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EWSB4

- How to break SUSY?
    - Spontaneous SUSY breaking?
    - Soft SUSY breaking
- Higgs potential
    - Higgs mass bounds
    - Decoupling
    - Higgs search strategies

How to Break Supersymmetry

- Supersymmetric generators, Q, have property:

$$\{Q_\alpha, \overline{Q}_{\dot\beta}\} = 2\sigma^\mu_{\alpha\dot\beta} P_\mu$$

Using $H = P_0$:

$$\langle 0 \mid H \mid 0 \rangle = \frac{1}{4}\langle 0 \mid \overline{Q}_1 Q_1 + Q_1 \overline{Q}_1 + \overline{Q}_2 Q_2 + Q_2 \overline{Q}_2 \mid 0 \rangle \geq 0$$

Unbroken SUSY $\longrightarrow$ $Q_\alpha \mid 0 \rangle = 0$

$$\langle 0 \mid H \mid 0 \rangle = \langle 0 \mid V \mid 0 \rangle \geq 0$$

Scalar potential:

$$V(\phi, \phi^*) = F^{*i} F_i + \frac{1}{2} D^a D^a = W_i^* W^i + \frac{1}{2} \Sigma_a g_a^2 (\phi^* T^a \phi)^2$$

[W is superpotential, $W^i = \frac{\partial W}{\partial \phi_i} = M^{ij} \phi_j + \frac{g^{ijk}}{2} \phi_j \phi_k$]

SUSY spontaneously broken if either:

$\langle 0 \mid F_i \mid 0 \rangle \neq 0$	O'Raifeartaigh
$\langle 0 \mid D^a \mid 0 \rangle \neq 0$	Fayet-Iliopoulos

Realistic models with spontaneous SUSY breaking difficult to construct because of $(mass)^2$ relationship:

Compute Scalar field-dependent mass-squared:

- Vector masses:

$$\left(M_V^2\right)_{ab} = 2g^2 \left(T^a T^b\right)_{ij} \phi_i^* \phi_j$$

$$[\text{From } (D_\mu \phi)^2 = (\partial_\mu \phi + igA_\mu^a (T^a \phi)_i)^2]$$

$$\begin{aligned} Tr\left(T^a T^a\right)_{ij} =& C_2\left(R\right)\delta_{ij} \\ Tr\left(M_V^2\right) =& 2g^2 C_2\left(R\right)\phi_i^*\phi_i \end{aligned}$$

- Fermion masses:

$$Tr\left(M_f^2\right) = 2 \mid \frac{\partial^2 W}{\partial \phi_i \phi_j} \mid^2 + 4g^2 C_2\left(R\right)\phi_i^*\phi_i$$

From:

$$\mathcal{L} = -\frac{1}{2}\frac{\partial^2 W}{\partial \phi_i \phi_j}\psi_i \psi_j - \sqrt{2} g \phi^* T^a \psi \lambda^a + c.c.$$

- Scalars:

$$Tr\left(M_\phi^2\right) = 4 \mid \frac{\partial^2 W}{\partial \phi_i \phi_j} \mid^2 + 2g^2 C_2\left(R\right)\phi_i^*\phi_i$$

From:

$$V = \frac{1}{2} g_a^2 \left(\phi_i^* T^a \phi_i\right)^2 + M_{ik}^* M^{kj} \phi^{*i} \phi_j$$

$$[W = \tfrac{1}{2} M^{ij} \phi_i \phi_j + ...]$$

Define supertrace:

$$\begin{aligned} STr\left(M^2\right) \equiv & \sum (-1)^{2s}(2s+1)\,Tr\left(M^2\right) \\ =& 3Tr\left(M_V^2\right) + Tr\left(M_\phi^2\right) - 2TrM_F^2 \\ =& \ 0 \end{aligned}$$

- Holds for arbitrary values of scalar fields
- Holds separately for gauge and matter sector

$$\tilde{m}_{e_L}^2 + \tilde{m}_{e_R}^2 = 2m_e^2$$

- Phenomenological disaster
- Attempts to use this mechanism require additional fields/interactions

