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

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Outline:
Introduction
The MSSM Higgs sector
Higgs branching ratio measurements at a linear collider
SUSY parameter extraction
Conclusions

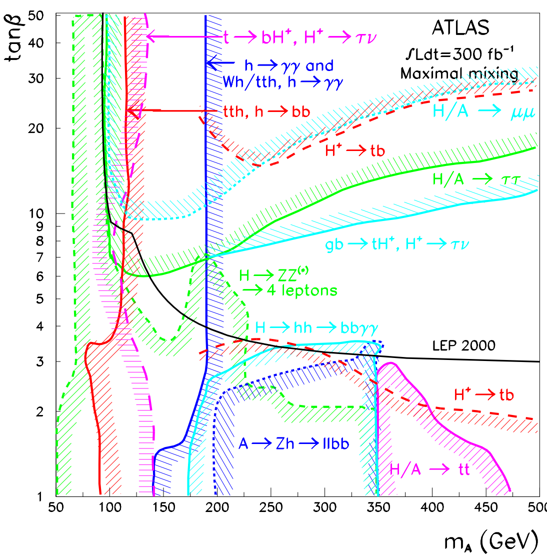
Based on work with M. Carena, H. Haber and S. Mrenna.

# Introduction

We consider the situation in which only one light, SM-like Higgs boson is discovered by the time that BR measurements are available from a LC.

Can we tell whether this Higgs boson is from the SM or MSSM?

There is a region of parameter space at moderate $\tan\beta$ where only the lightest MSSM Higgs $h^0$ would be discovered at the LHC:




(Preliminary plot from F. Gianotti)

Heavy Higgs search at a linear collider: $A^0H^0$, $H^+H^-$ pair produced when kinematically allowed.
For $m_A > \sqrt{s}/2$, $e^+e^- \to H^0A^0$ and $e^+e^- \to H^+H^-$ are kinematically forbidden.

Use LC measurements of Higgs properties to try to distinguish the MSSM $h^0$ from the SM Higgs.

# The MSSM Higgs sector

Two Higgs doublets, $H_u$ and $H_d$

$$H_u = \begin{pmatrix} \phi_u^+ \\ (v_u + \phi_u^{0,r} + i\phi_u^{0,i})/\sqrt{2} \end{pmatrix}$$

gives mass to up-type quarks

$$H_d^c = \begin{pmatrix} \phi_d^+ \\ (v_d + \phi_d^{0,r} + i\phi_d^{0,i})/\sqrt{2} \end{pmatrix}$$

gives mass to down-type quarks and charged leptons

8 degrees of freedom $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad$ $\tan\beta \equiv v_u/v_d$

EWSB: 3 d.o.f. get eaten by the $W^\pm, Z^0$, giving them mass: $m_W^2 = g^2(v_u^2 + v_d^2)/4$, $m_Z^2 = m_W^2/c_W^2$

$$\left.\begin{array}{l} G^\pm = \cos\beta\phi_d^\pm + \sin\beta\phi_u^\pm \\ G^0 = \cos\beta\phi_d^{0,i} + \sin\beta\phi_u^{0,i} \end{array}\right\} \text{would} - \text{be Goldstone bosons}$$

This leaves 5 physical d.o.f.:

$$H^\pm = -\sin\beta\phi_d^\pm + \cos\beta\phi_u^\pm \rightarrow \text{charged Higgs pair}$$
$$A^0 = -\sin\beta\phi_d^{0,i} + \cos\beta\phi_u^{0,i} \rightarrow \text{CP odd neutral}$$
$$h^0 = -\sin\alpha\phi_d^{0,r} + \cos\alpha\phi_u^{0,r} \rightarrow \text{lighter CP even}$$
$$H^0 = \cos\alpha\phi_d^{0,r} + \sin\alpha\phi_u^{0,r} \rightarrow \text{heavier CP even}$$

Two types of radiative corrections to $h^0$ BRs:

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

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

We use a version of HDECAY to which we have added the Yukawa vertex corrections both in the 2-loop mass matrix and the $b\bar{b}$ couplings.

## 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 $t$ and $\tilde{t}$ effects plus two-loop, leading log effects [Carena, Mrenna, Wagner] (approx.):

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

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

$m_t^4$-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.)

