WG Report results

- most challenging case: $M_h^{max} \approx$120 GeV but important regions of suppressed $h/Hb\bar{b}$ coupling



shaded areas: $p\bar{p} \to Vh/H \to Vb\bar{b}$



green/red lines: $p\bar{p} \to \phi b\bar{b} \to b\bar{b}b\bar{b}$
ϕ = A/h or A/H

black solid line: LEP limit

- good exclusion if no signal with 5–10 fb^{-1}/*exp.*
- good coverage for discovery $\longrightarrow$ > 15 fb^{-1}/*exp.*

MSSM Charged Higgs Searches

Run 1 analyses search for charged Higgs in top decays:
$H^+ \longrightarrow \tau^+\nu_\tau$ large $\tan\beta$
$H^+ \longrightarrow c\bar{s}$ low $\tan\beta$

Similar to neutral Higgs case, one has important radiative corrections for large $\tan\beta$

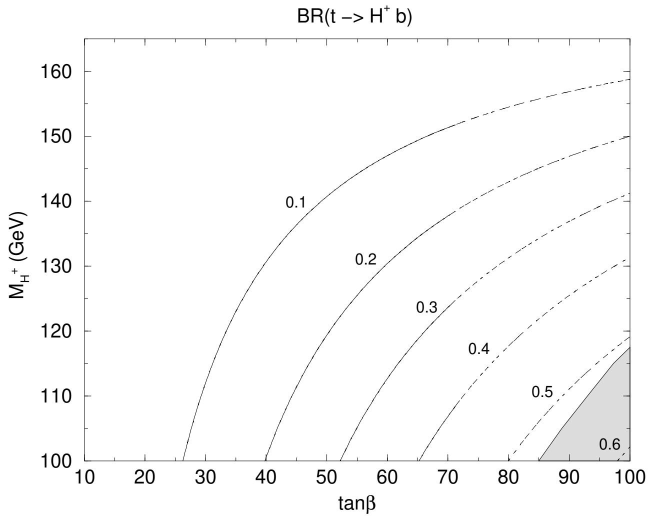
$$\begin{aligned} g_{H^- t\bar{b}} \quad \simeq \quad & \left\{ \frac{m_t}{v} \cot\beta \left[1 - \frac{1}{1+\Delta_t} \frac{\Delta h_t}{h_t} \tan\beta \right] P_R \right. \\ & \left. + \frac{m_b}{v} \tan\beta \left[\frac{1}{(1+\Delta_b)} \right] P_L \right\} \end{aligned}$$

also Δm_τ corrections in $g_{H^- \tau\nu_\tau}$ may be included

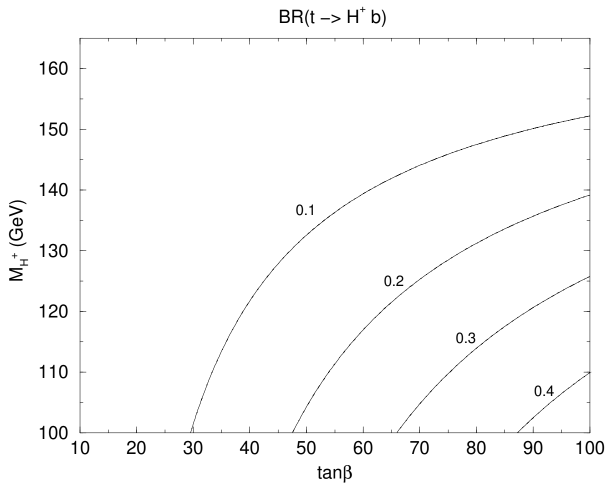
Drastic variations on $\tan\beta - m_{H^\pm}$ plane bounds, depending on MSSM parameter space

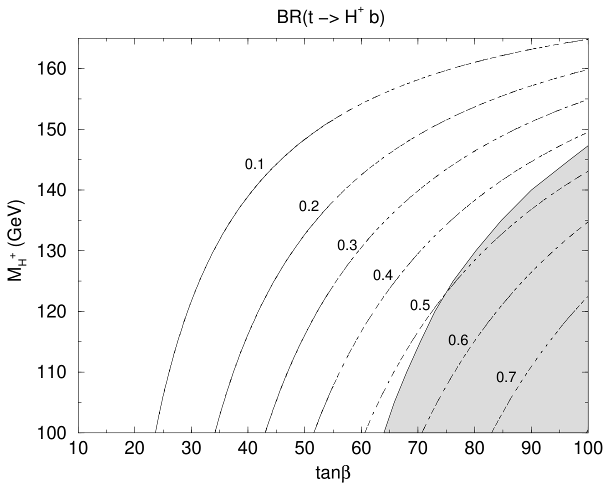
• Curves of constant BR for $t \longrightarrow bH^+$ after resummation of LO and NLO logarithms of QCD corrections included

M.C., Garcia, Nierste, Wagner



• Same as above, after including dominant SUSY correc. for large $\tan\beta$ for different sets of SUSY parameters. Shaded area excluded by Run1 DO frequentist analysis





RUN 2 studies for $p\bar{p} \longrightarrow tbH^{\pm}$:

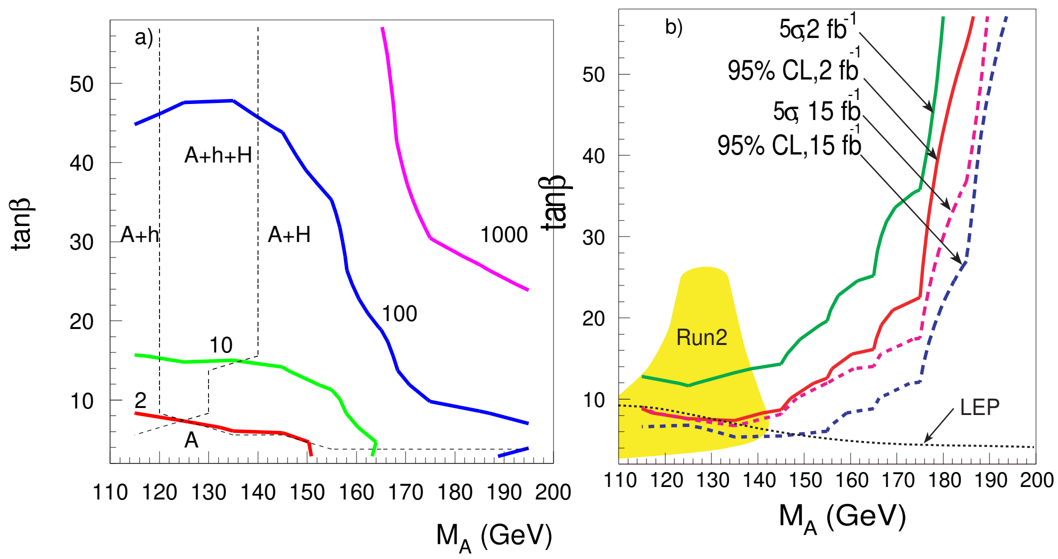
• charged Higgs signal may be viable in the 220–250 GeV mass range or excluded at 95 % C.L. up to 300 GeV

Belyaev,Garcia,Gausch,Sola

Neutral MSSM Higgs decay into τ pairs

$M_{\rm SUSY} = 1$ TeV, $\mu = 300$ GeV,
$A = \mu/\tan\beta + \sqrt{6} \times M_{SUSY}$ (max. mixing)

Belyaev, Han, Rosenfeld



– with the $\tau\tau$ mode could reach $5\sigma(2\sigma)$ full coverage for SUSY Higgs parameters with 15 fb^{-1} (2 fb^{-1})!

Note: No enhancement if in some region of the parameter space $hb\bar{b}$ Yukawa coupling is accidently suppressed: the increasing of the $h \to \tau\bar{\tau}$ branching fraction balanced by the reduction in the Higgs production via the $hb\bar{b}$ coupling.

CP violating phases and Supersymmetry

- Mechanism of SUSY breaking unknown
- Soft SUSY breaking parameters MAY BE COMPLEX and take any value allowed by phenomenological constraints

➡ Complex parameters may induce large values of the electron and neutron EDM's

at one loop $\rightarrow$ resolve the CP crisis by

- heavy 1. and 2. generation sfermions
- cancellations between different EDM's

at two loops $\rightarrow$ effects of 3. generation sfermions relevant to Higgs sector as well as to the generation of the observed Baryon Asymmetry

- either strong constraint on large $\tan\beta$ values ($\tan\beta \leq 10$)
- or cancellations of some type

CP violation in the Higgs Sector

- at tree level $\Longrightarrow$ MSSM Higgs potential invariant under CP
- After radiative corrections: CP violation induced through loop effects via 3. generation sfermion and gaugino mass parameters

– Many possible relevant phases to Higgs sector

$m_{\tilde{g}}$ (one phase if Univ. gaugino masses)

A_f μ and m_{12}^2

Due to U(1) symm.of the conformal inv. sector:

$\rightarrow$ one can redefine fields and absorbe two phases

rephasing inv. combinations

$\rightarrow$ if $\quad \mathrm{Im}\ ((m_{12}^2)^* A_f \mu) \neq 0$ and/or

$$\mathrm{Im}\ ((m_{12}^2)^* m_{\tilde{g}} \mu) \neq 0$$

$\Longrightarrow$ CP violating effects will be present in the MSSM

in practice m_{12}^2 and μ real and leave phases in A_f and $m_{\tilde{g}}$

Minimization should be performed with respect to real and imaginary parts of Higgs fluctuations

$H_1^0 = \phi_1 + iA_1 \qquad\qquad H_2^0 = \phi_2 + iA_2$

Performing a rotation: A_1, $A_2 \quad \Longrightarrow$ A, G^0 (Goldstone)

Main Effect of CP-Violation is the mixing between the three neutral Higgs boson states

$$\begin{pmatrix} A \\ \Phi_1 \\ \Phi_2 \end{pmatrix} = \mathcal{O} \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix} \tag{1}$$

In the base (A, ϕ_1, ϕ_2):

$$\mathcal{M}_N^2 = \begin{bmatrix} m_A^2 & \left(M_{SP}^2\right)^T \\ M_{SP}^2 & M_{SS}^2 \end{bmatrix}$$

where $M_{SP}^2 \propto \mathrm{Im}(\mu A_t)$
M_{SS}^2 similar to the mass matrix in CP conserving case and M_A^2 is the mass of the would be CP-odd Higgs

m_A^2 no longer a physical parameter, but the charged Higgs mass $M_{H^\pm}$ can be used as a physical parameter, together with M_S, $|\mu|$, $|A_t|$, $\arg(A_t)$ and $\arg(M_{\tilde{g}})$.

