Higgs Theory and Phenomenology

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SUSY-2002 at DESY
17 June 2002

For more details, see:

1. M. Carena and H.E. Haber, "Higgs Boson Theory and Phenomenology," FERMILAB-Pub-02/114-T and SCIPP 02/07.

2. M. Carena, D.W. Gerdes, H.E. Haber, A.S. Turcot and P.M. Zerwas, Executive summary of the Snowmass 2001 working group (P1) "Electroweak Symmetry Breaking", hep-ph/0203229.

3. M. Carena, H.E. Haber, H.E. Logan and S. Mrenna, hep-ph/0106116, *Phys. Rev.* **D65**, 055005 (2002).

4. J.F. Gunion and H.E. Haber, "The CP-conserving two-Higgs-doublet model: the approach to the decoupling limit," in preparation.

Outline

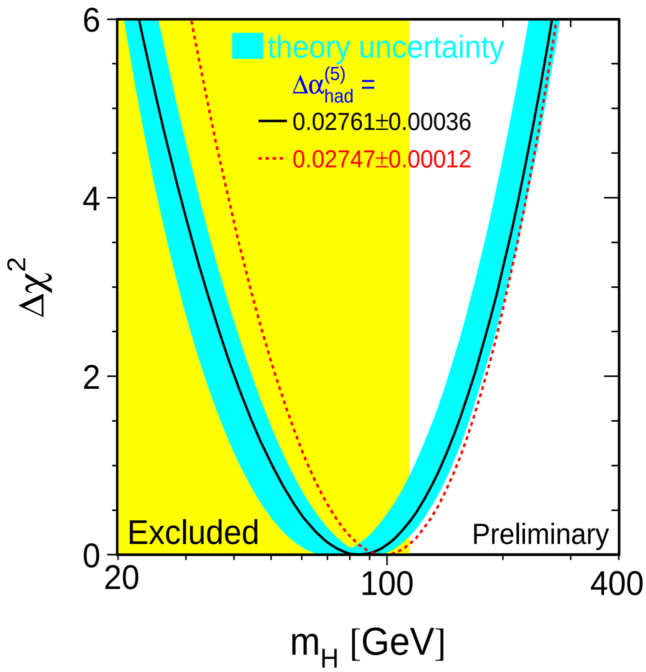
- Introduction
  - Where are the Higgs bosons?
- Higgs Phenomenology at Colliders
  - main goals of the Higgs Hunter
- The SM Higgs Boson
  - room for improvement
- The MSSM Higgs Sector
  - masses, couplings, and the approach to decoupling
- Corrections to the Decoupling Limit
- Conclusions

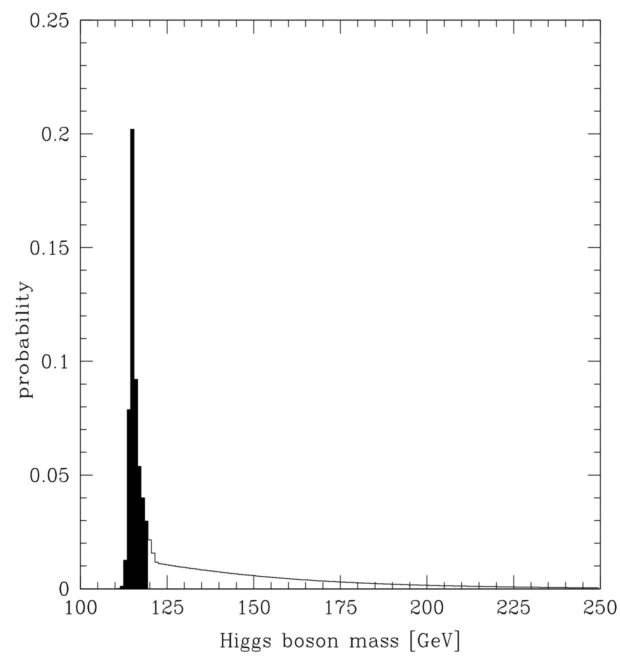
Where is the Higgs Boson?

LEPEWWG MSM fits to precision electroweak data*

$$\chi^2/\text{d.o.f.} = 19.6/14 \qquad [P = 14\%]$$

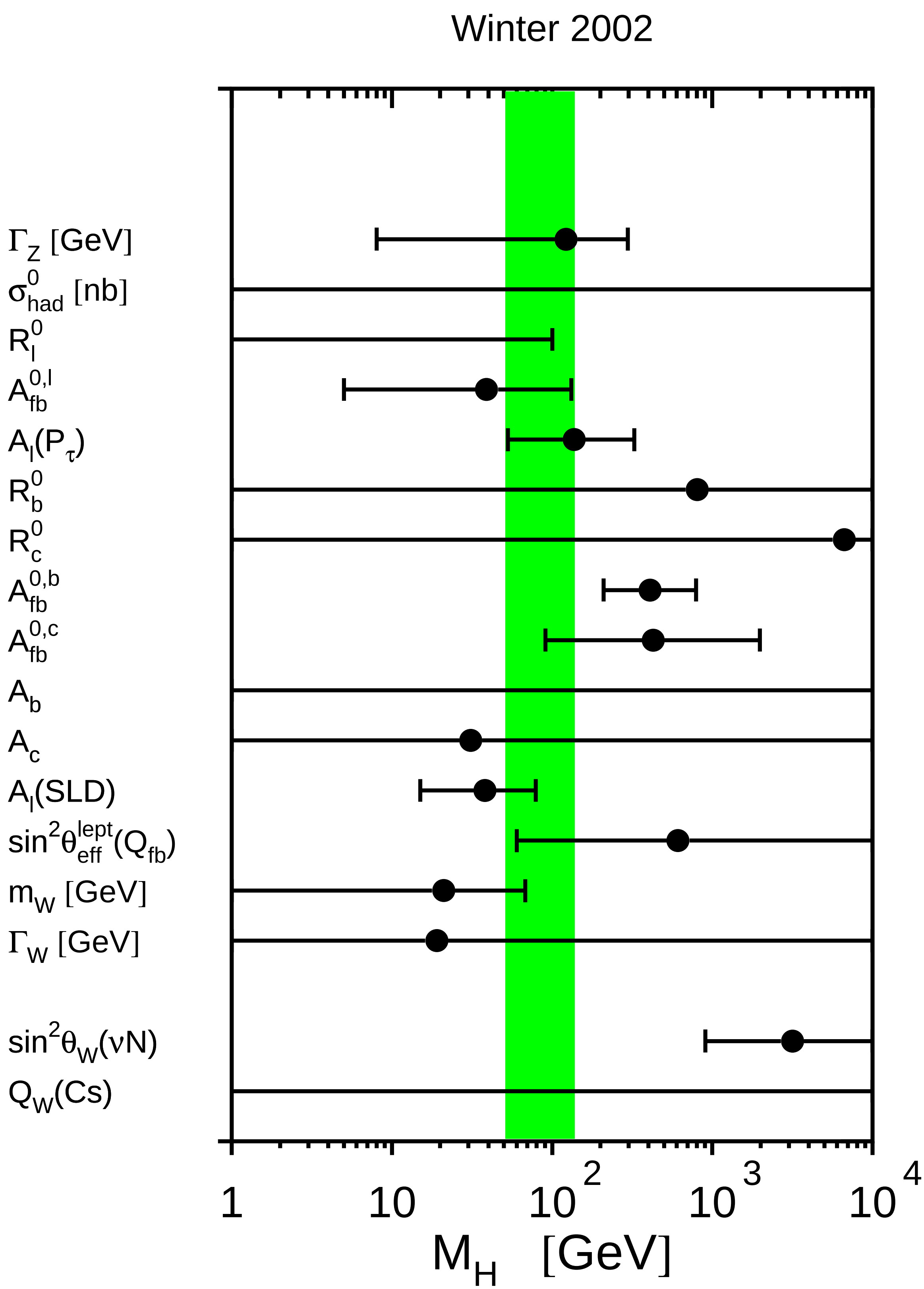
$$m_h = 81^{+49}_{-32}\ \text{GeV} \qquad [m_h < 196\ \text{GeV at 95\% CL}]$$





(a) The "blueband plot" shows $\Delta\chi^2 \equiv \chi^2 - \chi^2_{\rm min}$ as a function of m_h.
(b) Probability distribution function for m_h; the shaded and unshaded regions each correspond to an integrated probability of 50% [J. Erler].

*all data except NuTeV included

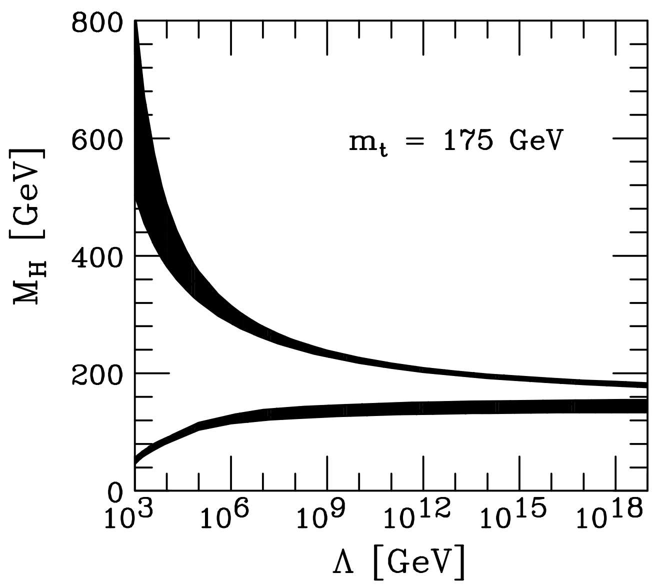


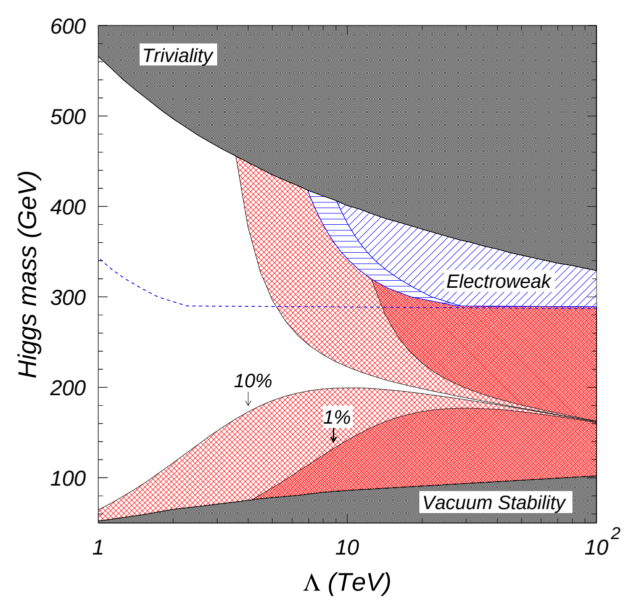
Winter 2002
Γ_Z [GeV]
σ^0_{had} [nb]
R^0_l
$A^{0,l}_{fb}$
$A_l(P_\tau)$
R^0_b
R^0_c
$A^{0,b}_{fb}$
$A^{0,c}_{fb}$
A_b
A_c
A_l(SLD)
$\sin^2\theta^{lept}_{eff}(Q_{fb})$
m_W [GeV]
Γ_W [GeV]
$\sin^2\theta_W(\nu N)$
Q_W(Cs)
1
10
10^2
10^3
10^4
M_H [GeV]

The Higgs mass and the Scale of New Physics

The SM does not predict the Higgs mass. But one can deduce constraints from three conditions

- the Higgs self-coupling does not blow up below Λ
- the Higgs potential does not develop a new minimum at large values of the scalar field of order Λ
- $m_{h_{\rm SM}} \sim \mathcal{O}(m_Z)$ is not a consequence of extreme fine-tuning





Beyond the Minimal Higgs Sector

New physics beyond the Standard Model can be of two types:

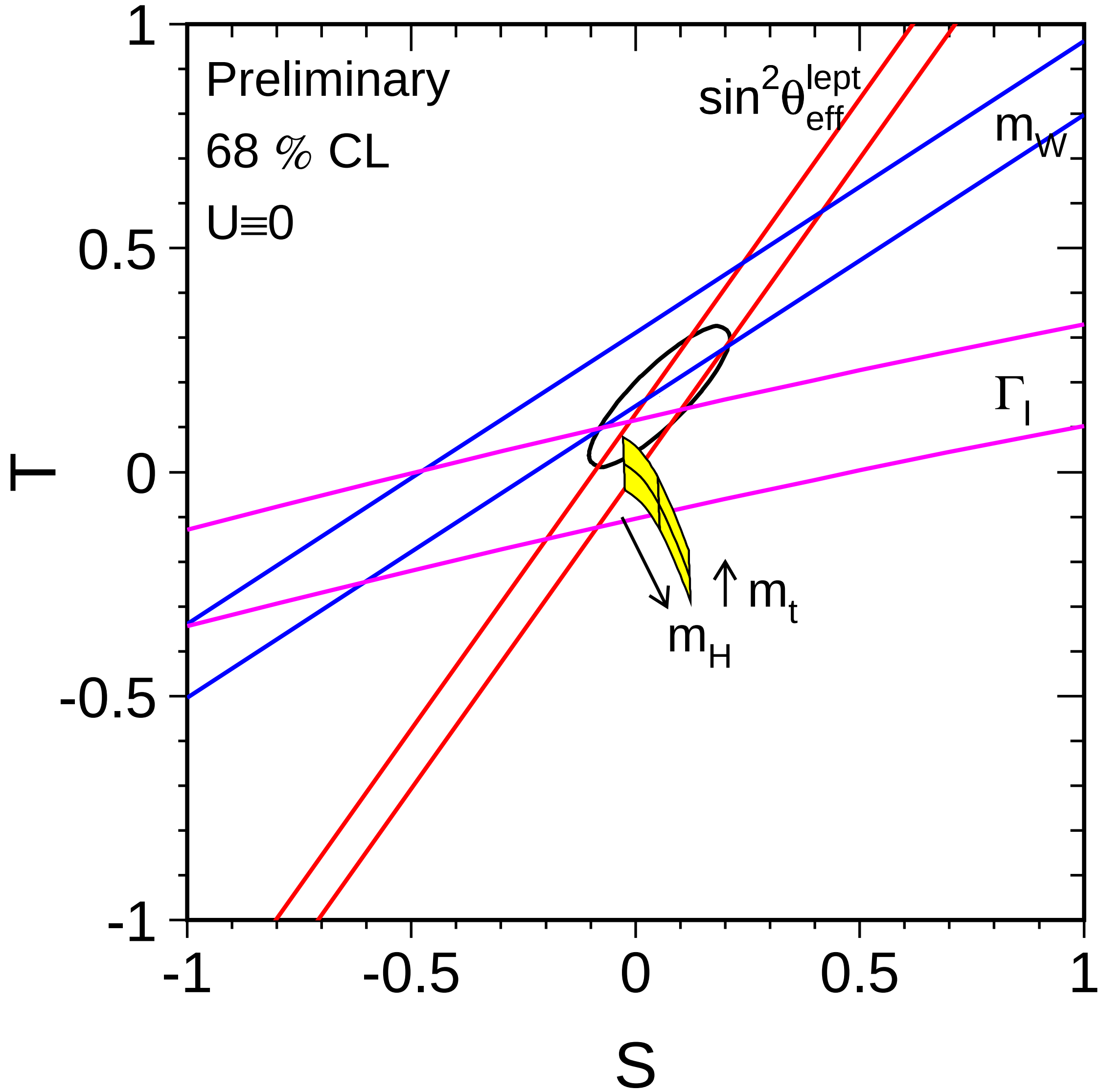
- decoupling

The effects on the MSM global fit scales as m_Z^2/M^2, where M is a scale characteristic of the new physics. example: supersymmetric particles, with soft-SUSY-breaking masses of $\mathcal{O}(M)$.

- non-decoupling

Effects on the MSM global fit do not vanish as the characteristic scale $M \to \infty$. examples: (i) fourth-generation fermion; (ii) technicolor.

The success of the MSM global fit places strong constraints on non-decoupling new physics.



S and T parameterize new physics that can enter the W and Z gauge boson two-point functions via one-loop radiative corrections.

What is the nature of EWSB dynamics?

- Weakly-coupled scalar dynamics?
  - strongly suggests low-energy supersymmetry
- Strongly-coupled dynamics of a new sector?
  - technicolor? top-color? deconstruction?
- Extra-dimensional?

But, recall the unification of couplings, a well-known success of the MSSM. In the absense of a compelling altermative, I will focus in the rest of this talk on Higgs bosons from weakly-coupled scalar dynamics.

For simplicity, narrow the focus to the SM Higgs boson ($h_{\rm SM}$) and the Higgs bosons of the MSSM: two CP-even scalars (h and H), one CP-odd scalar (A) and a charged Higgs pair ($H^\pm$).†

† The MSSM Higgs sector is CP-conserving at tree-level, but CP-violating effects can enter via radiative corrections.

Higgs Phenomenology at Colliders

A program of Higgs physics at colliders must address

- Discovery reach of colliders (Tevatron, LHC, LC, . . .) for the SM Higgs boson
- How many Higgs states are there?
- Assuming one Higgs-like state is discovered
  - Is it a Higgs boson?
  - Is it the SM Higgs boson?
- How will evidence emerge for a non-minimal Higgs sector?
  - deviations from SM Higgs behavior
  - discovery reach for the non-minimal Higgs states?
- Challenge of the decoupling limit
  - in which the lightest Higgs state closely resembles $h_{\rm SM}$

To fully address many of these questions will require a program of precision Higgs measurements.

- mass, width, CP-quantum numbers (CP-violation?)
- branching ratios and Higgs couplings
- reconstructing the Higgs potential

The Standard Model Higgs Boson

- The theory is simple.

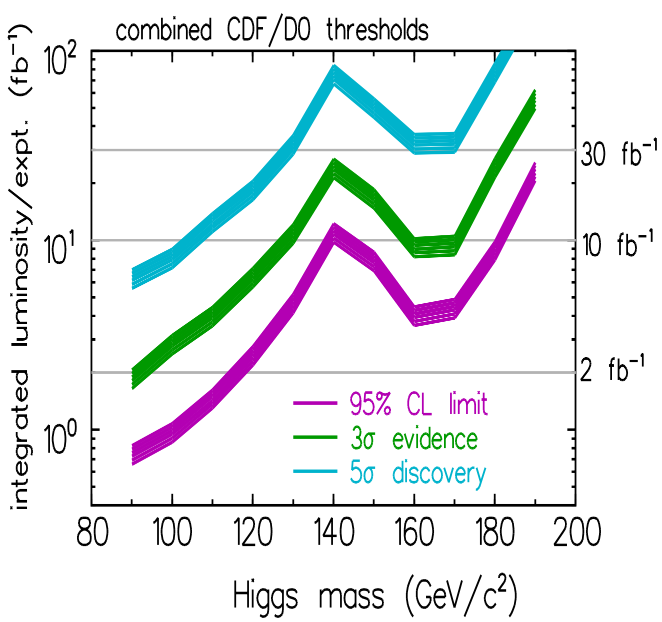
$$g_{hf\bar{f}} = \frac{m_f}{v}, \qquad g_{hVV} = \frac{2m_V^2}{v}, \qquad g_{hhVV} = \frac{2m_V^2}{v^2},$$

$$g_{hhh} = \frac{3m_{h_{\rm SM}}^2}{v}, \qquad g_{hhhh} = \tfrac{3}{2}\lambda = \frac{3m_{h_{\rm SM}}^2}{v^2},$$

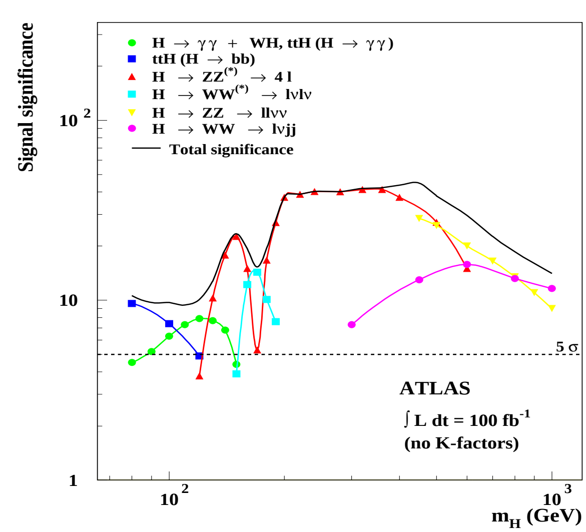
where $h \equiv h_{\rm SM}$, $V = W$ or Z and $v = 2m_W/g = 246$ GeV.

- Discovery reach at hadron colliders

Tevatron



LHC



Higgs production at hadron colliders

At hadron colliders, the relevant processes are

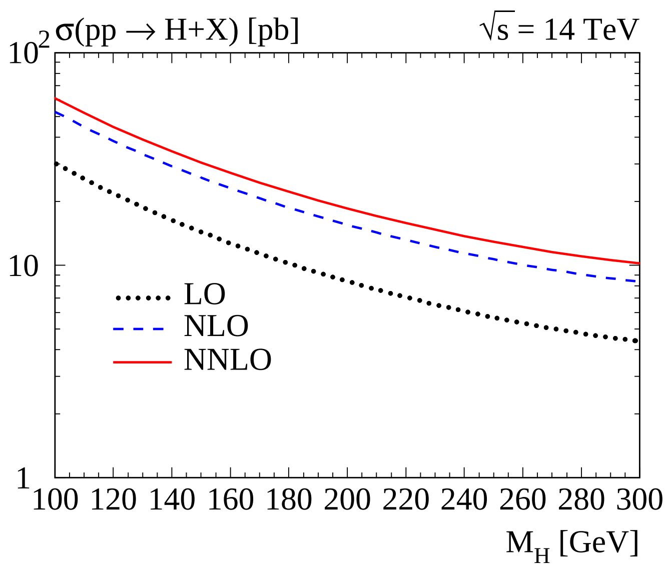
$$gg \to h_{\rm SM} \to \gamma\gamma\,,$$

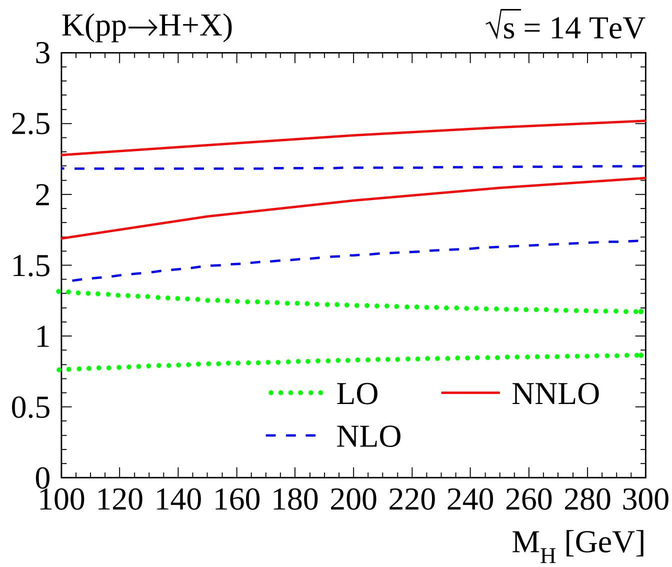
$$gg \to h_{\rm SM} \to VV^{(*)}\,,$$

$$qq \to qqV^{(*)}V^{(*)} \to qqh_{\rm SM}, \quad h_{\rm SM} \to \gamma\gamma,\, \tau^+\tau^-,\, VV^{(*)}\,,$$

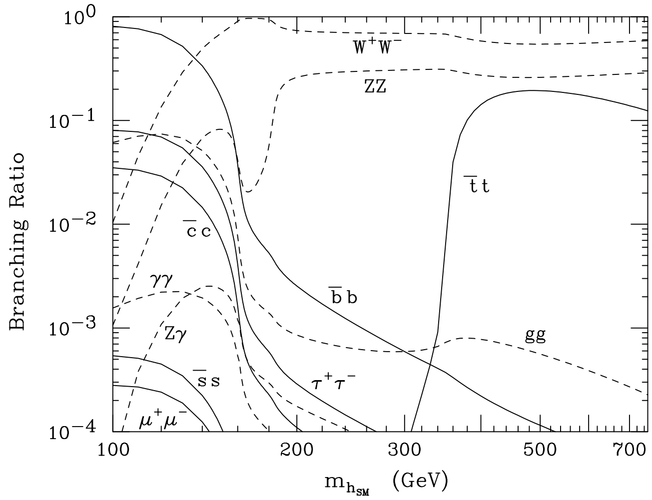
$$gg, q\bar{q} \to t\bar{t}h_{\rm SM}, \quad h_{\rm SM} \to b\bar{b},\, \gamma\gamma,\, WW^{(*)}\,.$$

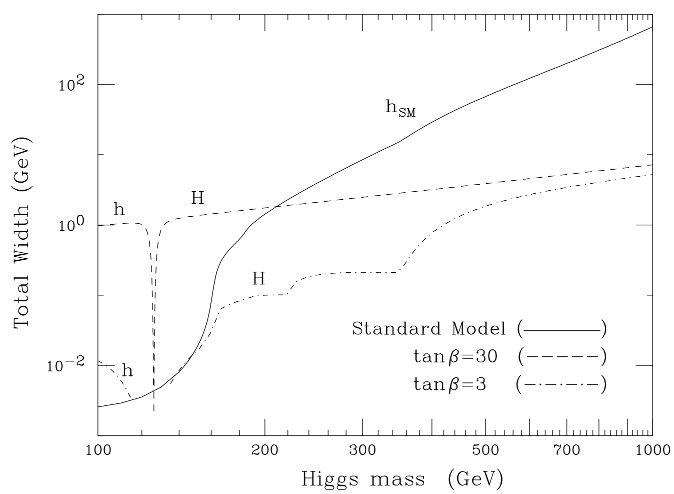
A recent NNLO computation of $gg \to h_{\rm SM}$ production demonstrates the prediction for this Higgs cross-section is under theoretical control [Harlander and Kilgore].