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

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

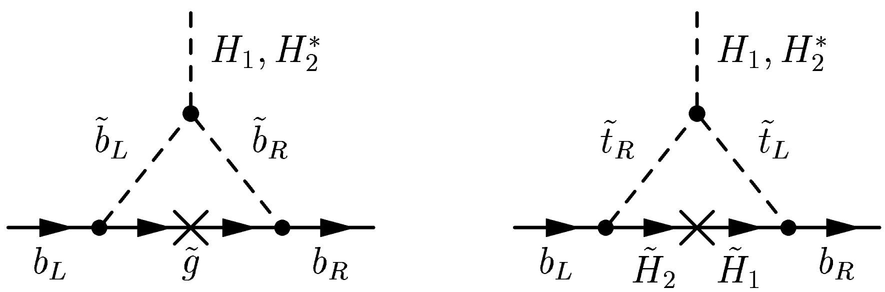
Loinaz, Wells; Kane, Kribs, Martin, Wells; Baer, Wells; Babu, Kolda

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 $H_d^0$. But SUSY is broken, and the $b$ quarks receive a small coupling to $H_u^0$ from radiative corrections:




[Hall, Rattazzi, Sarid]

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

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

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:

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

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

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

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

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

Note $I(m,m,m) = 1/2m^2$. [Carena, Mrenna, Wagner]

The $h^0 b\bar{b}$ coupling is modified by $\Delta_b$:

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

$$g_{h\tau\tau} \simeq \frac{g m_\tau \sin\alpha}{2 m_W \cos\beta}$$

Partial widths are given by: (modulo kinematics)

$$\Gamma(b) \propto 3 g_{hbb}^2$$
$$\Gamma(\tau) \propto g_{h\tau\tau}^2$$

Note that if $\Delta_b = 0$, $\Gamma(b)/\Gamma(\tau) = \mathrm{BR(b)}/\mathrm{BR}(\tau)$ is the same as in the SM.

# Sources of deviations in Higgs couplings

## 1. Two Higgs doublets

Decoupling limit of $m_A \gg m_Z$, also large $\tan\beta$:
$\cos(\beta-\alpha) \simeq -2cm_Z^2 \cot\beta/m_A^2$. [Haber, Nir]
$c$ parameterizes radiative corrections to $\alpha$.

$$\frac{g^2_{hWW}}{g^2_{hWW,SM}} = \sin^2(\beta-\alpha) \simeq 1 - \frac{4c^2 m_Z^4 \cot^2\beta}{m_A^4}$$

$$\frac{g^2_{hbb}}{g^2_{hbb,SM}} = (\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha))^2 \simeq 1 + \frac{4cm_Z^2}{m_A^2}$$

$$\frac{g^2_{htt}}{g^2_{htt,SM}} = (\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha))^2 \simeq 1 - \frac{4cm_Z^2 \cot^2\beta}{m_A^2}$$

