Composite Higgs Overview

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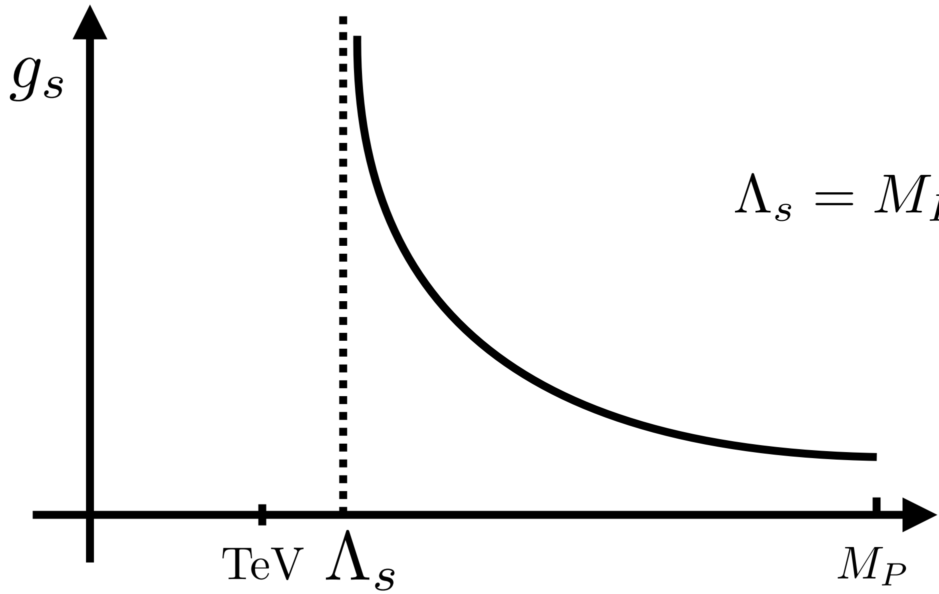
Composite Higgs

New strong force with coupling, g_s



$$\Lambda_s = M_P \, e^{-\frac{8\pi^2}{g_s^2 |b_s|}} \ll M_P$$

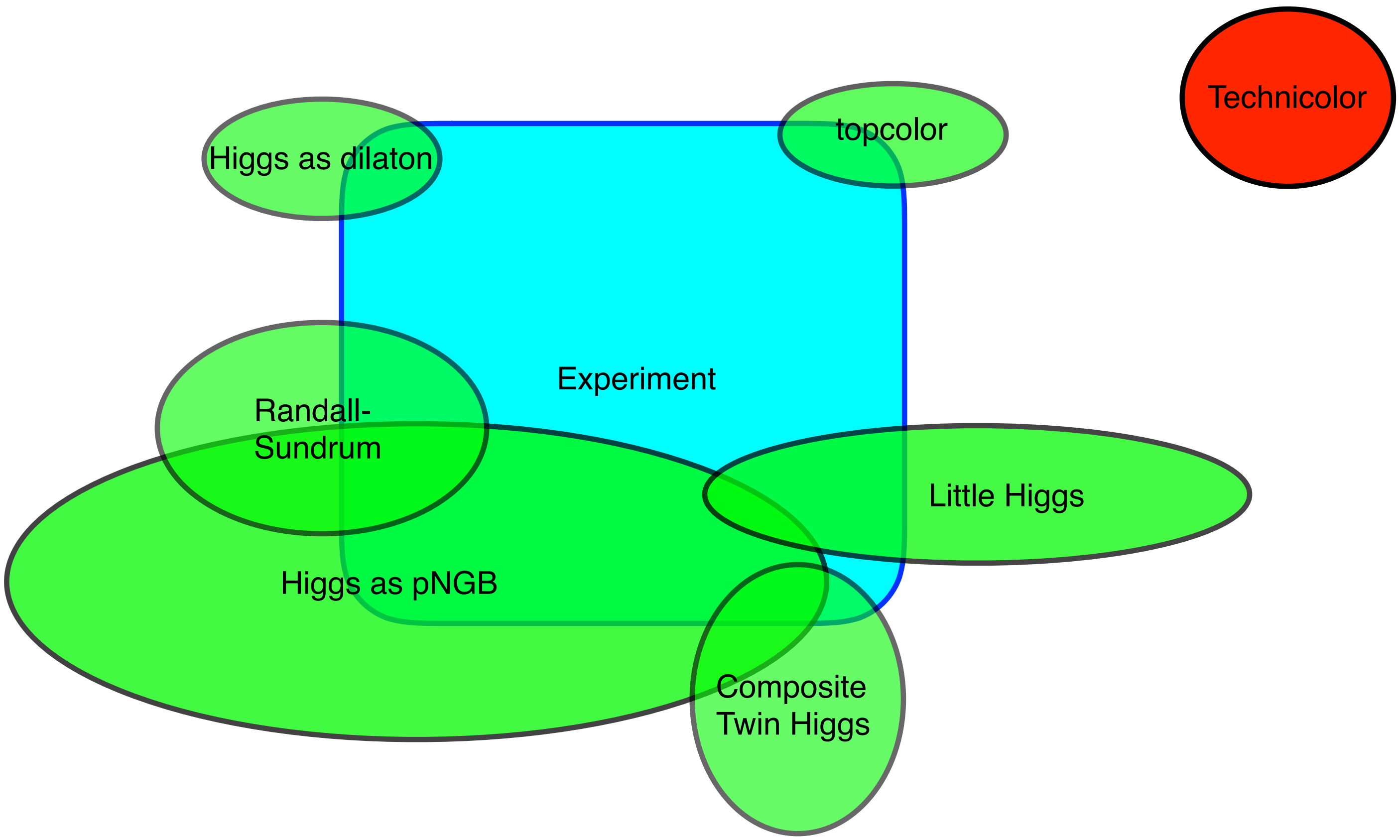
Higgs boson = *bound state* of **new** strong dynamics

$$\mu_h^2 \sim \Lambda_s^2 \ll M_P^2$$

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

BUT why is Higgs boson much lighter than other bound states?

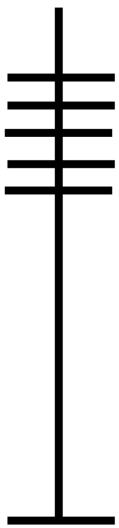
Possible New Dynamics



Higgs = 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: $m_\rho \sim g_\rho f \qquad 1 \lesssim g_\rho \lesssim 4\pi$

coset $G/H \supset h + W_L, Z_L$ } Higgs doublet

$e.g.\ SO(5)/SO(4)$

h

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

$h \to h + \mathrm{const.}$

Strong dynamics does NOT break electroweak symmetry!

