EWSB Beyond the Standard Model

S. Dawson (BNL)

XIII Mexican School of Particles and Fields

Lecture 3, October 2008

Supersymmetric Models as Alternative to SM

Many New Particles:

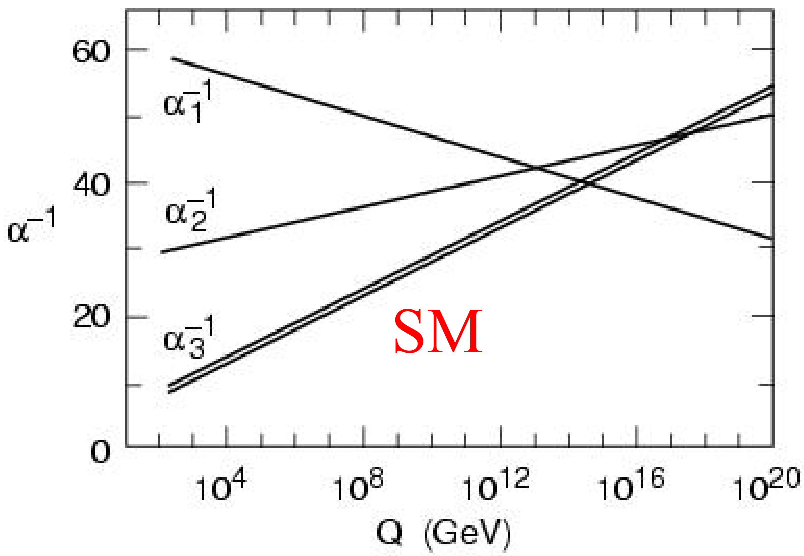
- Spin ½ quarks ⇒ spin 0 squarks
- Spin ½ leptons ⇒ spin 0 sleptons
- Spin 1 gauge bosons ⇒ spin ½ gauginos
- Spin 0 Higgs ⇒ spin ½ Higgsino

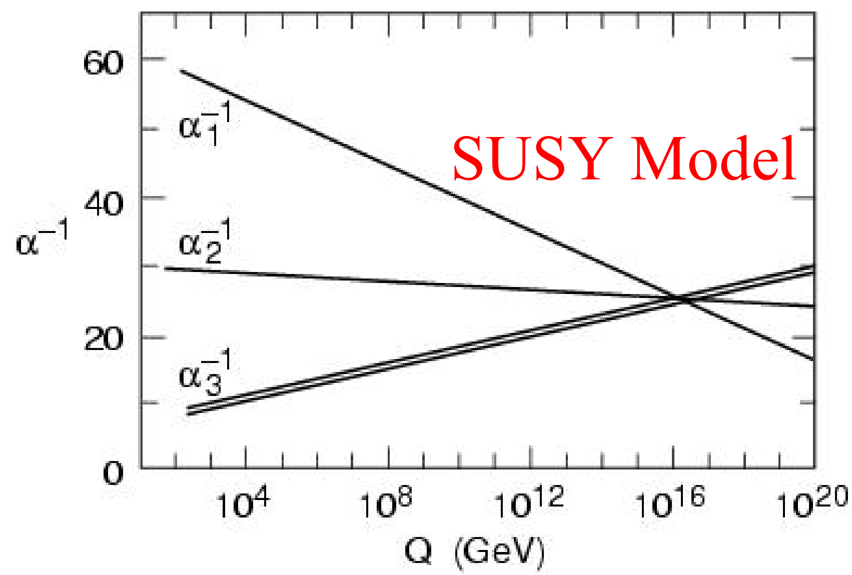
Supersymmetric Theories

- 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

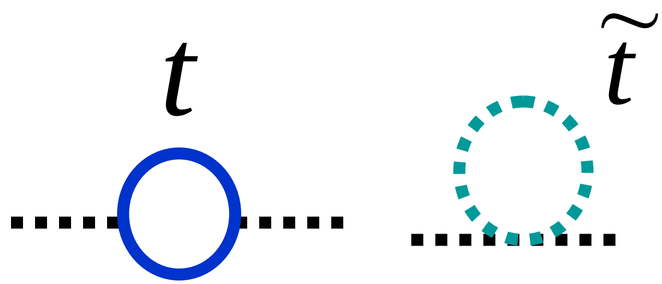
- Coupling constants change with energy
- Assume new particles at TeV scale





SUSY….Our favorite model

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

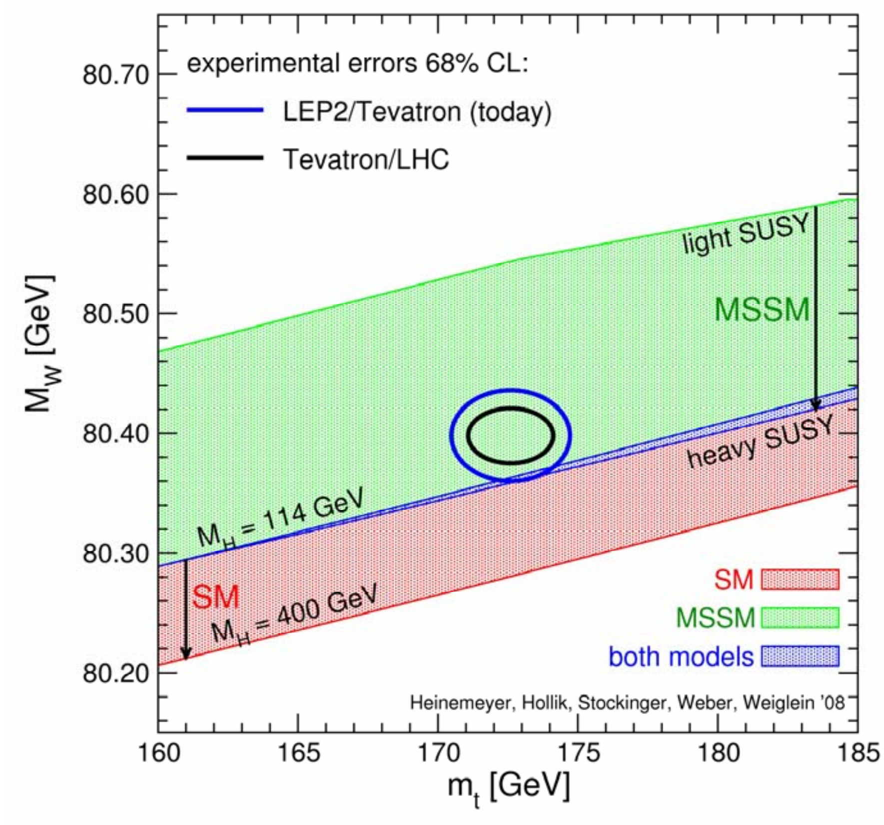


$$\delta M_h^{\;2} \approx (....) G_F \Lambda^2 (M_t^{\;2} - M_{\tilde{t}}^{\;2})$$

- 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 $\Phi_c = i\sigma_2\Phi^*$