Yukawa Couplings

$$-\mathcal{L}_{\phi b\bar{b}} = \left(h_b H_1^0 + \Delta h_b H_2^0\right) \bar{b}_L b_R + h.c. \qquad (2)$$

Coupling Δh_b generated by SUSY breaking effects

$$\Delta h_b \simeq \frac{\alpha_3}{3\pi} \frac{M_3^* \mu^*}{M_S^2}$$

The one loop corrections to the Yukawa couplings introduce CP-violating effects which are independent of Higgs mixing (like ϵ and $\epsilon^{'}$).

$$\begin{aligned} g^S_{H_i dd} &= \frac{1}{h_d \cos\beta + \Delta h_d \sin\beta} \left[Re(h_d) O_{1i} + Re(\Delta h_d) O_{2i} \right. \\ &+ \left. \left(Im(h_d) \sin\beta - Im(\Delta h_d) \cos\beta \right) O_{3i} \right] \qquad (3) \end{aligned}$$

$$\begin{aligned} g^P_{H_i dd} &= \frac{1}{h_d \cos\beta + \Delta h_d \sin\beta} \left[Im(h_d) O_{1i} + Im(\Delta h_d) O_{2i} \right. \\ &+ \left. \left(Re(h_d) \cos\beta - Re(\Delta h_d) \sin\beta \right) O_{3i} \right] \qquad (4) \end{aligned}$$

where we have defined the phase of the superfield b_R

$$m_b^2 \propto h_b + \delta h_b + \Delta h_b \tan\beta$$

to be real and positive

CP Violation & the MSSM Higgs Sector

SUSY Breaking parameters in the stop/sbottom/gluino sector *may be complex*
$\rightarrow$ CP Violation induced through loop effects

• mixing between the 3 neutral states

h, H, A $\rightarrow$ H_1, H_2 H_3 mixed CP parity states

• upper bound on lightest Higgs mass remains the same

$$m_{H_1} \leq 135\text{GeV}$$

• couplings of Higgs bosons to gauge bosons and fermions can crucially differ from CP conserving case

$\Longrightarrow$ CP violation $\rightarrow$ important phenomenological consequences on LEP results and on Tevatron/LHC expectations $\Longrightarrow$ *example*

Note: CPV necessary for Electroweak Baryogenesis $\Longrightarrow$ when testing ELW Baryogenesis through Higgs physics, CPV studies of Higgs sector neccesary

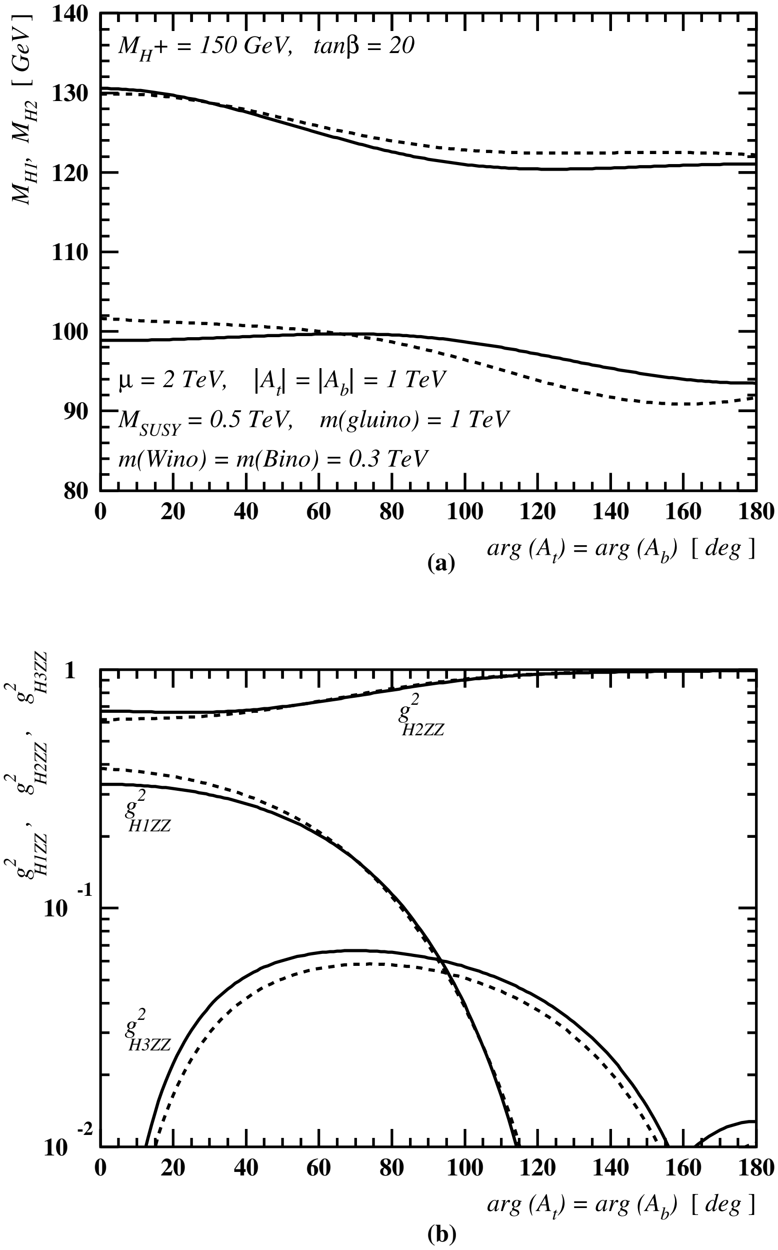
CP-Violating Higgs Bosons at the Tevatron

Large $\tan\beta$ scenario and sizeable phase of A_t (stop mixing param.), $arg(A_t) \geq 90^o$

- interesting case: $M_{H_1} \approx 90$ GeV but out of LEP reach, all other channels: ZH_2, ZH_3, H_1H_2, H_1H_3 kin. inaccessible.

