Behind!

~~Beyond~~ the Standard Model

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SUSY and Naturalness

Recall the Naturalness argument:

$$m_H^2 = \int_0^\infty dE \frac{dm_H^2}{dE}(E; p_{\mathrm{FT}}) = \int_0^{\lesssim \Lambda_{\mathrm{SM}}} dE(\ldots) + \int_{\lesssim \Lambda_{\mathrm{SM}}}^\infty dE(\ldots)$$

$$= \delta_{\mathrm{SM}} m_H^2 + \delta_{\mathrm{BSM}} m_H^2$$

Problem: $\delta_{\mathrm{SM}} m_H^2 = \frac{3y_t^2}{8\pi^2}\Lambda_{\mathrm{SM}}^2$

SUSY and Naturalness

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Low Higgs mass-term is Un-Natural because:

1. has dimension $2 > 0$ (given that $[H^\dagger H] = 2 < 4$)
2. is **not protected** by a symmetry

If any of the two was violated, no Naturalness problem.

SUSY and Naturalness

For example, consider the Yukawa couplings:

$$y = \int_0^\infty dE \frac{dy}{dE}(E; p_{\mathrm{FT}}) = \int_0^{\lesssim \Lambda_{\mathrm{SM}}} dE(\ldots) + \int_{\lesssim \Lambda_{\mathrm{SM}}}^\infty dE(\ldots)$$

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SM gains Flavor symmetry if $y = 0$

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$y_{d,e,\ldots} \ll y_t$ **is Natural**

that's why flavor origin might be at $\Lambda_{\rm SM} \gg \mathrm{TeV}$

SUSY and Naturalness

Other example: a **fermion with mass** (allowed by EW)

$$m_F = \int_0^\infty dE \frac{dm_F}{dE}(E; p_{\rm FT}) = \int_0^{\lesssim\Lambda} dE(\ldots) + \int_{\lesssim\Lambda}^\infty dE(\ldots)$$

$$= \delta_{\rm IR} m_F + \delta_{\rm UV} m_F$$

theory with new fermion is not the SM, Λ is its own cutoff.

Problem? $\delta_{\rm IR} m_F \overset{?}{\simeq} \dfrac{g^2}{16\pi^2}\Lambda$ **is allowed by dim. analysis.**

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$m_F \ll \Lambda$ **is Natural.**

Fermions can be **Naturally light**

SUSY and Naturalness

In SUSY: **Bosons = Fermions** ➡ $m_H \overset{\text{SUSY}}{=} m_F$

SUSY scalars can be Naturally light

Let us see how this works, focusing on top contribution

SM fields:		**Chiral SFs:**
h		$\Phi_h = \{h, \widetilde{h}\ \text{(Higgsino)}\}$
t_L	➡	$\Phi_{t_L} = \{t_L, \widetilde{t}_L\ \text{(stop Left)}\}$
t_R		$\Phi_{t_R} = \{t_R^c, \widetilde{t}_R^\dagger\ \text{(stop Right)}\}$

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Superpotential: $W[\Phi] = \dfrac{y_t}{\sqrt{2}} \Phi_h \Phi_{t_L} \Phi_{t_R}$

SM Yukawa:

$$-\frac{1}{2}\frac{\partial^2 W}{\partial \Phi_i \partial \Phi_j}\psi^i \psi^j = -\frac{y_t}{\sqrt{2}}\, h\, t_L t_R^c + \dots$$

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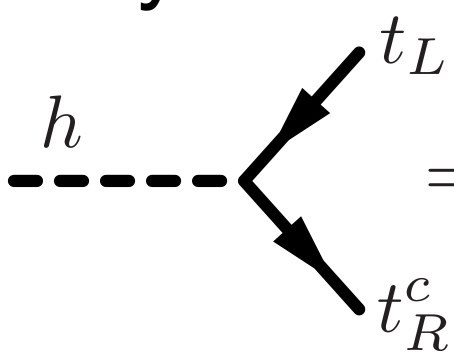
F-term potential:

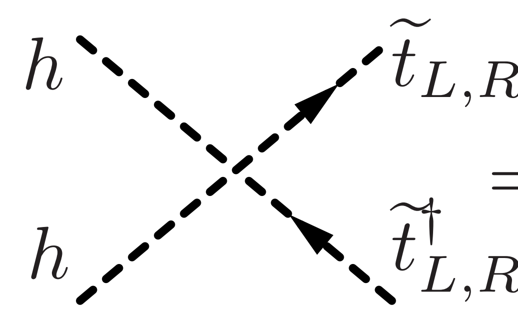
$$-\left|\frac{\partial W}{\partial \Phi_i}\right|^2 = -\frac{y_t^2}{2}\, h^2\,[|\widetilde{t}_L|^2 + |\widetilde{t}_R|^2] + \ldots$$

SUSY and Naturalness

The Feynman rules are:



$$= i\frac{y_t}{\sqrt{2}}$$



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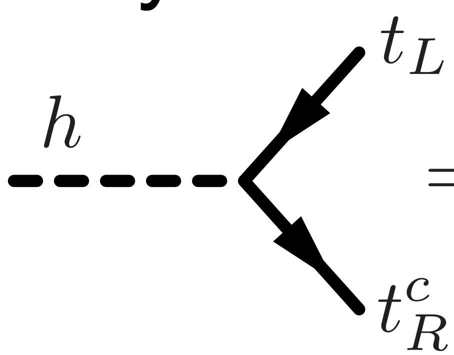

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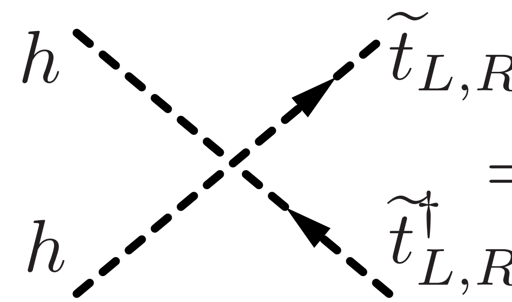