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

- 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

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, $M_{H\pm}$

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

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

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

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

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

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

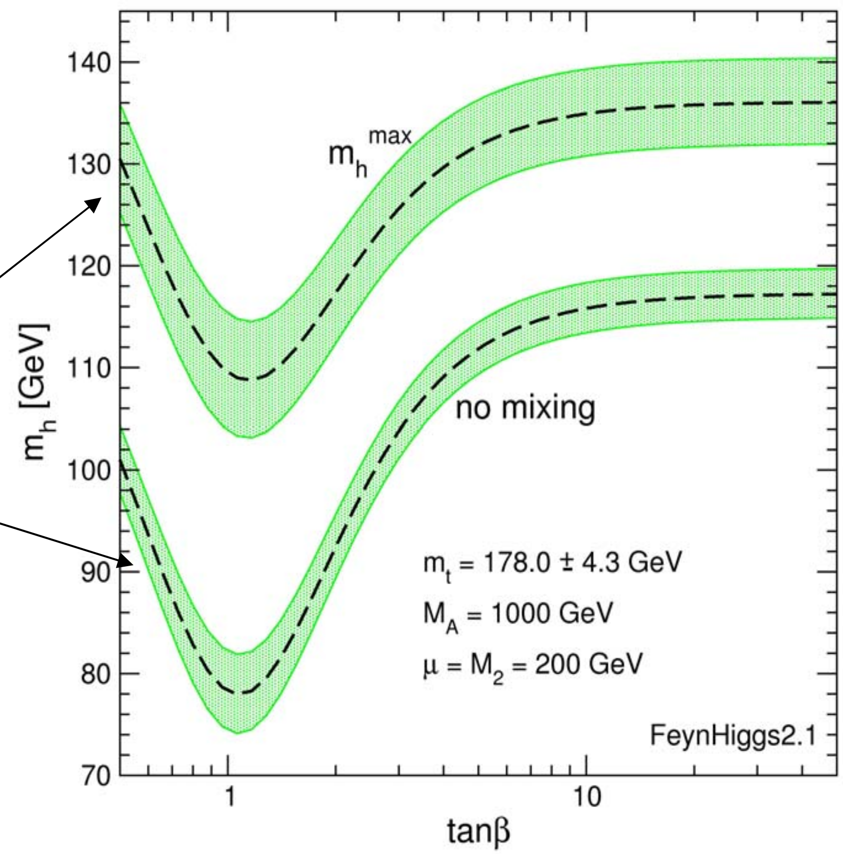
Average stop mass

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

- Stop mass should be TeV scale for naturalness

Theoretical Upper Bound on M_h

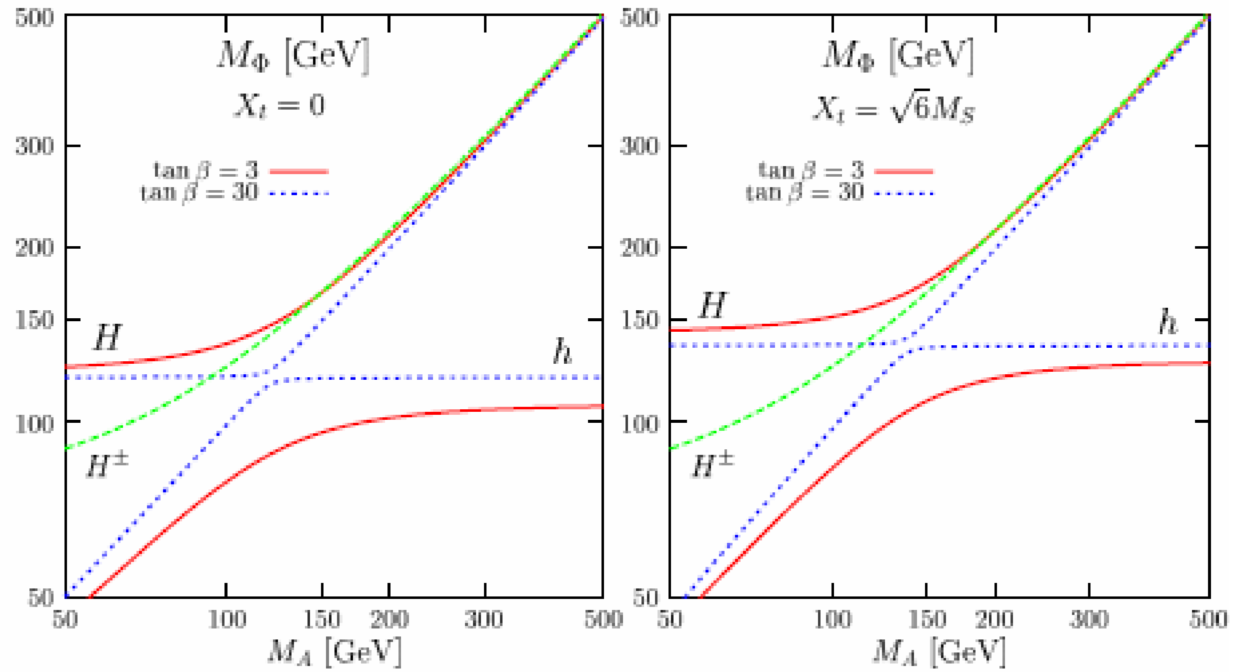
Upper bound on lightest neutral Higgs boson mass with m_{stop} = 1 TeV



- 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

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

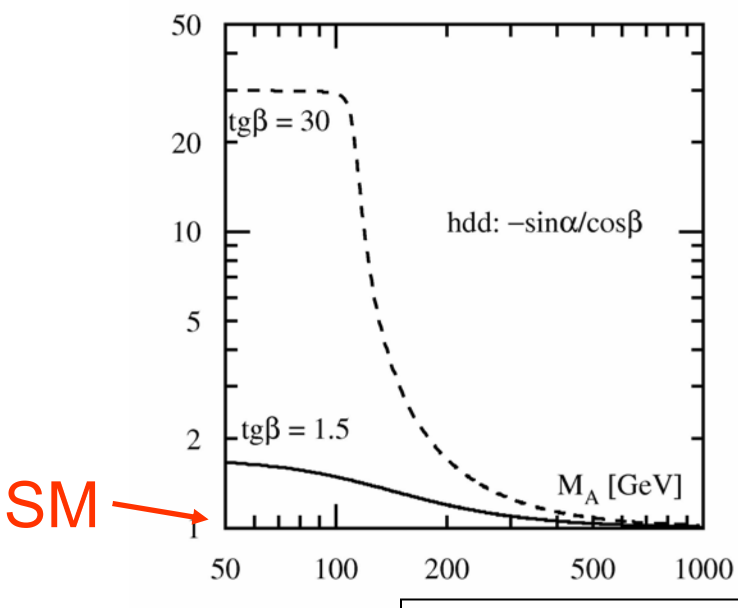
- Couplings given in terms of α, β
- Can be very different from SM
- No new free parameters

