Phenomenology of Induced EWSB

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2nd NPKI Workshop, Jeju Island

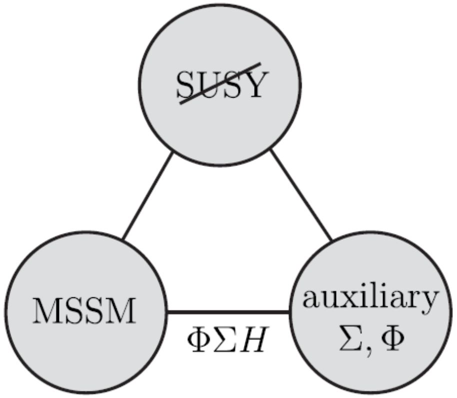
September 16, 2014

based on work to appear, with S.Chang, J.Galloway, M.Luty and Y.Tsai

Induced EWSB: introduction

- To obtain naturally $m_h \sim 125\,\mathrm{GeV}$ in SUSY, need to go beyond MSSM
- 'Traditional' approach: new contributions to Higgs quartic.

  Examples: **N**MSSM, extra D-terms, *…*
- Different approach: new sector of auxiliary Higgs fields with large tree-level quartics and no Yukawas. They couple to the MSSM Higgs doublets via superpotential and A-terms



- The VEVs of the auxiliary fields break EW.

  Main effect on the potential for the light Higgs is either an *induced quartic* or an ***induced tadpole***
- Tuning is mild over most of parameter space

Kagan 2008
Azatov, Galloway, Luty 2011
Galloway, Luty, Tsai, Zhao 2013

Simplified model

Consider simplified model: MSSM + 1 auxiliary doublet Σ_d :

$$\begin{aligned} V &= m_{H_u}^2 \left|H_u\right|^2 + m_{H_d}^2 \left|H_d\right|^2 + (B\mu H_u H_d + \text{h.c.}) \\ &+ m_{\Sigma}^2 \left|\Sigma_d\right|^2 + \underbrace{\lambda_\Sigma}_{\text{large-ish quartic}} \left|\Sigma_d\right|^4 + (B_u H_u \Sigma_d + \text{h.c.}) + \underbrace{V_D(H_u, H_d, \Sigma_d)}_{SU(2)_L \times U(1)_Y \text{ D-terms}} \end{aligned}$$

This can be obtained as low-energy limit of a perturbartive model where the quartic is generated by D-terms of a new gauge group $SU(2)_S$, broken at TeV by VEVs of singlets. Quartic for Σ_d has strength $\lambda_\Sigma \sim g_S^2$

	$SU(2)_S$	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
Φ	$\square$	1	1	0
$\bar{\Phi}$	$\square$	1	1	0
Σ_u	$\square$	1	$\square$	$\frac{1}{2}$
Σ_d	$\square$	1	$\square$	$-\frac{1}{2}$
T	$\square$	$\square$	1	$-\frac{2}{3}$
$\bar{T}$	$\square$	$\bar{\square}$	1	$\frac{2}{3}$

Table 1. Field content of the D-term model.

Galloway, Luty, Tsai, Zhao, 2013
(see also Alves, Fox, Weiner 2012)

Super-simplified model

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Further simplification: assume decoupling limit for one of the MSSM doublets, fixing $\tan\beta = v_u/v_d$

Notice that we **do not** need a large quartic for the light H

so no preference for large $\tan\beta$

- $\tan\beta = 1$ gives zero D-term quartic for H

$$V_D^{(\tan\beta=1)} = \frac{g^2+g'^2}{8} |\Sigma_d|^4$$

Super-simplified model (2)

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MSSM decoupling limit, $\tan\beta = 1$

$$V = m_H^2 |H|^2 + m_\Sigma^2 |\Sigma|^2 + (BH\,\Sigma + \text{h.c.}) + \left[\lambda_\Sigma + \frac{g^2 + g'^2}{8}\right] |\Sigma|^4$$

Only 2 indep parameters after fixing v, m_h

This very simple model captures well the main aspects of the idea.

EWSB from a tadpole

$$V \ = \ m_H^2 \, |H|^2 + m_\Sigma^2 \, |\Sigma|^2 + (B H \, \Sigma + \text{h.c.}) + \left[\lambda_\Sigma + \underbrace{\frac{g^2 + g'^2}{8}}_{\textbf{small correction}} \right] |\Sigma|^4$$

Treat B as a perturbation:

- For $B = 0$, H, Σ decouple, EW broken by $\langle \sigma \rangle^2 = -\frac{m_\Sigma^2}{\lambda_\Sigma} = f^2$
- Second *CP*-even Higgs has mass $m_\sigma^2 = 2\lambda_\Sigma f^2$

  for large λ_Σ can integrate it out: effective potential for light h

$$V_{\text{eff}} = \tfrac{1}{2} m_H^2 h^2 - f B h \left[1 + \underbrace{\epsilon \frac{h}{v_h} - \frac{\epsilon^2}{2} \frac{h^2}{v_h^2} + \ldots}_{\textbf{small}} \right]$$

