The Higgs and Naturalness:

Where do we stand after the LHC Run1?

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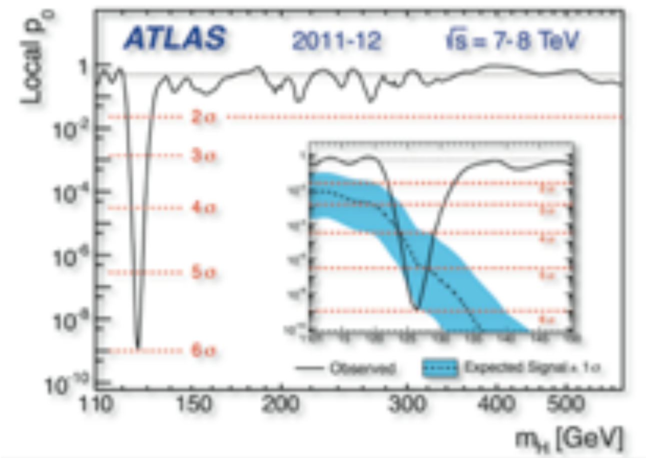
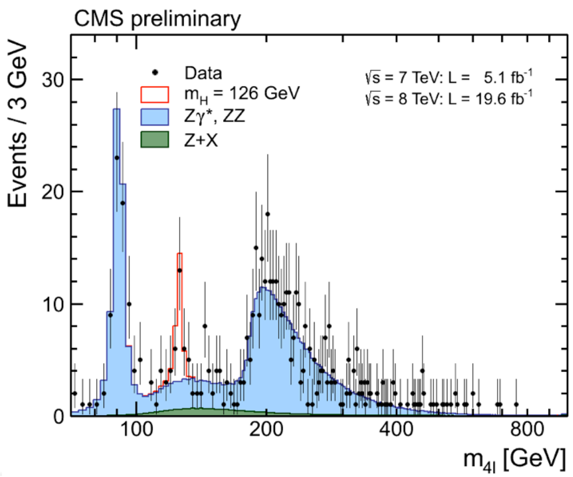
Johns Hopkins Workshop, Heidelberg, Germany, July 22, 2014

Based on recent work with *James Barnard, Ben von Harling, Anibal Medina, Tirtha Sankar Ray, Michael Schmidt*

Higgs discovery - Run I





Higgs Bosons — H^0 and $H^\pm$

PDG 2013

H^0 Mass $m = 125.9 \pm 0.4$ GeV

H^0 signal strengths in different channels [n]

Combined Final States $= 1.07 \pm 0.26$ (S = 1.4)

$W W^*$ Final State $= 0.88 \pm 0.33$ (S = 1.1)

$Z Z^*$ Final State $= 0.89^{+0.30}_{-0.25}$

$\gamma\gamma$ Final State $= 1.65 \pm 0.33$

$b\bar{b}$ Final State $= 0.5^{+0.8}_{-0.7}$

$\tau^+\tau^-$ Final State $= 0.1 \pm 0.7$

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

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

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

Standard Model and nothing else...?

"In this field, almost everything is already discovered, and all that remains is to fill a few unimportant holes."

[Max Planck's PhD adviser, Philipp von Jolly, 1878]

A few "holes" in the 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?

NATURAL explanations of ~126 GeV Higgs

HIGGS BOSON {

- Composite ⇨ New strong dynamics (e.g. extra dimensions)

OR

- Elementary ⇨ Supersymmetry

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

1. Composite Higgs

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

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

- 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]

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

Higgs potential

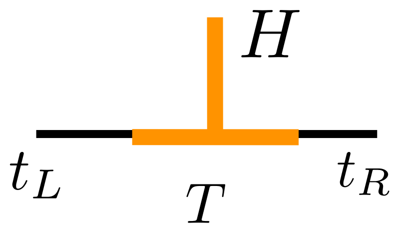
$V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$ where $\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2$ $\lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$

EWSB $\left(\langle H \rangle = \frac{v}{\sqrt{2}}\right)$ $v^2 = \frac{\mu_h^2}{\lambda_h}$ ⇨ **Tuning:** $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 10\%$

$(v = 246 \text{ GeV}, f \gtrsim 750 \text{ GeV})$

[See also Panico, Redi, Tesi, Wulzer 1210.7114]

Higgs mass: $m_h^2 \simeq \frac{N_c}{\pi^2} m_t^2 \frac{m_T^2}{f^2}$ $= g_T^2$



$m_T =$ fermion resonances (EM charges $5/3, 2/3, -1/3$)

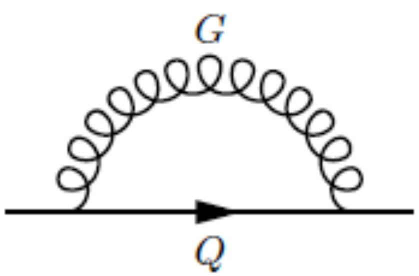
$m_h \sim 126\,\text{GeV}$ ➡ $m_T < m_\rho$ *light* fermion resonances

[Matsedonskyi, Panico, Wulzer `12]

[Marzocca, Serone, Shu `12; Pomarol, Riva `12]

e.g. LHC limit: $m_{T_{5/3}} \gtrsim 770\ \text{GeV}$

But, there are also gluon partners



gluon partner coupling

$$i\Sigma(p) = \frac{16\pi}{3}\alpha_G \int \frac{d^4k}{(2\pi)^4}\gamma^\mu \frac{1}{\not{k} - m_Q}\gamma^\nu \frac{\eta_{\mu\nu}}{(k-p)^2 - m_G^2}$$

gluon partner mass

where $\alpha_G \simeq \frac{g_3^2}{4\pi} \ln\left(\frac{\Lambda_{UV}}{\Lambda_{IR}}\right) \approx 3$

Contribution to Higgs mass:

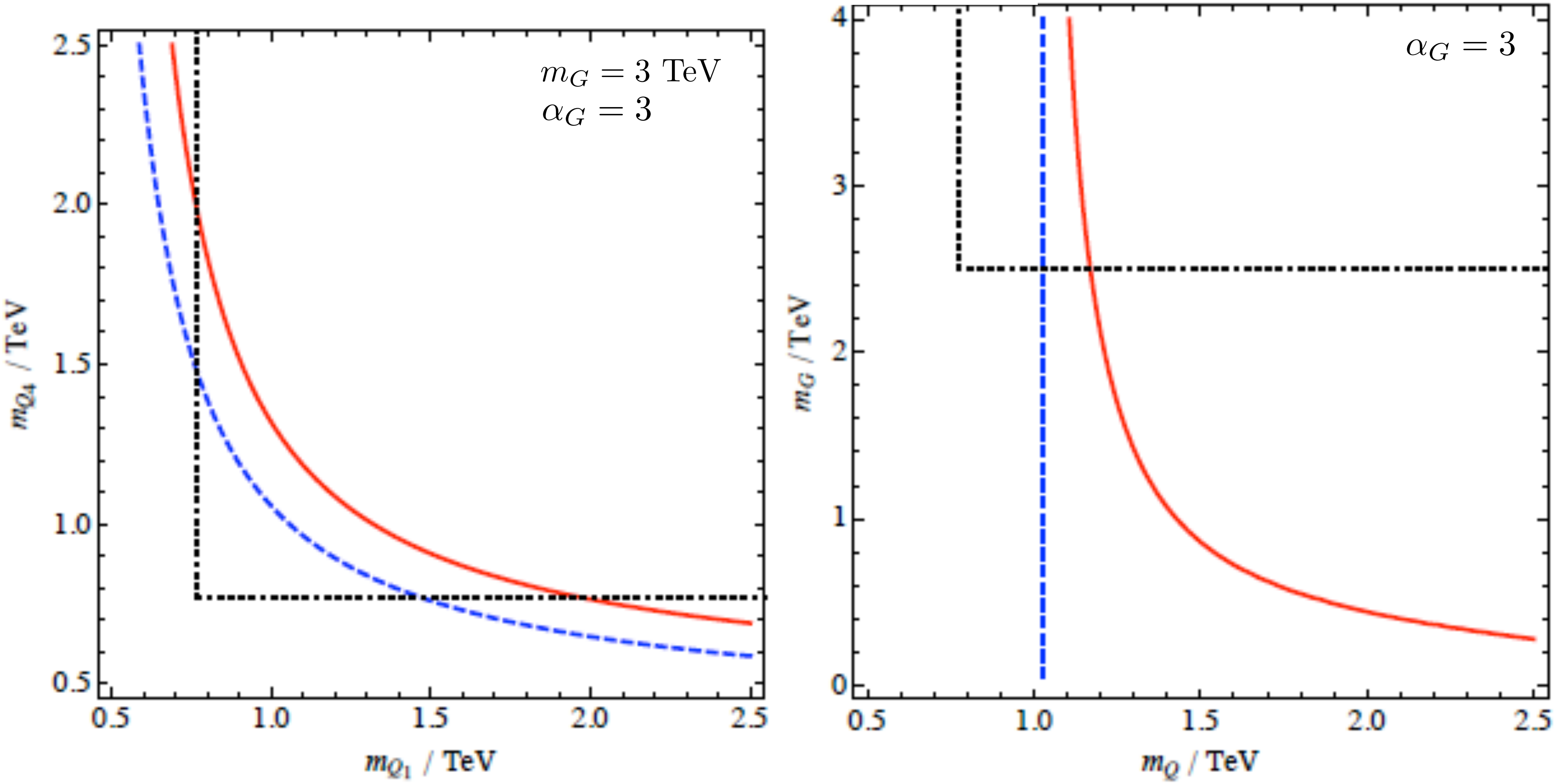
$$m_h^2 \approx \frac{8N_c v^2}{f^4}\int \frac{d^4 p_E}{(2\pi)^4}\left[\frac{1}{p_E^2}\left|M(p_E^2)\right|^2 + \frac{1}{4}\Pi_L^h(p_E^2)^2 + \Pi_R^h(p_E^2)^2\right]$$

$M, \Pi^h_{L,R}$ = 2-point functions

➡ *Gluon partner correction to Higgs mass is negative*

Contours of $m_h = 126$ GeV

[Barnard, TG, Medina, Sankar Ray 1307.4778]



For $\alpha_G = 3$ and $m_G = 3$ TeV obtain $\approx 10\%$ correction

➡ Eases tension of having light top partners!

UV description of Composite Higgs models

1. Where does global symmetry and spontaneous breaking come from?

2. How do you get a partially composite top?

Possible approach

- AdS/CFT -- D-brane engineering
- Supersymmetric (e.g. Seiberg duality)

} Involves scalars

[Caracciolo, Parolini, Serone 1211.7290]

Look for description *without* elementary scalars...

UV description of SO(6)/SO(5) model

[Barnard, TG, Sankar Ray 1311.6562]

$$SO(6)/SO(5) \sim SU(4)/Sp(4) = \underbrace{\mathbf{2}}_{\text{Higgs doublet}} \text{ of } SU(2)_L + \mathbf{1} \text{ singlet}$$

[See also Ferretti, Karateev 1312.5330]
[Ferretti 1404.7137]

Introduce new strong gauge group $Sp(2N_c)$
with 4 Weyl fermion flavors $\psi^a \quad (a = 1, \ldots, 4)$ ⇒ $SU(4)$ global symmetry

SU(4) gauged NJL model
$$\mathcal{L}_{\text{int}} = \frac{\kappa_A}{2N_c}(\psi^a\psi^b)(\bar{\psi}_a\bar{\psi}_b) + \frac{\kappa_B}{8N_c}\left[\epsilon_{abcd}(\psi^a\psi^b)(\psi^c\psi^d) + \text{h.c.}\right]$$

For $\xi = \frac{1}{4\pi^2}(\kappa_A + \kappa_B)\Lambda^2 > 1$ $\quad SU(4) \to Sp(4)$ with $\dim \psi\psi \gtrsim 1$

Large anomalous dimension

Top partners $(\psi^a \chi \psi^b)$ or $(\psi^a \tilde{\chi} \psi^b)$

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

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

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

⇒ Allows for order-one top Yukawa coupling

$\xi \gg \underbrace{\sqrt{\alpha}}_{\text{Sp(2Nc) gauge coupling}}$ ⇒ Top partners are naturally lighter than uncolored partners!