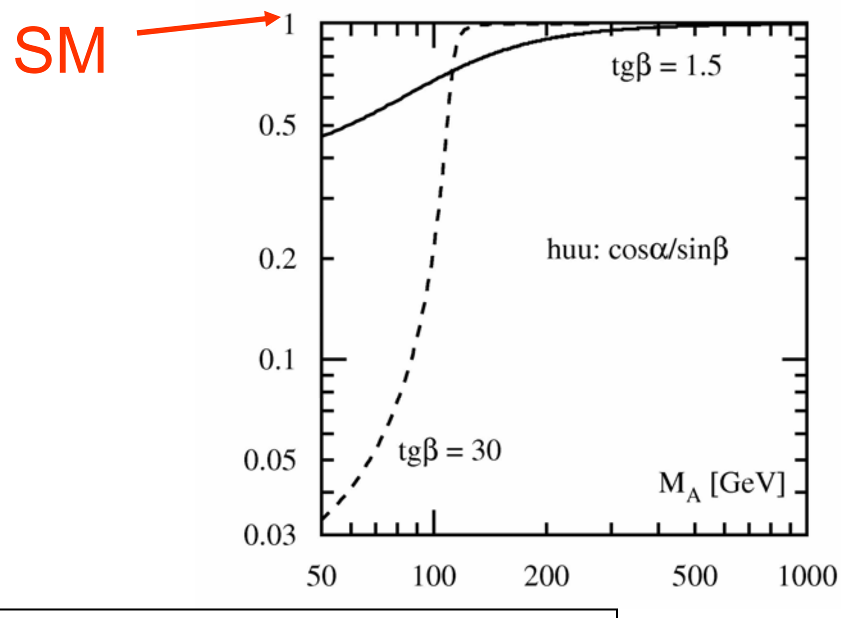
Higgs Couplings Different from SM

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



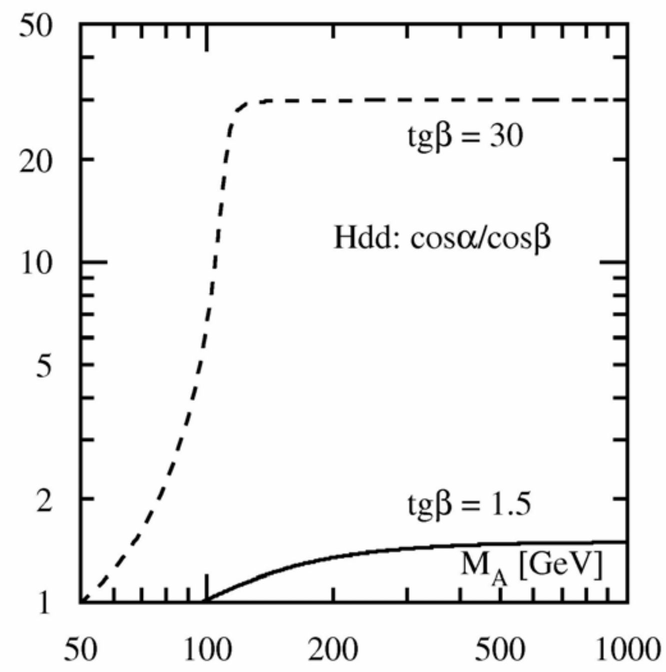


Decoupling limit: For $M_A \to \infty$, h couplings go to SM couplings

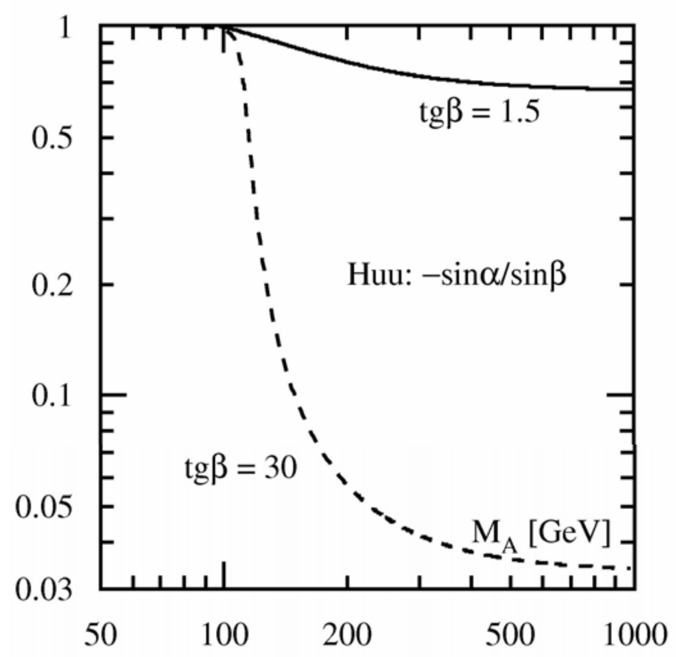
Higgs Couplings in SUSY

Heavier Neutral Higgs, H

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



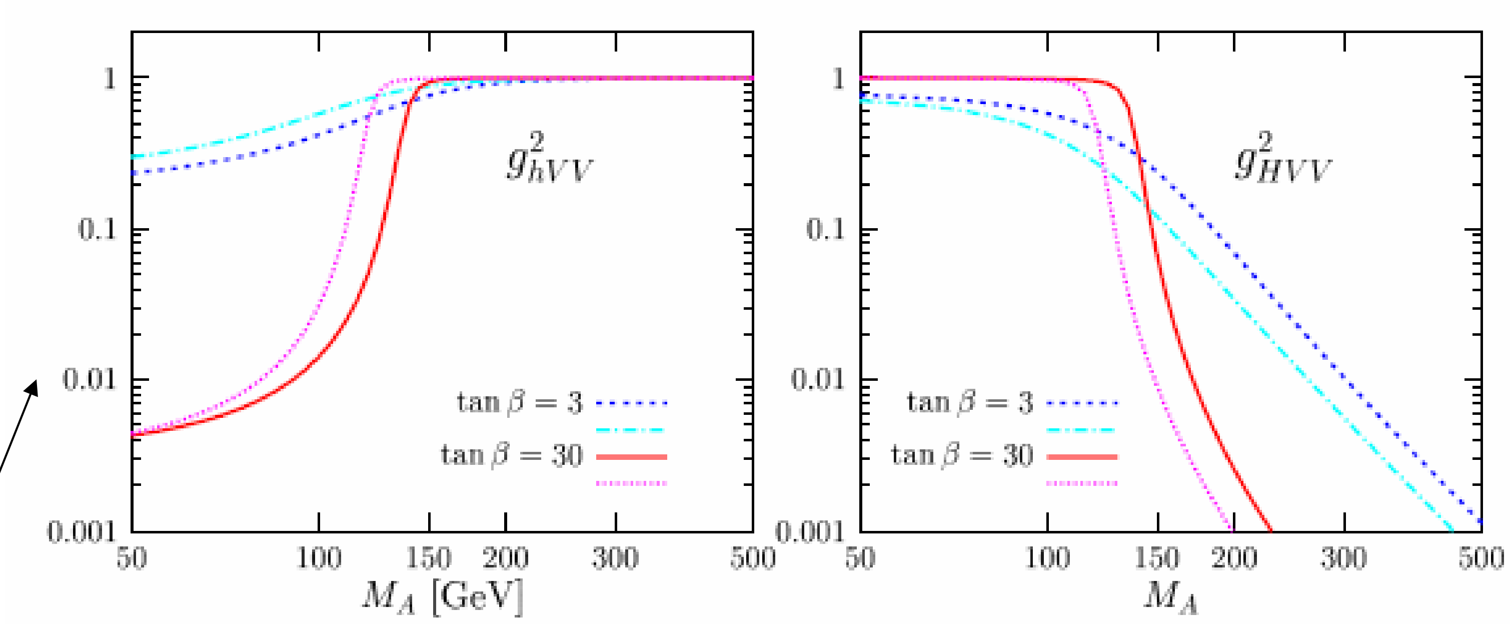
➢Couplings to u, c, t suppressed at large tan β



Gauge Boson Couplings to Higgs

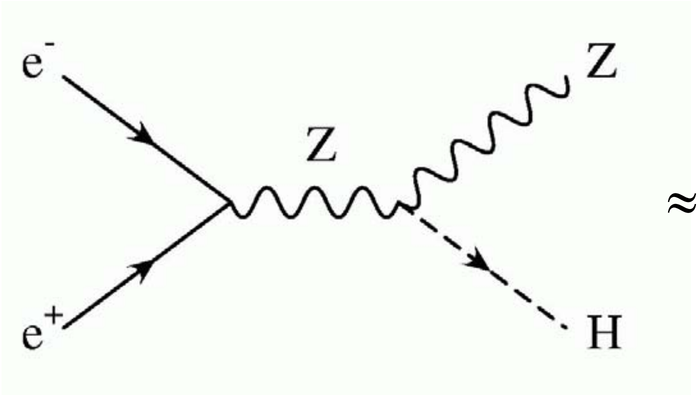
- $g_{hVV}^2 + g_{HVV}^2 = g_{hVV}^2(SM)$
- Vector boson fusion and Wh production always suppressed in MSSM

