EWSB and MSSM

Hana Hlucha

Seminar: Advanced Module Particle Physics - Electroweak symmetry breaking (Higgs mechanism)

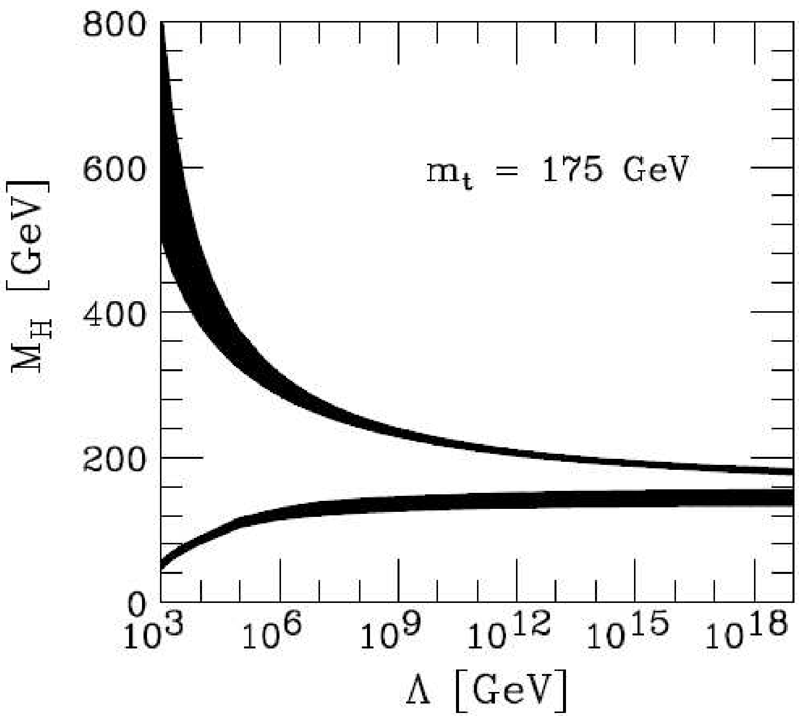
Program

- SM recapitulation
- Naturalness problem, Low-energy Susy
- MSSM Higgs sector
- Higgs couplings (to fermions and gauge bosons)
- radiatively-corrected Higgs masses
- LEP searches
- Higgs decays
- Higgs production at the LHC

SM recapitulation

- SM cannot be the ultimate theory (gravitation, neutrinos). It breaks down at M_{PL} or even below at some energy scale Λ ; Λ is constrained by $m_{H_{SM}}$ once H is found
- three Higgs boson mass ranges

1.	110 GeV	$\leq$	$m_{H_{SM}}$	$\leq$	130 GeV	Λ	2nd glob.min at Λ
2.	130 GeV	$\leq$	$m_{H_{SM}}$	$\leq$	180 GeV	M_{PL}	:)
3.	180 GeV	$\leq$	$m_{H_{SM}}$	$\leq$	190 GeV	Λ	λ blows up



190 GeV - upper limit from SM fit

given $\Lambda \rightarrow$ allowed max and min of Higgs mass

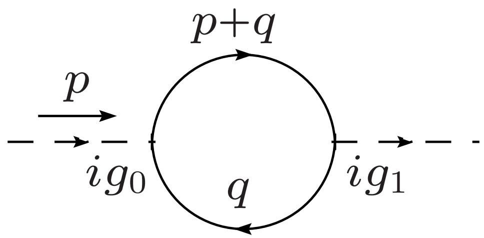
Naturalness

- nothing restricts the SM to survive up to the Planck scale if the Higgs mass is in the region (130 GeV,180 GeV). However, this is unlikely. Why?

- First consider this: In an EFT, all parameters of the low-energy theory (couplings, etc.) are calculable in terms of parameters of a more fundamental theory, that describes physics at the scale Λ. Most of the low-energy parameters are logarithmically sensitive to Λ but not scalar masses. They are quadratically sensitive. See below.

- Higgs boson self-energy

$$\mathscr{L} \leftrightarrow -y_f H \bar{f} f$$



$$\mathcal{M} = i\Pi(p^2), \qquad g_0 = g_1 = -\frac{m_f}{v} = -y_f$$

$$\mathcal{M} \;=\; \mu^{4-D} \int \frac{d^D q}{(2\pi)^D} \mathrm{Tr}\left[i g_1 \frac{i(\not{p} + \not{q} + m)}{(p+q)^2 - m_f^2 + i\varepsilon}\, i g_0\, \frac{i(\not{q} + m)}{q^2 - m_f^2 + i\varepsilon} \right] (-1)$$

$$
\begin{aligned}
&= \frac{i}{(4\pi)^2} g_0 g_1 \frac{(2\pi\mu)^{4-D}}{i\pi^2} \int d^D q \frac{-4(m_f^2 + p.q + q^2)}{\mathcal{D}_1 \mathcal{D}_0} \\
&= \frac{i}{(4\pi)^2} g_0 g_1 \int_q \frac{-2[(q^2 - m_f^2) + ((q+p)^2 - m_f^2) + 4m_f^2 - p^2]}{\mathcal{D}_1 \mathcal{D}_0} \\
&= \frac{-i g_0 g_1}{(4\pi)^2} [4A_0(m_f^2) + 2(p^2 - 4m_f^2) B_0(p^2, m_f^2, m_f^2)]
\end{aligned}
$$

- if we do not use DimReg but cut-off Λ instead

$$
\begin{aligned}
A_0(m^2) &= \frac{1}{i\pi^2} \int d^4 q \frac{1}{q^2 - m^2 + i\varepsilon} = [\text{Wick rotation}] = \frac{i(-1)^1}{i\pi^2} \int d^4 q_E \frac{1}{q_E^2 + m^2 - i\varepsilon} \\
&= \frac{-1}{\pi^2} \int d^4 \Omega_4 \int_0^\infty dq_E \; q_E^3 \frac{1}{q_E^2 + m^2} = \left[\Omega_4 = \frac{(2\pi)^{4/2}}{\Gamma(4/2)} = \frac{(2\pi)^2}{2} \right] \\
&= -2 \int_0^\Lambda \frac{q_E^3}{q_E^2 + m^2} = -\Lambda^2 + m^2 \ln\left(1 + \frac{\Lambda^2}{m^2}\right)
\end{aligned}
$$

$\Rightarrow A_0$ is quadratically divergent
note: B_0 is only logarithmically divergent

- Higgs mass: $m_H^2 = m_{H0}^2 - \delta m_H^2$, $\quad \delta m_H^2 = \Pi(m_H^2) = \underbrace{4 \sum_f \frac{m_f^2}{v^2 16\pi^2}}_{\text{c}} \Lambda^2 + \mathcal{O}(\ln \Lambda)$

  where m_{H0} is the parameter of the fundamental theory. The "natural" value for m_H^2 is $c\Lambda^2$.

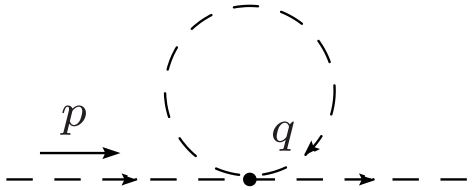
- expectation value for Λ :

$$\Lambda = \frac{m_H}{\sqrt{c}} \simeq \frac{120 v 2\pi}{m_t} \doteq 1060\,\mathrm{GeV}$$

  ◇ if Λ is much larger (hierarchy problem, fine-tuning problem): "unnatural" cancellation between m_{H0}^2 and δm_H^2 so that Higgs mass was associated with the scale of EWSB. But the two terms are of completely different origin.