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

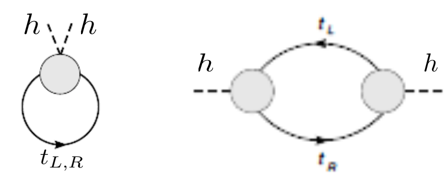
Global symmetry broken by *mixing* with elementary sector

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

SM matter and gauge fields Ψ_i, A_μ — - - - — strongly-coupled Higgs sector $\mathcal{O}_i$

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

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



where $\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2$ $\qquad \lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$ $\qquad$ [g_{SM} = SM gauge or Yukawa coupling]

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

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 $\qquad m_T \sim g_T f$

(= fermionic resonances)

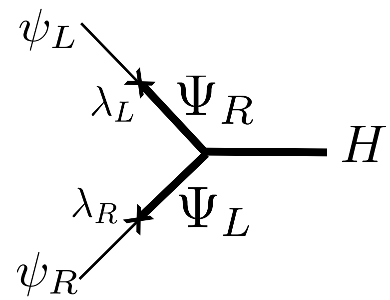
Bonus feature:

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

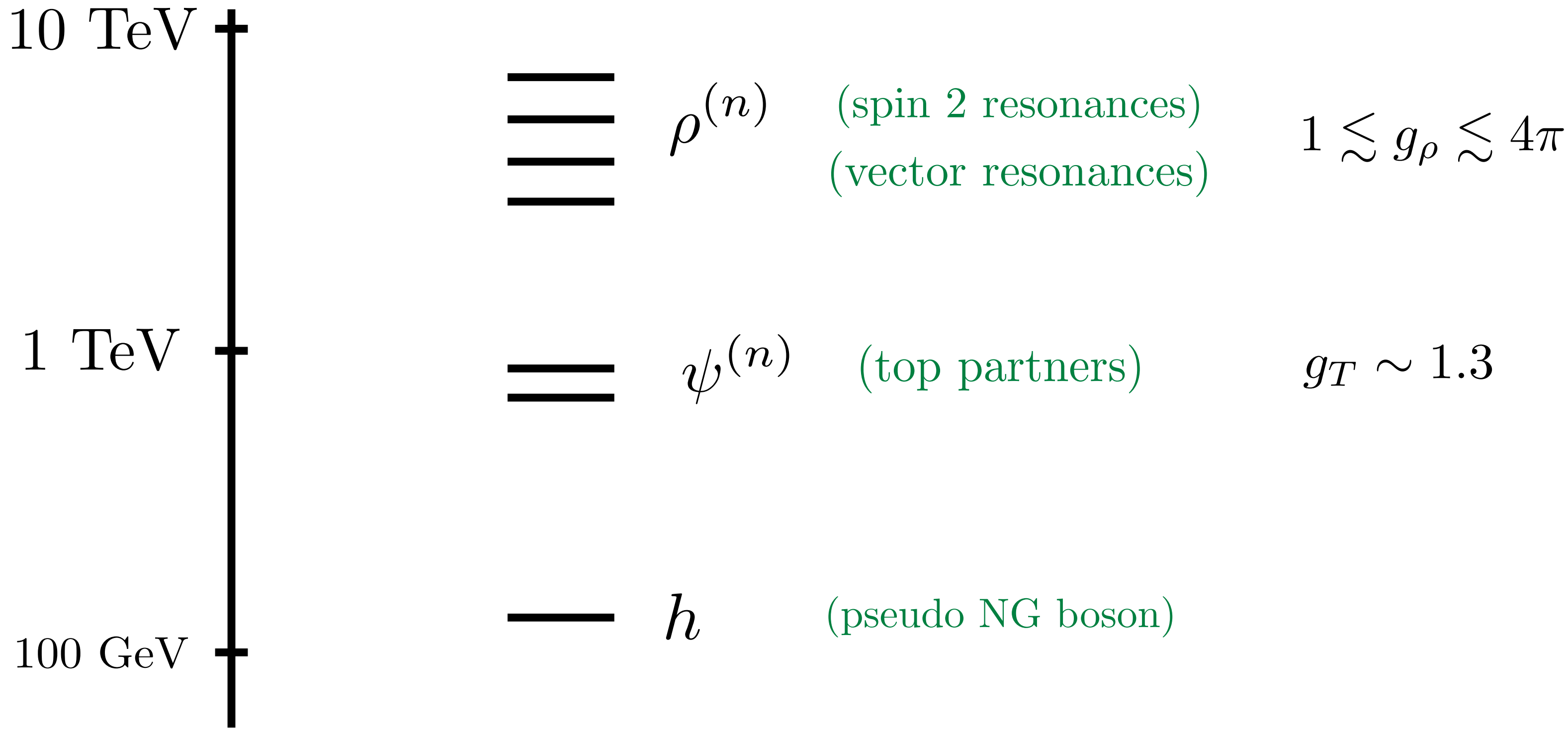


- Light fermions are mostly elementary ⇒ $\text{dim } \mathcal{O}_{L.R} > \frac{5}{2}$

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

A “Natural” Composite Higgs spectrum :

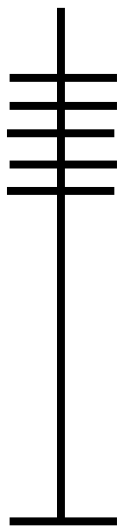
$$750 \text{ GeV} \lesssim f \lesssim 1 \text{ TeV}$$



Dark matter = pNGB (enlarged coset)

