Effective Field Theory for a very non-SM Higgs

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S. Chang, ML, E. Salvioni, to appear

Introduction

The discovery of the 125 GeV spin-0 boson at the LHC was a true revolution in particle physics.

- Discovery of an elementary scalar

  Naturalness?

- Couplings compatible with SM Higgs at 20% level

  $hVV\ (V = W, Z)$: gauge boson mass generation

  $hff\ (f = t, b, \tau)$: heavy fermion mass generation

LHC is now probing *large* deviations from SM Higgs:

$$\frac{\delta g_{hhh}}{\delta g_{hhh}^{(\mathrm{SM})}} \sim 1$$

large deviations in Higgs potential

Outline

This talk: argue that large deviations in the Higgs potential are possible only with *additional strongly-coupled* sources of EWSB below the TeV scale.

- Bottom-up argument
- Effective field theory
- Phenomenology
- Top-down argument (hierarchy problem)

Know Your Rights

As a consumer of EFT, you have the right to know:

- Light degrees of freedom
- Cutoff (range of validity)
- Small dimensionless parameters (if any)
- Power counting (size of general term in $\mathcal{L}_{\text{eff}}$)
- Existing experimental constraints compatible with power counting
- What new physics scenarios are described by EFT

A good EFT makes these features as explicit as possible.

SM as an EFT

If there are no new sources of EWSB below the TeV scale, then we can write theory in terms of a single Higgs doublet H (linear realization of EW gauge invariance).

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \text{dimension 6 operators} + \cdots$$

Example: non-standard Higgs cubic

$$\Delta V_{\text{eff}} = \delta\lambda v h^3 \supset \delta\lambda v h^3 \frac{\pi^2}{v^2}$$

$$\Rightarrow \ \mathcal{M}(W_L W_L \to hhh) \sim \frac{\delta\lambda}{v} \qquad \text{for } E \gg m_h, m_W$$

$$\Rightarrow \ \text{cutoff at } \Lambda \sim \frac{4\pi v}{\sqrt{\delta\lambda}} \sim \text{TeV} \qquad \text{for } \delta\lambda \sim 1$$

New physics at Λ necessarily violates EWSB

$\Rightarrow$ new sources of EWSB below Λ.

Auxiliary Higgs Sector

We want additional source of EWSB to be subleading to explain SM-like hVV, hff couplings:

$$v = \sqrt{v_h^2 + f^2} = 246 \text{ GeV}$$

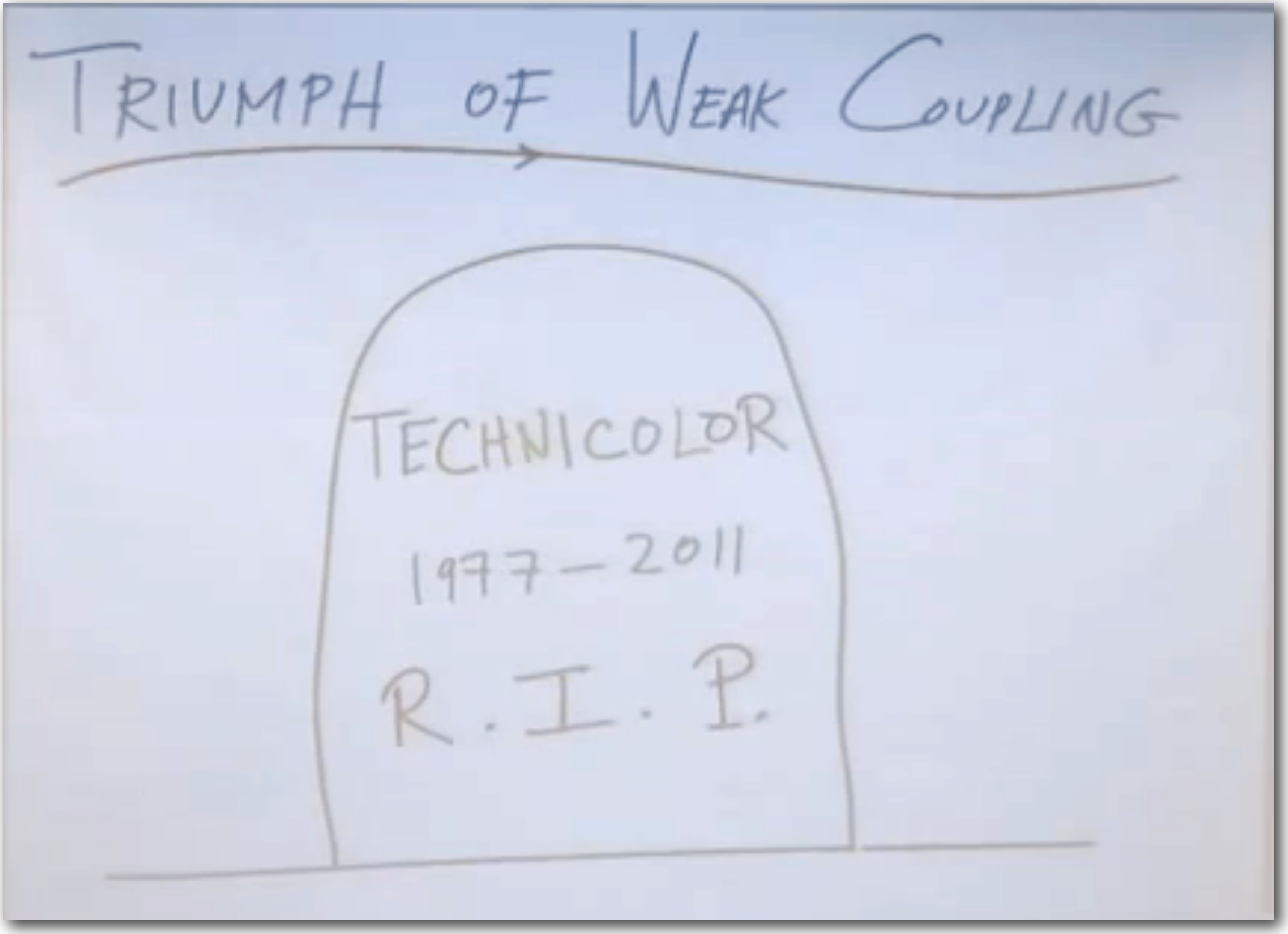
$$\frac{\delta g_{hVV}}{g_{hVV}^{(\text{SM})}} \sim \frac{\delta g_{hff}}{g_{hff}^{(\text{SM})}} \sim \frac{f^2}{v^2} \qquad \Rightarrow f \lesssim 80 \text{ GeV}$$

No new light states:

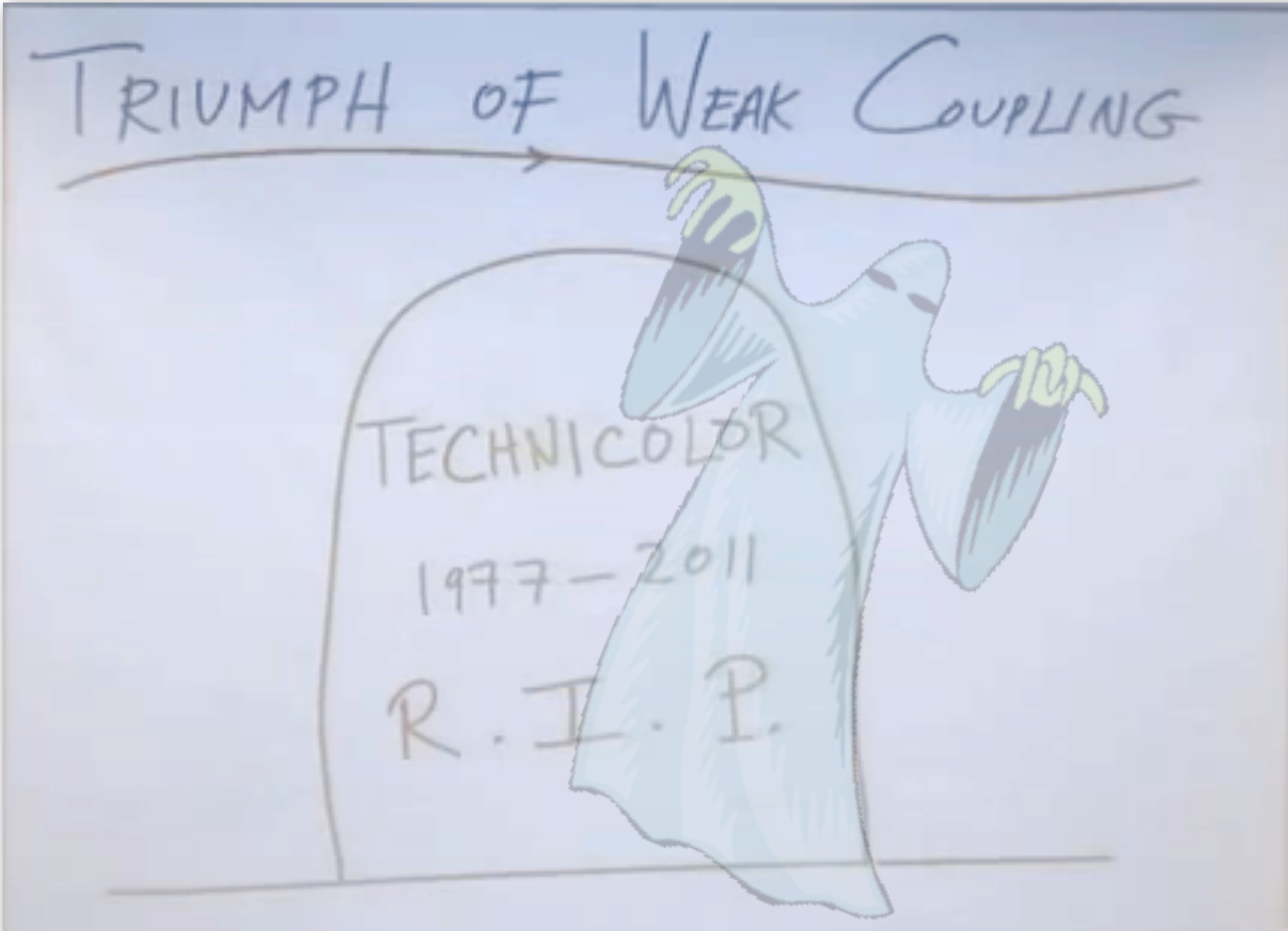
$$m_{\text{heavy}} \sim g_* f \gtrsim 500 \text{ GeV} \qquad \Rightarrow \; g_* \gtrsim 7$$

This motivates an additional technicolor-like sector that gives subleading contribution to EWSB.

...like QCD...



Arkani-Hamed, 2011



Arkani-Hamed, 2011

EFT of Auxiliary TC

EFT = TC chiral Lagrangian

Assume custodial symmetry:

$$SU(2)_L \times SU(2)_R \to SU(2)$$

$$\Sigma(x) = e^{i\tilde{\pi}_a(x)T_a} \in \frac{SU(2)_L \times SU(2)_R}{SU(2)} \qquad \Sigma \mapsto L\Sigma R^\dagger$$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{TC,eff}} + \mathcal{L}_{\text{int,eff}}$$

$$\mathcal{L}_{\text{TC,eff}} = \frac{N\Lambda^4}{16\pi^2} F\left(\frac{D_\mu}{\Lambda}, \tilde{\pi}\right) = \tfrac{1}{2}(\partial\pi_a)^2 + \frac{1}{f}\partial_\mu \pi_a J_a^\mu + \cdots$$

$$\pi_a = f\tilde{\pi}_a \qquad f \sim \frac{\Lambda}{g_*} \qquad g_* \sim \frac{4\pi}{N}$$

$$\text{loop} \sim \frac{1}{N} \quad \text{at } E \sim \Lambda$$

Higgs-TC Interactions

SM-like Higgs ⇒ SM weakly coupled to TC sector at $E \sim \Lambda$.

$$\mathcal{L}_{\text{int, fund}} = \kappa H \mathcal{O}_{\text{TC}}$$

κ may be relevant coupling if TC is conformal above Λ.

$$\Rightarrow \;\Delta V_{\text{eff}} \sim f^2 \Lambda^2 \left[1 + \frac{\kappa h}{\Lambda} + \left(\frac{\kappa h}{\Lambda} \right)^2 + \cdots \right]$$

