INDUCED EWSB

GGI, Florence
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NEW YORK UNIVERSITY

CCPP
CENTER FOR COSMOLOGY AND PARTICLE PHYSICS

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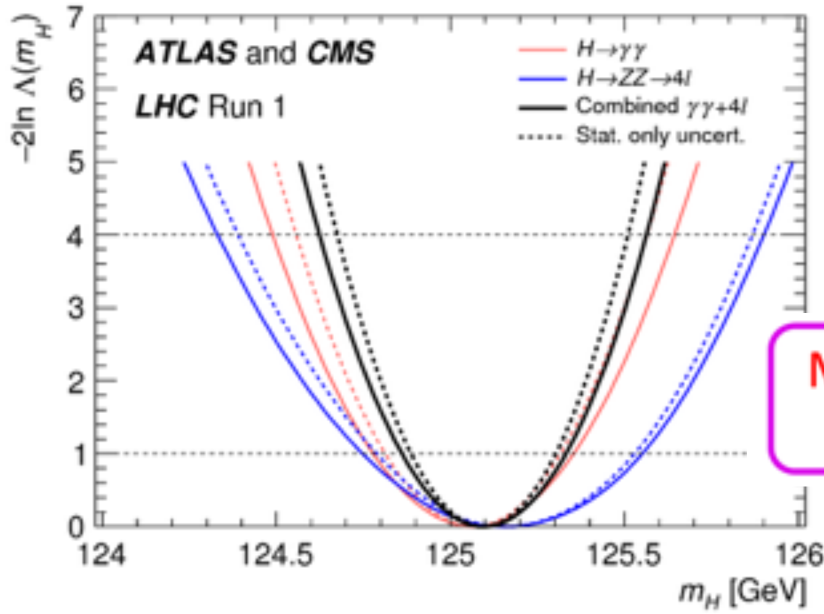
Based on work with:
A. Azatov, S. Chang, M. Luty, E. Salvioni, Y. Tsai, Y. Zhao

outline

- o Introduction/Motivation
- o Modeling, take one: realization with strong dynamics
- o Modeling, take two: realization with perturbative dynamics
- o Implications: phenomenology at the LHC
- o A conclusion or two

introduction

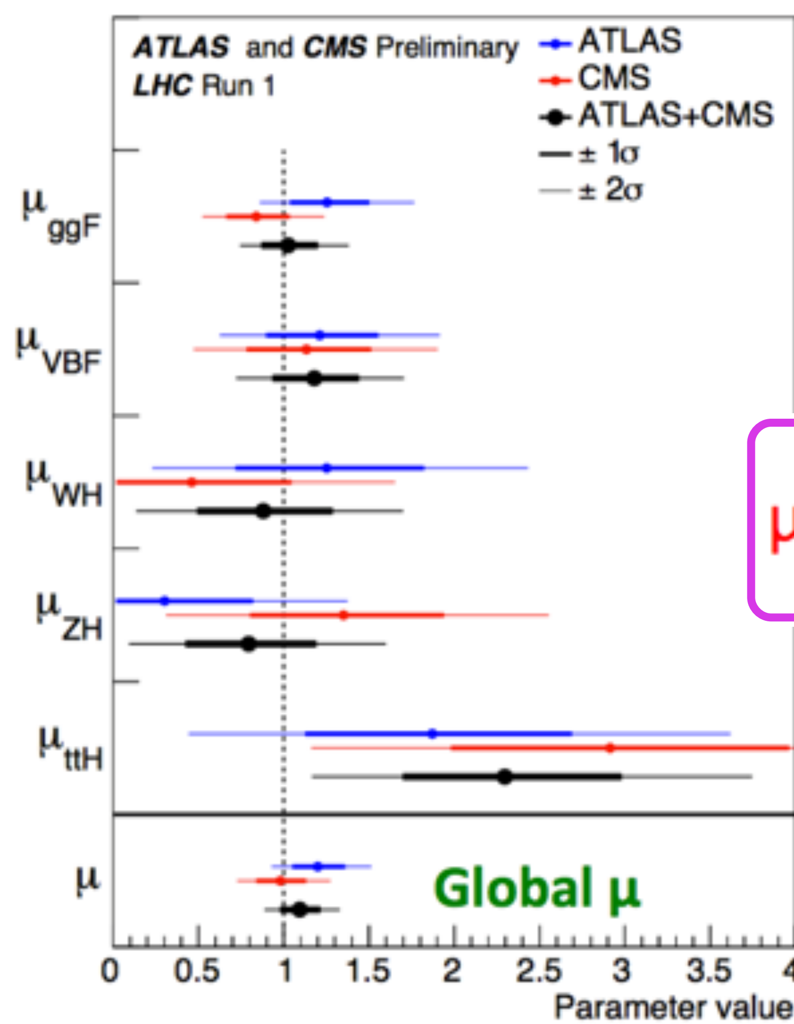
h mass:



$M_H = 125.09 \pm 0.24$ GeV
$= \pm 0.21$ (stat.) ± 0.11(syst.) GeV

h couplings:

(tree-level)



$\mu = 1.09^{+0.11}_{-0.10}$

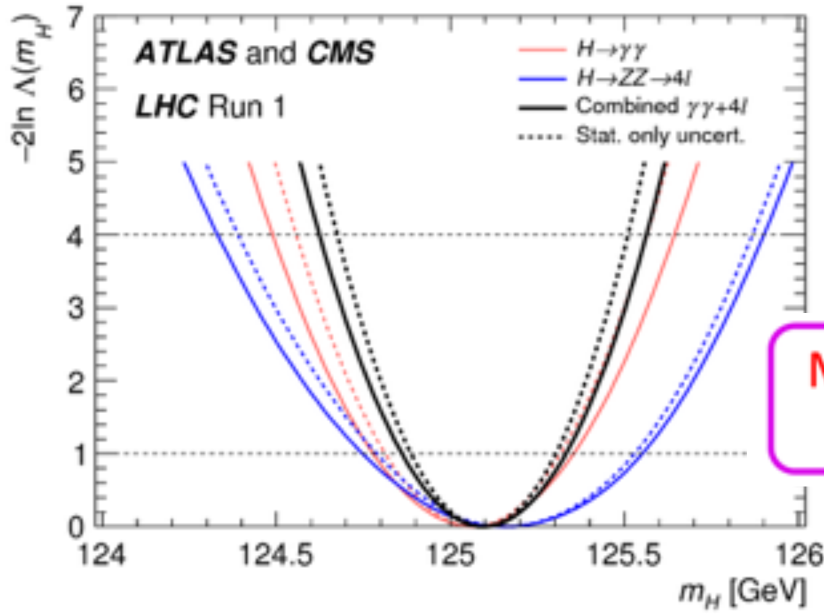
Examples:

- *v/f* in comp. *H* (MCHM4)
- 'non-alignment' in type-1 2HDM at large tan β
- Higgs mixing with singlet

*ref: M. Pieri @ LHCP 2015

introduction

h mass:



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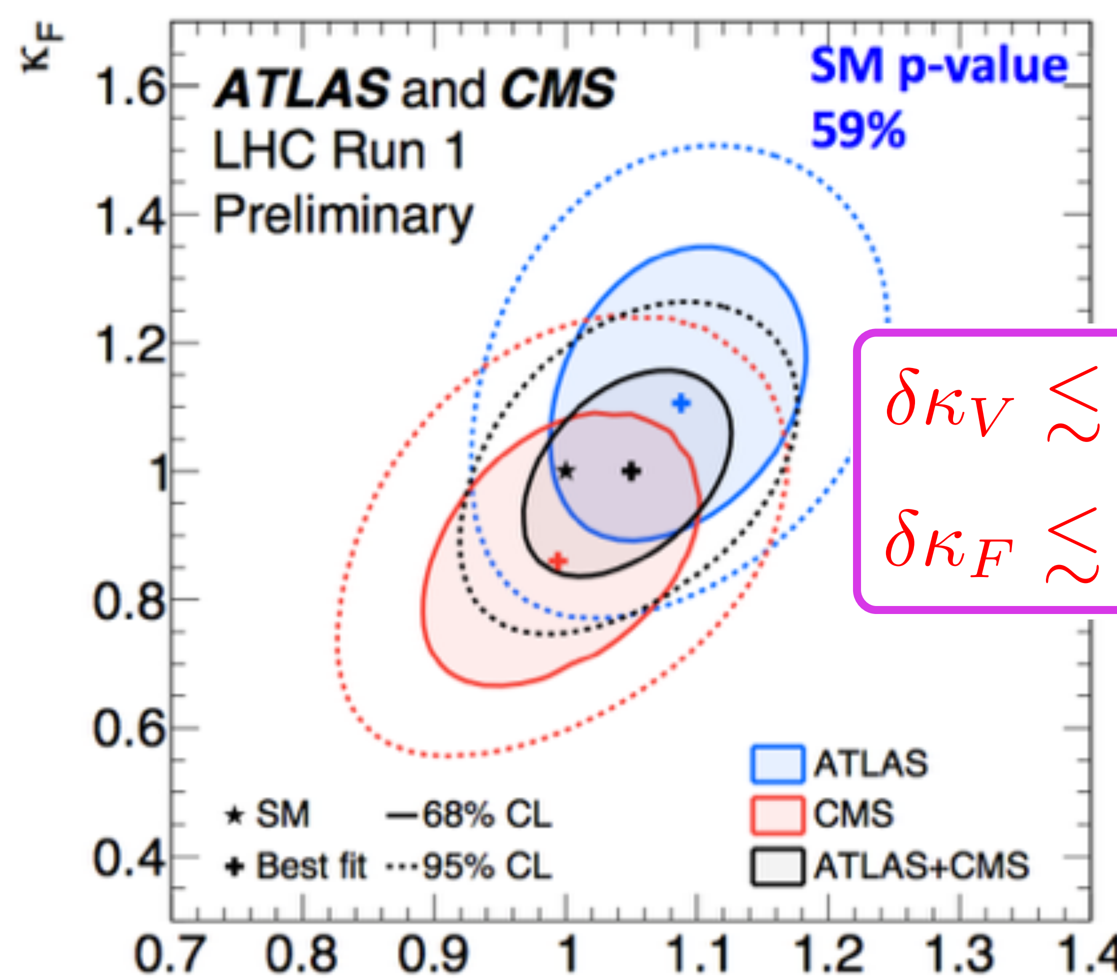


