The Unnatural Composite Higgs

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[James Barnard, TG, Tirtha Sankar Ray, Andrew Spray: 1409.7391]

What is the nature of the Higgs boson?

HIGGS BOSON

- Elementary? → Standard Model/ Supersymmetry

OR

- Composite? → New strong dynamics

Higgs potential: $V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$ $\langle H \rangle = \frac{1}{\sqrt{2}}(v+h)$

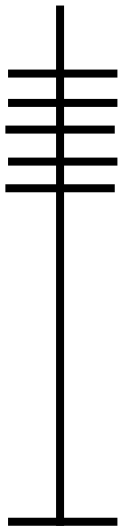
→ $\mu_h^2 \simeq (89\ \mathrm{GeV})^2$ $\lambda_h \simeq 0.13$

How to obtain a mass ~126 GeV much below the Planck scale?

Composite Higgs

Higgs as a pseudo Nambu-Goldstone boson [Georgi, Kaplan `84]

Global symmetry G spontaneously broken to subgroup H at scale f



$\rho^{(n)} \gtrsim \mathrm{TeV}$ Resonance mass: $m_\rho \sim g_\rho f$ $1 \lesssim g_\rho \lesssim 4\pi$

Higgs potential

$$V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$$

h where $\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2$ $\lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$

EWSB $\left(\langle H \rangle = \frac{v}{\sqrt{2}}\right)$ $v^2 = \dfrac{\mu_h^2}{\lambda_h}$ ⇨ Prefers: $v \sim f$

HOWEVER, precision electroweak, flavor constraints

$$\Rightarrow \quad f \gg v$$

e.g. FCNC $\epsilon_q^i \epsilon_q^j \epsilon_q^k \epsilon_q^l \frac{g_\rho^2}{m_\rho^2} \bar{q}^i q^j \bar{q}^k q^l \qquad \epsilon_q^i \sim \frac{g_i}{g_\rho}$ $\Rightarrow$ $f \gtrsim 10\,\mathrm{TeV} \quad (\epsilon_K)$

[Bellazzini, Csaki, Serra 1401.2457]

Tension alleviated by complicating minimal models
-- custodial symmetry, flavor symmetry,....

But, LHC limits:

$\Rightarrow$ ``Natural'' models increasingly tuned: $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 10\%$

Simple solution:

Assume $f \gtrsim 10\,\mathrm{TeV}$ *-- no need for custodial or flavor symmetries!*

Tuned Higgs potential

$$V \sim c_2 f^2 |H|^2 + c_4 |H|^4$$

tuning $\frac{v^2}{f^2} \gtrsim 10^{-4}$

This compares to $\sim 10^{-28}$ in SM!

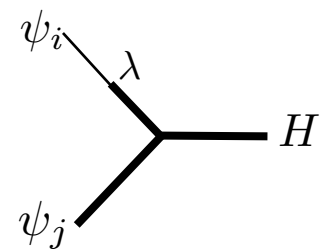
Is there a motivated upper bound for f ?

Yes!

Gauge coupling unification

Partial compositeness $\mathcal{L} = \lambda \psi \mathcal{O}$

- *Explains the fermion mass hierarchy*



Assume composite t_R and coset $\mathcal{G}/\mathcal{H}$ [Agashe, Contino, Sundrum '05]

$$(t_R, \underbrace{\chi^c}) = \text{complete}\, \mathcal{H}\, \text{multiplet}$$

