Exploring the Higgs Sector (Beyond the SM)

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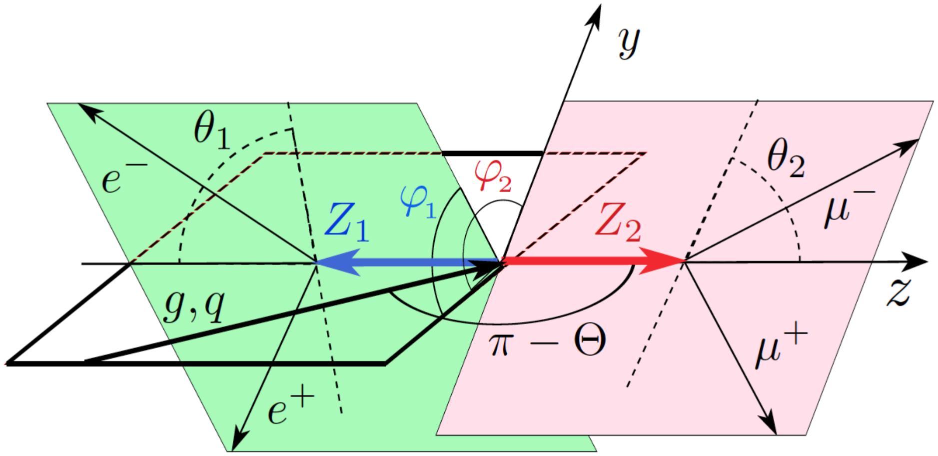
Fermilab, 2012

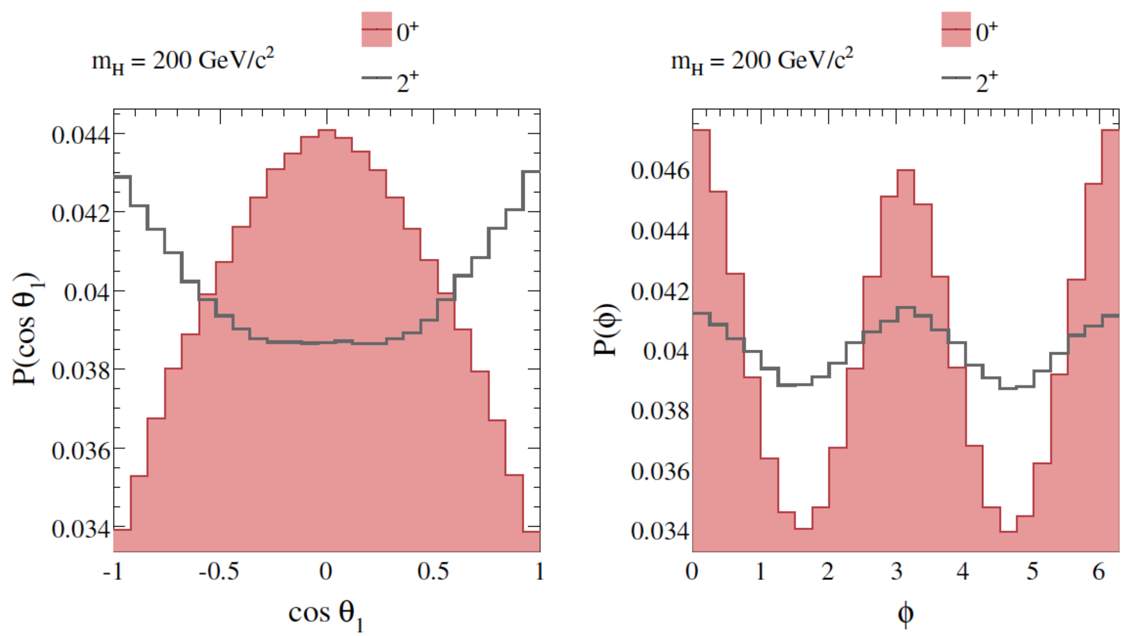
Lecture 4

Many, many possibilities

Reprise on spin



$H \rightarrow ZZ \rightarrow l^+l^- \, l^+ \, l^-$



[Lykken]

Is the Standard Model Self-Consistent?

- M_h is a free parameter in the Standard Model
- Can we derive limits on the basis of consistency?
- Consider a scalar potential:

$$V = \frac{M_h^2}{2} h^2 + \frac{\lambda}{4} h^4$$

- This is potential at electroweak scale
- Parameters evolve with energy in a calculable way

Standard Model: $\lambda = M_h^2/(2v^2) = .13$ for $M_h = 125$ GeV

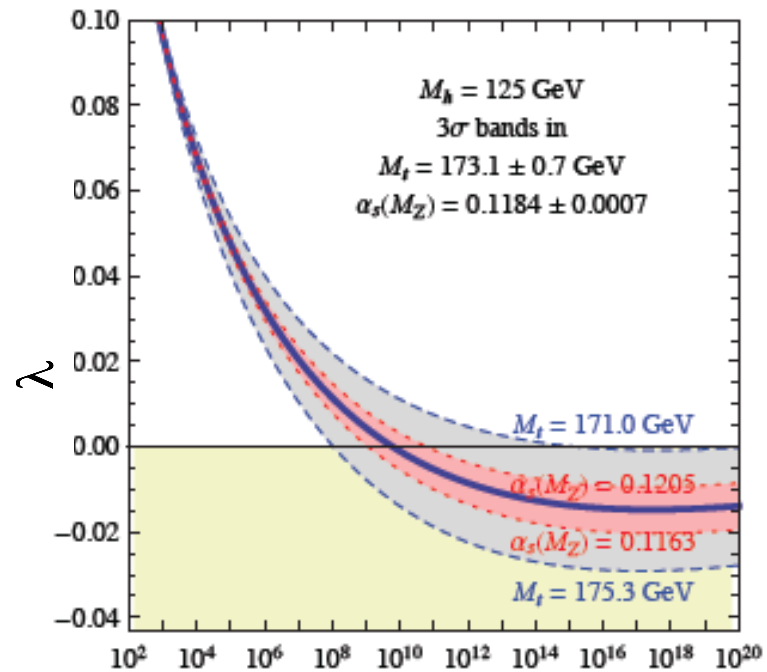
Perturbative Regime

Does Spontaneous Symmetry Breaking Happen?

- $\lambda(\Lambda) > 0$ gives lower bound on M_h

$$M_h^2 > \frac{3v^2}{2\pi^2} g_t^2 \log\left(\frac{\Lambda^2}{v^2}\right)$$

- For any given M_h, there is an upper bound on Λ



Λ [GeV]

This is very sensitive to M_h

[DeGrassi et al, 1205.6497]

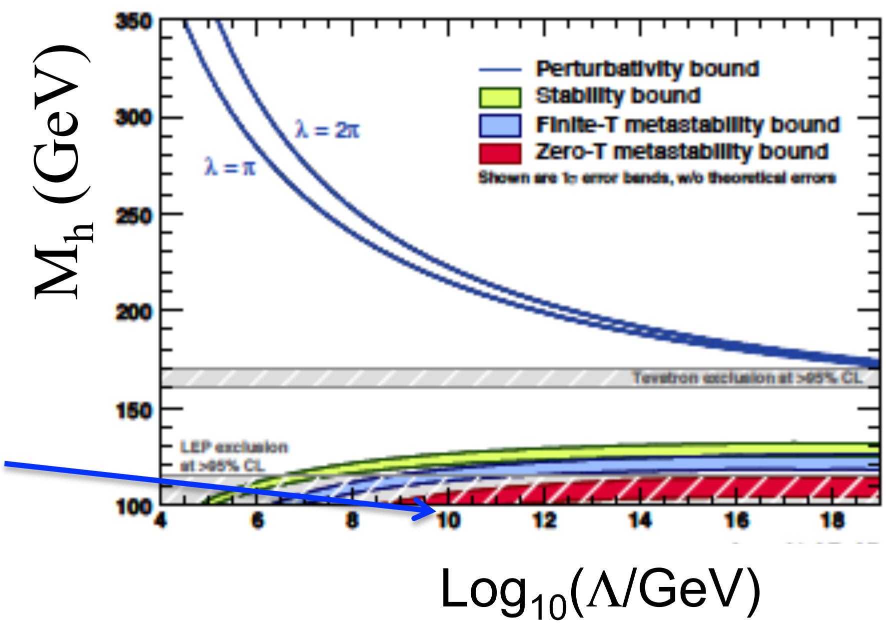
Don’t want λ to be infinite

- Point where $\lambda \rightarrow \infty$ called Landau pole
- Without λh^4 interactions, theory is non-interacting
- Require quartic coupling be finite gives upper bound

$$\frac{1}{\lambda(\Lambda)} > 0$$

$$M_h^2 < \frac{32\pi^2 v^2}{9\log\left(\frac{\Lambda^2}{v^2}\right)}$$

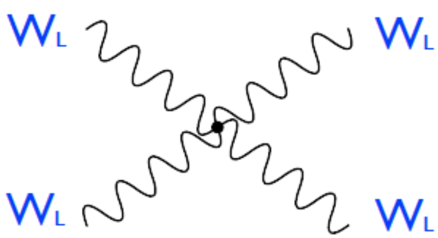
Maybe vacuum can be unstable if lifetime is longer than lifetime of the universe



[Ellis,0906.0954]

Does WW Scattering Make sense?

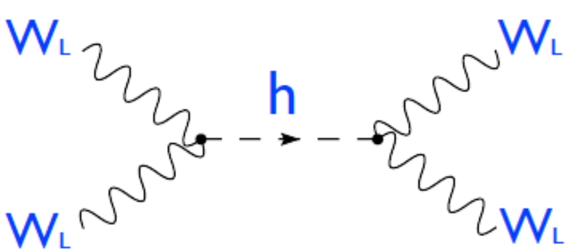
- Without a Higgs



$$\sigma \sim \frac{s}{v^4}$$

Not a sensible theory!