EW symmetry broken by tadpole: $\langle h \rangle = \frac{fB}{m_H^2} = v_h$

Terms of higher order in h are strongly suppressed by

$$\epsilon \sim \frac{m_h^2}{m_\sigma^2} \frac{v_h^2}{f^2} \ll 1$$

even for $f \lesssim v_h$, which allows perturbative Yukawas

Mass spectrum

$$V \;=\; m_H^2\,|H|^2 + m_\Sigma^2\,|\Sigma|^2 + (B H\,\Sigma + \text{h.c.}) + \left[\lambda_\Sigma + \frac{g^2 + g'^{\,2}}{8}\right] |\Sigma|^4$$

Light triplet of new scalars $A, H^\pm$ with mass

$$m_A \simeq m_h \tfrac{v}{f}$$

The second CP-even Higgs is heavier: $m_\sigma^2 \simeq m_A^2 + 2\lambda_\Sigma f^2$

pheno dominated by the pseudoscalar and charged Higgs

- The tadpole regime requires $m_\Sigma^2 < 0$: $\langle\sigma\rangle^2 = -\frac{m_\Sigma^2}{\lambda_\Sigma} = f^2$
- For $m_\Sigma^2 \gg 0$ the model has decoupling limit:

  low energy theory is quartic h potential with $\lambda \sim \lambda_\Sigma s_\alpha^4\,,\quad \tan\alpha = f/v_h$

- Model interpolates between *induced tadpole* and *induced quartic* regimes.

  Compass: Higgs cubic coupling

Pheno: bounds

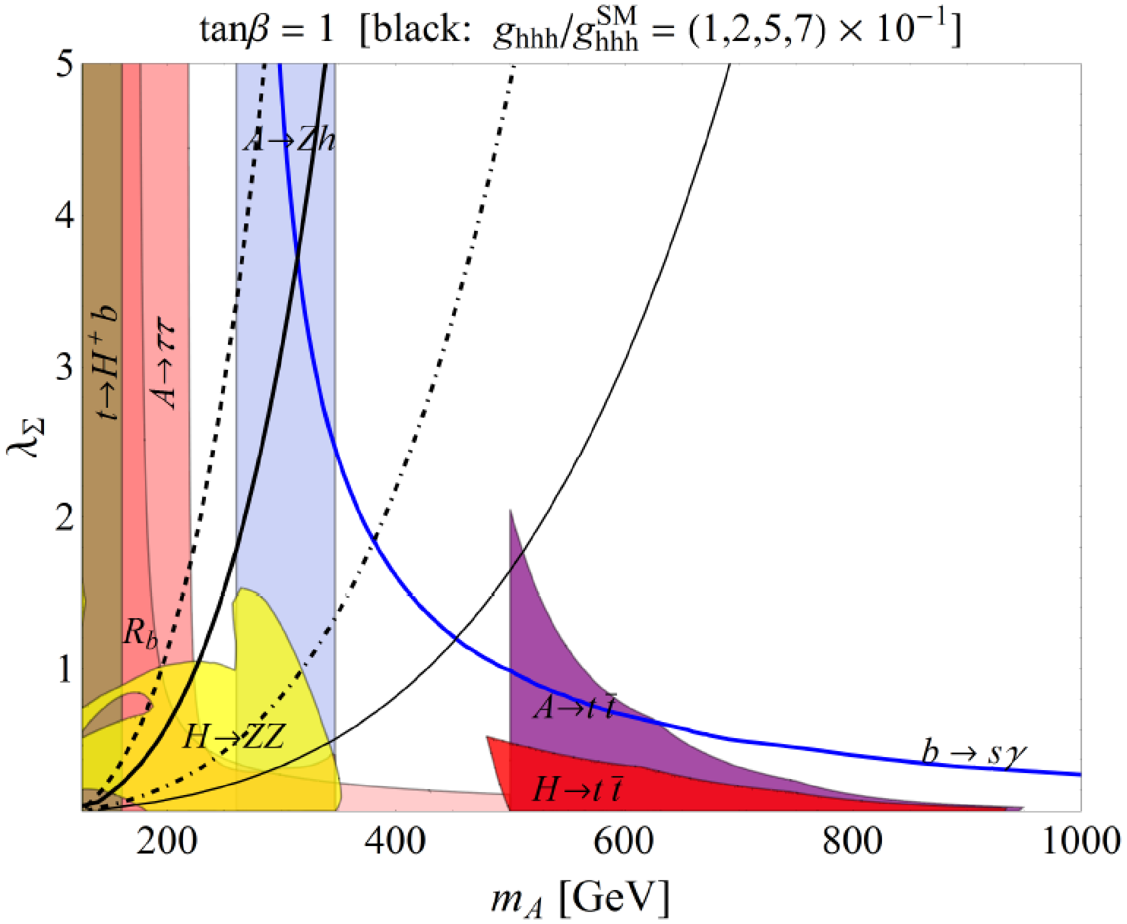
see also Chang, Evans, Luty 2011

Take as independent params

$$\lambda_\Sigma \,,\, m_A$$

$$(m_{H^\pm} = m_A)$$

Current bounds:



Higgs couplings fit gives bound weaker than $A \to Zh$

(in progress)

- A Higgs cubic coupling as small as 20% of the SM is consistent with all data!

