What's next after the HIGGS BOSON discovery?

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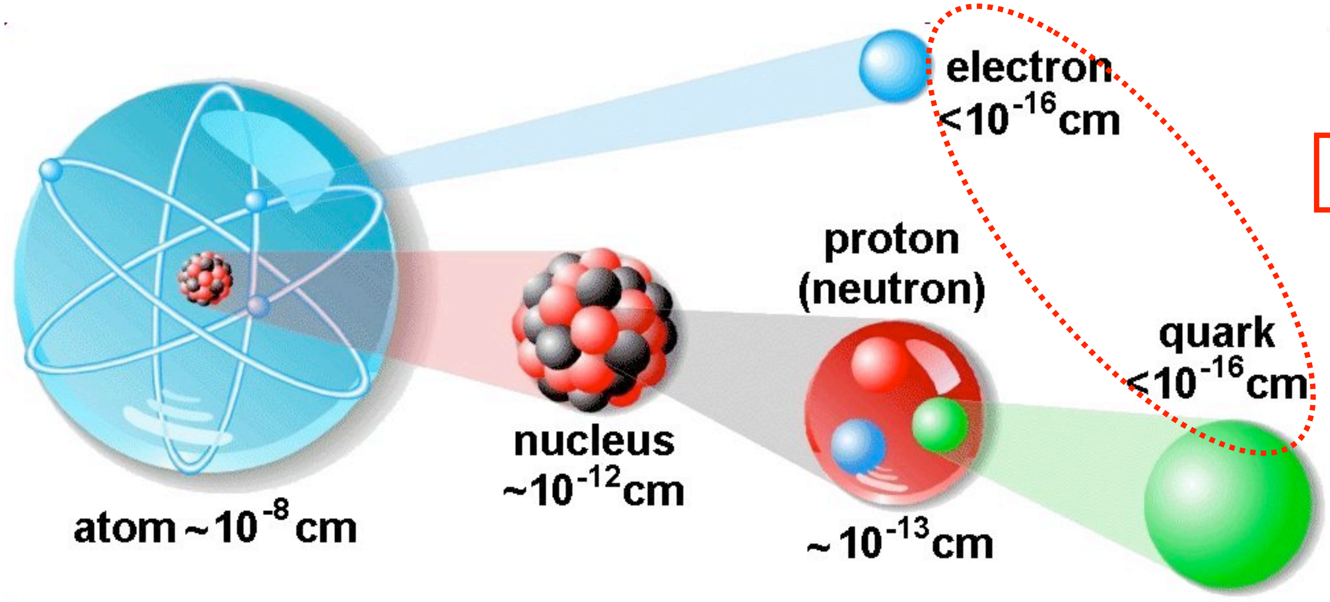
Particle Physics

What is the world made of? What holds it together?

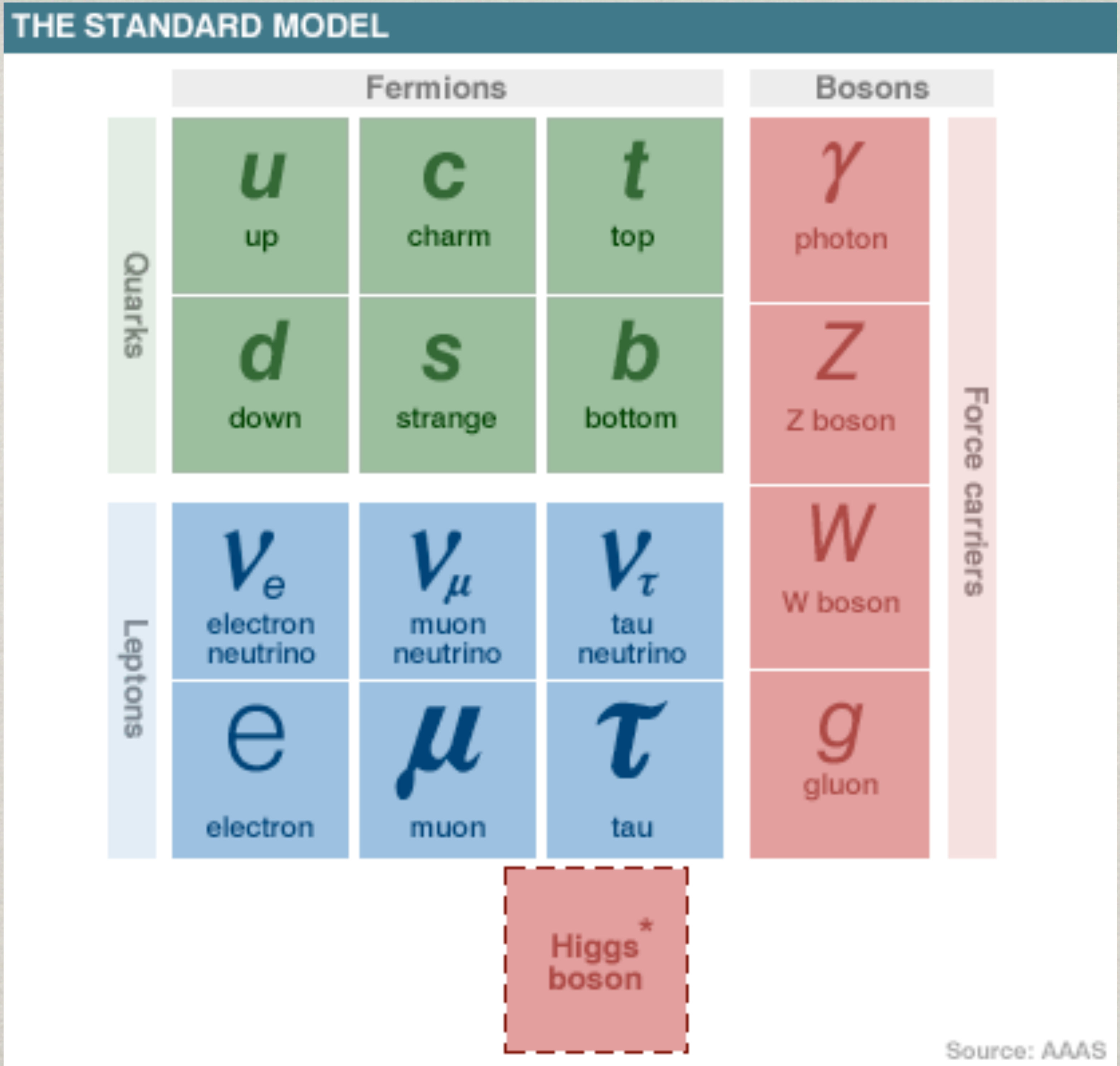


Standard Model

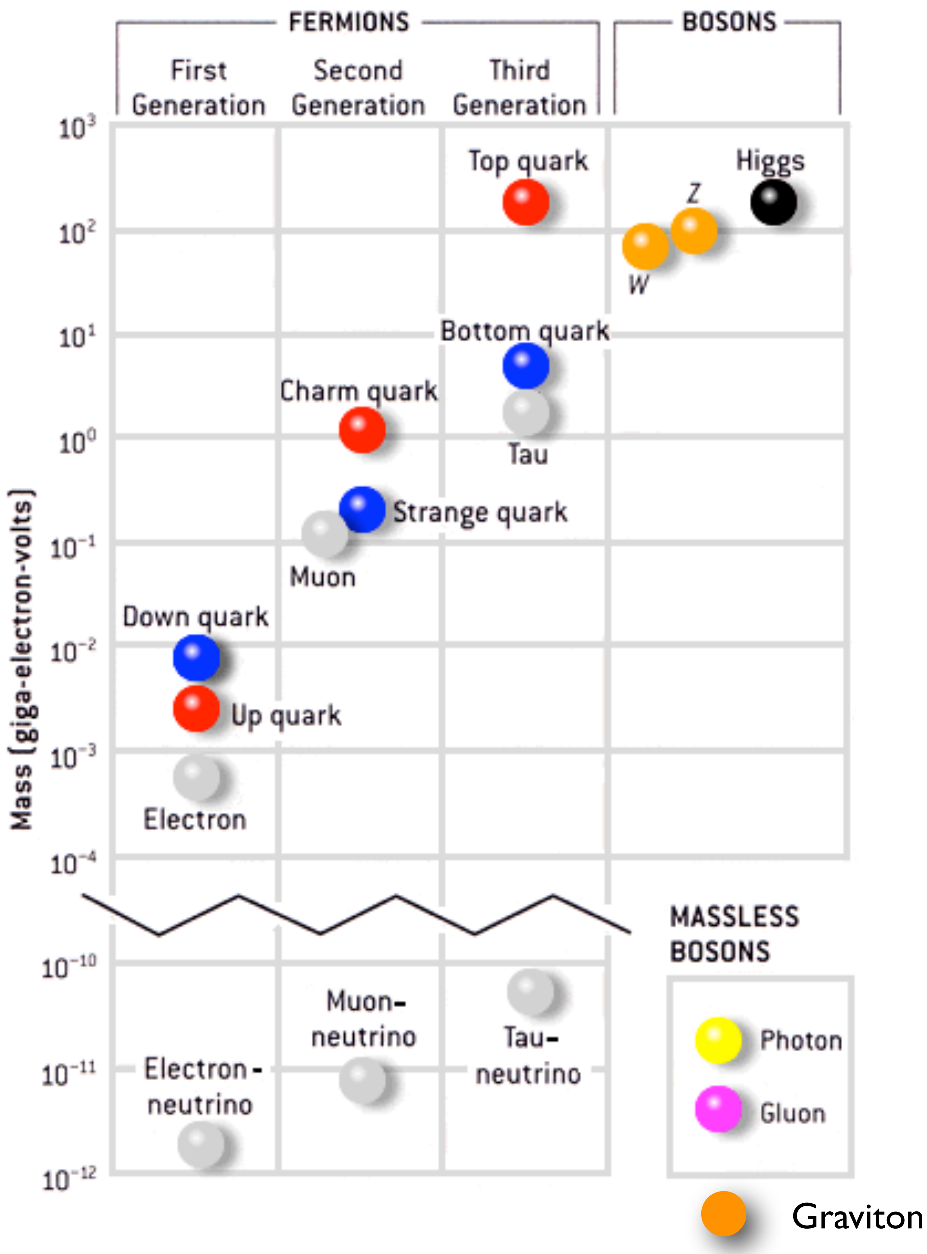
$100\,\mathrm{GeV} \leftrightarrow 10^{-16}\,\mathrm{cm}$

