New Dynamics in the Higgs Sector

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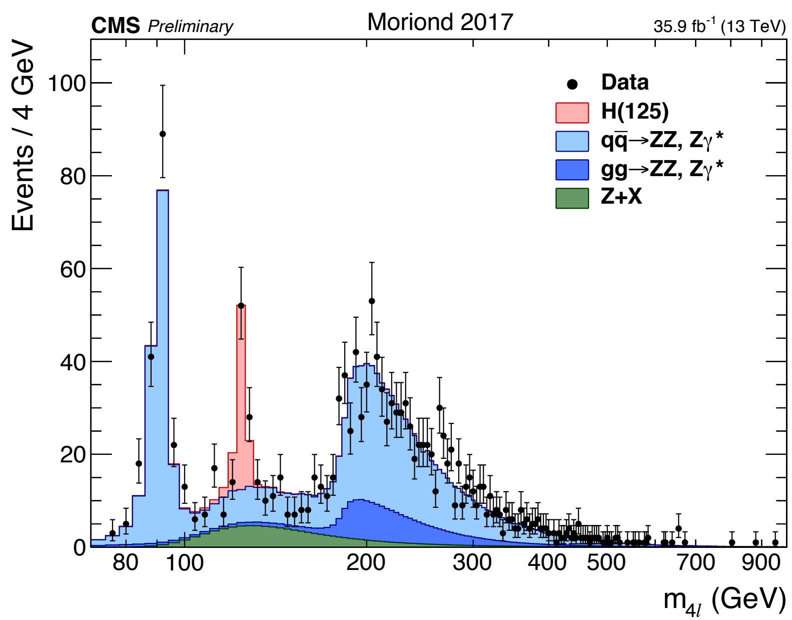
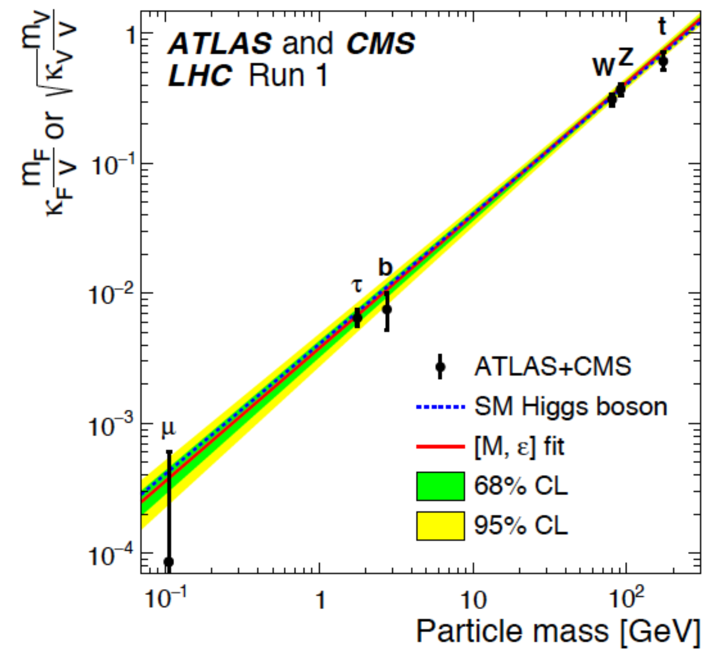
Pheno 2017 Symposium, Pittsburgh, PA
May 9, 2017

Higgs discovery - LHC Run I



arXiv: 1606.02266



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

$$\left.\begin{aligned} v^2 &= \frac{\mu_h^2}{\lambda_h} \simeq (246\ \text{GeV})^2 \\ m_h^2 &= 2\lambda_h v^2 \simeq (125\,\text{GeV})^2 \end{aligned}\right\} \Rightarrow \boxed{\mu_h^2 \simeq (89\ \text{GeV})^2} \quad \boxed{\lambda_h \simeq 0.13}$$

Higgs couplings ⇨ as expected in Standard Model! $\left(y_f = \sqrt{2}\frac{m_f}{v}\right)$

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

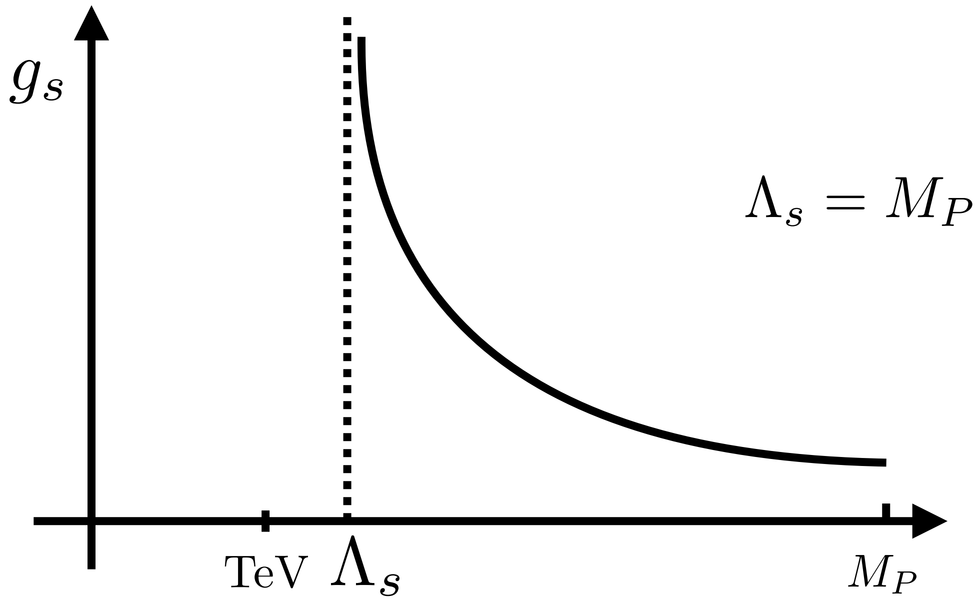
OR

- Composite? → New strong dynamics

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

Composite Higgs

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

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

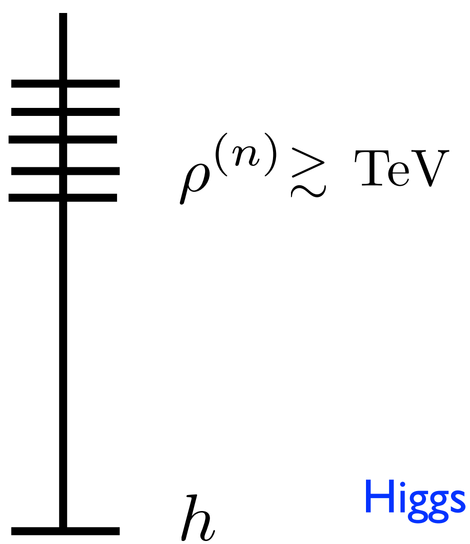
Similar to QCD: $\Lambda_{\rm QCD} \ll M_P$

