EWSB Beyond the Standard Model

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XIII Mexican School of Particles and Fields

Lecture 3, October 2008

Masses at One-Loop

- First consider a fermion coupled to a massive complex Higgs scalar

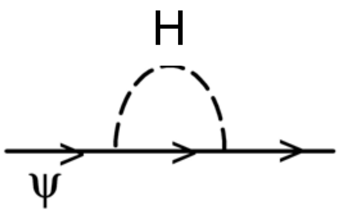
$$L = \overline{\Psi}(i\partial)\Psi + \left|\partial_\mu \phi\right|^2 - m_H \left|\phi\right|^2 - \left(\lambda_F \overline{\Psi}_L \Psi_R \phi + h.c.\right)$$

- Assume symmetry breaking as in SM:

$$\phi = \frac{(H+v)}{\sqrt{2}} \qquad\qquad m_F = \frac{\lambda_F v}{\sqrt{2}}$$

Masses at One-Loop, #2

- Calculate mass renormalization for Ψ



$$-i\Sigma_F(p) = \left(\frac{-i\lambda_F}{\sqrt{2}}\right)^2 (i)^2 \int \frac{d^4k}{(2\pi)^4} \frac{k + m_F}{[k^2 - m_F^2][(k-p)^2 - m_H^2]}$$

Renormalized Fermion Mass

$$\delta m_F = \Sigma_F(p)\big|_{p=m_F}$$

$$= i\frac{\lambda_F^2}{32\pi^4}\int_0^1 dx \int d^4k' \frac{m_F(1+x)}{[k'^2 - m_F^2x^2 - m_s^2(1-x)]^2}$$

- Do integral in Euclidean space

$$k_0 \to ik_4$$

$$d^4k' \to i d^4k_E$$

$$k'^2 = k_0^2 - \left|\vec{k}\right|^2 \to k_4^2 - \left|\vec{k}\right|^2 = -k_E^2$$

$$\int d^4k_E\, f(k_E^2) = \pi^2 \int_0^{\Lambda^2} y\, dy\, f(y)$$

Renormalized Fermion Mass, #2

- Renormalization of fermion mass:

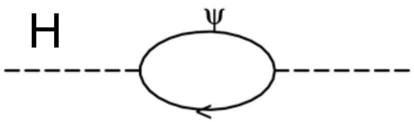
$$\delta m_F = -\frac{\lambda_F^2 m_F}{32\pi^2}\int_0^1 dx\ (1+x)\int_0^{\Lambda^2}\frac{y\,dy}{[y+m_F^2 x^2+m_H^2(1-x)]^2}$$

$$= -\frac{3\lambda_F^2 m_F}{32\pi^2}\log\left(\frac{\Lambda^2}{m_F^2}\right)+\ldots..$$

Symmetry and the Fermion Mass

- $\delta m_F \approx m_F$
  - m_F=0, then quantum corrections vanish
  - When m_F=0, Lagrangian is invariant under
    - $\Psi_L \rightarrow e^{i\theta L}\Psi_L$
    - $\Psi_R \rightarrow e^{i\theta R}\Psi_R$
  - $m_F \rightarrow 0$ increases the symmetry of the threoy
  - Yukawa coupling (proportional to mass) breaks symmetry and so corrections $\approx m_F$

Scalars are very different



$$-i\Sigma_H(p^2) = -\left(\frac{-i\lambda_F}{\sqrt{2}}\right)^2 (i)^2 \int \frac{d^4k}{(2\pi)^4} \frac{Tr\left[(k+m_F)((k-p)+m_F)\right]}{(k^2-m_F^2)[(k-p)^2-m_F^2]}$$

$$\delta M_H^2 = \Sigma_H(m_H^2) = -\frac{\lambda_F^2\Lambda^2}{8\pi^2} + \left(m_H^2 - m_F^2\right)\log\left(\frac{\Lambda}{m_F}\right)$$

$$+(2m_F^2 - \frac{m_H^2}{2})\left(1 + I_1\left(\frac{m_H^2}{m_F^2}\right)\right) + O\left(\frac{1}{\Lambda^2}\right)$$

$$I_1(a) = \int_0^1 dx \ \log\left(1 - ax(1-x)\right)$$

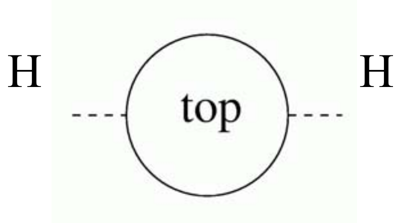
- M_H diverges quadratically!
- ***Quadratic sensitivity to high mass scales***

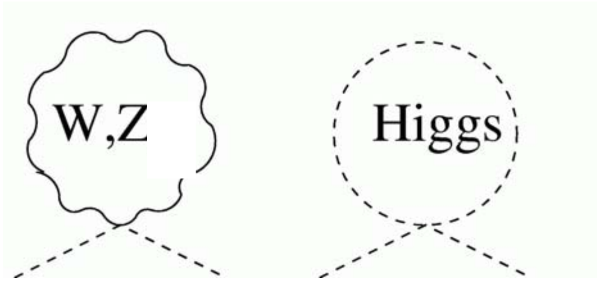
Scalars (#2)

- M_H diverges quadratically!
- Requires large cancellations (hierarchy problem)
- Can do this in Quantum Field Theory
- H does not obey decoupling theorem
  - Effects of heavy particle (H) does not decouple as $M_H \rightarrow \infty$
- $M_H \rightarrow 0$ doesn't increase symmetry of theory
  - Nothing protects Higgs mass from large corrections

Light Scalars are Unnatural

- Higgs mass grows with scale of new physics, Λ
- No additional symmetry for M_H=0, no protection from large corrections





$$\delta M_H^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_H^2 - 12M_t^2\right)$$

$$= -\left(\frac{\Lambda}{0.7\ \text{TeV}}\, 200\ \text{GeV}\right)^2$$

$M_H \leq$ 200 GeV requires large cancellations

What's the problem?

- Compute M_H in dimensional regularization and absorb infinities into definition of M_H

$$M_H^2 = M_{H0}^2 + \frac{1}{\varepsilon}(\ldots)$$

- Perfectly valid approach
- Except we know there is a high scale (associated with gravity)

Try to cancel quadratic divergences by adding new particles

- SUSY models add scalars with same quantum numbers as fermions, but different spin
- Little Higgs models cancel quadratic divergences with new particles with same spin

New particles assumed to be at TeV scale for cancellation of quadratic divergences

Supersymmetric Models as Alternative to SM

Many New Particles:

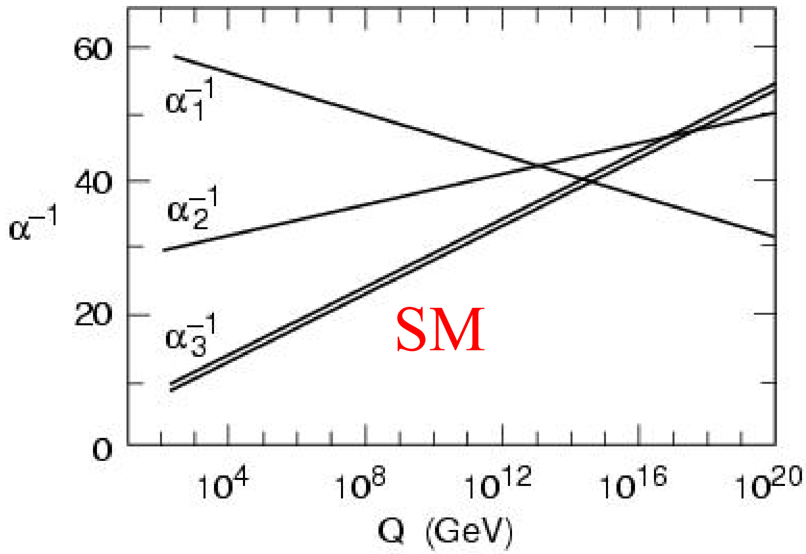
- Spin ½ quarks $\Rightarrow$ spin 0 squarks
- Spin ½ leptons $\Rightarrow$ spin 0 sleptons
- Spin 1 gauge bosons $\Rightarrow$ spin ½ gauginos
- Spin 0 Higgs $\Rightarrow$ spin ½ Higgsino