- $M_{H_1} \rightarrow$ also very difficult at the Tevatron due to small $g^2_{H_1VV}$ coupl.

M_{H_1}, M_{H_2}, small variation with CP violating phase of A_t, but strong variation of the couplings



– The Tevatron will detect $M_{H_2} \sim 120$ GeV if sufficient integrated Luminosity (≥ 15 fb^{-1}) collected

– CP Violation

• complex phases for all soft SUSY breaking parameters, but at least two cannot be rotated away choosing those as ϕ_μ and ϕ_A

$\Longrightarrow$ six param. determine the sparticle spectrum:

$$m_0,\ M_{1/2},\ A_0,\ \tan\beta,\ \phi_\mu,\ \phi_A$$

• Interesting constraints on SUSY param. space from EDM's of electron and u,d quarks

$$\left(\frac{d_f}{e}\right)^{1l.} \sim 10^{-25}\mathrm{cm}\frac{(\mathrm{Im}\mu, \mathrm{Im}A_f)}{max.(m_{\tilde{f}}, m_\lambda)}\left(\frac{1\mathrm{TeV}}{max.(m_{\tilde{f}}, m_\lambda)}\right)^2\left(\frac{m_f}{10\mathrm{MeV}}\right)$$

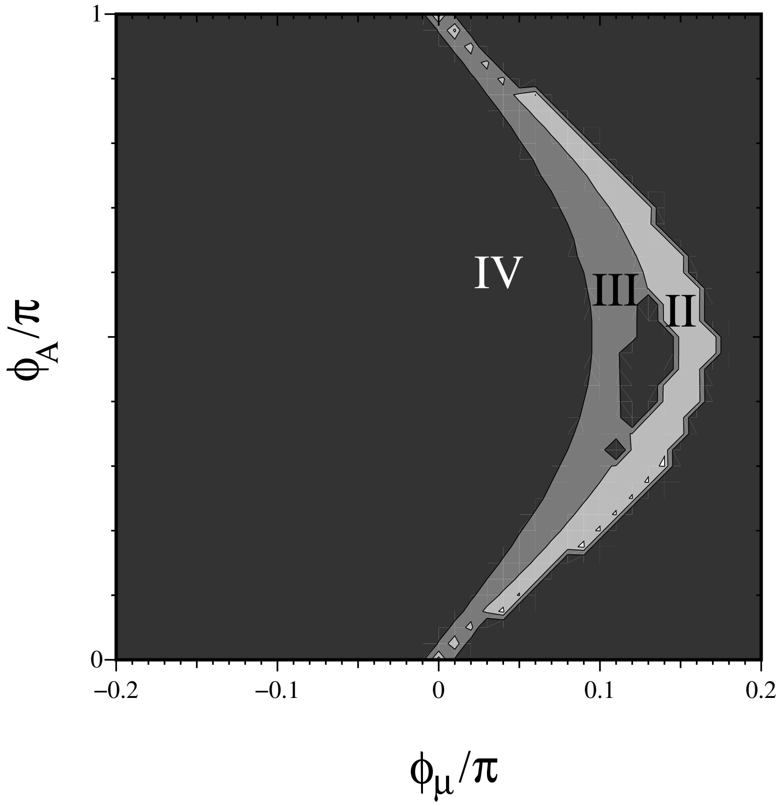
To resolve the one-loop CP crisis:

• $\mathrm{Im}\mu/|\mu|, \mathrm{Im}A_f/A_f \leq 10^{-2}$, with $(m_{\tilde{f}}, m_\lambda) \sim 200\,\mathrm{GeV}$

• CP phases ~ 1, <u>but</u> $m_{\tilde{f}} > 1$ TeV for $\tilde{f} = \tilde{e}, \tilde{u}, \tilde{d}, \tilde{\nu}_L$

• Cancellations between different EDM terms

$$\Downarrow$$



Required values of $M_{1/2}$ to satisfy electron and neutron EDM's for $\tan\beta$ =2, m_0 = 100 GeV, A_0 = 1 TeV.

