The Unnatural Composite Higgs

(a.k.a "Split" Composite Higgs)

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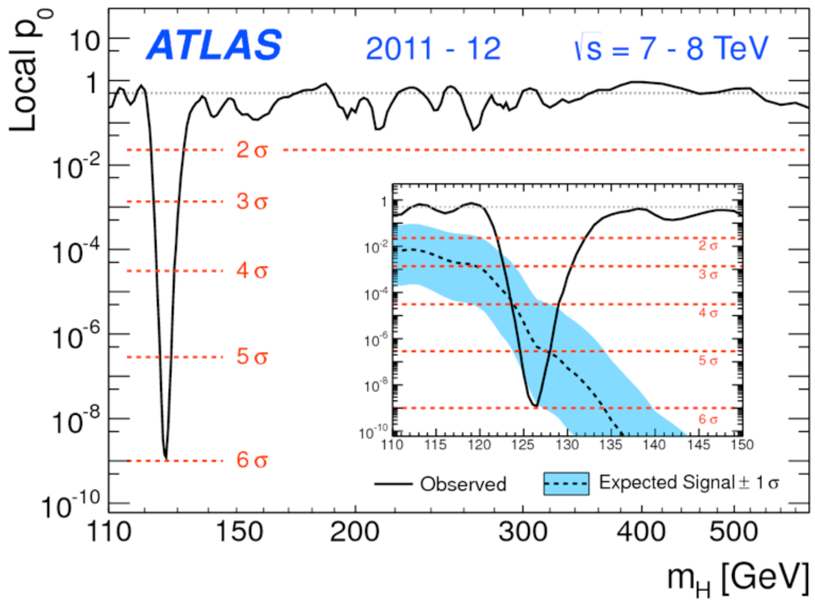
[James Barnard, TG, Tirtha Sankar Ray, Andrew Spray: 1409.7391]

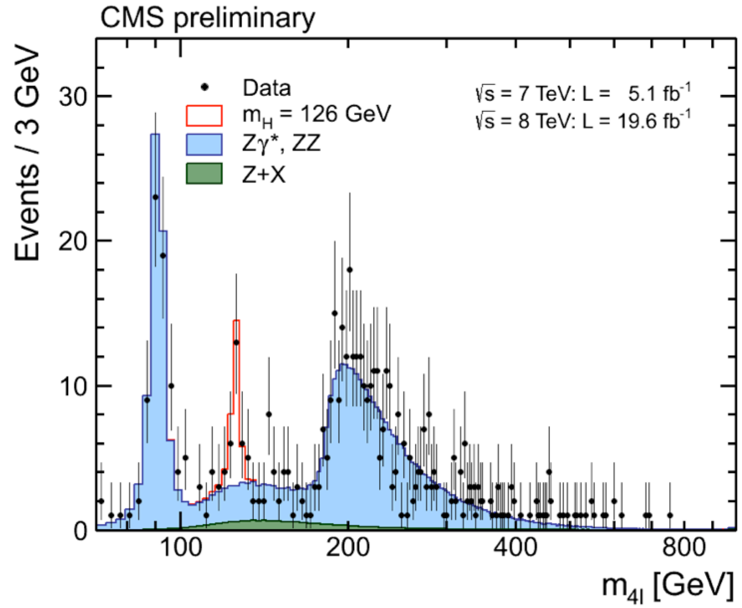
[James Barnard, Peter Cox, TG, Andrew Spray: 1510.06405]

Outline

- Introduction and motivation
- The "unnatural" composite Higgs
- Experimental signals of unnaturalness
- Conclusion