"nano – nano scale"

Energy Frontier: $1\mathrm{TeV} = 1000\,\mathrm{GeV}$

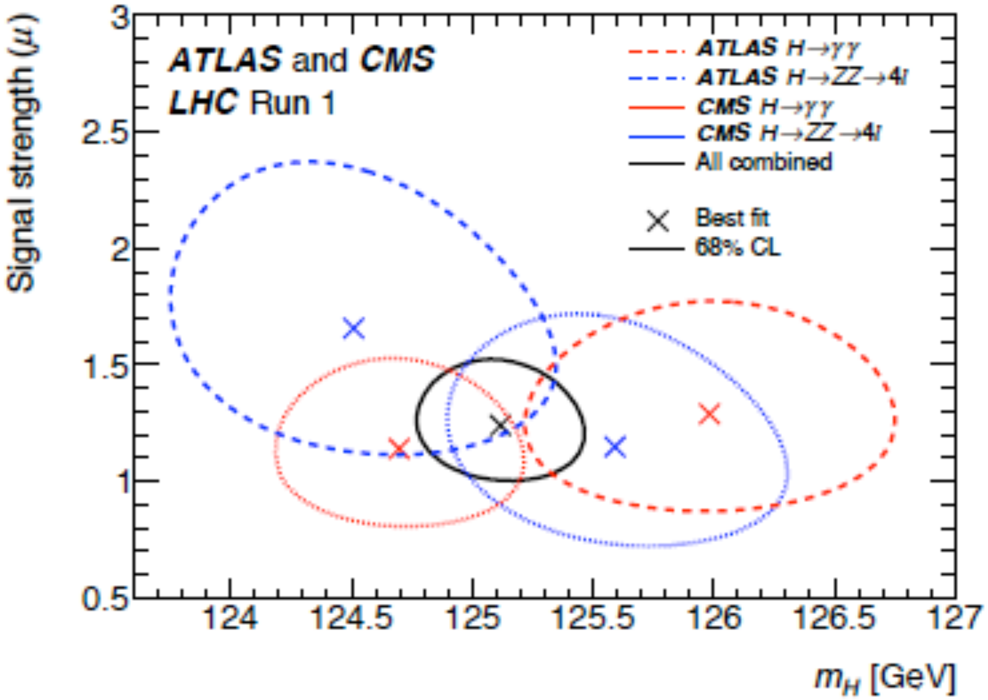

THE STANDARD MODEL
Fermions
Bosons
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
Z
Z boson
W
W boson
g
gluon
Force carriers
Higgs* boson
Source: AAAS

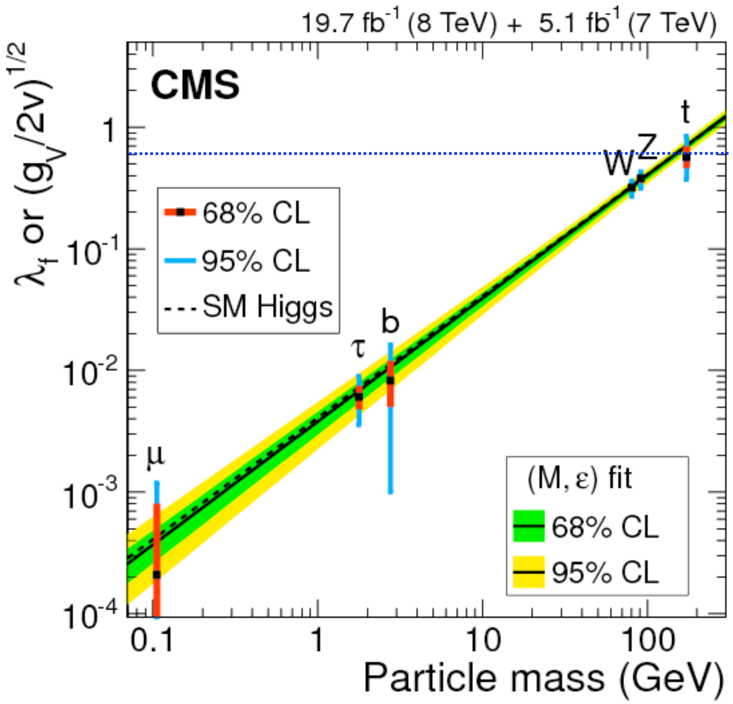
Mass spectrum of elementary particles



Higgs discovery - LHC Run I

"I think we have it" Rolf-Dieter Heuer, CERN Director General, July 4, 2012



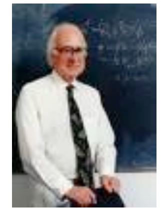


Higgs mass
(ATLAS + CMS)

$$m_h = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}$$

Higgs couplings ⇨ as expected in Standard Model!

The importance of the Standard Model Higgs

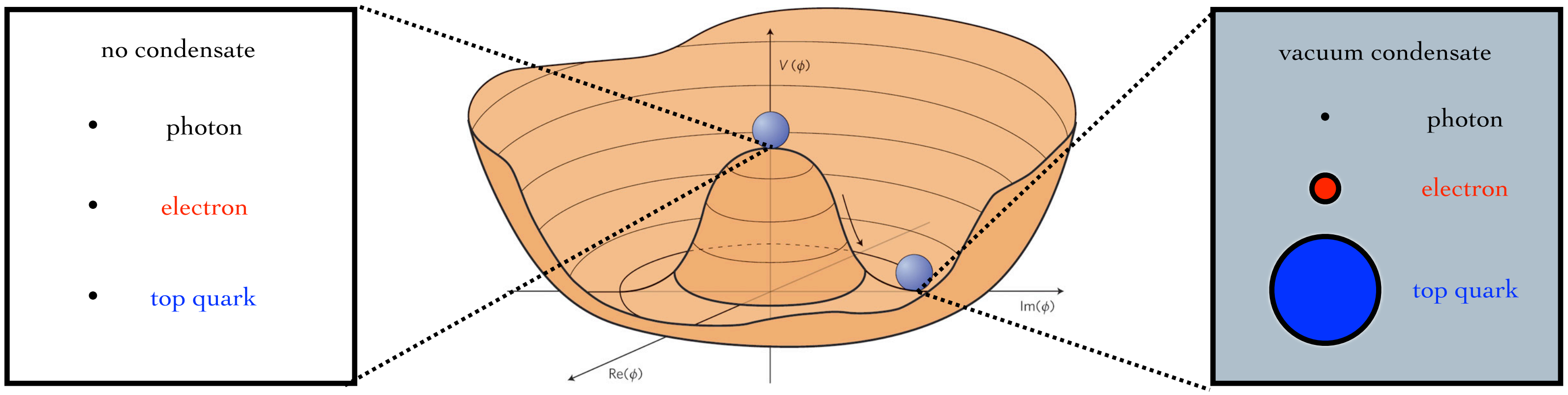


[Englert, Brout 1964; Higgs 1964; Guralnik, Hagen, Kibble 1964]

