Long-lived Color-Triplet Scalars from *Unnaturalness*

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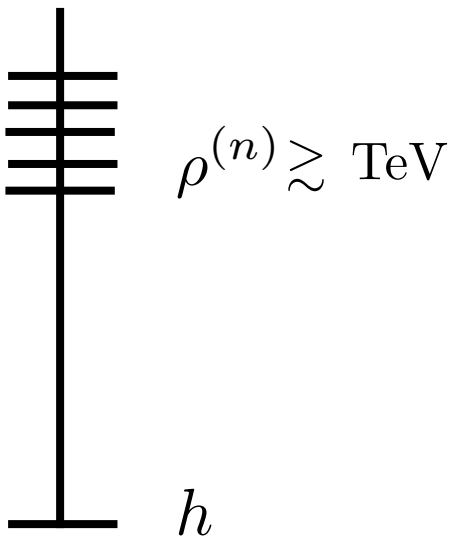
[James Barnard, TG, Tirtha Sankar Ray, Andrew Spray: 1409.7391]

[James Barnard, Peter Cox, TG, Andrew Spray: 1510.06405]

Composite Higgs

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

Global symmetry G spontaneously broken to subgroup H at scale f



Resonance mass: $m_\rho \sim g_\rho f$ $\quad 1 \lesssim g_\rho \lesssim 4\pi$

coset $G/H \supset h$

Higgs mass protected by shift symmetry
-- like pions in QCD

BUT global symmetry must be explicitly broken to generate $V(h) \neq 0$

Global symmetry broken by mixing with elementary sector

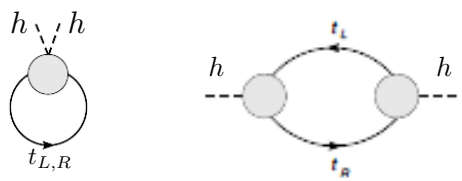
[Contino, Nomura, Pomarol `03; Agashe, Contino, Pomarol `04]

SM matter and gauge fields Ψ_i, A_μ

$\mathcal{L}_{mix} = \lambda_{L,R} \bar{\Psi}_{L,R} \mathcal{O}_\Psi + g_V A^\mu J_\mu$

strongly-coupled Higgs sector $\mathcal{O}_i$

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



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

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

Higgs mass: $m_h^2 = 2\lambda_h v^2 \simeq \frac{N_c}{\pi^2} m_t^2 g_T^2$ ⇒ $g_T \sim 1.3$

i.e. light top partners $m_T \sim g_T f$

HOWEVER, precision electroweak, flavor constraints

EWPT: $\frac{s}{16\pi^2 v^2} H^\dagger \tau^a H B^{\mu\nu} W_{a\mu\nu}$ $S = \frac{s}{2\pi} \sim \frac{m_W^2}{m_\rho^2}$ ➡ $f \gtrsim \frac{2.5\ \text{TeV}}{g_\rho}$

$\frac{-t}{16\pi^2 v^2}((D^\mu H)^\dagger H)(H^\dagger D_\mu H)$ $T = \frac{t}{8\pi e^2} \sim \frac{v^2}{f^2}$ ➡ $f \gtrsim 5.5\ \text{TeV}$

e.g. FCNC $\epsilon_q^i \epsilon_q^j \epsilon_q^k \epsilon_q^l \frac{g_\rho^2}{m_\rho^2} \bar{q}^i q^j \bar{q}^k q^l$ $\epsilon_q^i \sim \frac{g_i}{g_\rho}$ ➡ $f \gtrsim 10\,\text{TeV}$