Consider low scale SUSY ($\sim 1\ TeV$) as effective theory

- Break SUSY "softly" (terms of dimension ≤ 3)
- Add all possible terms which introduce $\log(\Lambda)$ divergences, but not Λ^2

[See EWSB2]

Allowed terms:

- Scalar Masses ($\phi^*\phi, \phi\phi$)
- Gaugino masses ($\lambda^a\lambda^a$)
- Cubic scalar couplings ($\phi_i\phi_j\phi_k$)

Theorem: Introduction of soft terms doesn't reintroduce Λ^2 divergences to all orders of PT in SUSY

Terms not allowed:

- $s^*\phi_j\phi_k$, (s is gauge singlet)
- $\phi_i\phi_j\phi_k\phi_l$

New particles (squarks, sleptons, gauginos) can have gauge invariant soft masses

Observed particles (quarks, leptons, gauge bosons) massless in absence of EWSB

$SU(3) \times SU(2) \times U(1)$ MSSM has new parameters:

- 5 3×3 Hermitian mass matrices for squarks and sleptons:

$$M_{\tilde{Q}}^2 \tilde{Q}^* \tilde{Q} + M_{\tilde{u}}^2 \tilde{u}_R^* \tilde{u}_R + M_{\tilde{d}}^2 \tilde{d}_R^* \tilde{d}_R + M_{\tilde{L}}^2 \tilde{L}^* \tilde{L} + M_{\tilde{e}}^2 \tilde{e}_R^* \tilde{e}_R$$

(45 new parameters)

- 2 (complex) Higgs scalar masses

$$m_1^2 H_1^2 + m_2^2 H_2^2$$

(4 new parameters)

- 3 gaugino masses (complex)

$$\Sigma_{a=1,2,3} M_{1/2}^a \lambda^a \lambda^a$$

(6 new parameters)

- 1 complex Higgs mixing parameter

$$m_{12}^2 H_1 H_2$$

(2 new parameters)

- 27 trilinear couplings for scalar fields (complex)

$$H_2 \tilde{Q} A_u \tilde{u}_R + H_1 \tilde{Q} A_d \tilde{d}_R + H_1 \tilde{L} A_l \tilde{e}_R$$

(54 new parameters)

111 new parameters

SM has 17 parameters $\longrightarrow$ 128 parameters

Scalar Potential

$$W = -\epsilon_{ij}\mu \hat{H}_1^i \hat{H}_2^j + \epsilon_{ij}\left[\lambda_L H_1^i L^{cj} E^c + \lambda_D H_1^i Q^j D^c + \lambda_U H_2^j Q^i U^c\right]$$

$$V = \sum_i \mid \frac{\partial W}{\partial \phi_i} \mid^2 + \frac{1}{2} D^a D^a$$

Assume color unbroken: $\langle \tilde{q} \rangle = \langle \tilde{d}_R \rangle = \langle \tilde{u}_R \rangle = 0$

$$\begin{aligned} V = & \mid \mu \mid^2 \mid H_1 \mid^2 + \mid \lambda_E \tilde{e}_R^* + \mu H_2 \mid^2 \\ & + \mid \lambda_E \tilde{e}_R^* H_1 \mid^2 + \mid \lambda_E \tilde{l} H_1 \mid^2 \\ & + \frac{g^2 + g'^2}{8}\left(\mid H_2 \mid^2 - \mid H_1 \mid^2\right)^2 + \frac{g^2}{2} \mid H_1^* \cdot H_2 \mid^2 \end{aligned}$$

Electric charge unbroken

Minimum at $\langle V \rangle = \langle H_1 \rangle = \langle H_2 \rangle = \langle \tilde{l} \rangle = \langle \tilde{e}_R \rangle = 0$

No EWSB, No SUSY breaking....