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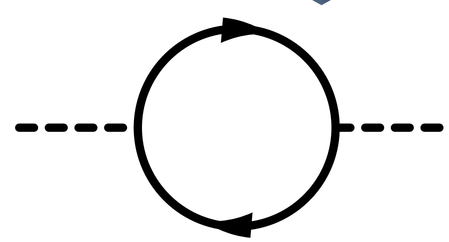
$\delta_{\mathrm{IR}} m_H^2 = \int_0^{\lesssim\Lambda} dE \, \Big[$  $+$  $\Big]$

$$= \frac{3}{8\pi^2}\Lambda^2 \left[y_t^2 - \widetilde{y}_t^2\right]$$

SUSY and Naturalness

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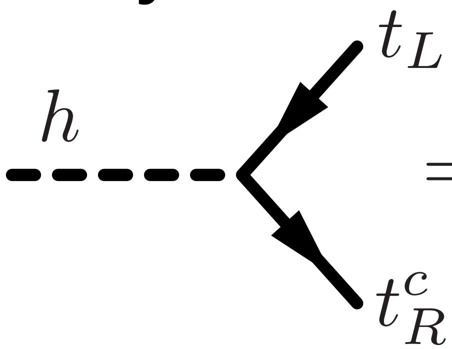

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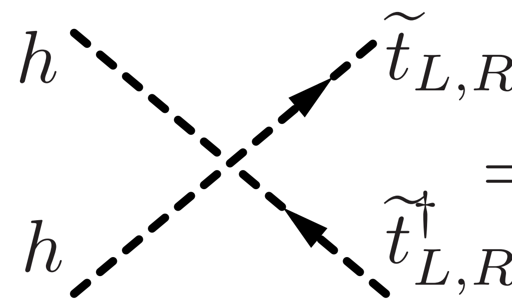

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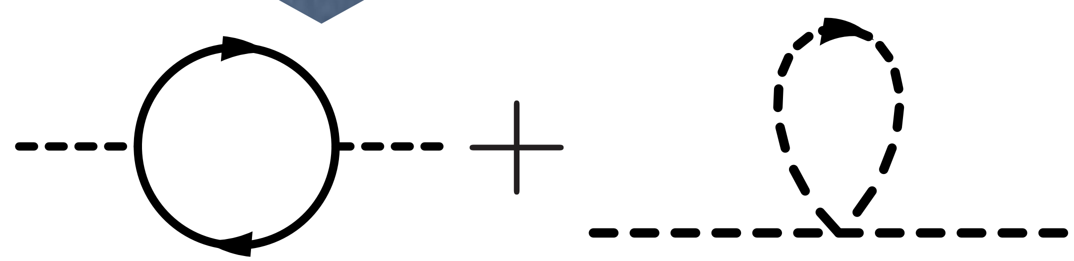

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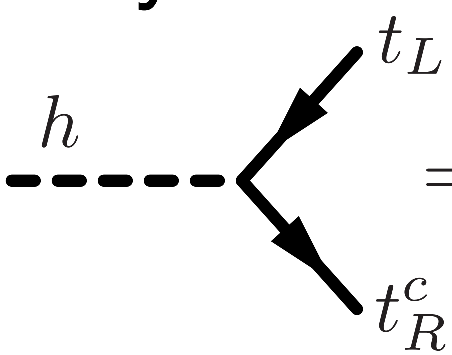

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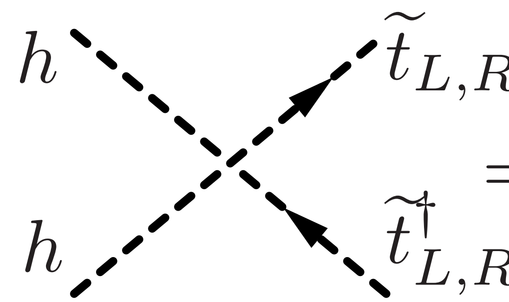

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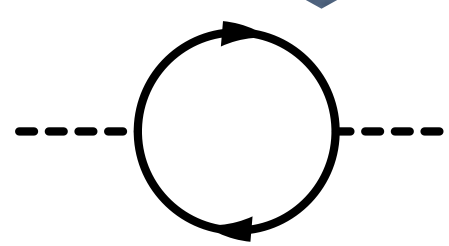

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time to celebrate?

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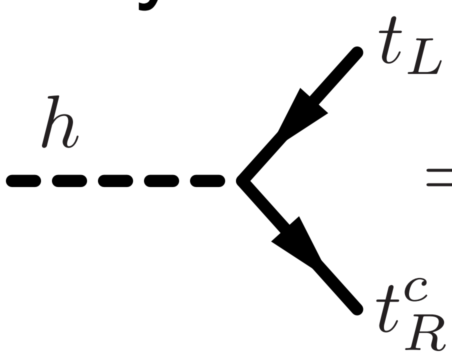

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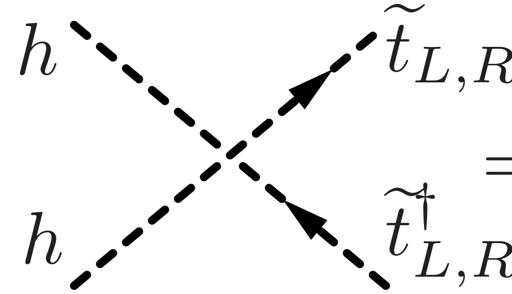

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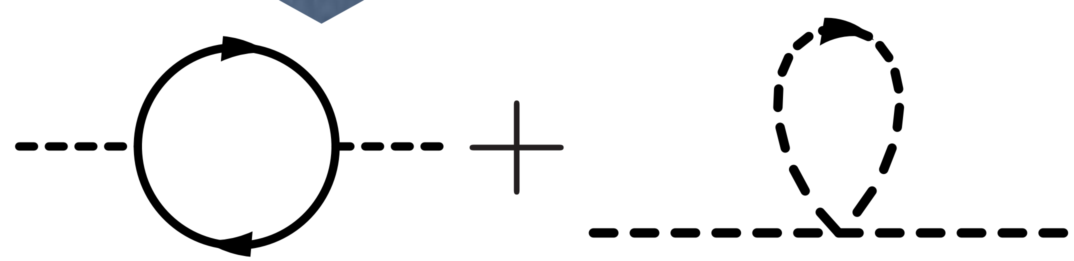

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not yet ...