- With a Higgs



σ finite at high energy

Higgs plays a special role

- Consider $2 \rightarrow 2$ particle elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|A|^2$$

- Partial wave decomposition of amplitude

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

- a_l are the spin *l* partial waves

Optical theorem requires: $|\mathrm{Re}(a_l)| \leq \frac{1}{2}$

UNITARITY CONSTRAINT

Use Unitarity to Bound Higgs

$W^+W^- \rightarrow W^+W^-$

- High energy limit:

$$a_0^0 \rightarrow -\frac{M_h^2}{8\pi v^2} \Rightarrow M_h < 800 \text{ GeV}$$

- Heavy Higgs limit:

$$a_0^0 \rightarrow -\frac{s}{32\pi v^2} \Rightarrow$$

$E_c \sim 1.7$ TeV

→ New physics at the TeV scale

Light Higgs Boson makes
Standard Model consistent

Problems with the Higgs Mechanism

- We often say that the Standard Model cannot be the entire story because of the quadratic divergences of the Higgs Boson mass

- But don't we just renormalize the mass using dimensional regularization ????

- Should experimentalists care about this?

Motivation for physics beyond the Standard Model

Renormalized Fermion Mass

- Renormalization of fermion mass:

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

Fermion mass renormalization is logarithmic

$\delta m_F \approx m_F$

- $m_F \rightarrow 0$ increases the symmetry of the theory
- Yukawa coupling (proportional to mass) breaks symmetry and so corrections $\approx m_F$

Scalars are very different

$$\delta M_h^2 = -\frac{\lambda_F^2 \Lambda^2}{8\pi^2} + \left(m_s^2 - m_F^2\right)\log\left(\frac{\Lambda}{m_F}\right) + \ldots.$$

M_h has quadratic sensitivity to high mass scales

$M_h \rightarrow 0$ doesn't increase symmetry of theory

Nothing protects Higgs mass from large corrections

What’s the problem?

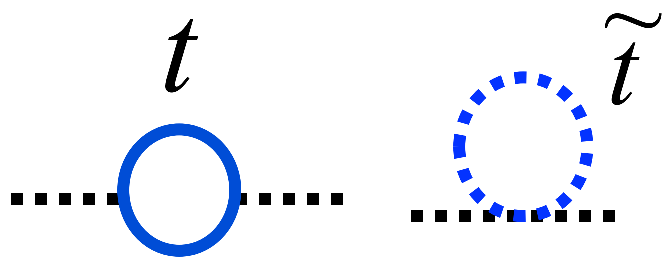
- Compute M_h in dimensional regularization and absorb infinities into definition of M_h

$$M_h^2 = M_{h0}^2 + \frac{1}{\varepsilon}(\ldots)$$

- Perfectly valid approach
- Except we know there is a high scale

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



- Stop mass should be TeV scale*

* Not an exact statement

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

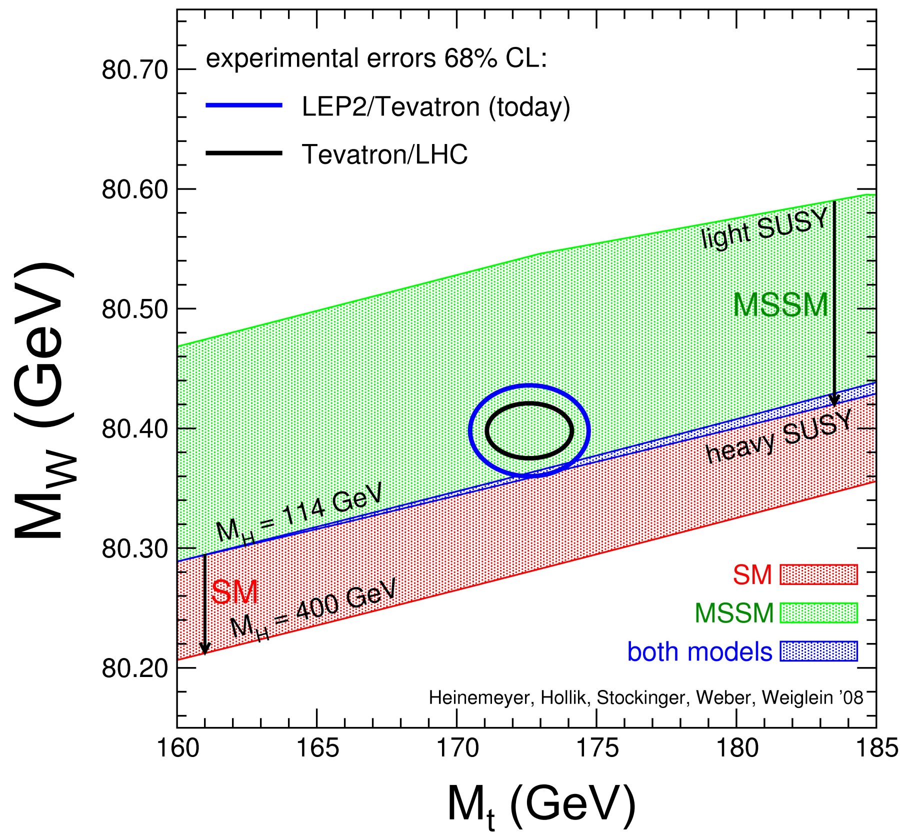
SUSY must be a broken symmetry

Supersymmetric Theories

- Predict many new undiscovered particles (>29!)
- Very predictive models
  - Can calculate particle interactions 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

Supersymmetry (MSSM version)

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



Fermion Masses

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

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

- 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

Two Higgs Doublet Models

- 8 degrees of freedom
- 3 form $W_L^{\pm}$, Z_L
- 5 physical Higgs bosons
  - h^0, H^0, A^0, $H^{\pm}$

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

Gives up quark mass

Gives down quark mass

General 2 Higgs Doublet Model

- 6 free parameters, plus a phase

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

- 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

$$H_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \qquad H_1 = \begin{pmatrix} \varphi_1^{0*} \\ -\varphi_1^- \end{pmatrix}$$

- Couplings fixed by supersymmetry

- H_1 has Y=-1/2, H_2 has Y=+1/2 [$Q_{em}=(T_3+Y)/2$]

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

V is positive definite: minimum at <V>=<H_1>=<H_2>=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

EWSB and SUSY Models

- Electroweak symmetry broken by vevs

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

- 5 Physical Higgs bosons, h^0, H^0, $H^{\pm}$, A^0
- W gets mass, $M_W^2 = g^2(v_1^2 + v_2^2)/2$
- 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!

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

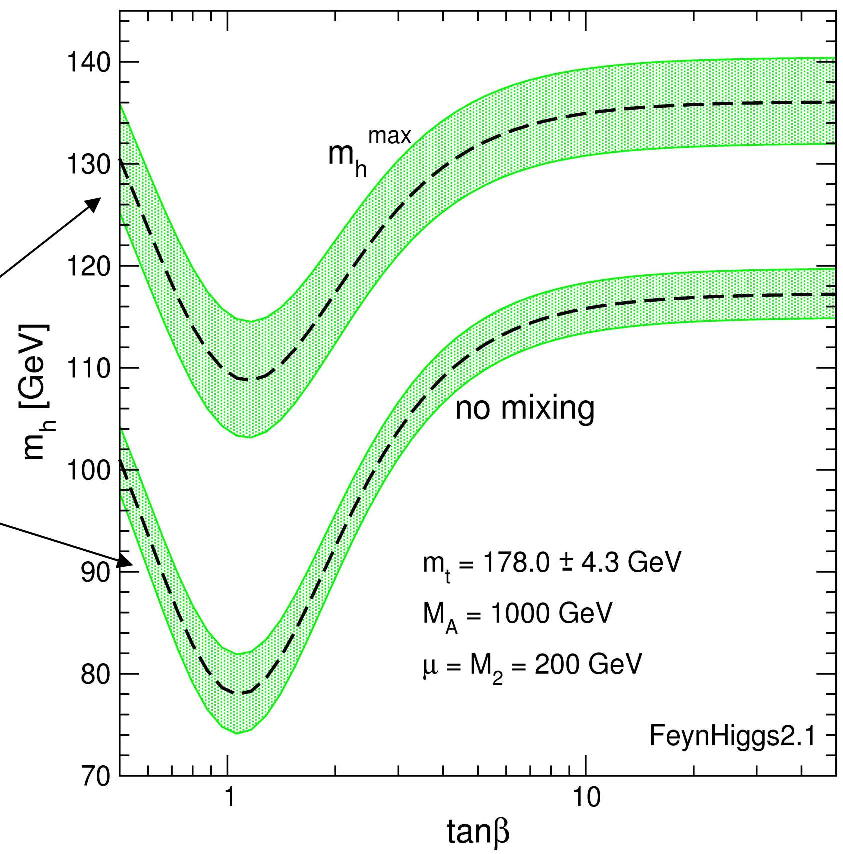
$$M_h^2 \le M_Z^2 \cos^2 2\beta + \frac{3 G_F m_t^4}{\sqrt{2}\pi^2 \sin^2\beta} \ln\left[\frac{\tilde{m}_t^2}{m_t^2}\right]$$

- Stop mass should be TeV scale for naturalness

MSSM predicts a light Higgs boson!!!

