The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2244

Summer School on Particle Physics

6 - 17 June 2011

Additional Material

Dawson Sally

Brookhaven National Laboratory
USA

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

EWSB Beyond the Standard Model

Trieste, 2011

S. Dawson (BNL)

Supersymmetric Models as Alternative to Standard Model

Many New Particles:

- Spin ½ quarks $\Rightarrow$ spin 0 squarks
- Spin ½ leptons $\Rightarrow$ spin 0 sleptons
- Spin 1 gauge bosons $\Rightarrow$ spin ½ gauginos
- Spin 0 Higgs $\Rightarrow$ spin ½ Higgsino

Unbroken supersymmetry $\Rightarrow$ degenerate masses of partners

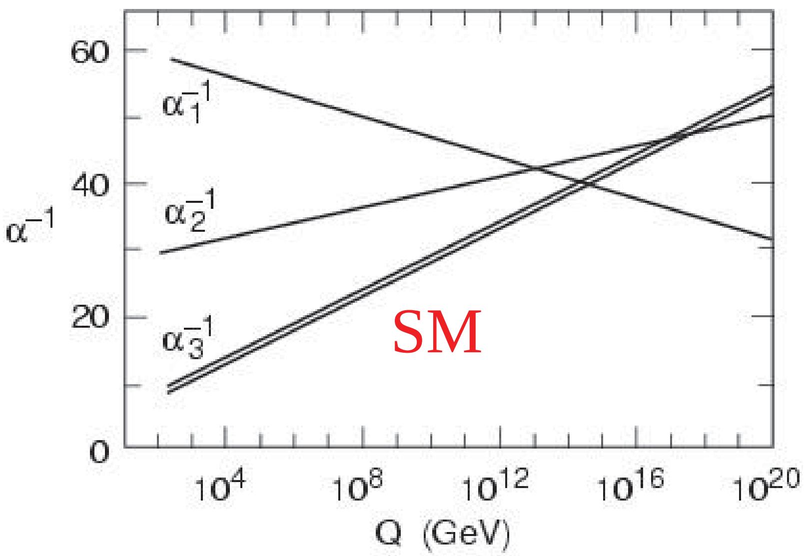
SUSY must be a broken symmetry

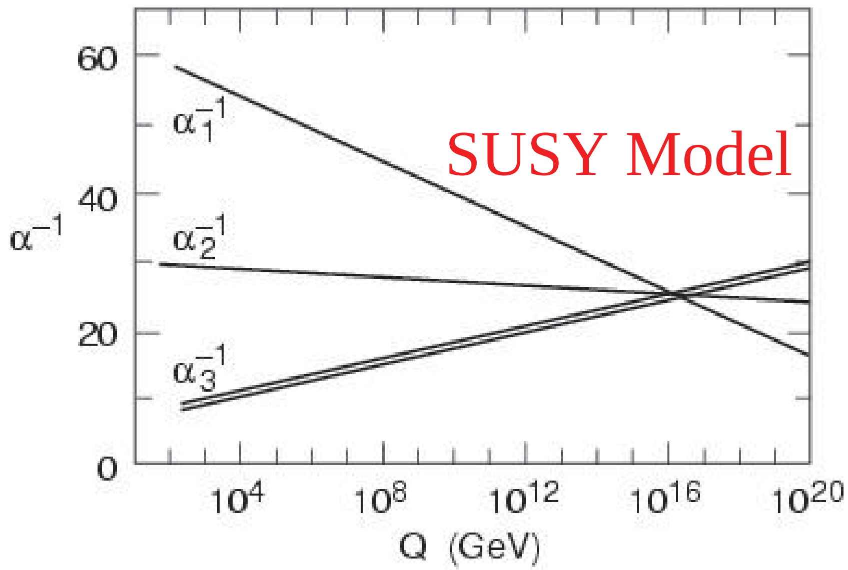
Supersymmetric Theories

- Predict many new undiscovered particles (>29!)
- Very predictive models
  - Can calculate particle masses, interactions, everything you want in terms of a few parameters
  - Solve naturalness problem of Standard Model
- Any Supersymmetric particle eventually decays to the lightest supersymmetric particle (LSP) which is stable and neutral (assuming R parity)
  - Dark Matter Candidate

SUSY Models Unify

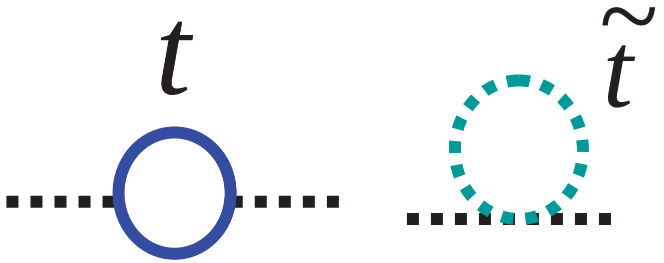
- Coupling constants change with energy
- Assume new particles at TeV scale





SUSY….Our favorite model

- Quadratic sensitivity to high scale physics cancelled automatically if SUSY particles at TeV scale
- Cancellation result of ***supersymmetry***, so happens at every order