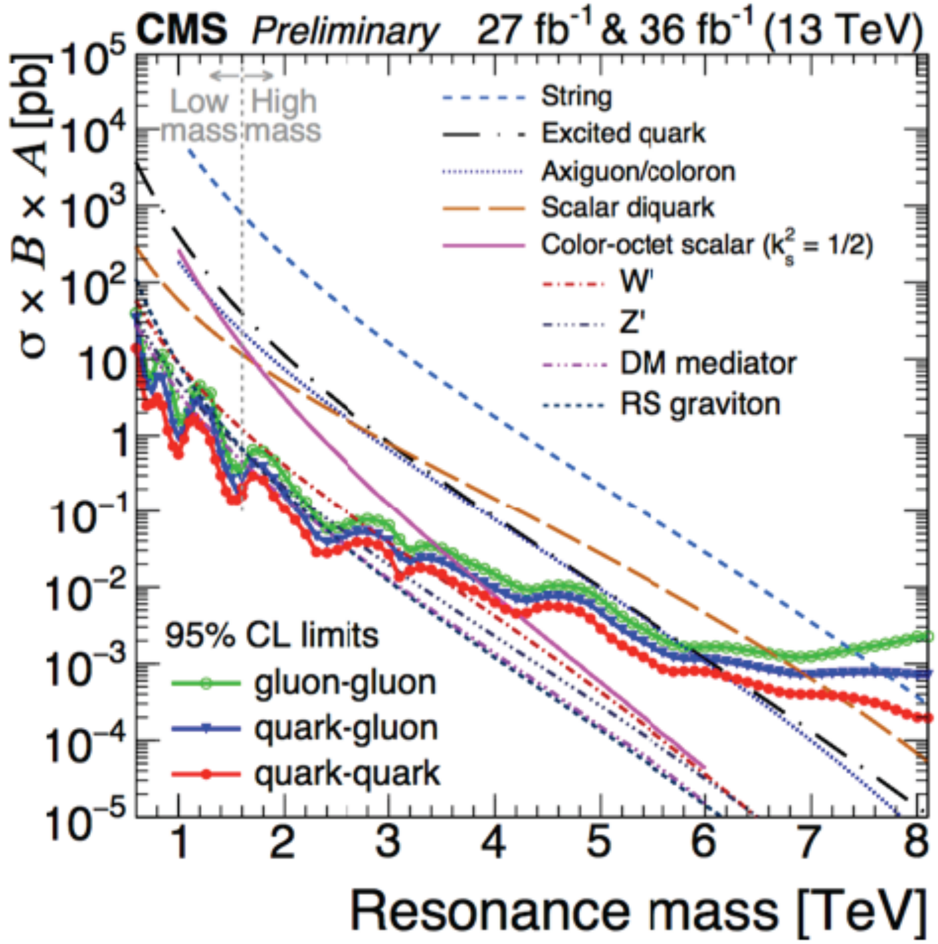
LHC Limits:

- Massive spin-1, spin-2 resonances

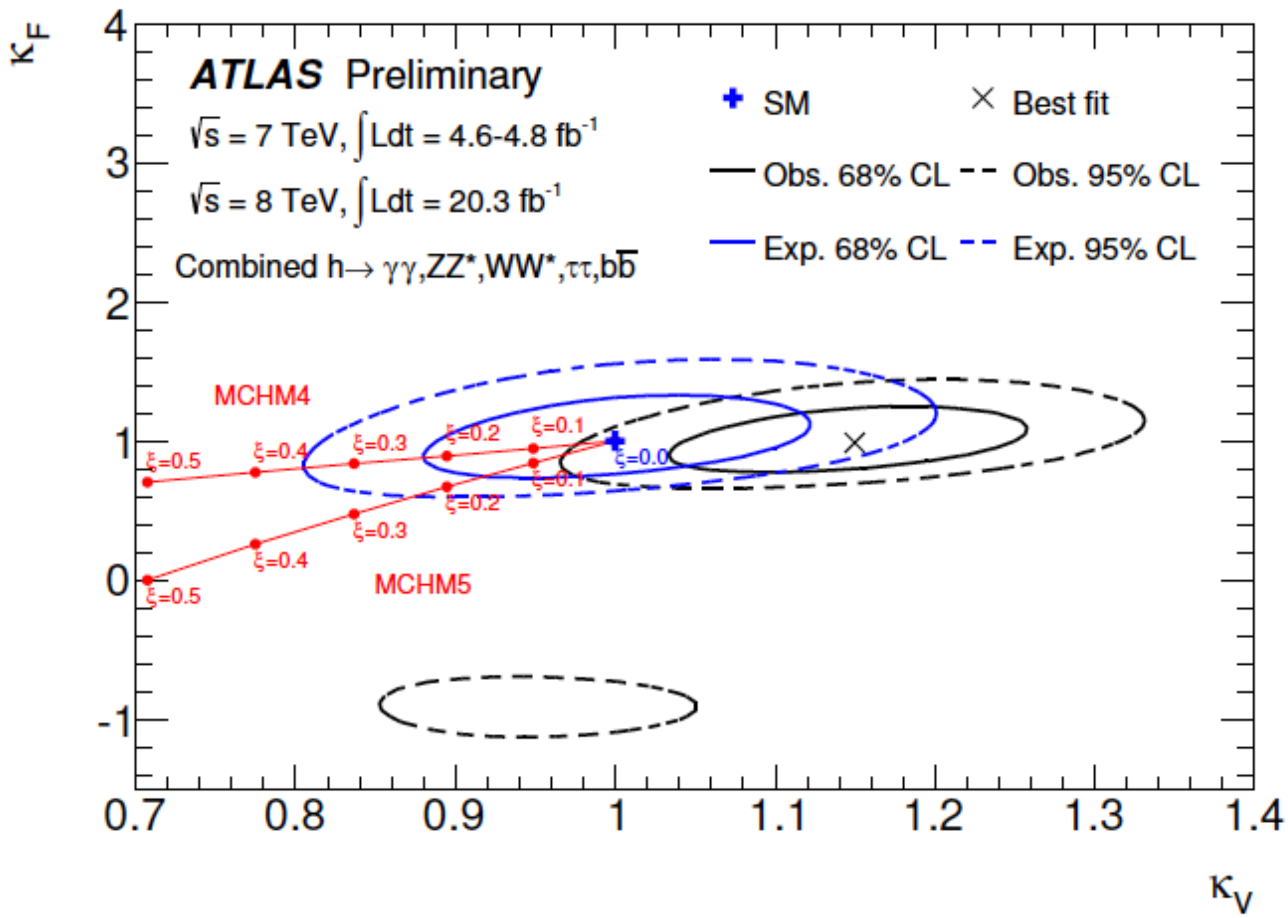


$\rho^{(n)} \gtrsim 3$ TeV

h

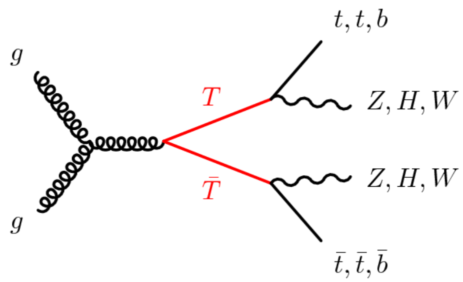


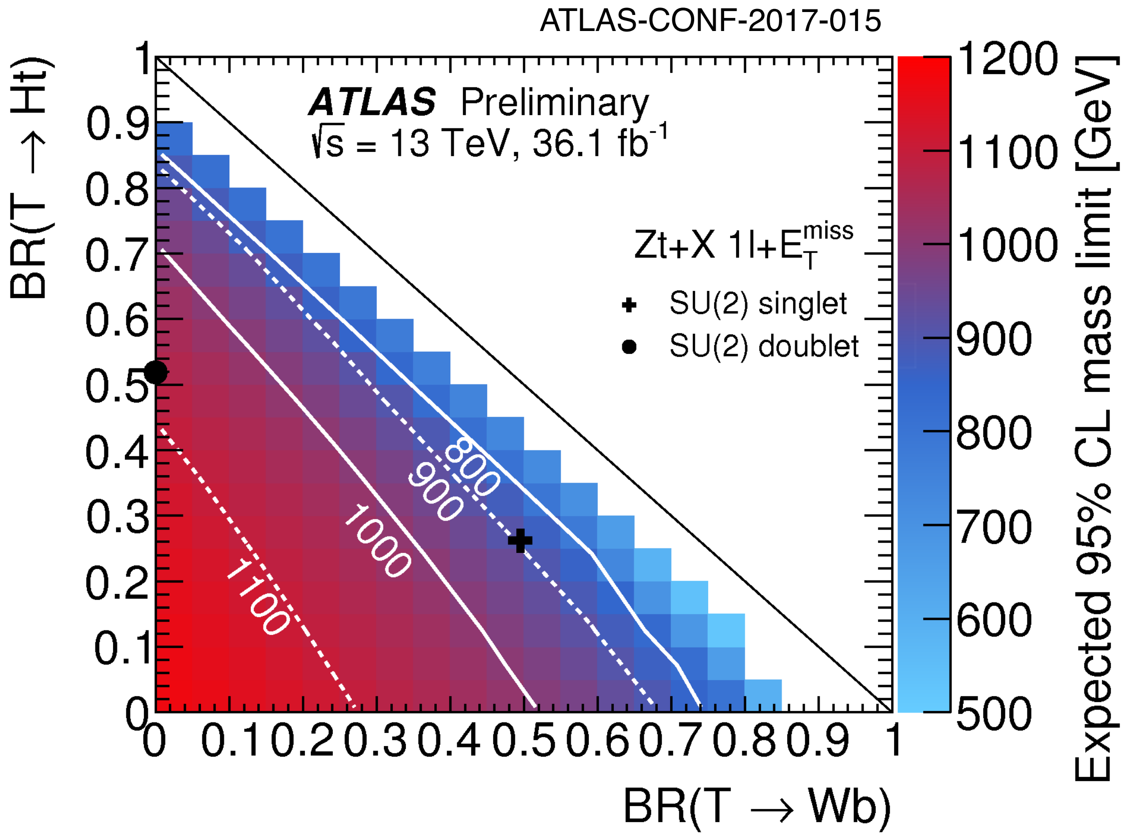
- Deviations in gauge, Yukawa couplings $\frac{g_{hWW}}{g_{hWW}^{SM}} \sim \frac{g_{hff}}{g_{hff}^{SM}} \sim \sqrt{1 - \frac{v^2}{f^2}}$



$$\xi \equiv \frac{v^2}{f^2} \lesssim 0.05$$

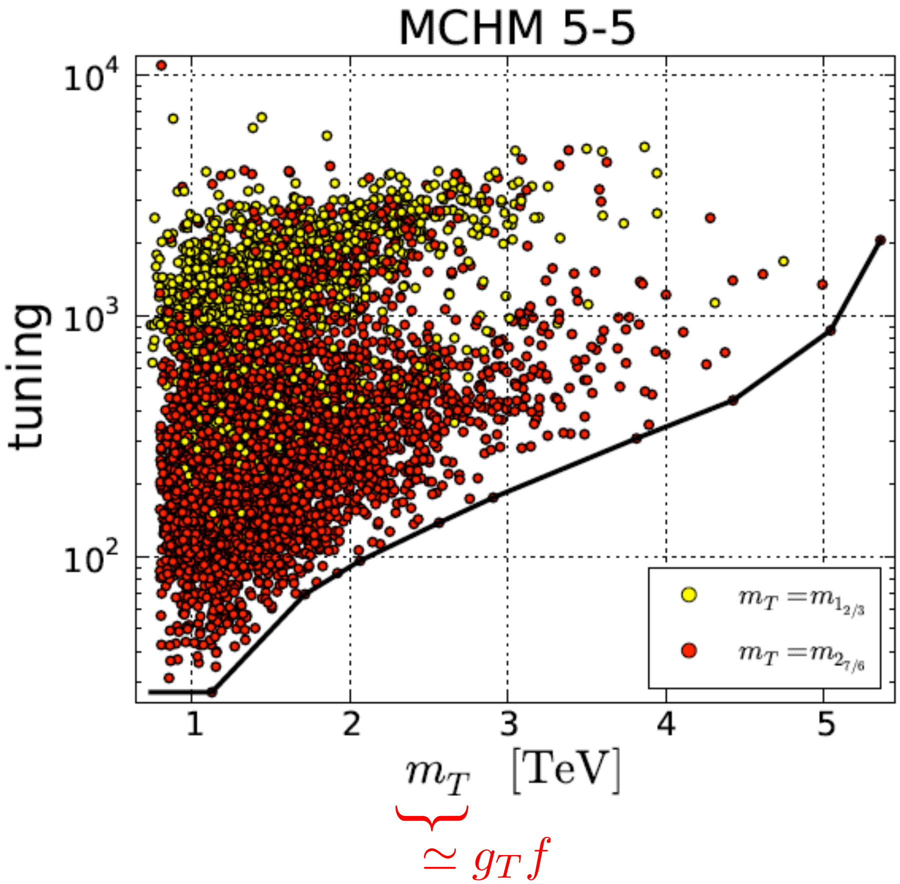
- Top partners $e.g.\ \mathbf{5_{2/3}} \to \mathbf{2_{7/6}} + \mathbf{2_{1/6}} + \mathbf{1_{2/3}} \supset \mathbf{T}$