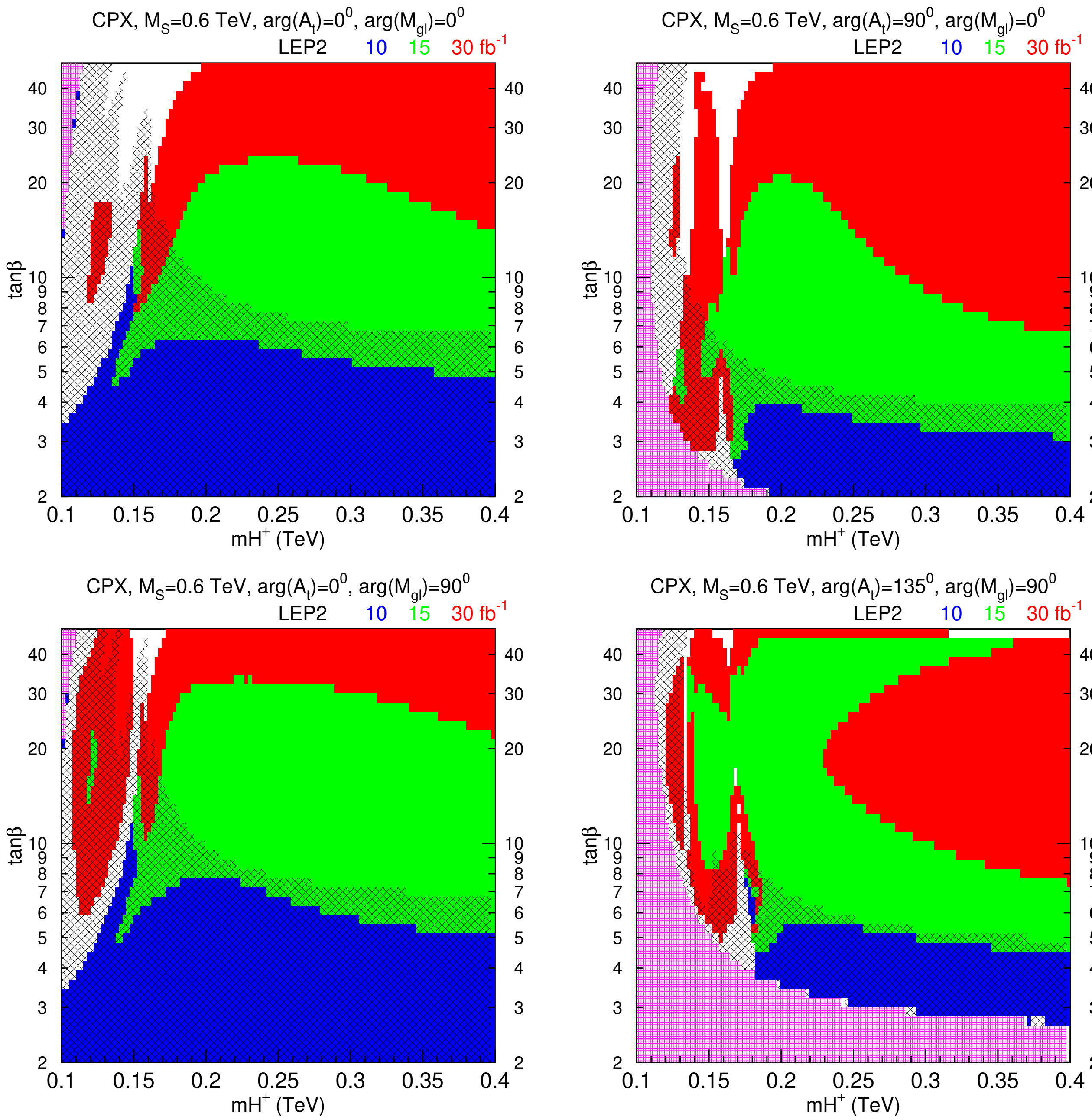
Zones labelled II, III and IV correspond to:

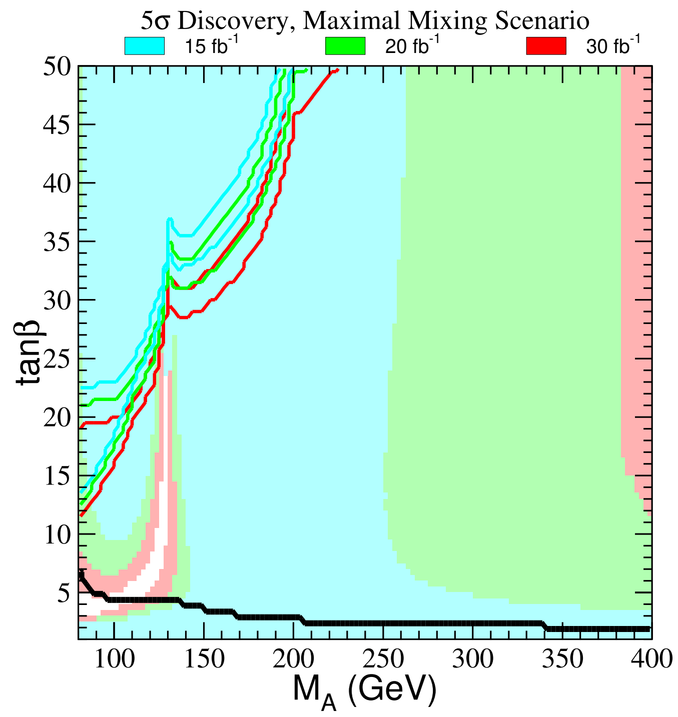
200 GeV $\leq M_{1/2}^{min} \leq$300 GeV, 300 GeV $\leq M_{1/2}^{min} \leq$450 GeV and $M_{1/2}^{min} \geq$450 GeV

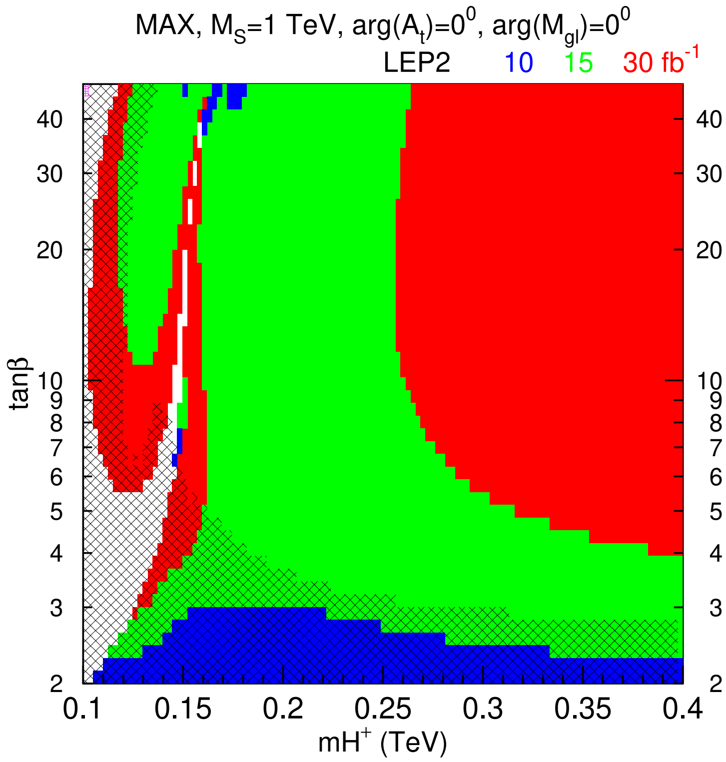
• Two-loop contributions to EDM's $\Longrightarrow$ constraints on CPV parameters of 3rd. gen. squarks, specially for large $\tan\beta \longrightarrow$ important for Higgs physics