1. Generates elementary particle mass

electron mass: 0.5 MeV ⇒ Bohr radius $a_0 = \dfrac{\hbar}{m_e c\, \alpha} \approx 0.53\,\text{Å}$ — existence of atoms

quark masses : $m_{down} > m_{up}$ ⇒ $m_{neutron} > m_{proton}$ — stable proton

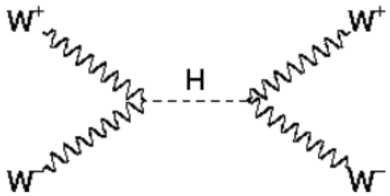


Higgs potential: $$V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4 \qquad \langle H \rangle = \frac{1}{\sqrt{2}}(v+h)$$

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

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

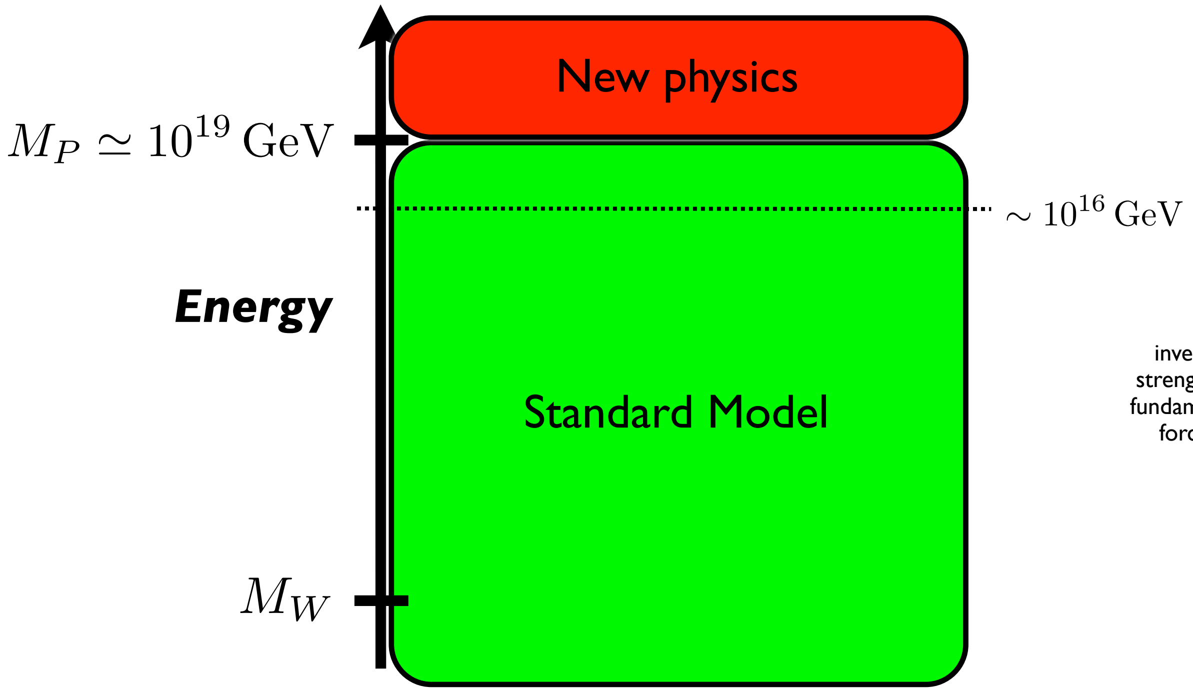
2. Restores perturbative unitarity

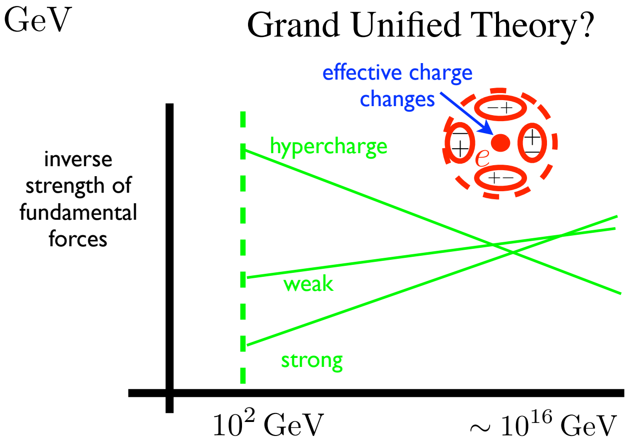


WW-scattering: $\mathcal{A}(E) \overset{E\to\infty}{\sim} \text{constant}$

Unitarity is restored (perturbatively)!

Standard Model is valid up to the Planck scale!





However, the Standard Model is ***not*** a complete description of Nature?

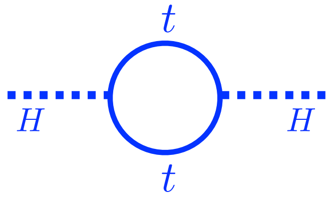
Questions:

- 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 should any be near the electroweak scale?

Quantum corrections to Higgs mass:

e.g. top quark



$$\mu_h^2 = a_0 \Lambda^2 - \frac{3y_t^2}{16\pi^2}\Lambda^2$$

Quadratic sensitivity to Λ !!

where Λ = proxy for massive particle scale in (finite) UV completion

Assuming $\Lambda \simeq 10^{16}\,\mathrm{GeV}$ then $\mu_h^2 \gg (100\,\mathrm{GeV})^2$!!

Unless: $\mu_h^2 \simeq (100\,\mathrm{GeV})^2 \sim (10^{16}\,\mathrm{GeV})^2 - (10^{16}\,\mathrm{GeV})^2$

Requires tuning to 1 part in 10^{28}!!

Why is $\mu_h \ll \Lambda \sim 10^{16}\,\mathrm{GeV}$?

HIERARCHY PROBLEM

NATURAL explanations of ~125 GeV Higgs

HIGGS BOSON

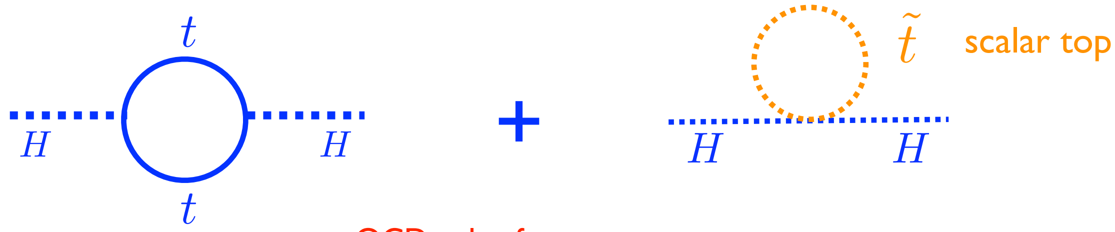
- Elementary ➡ Supersymmetry

OR

- Composite ➡ New strong dynamics (Extra dimensions)

1. Supersymmetry (SUSY)

Cancel quadratic sensitivity with new spacetime symmetry:



QCD color factor

$$\mu_h^2 \simeq m_0^2 - \frac{3y_t^2}{16\pi^2}\Lambda^2 + \frac{3y_t^2}{16\pi^2}\Lambda^2 + \frac{3y_t^2}{16\pi^2} m_{\tilde{t}}^2 \log\frac{\Lambda^2}{m_{\tilde{t}}^2}$$

Thus, $\mu_h \ll \Lambda$ provided $m_{\tilde{t}} \lesssim \mathcal{O}(\mathrm{TeV})$

Superpartners at the TeV scale!

	u	c	t	γ
	d	s	b	Z
H	ν_e	ν_μ	ν_τ	W
	e	μ	τ	g

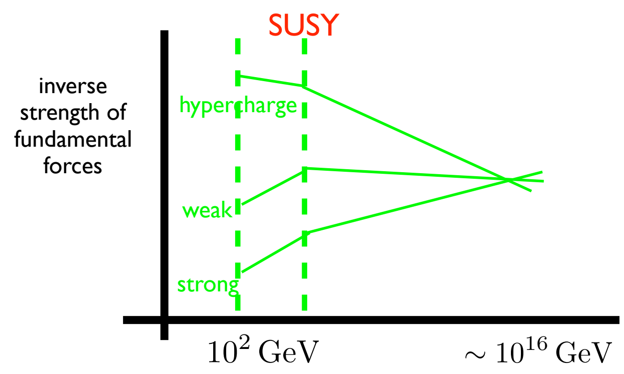
$\tilde{\gamma}$	$\tilde{u}$	$\tilde{c}$	$\tilde{t}$	
$\tilde{Z}$	$\tilde{d}$	$\tilde{s}$	$\tilde{b}$	
$\tilde{W}$	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$	$\tilde{H}$
$\tilde{g}$	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$	

Particle spectrum is doubled!