Expansion converges:

$$\epsilon = \text{expansion parameter} = \frac{\kappa v_h}{\Lambda} \ll 1 \quad (\text{or } \lesssim 1)$$

TC-induced contributions to Higgs potential nonlinearly realize EW gauge symmetry:

$$\Delta V_{\text{eff}} = f^2 \Lambda^2 \left\{ \frac{\kappa}{\Lambda} \operatorname{tr}(\Sigma^\dagger \mathcal{H}) + \text{h.c.} + \cdots \right\}$$

EWSB in EFT

Minimize Higgs potential in EFT.

Extreme example: tadpole domination

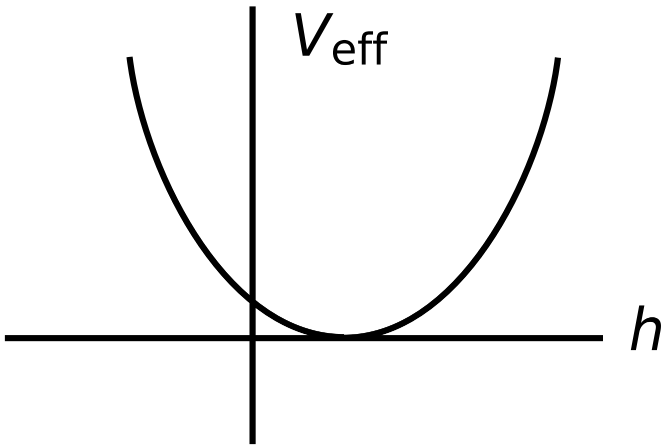
$$V_{\text{eff}} = m_H^2 H^\dagger H + \kappa \Lambda f^2 h + \cdots$$

$$\Rightarrow\ v_h = \frac{\kappa \Lambda f^2}{m_H^2} \qquad m_h^2 = m_H^2 = (125\ \text{GeV})^2$$

Note that SM Higgs quartic plays no role ⇒ can be small

...as is natural in both SUSY and composite Higgs models

$$\Rightarrow\ g_{hhh} \ll g_{hhh}^{(\text{SM})}$$




I don’t think we’re in the SM EFT anymore...

Some Numbers

$f = 80\ \text{GeV},\ N = 1\ \Rightarrow \Lambda \sim 4\pi f \sim 1\ \text{TeV}$

$\Rightarrow\ \epsilon \sim 0.15 \quad \Rightarrow$ tadpole dominance natural

$$\text{Higgs loop} \sim \frac{\kappa^2}{16\pi^2} \sim 0.05 \ \text{ at } E \sim \Lambda$$

$\Rightarrow$ Higgs weakly coupled to TC

$f = 50\ \text{GeV},\ N = 1\ \Rightarrow\ \Lambda \sim 630\ \text{GeV}$

$\Rightarrow\ \epsilon \sim 1 \quad \Rightarrow\ \Delta V_{\text{eff}}$ not predictive

Higgs loop ~ 0.2 at $E \sim \Lambda$

CP-odd Scalars

Two sets of would-be NGBs mix ⇒ one linear combination is massive:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} a^+ \\ h + i a^0 \end{pmatrix}$$