- Higgs boson self-energy revisited

$\mathscr{L} \leftrightarrow -\lambda_s |H|^2 |S|^2$



$\mathcal{M} = i\Pi(p^2)$,

$$\begin{aligned} \mathcal{M} &= \mu^{4-D} \int \frac{d^D q}{(2\pi)^D}\, i g_0 \,\frac{i}{q^2 - m^2 + i\varepsilon} = \frac{-i}{(4\pi)^2}\, g_0\, A_0(m^2) \\ \Pi(m^2) &= \frac{-g_0}{(4\pi)^2}\left[-\Lambda^2 + \mathcal{O}(\ln(\Lambda))\right], \qquad g_0 \equiv -\lambda_s \end{aligned}$$

- overall mass-shift:

$$\begin{aligned} \delta m_H^2 &= 4\sum_f \frac{y_f^2}{16\pi^2}\Lambda^2 - \sum_s \frac{\lambda_s}{16\pi^2}\Lambda^2 = \frac{1}{16\pi^2}\left[4\sum_f y_f^2 - \sum_s \lambda_s\right]\Lambda^2 + \cdots \\ &= 0 \quad \text{if } \lambda_s = 2y_f^2 \end{aligned}$$

- for each Dirac fermion $f = (f_L, f_R)$ there are two sfermions $\tilde{f}_L, \tilde{f}_R$ with quartic coupling $\lambda_s = 2y_f^2$. So, in unbroken supersymmetry $\rightarrow$ "naturalness" problem is solved

- supersymmetry is broken (we do not observe new particles with masses equal to masses of SM particles). Is broken softly (no dimensionless couplings in $\mathscr{L}_{\text{soft}}$)
$\rightarrow$ additional non-supersymmetric corrections to m_H^2. They must vanish in $m_{\text{soft}} \rightarrow 0$ limit.

$$\delta m_H^2 = m_{\text{soft}}^2 \left[\frac{-4y_f^2}{16\pi^2} \ln\left(\frac{\Lambda^2}{m_{\text{soft}}^2}\right) + \ldots \right]$$

- now if $\Lambda = M_{PL}$ then $m_{\text{soft}} \leq \mathcal{O}(1 \text{ TeV})$ so that MSSM scalar Higgs potential provides a Higgs VEV resulting in $m_W, m_Z = 80.4, 91.2$ GeV
$\rightarrow$ "naturalness" problem is solved in supersymmetric models with SUSY scale of order 1 TeV. Low-energy supersymmetry can be valid up to the Planck scale, while still being natural.

- matter superfield: $\hat{\Phi} = (\phi, \psi, F)$, vector superfield: $\hat{V} = (\lambda, V, D)$
- $\mathscr{L} = i\lambda^{(a)}\sigma^\mu \mathscr{D}_\mu \bar{\lambda}^{(a)} - \frac{1}{4}F^{(a)}_{\mu\nu}F^{(a)\ \mu\nu} + \frac{1}{2}D^{(a)}D^{(a)} + i(\bar{\psi}_i\bar{\sigma}^\mu \mathscr{D}_\mu \psi_i) + F^*_i F_i$
  $+ (\mathscr{D}_\mu \phi_i)^*(\mathscr{D}^\mu \phi_i) + i\sqrt{2}gT^{(a)}_{ij}[\phi^*_i(\lambda^{(a)}\psi_j) - (\bar{\lambda}^{(a)}\bar{\psi}_i)\phi_j] + gD^{(a)}T^{(a)}_{ij}\phi^*_i\phi_j$
  $+ W + \mathscr{L}_{\mathrm{soft}}$
- $W = (\frac{1}{2}m_{ij}\hat{\Phi}_i\hat{\Phi}_j + \frac{1}{3}\lambda_{ijk}\hat{\Phi}_i\hat{\Phi}_j\hat{\Phi}_k)_F \quad \rightarrow (\phi_i F_j, \phi_i\phi_j F_k, \psi_i\psi_j\phi_k)$
- $\mathscr{L}_{\mathrm{soft}} = -m^2_{H_d}|H_d|^2 - m^2_{H_u}|H_u|^2 - b\varepsilon_{ij}(H^i_d H^j_u + H^{\dagger i}_d H^{\dagger j}_u) + \dots$

  where the covariant derivatives and the non-abelian field strength tensor are

$$\begin{aligned} \mathscr{D}_\mu \bar{\lambda}^{(a)} &= \partial_\mu \bar{\lambda}^{(a)} - gf^{abc}V^{(b)}_\mu \bar{\lambda}^{(c)} \\ F^{(a)}_{\mu\nu} &= \partial_\mu V^{(a)}_\nu - \partial_\nu V^{(a)}_\mu - gf^{abc}V^{(b)}_\mu V^{(c)}_\nu \\ \mathscr{D}_\mu \psi &= \partial_\mu \psi + igV_\mu \psi \\ \mathscr{D}_\mu \phi &= \partial_\mu \phi + igV_\mu \phi \end{aligned}$$

"Derivation" of the Higgs potential

- relevant terms in the lagrangian: $H_u = (H_u^+, H_u^0)$, $H_d = (H_d^0, H_d^-)$

$$\mathscr{L} = \varepsilon_{ij}\mu(H_d^i F_{H_u}^j) + F^*_{H_d^0}F_{H_d^0} + F^*_{H_d^-}F_{H_d^-} + F^*_{H_u^+}F_{H_u^+} + F^*_{H_u^0}F_{H_u^0} + \mathrm{h.c.}$$
$$+ \tfrac{1}{2}D_B D_B + \tfrac{1}{2}D_{W^i}D_{W^i} + g' D_B (H_d)^*_a \left(\frac{Y}{2}\right)_{ab}(H_d)_b + g' D_B (H_u)^*_a \left(\frac{Y}{2}\right)_{ab}(H_u)_b$$
$$+ g\textstyle\sum_i D_{W^i}(H_d)^*_a \left(\frac{\tau^i}{2}\right)_{ab}(H_d)_b + g\sum_i D_{W^i}(H_u)^*_a \left(\frac{\tau^i}{2}\right)_{ab}(H_u)_b$$
$$- m^2_{H_u}|H_u|^2 - m^2_{H_d}|H_d|^2 - b\varepsilon_{ij}(H_d^i H_u^j + H_d^{\dagger i} H_u^{\dagger j})$$

F-terms, D-terms, Susy-breaking terms

- E-L equations: $F^*_{H_d^-} = -\mu H_u^+ + \cdots$

$$D_B = \frac{g'}{2}(|H_d|^2 - |H_u|^2) + \dots$$
$$D_{W^i} = -g\left((H_d^*)_a \left(\frac{\tau^i}{2}\right)_{ab}(H_d)_b + (H_u^*)_a \left(\frac{\tau^i}{2}\right)_{ab}(H_u)_b\right) + \dots$$

we substitute back to the lagrangian and we obtain

EWSB and MSSM Higgs sector

- there are two comlex Higgs doublets $H_u = (H_u^+, H_u^0)$ and $H_d = (H_d^0, H_d^-)$. The classical scalar potential is given by

$$
\begin{aligned}
V &= (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2) \\
&+ [b(H_u^+ H_d^- - H_u^0 H_d^0) + \mathrm{c.c}] + \frac{1}{2} g^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2 \\
&+ \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2
\end{aligned}
$$

- we demand that the minimum of this potential breaks electroweak symmetry down to electromagnetism. To simplify the analysis we first make SU(2) gauge transformation to rotate away possible VEV of H_u^+. One then finds that at the minimum also $H_d^- = 0$. So we are left to consider

$$
\begin{aligned}
V &= (|\mu|^2 + m_{H_u}^2)|H_u^0|^2 + (|\mu|^2 + m_{H_d}^2)|H_d^0|^2 - (b H_u^0 H_d^0 + \mathrm{c.c}) \\
&+ \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 - |H_d^0|^2)^2
\end{aligned}
$$

- only b-term depends on the phases of the Higgs fields. Phases redefinition $\longrightarrow$ real b > 0

EWSB and MSSM Higgs sector

- minimum requires that $H_u^0 H_d^0$ is real and positive as well. It follows that $\langle H_u^0 \rangle$ and $\langle H_d^0 \rangle$ have opposite phases. Since H_u and H_d have opposite hypercharges we can make both $\langle H_u^0 \rangle$, $\langle H_d^0 \rangle$ real and positive at the same time by using $U(1)_Y$ gauge transformation. It follows that tree level Higgs sector is CP conserving.