➡ **tadpole potential is open possibility for EWSB**

- Strong correlation between light A and suppression in Higgs cubic coupling

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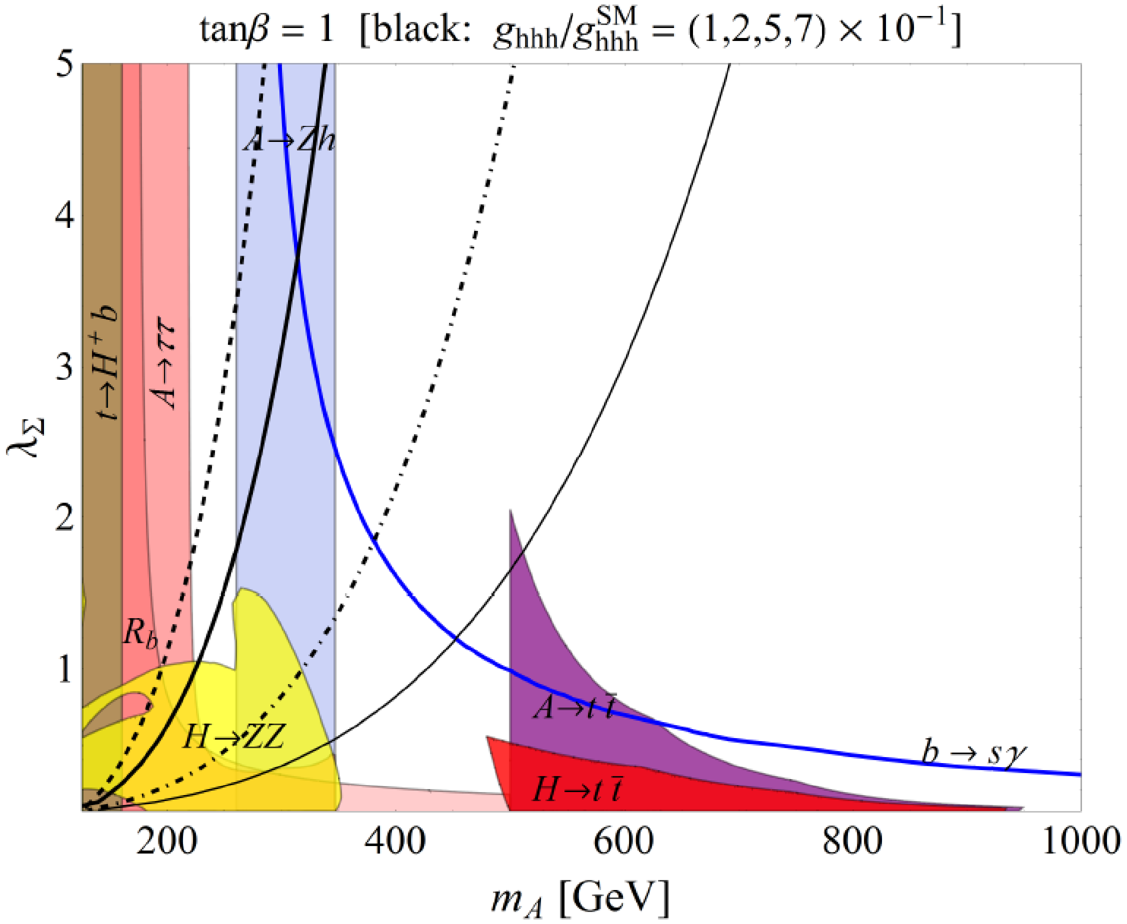

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- Strong correlation between light A and suppression in Higgs cubic coupling