2. Elementary Higgs

Supersymmetric Standard Model

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

SUSY

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

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

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

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

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

$\lambda_h \simeq 0.13 \Rightarrow m_{\tilde{t}} \gtrsim 1\ \mathrm{TeV}$ $\quad (X_t \sim m_{\tilde{t}})$

$\mu_h^2 \simeq (89\ \mathrm{GeV})^2 \Rightarrow m_{\tilde{t}} \lesssim 400\ \mathrm{GeV}$ $\quad$ ("natural")

Also: $\delta m_{\tilde{t}}^2 = \frac{2g_s^2}{3\pi^2} m_{\tilde{g}}^2 \log \frac{\Lambda_{mess}}{m_{\tilde{g}}} \Rightarrow m_{\tilde{g}} \lesssim 2 m_{\tilde{t}}$

Natural SUSY = $m_{\tilde{t}_{1,2}}, m_{\tilde{b}_L} \lesssim 500 - 700\ \mathrm{GeV}$

(minimal requirement from EWSB)

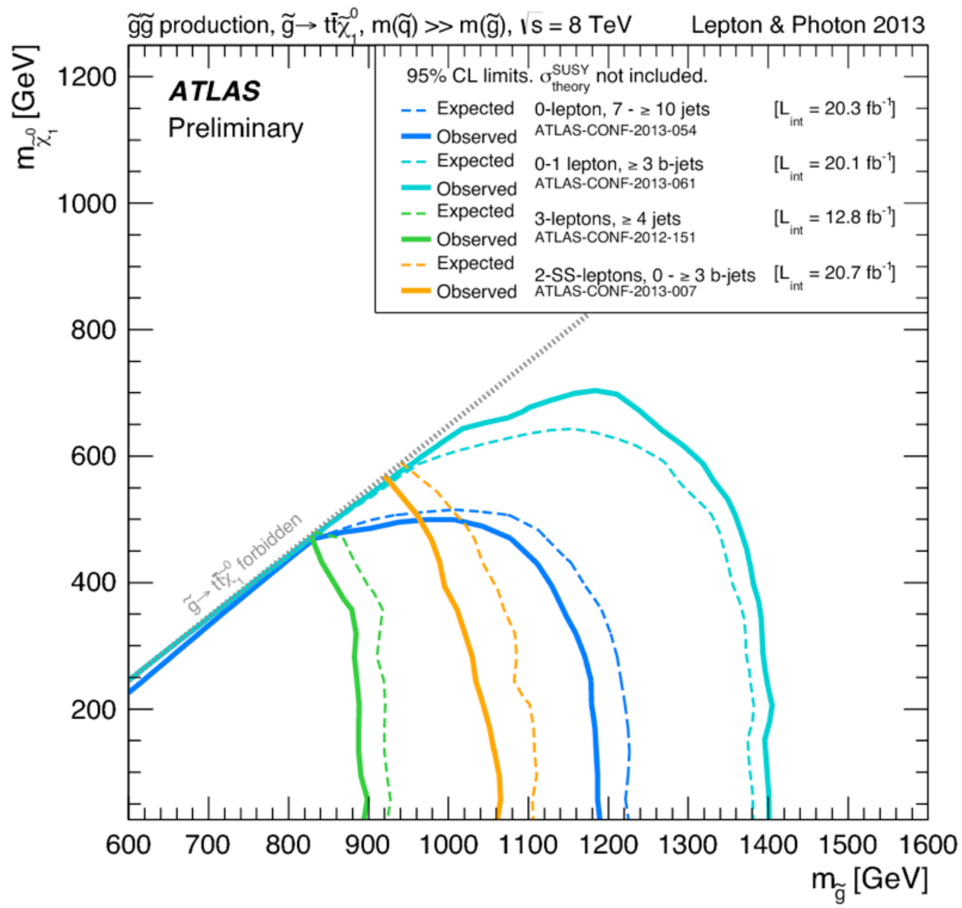
$m_{\tilde{g}} \lesssim 900\ \mathrm{GeV} - 1.5\ \mathrm{TeV}$

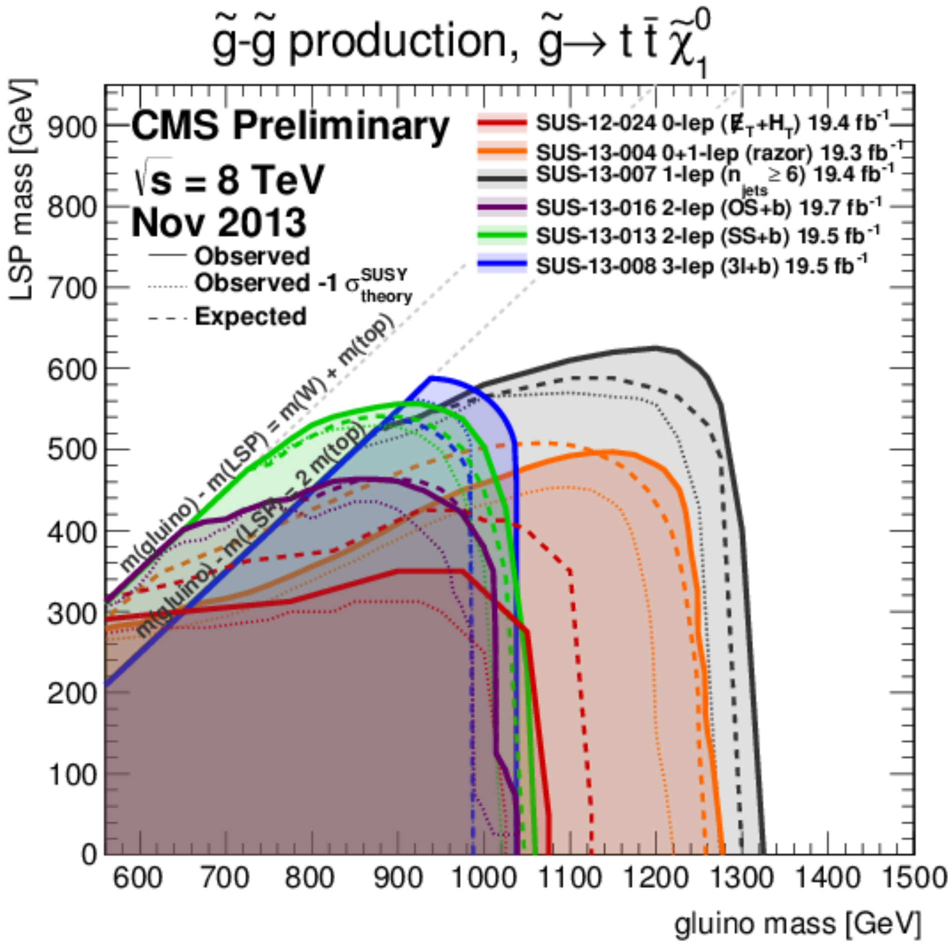
$\mu \lesssim 200 - 350\ \mathrm{GeV}$

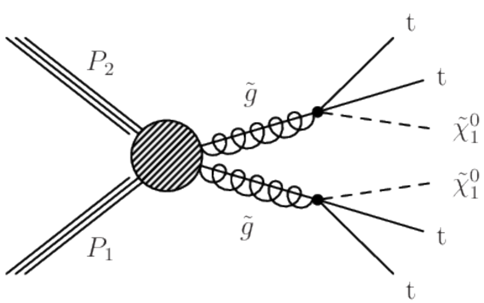
All other superparticles are heavy $\gtrsim 2\ \mathrm{TeV}$