Higgs discovery - LHC Run I



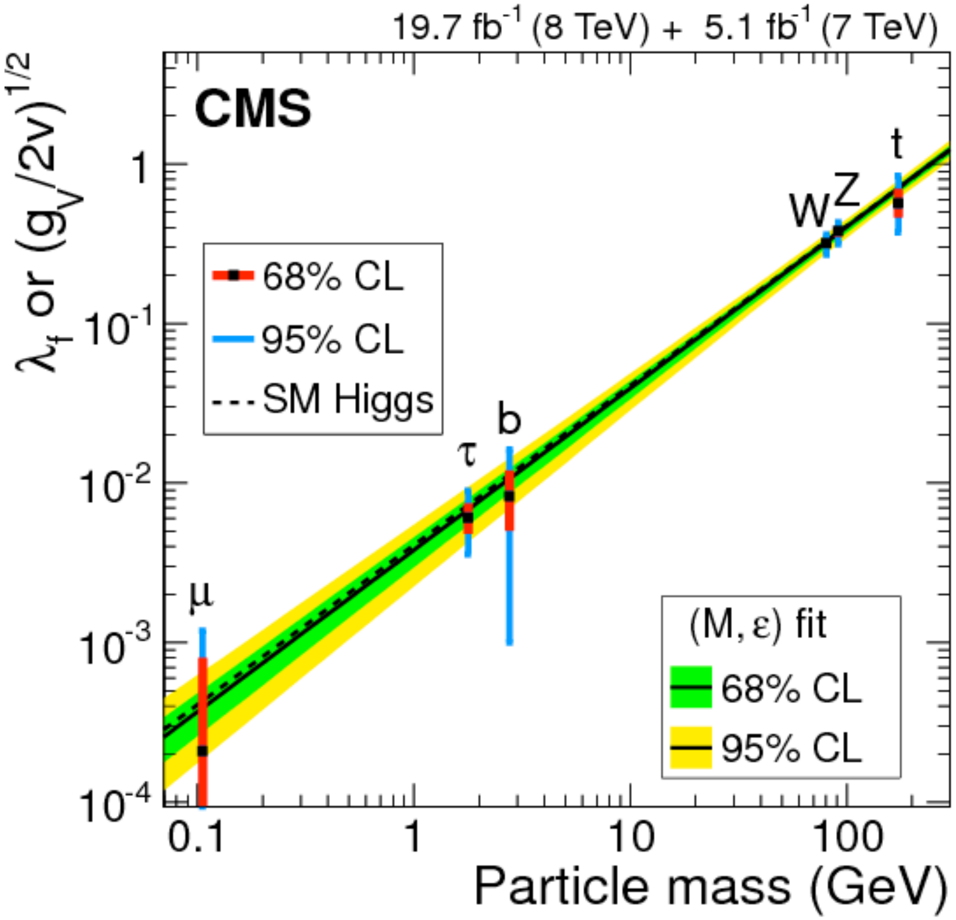


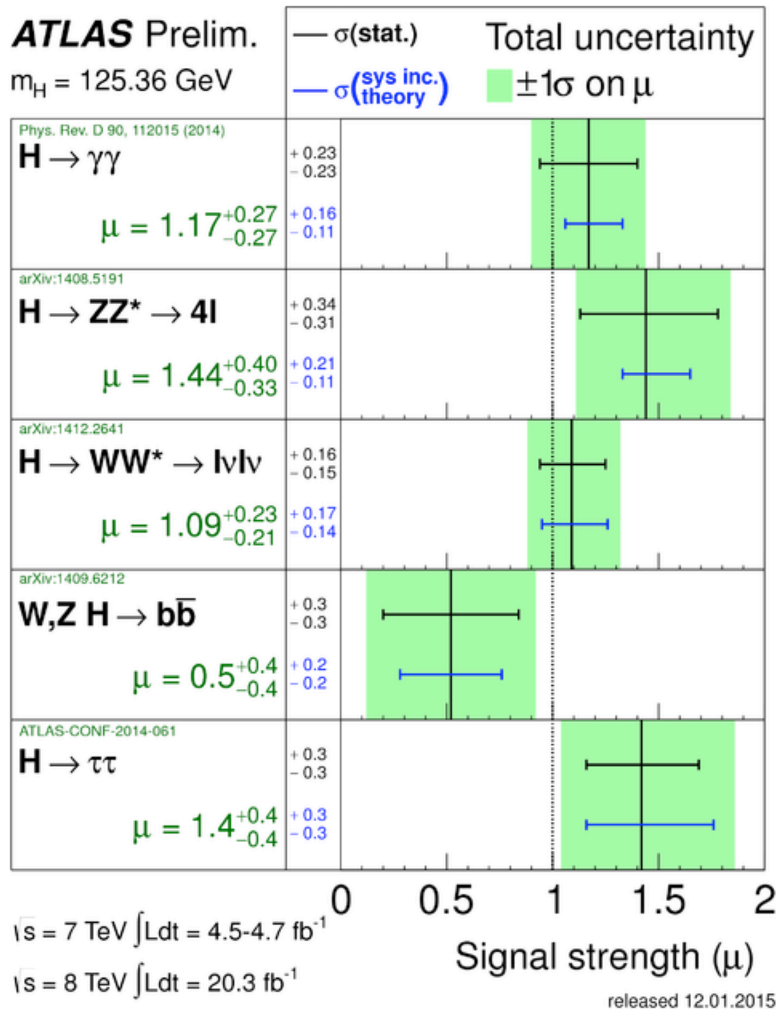
Higgs potential: $V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$ $\quad \langle H \rangle = \frac{1}{\sqrt{2}}(v+h)$

$$v^2 = \frac{\mu_h^2}{\lambda_h} \simeq (246 \text{ GeV})^2 \qquad m_h^2 = 2\lambda_h v^2 \simeq (126 \text{ GeV})^2$$

$$\mu_h^2 \simeq (89 \text{ GeV})^2 \qquad \lambda_h \simeq 0.13$$

Higgs couplings





➡ Looks very much like a SM Higgs boson!

However, SM is ***not*** a complete theory of Nature!

Questions:

- Planck/weak scale hierarchy? $(m_h \ll M_p)$
- Fermion mass hierarchy? Neutrino masses?
- GUTS? 3 fermion generations?
- Dark matter?
- Baryon asymmetry?
- Strong CP problem?
- Inflaton? Cosmological constant?
- UV completion of gravity?

What is the nature of the Higgs boson?

HIGGS BOSON

- Elementary? → Standard Model/ Supersymmetry

OR

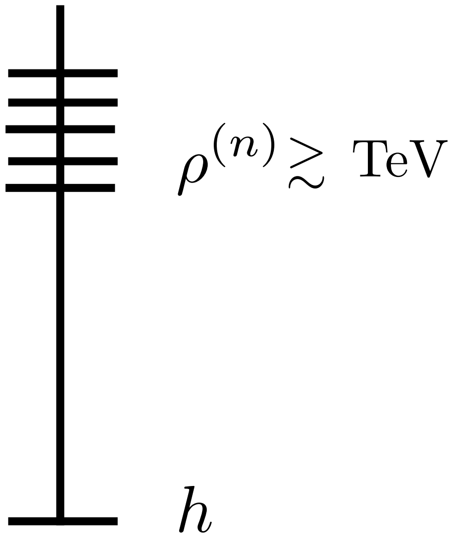
- Composite? → New strong dynamics

Understanding why $m_h \ll M_p$ can help address shortcomings in the SM

Composite Higgs

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

Global symmetry G spontaneously broken to subgroup H at scale f



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

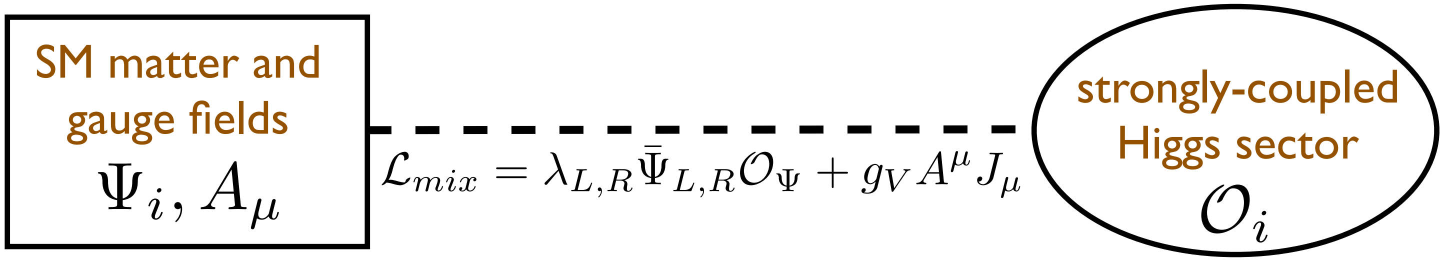
coset $G/H \supset h$

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

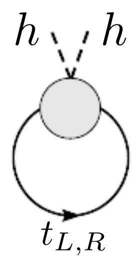
BUT global symmetry must be explicitly broken to generate $V(h) \neq 0$

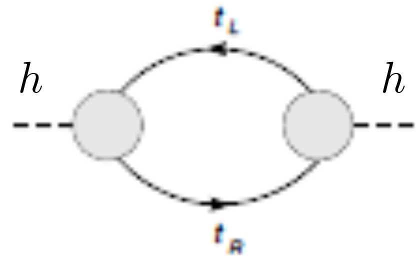
Global symmetry broken by mixing with elementary sector

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



Higgs potential:



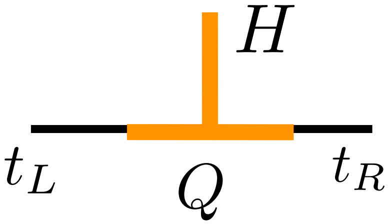


$$V(h) = -\mu_h^2|H|^2 + \lambda_h|H|^4$$ where $$\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2 \qquad \lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$$

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

Prefers: $f \sim v$

Higgs mass: $m_h^2 \simeq \frac{N_c}{\pi^2} m_t^2 \frac{m_Q^2}{f^2}$ $\left(\frac{m_Q^2}{f^2} = g_Q^2\right)$



$m_Q =$ fermion resonance mass

$$m_Q \sim m_\rho \gtrsim 2.5\ \text{TeV} \quad (g_Q \sim g_\rho \gtrsim 3) \quad \Rightarrow \quad m_h \gtrsim m_t$$