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

Higgs = pseudo Nambu-Goldstone boson

[Georgi, Kaplan `84]

Global symmetry, G *spontaneously* broken to subgroup, H at scale, f



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

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

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

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

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

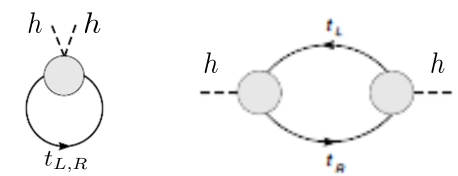
BUT global symmetry must be *explicitly* broken to generate $V(h) \neq 0$

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 — $\mathcal{L}_{mix} = \lambda_{L,R}\Psi_{L,R}\mathcal{O}_\Psi + g_V A^\mu J_\mu$ — strongly-coupled Higgs sector $\mathcal{O}_i$

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



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

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

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

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

(= fermionic resonances)

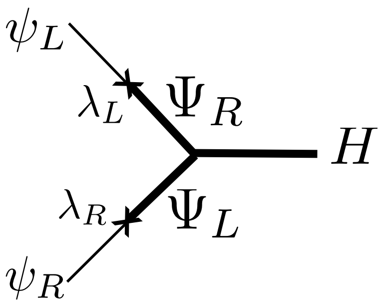
Bonus feature:

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

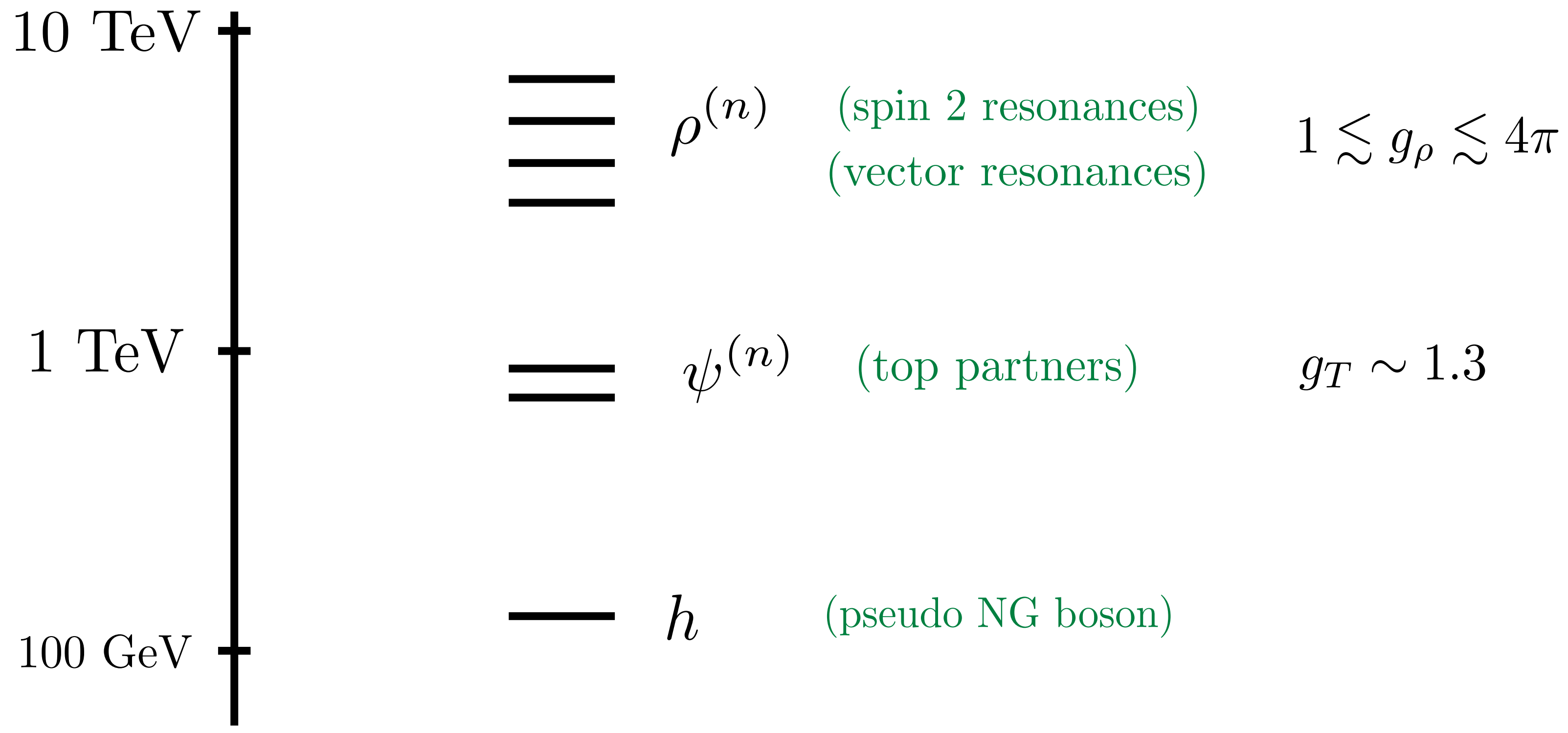


- Light fermions are mostly elementary ⇨ $\text{dim } \mathcal{O}_{L.R} > \frac{5}{2}$

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

A “Natural” Composite Higgs spectrum :