- Potential must be bounded form below for large values of neutral Higgs fields. Quartic couplings will do the job up to the case when $|H_u^0| = |H_d^0|$. For the potential to be bounded from below in this special case we further must require

$$2b < 2|\mu|^2 + m_{H_u}^2 + m_{H_d}^2$$

- to obtain a stable minimum different from zero the following condition must be satisfied

$$\det < 0 : \qquad b^2 > (|\mu|^2 + m_{H_u}^2)(|\mu|^2 + m_{H_d}^2)$$

- minimum conditions: $b \cot\beta = m_{H_u}^2 + |\mu|^2 - (m_Z^2/2)\cos 2\beta$

$$b \tan\beta = m_{H_d}^2 + |\mu|^2 + (m_Z^2/2)\cos 2\beta \qquad \beta \epsilon (0, \pi/2)$$

- if $m_{H_u}^2 < m_{H_d}^2$ then $\cos 2\beta$ is negative, otherwise is positive

Tree-level MSSM Higgs sector

- Two Higgs doublets are required in supersymmetric theories to generate mass for both "up" type and "down" type quarks and charged leptons. They receive mass and VEVs from generalized Higgs potential.

$$H_d = \begin{pmatrix} (v_d + \phi_d^0 + i\chi_d^0)/\sqrt{2} \\ \phi_d^- \end{pmatrix} \quad H_u = \begin{pmatrix} \phi_u^+ \\ (v_u + \phi_u^0 + i\chi_u^0)/\sqrt{2} \end{pmatrix}$$

normalization: $v^2 \equiv v_d^2 + v_u^2 = 4m_W^2/g^2 = (246\,\mathrm{GeV})^2$

- mass eigenstates:

Neutral sector		Charged sector	
2 CP even Higgs bosons:	h, H	charged Higgs bosons:	$H^\pm$
1 CP odd Higgs boson:	A	charged Goldstone bosons:	$G^\pm$
1 Goldstone boson:	G^0		

Tree-level MSSM Higgs sector

- two doublet Higgs fields expanded in mass-eigenstates

$$H_u = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}[H^- \sin\beta - G^- \cos\beta] \\ v_u + [H \cos\alpha - h \sin\alpha] + i[A \sin\beta + G^0 \cos\beta] \end{pmatrix}$$

$$H_d = \frac{1}{\sqrt{2}} \begin{pmatrix} v_d + [H \sin\alpha + h \cos\alpha] + i[A \cos\beta - G^0 \sin\beta] \\ \sqrt{2}[H^+ \cos\beta + G^+ \sin\beta] \end{pmatrix}$$

- the angle β is determined by the VEVs

$$v_d = v\cos\beta, \qquad v_u = v\sin\beta, \qquad \Rightarrow \frac{v_u}{v_d} = \tan\beta, \quad \beta\epsilon(0,\tfrac{\pi}{2})$$

- all Higgs sector parameters at tree-level are determined by two parameters:
  $\longrightarrow$ $\tan\beta$ and one Higgs mass, convienently chosen to be m_A

- in particular, $\quad m^2_{H^\pm} = m^2_A + m^2_W$

Tree-level MSSM Higgs sector

- squared masses of h, H are eigenvalues of the following matrix

$$\mathcal{M}_0^2 = \begin{pmatrix} m_A^2 \sin^2\beta + m_Z^2 \cos^2\beta & -(m_A^2 + m_Z^2)\sin\beta\cos\beta \\ -(m_A^2 + m_Z^2)\sin\beta\cos\beta & m_A^2\cos^2\beta + m_z^2 \sin^2\beta \end{pmatrix}$$

that is: $m_{H,h}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right)$

- and α is the angle that diagonalizes $\mathcal{M}_0^2$. From the above results one obtain

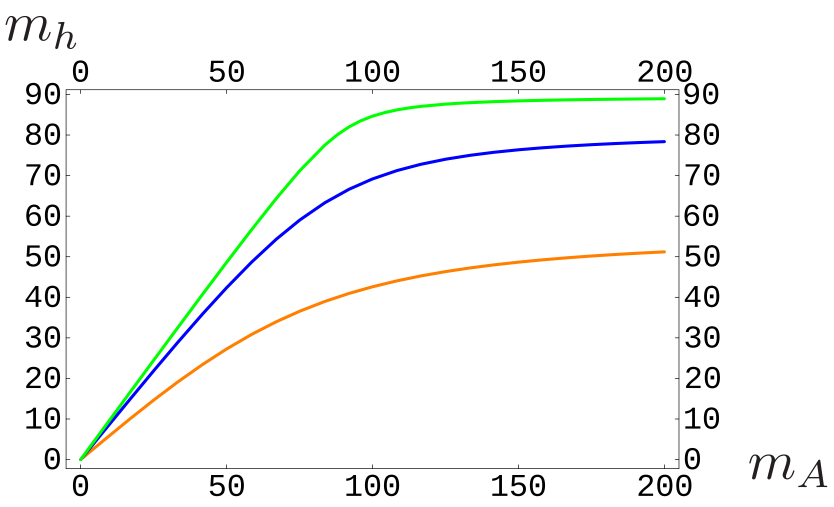
$$\cos^2(\beta-\alpha) = \frac{m_h^2(m_Z^2-m_h^2)}{m_A^2(m_H^2-m_h^2)}$$

convention: positive $\tan\beta$ $(0 \le \beta \le \pi/2) \to \alpha$ lies in the range $-\pi/2 \le \alpha \le 0$

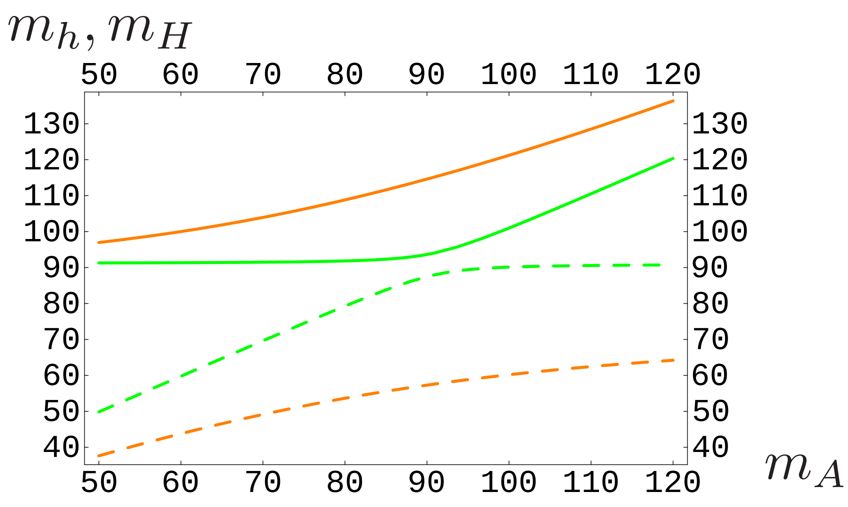
- from equation for m_h^2 one can derive an upper bound to the light CP even Higgs boson h

$$m_h^2 = \frac{2m_Z^2 m_A^2 \cos^2 2\beta}{m_A^2+m_Z^2+\sqrt{(m_A^2+m_Z^2)^2-4m_Z^2m_A^2\cos^2 2\beta}} \le m_Z^2\cos^2 2\beta$$

- m_h as a function of m_A



$\tan\beta = 2$, $\tan\beta = 4$, $\tan\beta = 10$



$\tan\beta = 3$, $\tan\beta = 30$

note 1: $m_h^2 \leq m_Z^2 \cos^2 2\beta \to m_h \leq m_Z$ is ruled out by LEP data $\Rightarrow$ need to include radiative corrections

note 2: SM does not constrain the value of $m^2_{h_{\rm SM}}$ at tree level. In SM $m^2_{h_{\rm SM}} = \lambda v^2$ and λ is free parameter. In MSSM Higgs self-couplings are related to electroweak couplings.

Tree-level MSSM Higgs sector

- the m_h^2 reaches its upper bound value in the limit of large m_A. In this limit we found

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

$$m_H^2 \simeq m_A^2 + m_Z^2 \frac{1-2\cos^2 2\beta}{2} \qquad m_{H^\pm}^2 = m_A^2 + m_W^2$$

  ◇ $m_A \simeq m_H \simeq m_{H^\pm}$
  ◇ $\cos(\beta-\alpha) \simeq 0 \quad \longrightarrow \quad$ decoupling limit

- if we now focus on an effective-field theory below m_A the effective Higgs sector consists only of one Higgs boson h. Moreover, the tree-level couplings of h are precisely those of SM Higgs boson when $\cos(\beta-\alpha) = 0$.