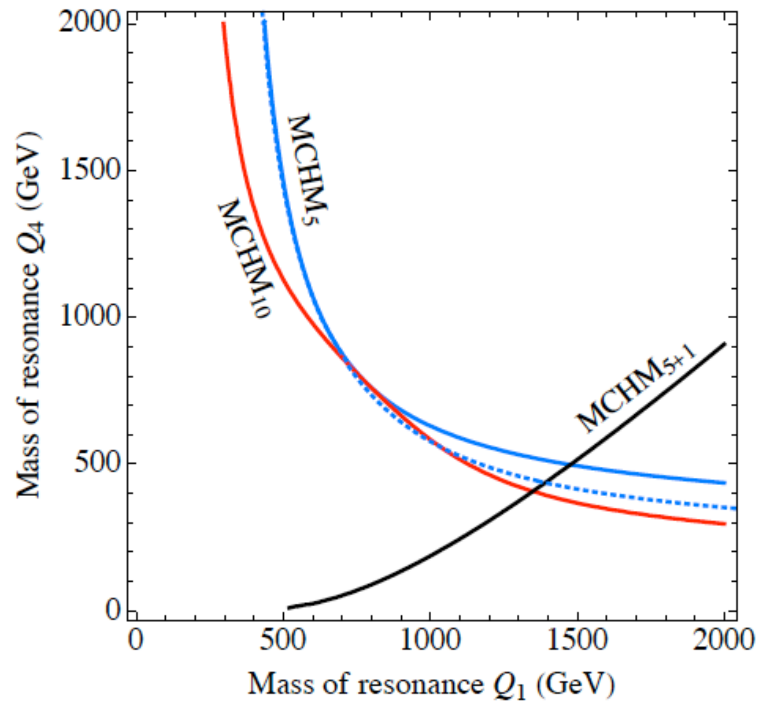
But, no need for $m_Q \sim m_\rho$

$$m_h \sim 125\,\text{GeV}$$

$$\Rightarrow \quad m_Q < m_\rho$$

light fermion resonances

[Marzocca, Serone, Shu 2012; Pomarol, Riva 2012]



HOWEVER, precision electroweak, flavor constraints

EWPT:

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

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

e.g. FCNC

$$\epsilon_q^i \epsilon_q^j \epsilon_q^k \epsilon_q^l \frac{g_\rho^2}{m_\rho^2} \bar{q}^i q^j \bar{q}^k q^l \qquad \epsilon_q^i \sim \frac{g_i}{g_\rho} \Rightarrow f \gtrsim 10\ \mathrm{TeV}$$

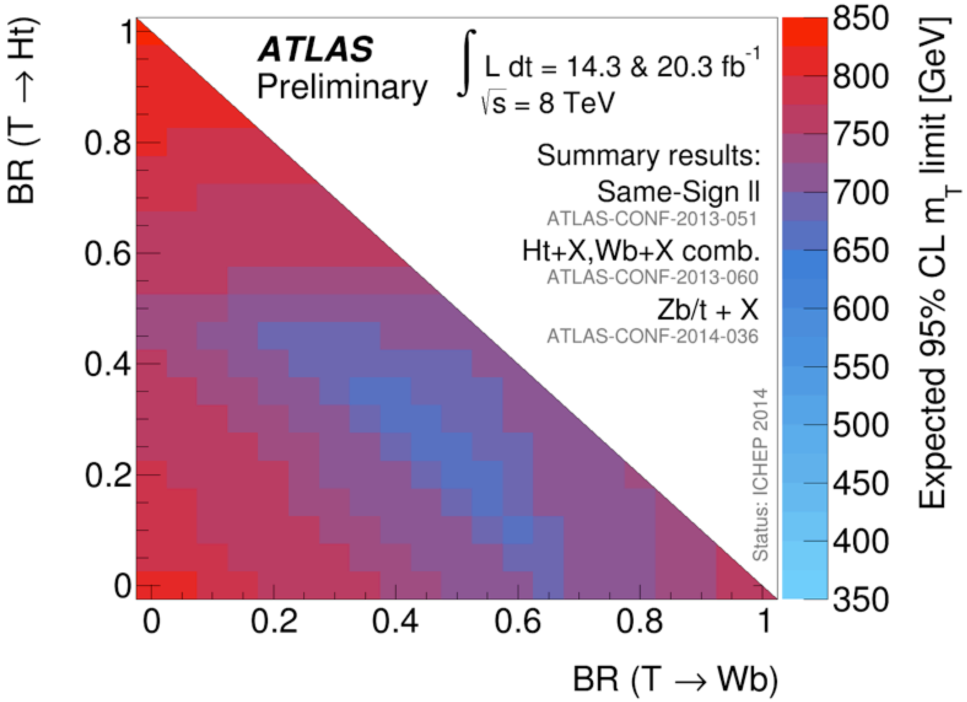
[Bellazzini, Csaki, Serra 1401.2457]
[Panico, Wulzer 1506.01961]

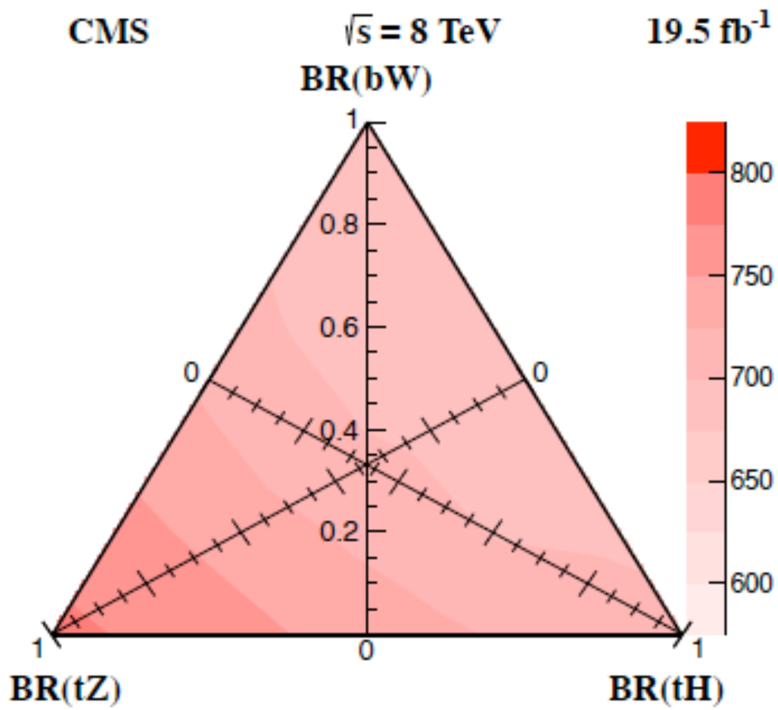
$\Rightarrow$ $$f \gg v$$ *"Little" hierarchy*