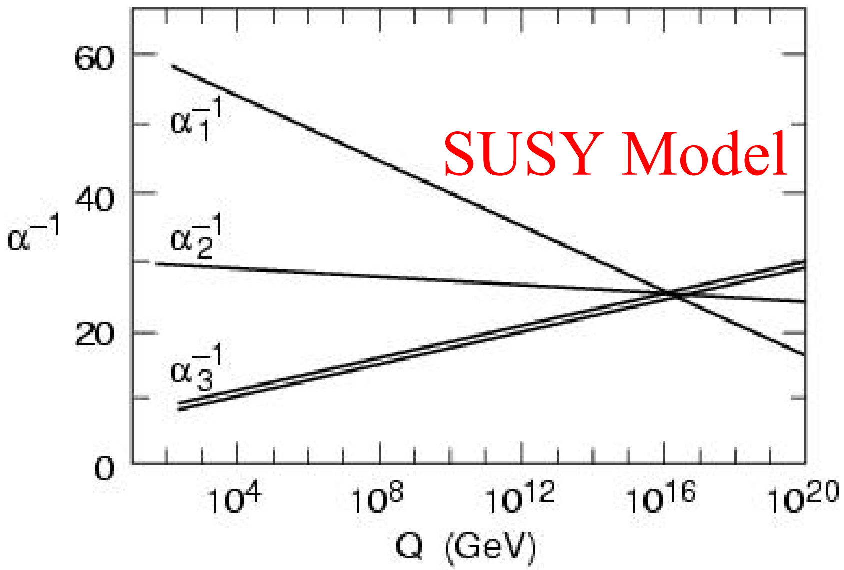
Supersymmetric Theories

- 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

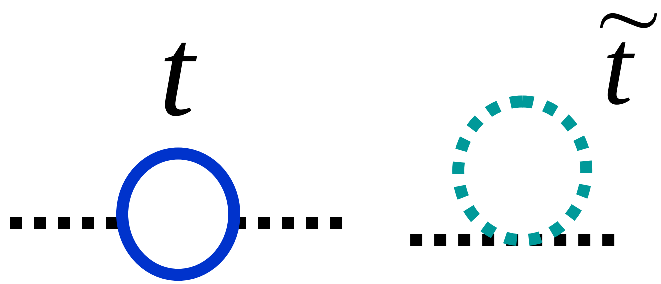
- Coupling constants change with energy
- Assume new particles at TeV scale





SUSY….Our favorite model

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

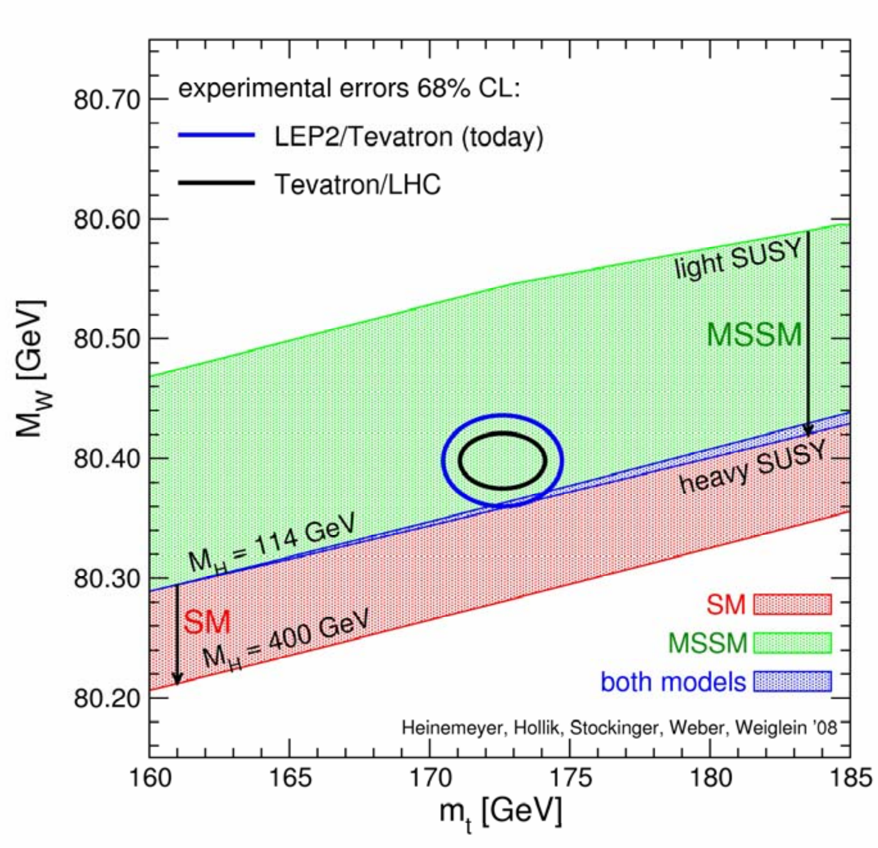


$$\delta M_h^{\;2} \approx (....) G_F \Lambda^2 (M_t^{\;2} - M_{\tilde{t}}^{\;2})$$

- Stop mass should be TeV scale

Supersymmetry (MSSM version)

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



Fermion Masses

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

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

- 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

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 SUSY

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

Gauge Couplings

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

$m_{12}^2 = B\mu$

EWSB and SUSY Models

- EW 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, $M_W^2 = g^2(v_1^2 + v_2^2)/4$
- 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, $M_{H\pm}$

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

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

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

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

Many radiative corrections can be included by calculating effective angle, α^*

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

$$M_h^2 \le M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta}\left(\ln\left[\frac{\tilde{m}_t^2}{m_t^2}\right] + \frac{X_t^2}{\tilde{m}_t^2}\left(1 - \frac{X_t^2}{12\tilde{m}_t^2}\right)\right)$$