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



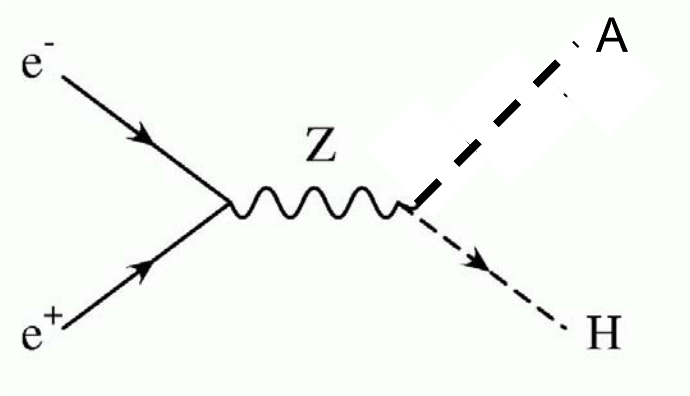
Normalized to SM couplings

Limits from LEP



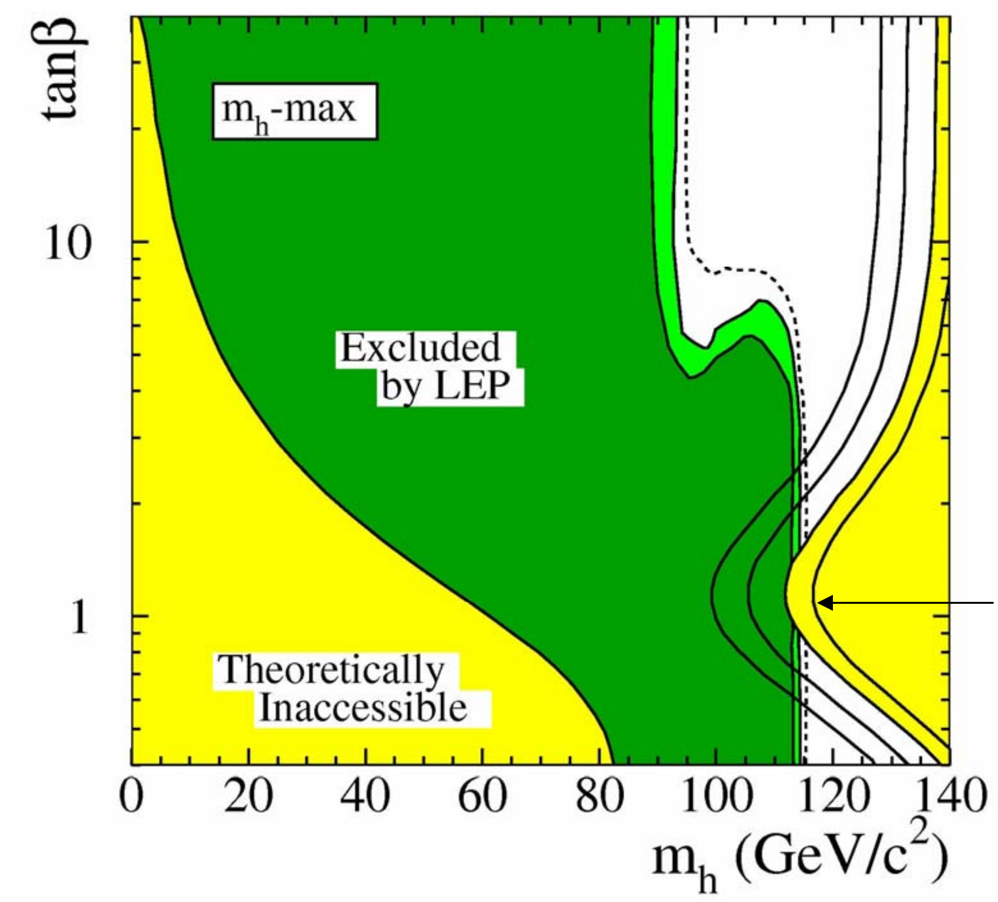
$\approx \cos(\alpha - \beta)$

Complementary processes



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

Limits on SUSY Higgs from LEP

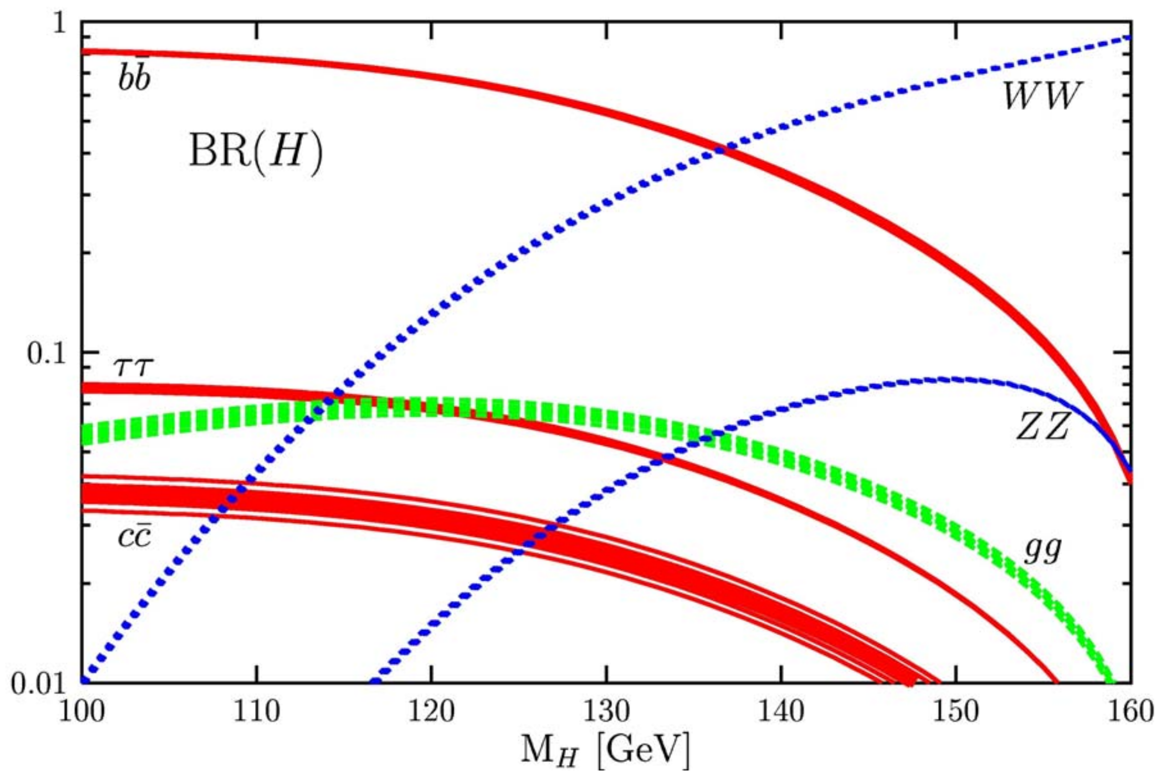


Active work on evading assumptions of this plot!

M_t=169.3,174.3, 179.3, 183 GeV

Remember Higgs Decays in SM

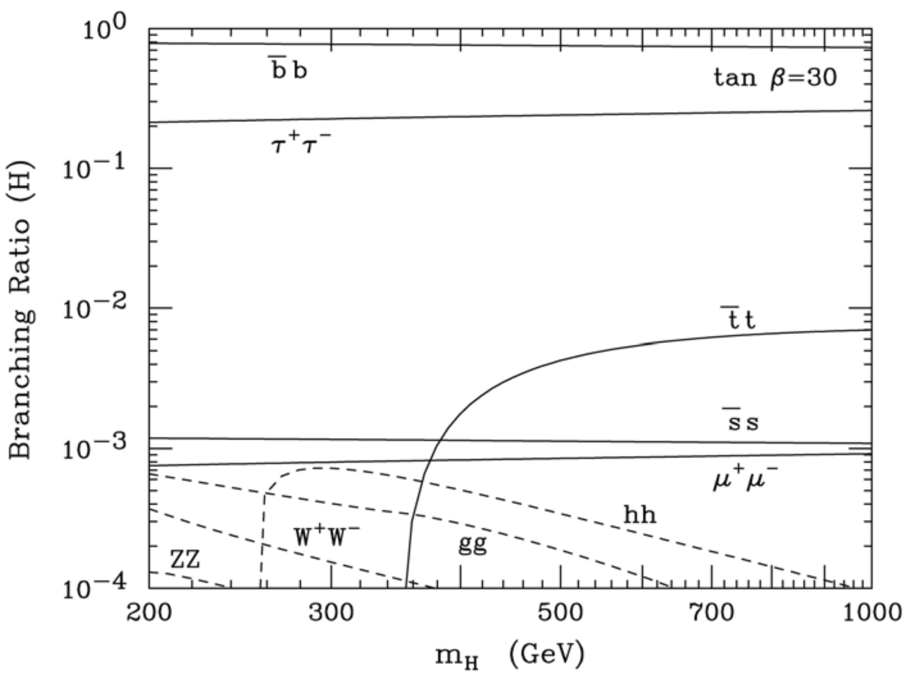
- SM: Higgs branching rates to $b\bar{b}$ and $\tau^+\tau^-$ turn off as rate to W^+W^- turns on (M_h > 160 GeV)



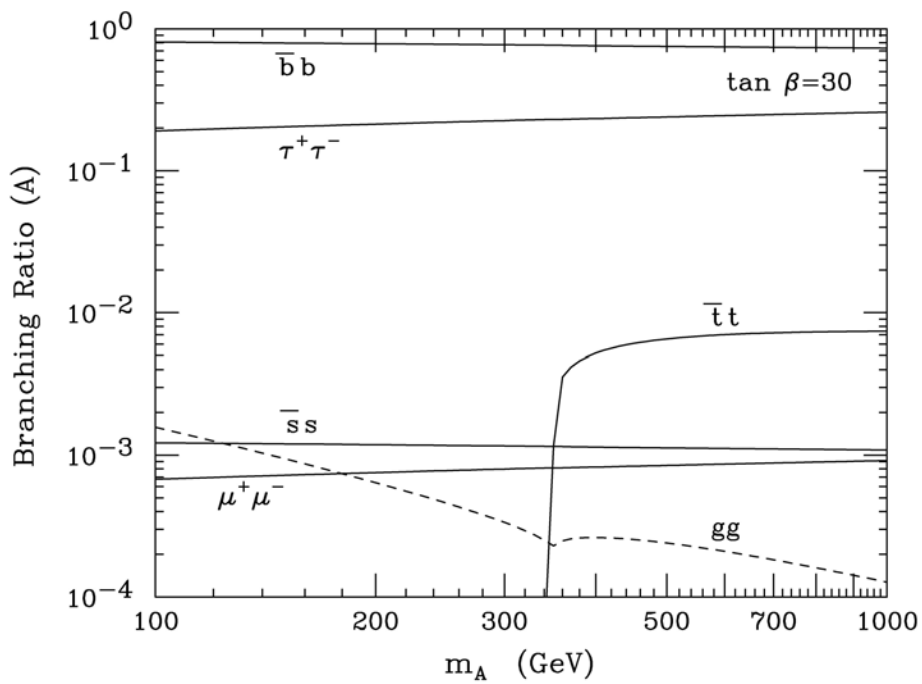
Higgs Decays Changed at Large tan β

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

Heavy H^0 MSSM BRs

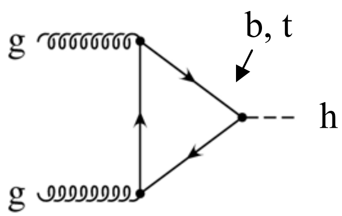


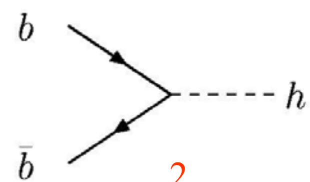
A^0 MSSM BRs



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

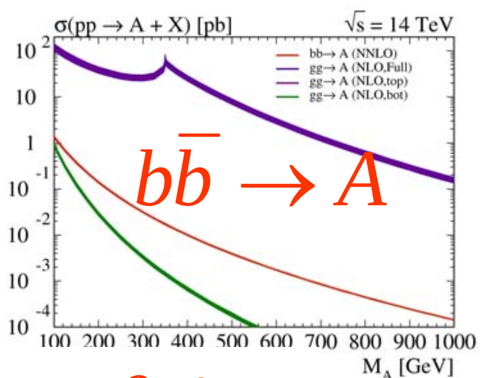
Large tanβ Changes Relative Importance of Production Modes



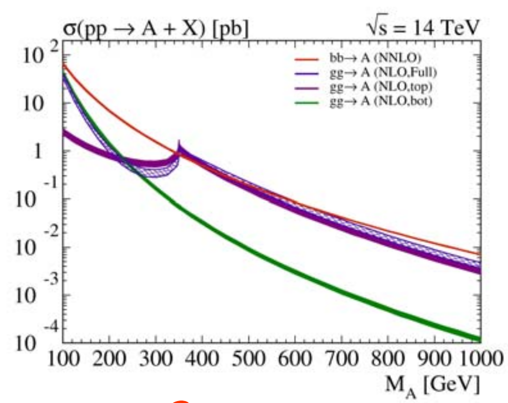


$$\sigma_{gg} = \frac{1}{M_h^2}\left(c_1 \cot^2\beta + c_2 \frac{m_b^2}{M_h^2} + c_3 \frac{m_b^4}{M_h^4}\tan^2\beta\right)$$