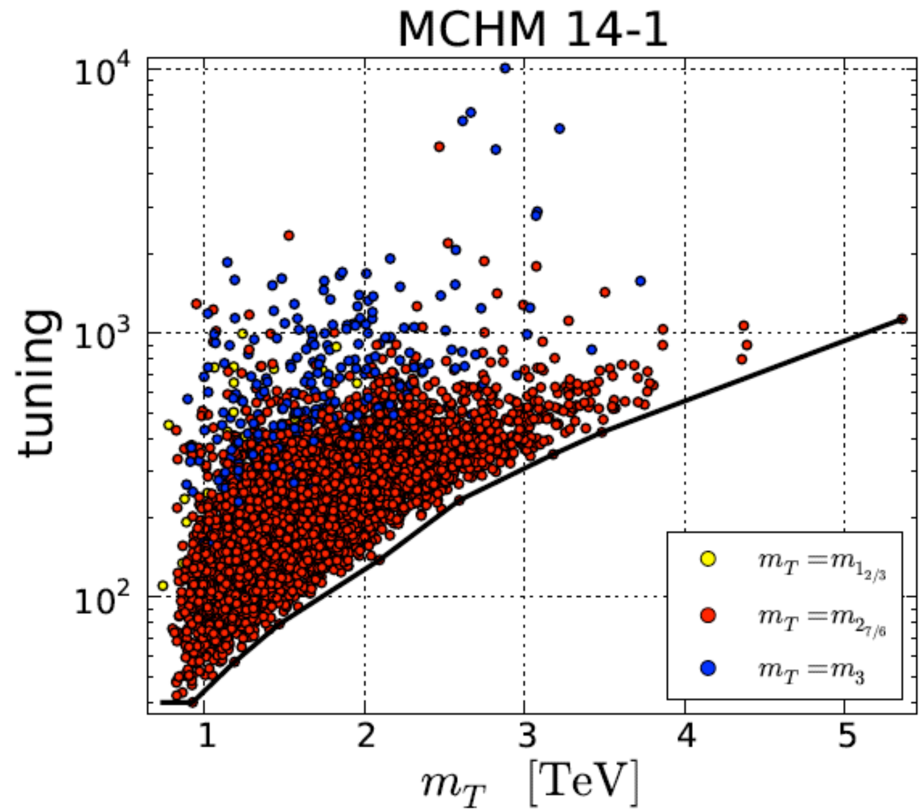




$$m_T \gtrsim 1050\ \mathrm{GeV}$$

[Barnard, White 1507.02332]





$$m_T \gtrsim 1050 \text{ GeV} \quad \Rightarrow \quad \text{tuning} \sim \frac{v^2}{f^2} \lesssim 5\%$$

“Natural” models provide “complete” picture BUT :

- UV completion?

  --- What are UV d.o.f that lead to global symmetry breaking pattern?

  --- Can partial compositeness be realised without elementary scalars?

- What about the tuning?

  --- Tuning worse if include flavor constraints

  --- How to eliminate electroweak and flavor constraints?

1. UV completion

Candidate: $SO(6)/SO(5) \sim SU(4)/Sp(4)$ [Other possibilities classified by Ferretti, Karateev 1312.5330]

Symmetry breaking-pattern $SU(4) \overset{f}{\rightarrow} Sp(4)$

What is the dynamics that realizes this?

SU(4) gauged NJL model [Barnard, TG, Sankar Ray 1311.6562]

$$\mathcal{L}_{\rm int} = \frac{\kappa_A}{2N_c}(\psi^a\psi^b)(\bar\psi_a\bar\psi_b) + \frac{\kappa_B}{8N_c}\left[\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d) + \text{h.c.}\right]$$

	$\mathrm{Sp}(2N_c)$	$\mathrm{SU}(4)$	$\mathrm{SU}(3)_c \times \mathrm{U}(1)$
ψ	$\square$	$\mathbf{4}$	$\mathbf{1}_0$
χ	$\boxminus$	$\mathbf{1}$	$\mathbf{3}_{+2/3}$
$\tilde\chi$	$\boxminus$	$\mathbf{1}$	$\bar{\mathbf{3}}_{-2/3}$

*Spontaneous breaking of global symmetry driven **mainly** by 4-fermion interaction!*

Partial compositeness: $\mathcal{L} = \lambda_L t_L \mathcal{O}_R + \lambda_R t_R \mathcal{O}_L$

UV description: $\mathcal{O}_{L,R} \leftrightarrow \underbrace{\psi\chi\psi}$

= tightly bound $\psi\psi$ by 4-fermion interaction, bound to χ by Sp(2Nc) gauge interaction $(\xi \gg \sqrt{\alpha})$

$$\dim \mathcal{O}_{L,R} = \dim \psi\chi\psi \approx \underbrace{\dim \psi\psi}_{3-\gamma_m} + \frac{3}{2} \gtrsim \frac{5}{2}$$

Marginally irrelevant!

⇨ Allows for order-one top Yukawa coupling

$\xi \gg \sqrt{\alpha}$

⇨ Top partners are naturally lighter than uncolored partners!

Interesting UV completion for lattice studies

2. Indirect Constraints

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

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

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

[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, twin parity….

Embrace Unnaturalness!

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!

Is there a motivated upper bound for f ?

Yes! 

Gauge coupling unification

[Agashe, Contino, Sundrum '05]

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

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

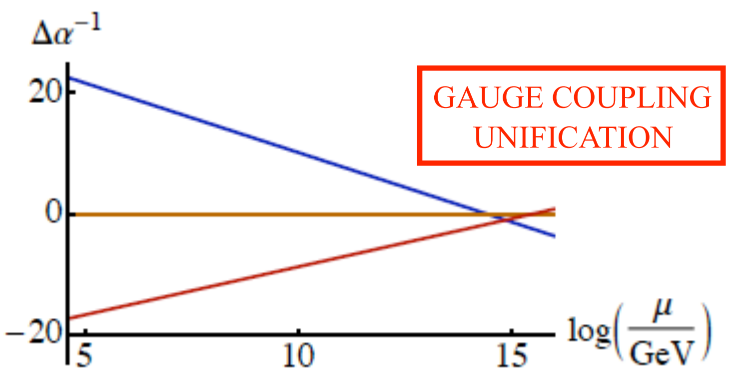
Decoupled with top "companions" χ Dirac mass: $m_\chi \sim \lambda_\chi f$

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



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

$B_{strong} \sim 9b_{strong}$ $C \sim 3\lambda_\chi b_{strong}$ $b_{strong} = 1, 5$

