Phenomenology of Induced Electroweak Symmetry Breaking

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Motivation

The Higgs discovery and ongoing coupling constant measurements are consistent with a SM Higgs.

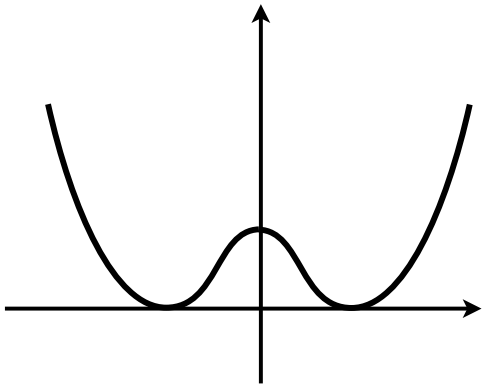
Motivation for non-SM Higgs:

- Phenomenology:
  Explore all possible realizations of EWSB

- Theory:
  Big hierarchy problem ⇒ SUSY or composite Higgs
  Both have little hierarchy problem

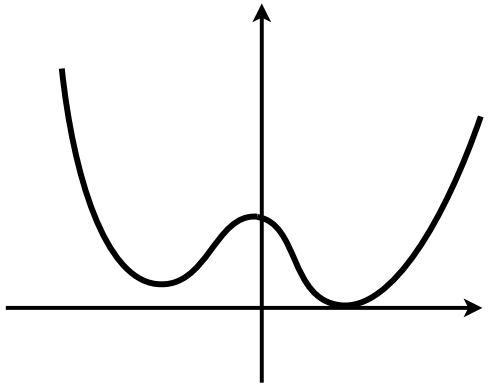
Higgs Potential

SM, SUSY



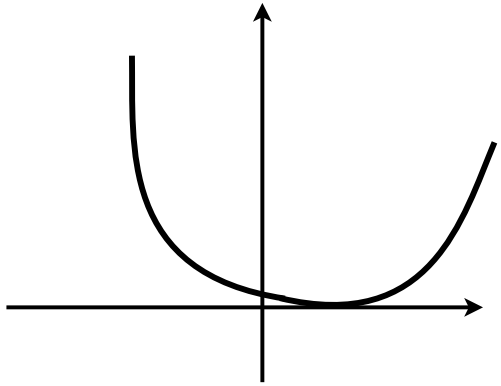
"Mexican hat"

Composite Higgs



“tilted hat”

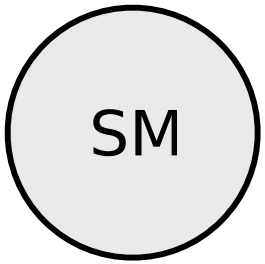
Induced EWSB

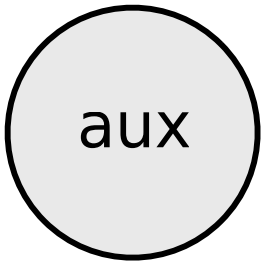


“tilted bowl”

Induced EWSB

$\epsilon \to 0$: decoupled "auxiliary" Higgs sector



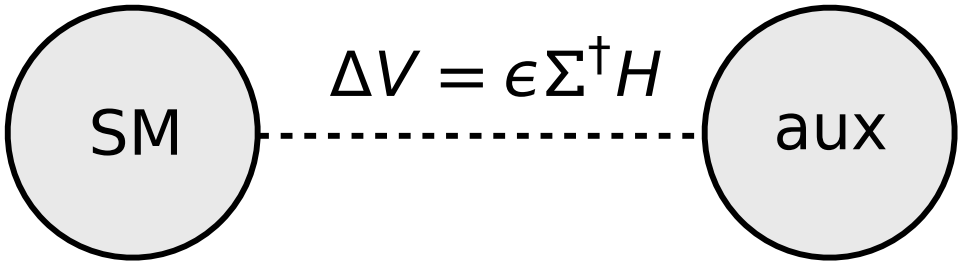


$$\Rightarrow\ m_W = \tfrac{1}{2} g f$$
$$m_t = 0$$
$$\vdots$$

$$\langle H \rangle = 0 \qquad \langle \Sigma \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ f \end{pmatrix}$$

$\epsilon \neq 0$:

$$\Rightarrow\ m_W = \tfrac{1}{2} g v$$
$$m_t = y_t v_H$$
$$\vdots$$

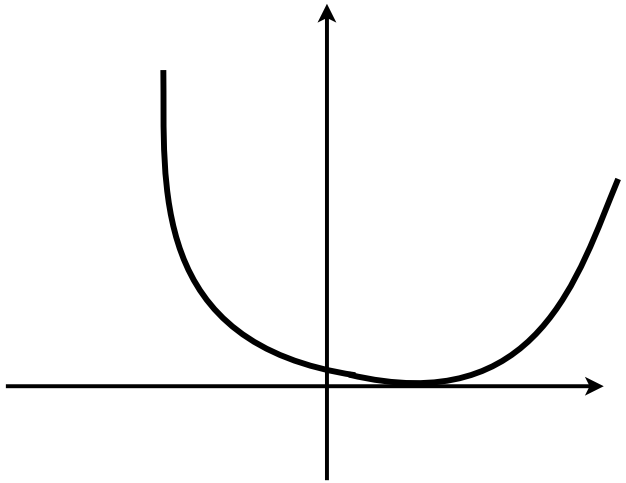


$$\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_H \end{pmatrix} \qquad \langle \Sigma \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ f \end{pmatrix} \qquad v = \sqrt{v_H^2 + f^2}$$

Induced EWSB

$\langle H \rangle$ arises from induced tadpole.

$$V_{\text{eff}} \simeq \underbrace{m_H^2 H^\dagger H}_{m_H^2 > 0} + \epsilon(\Sigma^\dagger H + \text{h.c.}) + \underbrace{\cdots}_{\text{neglect quartic}}$$



$m_H \simeq 125$ GeV

Induced EWSB

$\epsilon =$ perturbation?

$$\frac{\Delta g_{hVV}}{g_{hVV}^{(\mathrm{SM})}} \sim 10\% \quad \Rightarrow \quad \underbrace{f \lesssim 0.3 v}$$