Tension partly alleviated by complicating minimal models

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

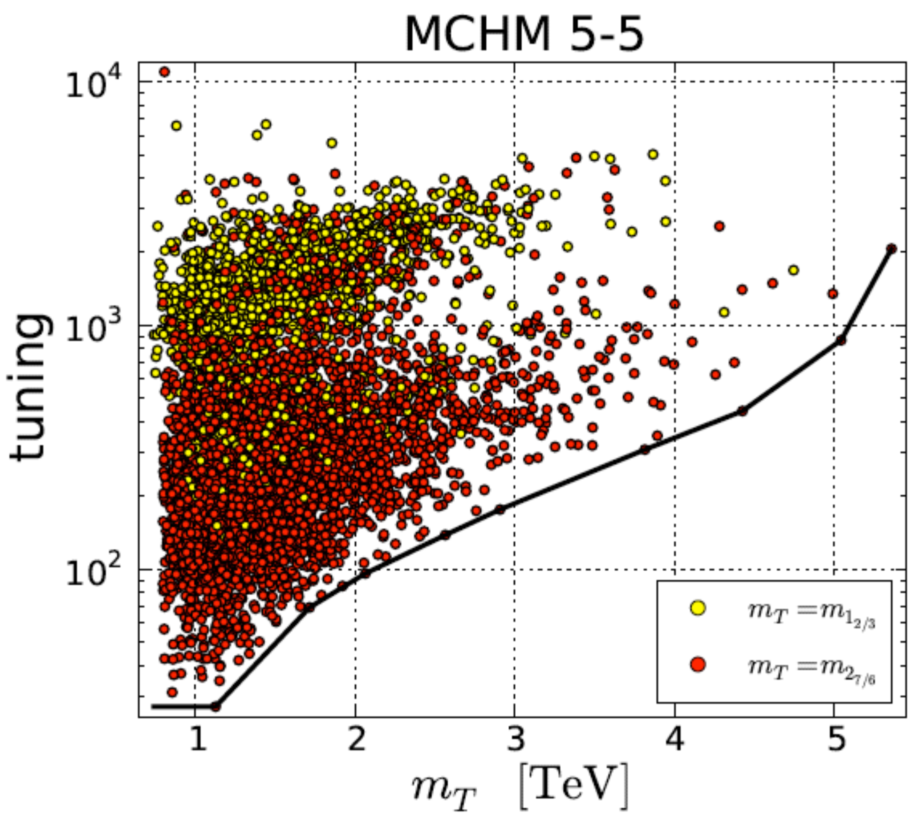
LHC Limits: *The Missing Resonances Problem*

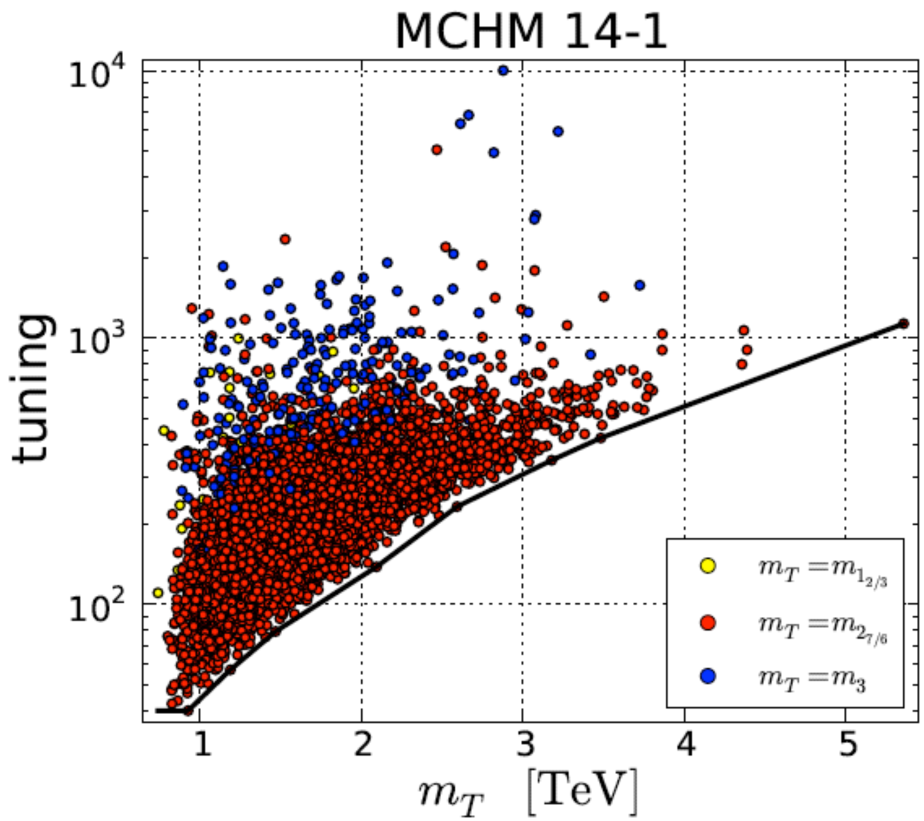




$$m_T \gtrsim 600 - 800\,\mathrm{GeV}$$

[Barnard, White 1507.02332]





"Natural" models increasingly elaborate and tuned: $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 5\%$

Simple solution:

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

Tuned Higgs potential

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

tuning $\dfrac{v^2}{f^2} \lesssim 10^{-4}$

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

e.g. QCD - sensitivity in neutron, proton mass $\dfrac{m_{u,d}}{m_{nucleon}} \sim 10^{-3}$

Is there a motivated upper bound for f ?

Yes! 

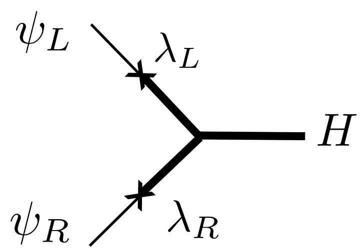
Partial compositeness:

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

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

$$m_f \sim \lambda_L \lambda_R v$$

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



- Light fermions are mostly elementary ⇒ $\text{dim } \mathcal{O}_{L.R} > \frac{5}{2}$

- Top quark is mostly composite! ⇒ $\text{dim } \mathcal{O}_{L,R} \sim \frac{5}{2}$

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

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

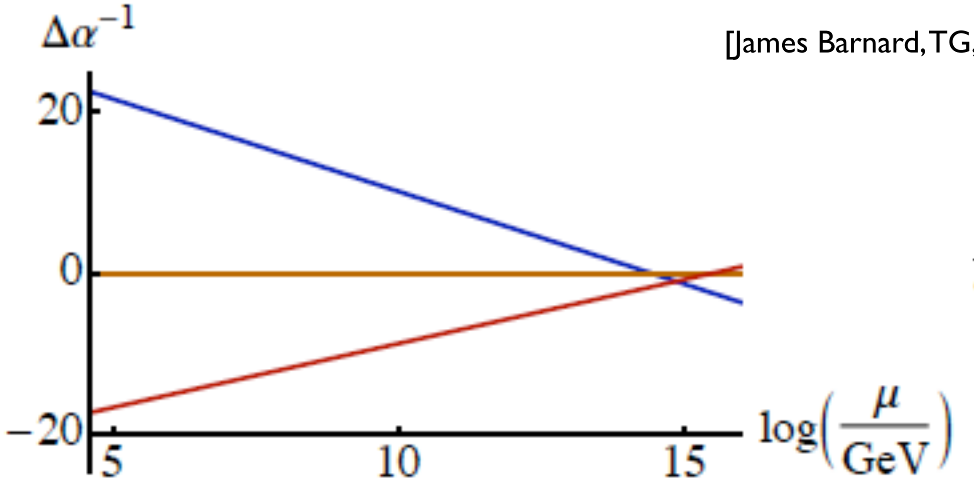
composite Higgs, top

One-loop beta function coefficients:

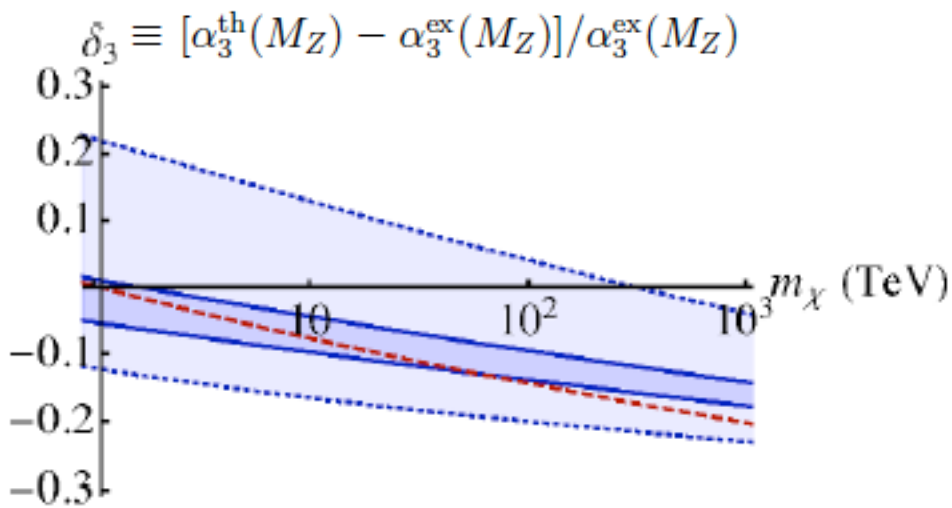
$$b_1 - b_2 = \frac{94}{15} \qquad b_2 - b_3 = \frac{13}{3} \qquad \Rightarrow \qquad \boxed{\frac{b_2 - b_3}{b_1 - b_2} \simeq 0.69}$$

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 $\delta_3 = 0$ $(b_{strong} = 5)$ ⇨ $f \lesssim 500$ 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

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

Matter embeddings

SM matter embedding under $SU(5)\times U(1)_L\times U(1)_B$

$q\in\mathbf{10}_{0,\frac{1}{3}}$ $u^c\in\mathbf{10}_{0,-\frac{1}{3}}$ $d^c\in\overline{\mathbf{5}}_{0,-\frac{1}{3}}$ $e^c\in\mathbf{10}_{-1,0}$ $l\in\overline{\mathbf{5}}_{1,0}$

Composite top $t_R\subset\mathbf{15}$ of SU(6)

Top companions $\chi\subset\overline{\mathbf{15}}$

$$\chi\equiv\tilde{q}^c\oplus\tilde{e}\oplus\tilde{d}^c\oplus\tilde{l}=(\overline{\mathbf{3}},\mathbf{2})_{-\frac{1}{6}}\oplus(\mathbf{1},\mathbf{1})_{-1}\oplus(\overline{\mathbf{3}},\mathbf{1})_{\frac{1}{3}}\oplus(\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$$

Mixing Lagrangian

$$\mathcal{L}\supset(\tilde{q}^c,\tilde{e})\lambda_\chi^{\mathbf{10}}\mathcal{O}_t^{\mathbf{35}}+(\tilde{d}^c,\tilde{l})\lambda_\chi^{\mathbf{5}}\mathcal{O}_t^{\mathbf{35}}+q\lambda_t\mathcal{O}_t^{\mathbf{35}}+q\lambda_b\mathcal{O}_b^{\overline{\mathbf{35}}}+b^c\lambda_{b^c}\mathcal{O}_{b^c}^{\mathbf{35}}$$
$$+l\lambda_\nu\mathcal{O}_\nu^{\mathbf{21}}+l\lambda_\tau\mathcal{O}_\tau^{\mathbf{21}}+N^c\lambda_{N^c}\mathcal{O}_{N^c}^{\overline{\mathbf{21}}}+\tau^c\lambda_{\tau^c}\mathcal{O}_{\tau^c}^{\overline{\mathbf{21}}}+m_N N^c N^c$$

Effective Lagrangian

Integrate out strong sector

$$\mathcal{L}_{\text{eff}} \supset (\bar{\tilde{q}}^c, \bar{\tilde{e}})_{i_4 i_2} \not{p} (\tilde{q}^c, \tilde{e})^{j_4 j_2} \left[\Pi^{\chi\chi} (\lambda_\chi^{\mathbf{10}*})^{i_4 i_2}_{IJK} (\lambda_\chi^{\mathbf{10}})^{IJL}_{j_4 j_2} \right] \Sigma^K_L$$

$$+ (\bar{\tilde{q}}^c, \bar{\tilde{e}})_{i_4 i_2} \not{p} (\tilde{d}^c, \tilde{l})^{j_5} \left[\Pi^{\chi\chi} (\lambda_\chi^{\mathbf{10}*})^{i_4 i_2}_{IJK} (\lambda_\chi^{\mathbf{5}})^{IJL}_{j_5} \right] \Sigma^K_L + \text{h.c.}$$

$$+ (\bar{\tilde{d}}^c, \bar{\tilde{l}})_{i_5} \not{p} (\tilde{d}^c, \tilde{l})^{j_5} \left[\Pi^{\chi\chi} (\lambda_\chi^{\mathbf{5}*})^{i_5}_{IJK} (\lambda_\chi^{\mathbf{5}})^{IJL}_{j_5} \right] \Sigma^K_L$$

$$+ \bar{q}^{i_3 i_2} \not{p} q_{j_3 j_2} \left[\Pi^{tt} (\lambda_t^*)_{i_3 i_2, IJK} (\lambda_t)^{j_3 j_2, IJL} + \Pi^{bb} (\lambda_b^*)^{IJL}_{i_3 i_2} (\lambda_b)^{j_3 j_2}_{IJK} \right] \Sigma^K_L$$

$$+ \bar{b}^c_{i_3} \not{p} b^{c j_3} \left[\Pi^{b^c b^c} (\lambda_{b^c}{}^*)^{i_3}_{IJK} (\lambda_{b^c})^{IJL}_{j_3} \right] \Sigma^K_L$$

$$+ (\bar{\tilde{q}}^c, \bar{\tilde{e}})_{i_4 i_2} \not{p} q_{j_3 j_2} \left[\Pi^{\chi t} (\lambda_\chi^{\mathbf{10}*})^{i_4 i_2}_{IJK} (\lambda_t)^{j_3 j_2, IJL} \right] \Sigma^K_L + \text{h.c.}$$

$$+ (\bar{\tilde{d}}^c, \bar{\tilde{l}})_{i_5} \not{p} q_{j_3 j_2} \left[\Pi^{\chi t} (\lambda_\chi^{\mathbf{5}*})^{i_5}_{IJK} (\lambda_t)^{j_3 j_2, IJL} \right] \Sigma^K_L + \text{h.c.}$$

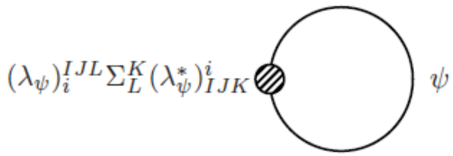
$$+ q_{i_3 i_2} b^{c j_3} \left[M^{b b^c} (\lambda_b)^{i_3 i_2}_{IJK} (\lambda_{b^c})^{IJL}_{j_3} \right] \Sigma^K_L + \text{h.c.}$$

where $\Sigma = w^\dagger w$ = adjoint spurion (contains D,T and S)

Π, M^{bb^c} = momentum dependent form factors

pNGB potential

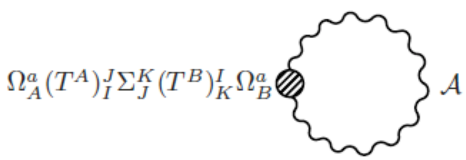
Elementary fermion contribution:

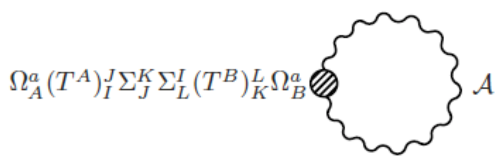


$$\int \frac{d^4p}{(2\pi)^4}\Pi^\psi(p) = c_1^\psi \frac{g_\rho^2}{16\pi^2} f^4$$

$$\Rightarrow \quad V_{\rm matter} = \frac{g_\rho^2 f^2}{24\pi^2} c_1^\chi |\lambda_\chi|^2 \left(12 - 9|T|^2 - 7|D|^2 - 7|S|^2\right) + \frac{g_\rho^2 f^2}{24\pi^2} c_1^t |\lambda_t|^2 \left(4|T|^2 + 3|D|^2\right)$$
$$+ \frac{g_\rho^2 f^2}{24\pi^2} c_1^b |\lambda_b|^2 \left(2|T|^2 + 3|D|^2 + 6|S|^2\right) + \frac{g_\rho^2 f^2}{24\pi^2} c_1^{b^c} |\lambda_{b^c}|^2 \left(3 - 2|T|^2 - 3|D|^2\right).$$

Elementary gauge boson contribution:





$$\int \frac{d^4p}{(2\pi)^4} \frac{\Pi_{1,2}^A(p)}{p^2} = c_{1,2}^A \frac{g_\rho^2}{16\pi^2} f^4$$

$$\Rightarrow \quad V_{\rm gauge} = \frac{3 g_\rho^2 f^2}{16\pi^2} c_1^A \left(\frac{4}{3} g_3^2 |T|^2 + \frac{3}{4} g_2^2 |D|^2\right) + \frac{3 g_\rho^2 f^2}{16\pi^2} c_2^A \left(\frac{1}{3} g_3^2 |T|^4 + \frac{1}{4} g_2^2 |D|^4\right)$$

Obtain:

$$V(|D|) = -\frac{\alpha}{f^2}|D|^2 + \frac{\beta}{f^4}|D|^4$$

HIGGS POTENTIAL

must be tuned

Electroweak VEV: $v = f\sqrt{\frac{\alpha}{\beta}}$

W-boson mass

Higgs mass: $m_h^2 = \frac{2\beta v^2}{f^4} = \frac{3c_2^A g_\rho^2}{8\pi^2} M_W^2$

Requires: $c_2^A \sim \frac{64}{g_\rho^2} \sim 0.5 - 4$

where

$$\alpha = \frac{g_\rho^2}{16\pi^2} f^4 \left(\frac{14}{3} c_1^\chi |\lambda_\chi|^2 - 2c_1^t |\lambda_t|^2 - 2c_1^b |\lambda_b|^2 + 2c_1^{b^c} |\lambda_{b^c}|^2 - \frac{9}{4} c_1^A g_2^2\right)$$

$$\beta = \frac{g_\rho^2}{16\pi^2} f^4 \left(\frac{3}{4} c_2^A g_2^2\right).$$

Also have $\langle|S|\rangle = \langle|T|\rangle = 0$ with

$$m_T^2 \approx \frac{g_\rho^2}{16\pi^2} f^2 \left(-6c_1^\chi |\lambda_\chi|^2 + \frac{8}{3} c_1^t |\lambda_t|^2 + \frac{4}{3} c_1^b |\lambda_b|^2 - \frac{4}{3} c_1^{b^c} |\lambda_{b^c}|^2 + 4 c_1^A g_3^2 \right)$$

$$m_S^2 \approx \frac{g_\rho^2}{16\pi^2} f^2 \left(-\frac{14}{3} c_1^\chi |\lambda_\chi|^2 + 4 c_1^b |\lambda_b|^2 \right)$$

➡ *triplet mass* $\quad m_T \sim \frac{g_\rho}{4\pi} \max\left[|\lambda_\psi|, g_3\right] f$

singlet mass $\quad m_S \sim \begin{cases} \frac{g_\rho}{4\pi}|\lambda_b| f \sim \frac{g_\rho}{4\pi}\frac{|\lambda_b|}{|\lambda_\chi|} m_\chi & |\lambda_\chi| \lesssim |\lambda_b| \\ \frac{g_\rho}{4\pi}|\lambda_\chi| f \sim \frac{g_\rho}{4\pi} m_\chi & |\lambda_\chi| \gtrsim |\lambda_b| \\ \ll \frac{g_\rho}{4\pi}|\lambda_\chi| f \lesssim m_\chi & |\lambda_\chi| \sim |\lambda_b| \end{cases}$

Possible light singlet

Dark matter stability

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

		$U(1)_{\not q}$	$U(1)_{\not l}$	$U(1)_{\not H}$	$U(1)_L$	$U(1)_B$	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 triality leads to stability!

The "Unnatural" Composite Higgs model

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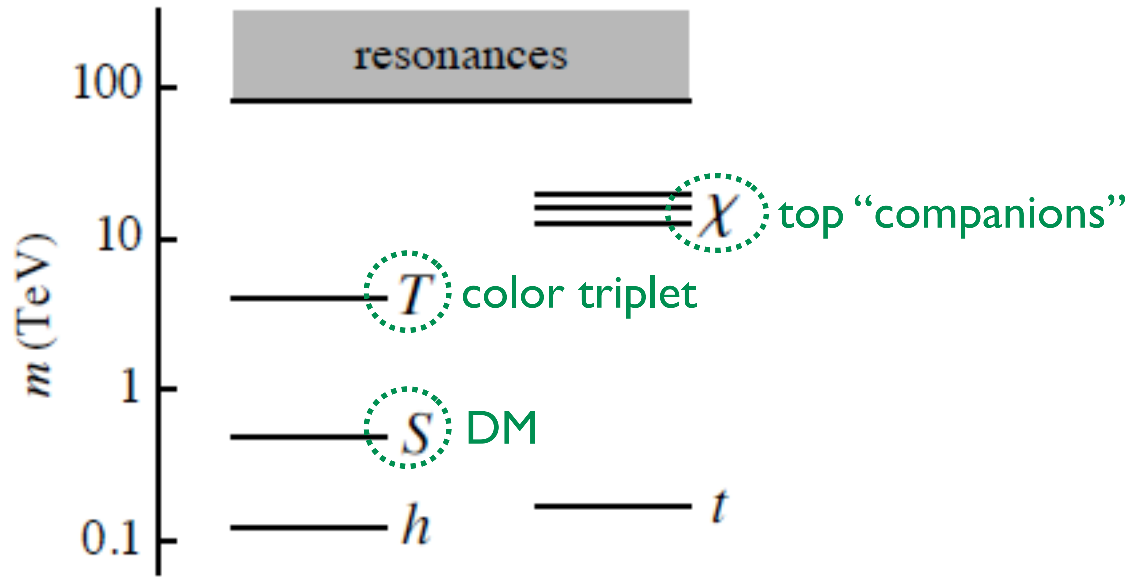