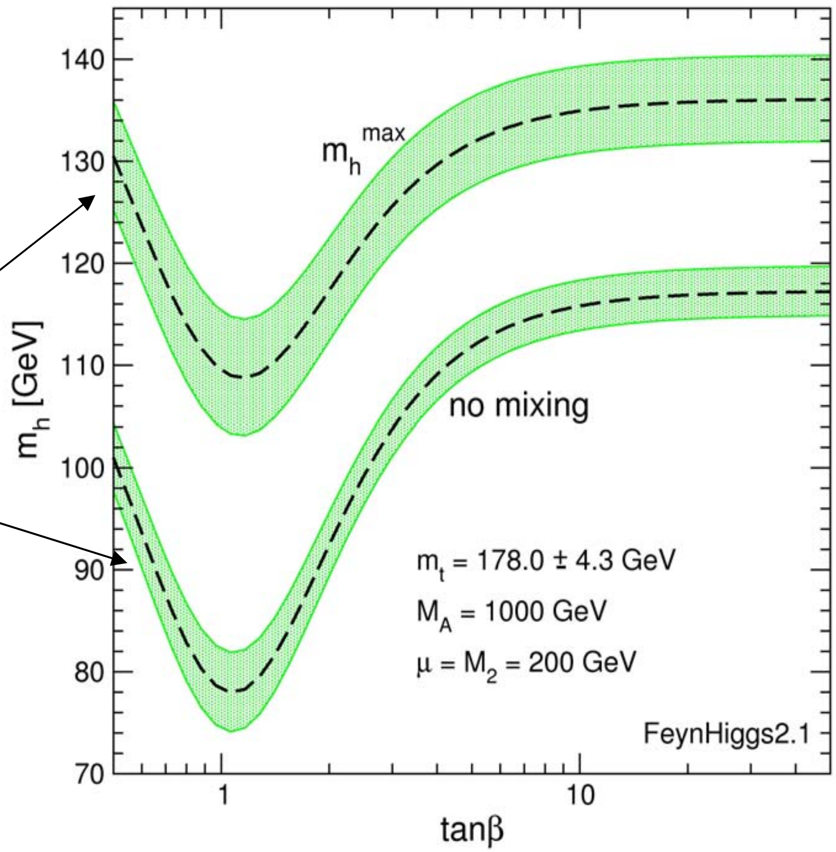
Average stop mass

$$X_t = A_t - \frac{\mu}{\tan\beta}$$

- Stop mass should be TeV scale for naturalness

Theoretical Upper Bound on M_h

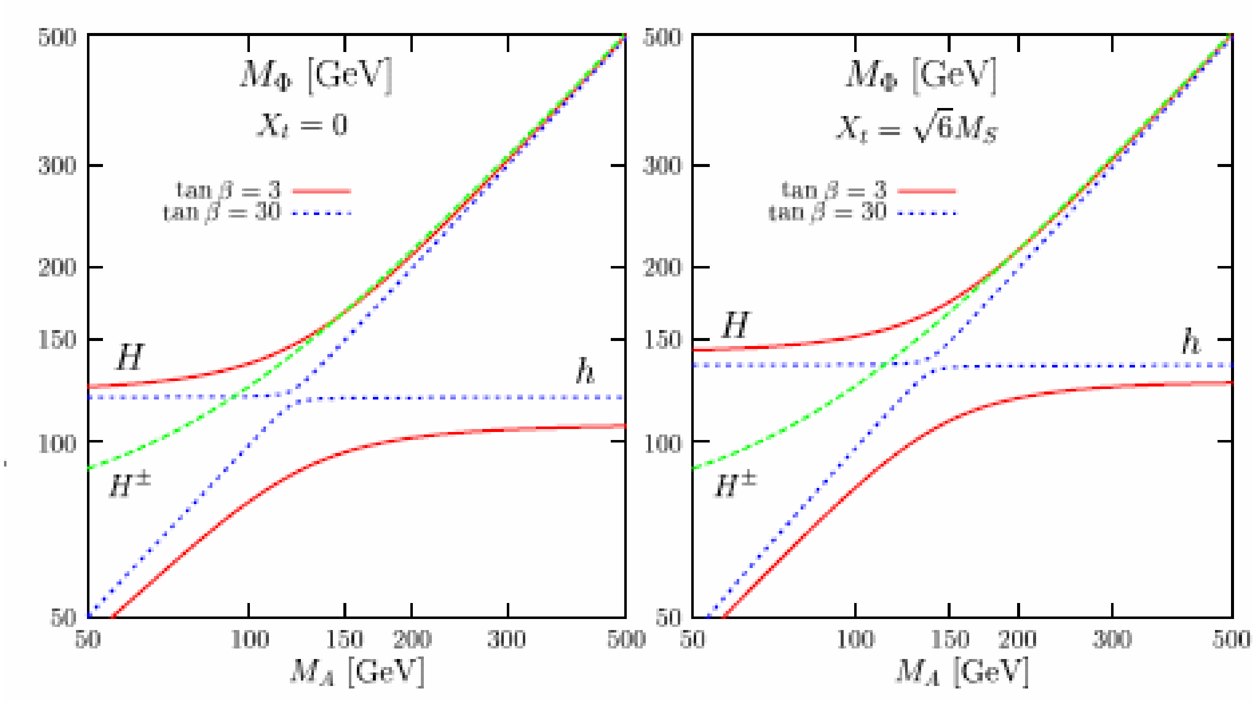
Upper bound on lightest neutral Higgs boson mass with m_{stop} = 1 TeV



- 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 from superpotential

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

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

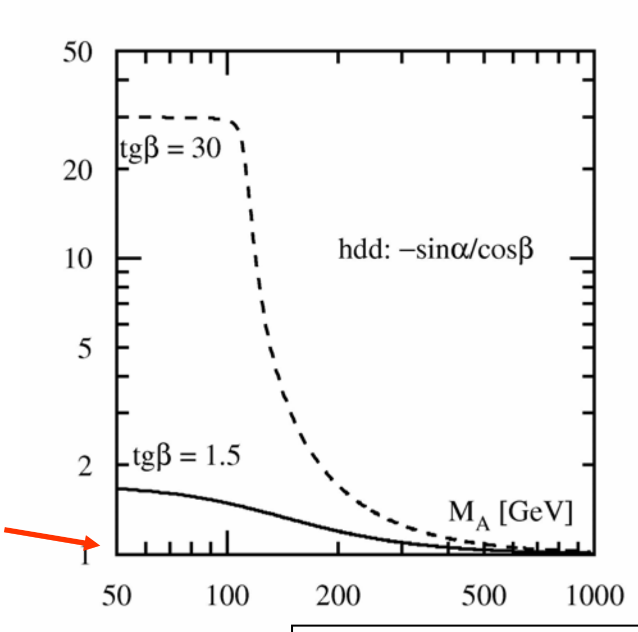
Higgs Couplings Different from SM

Lightest Neutral Higgs, h

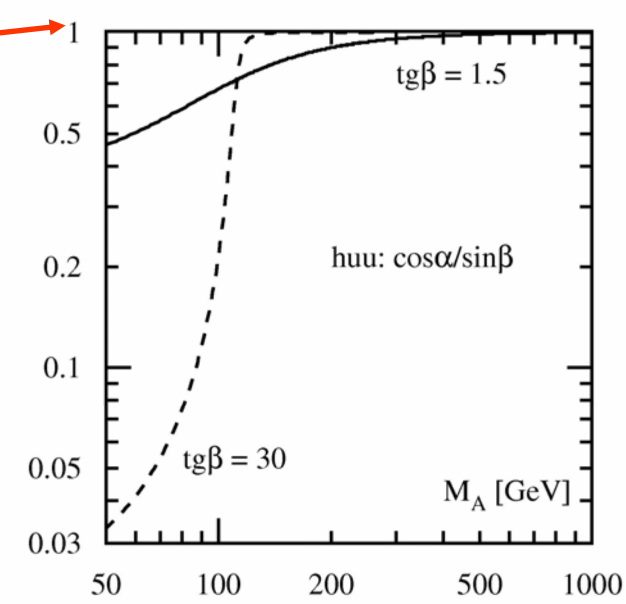
- Couplings to d, s, b enhanced at large tan β for moderate M_A