Potential with soft SUSY breaking terms

$$
\begin{aligned}
V = & \left(m_1^2+ \mid \mu \mid^2\right) \mid H_1 \mid^2 + \left(m_2^2+ \mid \mu \mid^2\right) \mid H_2 \mid^2 \\
& - m_{12}^2 \left(\epsilon_{ij} H_1^i H_2^j + h.c.\right) \\
& + \frac{g^2+g'^2}{8} \left(\mid H_2 \mid^2 - \mid H_1 \mid^2\right)^2 + \frac{g^2}{2} \mid H_1^* \cdot H_2 \mid^2
\end{aligned}
$$

$$
H_1 = \begin{pmatrix} \phi_1^{0*} \\ -\phi_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}
$$

$$
\langle H_1^1 \rangle = v_1 \qquad \langle H_2^2 \rangle = v_2
$$

Potential has 3 parameters. Trade 1 for $\tan\beta = \frac{v_2}{v_1}$

Conditions for EWSB:

$\longrightarrow$ if $m_{12}^2 = 0$ potential positive definite

"D-flat" direction: $\mid H_1^0 \mid = \mid H_2^0 \mid$
$\longrightarrow$ quartic contributions vanish

Quadratic term in this direction must be positive:

$$
m_1^2 + m_2^2 + 2 \mid \mu \mid^2 > 2 m_{12}^2
$$

Broken $SU(2) \times U(1)$:

$$
\left(m_1^2+ \mid \mu^2 \mid\right)\left(m_2^2+ \mid \mu \mid^2\right) < \mid m_{12} \mid^2
$$

Minimization condition requires:

$$\mu^2 = \frac{m_1^2 - m_2^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{M_Z^2}{2}$$

Cannot turn off $\mu \longrightarrow$ the μ problem

EWSB as in SM $\longrightarrow W, Z$ masses

$$M_W^2 = \frac{g^2}{2}\left(v_1^2 + v_2^2\right)$$
$$v_1^2 + v_2^2 = (174\ GeV)^2$$

- Higgs sector determined by M_A, $\tan\beta$ at tree level

Now find mass eigenstates:

[Higg's Hunter's Guide]

$$
\begin{aligned}
H_2^1 &= H^+ \cos\beta + G^+ \sin\beta \\
H_1^2 &= H^- \sin\beta - G^- \cos\beta \\
H_2^2 &= v_2 + \frac{1}{\sqrt{2}}\left(H\sin\alpha + h\cos\alpha + iA\cos\beta + iG^0\sin\beta\right) \\
H_1^1 &= v_1 + \frac{1}{\sqrt{2}}\left(H\cos\alpha - h\sin\alpha + iA\sin\beta - iG^0\cos\beta\right)
\end{aligned}
$$

α is mixing angle from diagonalizing 2×2 neutral mass matrix

$$\tan 2\alpha = \frac{M_H^2 + m_h^2}{M_A^2 - M_Z^2}$$

Pseudoscalar mass:

$$M_A^2 = \frac{2m_{12}^2}{\sin 2\beta}$$

Typically trade $m_{12}^2 \to M_A^2$

Charged scalars:

$$M_{H^\pm}^2 = M_A^2 + M_W^2 > M_W^2$$

Neutral Scalars, h, H

$$M_{h,H}^2 = \frac{1}{2}\left(M_A^2 + M_Z^2 \mp \sqrt{\left(M_A^2 + M_Z^2\right)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta}\right)$$

- Upper bound on lightest Higgs mass:

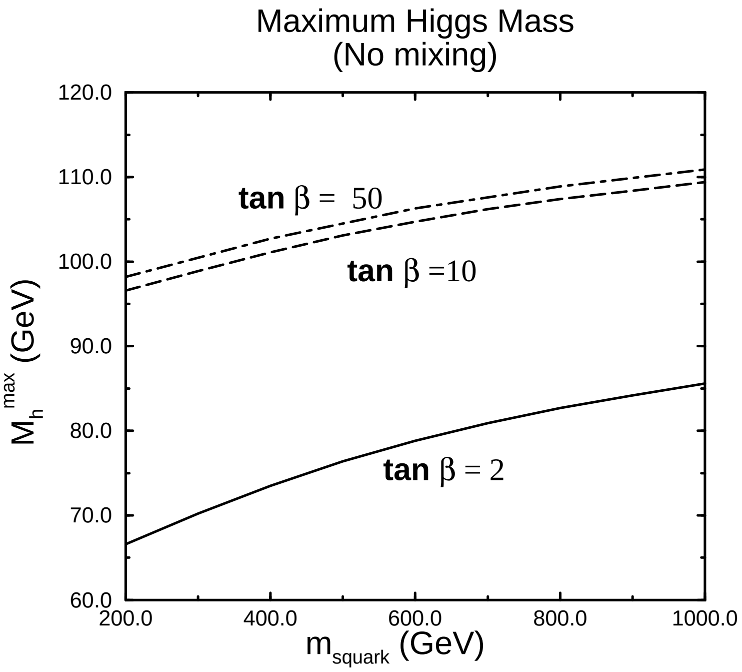
$$M_h < M_Z \mid \cos 2\beta \mid$$

- Large radiative corrections from top/stop loops
- At 1-loop:

$$\begin{aligned} M_h^2 \sim & \frac{M_A^2 + M_Z^2 + \epsilon}{2} \\ & - \frac{1}{2}\left(M_A^2 + M_Z^2 + \epsilon\right)^2 - 4M_Z^2 M_A^2 \cos^2 2\beta \\ & - 4\epsilon \left(M_A^2 \sin^2\beta + M_Z^2 \cos^2\beta\right)^{-1/2} \end{aligned}$$

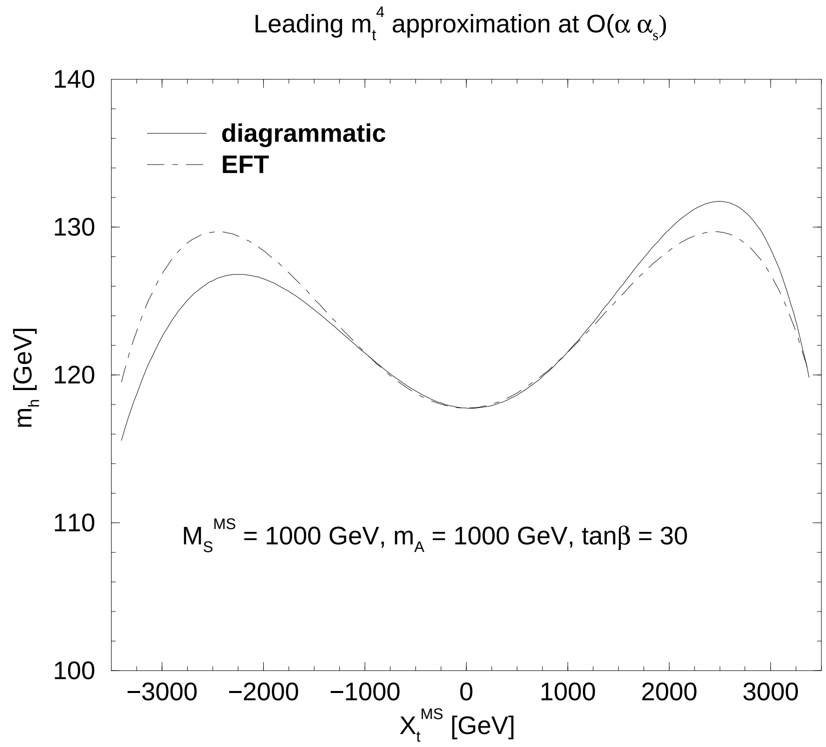
$$\epsilon \sim \frac{3G_F}{\sqrt{2}\pi^2} \frac{M_t^4}{\sin^2\beta} \log\left(\frac{\tilde{M}_t^2}{M_t^2}\right)$$

- Upper bound on Higgs mass: $M_h^2 < M_Z^2 \cos^2 2\beta + \epsilon \sin^2\beta$



State of the art:

- 2-loop diagramatic calculation / 2-loop effective potential
- Results agree within 1-2 GeV
- X_t is mixing parameter in stop sector