Theoretical Upper Bound on M_h

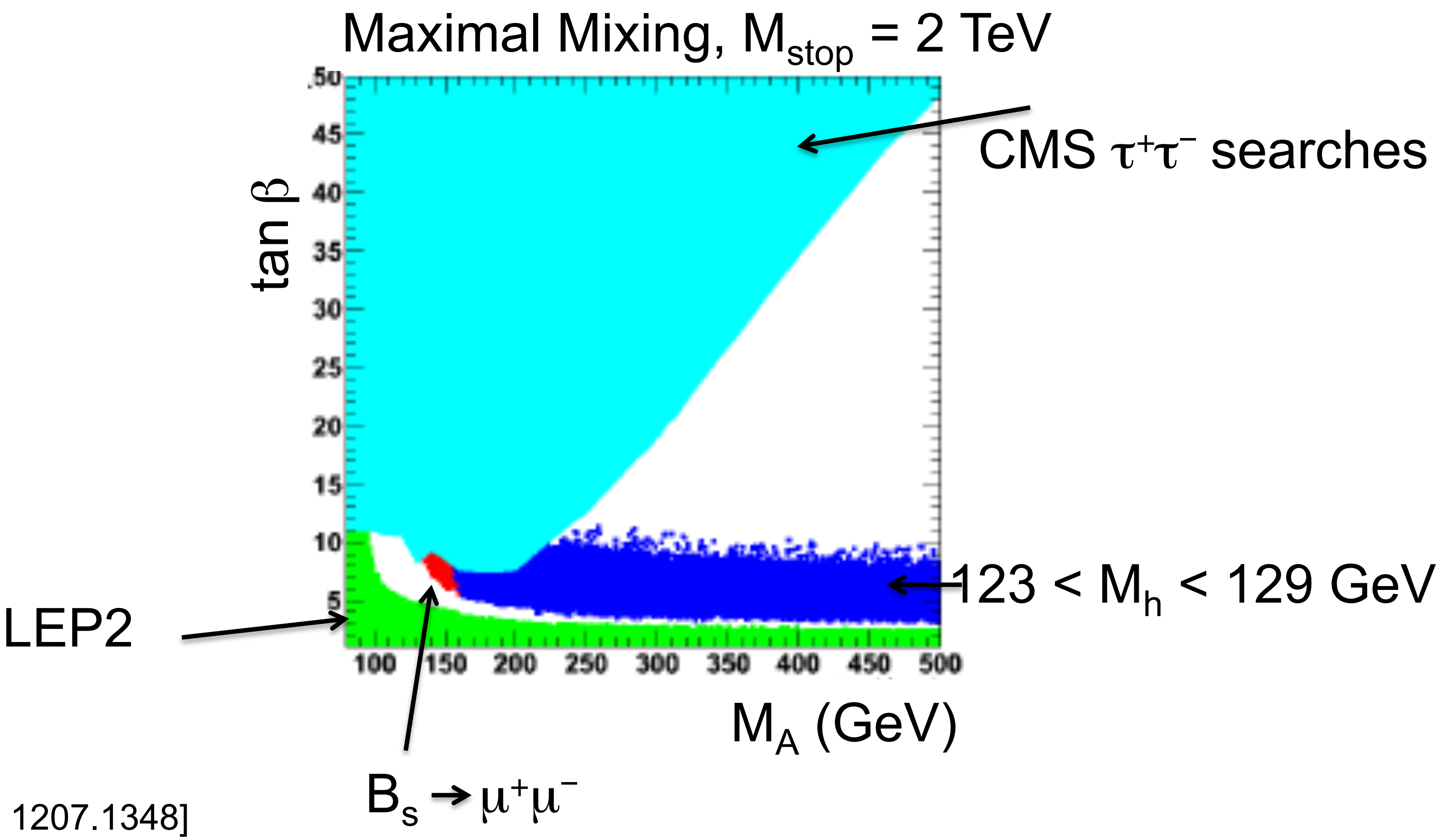
Upper bound on lightest neutral Higgs boson mass with m_{stop} = 1 TeV



- M_t^4 enhancement
- Logarithmic dependence on stop mass

Now that we've found M_h=125 GeV….

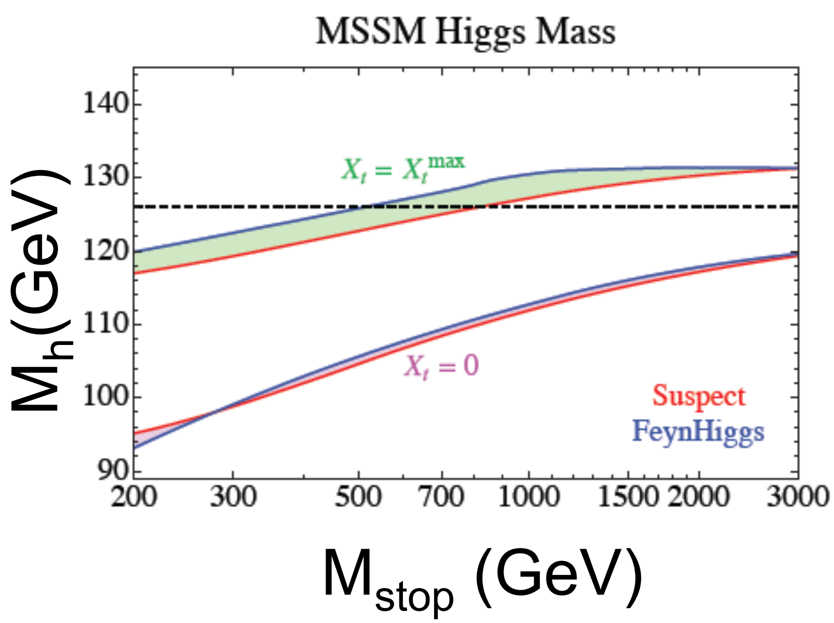
- Maybe very heavy stops?
- Parameter space becomes quite restricted

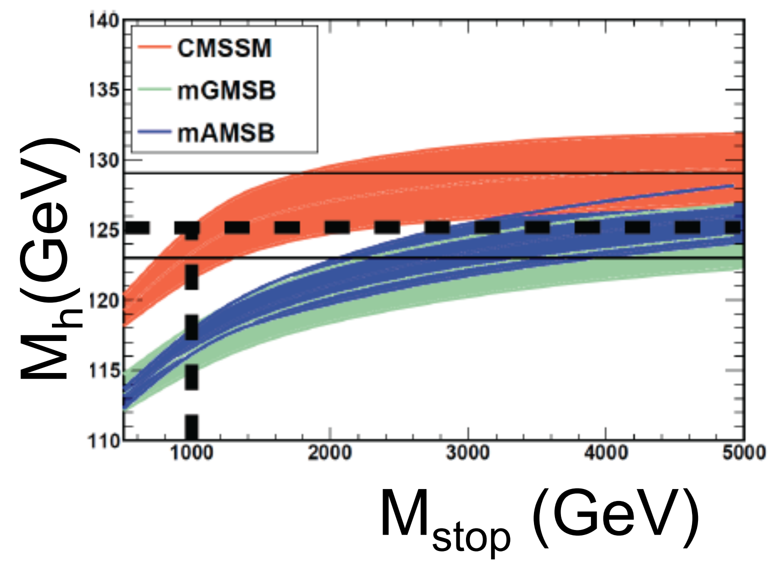


[Arbey, 1207.1348]

SUSY is being Squeezed

- Need large stop masses or large SUSY breaking trilinear couplings to get M_h=125 GeV

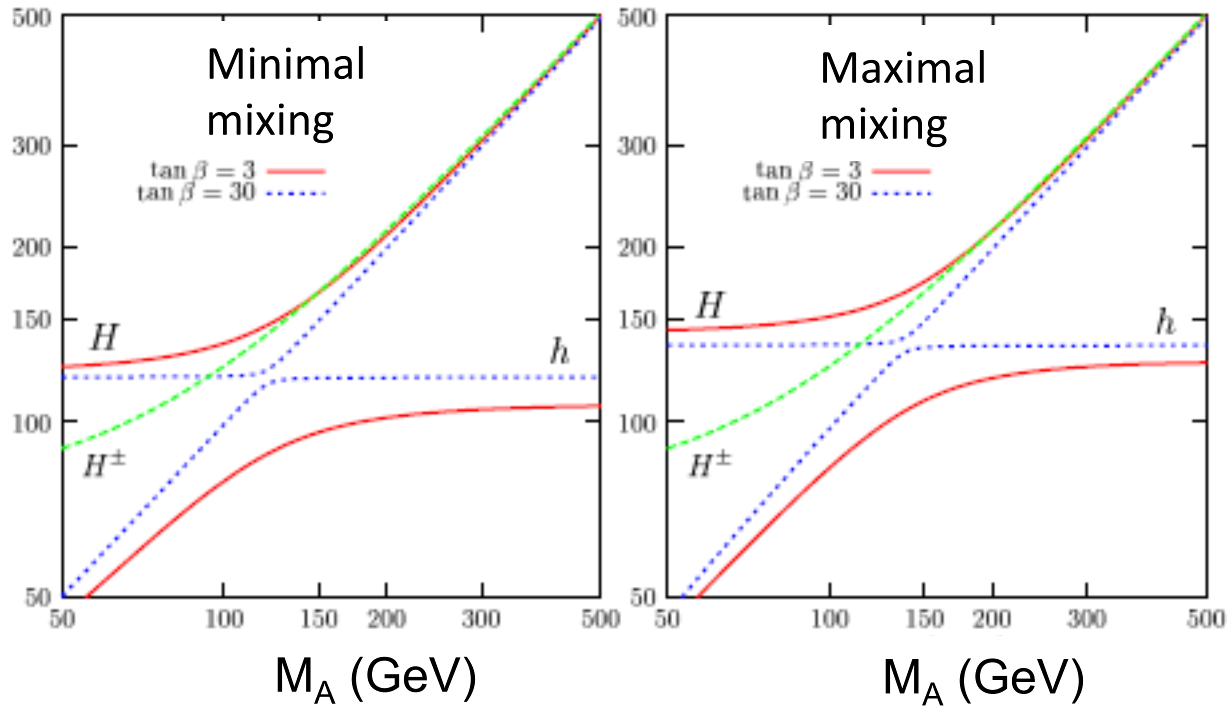




[Pomarol]