- relevant Lagrangian reads

$$\begin{aligned}\mathscr{L} &= (\mathcal{D}^\mu H_u)^\dagger D_\mu H_u + (\mathcal{D}^\mu H_d)^\dagger D_\mu H_d \\ &= \frac{1}{2}|\partial_\mu \phi_u^0|^2 + \frac{1}{2}|\partial_\mu \phi_d^0|^2 + \left(\frac{g_Z^2}{8} Z_\mu Z^\mu + \frac{g^2}{4} W_\mu^+ W^{-\mu}\right)\left[(v_u + \phi_u^0)^2 + (v_d + \phi_d^0)^2\right]\end{aligned}$$

- weak boson masses: $m_W^2 = \frac{g^2 v^2}{4}$ $\qquad m_Z^2 = \frac{g^2+g'^2}{4} v^2 = \frac{m_W^2}{\cos^2\theta_W}$ $\qquad v^2 = v_u^2 + v_d^2$

- couplings arise from: $2v_u\phi_u + 2v_d\phi_d = 2v[H\cos(\beta-\alpha) + h\sin(\beta-\alpha)]$

$$\begin{aligned} g_{hWW} &= g\ m_W \sin(\beta-\alpha) & \qquad g_{HWW} &= g\ m_W \cos(\beta-\alpha) \\ g_{hZZ} &= \frac{g}{\cos_{\theta_W}}\ m_Z \sin(\beta-\alpha) & \qquad g_{HZZ} &= \frac{g}{\cos_{\theta_W}}\ m_Z \cos(\beta-\alpha)\end{aligned}$$

- decoupling limit: $\cos(\beta-\alpha) \to 0 \Rightarrow H$ decouples from W, Z
  $\sin(\beta-\alpha) \to 1 \Rightarrow h$ couples like SM Higgs boson

- there are no tree level couplings of $A, H^\pm$ to VV (where $V = W, Z$)

Higgs couplings to gauge bosons

- summary of Higgs couplings to gauge bosons

$\cos(\beta-\alpha)$	$\sin(\beta-\alpha)$
HW^+W^-	hW^+W^-
HZZ	hZZ
ZAh	ZAH
$W^\pm H^\mp h$	$W^\pm H^\mp H$
$ZW^\pm H^\mp h$	$ZW^\pm H^\mp H$
$\gamma W^\pm H^\mp h$	$\gamma W^\pm H^\mp H$

- vertices that contain at least one vector boson and *exactly* one non-minimal (H, A, or $H^\pm$) are proportional to $\cos(\beta-\alpha)$

Higgs couplings to fermions

- Yukawa Lagrangian:

$$-\mathscr{L} \quad = \quad h_t(\bar{t}P_L t H_u^0 - \bar{t}P_L b H_u^+) + h_b(\bar{b}P_L b H_d^0 - \bar{b}P_L t H_u^-) + \text{h.c.}$$

$$h_b = \frac{\sqrt{2}m_b}{v_d} = \frac{\sqrt{2}m_b}{v\cos\beta} \qquad h_t = \frac{\sqrt{2}m_t}{v_u} = \frac{\sqrt{2}m_t}{v\sin\beta}$$

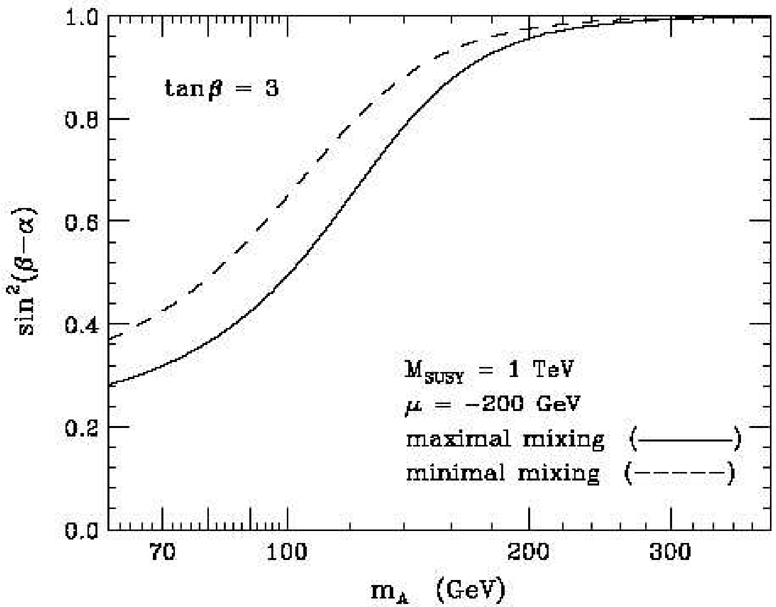
$$= \tfrac{m_t}{v}\bar{t}\left(v + H\tfrac{\sin\alpha}{\sin\beta} + h\tfrac{\cos\alpha}{\sin\beta} - i\gamma^5 A\cot\beta\right)t + \tfrac{m_b}{v}\bar{b}\left(v + H\tfrac{\cos\alpha}{\cos\beta} - h\tfrac{\sin\alpha}{\cos\beta} - i\gamma^5 A\cot\beta\right)b$$

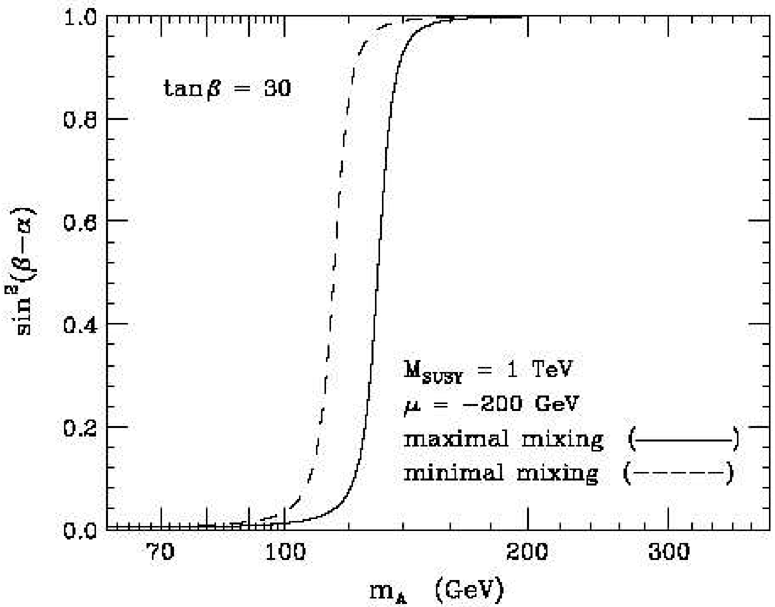
- couplings relative to SM values: decoupling limit

$$\begin{aligned}
h\bar{b}b&: \quad -\tfrac{\sin\alpha}{\cos\beta} = \sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha) && \to 1\\
h\bar{t}t&: \quad \tfrac{\cos\alpha}{\sin\beta} = \sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha) && \to 1\\
H\bar{b}b&: \quad \tfrac{\cos\alpha}{\cos\beta} = \cos(\beta-\alpha) + \tan\beta\sin(\beta-\alpha) && \to \tan\beta\\
H\bar{t}t&: \quad \tfrac{\sin\alpha}{\sin\beta} = \cos(\beta-\alpha) - \cot\beta\sin(\beta-\alpha) && \to -(\tan\beta)^{-1}\\
A\bar{b}b&: \quad \gamma_5\tan\beta\\
A\bar{t}t&: \quad \gamma_5\cot\beta
\end{aligned}$$