Decoupled with top "companions" $m_\chi \sim \lambda_\chi f$

- *New contribution to the running of SM gauge couplings*

$$\alpha_i(\mu) - \alpha_j(\mu) = \text{SM} - \{H, t^c, \bar{t}^c\}$$

top "companions" contribution

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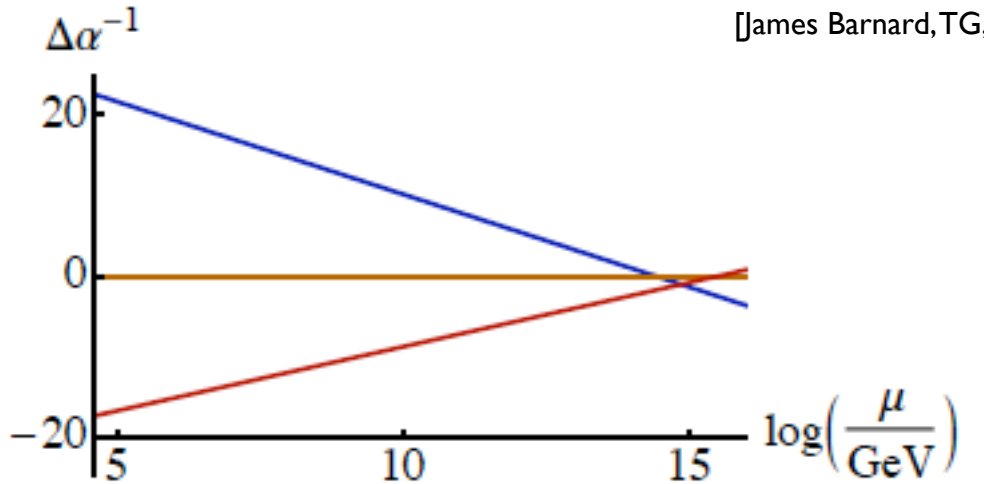

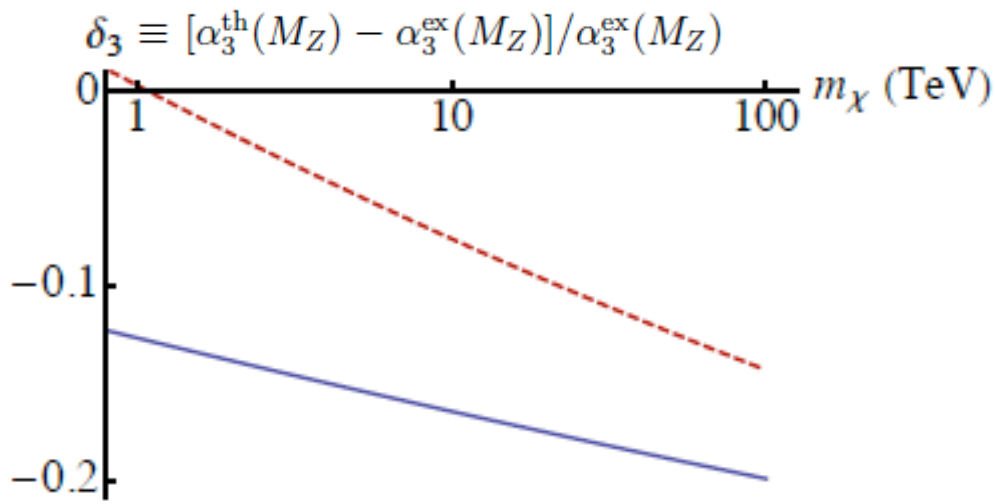

Requiring 20% accuracy ⇒ $f \lesssim 100\,\mathrm{TeV}$

Minimal Coset: SU(7)/SU(6)xU(1)

[James Barnard, TG, Tirtha Sankar Ray, Andrew Spray: 1409.7391]

- contains SU(5) --universal corrections to running
- scalar singlet dark matter [Frigerio, Pomarol, Riva, Urbano 1204.2808]

$$w = e^{i\Pi}\begin{pmatrix} 0_{(6)} \\ 1 \end{pmatrix} = \frac{1}{f}\begin{pmatrix} H \\ S \\ \sqrt{f^2 - |H|^2 - |S|^2} \end{pmatrix}$$

12 Nambu-Goldstone bosons

$$= \underbrace{\mathbf{5}}_{\text{= Higgs doublet, H + SU(3) triplet, T}} \text{ of } SU(5) + \overbrace{\mathbf{1}}^{\text{= S}} \text{ singlet}$$