$\delta\kappa_V \lesssim 0.08$

$\delta\kappa_F \lesssim 0.16$

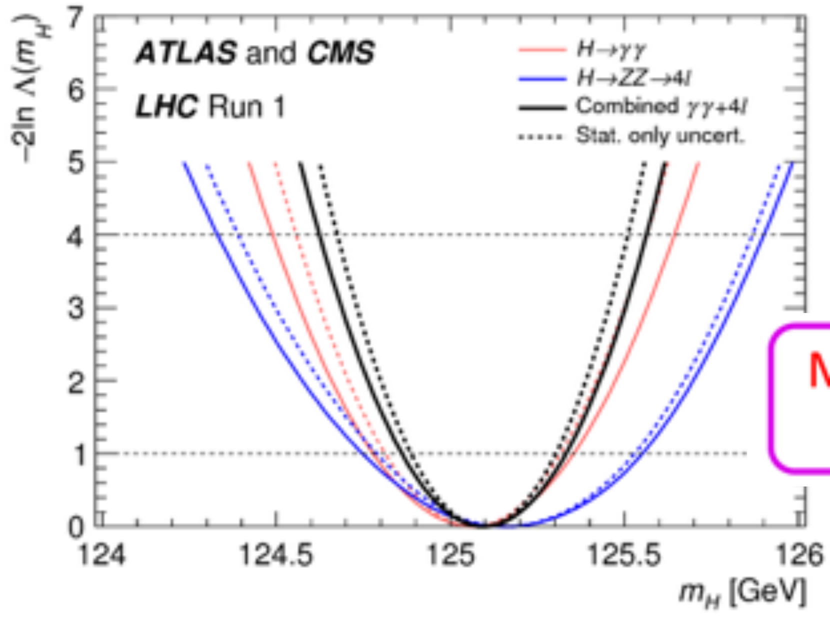
Examples:

- type-1 2HDM at variable tan β

*ref: M. Pieri @ LHCP 2015

introduction

***h* mass:**



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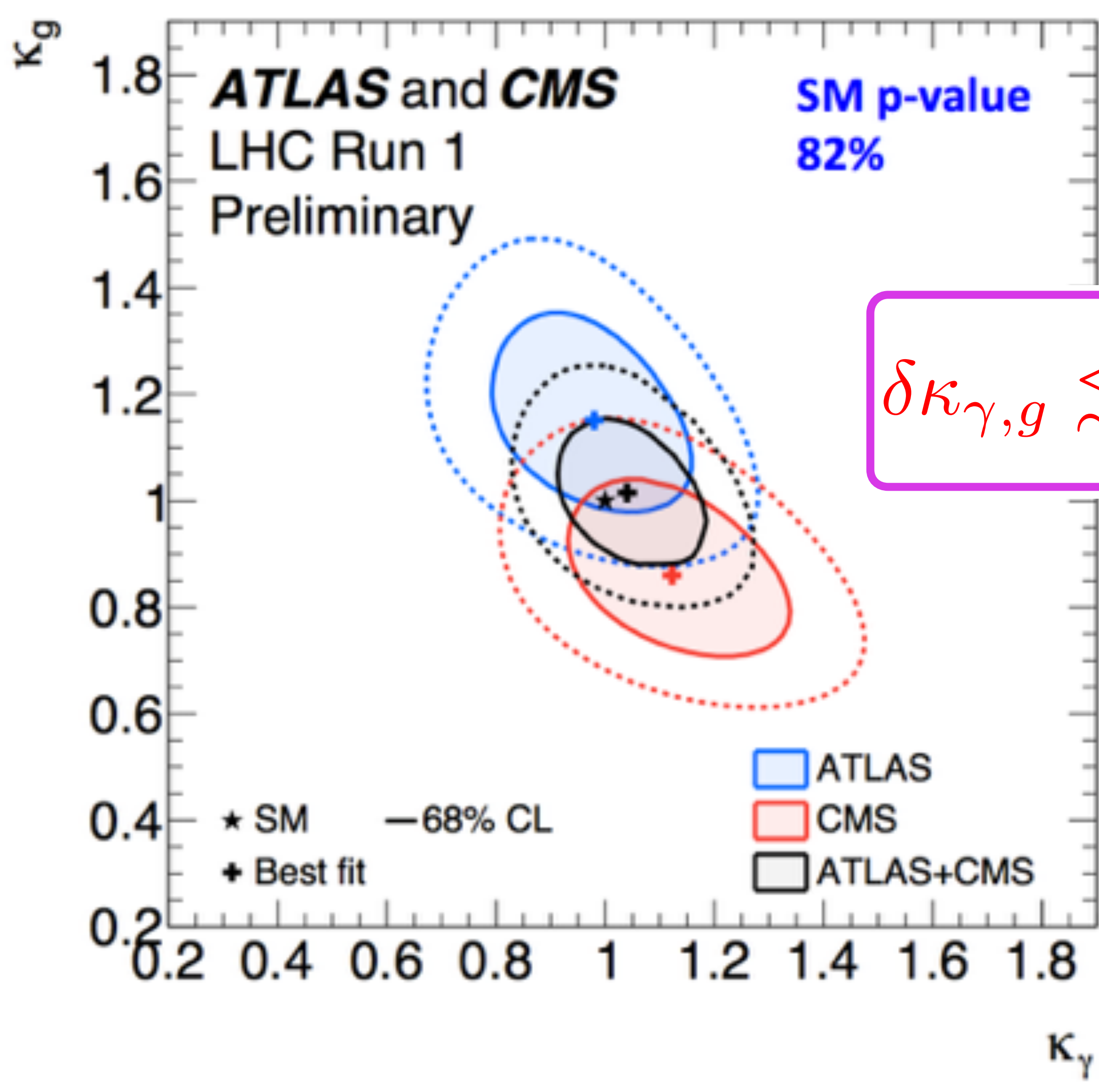
***h* couplings:**
(loop-level)



$\delta\kappa_{\gamma,g} \lesssim 0.14$

Examples:

- light top partners
- charged Higgses

*ref: M. Pieri @ LHCP 2015

takeaway (and assumptions going forward)

- h confirmed at 125 GeV
- Tree-level couplings are already at ~SM ± 10%
- Loop-level at ~SM ± 15%, consistent with…
- …null results from partner searches up to ~600 GeV

takeaway (and assumptions going forward)

- h confirmed at 125 GeV

****~ SUSYish****

- Tree-level couplings are already at ~SM ± 10%

****composite *H* tuned at least at 10%****

- Loop-level at ~SM ± 15%, consistent with…

****~inconclusive****

- …null results from partner searches up to ~600 GeV

****still room for (somewhat) natural elementary *H*****

I'll take this circumstantial evidence for an *elementary* Higgs seriously; assume SUSY stabilization and focus on the question of **mass**