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

SM



SM

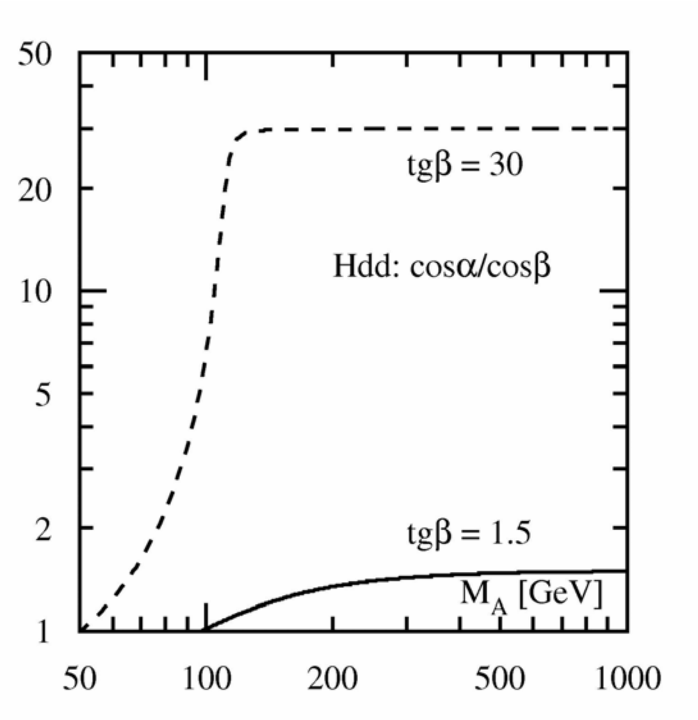


Decoupling limit: For $M_A \rightarrow \infty$, h couplings go to SM couplings

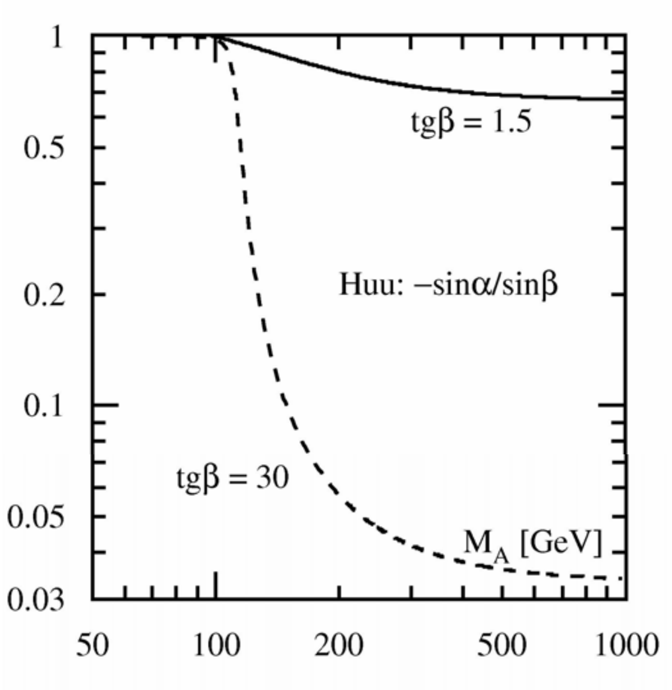
Higgs Couplings in SUSY

Heavier Neutral Higgs, H

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



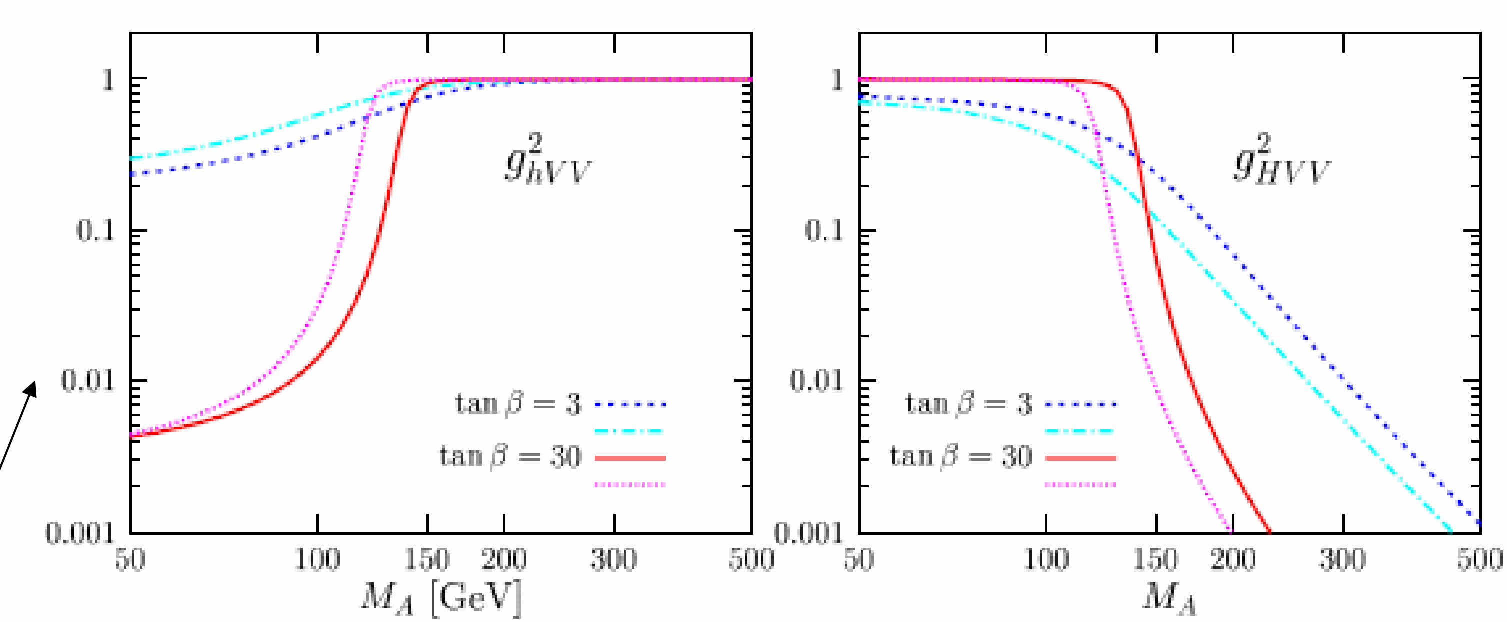
➢Couplings to u, c, t suppressed at large tan β



Gauge Boson Couplings to Higgs

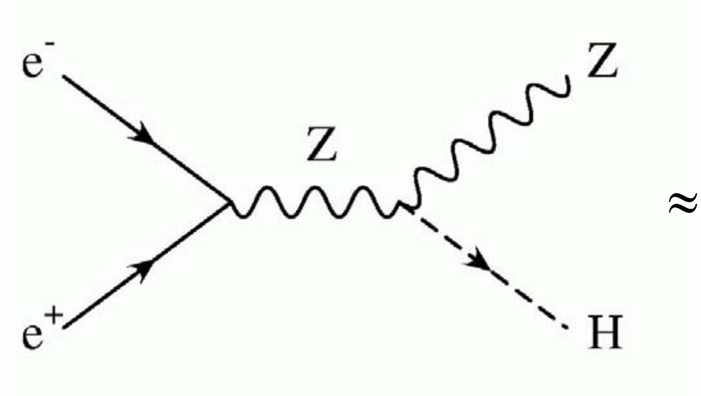
- $g_{hVV}^2 + g_{HVV}^2 = g_{hVV}^2(SM)$
- Vector boson fusion and Wh production always suppressed in MSSM

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



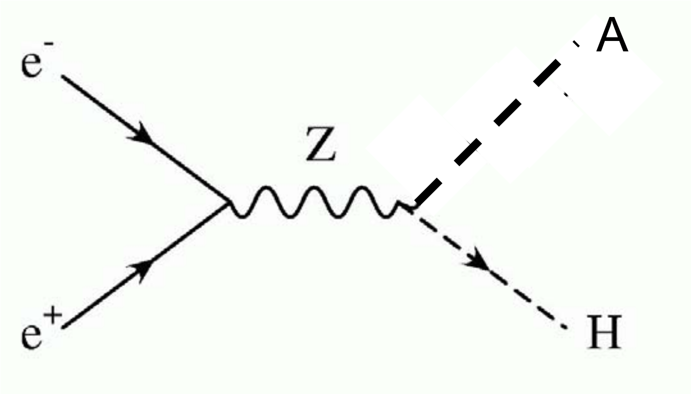
Normalized to SM couplings

Limits from LEP



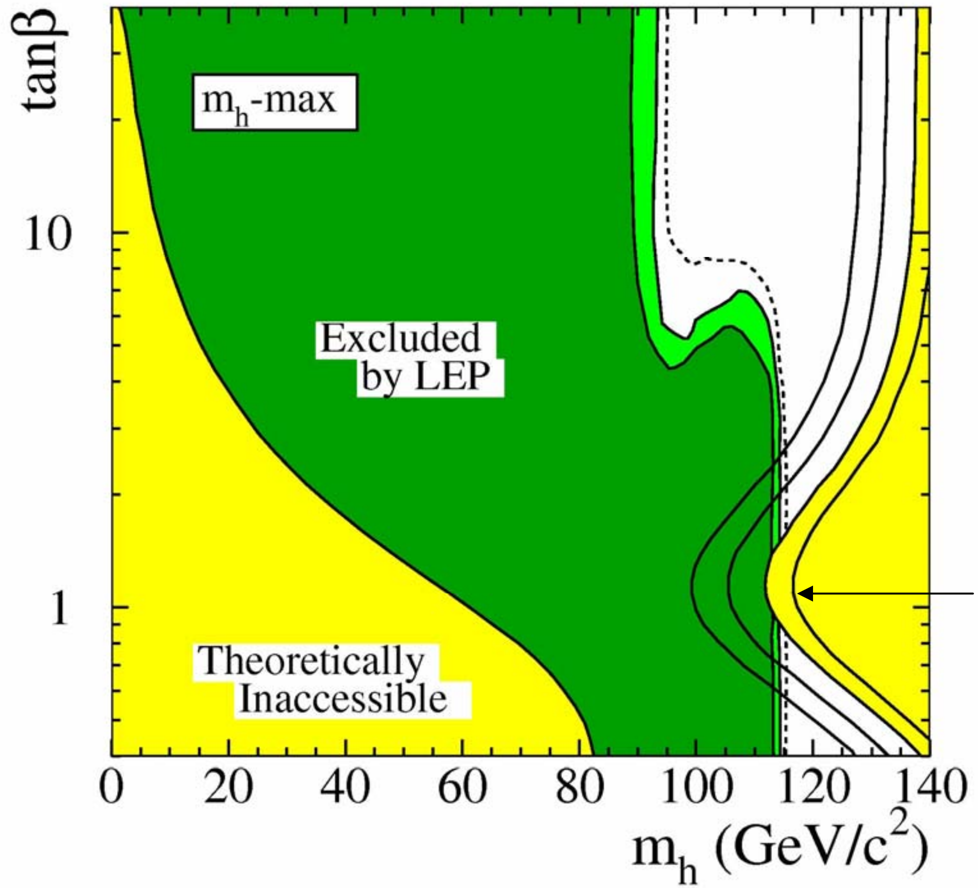
$$\approx \cos(\alpha - \beta)$$

Complementary processes



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

Limits on SUSY Higgs from LEP

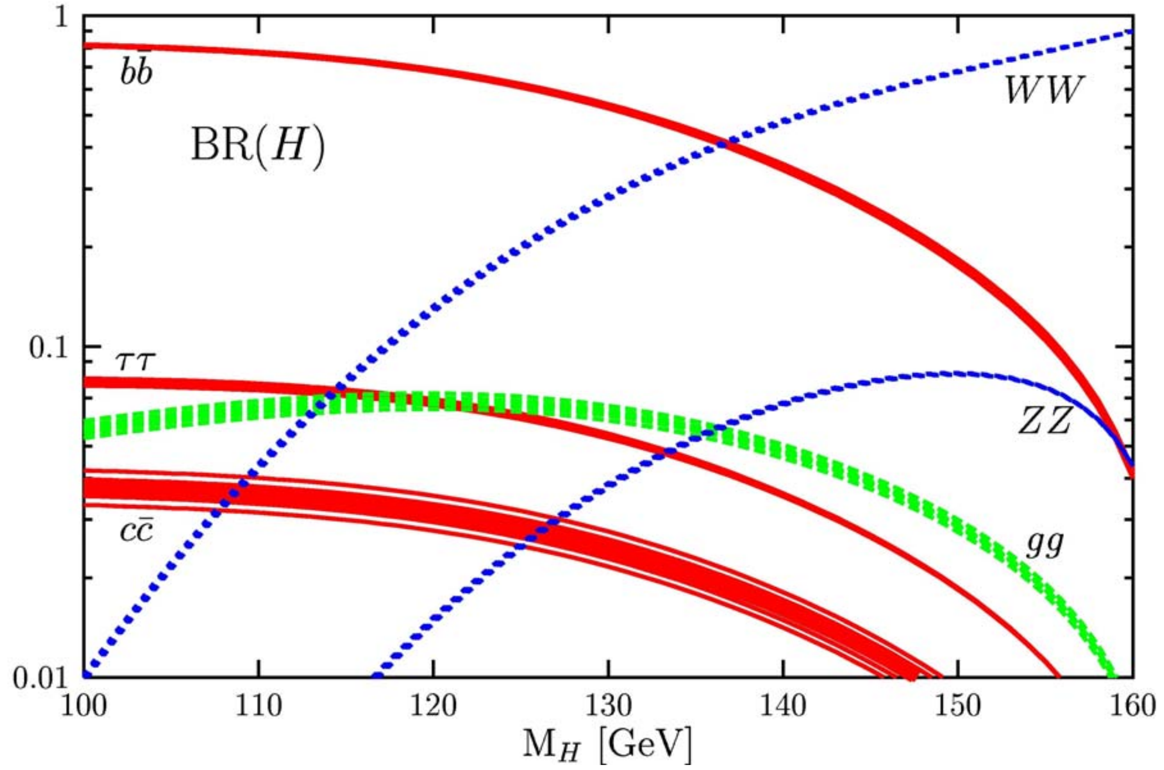


Active work on evading assumptions of this plot!