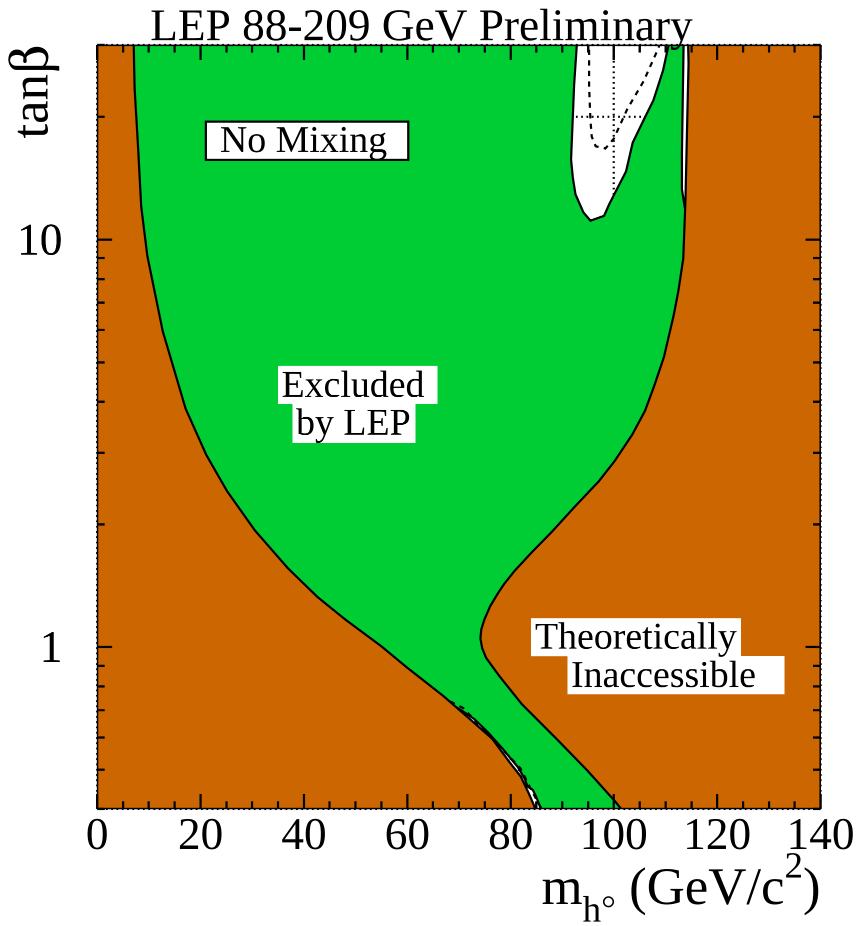
[Carena et al, NPB580 (2000) 29]

- Higgs couplings to gauge bosons fixed by gauge invariance:

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

- Cannot suppress both $e^+e^- \to Zh$ and $e^+e^- \to Ah$ (if kinematically allowed)

- LEP2 limits: $M_{h,A} > 91\ GeV$



[Combined LEP2 limits, hep-ph/0107030]

Find Higgs couplings:

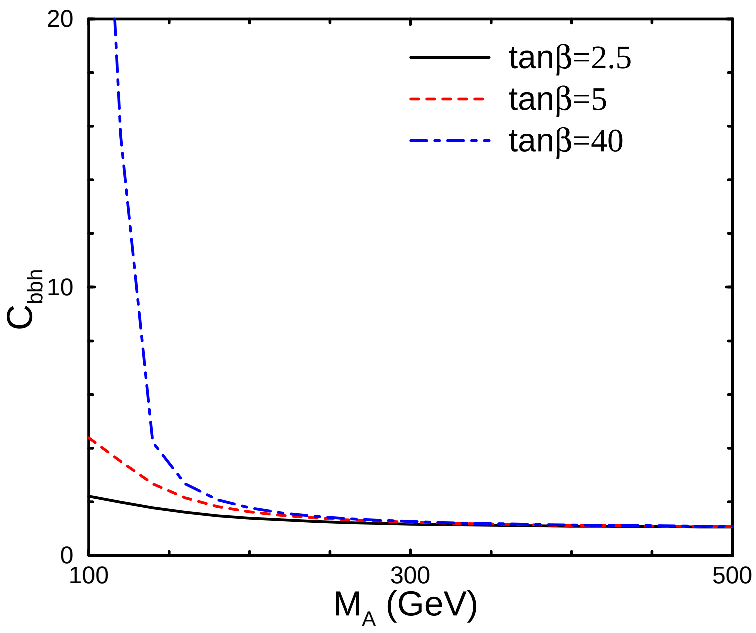
$$\mathcal{L}_W = \frac{\partial^2 W}{\partial \phi_i \partial \phi_j} \psi_i \psi_j + \text{c.c.}$$