Bonus features:

- Dark matter from lightest supersymmetric particle (LSP)

- Gauge coupling unification from Higgsinos, gauginos



- No obstacle to UV completion

- Light colored states (gluino, stop) can be produced at LHC

Impact of 125 GeV Higgs:

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

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

[Haber, Hempfling '91] [Ellis, Ridolfi, Zwirner '91]

SUSY

$$\lambda_h = \frac{1}{8}(g^2 + g'^2) + \frac{3y_t^4}{64\pi^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

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

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

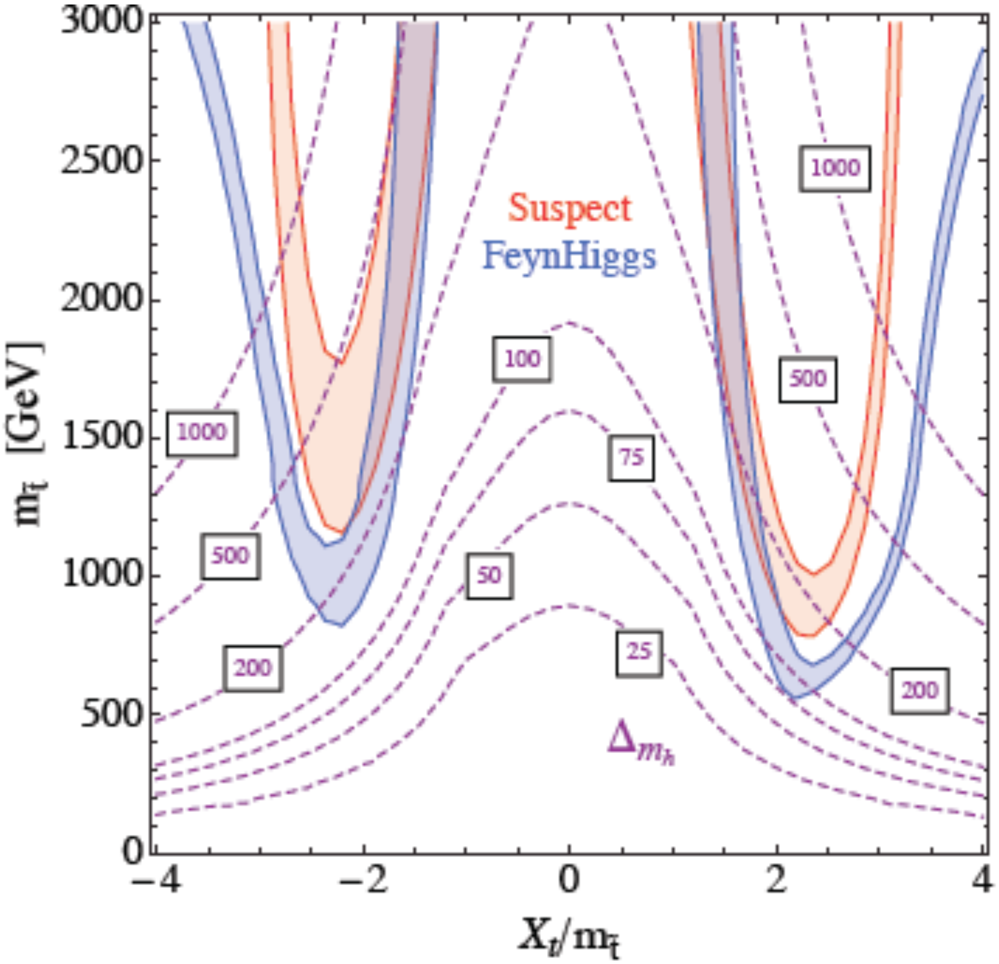
$$-\mu_h^2 \simeq |\mu|^2 - \frac{3y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\frac{\Lambda_{mess}}{m_{\tilde{t}}}$$ $(\tan\beta \gg 1)$

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

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

⚠

[Hall, Pinner, Ruderman '11]

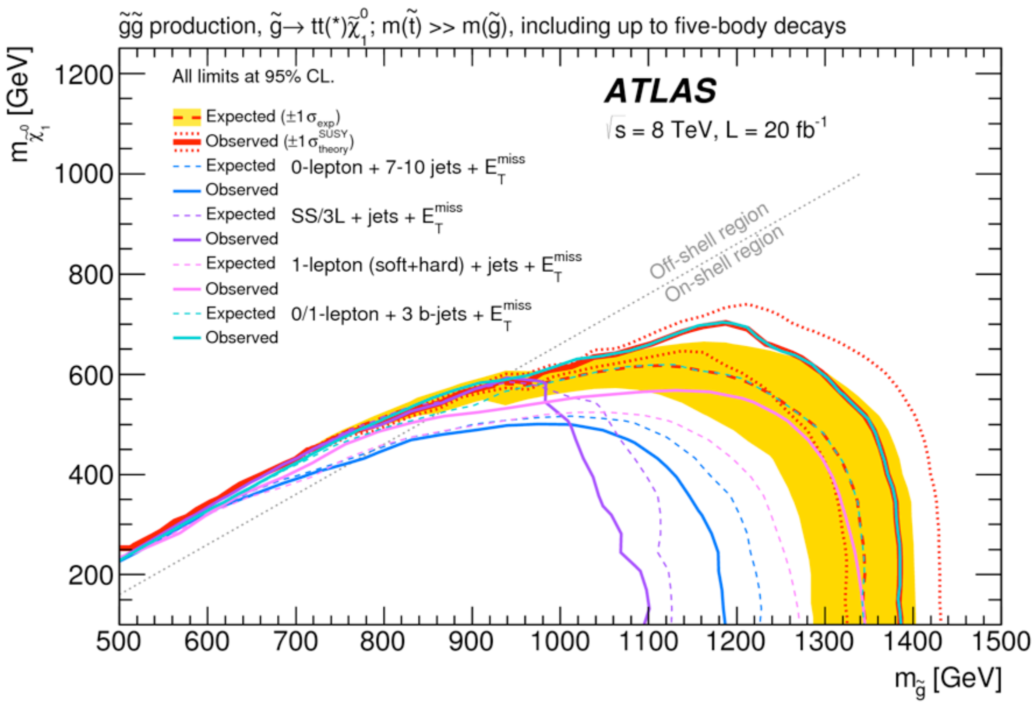


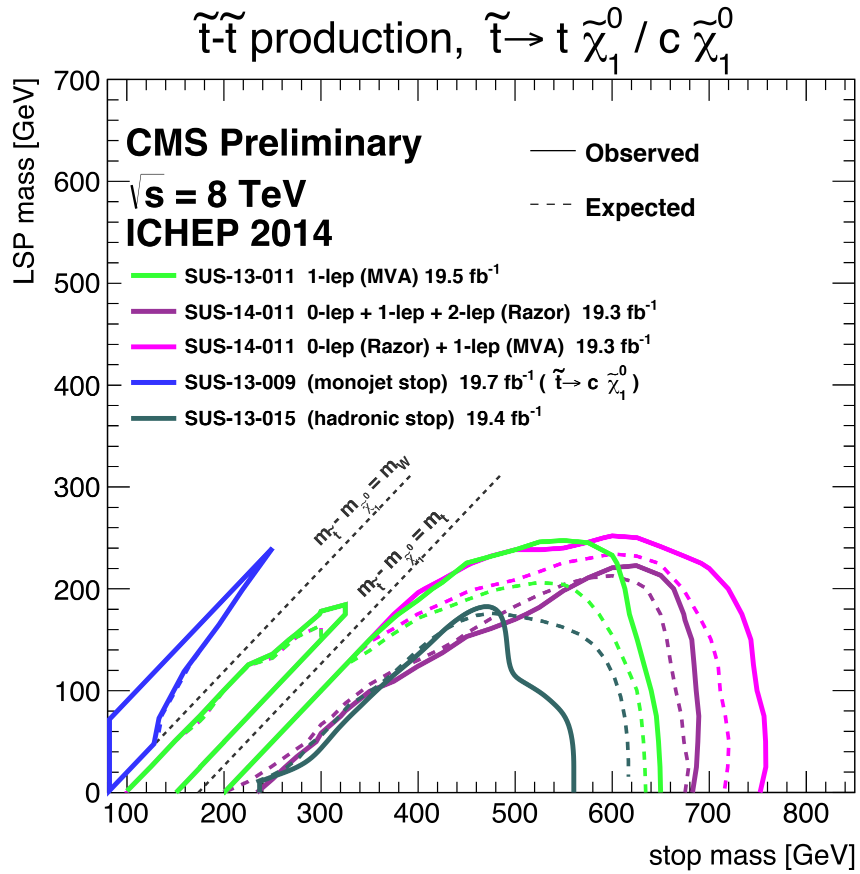
red/blue bands = 124-126 GeV
Higgs mass contours

tuning = $\frac{1}{\Delta_{m_h}}$

Tuning is $\lesssim 1\%$
$(\Lambda_{mess} \sim 10\,\mathrm{TeV})$

LHC Run-I Limits:





$\Rightarrow$ $m_{\tilde{g}} \gtrsim 1400 \text{ GeV}$ $m_{\tilde{t}_1} \gtrsim 700\,\text{GeV}$

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

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

$S =$ singlet

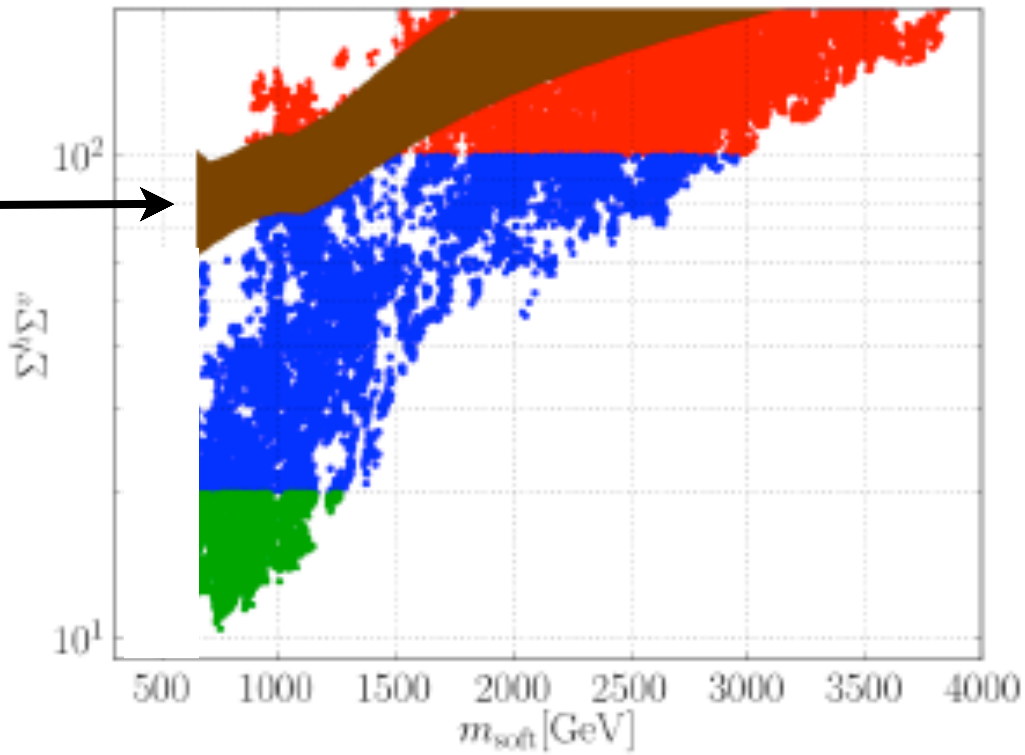
Higgs mass: $m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$

new parameter to increase Higgs mass

How natural is "*natural* SUSY"?

[TG, von Harling, Medina, Schmidt '12]

MSSM →



where

$$\Lambda_{mess} = 20\,\text{TeV}$$

$$\Sigma^h \equiv \max_{\xi_i} \left| \frac{d \log m_h^2}{d \log \xi_i} \right|$$

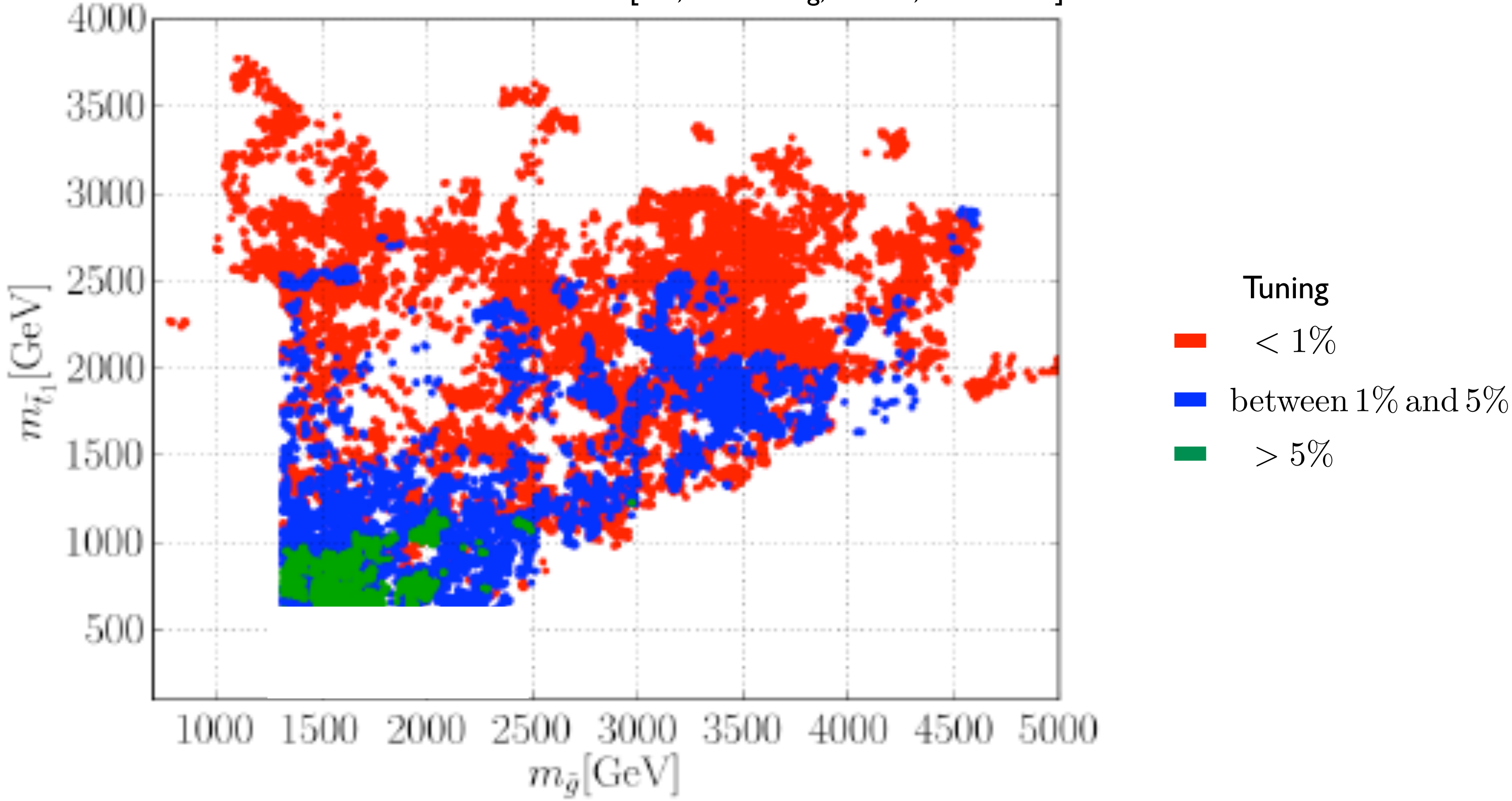
$$\Sigma^v \equiv \max_i \left| \frac{d \log v^2}{d \log \xi_i(\Lambda_{\rm mess})} \right|$$

LHC Run I

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

Gluino-stop masses

[TG, von Harling, Medina, Schmidt '12]



