Beyond the Higgs

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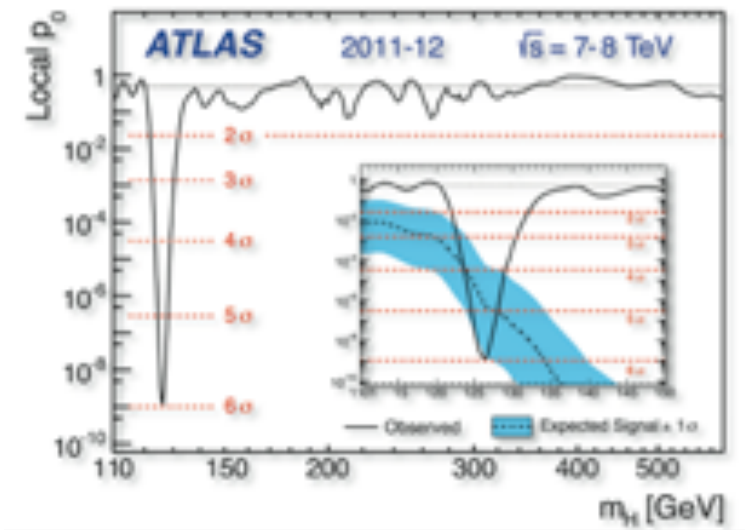
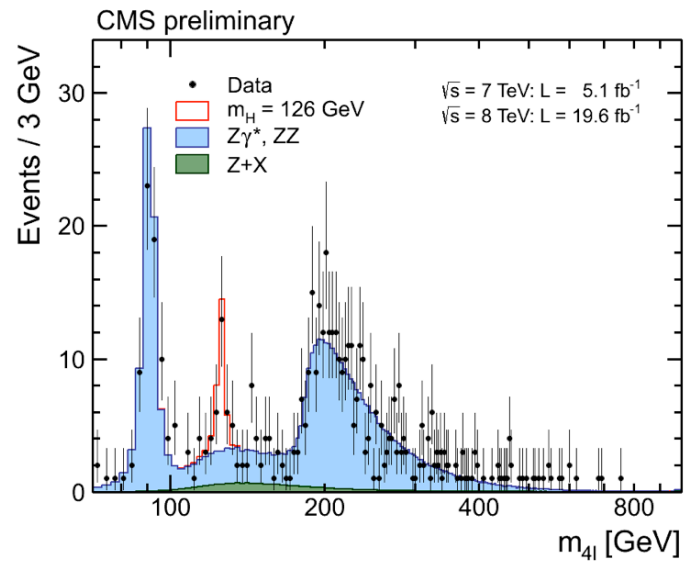
Higgs discovery - Run I



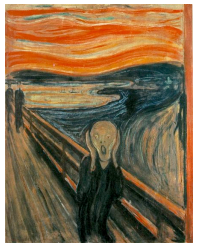


Higgs potential: $V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$ $\langle H \rangle = \frac{1}{\sqrt{2}}(v+h)$

$$v^2 = \frac{\mu_h^2}{\lambda_h} \simeq (246\ \mathrm{GeV})^2 \qquad m_h^2 = 2\lambda_h v^2 \simeq (125\,\mathrm{GeV})^2$$

$$\Rightarrow \quad \boxed{\mu_h^2 \simeq (89\ \mathrm{GeV})^2} \qquad \boxed{\lambda_h \simeq 0.13}$$

Standard Model and nothing else...?



Questions not addressed in Standard Model:

- Planck/weak scale hierarchy? $(\mu_h \ll M_P)$
- Fermion mass hierarchy? Neutrino masses?
- Dark matter?
- Baryon asymmetry?
- Strong CP problem?
- GUTS? Inflation?
- UV completion of gravity?
- Cosmological constant?

Clearly requires new physics...but why near the electroweak scale?

NATURALNESS?

NATURAL explanations of ~125 GeV Higgs

HIGGS BOSON

- Elementary → ***Supersymmetry***

OR

- Composite → ***New strong dynamics***

How "natural" are these two possibilities after Run 1?

[New alternative: Neutralising the Higgs mass -- "relaxion" - see G. Servant's talk]

1. Elementary Higgs

Supersymmetric Standard Model

EWSB $\quad V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4 \qquad (m_A \gg m_Z, \tan\beta \gg 1)$

want large $m_{\tilde{t}}$ [Haber, Hempfling '91] [Ellis, Ridolfi, Zwirner '91]

SUSY

$$\lambda_h = \frac{1}{4}(g^2 + g'^2) + \frac{3}{32\pi^2} y_t^4 \left[\ln \frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2} \right) \right]$$

where $X_t = A_t - \mu \cos\beta$

want small $m_{\tilde{t}}$

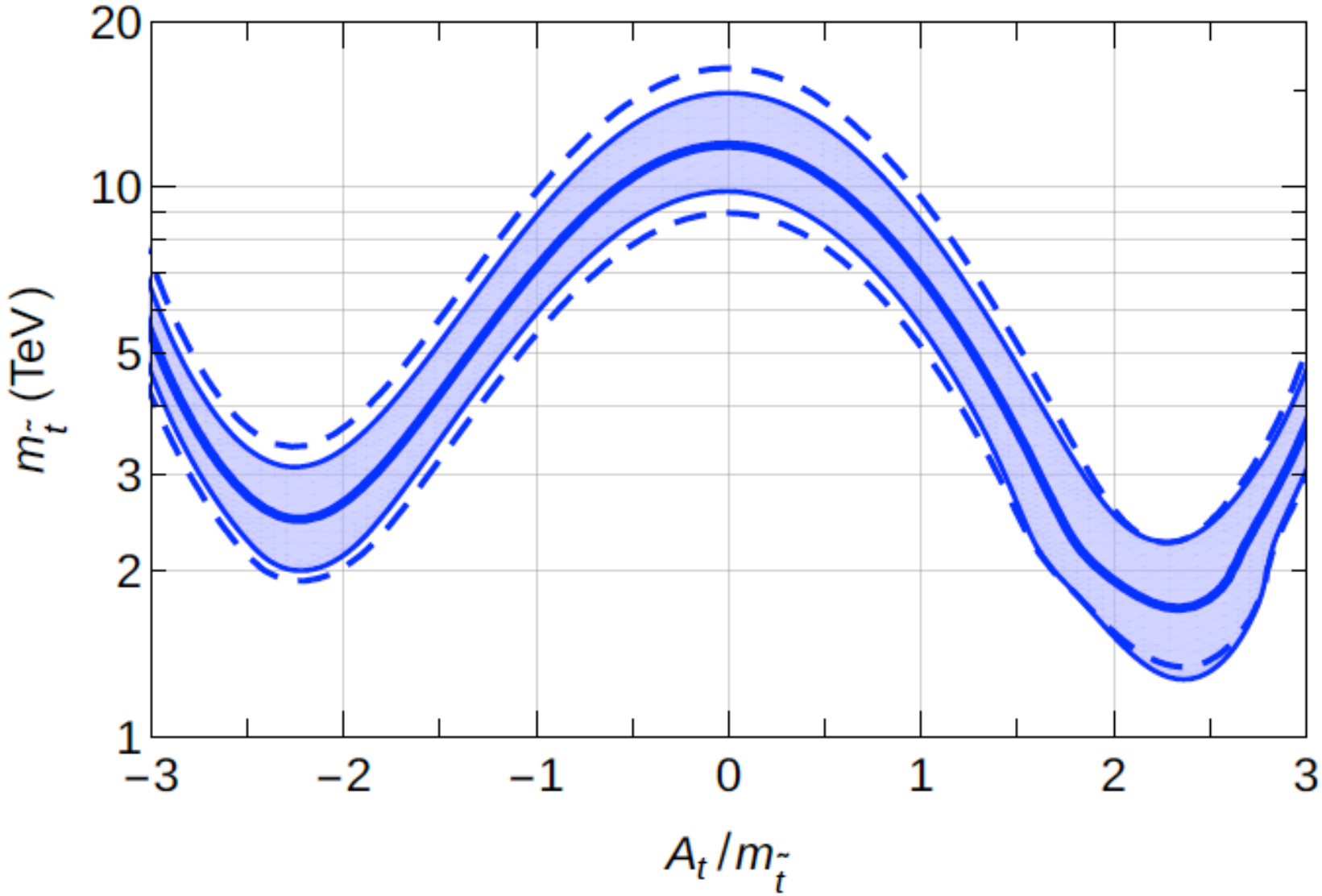
$$\mu_h^2 \simeq |\mu|^2 - \frac{3 y_t^2}{4\pi^2} m_{\tilde{t}}^2 \log \frac{\Lambda_{mess}}{m_{\tilde{t}}} \qquad (\tan\beta \gg 1)$$