## 2. Loop induced couplings

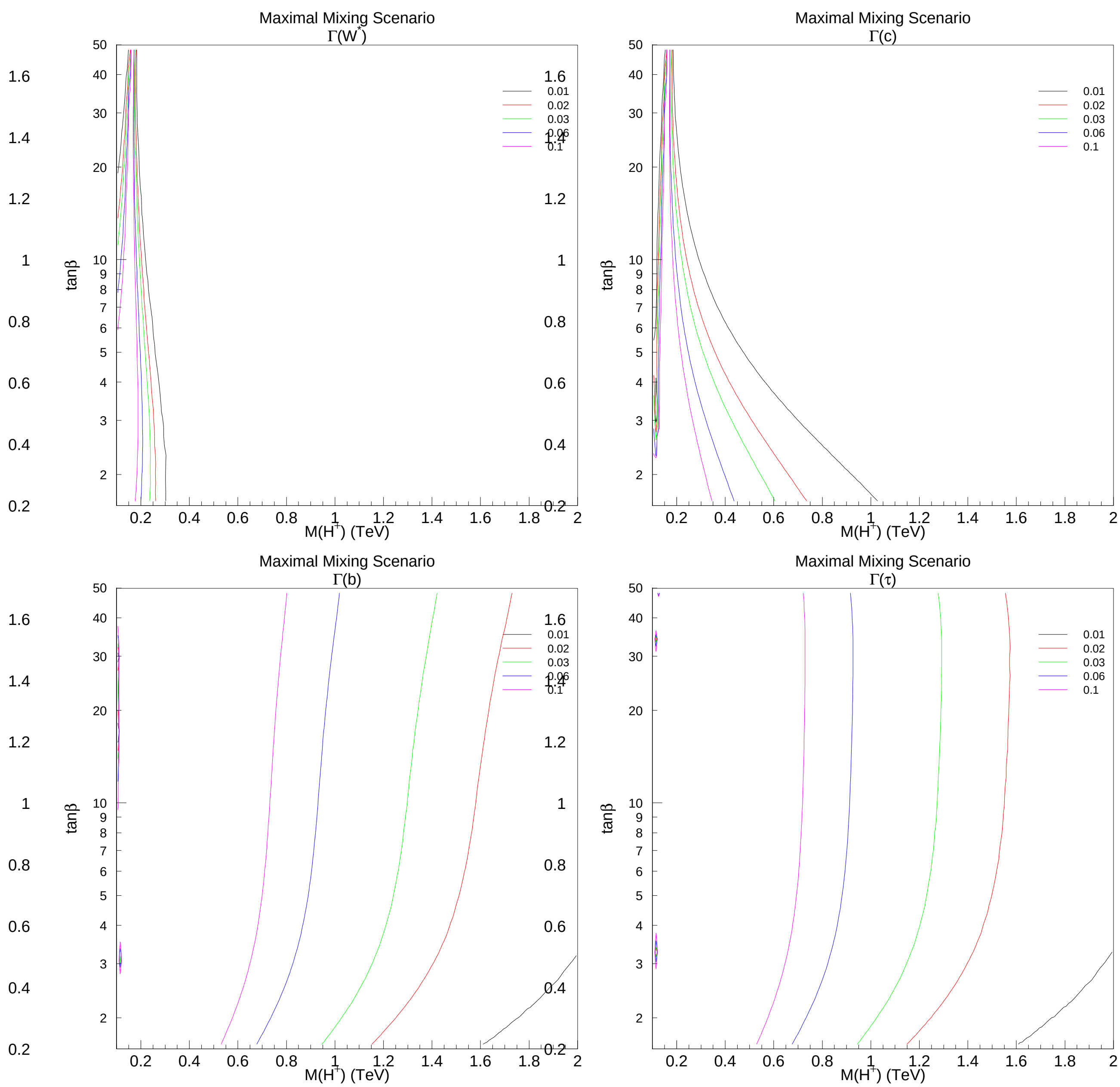
$h^0 \to gg$, $h^0 \to \gamma\gamma$

Squarks, charginos in the loop. Decouple like $1/M^2_{SUSY}$ due to heavy masses in the loop.

Three "benchmark" scenarios:

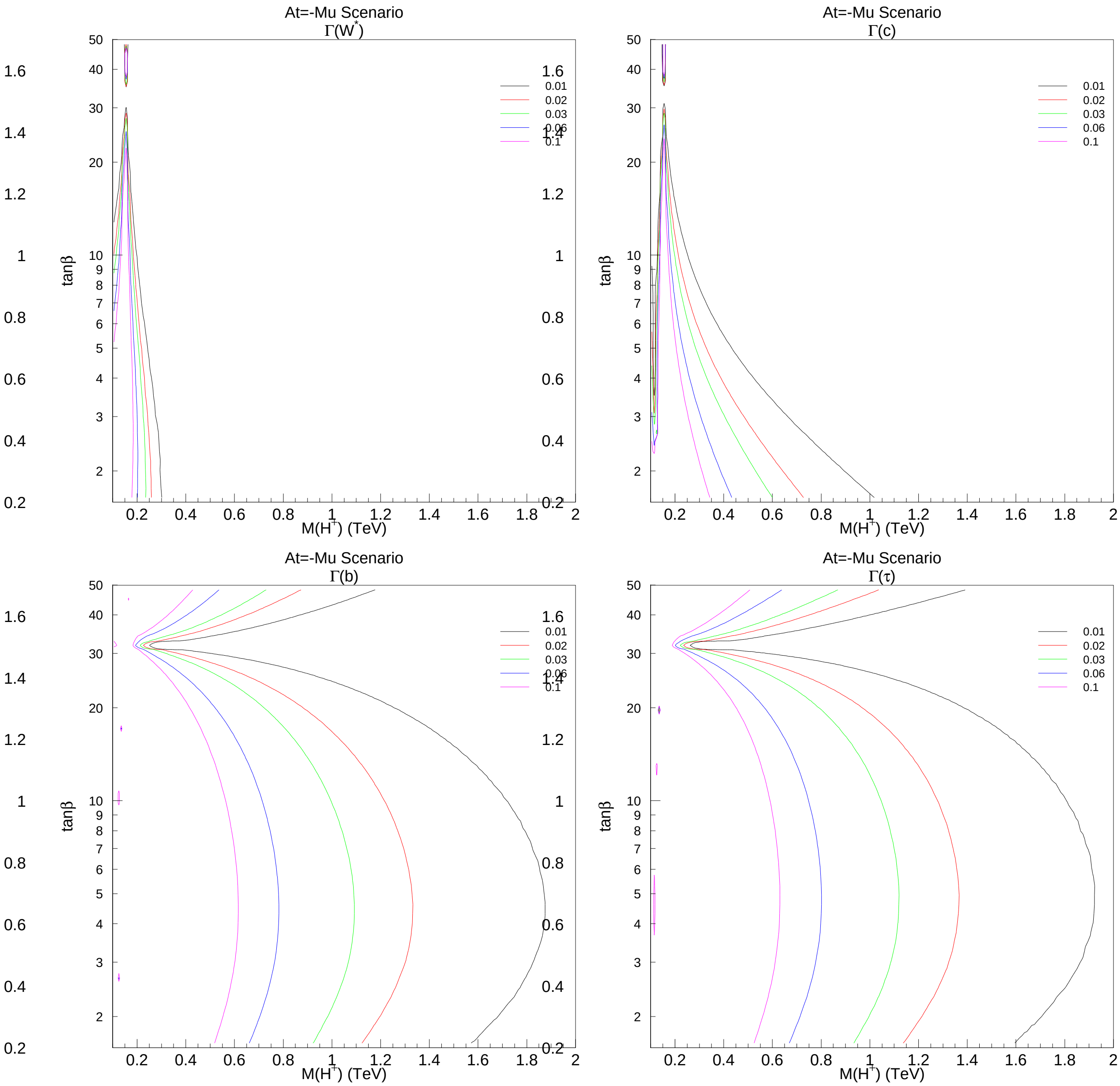
| | | Mass parameters [TeV] | | | |
|---|---|---|---|---|---|
| Benchmark | $\mu$ | $X_t \equiv A_t - \mu\cot\beta$ | $A_b$ | $M_S$ | $M_{\tilde{g}}$ |
| No Mixing | $-0.2$ | 0 | $A_t$ | 1.5 | 1 |
| Maximal Mixing | $-0.2$ | $\sqrt{6}M_S$ | $A_t$ | 1 | 1 |
| Large $\mu$ and $A_t$ | $\pm 1.2$ | $\mp 1.2(1+\cot\beta)$ | 0 | 1 | 0.5 |

# Maximal mixing scenario:




$$\delta\Gamma = (\Gamma_{\rm MSSM} - \Gamma_{\rm SM})/\Gamma_{\rm SM}$$

Large $\mu$ and $A_t$ scenario:




"Premature decoupling"

## Loop induced couplings: $h^0 \to gg$

$h^0 \to gg$ gets contributions from $t$, $\tilde{t}_{1,2}$, $b$, $\tilde{b}_{1,2}$

$$\begin{aligned} h^0\tilde{t}_{1,2}\tilde{t}_{1,2} : & \frac{igm_Z}{c_W}\left(I_3^t \cos^2\theta_{\tilde{t}} \mp Q_t s_W^2 \cos 2\theta_{\tilde{t}}\right)\sin(\alpha+\beta) \\ & -\frac{igm_t^2 \cos\alpha}{m_W \sin\beta} \\ & \mp \frac{igm_t}{2m_W \sin\beta}(\mu \sin\alpha + A_t \cos\alpha)\sin 2\theta_{\tilde{t}} \end{aligned}$$

For large $m_A$ and $\tan\beta$, $(\mu \sin\alpha + A_t \cos\alpha) \simeq \sin\beta X_t$.