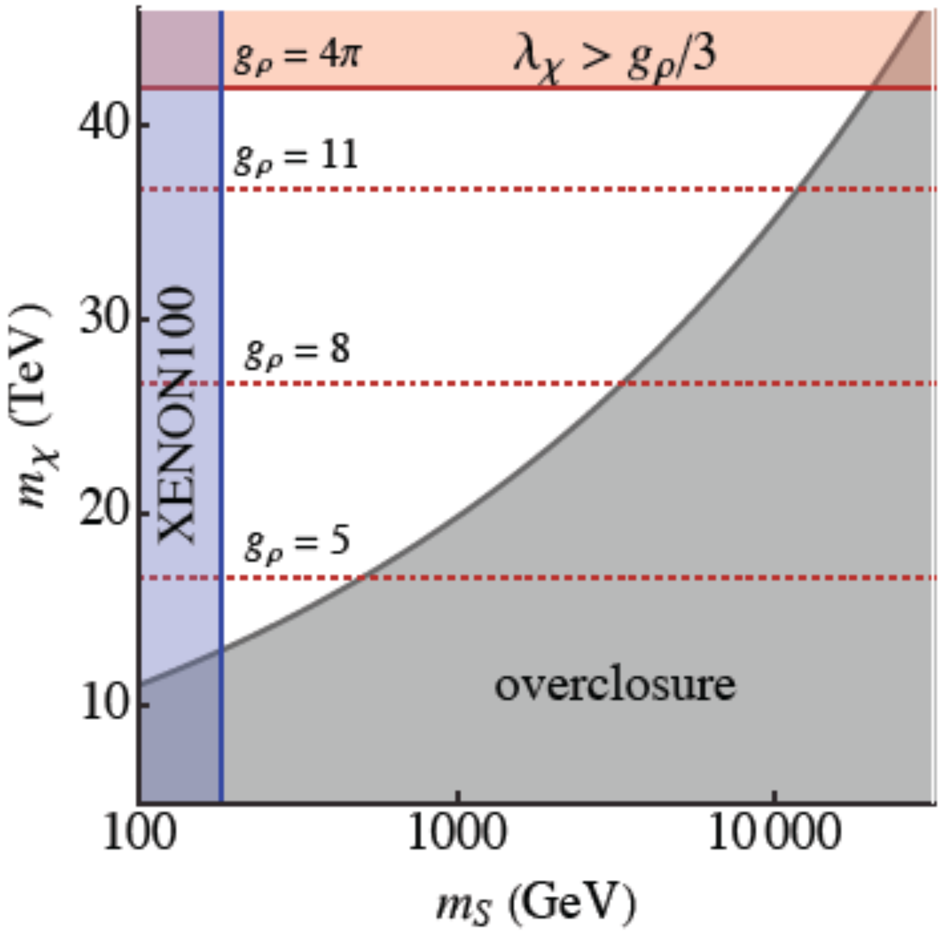
Low-energy spectrum: Standard Model + S + T + χ

What are experimental signals?

Dark matter constraints

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

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



$f = 10$ TeV

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

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

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!

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

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

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

Can be searched for at a future 100 TeV collider!

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

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

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

dimension-6 term

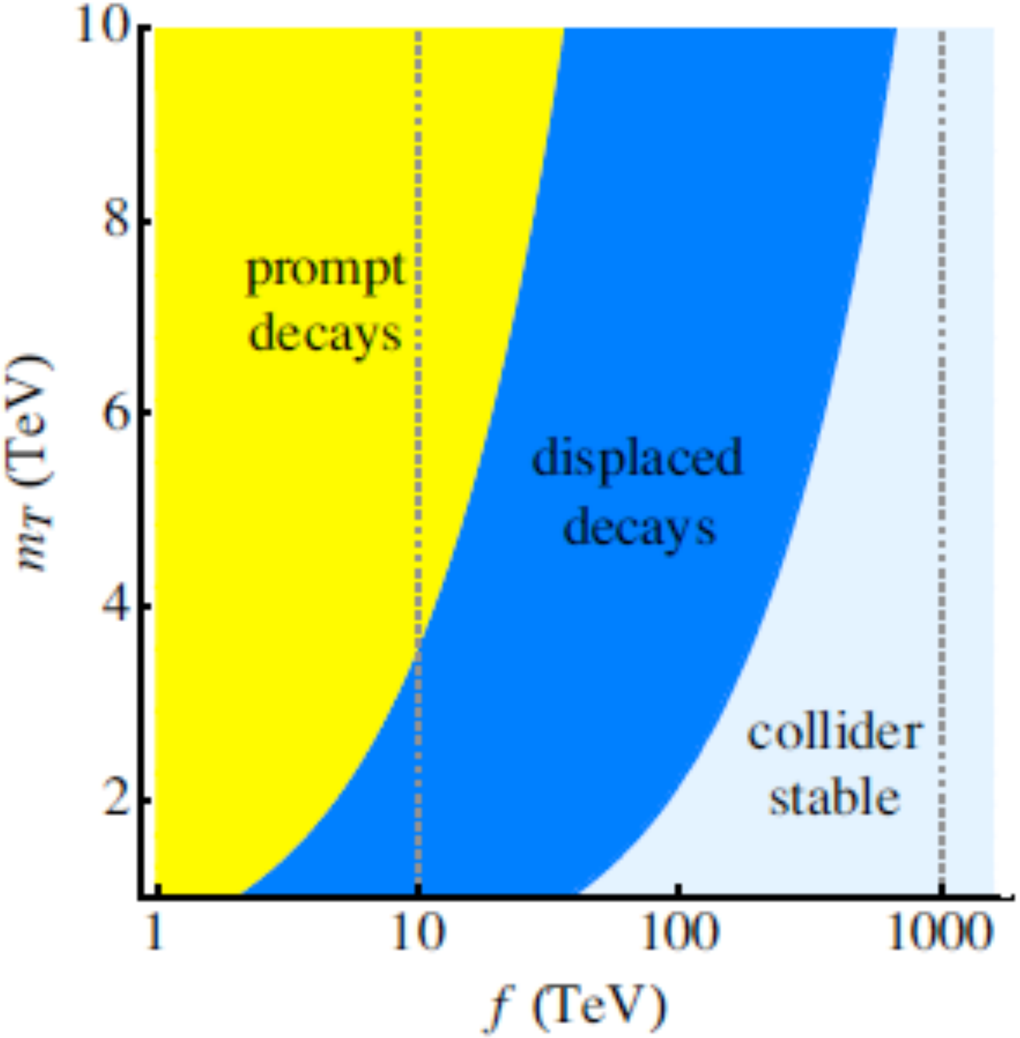
f > 10 TeV = long-lived decay

$$T \to tbSS \quad \Rightarrow \quad c\tau \approx 0.2\,\text{mm}\left(\frac{1}{c_3^T}\right)^2\left(\frac{8}{g_\rho}\right)^3\left(\frac{3\ \text{TeV}}{m_T}\right)^5\left(\frac{f}{10\ \text{TeV}}\right)^4$$

can produce a displaced vertex!