$\lambda_h \simeq 0.13 \Rightarrow m_{\tilde{t}} \gtrsim 1\,\text{TeV} \qquad (X_t \sim m_{\tilde{t}})$

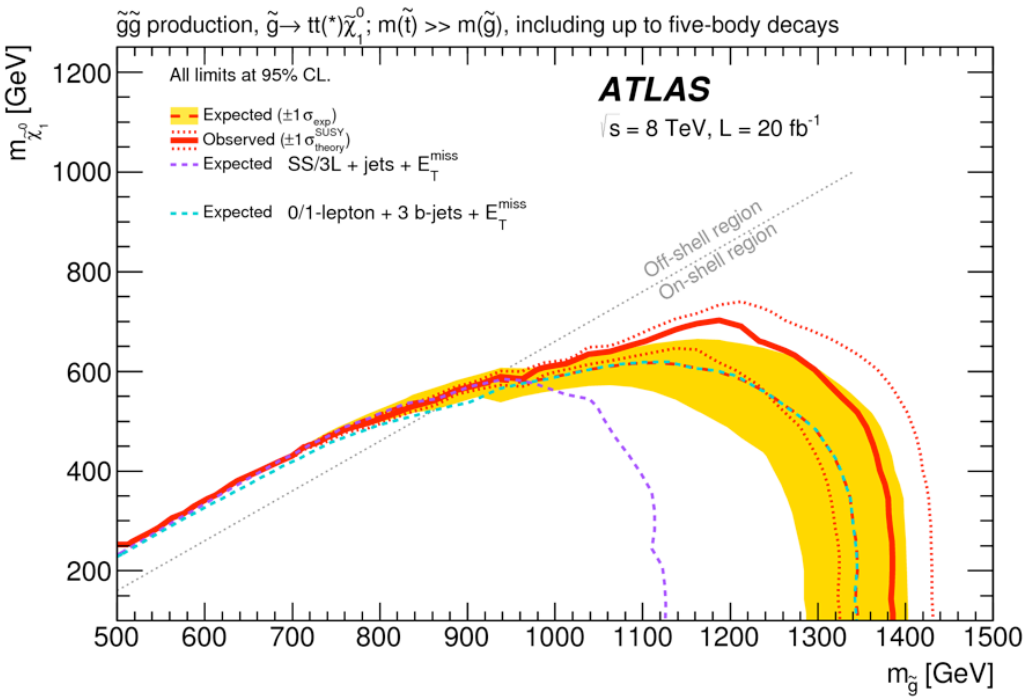
$\mu_h^2 \simeq (89\ \text{GeV})^2 \Rightarrow m_{\tilde{t}} \lesssim 400\ \text{GeV} \qquad (\text{“natural”})$

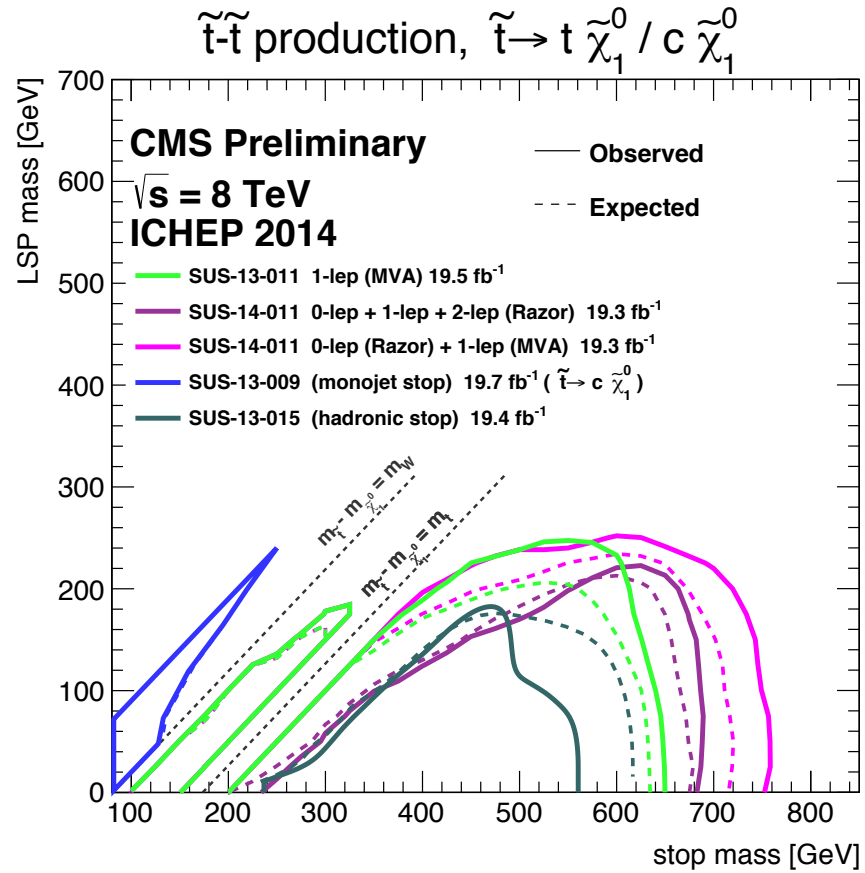
Higgs mass in MSSM

[Pardo Vega, Villadoro 1504.05200]