[Kats, Meade, Reece, Shih `11; Brust, Katz, Lawrence, Sundrum `11; Essig, Izaguirre, Kaplan, Wacker `11; Papucci, Ruderman, Weiler `11]

Natural SUSY LHC limits:

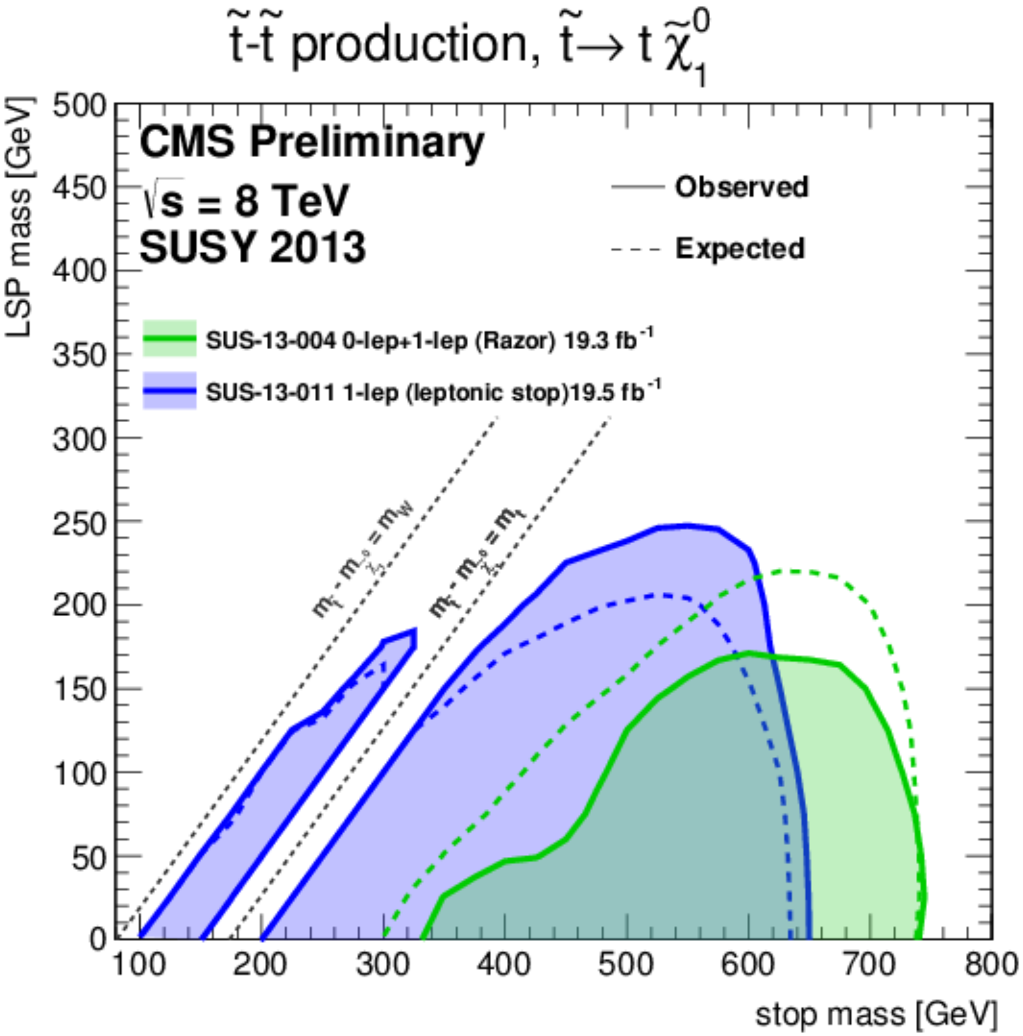


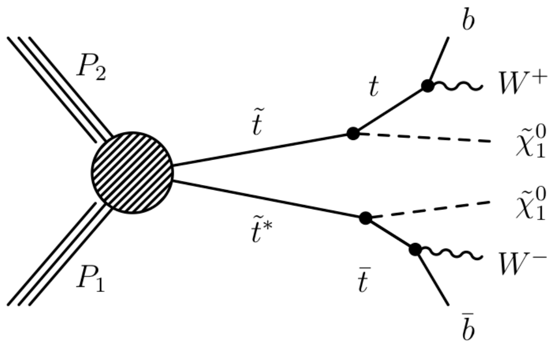




$$m_{\tilde{g}} \gtrsim 1400\ \text{GeV}$$

Direct stop production



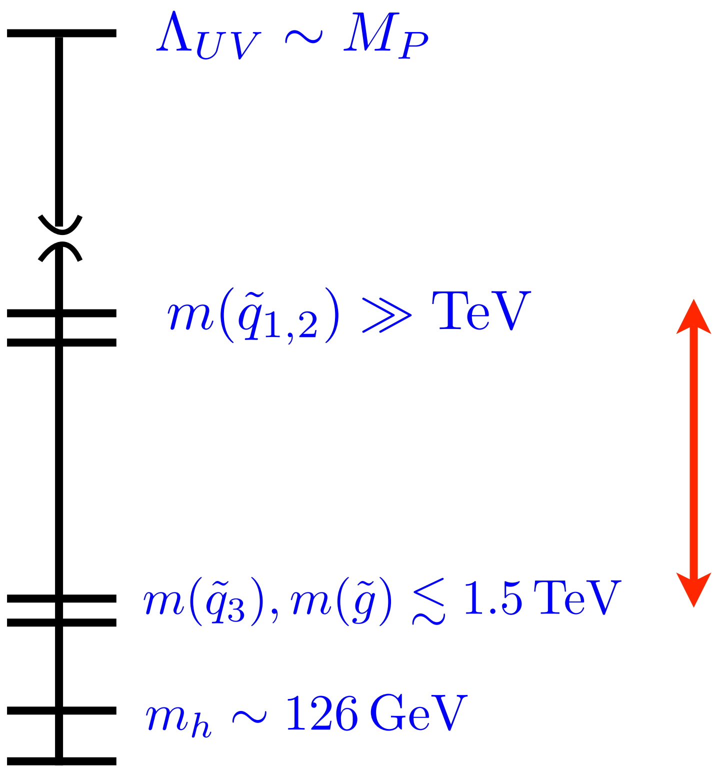


$$m_{\tilde{t}_1} \gtrsim 650 - 740 \text{ GeV}$$

A consistent *natural* SUSY scenario based on Run1:

(i) weakly-coupled Higgs (~126 GeV)

(ii) $m(\tilde{q}_{1,2}) \gg m(\tilde{g}), m(\tilde{q}_3)$ SUSY breaking is ***flavour dependent***!