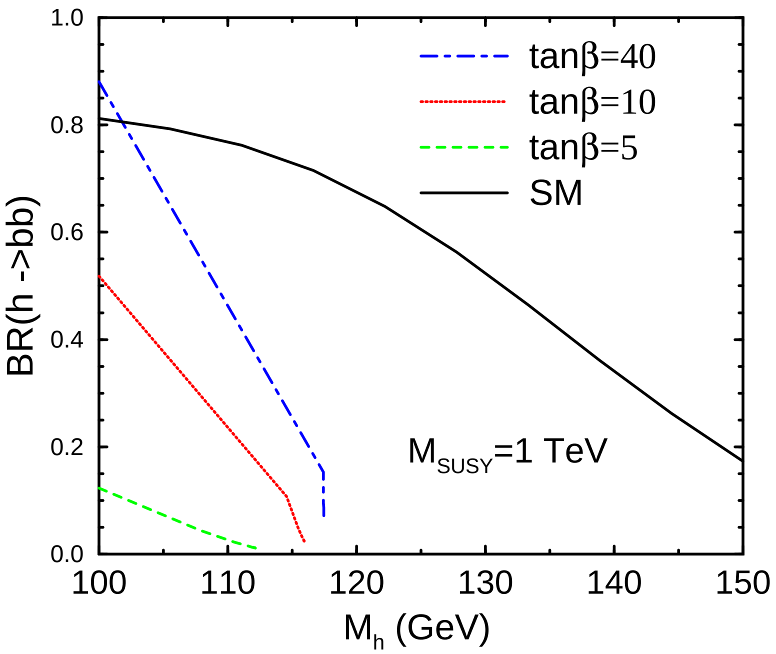
$$W \sim \epsilon_{ij} \left[\lambda_L \hat{H}_1^i \hat{L}^{cj} \hat{E}^c + \lambda_D \hat{H}_1^i \hat{Q}^j \hat{D}^c + \lambda_U \hat{H}_2^j \hat{Q}^i \hat{U}^c \right]$$

Yukawa interactions give mass matrices:

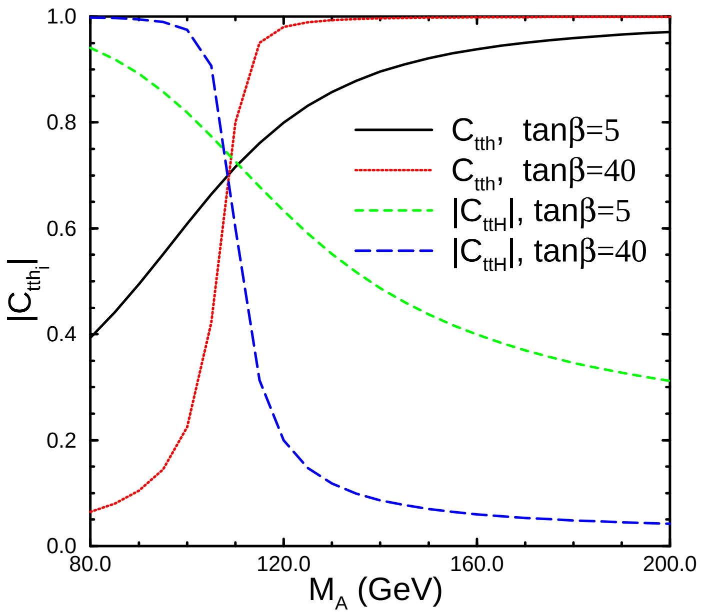
$$m_d = \lambda_D v_1 \qquad \lambda_D = \frac{g m_d}{\sqrt{2} \sin \beta M_W}$$
$$m_u = \lambda_U v_2 \qquad \lambda_U = \frac{g m_u}{\sqrt{2} \cos \beta M_W}$$

