Title: Induced Electroweak Symmetry Breaking and Supersymmetry

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Abstract: I'll discuss a class of supersymmetric models in which the physical Higgs mass is freed from the quartic coupling, thereby allowing for a 125 GeV Higgs state whose self-interaction can be much smaller than in the SM via a mechanism of 'induced EWSB'. This class of models provides a unique alternative to other realizations of natural SUSY, and the simplest realizations necessitate additional characteristic scalars below the TeV scale, thus altering phenomenological predictions for additional Higgses at the LHC.

INDUCED EWSB

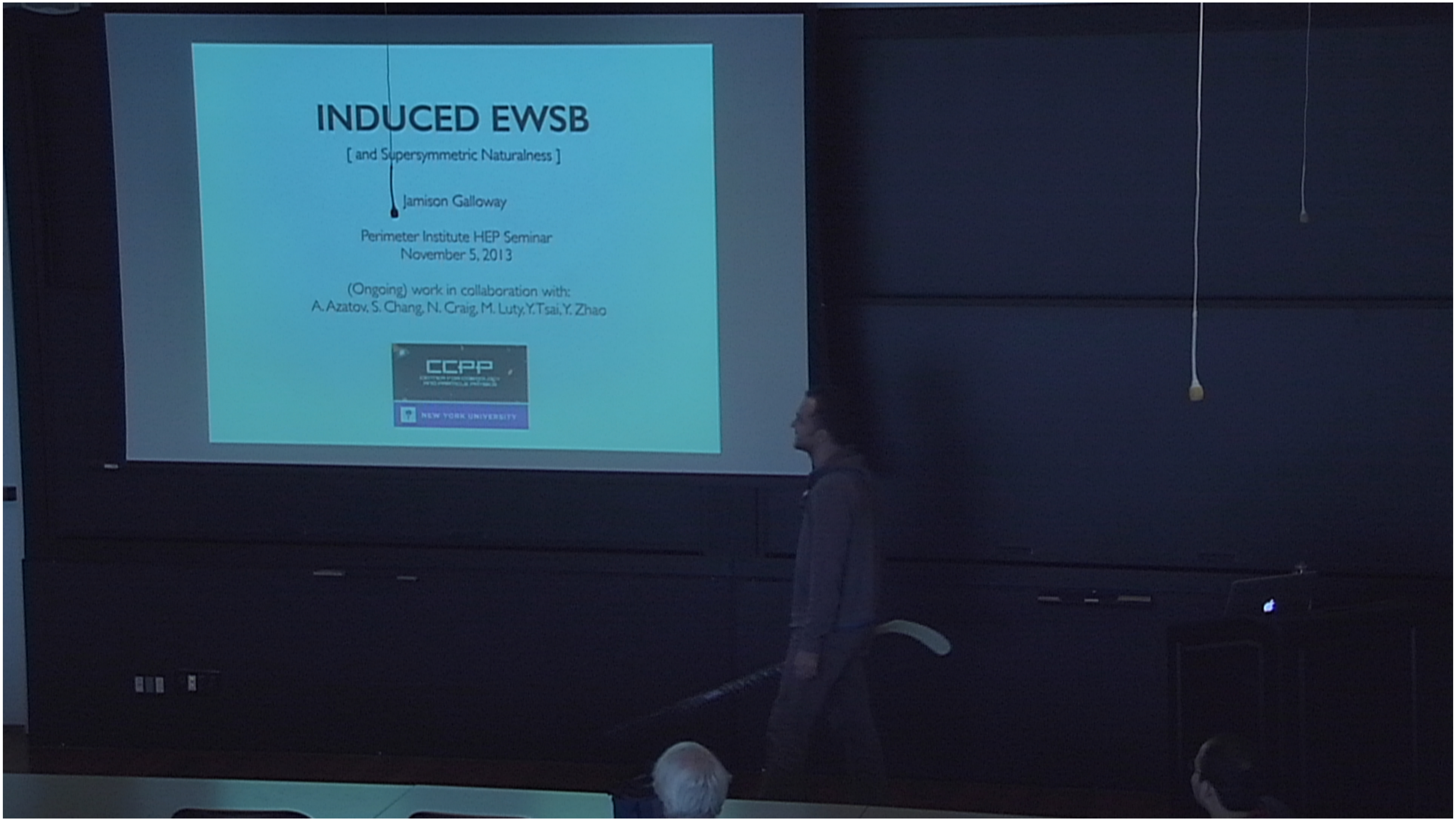
[and Supersymmetric Naturalness]

Jamison Galloway

Perimeter Institute HEP Seminar
November 5, 2013

(Ongoing) work in collaboration with:
A. Azatov, S. Chang, N. Craig, M. Luty, Y. Tsai, Y. Zhao