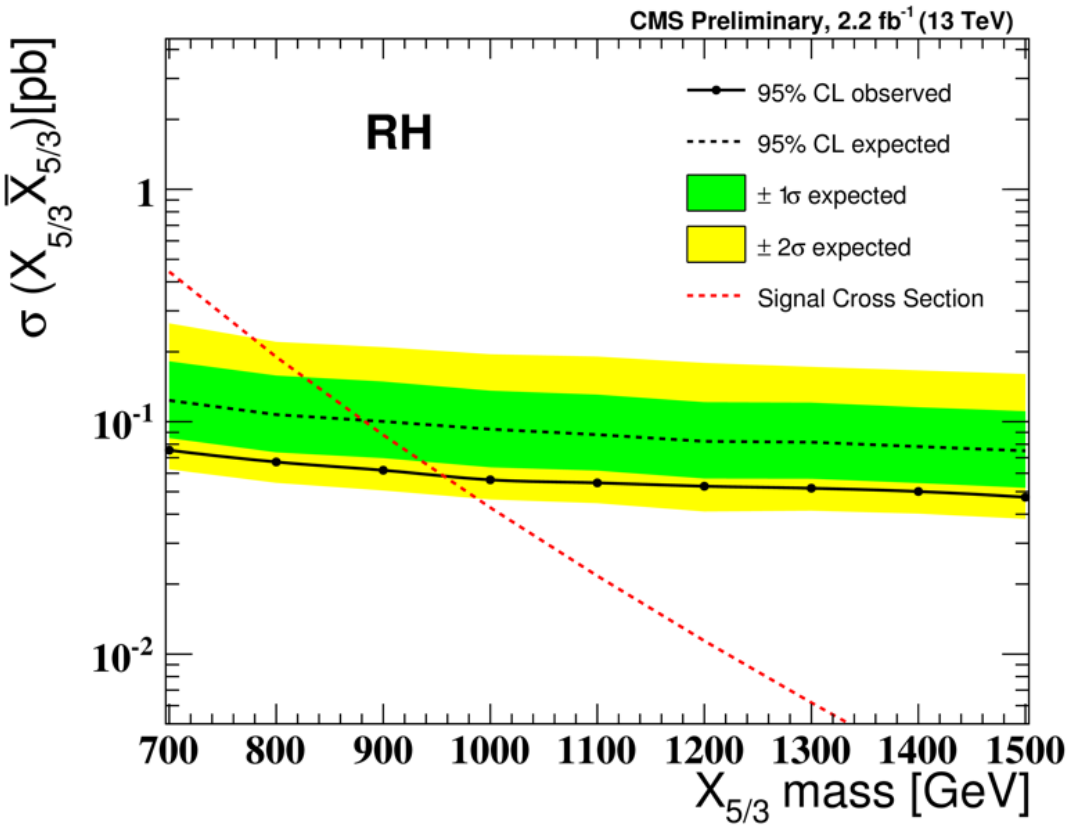
[Bellazzini, Csaki, Serra 1401.2457]
[Panico, Wulzer 1506.01961]

➡ $f \gg v$ *"Little" hierarchy*

Tension partly alleviated by complicating minimal models

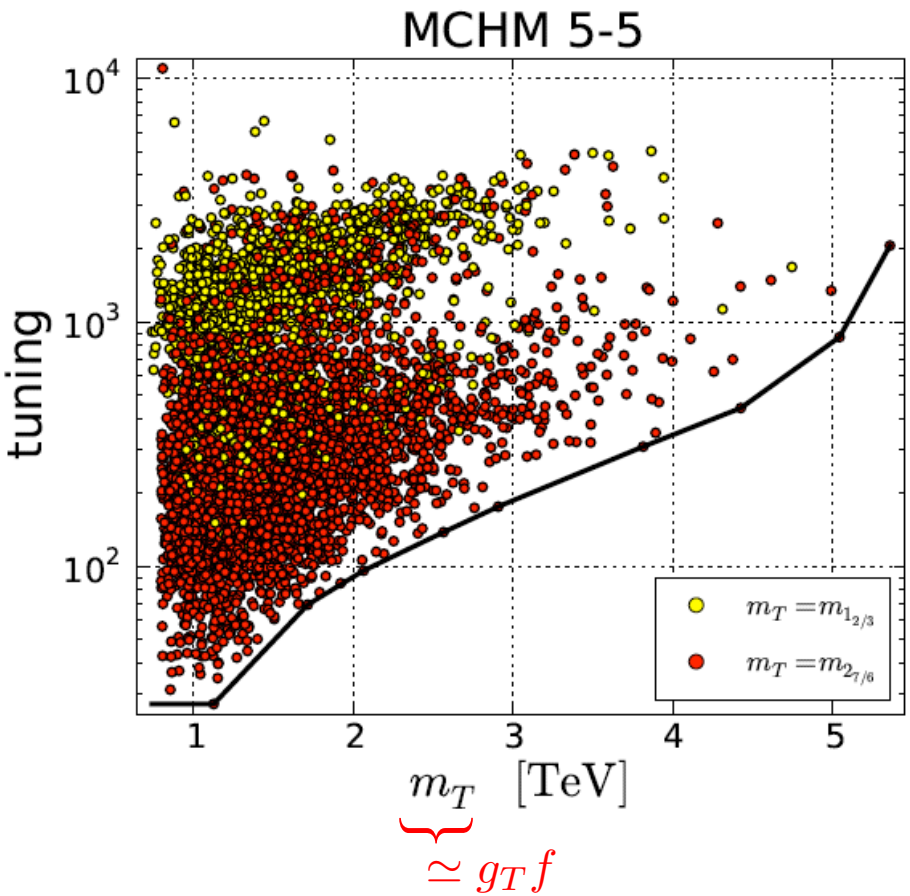
e.g. custodial symmetry, flavor symmetry....