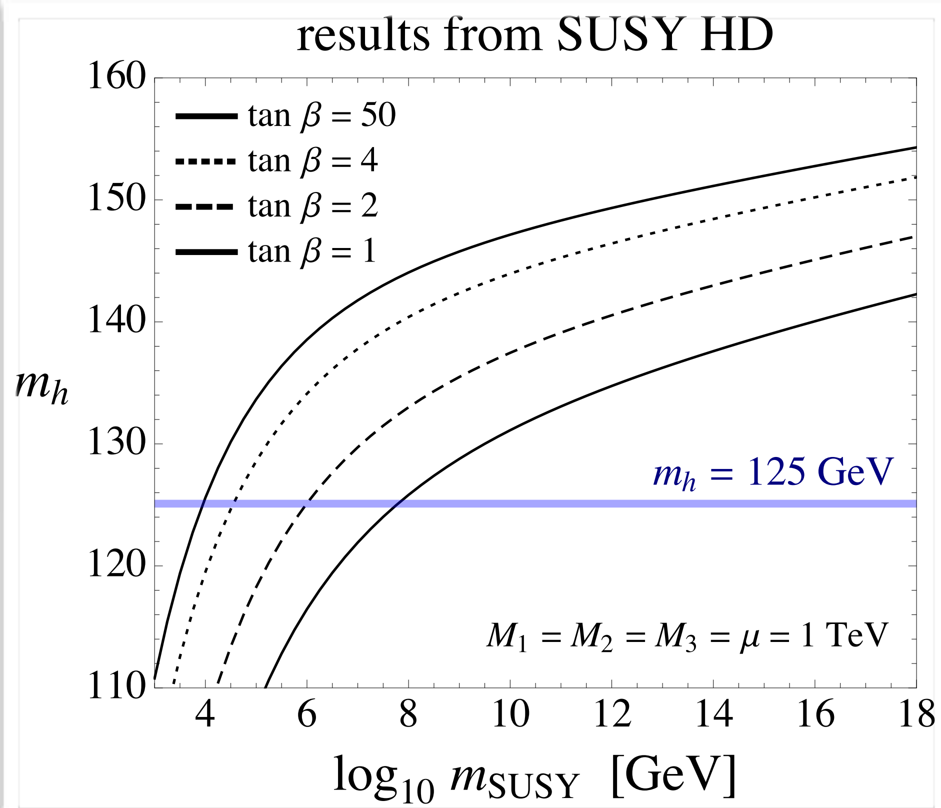
SUSY Higgs and its mass

$$m_h^2 = 2\lambda v^2 \qquad \lambda \leq \frac{1}{8}(g^2 + g'^2) \qquad m_h \leq m_Z$$

SUS'ic relation for H quartic is too small by a factor of 2…

⇒ need an order one breaking!

Can be done with spectrum, but not very naturally



*ref: Vega, Villadoro (JHEP 2015)

$\tan\beta$	m_{SUSY} (GeV)
1	3×10^7
2	10^6
4	35×10^3
50	10^4

problem: $\delta m_H^2 \propto m_{SUSY}^2$

High SUSY scale (and thus pressure on naturalness) boils down to very special role of quartic (and very 'special' smallness of it)

unavoidable consequence of V(H) with negative quadratic

induced EWSB: a strong model

[turn that frown upside down]

what if… $V(H) \sim \oplus (125)^2 \, |H|^2 + \lambda \, |H|^4$

naively:
- o EW intact
- o massless W, Z, fermions
- o physical mass approximately independent of quartic

less naively:
- o EW broken by QCD
- o W, Z acquire mass $\sim g f_\pi / 2 \sim 50\,\mathrm{MeV}$
- o electron mass $m_e \sim y_e y_q \times 4\pi f_\pi^3 / m_h^2 \sim 10^{-5}\,\mathrm{eV}$

4 strong NO votes
~1.5 yes votes

(consensus may well be misguided;
cf. Trump leading GOP)

induced EWSB: a strong model

Higgs 'VEV' in previous example fixed by QCD…
…consider instead a TC-like sector

$$\text{“}v\text{''} \sim \frac{y_u \Lambda_{\rm QCD}^3}{16\pi^2 m_h^2} \to \frac{\lambda \Lambda_{\rm TC}^3}{16\pi^2 m_h^2}$$

$$\left.\right\} \quad \begin{array}{l} \Lambda_{\rm TC} = \text{TeV} \\ \text{“}v\text{''} \to \lambda \times \text{TeV} \end{array}$$

$$\Delta V_{\rm UV} = m_H^2 \left|H\right|^2 - (\lambda H \psi \psi' + \text{h.c.}); \quad \psi = (\Box, 2)_0, \ \psi' = (\overline{\Box}, 1)_{-1/2}$$

$$\Rightarrow \quad \Delta V(\mu < \text{TeV}) = m_H^2 \left|H\right|^2 - c_1 \left(\frac{\lambda \Lambda_{\rm TC}^3}{16\pi^2} H + \text{h.c.} \right)$$

*contrast e.g. SILH

induced EWSB: a strong model

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Upshot:

- o Confining dynamics induces $\langle H \rangle \neq 0$
- o Elementary Higgs VEV naturally right size.
- o Elementary Higgs mass is independent of quartic.*
- o New isotriplet (minimally) of scalars exists below ~TeV.

* Corrections from quartic < 20%

induced EWSB: a strong model

EFT coupling H to TeV scale strong sector (w/ nonlinear sigma field)

*ref: Azatov, Galloway, Luty (PRL 2012)

kinetic: $$\Delta\mathcal{L} = \frac{f_{\rm TC}^2}{4}\,\mathrm{tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right] + \frac{1}{2}\,\mathrm{tr}\left[(D_\mu\mathcal{H})^\dagger(D^\mu\mathcal{H})\right]$$

$$\Rightarrow m_W^2 = \frac{g^2}{4}(f_{\rm TC}^2 + v_h^2)$$

"bipartisan EWSB"

interaction: $$\Delta\mathcal{L} = \sum_{n\geq 1} c_n \frac{\Lambda^{4-n}}{16\pi^2}\,\mathrm{tr}\left(\mathcal{H}^\dagger\lambda\Sigma\right)^n$$

controlled expansion parameter $\epsilon \equiv \dfrac{\lambda v_h}{\Lambda} \ll 1$

$\epsilon \lesssim 0.1$ with $v_h = 230\,\mathrm{GeV}$, $\lambda = 0.5$

constraint from Higgs @ LHC:

$$\frac{\delta g_{VVH}}{g_{VVH}^{(\rm SM)}} \lesssim 0.08 \quad\Rightarrow\quad f < v\times\sqrt{(2-\delta)\delta} \approx 95\,\mathrm{GeV}$$

induced EWSB: a strong model

Recap: an 'induced' VEV for the elementary field

$$v_h \sim \frac{\lambda}{4\pi}\frac{\Lambda^2}{m_h^2} \times f$$

$$[\text{sensible for } \lambda = \mathcal{O}(1),\ \Lambda \sim \text{TeV}]$$

…(recklessly) reimagine as a linear sigma model

$$v_h \sim \frac{\lambda}{4\pi}\frac{m_{\sigma_{\rm TC}}^2}{m_h^2} \times f_{\sigma_{\rm TC}}$$

[i.e. treat $\Lambda \sim 4\pi f \to m_\sigma$]

$$\Rightarrow \epsilon \equiv \frac{\lambda v_h}{\Lambda} \to \boxed{\frac{v_h^2}{f^2}\frac{m_h^2}{m_\sigma^2}}$$

induced EWSB: a strong model

Recap:

Criteria for generalized induced EWSB

- H in isolation does NOT break EW
- EW broken appreciably by heavy fields: appreciably $(f \sim v_h)$, heavy fields $(m_\sigma \gg m_h)$
- i.e. EW nonlinearly realized at scales > 125
- coupling H to heavy EWSB source induces <H>
- can be realized in 2HDM (with weaker couplings)…

$$\Rightarrow \epsilon \equiv \frac{\lambda v_h}{\Lambda} \rightarrow \frac{v_h^2}{f^2}\frac{m_h^2}{m_\sigma^2}$$

induced EWSB: a perturbative model

[considering a single H doublet]

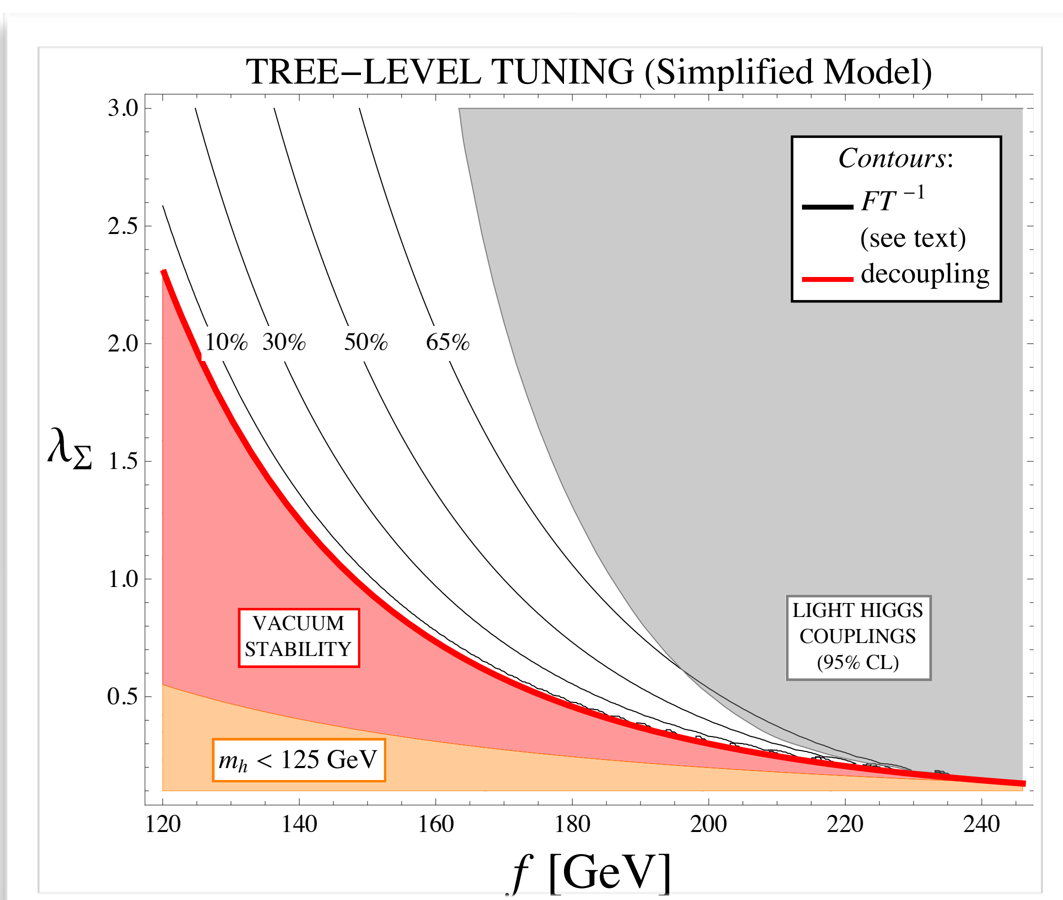
$$V = m_H^2|H|^2 - m_\Sigma^2|\Sigma|^2 - \kappa^2(H^\dagger\Sigma + \text{h.c.}) + \lambda_\Sigma|\Sigma|^4$$