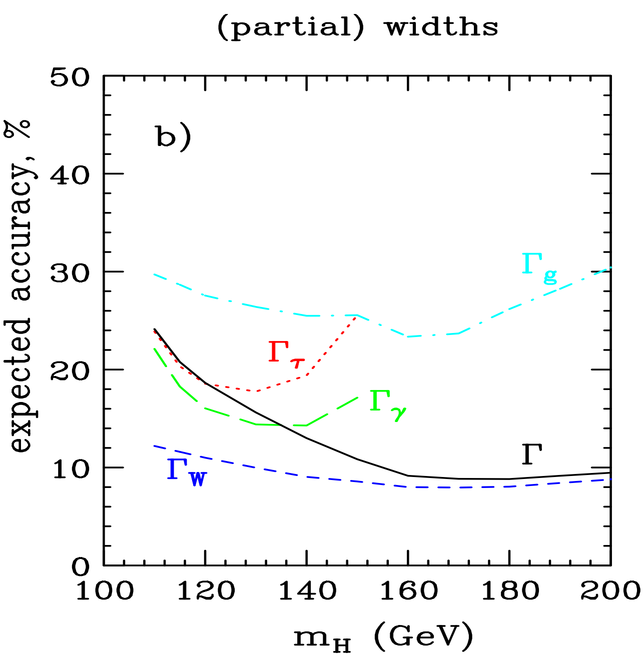
SM Higgs Branching Ratios and Width



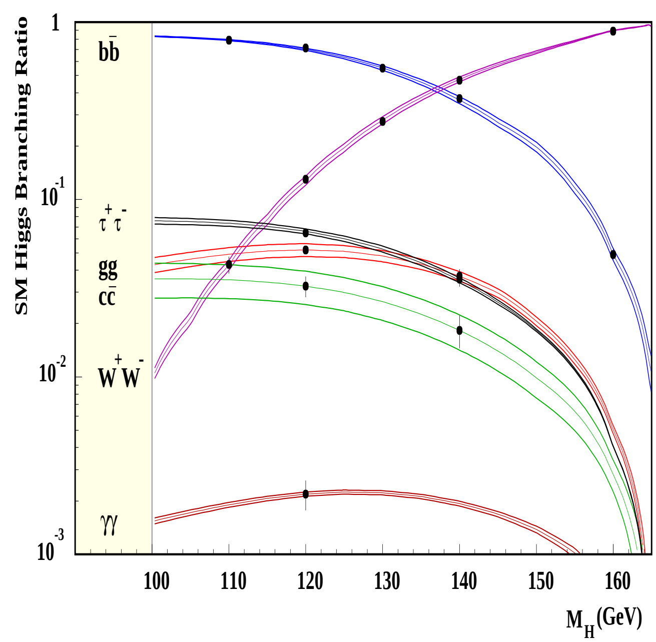


A program of precision measurements will begin at the LHC and will reach maturity at the LC.

LHC



LC



Precision Higgs Physics at the LC

Higgs production at the LC is mainly due to

- Higgs-strahlung ($e^+e^- \to Z^* \to Zh_{\rm SM}$)
- Vector boson fusion ($e^+e^- \to \nu\bar{\nu}W^*W^* \to \nu\bar{\nu}h_{\rm SM}$)
- Radiation off the top quark ($e^+e^- \to t\bar{t}h_{\rm SM}$)

Higgs couplings for $m_{h_{\rm SM}} = 120$ GeV at $\sqrt{s} = 500$ GeV [800 GeV for $h_{\rm SM}t\bar{t}$] can be extracted (Battaglia and Desch)

Higgs coupling	δBR/BR	$\delta g/g$	$\mathcal{L}$ (fb^{-1})
$h_{\rm SM}WW$	5.1%	1.2%	500
$h_{\rm SM}ZZ$	—	1.2%	500
$h_{\rm SM}t\bar{t}$	—	2.2%	1000
$h_{\rm SM}b\bar{b}$	2.4%	2.1%	500
$h_{\rm SM}c\bar{c}$	8.3%	3.1%	500
$h_{\rm SM}\tau\tau$	5.0%	3.2%	500
$h_{\rm SM}gg$	5.5%		500
$h_{\rm SM}\gamma\gamma$	16%		1000

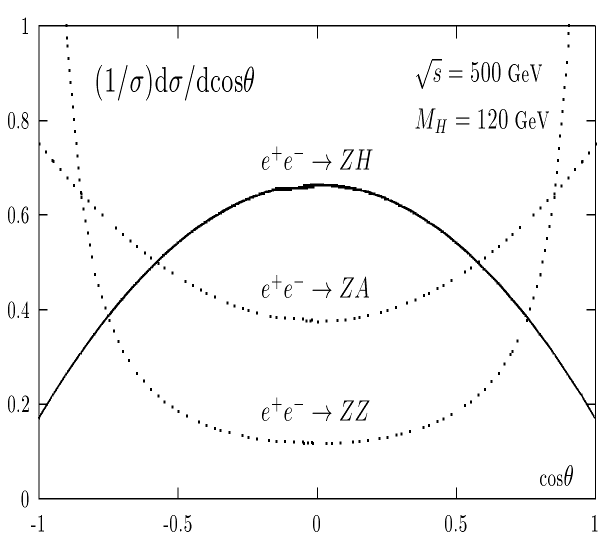
Beware: theoretical uncertainty in $h_{\rm SM} c\bar{c}$ [$h_{\rm SM} b\bar{b}$] coupling due to uncertainty in m_c [m_b] and α_s is about 12% [1.8%].

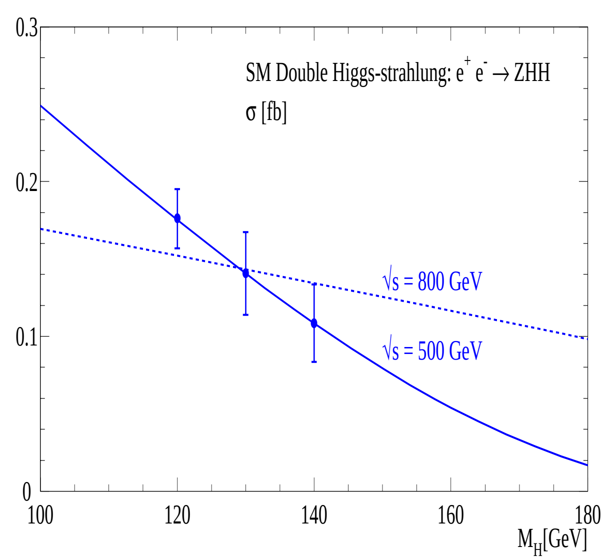
Other precision measurements:

- Total width: use $\Gamma_{\rm tot} = \Gamma_{h_{\rm SM} WW} / {\rm BR}(h_{\rm SM} \to WW^*)$. $\delta\Gamma/\Gamma \simeq 6\%$ for $m_{h_{\rm SM}} = 120$ GeV.

- Spin and CP quantum number

- Reconstructing the Higgs potential. For $m_{h_{\rm SM}} = 120$ GeV, using $e^+e^- \to Zh^* \to Zhh$ ($h = h_{\rm SM}$), one can measure $\delta g_{hhh}/g_{hhh} \simeq 20\%$.





MSSM Higgs sector at Tree-Level

Five physical Higgs scalars:

- $H^{\pm}$: a charged Higgs pair
- h, H: two CP-even Higgs scalars ($m_h \leq m_H$)
- A: a CP-odd Higgs scalar

All Higgs masses and couplings can be expressed in terms of two parameters usually chosen to be m_A and $\tan\beta \equiv v_u/v_d$. The CP-even Higgs mixing angle, α, is given by

$$\cos^2(\beta - \alpha) = \frac{m_h^2(m_Z^2 - m_h^2)}{m_A^2(m_H^2 - m_h^2)}\,.$$

Note: as $m_A \gg m_Z$, $\cos^2(\beta - \alpha) \to 0$. This is called the decoupling limit. In this limit , the couplings of h are precisely those of the SM Higgs boson.

MSSM Higgs couplings at Tree-Level

Higgs couplings to gauge bosons: suppression factors

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$	no angle factor
HW^+W^-	hW^+W^-	
HZZ	hZZ	
ZAh	ZAH	$ZH^+H^-, \gamma H^+H^-$
$W^\pm H^\mp h$	$W^\pm H^\mp H$	$W^\pm H^\mp A$

Higgs couplings to fermion pairs

$$hb\bar{b}: \quad -\frac{\sin\alpha}{\cos\beta} = 1\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)\,,$$

$$ht\bar{t}: \quad \frac{\cos\alpha}{\sin\beta} = 1\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)\,,$$

$$Hb\bar{b}: \quad \frac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\,\sin(\beta-\alpha)\,,$$

$$Ht\bar{t}: \quad \frac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\,\sin(\beta-\alpha)\,.$$

Decoupling Limit of the MSSM Higgs Sector

In the limit $m_A \gg m_Z$, tree-level Higgs masses are given by:

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta \,,$$

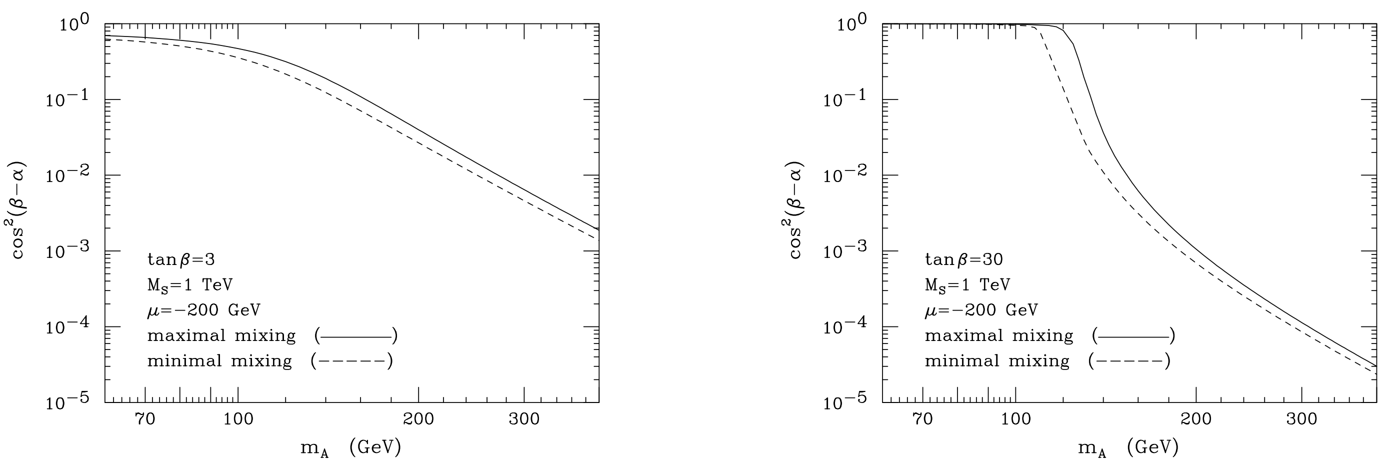
$$m_H^2 \simeq m_A^2 + m_Z^2 \sin^2 2\beta \,,$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2 \,,$$

$$\cos^2(\beta - \alpha) \simeq \frac{m_Z^4 \sin^2 4\beta}{4m_A^4} \,,$$

$$\cot\alpha + \tan\beta = -\frac{2m_Z^2}{m_A^2} \tan\beta \cos 2\beta + \mathcal{O}(m_Z^4/m_A^4) \,.$$

Thus, $m_A \simeq m_H \simeq m_{H^\pm}$, up to corrections of $\mathcal{O}(m_Z^2/m_A)$, and $\cos(\beta - \alpha) = 0$ up to corrections of $\mathcal{O}(m_Z^2/m_A^2)$.



The effective low-energy theory below the scale m_A is a theory with an effective Higgs sector consisting of a SM-like CP-even Higgs boson, h.