LHC Limits: *The Missing Resonances Problem*

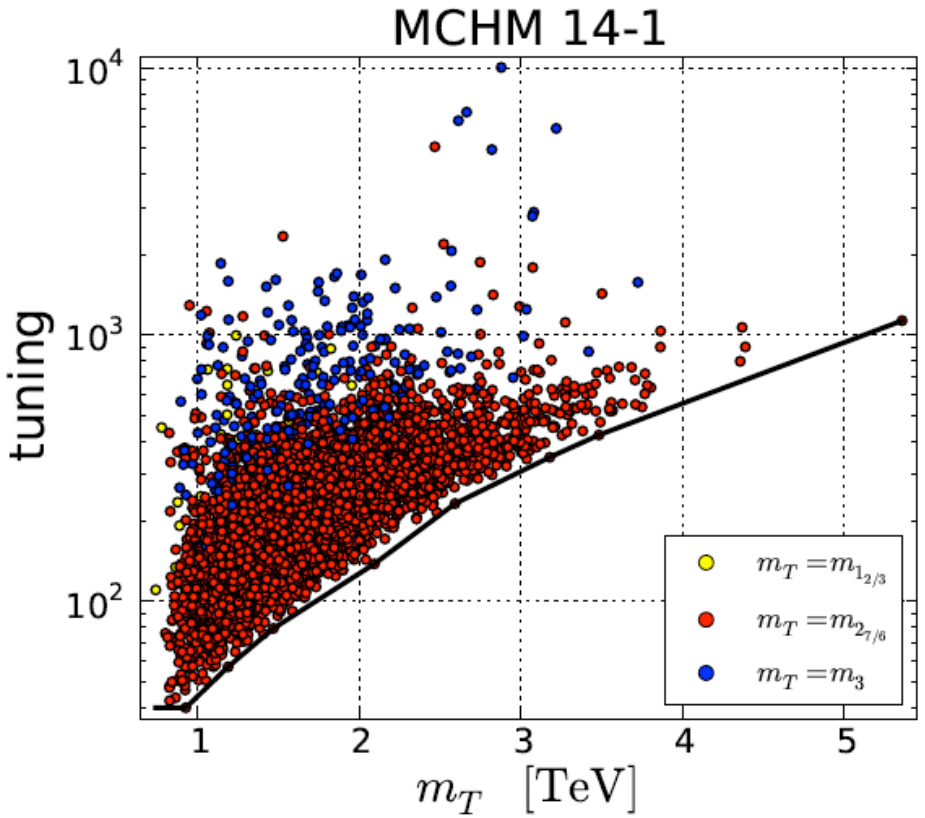


$$m_T \gtrsim 940 - 960 \text{ GeV}$$

[Barnard, White 1507.02332]



$m_T \simeq g_T f$



"Natural" models increasingly elaborate and tuned:

$$\text{tuning} \sim \frac{v^2}{f^2} \lesssim 5\%$$

Simple solution:

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

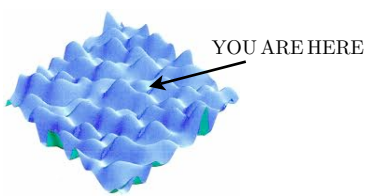
Tuned Higgs potential: $V \sim c_2 f^2 |H|^2 + c_4 |H|^4$

$$\text{tuning} \sim \frac{v^2}{f^2} \lesssim 10^{-4}$$

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

Possible reasons:

- new sector e.g. QCD nucleon mass sensitive to quark mass $\frac{m_{u,d}}{m_{nucleon}} \sim 10^{-3}$
- anthropic- we live in a multiverse



Is there a motivated upper bound for f ?

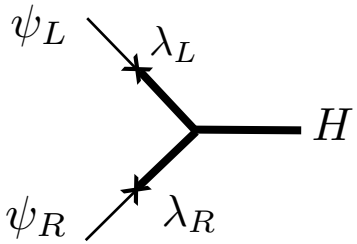
Yes!

Partial compositeness:

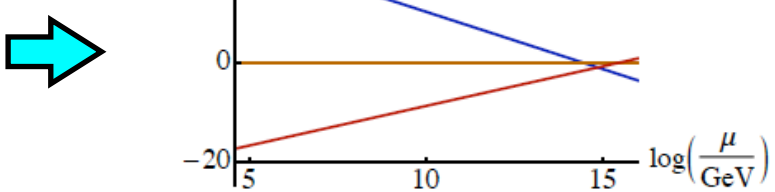
$$\mathcal{L} = \lambda_L \psi_L \mathcal{O}_R + \lambda_R \psi_R \mathcal{O}_L$$

Explains the fermion mass hierarchy [Kaplan 91; TG, Pomarol 00]

$$m_f \sim \lambda_L \lambda_R v \qquad \text{where} \qquad \lambda_{L,R} \sim \left(\frac{\Lambda}{\Lambda_{UV}}\right)^{\dim \mathcal{O}_{L,R} - \frac{5}{2}}$$



Composite (RH) top quark



GAUGE COUPLING UNIFICATION [Agashe, Contino, Sundrum '05]

Requires: $f \lesssim 500$ 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]