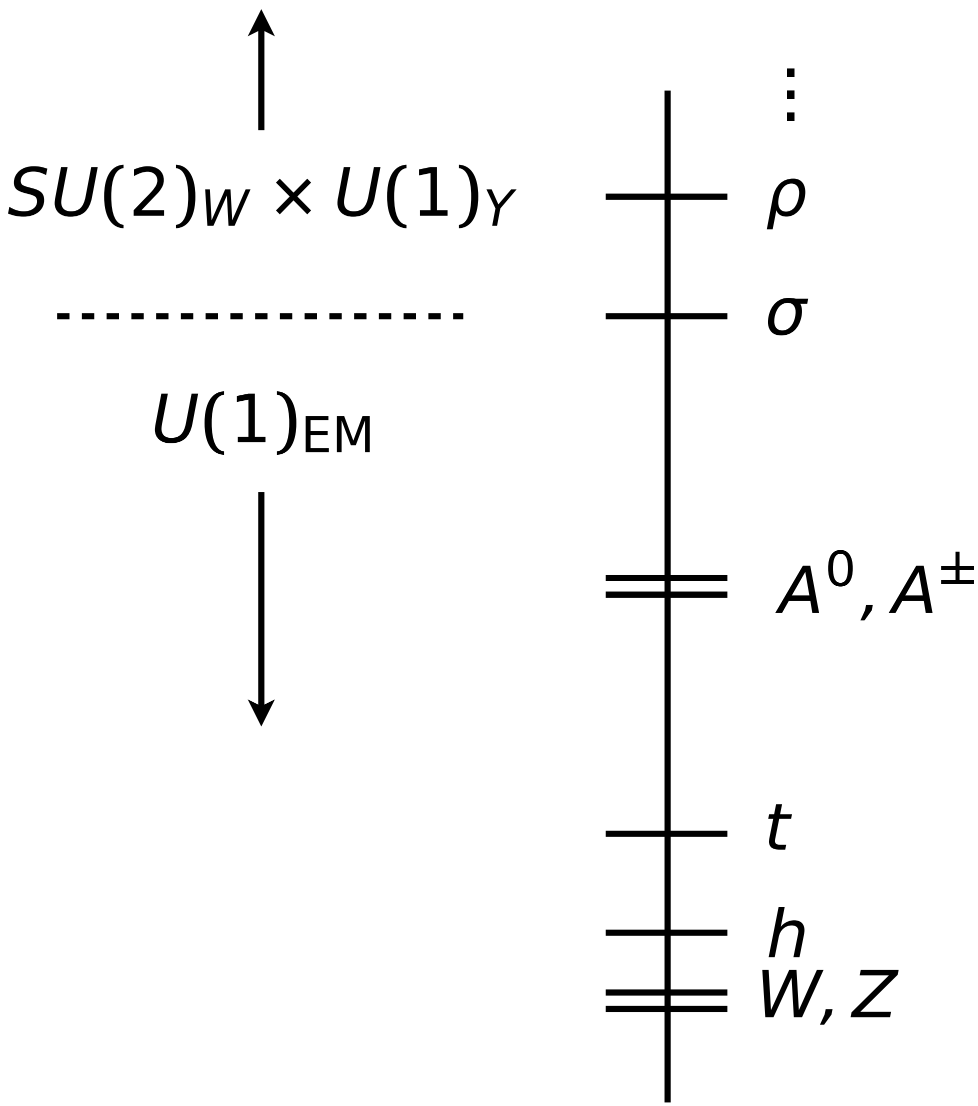
$$V_{\text{eff}} = \frac{1}{2} \begin{pmatrix} a^0 \\ \pi^0 \end{pmatrix}^T m_h^2 \begin{pmatrix} 1 & v_h/f \\ v_h/f & v_h^2/f^2 \end{pmatrix} \begin{pmatrix} a^0 \\ \pi^0 \end{pmatrix} + \cdots$$

Physical pseudoscalar: $A^0 = \frac{1}{v}(f a^0 + v_H \pi^0) = \text{mostly } \Sigma$

Eaten Goldstone: $G^0 = \frac{1}{v}(v_H a^0 - f \pi^0) = \text{mostly } H$

$$m_A^2 = m_h^2 \frac{v_h^2}{f^2} > m_h^2$$

Spectrum



$$m_\sigma, m_\rho \sim \Lambda$$

$$m_A \sim m_H \frac{v}{f} \sim \sqrt{\epsilon}\Lambda$$

complete custodial multiplet

Technicolor Lives!

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Technicolor is phenomenologically acceptable as a sub-leading contribution to EWSB (*c.f.* QCD).

- Flavor from H Yukawa couplings

- Precision EW

  $\Delta S \sim \frac{1}{2} S_{\mathrm{TC}}$ (“technipions” massive)

  Can get good EW fit if $\Delta T > 0$

  $Z \to \bar{b}b$ OK for $v \lesssim 6f$

- Light Higgs with SM-like couplings

  $v \gtrsim 3f$

Collider Phenomenology

Triplet of technipions with mass $m_A \sim \sqrt{\epsilon}\Lambda$.