- large $\tan\beta \rightarrow$ enhancement in some Higgs couplings
  - ◇ $m_A \gg m_Z$:
    - ∗ decoupling limit is reached
    - ∗ equal strength of $b\bar{b}H, b\bar{b}A$ couplings, $\tan\beta$ enhancement
    - ∗ VVH coupling is negligibly small
    - ∗ $VVh, b\bar{b}h$ couplings are equal to those in SM ($\tan\beta\cos(\beta-\alpha) \ll 1$, see p.17)
  - ◇ $m_A \lesssim m_Z$
    - ∗ if $\tan\beta \gg 1$ then $|\sin(\beta-\alpha)| \ll 1$ and $m_h \simeq m_A$

rad. corr. included



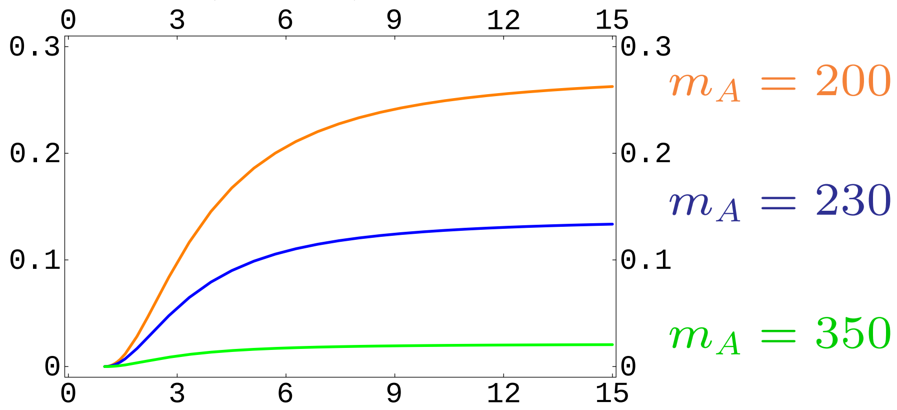


- $b\bar{b}h, b\bar{b}A$ have equal strength, $\tan\beta$ enhanced
- VVh coupling is negligibly small
- VVH coupling is equal to VVh_{SM}
- $b\bar{b}H$ coupling may differ from $b\bar{b}h_{SM}$ ($\tan\beta\sin(\beta-\alpha)$ is not negligibly small)

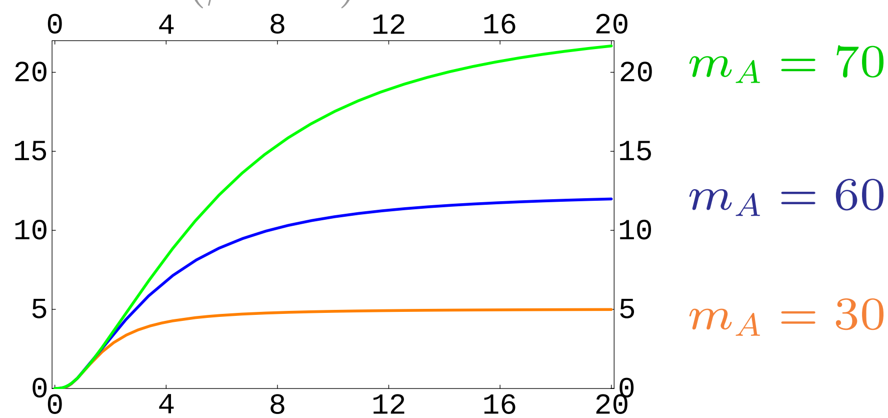
• in both cases only two of three Higgs bosons have enhanced coupling to $b\bar{b}$

note: The decoupling limit is effective for all values of $\tan\beta$. Since $\sin(\beta-\alpha)$ approaches 1 quite rapidly if m_A is larger than 200 GeV, the region of MSSM Higgs sector parameter space in which the decoupling limit is applicable is large. Consequently, the search for the lightest CP even Higgs boson is equivalent to the search of SM Higgs boson.

$\tan^2\cos^2(\beta-\alpha)$



$\tan^2\sin^2(\beta-\alpha)$



- radiative corrections must be considered since tree level upper bound on a Higgs mass $m_h < m_Z$ does not hold

- dominant effects arise from loops involving the 3rd generation quarks and squarks and are proportional to large Yukawa couplings

- squarks
  - ◇ for left-handed and right-handed quark there is a supersymmetric partner $\tilde{q}_L$ and $\tilde{q}_R$
  - ◇ $\tilde{q}_L, \tilde{q}_R$ are interaction eigenstates; the corresponding mass-matrix is not diagonal

$$\begin{pmatrix} M_Q^2 + m_f^2 + D_L & m_f X_f \\ m_f X_f & M_R^2 + m_f^2 + D_R \end{pmatrix}$$

  where $D_L \equiv (T_{3f} - e_f \sin^2\theta_W)m_Z^2 \cos 2\beta$ and $D_R \equiv e_f \sin^2\theta_W m_Z^2 \cos 2\beta$,
  $M_R \equiv M_U(M_D)$ for the top-squark (bottom squark)

  - ◇ squark mixing parameters: $X_t \equiv A_t - \mu \cot\beta$, $X_b \equiv A_b - \mu \tan\beta$

- When $\tan\beta$ is large and $m_A \gg m_Z$ then tree $m_h < m_Z$. Dominant effects in radiative corrections - incomplete cancellation of top and stop loops. The qualitative behaviour of radiative corrections is easily seen in the limit of large stop quark mass

  the upper bound on the lightest CP-even Higgs mass is approximately given by

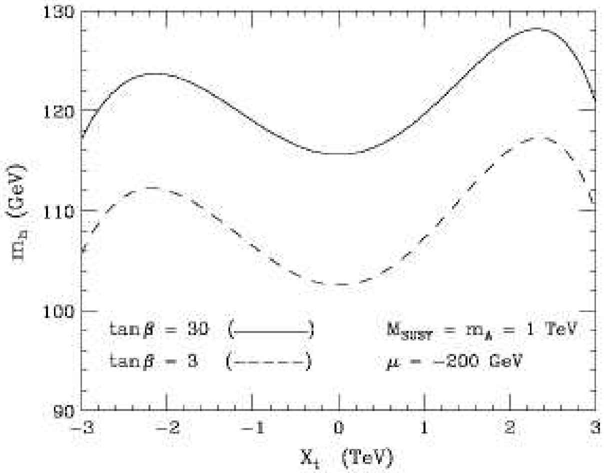
$$m_h^2 \lesssim m_Z^2 + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$

  where $M_S^2 \equiv \frac{1}{2}(M_{\tilde{t}_1}^2 + M_{\tilde{t}_2}^2)$, $x_t \equiv X_t/M_S$

  this relation correctly reflects following:

  ◇ increase of the Higgs mass upper-bound (due to m_t^4 enhancement)
  ◇ dependence of Higgs mass on the X_t, maximal value at $X_t = \sqrt{6}M_S$ - maximal mixing scenario (more precise calculations - asymmetry under $X_t \to -X_t$)
  ◇ logarithmic sensitivity to stop quark masses

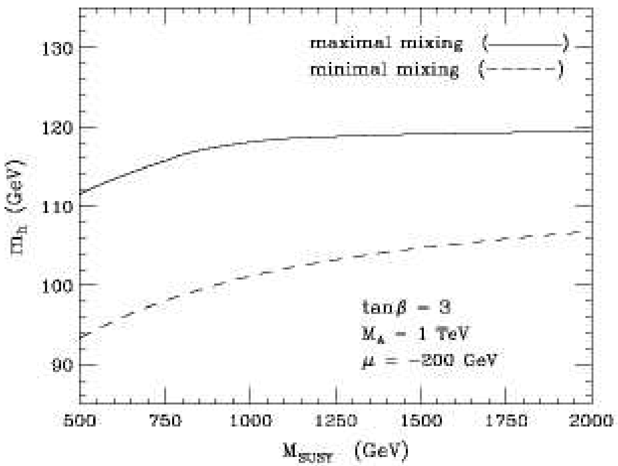
- X_t dependence

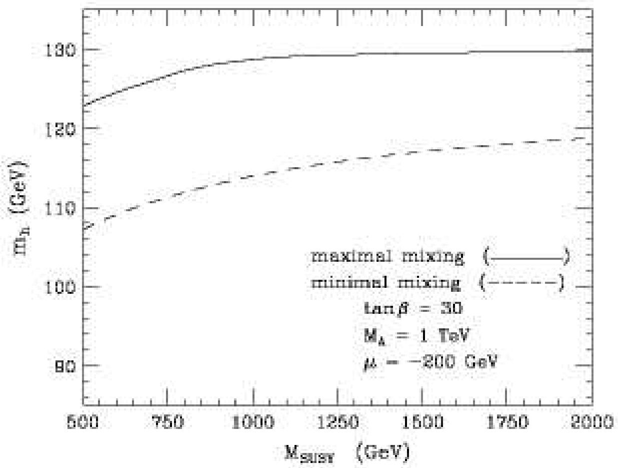


from a more complete computation: maximal mixing case and minimal mixing case values $(X_t = 0, \sqrt{6}M_S)$ are shifted