Dark matter stability

Enlarge global group: $U(7) \equiv SU(7) \times U(1)_E$

		$U(1)_q$	$U(1)_l$	$U(1)_H$	$U(1)_L$	$U(1)_B$	Z_3
NG bosons	T	0	0	-2	0	0	-1
	D	0	0	-2	0	0	0
	S	0	7	10	0	$\frac{1}{3}$	1
SM fermions	$q_{(u)}$	-1	6	11	0	$\frac{1}{3}$	0
	$q_{(d)}$	1	6	11	0	$\frac{1}{3}$	0
	u^c	1	-6	-9	0	$-\frac{1}{3}$	0
	d^c	1	-6	-13	0	$-\frac{1}{3}$	0
	$l_{(\nu)}$	0	0	2	1	0	0
	$l_{(e)}$	0	2	2	1	0	0
	N^c	0	0	0	-1	0	0
	e^c	0	-2	-4	-1	0	0
top companions	$\tilde{q}^c$	-1	6	9	0	$\frac{1}{3}$	-1
	$\tilde{e}$	-1	6	9	0	$\frac{1}{3}$	1
	$\tilde{d}^c$	-1	-1	-3	0	0	1
	$\tilde{l}$	-1	-1	-3	0	0	0

Nonzero baryon number

The "Unnatural" Composite Higgs model

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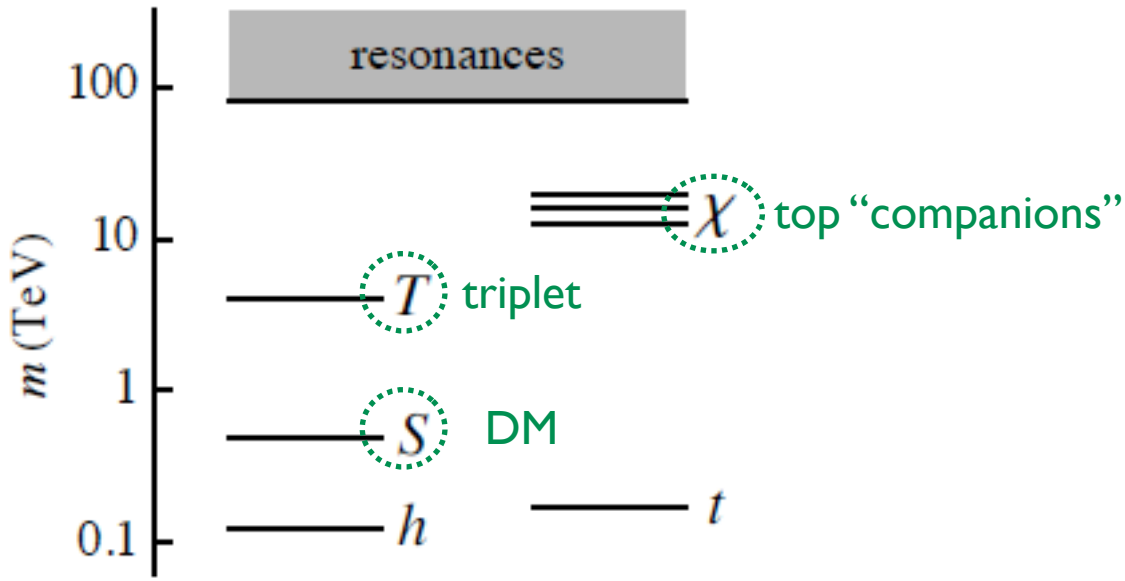
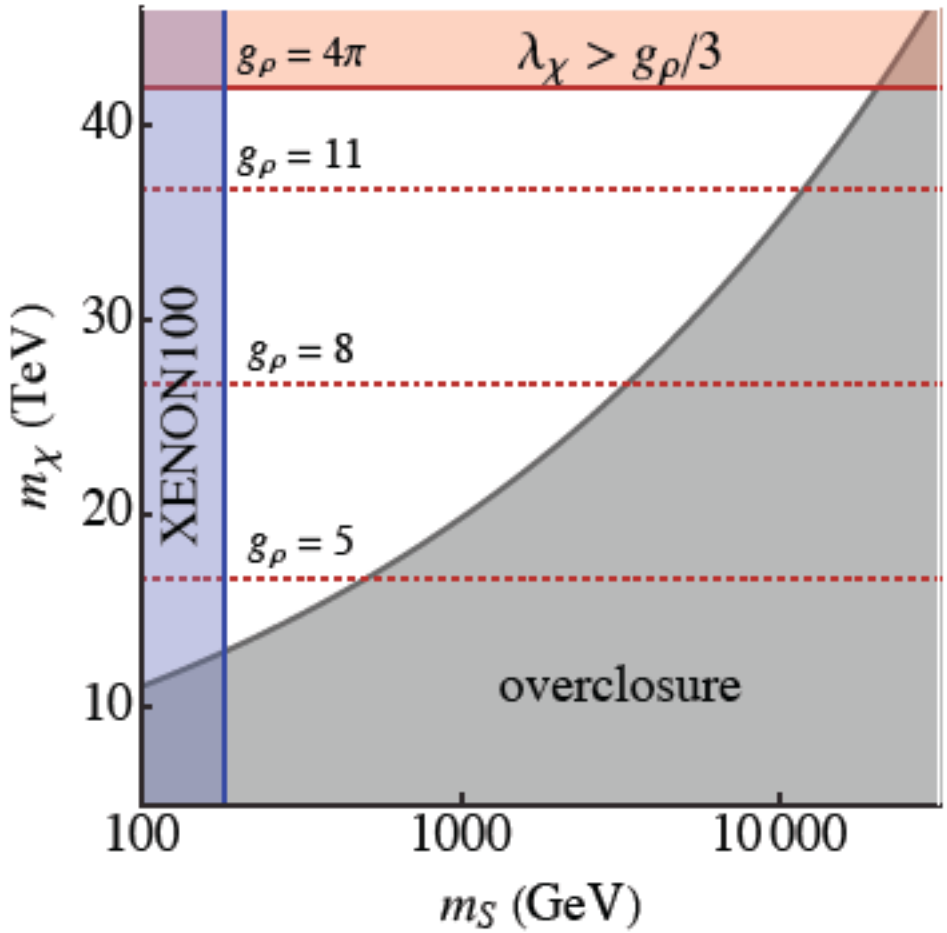


