Physics beyond the Standard Model: Supersymmetry and composite Higgs

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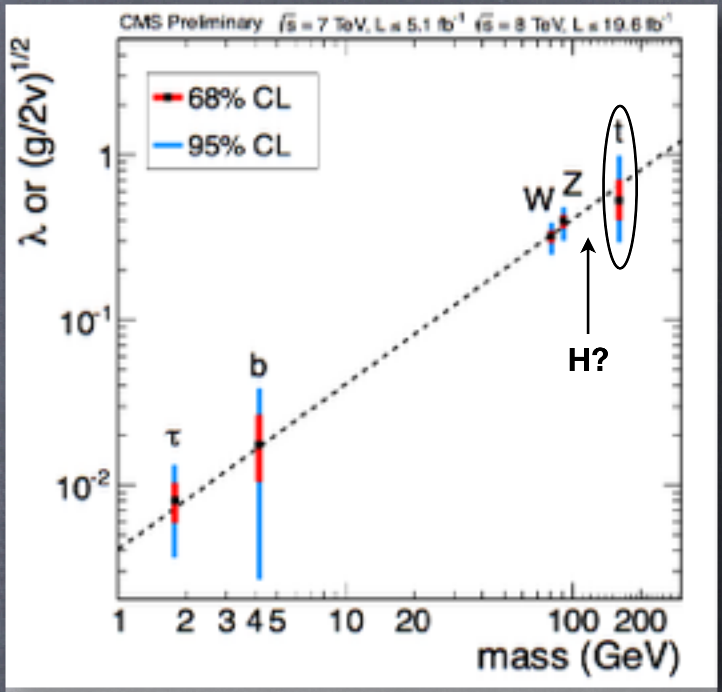
Outline

- TODAY
  - General considerations on BSM physics
    (including a critical appraisal of the naturalness argument)
  - Supersymmetric lagrangians, the MSSM, and beyond
- TOMORROW
  - Model-independent description of the SM Higgs sector
  - Composite Higgs and other extensions

Understanding the EW scale

- IS THE SM DESCRIPTION CORRECT?
  - “h” is $SU(3)_c \times U(1)_{em}$ neutral
  - “h” has S = 0 and P = 1
  - “h” couplings prop. to masses



- IS THE SM DESCRIPTION COMPLETE?

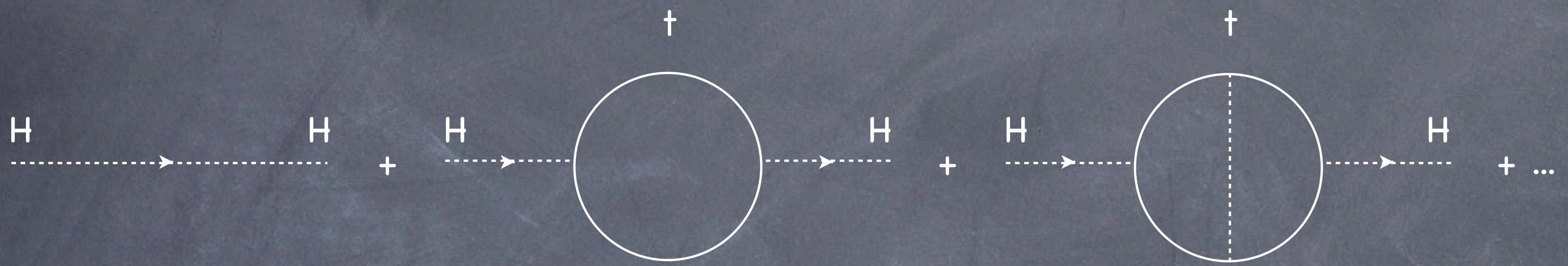
$$V = \mu^2 |H|^2 + \lambda |H|^4$$

- μ^2 Higgs potential parameter (tree level)
- M^2 scale of superheavy dofs with coupling g to H, e.g. $O(10^{16}\mathrm{GeV})$

$$\boxed{m_H^2 \sim -2\mu^2 + \frac{g^2}{(4\pi)^2} M^2}$$

A critical appraisal of the naturalness argument

The unbearable lightness of the Higgs

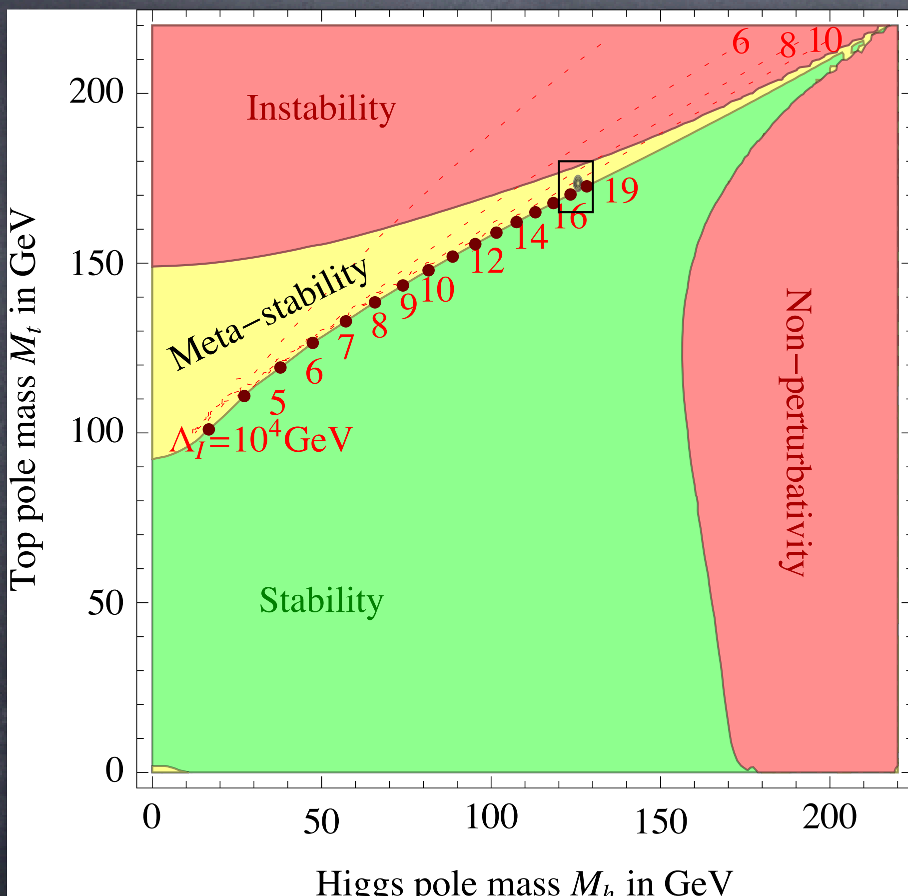


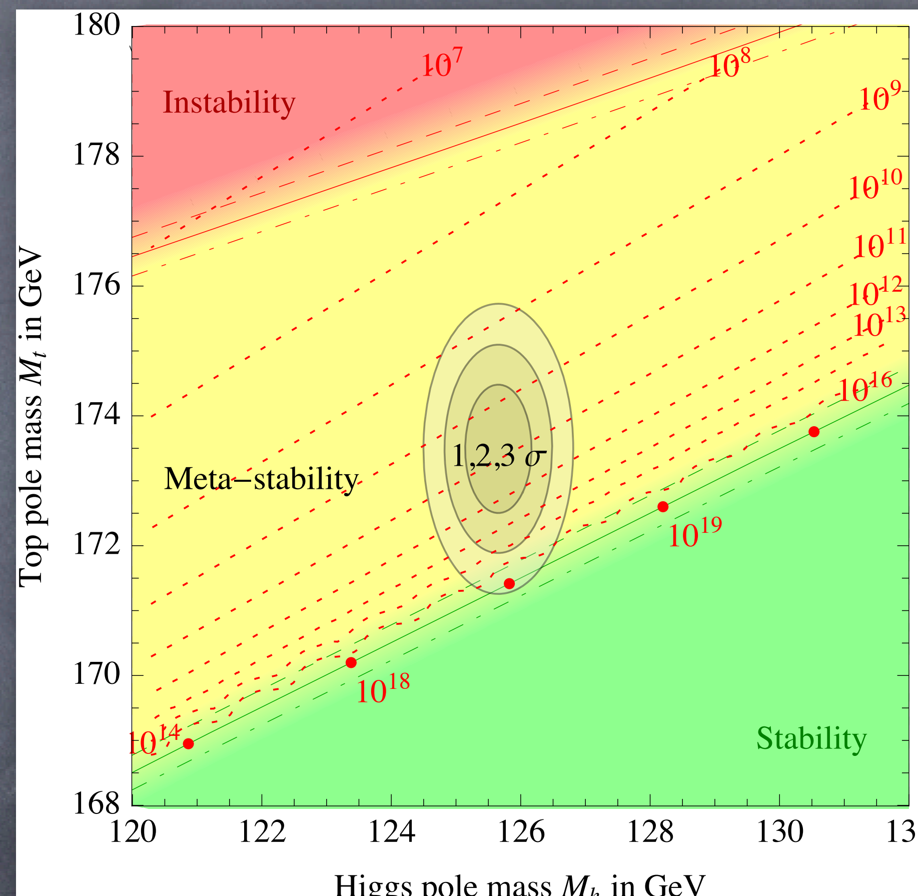
$$\delta m_h^2 \sim 12\,\lambda_t^2 \int \frac{k^3 dk}{8\pi^2}\frac{1}{k^2} \xrightarrow{\text{cut-off}} 12\frac{\lambda_t^2}{(4\pi)^2}Q_{\max}^2$$