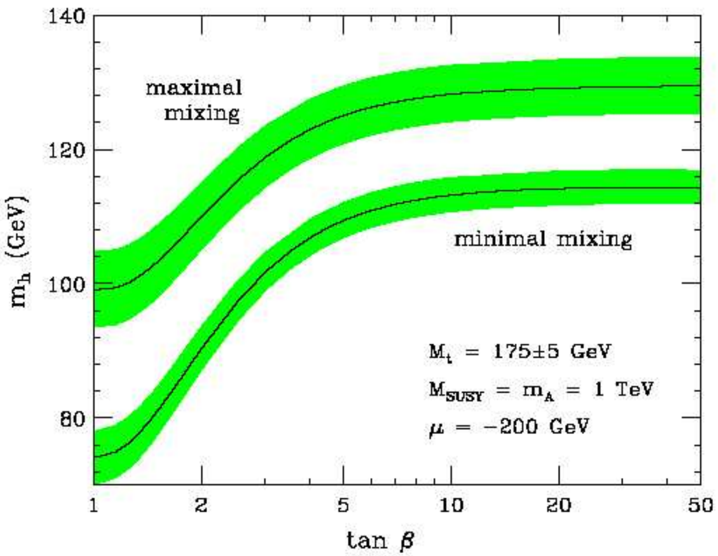
upper bound Higgs mass depends on the upper limit of stop masses
$m_{\text{soft}} = M_{\text{SUSY}} = M_Q = M_U = M_D$

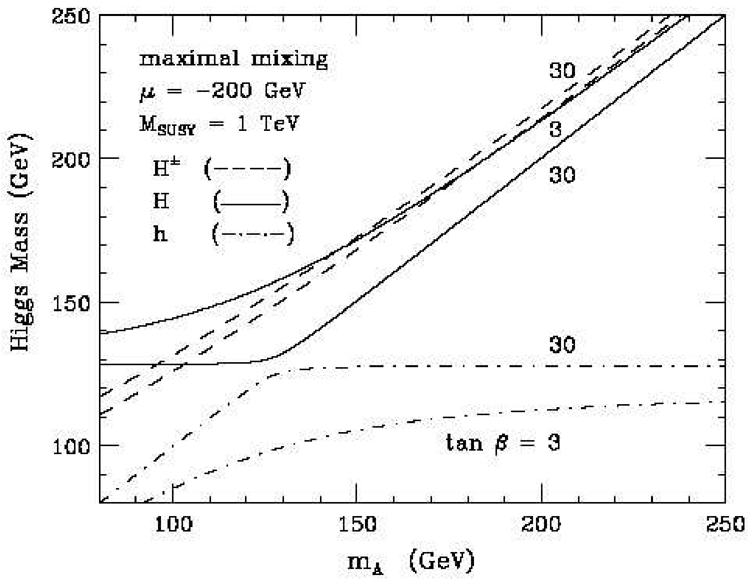
- m_{soft} sensitivity





maximal value of m_h

- 

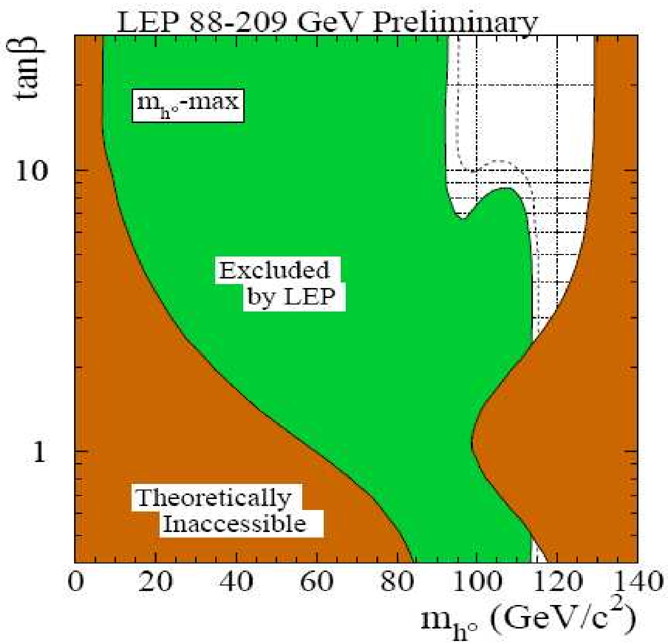


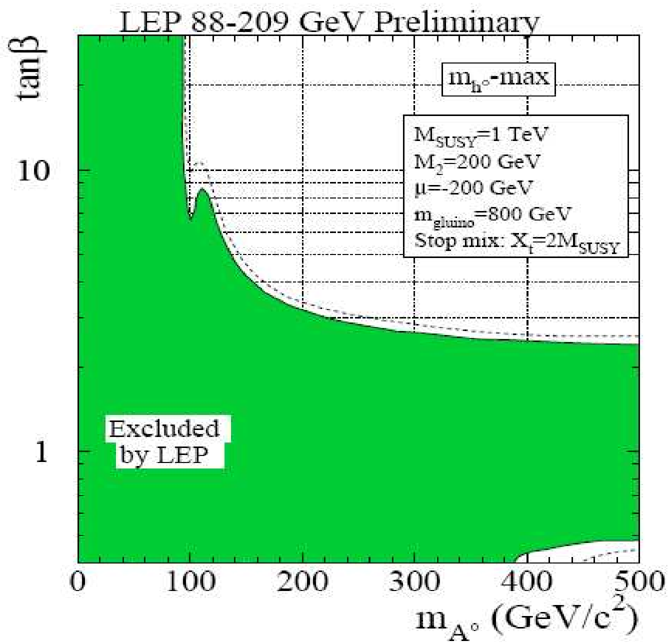
- in the region of large $\tan\beta$: $m_h^{\max} \simeq 122GeV$, if maximal stop mixing
  $m_h^{\max} \simeq 135GeV$, if minimal stop mixing

- in practice, maximal mixing scenario is not expected $\longrightarrow$ $m_h^{\max}$ is somewhere between

- if $m_A > m_h^{\max}$ then $m_h \simeq m_h^{\max}$ and $m_H \simeq m_A$
  if $m_A < m_h^{\max}$ then $m_h \simeq m_A$ and $m_h \simeq m_h^{\max}$

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

- 



$ZZh \sim \sin(\beta - \alpha)$
$ZhA \sim \cos(\beta - \alpha)$

- production processes: $e^+e^- \rightarrow Z^* \rightarrow Zh$ and hA (in tiny region - production of H)

  large m_A: hZ searches — $m_h > 91.0$ GeV $\leftarrow$ non observation of hA
  low m_A, large $\tan\beta$: hA searches — $m_A > 91.9$ GeV $\leftarrow$ at large $\tan\beta$ when
  low m_A, low $\tan\beta$: both channels — Zh is suppressed

- as $\tan\beta$ is lowered the limits on m_h and m_A become more stringent. Then hA production is suppressed while Zh rate approaches SM value $\longrightarrow$ SM Higgs limit applies ($m_h >$ 114 GeV).