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

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

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

= S

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

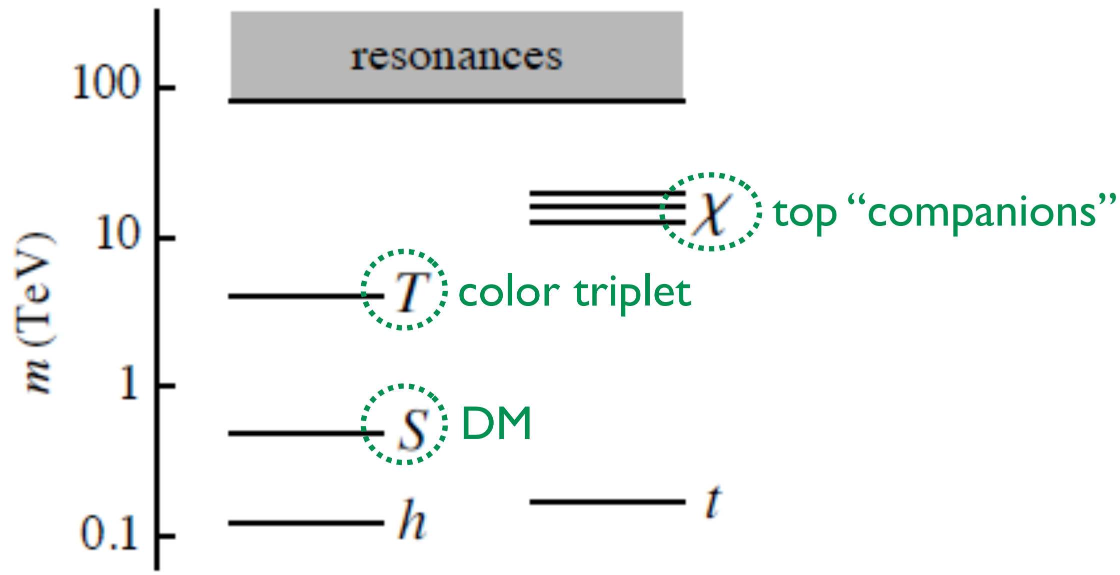
Dark matter stability

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	← Nonzero baryon triality leads to stability!
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	

The Unnatural or "Split" Composite Higgs model

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



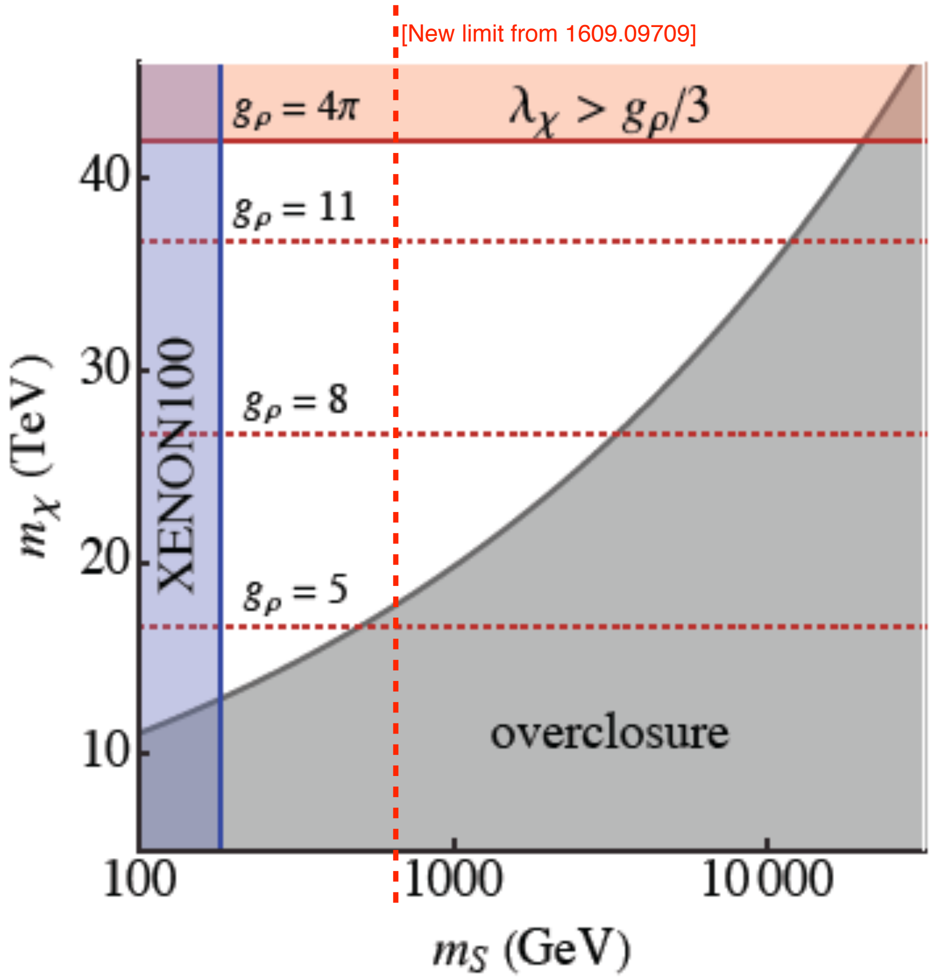
Low-energy spectrum: Standard Model + S + T + χ

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

$840 \text{ GeV} \lesssim m_S \lesssim 10 \text{ TeV}$ $\quad$ $10 \text{ TeV} \lesssim m_\chi \lesssim 40 \text{ TeV}$

Collider searches:

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

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

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

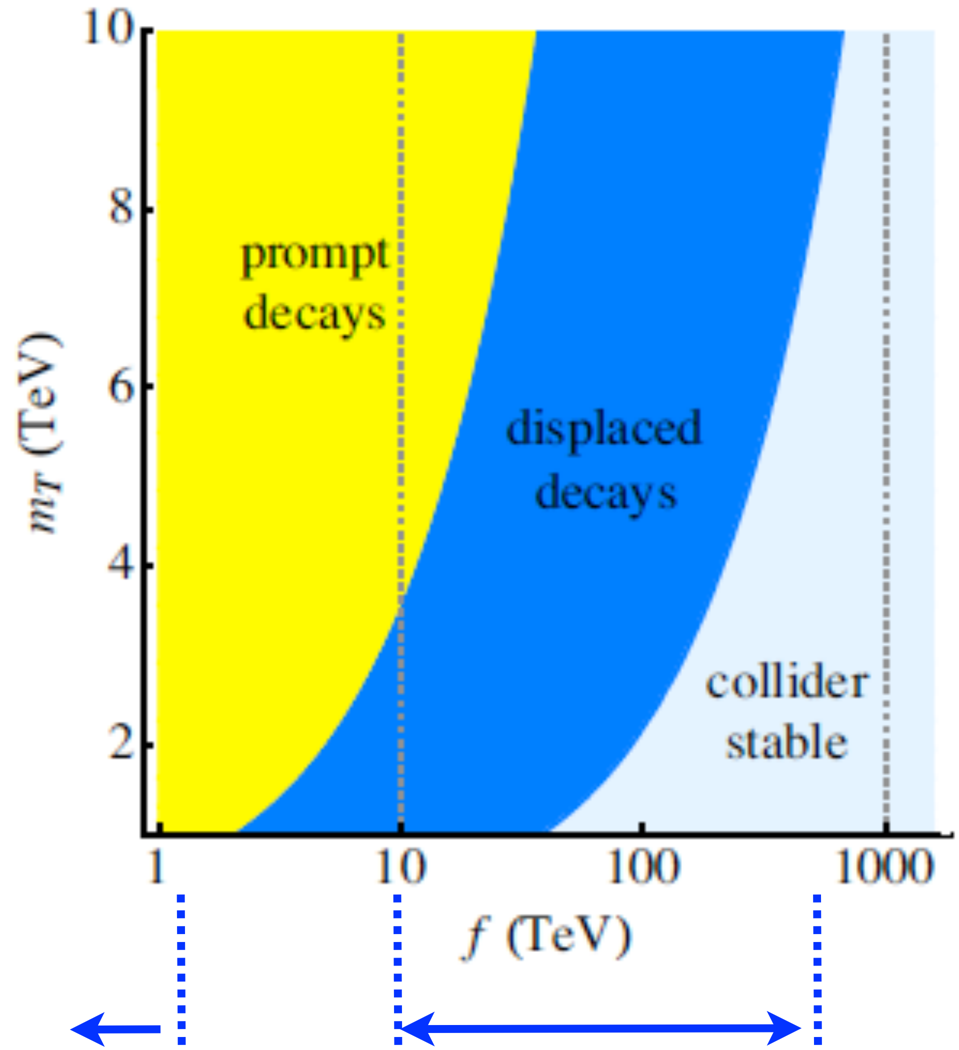
f > 10 TeV = long-lived decay

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

can produce a displaced vertex!

Color triplet decay

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



"natural" composite Higgs:

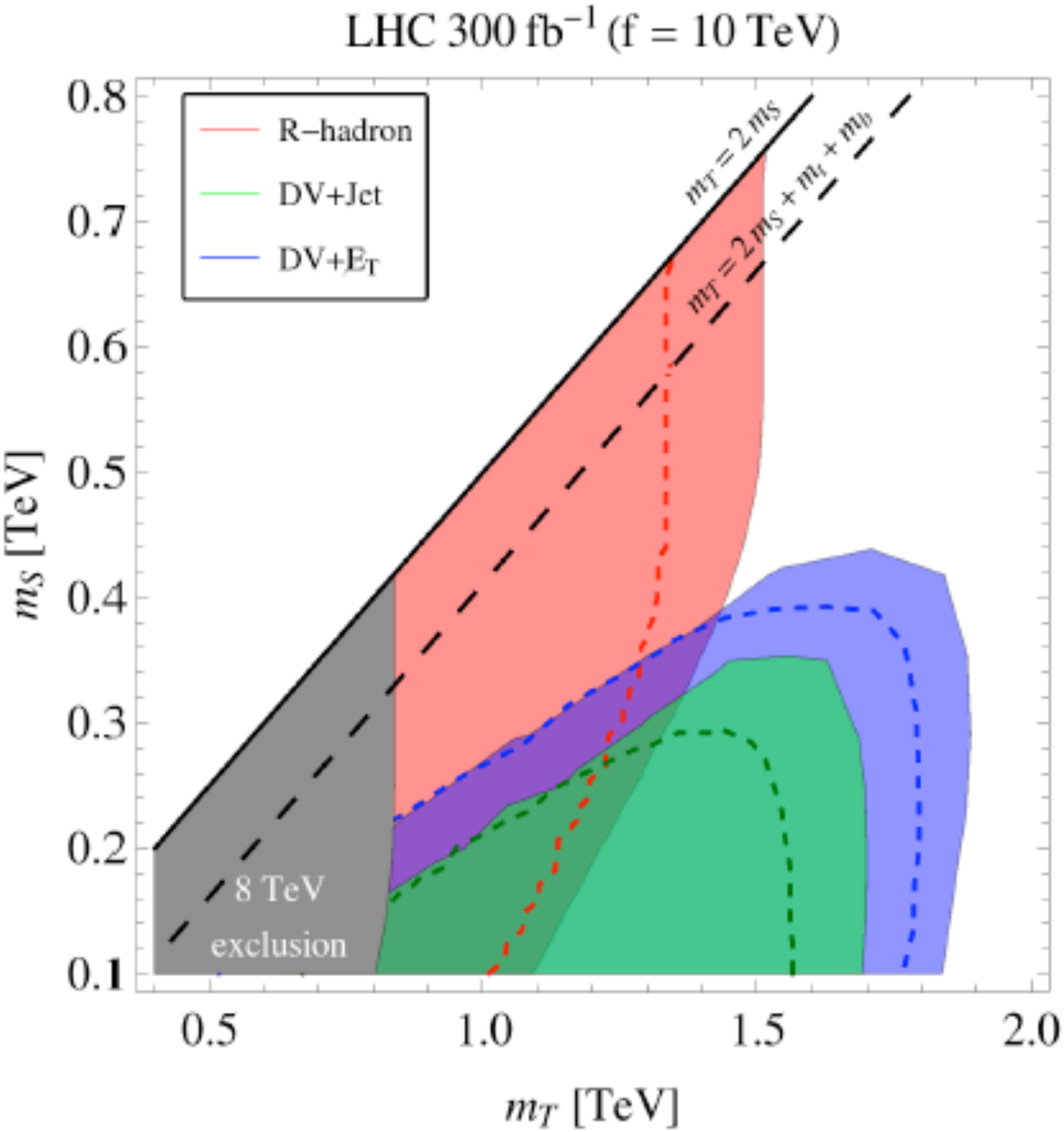
$f \lesssim 1$ TeV

Unnatural or "split" composite Higgs:

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

LHC:

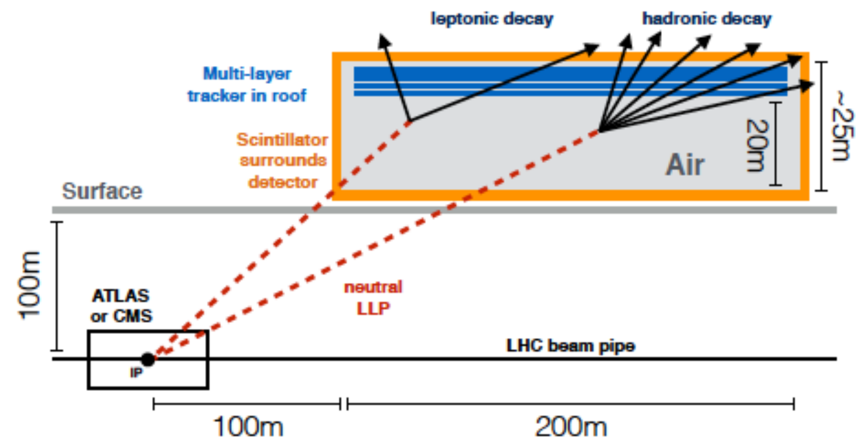
[Barnard, Cox, TG, Spray: 1510.06405]