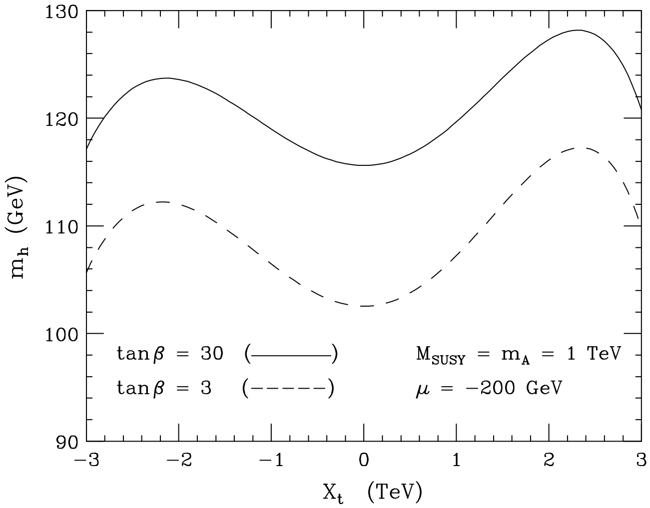
Radiatively-corrected MSSM Higgs mass bound

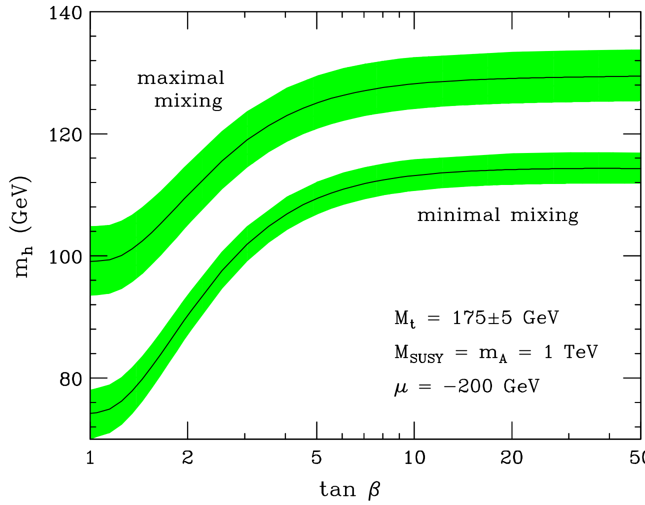
Due to supersymmetric relations among couplings, one finds that $m_h \leq m_Z$ (a result already ruled out by LEP data). But, this inequality receives quantum corrections. The Higgs mass can be shifted due to loops of particles and their superpartners (an incomplete cancelation, which would have been exact if supersymmetry were unbroken):

$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2} \left[\ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right],$$

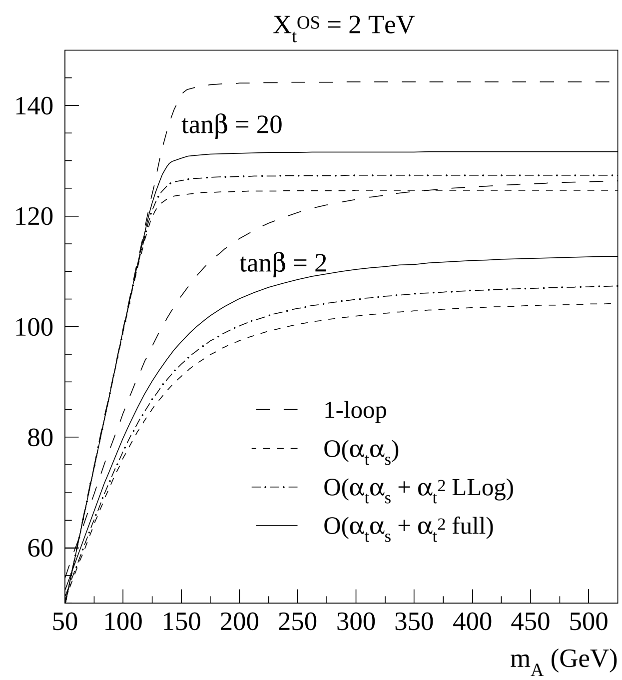
where $X_t \equiv A_t - \mu \cot\beta$ governs stop mixing and M_S^2 is the average stop squared-mass.

End result: $m_h \lesssim 130$ GeV [assuming that the top-squark mass is no heavier than about 2 TeV].

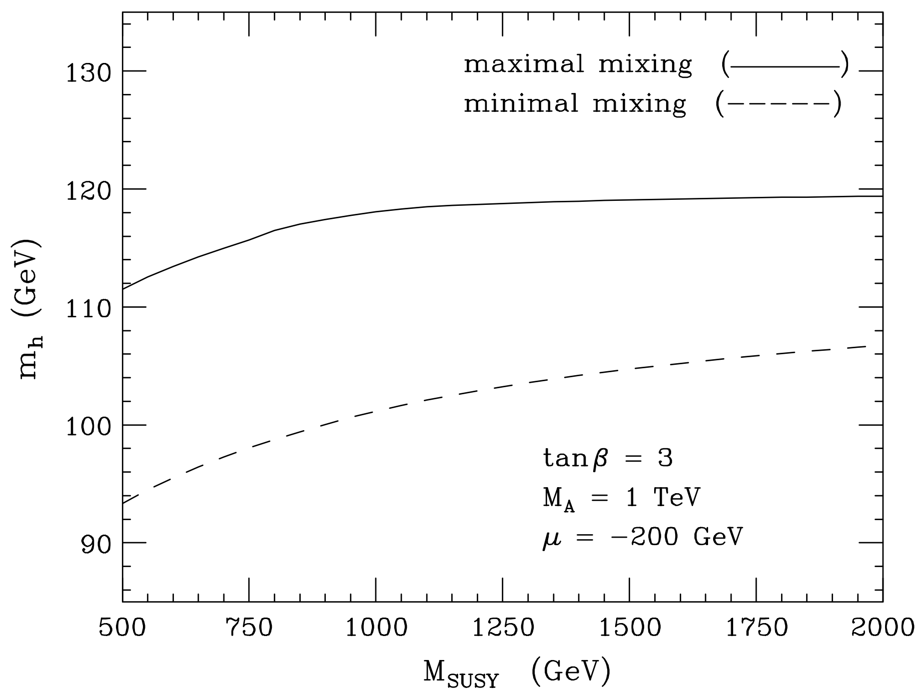


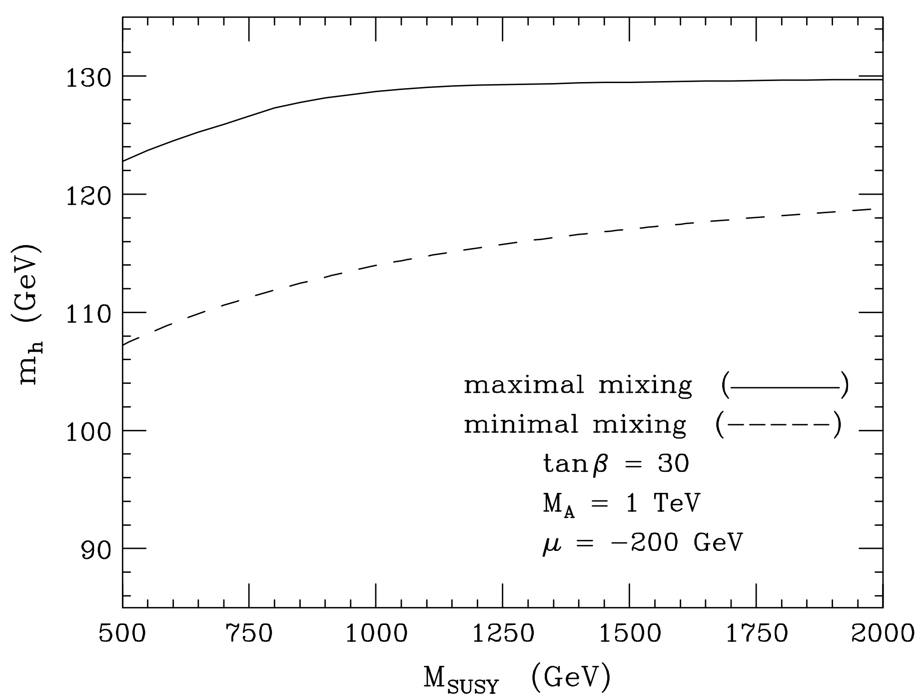


Maximal mixing corresponds to choosing the MSSM Higgs parameters in such a way that m_h is maximized (for a fixed $\tan\beta$). This occurs for $X_t/M_S \sim 2$. As $\tan\beta$ varies, m_h reaches is maximal value, $(m_h)_{\rm max} \simeq 130$ GeV, for $\tan\beta \gg 1$ and $m_A \gg m_Z$.



recent calculation including new 2-loop contributions (Brignole et al.)


maximal mixing (———)
minimal mixing (– – – – –)
130
120
110
100
90
m_h (GeV)
$\tan\beta$ = 3
M_A = 1 TeV
μ = −200 GeV
500
750
1000
1250
1500
1750
2000
M_{SUSY} (GeV)


130
120
110
100
90
m_h (GeV)
maximal mixing (———)
minimal mixing (– – – – –)
$\tan\beta$ = 30
M_A = 1 TeV
μ = −200 GeV
500
750
1000
1250
1500
1750
2000
M_{SUSY} (GeV)

Leading radiative corrections to h couplings

For Higgs couplings to vector bosons, the dominant corrections arise from corrections to $\cos(\beta-\alpha)$.

For Higgs couplings to fermions, in addition to corrections to $\cos(\beta-\alpha)$, one must also consider Yukawa vertex corrections, which modify the effective Lagrangian that describes the coupling of the Higgs bosons to the third generation quarks:

$$-\mathcal{L}_{\rm eff} = \epsilon_{ij}\left[(h_b+\delta h_b)\bar{b}_R H_d^i Q_L^j + (h_t+\delta h_t)\bar{t}_R Q_L^i H_u^j\right] \\ +\Delta h_b \bar{b}_R Q_L^k H_u^{k*} + \Delta h_t \bar{t}_R Q_L^k H_d^{k*} + {\rm h.c.}\,,$$

resulting in a modification of the tree-level relation between h_t $[h_b]$ and m_t $[m_b]$ as follows:

$$m_b = \frac{h_b v}{\sqrt{2}}\cos\beta\left(1+\frac{\delta h_b}{h_b}+\frac{\Delta h_b\tan\beta}{h_b}\right) \equiv \frac{h_b v}{\sqrt{2}}\cos\beta(1+\Delta_b)\,,$$

$$m_t = \frac{h_t v}{\sqrt{2}}\sin\beta\left(1+\frac{\delta h_t}{h_t}+\frac{\Delta h_t\cot\beta}{h_t}\right) \equiv \frac{h_t v}{\sqrt{2}}\sin\beta(1+\Delta_t)\,.$$

The dominant contributions to Δ_b are $\tan\beta$-enhanced. In particular, for $\tan\beta\gg 1$, $\Delta_b \simeq (\Delta h_b/h_b)\tan\beta$; whereas $\delta h_b/h_b$ provides a small correction to Δ_b. In the same limit, $\Delta_t \simeq \delta h_t/h_t$, with the additional contribution of $(\Delta h_t/h_t)\cot\beta$ providing a small correction.

Explicit expressions

For $\tan\beta \gg 1$,

$$\Delta_b \simeq \left[\frac{2\alpha_s}{3\pi}\mu M_{\tilde{g}}\, I(M^2_{\tilde{b}_1}, M^2_{\tilde{b}_2}, M^2_{\tilde{g}}) + \frac{h_t^2}{16\pi^2}\mu A_t\, I(M^2_{\tilde{t}_1}, M^2_{\tilde{t}_2}, \mu^2)\right] \tan\beta$$

$$\Delta_t \simeq -\frac{2\alpha_s}{3\pi} A_t M_{\tilde{g}} I(M^2_{\tilde{t}_1}, M^2_{\tilde{t}_2}, M^2_{\tilde{g}}) - \frac{h_b^2}{16\pi^2}\mu^2 I(M^2_{\tilde{b}_1}, M^2_{\tilde{b}_2}, \mu^2)\,,$$

and the function I is defined by:

$$I(a,b,c) = \frac{ab\ln(a/b) + bc\ln(b/c) + ca\ln(c/a)}{(a-b)(b-c)(a-c)},$$

Note that I is manifestly positive and $I(a,a,a) = 1/(2a)$.

The τ couplings are obtained by replacing m_b, Δ_b and δh_b with m_τ, Δ_τ and δh_τ, respectively. At large $\tan\beta$,

$$\Delta_\tau \simeq \left[\frac{\alpha_1}{4\pi} M_1 \mu I(M^2_{\tilde{\tau}_1}, M^2_{\tilde{\tau}_2}, M_1^2) - \frac{\alpha_2}{4\pi} M_2 \mu\, I(M^2_{\tilde{\nu}_\tau}, M_2^2, \mu^2)\right] \tan\beta\,,$$

where $\alpha_2 \equiv g^2/4\pi$ and $\alpha_1 \equiv g'^2/4\pi$ are the electroweak gauge couplings. One expects that $|\Delta_\tau| \ll |\Delta_b|$.