$\langle H \rangle$ dominates EWSB

No conflict: expansion in $\left(\frac{\epsilon}{m_{\mathrm{aux}}^2} \right)^n$

$$m_{\mathrm{aux}}^2 \sim \lambda_{\mathrm{aux}} f^2 \gg \frac{v_H}{f} m_H^2$$

$\Rightarrow$ requires large quartic λ_{aux} in auxiliary Higgs sector

- strong coupling $(\lambda_{\mathrm{aux}} \sim (4\pi)^2)$
- perturbative models

Effective Theory of EWSB

Integrate out auxiliary Higgs sector

$\Rightarrow$ nonlinear realization of EWSB + light Higgs doublet

$\Sigma = e^{i\Pi/f} \in [SU(2) \times SU(2)]/SU(2)$

$=$ Goldstone modes from auxiliary Higgs sector

$H =$ elementary Higgs field

$V(H) = m_H^2 H^\dagger H + \epsilon(\Sigma^\dagger H + \text{h.c.}) + \cdots$

Pseudoscalar mixing: $\mathcal{M}_A^2 = m_H^2 \begin{pmatrix} 1 & v_H/f \\ v_H/f & v_H^2/f^2 \end{pmatrix}$

$$\Rightarrow m_A^2 = m_H^2 \frac{v^2}{f^2}$$

Theory Motivation

SUSY ⇒ light Higgs Too light?

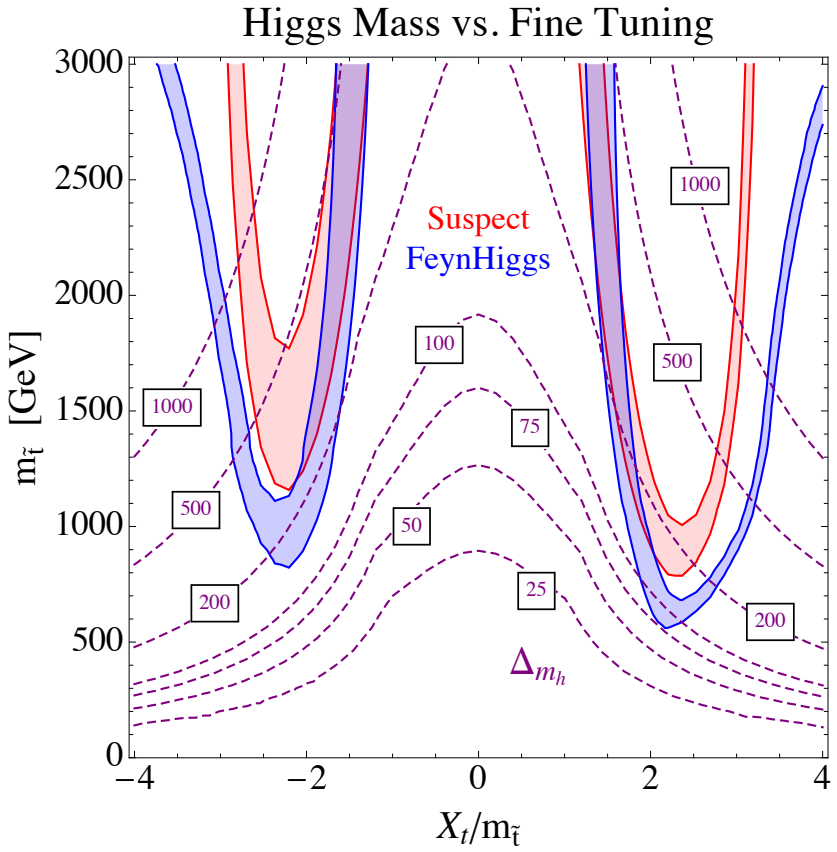
MSSM tree level: $m_h^2 \sim \lambda_h v^2 \sim g^2 v^2 \Rightarrow m_h \leq m_Z$

loops: $\Delta\lambda_h \sim \frac{3y_t^4}{16\pi^2} \ln \frac{m_{\tilde{t}}}{m_t}$

$\Delta m_H^2 \sim \frac{3y_t^2}{16\pi^2} m_{\tilde{t}}^2$

⇒ ~ 1% tuning

Motivates extensions of MSSM



Hall, Pinner, Ruderman 2011

Beyond the MSSM

Additional contributions to Higgs quartic ⇒ naturalness

- NMSSM

$$\Delta W = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \quad \Rightarrow \quad \Delta\lambda_h \sim \lambda^2$$