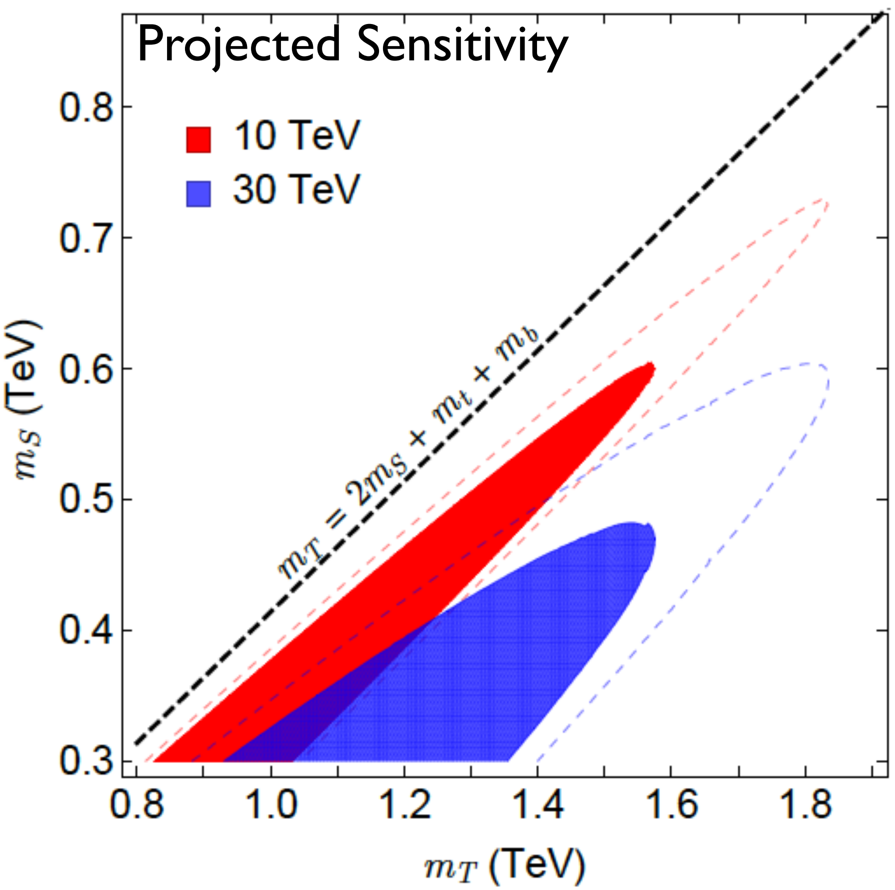
MATHUSLA:

(**MA**ssive **T**iming **H**odoscope for **U**ltra **S**table neutra**L** p**A**rticles)

[see for example Curtin, Peskin: 1705.06327]



[Cox, TG, Spray: in preparation]

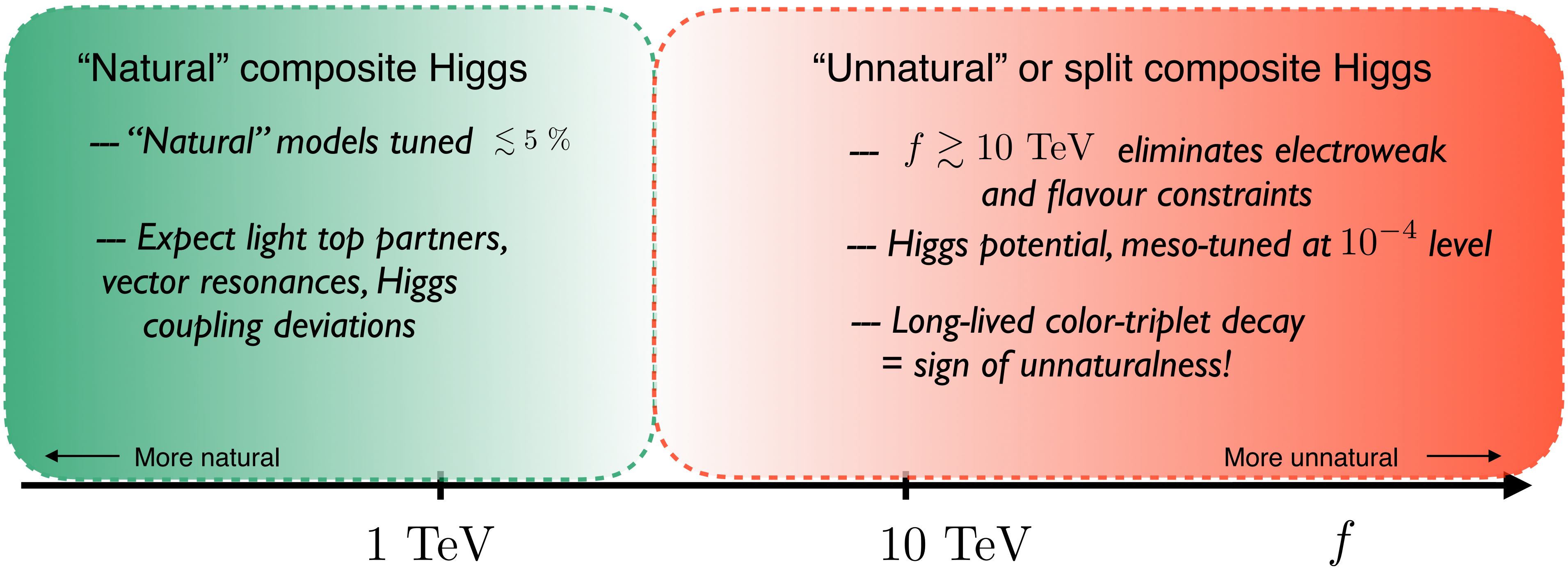


Complements LHC searches

Summary

--- *Higgs = pseudo Nambu-Goldstone boson*

--- *Explains electroweak and fermion mass hierarchy*



Future Directions

- Other signs of unnaturalness?
  - — *long-lived neutral top companions or neutral pNGBs?*
- Other "unnatural" possibilities?
  - — *larger cosets* $e.g.\ SU(6) \times SU(6)/SU(6)$ [contains neutral color octet]
- UV completion?
  - — *reason for tuning?*
- Alternate ways to deal with tuning?
  - — *composite twin Higgs* [e.g. 1501.07803]
  - — *relaxation of composite little hierarchy* [e.g. 1705.09666]