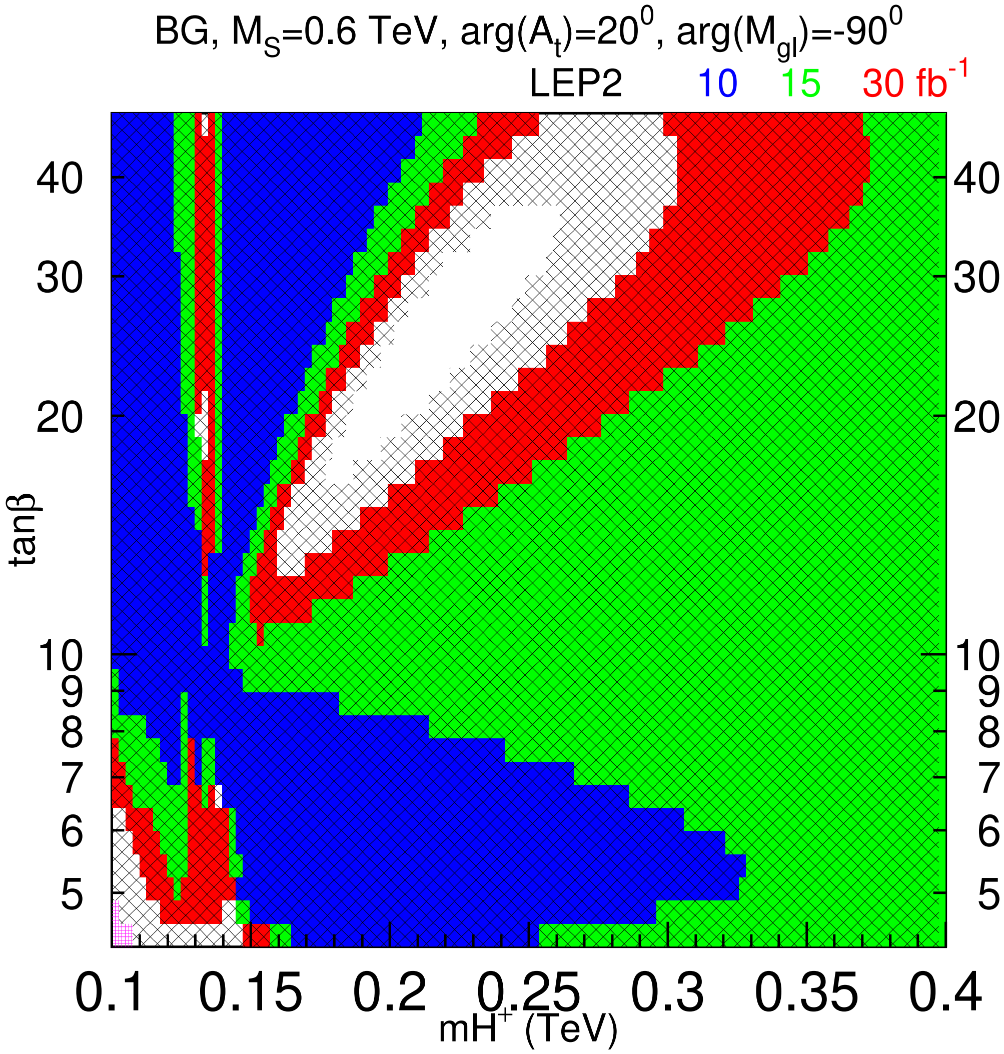
– CPV makes more difficult to reconstruct param. of SUSY particles from experimental data

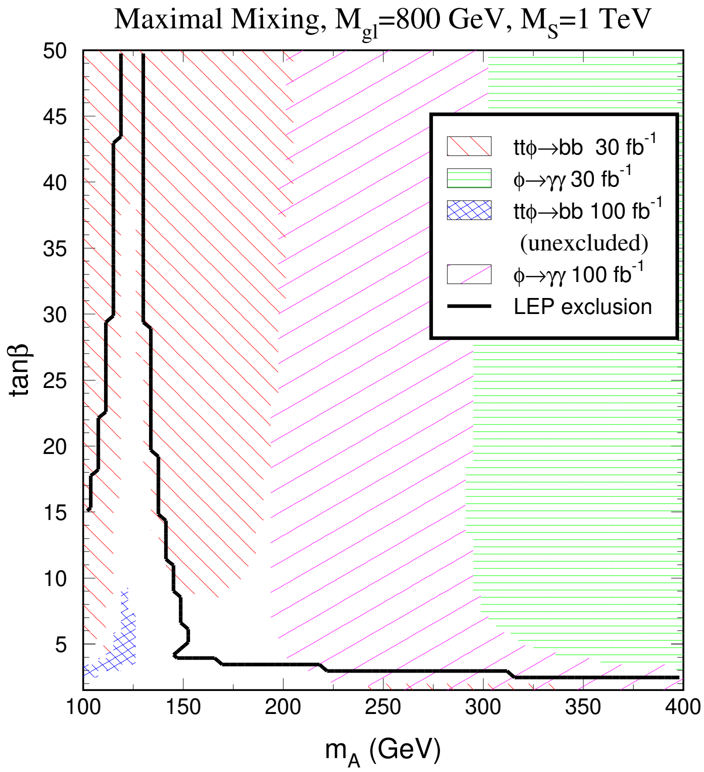
Effect of CP-violating Phases on the Tevatron Higgs Discovery Reach