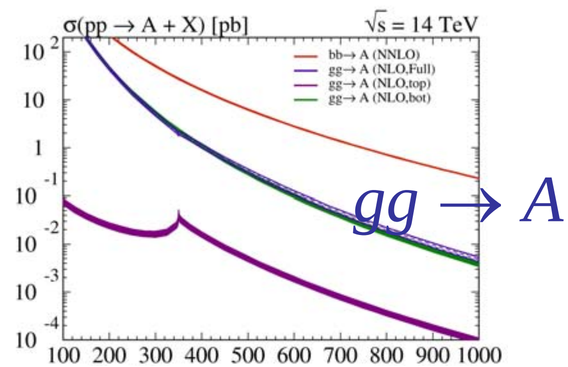
$$\sigma_{bb} = \frac{m_b^2}{M_h^4} c_4 \tan^2\beta$$



tanβ=1



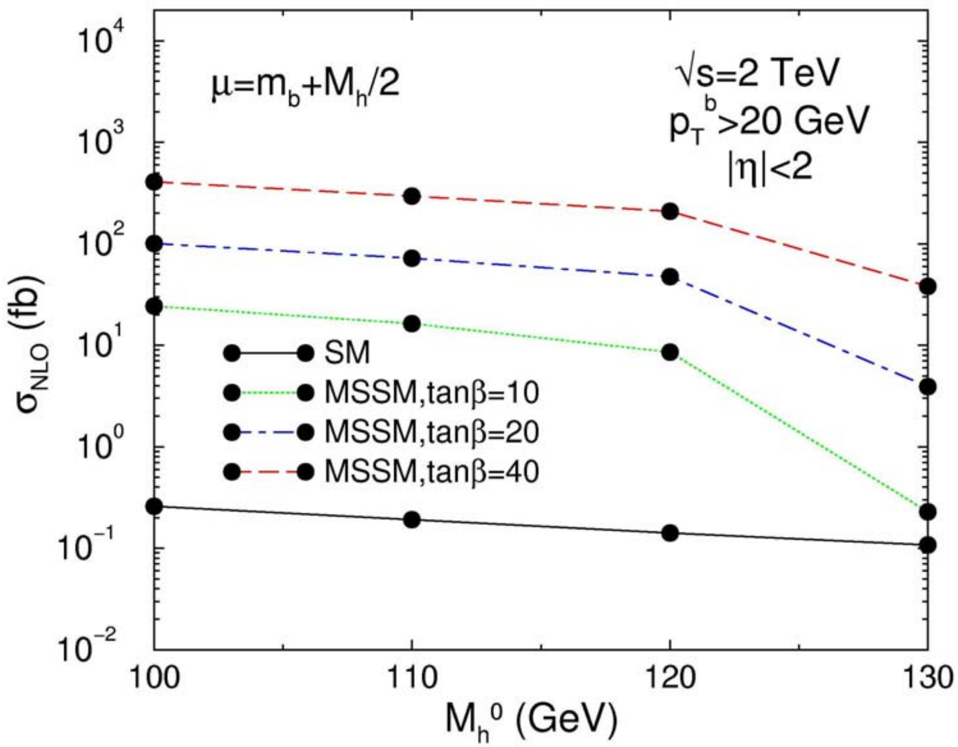
tanβ=7



tanβ=40

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

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

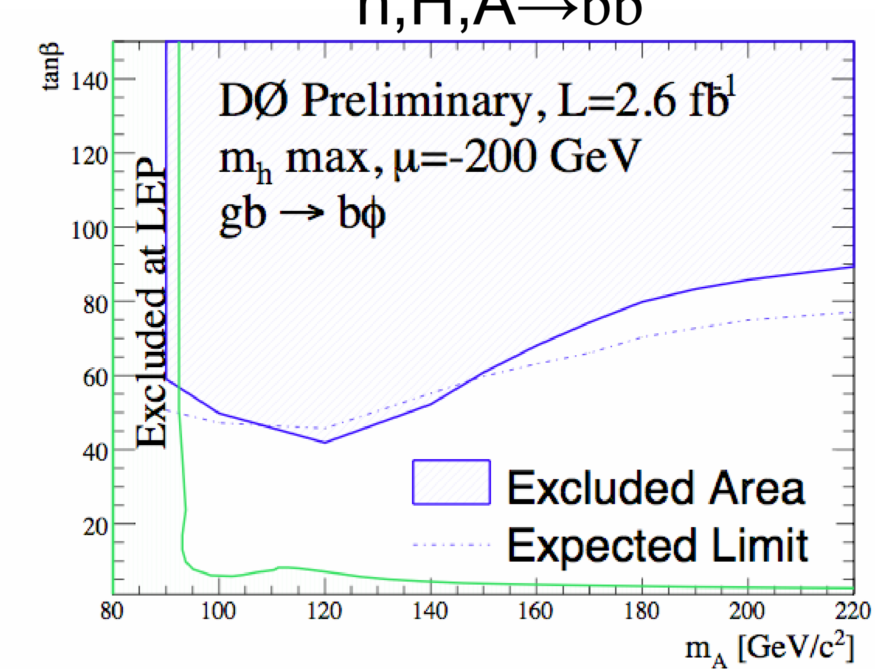


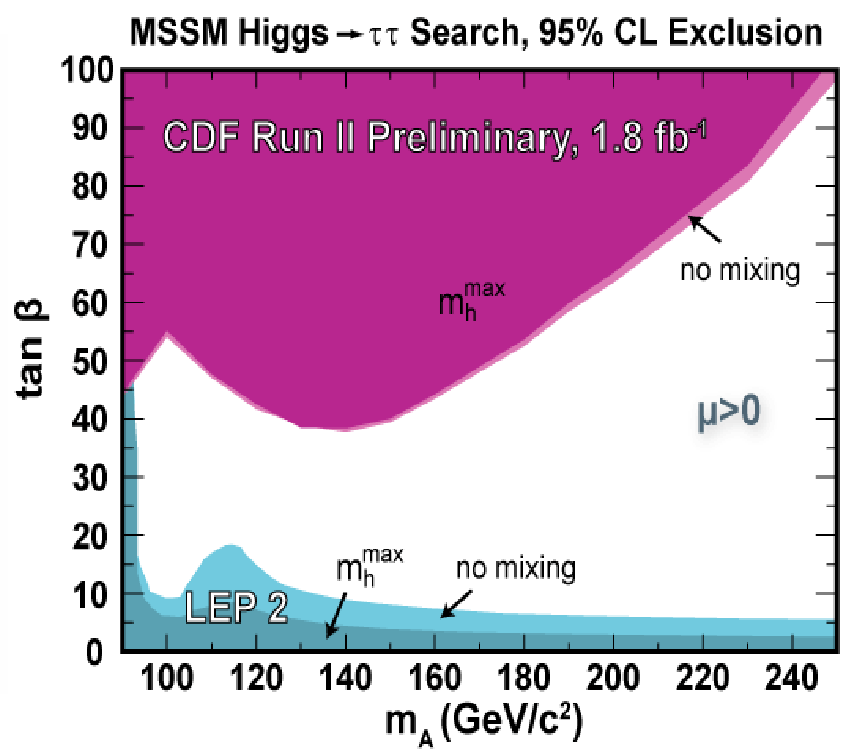
Huge enhancements in SUSY from SM Rate

Couplings/masses with FeynHiggs

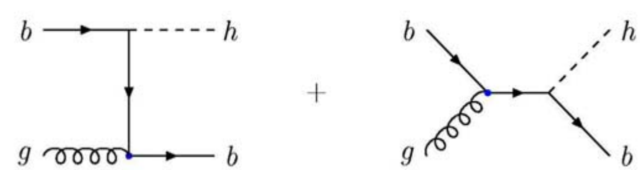
New Higgs Discovery Channels in SUSY

h,H,A→bb



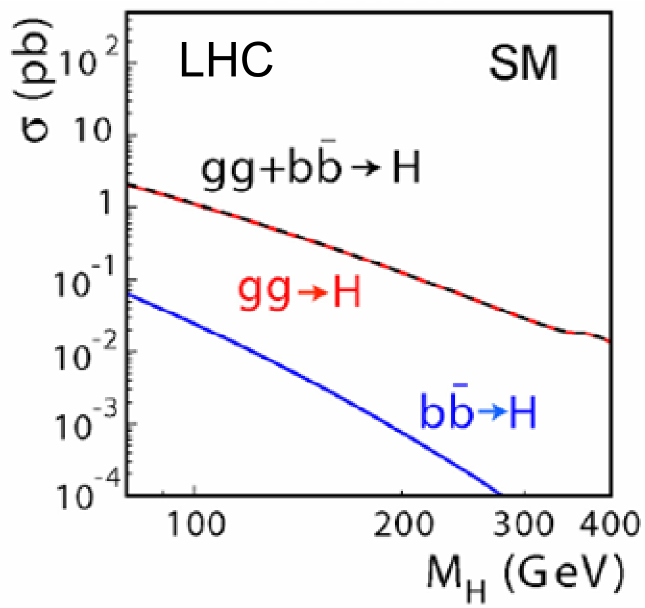