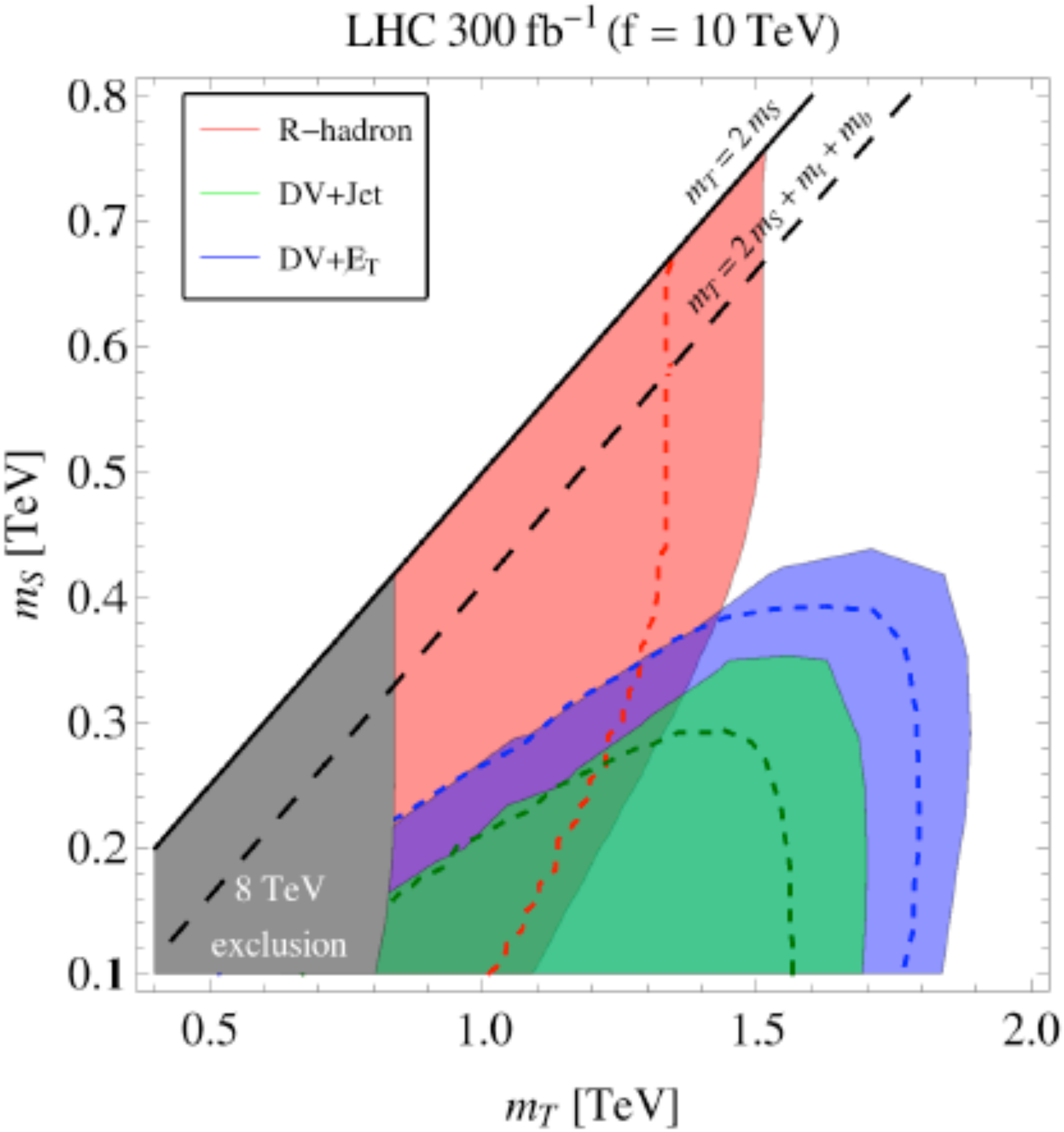
Color triplet decay

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



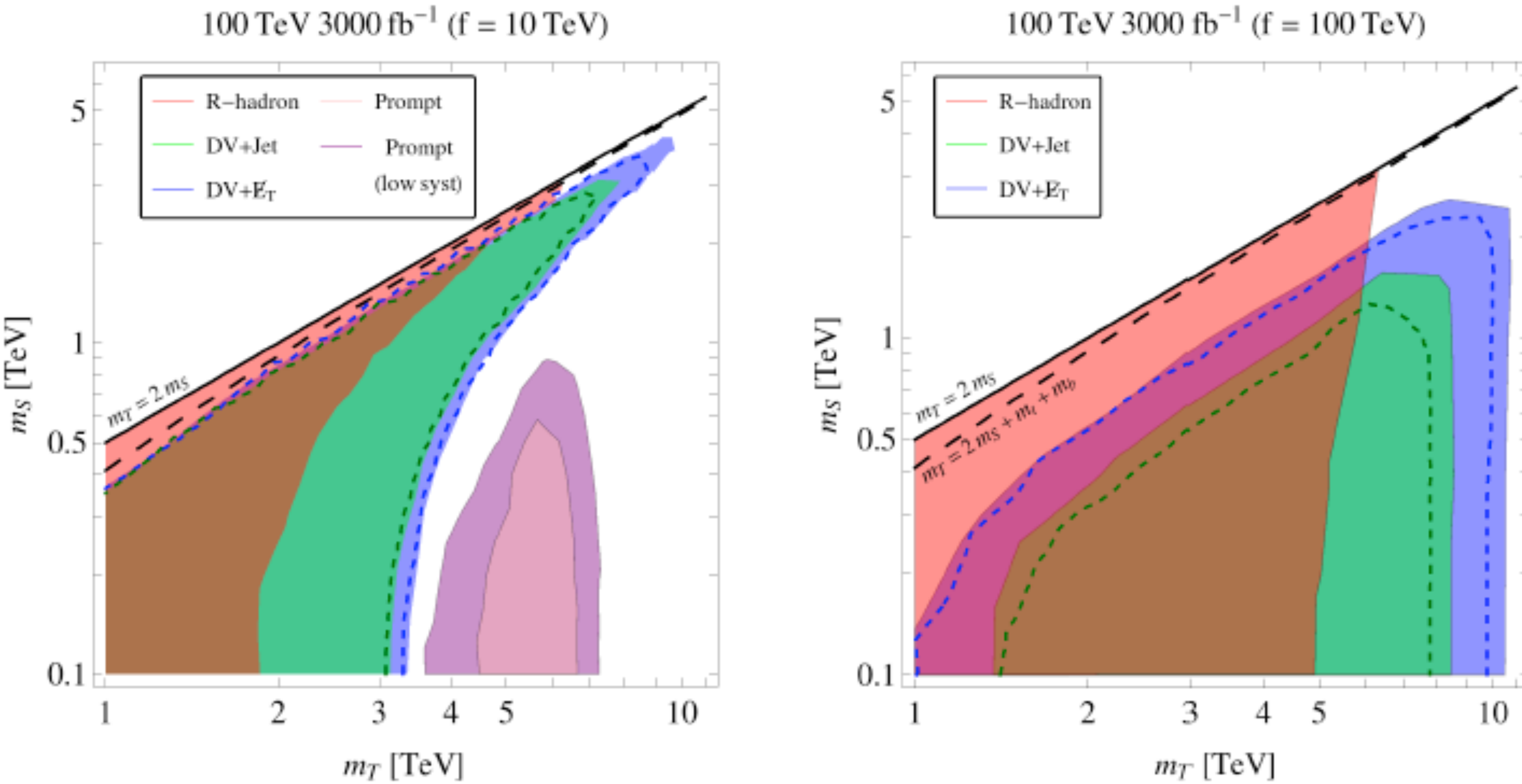
LHC:

[Barnard, Cox, TG, Spray: 1510.06405]



Future100 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*
  - --- *Explains fermion mass hierarchy*
- Higgs partners: S = dark matter, T= color triplet
- Long-lived T decays = sign of unnaturalness!