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

[Spira]

Find Higgs Couplings

- Higgs-fermion couplings:

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

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

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

α is angle that diagonalizes neutral Higgs mixing matrix

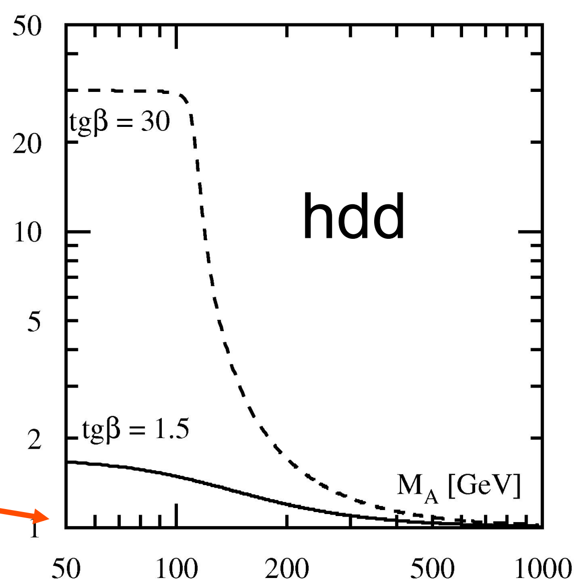
Higgs Couplings Different from SM

Lightest Neutral Higgs, h

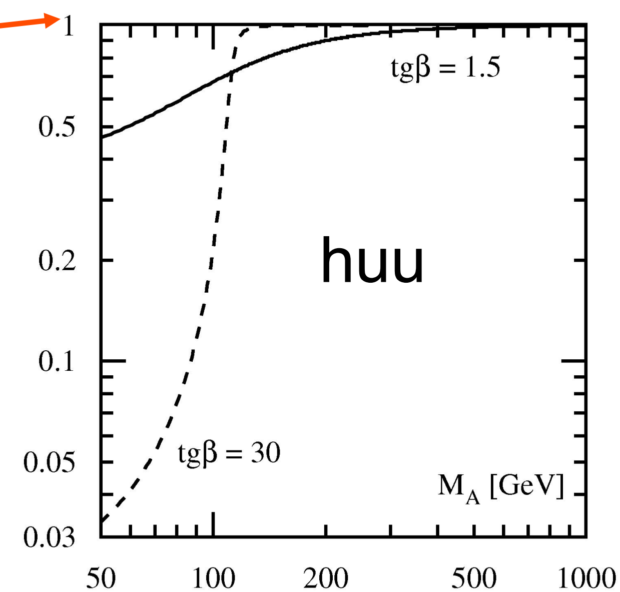
Couplings to d, s, b enhanced at large tan β for moderate M_A

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

SM



SM



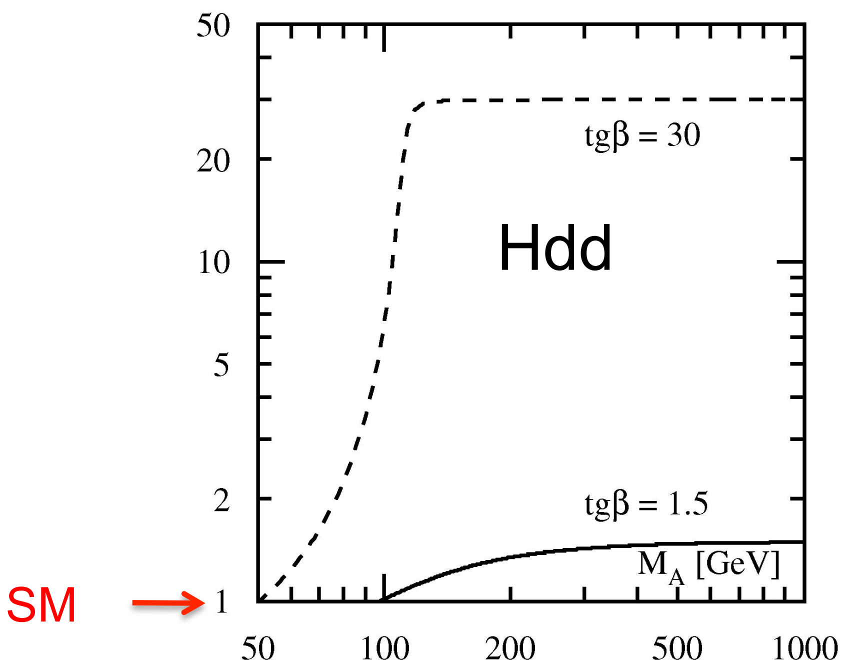
Decoupling limit: For $M_A \rightarrow \infty$, h couplings go to SM couplings

[Spira]

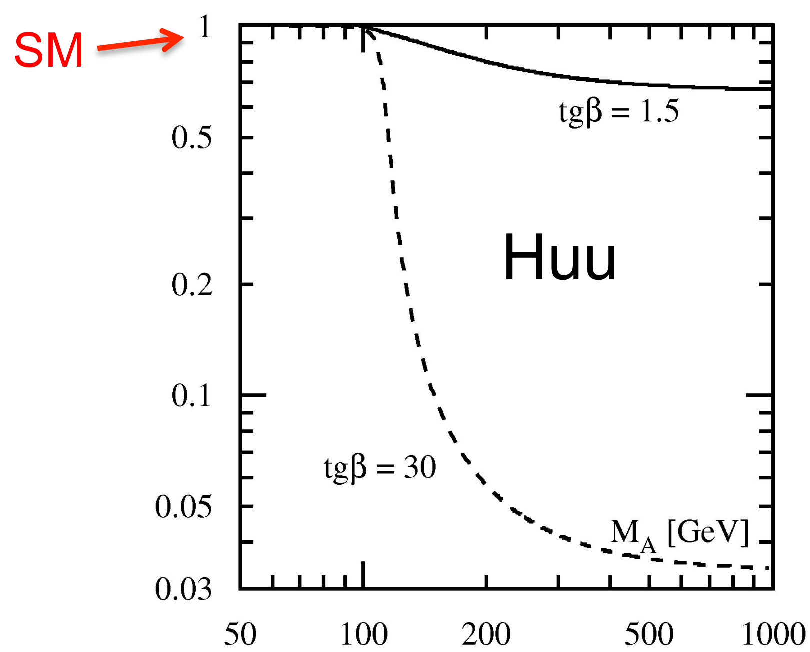
Higgs Couplings in SUSY

Heavier Neutral Higgs, H

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



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



Higgs Couplings in MSSM

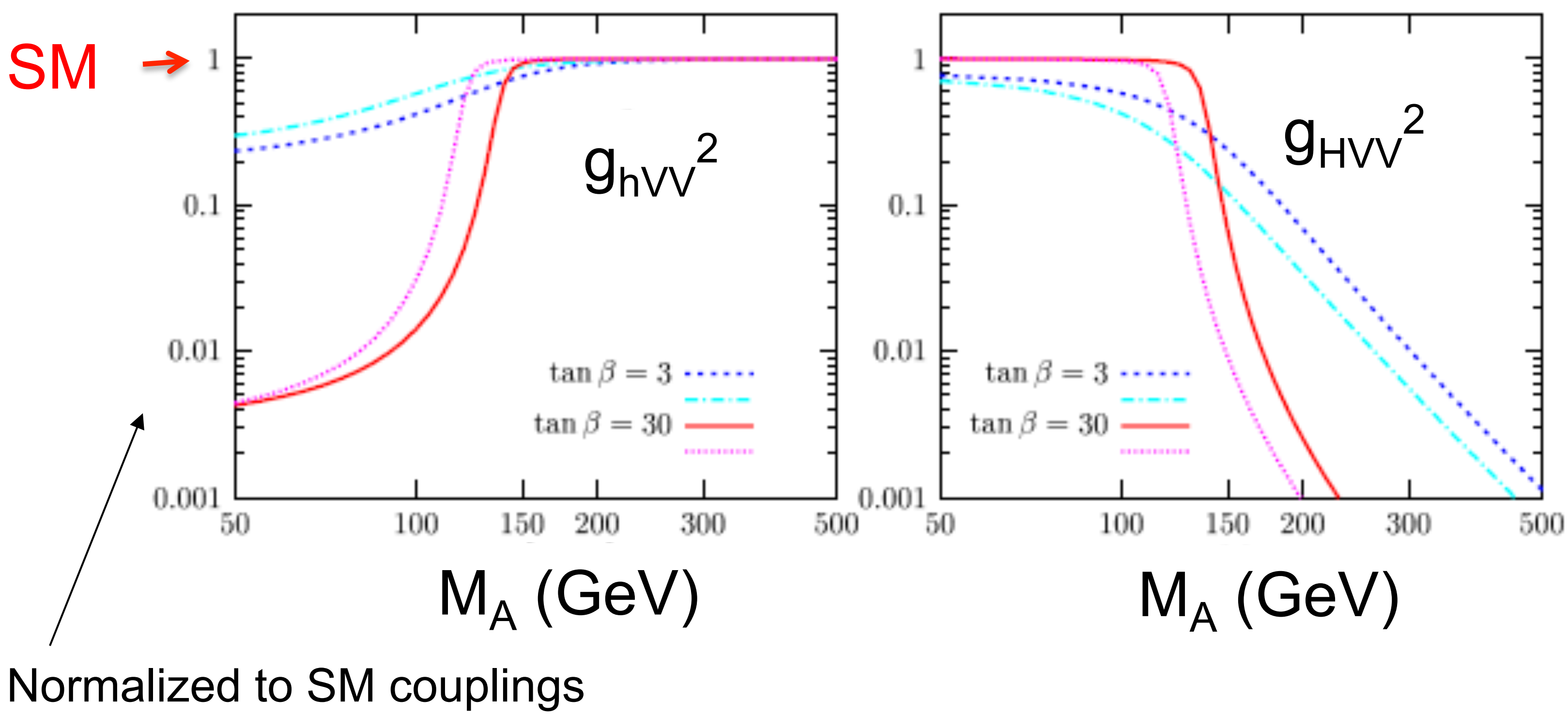
- At tree level, 2 free parameters (M_A, tan β)
  - At one loop tri-linear mixing terms and stop mass
- Lightest neutral Higgs
  - $M_A \rightarrow \infty$, h couplings look SM-like
- Heavier neutral Higgs, H^0,A^0,$H^{\pm}$
  - $M_A \rightarrow \infty$, masses degenerate
  - Couplings to charge -1/3 enhanced for 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