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

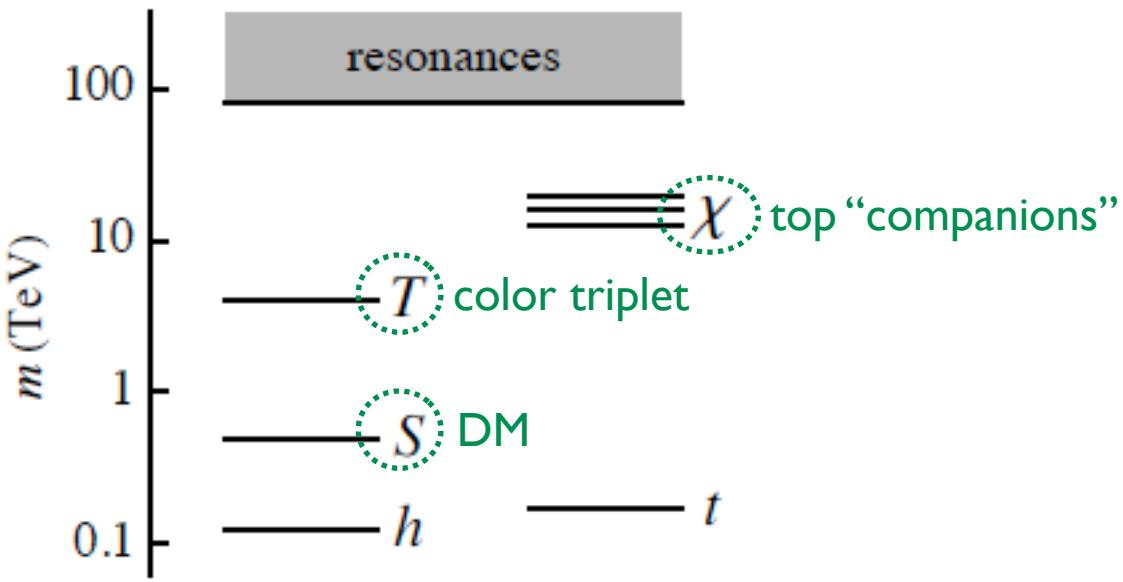
12 Nambu-Goldstone bosons

$$= \underbrace{\mathbf{5}}\,\text{of}\,SU(5) + \overbrace{\mathbf{1}}^{=S}\,\text{singlet}$$

H = Higgs doublet, D + SU(3) triplet, T

The Unnatural or "Split" Composite Higgs model

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

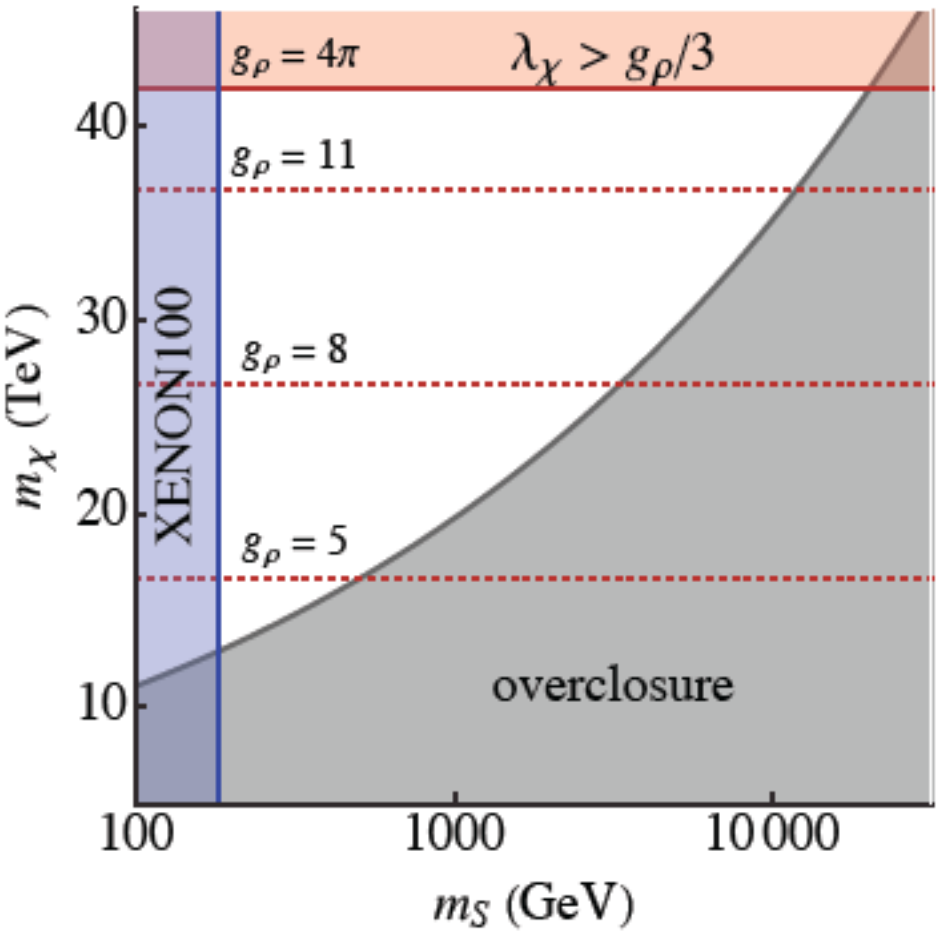


Low-energy spectrum: Standard Model + S + T + χ

What are experimental signals?