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



HOWEVER, precision electroweak, flavor constraints

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

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

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

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

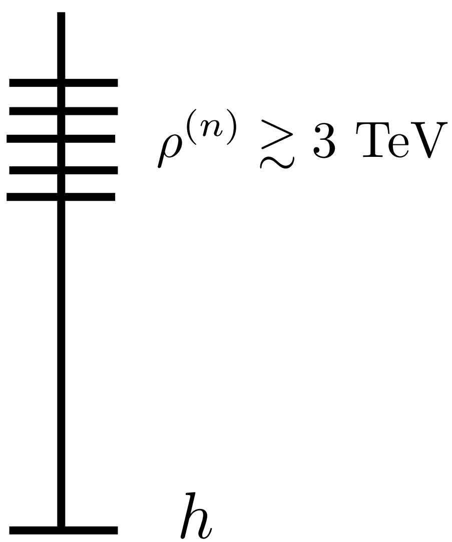
➡ $f \gg v$ *"Little" hierarchy*

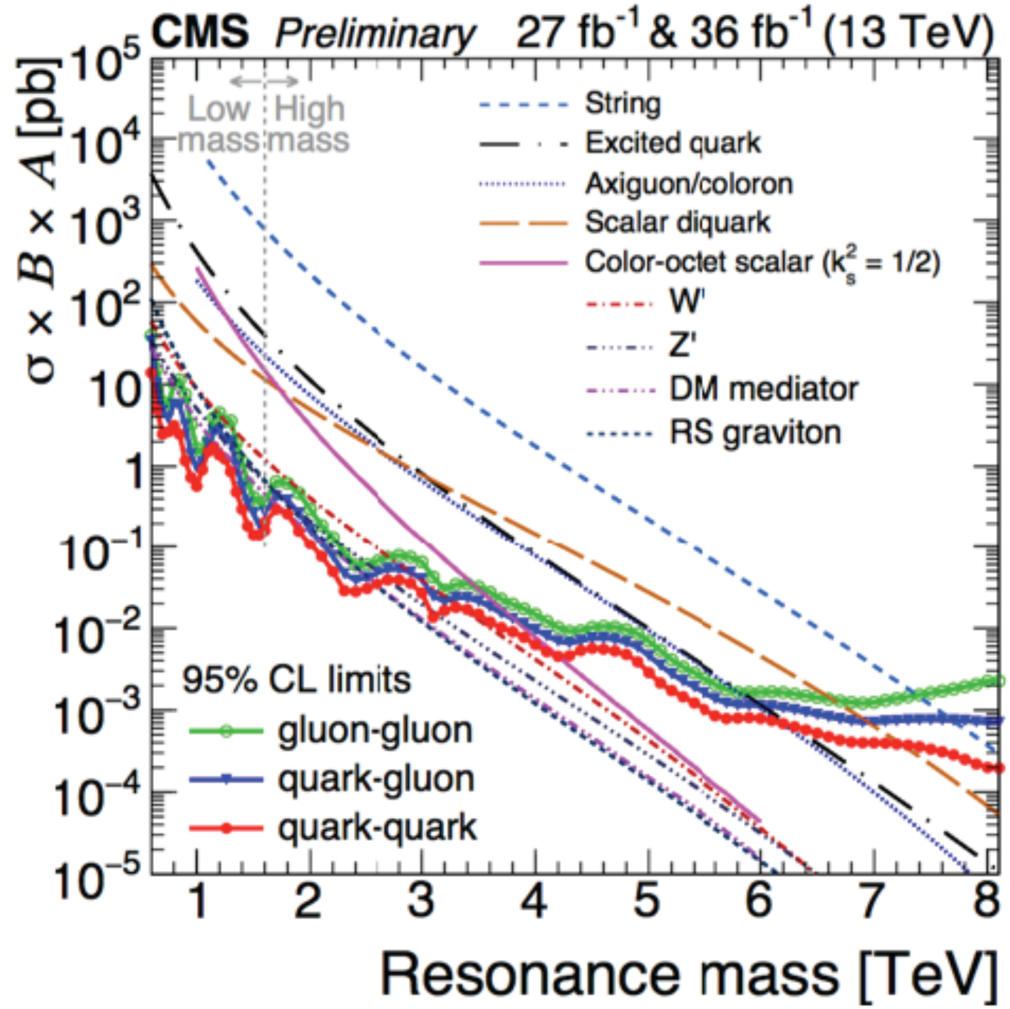
Tension partly alleviated by complicating minimal models

e.g. custodial symmetry, flavor, symmetry, twin parity….

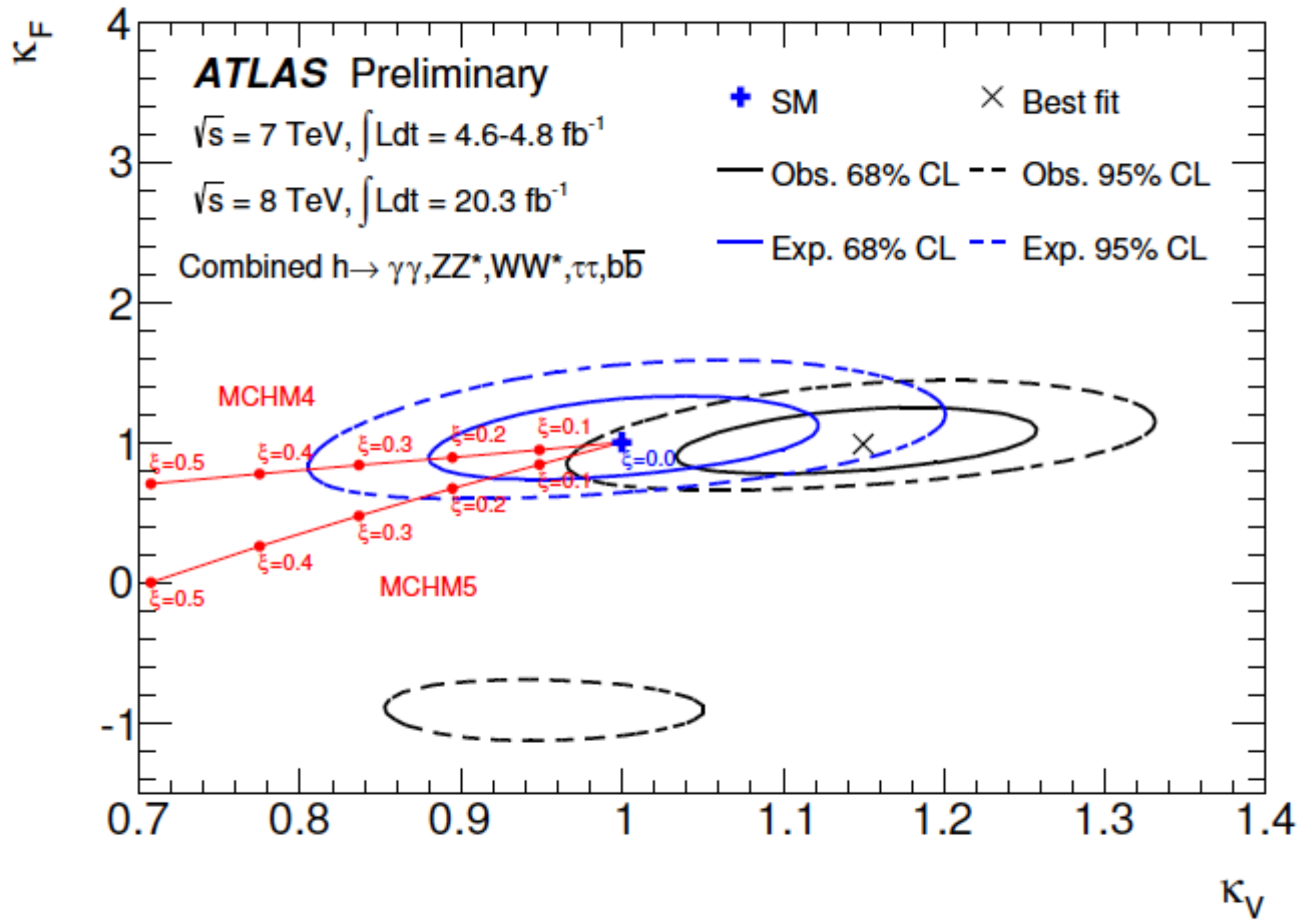
LHC Limits: *The Missing Resonances Problem*