- Quadratic divergences "per se" do not mean much (e.g. disappear in dimensional regularization)
- If the SM is the ultimate (renormalizable) theory of everything: $Q_{max} \to \infty$ mathematical problem (renormalization theory)
- If the SM is the low energy limit of a more fundamental theory: $Q_{max} \to m_{NP}$ physical (calculability) problem IF $m_{NP} \gg m_H$

Are superheavy dofs required?

The SM can be extrapolated up to M_{Pl}





Buttazzo et al

Many reasons to go beyond the SM

- Experimental "problems" of the SM
  - Gravity
  - Dark matter
  - Baryon asymmetry
- Experimental "hints" of physics beyond the SM
  - Neutrino masses
  - Quantum number unification
- Theoretical puzzles of the SM
  - $\langle H \rangle \ll M_{Pl}$
  - Family replication
  - Small Yukawa couplings, pattern of masses and mixings
  - Gauge group, no anomaly, charge quantization, quantum numbers
- Theoretical problems of the SM
  - Naturalness problem
  - Cosmological constant problem
  - Strong CP problem
  - Landau poles

- Experimental "hints" of physics MUCH beyond the SM
  - M_{Pl}
  - Quantum number unification
  - Neutrino masses

M_{Pl}

$$M_{\mathrm{Pl}} = (G_{\mathrm{N}})^{-1/2} \approx 1.2 \times 10^{19}\,\mathrm{GeV}$$

but who knows?

(and Landau poles)

Unification

	SU(3)	SU(2)	U(1)
L	1	2	-1/2
e	1	1	1
Q	3	2	1/6
u	3	1	-2/3
d	3	1	1/3
			Y

$\Rightarrow$

SO(10)
16

p-decay bounds: $M \gg m_H$

an accident?

Neutrino masses

- ASSUME: the origin of neutrino masses is at Λ » M_Z

- THEN:

$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm SM}^{\rm ren} + \frac{c_{ij}}{2\Lambda}(L_i H)(L_j H) + \ldots$$

$$m_{ij}^{E,D,U} = \lambda_{ij}^{E,D,U}\, v \qquad m_{ij}^{\nu} = c_{ij} v \times \frac{v}{\Lambda}$$

$$\Lambda \sim 0.5 \times 10^{15}\,\mathrm{GeV}\, c \left(\frac{0.05\,\mathrm{eV}}{m_\nu}\right)$$

- ALTERNATIVELY:

$$\mathcal{L}_{\nu\rm SM}^{\rm ren} = \mathcal{L}_{\rm SM}^{\rm ren} + \lambda_{ij}^{\nu}\,\overline{\nu_{iR}} L_j H + \mathrm{h.c.} \qquad m_{ij}^{\nu} = \lambda_{ij}^{\nu}\, v$$

If superheavy dofs exist

- Strong CP problem $\theta\, G_{\mu\nu}\tilde{G}^{\mu\nu} \quad D = 4$
- Naturalness problem $\alpha\, Q^2_{\max} H^\dagger H \quad D = 2$
- Cosmological constant problem $\beta\, Q^4_{\max} \sqrt{g} \quad D = 0$

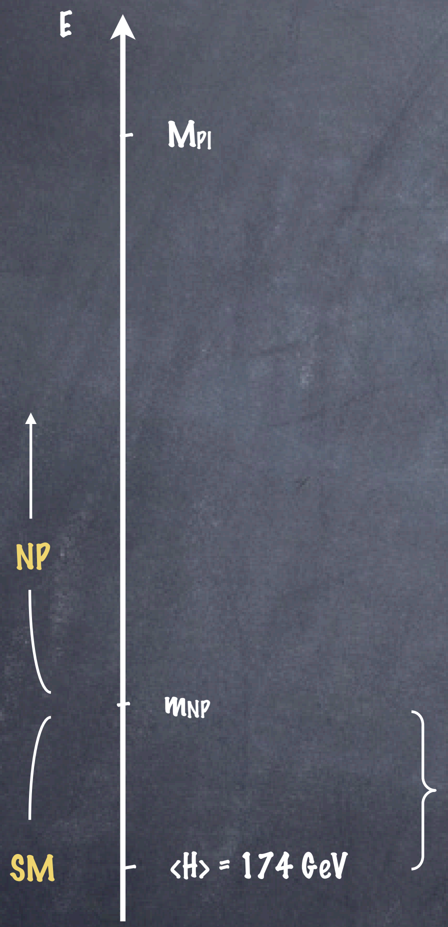
In summary

- No superheavy (coupled) degrees of freedom
  (finite naturalness?)

- Cancellation not accidental
  (environmental selection? unknown dynamics?)

- New TeV physics taming sensitivity to high scales

The naturalness argument and the scale of new physics



$$\delta m_h^2 \sim 12 \frac{\lambda_t^2}{(4\pi)^2} m_{\rm NP}^2 \approx (125\,\mathrm{GeV})^2 \left(\frac{m_{\rm NP}}{0.5\,\mathrm{TeV}}\right)$$

Comments

1. m_{NP} is not precisely determined: any value of m_{NP} is viable as long as a cancellation of one part out of

$$\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5\,\rm TeV}\right)^2$$

is accepted.

E.g.

m_{NP} > 1.5 TeV $\leftrightarrow$ Δ > 10

m_{NP} > 5 TeV $\leftrightarrow$ Δ > 100

NOTE: $\boxed{m_{NP} \times 2 \to \Delta \times 4}$

Comments

2. The bound $\Delta \gtrsim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$ is model dependent

For example:

- Supersoft theories $\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2$
- Soft theories $\Delta \sim \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right)$

(e.g. **supersymmetry** with mediation scale M)

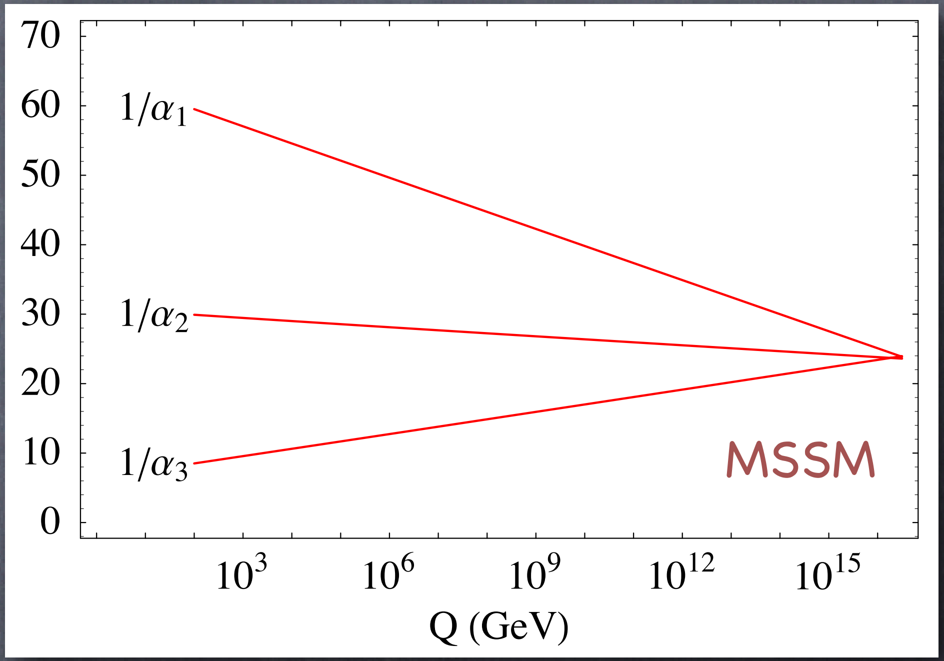
Supersymmetry

- Theoretical motivations
    - Unification of fermions and bosons
    - Local supersymmetry = supergravity + crucial in string theory
    - Completes the list of possible symmetries of S
    - Powerful technical tool