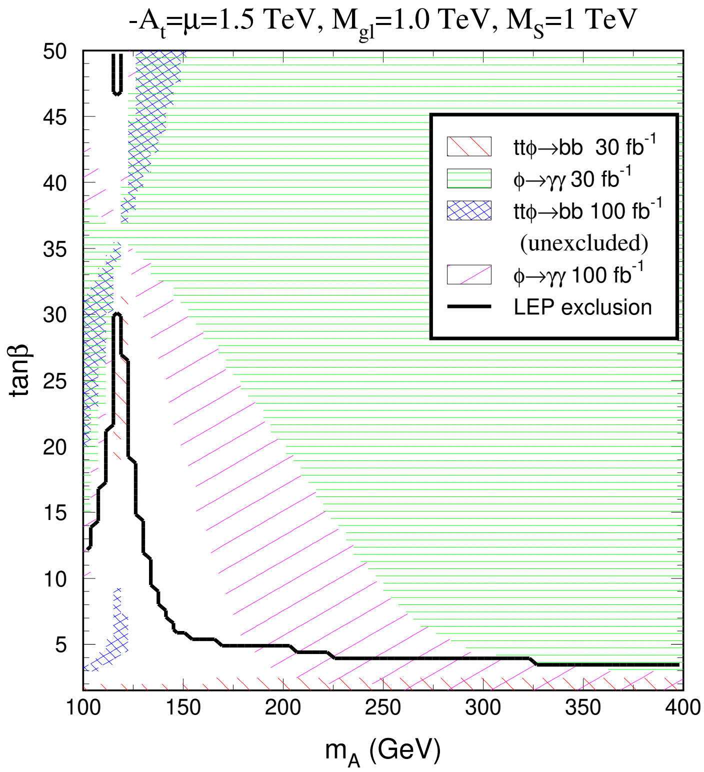

5σ Discovery, Maximal Mixing Scenario
15 fb-1
20 fb-1
30 fb-1
tanβ
M_A (GeV)


MAX, M_S=1 TeV, arg(A_t)=0^0, arg(M_gl)=0^0
LEP2
10
15
30 fb-1
tanβ
mH+ (TeV)


BG, M_S=0.6 TeV, arg(A_t)=20^0, arg(M_{gl})=-90^0
LEP2
10
15
30 fb^{-1}
tanβ
40
30
20
10
9
8
7
6
5
0.1
0.15
0.2
0.25
0.3
0.35
0.4
mH^+ (TeV)

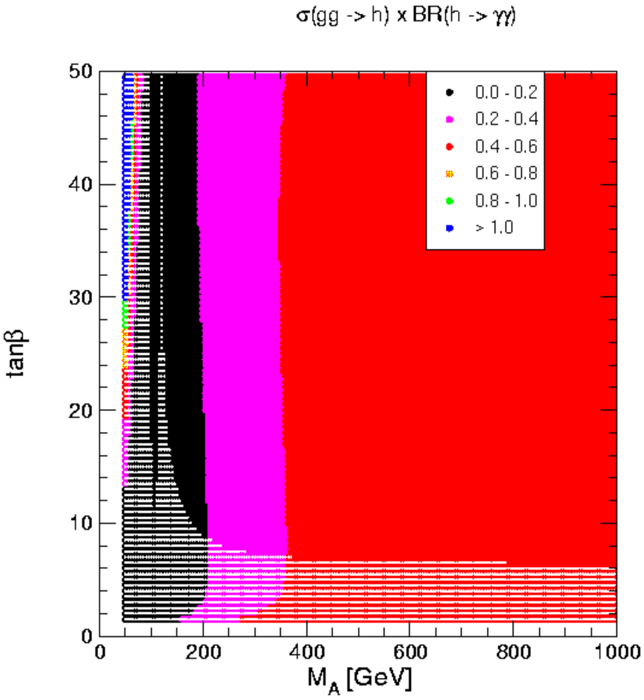


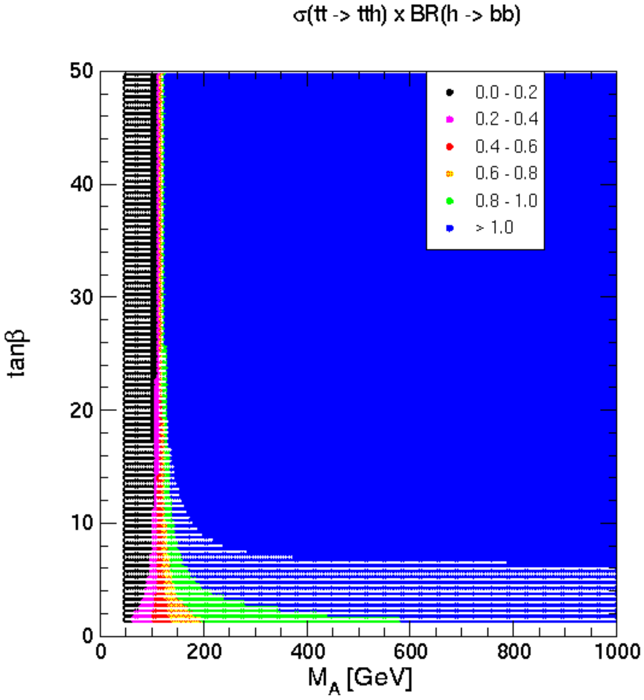
Maximal Mixing, M$_{gl}$=800 GeV, M$_S$=1 TeV
tanβ
m$_A$ (GeV)
ttφ→bb 30 fb^{-1}
φ→γγ 30 fb^{-1}
ttφ→bb 100 fb^{-1}
(unexcluded)
φ→γγ 100 fb^{-1}
LEP exclusion