Searches for $e^+e^- \to h^0 A^0$

Experiment:	ALEPH	DELPHI	L3	OPAL
192 GeV: Integrated luminosity (pb^{-1}):	28.9	25.9	29.7	28.7-28.9
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	4.8/3	5.7/6	1.2//1	1.5/4
$\tau^+\tau^- b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	0.3/0	0.8/0	0.2/0	1.2/1
196 GeV: Integrated luminosity (pb^{-1}):	79.9	76.9	83.7	74.7-74.8
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	14.8/8	18.6/21	3.4/3	3.6/7
$\tau^+\tau^- b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	0.8/0	2.4/3	0.5/0	2.9/2
200 GeV: Integrated luminosity (pb^{-1}):	86.3	84.3	82.7	74.8-77.2
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	17.5/16	17.8/14	5.5/5	3.6/4
$\tau^+\tau^- b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	1.1/1	2.6/3	0.4/0	2.7/1
202 GeV: Integrated luminosity (pb^{-1}):	41.9	41.1	37.0	35.4-36.1
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	9.3/3	9.0/6	3.6/1	1.8/1
$\tau^+\tau^- b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	0.5/0	1.3/0	0.2/0	0.9/2
Total: Integrated luminosity (pb^{-1}):	237.0	228.2	233.1	214-217
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	46.4/30	51.1/47	13.7/10	10.5/16
$\tau^+\tau^- b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	2.7/1	7.1/6	1.3/0	7.7/6
Events in all channels:	49.1/31	58.2/53	15.0/10	18.2/22
Limit exp.(median)/obs. for m_h (GeV/c^2):	88.9/91.5	85.3/85.0	85.5/80.5	83.7(*)/79.2
Limit exp.(median)/obs. for m_A (GeV/c^2):	89.3/91.9	87.1/86.2	86.0/81.0	85.4(*)/80.2

Table 2: *Information related to searches of the four LEP experiments for the process* $e^+e^- \to hA$ *at energies from 192 to 202 GeV. In the L3 analysis the event selection, and thus the expected background and observed number of events, depend on the Higgs boson mass hypothesis; they are given here for* $m_H \approx m_A = 90$ GeV/c^2. *The limits quoted in the last two lines are obtained by combining the searches for* $e^+e^- \to hZ$ *and* $e^+e^- \to hA$*, and correspond to the mh-max benchmark scenario. (*) In the OPAL publication the expected "mean" is quoted, not the "median".*

no Higgs signal?

models with $\cos^2\beta - \alpha \neq 0$
have $m_h \approx m_A$
dominant $b\bar{b}, \tau^+\tau^-$ decays

$m_h \approx m_A = 90$ GeV

MSSM HIGGS - PRELIMINARY

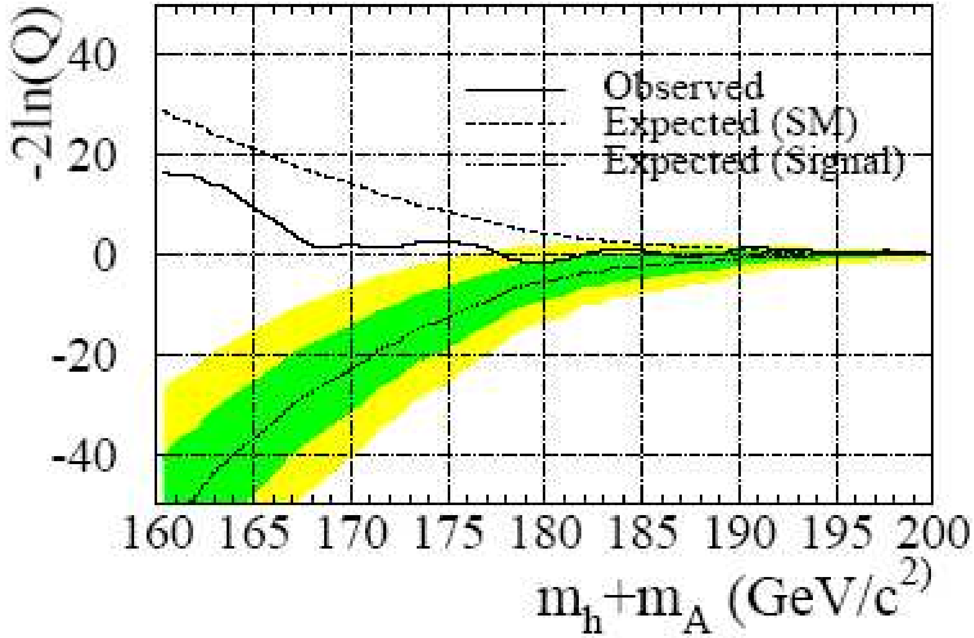


Figure 6: *The negative log-likelihood ratio (test-statistic) as a function of* $m_H + m_A$. *The dashed line shows the expectation for the background-only hypothesis and the full line the values computed from the observed results. The dotted line and the shaded areas show the central value and the* 1σ *and* 2σ *probability bands for the signal at the "true" mass sum.*

Higgs boson decay modes

- $m_A \gg m_Z$
  - ◇ and large masses of susy particles $\longrightarrow$ decoupling limit applies $\longrightarrow$ h indistinguishable from SM Higgs
  - ◇ light susy masses $\longrightarrow$ decoupl. limit does not apply b/c of modified BRs due to new allowed decay channels

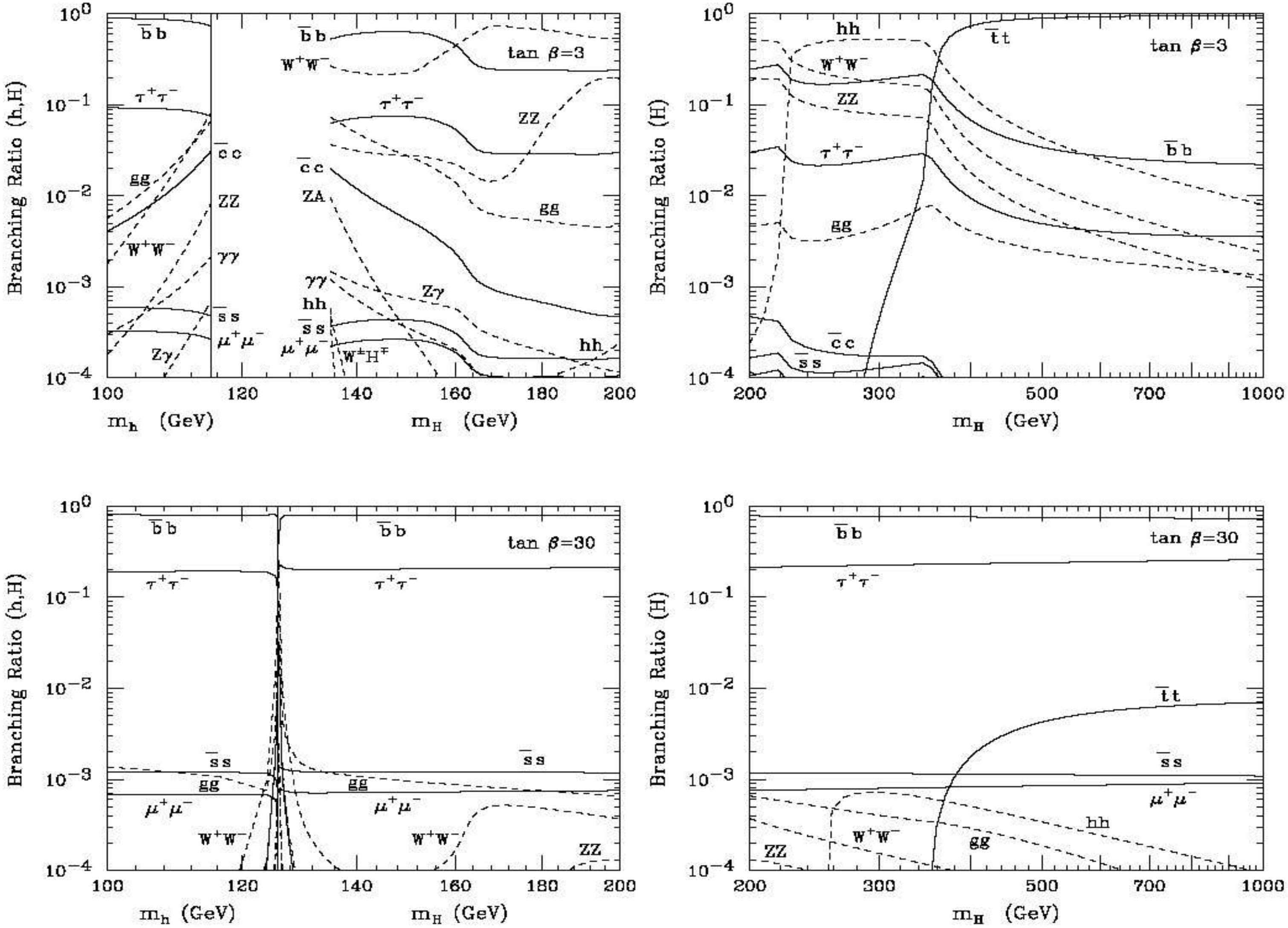
  in both cases: $H, A, H^{\pm}$ are mass degenerate and their BRs depend crucially on $\tan\beta$