Can be extrapolated up to the Planck scale

Unification

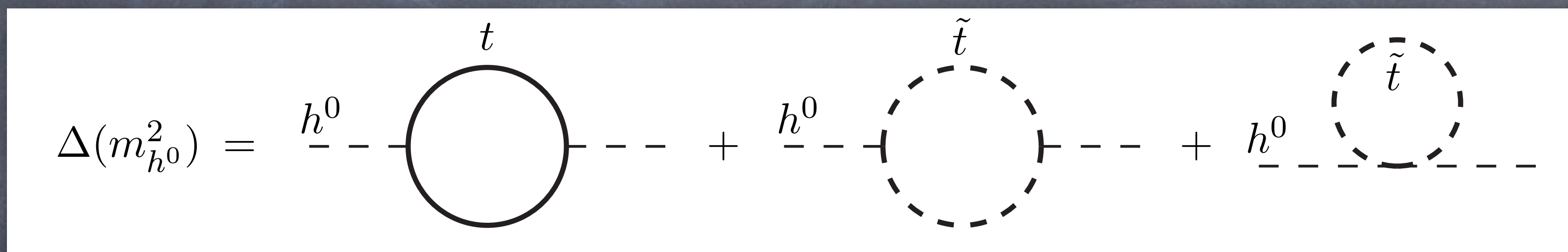
	SU(3)	SU(2)	U(1)		SO(10)
L	1	2	-1/2		
e	1	1	1		
Q	3	2	1/6	⇒	16
u	3	1	-2/3		
d	3	1	1/3		
			Y		



+ M_{GUT} prediction: $\Lambda_B < M_{GUT} < M_{Pl}$

Solves (the bulk of) the hierarchy problem

$$\frac{3}{4\pi^2}\lambda_t^2 Q^2 \qquad\qquad -\frac{3}{4\pi^2}\tilde{\lambda}_t Q^2$$



$$\boxed{\lambda_t^2 = \tilde{\lambda}_t}$$

$$\frac{3}{4\pi^2}\lambda_t^2 Q^2 \to \frac{3}{4\pi^2}\lambda_t^2 \tilde{m}^2 \log\frac{Q^2}{\tilde{m}^2} \qquad \tilde{m} \lesssim \text{few TeV?}$$

The cancellation of quadratic divergences holds at all orders in perturbation theory

Provides a dark matter candidate

- More precisely

  it turns a drawback (L and B not accidental symmetries anymore)

  into a virtue (the solution to the above problem makes the LSP stable)

The general (N=1 D=4 ren globally) supersymetric gauge lagrangian

Supersymmetry generators

- General set of symmetry generators G such that [G,S] = 0 (Lorentz + spin-statistics + other Hp)
- Bosonic: Poincaré + internal (compact semisimple $\oplus$ abelian)
- Fermionic: b $\leftrightarrow$ f, N supersymmetry generators
  - $j \leq 2 \Longrightarrow N \leq 8$
  - $j \leq 1 \Longrightarrow N \leq 4$
  - chiral gauge theory $\Longrightarrow N \leq 1$

[Sohnius, Phys Rept 128 (1985)
Wess and Bagger, Supersymmetry and supergravity, Univ. Pr. (1992)
Martin, hep-ph/9709356
Nilles, Phys Rept 110 (1984)]

[Coleman Mandula, Phys Rev 159 (1967)
Haag Lopuszanski Sohniius, Nucl. Phys B88 (1975)]

- General properties
  - #b = #f $\qquad m_B = m_F$
  - $\langle\Omega|H|\Omega\rangle \geq 0 \qquad$ SSSB $\Leftrightarrow$ vacuum energy > 0

The MSSM

SM field content

	g	W	B	q	u	d	l	e	h
SU(3)	8	1	1	3	$\bar{3}$	$\bar{3}$	1	1	1
SU(2)	1	3	1	2	1	1	2	1	2
U(1)	0	0	0	1/6	-2/3	1/3	-1/2	1	1/2
spin	1	1	1	1/2	1/2	1/2	1/2	1/2	0

MSSM super-field content

	$\hat{g}$	$\hat{W}$	$\hat{B}$	$\hat{q}$	$\hat{u}$	$\hat{d}$	$\hat{l}$	$\hat{e}$	$\hat{h}$	$\hat{h}$
SU(3)	8	1	1	3	$\bar{3}$	$\bar{3}$	1	1	1	1
SU(2)	1	3	1	2	1	1	2	1	2	2
U(1)	0	0	0	1/6	-2/3	1/3	-1/2	1	1/2	-1/2
spin	vector			chiral						

SM field content + gauginos, sfermions, Higgsinos (and 1 extra Higgs doublet)

"sparticles" , **s** for "supersymmetric"

Gauge rep not (fully) chiral, unlike in the SM $\rightarrow$ μ problem

Analysis of the MSSM

$$\langle h_u \rangle = v \sin\beta \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad \langle h_d \rangle = v \cos\beta \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

$$v \approx 174\,\mathrm{GeV}$$

$$0 \leq \beta \leq \pi/2$$

Spectrum

MSSM fields:

$$g_\mu \; W_\mu \; B_\mu \quad \tilde{g} \; \tilde{W} \; \tilde{B} \quad q_i \; u_i^c \; d_i^c \; l_i \; e_i^c \; \tilde{h}_u \; \tilde{h}_d \quad \tilde{q}_i \; \tilde{u}_i^c \; \tilde{d}_i^c \; \tilde{l}_i \; \tilde{e}_i^c \; h_u \; h_d$$

Conserved quantum numbers: spin, color, charge, R_P

Gauge bosons

$g^A_\mu \quad W^a_\mu \quad B_\mu$

$$\boxed{M_W^2 = \frac{g^2}{2} v^2}$$

$$\boxed{M_Z^2 = \frac{g^2 + g'^2}{2} v^2}$$

$$\boxed{\begin{aligned} & g_s g_\mu^A T_A + g W_\mu^a T_a + g' B_\mu Y \\ & \qquad = g_s g_\mu^A T_A + \frac{g}{\sqrt{2}}(W_\mu^+ T_+ + W_\mu^- T_-) + \frac{g}{c_W} Z_\mu (T_3 - s_W^2 Q) + e A_\mu Q \end{aligned}}$$

Same as in the SM, with $v^2 = v_u^2 + v_d^2$

$R_P = 1$ (SM) fermions

* $q_i \quad u^c_i \quad d^c_i \quad l_i \quad e^c_i$

* $-\mathcal{L} \supseteq \lambda^U_{ij} u^c_i q_j h_u + \lambda^D_{ij} d^c_i q_j h_d + \lambda^E_{ij} e^c_i l_j h_d \quad \longrightarrow \quad \begin{aligned} m_U &= \lambda_U v \sin\beta \\ m_D &= \lambda_D v \cos\beta \\ m_E &= \lambda_E v \cos\beta \end{aligned}$

* $\dfrac{m_t}{m_b} = \dfrac{\lambda_t}{\lambda_b} \tan\beta$: $m_b \ll m_t$ either because $\lambda_b \ll \lambda_t$ (as in the SM)
  or because $\tan\beta \gg 1$
  (allows $\lambda_b \sim \lambda_t$, relevant for rad corrs, Yukawa unification)

* $\lambda_t = \dfrac{m_t}{v \sin\beta}$: $\lambda_t(M_{GUT}) < \infty \Rightarrow \tan\beta \gtrsim 1$ (depending on what goes on from M_Z to M_{GUT})

$R_P = -1$ fermions (gauginos and Higgsinos)

* $\tilde{g}_A$ $\tilde{W}_a$ $\tilde{B}$ $\tilde{h}_u$ $\tilde{h}_d$
* $\tilde{h}_u = \begin{pmatrix} \tilde{h}_u^+ \\ \tilde{h}_u^0 \end{pmatrix}$ $\quad \tilde{h}_d = \begin{pmatrix} \tilde{h}_d^0 \\ \tilde{h}_d^- \end{pmatrix}$ $\quad \tilde{W}^\pm = \frac{\tilde{W}_1 \mp i\tilde{W}_2}{\sqrt{2}}$ $\quad \tilde{W}^0 = \tilde{W}^3$
* $\tilde{g}_A$ have mass M_3
* $\tilde{h}^+_u$ $\tilde{W}^+$ / $\tilde{h}^-_d$ $\tilde{W}^-$ can mix ("charginos")
* $\tilde{h}^0_u$ $\tilde{h}^0_d$ $\tilde{W}^0$ $\tilde{B}$ can mix ("neutralinos")

