# Distinguishing an MSSM Higgs from a SM Higgs at a Linear Collider

Heather Logan* (M. Carena, H. Haber, S. Mrenna)
*Fermilab*

Linear Collider Workshop 2000
Fermilab, October 24 - 28, 2000

- Distinguish MSSM Higgs from SM Higgs by measuring its BRs
- Radiative corrections to the MSSM Higgs sector affect the BRs:
  → dependence on SUSY parameters as well as $M_A$ and $\tan\beta$
- How well can a LC do in various scenarios

Talk available at http://www-theory.fnal.gov/people/logan/lcws.ps.gz

Two sources of contributions to $h^0$ BRs:

- Renormalization of Higgs mass matrix $\to$ mixing angle $\alpha$:
  Radiative corrections well known up to two loops
  Okada, Yamaguchi, Yanagida; Ellis, Ridolfi, Zwirner; Li, Sher; Barbieri, Frigeni; Drees, Nojiri; Casas, Espinosa, Quiros, Riotto; Brignole, Ellis, Ridolfi, Zwirner; Zhang; Espinosa, Zhang; Gunion, Turski; Haber, Hempfling; Brignole; Diaz, Haber; Berger; Chankowski, Pokorski, Rosiek; Yamada; Dabelstein; Pierce, Bagger, Matchev, Zhang; Hempfling, Hoang; Heinemeyer, Hollik, Weiglein; Carena, Heinemeyer, Wagner, Weiglein; Barbieri, Frigeni, Caravaglios; Pierce, Papadopoulos, Johnson; Sasaki, Carena, Wagner; Hempfling; Kodaira, Yasui, Sasaki; Espinosa, Quiros; Carena, Espinosa, Quiros, Wagner; Carena, Quiros, Wagner; Carena, Haber, Heinemeyer, Hollik, Wagner, Weiglein

- Vertex corrections to fermion Yukawa couplings:
  Corrections to the relation between the fermion masses and their Yukawa couplings. $\tan\beta$ enhanced for down-type fermions $\to$ can be very significant.
  Coarasa, Jimenez, Sola; Jimenez, Sola; Bartl, Eberl, Hikasa, Kon, Majerotto, Yamada; Hall, Rattazzi, Sarid; Hempfling; Carena, Olechowski, Pokorski, Wagner; Pierce, Bagger, Matchev, Zhang; Dabelstein; Haber, Herrero, H.L., Penaranda, Rigolin, Temes; Heinemeyer, Hollik, Weiglein

We use a version of HDECAY with these corrections included, put together by Steve Mrenna.

## Radiatively corrected Higgs mass matrix and $\alpha$

The tree-level Higgs mass matrix

$$\mathcal{M}_0^2 = \begin{pmatrix} m_A^2 s_\beta^2 + m_Z^2 c_\beta^2 & -(m_A^2+m_Z^2) s_\beta c_\beta \\ -(m_A^2+m_Z^2) s_\beta c_\beta & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 \end{pmatrix} = \begin{pmatrix} \mathcal{M}_{11}^2 & \mathcal{M}_{12}^2 \\ \mathcal{M}_{12}^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

is diagonalized by the mixing angle $\alpha$:

$$s_\alpha c_\alpha = \frac{\mathcal{M}_{12}^2}{\sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\det\mathcal{M}^2}}, \qquad c_\alpha^2 - s_\alpha^2 = \frac{\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2}{\sqrt{(\mathrm{Tr}\mathcal{M}^2)^2 - 4\det\mathcal{M}^2}}$$

If $\mathcal{M}_{12}^2 \to 0$, then either $\sin\alpha \to 0$ or $\cos\alpha \to 0$.

Radiatively corrected $\mathcal{M}_{12}^2$: dominant one-loop top squark effects plus two-loop, leading log effects [Carena, Mrenna, Wagner] (approx.):

$$\mathcal{M}_{12}^2 \simeq -[m_A^2 + m_Z^2] s_\beta c_\beta$$
$$- \left[ \frac{3h_t^4 v^2}{48\pi^2 M_S} \mu x_t (6 - x_t a_t) s_\beta^2 - \frac{3h_t^2 m_Z^2}{32\pi^2} \mu x_t \right] \left[ 1 + \frac{9h_t^2 - 32 g_s^2}{32\pi^2} \ln\left( \frac{M_S^2}{m_t^2} \right) \right]$$

($a_t = A_t/M_S$, $x_t = X_t/M_S$) $\to$ $\alpha$ gets corrected. (Full result used in numerical calcs.)

$m_t^4$-dependent rad. corrs. to $\mathcal{M}_{12}^2$ depend strongly on the sign of $\mu X_t$. (Note $A_t \simeq X_t$ for large $\tan\beta$ and $\mu$ not too big.)

$|a_t| \lesssim \sqrt{11/2} \to hbb$ coupling suppressed for $\mu A_t < 0$ and enhanced for $\mu A_t > 0$

$|a_t| \gtrsim \sqrt{11/2} \to$ vice versa

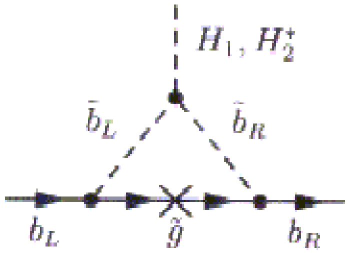
Loinaz, Wells; Kane, Kribs, Martin, Wells; Baer, Wells; Babu, Kolda

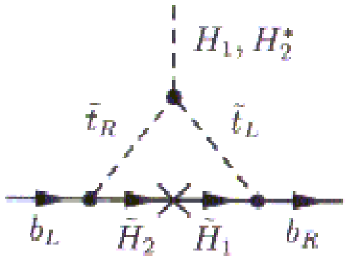
Correction to $\alpha$ affects BR($b$) and BR($\tau$) in the same way: Ignoring the correction to the Yukawa couplings (next slide),

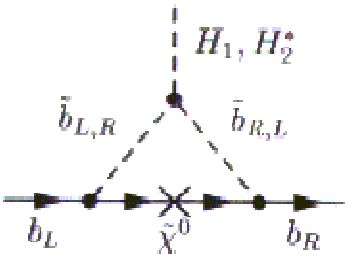
$hb\bar{b}$, $h\tau^+\tau^- \sim -(\sin\alpha/\cos\beta)\times$ SM coupling.