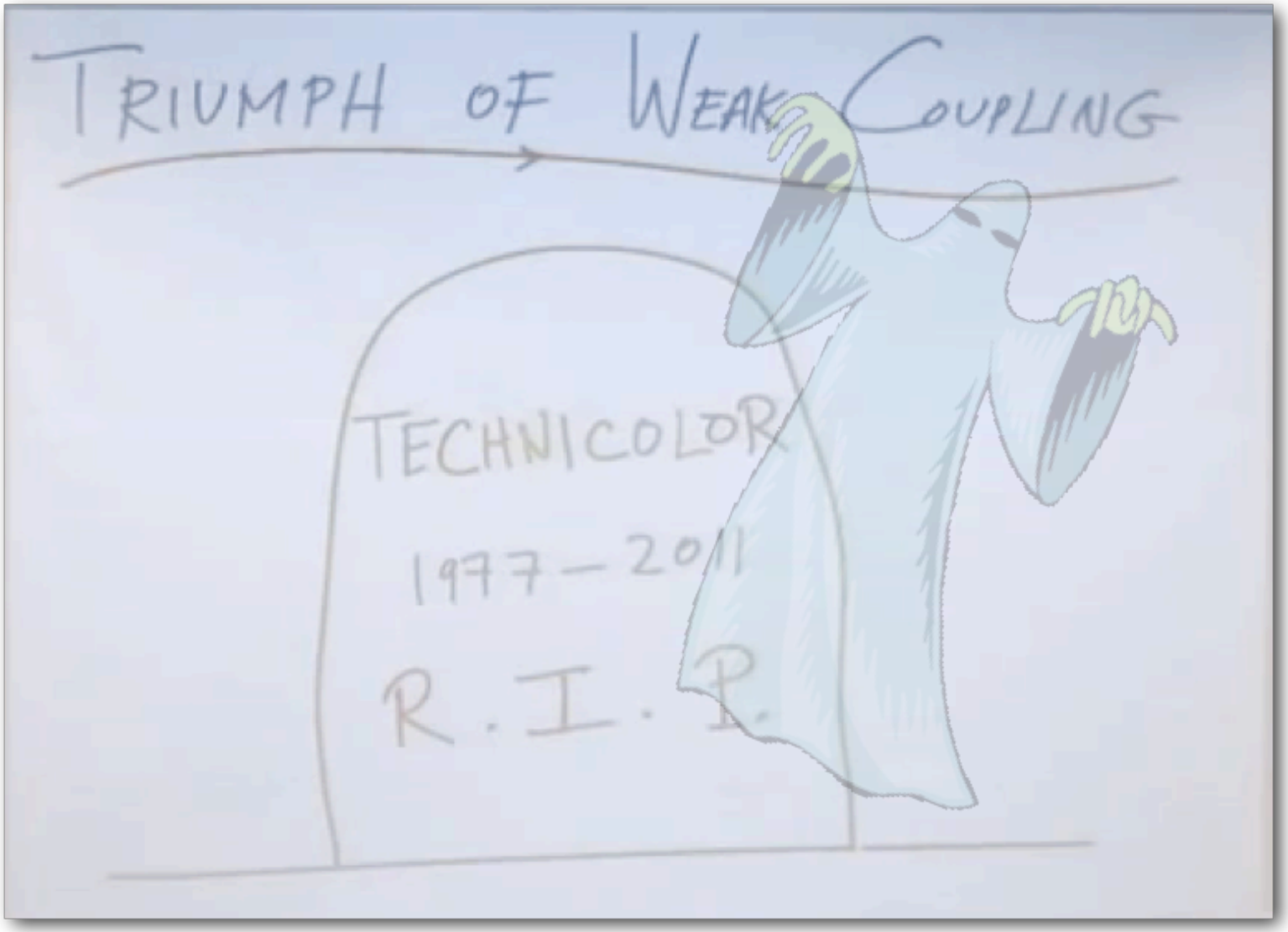
- Non-decoupling D terms

  (Batra, Delgado, Kaplan, Tait 2004)

$$\Delta\lambda_h \sim \tilde{g}^2 \qquad \tilde{g} = \text{new gauge coupling}$$

- Induced tadpole

Superconformal Technicolor



N. Arkani-Hamed, 2011

Superconformal Technicolor

Azatov, Galloway, ML 2011

Auxiliary Higgs sector = strong superconformal sector

~~SUSY~~ $\Rightarrow$ strong EWSB at TeV scale

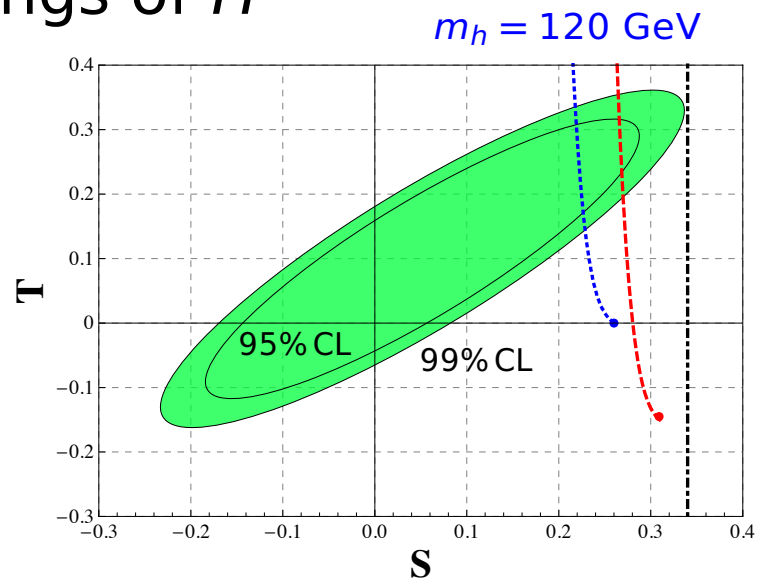
Intuitive picture: integrate out massive scalars

$\Rightarrow \beta < 0 \quad \Rightarrow$ fermion condensation

Technicolor problems are absent:

- Flavor from Yukawa couplings of H
- Precision EW tests

  $\Delta T > 0$ from $\epsilon_u \neq \epsilon_d$
- *Motivated* by light Higgs

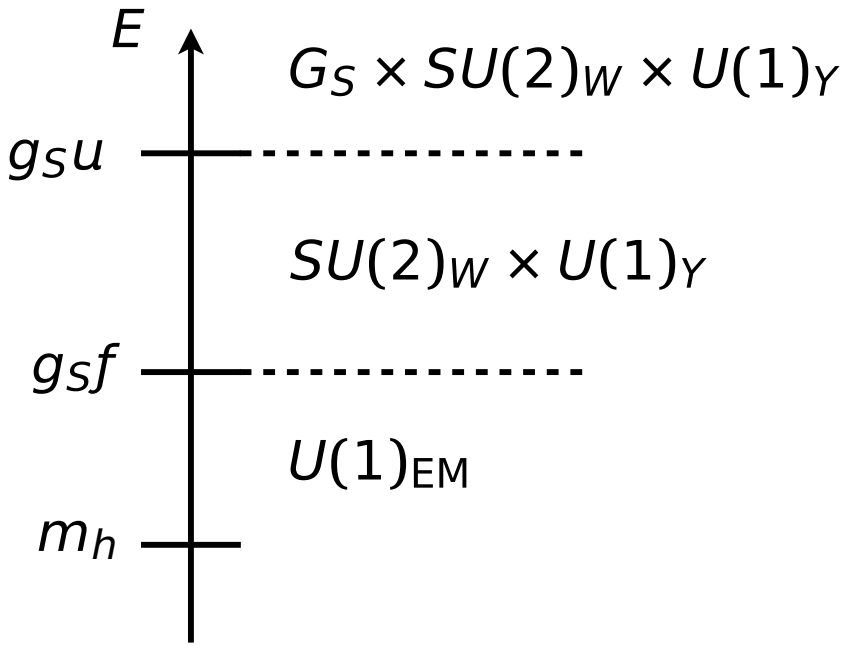


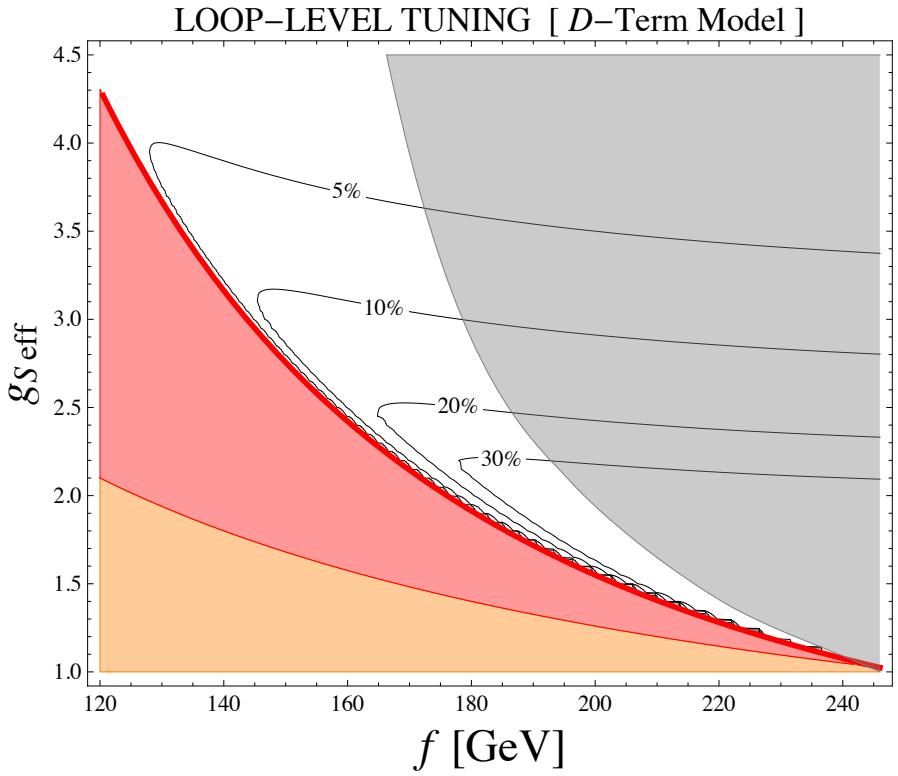
Perturbative Models

Galloway, ML, Tsai, Zhao 2013

Auxiliary Higgs fields charged under new gauge group G_S

$\Rightarrow \lambda_{\text{aux}} \sim g_S^2$





~ 10% tuning in all of parameter space

⇒ robust solution of fine-tuning problem

Phenomenology

Induced EWSB ⇒ additional Higgs states cannot decouple

- Higgs coupling measurements

  Generically $g_{hhh} \ll g_{hhh}^{(\mathrm{SM})}$

- Direct Higgs searches

- Indirect constraints (R_b, $b \to s\gamma$)

Current bounds?

Prospects for upcoming 14 TeV run?

Phenomenological Model

Auxiliary Higgs sector = single Higgs doublet Σ

+ MSSM Higgs fields H_u, H_d

Assume one linear combination of H_u, H_d decouples:

$$H' = H_u \sin\beta + \tilde{H}_d \cos\beta$$

$$= \text{heavy mass eigenstate} \quad \langle H' \rangle = 0$$

$$H = H_u \cos\beta - \tilde{H}_d \sin\beta$$

$$= \text{light doublet}$$

Only H couples to fermions $\Rightarrow$ effective type I 2HDM

$$y_u = \frac{y_u^{(\mathrm{SM})}}{\sin\beta}, \qquad y_d = \frac{y_d^{(\mathrm{SM})}}{\cos\beta}$$

Phenomenological Model

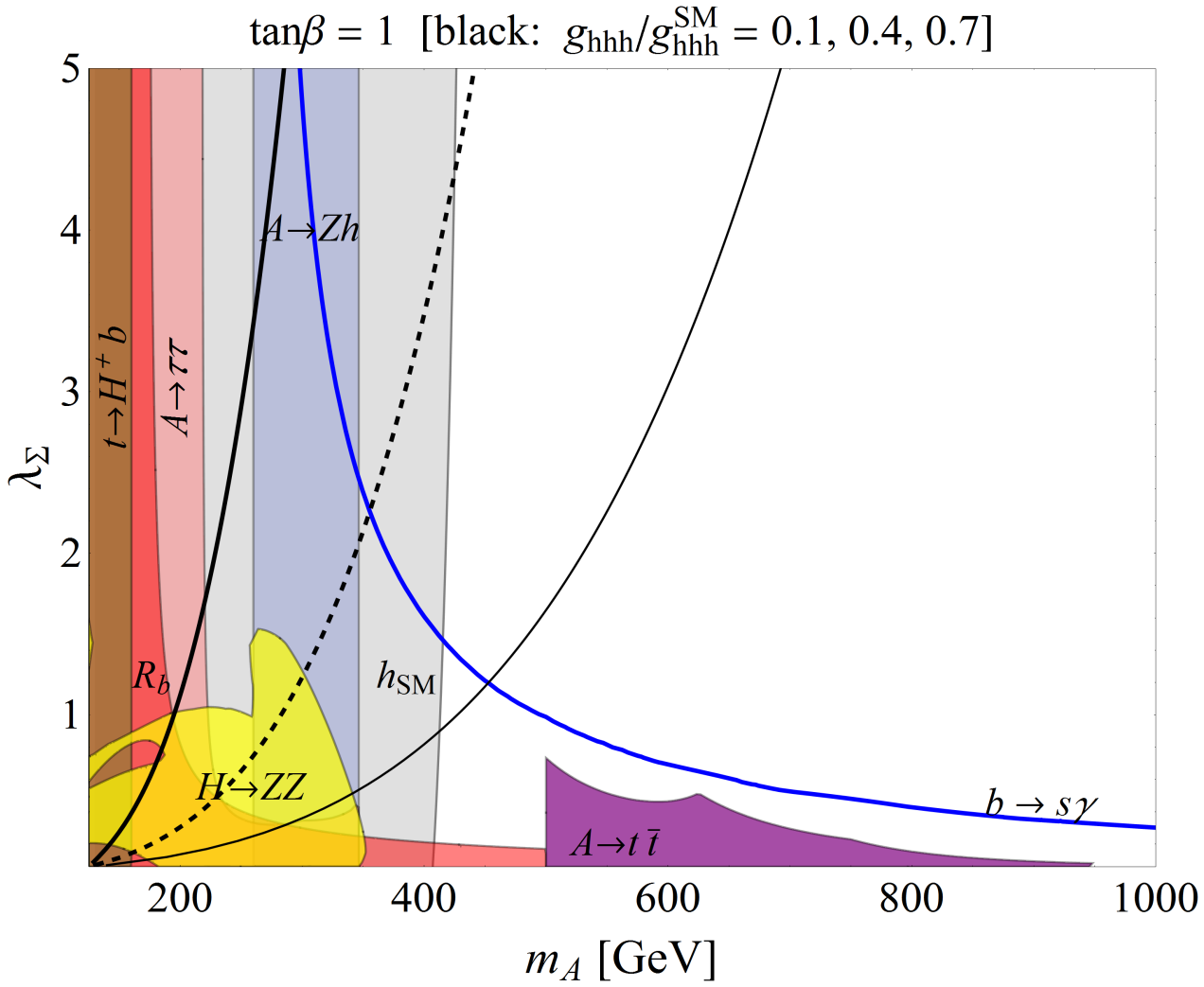
$$V_{\text{eff}} = m_H^2 H^\dagger H + m_\Sigma^2 \Sigma^\dagger \Sigma - \epsilon(\Sigma^\dagger H + \text{h.c.}) + \lambda_\Sigma (\Sigma^\dagger \Sigma)^2 + \underbrace{V_D}$$