CCPP
CENTER FOR COSMOLOGY AND PARTICLE PHYSICS
NEW YORK UNIVERSITY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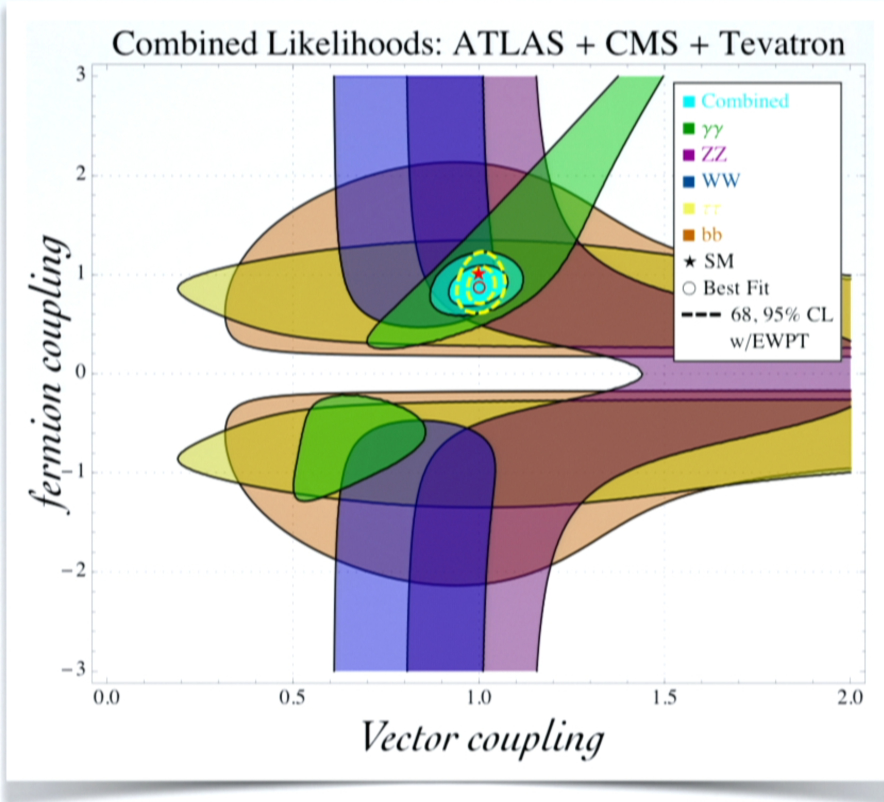
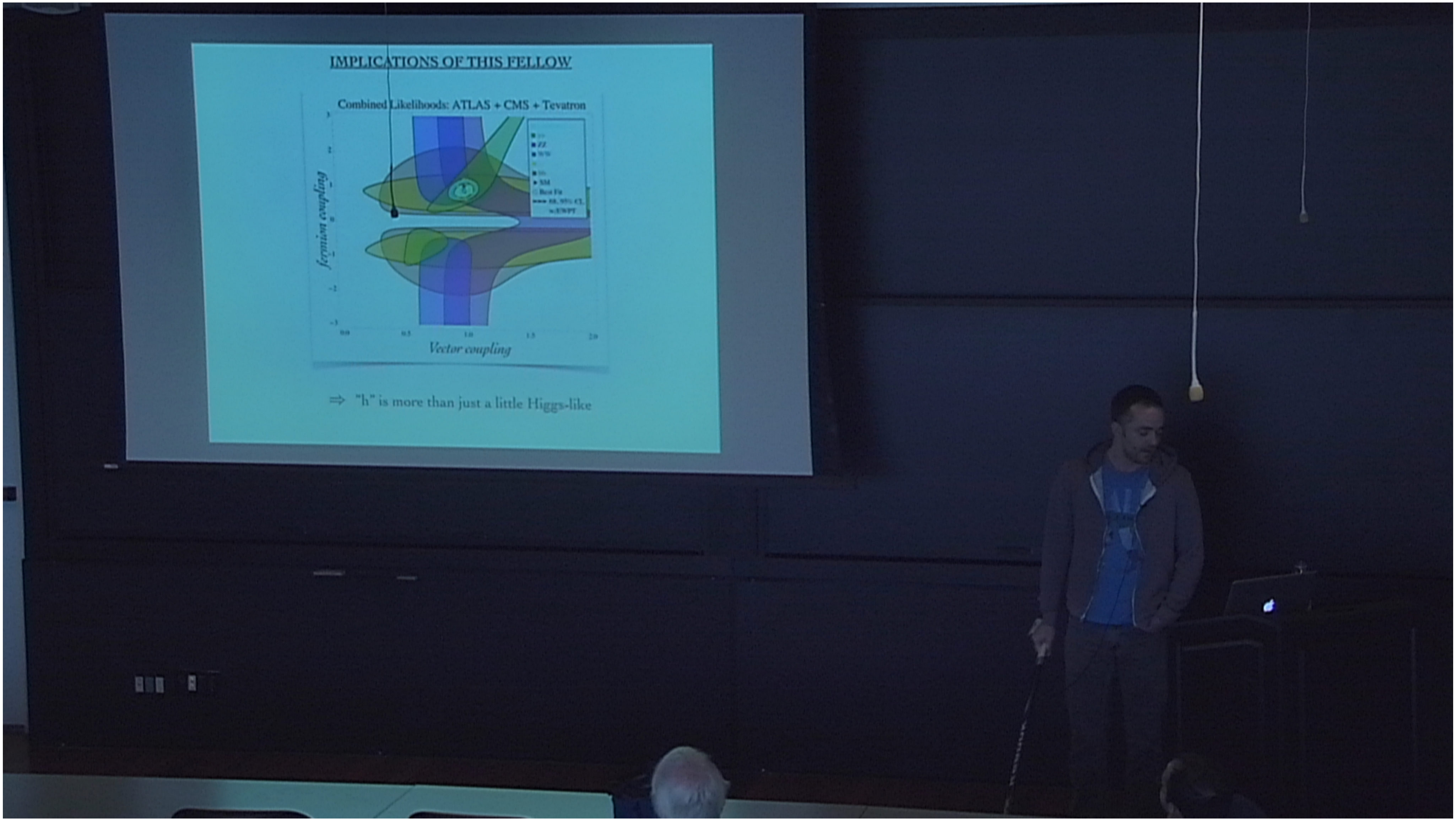
[AKA]