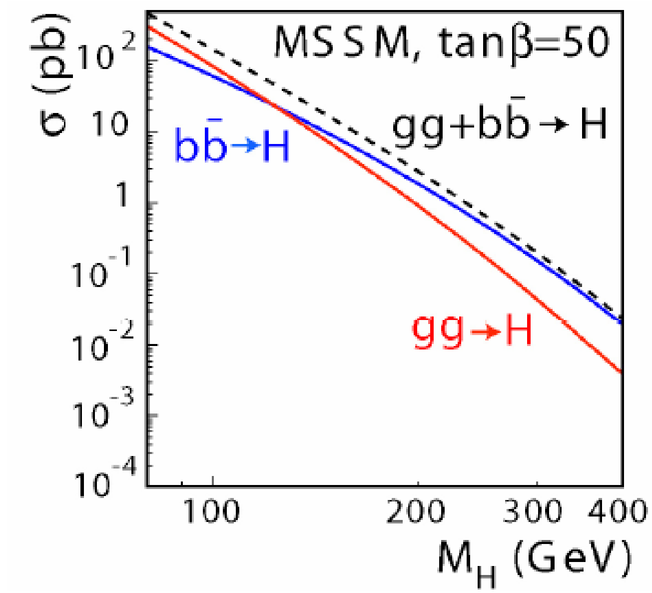
bbφ coupling enhanced for large tanβ



Higgs Production Can be Larger than SM

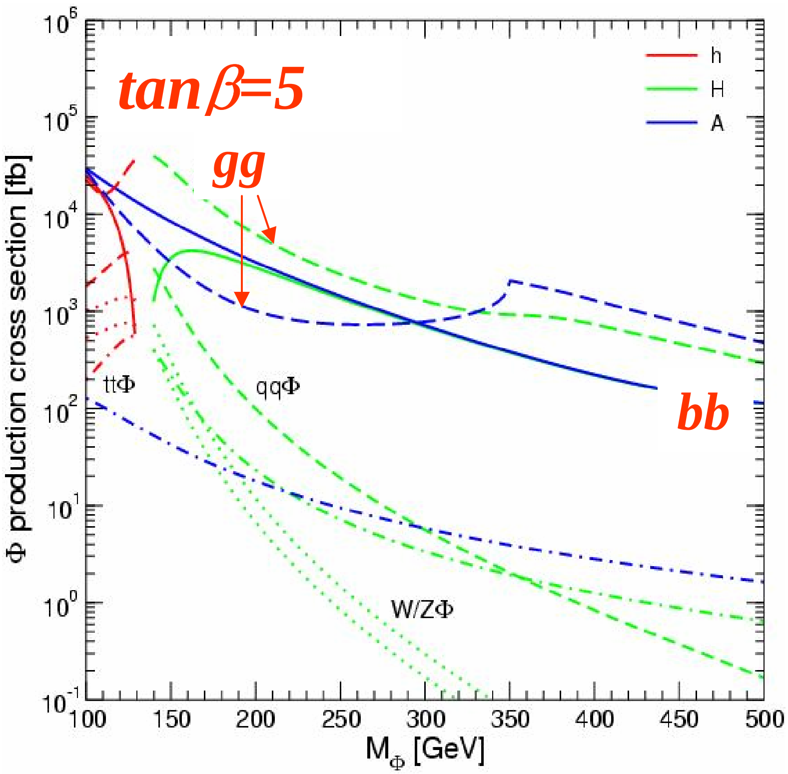
- SUSY Higgs: tanβ enhanced couplings to b and τ for H,A
- Production with b's dominates for large M_H

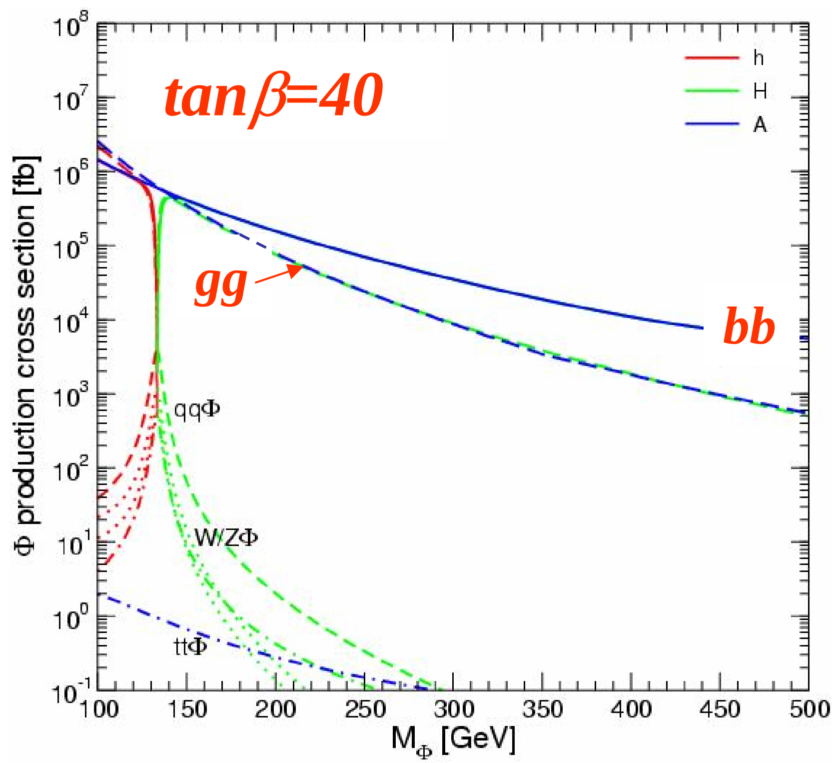




Heavier neutral SUSY Higgs

SUSY Higgs Rates at the LHC



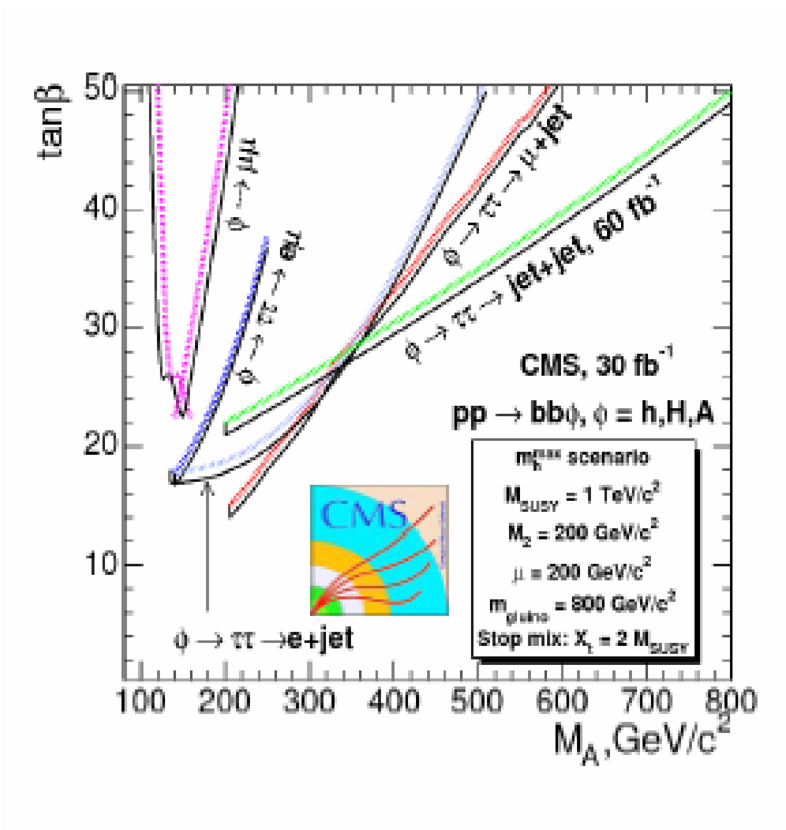


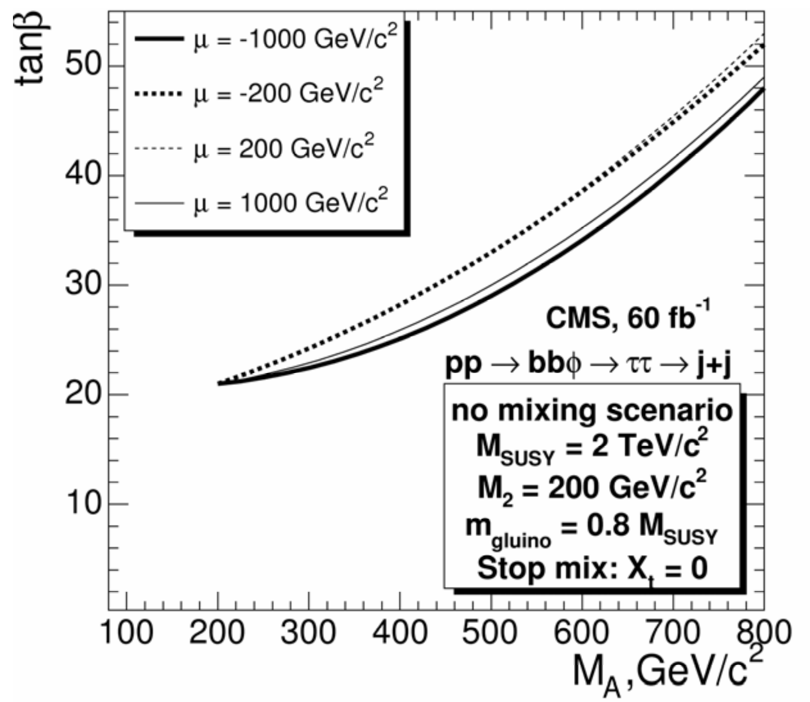
- For large tan β, dominant production mechanism is with b's
- bbH can be 10x's SM Higgs rate in SUSY for large tan β