'auxiliary Higgs' $\lambda_\Sigma \gg \lambda_H$

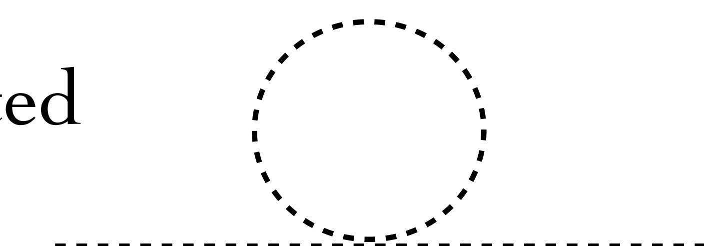
small mixing $\Rightarrow \langle\Sigma\rangle = f \propto \frac{|m_\Sigma|}{\sqrt{\lambda_\Sigma}},\ m_\sigma^2 \propto \lambda_\Sigma f^2 \gg m_h^2$

$$\hookrightarrow\ V_{\text{eff}}(h) = \frac{1}{2}m_H^2 h^2 - \kappa^2 f h + \mathcal{O}(\kappa^4) \Rightarrow v_h \propto \frac{\kappa^2 f}{m_H^2}$$

*ref: Galloway, Luty, Tsai, Zhao (PRD 2014); Alves, Fox, Weiner (PRD 2015)



Higgs mass corrected via coupling to Σ:



$$\Rightarrow \delta m_h^2 \propto \frac{\lambda}{16\pi^2} m_\sigma^2\ (\times \text{mixing angles})$$

(reminiscent of corrections from stops with important distinction that σ needn't be pushed to >>TeV scales)

phenomenology: TC-like model

$$(H_u,\ H_d,\ \Sigma) \Rightarrow 8 \text{ physical scalars:}$$

$$\text{MSSM}\ \left\{ \begin{pmatrix} H_2^{\pm}, A_2^0 \\ H_1^0, H_1^{\pm}, A_1^0 \\ h \\ G^{\pm}, G^0 \end{pmatrix} \right. \quad \} \, \pi_{\rm TC}^{(1,2,3)}$$

$$\Delta\mathcal{L} \supset \lambda(v_h + H)\psi\psi' \Rightarrow \boxed{m_\pi^2 \sim (\lambda_u v_u + \lambda_d v_d) \times \Lambda}$$

$$\equiv (\epsilon_u + \epsilon_d) \times \Lambda^2 \approx (500\,\text{GeV})^2$$

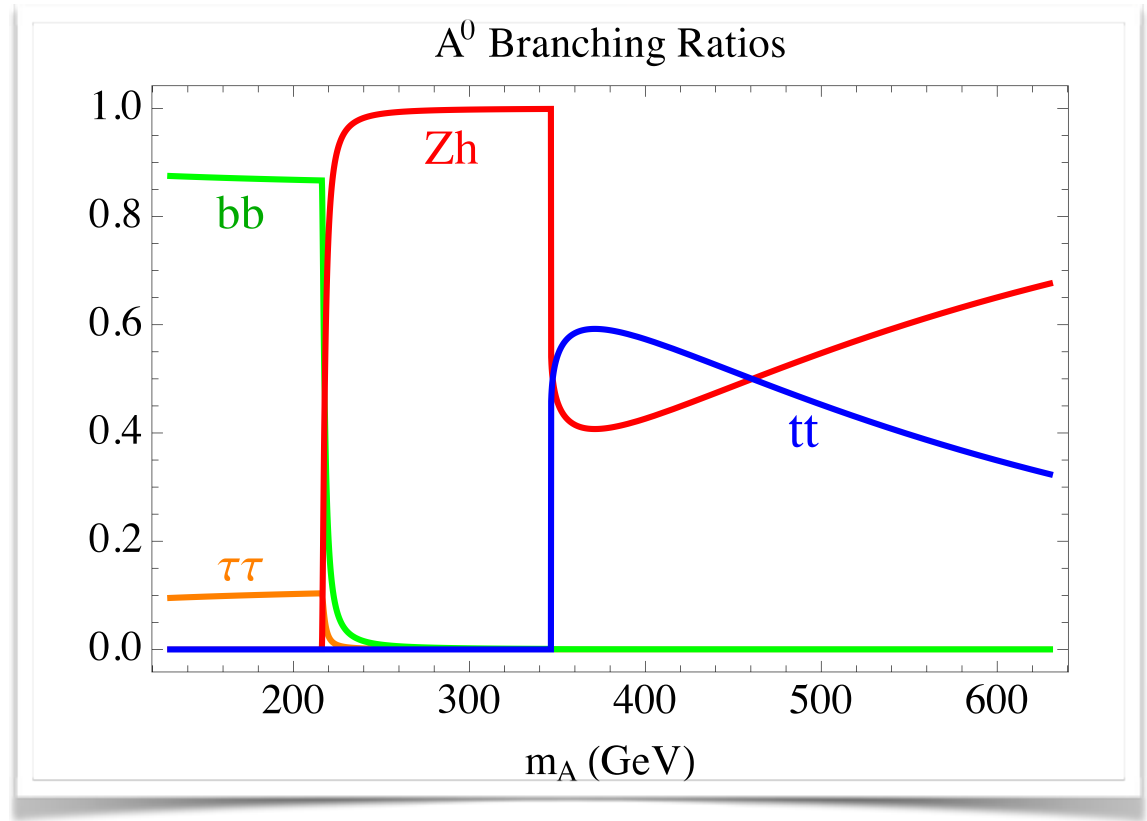
Heavy Higgses (pions) produced by, decay to, SM via mixing
or through auxiliary fields' SU(2) couplings

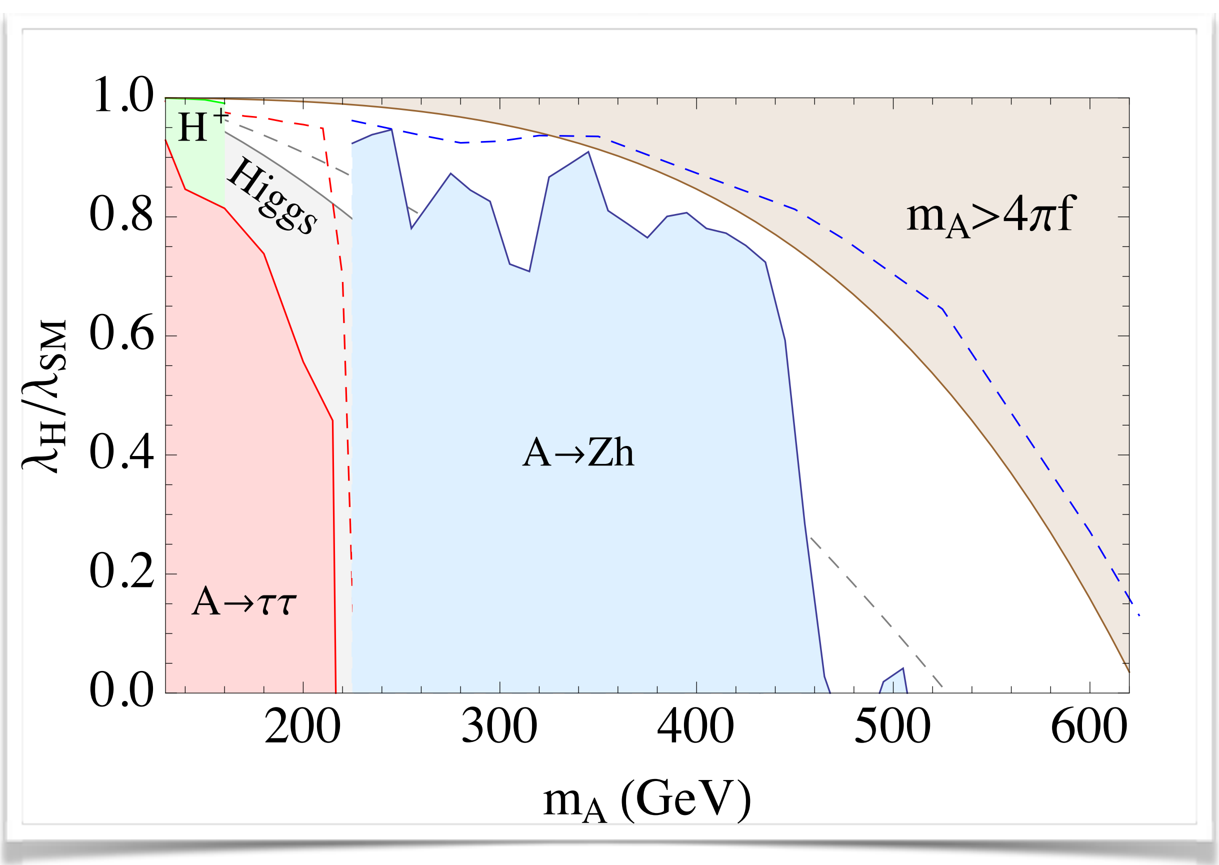
UNIQUE signals: compare with MSSM (*H* couples to *f*),
NMSSM ("*S*" inherits *all* quantum numbers from mixing),