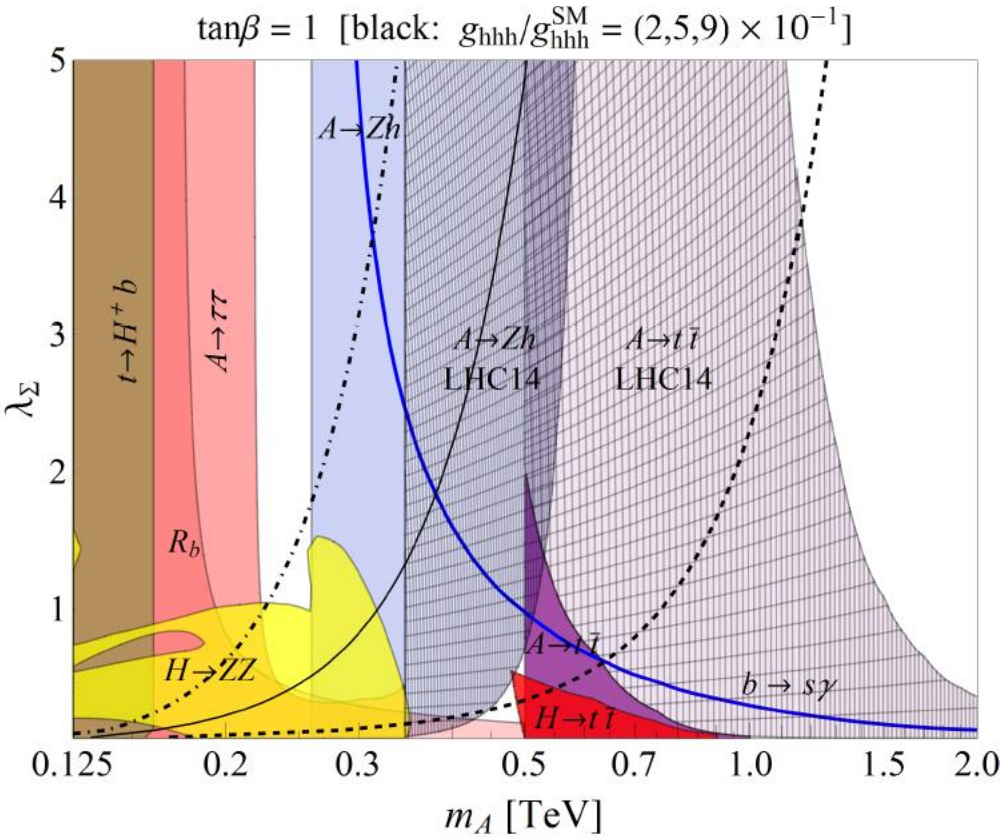
(→ enhancement of double Higgs production rate)

LHC 14 projection

Salam and Weiler

- Most relevant searches are $A \to Zh, \; A \to t\bar{t}$
- Do simple projection to 14 TeV, 300/fb using ‘Collider Reach’ method

  (require same number of signal events at 8 and 14 TeV)



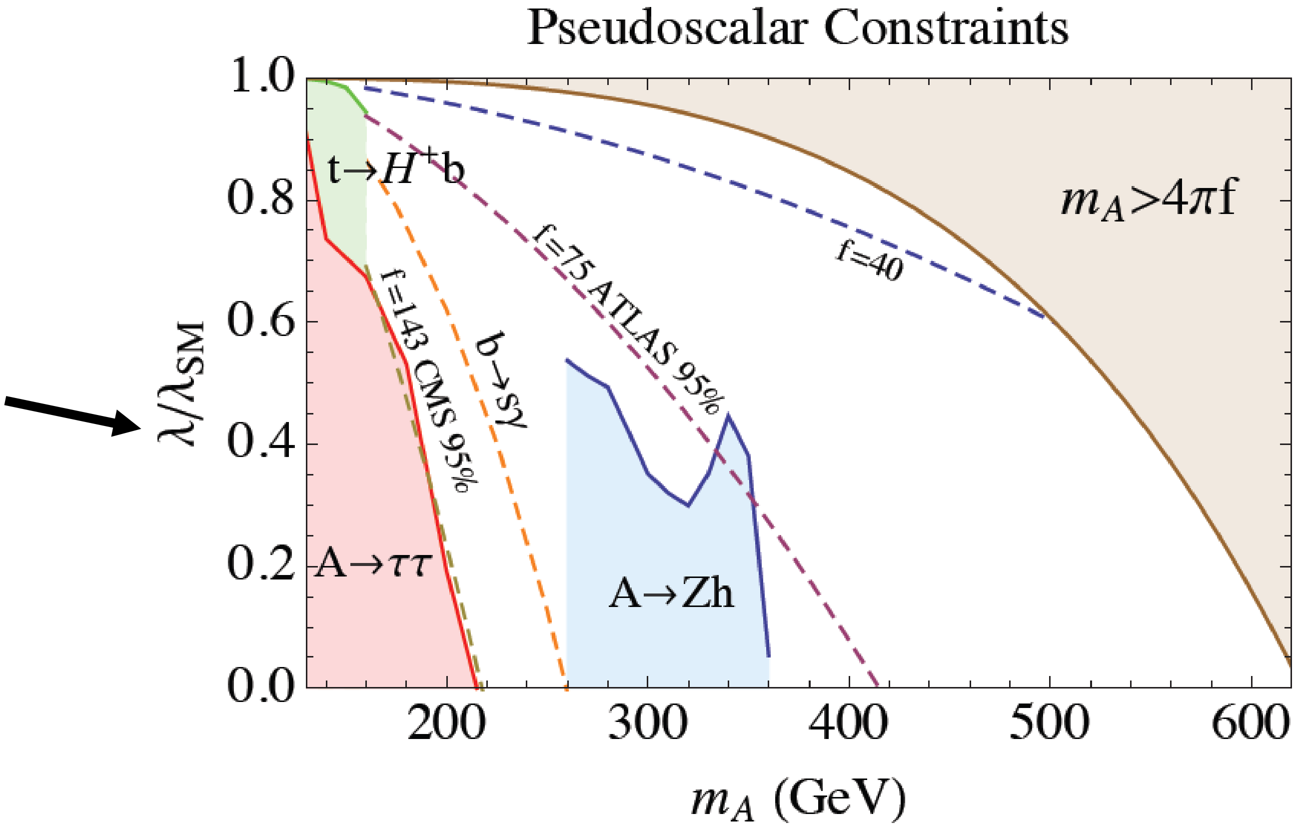
- Searches for A can constrain the model to far decoupling region, *independently* of double Higgs production