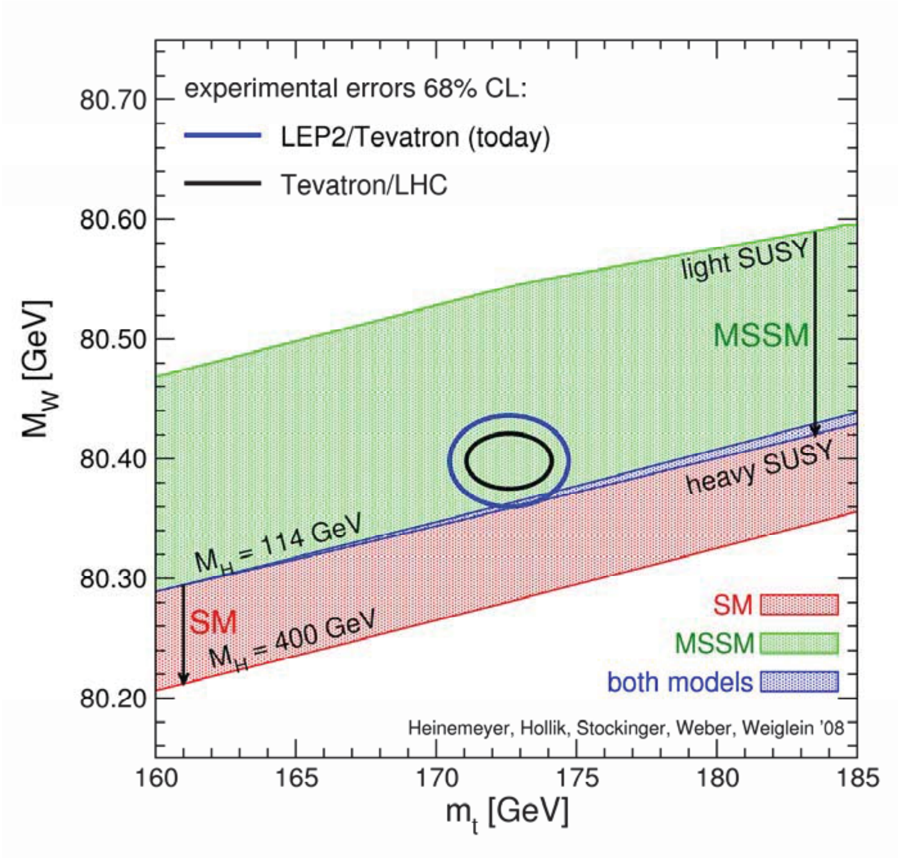


$$\boxed{\delta M_h^{\ 2} \approx (....) G_F \Lambda^2 (M_t^{\ 2} - M_{\tilde{t}}^{\ 2})}$$

- Stop mass should be TeV scale

Supersymmetry (MSSM version)

- Good agreement with EW measurements if SUSY masses are 1-2 TeV



Fermion Masses

- In Standard Model, m_u from $\Phi_c = i\sigma_2 \Phi^*$

$$L_{SM} = -\lambda_u \overline{Q}_L \Phi_c u_R + hc \qquad \Phi_c = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix} \qquad \boxed{\lambda_u = -\frac{m_u \sqrt{2}}{v_{SM}}}$$

- SUSY models don't allow Φ_c interactions
- Supersymmetric models always have at least ***two Higgs doublets*** with opposite hypercharge in order to give mass to up and down quarks

General 2 Higgs Doublet Model

- 6 free parameters, plus a phase

$$
\begin{aligned}
V(H_1, H_2) &= \lambda_1 (H_1^+ H_1 - v_1^2)^2 + \lambda_2 (H_2^+ H_2 - v_2^2)^2 \\
&+ \lambda_3 \left[(H_1^+ H_1 - v_1^2) + (H_2^+ H_2 - v_2^2) \right]^2 \\
&+ \lambda_4 \left[(H_1^+ H_1)(H_2^+ H_2) - (H_1^+ H_2)(H_2^+ H_1) \right] \\
&+ \lambda_5 \left[\mathrm{Re}(H_1^+ H_2) - v_1 v_2 \cos\xi \right]^2 \\
&+ \lambda_6 \left[\mathrm{Im}(H_1^+ H_2) - v_1 v_2 \sin\xi \right]^2
\end{aligned}
$$

$$
\langle H_1 \rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 e^{i\xi} \end{pmatrix}
$$

- W and Z masses just like in Standard Model $M_W^2 = \dfrac{g^2 (v_1^2 + v_2^2)}{2}$
- ρ parameter:

$$
\rho = \frac{M_W}{M_Z \cos\theta_W} = 1
$$

ρ=1 for any number of Higgs doublets or singlets

Higgs Potential Restricted in SUSY Models

- Two Higgs doublets with opposite hypercharge

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

- Quartic couplings fixed by supersymmetry
- H_1 has Y=-1/2, H_2 has Y=+1/2   [$Q_{em}=(T_3+Y)/2$]
- SUSY Potential has "F" and "D" terms:

$$V_F = |\mu|^2 \left(|H_1|^2 + |H_2|^2 \right) \qquad U(1): \quad \left[\frac{g'}{2} \left(|H_2|^2 - |H_1|^2 \right) \right]^2$$

$$V_D = \frac{1}{2} \sum_a \left(g_a H_i^* T^a H_i \right)^2 \qquad SU(2): \quad \left[\frac{g}{2} \left(H_1^{i*} \sigma_{ij}^a H_1^j + H_2^{i*} \sigma_{ij}^a H_2^j \right) \right]^2$$

Gauge couplings / generators

SUSY Potential

- SU(2) identity: $\sigma^a_{ij}\sigma^a_{kl} = 2\delta_{il}\delta_{jk} - \delta_{ij}\delta_{kl}$

$$V_D = \frac{g^2}{8}\left(4\left|H_1^* \cdot H_2\right|^2 - 2\left(H_1^* \cdot H_1\right)\left(H_2^* \cdot H_2\right) + \left(\left|H_1\right|^2\right)^2 + \left(\left|H_2\right|^2\right)^2\right) + \frac{g'^2}{8}\left(\left|H_2\right|^2 - \left|H_1\right|^2\right)^2$$

- Scalar potential

$$\boxed{V = |\mu|^2\left(\left|H_1\right|^2 + \left|H_2\right|^2\right) + \frac{g^2 + g'^2}{8}\left(\left|H_2\right|^2 - \left|H_1\right|^2\right)^2 + \frac{g^2}{2}\left|H_1^* \cdot H_2\right|^2}$$

- V is positive definite: minimum at $\langle V\rangle = \langle H_1\rangle = \langle H_2\rangle = 0$

No electroweak symmetry breaking!

The MSSM Philosophy

- Add all soft (dimension 3 or less) terms allowed
  - They don't introduce quadratic Λ^2 contributions
- Potential has 3 free parameters (1 of which is fixed by M_W)

$$V = \left(m_1^2 + |\mu|^2\right) H_1 H_1^+ + \left(m_2^2 + |\mu|^2\right) H_2 H_2^+ - m_{12}^2 (\varepsilon_{ab} H_1^a H_2^b + h.c.)$$
$$+ \left(\frac{g'^2 + g^2}{8}\right)\left(H_1 H_1^+ - H_2 H_2^+\right)^2 + \frac{g^2}{2}\left|H_1 H_2^+\right|^2$$

Gauge Couplings

- If m_{12}=0, potential is positive definite and no symmetry breaking

Minimize Potential

- Minimize potential

$$\boxed{\begin{aligned}\frac{\partial V}{\partial h_1^0} &= 2\left(m_1^2+|\mu|^2\right)h_1^0 - 2m_{12}^2 h_2^{0*} + \frac{g^2+g'^2}{2}h_1^0\left(\left|h_1^0\right|^2-\left|h_2^0\right|^2\right)=0\\ \frac{\partial V}{\partial h_2^0} &= 2\left(m_2^2+|\mu|^2\right)h_2^0 - 2m_{12}^2 h_1^{0*} - \frac{g^2+g'^2}{2}h_2^0\left(\left|h_1^0\right|^2-\left|h_2^0\right|^2\right)=0\end{aligned}}$$