important only for g_{hhh}

5 parameters: m_H^2, m_Σ^2, κ, λ_Σ, $\tan\beta$

$\longleftrightarrow f$, λ_Σ, $\tan\beta$ $\quad$ ($m_h = 125$ GeV, $v = 246$ GeV)

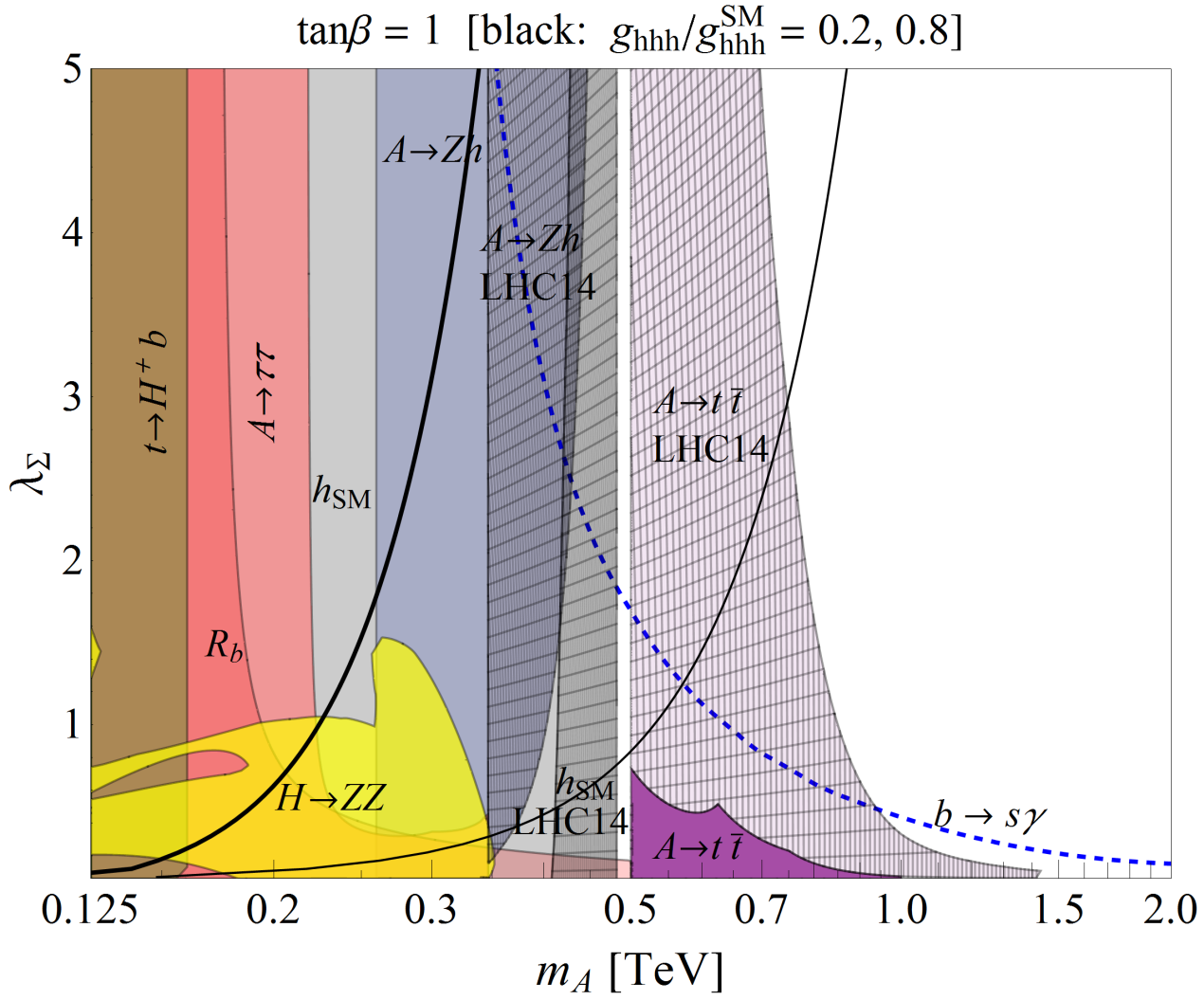
LHC8 Constraints



$g_{hhh} \simeq 0.5 \times g_{hhh}^{(SM)}$ still allowed

tt resonance search below 500 GeV has discovery reach!