## $\Delta_b$ and corrections to Yukawa couplings

In unbroken supersymmetry, $b$ quarks couple only to $\Phi_d^0$. But SUSY is broken, and the $b$ quarks receive a small coupling to $\Phi_u^0$ from radiative corrections:




The effective Yukawa Lagrangian becomes (keeping only dimension $\leq$ 4 terms):

$$-\mathcal{L}_{\text{Yuk.}} \simeq h_b \Phi_d^0 \bar{b} b + (\Delta h_b) \Phi_u^0 \bar{b} b$$

Although $\Delta h_b$ is loop suppressed compared to $h_b$, for sufficiently large $\tan\beta = v_u/v_d$ the contribution of both terms to the $b$ mass can be comparable:

$$m_b = \frac{h_b v_d}{\sqrt{2}} + \frac{(\Delta h_b) v_u}{\sqrt{2}} = \frac{h_b v_d}{\sqrt{2}}(1 + \Delta_b)$$

Main contributions to $\Delta_b$ come from a bottom squark-gluino loop and a top squark-higgsino loop. Neglecting terms suppressed by powers of $1/M_{SUSY}$,

$$\Delta_b \simeq \frac{2\alpha_s}{3\pi} M_{\tilde{g}} \mu \tan\beta I(M_{\tilde{b}_1}, M_{\tilde{b}_2}, M_{\tilde{g}}) + \frac{Y_t}{4\pi} A_t \mu \tan\beta I(M_{\tilde{t}_1}, M_{\tilde{t}_2}, \mu)$$

$(Y_t \equiv h_t^2/4\pi)$

$$I(a,b,c) = \frac{a^2b^2 \ln(a^2/b^2) + b^2c^2 \ln(b^2/c^2) + c^2a^2 \ln(c^2/a^2)}{(a^2-b^2)(b^2-c^2)(a^2-c^2)} > 0$$

There are similar corrections to the relation between the $\tau$ mass and its Yukawa coupling:

$$m_\tau = \frac{h_\tau v_d}{\sqrt{2}}(1 + \Delta_\tau)$$

$\Delta_\tau$ comes from a tau slepton-neutralino loop and a tau sneutrino-chargino loop; it is expected to be much smaller than $\Delta_b$ because it depends on the electroweak gauge couplings:

$$\Delta_\tau = \frac{\alpha_1}{4\pi} M_1 \mu \tan\beta I(M_{\tilde{\tau}_1}, M_{\tilde{\tau}_2}, M_1) + \frac{\alpha_2}{4\pi} M_2 \mu \tan\beta I(M_{\tilde{\nu}_\tau}, M_2, \mu)$$

$\rightarrow$ we do not include it in our analysis.

The couplings to $h^0$ are modified by $\Delta_b$, $\Delta_\tau$:

$$g_{hbb} = \frac{g m_b \sin\alpha}{2 m_W \cos\beta} \frac{1}{1+\Delta_b} \left[1 - \frac{\Delta_b}{\tan\alpha \tan\beta}\right]$$

$$g_{h\tau\tau} = \frac{g m_\tau \sin\alpha}{2 m_W \cos\beta} \frac{1}{1+\Delta_\tau} \left[1 - \frac{\Delta_\tau}{\tan\alpha \tan\beta}\right] \simeq \frac{g m_\tau \sin\alpha}{2 m_W \cos\beta}$$

Partial widths are given by:

$$\Gamma(b) \propto g_{hbb}^2 \quad \text{(modulo kinematics)}$$
$$\Gamma(\tau) \propto g_{h\tau\tau}^2$$

Branching ratios:

$$BR = \frac{\Gamma}{\Gamma_{total}}$$

Even if $\Delta_\tau$ is negligible, BR($\tau$) is still affected:
$\Delta_b$ changes $\Gamma(b)$ and thus affects all the BRs by changing the $h^0$ total width.

## Some generalities:

- Correction to $\alpha$ depends on sign of $\mu A_t$, while $\Delta_b$ depends on sign of $\mu M_{\tilde{g}}$.
  $\rightarrow$ Flip sign of both $\mu$ and $A_t \rightarrow \alpha$ remains the same while $\Delta_b$ flips sign.

- Correction to $\alpha$ affects BR($b$) and BR($\tau$) in the same way.
  In contrast, $\Delta_b$ affects $\Gamma(b)$ but not $\Gamma(\tau)$; however it affects all the BRs because it changes the total width.

Three "benchmark" scenarios:

1. Minimal stop mixing, $X_t = 0$
   Parameters: $M_S = 1.5$ TeV, $M_{\tilde{g}} = 1$ TeV, $\mu = -200$ GeV, $M_2 = 200$ GeV

2. Maximal mixing, $X_t = \sqrt{6} M_S$ – Maximises $h^0$ mass
   Parameters: $M_S = 1$ TeV, $M_{\tilde{g}} = 1$ TeV, $\mu = -200$ GeV, $M_2 = 200$ GeV

3. Large $\mu$, $A_t \rightarrow$ large contributions to both $\alpha$ and $\Delta_b$
   Parameters: $M_S = 1$ TeV, $M_{\tilde{g}} = 500$ GeV, $M_2 = 200$ GeV, $\mu = -A_t = \pm 1.2$ TeV

We plot contours of:

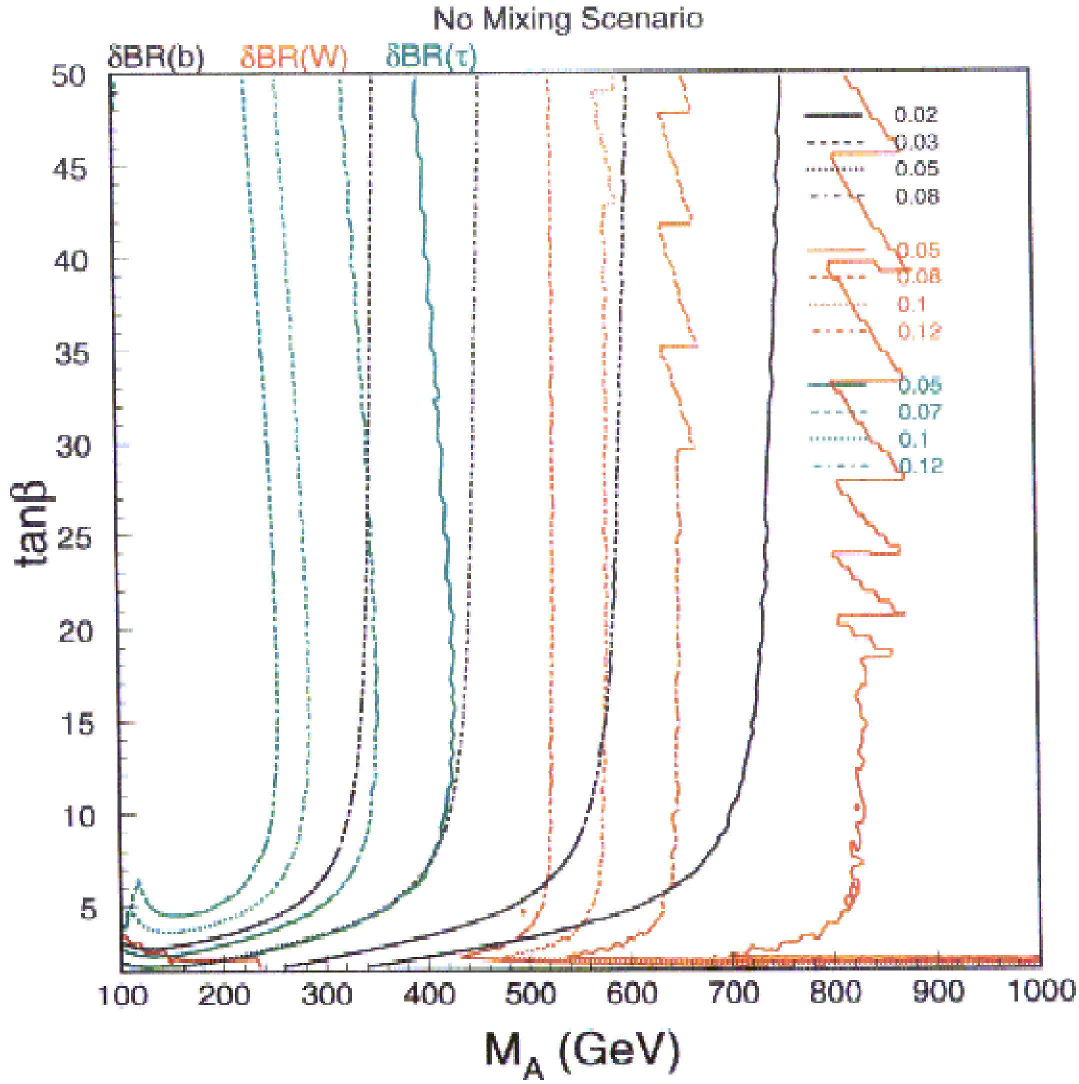
$$\frac{|BR(MSSM) - BR(SM)|}{BR(SM)}$$

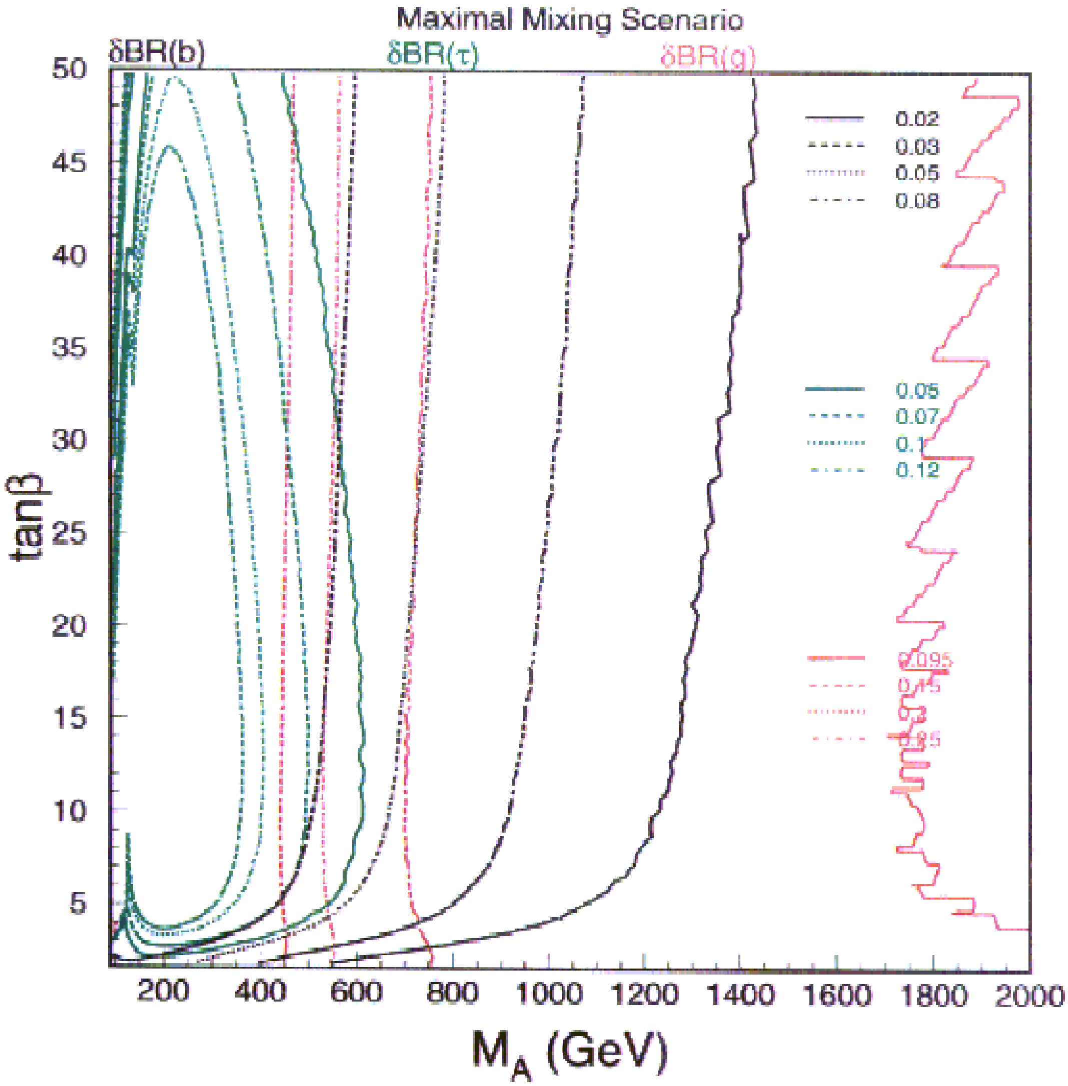
over the $M_A$ - $\tan\beta$ plane.
We use HDECAY with $\Delta_b$ corrections inside.
Plots made by Steve Mrenna.