LHC Limits: *The Missing Superpartners Problem*





$$m_{\tilde{g}} \gtrsim 1400 \text{ GeV}$$

$$m_{\tilde{t}_1} \gtrsim 700 \text{ GeV}$$

Best case scenario "*natural* SUSY"

To minimize tuning:

(i) Low messenger scale $\Lambda_{mess} = 20\,\mathrm{TeV}$

$\log \frac{\Lambda_{mess}}{m_{\tilde{t}}} \sim 3$

(ii) Add new contribution to Higgs quartic coupling

No need for heavy stop, A-term

(scale-invariant) NMSSM

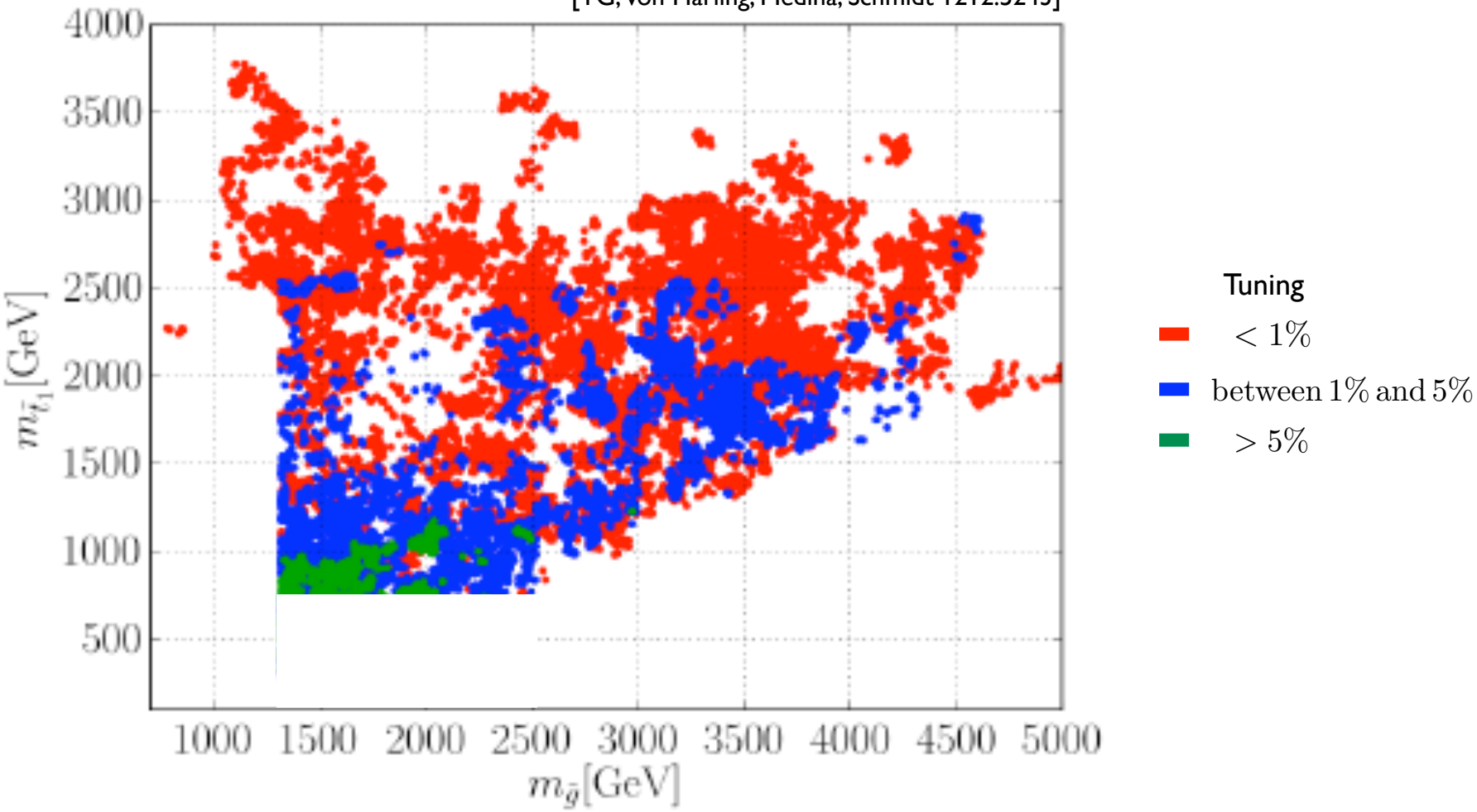
$$W_{\mathrm{NMSSM}} = \lambda S H_u H_d + \frac{\kappa}{3} S^3 \qquad S = \text{ singlet}$$

Higgs mass: $m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$

new parameter to increase Higgs mass

Tuning: Gluino-stop masses

[TG, von Harling, Medina, Schmidt 1212.5243]



For tuning $\sim 5\%$

$$m_{\tilde{g}} \lesssim 2\,\mathrm{TeV} \qquad m_{\tilde{t}_1} \lesssim 1.2\,\mathrm{TeV}$$

Caveat: Bottom-up approach is naive sampling of parameter space

⇨ Tuning is probably worse!

Natural SUSY models: "Baroque"

- Split families
- R-parity violation
- Dirac gauginos
- Neutral naturalness (e.g. folded SUSY)
- .....

Increasingly elaborate and tuned...

Simple alternative:

[Wells 2003; Arkani-Hamed, Dimopoulos 2004]

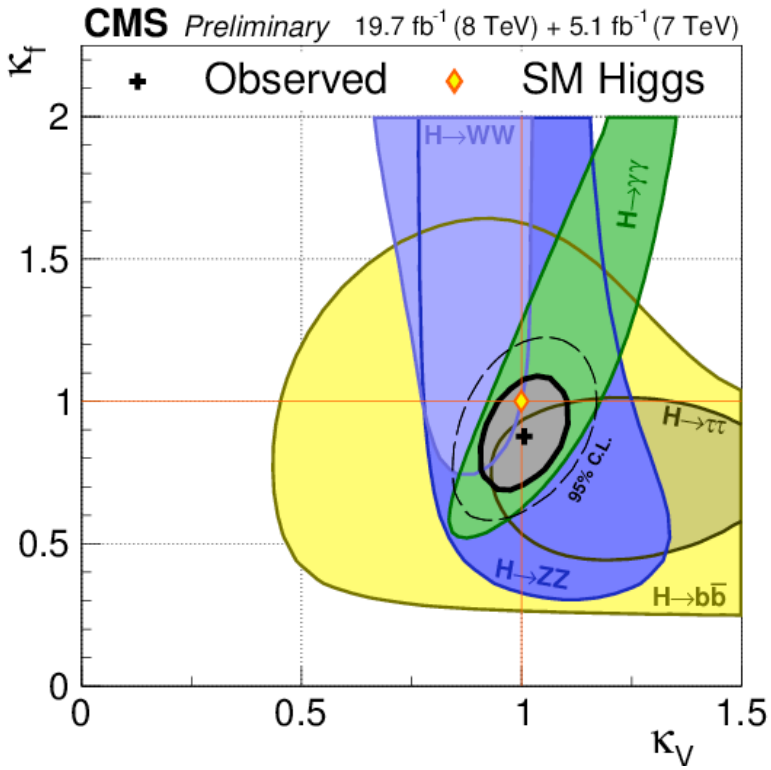
"Unnatural" Split SUSY

TUNED

$(\sim 10^{-4})$

What about Higgs couplings?