* **Charginos:** $-\mathcal{L} \supseteq \begin{pmatrix} \tilde{W}^- & \tilde{h}_d^- \end{pmatrix} M_C \begin{pmatrix} \tilde{W}^+ \\ \tilde{h}_u^+ \end{pmatrix} + \text{h.c.}$

$$\boxed{M_C = \begin{pmatrix} M_2 & \sqrt{2} M_Z c_W s_\beta \\ \sqrt{2} M_Z c_W c_\beta & |\mu| e^{i\phi_\mu} \end{pmatrix}}$$

e.g. $\sqrt{2} M_Z c_W c_\beta$ from $\sqrt{2} h_u^\dagger (g \frac{\sigma_a}{2} \tilde{W}_a + g' \frac{1}{2} \tilde{B}) \tilde{h}_u + \sqrt{2} h_d^\dagger (g \frac{\sigma_a}{2} \tilde{W}_a - g' \frac{1}{2} \tilde{B}) \tilde{h}_d$

* **Neutralinos:** $-\mathcal{L} \supseteq \frac{1}{2} \begin{pmatrix} \tilde{B} & \tilde{W}^3 & \tilde{h}_d^0 & \tilde{h}_u^0 \end{pmatrix} M_N \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{h}_d^0 \\ \tilde{h}_u^0 \end{pmatrix} + \text{h.c.}$

$$\boxed{M_N = \begin{pmatrix} M_1 & 0 & -\sqrt{2} M_Z s_W c_\beta & \sqrt{2} M_Z s_W s_\beta \\ 0 & M_2 & \sqrt{2} M_Z c_W c_\beta & -\sqrt{2} M_Z c_W s_\beta \\ -\sqrt{2} M_Z s_W c_\beta & \sqrt{2} M_Z c_W c_\beta & 0 & -|\mu| e^{i\phi_\mu} \\ \sqrt{2} M_Z s_W s_\beta & -\sqrt{2} M_Z c_W s_\beta & -|\mu| e^{i\phi_\mu} & 0 \end{pmatrix}}$$

* The LSP can easily be a neutralino

$R_P = 1$ scalars (Higgs sector)

* h_u h_d 8 real dofs: 2x(Q=1) + 2x(Q=-1) + 2x(Q=0,CP+) + 2x(Q=0,CP-)

$V(h_u, h_d)$ breaks $SU(2)_W \times U(1)_Y$, preserves $U(1)_{em}$, CP

(barring $\varphi_{\mu,A}$ effects through loop corrections, neglecting δ_{CKM})

* 3 massless Goldstones G^+ G^- G^0 (CP-)

* 5 physical dofs: H^+ H^- A (CP-) φ_u φ_d (CP+)

$$\boxed{h_u = \begin{pmatrix} c_\beta H^+ + i s_\beta G^+ \\ v s_\beta + \dfrac{\phi_u - i(s_\beta G^0 + c_\beta A)}{\sqrt{2}} \end{pmatrix} \qquad h_d = \begin{pmatrix} v c_\beta + \dfrac{\phi_d + i(c_\beta G^0 - s_\beta A)}{\sqrt{2}} \\ s_\beta H^- + i c_\beta G^- \end{pmatrix}}$$

* Masses: the 8x8 mass matrix decomposes into

  - a vanishing 3x3 block corresponding to the Goldstones G^+ G^- G^0
  - a mass term for H^+H^-: $m^2_{H^\pm} = \left.\frac{\partial^2 V_\pm}{\partial H^+ \partial H^-}\right|_{H^\pm=0}$ $\quad V_\pm = V\left(\begin{pmatrix} c_\beta H^+ \\ v s_\beta \end{pmatrix}, \begin{pmatrix} v c_\beta \\ s_\beta H^- \end{pmatrix}\right)$
  - a mass term for A: $m^2_A = \left.\frac{\partial^2 V_A}{\partial A^2}\right|_{A=0}$
  - a 2x2 mass matrix for φ_u φ_d: $-\mathcal{L} \supseteq -\frac{1}{2}\left(\phi_u \; \phi_d\right) M^2_\phi \begin{pmatrix} \phi_u \\ \phi_d \end{pmatrix}$

$$M^2_\phi = R(\alpha)\begin{pmatrix} m^2_H & \\ & m^2_h \end{pmatrix} R(\alpha)^{-1} \quad m^2_h < m^2_H \quad R(\alpha) = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

$$\boxed{\begin{aligned} \phi_d &= c_\alpha H - s_\alpha h \\ \phi_u &= c_\alpha h + s_\alpha H \end{aligned}}$$

* Decoupling limit: $m_A \gg v \Leftrightarrow m_{H\pm} \gg v \Leftrightarrow m_H \gg v$ ($m_h \sim v$) $\alpha \approx \beta - \pi/2$

In the MSSM

- m^2_h m^2_H $m^2_{H\pm}$ m^2_A α β $\leftrightarrow$ MSSM parameters

$$\boxed{\begin{aligned} m_A^2 &= m_u^2 + m_d^2 = m_{h_u}^2 + m_{h_d}^2 + 2|\mu|^2 \\ m_{H^\pm}^2 &= m_A^2 + M_W^2 \end{aligned}}$$

$$M_\phi^2 = \begin{pmatrix} m_A^2 s_\beta^2 + M_Z^2 c_\beta^2 & -s_\beta c_\beta (m_A^2 + M_Z^2) \\ -s_\beta c_\beta (m_A^2 + M_Z^2) & m_A^2 c_\beta^2 + M_Z^2 s_\beta^2 \end{pmatrix}$$

- Decoupling limit: $m^2_h \approx M^2_Z \cos^2 2\beta$
- In general: $\boxed{m_{h,H}^2 = \frac{1}{2}\left[M_Z^2 + m_A^2 \pm \sqrt{(M_Z^2 + m_A^2)^2 - 4M_Z^2 m_A^2 \cos^2 2\beta}\right]}$

$$\boxed{\tan 2\alpha = \frac{m_A^2 + M_Z^2}{m_A^2 - M_Z^2} \tan 2\beta}$$

$$\begin{pmatrix} \cos 2\alpha = \dfrac{M_Z^2 - m_A^2}{m_H^2 - m_h^2} \cos 2\beta \\ \sin 2\alpha = -\dfrac{M_Z^2 + m_A^2}{m_H^2 - m_h^2} \sin 2\beta \end{pmatrix}$$

- $m_h^2 \leq M_Z^2 \cos^2 2\beta \quad \text{(tree level)}$

[Ellis Ridolfi Zwirner]

- 1-loop corrections (very basic approx): $m_h^2 \lesssim M_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} h_t^2 m_t^2 \log \frac{\tilde{m}_t^2}{m_t^2} \lesssim 130\,\text{GeV}$ for $\tilde{m}_t \lesssim$ 1-2 TeV
  - Lower limit on m^2_h $\to$ lower limit on $\tilde{m}_t$ $\to$ lower limit on FT
  - lower $\tan\beta$ requires a larger correction (upper limit on m_t $\to$ lower limit on $\tan\beta$)
  - m^2_h > 115 GeV (≈125 GeV?) can be evaded in the MSSM but requires even more FT

Radiative corrections to m_h

* Full 1-loop computation: Coleman-Weinberg potential + self-energy
* Moderate tanβ: corrections dominated by top-stop sector
* The stop mixing ($A_t + \mu\cot\beta$) has a significant impact on the results
* $\log(\tilde{m}_t^2/m_t^2)$-enhanced contributions:
  - consider the limit $\tilde{m}_t^2 \gg m_t^2$
  - match the MSSM at $Q > \tilde{m}$ with the SM at $Q < \tilde{m}$:

$$\begin{cases} \lambda_h(\tilde{m}_t) = \dfrac{g^2+g'^2}{4}\cos^2 2\beta + 6\dfrac{h_t^2}{(4\pi)^2}\dfrac{X_t^2}{\tilde{m}_t^2}\left(1-\dfrac{X_t^2}{12\tilde{m}_t^2}\right) \\ h_t = \lambda_t \sin\beta = m_t/v \end{cases} \qquad X_t = A_t - \mu\cot\beta$$