phenomenology: TC-like model

[examples, exclusions]

- Decouple second H (to simplify)
- sub-TeV pseudoscalar remains from TC sector
- couples to fermions only through mixing: Zh persists even at m>350



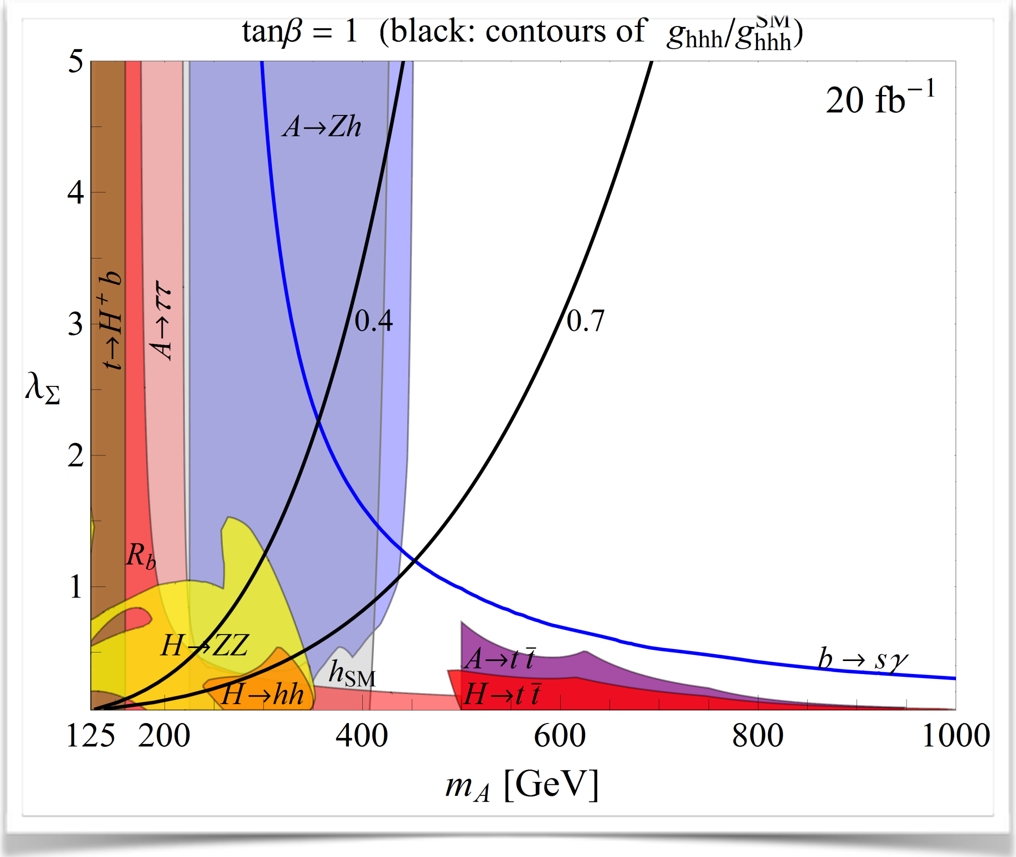


- A > Zh to cover most space @ LHC
- powerful exclusion for strong model due to small ff couplings

*ref: Chang, Galloway, Luty, Salvioni, Tsai (JHEP 2015)

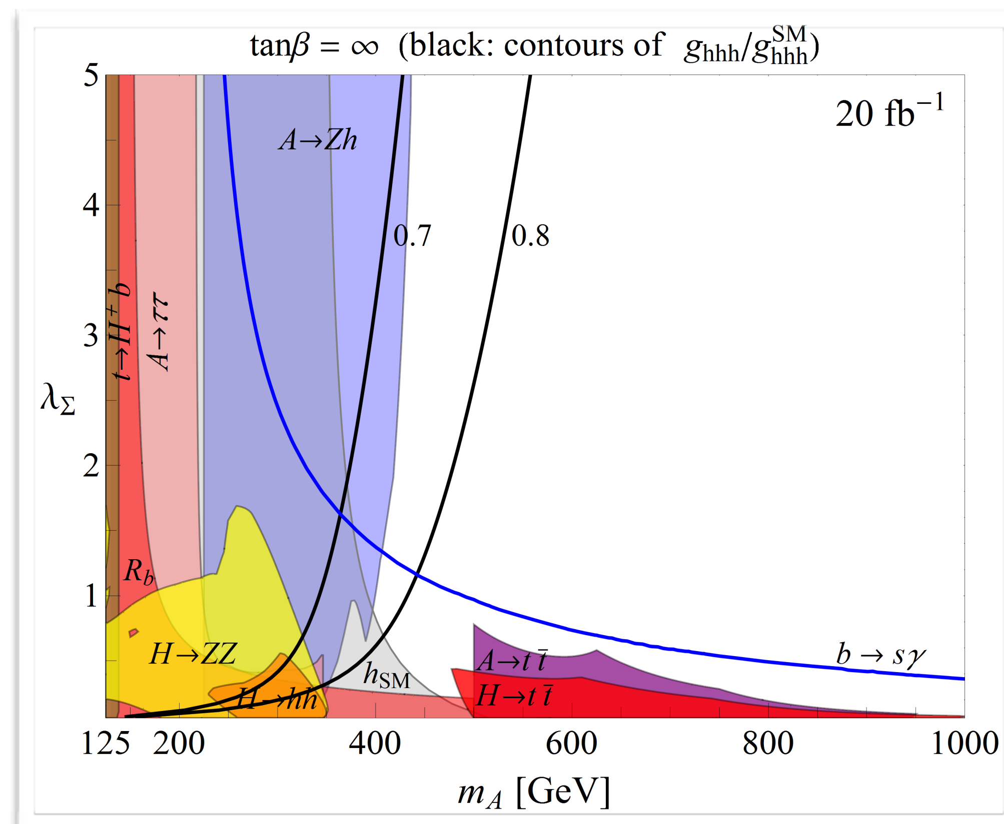
phenomenology: 2HDM-like model

[illustrating possibility of reduced trilinear]



- direct searches exclude up to m ~ 400
- 50% reduction in H trilinear remains possible (!)

- even at large tan β significant reduction persists (~30%) for large 'auxiliary' self-interactions



conclusions

- h @ LHC still allows ~1/3 of W mass to be generated elsewhere

- If excitations of this other EWSB source are heavy and
  couple to H, the Higgs EFT contains a tadpole

- non-zero Higgs VEV may not require negative quadratic;
  H may not break EW at all *in isolation*

- Higgs quartic is consequently untethered from mass
  > may provide breathing room in SUSY theories especially
  > can generate large deviations in Higgs self-couplings

- appearance of light stops will require explanation of Higgs mass;
  physical mass is essentially free parameter in induced EWSB

- rich spectrum contains sub-TeV scalars with unique
  (i.e. non-MSSM) footprints

- Nonstandard Higgs and add'l scalars still in play…
  …any surprise is welcome; many nicely motivated, *and* still viable!