M_t=169.3,174.3, 179.3, 183 GeV

Remember Higgs Decays in SM

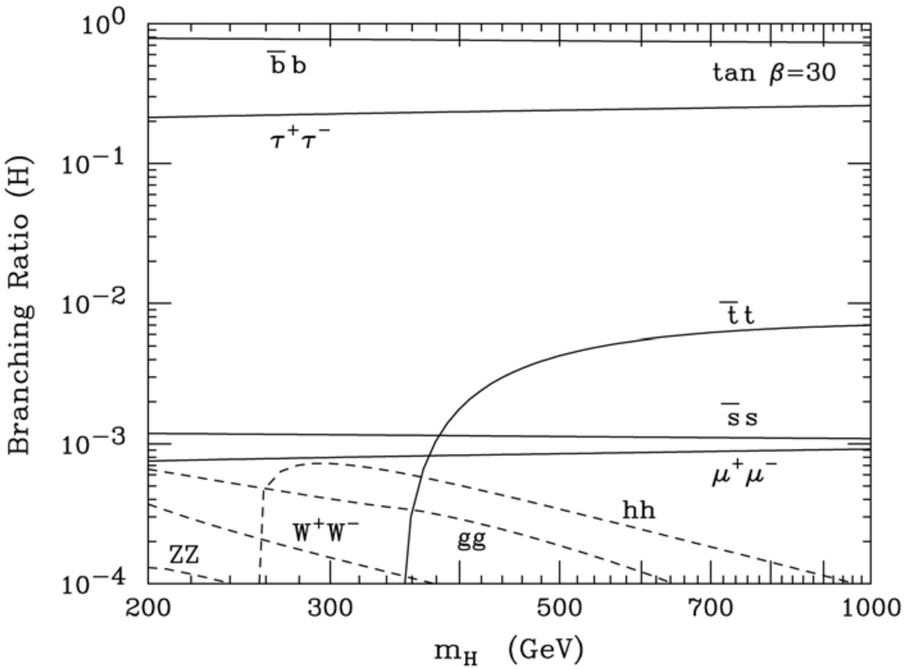
- SM: Higgs branching rates to $b\bar{b}$ and $\tau^+\tau^-$ turn off as rate to W^+W^- turns on (M_h > 160 GeV)



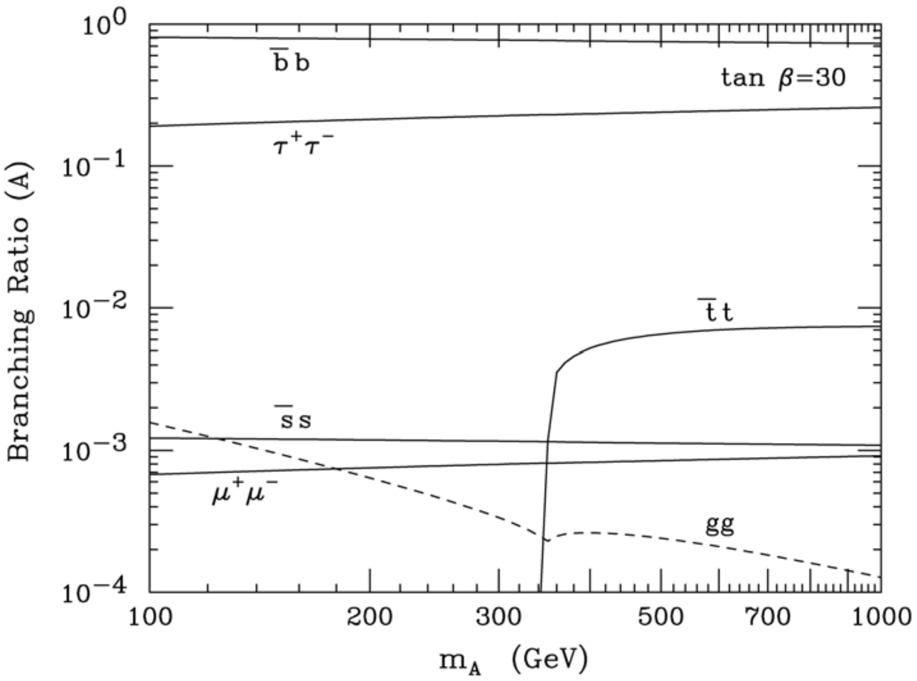
Higgs Decays Changed at Large tan β

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

Heavy H^0 MSSM BRs

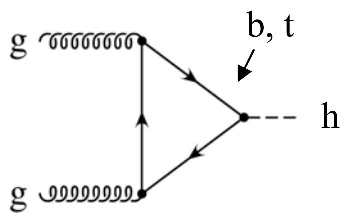


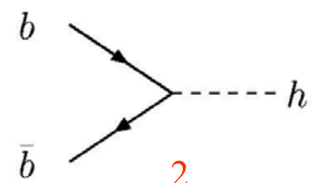
A^0 MSSM BRs



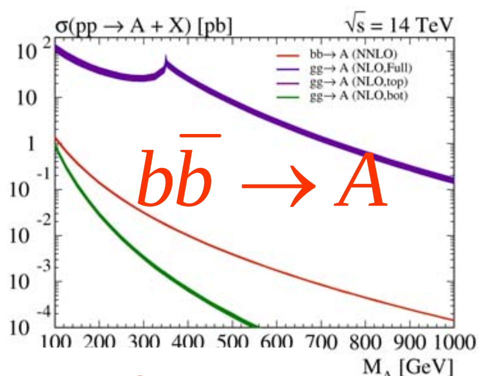
Rate to $b\bar{b}$ and $\tau^+\tau^-$ almost constant in MSSM for H, A

Large tanβ Changes Relative Importance of Production Modes

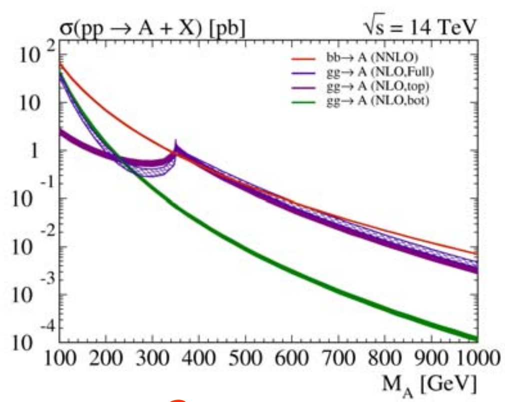




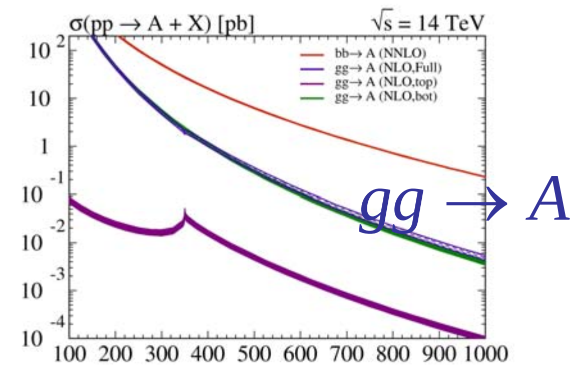
$$\sigma_{gg} = \frac{1}{M_h^2}\left(c_1 \cot^2\beta + c_2 \frac{m_b^2}{M_h^2} + c_3 \frac{m_b^4}{M_h^4}\tan^2\beta\right) \qquad \sigma_{bb} = \frac{m_b^2}{M_h^4} c_4 \tan^2\beta$$