Low-energy spectrum: Standard Model + S + T + χ

What are experimental signals?

Dark matter constraints

singlet Higgs partner S -- Higgs portal coupling $V \supset \kappa |H|^2 |S|^2$



$f = 10$ TeV

$180 \text{ GeV} \lesssim m_S \lesssim 10 \text{ TeV}$ $\quad$ $10 \text{ TeV} \lesssim m_\chi \lesssim 40 \text{ TeV}$

Exotic state phenomenology

top companions χ

$$\tilde{q}^c \in (\overline{\mathbf{3}}, \mathbf{2})_{-\frac{1}{6}} \qquad \tilde{e} \in (\mathbf{1}, \mathbf{1})_{-1} \qquad \tilde{d}^c \in (\overline{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}} \qquad \tilde{l} \in (\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$$

$$f = 10\,\mathrm{TeV} \quad \Rightarrow \quad m_\chi \sim (1\text{–}2) f \sim 10\text{–}20\ \mathrm{TeV}$$

- Decays are collider-prompt

$$e.g. \quad \tilde{q}^c \to Tq, \quad \tilde{d}^c \to t^c TS$$

$$e.g. \quad \tilde{e} \to bTT, \quad \tilde{l} \to qTS$$

Phenomenology @100 TeV collider -- [in progress]

triplet Higgs partner T $T \in (\mathbf{3}, \mathbf{1})_{-\frac{1}{3}}$ (like sbottom in SUSY)

$$f = 10\,\mathrm{TeV} \Rightarrow m_T \sim (1\text{–}2)\frac{f}{\pi} \sim 3\text{–}5\ \mathrm{TeV}$$

$$\mathcal{L} \supset \frac{c_3^T}{24\pi^2 f^2} |\lambda_{b^c}||\lambda_\nu||\lambda_\tau|\, S^2 (T^\dagger t^c b^c)$$ dimension-6 term

f > 10 TeV = long-lived decay

$$T \to tbSS \Rightarrow c\tau \approx \underbrace{0.2\,\mathrm{mm}}_{\text{can produce a displaced vertex!}} \left(\frac{1}{c_3^T}\right)^2 \left(\frac{8}{g_\rho}\right)^3 \left(\frac{3\ \mathrm{TeV}}{m_T}\right)^5 \left(\frac{f}{10\ \mathrm{TeV}}\right)^4$$