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

TeV4LHC Report

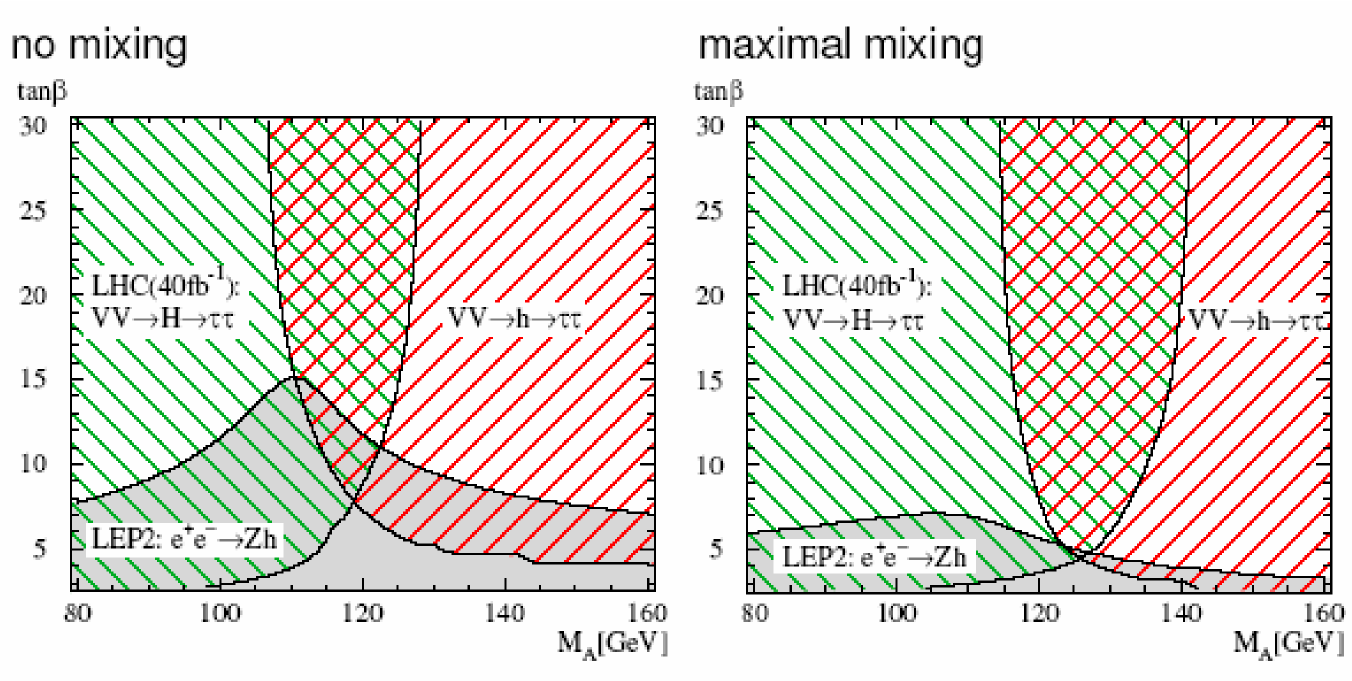
Associated bbH Production at the LHC

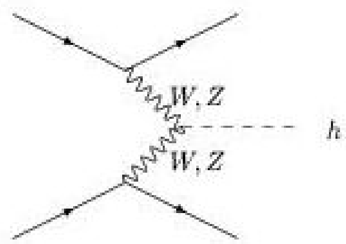




LHC sensitive down to tan β~20-40

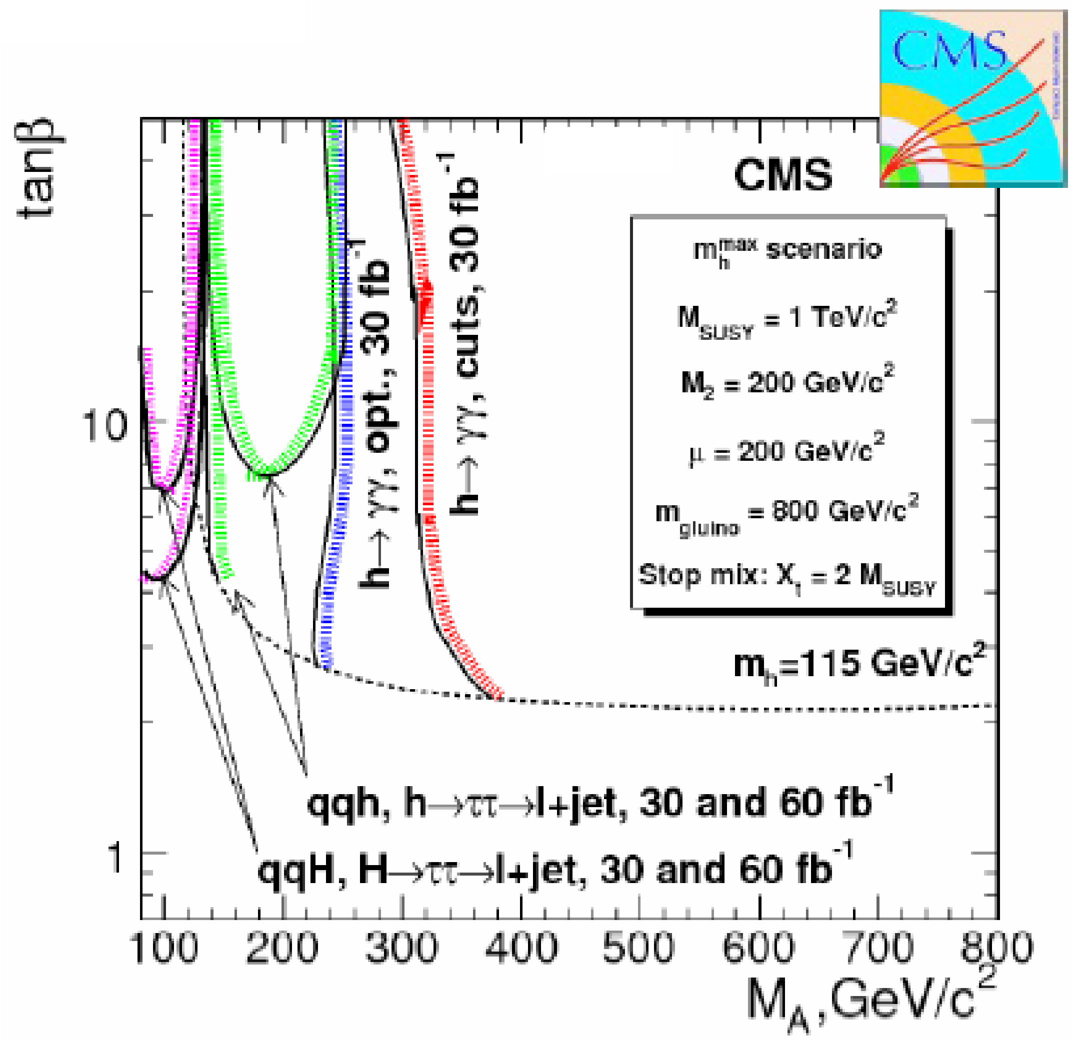
LHC Can Find h and H in Weak Boson Fusion





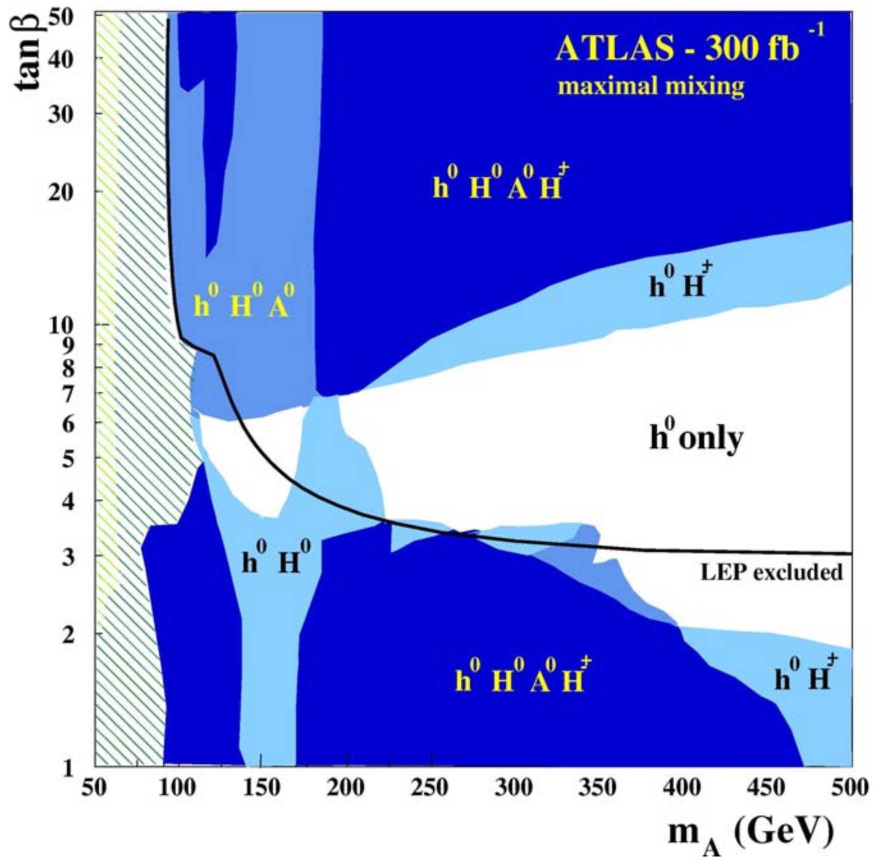
Decays to $\tau^+\tau^-$ needed

SUSY Higgs Searches in γγ Mode



MSSM discovery

- For large fraction of M_A-$\tan\beta$ space, more than one Higgs boson is observable
- For $M_A \rightarrow \infty$, 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