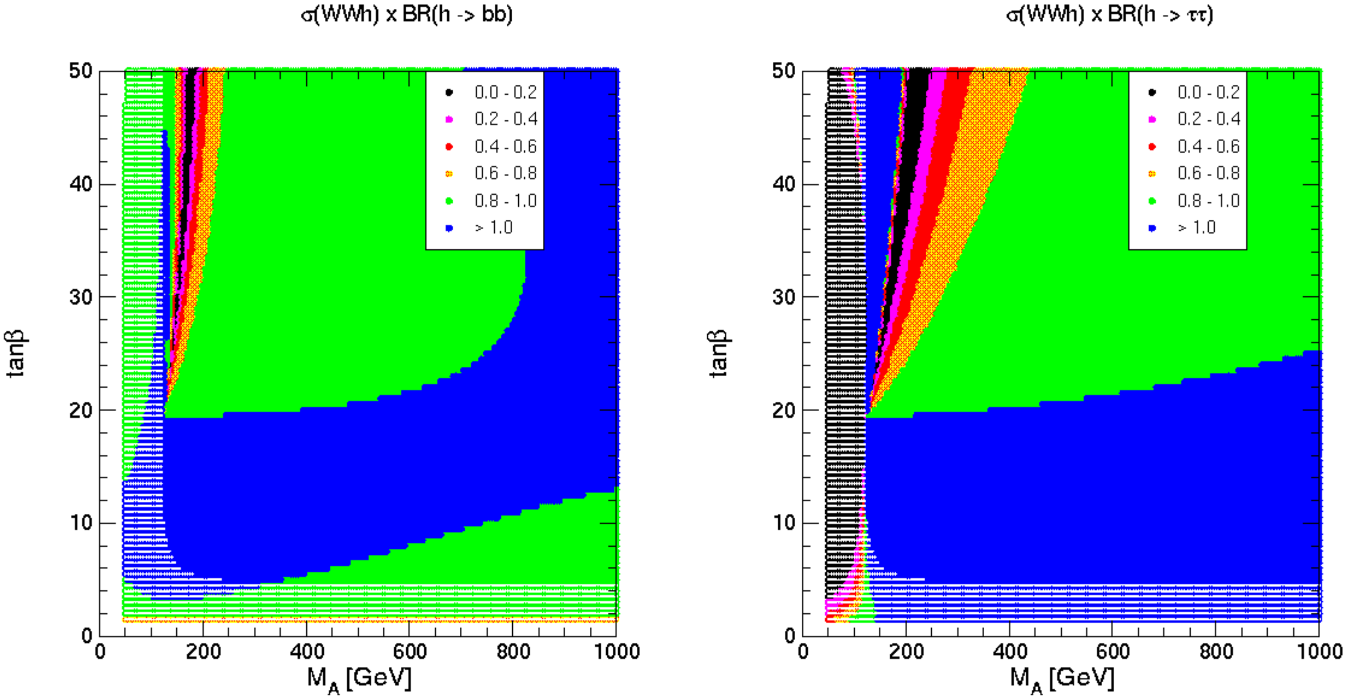
-A$_t$=μ=1.5 TeV, M$_{gl}$=1.0 TeV, M$_S$=1 TeV
tanβ
m$_A$ (GeV)
ttφ→bb 30 fb^{-1}
φ→γγ 30 fb^{-1}
ttφ→bb 100 fb^{-1}
(unexcluded)
φ→γγ 100 fb^{-1}
LEP exclusion

‘gluophobic Higgs scenario’





‘small $\alpha_{\rm eff}$ Higgs scenario’



Conclusions

Tevatron Run 2 $\Longrightarrow$ very rich and broad physics potential

– For a SM Higgs, test the region of mass preferred by precision data with 10 fb^{-1} of total integrated luminosity

– With 2 fb^{-1} can test LEP hint of a Higgs with mass of about 115 GeV

and with 5 (15) fb^{-1} can confirm such a SM Higgs at the 3 (5) sigma level

– With 5 fb^{-1} can explore most of the MSSM parameters space via SM-like Higgs searches
• Wh/H and Zh/H with $H, h \to b\bar{b}$

and with 15 to 20 fb^{-1} has discovery reach of a SM-like Higgs over a vast region of SUSY parameter space.

– Search for non-SM Higgs bosons in a variety of channels

- $b\bar{b}H, h, A$ with $H, h, A \to b\bar{b},\ \tau^+\tau^-$;
- $gg \to h, H, A$, with $h, H, A \to \tau\tau$;
- $\bar{t}H^+b$, with $H^+ \to \tau^+\nu,\ t\bar{b}$.

with sensitivity up to masses of about 300 GeV.

– If nature is kind, the Tevatron has a real chance of discovering one or more Higgs bosons in the coming years !