Expected LC precision for BRs:

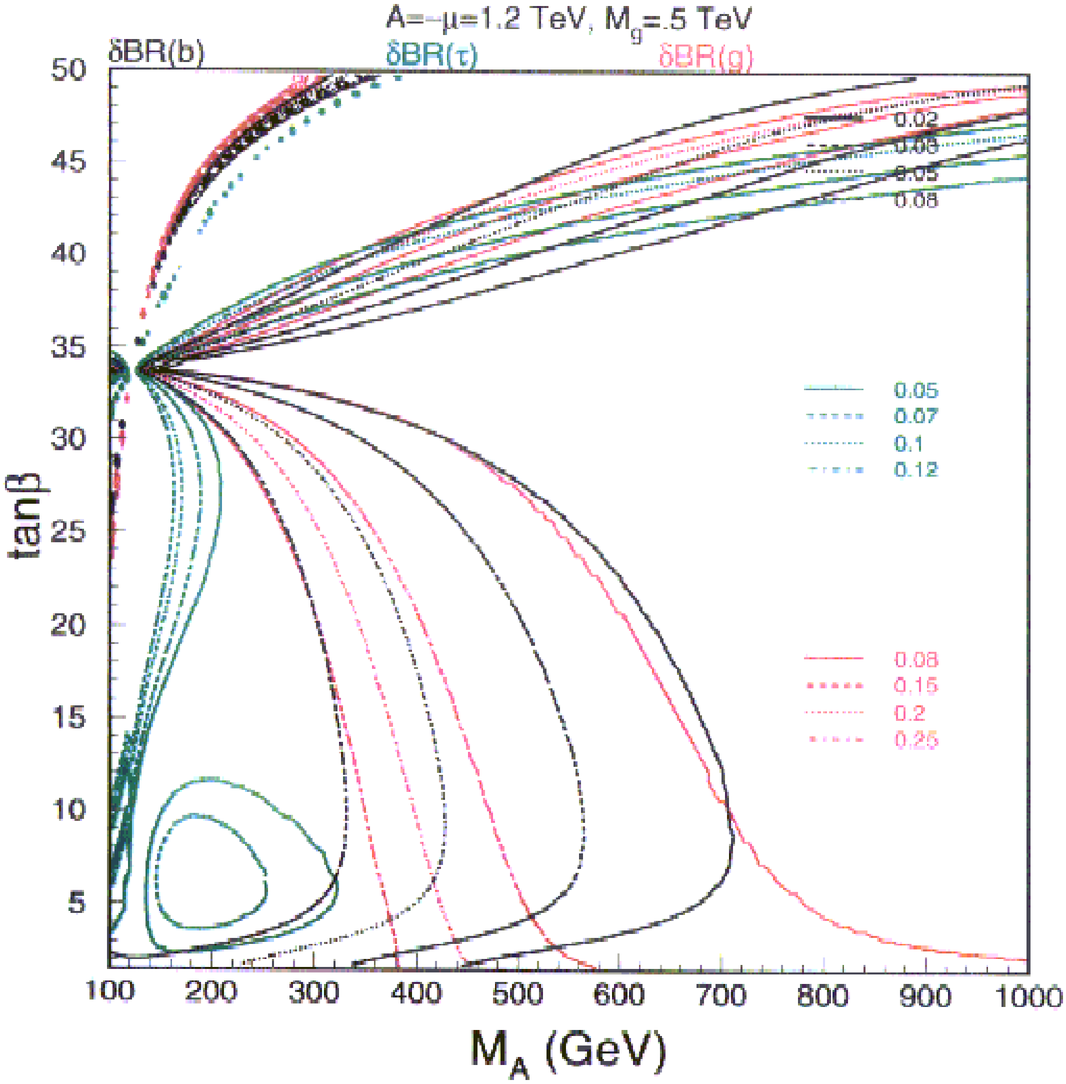
| BR | (a) | (b) |
|---|---|---|
| bb | 3% | 2.4% |
| $WW^*$ | 8% | 5.4% |
| $\tau\tau$ | 7% | 8.3 - 13.5% |
| cc | 15% | – |
| gg | 8% | 5.5% |
| $\gamma\gamma$ | 22% | – |

(a) Rick Van Kooten at March LC meeting at LBL for SM $H^0$ at 120 GeV with $\sqrt{s} = 500$ GeV and 200 $\text{fb}^{-1}$
(b) Marco Battaglia, LCWS99, Sitges: for SM $H^0$ at 120 GeV with $\sqrt{s} = 350$ or 500 GeV and 500 $\text{fb}^{-1}$