Strongly coupled models

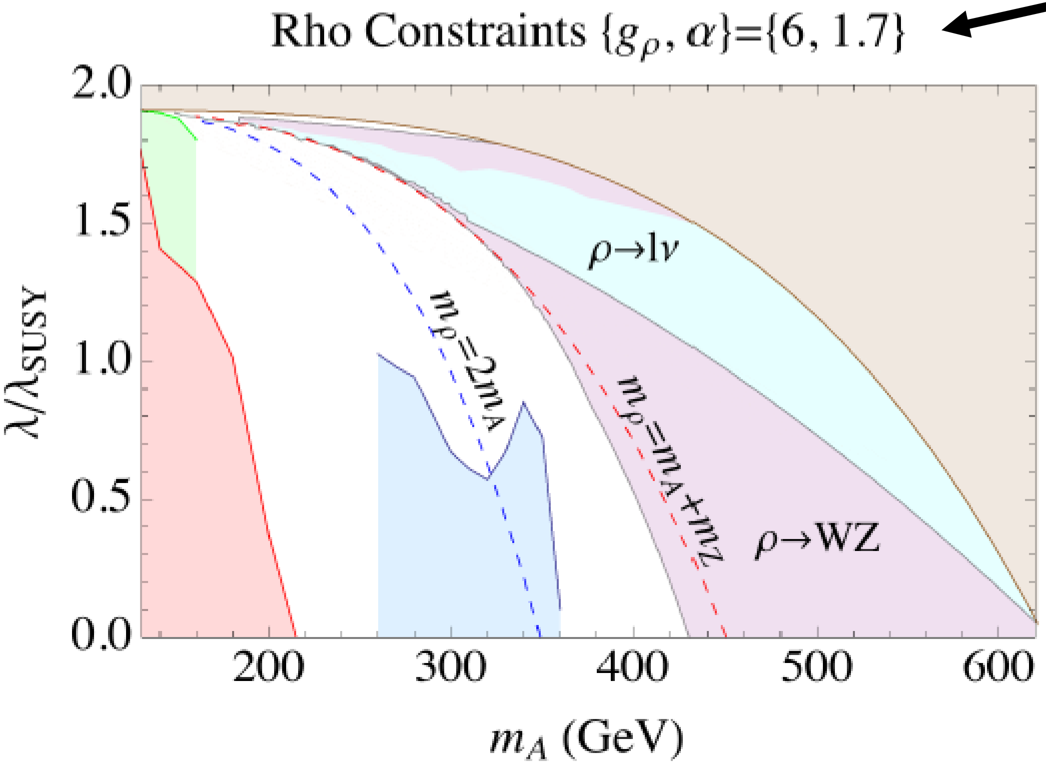
Superconformal TC, Azatov, Galloway, Luty, 2011

- Σ is a nonlinear sigma field coupled to Higgs doublet H
- Corresponds to limit of perturbative model for very large λ_Σ

extra quartic for H



Strongly coupled models (2)