- Prompt $m_T \gtrsim 1300\,\mathrm{GeV}$ e.g. gluino limits
- Long-lived $m_T \gtrsim 800\,\mathrm{GeV} - 1\,\mathrm{TeV}$ e.g. R-hadron searches

Collider analysis -- [in progress]

Scalar triplet decay

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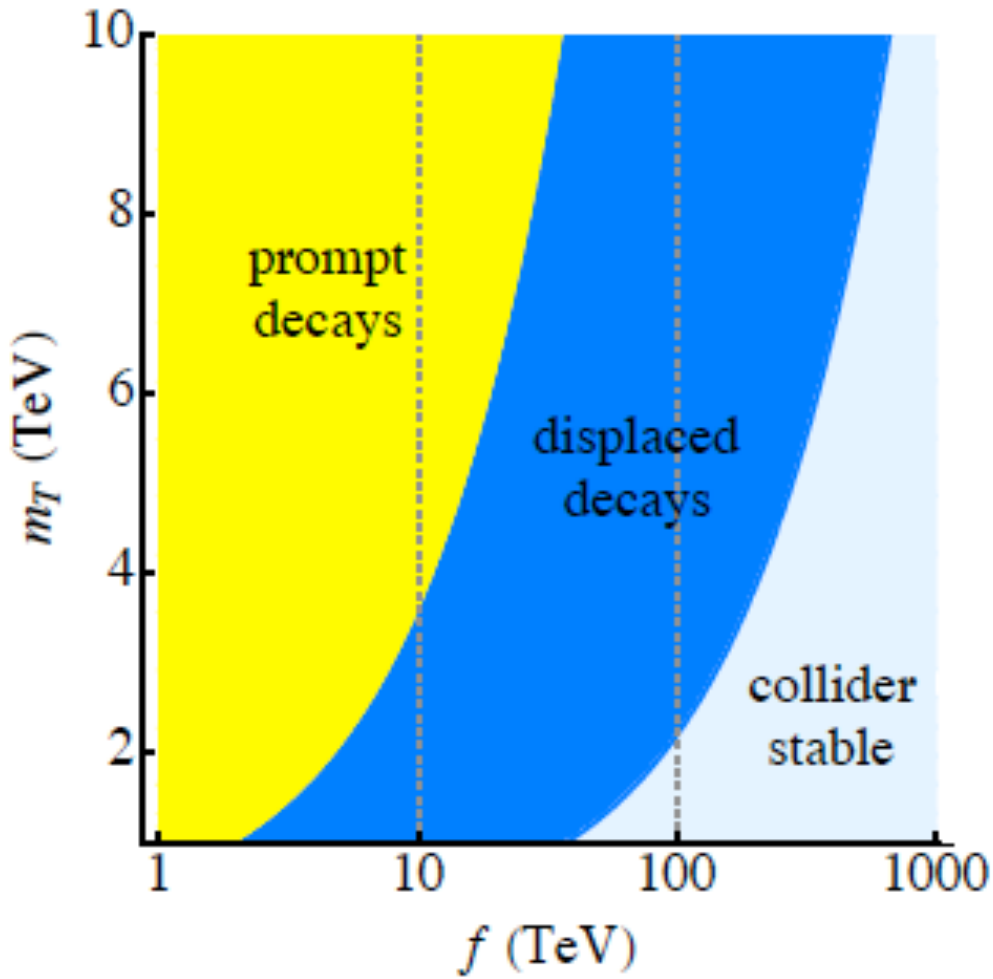

Summary

- $f \gtrsim 10$ TeV simply eliminates all precision electroweak and flavor constraints
  - --- Higgs potential is tuned at 10^-4 level
  - --- "Unnatural" composite Higgs
- SU(7)/SU(6)xU(1) minimal model
  - --- Improves gauge coupling unification
  - --- Explains fermion mass hierarchy
- Higgs partners, S = dark matter, T= scalar triplet
- Long-lived T decays = sign of unnaturalness!