[TG, von Harling, Medina, Schmidt 1401.8291]
[see also Farina, Perelstein, Shakya 1310.0459]



Define

$$r_u \equiv \frac{\text{Higgs coupling to up-type fermions}}{\text{SM Higgs coupling to up-type fermions}}$$

similarly r_d, r_V

where for NMSSM

$$r_u \simeq 1 - \frac{m_{hH}^4}{2m_H^4} - \frac{m_{hs}^4}{2m_s^4} + \cot\beta \left(\frac{m_{hH}^2}{m_H^2} - \frac{m_{hs}^2 m_{Hs}^2}{m_H^2 m_s^2} + \frac{m_h^2 m_{hH}^2}{m_H^4} \right)$$

$$r_d \simeq 1 - \frac{m_{hH}^4}{2m_H^4} - \frac{m_{hs}^4}{2m_s^4} - \tan\beta \left(\frac{m_{hH}^2}{m_H^2} - \frac{m_{hs}^2 m_{Hs}^2}{m_H^2 m_s^2} + \frac{m_h^2 m_{hH}^2}{m_H^4} \right)$$

$$r_V \simeq 1 - \frac{m_{hH}^4}{2m_H^4} - \frac{m_{hs}^4}{2m_s^4} .$$

with CP even mass-squared matrix

SM Higgs

$$\mathcal{M}^2 = \begin{pmatrix} m_h^2 & m_{hH}^2 & m_{hs}^2 \\ m_{hH}^2 & m_H^2 & m_{Hs}^2 \\ m_{hs}^2 & m_{Hs}^2 & m_s^2 \end{pmatrix}$$

SM-like couplings ➡ $m_{hs}, m_{hH} \ll m_h \ll m_H, m_s$

➡ ***new source of tuning***

NMSSM

$$W \supset \lambda S H_u H_d + \kappa S^3$$

$$V = (m_{H_u}^2 + \lambda^2|S|^2)|H_u^0|^2 + (m_{H_d}^2 + \lambda^2|S|^2)|H_d^0|^2 + \lambda^2|H_u^0 H_d^0|^2 + m_S^2|S|^2 + \kappa^2|S|^4 + \left[\frac{a_\kappa}{3}S^3 - (a_\lambda S + \lambda\kappa S^2)H_u^0 H_d^0 + \text{h.c.}\right] + \tilde{g}^2\left(|H_u^0|^2 - |H_d^0|^2\right)^2$$

with

$$m_h^2 = 2\,\tilde{g}^2 v^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta$$

$$m_H^2 = \csc 2\beta \left(\sqrt{2} v_s a_\lambda + \kappa\lambda v_s^2 - \frac{v^2}{2}\sin^3 2\beta\,(\lambda^2 - 4\tilde{g}^2)\right)$$

$$m_s^2 = \frac{a_\kappa v_s}{\sqrt{2}} + 2\kappa^2 v_s^2 + \frac{a_\lambda v^2 \sin 2\beta}{\sqrt{8}\, v_s}$$

$$m_{hs}^2 = v\left(\lambda^2 v_s - \sin\beta\cos\beta(\sqrt{2}a_\lambda + 2\kappa\lambda v_s)\right)$$

$$m_{hH}^2 = \frac{v^2}{4}\sin 4\beta\,(4\tilde{g}^2 - \lambda^2)$$

$$m_{Hs}^2 = \frac{v}{2}\cos 2\beta\,(\sqrt{2}a_\lambda + 2\kappa\lambda v_s)\,.$$

Tuning:

$$\Sigma \gtrsim \frac{1}{4}(4\tilde{g}^2 - \lambda^2)\, f(\lambda, \kappa, \tan\beta, \tilde{g}) \cdot \begin{cases} \dfrac{\cot\beta\,\sin 4\beta}{|r_u - 1|} \\ \dfrac{\tan\beta\,\sin 4\beta}{|r_d - 1|} \end{cases}$$

$$\Sigma \gtrsim \frac{1}{4}(4\tilde{g}^2 - \lambda^2)\, f(\lambda, \kappa, \tan\beta, \tilde{g})\, \frac{\sin 4\beta}{\sqrt{2(1 - r_V)}}$$