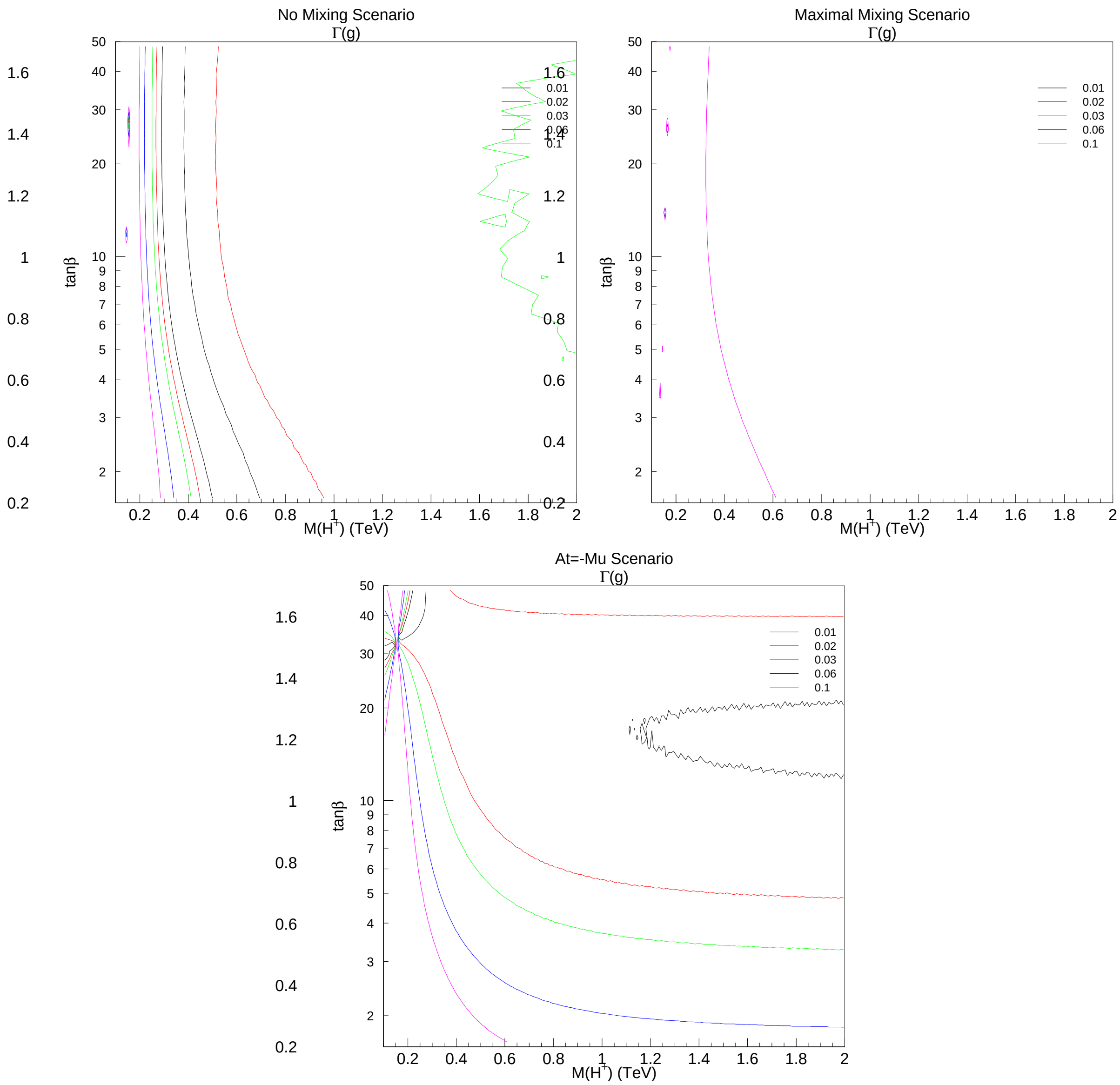
If $X_t$ is large (as in max. mixing scenario):
3rd term: Amplitude $\sim m_t X_t \sin 2\theta_{\tilde{t}}/M_{\tilde{t}}^2$.