SUSY and Naturalness

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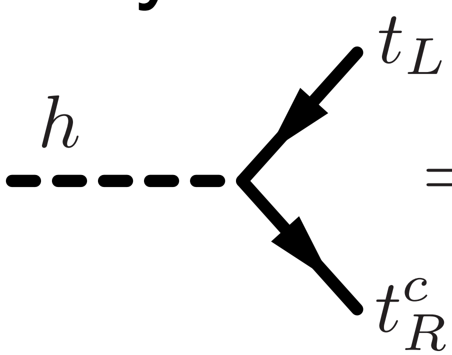

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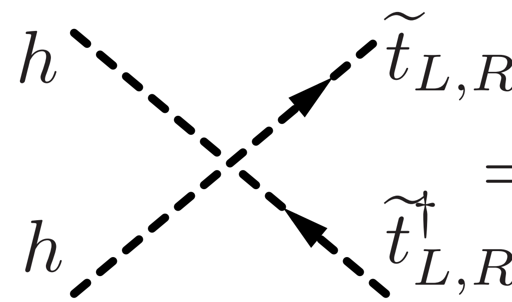

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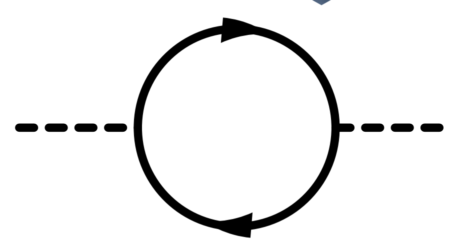

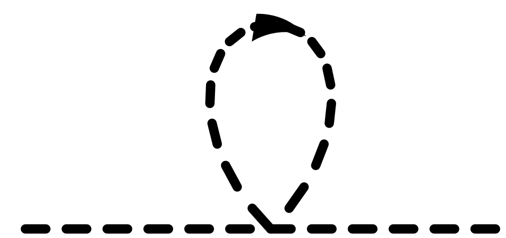

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We must break SUSY, easy to do it preserving Naturalness

Add **stop mass-term** $M_{\widetilde{t}}^2 |\widetilde{t}_{L,R}|^2$, and use **dim. an.:**

$$\delta_{\text{IR}} m_H^2 \simeq \frac{3}{8\pi^2}\Lambda^2 \cancel{\left[y_t^2 - \widetilde{y}_t^2\right]} + \frac{3y_t^2}{8\pi^2} M_{\widetilde{t}}^2 \log(\Lambda/M_{\text{EW}})$$

SUSY and Naturalness

SOFT BREAKING

all terms that break SUSY preserving Naturalness

- scalar mass terms $-m^2_{\phi_i}\,|\phi_i|^2$, and
- trilinear scalar interactions $-A_{ijk}\phi_i\phi_j\phi_k + h.c.$
- gaugino mass terms $-\frac{1}{2}m_l\bar{\lambda}_l\lambda_l$, where l again labels the group factor;
- bilinear terms $-B_{ij}\phi_i\phi_j + h.c.$; and
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only d>0 ~~SUSY~~ parameters (not all d>0)

for sure you **cannot** have $y_t \neq \widetilde{y}_t$.

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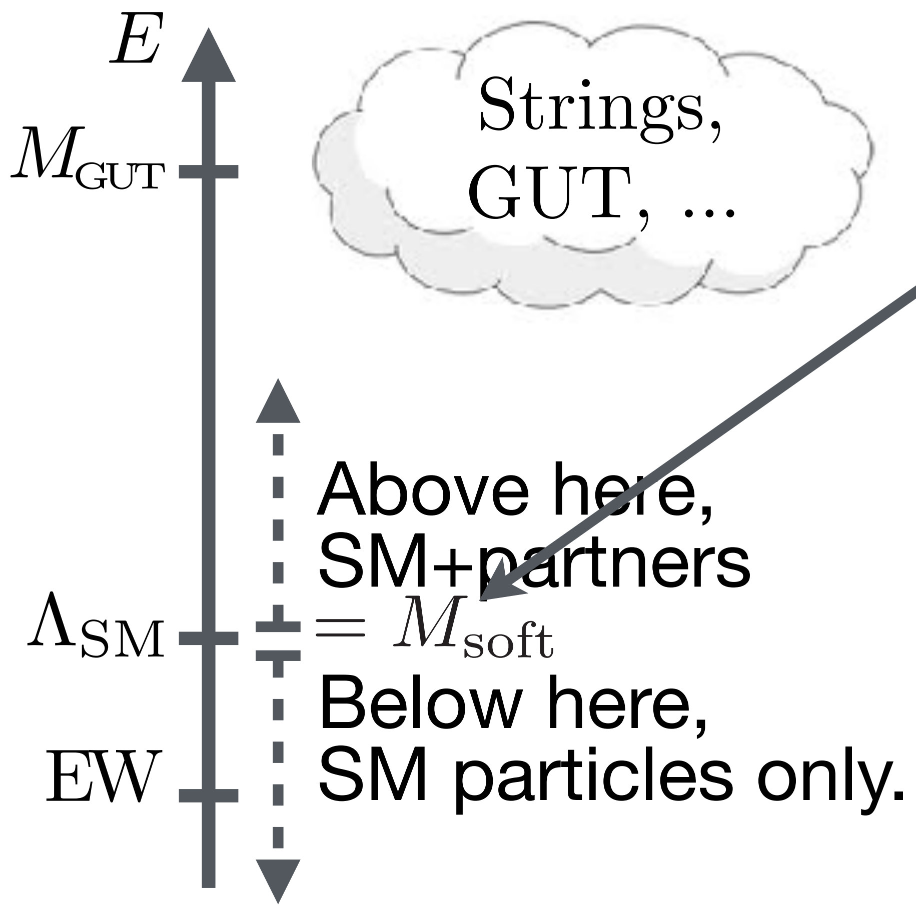
SUSY and Naturalness