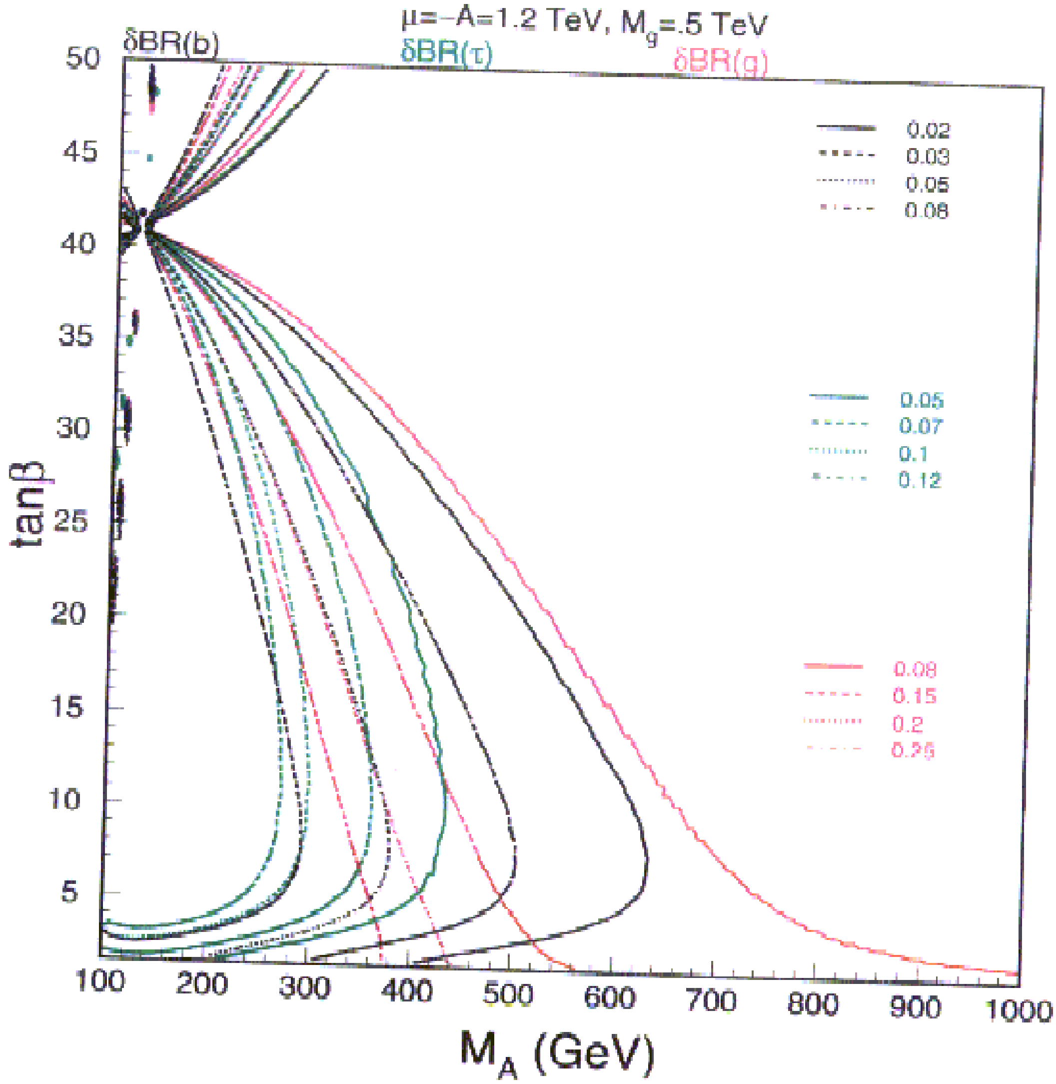

No Mixing Scenario
δBR(b)
δBR(W)
δBR(τ)
0.02
0.03
0.05
0.08
0.05
0.08
0.1
0.12
0.05
0.07
0.1
0.12
tanβ
M_A (GeV)


Maximal Mixing Scenario
δBR(b)
δBR(τ)
δBR(g)
tanβ
M_A (GeV)
0.02
0.03
0.05
0.08
0.05
0.07
0.1
0.12
0.095
50
45
40
35
30
25
20
15
10
5
200
400
600
800
1000
1200
1400
1600
1800
2000

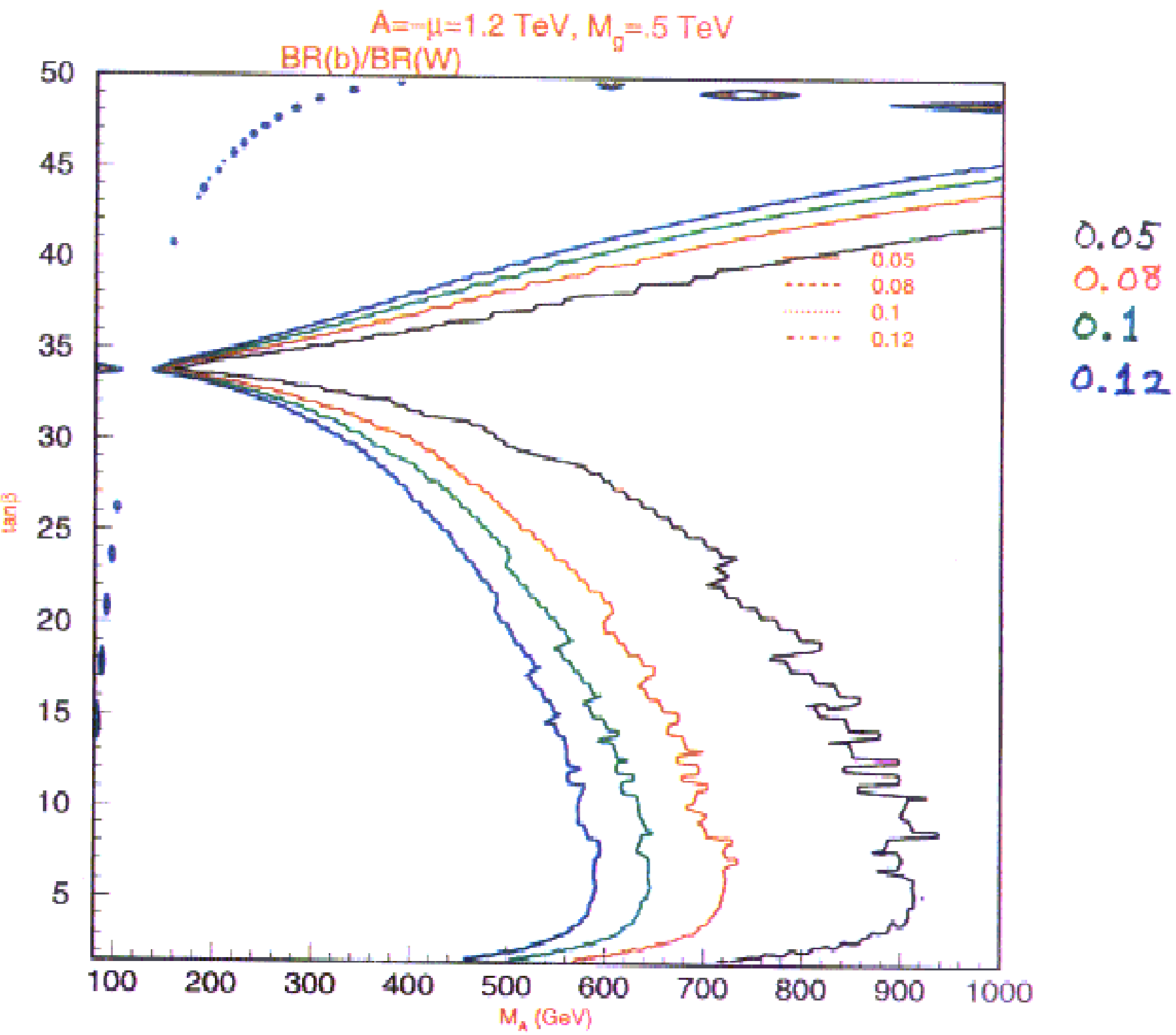
Large $\mu$ and $A_t$ scenario with $\mu < 0$ ($y_b$ increased)