- Decouples like $m_t/M_{\rm SUSY}$ at large $M_{\rm SUSY}$.
- $\delta\Gamma(g)$ asymptotes to $\sim$ 6% at large $m_A$ in max. mixing scenario.

If $X_t$ is small (as in no mixing scenario):
2nd term: Amplitude $\sim m_t^2/M_{\tilde{t}}^2$.

- Decouples like $m_t^2/M_{\rm SUSY}^2$ at large $M_{\rm SUSY}$.

Large $\mu$ and $A_t$ scenario:
$X_t$ varies by a factor of 2 with $\tan\beta$. Largest at low $\tan\beta$ $\to$ 3rd term important there.



No Mixing Scenario
Γ(g)
tanβ
M(H+) (TeV)
0.01
0.02
0.03
0.06
0.1
Maximal Mixing Scenario
Γ(g)
tanβ
M(H+) (TeV)
0.01
0.02
0.03
0.06
0.1
At=-Mu Scenario
Γ(g)
tanβ
M(H+) (TeV)
0.01
0.02
0.03
0.06
0.1

## Measurements of Higgs properties at a LC

Expected uncertainty of BR measurements at an $e^+e^-$ LC for a 120 GeV SM-like Higgs boson:

| | $b\bar{b}$ | $WW^*$ | $\tau^+\tau^-$ | $c\bar{c}$ | $gg$ | $\gamma\gamma$ |
|---|---|---|---|---|---|---|
| [1] | 2.4% | 5.1% | 5.0% | 8.5% | 5.5% | 19% |
| [2] | 3.6% | 7.7% | 7.5% | 12.8% | 8.3% | 29% |
| [3] | 2.9% | 9.3% | 7.9% | 39% | 18% | |
| [4] | | | | | | 14% |

[1] Battaglia & Desch, hep-ph/0101165: 500 fb$^{-1}$ at $\sqrt{s} = 350$ GeV.

[2] Battaglia & Desch, hep-ph/0101165, naively scaled to 500 fb$^{-1}$ at $\sqrt{s} = 500$ GeV. Cross section for $Zh^0$ down by about a factor of 2.

[3] Brau, Potter & Iwasaki, talk at Johns Hopkins LC Workshop, Baltimore, 19–21 March 2001: 500 fb$^{-1}$ at $\sqrt{s} = 500$ GeV.

[4] Boos et al., hep-ph/0011366, dedicated $\gamma\gamma$ study, 500 fb$^{-1}$ at $\sqrt{s} = 500$ GeV with beam pol'n.

Use BR measurements to distinguish the MSSM Higgs from the SM Higgs.

We plot contours of

$$\delta \text{BR} = \frac{\text{BR}_{\text{MSSM}} - \text{BR}_{\text{SM}}}{\text{BR}_{\text{SM}}}$$

over the $m_A - \tan\beta$ plane.

Contours shown here are for:
$\delta$BR(b) $=$ 3% and 6%
$\delta$BR(W) $=$ 8% and 16%
$\delta$BR(g) $=$ 8% and 16%

These numbers correspond roughly to 1 and 2$\times$ the expected experimental precisison on the BRs.