"Split families"

[Dimopoulos, Guidice 95;
Pomarol, Tommasini 95;
Cohen, Kaplan, Nelson 96]

However, *natural* SUSY requires a ***new*** contribution to Higgs quartic coupling:

$$\lambda_h \to \underbrace{\lambda_h^{(min)}}_{\text{difficult to naturally accommodate } m_h \sim 126\,\mathrm{GeV}} + \delta\lambda_h$$

Possibilities:

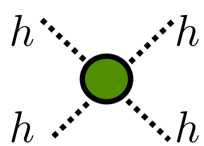
(i) NMSSM $\quad W = \lambda S H_u H_d \quad \Rightarrow \quad \delta\lambda_h \simeq \frac{4\lambda^2}{\tan^2\beta}$

(ii) DMSSM $\quad$ Extra gauge group $\quad \Rightarrow \quad \delta\lambda_h \simeq g^2(1+\Delta)$

$\Delta \sim \mathcal{O}(1)$

(iii) Strong dynamics $\quad \Delta\mathcal{L} = \xi H \mathcal{O}$

[TG, Pomarol 1107.4697]



$\Rightarrow \quad \delta\lambda_h \simeq \epsilon^4 \frac{16\pi^2}{N}$

How natural is "*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

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

$$V = (m_{H_d}^2 + \lambda^2 S^2)|H_d|^2 + (m_{H_u}^2 + \lambda^2 S^2)|H_u|^2 + \lambda^2 |H_d H_u|^2 + m_S^2 |S|^2 + \kappa^2 |S|^4 + [(a_\lambda S + \lambda\kappa S^2) H_u H_d + \frac{a_\kappa}{3} S^3 + h.c.] + V_D$$

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

Naturalness constraints

[Agashe, Cui, Franceschini 1209.2115]
[TG, von Harling, Medina, Schmidt 1212.5243]

(i) Electroweak VEV tuning

$$\lambda^2 v^2 = 2\frac{(a_\lambda v_S + \lambda\kappa v_S^2)}{\sin 2\beta} - \widehat{m}_{H_u}^2 - \widehat{m}_{H_d}^2 - 2\lambda^2 v_S^2$$

where $\hat{m}^2_{H_{u,d}} \equiv m^2_{H_{u,d}} + \frac{d}{dv^2_{u,d}} V_1$

➡ Large λ helps

(ii) Higgs mass tuning $m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta m^2_{h,mix}$

$$\delta m^2_{h,\text{mix}} \simeq -\lambda^2 v^2 \frac{\left(\frac{\lambda}{\kappa} - \sin 2\beta \left[1 + \frac{a_\lambda}{2\lambda\kappa v_S}\right]\right)^2}{1 + \frac{a_\kappa}{4\kappa^2 v_S} + \frac{a_\lambda \sin 2\beta\, v^2}{8\kappa^2 v_S^3}}$$

➡ Large λ hurts

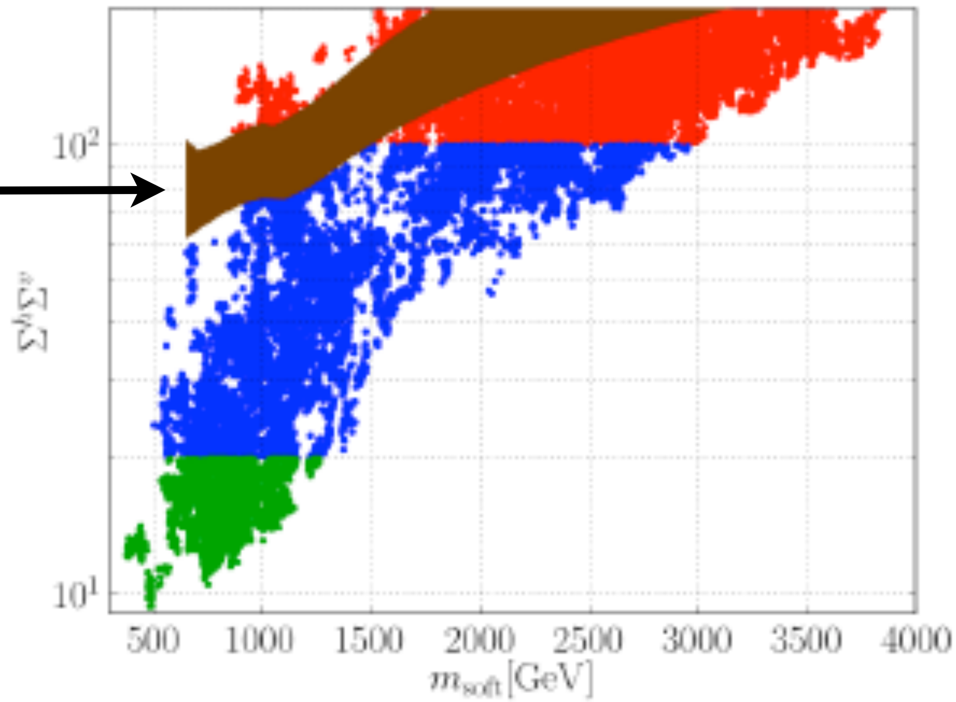
Result: Optimal value $\lambda \sim 1$

Combined tuning $\Sigma^v \Sigma^h$

where $\Sigma^v \equiv \max_i \left| \frac{d \log v^2}{d \log \xi_i(\Lambda_{\rm mess})} \right|$ $\qquad$ $\Sigma^h \equiv \max_{\xi_i} \left| \frac{d \log m_h^2}{d \log \xi_i} \right|$

[TG, von Harling, Medina, Schmidt 1212.5243]