  - compute leading-log corrections to the SM Higgs coupling

$$\lambda_h(m_t) = \lambda_h(\tilde{m}_t) + 6\frac{h_t^2}{(4\pi)^2}\log\frac{\tilde{m}_t^2}{m_t^2}$$

$$m_h^2 = 2\lambda_h(m_t)v^2 = M_Z^2\cos^2 2\beta + 12\frac{h_t^2 m_t^2}{(4\pi)^2}\left[\log\frac{\tilde{m}_t^2}{m_t^2} + \frac{X_t^2}{\tilde{m}_t^2}\left(1-\frac{X_t^2}{12\tilde{m}_t^2}\right)\right]$$

R_P = -1 scalars (squarks and sleptons)

* $\tilde{q}_i = \begin{pmatrix} \tilde{u}_i \\ \tilde{d}_i \end{pmatrix} \quad \begin{matrix} \tilde{u}_i^c \\ \tilde{d}_i^c \end{matrix} \quad \tilde{l}_i = \begin{pmatrix} \tilde{\nu}_i \\ \tilde{e}_i \end{pmatrix} \quad \tilde{e}_i^c \quad \tilde{q}_i^* = \begin{pmatrix} \tilde{u}_i^* \\ \tilde{d}_i^* \end{pmatrix} \quad \begin{matrix} \tilde{u}_i^{c*} \\ \tilde{d}_i^{c*} \end{matrix} \quad \tilde{l}_i^* = \begin{pmatrix} \tilde{\nu}_i^* \\ \tilde{e}_i^* \end{pmatrix} \quad \tilde{e}_i^{c*}$
* Possible mixing between
    - $SU(3)_c$ triplets, Q=2/3 (up squarks): $\tilde{u}_i$ $\tilde{u}^c{}_i{}^*$
    - $SU(3)_c$ triplets, Q=-1/3 (down squarks): $\tilde{d}_i$ $\tilde{d}^c{}_i{}^*$
    - $SU(3)_c$ singlets, Q=-1 (charged sleptons): $\tilde{e}_i$ $\tilde{e}^c{}_i{}^*$
    - $SU(3)_c$ singlets, Q=0 (sneutrinos): $\tilde{\nu}_i$

$$-\mathcal{L} = (\tilde{u}^* \ \tilde{u}^c)\mathcal{M}_U^2 \begin{pmatrix} \tilde{u} \\ \tilde{u}^{c*} \end{pmatrix} + (\tilde{d}^* \ \tilde{d}^c)\mathcal{M}_D^2 \begin{pmatrix} \tilde{d}_i \\ \tilde{d}_i^{c*} \end{pmatrix} + (\tilde{e}^* \ \tilde{e}^c)\mathcal{M}_E^2 \begin{pmatrix} \tilde{e} \\ \tilde{e}^{c*} \end{pmatrix} + \tilde{\nu}^* M_\nu^2 \tilde{\nu}$$

$$\mathcal{M}_U^2 = \begin{pmatrix} \tilde{m}_q^2 + M_U^\dagger M_U + M_Z^2 z_u c_{2\beta}\mathbf{1} & -(\hat{A}_U^\dagger + \mu \cot\beta)M_U^\dagger \\ -M_U(\hat{A}_U + \mu^* \cot\beta) & \tilde{m}_{u_R}^2 + M_U M_U^\dagger + M_Z^2 z_{u_c} c_{2\beta}\mathbf{1} \end{pmatrix} = \begin{pmatrix} \mathrm{LL} & \mathrm{LR} \\ \mathrm{RL} & \mathrm{RR} \end{pmatrix}$$

$$\mathcal{M}_D^2 = \begin{pmatrix} \tilde{m}_q^2 + M_D^\dagger M_D + M_Z^2 z_d c_{2\beta}\mathbf{1} & -(\hat{A}_D^\dagger + \mu \tan\beta)M_D^\dagger \\ -M_D(\hat{A}_D + \mu^* \tan\beta) & \tilde{m}_{d_R}^2 + M_D M_D^\dagger + M_Z^2 z_{d_c} c_{2\beta}\mathbf{1} \end{pmatrix}$$

$$\mathcal{M}_E^2 = \begin{pmatrix} \tilde{m}_l^2 + M_E^\dagger M_E + M_Z^2 z_e c_{2\beta}\mathbf{1} & -(\hat{A}_E^\dagger + \mu \tan\beta)M_E^\dagger \\ -M_E(\hat{A}_E + \mu^* \tan\beta) & \tilde{m}_{e_R}^2 + M_E M_E^\dagger + M_Z^2 z_{e_c} c_{2\beta}\mathbf{1} \end{pmatrix}$$

$$M_\nu^2 = \tilde{m}_l^2 + M_Z^2 z_\nu c_{2\beta}\mathbf{1}$$

$$A_{U,D,E} \equiv \lambda_{U,D,E}\hat{A}_{U,D,E} \quad m_R^2 \equiv (m_c^2)^*$$

$$z_A \equiv t_3(A) - \sin^2\theta_W q(A)$$

- Super-CKM basis: write the scalar mass matrices in the basis in flavour space in which the corresponding fermions are diagonal (U **or** D)

* FCNC/sugra-inspired ansatz for colliders: (neglecting small off-diagonal entries, $V_{cb,ub}$)

$$(\tilde{m}^2_{ij}) = \begin{pmatrix} \tilde{m}^2 & & \\ & \tilde{m}^2 & \\ & & \tilde{m}^2_3 \end{pmatrix}$$

* I and II families up squarks:

$$\tilde{m}^2_{u_{1,2}} = \tilde{m}^2_q + z_u c_{2\beta} M_Z^2$$
$$\tilde{m}^2_{u^c_{1,2}} = \tilde{m}^2_{u^c} + z_{u^c} c_{2\beta} M_Z^2$$

* III family (stops):

$$\begin{pmatrix} \tilde{m}^2_{q_3} + m_t^2 + z_u c_{2\beta} M_Z^2 & -m_t(A_t + \mu \cot\beta) \\ -m_t(A_t + \mu\cot\beta) & \tilde{m}^2_{u^c_3} + m_t^2 + z_{u^c} c_{2\beta} M_Z^2 \end{pmatrix}$$

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} c_\theta & s_\theta \\ -s_\theta & c_\theta \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix} \qquad 0 \leq \theta \leq \pi, \quad \tilde{m}_{t_1} < \tilde{m}_{t_2}$$

* Analogously in the D, E sectors. Relevant LR mixing in the third family only for large $\tan\beta$

Is supersymmetry in trouble?

- Not chiral (explicit, supersymmetric mass term for the Higgsinos)
  ➥ Giudice-Masiero, NMSSM

- Correct symmetry breaking not guaranteed (CCLB minima)
  ➥ radiative EWSB

- L, B not accidental symmetries anymore
  ➥ R-parity
    ➥ Lightest Supersymmetric Particle (LSP) is stable (DM, missing E_T)
    ➥ SUSY corrections to SM processes only via loops