BACKUP

coincidence issue

The active participants:

	$SU(2)_{\rm TC}$	$SU(2)_L$	$SU(2)_R$
ψ	$\square$	$\square$	1
ψ'	$\square$	1	$\square$
$\mathcal{H}$	1	$\square$	$\square$

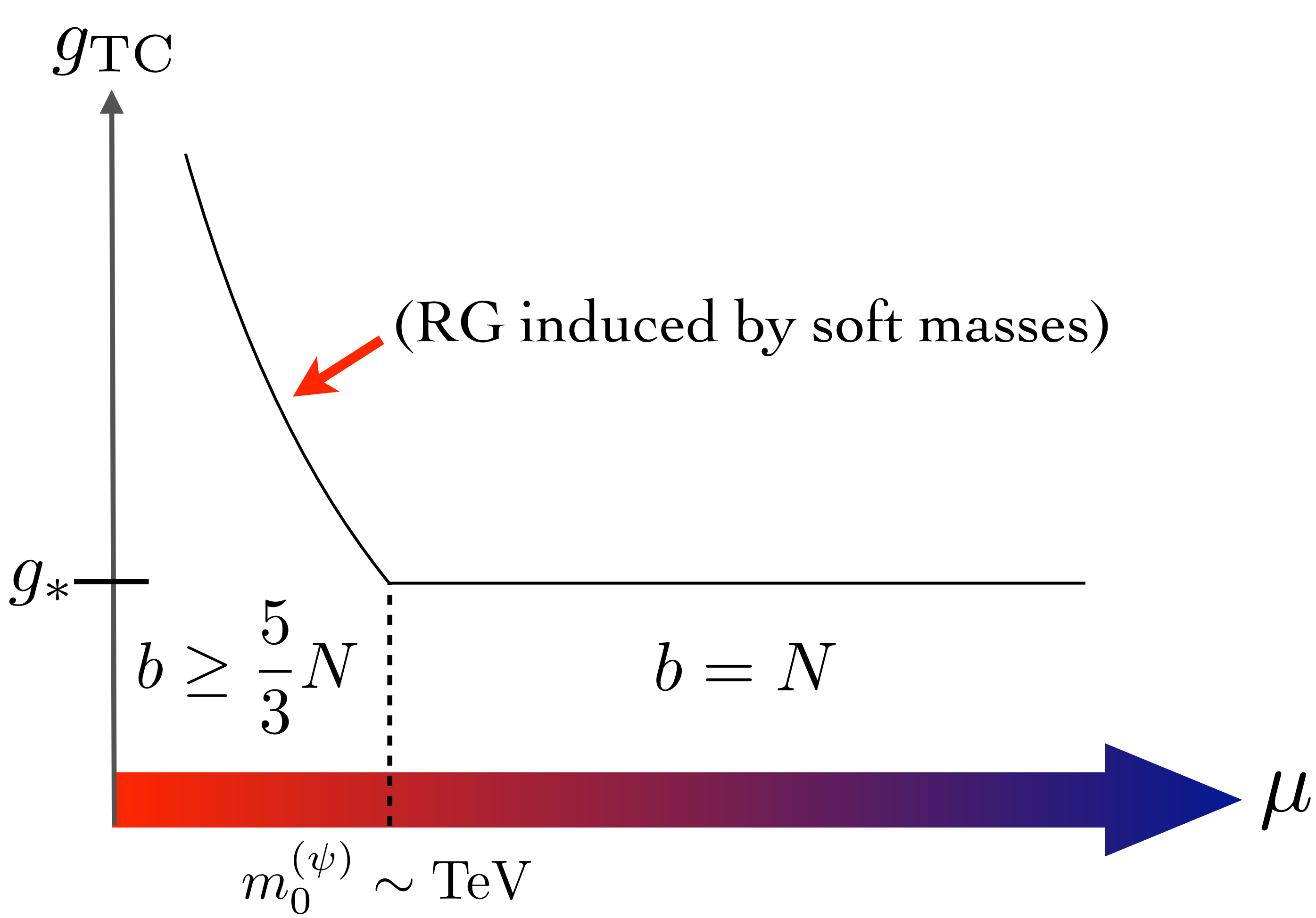
with potential $\Delta W = \lambda \mathcal{H} \psi \psi'$

plus two sterile flavors:

$$b = N$$

$\Longrightarrow$ IR fixed point

- o Strongly coupled
- o Self-dual



- o Phase transition induced by SUSY breaking
- o STRONG fixed point above m_0 sets $\Lambda_{\rm TC} \sim m_h$ without conspiracy
- o As in the QCD toy case: m_h is *free*, independent of quartic at leading order

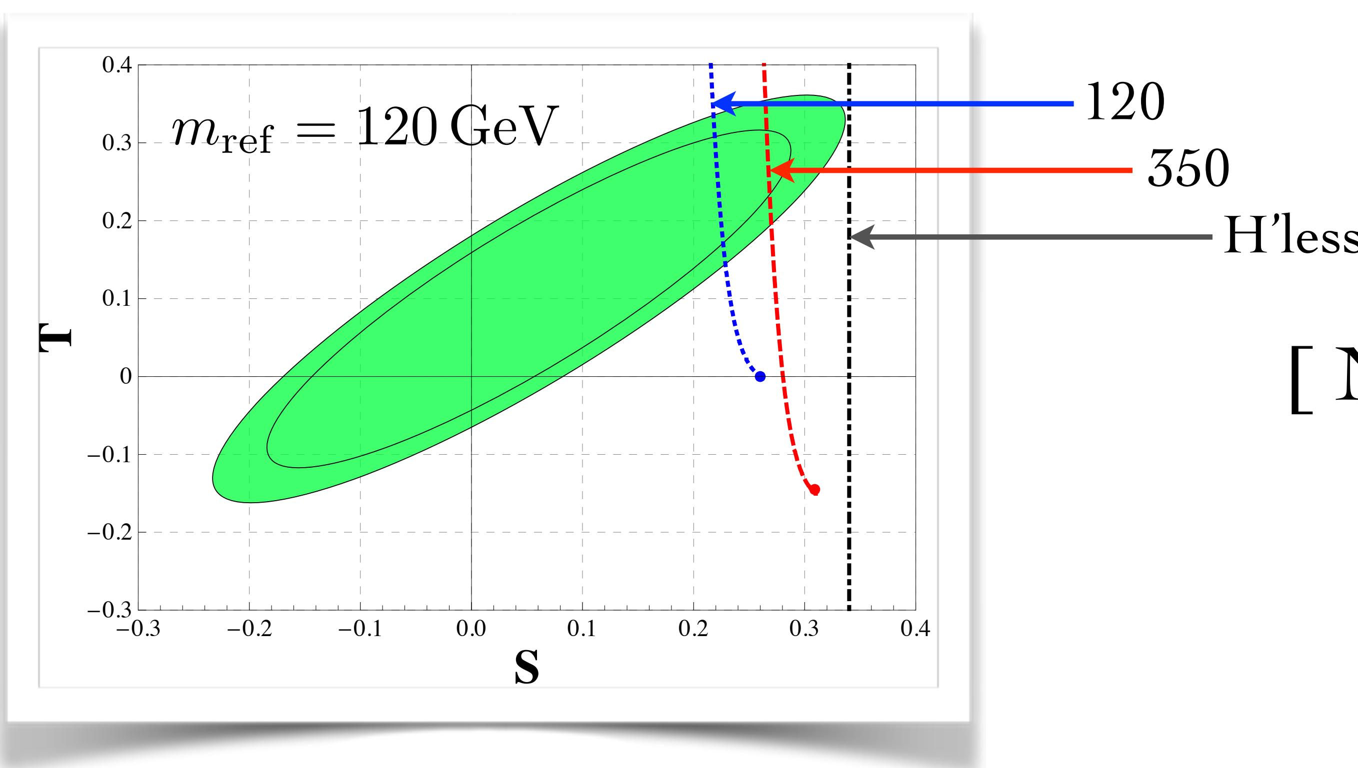
EWPT and strong model

S Parameter:

$$\Delta S_{\text{TC}}^{(\text{IR})} \simeq \frac{1}{12\pi} \log \underbrace{\left(\frac{\Lambda^2}{m_h^2}\right)}_{\sim 16\pi^2} \quad \text{vs.} \quad \Delta S_{\text{Ind.}}^{(\text{IR})} \simeq \frac{1}{12\pi} \log \underbrace{\left(\frac{\Lambda^2}{m_\pi^2}\right)}_{\sim 4\pi}$$