- Couplings to b quarks enhanced at large $\tan\beta$, small M_A
- Couplings $\to SM$ as $M_A \to \infty$





tanβ=40
tanβ=10
tanβ=5
SM
M_SUSY=1 TeV
BR(h ->bb)
M_h (GeV)
1.0
0.8
0.6
0.4
0.2
0.0
100
110
120
130
140
150

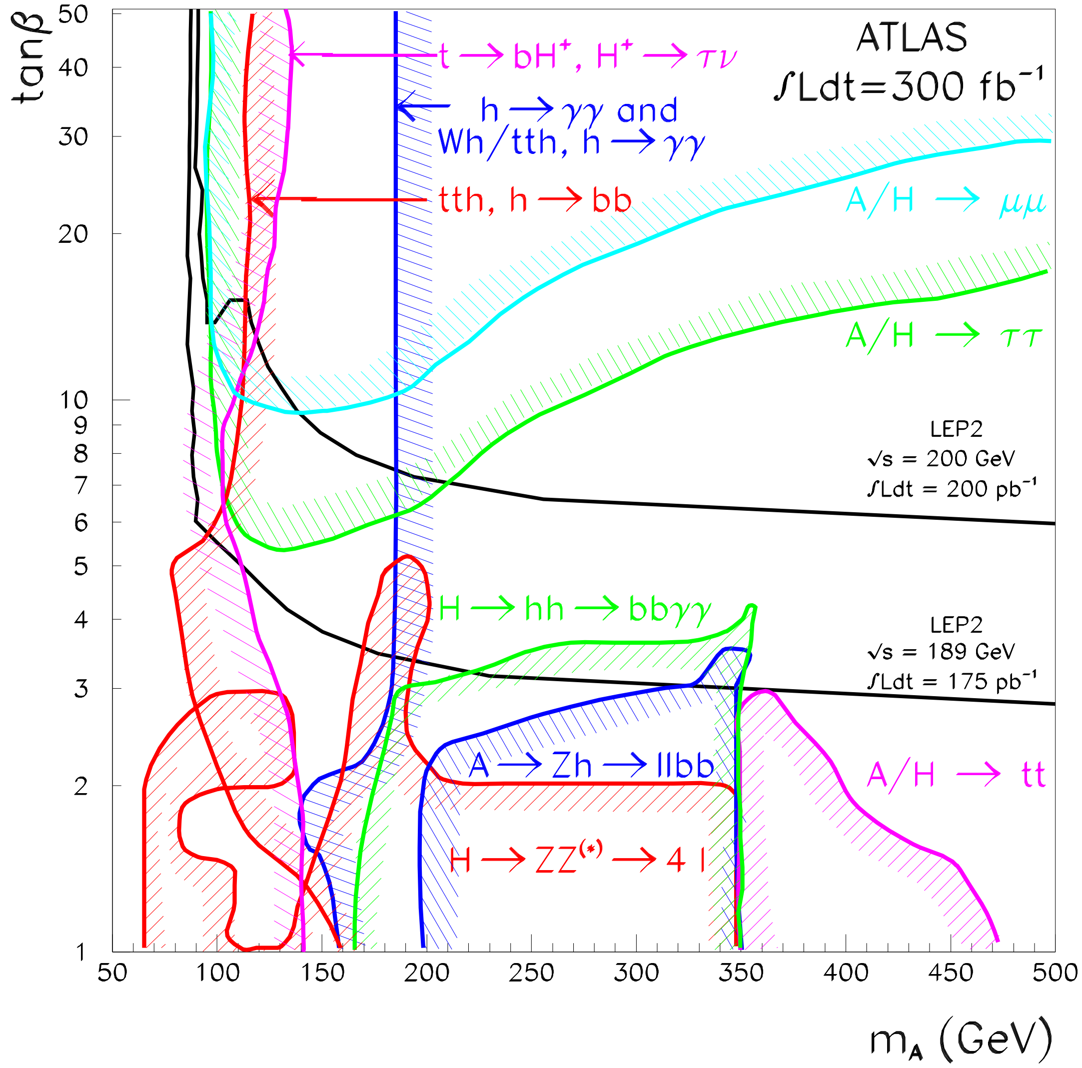