Radiative corrections to $\cos(\beta-\alpha)$ and implications for decoupling

Writing the CP-even Higgs mass matrix:

$$\mathcal{M}^2 = \begin{pmatrix} m_A^2 s_\beta^2 + m_Z^2 c_\beta^2 & -(m_A^2+m_Z^2)s_\beta c_\beta \\ -(m_A^2+m_Z^2)s_\beta c_\beta & m_A^2 c_\beta^2 + m_Z^2 s_\beta^2 \end{pmatrix} + \delta\mathcal{M}^2 \,,$$

and noting that $\delta\mathcal{M}^2_{ij} \sim \mathcal{O}(m_Z^2)$, and $m_H^2 - m_h^2 = m_A^2 + \mathcal{O}(m_Z^2)$, one obtains for $m_A \gg m_Z$

$$\cos(\beta-\alpha) = c\left[\frac{m_Z^2 \sin 4\beta}{2m_A^2} + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right)\right] \,,$$

where

$$c \equiv 1 + \frac{\delta\mathcal{M}^2_{11} - \delta\mathcal{M}^2_{22}}{2m_Z^2 \cos 2\beta} - \frac{\delta\mathcal{M}^2_{12}}{m_Z^2 \sin 2\beta} \,.$$

These formulae exhibit the expected decoupling behavior for $m_A \gg m_Z$. But, they also allow for an unexpected m_A-independent decoupling corresponding to $c = 0$. Assuming large $\tan\beta$, a solution to $c = 0$ arises for:

$$\tan\beta \simeq \frac{2m_Z^2 - \delta\mathcal{M}^2_{11} + \delta\mathcal{M}^2_{22}}{\delta\mathcal{M}^2_{12}} \,.$$

Leading corrections to Higgs-fermion couplings

$$h b\bar{b}: \qquad -\frac{m_b}{v}\frac{\sin\alpha}{\cos\beta}\left[1+\frac{1}{1+\Delta_b}\left(\frac{\delta h_b}{h_b}-\Delta_b\right)(1+\cot\alpha\cot\beta)\right]$$

$$H b\bar{b}: \qquad \frac{m_b}{v}\frac{\cos\alpha}{\cos\beta}\left[1+\frac{1}{1+\Delta_b}\left(\frac{\delta h_b}{h_b}-\Delta_b\right)(1-\tan\alpha\cot\beta)\right]$$

$$A b\bar{b}: \qquad \frac{m_t}{v}\frac{\cos\alpha}{\sin\beta}\left[1-\frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}(\cot\beta+\tan\alpha)\right]\gamma_5$$

$$h t\bar{t}: \qquad \frac{m_t}{v}\frac{\cos\alpha}{\sin\beta}\left[1-\frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}(\cot\beta+\tan\alpha)\right]$$

$$H t\bar{t}: \qquad \frac{m_t}{v}\frac{\sin\alpha}{\sin\beta}\left[1-\frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}(\cot\beta-\cot\alpha)\right]$$

$$H t\bar{t}: \qquad \frac{m_t}{v}\cot\beta\left[1-\frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}(\cot\beta+\tan\beta)\right]\gamma_5$$

where $\Delta_b \sim \alpha_s \tan\beta\, f(M_S)$, and $f(M_S)$ is a dimensionless function of supersymmetric masses.

The Decoupling Limit Revisited

Working to first order in $\cos(\beta-\alpha)$, and using

$$\tan\alpha\tan\beta = -1+(\tan\beta+\cot\beta)\cos(\beta-\alpha)+\mathcal{O}\left(\cos^2(\beta-\alpha)\right)\,,$$

it follows that

$$g_{hbb} \simeq g_{h_{\rm SM}bb}\Bigg[1+(\tan\beta+\cot\beta)\cos(\beta-\alpha) \times\left(\cos^2\beta-\frac{1+\delta h_b/h_b}{1+\Delta_b}\right)\Bigg]\,.$$

Note that $(\tan\beta+\cot\beta)\cos(\beta-\alpha)\simeq\mathcal{O}(m_Z^2/m_A^2)$, even if $\tan\beta$ is very large (or small). Thus, the deviation from decoupling limit vanishes as m_Z^2/m_A^2 for all values of $\tan\beta$.

Similarly,

$$g_{htt} \simeq g_{h_{\rm SM}tt}\left[1+\cos(\beta-\alpha)\left(\cot\beta-\frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}\frac{1}{\sin^2\beta}\right)\right]\,.$$

The deviation from the decoupling limit is suppressed at large $\tan\beta$.

A SM-Like H

If $\sin(\beta-\alpha)=0$, then $g_{HVV}=g_{h_{\rm SM}VV}$ $[V=W$ or $Z]$. Expanding about $\sin(\beta-\alpha)=0$ yields:

$$g_{Hbb} \simeq g_{h_{\rm SM}bb}\Bigg[1-(\tan\beta+\cot\beta)\sin(\beta-\alpha) \times\left(\cos^2\beta-\frac{1+\delta h_b/h_b}{1+\Delta_b}\right)\Bigg].$$

In this case, $g_{Hbb}=g_{h_{\rm SM}bb}$ only if $|(\tan\beta+\cot\beta)\sin(\beta-\alpha)|\ll 1$, which need not be satisfied if $\tan\beta$ is very large (or small).

Similarly,

$$g_{Htt} \simeq g_{h_{\rm SM}tt}\left[1-\sin(\beta-\alpha)\left(\cot\beta-\frac{1}{1+\Delta_t}\frac{\Delta h_t}{h_t}\frac{1}{\sin^2\beta}\right)\right].$$

The parameter region where $\sin(\beta-\alpha)\simeq 0$ corresponds to large $\tan\beta$ and $m_A<(m_h)_{\rm max}$. In this region, H has SM-like couplings to vector bosons and up-type fermions. However, $\tan\beta\sin(\beta-\alpha)$ need not be small in this regime, and so the Hbb couplings deviate from the corresponding SM value.

Summary: the Approach to Decoupling

If we only keep the leading $\tan\beta$-enhanced radiative corrections, then

$$\frac{g^2_{hVV}}{g^2_{h_{\rm SM}VV}} \simeq 1 - \frac{c^2 m_Z^4 \sin^2 4\beta}{4m_A^4}\,,$$

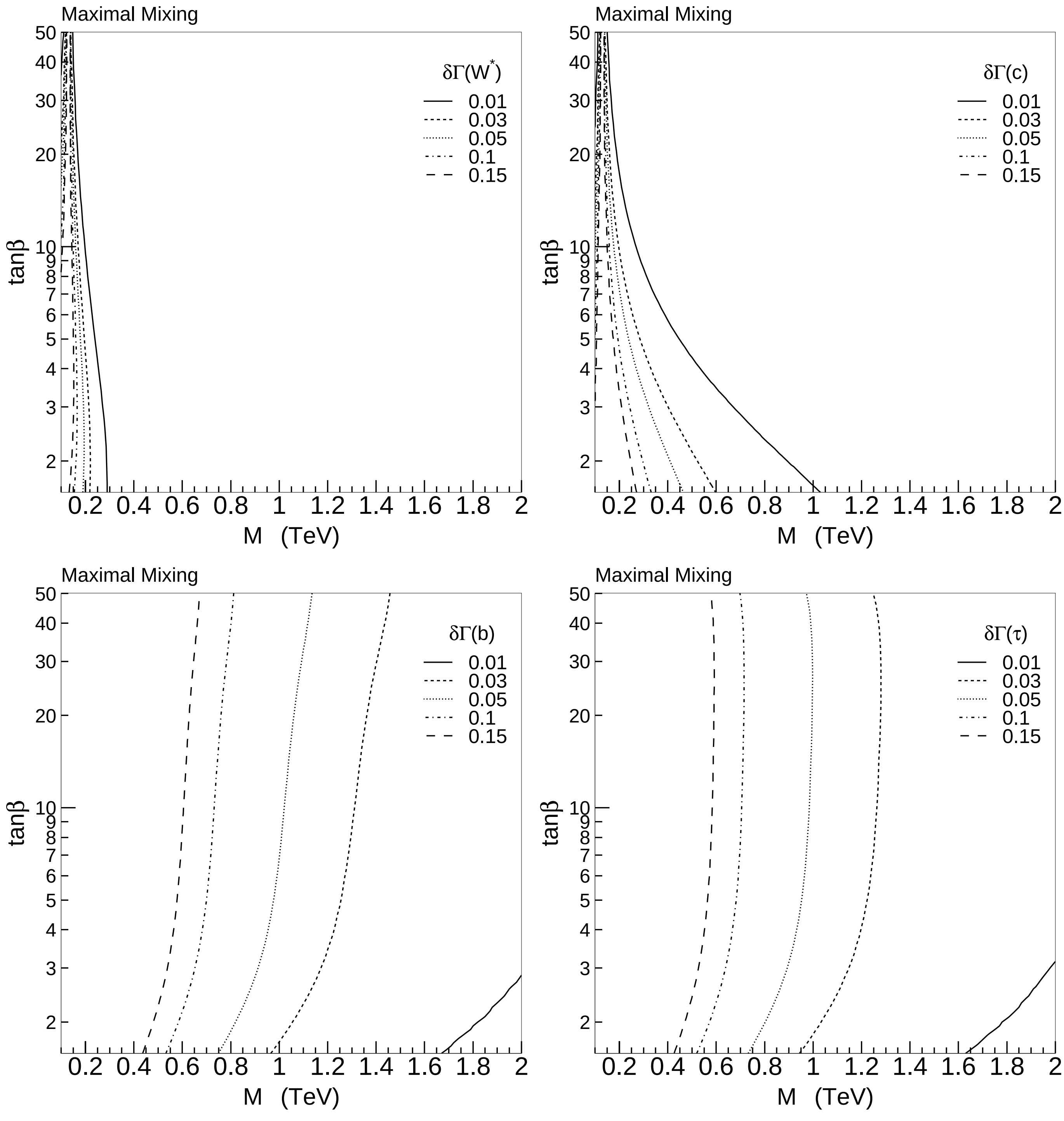
$$\frac{g^2_{htt}}{g^2_{h_{\rm SM}tt}} \simeq 1 + \frac{c m_Z^2 \sin 4\beta \cot\beta}{m_A^2}\,,$$

$$\frac{g^2_{hbb}}{g^2_{h_{\rm SM}bb}} \simeq 1 - \frac{4c m_Z^2 \cos 2\beta}{m_A^2}\left[\sin^2\beta - \frac{\Delta_b}{1+\Delta_b}\right]\,.$$

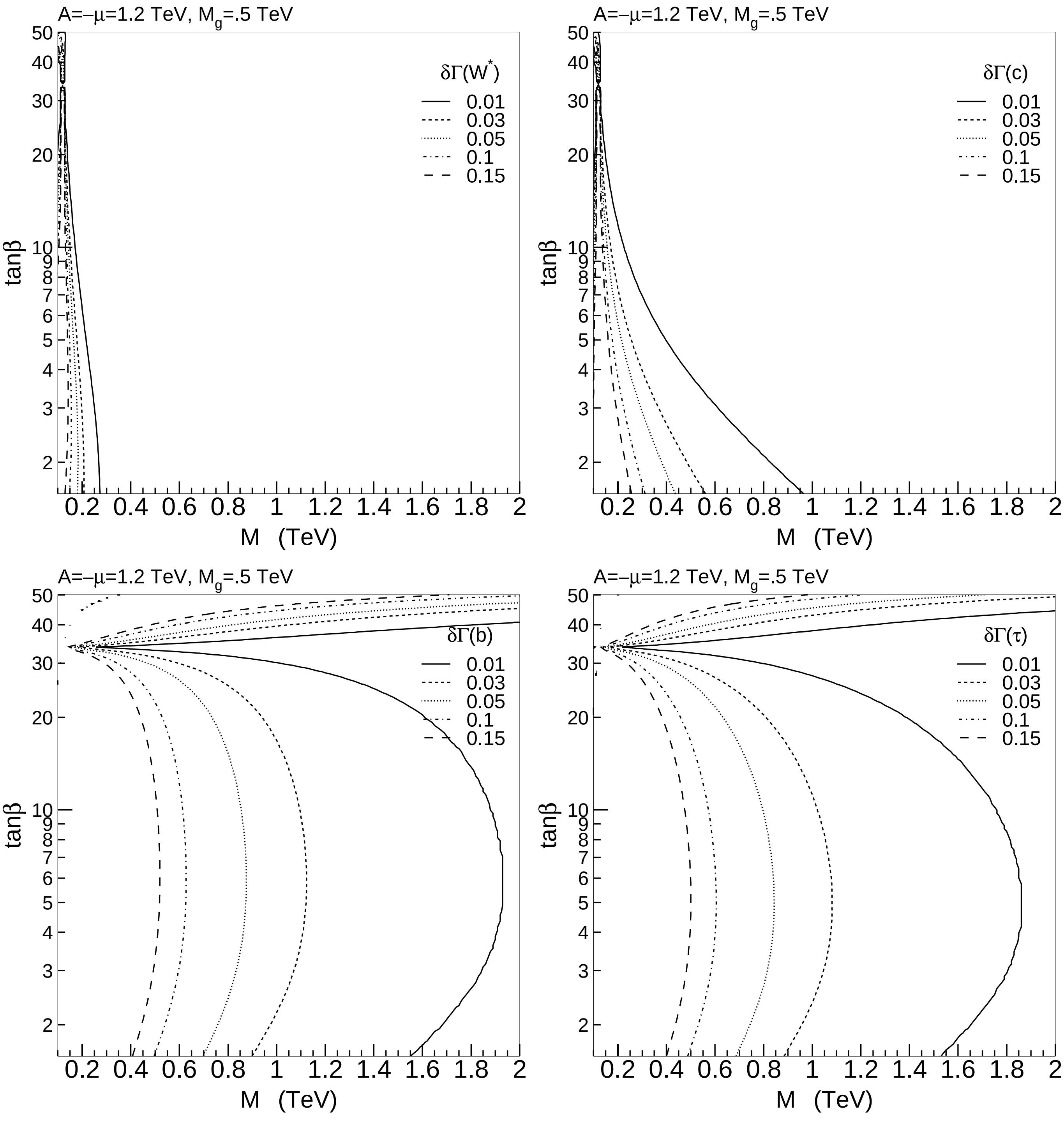
The approach to decoupling is fastest for the h couplings to vector bosons and slowest for the couplings to down-type quarks.