T Parameter: $\lambda_u v_u = \lambda_d v_d \Rightarrow$ custodial limit

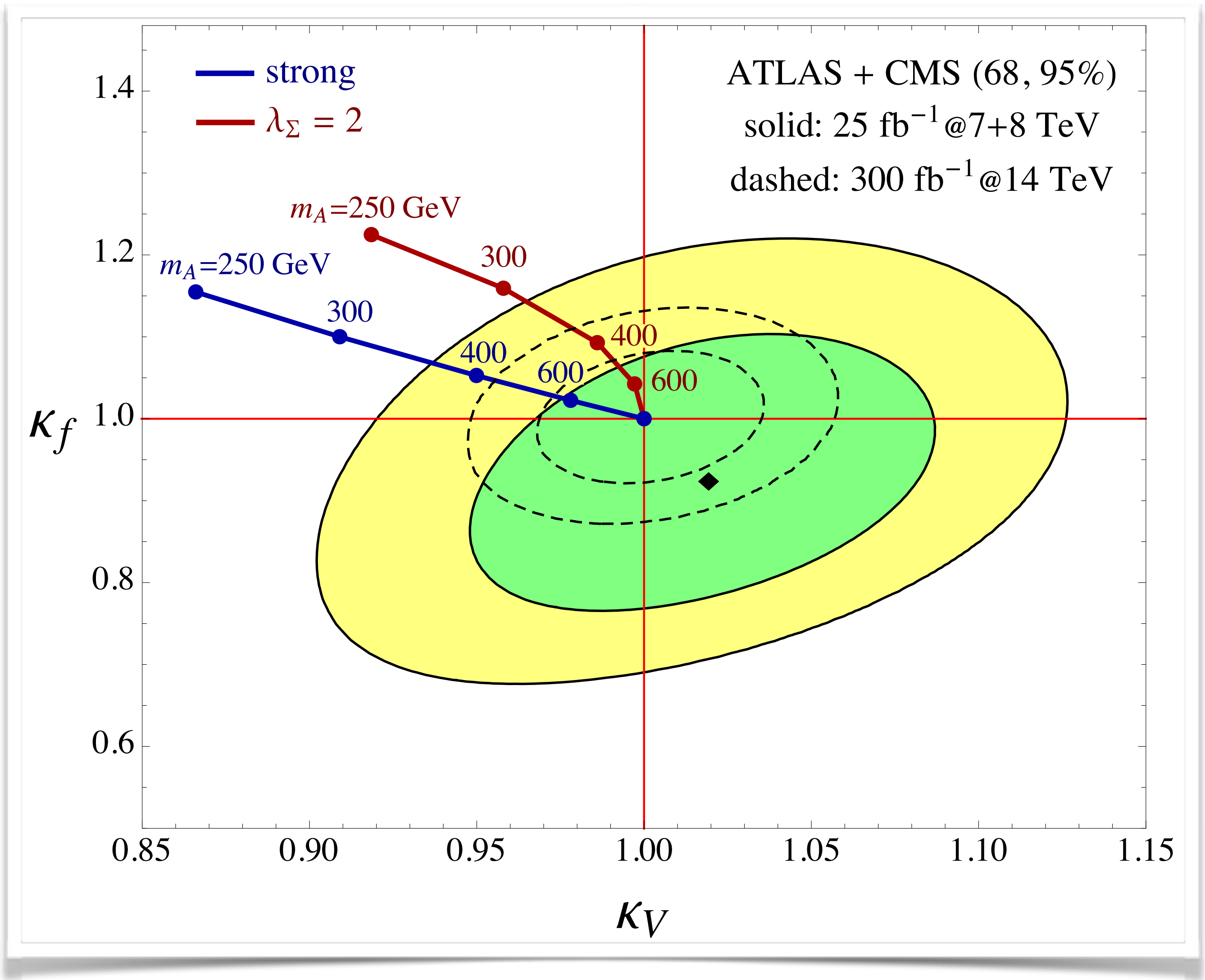
$\hookrightarrow$ T corresponds to a variable parameter of the theory



$$\alpha T = (\epsilon_u - \epsilon_d)^2$$

[Notice that increasing T tends to decrease S above]

‘universal’ phenomenology: H couplings



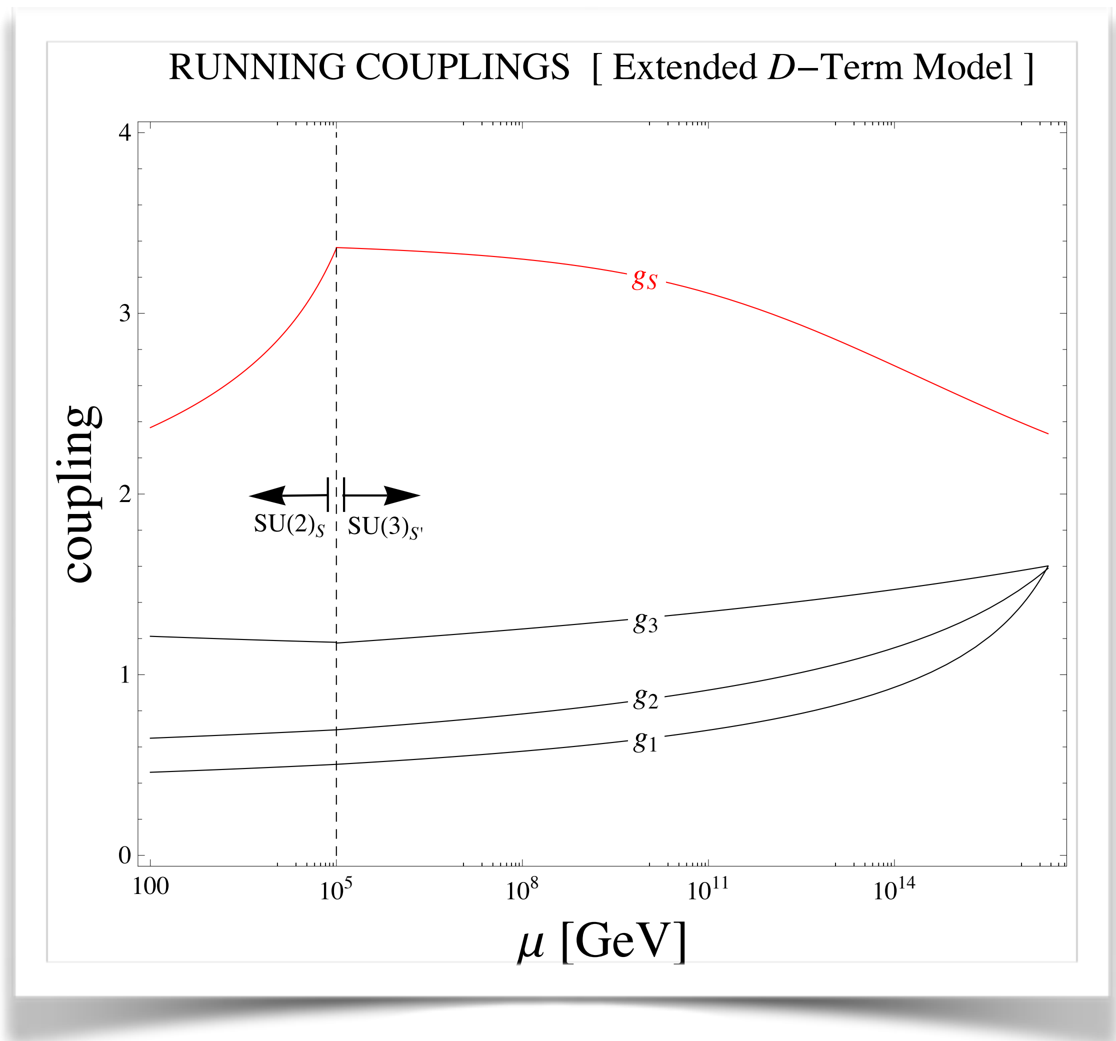
generation of auxiliary quartics

D-Terms

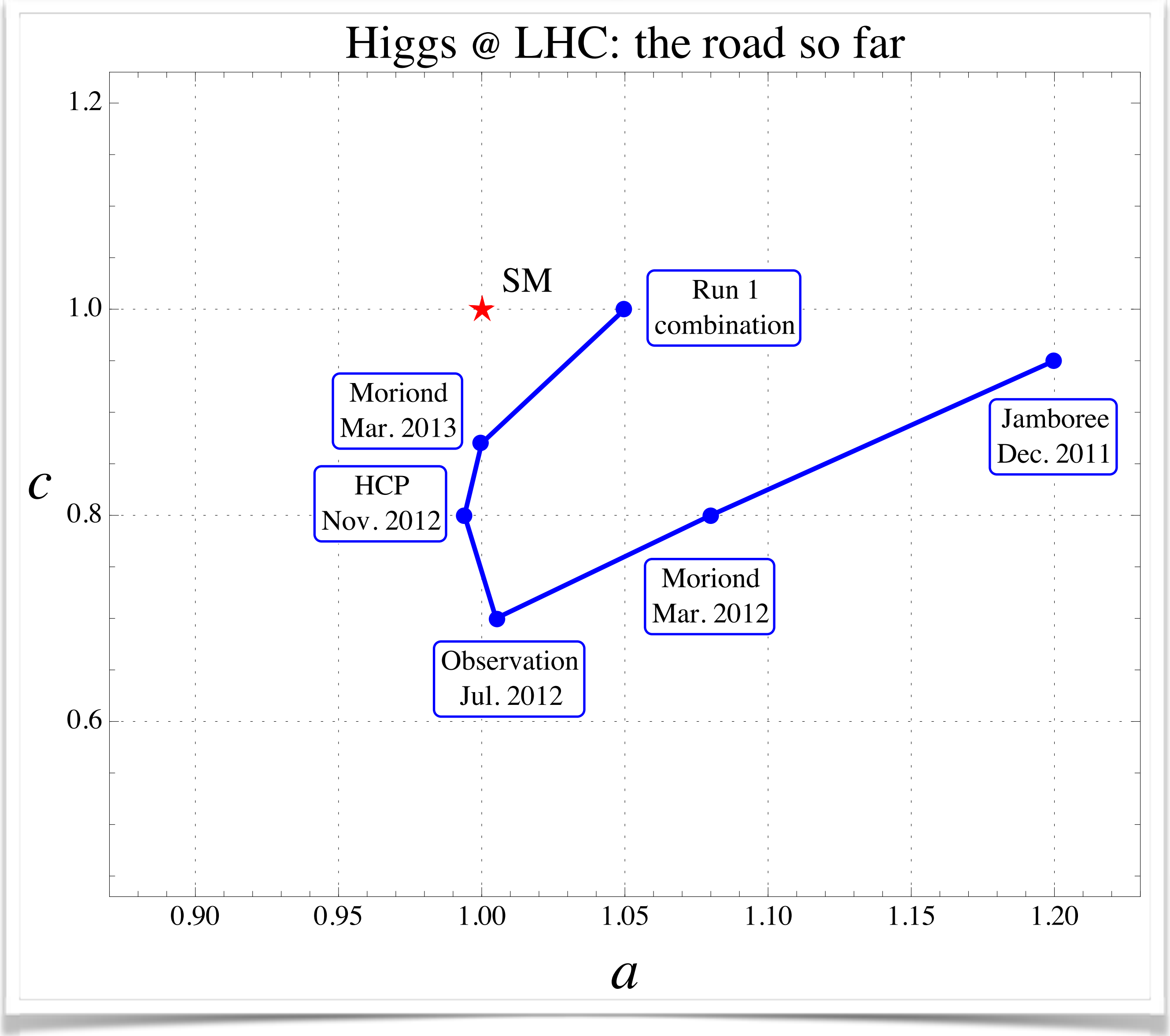
$$\begin{cases} \Delta K = \Sigma^{\dagger}_{u,d} \exp(g_S V^a T^a) \Sigma_{u,d}; \;\; T^a \in SU(2)_S \\ \Sigma \in \Psi_5; \;\; \Psi_5 = (T, \Sigma) \qquad [SU(2)_S \text{ broken by } \langle \Phi \rangle] \end{cases}$$