values taken from QCD rho

$$m_\rho \approx \sqrt{\alpha} g_\rho f$$

If rho is heavier than $m_{H^\pm} + m_Z$ or $2m_A$,

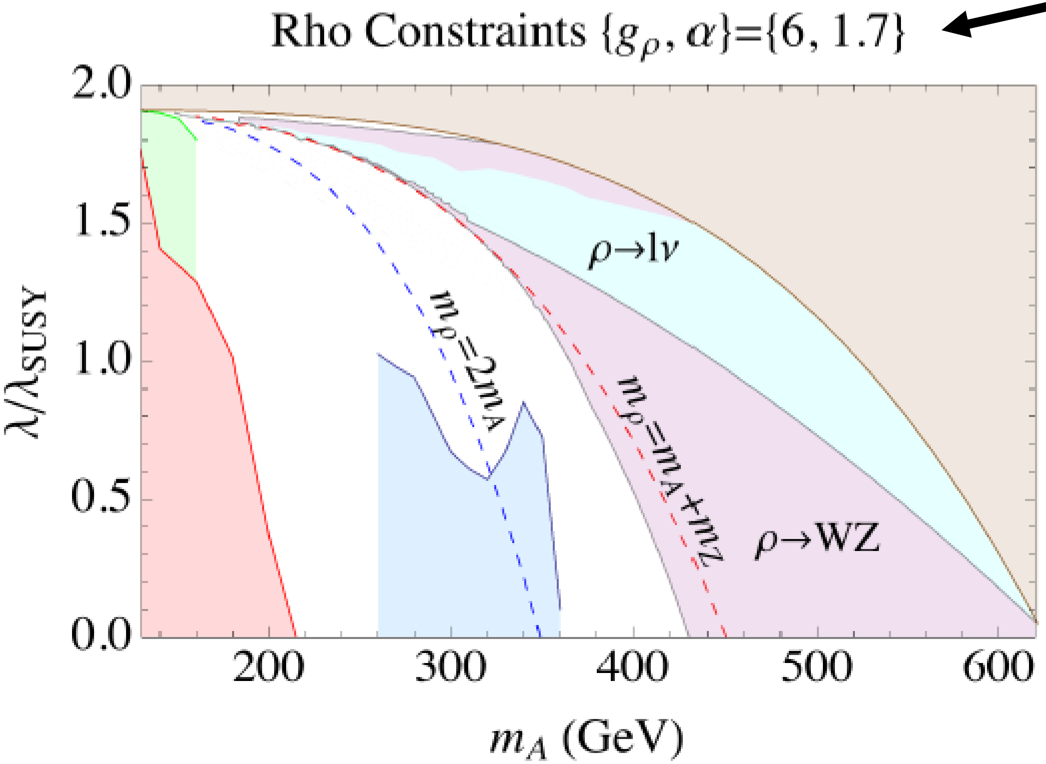
decays $\rho^+ \to H^+Z$, $\rho^+ \to H^+A$ open up and

constraints from heavy vector searches can be evaded

Cascade decays give striking new signals, e.g.

$$\rho^+ \to H^+A \to t\bar{b}Zh \qquad \rho^+ \to W^+A \to W^+Zh$$

Strongly coupled models (2)



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$$\left(\hat{S} \sim \frac{g^2}{4g_\rho^2} \sim 2.5 \times 10^{-3} \quad \text{for} \quad g_\rho = 6\right)$$

Summary

- Models of induced EWSB are an attractive possibility for generating a 125 GeV Higgs in SUSY.
- Electroweak symmetry is broken thanks to a tadpole, induced by auxiliary fields with large quartics.

  The model predicts light pseudoscalar and charged Higgs.
- The mechanism is consistent with all current bounds.

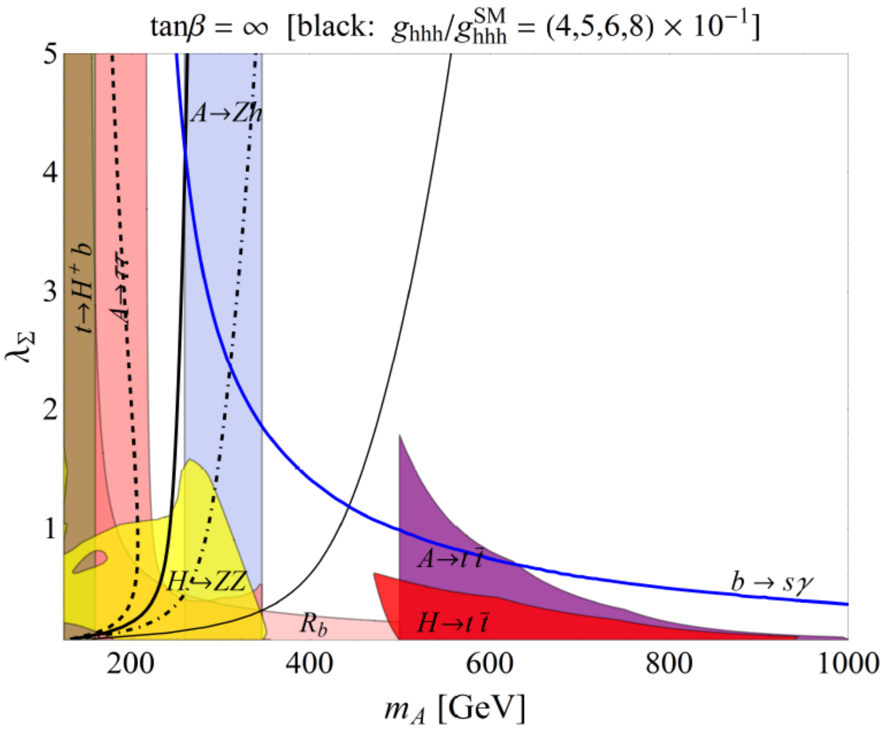
  Searches for $A \to Zh, t\bar{t}$ can test it at 14 TeV.
- In the strongly coupled realization, vector resonances can decay dominantly to new scalars:

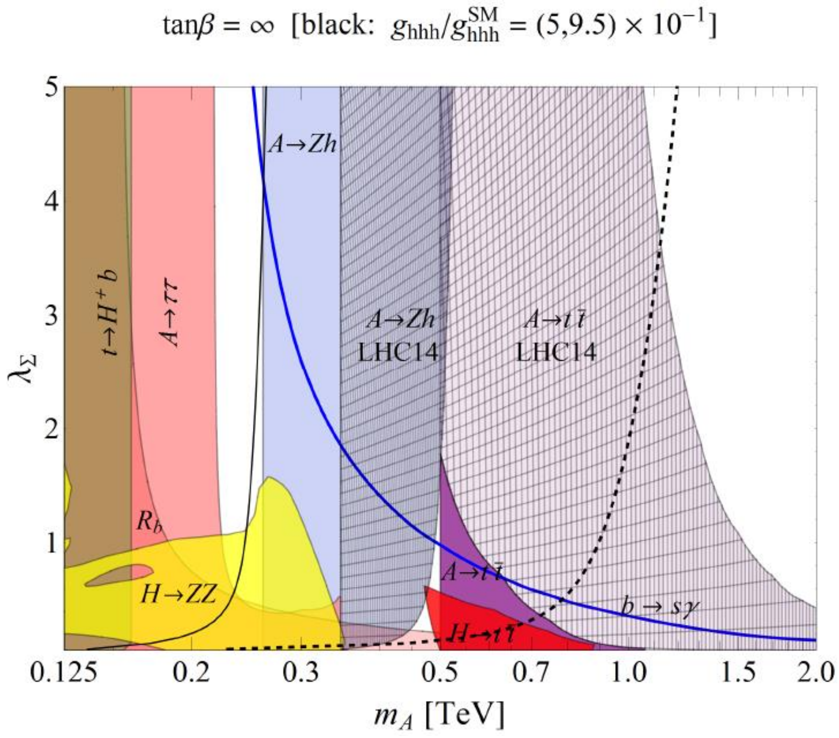
  weaker bounds, new multi-particle signals from cascade decays

Backup

Large tanβ

$$V_D^{(\tan\beta=\infty)} = \frac{g^2+g'^2}{8}\left(|H|^2-|\Sigma_d|^2\right)^2 + \frac{g^2}{2}H^\dagger\Sigma_d\Sigma_d^\dagger H$$





Bounds are very similar to case $\tan\beta = 1$, but now quartic for *H* of size $\sim \lambda_{\rm SM}/2$

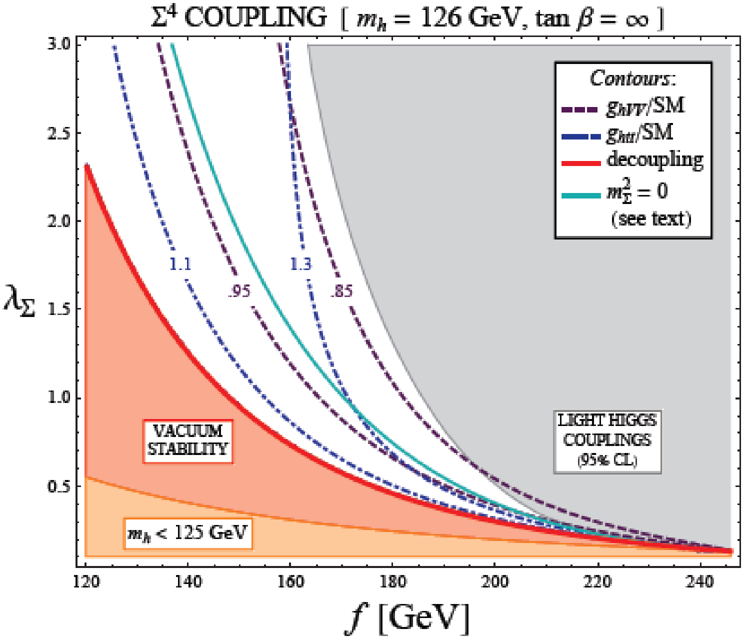
Induced EWSB: simplified model

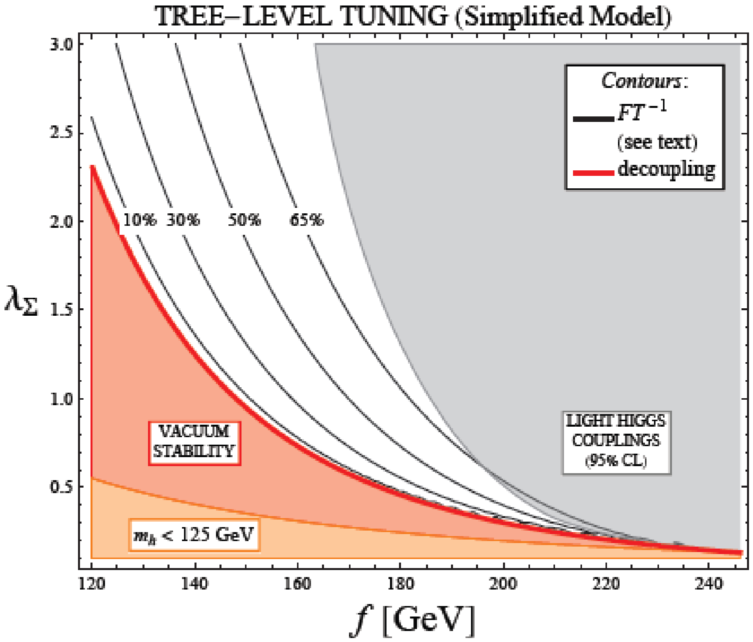
Two-doublet model: *H* (‘MSSM’ doublet) and *Σ* (auxiliary, has no Yukawas)

$$V \simeq m_H^2 \left|H\right|^2 + m_\Sigma^2 \left|\Sigma\right|^2 + (BH\Sigma + \mathrm{h.c.}) + \lambda_\Sigma \left|\Sigma\right|^4$$