ELEMENTARY SCALARS IN/AND/OR THE NATURALNESS DOCTRINE

IMPLICATIONS OF THIS FELLOW



⇒ “h” is more than just a little Higgs-like


IMPLICATIONS OF THIS FELLOW
Combined Likelihoods: ATLAS + CMS + Tevatron
fermion coupling
Vector coupling
⇒ "h" is more than just a little Higgs-like

IMMEDIATE IMPLICATION FOR SUSY

125 GeV : *at least* mildly irritating

$$m_h^2 \sim \lambda_h v^2 \xrightarrow{\text{SUSY}} g^2 v^2$$ assuming maximal misalignment with D-flat

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A Higgs obeying this mass relation must obtain a substantial fraction of its mass from SUSY breaking:

The physical quartic we've inferred from observation requires an order one correction to the SUS'ic value $(m_h \simeq \sqrt{2} m_Z)$ ...

...typically this breaking feeds into the Higgs soft mass and can jeopardize stability of the weak scale

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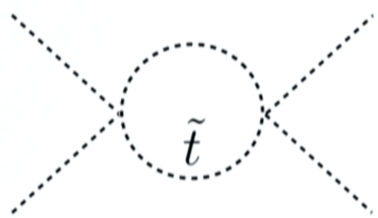
Especially acute in the MSSM:



$$\delta\lambda_h \sim \log m_{\tilde{t}} \text{ @ large } \tan\beta$$

$$\delta m_{H_u}^2 \sim m_{\tilde{t}}^2$$

grows exponentially with $\delta\lambda_h$.

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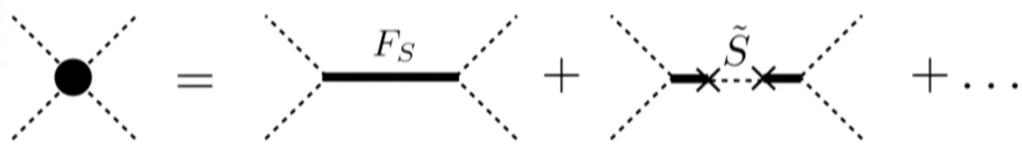
even simplest non-decoupling schemes face tension

$$\Delta W_{\text{NMSSM}} = \lambda S H_u H_d + \mu S S \quad \Rightarrow \quad \delta\lambda_h \sim |\lambda|^2 \sin^2 2\beta$$

and



$$\sim |\lambda|^2 \left(1 - \frac{\mu_S^2}{m_{\tilde{S}}^2} + \dots\right) \quad \rightarrow \quad |\lambda|^2 \left(1 + \frac{\mu_S^2}{m_0^2}\right)^{-1}$$

$\Rightarrow$

; $\delta m_{H_u}^2 \sim |\lambda|^2 m_{\tilde{S}}^2$

less sensitive to $\delta\lambda_h$ than MSSM, but not *in*sensitive

OUTLINE

1. Induced EWSB ($m_h^2 \not\propto \lambda v^2$)

2. Perturbative model

3. Conclusions

0. QUESTION

THE QUESTION: HIGGS MASS PARAMETER

$$V(H) \sim -(125)^2\,|H|^2 + \lambda\,|H|^4 \quad \Rightarrow v \neq 0;\ m_h^2 \sim \lambda v^2$$

what if...

$$V(H) \sim +(125)^2\,|H|^2 + \lambda\,|H|^4$$

...while keeping the rest of the SM as is?
(How much partial credit would we assign nature for this sign error?)

[disclaimer: 2=1 in the convention employed here]

THE (QUICK) ANSWER

EW remains intact.

SM gauge and fermion fields are massless.

.
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.

Qualitatively that world looks nothing like ours.

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but of course...