Dark matter:

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



where $\kappa \sim 0.02 \left(\frac{m_\chi}{f}\right)^4$

$f = 10$ TeV

$180 \text{ GeV} \lesssim m_S \lesssim 10 \text{ TeV}$

$10 \text{ TeV} \lesssim m_\chi \lesssim 40 \text{ TeV}$

Collider searches:

- *top companions* χ $\quad \tilde{q}^c \in (\overline{3},2)_{-\frac{1}{6}} \quad \tilde{e} \in (1,1)_{-1} \quad \tilde{d}^c \in (\overline{3},1)_{\frac{1}{3}} \quad \tilde{l} \in (1,2)_{-\frac{1}{2}}$

$$f = 10\,\text{TeV} \Rightarrow m_\chi \sim (1\text{–}2) f \sim 10\text{–}20\ \text{TeV} \longrightarrow \text{future 100 TeV collider}$$

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

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

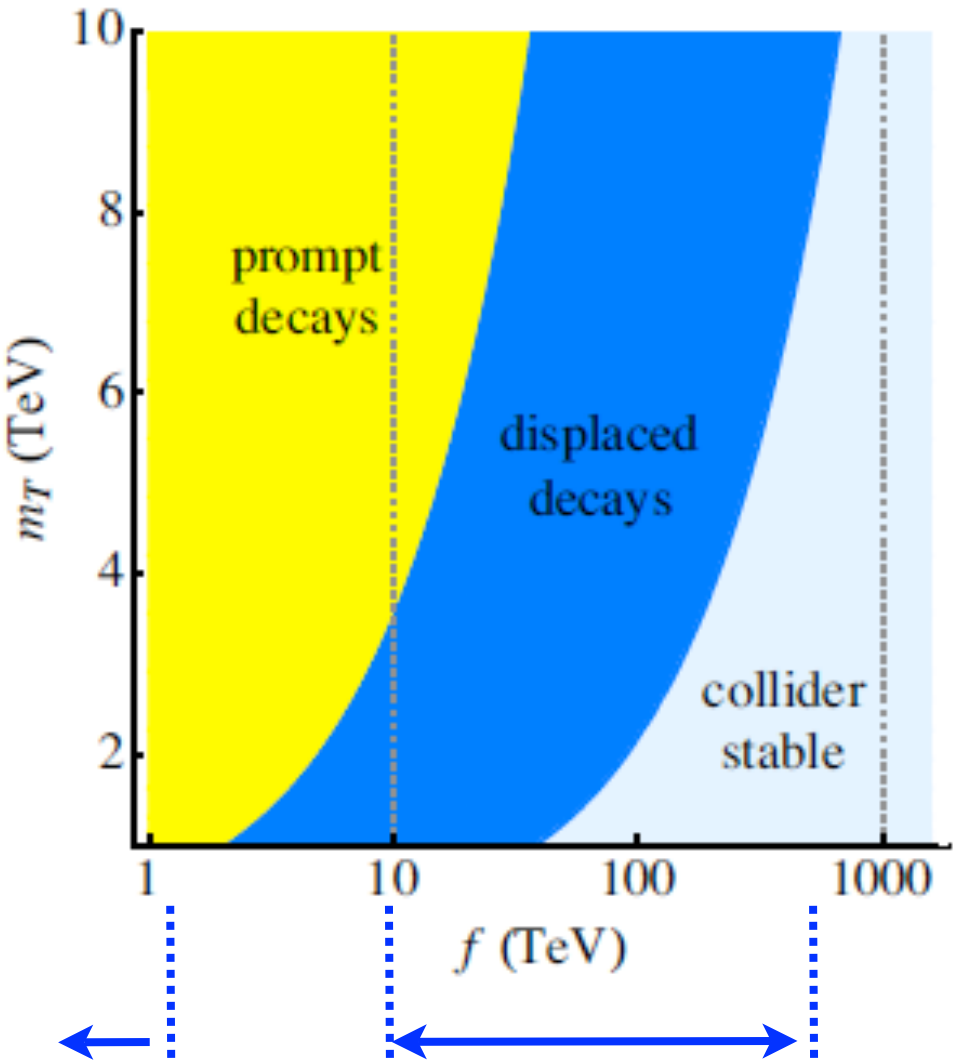
$$\mathcal{L} \supset \frac{c_3^T}{24\pi^2 f^2} |\lambda_{b^c}||\lambda_\nu||\lambda_\tau|\, S^2 (T^\dagger t^c b^c)$$ dimension-6 term

f > 10 TeV = long-lived decay

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

Color triplet decay

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



"natural" composite Higgs:

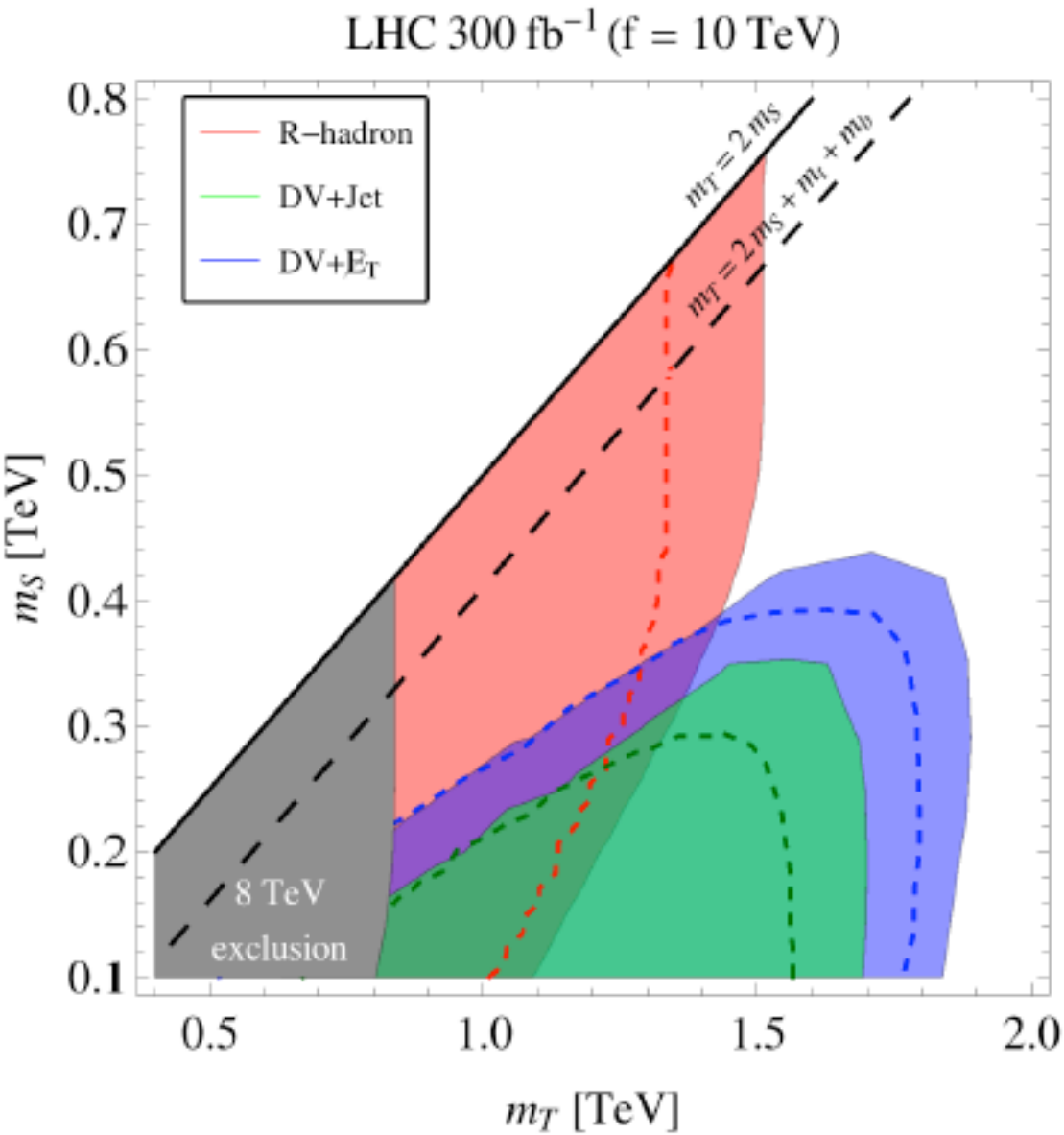
$f \lesssim 1$ TeV

Unnatural or "split" composite Higgs:

$10 \text{ TeV} \lesssim f \lesssim 500 \text{ TeV}$

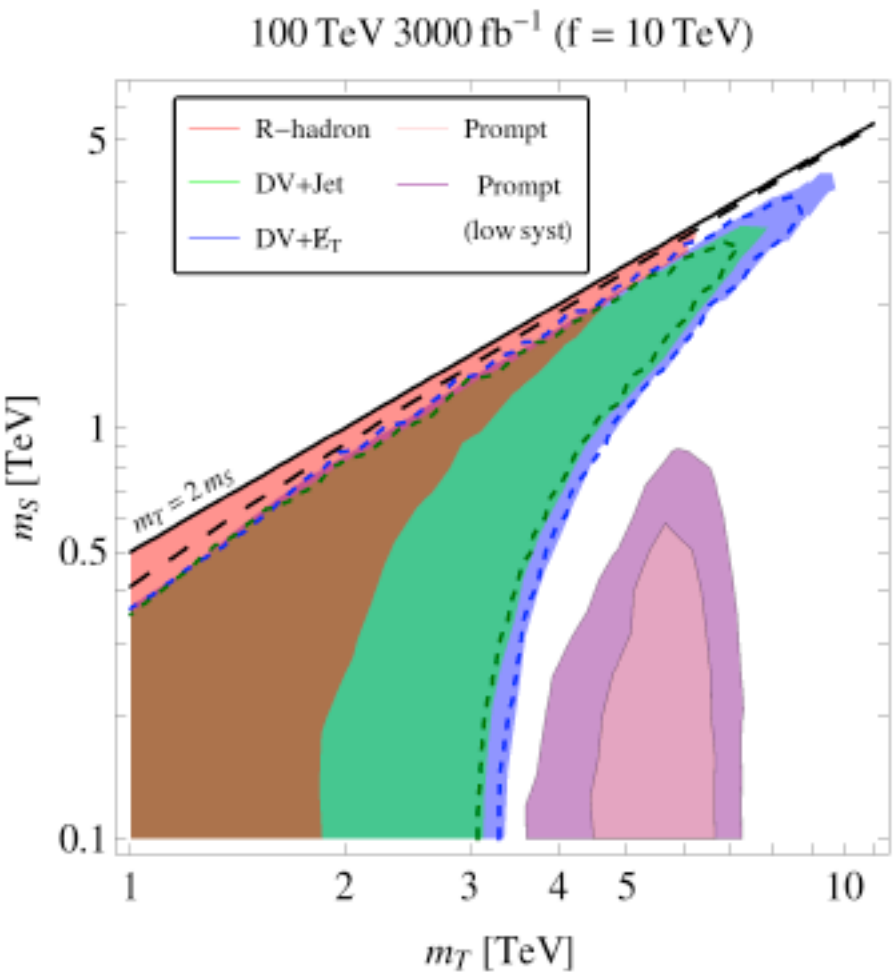
LHC:

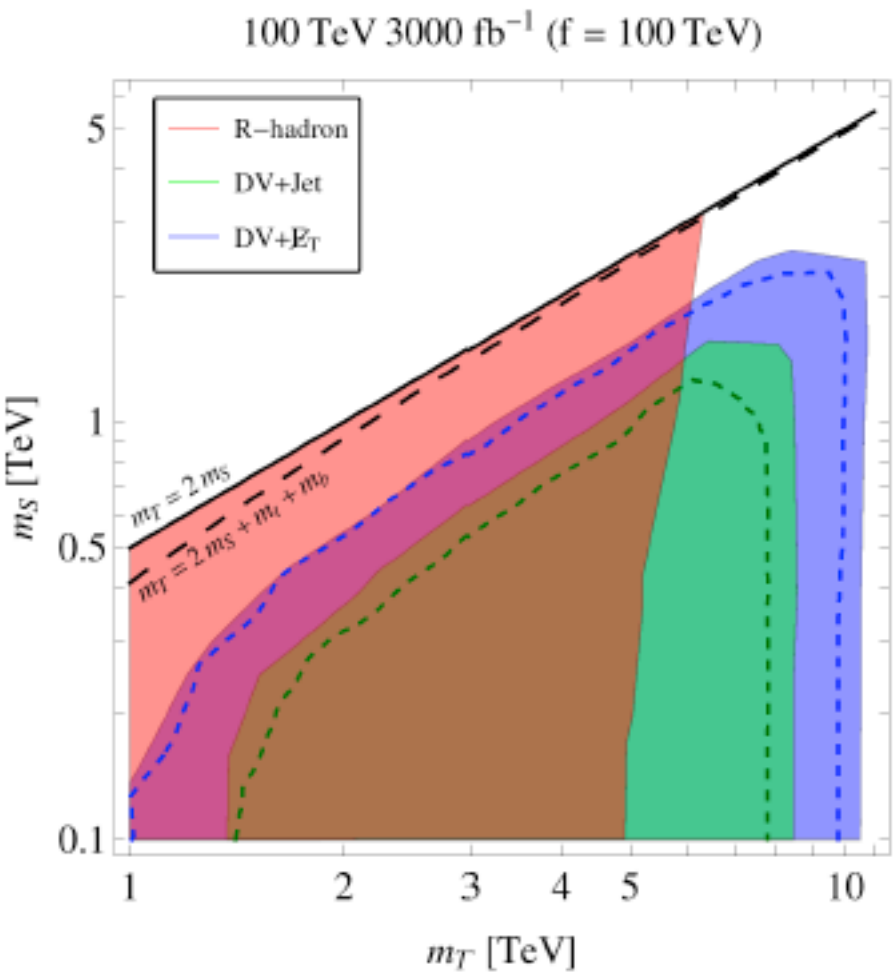
[Barnard, Cox, TG, Spray: 1510.06405]



Future 100 TeV collider:

[Barnard, Cox, TG, Spray: 1510.06405]





Summary

- $f \gtrsim 10$ TeV simply eliminates all precision electroweak and flavor constraints
  - --- *Higgs potential is tuned at* 10^{-4} *level*
  - --- *Unnatural or "split" composite Higgs*
- SU(7)/SU(6)xU(1) minimal model
  - --- *Improves gauge coupling unification* $(f \lesssim 500\ \mathrm{TeV})$
  - --- *Explains fermion mass hierarchy*
- Higgs partners: S = dark matter, T= color triplet
- Long-lived T decays = sign of unnaturalness!