LHC14 Projections



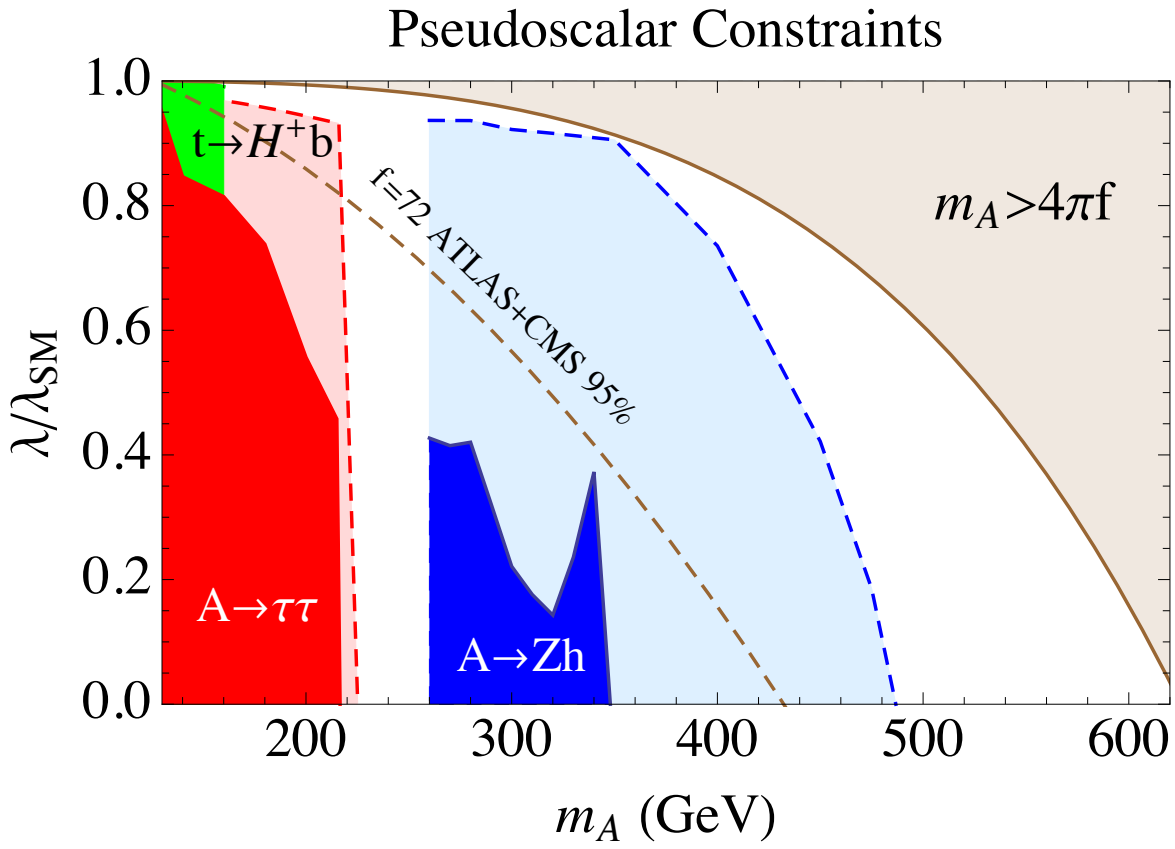
Probes parameter space up to $g_{hhh} \sim 0.8 \times g_{hhh}^{(SM)}$

tt resonance search below 500 GeV still important

Strongly Coupled Models

Nonlinear sigma model coupled to *H*

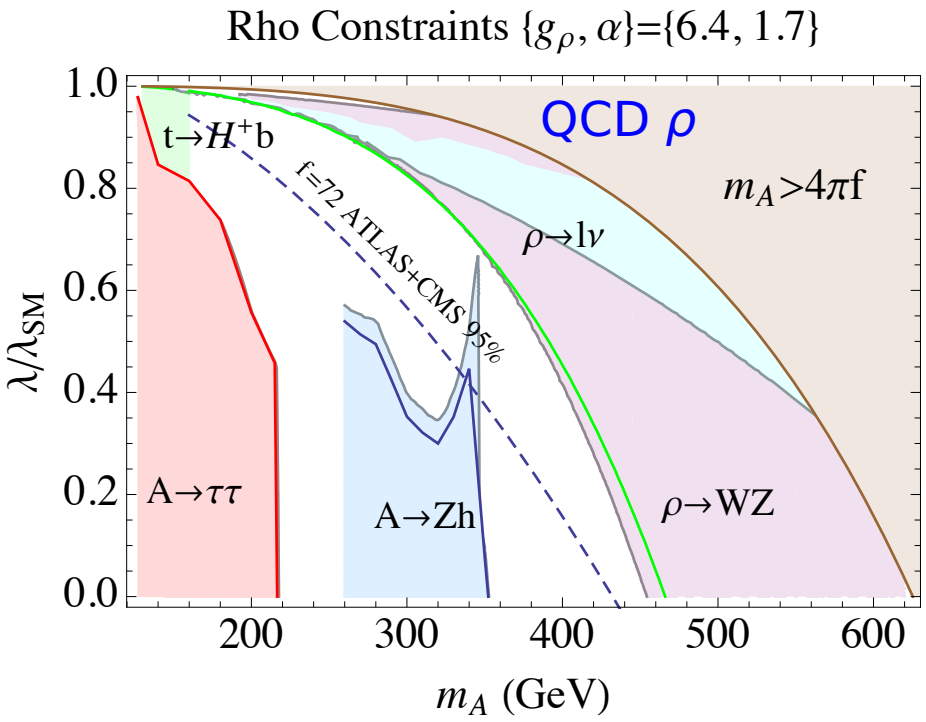
Corresponds to limit $\lambda_\Sigma \to \infty$