For tuning $\sim 5 - 10\%$

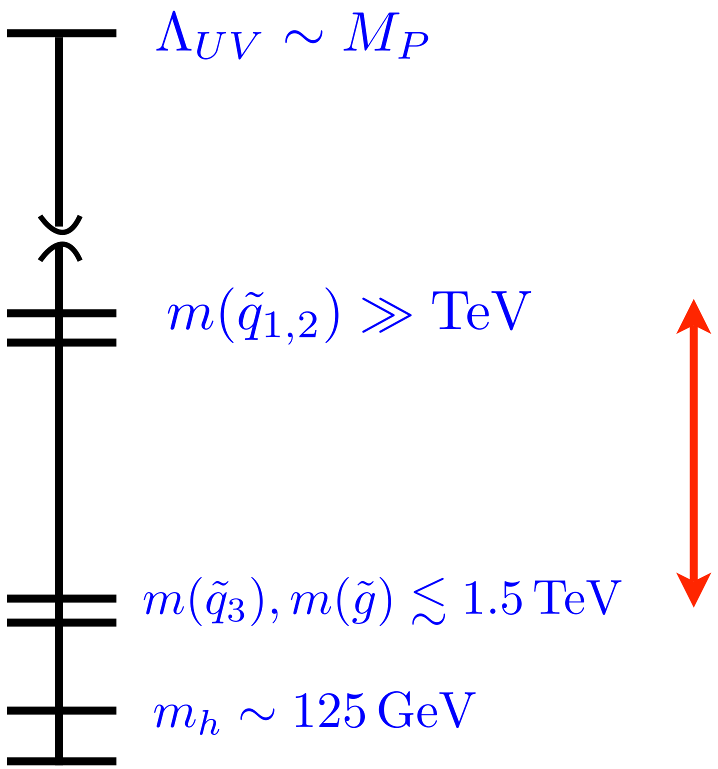
$$\Rightarrow \quad m_{\tilde{g}} \lesssim 2\,\text{TeV} \qquad m_{\tilde{t}_1} \lesssim 1.2\,\text{TeV}$$

[***Caveat***: Bottom-up approach is naive sampling of parameter space -- tuning could be worse!]

A consistent *natural* SUSY scenario based on Run1:

(i) weakly-coupled Higgs (~125 GeV)

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

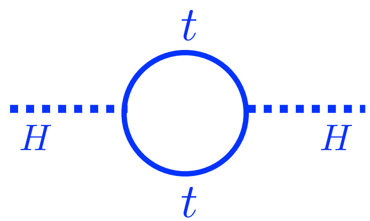


"Split families"

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

2. Compositeness/Extra dimensions

HIERARCHY PROBLEM



$$\mu_h^2 = a_0 \Lambda^2 - \frac{3y_t^2}{16\pi^2}\Lambda^2$$

If $\Lambda \simeq \mathrm{TeV}$ ⇒ mass correction $\simeq 100\,\mathrm{GeV}$ ✓O.K.

Higgs boson no longer elementary at TeV scale!

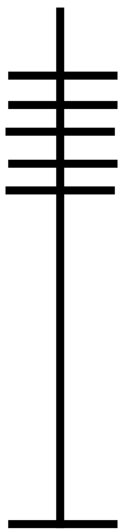
EITHER Flat extra dimensions ⇒ Quantum gravity/string theory at TeV scale!

OR Warped extra dimension ⇒ (AdS/CFT) Composite Higgs!

Higgs as a pseudo Nambu-Goldstone boson

[Georgi, Kaplan `84]

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



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

h

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

[Agashe, Contino, Pomarol 2004]

SM matter and gauge fields

Ψ_i, A_μ

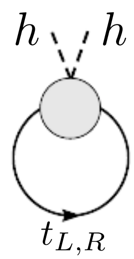
$$\mathcal{L}_{mix} = \lambda_{L,R} \bar{\Psi}_{L,R} \mathcal{O}_\Psi + g_V A^\mu J_\mu$$

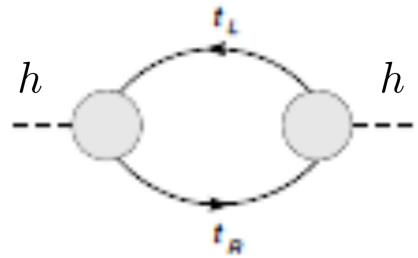
proto-Yukawa   gauge coupling

strongly-coupled Higgs sector

$\mathcal{O}_i$

Higgs potential:



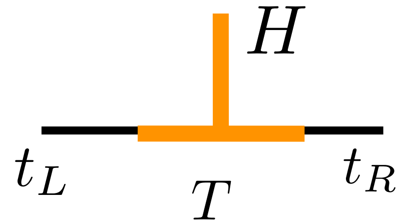


$$V(h) = -\mu_h^2 |H|^2 + \lambda_h |H|^4$$ where $$\mu_h^2 \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2 f^2 \qquad \lambda_h \sim \frac{g_{SM}^2}{16\pi^2} g_\rho^2$$

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

Tuning: $\Delta^{-1} \sim \frac{v^2}{f^2}$

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 resonance mass

$m_T \sim m_\rho \gtrsim 2.5\,\text{TeV} \quad (g_T \sim g_\rho \gtrsim 3)$ ⇒ $m_h \gtrsim m_t$