MSSM

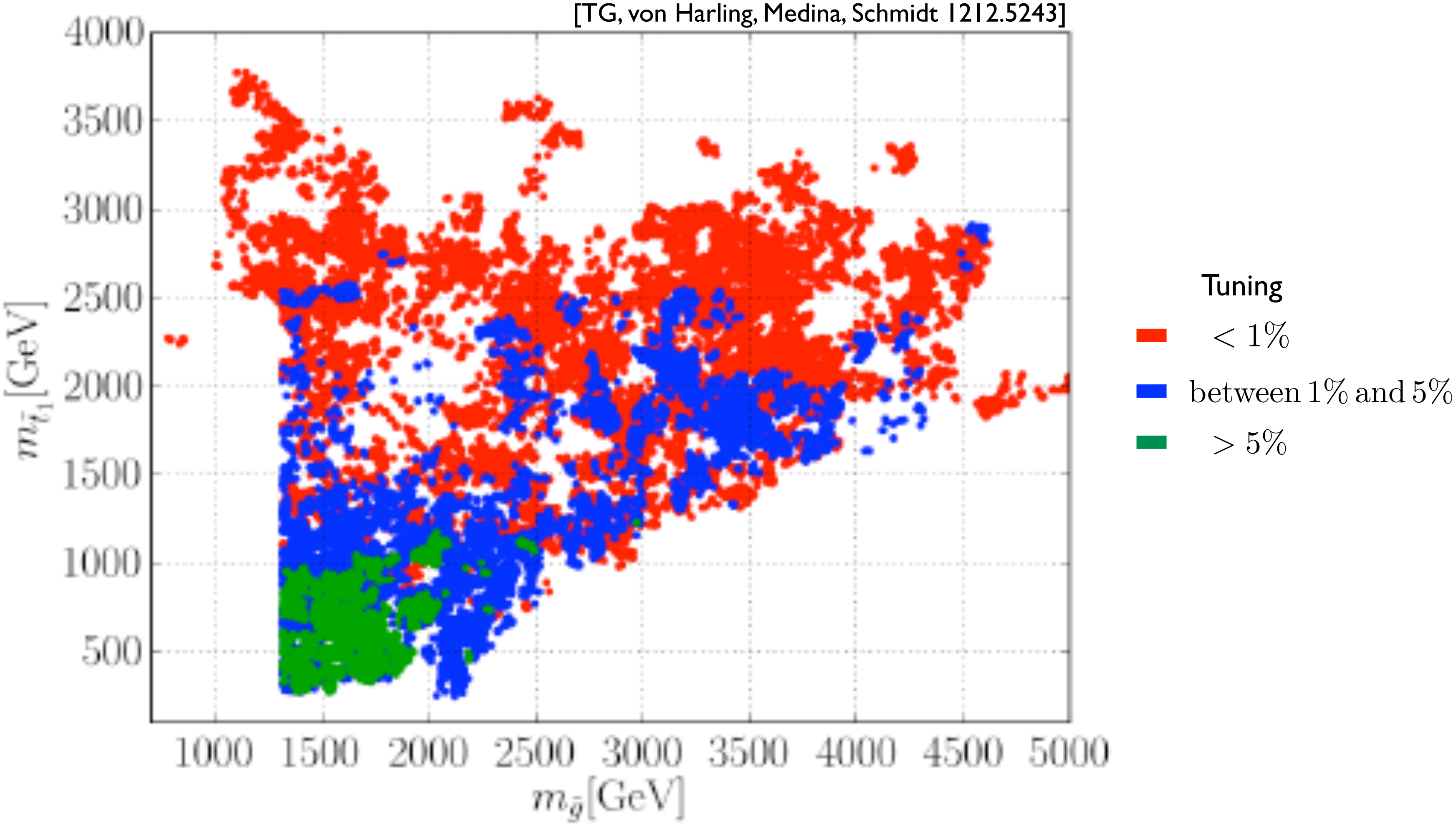


LHC Run I

➪ *natural* SUSY $(\sim 20\%)$ has become $< 10\%$ tuning

Gluino-stop masses

[TG, von Harling, Medina, Schmidt 1212.5243]



For tuning $\sim 5-10\%$

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

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

⇨ Tuning is probably worse!

Important question:

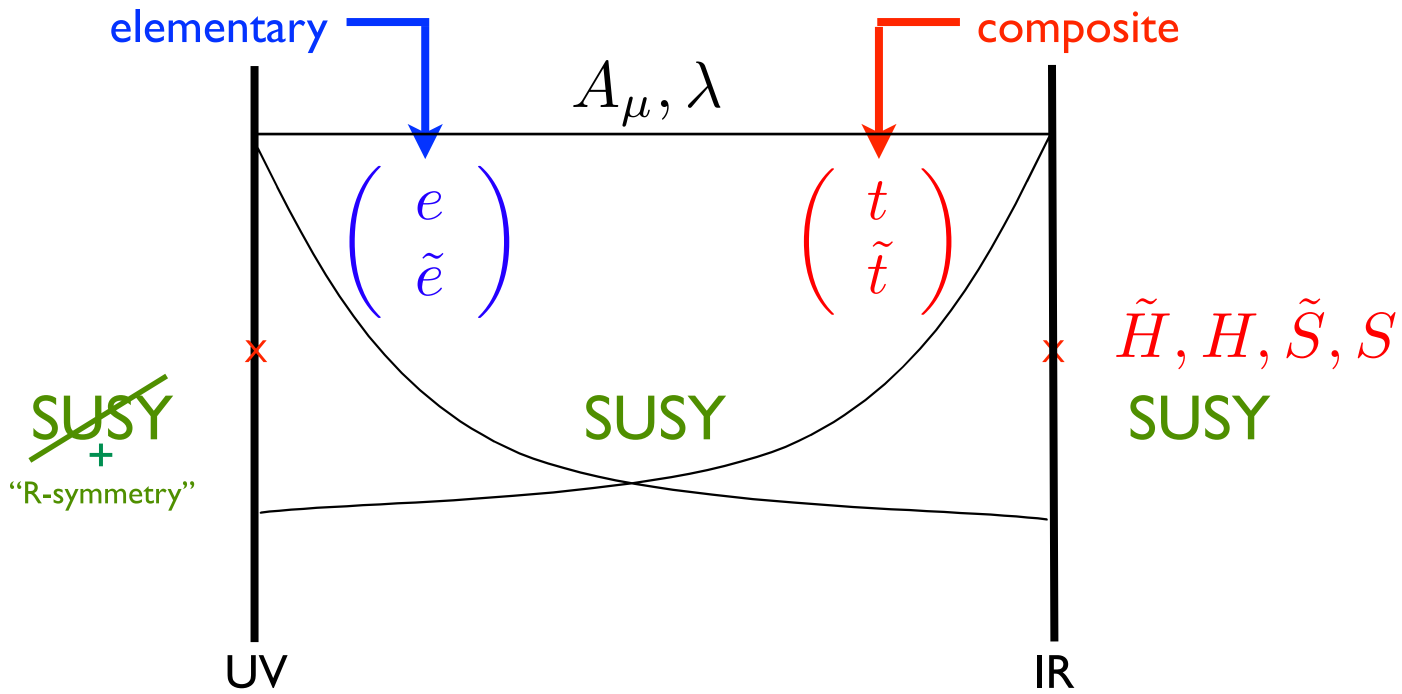
What about explicit supersymmetry breaking models?