- Massive spin-1, spin-2 resonances



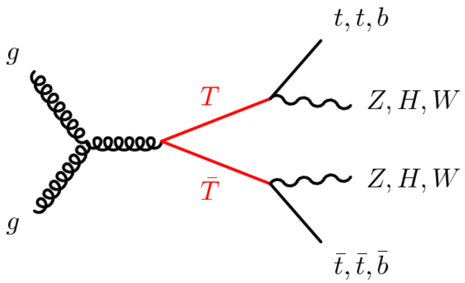


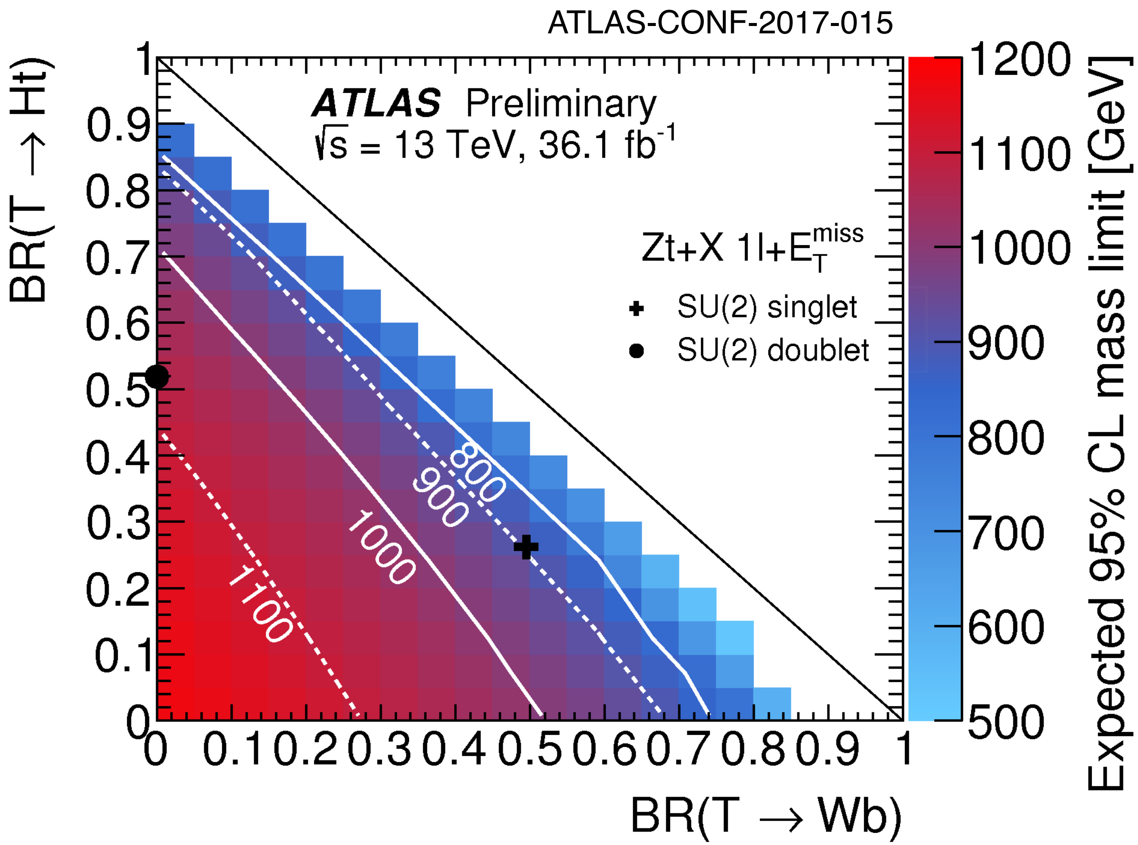
- Deviations in gauge, Yukawa couplings $\frac{g_{hWW}}{g_{hWW}^{SM}} \sim \frac{g_{hff}}{g_{hff}^{SM}} \sim \sqrt{1-\frac{v^2}{f^2}}$