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

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



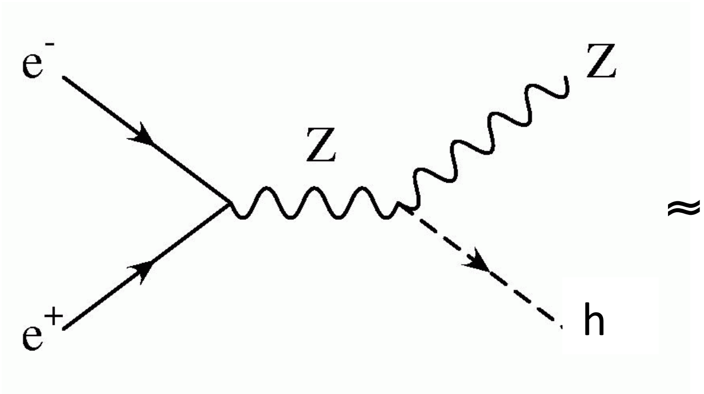
Tools

- 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/

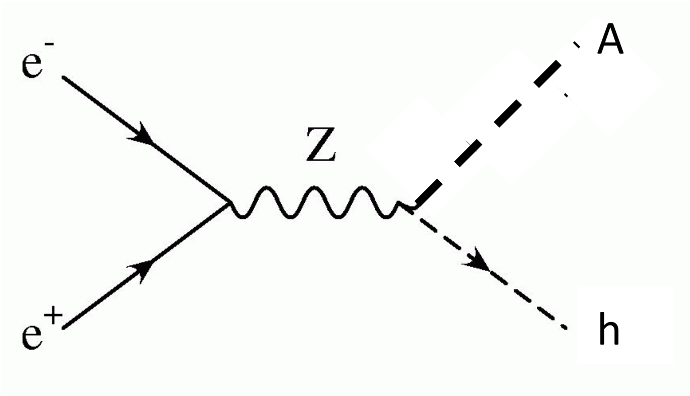
Both of these programs are very easy to use!