- Low messenger scale
- Split family spectrum
- Dark matter
- Gauge coupling unification

A 5D model: "Accidental SUSY"

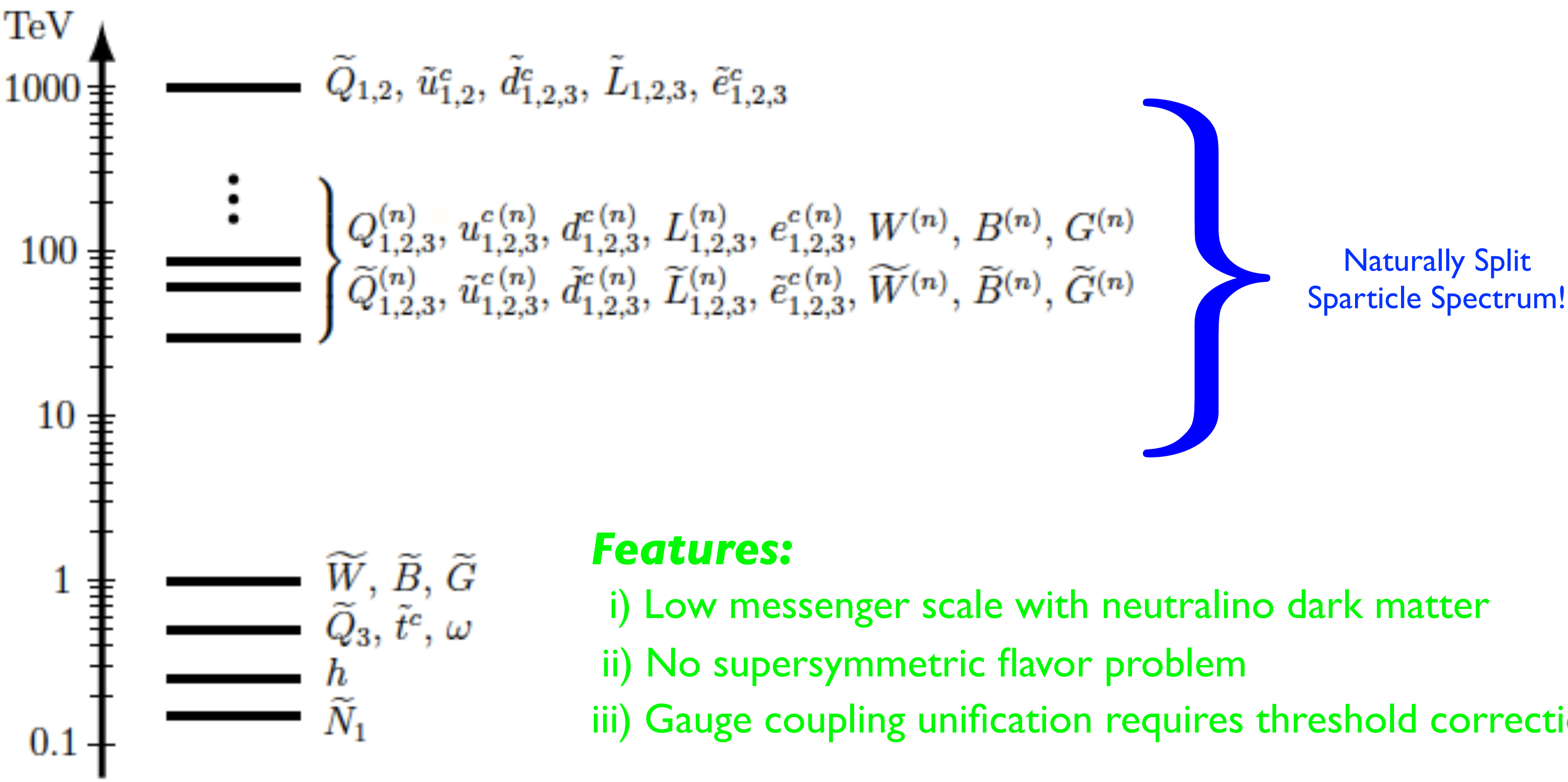
[TG, Pomarol `03; Sundrum `09]
[TG, von Harling, Setzer arXiv:1104.3171]

SUSY broken at UV scale!



Fermion mass spectrum determines ***sfermion*** spectrum!

Particle spectrum:



Features:

i) Low messenger scale with neutralino dark matter

ii) No supersymmetric flavor problem

iii) Gauge coupling unification requires threshold corrections

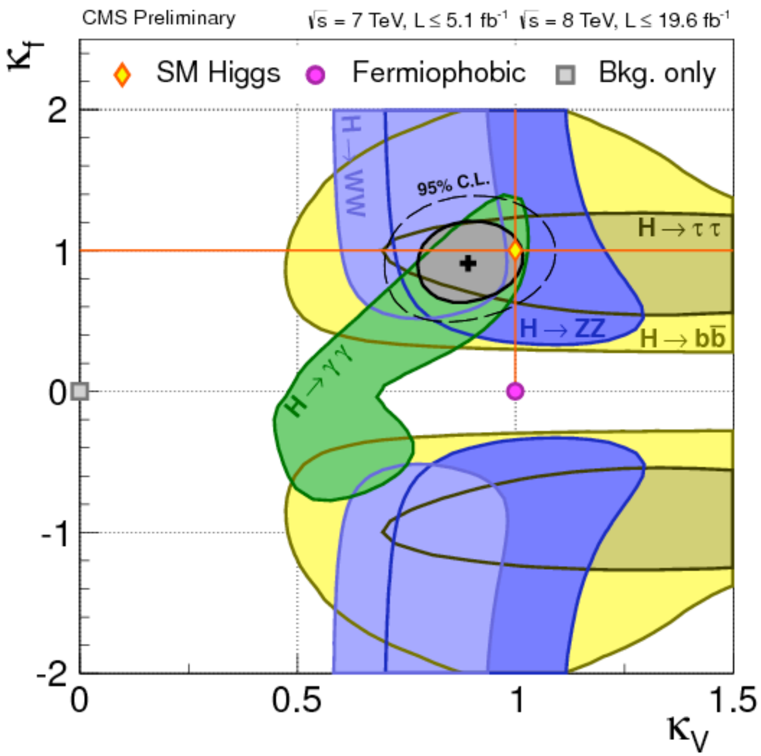
Other possibilities: Dirac gauginos, RPV, Susy Twin Higgs,....

Natural SUSY model building worth exploring!