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

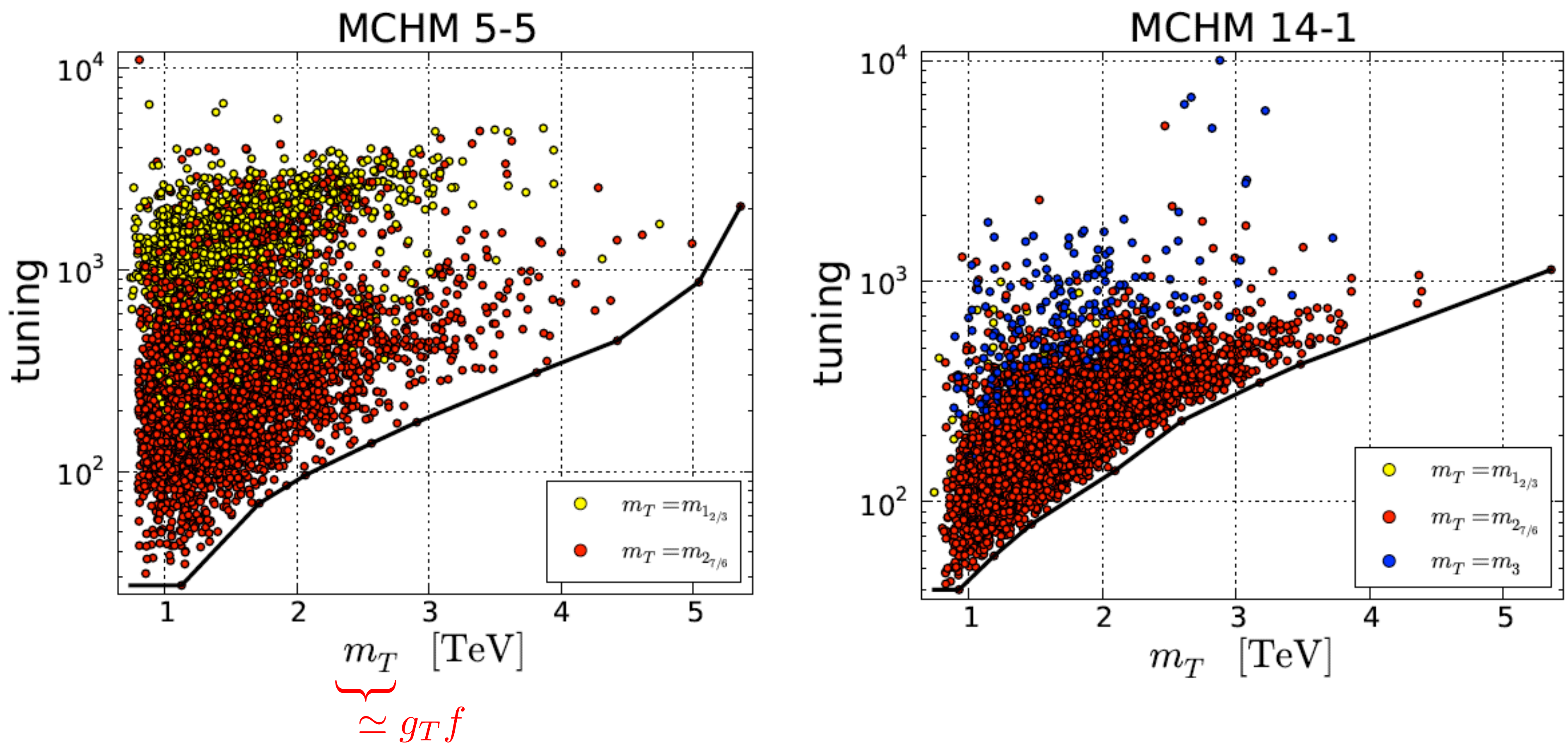
• Top partners $e.g.\ \mathbf{5_{2/3}} \rightarrow \mathbf{2_{7/6}} + \mathbf{2_{1/6}} + \mathbf{1_{2/3}} \supset \mathbf{T}$





$$\Rightarrow \quad m_T \gtrsim 1050\ \text{GeV}$$

[Barnard, White 1507.02332]



"Natural" models increasingly elaborate and tuned:

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

Embrace Unnaturalness!

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

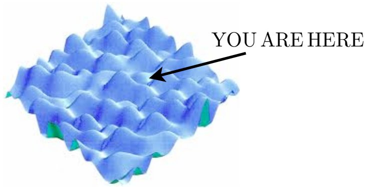
Tuned Higgs potential: $V \sim c_2 f^2 |H|^2 + c_4 |H|^4$

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

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!

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

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

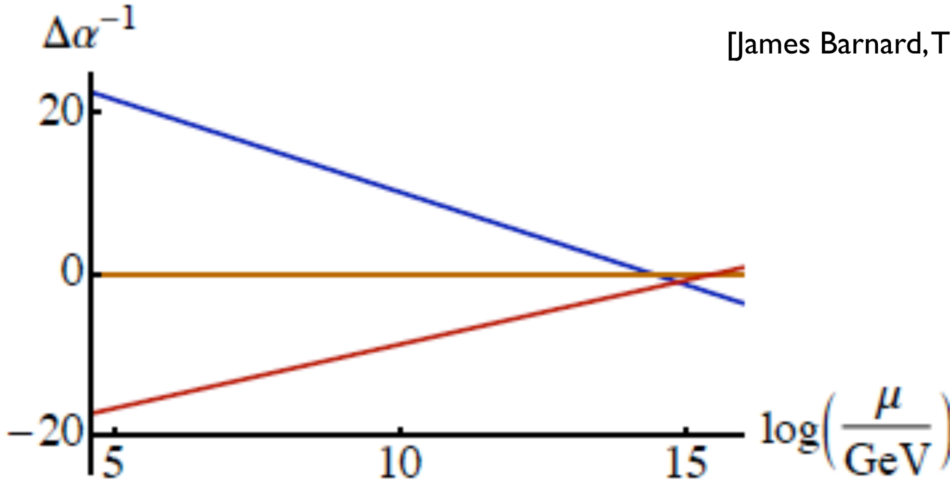
composite Higgs, top

One-loop beta function coefficients:

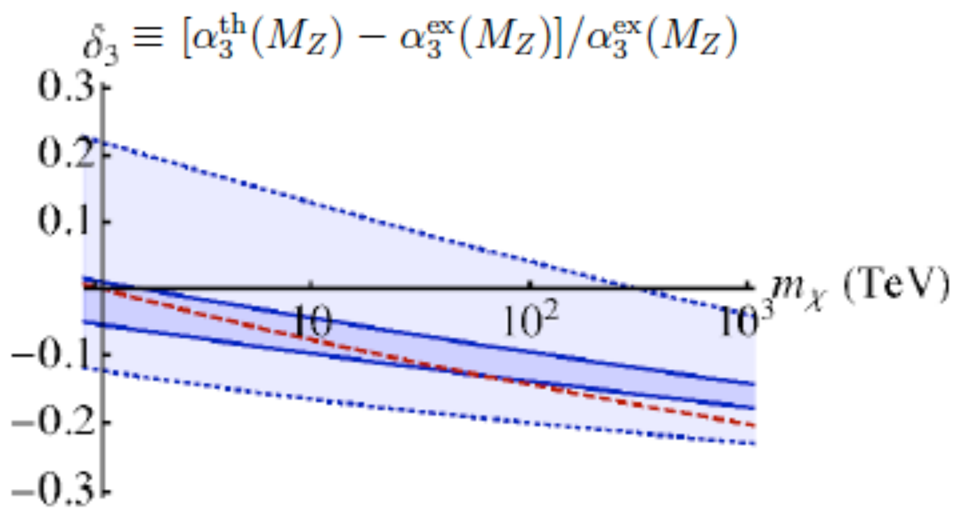
$$b_1 - b_2 = \frac{94}{15} \qquad b_2 - b_3 = \frac{13}{3} \qquad \Rightarrow \qquad \boxed{\frac{b_2 - b_3}{b_1 - b_2} \simeq 0.69}$$

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 $\delta_3 = 0$ $(b_{strong} = 5)$ ⇒ $f \lesssim 500\ \mathrm{TeV}$

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]

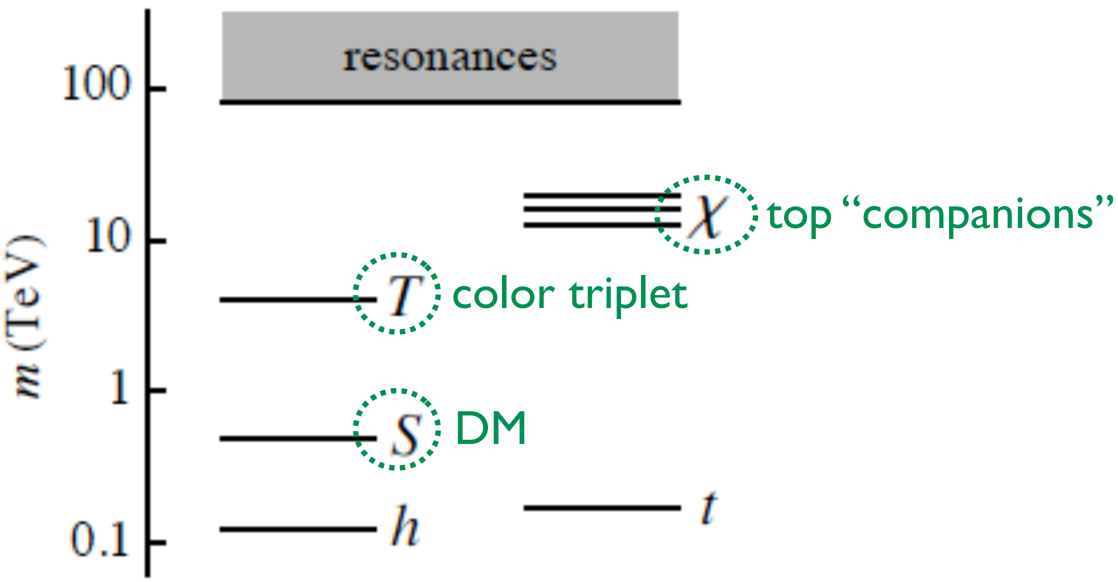
$$w = e^{i\Pi} \begin{pmatrix} 0_{(6)} \\ 1 \end{pmatrix} = \frac{1}{f} \begin{pmatrix} H \\ S \\ \sqrt{f^2 - |H|^2 - |S|^2} \end{pmatrix}$$

12 Nambu-Goldstone bosons

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

The Unnatural or "Split" Composite Higgs model

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



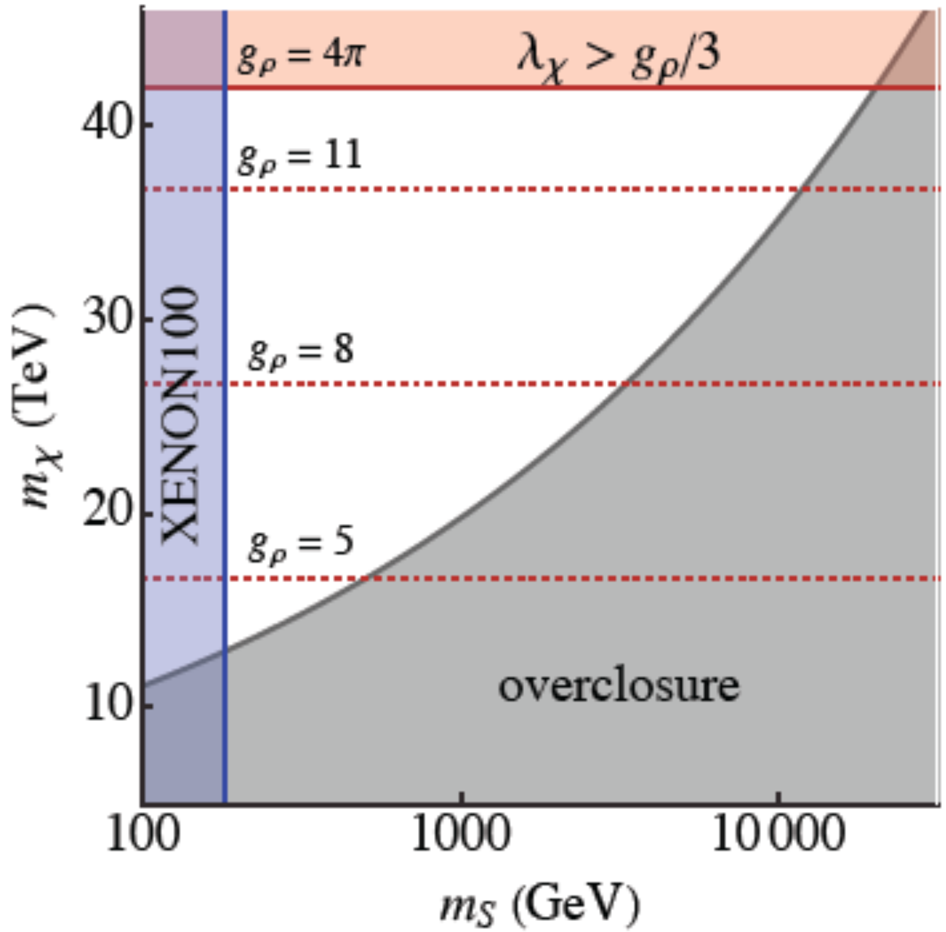
Low-energy spectrum: Standard Model + S + T + χ