| | | Mass parameters [TeV] | | | |
|---|---|---|---|---|---|
| Benchmark | $\mu$ | $X_t \equiv A_t - \mu \cot\beta$ | $A_b$ | $M_S$ | $M_{\tilde{g}}$ |
| No Mixing | $-0.2$ | 0 | $A_t$ | 1.5 | 1 |
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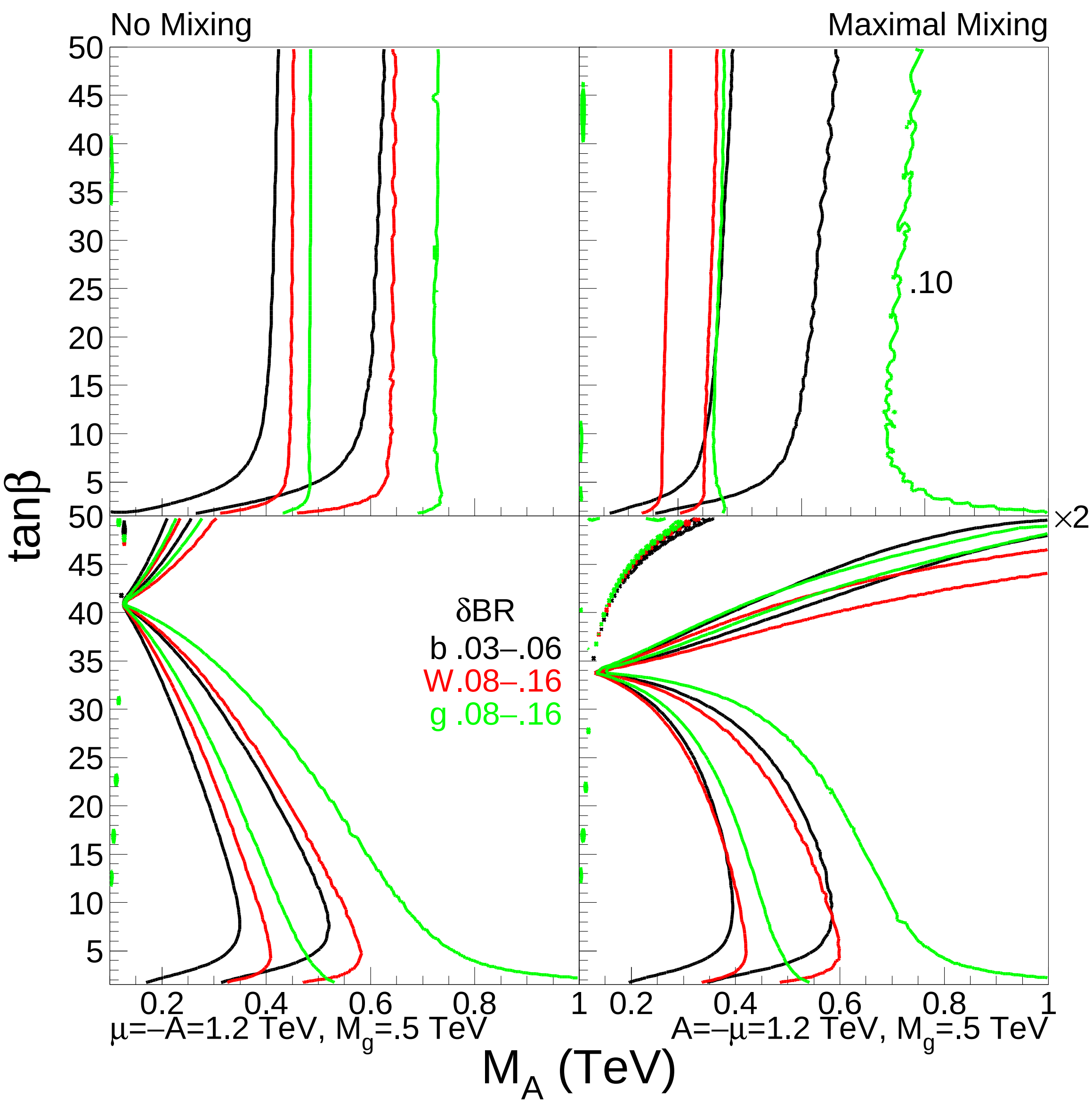


No Mixing
Maximal Mixing
tanβ
.10
×2
δBR
b .03–.06
W.08–.16
g .08–.16
μ=–A=1.2 TeV, M_g=.5 TeV
A=–μ=1.2 TeV, M_g=.5 TeV
M_A (TeV)