$m^2_{h,\text{phys}} \sim m^2_H$; $\sim$ independent of quartic

THE NOT-SO-QUICK ANSWER

The story we already knew:

Massless QCD ($F = 2$) breaks EW in the same way as the SM Higgs

$$\langle \bar{q}_L q_R \rangle \neq 0 \quad \Longrightarrow \quad SU(2)_L \times SU(2)_R \to SU(2)_V$$

Three composite Goldstones are eaten by the otherwise massless W, Z

$$m_{W,Z} \sim g f_\pi / 2 \sim 50\,\mathrm{MeV}$$

} Qualitatively correct
Quantitatively dead wrong

Saying the same thing in terms of IR dof:

$$\Sigma = \exp[i\Pi(x)/f_\pi] \mapsto L \Sigma R^\dagger$$

$$\Delta\mathcal{L}(\mu < \Lambda_{\mathrm{QCD}}) = f_\pi^2 \,\mathrm{tr}\left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma)\right] \supset \frac{f_\pi^2 g^2}{4} W_\mu^+ W^{\mu -} + \ldots$$

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BUT WAIT, THERE'S MORE

The story we *didn't* account for:

There's a custodial-singlet scalar in the UV and it couples to fermions

$$\Delta\mathcal{L} = -(125)^2 \det\mathcal{H} - (y_e L_L^\dagger \mathcal{H} e_R + y_q q_L^\dagger \mathcal{H} q_R + \text{h.c.})$$

where $\mathcal{H} = (\epsilon H^* \, H) \mapsto L\mathcal{H}R^\dagger$ and leptons couple to the EWSB vacuum

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Again going to the IR theory:

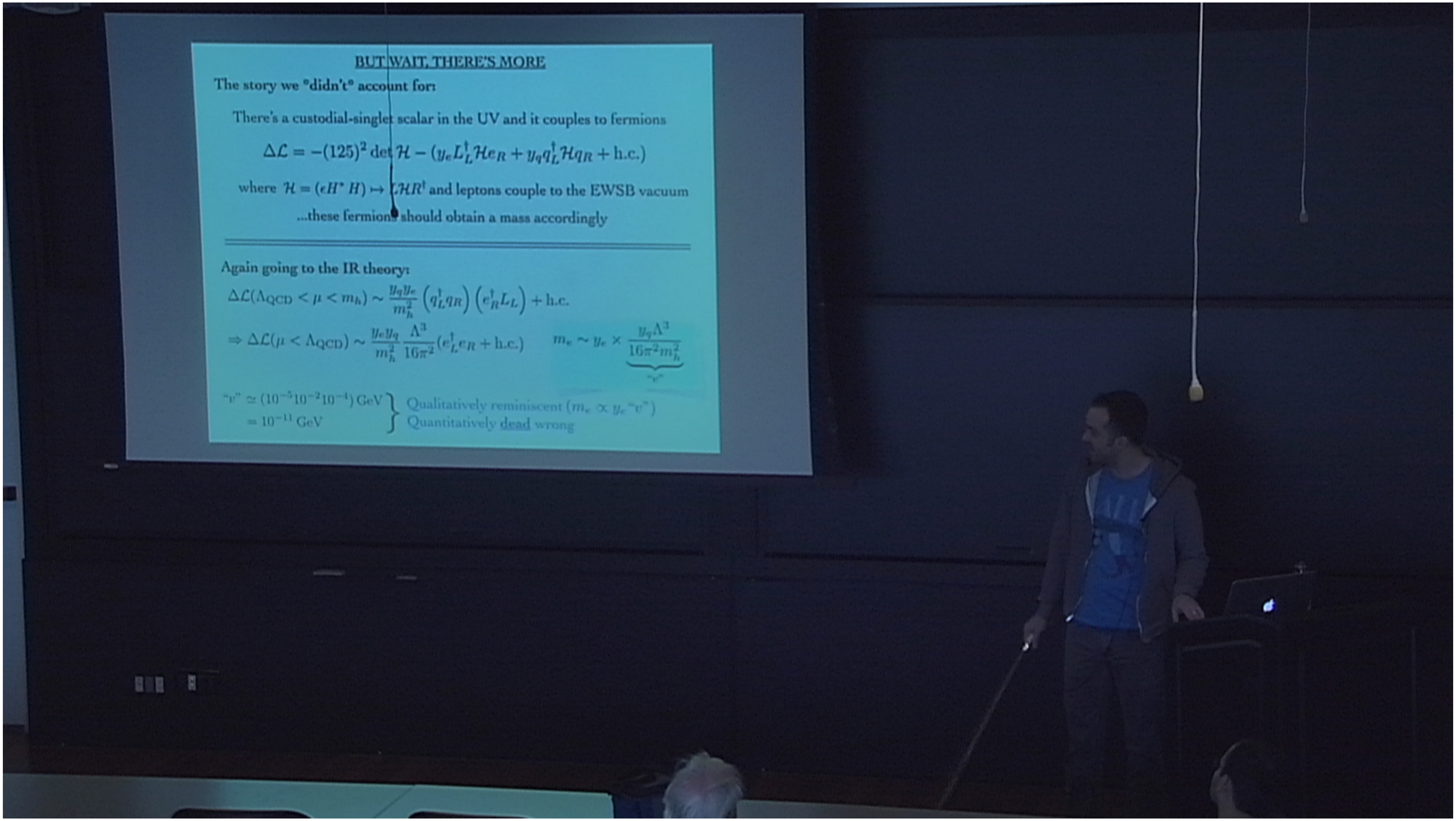
$$\Delta\mathcal{L}(\Lambda_{\text{QCD}} < \mu < m_h) \sim \frac{y_q y_e}{m_h^2}\left(q_L^\dagger q_R\right)\left(e_R^\dagger L_L\right) + \text{h.c.}$$