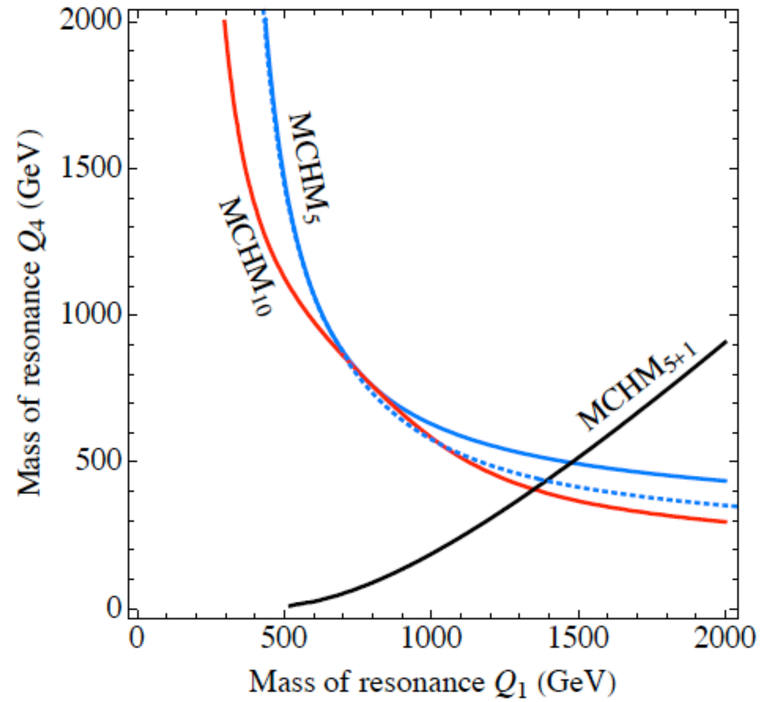
But, no need for $m_T \sim m_\rho$

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

⇒ $m_T < m_\rho$

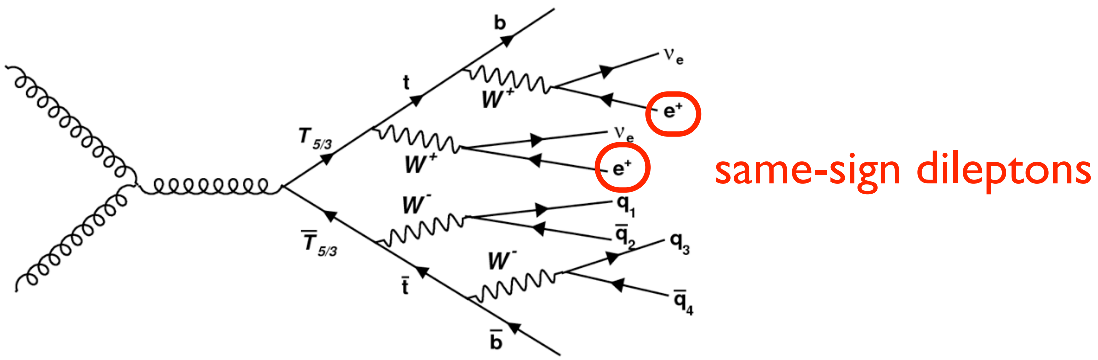
light fermion resonances

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

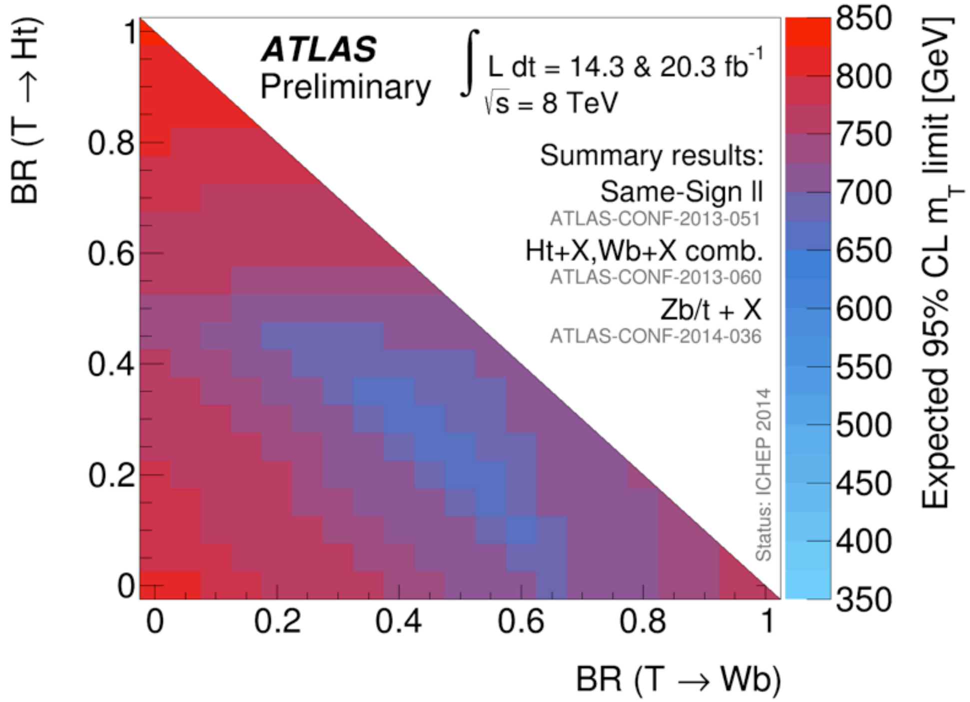


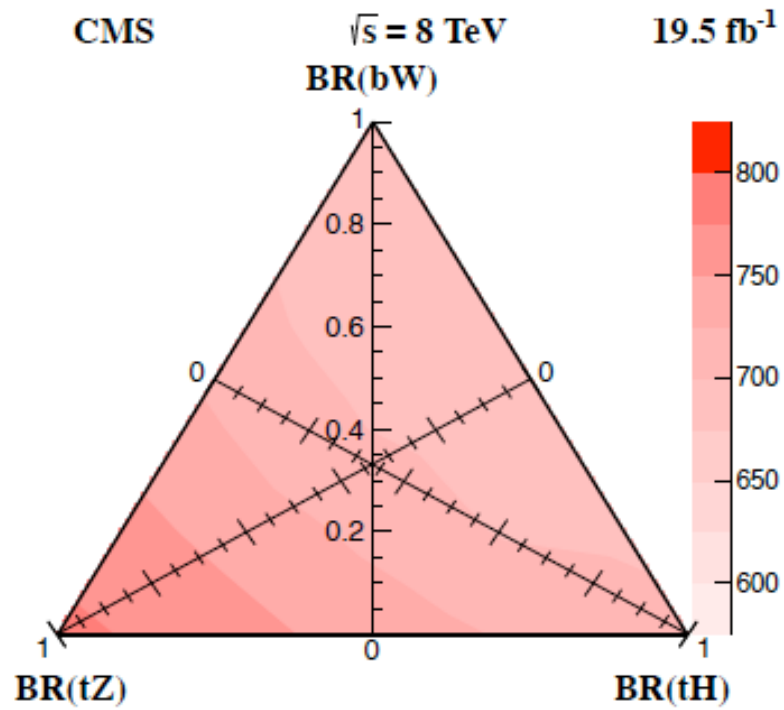
Bonus features:

- Dark matter from singlet scalar
- Composite top quark can explain:
  - -- fermion mass hierarchy
  - -- gauge coupling unification
- Light fermion resonances can be produced at LHC



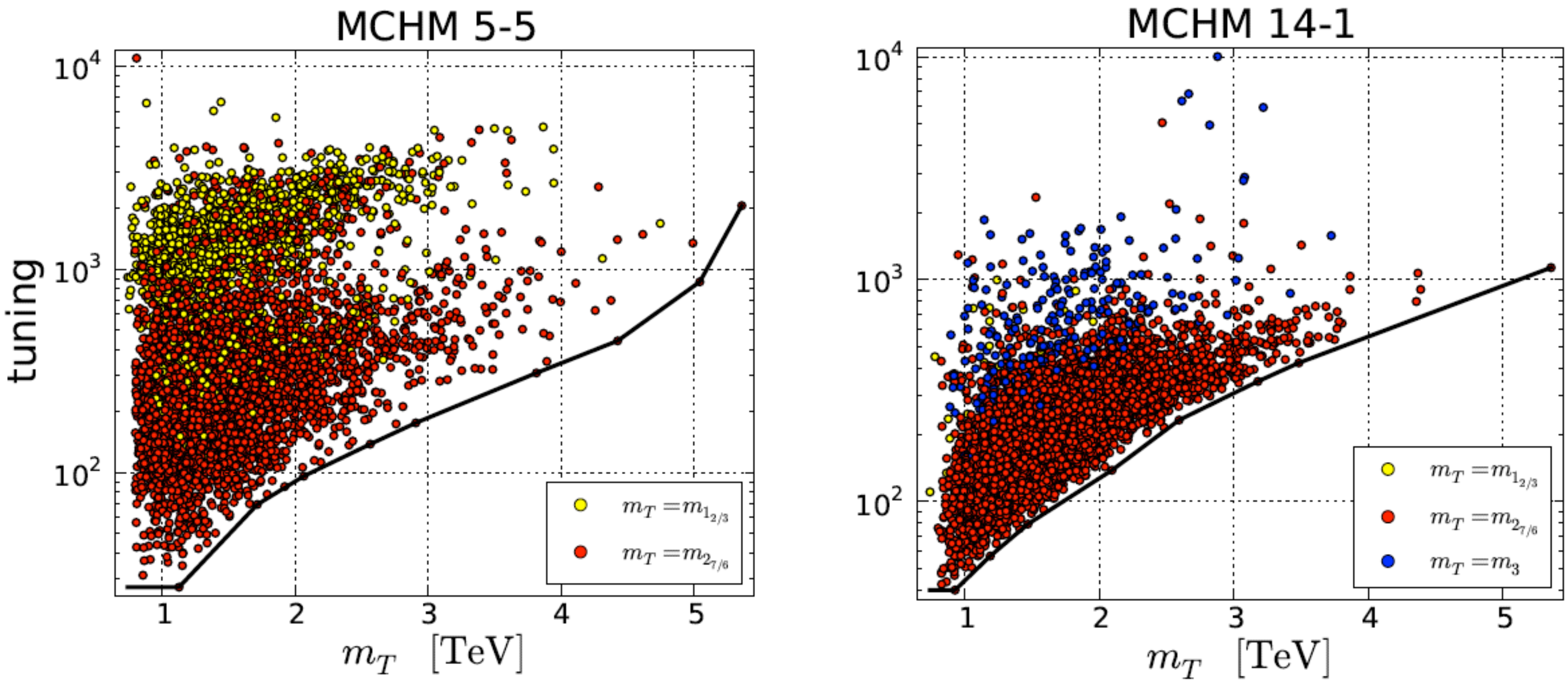
LHC Run-I Limits:





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

[Barnard, White '15]



"Natural" models are tuned at level: $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 5\%$

$$\lambda_h \simeq 0.13 \quad \Rightarrow \quad g_T = \frac{m_T}{f} \sim 1 \quad (f \gtrsim 600 - 800\,\mathrm{GeV})$$

$$\mu_h^2 \simeq (89\ \mathrm{GeV})^2 \quad \Rightarrow \quad f \lesssim 500\,\mathrm{GeV} \qquad (\text{“natural”})$$

How "bad" is this tuning?

Other coincidences:

- Solar eclipse: ~5%
  (moon/sun diameter and distance from earth)

- Hadron physics -- dineutron resonance ~ 5%
  $(\text{unbound by amount}: \; E_b \sim 100\,\text{keV})$

- Proton stability -- quark masses $\frac{m_{u,d}}{m_{proton}}$ ~ 0.5%

To reduce tuning can make "natural" models more elaborate:

Supersymmetry

i) Compressed sparticle spectrum;
Stealth supersymmetry; R-parity violation } Little or no missing energy -- Signal hidden in QCD background

ii) Dirac Gauginos

iii) Color-neutral naturalness (e.g. folded supersymmetry)
-- color factor of scalar-top comes from hidden QCD

Composite Higgs

i) Twin composite Higgs models

ii) Supersymmetric composite Higgs models...