- Minimization conditions:

$$m_{12}^2 = \frac{\left(m_1^2+m_2^2+2\mu^2\right)\sin 2\beta}{2}$$

$$\mu^2 = \frac{m_2^2 - m_1^2\tan^2\beta}{\tan^2\beta - 1} - \frac{g^2+g'^2}{4}\left(v_1^2+v_2^2\right)$$

$$\frac{M_Z^2}{2}$$

μ is naturally of $O(M_Z)$

EWSB and SUSY Models

- Electroweak symmetry broken by vevs

$$\langle H_1 \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix} \qquad \langle H_2 \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

- W gets mass, $M_W^2 = g^2(v_1^2 + v_2^2)/2$
- 5 Physical Higgs bosons, h^0, H^0, $H^\pm$, A^0
- 2 free parameters, typically pick

M_A, $\tan\beta = v_2/v_1$

- Predict M_h, M_H, $M_{H\pm}$

$$M_A^2 = m_{12}^2(\tan\beta + \cot\beta)$$

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

Neutral Higgs Masses

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

- $M_h < M_Z \cos 2\beta$
- Theory implies light Higgs boson!
- Neutral Higgs mass matrix diagonalized with mixing angle α

$$\cos 2\alpha = -\cos 2\beta \left(\frac{M_A^2 - M_Z^2}{M_H^2 - M_h^2}\right)$$

Theoretical Upper Bound on M_h

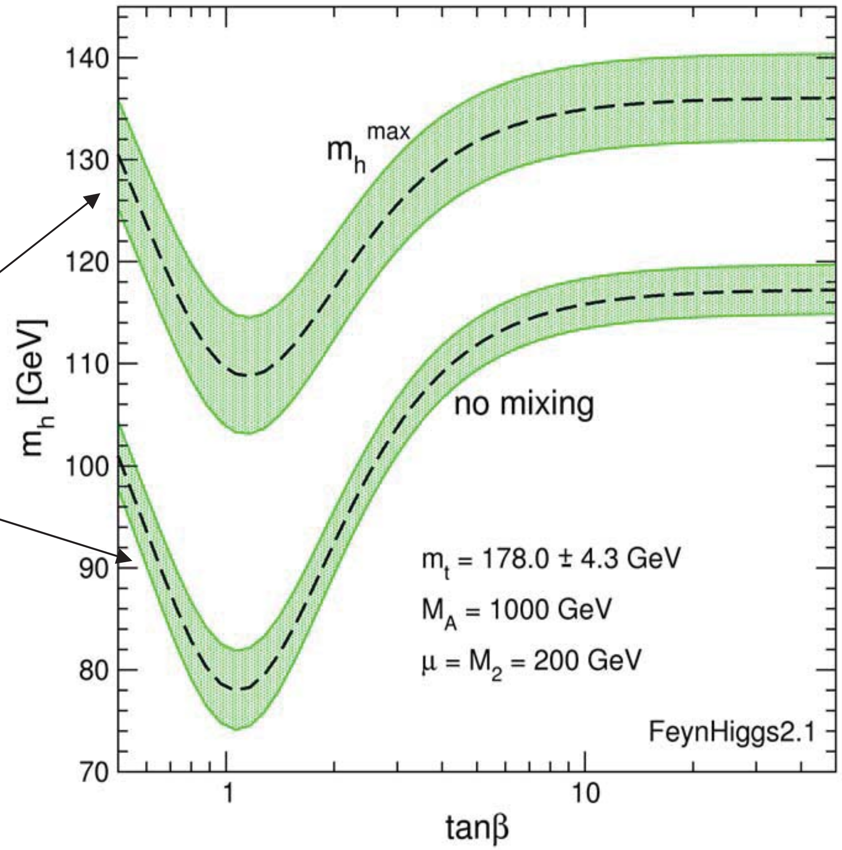
- At tree level, $M_h < M_Z$
- Large corrections $O(G_F m_t^2)$
  - Predominantly from stop squark loop

$$\boxed{M_h^2 \le M_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2 \sin^2 \beta} \ln\left[\frac{\tilde{m}_t^2}{m_t^2}\right]}$$

- Stop mass should be TeV scale for naturalness

Theoretical Upper Bound on M_h

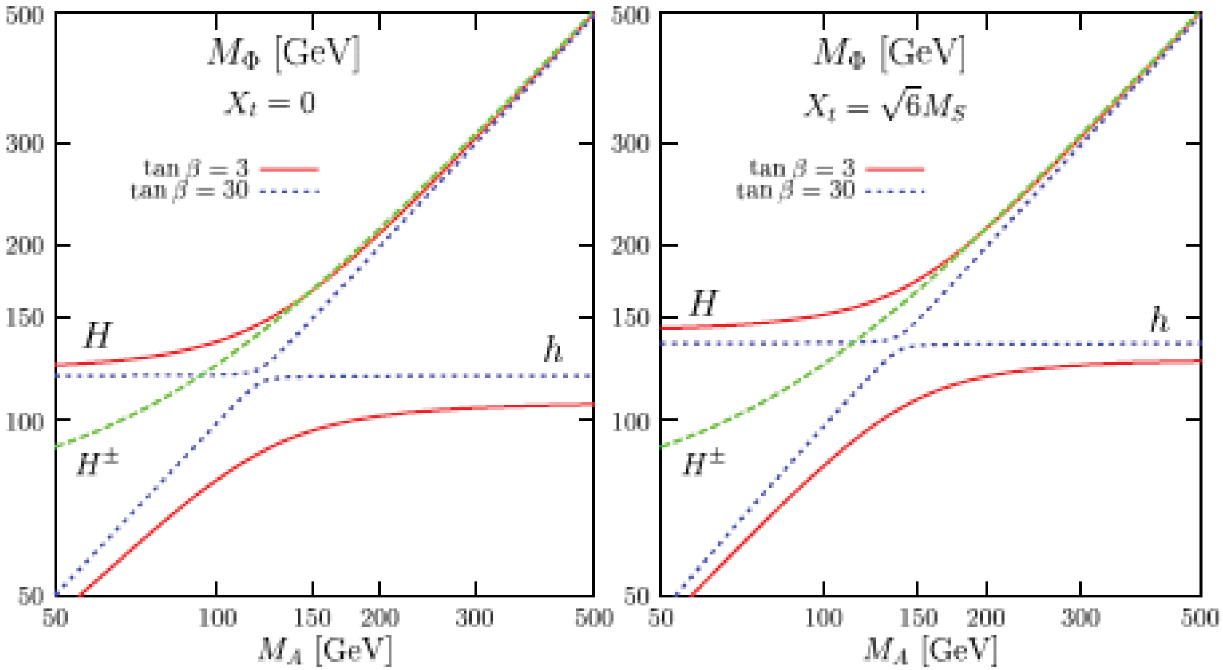
Upper bound on lightest neutral Higgs boson mass with m_{stop} = 1 TeV