In general, VEV of *H* is **induced** by auxiliary field *Σ* : for the mass matrix of *CP*-even Higgses have $\det \mathcal{M}^2 = 2\lambda_\Sigma f^2 m_H^2$

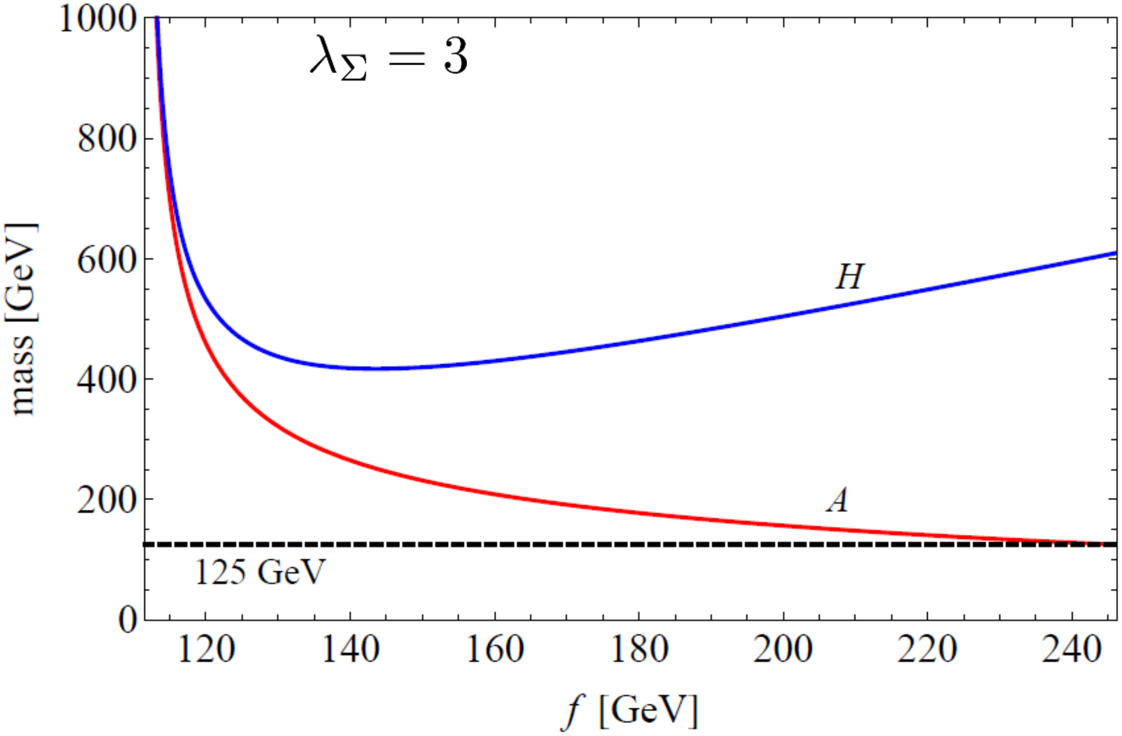
➡ vacuum stability requires $m_H^2 > 0$, so EW unbroken in the absence of *Σ*





Separation between induced quartic and induced tadpole regimes ~ $m_\Sigma^2 = 0$

Mass spectrum



$$(m_{H^\pm} = m_A)$$

Induced EWSB: decoupling limit

Two-doublet model: *H* (‘MSSM’ doublet) and *Σ* (‘auxiliary’, has no Yukawas)

$$V = m_H^2 \left|H\right|^2 + m_\Sigma^2 \left|\Sigma\right|^2 + (BH\Sigma + \text{h.c.}) + \lambda_\Sigma \left|\Sigma\right|^4$$

Consider two different limits:

1) One linear combination of H, Σ has large and positive mass squared m_2^2

➡ it has no VEV.

Diagonalize quadratic terms by $\begin{pmatrix} H \\ \Sigma \end{pmatrix} \to \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} H_1 \\ H_2 \end{pmatrix}$ $\left(\tan\alpha = \frac{f}{v_h}\right)$

leading to $V_{\text{eff}} = m_1^2 \left|H_1\right|^2 + \lambda_\Sigma s_\gamma^4 \left|H_1\right|^4$: **induced quartic**

In the decoupling limit, only one doublet relevant at low energies, light Higgs couplings approach their SM values