Typically $$\text{tuning} \sim \frac{1}{\text{complexity}}$$

Is naturalness relevant for Higgs mass?

e.g. pion mass difference:

$$M^2_{\pi^+} - M^2_{\pi^0} = \frac{3\alpha}{4\pi}\Lambda^2 \approx (35\,\mathrm{MeV})^2 \quad \Rightarrow \quad \Lambda \lesssim 850\,\mathrm{MeV}$$

new physics: **rho meson 770 MeV!**

Higgs mass:

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2}\left(4m_t^2 - 2m_W^2 - m_Z^2 - m_H^2\right)\Lambda^2 \simeq (125\,\mathrm{GeV})^2$$

$$\Rightarrow \quad \Lambda \sim 700\,\mathrm{GeV}$$

new physics: ***????***

Abandon naturalness as a criterion for Higgs mass!

Already failed for the cosmological constant!

-- no new physics (supersymmetry!) at $\sim 10^{-3}\,\mathrm{eV}$

$$\mathcal{L}_{SM} = \Lambda_{UV}^4 + \Lambda_{UV}^2 H^\dagger H + \ldots$$

Positive mass dimension terms not determined by naturalness?

Instead, construct *minimal* model with:

- Gauge coupling unification
- Dark matter candidate
- UV completion

Simple alternative:

[Wells 2003; Arkani-Hamed, Dimopoulos 2004]

“Unnatural” Split SUSY

TUNED

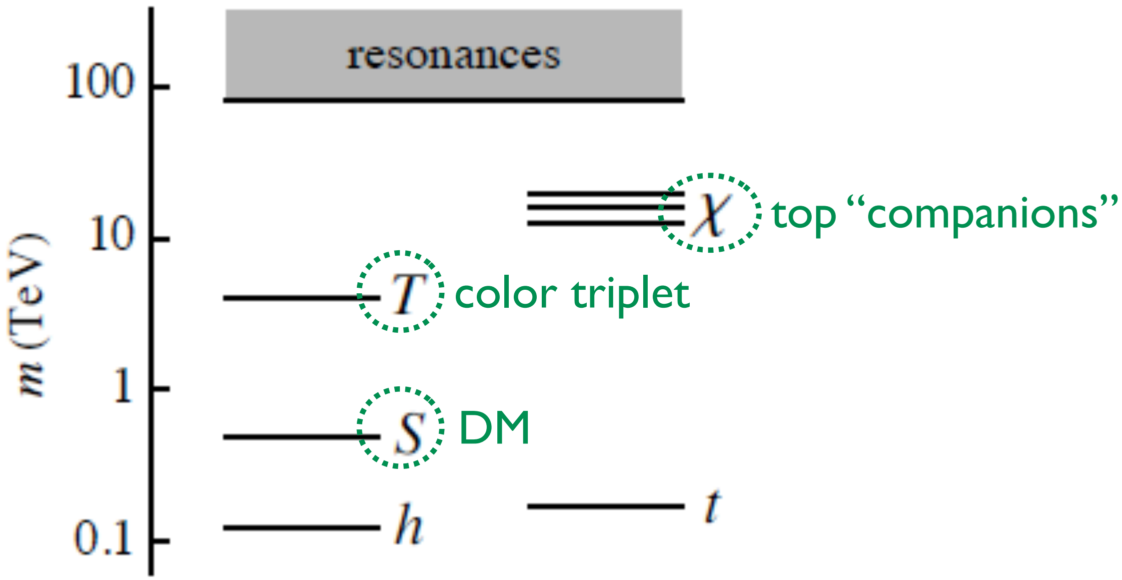
$(\sim 10^{-4})$

Collider signal: Long-lived gluino!

"Split" Composite Higgs

[James Barnard, TG, Tirtha Sankar Ray, Andrew Spray 2014]

- Spontaneous symmetry breaking scale $f \gtrsim 10\,\mathrm{TeV}$ (eliminates bounds from indirect constraints)
- Tuned Higgs potential $\sim 10^{-4}$
- Minimal coset: SU(7)/SU(6)xU(1) --- doublet H, triplet T and singlet S



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

Color triplet decay:

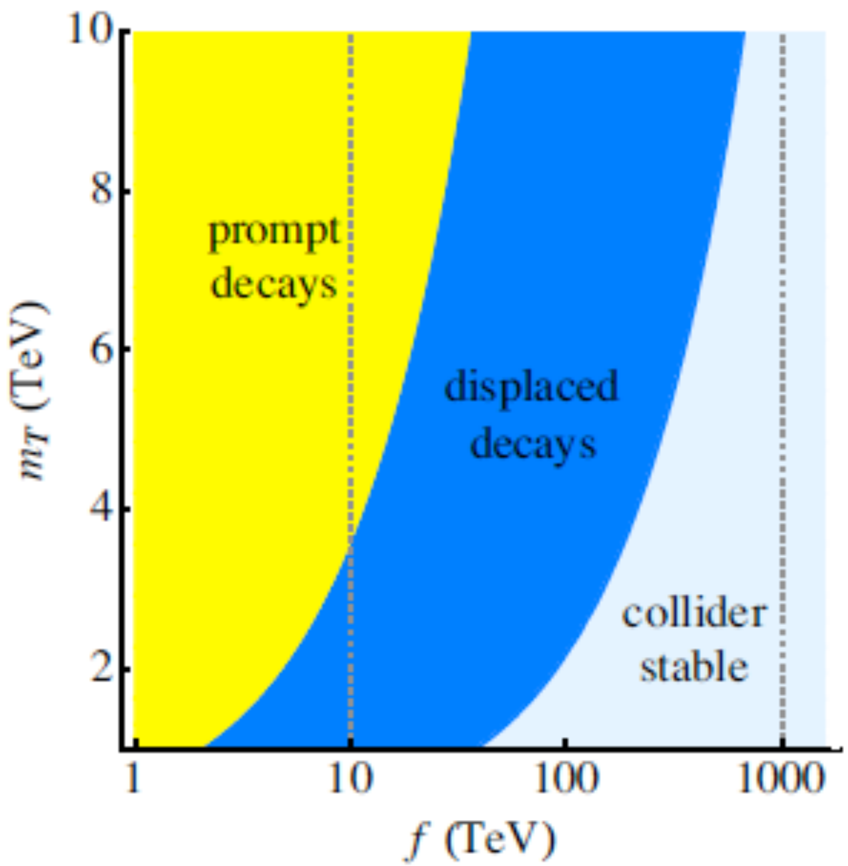
$$\mathcal{L} \supset \frac{c_3^T}{24\pi^2 f^2} |\lambda_{b^c}||\lambda_\nu||\lambda_\tau| \, S^2 (T^\dagger t^c b^c)$$

dimension-6 term

f > 10 TeV = long-lived decay

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

can produce a displaced vertex!



⇒ *Sign of unnaturalness!*

PARTICLE PHYSICS at the CROSSROADS

Natural Higgs
~125 GeV

Unnatural Higgs
~125 GeV

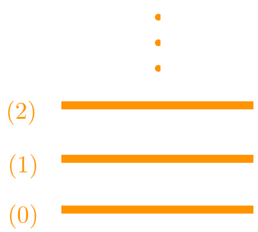
Models are increasingly elaborate and tuned $\lesssim 5\%$

Electroweak scale is meso-tuned $\sim 10^{-4} - 10^{-6}$

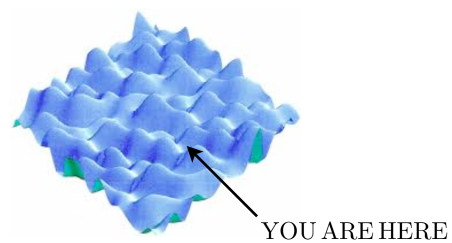
Nonetheless, a colored superpartner or resonance could still show up at Run 2!

Long-lived gluino (split SUSY) or color-triplet (split composite Higgs)

$\tilde{\gamma}$	$\tilde{u}$	$\tilde{c}$	$\tilde{t}$
$\tilde{Z}$	$\tilde{d}$	$\tilde{s}$	$\tilde{b}$
$\tilde{W}$	$\tilde{\nu}_e$	$\tilde{\nu}_\mu$	$\tilde{\nu}_\tau$
$\tilde{g}$	$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$



Evidence that we live in a Multiverse?



LHC Run II

- LHC will run at 13-14 TeV until end of 2018
- Expect $\sim 100\,\mathrm{fb}^{-1}$ (2015 to date: $\sim 4\,\mathrm{fb}^{-1}$)

STAY TUNED! [pun intended]