- M_t^4 enhancement
- Logarithmic dependence on stop mass

Higgs Masses in MSSM

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



Large M_A: Degenerate A, H, $H^\pm$ and light h

Find Higgs Couplings

- Higgs-fermion couplings:

$$
\begin{aligned}
L = & -\frac{gm_d}{2M_W \cos\beta}\bar{d}d\left(H\cos\alpha - h\sin\alpha\right) + \frac{igm_d\tan\beta}{2M_W}\bar{d}\gamma_5 dA \\
& -\frac{gm_u}{2M_W \sin\beta}\bar{u}u\left(H\sin\alpha + h\cos\alpha\right) + \frac{igm_d\cot\beta}{2M_W}\bar{u}\gamma_5 uA
\end{aligned}
$$

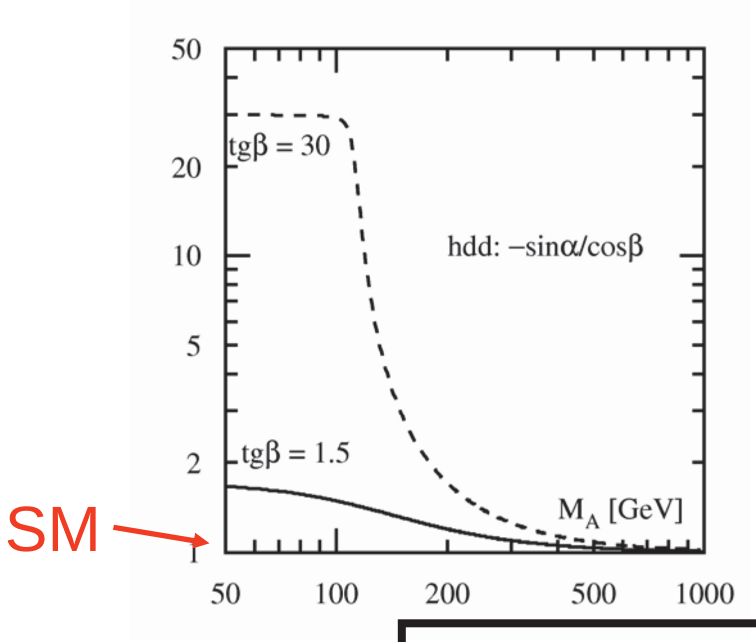
- Couplings given in terms of α, β
- Can be very different from Standard Model
- No new free parameters