$$\Rightarrow \Delta\mathcal{L}(\mu < \Lambda_{\text{QCD}}) \sim \frac{y_e y_q}{m_h^2}\frac{\Lambda^3}{16\pi^2}(e_L^\dagger e_R + \text{h.c.})$$

$$m_e \sim y_e \times \underbrace{\frac{y_q \Lambda^3}{16\pi^2 m_h^2}}_{\text{“}v\text{”}}$$

$$\text{“}v\text{”} \simeq (10^{-5}10^{-2}10^{-4})\,\text{GeV} = 10^{-11}\,\text{GeV}$$

Qualitatively reminiscent ($m_e \propto y_e \text{“}v\text{”}$)
Quantitatively **dead** wrong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A FAMILIAR IDEA: SIMPLY SCALE UP QCD

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

$$\left.\begin{aligned} \Lambda_{\rm TC} &= \text{TeV} \\ \text{“}v\text{”} &\to \lambda \times \text{TeV} \end{aligned}\right\}$$

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

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Upshot:

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

* Corrections from quartic < 20%

INTERACTIONS AND THE EFFECTIVE THEORY

Induced EWSB = Shared EWSB (two bidoublets)

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

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perturbative regime:

$$\epsilon \equiv \frac{\lambda v_h}{\Lambda} \ll 1$$

[The strong dynamics is stable against perturbations from H]

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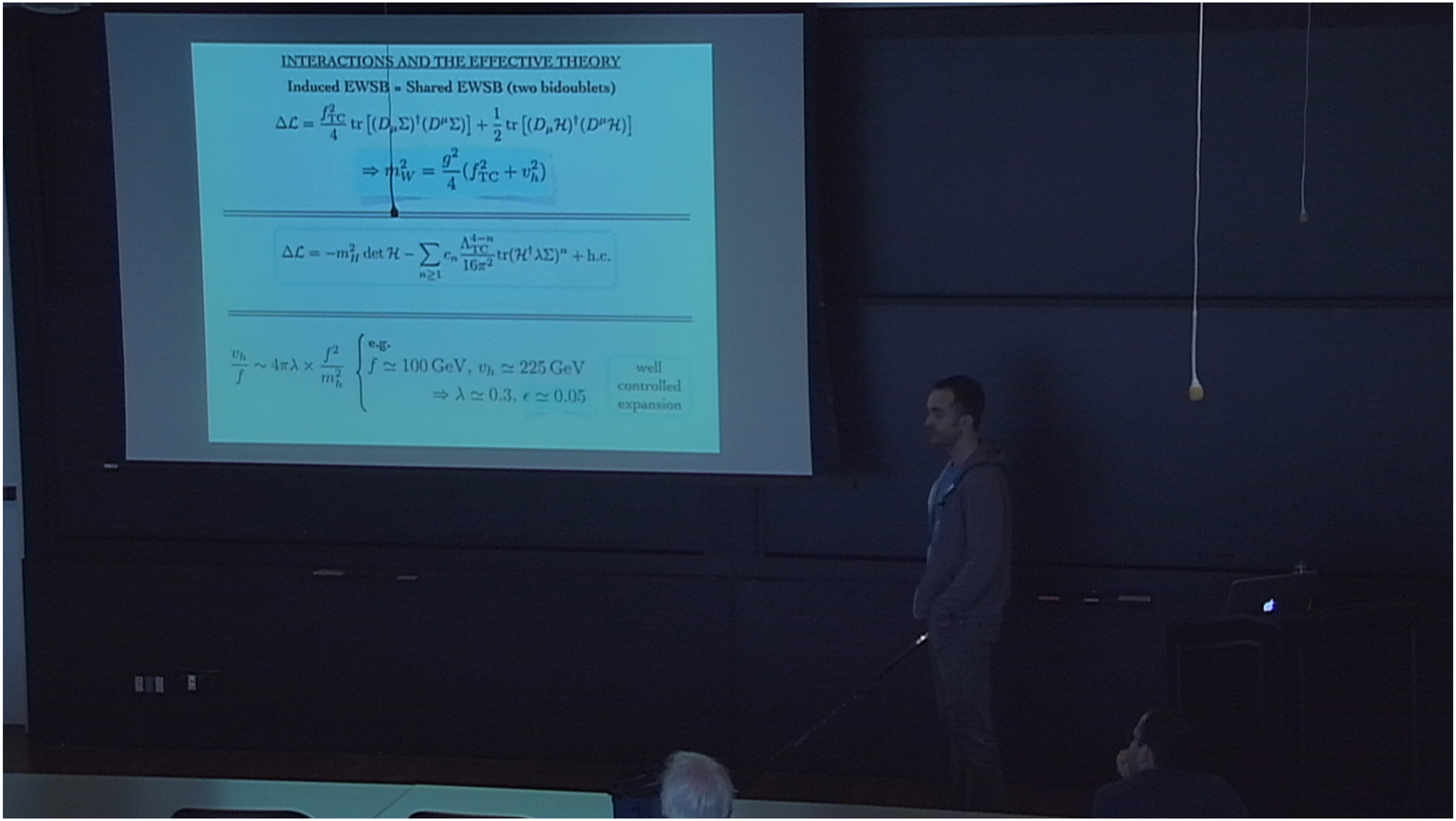
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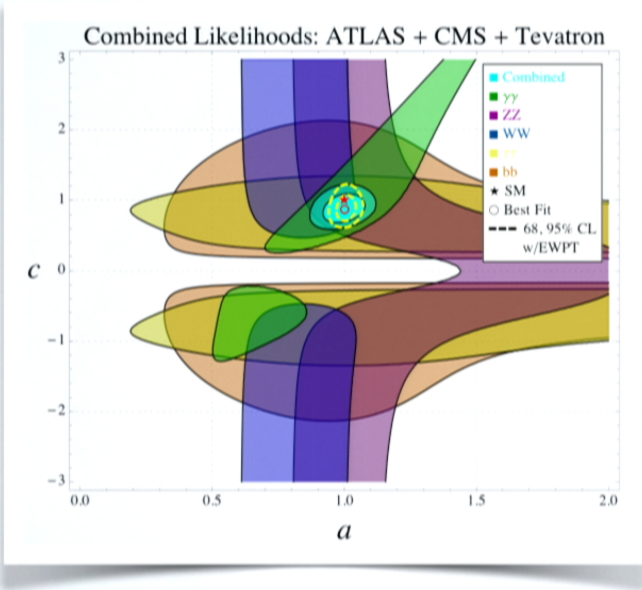
$\frac{v_h}{f} \sim 4\pi\lambda \times \frac{f^2}{m_h^2}$
e.g.
$f \simeq 100\,\mathrm{GeV},\ v_h \simeq 225\,\mathrm{GeV}$
$\Rightarrow \lambda \simeq 0.3,\ \epsilon \simeq 0.05$
well
controlled
expansion