- Trouble with supersymmetry breaking

Trouble with supersymmetry breaking

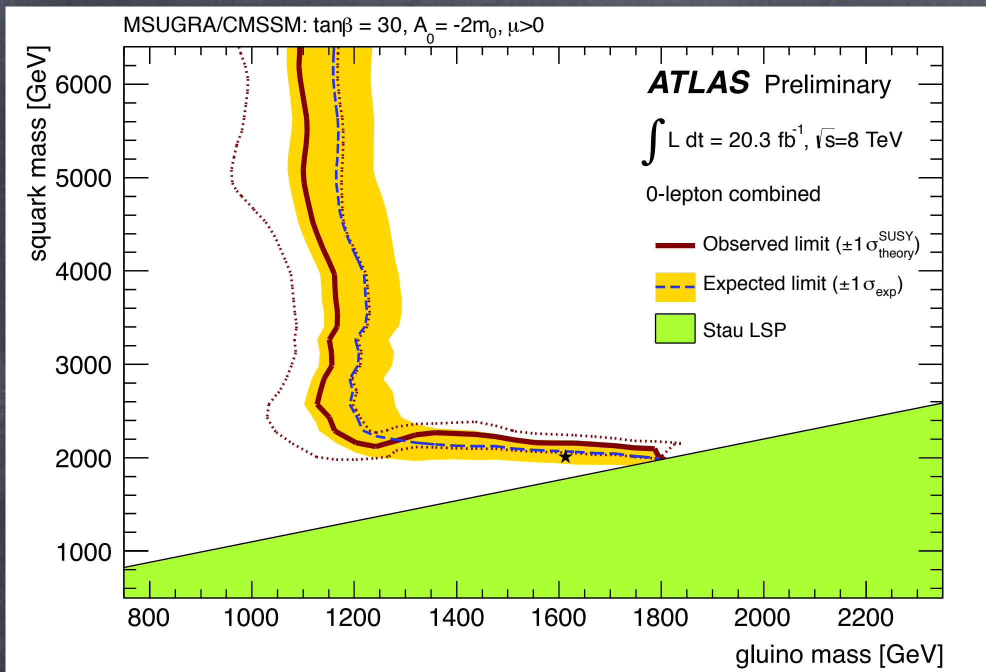
- Supersymmetry predicts m = m̃

- Needs to be broken, hopefully spontaneously

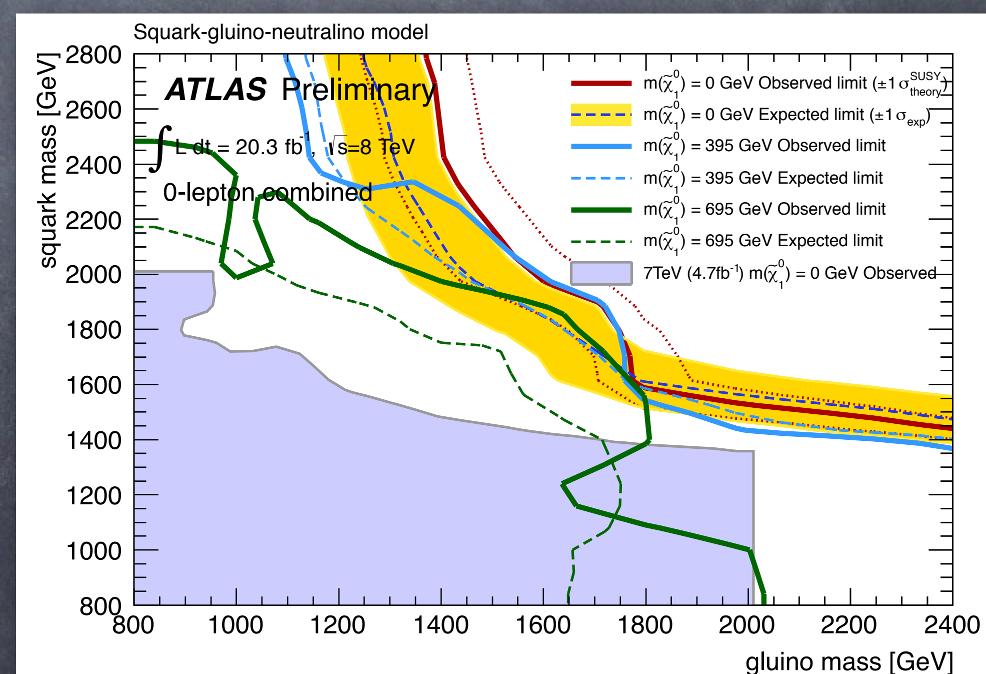
    - Effective description in terms of O(100) parameters

$$
\begin{aligned}
-\mathcal{L}_{\text{soft}} = {} & A^U_{ij}\tilde{u}^c_i\tilde{q}_j h_u + A^D_{ij}\tilde{d}^c_i\tilde{q}_j h_d + A^E_{ij}\tilde{e}^c_i\tilde{l}_j h_d + m^2_{ud} h_u h_d + \text{h.c.} \\
& + (\tilde{m}^2_q)_{ij}\tilde{q}^\dagger_i\tilde{q}_j + (\tilde{m}^2_{u^c})_{ij}(\tilde{u}^c_i)^\dagger\tilde{u}^c_j + (\tilde{m}^2_{d^c})_{ij}(\tilde{d}^c_i)^\dagger\tilde{d}^c_j + (\tilde{m}^2_l)_{ij}\tilde{l}^\dagger_i\tilde{l}_j \\
& + (\tilde{m}^2_{e^c})_{ij}(\tilde{e}^c_i)^\dagger\tilde{e}^c_j + m^2_{h_u} h^\dagger_u h_u + m^2_{h_d} h^\dagger_d h_d \\
& + \frac{M_3}{2}\tilde{g}_A\tilde{g}_A + \frac{M_2}{2}\tilde{W}_a\tilde{W}_a + \frac{M_1}{2}\tilde{B}\tilde{B} + \text{h.c.}
\end{aligned}
$$

(Vanilla) direct experimental constraints



- Based on missing E_T
- First family squarks
- One slice of the par space



How bad is it?

Supersymmetry is a soft theory

$$\Delta \approx \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}}\right)^2 \times \log\left(\frac{M^2}{m_{\rm NP}^2}\right)$$

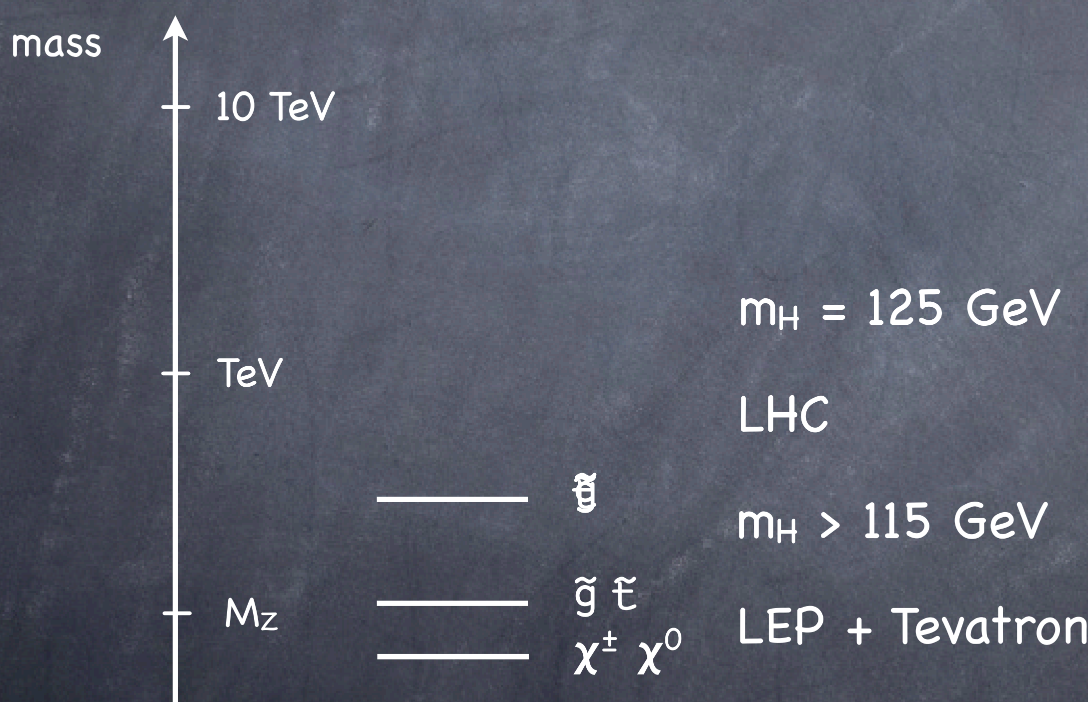
$$\approx \left(\frac{m_{\rm NP}}{0.5\,{\rm TeV}/\sqrt{\log}}\right)^2$$