The **"low-energy SUSY"** picture for high energy physics



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SUSY and Naturalness

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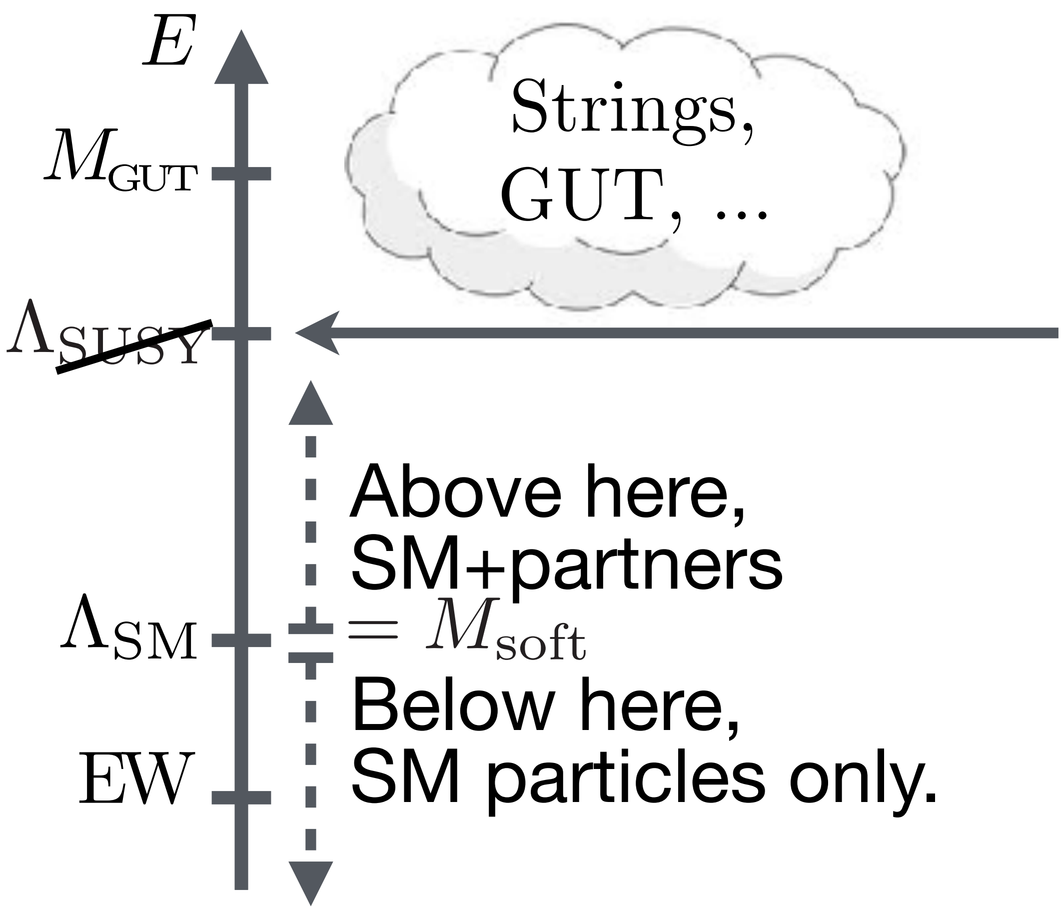

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SUSY and Naturalness

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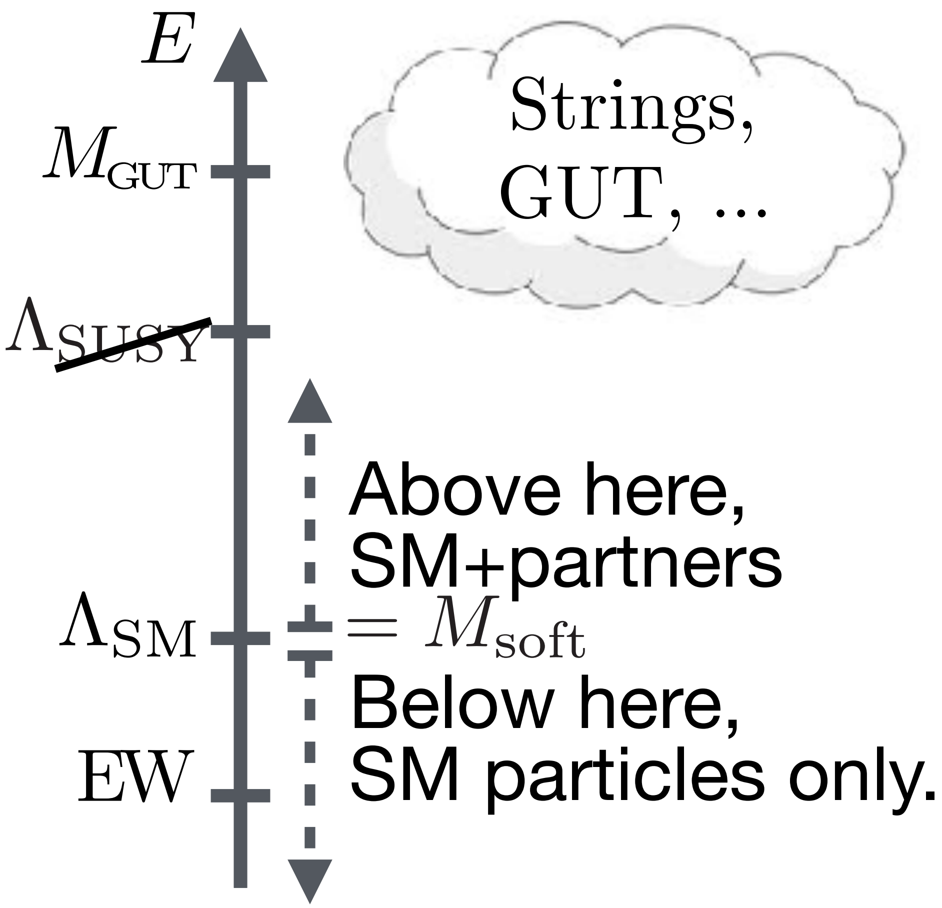

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$$\delta m_H^2 \sim \frac{3y_t^2}{8\pi^2} M_{\rm soft}^2 \log(\Lambda_{\cancel{\rm SUSY}}/M_{\rm EW})$$

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\,\mathrm{GeV}}{m_H}\right)^2 \left(\frac{M_{\rm soft}}{500\,\mathrm{GeV}}\right)^2 \log(\Lambda_{\cancel{\rm SUSY}}/M_{\rm EW})$$

Natural SUSY cannot hide above the TeV scale.