If $c = 0$, which can occur at large $\tan\beta$, then we have m_A-independent decoupling.

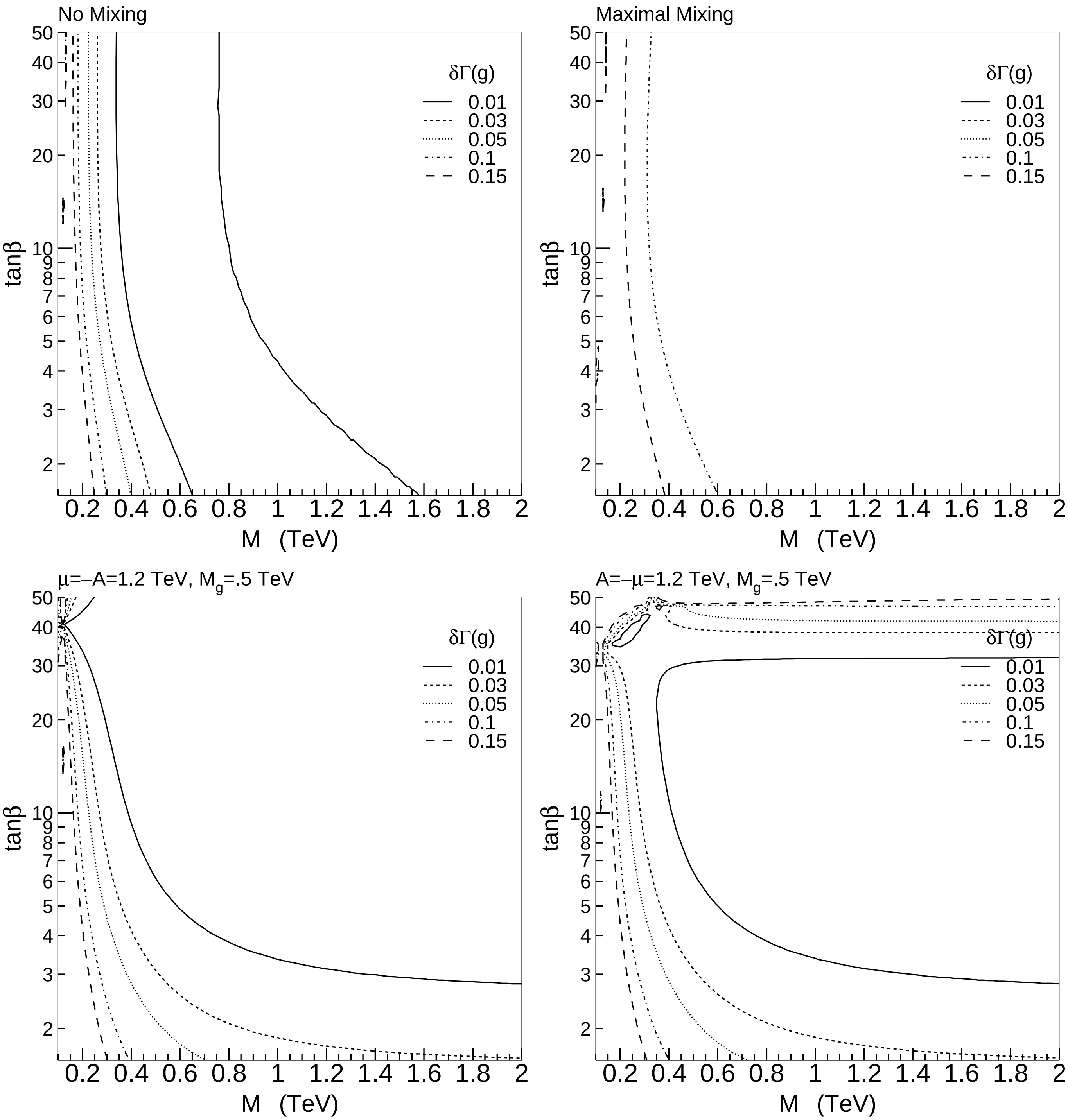
For loop-induced Higgs decays, such as $h \to gg$ or $\gamma\gamma$ there are two decoupling limits of relevance: $m_A \gg m_Z$ and $M_{\rm SUSY} \gg m_Z$. If only the former holds, then squark-loops can generate a small deviation in the loop-induced partial widths from the corresponding SM values.



Deviations of Higgs partial widths from their SM values in the maximal-mixing scenario.



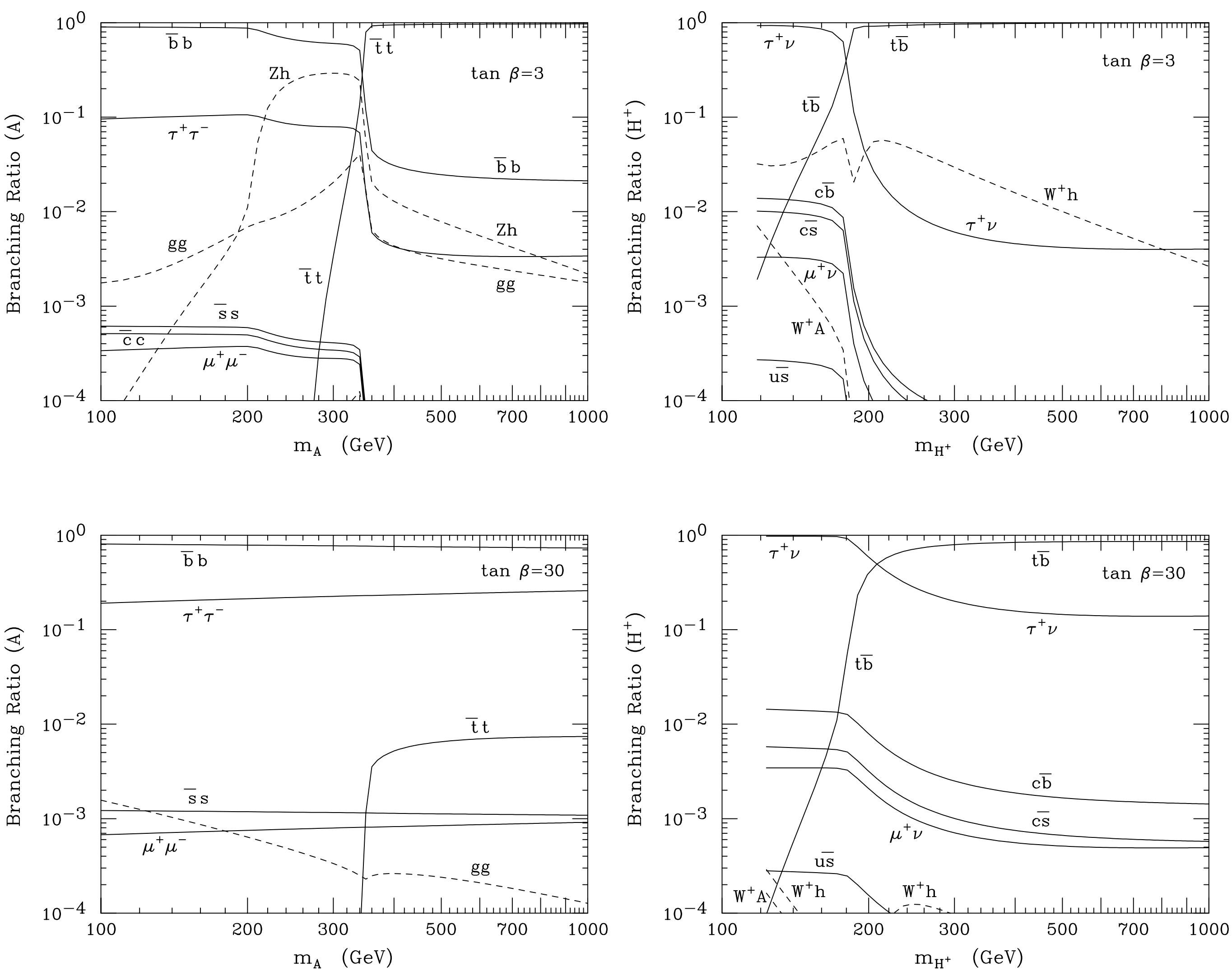
Deviations of Higgs partial widths from their SM values in the large μ and A_t scenario, with $A_t = -\mu = 1.2$ TeV.

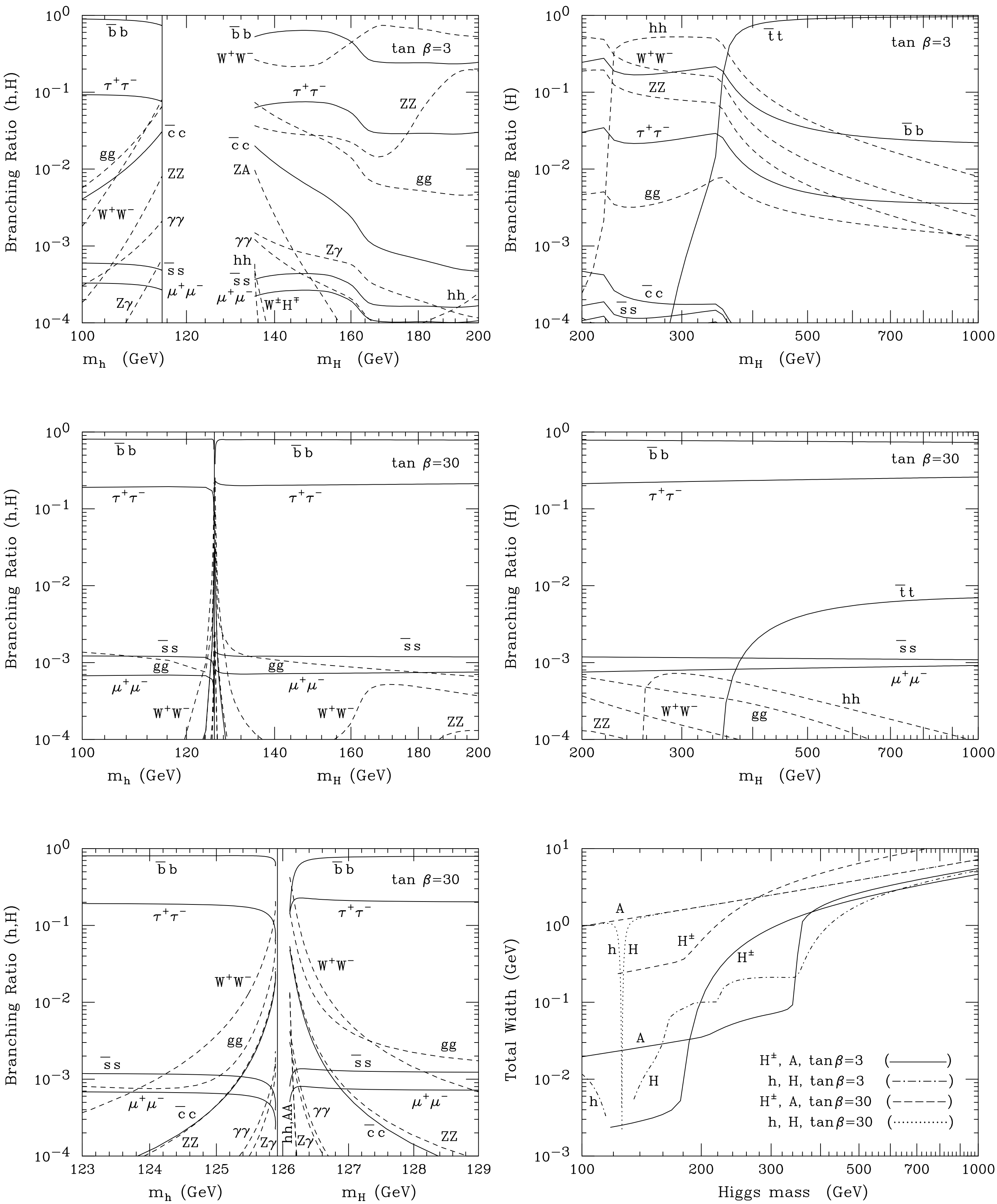


Deviations of the partial width $\Gamma(g)$ from its SM value. Part of the effect shown is due to supersymmetric loop contributions to $h \to gg$.