tanβ=1



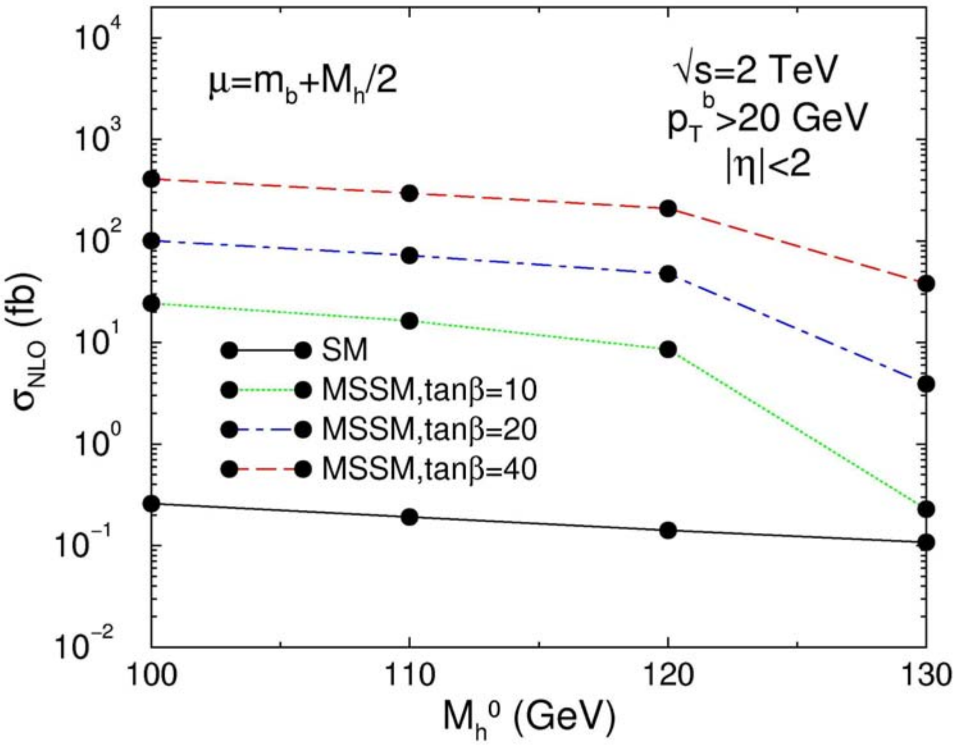
tanβ=7



tanβ=40

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

$gg \to b\bar{b}h$ in SUSY Models at Tevatron



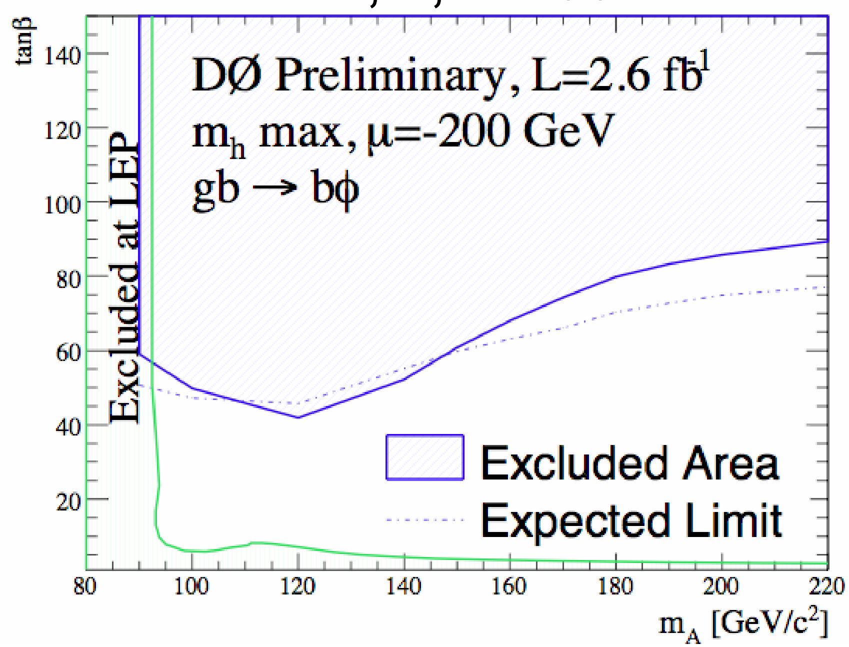
Huge enhancements in SUSY from SM Rate

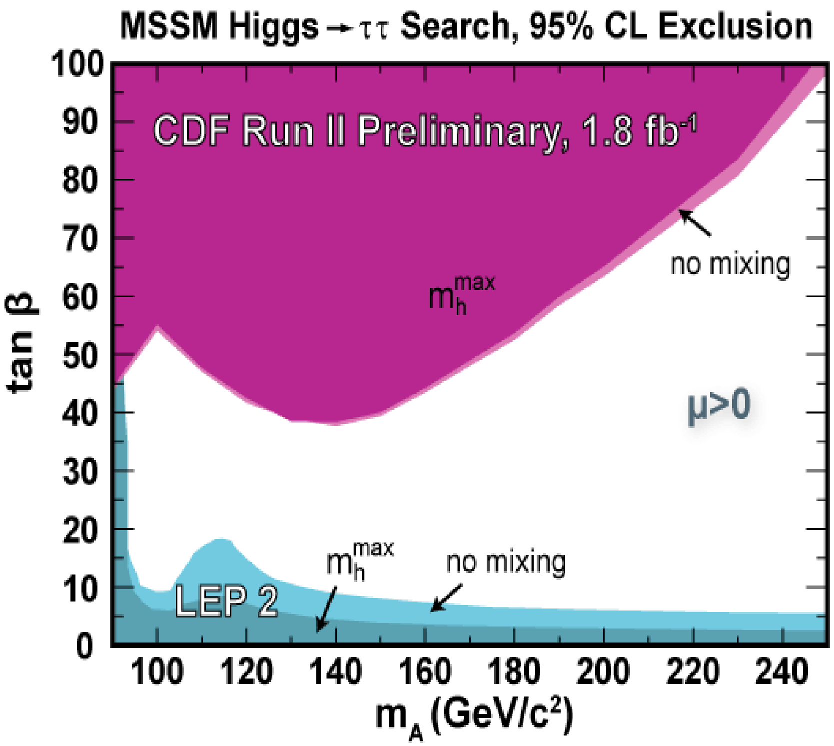
Couplings/masses with FeynHiggs

New Higgs Discovery Channels in SUSY

Tevatron

h,H,A→bb

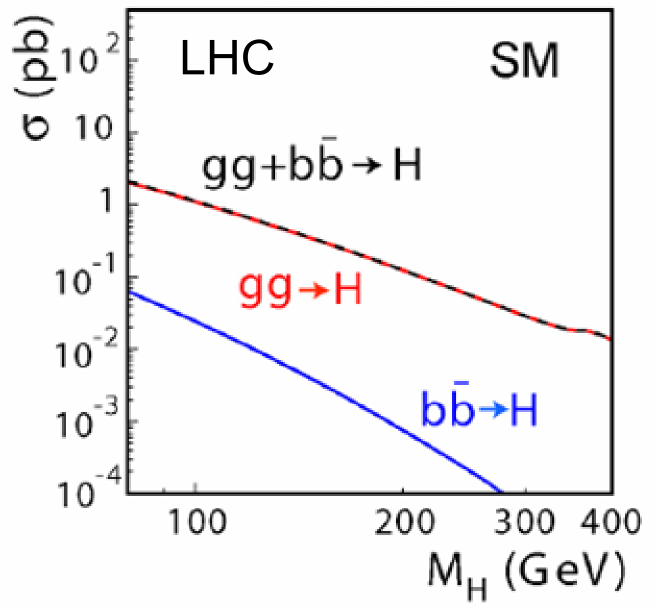


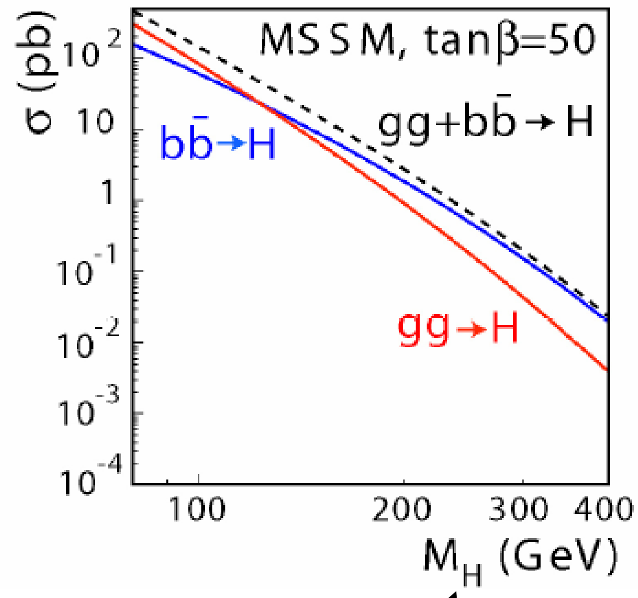


bbφ coupling enhanced