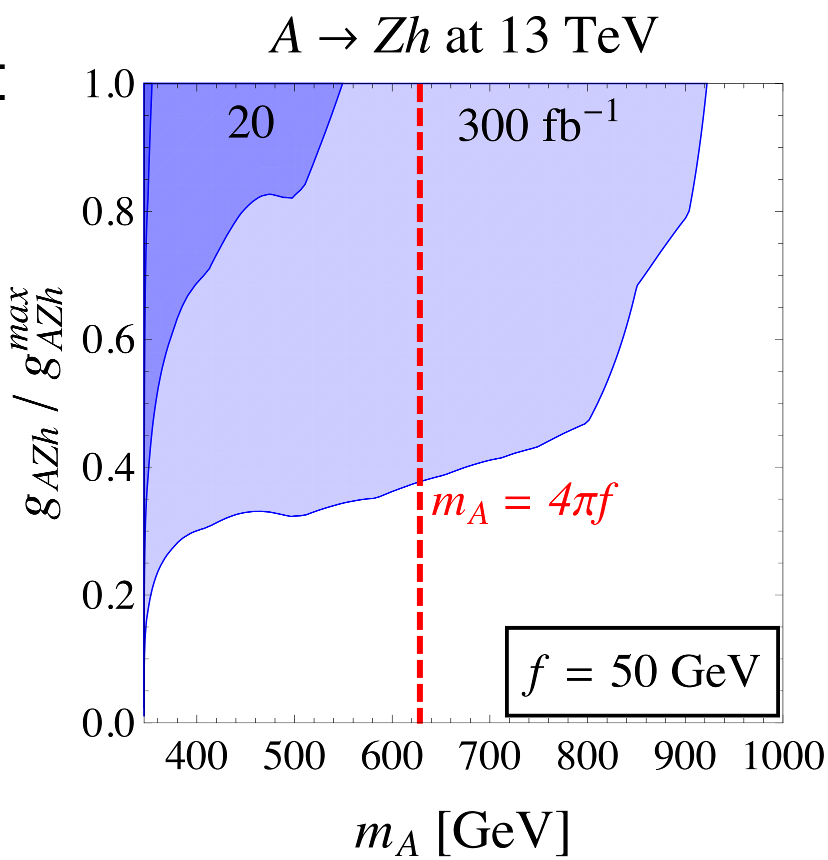
$A \to Zh$ is an important constraint

$$g_{AZh} = \frac{g}{2c_W v}(f\cos\gamma - v_h \sin\gamma)$$

$\gamma = h$–σ mixing angle

$$\sim \epsilon \frac{f}{v_h}$$

$\Rightarrow$ cancelations natural for $\epsilon \sim 1$



Constraints on other TC resonances are weak

S. Chang, ML, E. Salvioni
to appear

Low-scale TC could be hiding in plain sight even after 300 fb^{-1} LHC!

Top Down

Tadpole-induced EWSB is also motivated by the hierarchy problem.

MSSM: $\lambda_{\text{tree}} \sim g^2$ $\Rightarrow$ too small

Large $m_{\tilde{t}}$ $\Rightarrow$ fine tuning

Induced EWSB solves "SUSY little hierarchy problem."

Composite Higgs:

$$V_{\text{eff}}(h) = \frac{3y_t^2}{16\pi^2} m_T^2 f'^2 F(h/f')F(h/f') \qquad f' \gg v$$

$m_T \sim 500$ GeV allows $m_H^2 = m_h^2 > 0$ with no fine tuning but quartic is too small

Tadpole gives correct v, m_h without v^2/f'^2 fine tuning.