Extra slides

Gauge coupling unification

[Agashe, Contino, Sundrum '05]

Assume composite t_R and coset $\mathcal{G}/\mathcal{H}$

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

Decoupled with top "companions" χ Dirac mass: $m_\chi \sim \lambda_\chi f$

New contribution to the running of SM gauge couplings

top "companions" contribution

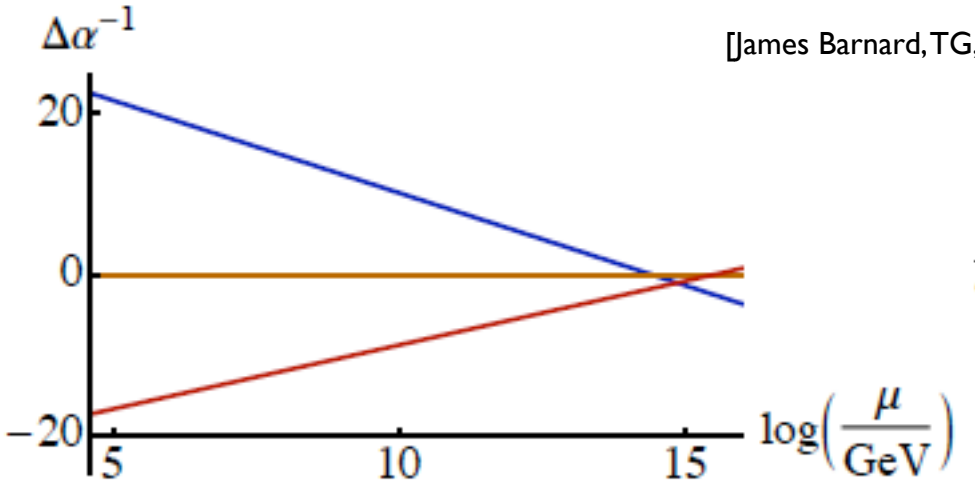
$$\alpha_i(\mu) - \alpha_j(\mu) = \text{SM} - \{\underbrace{H, t^c}, \overline{t^c}\}$$

composite Higgs, top

One-loop beta function coefficients:

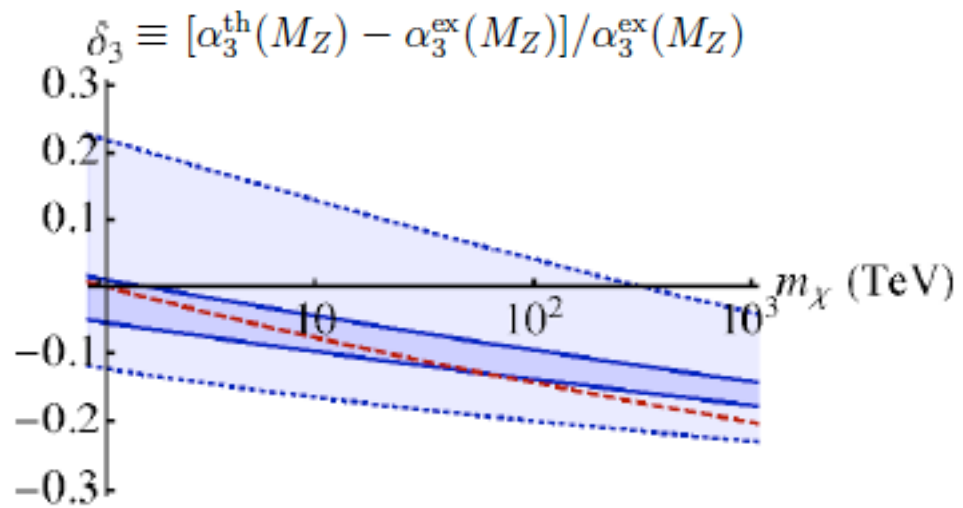
$$b_1 - b_2 = \frac{94}{15} \qquad b_2 - b_3 = \frac{13}{3} \quad \Rightarrow \quad \frac{b_2 - b_3}{b_1 - b_2} \simeq 0.69$$

c.f. MSSM value = 0.71



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

$$\frac{d}{d\ln\mu}\left(\frac{1}{\alpha_i}\right) = \frac{b_i}{2\pi} + \frac{B_{ij}}{2\pi}\frac{\alpha_j}{4\pi} + \frac{C_{i\alpha}}{2\pi}\frac{\lambda_\alpha^2}{16\pi^2}$$



$$B_{strong} \sim 9 b_{strong}$$

$$C \sim 3\lambda_\chi b_{strong}$$

$$b_{strong} = 1, 5$$

Requiring $\delta_3 = 0$

$(b_{strong} = 5)$

$$f \lesssim 500 \text{ TeV}$$

Higgs couplings

LHC: 1-5 % precision ILC: 0.5 - 1% precision

$$f \gtrsim 10 \text{ TeV} \quad \Rightarrow \quad \frac{v^2}{f^2} \lesssim 10^{-4}$$

$$\frac{g_{hWW}}{g_{hWW}^{SM}} \sim \frac{g_{hff}}{g_{hff}^{SM}} \sim \sqrt{1 - \frac{v^2}{f^2}}$$

Tiny deviations --too small to be seen at LHC/ILC

Higgs boson is very SM-like!