for large tanβ

Higgs Production Can be Larger than SM

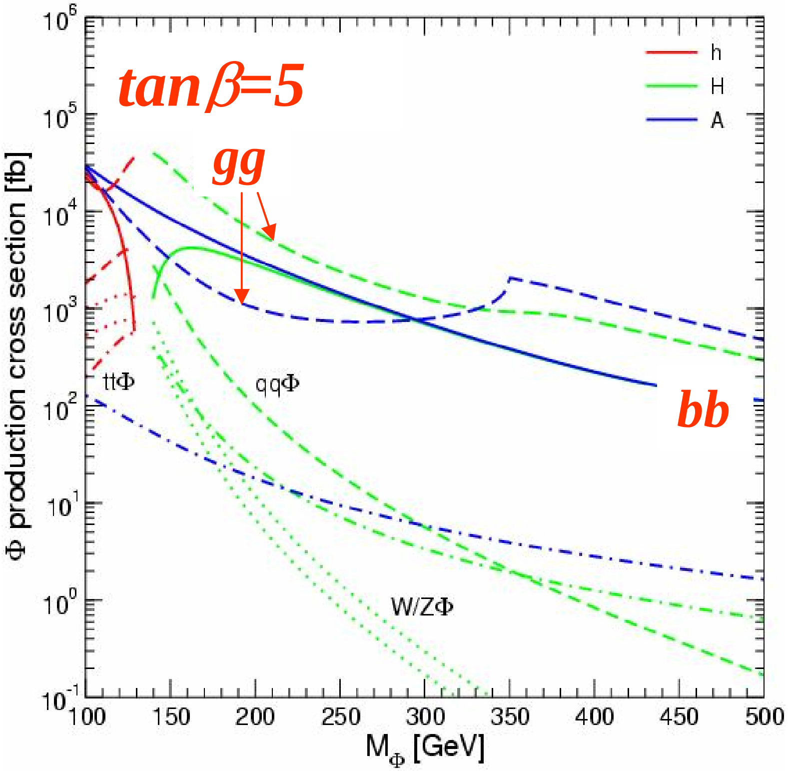
- SUSY Higgs: tanβ enhanced couplings to b and τ for H,A
- Production with b's dominates for large M_H

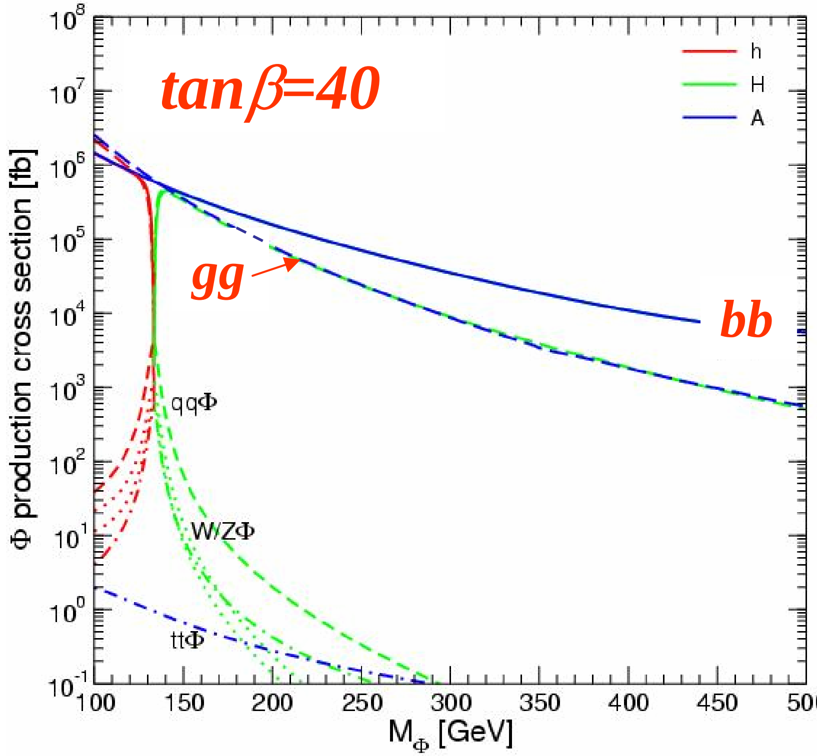




Heavier neutral SUSY Higgs

SUSY Higgs Rates at the LHC



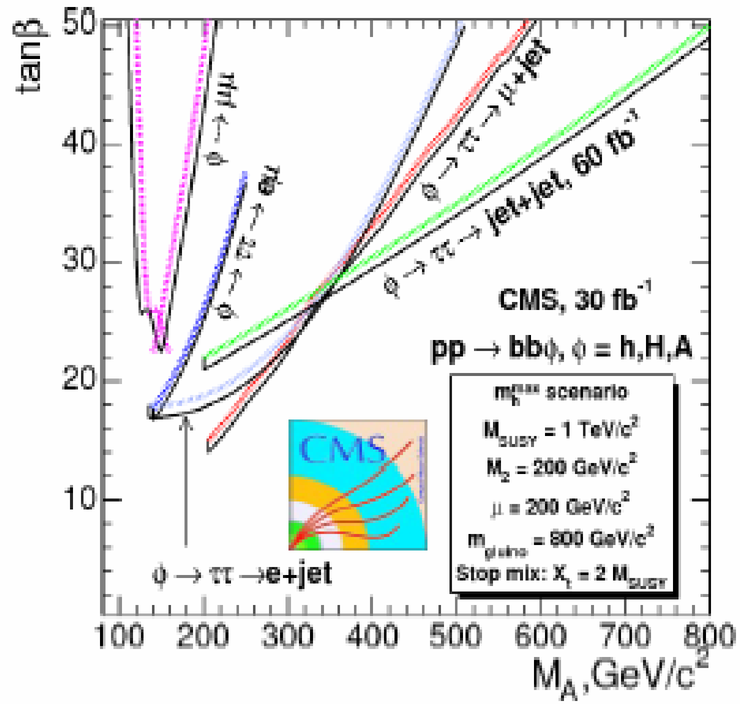


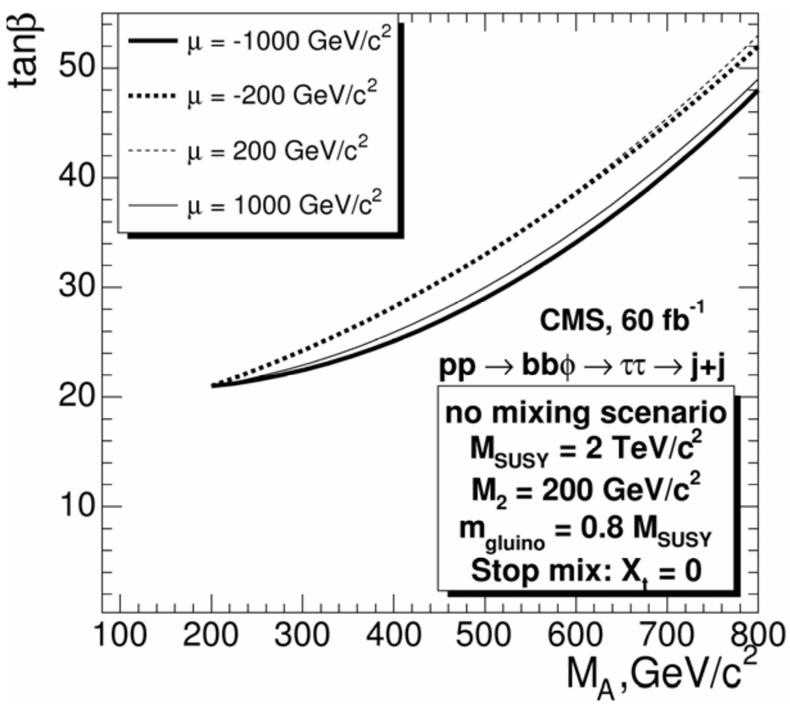
- For large tan β, dominant production mechanism is with b's
- bbH can be 10x's SM Higgs rate in SUSY for large tan β