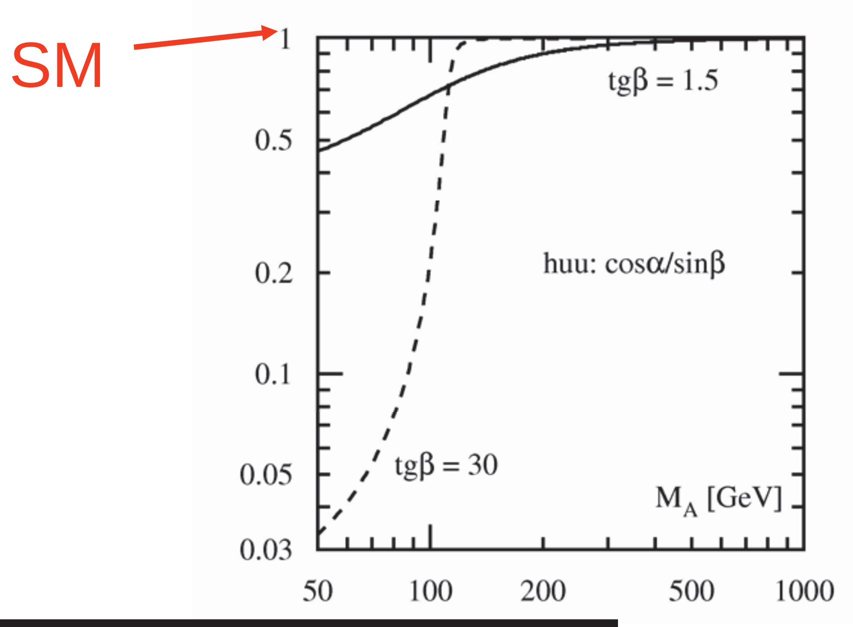
Higgs Couplings Different from SM

Lightest Neutral Higgs, h

Couplings to d, s, b enhanced at large tan β for moderate M_A

Couplings to u, c, t suppressed at large tan β for moderate M_A



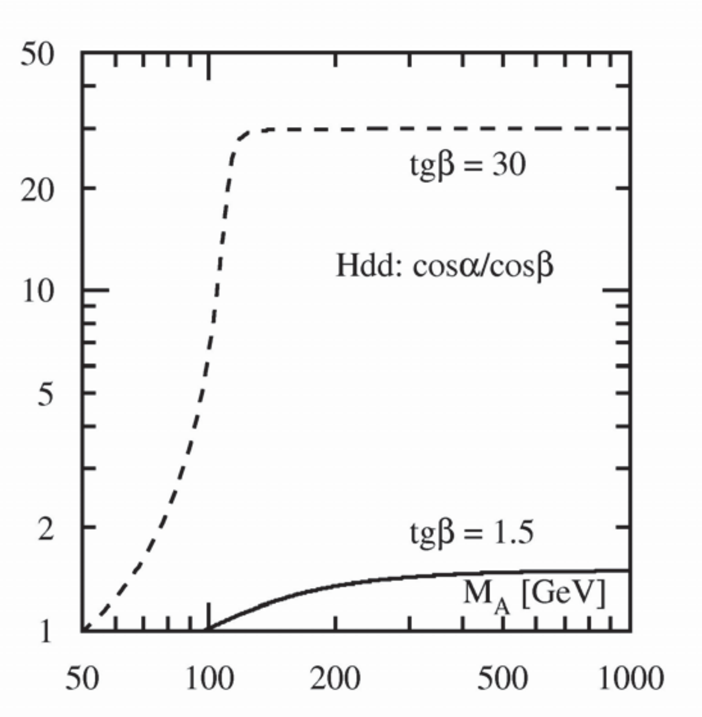


Decoupling limit: For $M_A \rightarrow \infty$, h couplings go to SM couplings

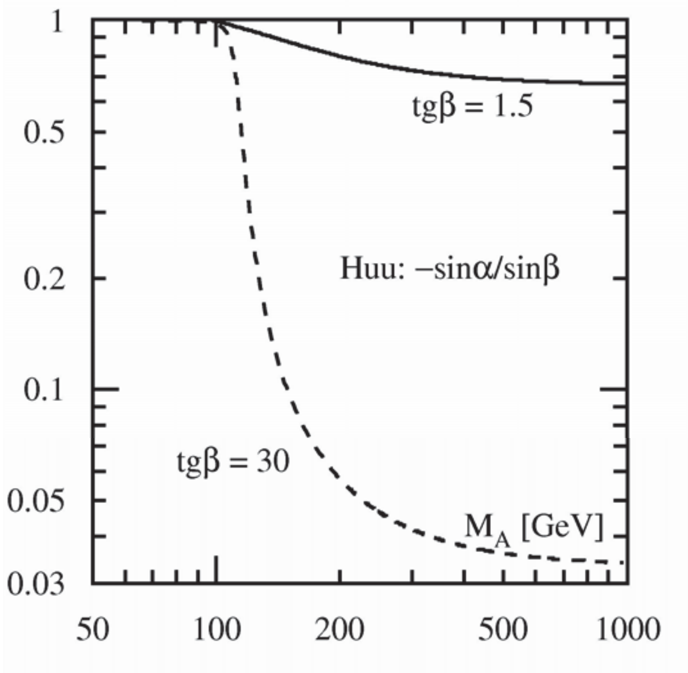
Higgs Couplings in SUSY

Heavier Neutral Higgs, H

Couplings to d, s, b enhanced at large tan β



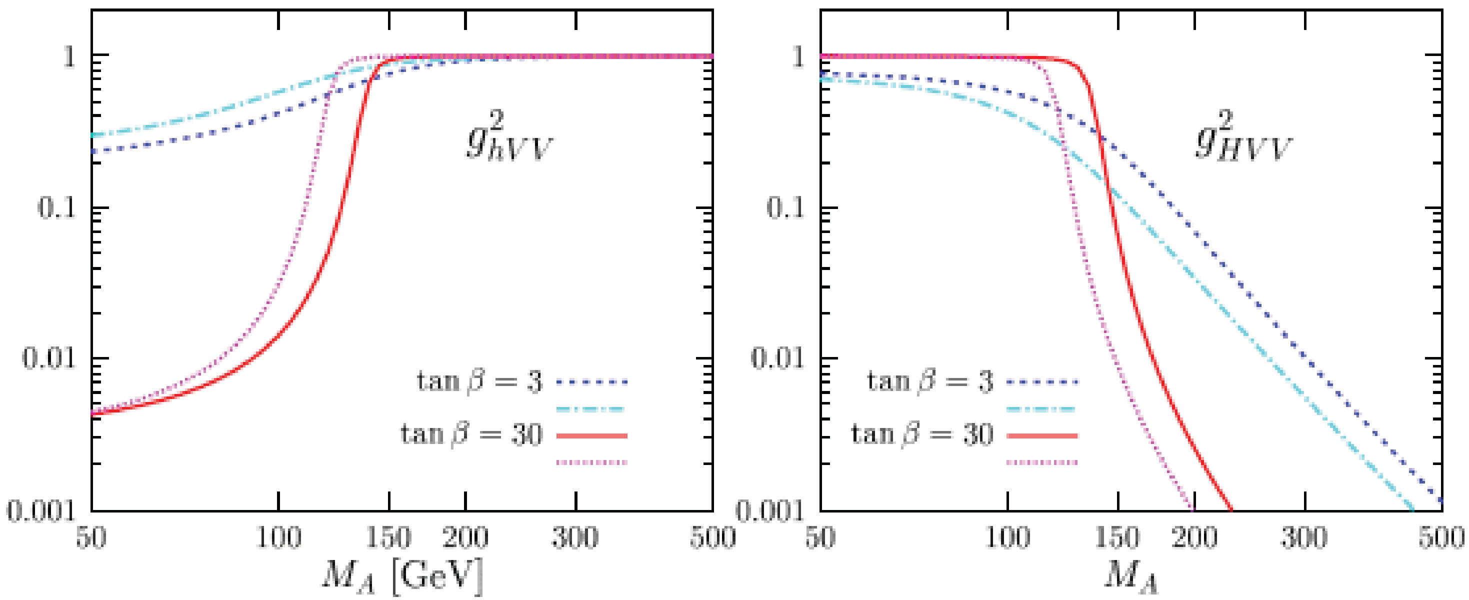
Couplings to u, c, t suppressed at large tan β



Gauge Boson Couplings to Higgs

- $g_{hVV}^2 + g_{HVV}^2 = g_{hVV}^2(SM)$
- Vector boson fusion and Wh production always suppressed in MSSM

$$\frac{g_{hVV}}{g_{h,smVV}} = \sin(\beta - \alpha)$$
$$\frac{g_{HVV}}{g_{h,smVV}} = \cos(\beta - \alpha)$$



Normalized to SM couplings

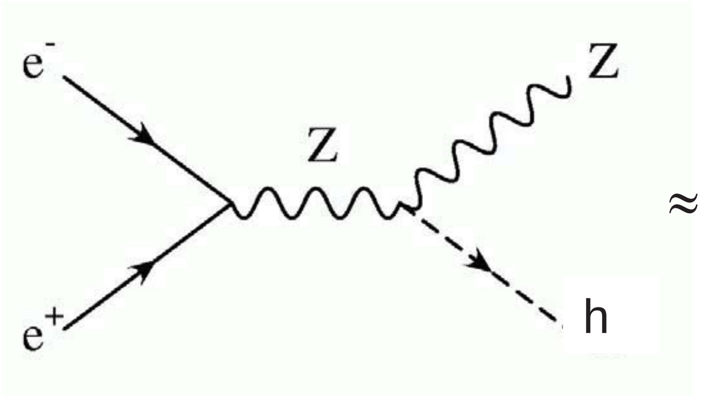
Tools

- Calculate SM and MSSM Higgs branching ratios:
  - HDECAY
  - http://people.web.psi.ch/spira/hdecay/

- Calculate MSSM Higgs masses and Higgs branching ratios:
  - FEYNHIGGS
  - http://www.feynhiggs.de/

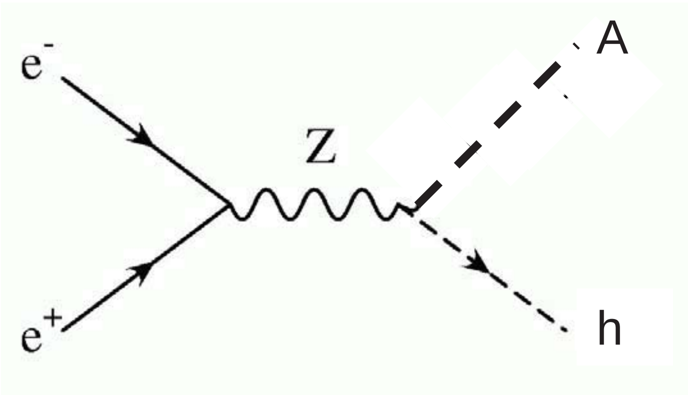
Both of these programs are very easy to use!