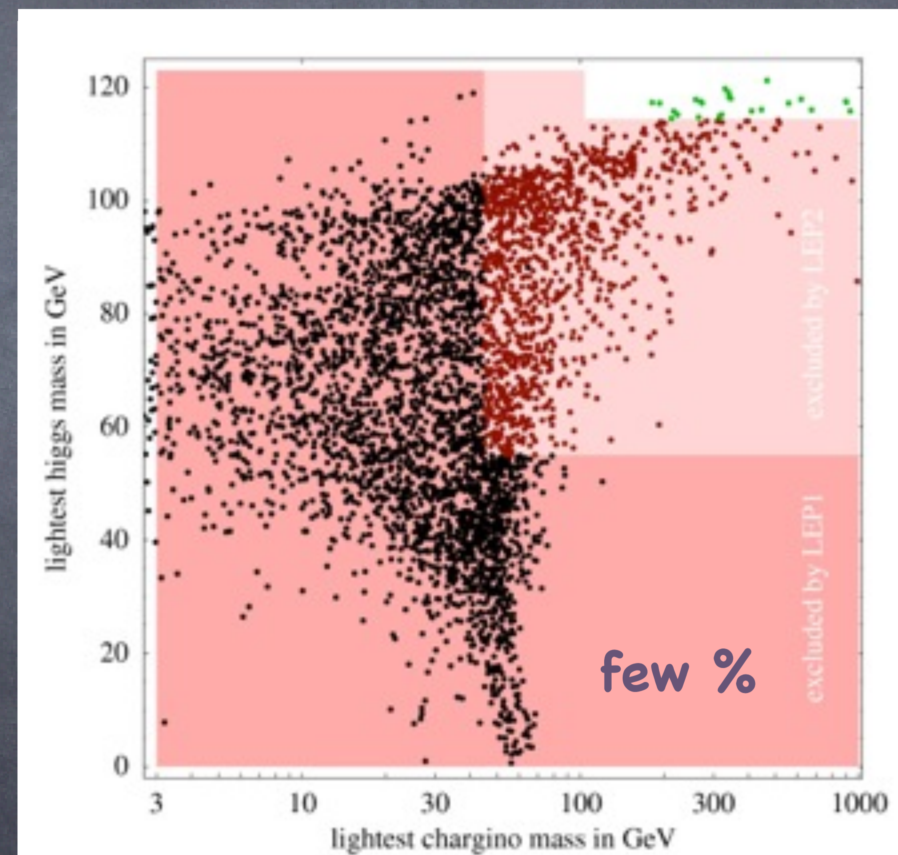
M = mediation scale

E.g. in supergravity $M = M_{Pl}$

A tale of naturalness

- Supergravity: $\Lambda_{NP} = M = M_{Planck}$
- log = O(70) $\Longrightarrow$ natural expectation: m_{NP} around M_Z!





[Giusti R Strumia, 1998]

The lack of susy signal **may** indicate a **low M**

Where does FT come from?

$$m_Z^2 \approx -2m_{H_u}^2 - 2|\mu|^2$$

$$\downarrow$$

$$\delta m_{H_u}^2 \sim -12\frac{\lambda_t^2}{(4\pi)^2}\tilde{m}_t^2 \log\frac{M}{\tilde{m}_t}$$

$$\downarrow$$

$$\delta\tilde{m}_t^2 = \frac{32}{3}\frac{g_3^2}{(4\pi)^2}M_3^2 \log\frac{M}{M_3}$$

+ experimental constraints
+ indirect bounds from m_H

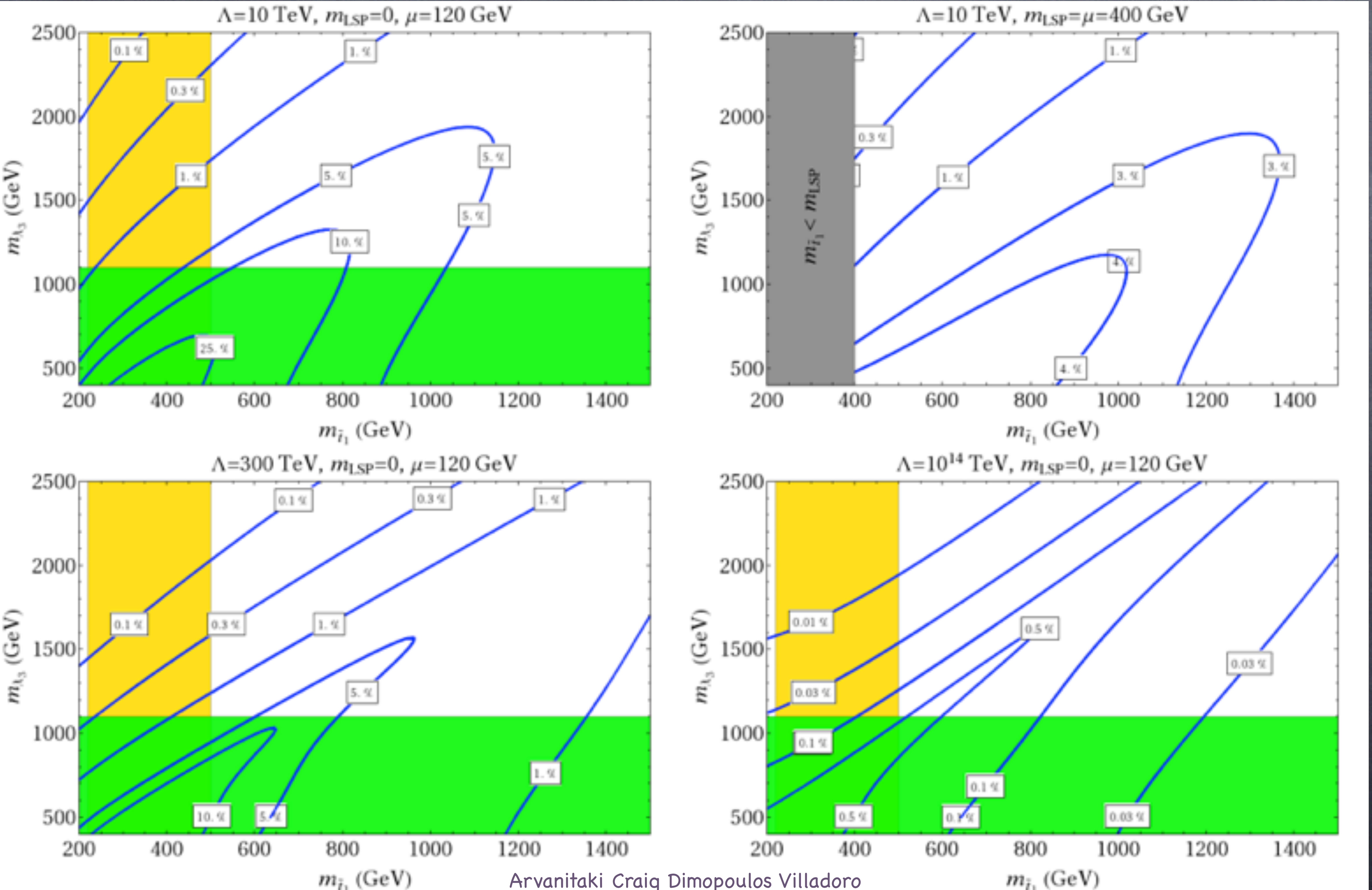
Ways out

- $\boxed{\text{Lower M}}$
- $\boxed{\text{Decouple stop from sup, scharm}}$
- $\boxed{\text{NMSSM}}$
- Dirac gluinos
- Weakly constrained regions
- Give up E_T-miss signature

Enhancement of Higgs mass: how?

- NMSSM: MSSM + $\hat{S}$
  - harmless (unification OK)
  - minimal $\lambda S H_u H_d$ (symmetries forbid $\mu H_u H_d$)
  - welcome ($\mu = \lambda \langle S \rangle \approx$ susy scale)
- $$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \text{loops}$$

All this helps... to some extent



Arvanitaki Craig Dimopoulos Villadoro

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Give up naturalness

Is the naturalness criterium really relevant?

Though general, the naturalness argument rests on assumptions

- the cancellation in the Higgs mass is accidental
  - environmental selection
  - only understanding available for cosmological constant

- existence of superheavy physics
  - maybe there are no dofs much heavier than TeV
  - then quadratic corrections do not matter

No superheavy physics?

Strumia et al

Neutrino mass models add extra particles with mass M

$$M \lesssim \begin{cases} 0.7\ 10^7\,\text{GeV} \times \sqrt[3]{\Delta} & \text{type I see-saw model,} \\ 200\,\text{GeV} \times \sqrt{\Delta} & \text{type II see-saw model,} \\ 940\,\text{GeV} \times \sqrt{\Delta} & \text{type III see-saw model.} \end{cases}$$

Leptogenesis is compatible with FN only in type I.

Axion and LHC usually are like fish and bicycle because $f_a \gtrsim 10^9\,\text{GeV}$. Axion models can satisfy FN, e.g. KSVZ models employ heavy quarks with mass M

$$M \lesssim \sqrt{\Delta} \times \begin{cases} 0.74\,\text{TeV} & \text{if } \Psi = Q \oplus \bar{Q} \\ 4.5\,\text{TeV} & \text{if } \Psi = U \oplus \bar{U} \\ 9.1\,\text{TeV} & \text{if } \Psi = D \oplus \bar{D} \end{cases}$$

Inflation does not need big scales and anyhow flatness implies small couplings. Absolute gravitational limit on H_I and on any mass [Arvinataki, Dimopoulos..]