INTERACTIONS AND THE EFFECTIVE THEORY

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

Higgs couplings suppressed to vectors

What do we learn from the LHC?



$a \equiv g_{hVV}/\mathrm{SM} \gtrsim 90\%$

Compare to model prediction:

$$a \to \frac{v_h}{v}$$

$$\Rightarrow f < v \times \sqrt{(2-\sigma_a)\sigma_a} \simeq 110\,\mathrm{GeV}$$

[Aside: even with $\sigma_a = 5\%$, we're safe with $f \simeq 75\,\mathrm{GeV}$.]

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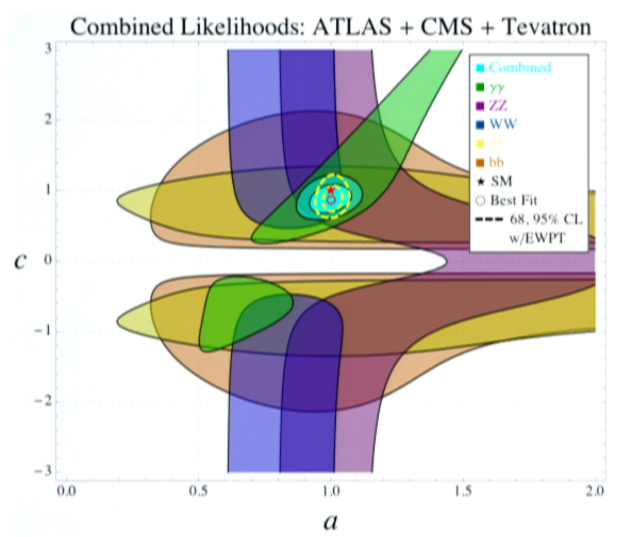

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SUPERSYMMETRIC THEORY

The active participants:

	$SU(2)_{\mathrm{TC}}$	$SU(2)_L$	$SU(2)_R$
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

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MINIMAL PHENO

$(H_u,\, H_d,\, \Sigma) \Rightarrow 8$ 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 weak gauge bosons

UNIQUE signals: compare with MSSM (H couples to f),
NMSSM ("S" inherits *all* quantum numbers from mixing),
...
[WORK IN PROGRESS w/ Chang, Craig, Luty]

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...
[WORK IN PROGRESS w/ Chang, Craig, Luty]

RECAP: GENERAL SCHEME

recklessly imagined 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 $\Lambda \sim 4\pi f \to m_\sigma$]

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

A SIMPLIFIED PERTURBATIVE APPROACH

(simplified = focus on just the up-type Higgs)