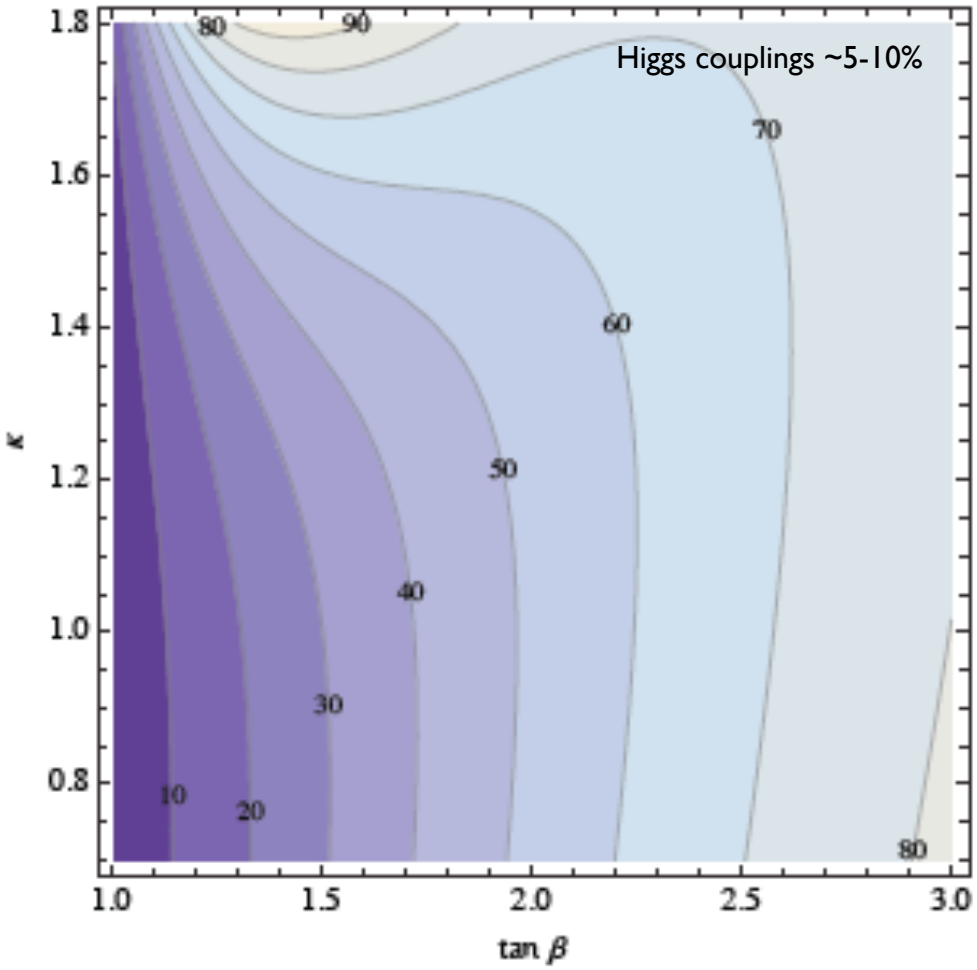
Fine-tuning grows as $r_{u,d,V} \to 1$

Note: EWPT ➡ $\tan\beta \lesssim 4$ So tuning cannot be offset with large $\tan\beta$

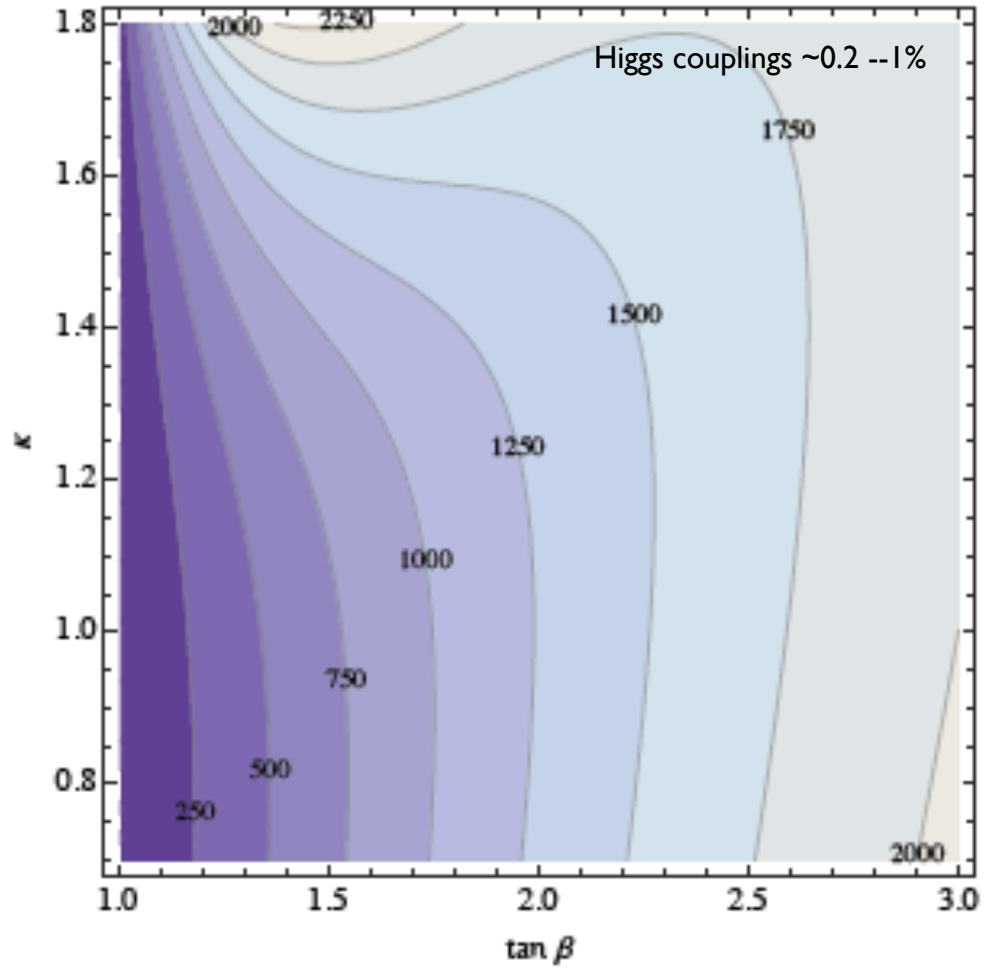
Contours of fine tuning measure Σ

[TG, von Harling, Medina, Schmidt 1401.8291]

LHC 14 TeV $300\ \mathrm{fb}^{-1}$



ILC 1TeV $2500\ \mathrm{fb}^{-1}$



2. Composite Higgs

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

$$G \to H \quad \text{at scale} \quad f \quad \text{where} \quad H \supset SO(4) \sim SU(2)_L \times SU(2)_R$$

- Partially composite top $\mathcal{L} = \lambda_L t_L \mathcal{O}_R + \lambda_R t_R \mathcal{O}_L$

[Kaplan `91; Agashe, Contino, Pomarol '04]

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

Higgs potential

symmetry-breaking scale

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

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

HOWEVER, precision electroweak, flavor constraints

EWPT:

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

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

e.g. FCNC

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

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

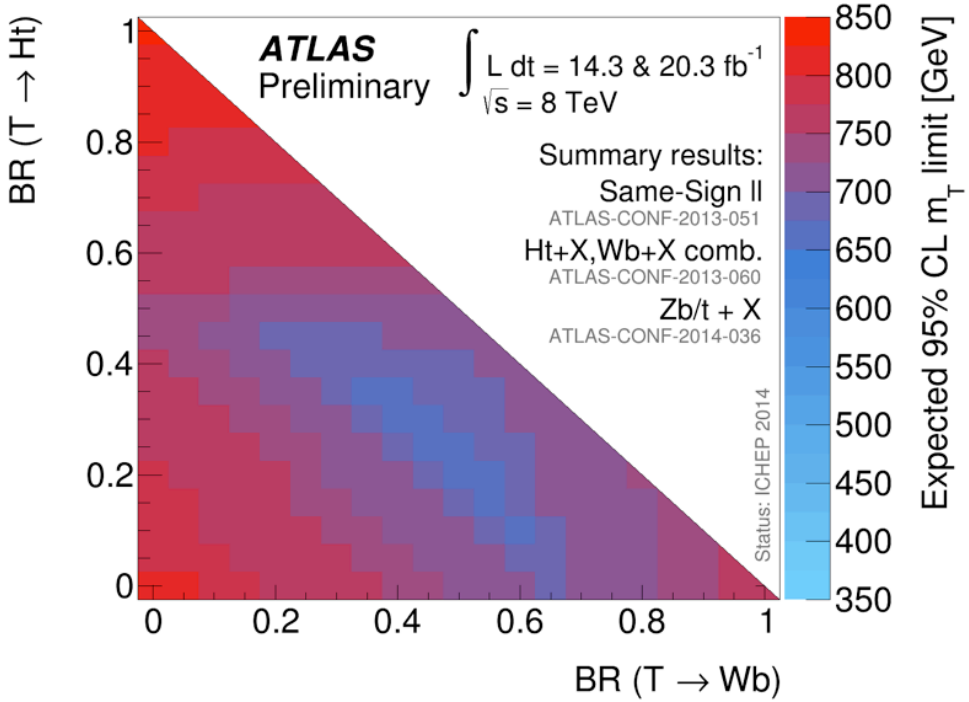
$$\Rightarrow \quad \boxed{f \gg v}$$

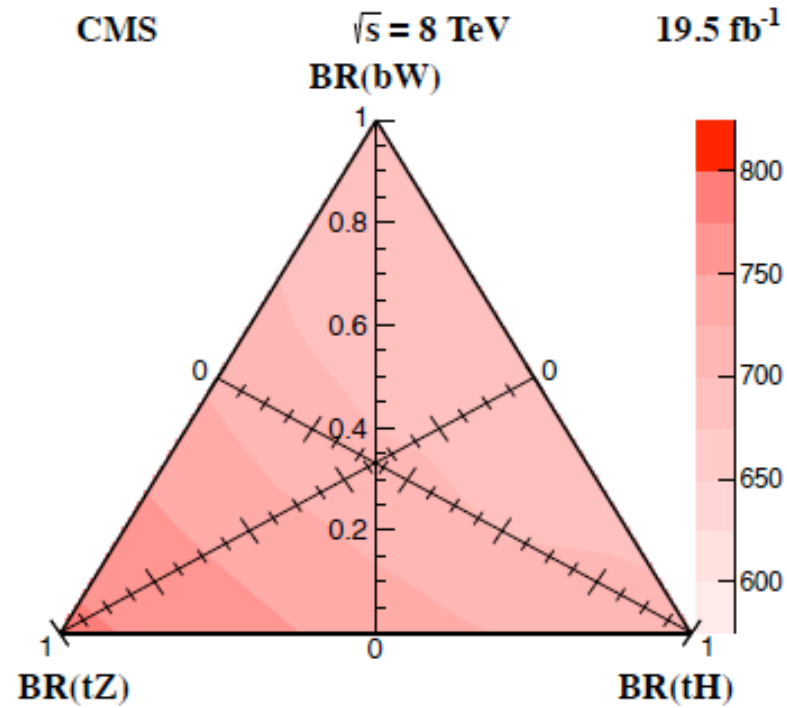
"Little" hierarchy

Tension partly alleviated by complicating minimal models

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

LHC Limits: *The Missing Resonances Problem*

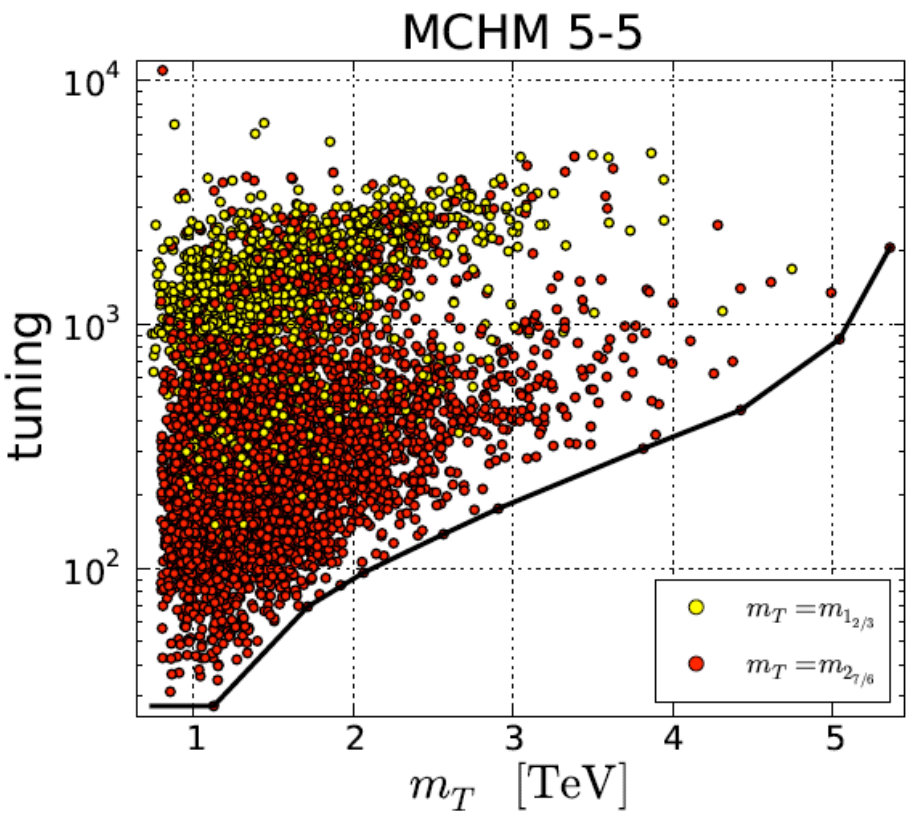


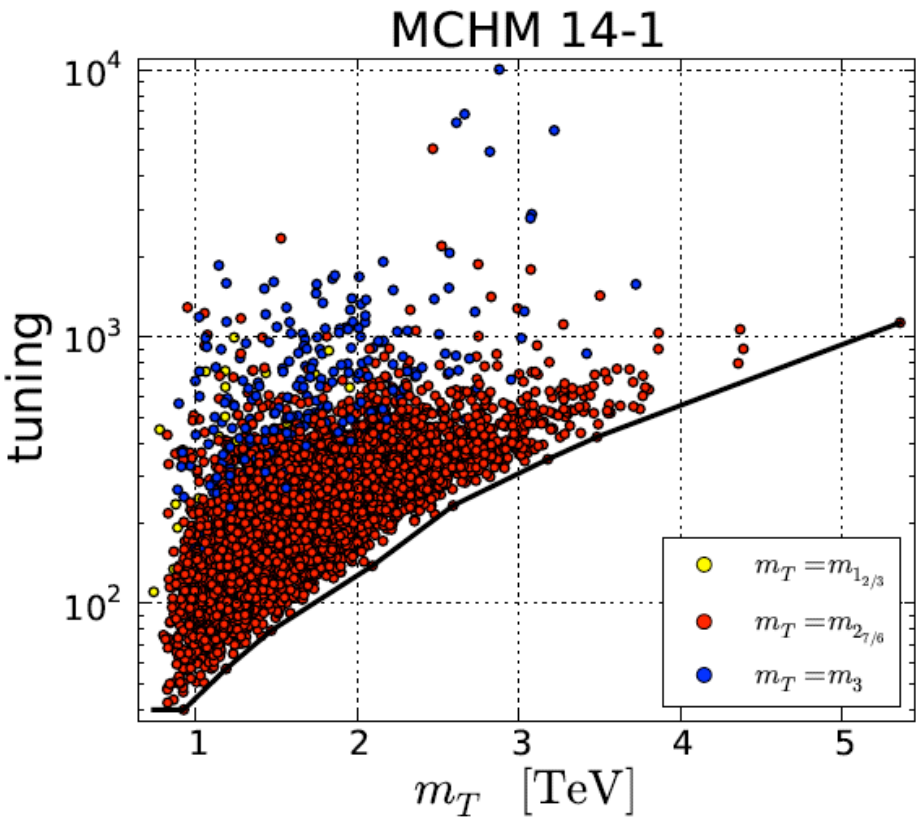


$$m_T \gtrsim 600 - 800\,\mathrm{GeV}$$

Tuning: Top partner masses

[Barnard, White 1507.02332]





"Natural" models increasingly elaborate and tuned:

$$\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 5\%$$