SUSY and Naturalness

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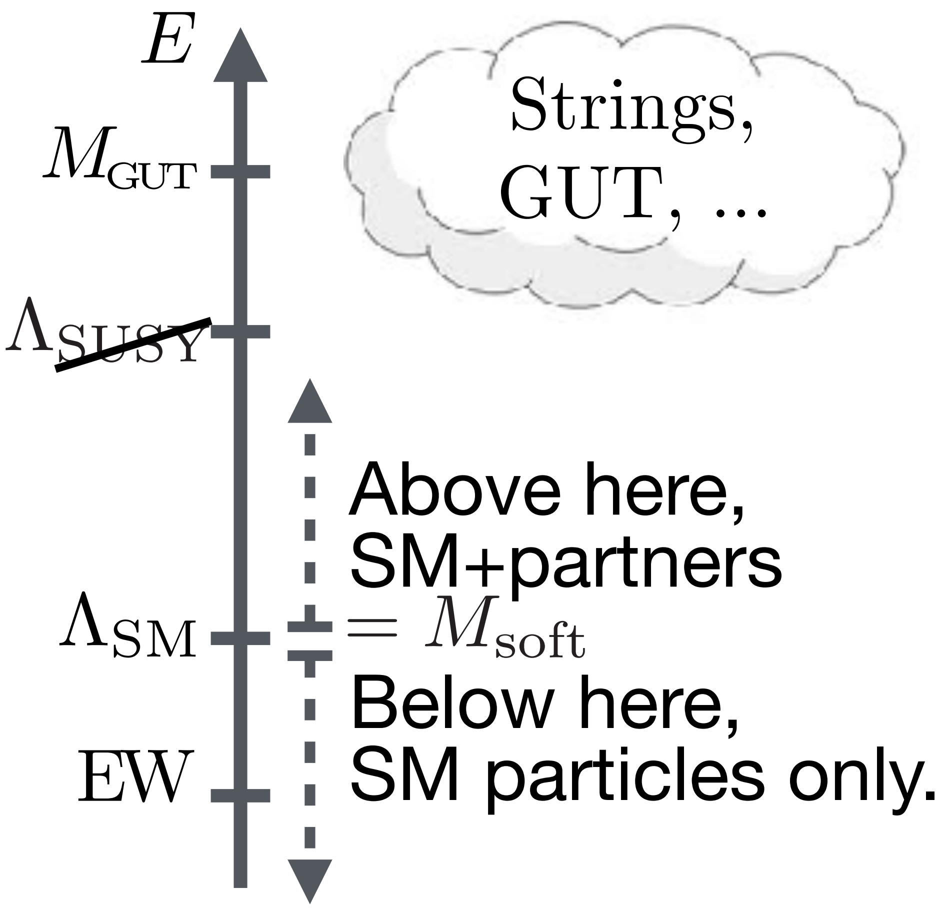

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Natural SUSY cannot hide above the TeV scale.
General tuning estimate **worsened** by the log term.

Other virtues of SUSY

SUSY and GUT:

SM gauge group can be viewed as the subgroup of one single **simple (1 coupling constant) Lie group:**

e.g.

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \subset \mathrm{SU}(5)$$

or

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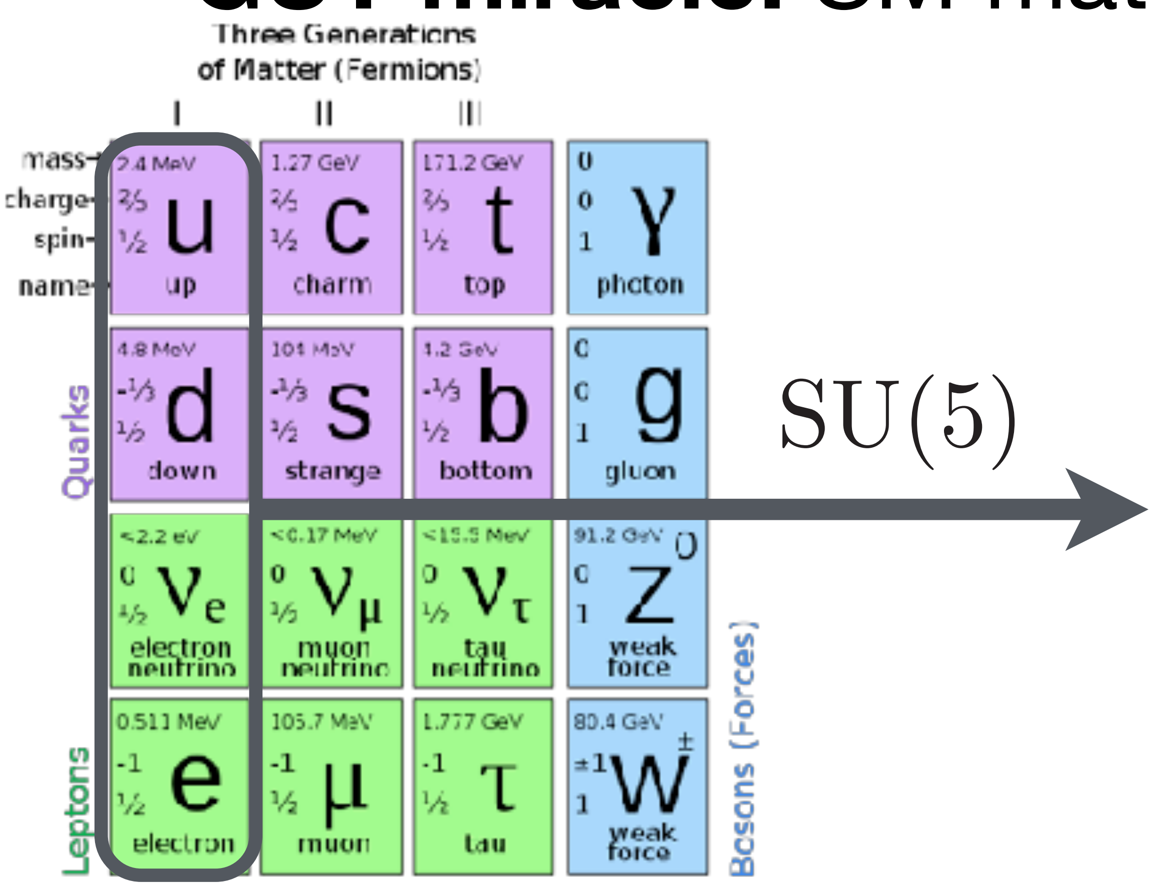
GUT miracle: SM matter fits in GUT group multiplets



$$\mathbf{5} = \{[d_R^c]^{\alpha_c}, L_L\}$$

$$\mathbf{10} = \{[u_R^c]^{\alpha_c}, [u_L]^{\alpha_c}, [d_L]^{\alpha_c}, e_R^c\}$$