Limits from LEP



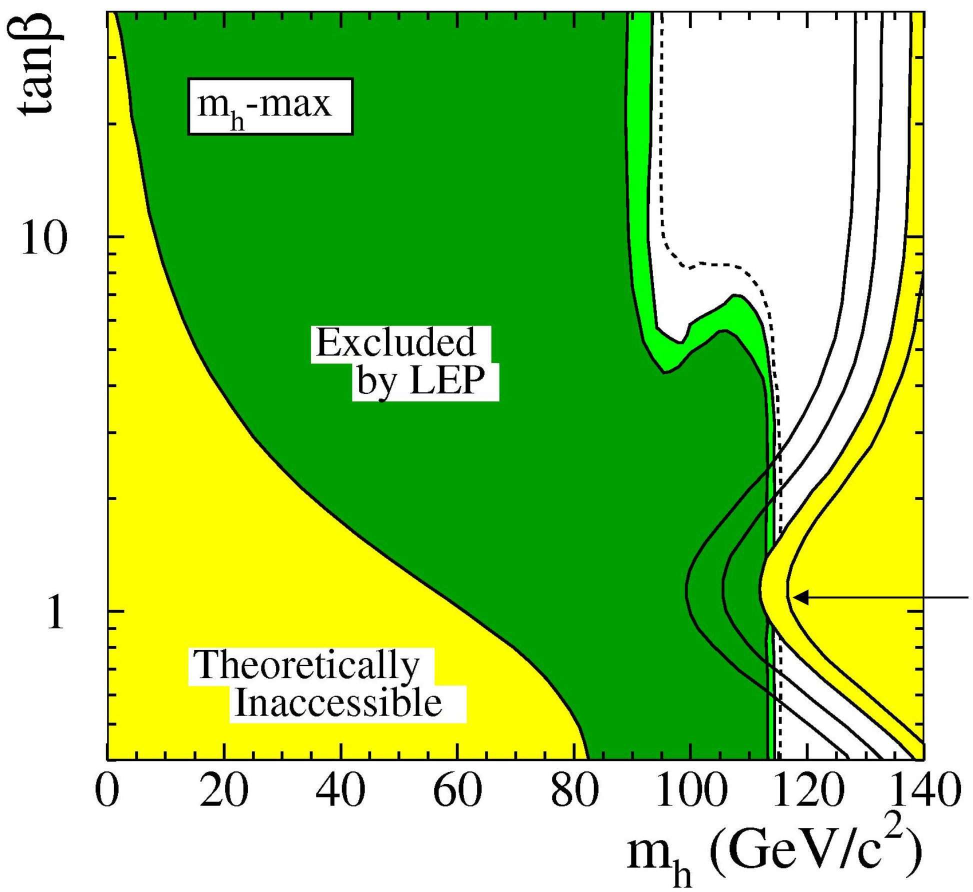
$\approx \cos(\alpha - \beta)$

Complementary processes



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

Limits on SUSY Higgs from LEP



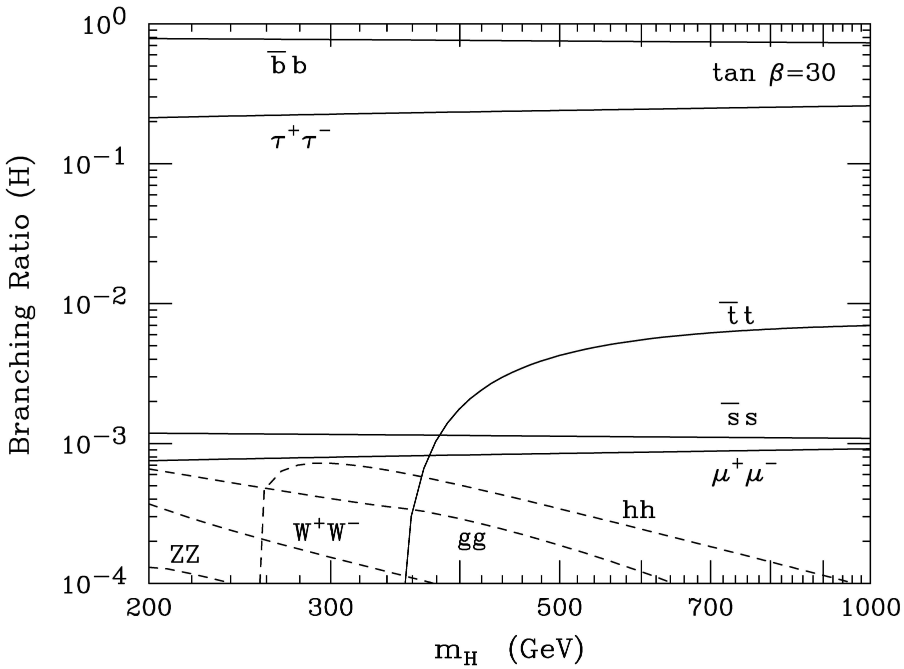
M_t=169.3,174.3,

179.3, 183 GeV

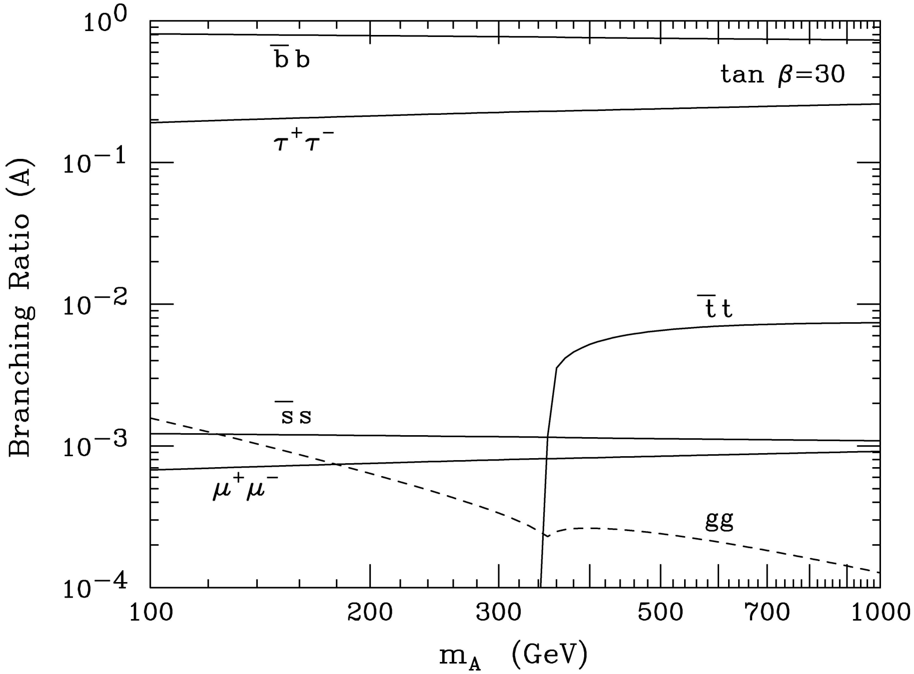
Higgs Decays Changed at Large tan β

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

Heavy H^0 MSSM BRs

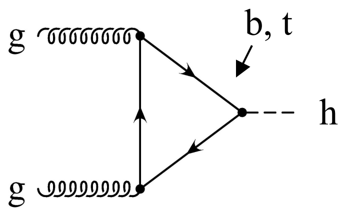


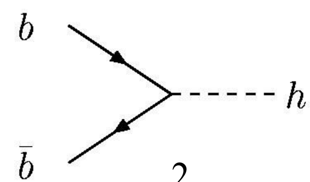
A^0 MSSM BRs



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

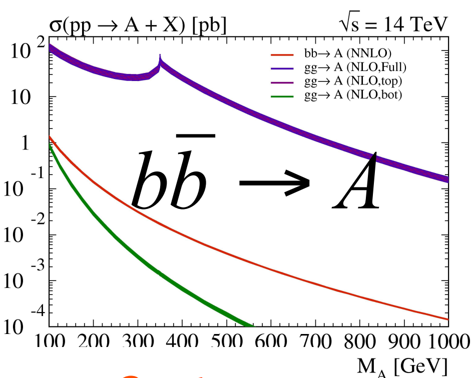
Large tanβ Changes Relative Importance of Production Modes



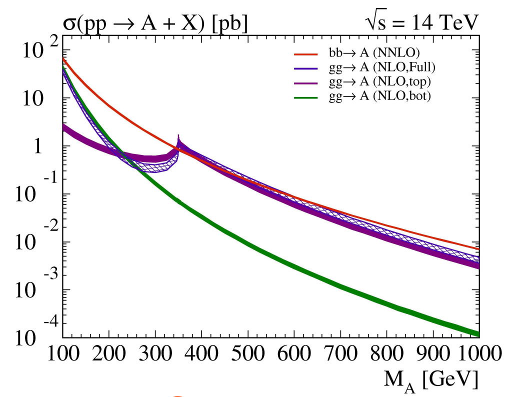


$$\sigma_{gg} = \frac{1}{M_h^2}\left(c_1 \cot^2\beta + c_2 \frac{m_b^2}{M_h^2} + c_3 \frac{m_b^4}{M_h^4} \tan^2\beta \right)$$

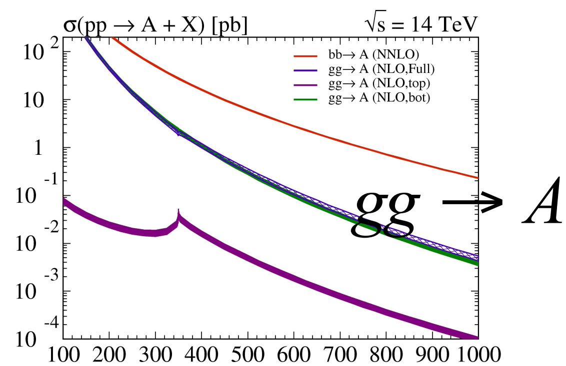
$$\sigma_{bb} = \frac{m_b^2}{M_h^4} c_4 \tan^2\beta$$



tanβ=1



tanβ=7

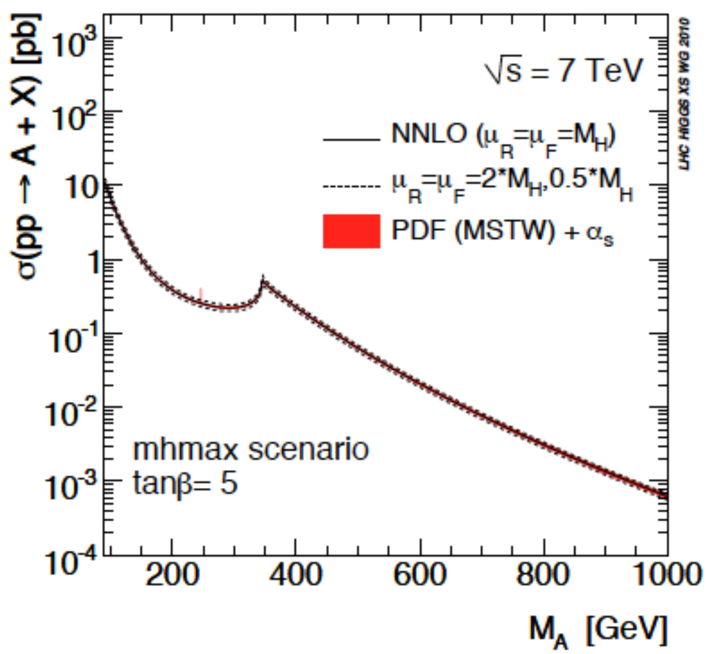


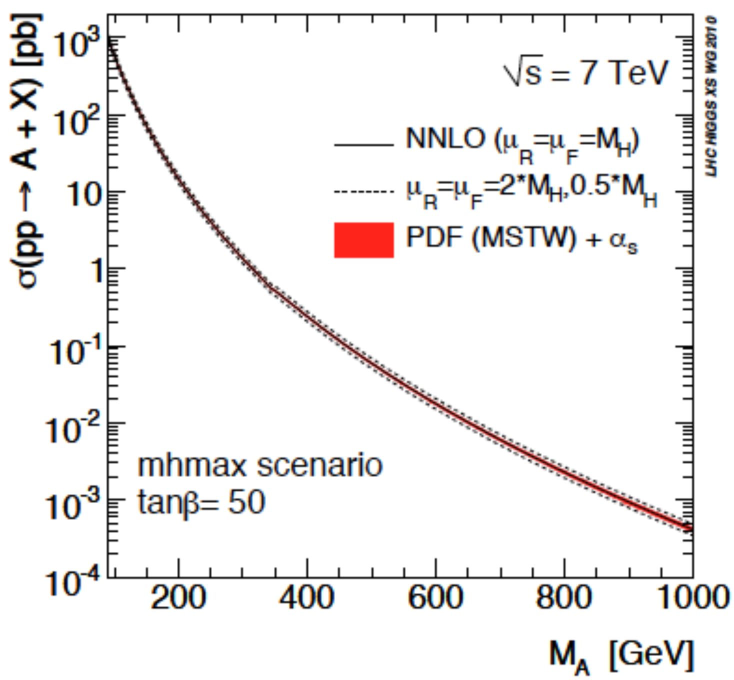
tanβ=40

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

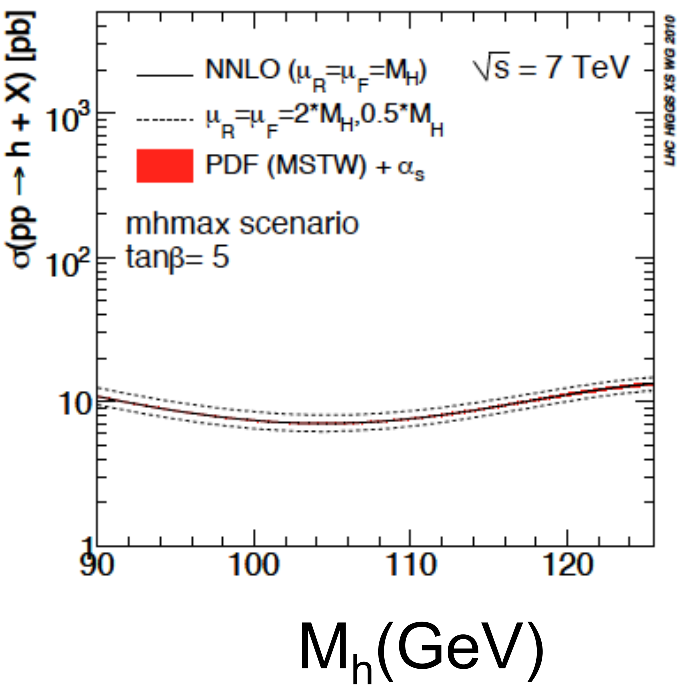
[Kilgore]