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

↑

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

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

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

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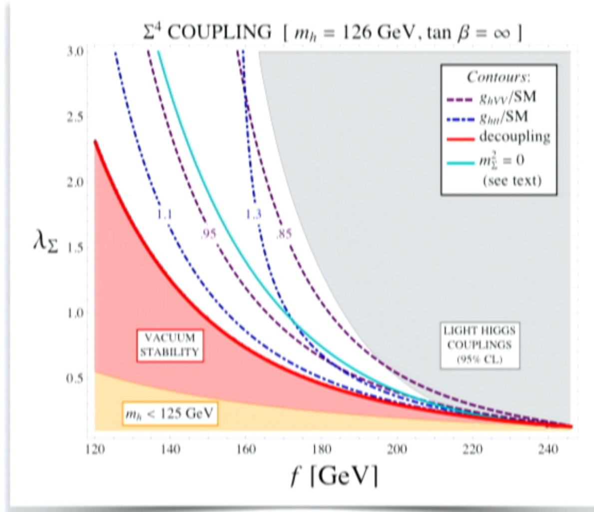
Simplified parameter space:

$$\frac{g_{hVV}}{\text{SM}} = \frac{v_h}{v} \qquad \frac{g_{htt}}{\text{SM}} \propto \frac{v}{v_h}$$

$$\frac{g_{HVV}}{\text{SM}} = \frac{f}{v} \lesssim 0.4$$

*additional scalar couples
~ only to vectors*
Signals primarily in VBF/VH -> WW
[work in progress]



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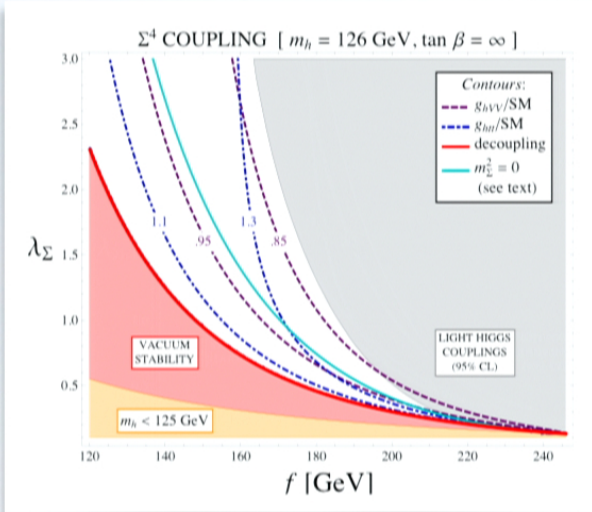

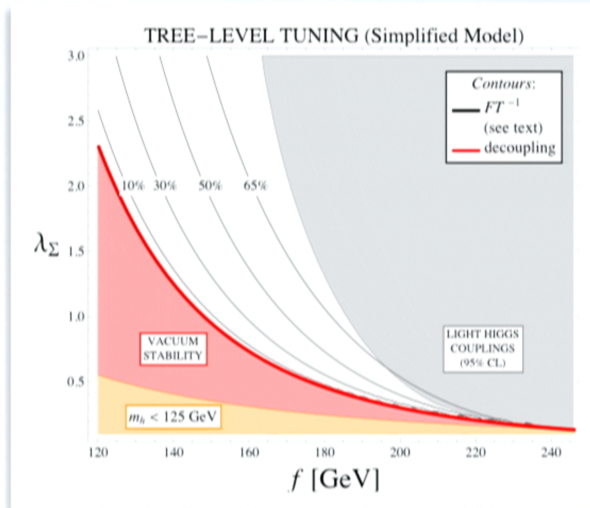

$$\Rightarrow \delta m_h^2 \propto \frac{\lambda}{16\pi^2} m_\sigma^2 \ (\times\text{mixing angles})$$

BUT the RHS mass need not be large in the interest of maximizing quartic.
SUSY Higgs mass here doesn't require large quartic,
Sigma can remain safely sub-TeV.

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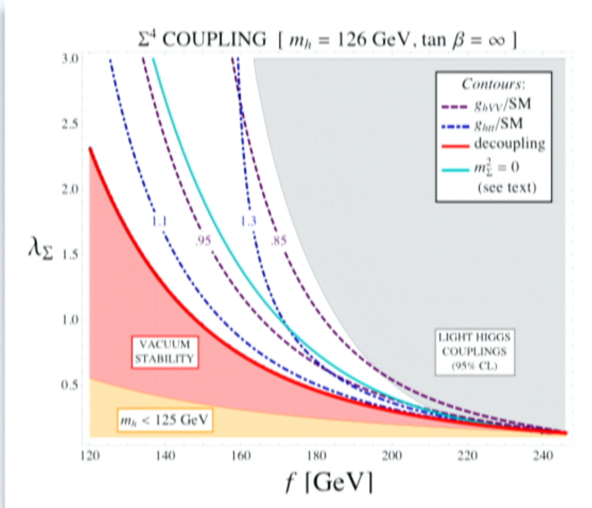