Simple solution:

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

Tuned Higgs potential

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

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

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

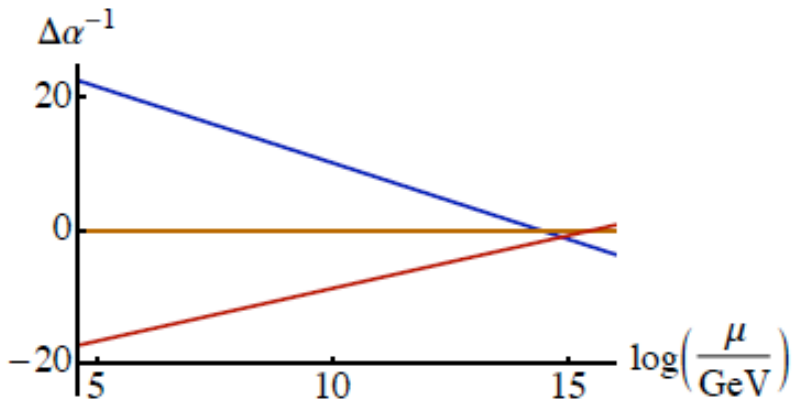
e.g. QCD - sensitivity in neutron, proton mass $\frac{m_{u,d}}{m_{nucleon}} \sim 10^{-3}$

Is there a motivated upper bound for f ?

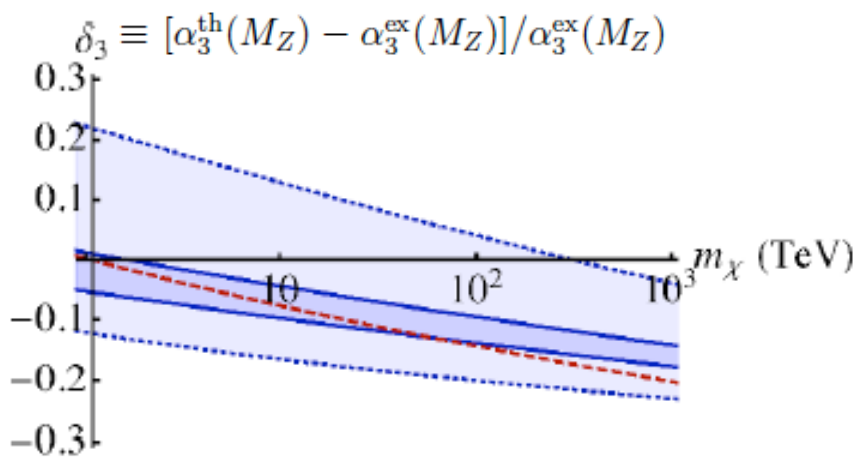
Yes!

Gauge Coupling Unification:

[Agashe, Contino, Sundrum 2005]
[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]

Symmetry breaking:

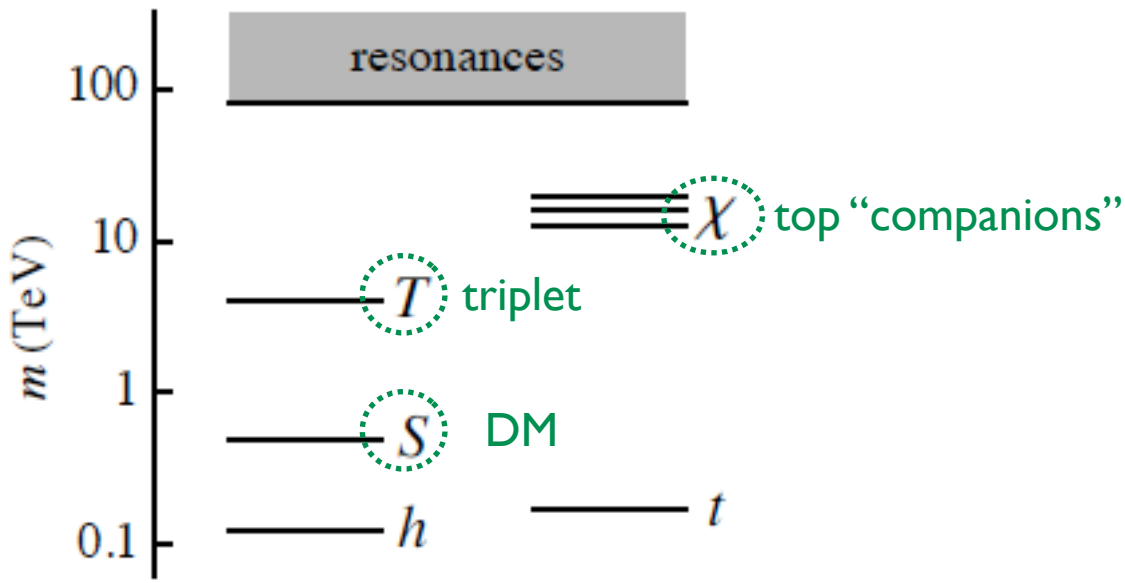
$$w = e^{i\Pi}\begin{pmatrix} 0_{(6)} \\ 1 \end{pmatrix} = \frac{1}{f}\begin{pmatrix} H \\ S \\ \sqrt{f^2 - |H|^2 - |S|^2} \end{pmatrix}$$