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

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

→ 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

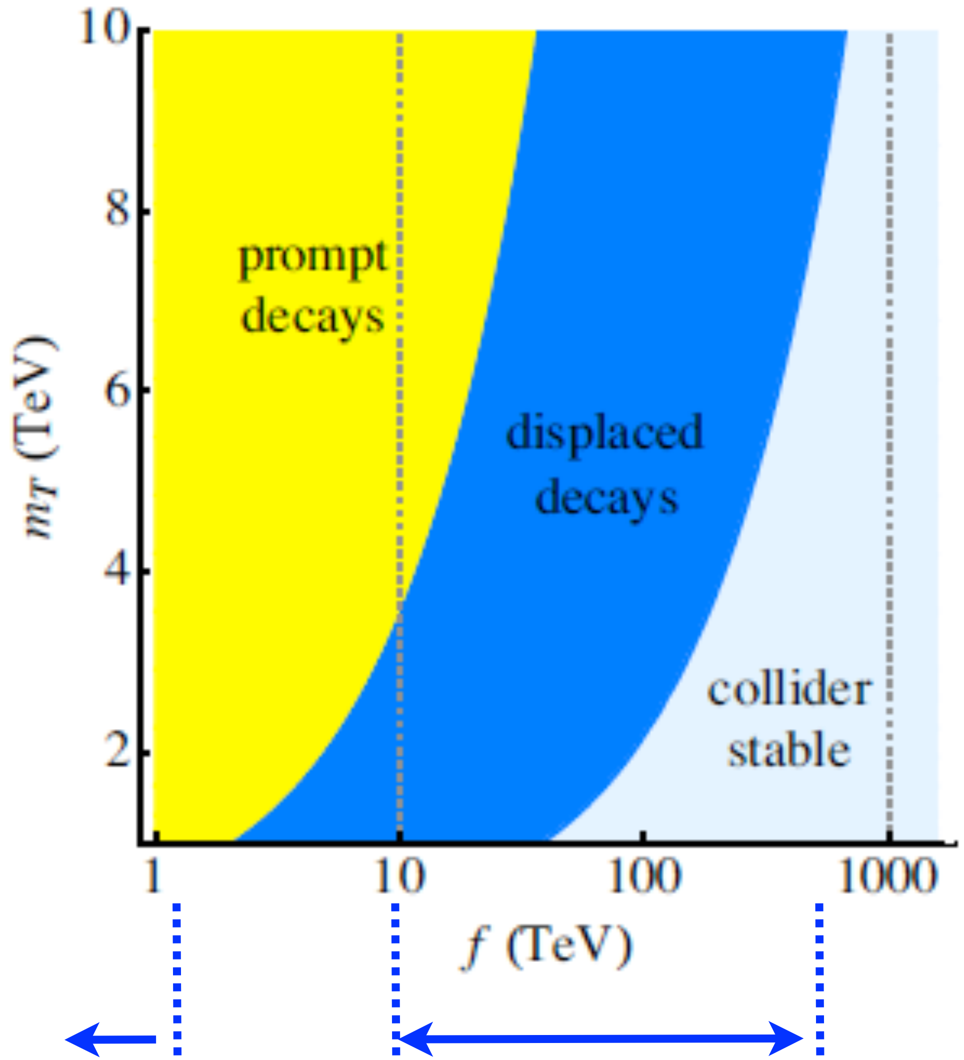
f > 10 TeV = long-lived decay

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

can produce a displaced vertex!

Color triplet decay

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



"natural" composite Higgs:

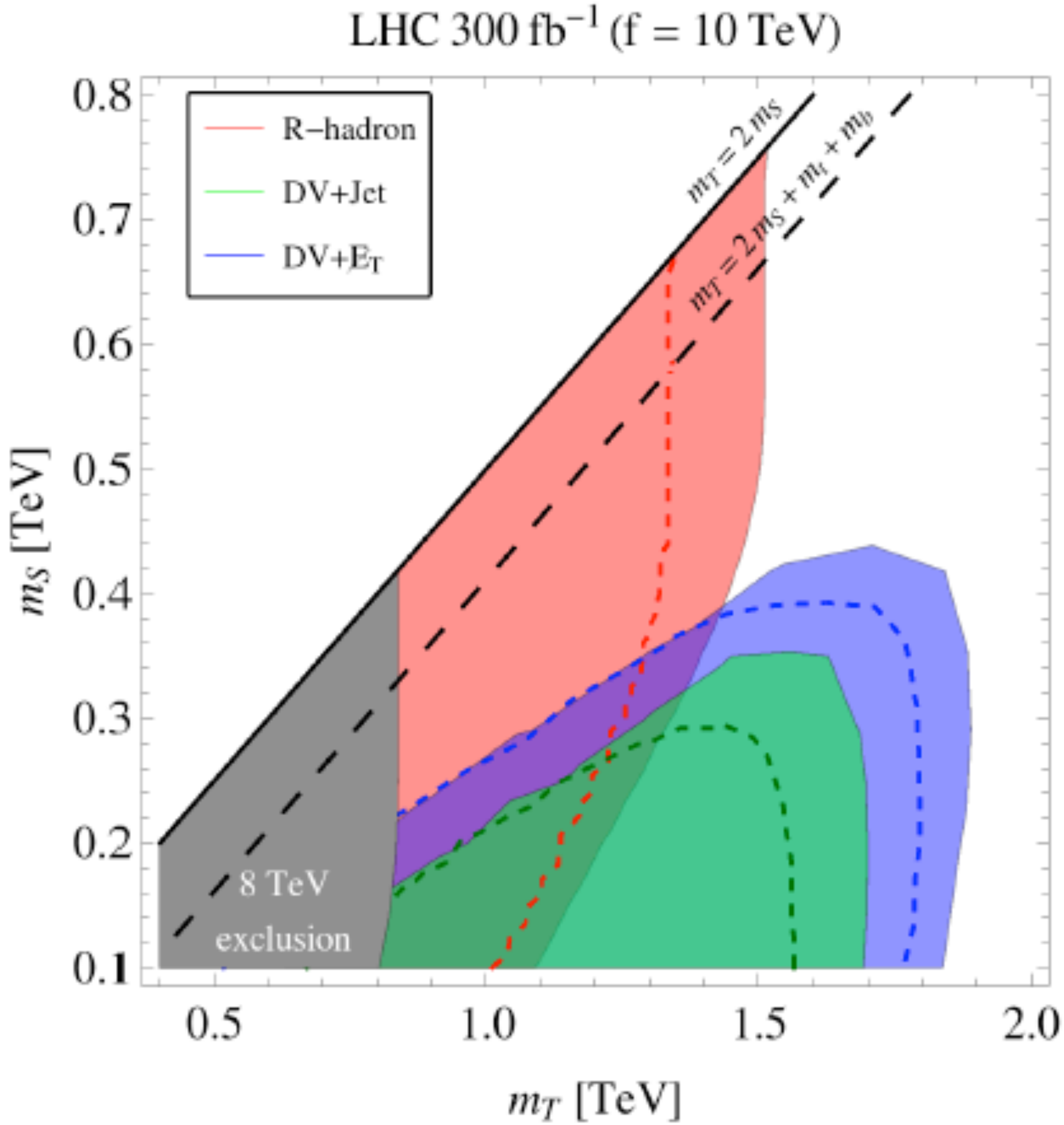
$f \lesssim 1$ TeV

Unnatural or "split" composite Higgs:

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

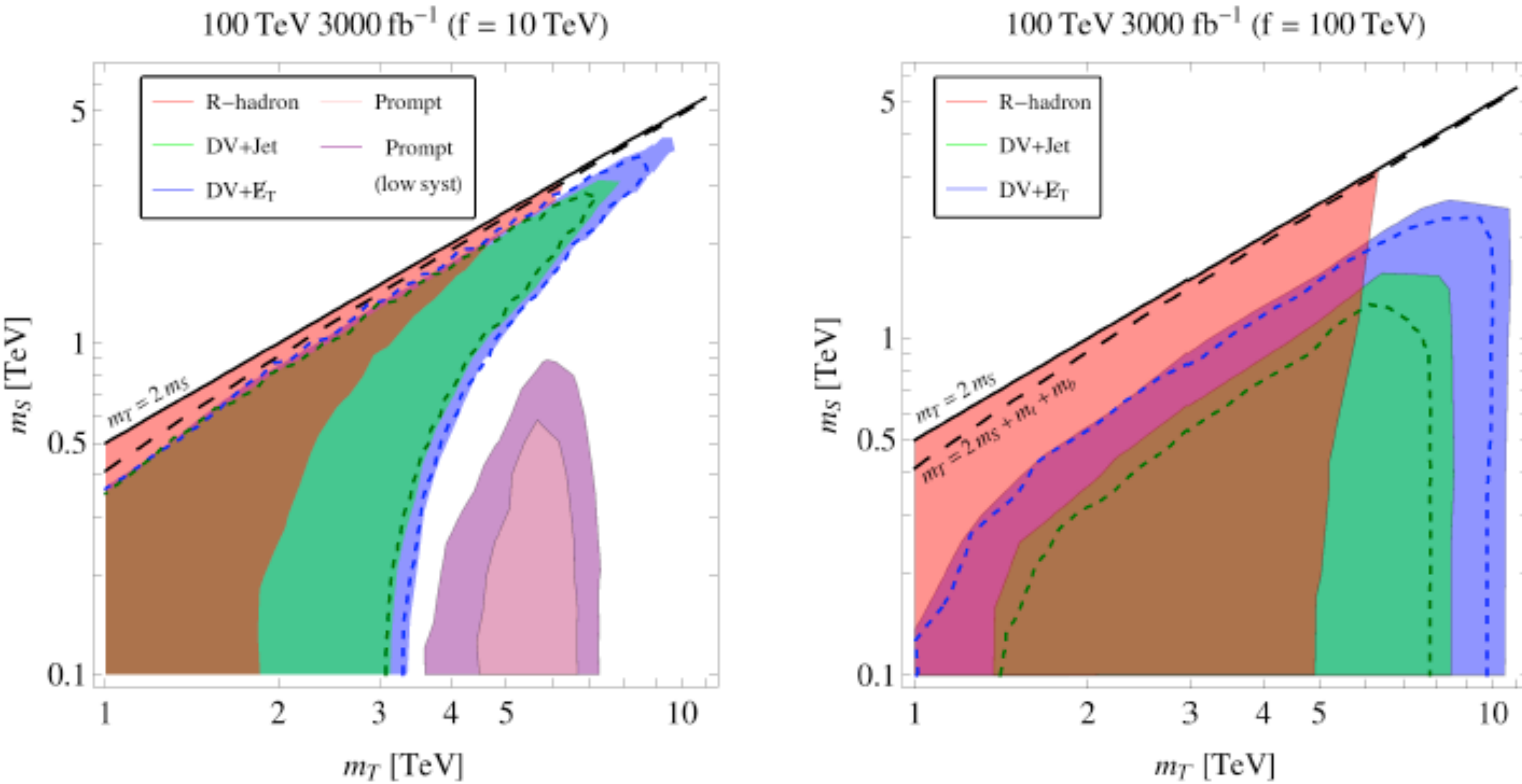
LHC:

[Barnard, Cox, TG, Spray: 1510.06405]



Future100 TeV collider:

[Barnard, Cox, TG, Spray: 1510.06405]



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!

Summary

- Higgs could be composite!
  - *--- Explains electroweak and fermion mass hierarchy*
  - *--- "Natural" models tuned* $(\lesssim 5\%)$
- Unnatural or "split" composite Higgs
  - *---* $f \gtrsim 10\ \mathrm{TeV}$ *eliminates electroweak and flavour constraints*
  - *--- Higgs potential is meso-tuned at* 10^{-4} *level*
- SU(7)/SU(6)xU(1) minimal model
  - *--- Improves gauge coupling unification* $(f \lesssim 500\ \mathrm{TeV})$
  - *--- Higgs partners: S = dark matter, T = color triplet*
- Long-lived T decays = sign of unnaturalness!