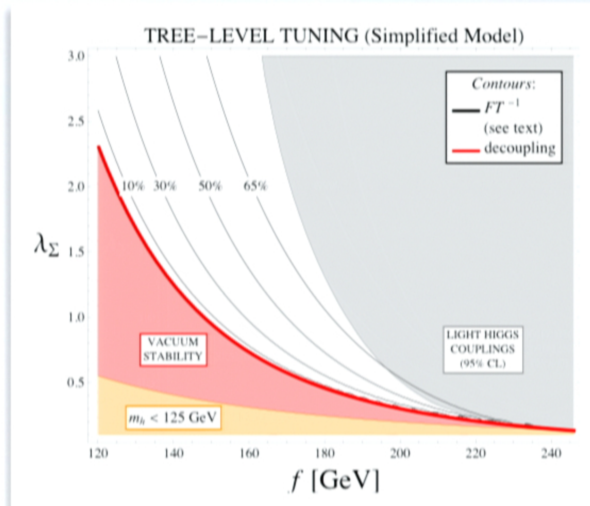

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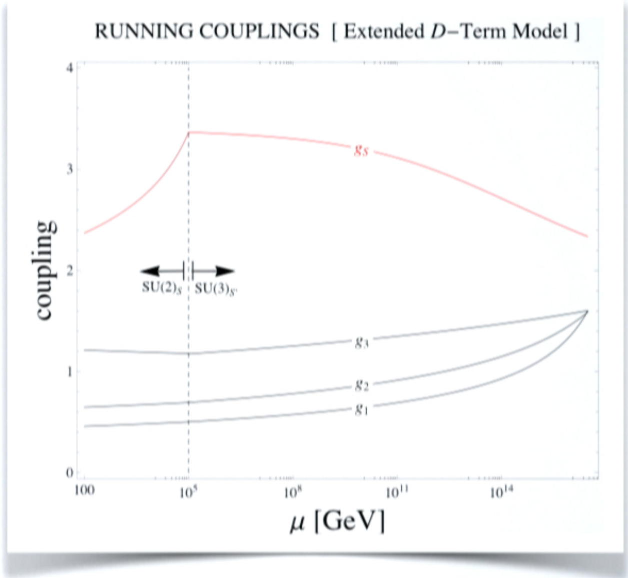
A NON-SIMPLIFIED PERTURBATIVE APPROACH

[how to generate auxiliary quartic]

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

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

running starts at two loops;
some completion still required



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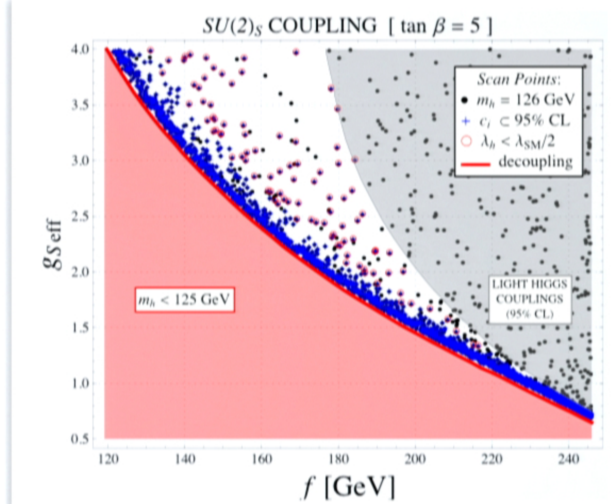
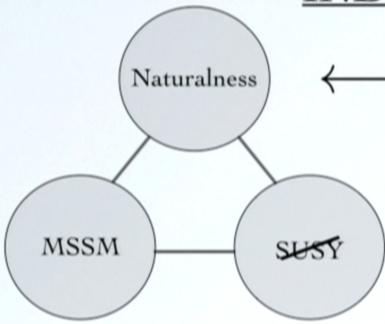
but the IR "smoking gun" is unique & significant



INDUCED EWSB IN NATURAL SUSY



$\longleftarrow$ necessitated by $m_h = 125\,\mathrm{GeV}$

if 

$\supset$ EWSB (doublets rather than singlets)

...then $m_h^2 \not\propto \lambda_h$

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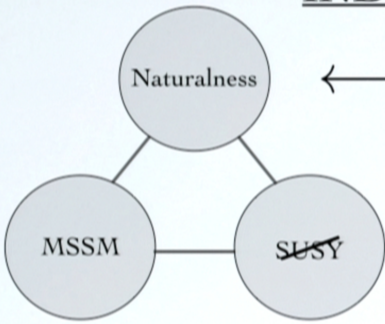

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...then $m_h^2 \not\propto \lambda_h$

Implications

- o Dramatically reduced quartic/cubic (long term)
- o New scalar states < TeV : minimally an isotriplet ($H_2^{\pm}, A_2^0$)

$$m_\pi^2 \sim \epsilon\Lambda^2 \sim (500\,\mathrm{GeV})^2$$

- o Weakly-coupled models with a nonstandard H_2^0 state

$$m_{H_2^0}^2 \sim \frac{1}{\epsilon}\frac{v_h^2}{f^2} m_h^2 \gtrsim (600\,\mathrm{GeV})^2$$

- o All with reduced fermionic decays; very different from standard *H, A, S*