12 Nambu-Goldstone bosons

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

The "Unnatural" Composite Higgs model

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

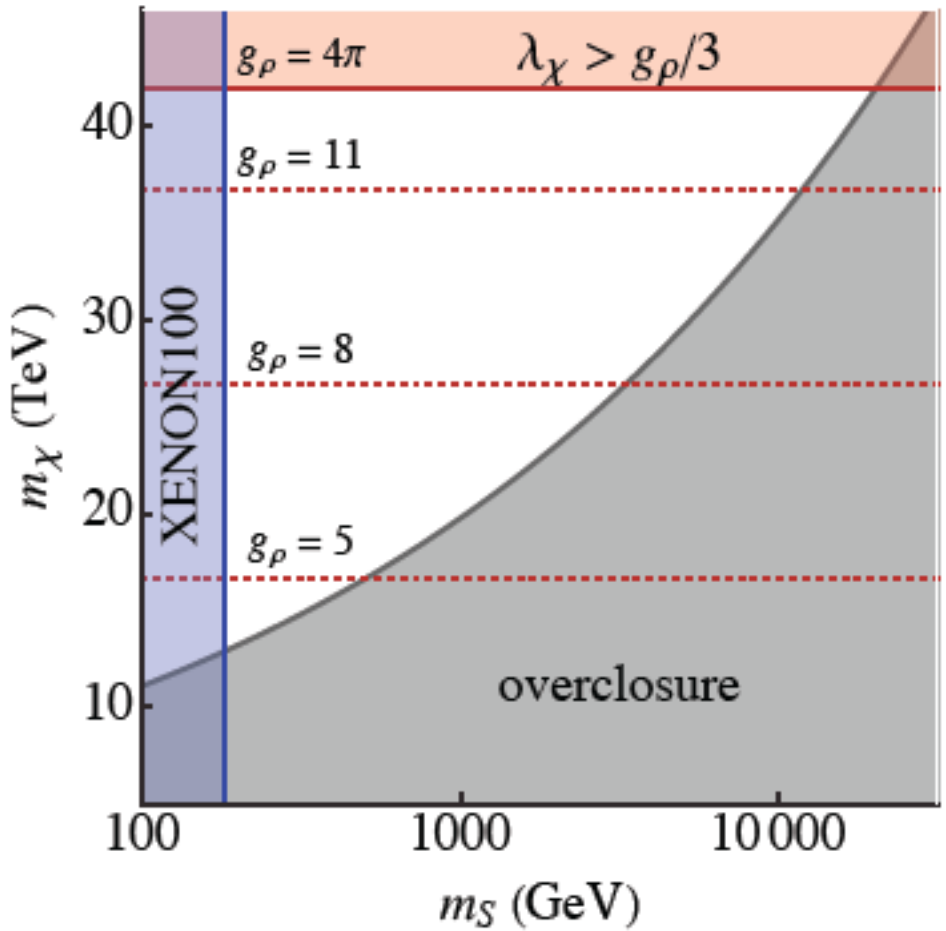


Low-energy spectrum: Standard Model + S + T + χ

What are experimental signals?

Dark matter 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

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

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

Phenomenology @100 TeV collider -- [in progress]

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

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

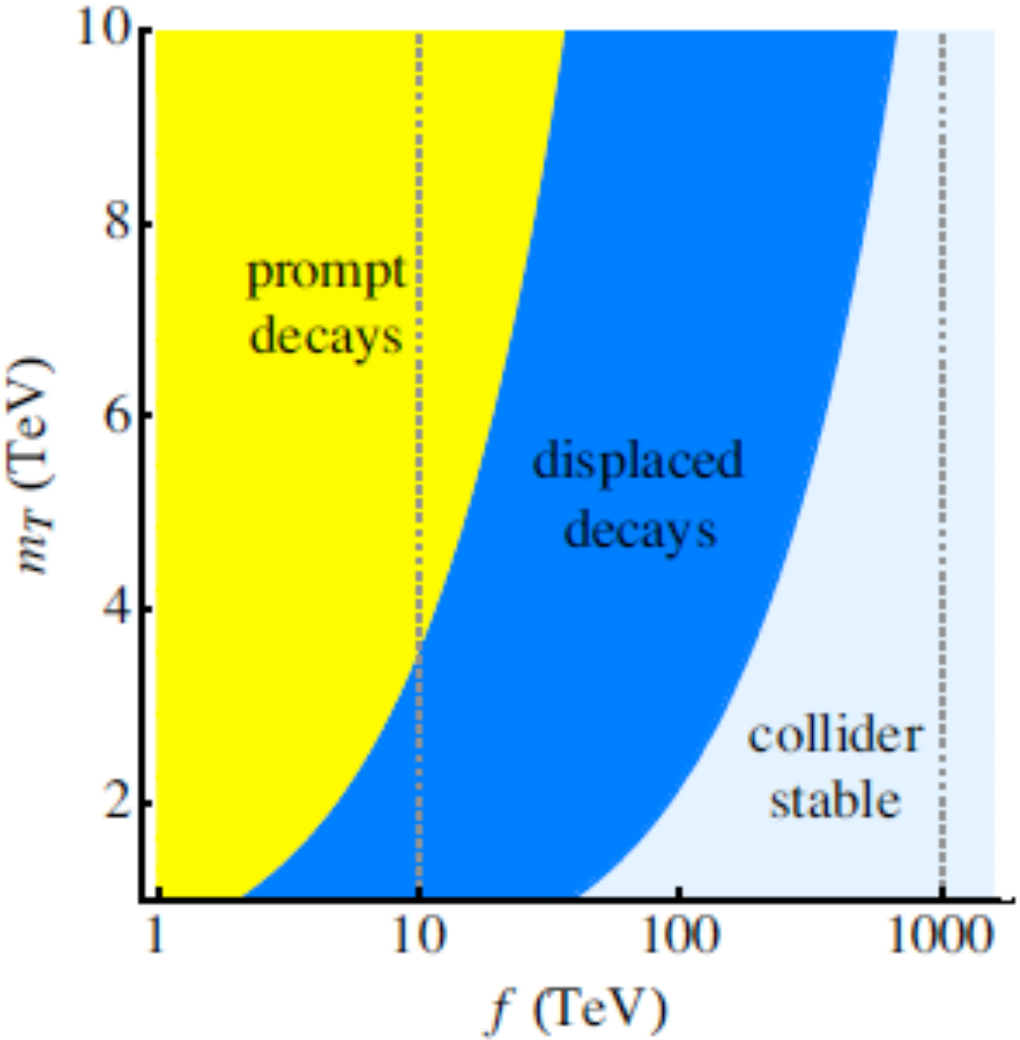
Prompt: $m_T \gtrsim 1300\,\text{GeV}$ e.g. gluino limits

Long-lived: $m_T \gtrsim 800\,\text{GeV} - 1\,\text{TeV}$ e.g. R-hadron searches

Collider analysis -- [in progress]

Higgs color triplet decay

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



Summary

- Natural SUSY/Composite Higgs models are increasingly elaborate ("Baroque") and tuned
  - --- Composite Higgs: tuning $\lesssim 5\%$
  - --- Natural SUSY: tuning $\lesssim 5\%$
- Nonetheless, a resonance or superpartner could still show up at LHC Run II!
- Unnatural "Split" Composite Higgs
  - --- Look for long-lived Higgs color triplet

STAY TUNED! [pun intended]