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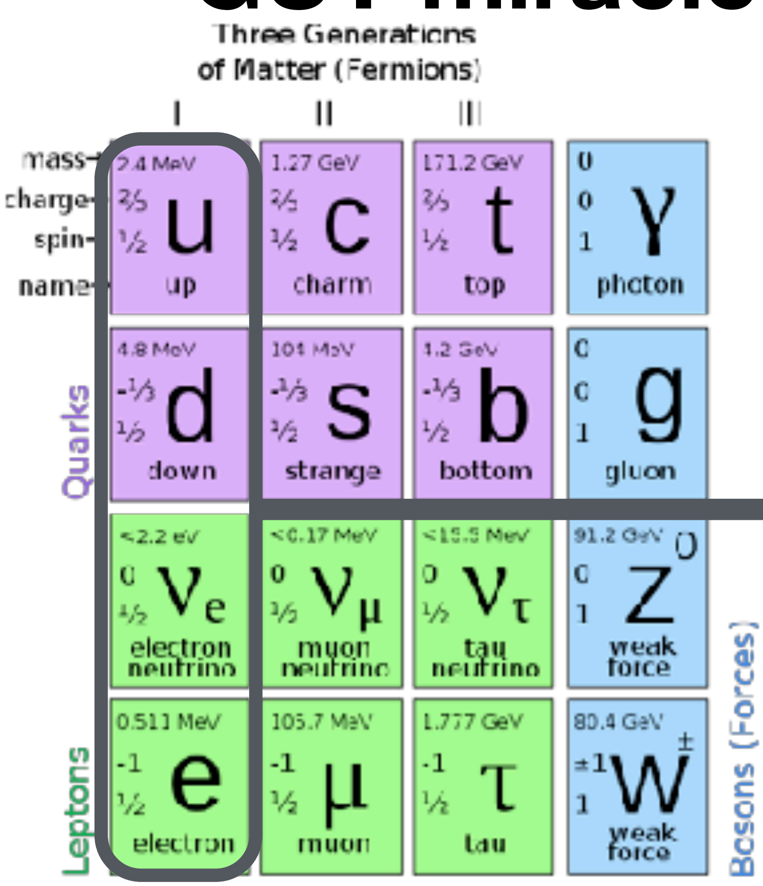

$$\xrightarrow{\mathrm{SO}(10)} \mathbf{16} = \{[u_R^c]^{\alpha_c}, [d_R^c]^{\alpha_c}, [u_L]^{\alpha_c}, [d_L]^{\alpha_c}, L_L, e_R^c, \nu_R^c\}$$

Other virtues of SUSY

The 3 gauge forces might have a **common origin!**

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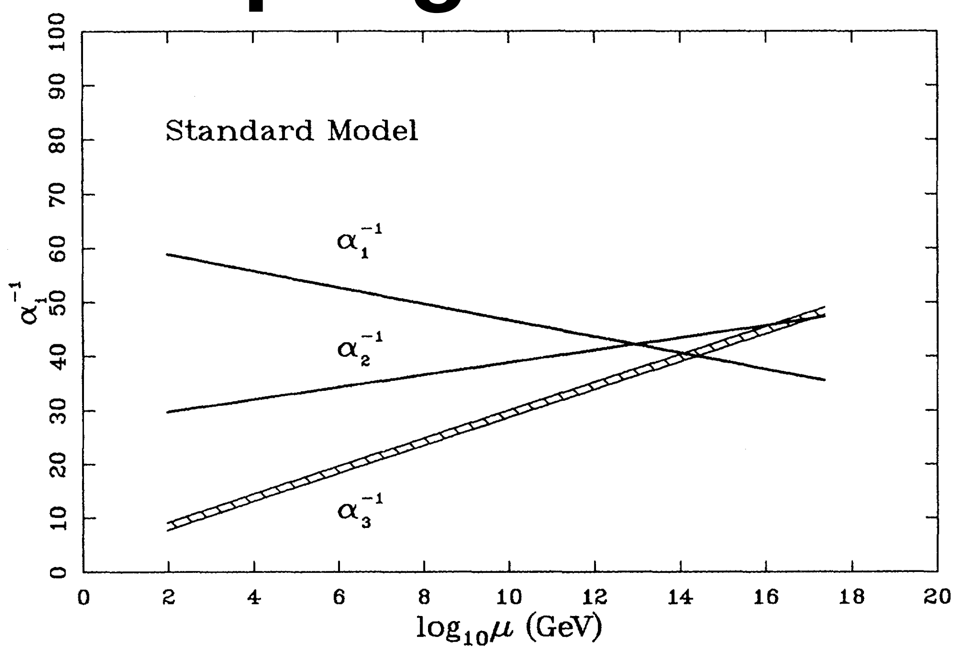
The 3 gauge forces might have a **common origin!**
For this being true:

1. **Couplings must unify:**



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Other virtues of SUSY

The 3 gauge forces might have a **common origin!**
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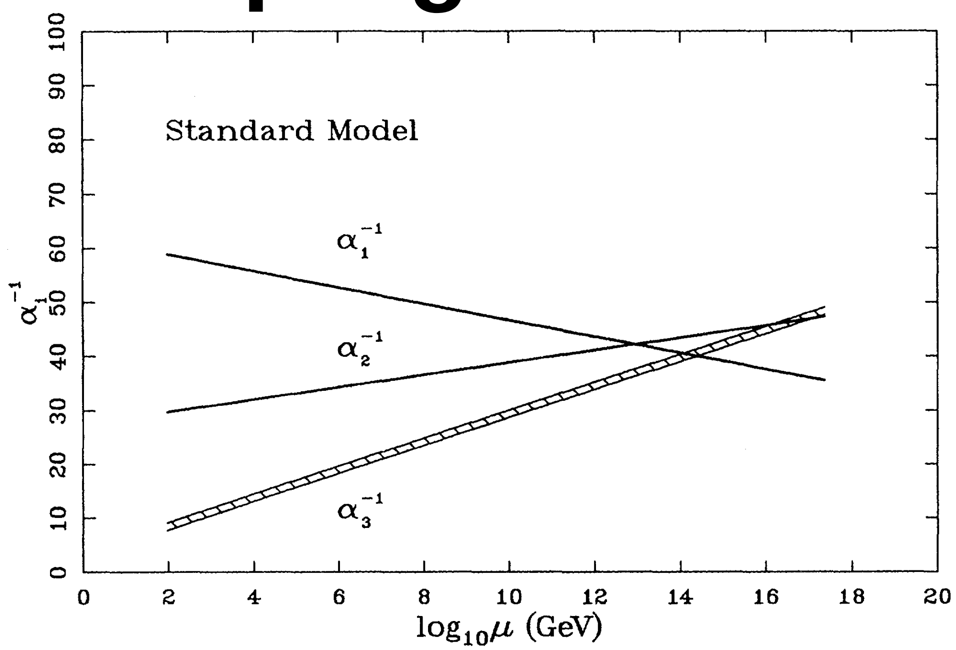