The Higgs and the Dark Side

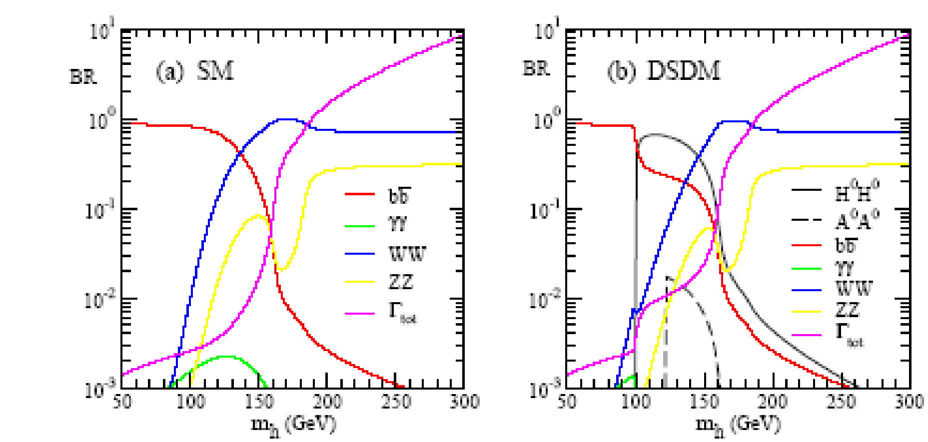
- SM has only 2 dimension 2 scalar operators: $\Phi^+\Phi$, L^+L
- Higgs could provide window to high scale hidden sector

$$L \approx \frac{c_n}{\Lambda^n} \left|\Phi^+\Phi\right| O^{n-2}$$

- Such an operator could be generated by additional Higgs singlets or doublets which couple only to SM Higgs

Singlet/Inert Doublet

- New Higgs mixes with SM Higgs
  - Inert doublet, or 1 singlet, gives 2 neutral Higgs bosons: H, h
  - Construct model so h is light (few GeV) and stable
- New decay: H→hh
- h could be dark matter candidate



Connection between EWSB and dark matter!

Cao, Ma, Rajasekaran, arXiv:0708.2929

No Higgs?

- Remember, Higgs is used to unitarize the SM
- Unitarity violated at 1.7 TeV without a Higgs
  - Cross sections increase with energy
- This sets the scale for something new
- Construct the Standard Model without a Higgs
  - Higgs is only piece we haven’t seen experimentally
  - Model must reduce to the SM at electroweak scales
  - Expand in powers of E^2/Λ^2
  - Derivative expansion

Higgsless Standard Model

Gauge theory: $L = \frac{v^2}{4} Tr\left[D_\mu \Sigma D^\mu \Sigma^+\right] + (kinetic)$

$$D_\mu\Sigma = \partial_\mu\Sigma - igW_\mu\sigma/2 + ig'B_\mu\Sigma\sigma^3/2$$

- Unitary gauge is $\Sigma=1$, $\Sigma=\exp(i\omega\bullet\sigma/v)$
- This is SM with massive gauge bosons and Goldstone bosons, ω
- At $O(E^2/\Lambda^2)$ gauge couplings are identical to those of the SM

Higgsless Standard Model

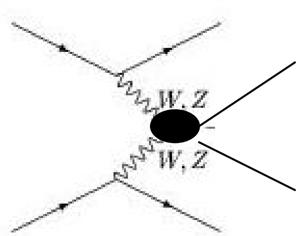
- Add $O(E^4/\Lambda^4)$ operators
  - Contributions from $O(E^2/\Lambda^2)$ operators generate infinities (SM is not renormalizable without Higgs)
  - These infinities absorbed into definitions of $O(E^4/\Lambda^4)$ operators
  - Can do this at every order in the energy expansion
- Coefficients are unknown but limited by precision measurements
  - A particular model of high scale physics will predict these coefficients
- The $O(E^4/\Lambda^4)$ terms will change 3 and 4 gauge boson interactions

WW Scattering without a Higgs

- Add terms of $O(E^4/\Lambda^4)$ to effective L

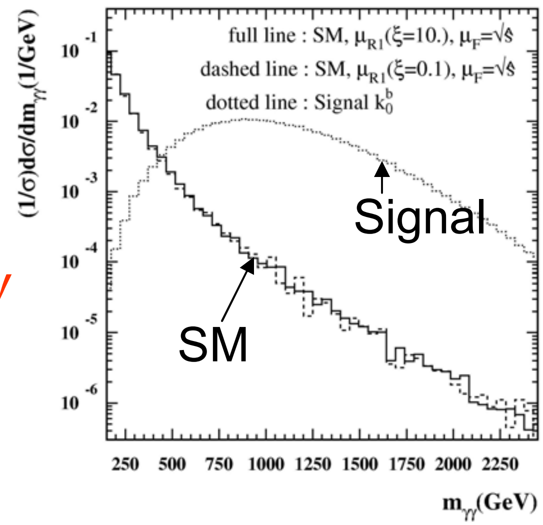
$$L = ... + L_1\left(Tr\left(D_\mu \Sigma D^\mu \Sigma^+\right)\right)^2 + L_2\left(Tr\left(D_\nu \Sigma D^\nu \Sigma^+\right)\right)^2 + ...$$

  - This Lagrangian violates unitarity
- This is counting experiment (no resonance)
  - Example: Search for anomalous $WW\gamma\gamma$ vertex through gauge boson fusion



Hard!

LHC

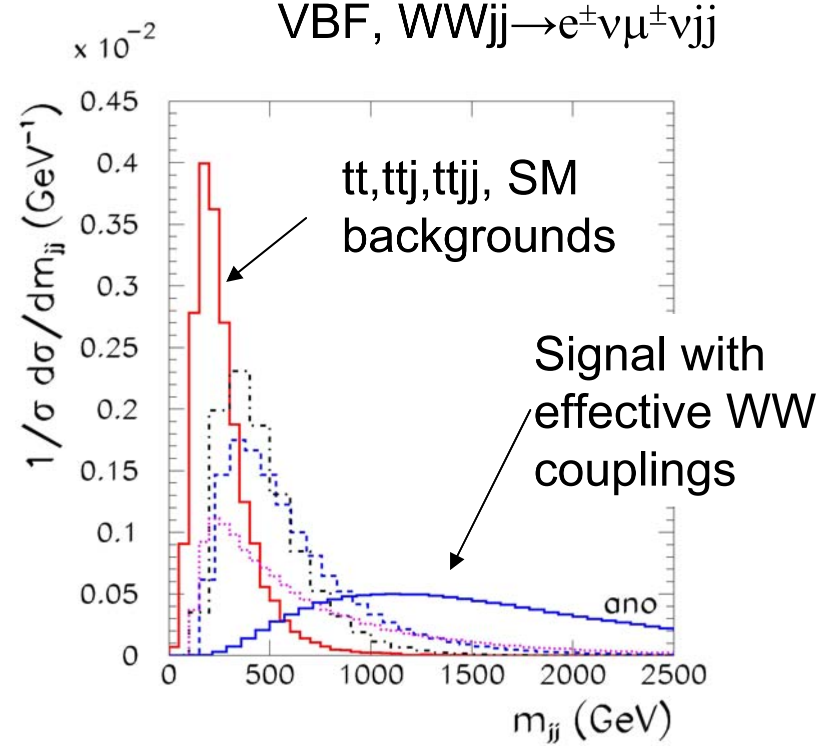


Normalized to show difference in shape of signal and background

Eboli et al, hep-ph/0310141

No light Higgs/No KK particles/No techni-ρ Scenario

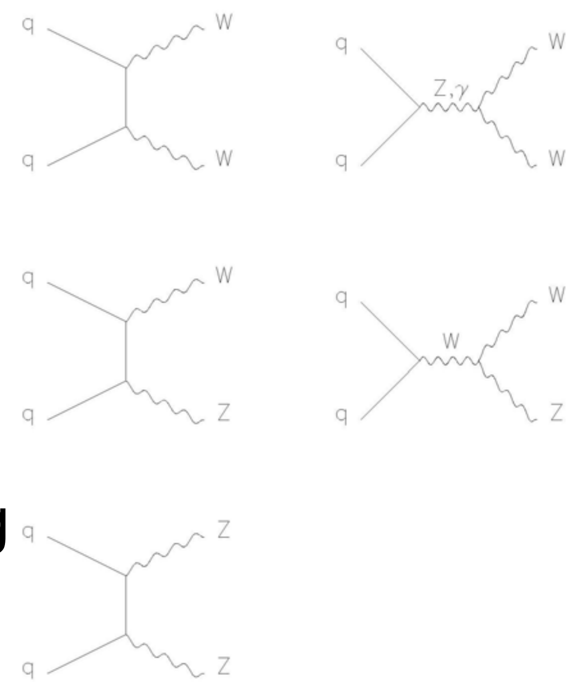
- No resonance
  - Effective Lagrangian couplings grow with energy
- Counting experiments
- Very hard!



Eboli, Gonzales-Garcia, Mizukoshi, hep-ph/0606118, Zeppenfeld et al

Gauge Boson Pair Production

- W^+W^-, $W^\pm\gamma$, etc, production sensitive to new physics
- Expect effects which grow with energy
  - $A_t \sim (\ldots)(s/v^2)+O(1)$
  - $A_s \sim -(\ldots)(s/v^2)+O(1)$
  - $\sigma_{TOT} \sim O(1)$
- Interesting angular correlations: eg $W^\pm\gamma$, has radiation zero at LO



Non-SM 3 gauge boson couplings spoil unitarity cancellation

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