$\sigma_{SM}^{gg}(M_h=200\text{ GeV}) \sim 1.5 \times 10^4$ fb

TeV4LHC Report

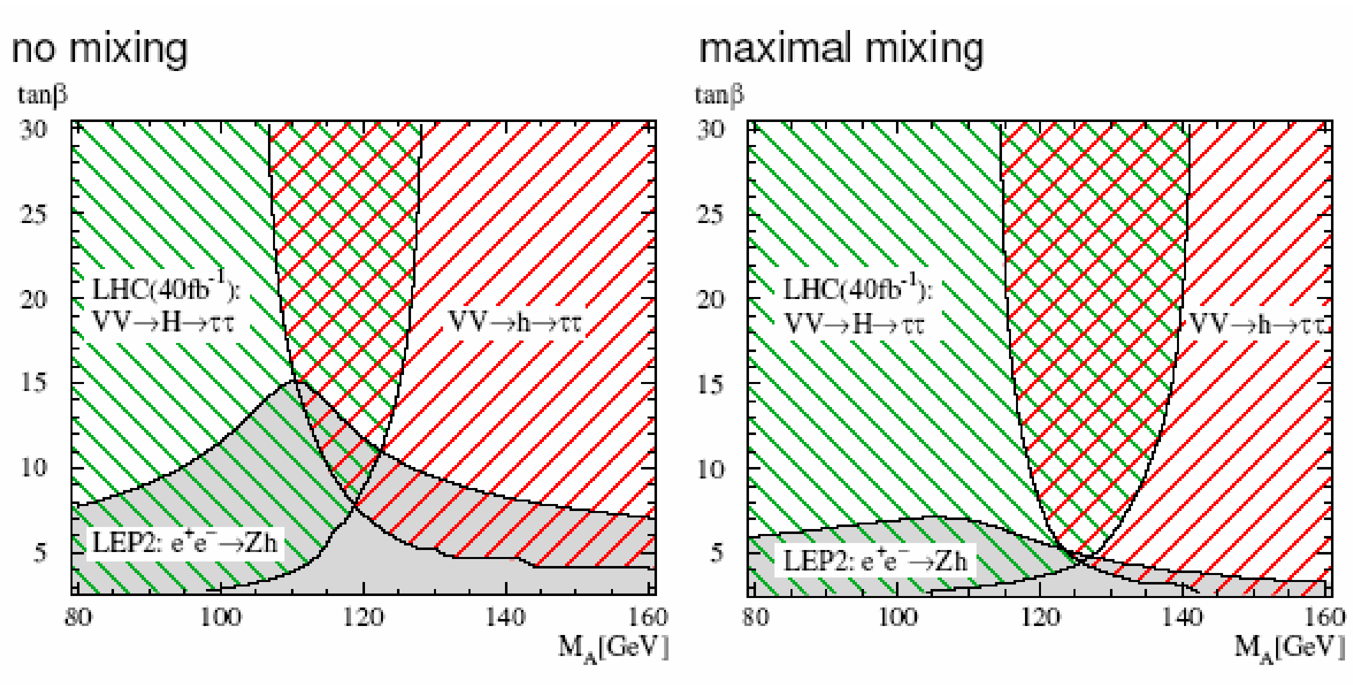
Associated bbH Production at the LHC

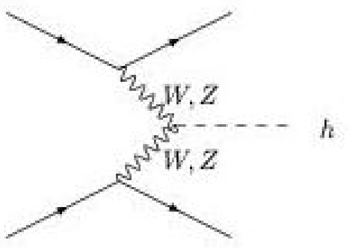




LHC sensitive down to tan β~20-40

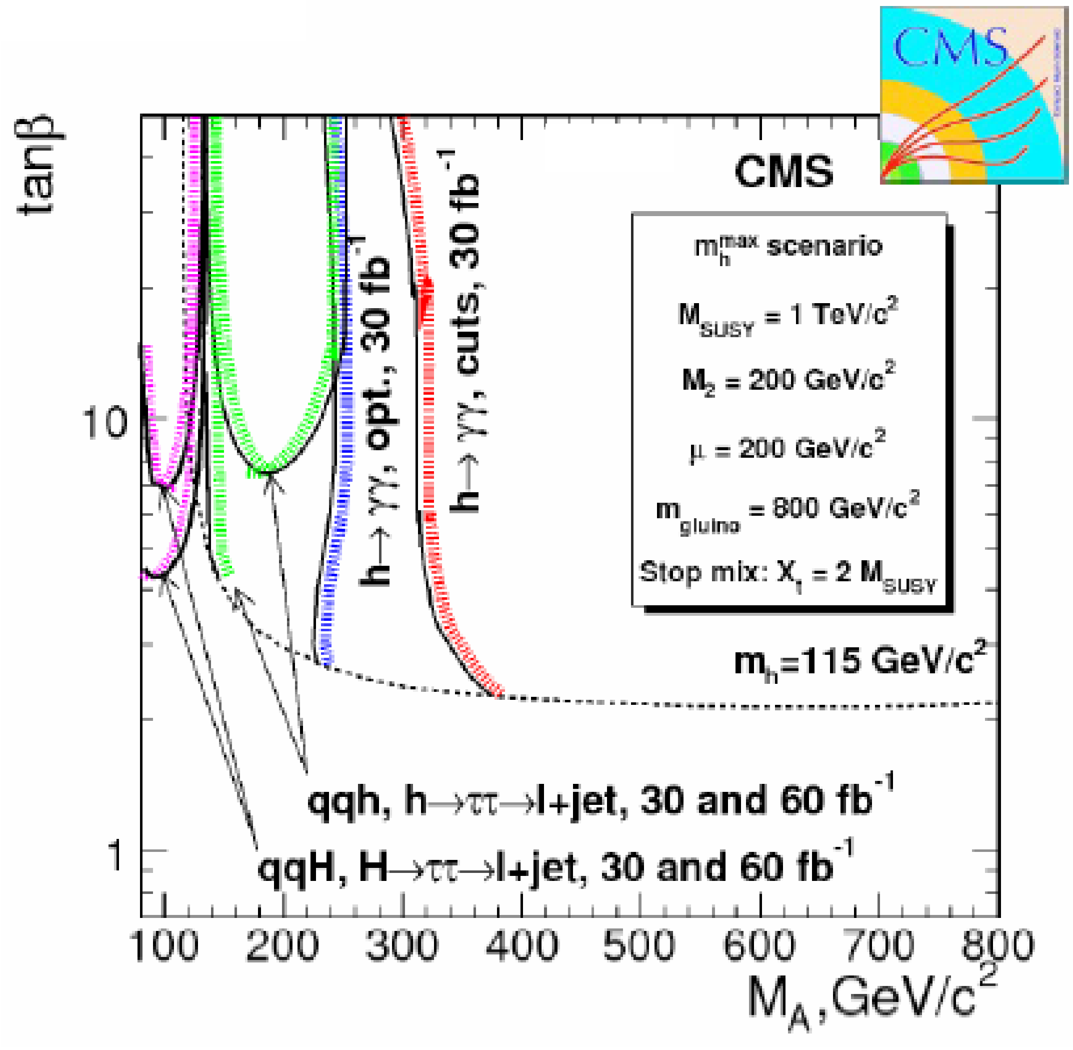
LHC Can Find h and H in Weak Boson Fusion





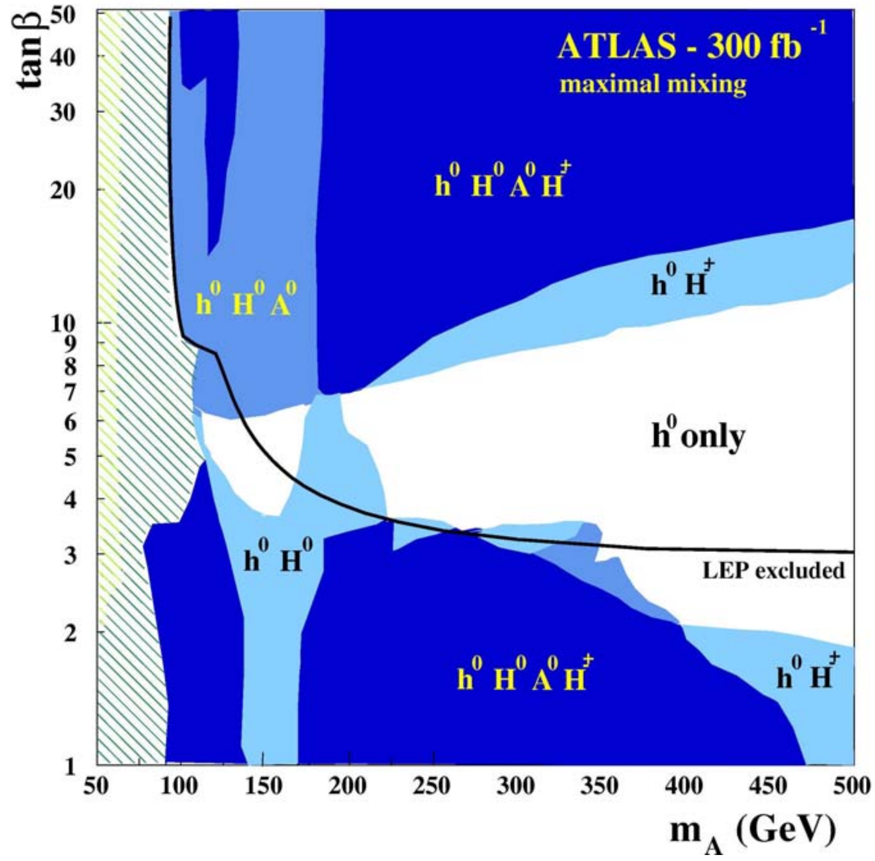
Decays to $\tau^+\tau^-$ needed

SUSY Higgs Searches in $\gamma\gamma$ Mode



MSSM discovery

- For large fraction of M_A-$\tan\beta$ space, more than one Higgs boson is observable
- For $M_A \rightarrow \propto$, MSSM becomes SM-like
- Plot shows regions where Higgs particles can be observed with > 5σ



Need to observe multiple Higgs bosons and measure their couplings

Many Possibilities Beyond SUSY

- Add singlet Higgs and try to evade LEP bounds
- Two Higgs doublet, 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