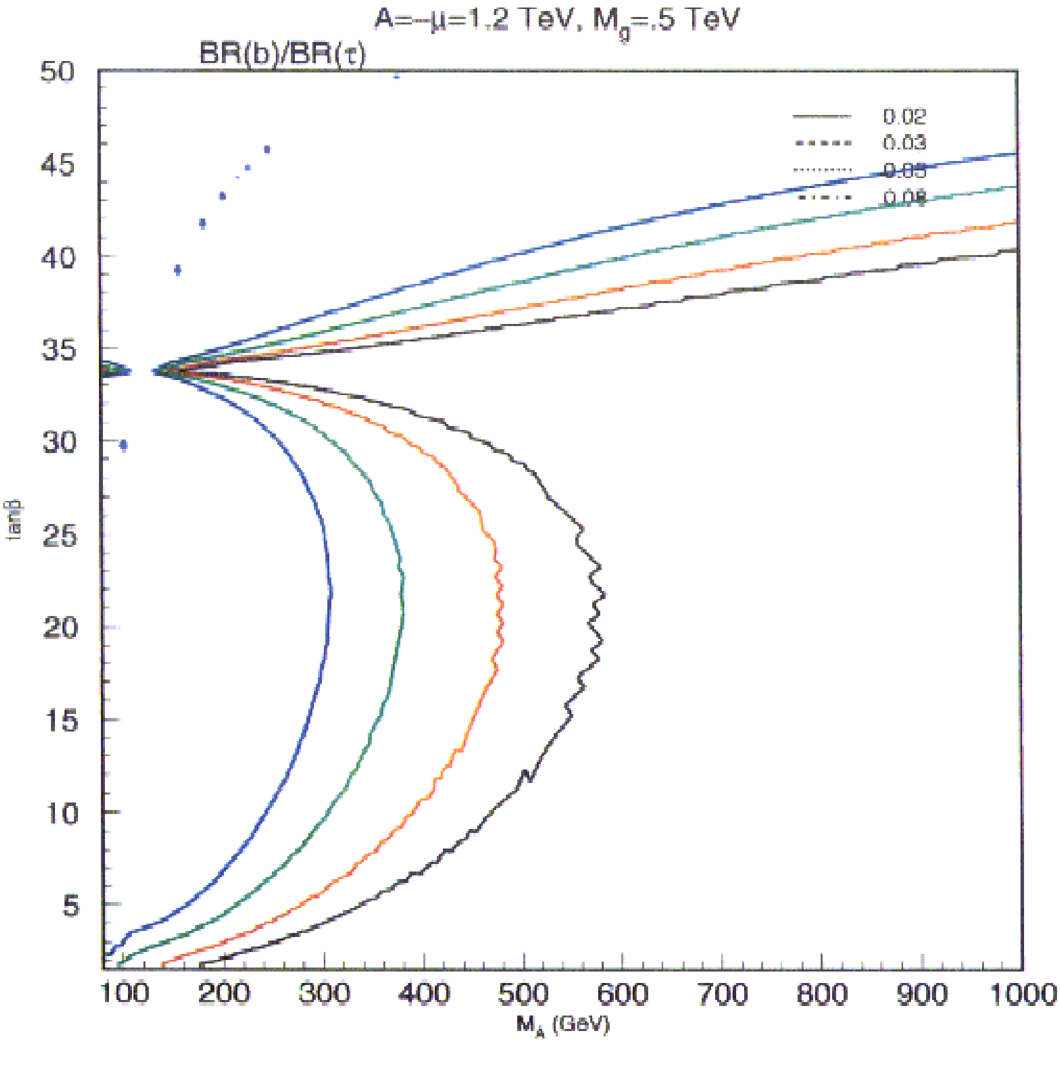
Large $\mu$ and $A_t$ scenario with $\mu > 0$ ($y_b$ decreased)



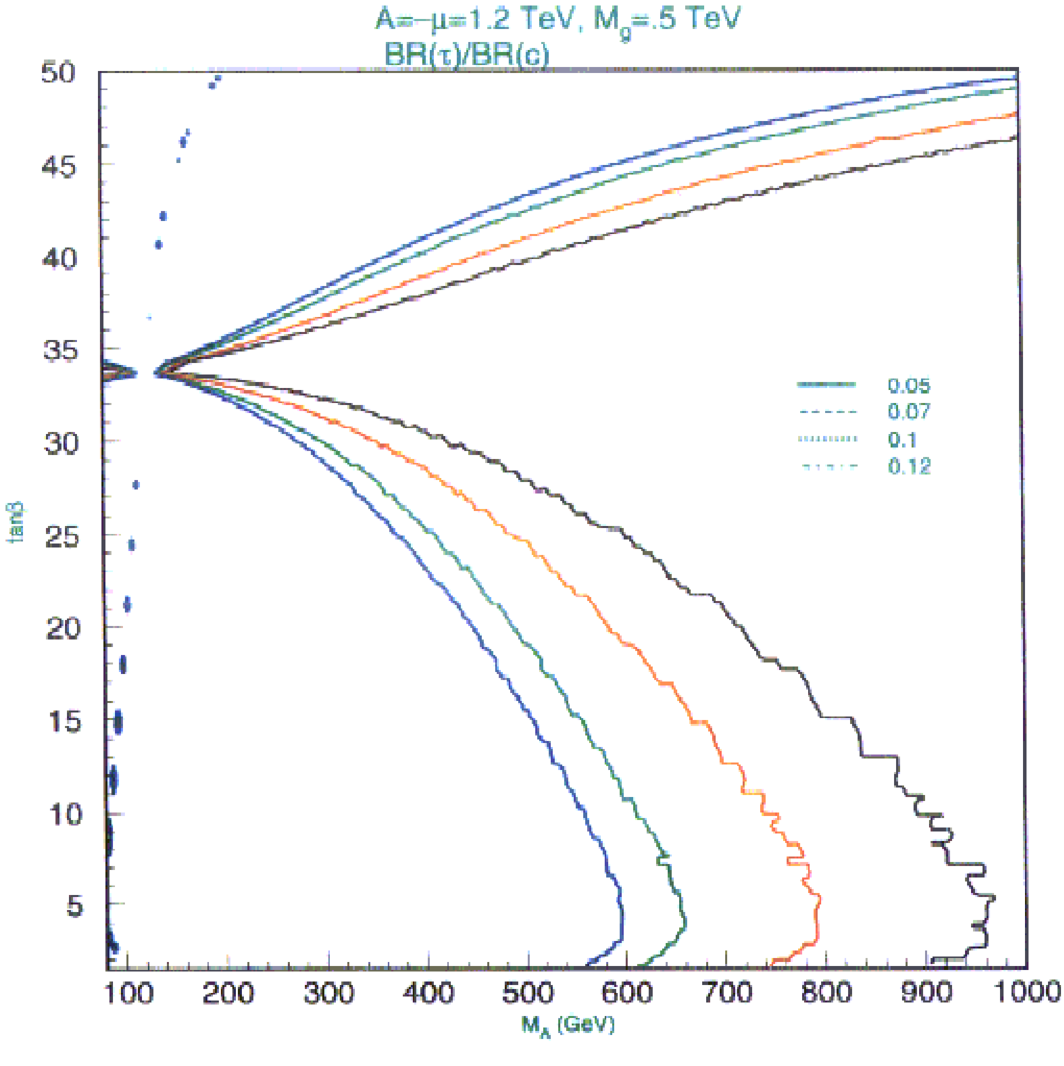
Measuring ratios of BRs can increase the sensitivity:



Measuring ratios of BRs can increase the sensitivity:



Measuring ratios of BRs can increase the sensitivity:



Can extract $\Delta_b$ in some regions of parameter space:

$$\frac{g_{hbb}}{g_{hbb}^{SM}} = -\frac{\sin\alpha}{\cos\beta}\frac{1}{1+\Delta_b}\left[1 - \frac{\Delta_b}{\tan\alpha\tan\beta}\right]$$

$$\frac{g_{h\tau\tau}}{g_{h\tau\tau}^{SM}} = -\frac{\sin\alpha}{\cos\beta}$$

so,

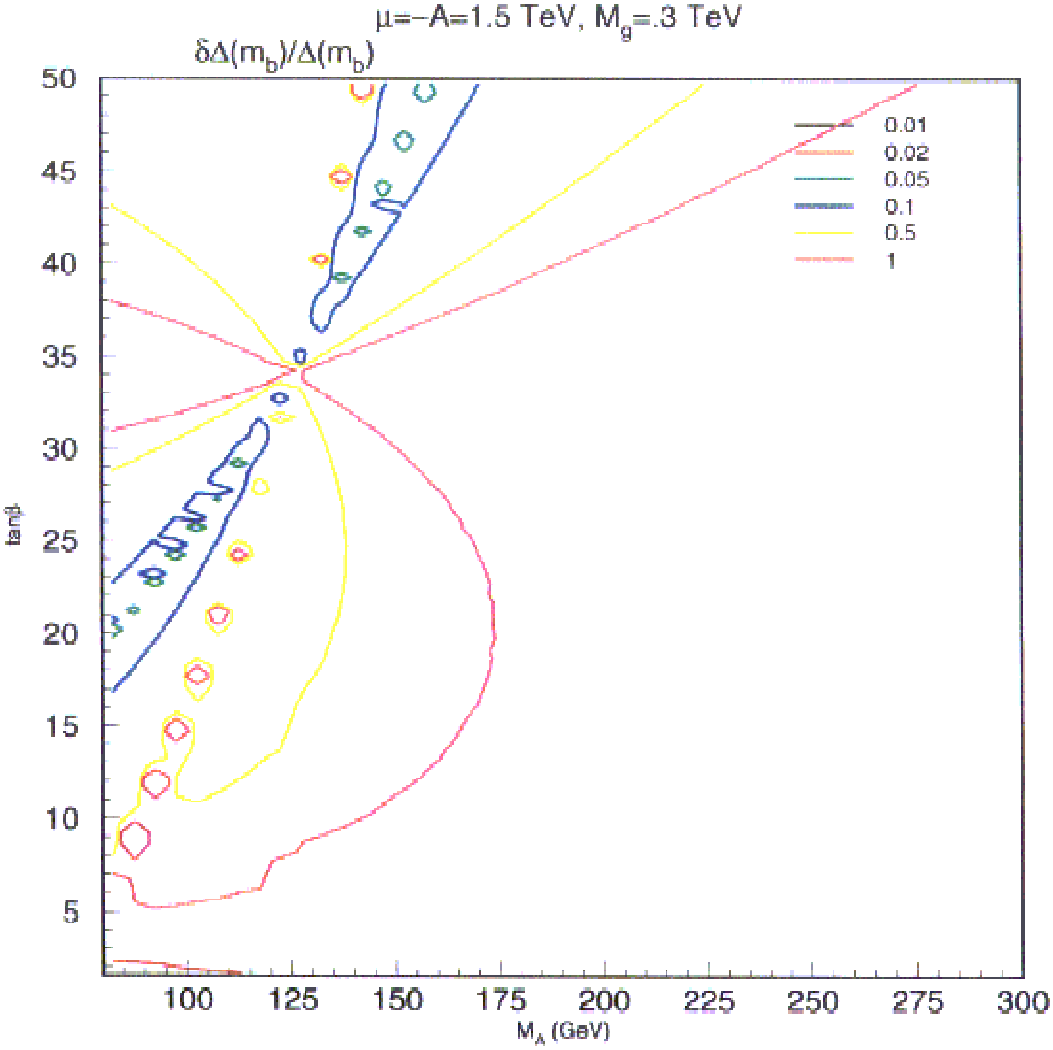
$$\frac{g_{hbb}/g_{hbb}^{SM}}{g_{h\tau\tau}/g_{h\tau\tau}^{SM}} = \frac{1}{1+\Delta_b}\left[1 - \frac{\Delta_b}{\tan\alpha\tan\beta}\right]$$

Get this from ratios of branching ratios:

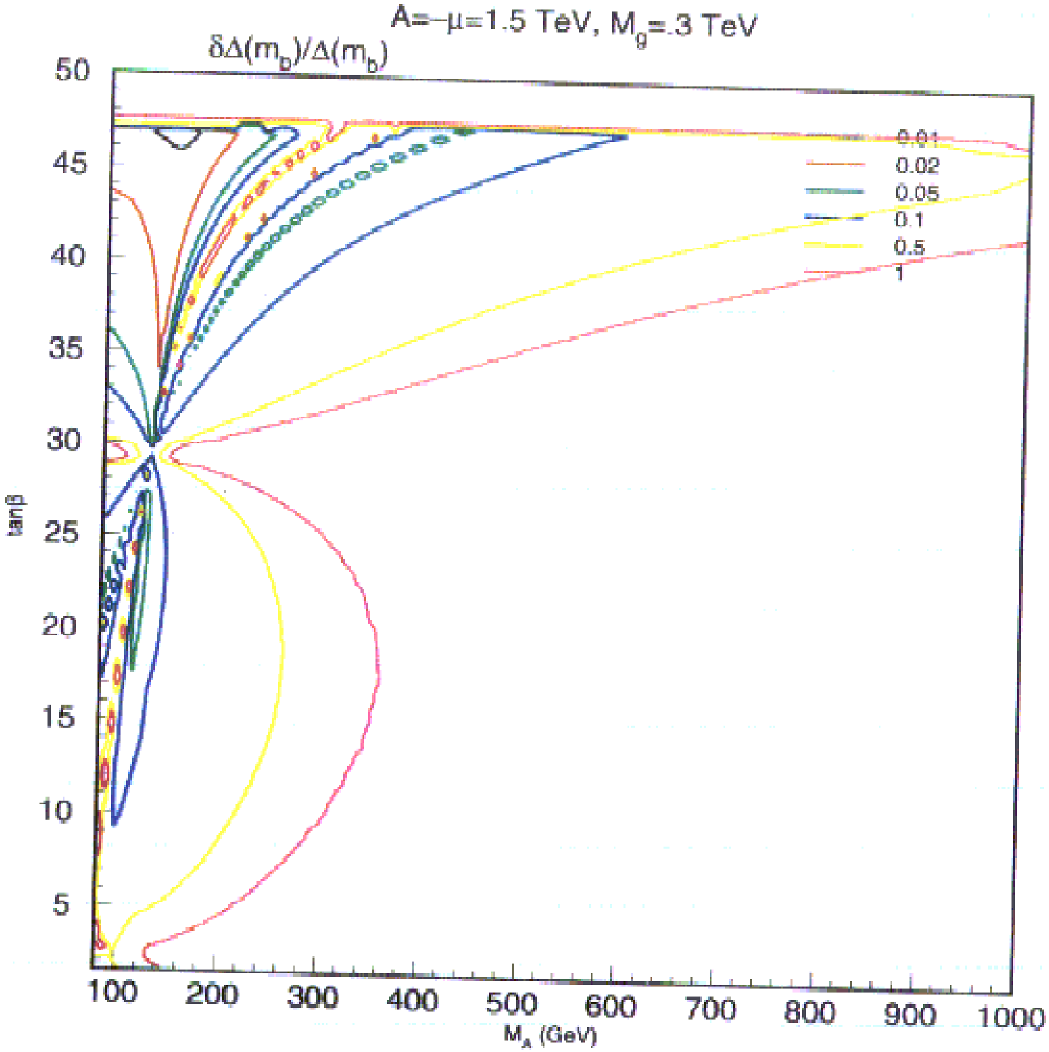
$$\frac{BR(b)/BR(b)_{SM}}{BR(\tau)/BR(\tau)_{SM}} = \left(\frac{g_{hbb}/g_{hbb}^{SM}}{g_{h\tau\tau}/g_{h\tau\tau}^{SM}}\right)^2 = \left(\frac{1}{1+\Delta_b}\left[1 - \frac{\Delta_b}{\tan\alpha\tan\beta}\right]\right)^2$$

Still need $\tan\alpha\tan\beta$: extract it from the ratio of the $\tau\tau$ and $cc$ branching ratios:

$$\frac{BR(\tau)/BR(\tau)_{SM}}{BR(c)/BR(c)_{SM}} = \left(\frac{g_{h\tau\tau}/g_{h\tau\tau}^{SM}}{g_{hcc}/g_{hcc}^{SM}}\right)^2 = \left(\frac{\sin\alpha/\cos\beta}{\cos\alpha/\sin\beta}\right)^2 = (\tan\alpha\tan\beta)^2$$



μ=-A=1.5 TeV, M_g=.3 TeV
δΔ(m_b)/Δ(m_b)
0.01
0.02
0.05
0.1
0.5
1
tanβ
M_A (GeV)


A=−μ=1.5 TeV, M_g=.3 TeV
δΔ(m_b)/Δ(m_b)
50
45
40
35
30
25
20
15
10
5
tanβ
100
200
300
400
500
600
700
800
900
1000
M_A (GeV)
0.01
0.02
0.05
0.1
0.5
1

# Conclusions

- Different MSSM parameter space regions
  → different reach in distinguishing SM from MSSM Higgs.
  $\sqrt{s} = 500$ GeV, 200 fb$^{-1}$ (Van Kooten):
  - No mixing scenario is the usual benchmark: Can distinguish MSSM Higgs from SM Higgs up to $M_A \sim 600 - 700$ GeV using sensitivity to deviations from SM BR(W) (500 - 600 GeV with BR(b))
  - But you can do much better in some regions of parameter space: Can distinguish MSSM Higgs from SM Higgs up to $M_A \sim 900 - 1000$ GeV in the maximal mixing scenario using BR(b)
  - ... and in others you can do much worse: In the large $\mu$ and $A_t$ scenario it can be very hard to distinguish MSSM Higgs from SM Higgs at moderate $\tan\beta$, even for $M_A$ as light as 200 GeV.

- In some regions of parameter space, can extract $\Delta_b$ from the BR(b)/BR($\tau$) and BR($\tau$)/BR(c) measurements.
  More work being done.

- Important to measure all the BRs that we can as accurately as possible:
  $\rightarrow$ Different BRs more sensitive in different regions of parameter space
  $\rightarrow$ Ratios of BRs sometimes more sensitive than individual BRs

- Ultimately use Higgs sector (and SUSY sector) to do precision measurements of SUSY parameters.