Limits from LEP



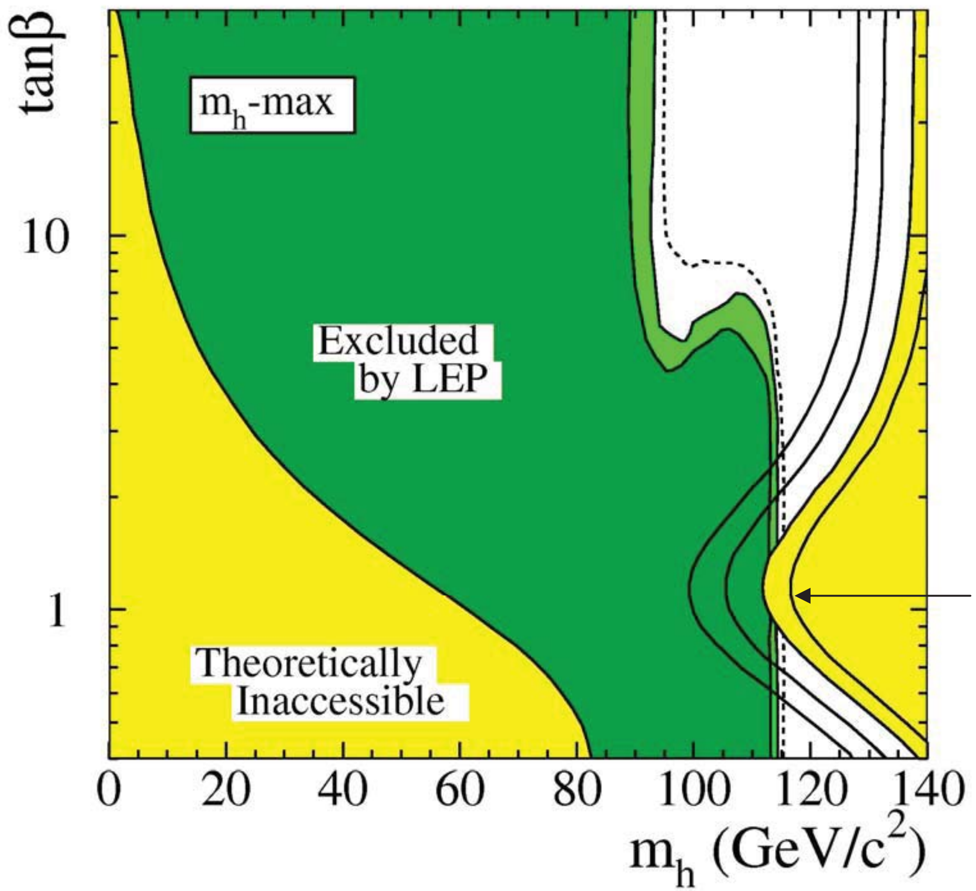
$$\approx \cos(\alpha - \beta)$$

Complementary processes



$$\approx \sin(\alpha - \beta)$$

Limits on SUSY Higgs from LEP

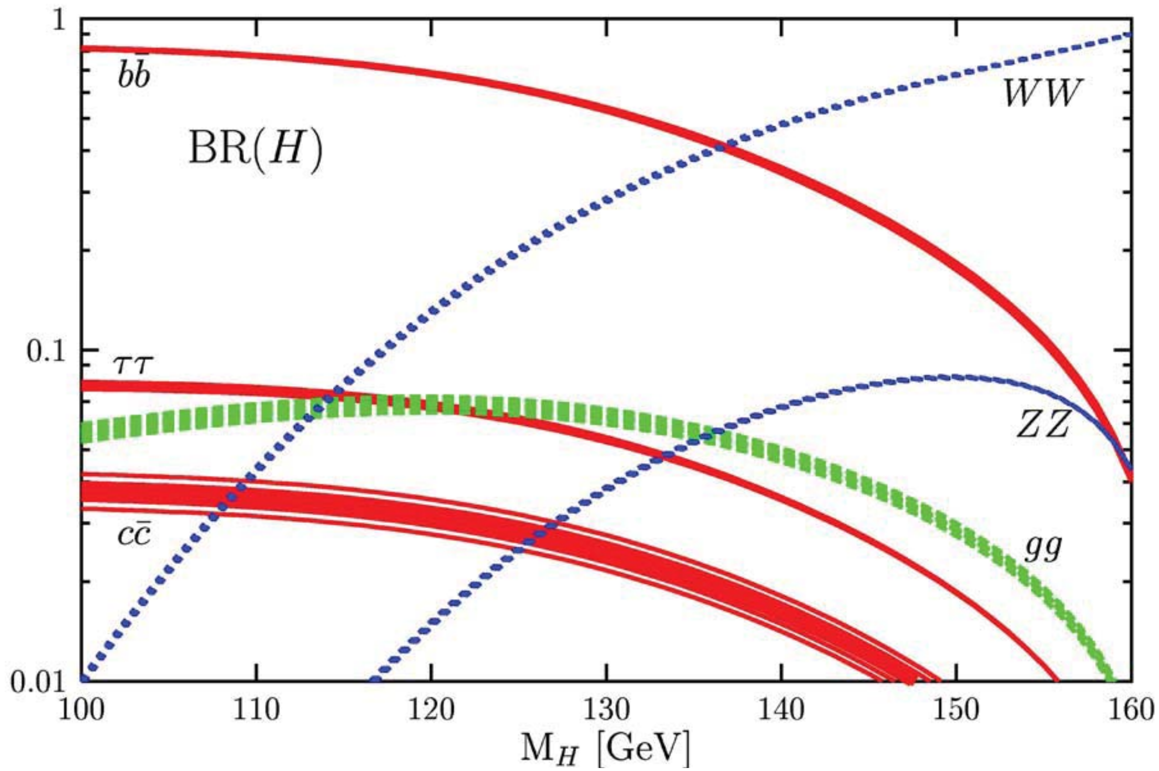


Active work on evading assumptions of this plot!