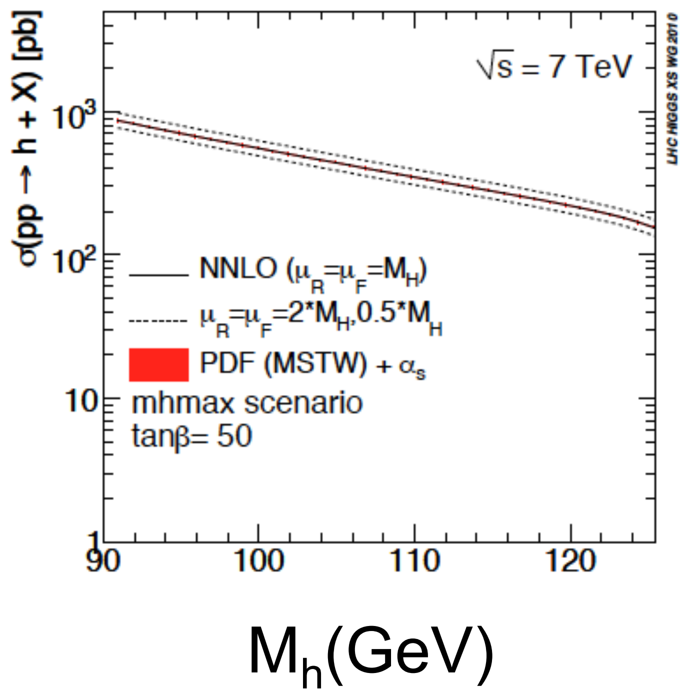
Large Enhancements for large tan β





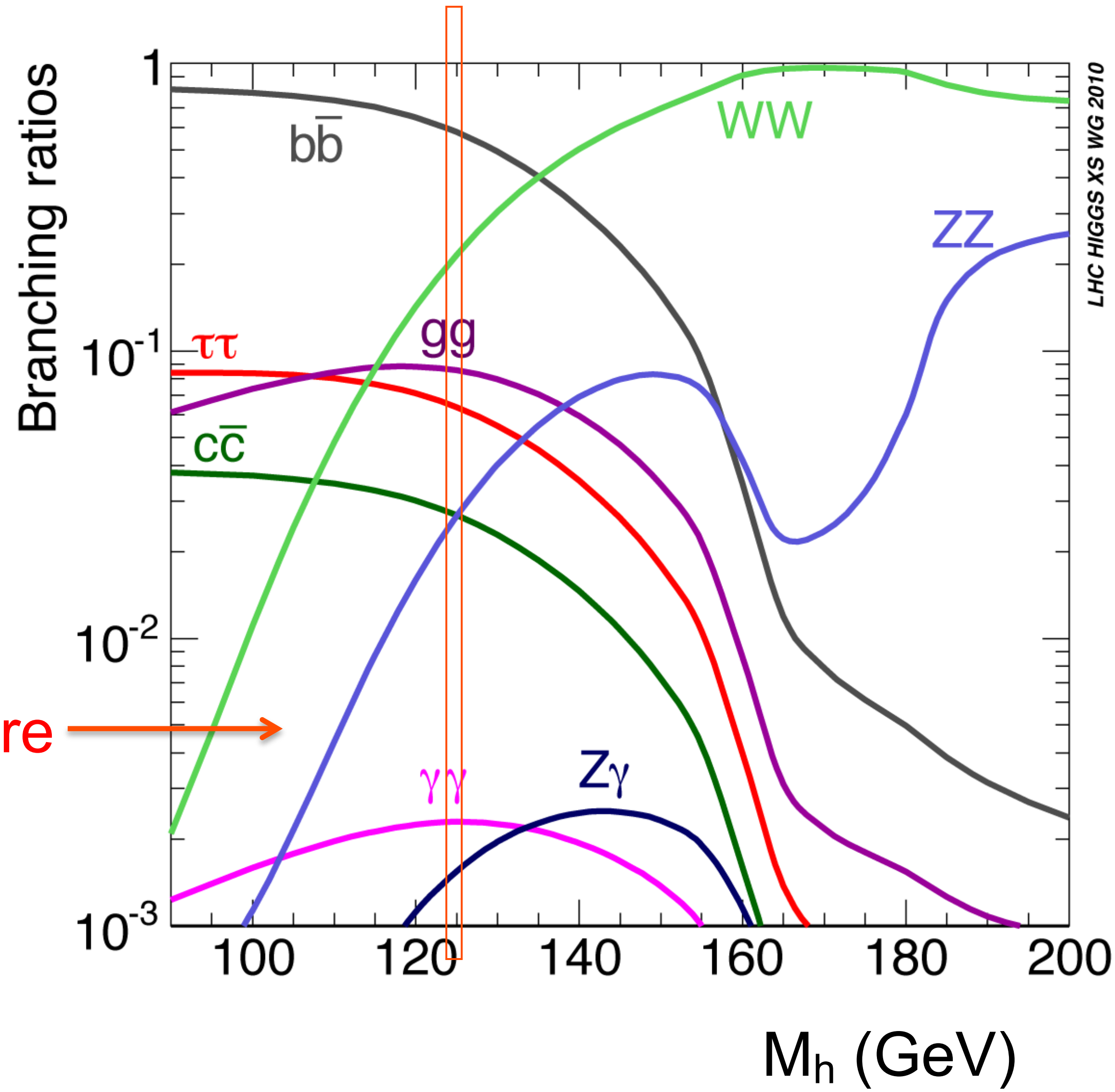
Light h (gluon fusion + bbh)





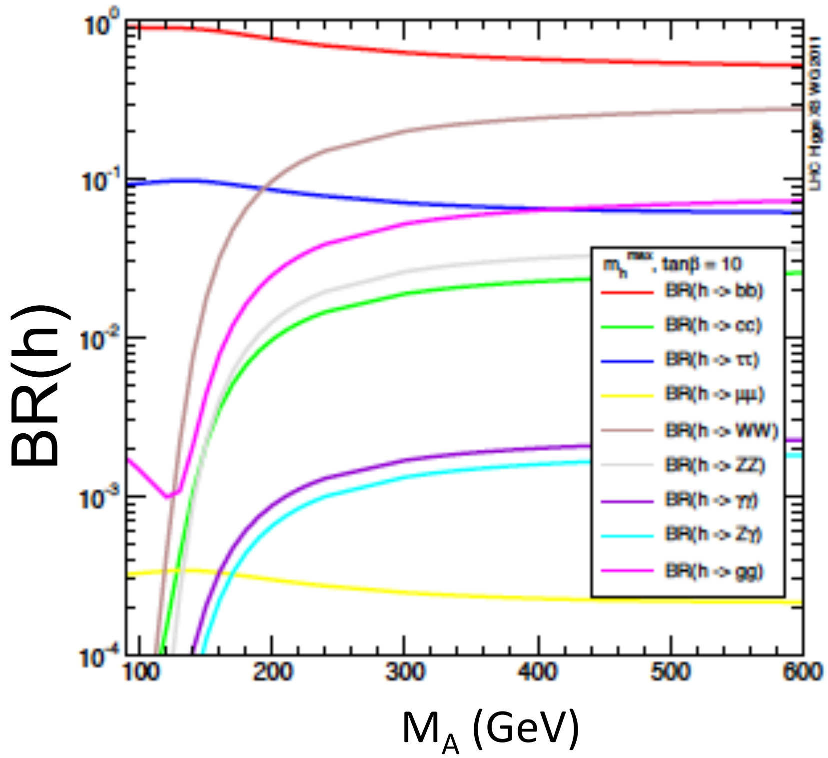
$\sigma_{SM}(M_h=125\text{ GeV}) = 19$ pb