Note decoupling limit: $M_A >> M_Z$

$$M_{H^\pm} \to M_A$$
$$M_H \to M_A$$
$$C_{iih} \to 1$$

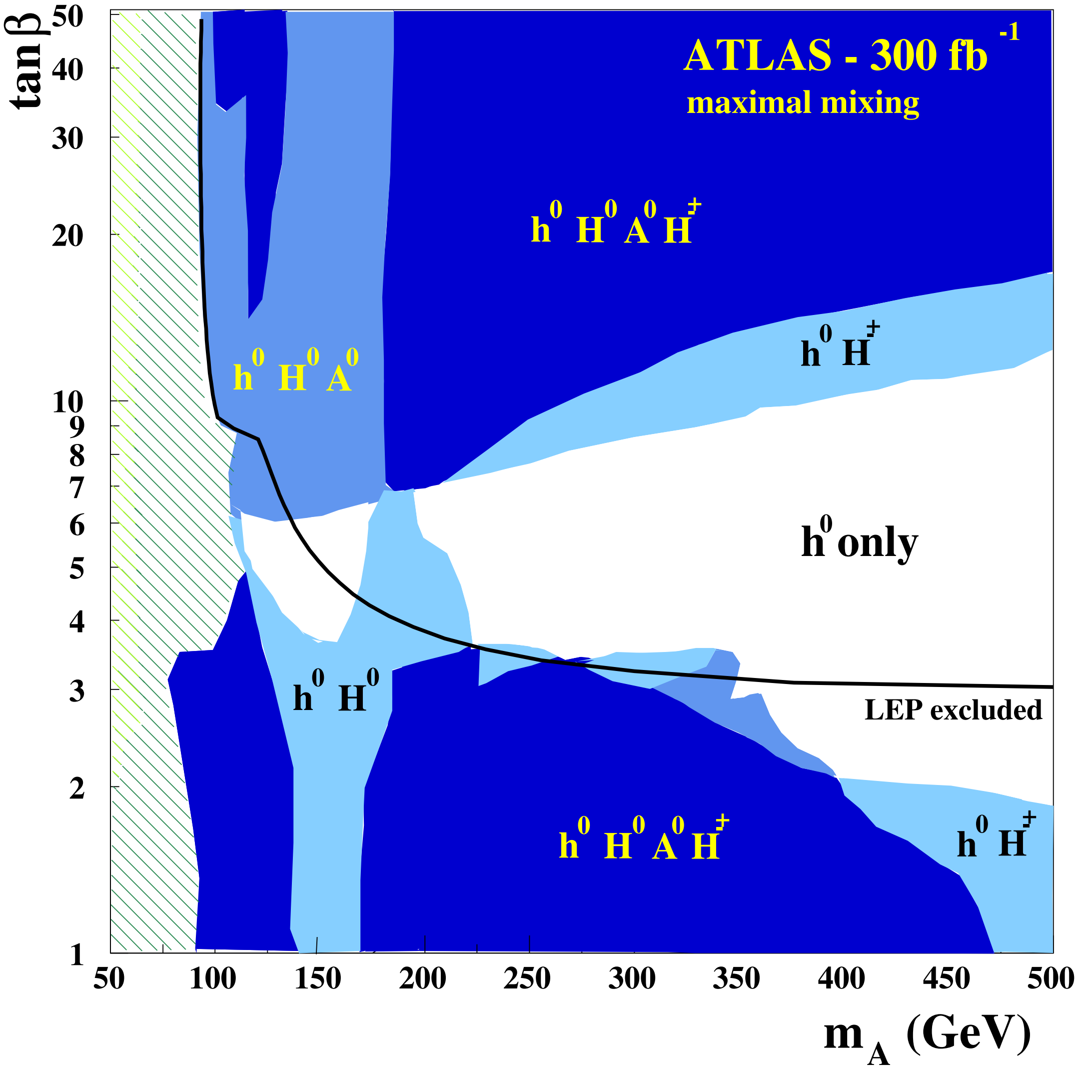
Only h remains in spectrum with SM couplings

Higgs search strategy very complicated at LHC:



[ATLAS TDR]

The wedge



[TESLA TDR]