M_t=169.3,174.3, 179.3, 183 GeV

Remember Higgs Decays in SM

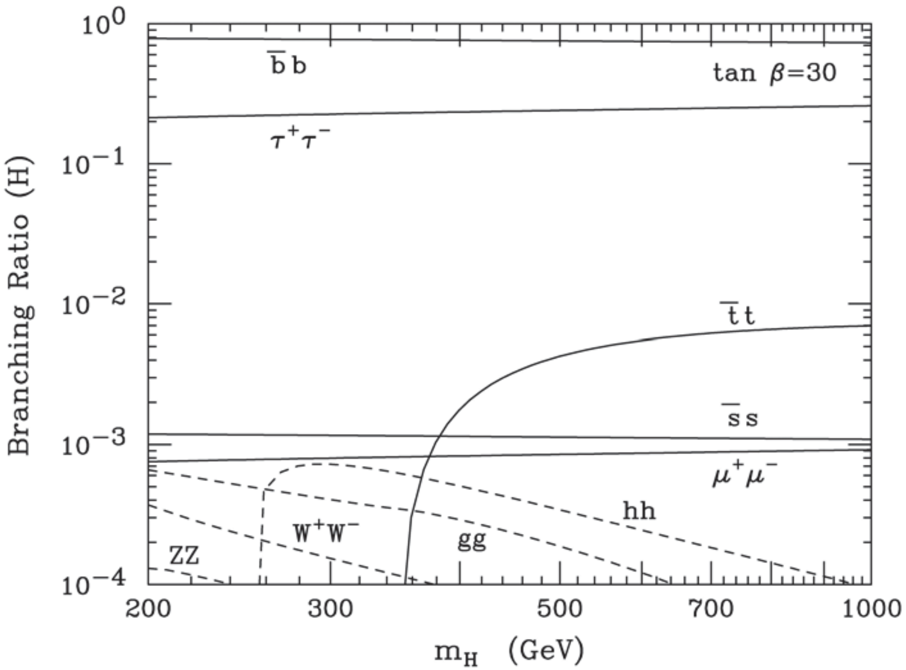
- SM: Higgs branching rates to $b\bar{b}$ and $\tau^+\tau^-$ turn off as rate to W^+W^- turns on (M_h > 160 GeV)



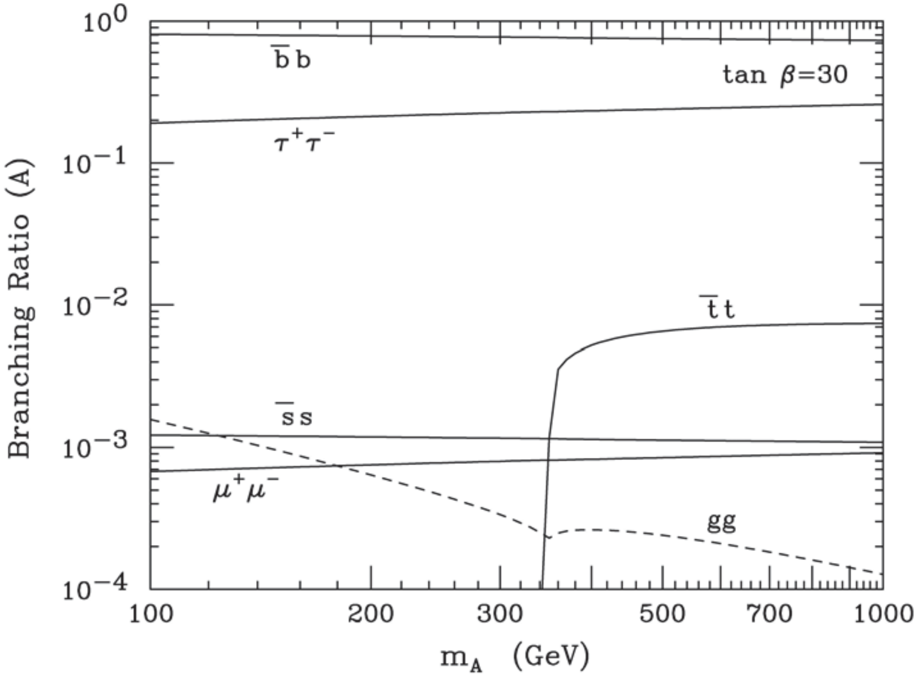
Higgs Decays Changed at Large tan β

- MSSM: At large tan β, rates to $\bar{b}b$ and $\tau^+\tau^-$ large

Heavy H^0 MSSM BRs

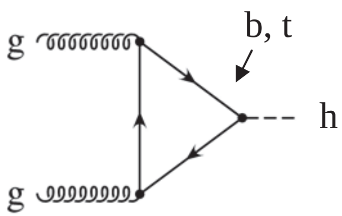


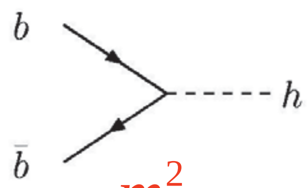
A^0 MSSM BRs



Rate to $\bar{b}b$ and $\tau^+\tau^-$ almost constant in MSSM for H, A

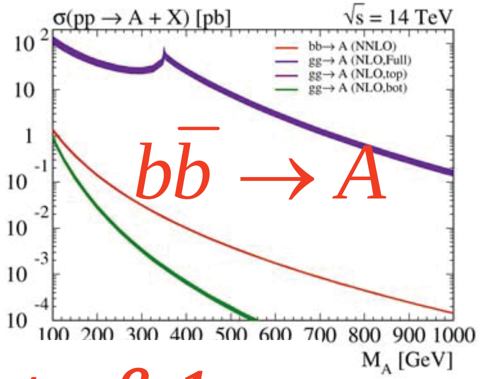
Large tanβ Changes Relative Importance of Production Modes



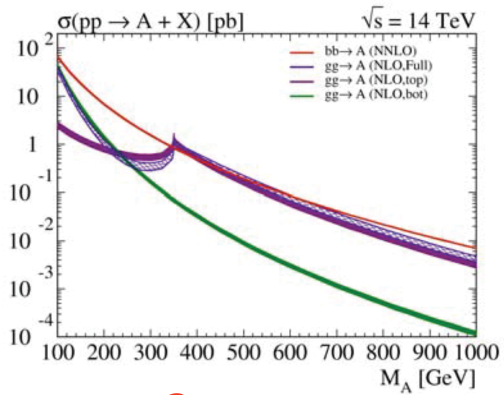


$$\sigma_{gg} = \frac{1}{M_h^2}\left(c_1 \cot^2\beta + c_2 \frac{m_b^2}{M_h^2} + c_3 \frac{m_b^4}{M_h^4} \tan^2\beta \right)$$