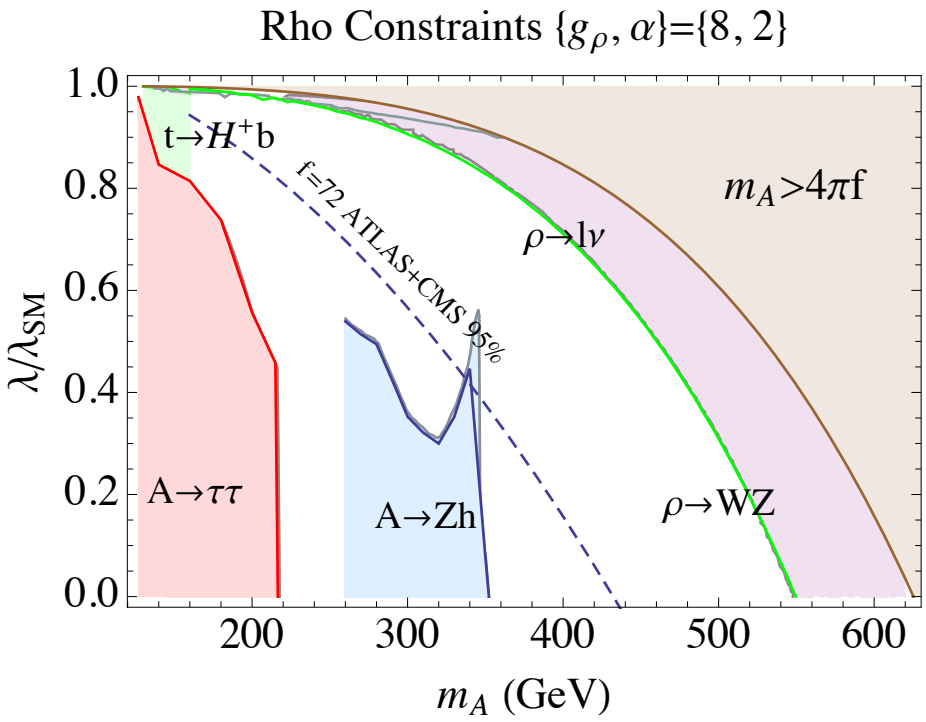


Strongly Coupled Models

Model vector resonances from strong auxiliary Higgs sector

(Falkowski, Grojean, Kaminska, Pokorski, Weiler 2011)