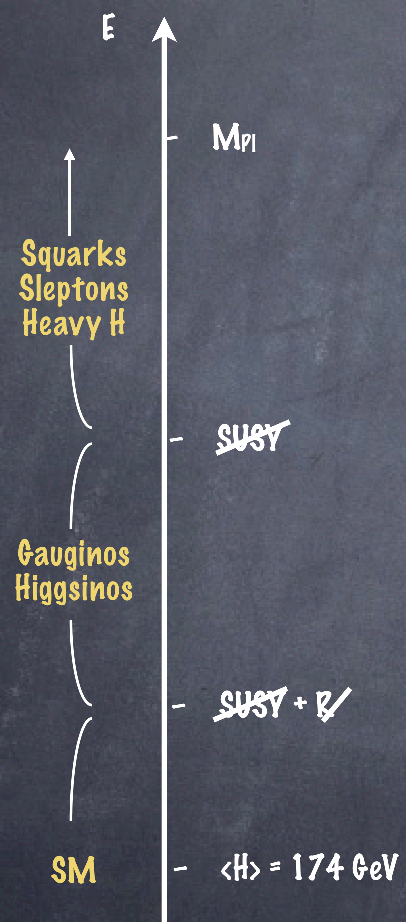
$$\delta m^2 \sim \frac{y_t^2 M^6}{M_{\text{Pl}}^4 (4\pi)^6} \qquad \text{so} \qquad M \lesssim \Delta^{1/6} \times 10^{14}\,\text{GeV}$$

Dark Matter: extra scalars/fermions with/without weak gauge interactions.

- What about gravity? → Adimensional gravity
  - renormalizable gravity + no mass scale inducing physical quadratic corrections
  - (but a ghost)
  - r ≈ 1.3

Giving up naturalness: Split Supersymmetry

[Arkani-Hamed Dimopoulos
Giudice R
Arkani-Hamed Dimopoulos Giudice R]



- $m^2_h \ll \delta m^2_h$ accidentally or because of unspeakable reasons
- Dark matter and unification keep part of spectrum near TeV

An (almost) troubleless MSSM

- Issues
  - Potentially > 100 parameters (CMSSM)
  - FCNCs and CP-violation in particular EDMs (SUSY breaking mechanism, symmetries)
  - Proton decay from dimension 5 operators (non minimal models)
  - Gravitino and moduli problem (low reheating T)
  - Fine-tuning (NMSSM)

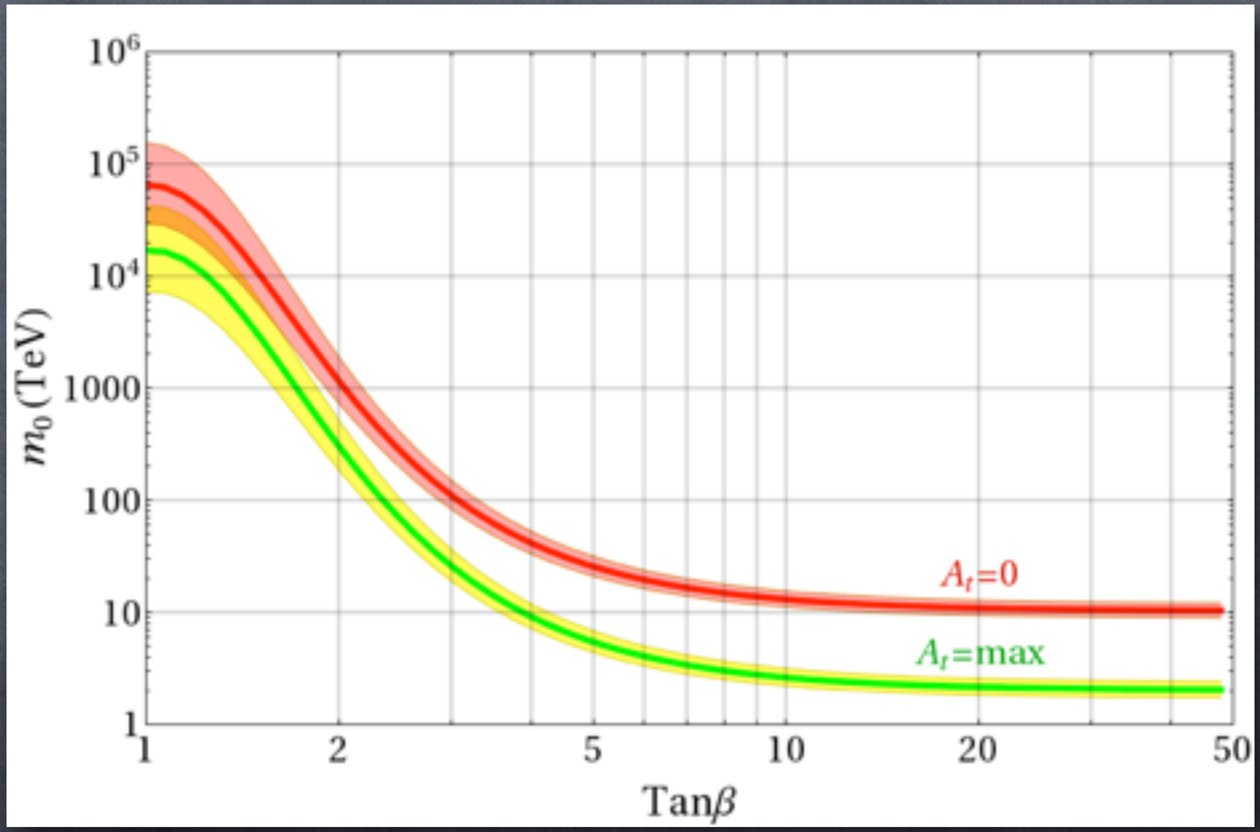
scalars

- Successes of the MSSM
  - Gauge coupling unification
  - Natural dark matter candidate (with R-parity)

fermions

Back to the MSSM

Sfermion (stop) masses from m_H = 126 GeV



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Composite Higgs models

Ingredients for a (appealing) strongly interacting solution of the naturalness problem

- The Higgs is a composite object (made of fermions) arising from new strong interactions at Λ_{strong}

  Radiative corrections to Higgs mass cut-off by Higgs form factor at Λ_{strong}

$$\delta m_h^2 \sim 12 \frac{\lambda_t^2}{(4\pi)^2} \Lambda^2_{\text{strong}}$$

  Analogy: pions, mesons, baryons arise from QCD interactions "at" Λ_{QCD}

- EWPT: Λ_{strong} > 5 TeV (just a reference scale)

  Why $m_H \ll \Lambda_{\text{strong}}$? The Higgs is a pNG boson

  Analogy: $m_\pi \ll \Lambda_{\text{QCD}}$

- Trouble with flavour: partial compositeness

Technical tool

- Strong interacting theory not calculable (e.g. QCD)

- Effective lagrangian for pNG bosons below Λ_{strong}

  Coleman Wess Zumino PRD 177 1969
  Callan Coleman Wess Zumino PRD 177 1969

Manohar 9606222
Colangelo Isidori 0101264
Ecker 9501357
Contino 1005.4269

- The lagrangian is independent of the strong theory (only the spontaneous breaking pattern matters), most often not specified

Minimal composite Higgs models

- Pseudo Goldstone bosons below Λ_{strong}: G_1 G_2 G_3 φ
- $\mathscr{L}_{\text{SM}}$ is a special case: contains G^+ G^- G^0 φ through

$$H = \begin{pmatrix} G^+ \\ v + \dfrac{\varphi + iG^0}{\sqrt{2}} \end{pmatrix}$$

1. General form of $\mathscr{L}$ as dictated by CCWZ for G_a from $SU(2) \times U(1) \to U(1)_{em}$
2. General form of $\mathscr{L}$ as dictated by CCWZ assuming H from $SO(5) \to SO(4)$

How does SUSY compares with composite Higgs?

- "Natural" susy: $\Delta \sim 35 \left(\frac{\tilde{m}_t}{\mathrm{TeV}}\right)^2 \left[\frac{\log(M/\tilde{m}_t)^2}{\log(100\,\mathrm{TeV}/\tilde{m}_t)^2}\right]$

- Composite Higgs: $\Delta \sim 100 \left(\frac{\Lambda}{5\,\mathrm{TeV}}\right)^2$ (if resonances ≈ compositeness scale Λ > 5 TeV)

- But $m_h^2 = \delta m_h^2$ needs $m_{res} \sim$ 1 TeV < 5 TeV:

$$\Delta \sim 13 \left(\frac{m_{\rm res}}{\mathrm{TeV}}\right)^2 \left[\frac{\log(\Lambda/m_{\rm res})^2}{\log(5\,\mathrm{TeV}/m_{\rm res})^2}\right] \times ?$$

- Gain log (100TeV)/(5TeV), loose possible fine-tuning to get m_{res} < 5 TeV