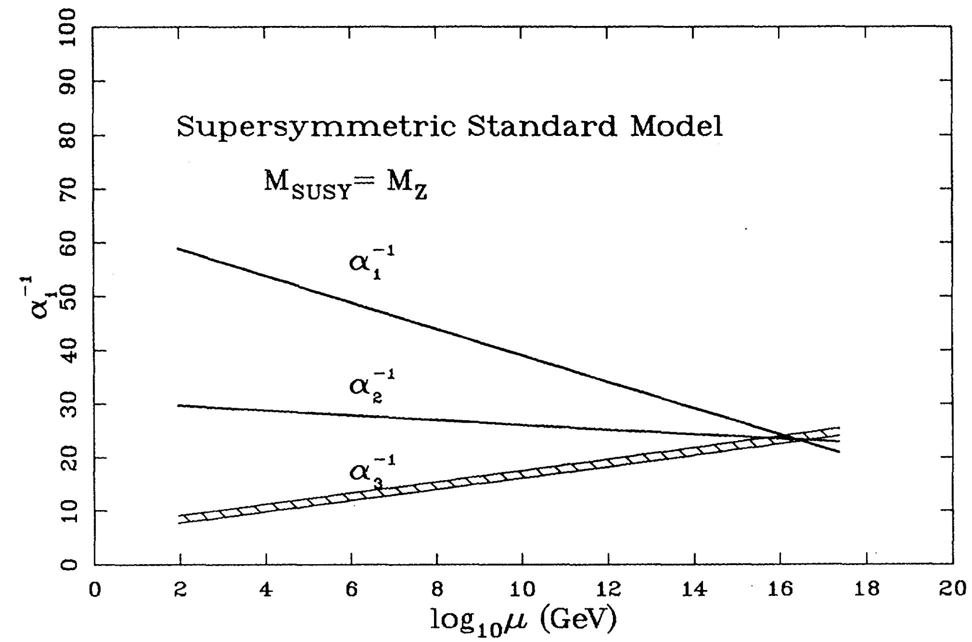

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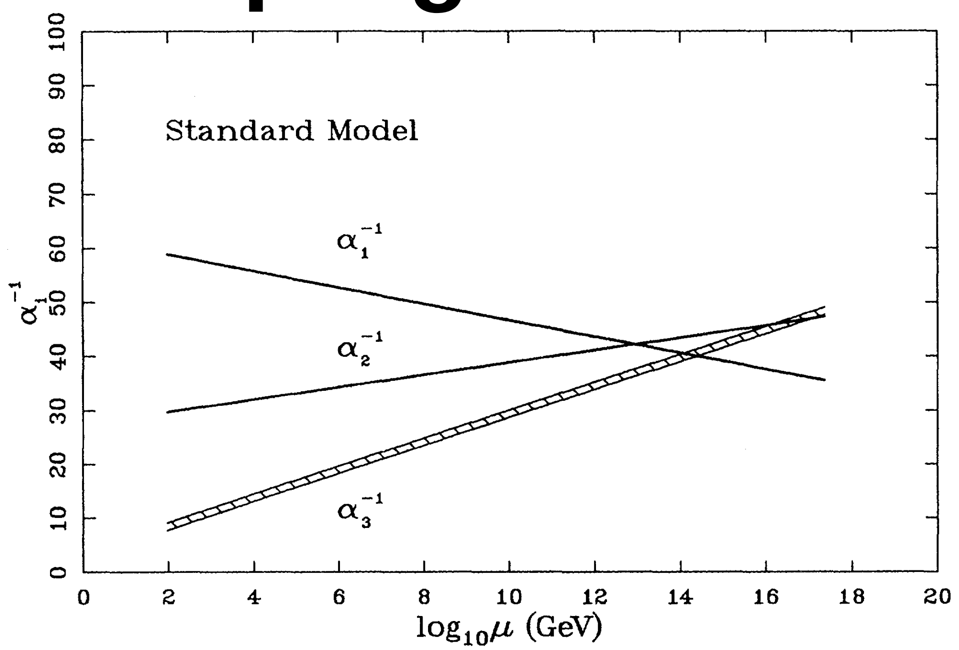

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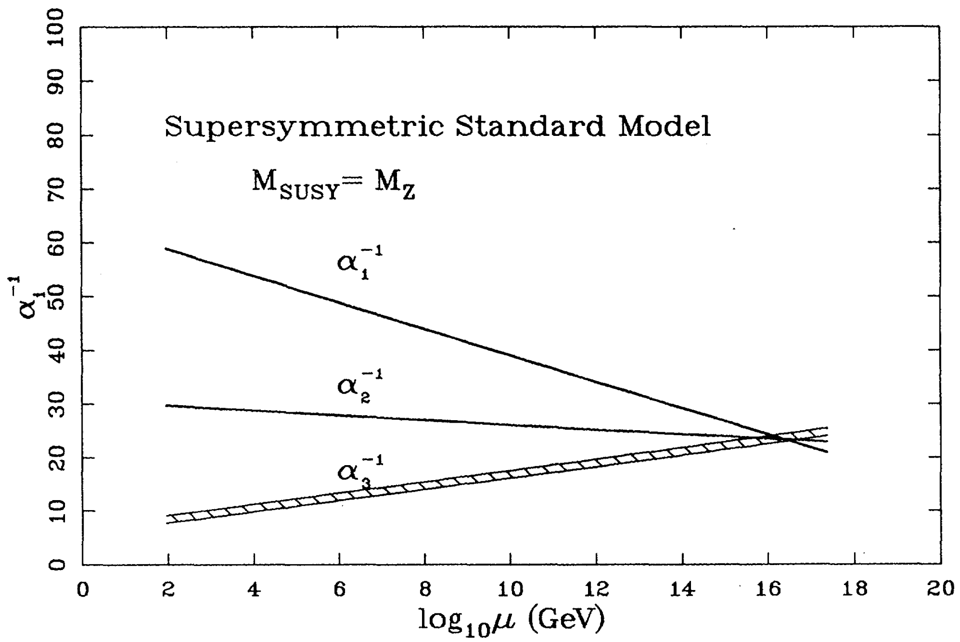