# Extracting SUSY parameters: an example

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

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

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

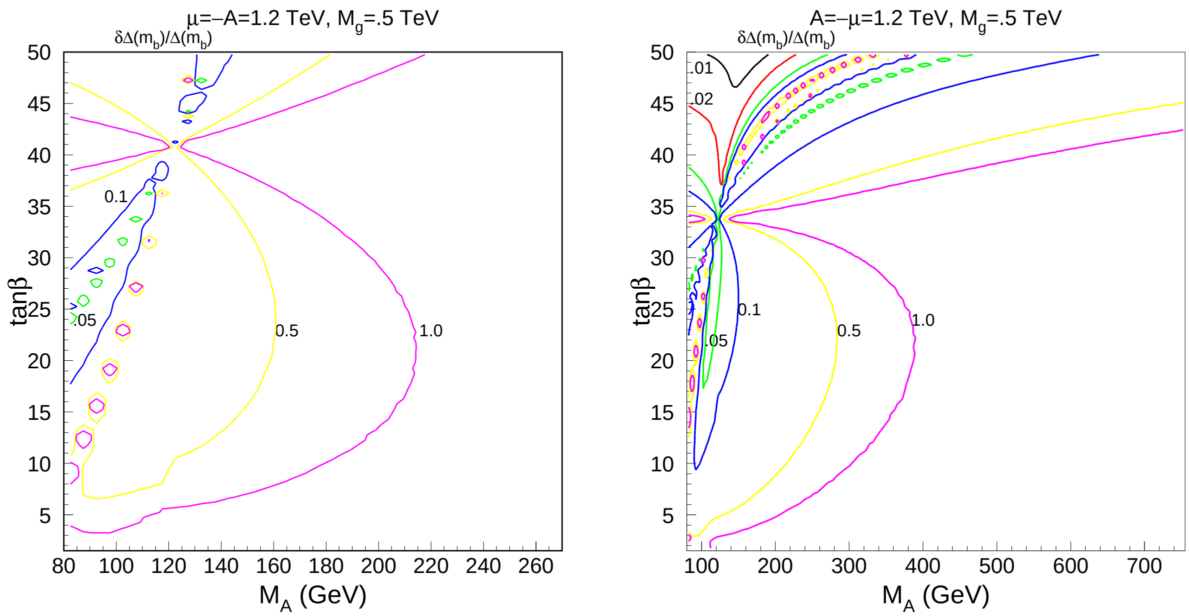
so,

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

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

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

Such a measurement of $\Delta_b$ may ultimately be combined with other measurements to determine the underlying MSSM parameters.




Using $\delta$BR(b) $= 3\%$, $\delta$BR($\tau$) $= 7\%$ and $\delta$BR(c) $= 15\%$. These numbers correspond roughly to the expected experimental precisions.

The difference in resolution for positive and negative $\mu$ is due to two effects:

- For negative $\mu$, the $\tilde{b} - \tilde{g}$ and $\tilde{t} - \tilde{\chi}^+$ contributions to $\Delta_b$ have the same (negative) sign, while for positive $\mu$ they have opposite signs. Thus for equal absolute parameter values, $|\Delta_b|$ is larger for negative $\mu$ than for positive $\mu$.

- The $b$ quark Yukawa coupling goes like $1/(1 + \Delta_b)$.
$\mu < 0 \rightarrow \Delta_b < 0 \rightarrow$ denominator suppressed.
$\mu > 0 \rightarrow \Delta_b > 0 \rightarrow$ denominator increased.
Even for equal $|\Delta_b|$, a suppression of the denominator has a larger effect on the $hb\bar{b}$ coupling.

# Conclusions

If only one light SM-like Higgs boson is discovered at the LHC, it could be the SM Higgs or $h^0$ of the MSSM. Must do all we can to distinguish the two possibilities: measure Higgs properties at LC.

Deviations in $h^0$ properties from SM due to:

1. Two Higgs doublets. Effects decouple in large $m_A$ limit.

2. True SUSY loop contributions: $h^0 \to gg$

The "reach" in $m_A$ for distinguishing the MSSM Higgs from the SM Higgs depends strongly on the MSSM parameters.

- BR(g) in max. mixing scenario

- Large $\mu$ and $A_t$ scenario region of indistinguishability ("premature decoupling")

Future directions:

- Extracting SUSY parameters
  We have looked at $\Delta_b$ so far.

- What can we do if more than one Higgs is discovered