Constraints weaker for smaller g_ρ

BR($\rho^+ \to WZ$) suppressed when $\rho^+ \to H^+A$ opens up

$\Rightarrow$ new signals: $\rho^+ \to H^+A \to tbZh$, $\rho^+ \to WA \to WZh$

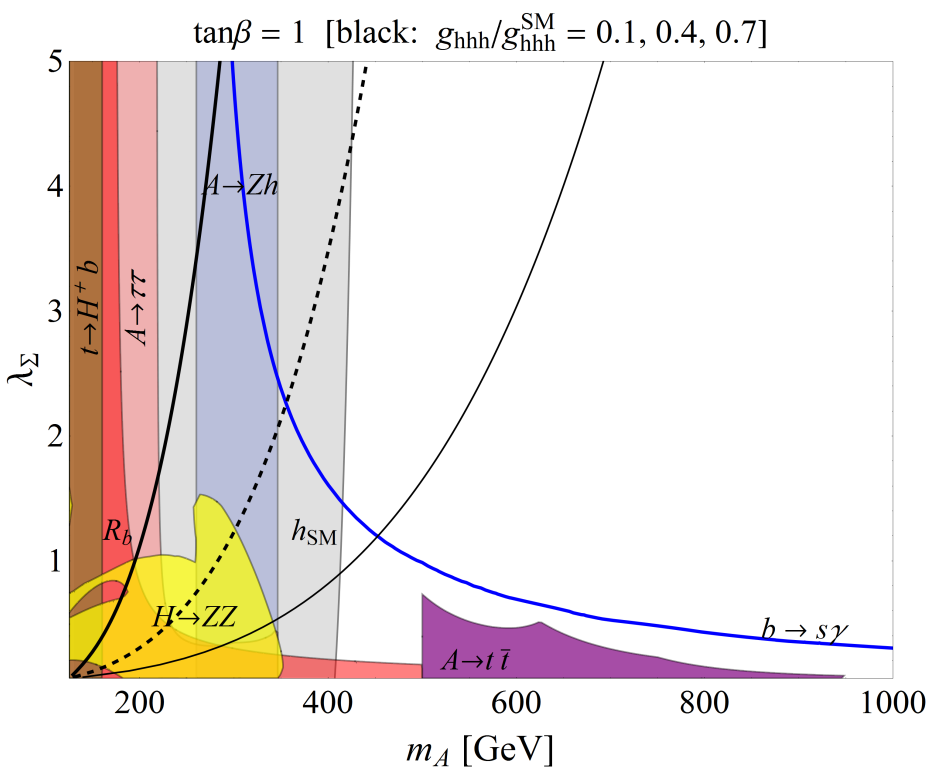
Conclusions

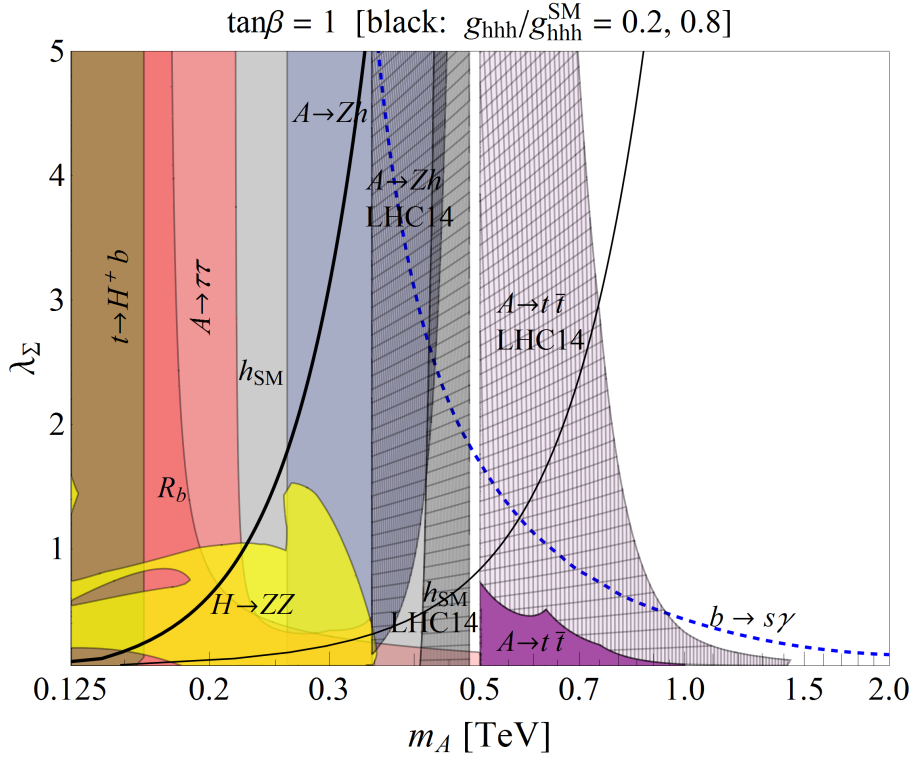
- Induced EWSB is an attractive possibility to generate a 125 GeV Higgs in SUSY
- Motivates a nonlinear realization of EWSB coupled to a light Higgs
- Consistent with all bounds
- Will be stringently tested at LHC14
- tt resonance search for $m_{tt} < 500$ GeV has discovery potential
- Potential new signal: heavy resonances decaying through Higgs cascades

Backup

Bounds/Projections

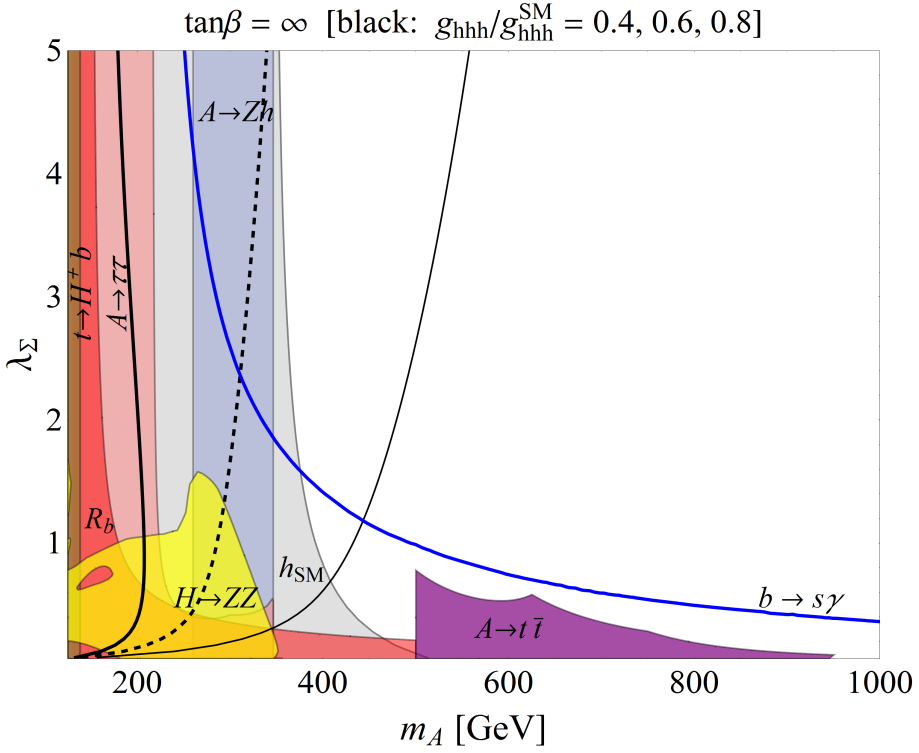
$\tan\beta = 1$

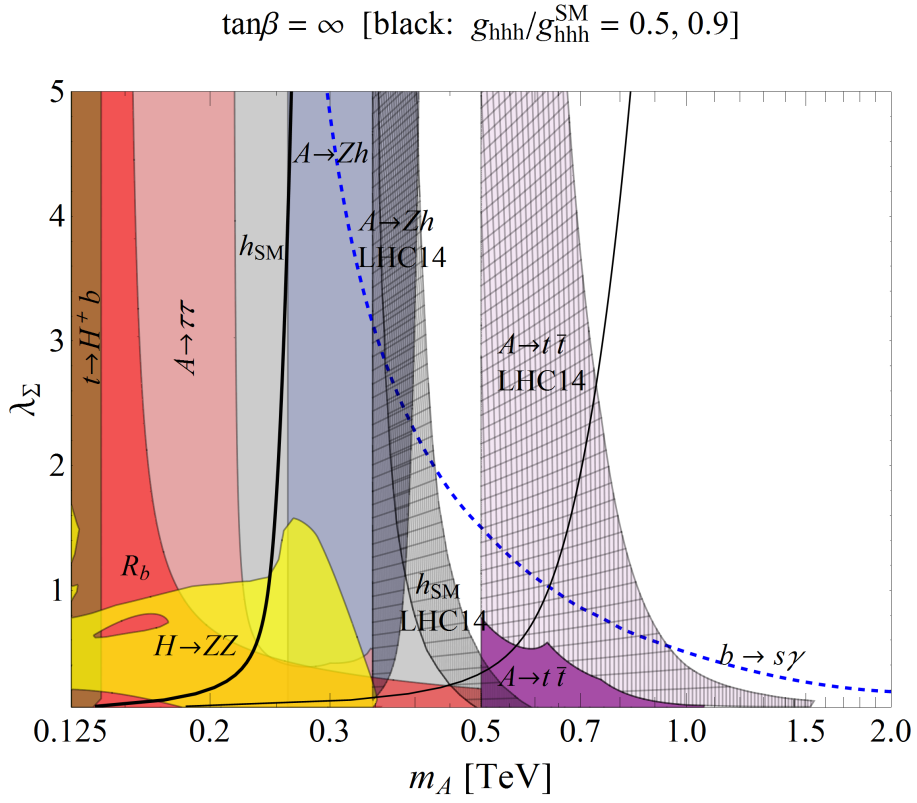




Bounds/Projections

$\tan\beta = \infty$





g_{hhh} more constrained due to MSSM contribution