MSSM Higgs Branching Ratios and Widths

With the help of the `HDECAY` program (Djouadi, Kalinowski and Spira, with recent modifications by Mrenna)



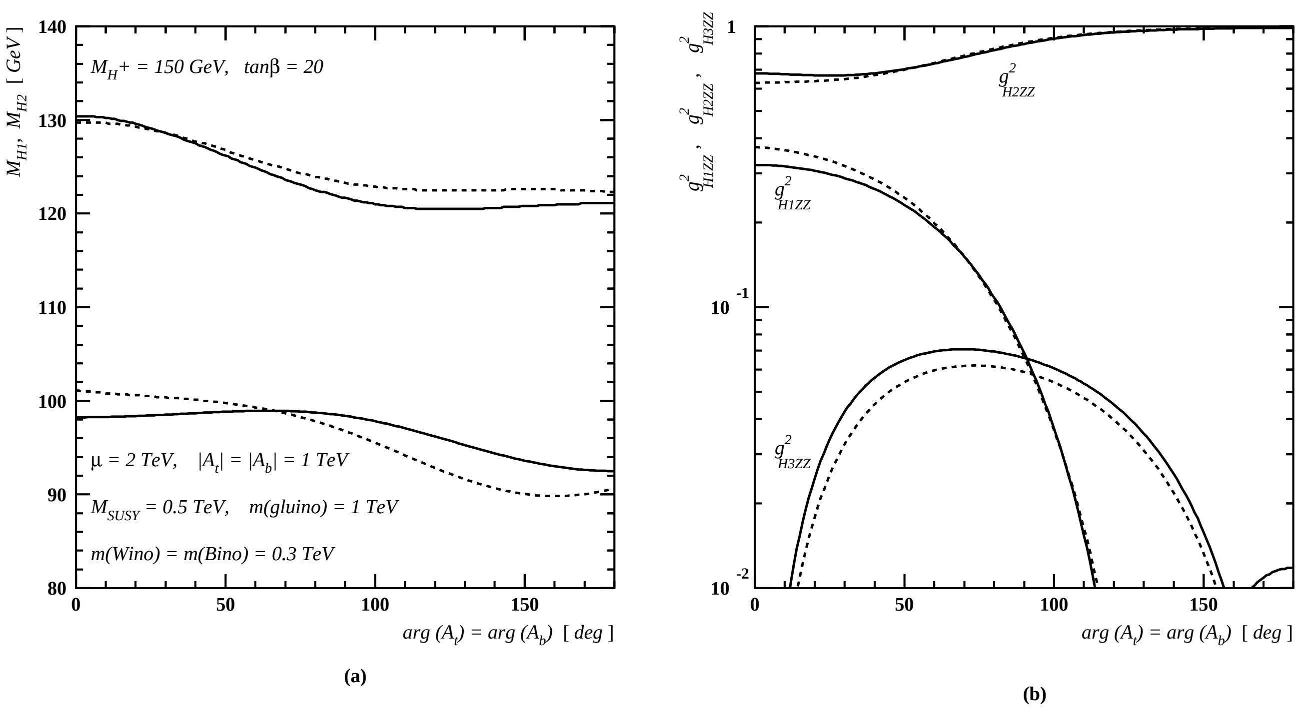


Branching Ratio (h,H)
m_h (GeV)
m_H (GeV)
tan β=3
b̄b
W⁺W⁻
τ⁺τ⁻
c̄c
gg
ZZ
γγ
ZA
Zγ
s̄s
μ⁺μ⁻
hh
W±H∓
Branching Ratio (H)
t̄t
tan β=30
Total Width (GeV)
Higgs mass (GeV)
A
h H
H±
H
h
hh,AA
H±, A, tanβ=3
h, H, tanβ=3
H±, A, tanβ=30
h, H, tanβ=30

CP-violation induced by radiative corrections

CP-violation can enter through the MSSM parameters that control the loop corrections to the Higgs mass matrix and couplings. As a result δh_b, Δh_b, δh_t and δh_t can be complex. Three immediate consequences:

- Mixing of h, H, and A
- Generation of CP-violating Higgs fermion couplings
- Higgs-vector-vector and Higgs-Higgs-vector couplings exist for all combinations of neutral Higgs bosons



(Carena, Ellis, Pilaftsis, Wagner)

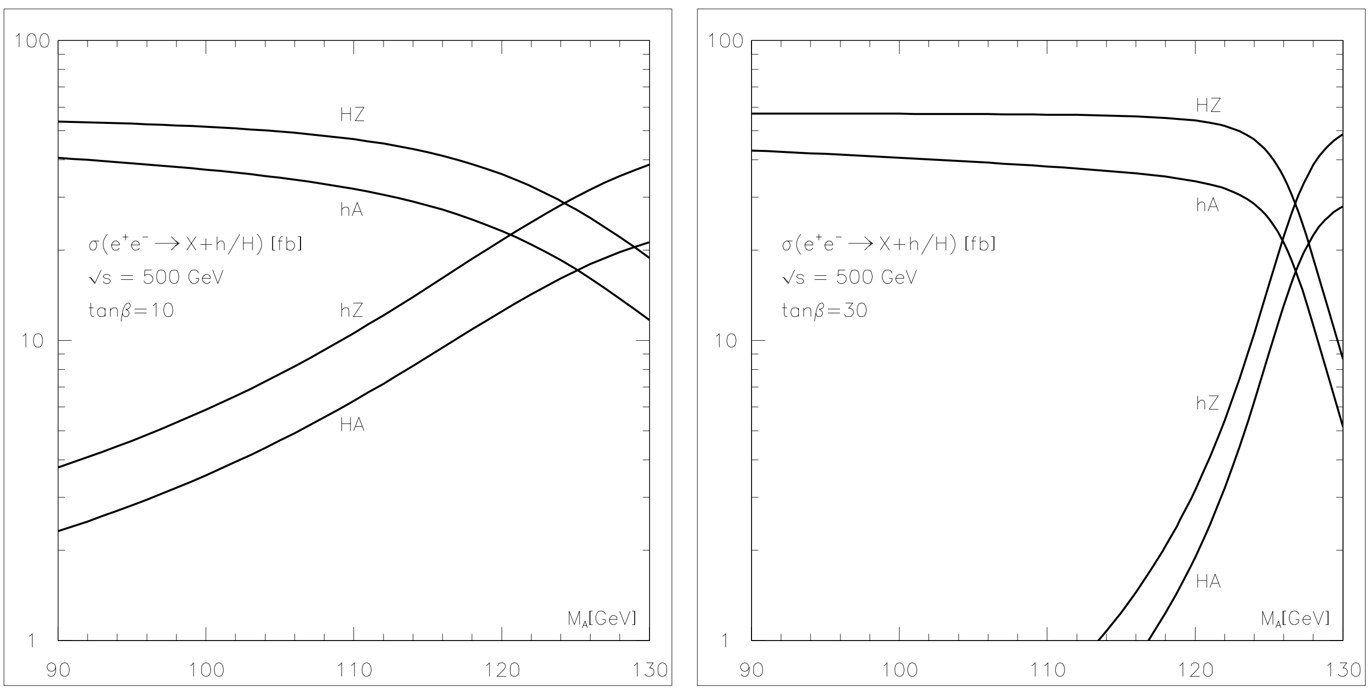
When CP-violation effects are included, we denote the three neutral Higgs bosons (of indefinite CP) by H_1, H_2 and H_3, where H_1 is the lightest neutral Higgs boson. In this case, the decoupling limit is governed by the condition $m_{H^\pm} \gg m_W$. In this limit, one can show that

- The properties of H_1 are identical to those of the SM Higgs boson. That is, H_1 is a pure CP-even state, up to corrections of $\mathcal{O}(m_W^2/m_{H^\pm}^2)$.
- There can still be large mixing between H and A (*i.e.*, H_2 and H_3 can have large admixtures of CP-even and odd components). However, H_2 and H_3 will be nearly mass-degenerate.

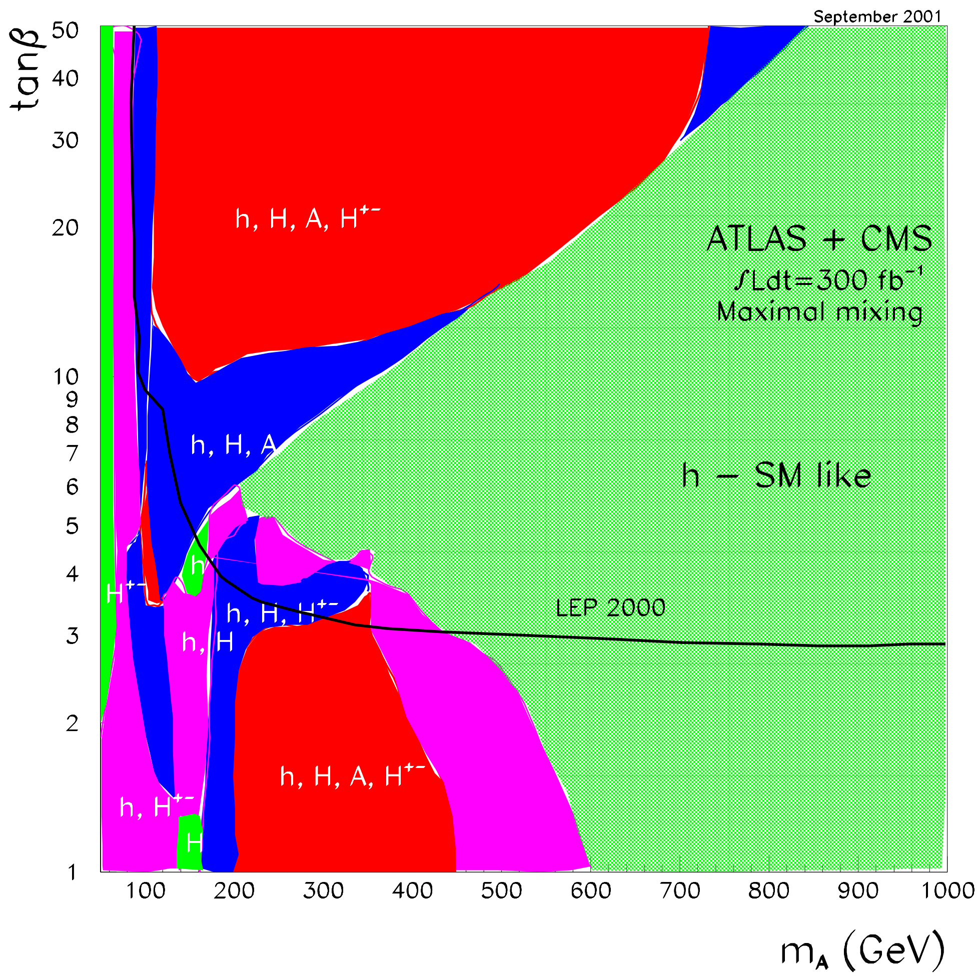
Two interesting parameter regimes

Note that at large $\tan\beta$,

$$\cos(\beta - \alpha) \simeq \begin{cases} 1\,, & \text{for } m_A < (m_h)_{\max}\,, \\ 0\,, & \text{for } m_A > (m_h)_{\max}\,. \end{cases}$$



Boos, Djouadi, Mühlleitner and Vologdin call the region of large $\tan\beta$ and low m_A the "intense-coupling" scenario. In this region, either H is SM-like or H and h share the coupling to VV. All MSSM Higgs bosons have masses $\lesssim 150$ GeV, yielding a rich phenomenology at the LHC and LC.



At LHC, more than one Higgs state will often be observed if $\tan\beta \gg 1$ (due to enhanced couplings to down-type fermions). But, there is also a substantial region in which only h is observed.

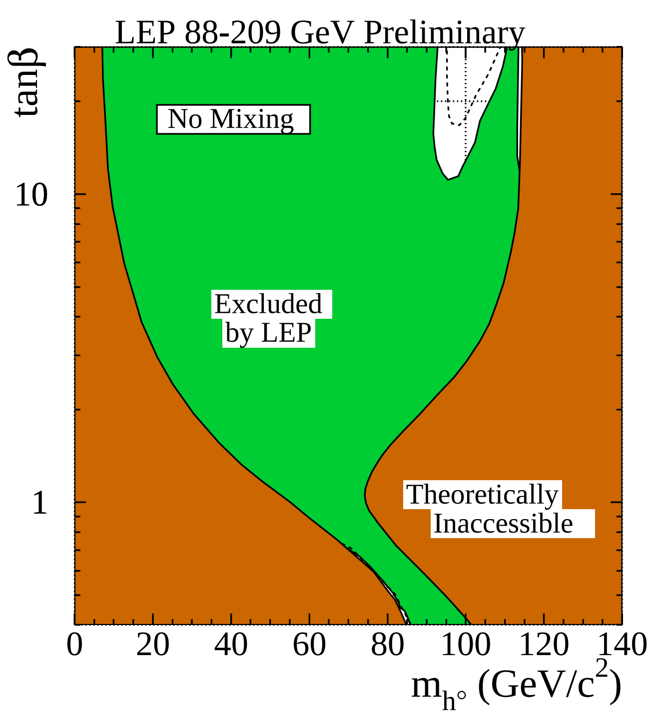
In particular, this illustrates the challenge of the decoupling limit, in which $h \simeq h_{\rm SM}$. If one cannot detect the non-minimal Higgs states, one must look for a deviation of the h couplings from SM expectations.