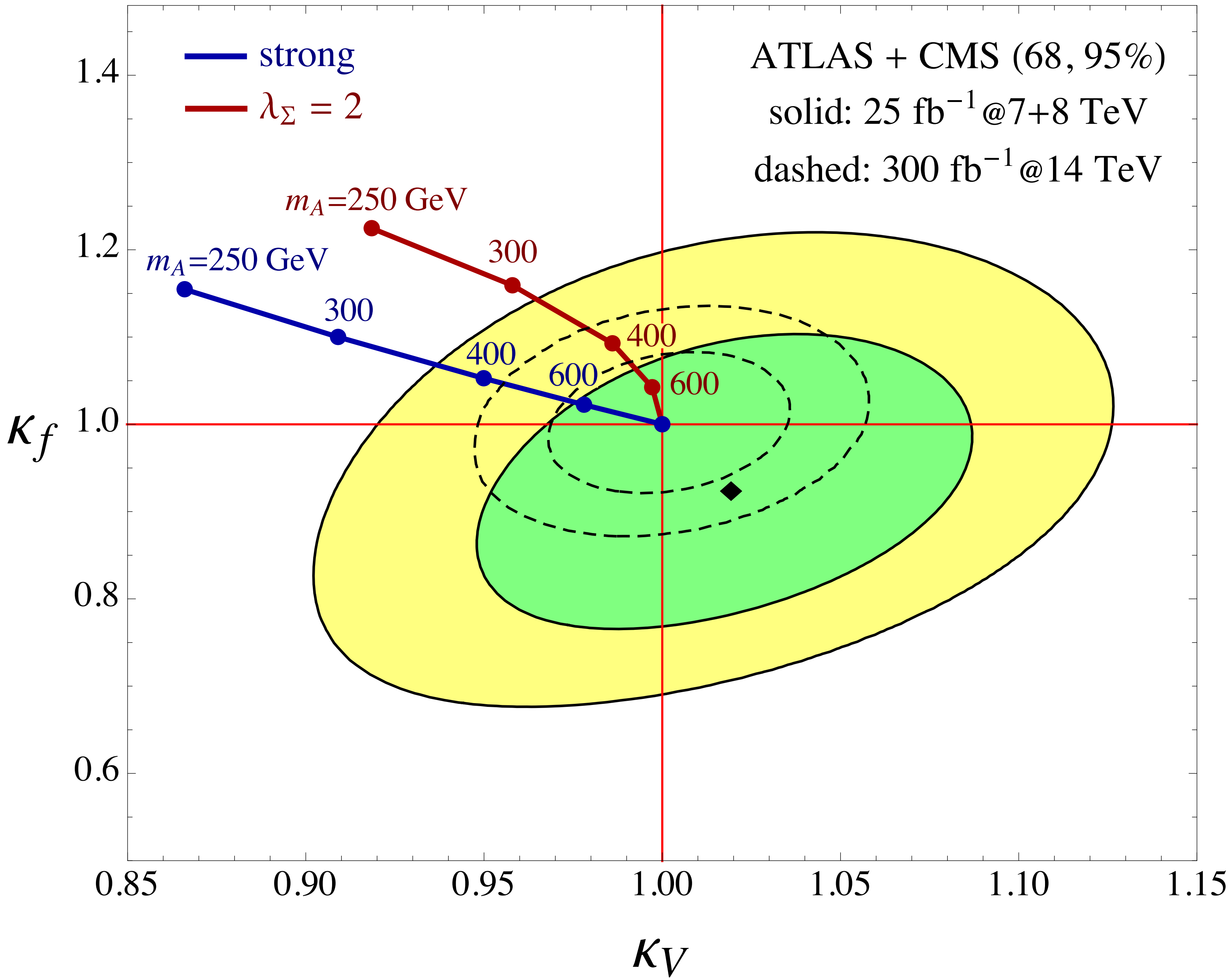
(R. Harnik, K. Howe, J. Kearny, 2016)

Conclusions

- Large deviations in Higgs potential are compatible with SM-like hVV, hff
- Motivates low-scale TC sector
- May play a role in the hiearchy problem
- EFT = SM + TC chiral Lagrangian
- Allowed by current data, may be around for awhile...

Motivates systematic study of EFT (in progress)

Backup



strong
λ_Σ = 2
ATLAS + CMS (68, 95%)
solid: 25 fb^{-1}@7+8 TeV
dashed: 300 fb^{-1}@14 TeV
m_A=250 GeV
300
400
600
m_A=250 GeV
300
400
600
1.4
1.2
1.0
0.8
0.6
κ_f
0.85
0.90
0.95
1.00
1.05
1.10
1.15
κ_V