$$(\Psi,\ \bar{\Psi},\ \Phi,\ \bar{\Phi}) = 6 \text{ flavors}$$

running starts at two loops;
some completion still required

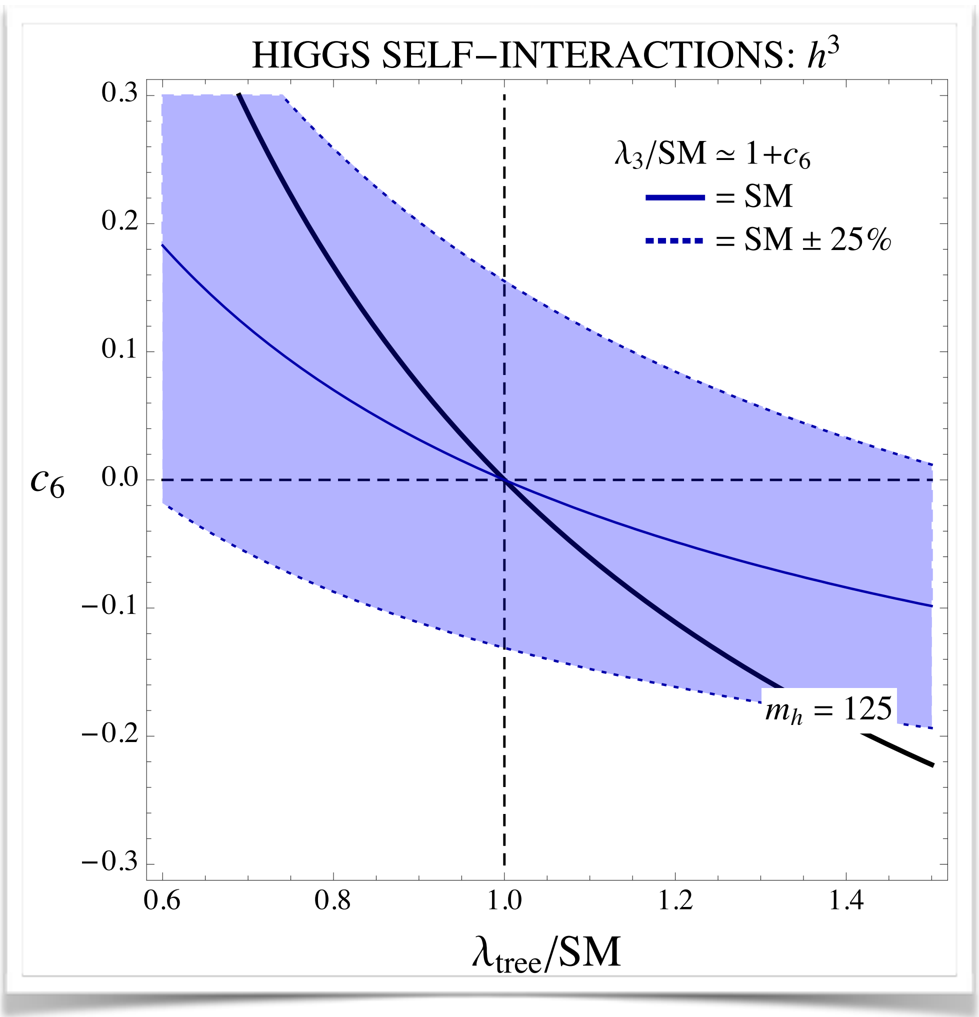


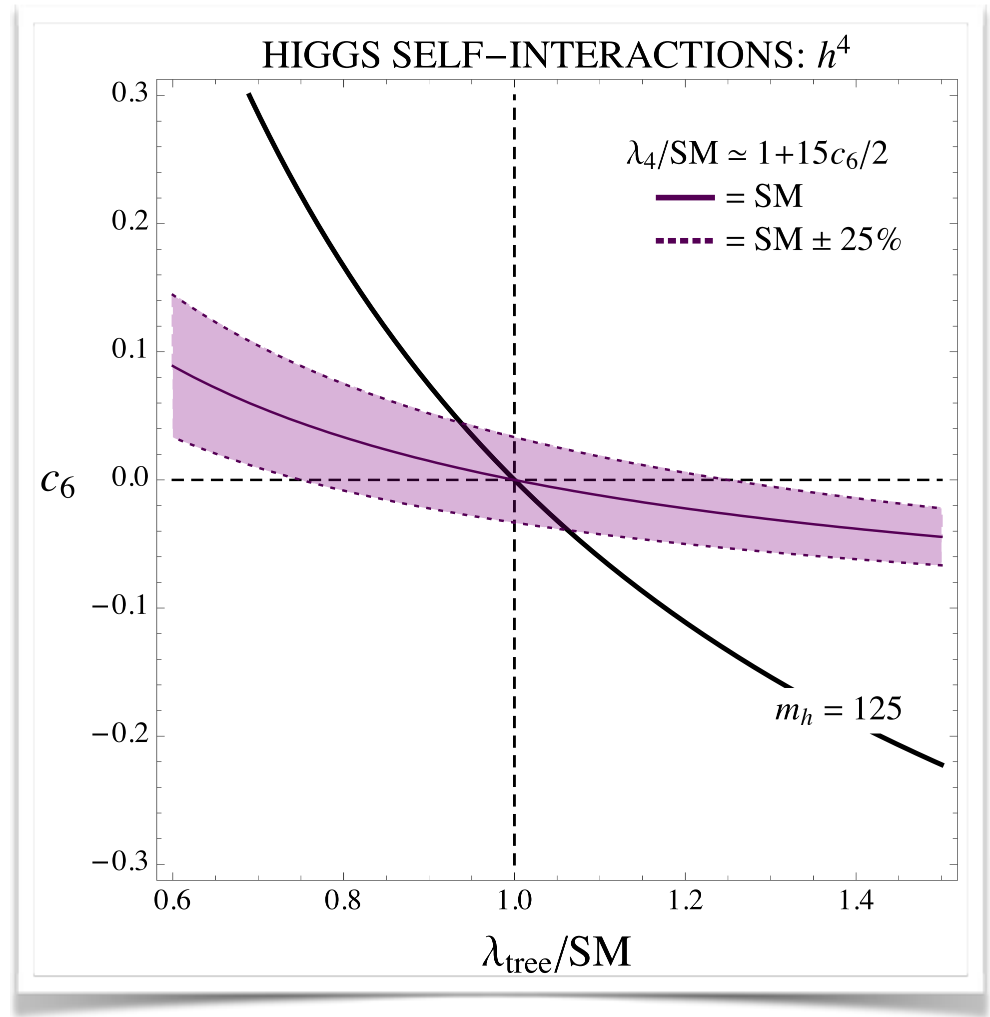
history of Higgs @ LHC



Higgs self-interaction: comparison with SILH

H carries all light scalars of the theory.
Self-interactions modified by $(H^\dagger H)^3$, $(\partial_\mu (H^\dagger H))^2$:





Small cubic implausible: M < 500 GeV for vectors!
hVV and hff ~ SM *does* paint us into a corner