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

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

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

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

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

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

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

Tuning:

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

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

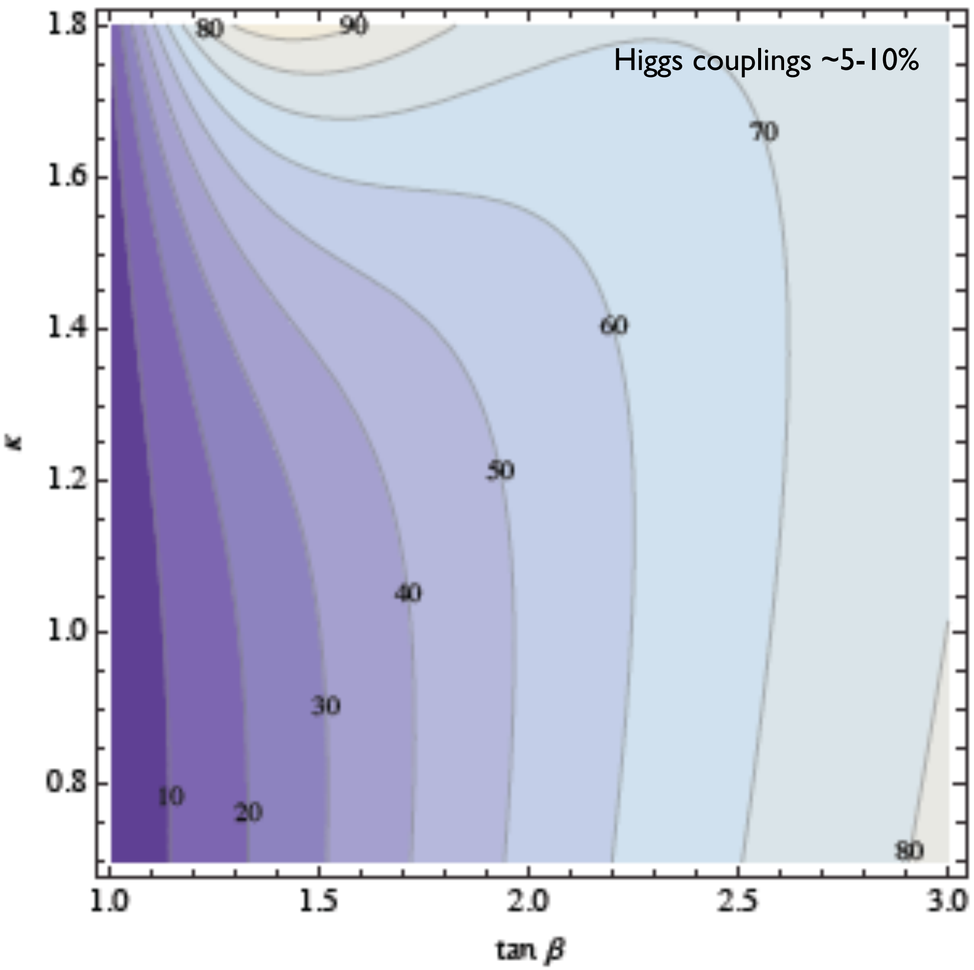
Fine-tuning grows as $r_{u,d,V} \to 1$

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

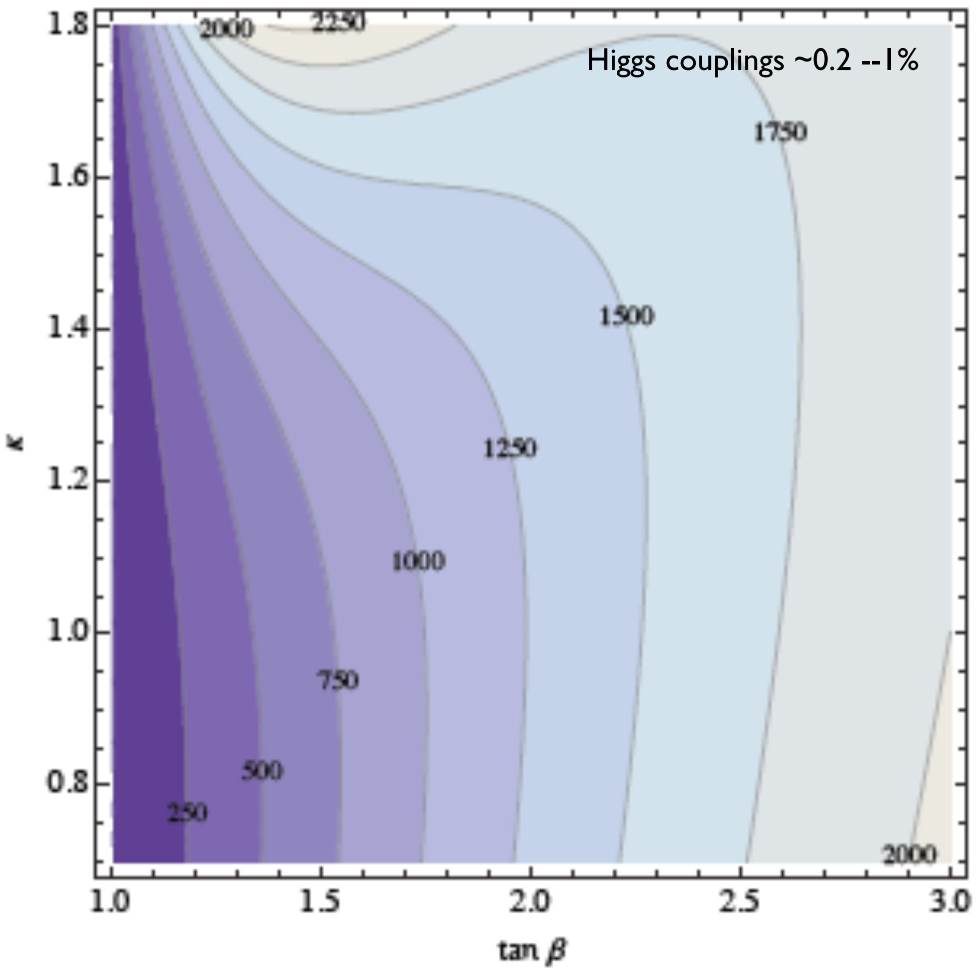
Contours of fine tuning measure Σ

[TG, von Harling, Medina, Schmidt 1401.8291]

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



$\text{ILC 1TeV} \;\; 2500\ \text{fb}^{-1}$



Conclusion

- Naturalness not yet ruled out
  - --- Composite Higgs: tuning $\lesssim 10\%$
  - --- Natural SUSY: tuning $\lesssim 5\%$
- SO(6)/SO(5) composite Higgs model has a simple UV description
- Natural SUSY models require some elaborate structure
- A resonance or superpartner could still show up at Run II! If not, SM-like Higgs couplings will further test naturalness at ILC