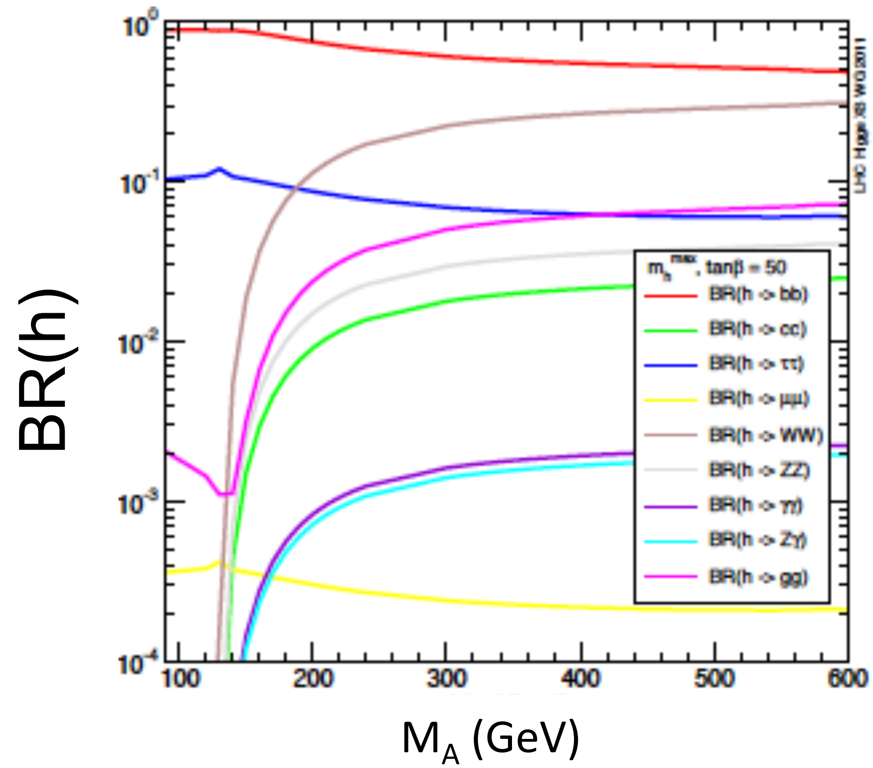
SM Higgs Branching Ratios



We are here

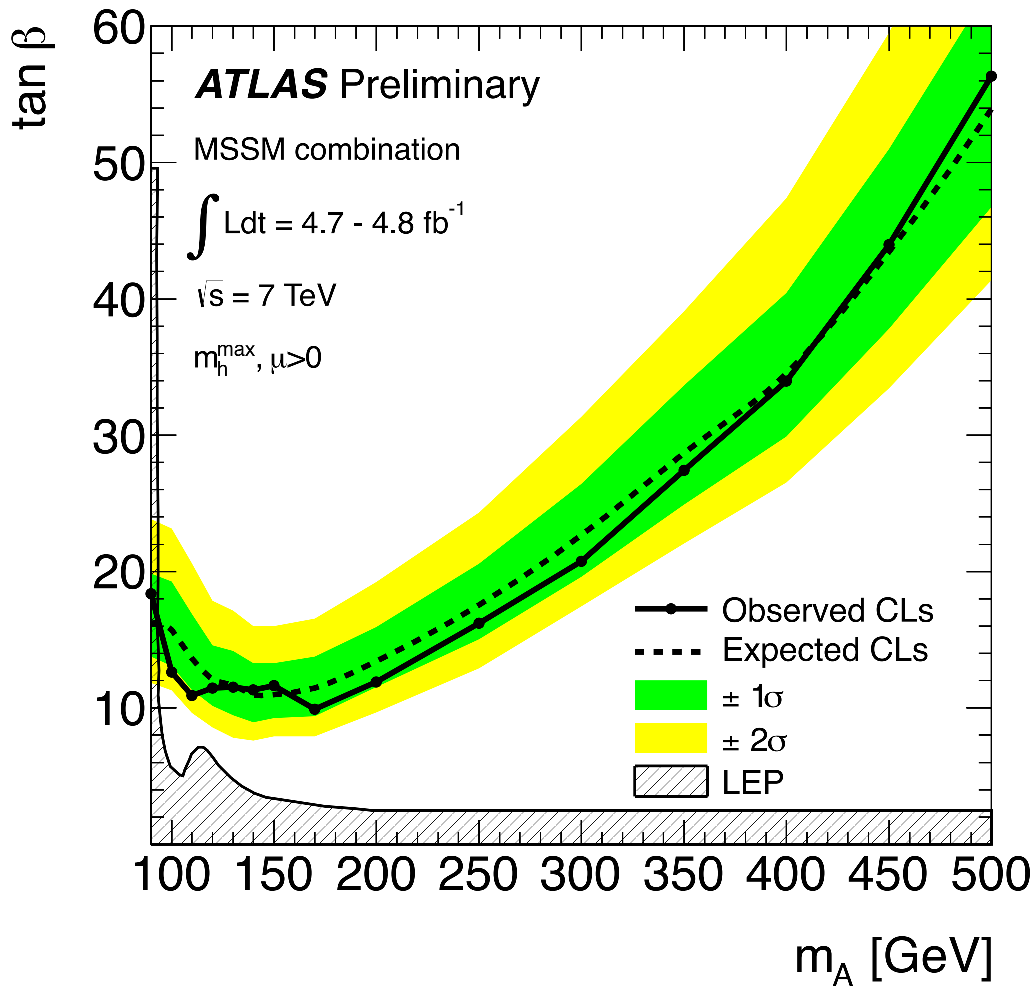
Light Higgs Branching ratios in MSSM





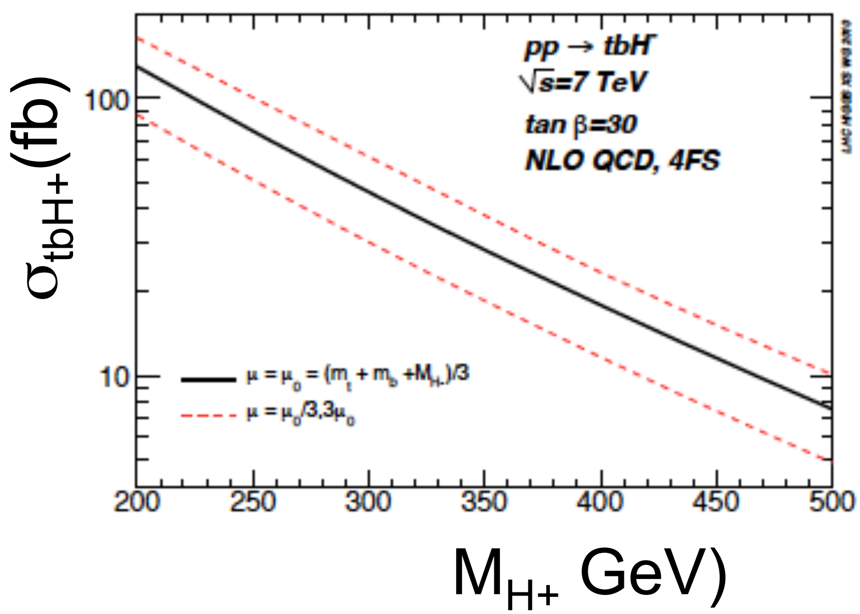
tan β=50, M_A=120 GeV, M_{stop}=1 TeV → M_h =120 GeV

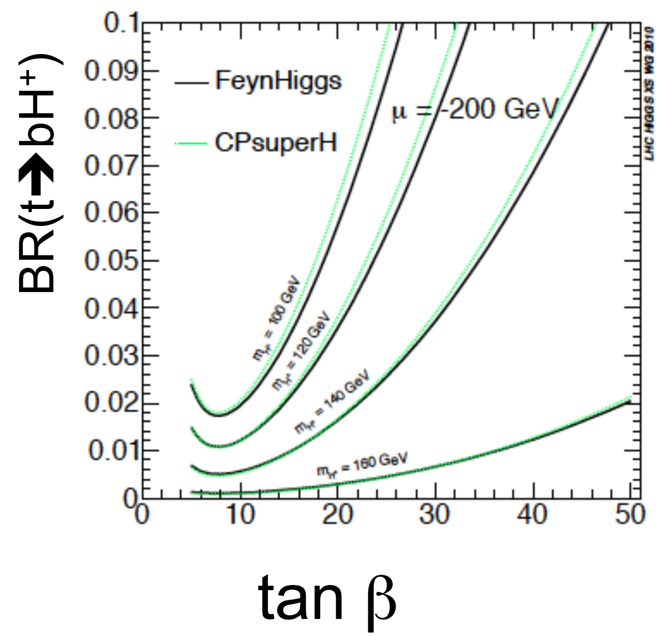
ATLAS Exclusion



Can also look for charged H^+

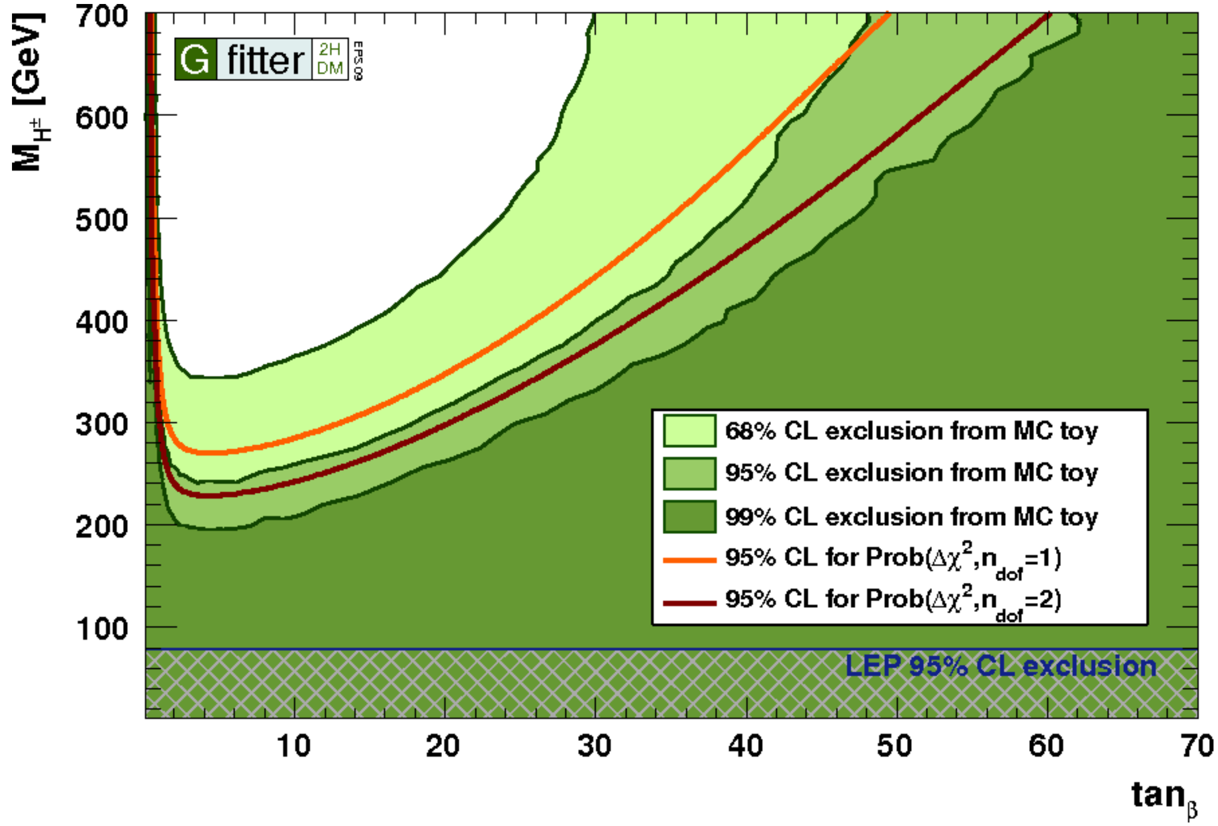
- pp $\rightarrow tbH^+$ is largest production mode
- t $\rightarrow bH^+$ if kinematically allowed





Charged Higgs Limits

- Mostly from B decays



Many Possibilities

- Generic 2 Higgs doublet model (not SUSY)
  - Similar decoupling features as MSSM
- More complicated SUSY model
  - NMSSM is SUSY model with additional singlet
- Extra Higgs singlets which mix with Higgs but don't couple to anything else
  - Reduces all Higgs couplings

Finale

- It's going to be a fun year!
- With 20-30 fb^{-1} we will be firmly in the era of precision Higgs physics