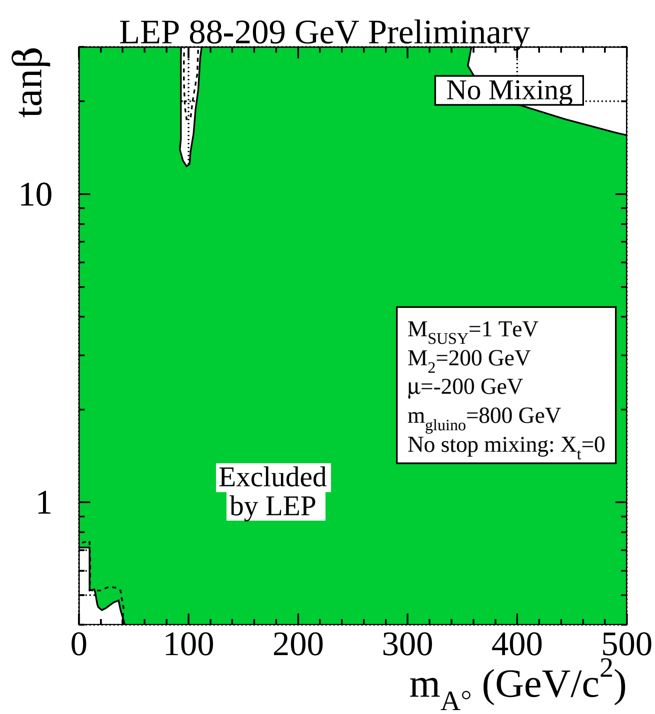
Challenge of the Decoupling Limit

- To summarize, the decoupling limit corresponds to the parameter regime in which all but one CP-even Higgs scalar is significantly heavier than the Z. The properties of the lightest CP-even Higgs boson are nearly indistinguishable from those of the Standard Model (SM) Higgs boson.
- Many models with non-minimal Higgs sectors possess a decoupling limit. Thus, discovery of the SM-like Higgs boson is not sufficient to reveal the underlying electroweak symmetry breaking dynamics.
- It is crucial to find evidence for Higgs physics beyond the SM Higgs boson. Either one must directly discover the non-minimal Higgs states (perhaps difficult, if they are too heavy), or one must detect deviations from SM Higgs predictions.
- In the latter case, precision Higgs measurements are essential for detecting deviations from the SM of branching ratios, coupling strengths, cross-sections, *etc.*

Are we being forced into the decoupling regime?

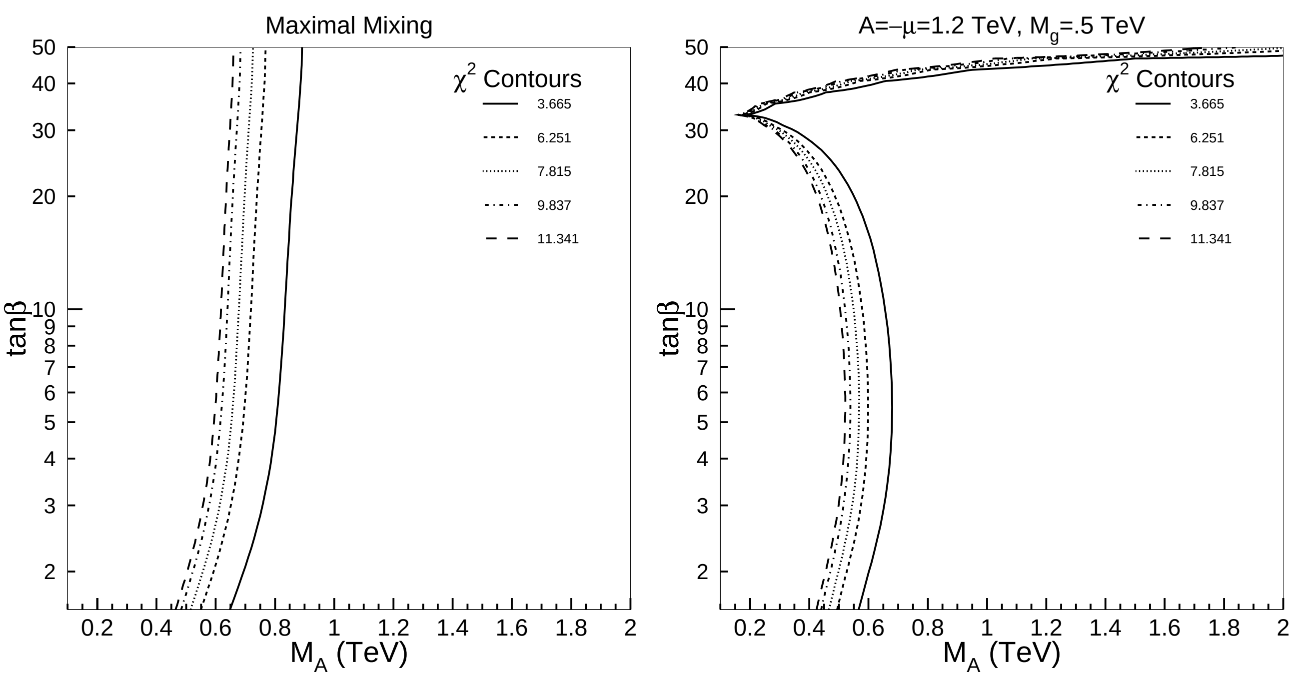
The present MSSM limit of $m_A > 91.9$ GeV is based on the *maximal-mixing scenario* where the value of X_t is chosen to maximize the predicted value of m_h [$X_t \sim 2M_S$]. The allowed region of the m_A–$\tan\beta$ plane shrinks significantly as one moves away from the maximal mixing case. At the other extreme is the *minimal-mixing scenario* corresponding to $X_t \sim 0$ (where the value of m_h as a function of X_t is minimized). LEP limits in this case are:





Implications of Precision Higgs Measurements at the LC

In the decoupling regime, one can measure the h branching ratios and couplings, and test for deviations of the h couplings from SM predictions. The size of the deviation measures the departure from decoupling. If no deviation is seen, then one can deduce a bound on m_A, which depends on the choice of MSSM parameters.



Contours of χ^2 for Higgs boson decay observables. The contours correspond to 68, 90, 95, 98 and 99% CLs (right to left) for the three observables g^2_{hbb}, $g^2_{h\tau\tau}$, and g^2_{hgg}. Note the region of m_A-independent decoupling in the right panel. (Carena, Haber, Logan and Mrenna)

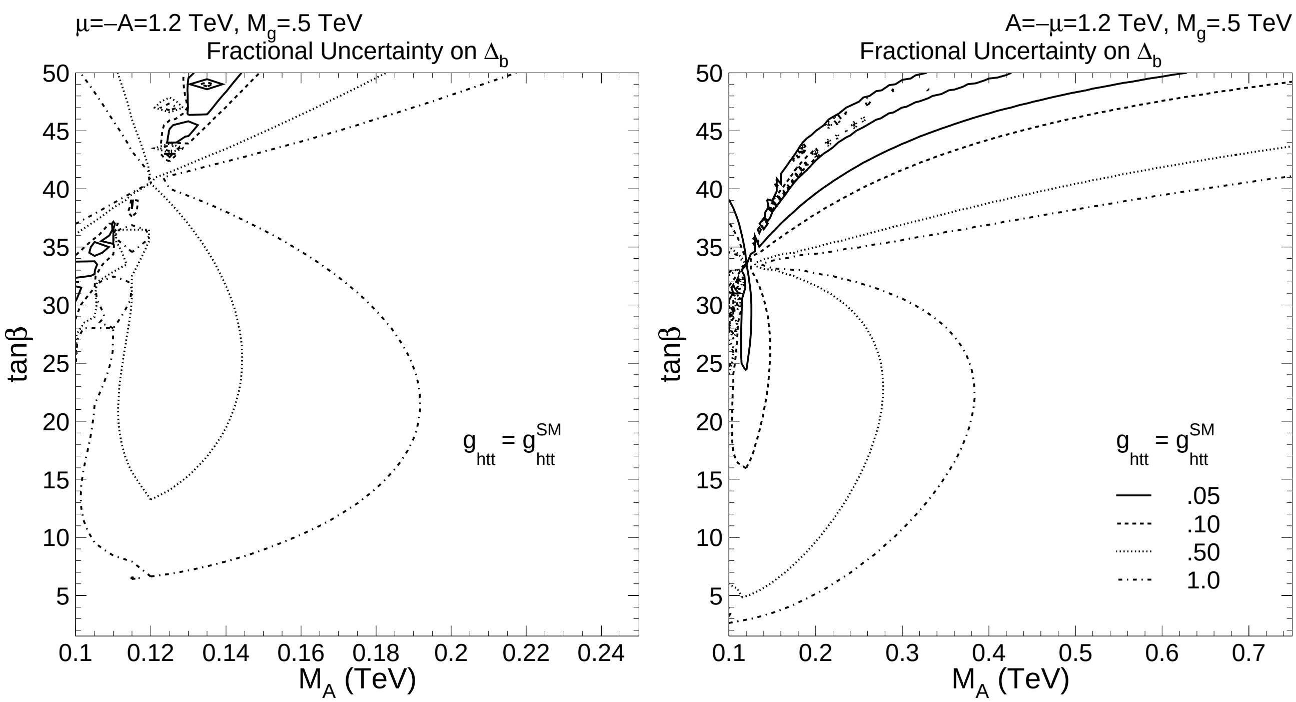
Extracting the SUSY parameter Δ_b

Consider the ratio of couplings

$$\frac{\hat{g}_{hbb}-\hat{g}_{h\tau\tau}}{\hat{g}_{htt}-\hat{g}_{hbb}}=\frac{\hat{g}_{Hbb}-\hat{g}_{H\tau\tau}}{\hat{g}_{Htt}-\hat{g}_{hbb}}\simeq\frac{\dfrac{\Delta_b-\Delta_\tau}{1+\Delta_\tau}-\dfrac{\delta h_b}{h_b}+\left(\dfrac{1+\Delta_b}{1+\Delta_\tau}\right)\dfrac{\delta h_\tau}{h_\tau}}{1-\left(\dfrac{1+\Delta_b}{1+\Delta_t}\right)\dfrac{\Delta h_t}{h_t}\cot\beta+\dfrac{\delta h_b}{h_b}},$$

where $\hat{g}_{\phi ff}\equiv g_{\phi ff}/g_{h_{SM}ff}$ $[\phi\equiv h,\,H]$. If desired, $t\bar{t}$ couplings can be replaced by $c\bar{c}$ couplings. Keeping only the leading $\tan\beta$-enhanced one-loop terms, and assuming $|\Delta_\tau|\ll 1$,

$$\frac{\hat{g}_{hbb}-\hat{g}_{h\tau\tau}}{\hat{g}_{htt}-\hat{g}_{hbb}}=\frac{\hat{g}_{Hbb}-\hat{g}_{H\tau\tau}}{\hat{g}_{Htt}-\hat{g}_{hbb}}\simeq\frac{\Delta_b-\Delta_\tau}{1+\Delta_\tau}\simeq\Delta_b\,,$$



Departures from decoupling in the 2HDM

One can be more general, and discuss departures from the decoupling limit in the most general 2 Higgs doublet Model (2HDM). Allowing for the most general Higgs-fermion coupling, one obtains tree-level Higgs-mediated FCNCs. Nevertheless, in the decoupling limit:

- The couplings of h to fermion pairs are identical to those of $h_{\rm SM}$, with FCNC couplings suppressed by $\cos(\beta-\alpha) \sim \mathcal{O}(m_Z^2/m_A^2)$. Likewise, any CP-violating couplings are also suppressed by $\cos(\beta-\alpha)$.
- FCNC and CP-violating effects mediated by A and H are suppressed by the square of the heavy Higgs masses (relative to m_Z), due to the propagator suppression. Since $m_h \ll m_H, m_A$ near the decoupling limit, FCNC and CP-violating processes mediated by h, H and A are all suppressed by the same factor of $\cos(\beta-\alpha)$.

Thus, the decoupling limit provides a natural mechanism for suppressed Higgs-mediated FCNCs and CP-violating effects in the most general 2HDM.

Conclusions

• Precision electroweak data suggests a weakly-coupled Higgs boson. The MSSM Higgs sector provides a potentially rich phenomenology to be unraveled at future colliders.

• It is essential to find evidence for departures from Standard Model Higgs predictions. Such departures will reveal crucial information about the nature of the electroweak symmetry breaking dynamics.

• Precision Higgs measurements can provide critical tests of the supersymmetric interpretation of new physics beyond the SM.

• Deviations from the decoupling limit provide useful information about the non-minimal Higgs sector and can yield indirect information about the MSSM parameters. At large $\tan\beta$, there can be additional sensitivity to MSSM parameters via enhanced radiative corrections.

• It is possible that more than one Higgs boson is accessible to future colliders, in which case there will be many Higgs boson observables to measure and interpret. In contrast, the decoupling limit presents a severe challenge for future Higgs studies. A program of precision Higgs measurements will begin at the LHC, but will only truly blossom at a future high energy e^+e^- linear collider.