- $m_A \sim m_Z$
  - ◇ all Higgs bosons masses below 200 GeV - non has properties of SM Higgs boson,
  - ◇ $\tan\beta \gg 1 : b\bar{b}$ and $\tau^+\tau^-$ decay rates significantly modified due to radiative corrections
  - ◇ new Higgs boson decay channels

- big difference between "low" and 'high" $\tan\beta$ regime

- next figures: BRs for h and H as functions of mass; m_A varies from 90 GeV to 1 TeV

Higgs boson decay modes

- 

$M_{SUSY} = 1TeV$

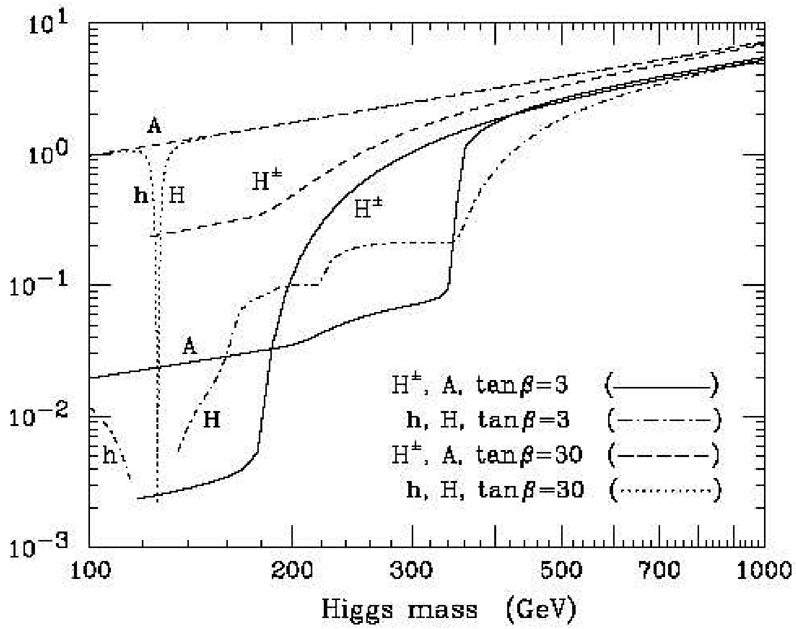
$X_t = 2.4 M_{SUSY}$

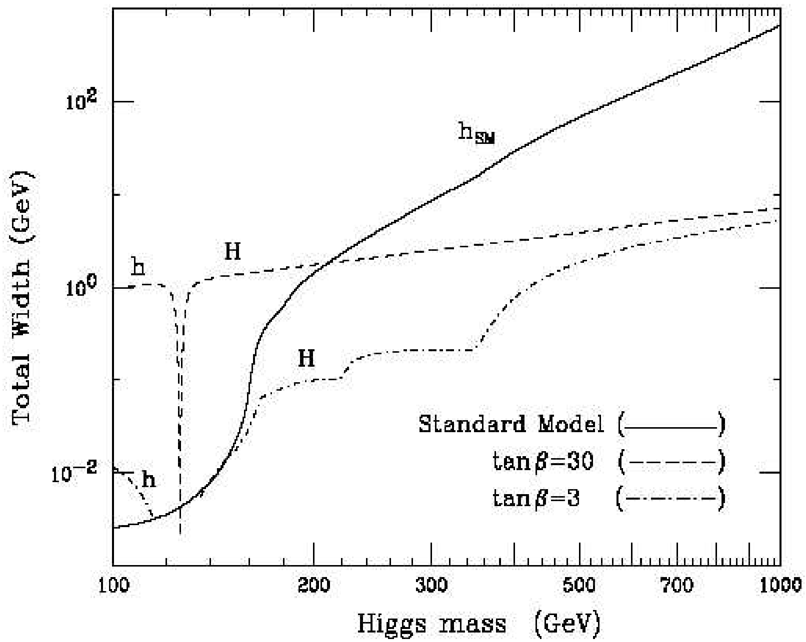
$\mu = M_2 = 1TeV$

$2M_1 \simeq 1TeV$

m_h close to $m_{h_{max}}$

Higgs boson total widths

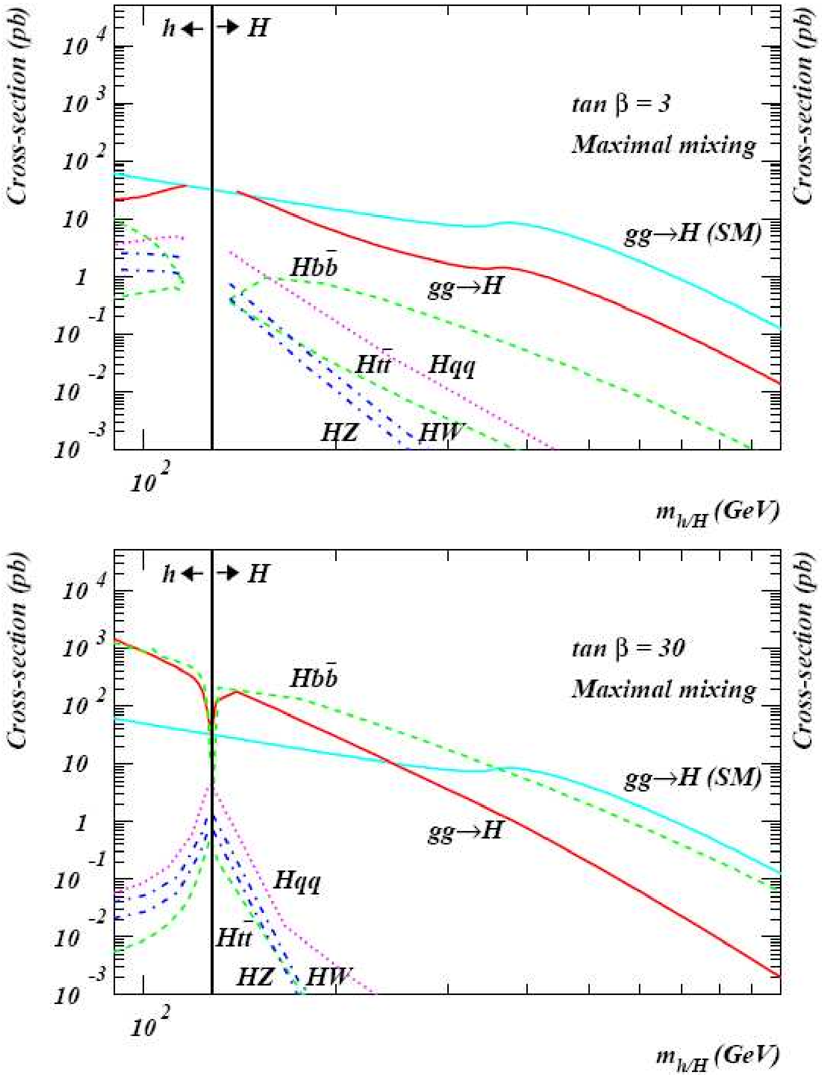
- 



- large Higgs masses - smaller widths compared to SM (suppressed HVV, no tree AVV, H^+W^-Z)

  decoupling limit - same widths for h and h_{SM} (as m_h reaches its maximum)

  small m_A (large $\tan\beta$) - H approaches h_{SM} properties, but deviations in $Hb\bar{b}$ coupling at large $\tan\beta \rightarrow$ discrepancy between H and h_{SM} contours

- 

dominant gluon-gluon-fusion mediated by heavy top, stop, bottom, sbottom triangle loops

$qq \to qqV^*V^* \to qq\phi$ (gauge boson fusion)
$q\bar{q} \to V^* \to V\phi$ (V-B bremsstrahlung)
also relevant

$gg, q\bar{q} \to \phi b\bar{b}/\phi t\bar{t}$ (associated production)
Higgs boson radiation of bottom quarks important at large $\tan\beta$ (enhanced $Hb\bar{b}$)

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