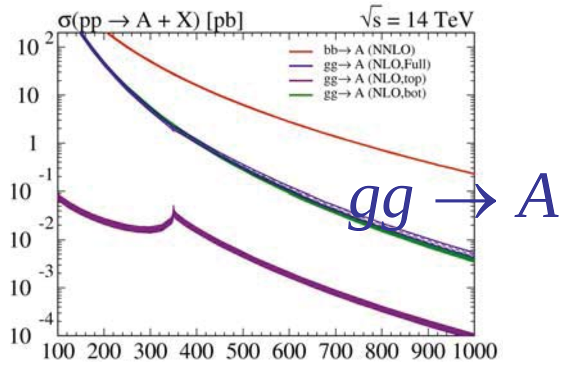
$$\sigma_{bb} = \frac{m_b^2}{M_h^4} c_4 \tan^2\beta$$



tanβ=1



tanβ=7

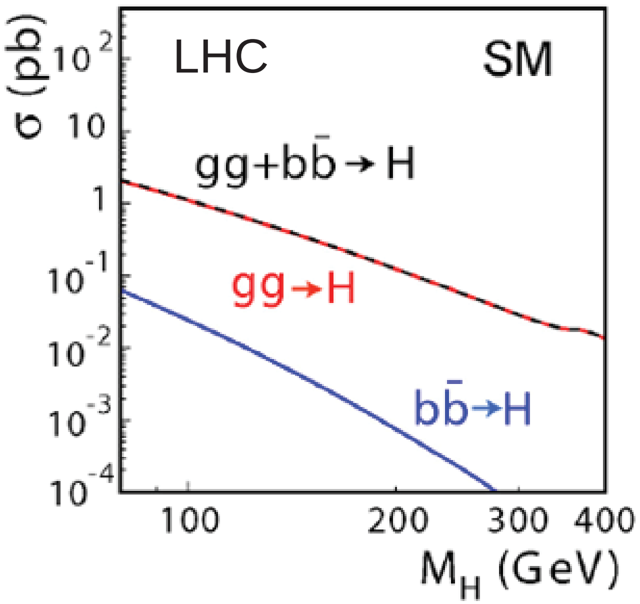


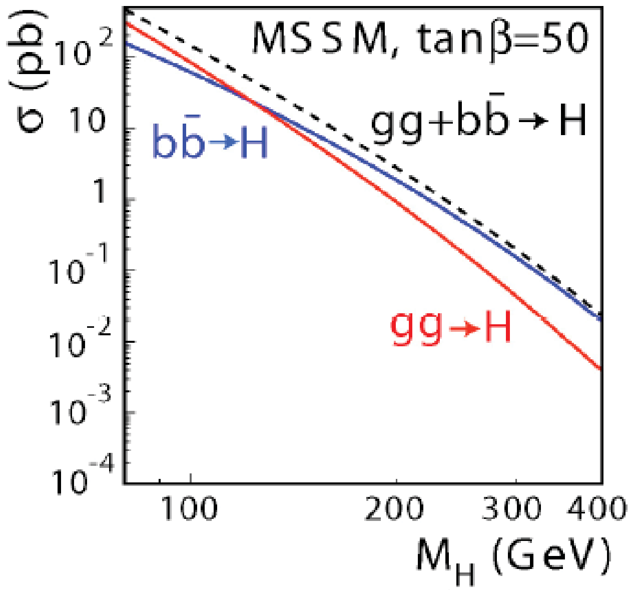
tanβ=40

tanβ ≥ 7, $b\bar{b}$ production mode larger than gg

Higgs Production Can be Larger than SM

- SUSY Higgs: tanβ enhanced couplings to b and τ for H,A
- Production with b's dominates for large M_H

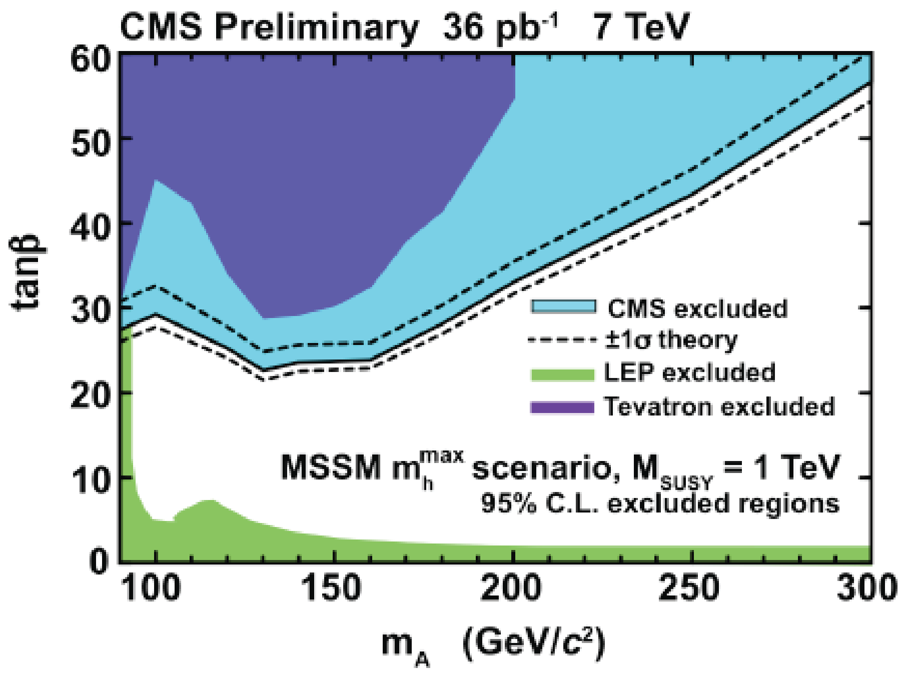




Heavier neutral SUSY Higgs

New Higgs Discovery Channels in SUSY

bbφ coupling enhanced for large tanβ



Many Possibilities Beyond SUSY

- Add singlet Higgs and try to evade LEP bounds
- Two Higgs doublets, but not SUSY
  - Same spectrum as SUSY
  - Must measure Higgs couplings
- Little Higgs Models
  - Have extended gauge sectors and new charge 2/3 quarks

Effective Lagrangian approach needed to study EWSB sector if no new particles found at LHC

Possibilities at the LHC

- We find a light Higgs with SM couplings and nothing else
  - How to answer our questions?
- We find a light Higgs, but it doesn't look SM like
  - Most models (SUSY, Little Higgs, etc) have other new particles
- We don't find a Higgs (or any other new particles)
  - How can we reconcile precision measurements?
  - This is the hardest case

The fun is just beginning

Happy Higgs Hunting!