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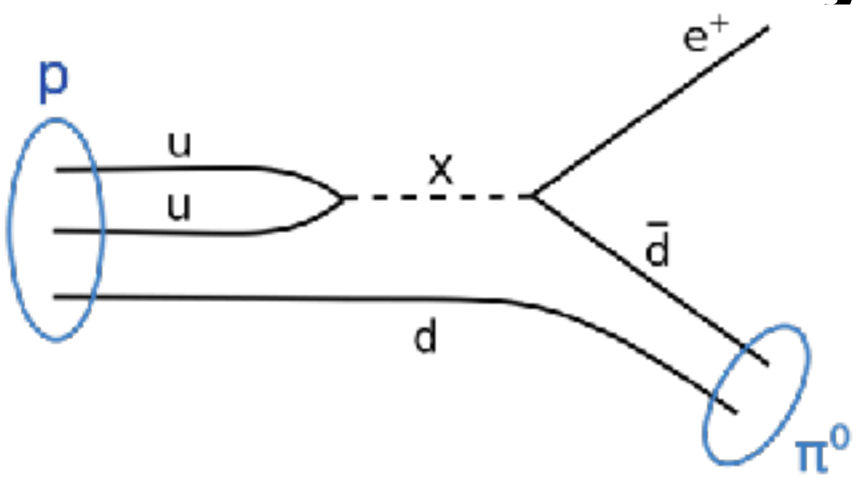
2. **Proton must decay:**



$$\tau(p \to \pi^0 e^+) \sim 10^{34}{\rm years}\left(\frac{3\,10^{15}{\rm GeV}}{M_{\rm GUT}}\right)^4$$

GUT excluded in SM.
Viable in SUSY-SM

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SUSY, R-Parity and DM: (or, how a problem turns in a virtue)

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$$\theta \to -\theta$$

$$\mathrm{SF}_{\mathrm{matter}} \to -\mathrm{SF}_{\mathrm{matter}} \qquad \mathrm{SF}_{\mathrm{Higgs,gauge}} \to +\mathrm{SF}_{\mathrm{Higgs,gauge}}$$

$$\Phi = \phi(y) + \sqrt{2}\theta\psi(y) - \theta\theta F(y)$$

$$V = \theta\sigma^\mu\overline{\theta}A_\mu(x) + i\theta\theta\overline{\theta\lambda}(x) - i\overline{\theta\theta}\theta\lambda(x) + \frac{1}{2}\theta\theta\overline{\theta\theta}D(x)$$

SM particles are **EVEN**
Associated **Sparticles are ODD**

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$\Downarrow$

Virtue: lightest SUSY particle (**LSP**) is **stable**
(can be DM, thanks to WIMP Miracle)

Summary

Low-energy SUSY provides:

1. A **Natural** theory
2. Viable **GUT**
3. A **Dark Matter** Candidate
4. A **string-friendly** UV picture

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In these lectures I hope to convince you that supersymmetry (SUSY)[1] will soon provide you with a whole new spectroscopy to investigate. Indeed, it may even be that experiments[2,3] are already starting to reveal this spectroscopy to us.

From John Ellis’ lecture notes:

SUPERSYMMETRY --SPECTROSCOPY OF THE FUTURE?

OR OF THE PRESENT?

1984

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“If SUSY will not be found at LEP, I will **cut my ba…**”

Riccardo Barbieri
private communication (secondhand)
circa 1989

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But life is not that easy…

The SUSY Higgs

In SUSY, fields are promoted to **SuperFields.**
One would thus naively expect:

SM Higgs field → **SUSY Higgs SF**

$H \in \mathbf{2_{1/2}}$ → $\Phi \in \mathbf{2_{1/2}}$

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$$\mathcal{L}_\mathrm{Y}^\mathrm{u} = y_\mathrm{u} q_L H u_R^c \qquad\qquad \mathcal{L}_\mathrm{Y}^\mathrm{d} = y_\mathrm{d} q_L H^c d_R^c$$

$$\mathbf{2}_{\mathbf{1/6}} \otimes \mathbf{2}_{\mathbf{1/2}} \otimes \mathbf{1}_{\mathbf{-2/3}} \supset \mathbf{1}_{\mathbf{0}} \qquad\qquad \mathbf{2}_{\mathbf{1/6}} \otimes \mathbf{2}_{\mathbf{-1/2}} \otimes \mathbf{1}_{\mathbf{1/3}} \supset \mathbf{1}_{\mathbf{0}}$$

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$$\Downarrow \qquad\qquad \Downarrow$$

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The SUSY Higgs**es** scalar potential:

$$
\begin{aligned}
V[H_{\mathrm{u}}, H_{\mathrm{d}}] &= \mu^2 \left[|H_{\mathrm{u}}|^2 + |H_{\mathrm{d}}|^2\right] \\
&+ \frac{g^2 + g'^2}{8} \left[|H_{\mathrm{u}}|^2 - |H_{\mathrm{d}}|^2\right]^2 + \frac{g^2}{2}|H_{\mathrm{u}}^\dagger H_{\mathrm{d}}|^2 \\
&+ m_{\mathrm{u}}^2|H_{\mathrm{u}}|^2 + m_{\mathrm{d}}^2|H_{\mathrm{d}}|^2 + B\left[H_{\mathrm{u}} H_{\mathrm{d}} + H_{\mathrm{u}}^* H_{\mathrm{d}}^*\right]
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F-Term ($|\partial W/\partial \Phi|^2$)
from
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EW int. + SUSY

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Particular case of generic 2 Higgs doublet model

The SUSY Higgs

Four implications of the SUSY Higgs sector structure

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Implication #0: (actually 5 impl.) vacuum is **viable**
(no e.m., color, L and B breaking)

The SUSY Higgs

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Implication #1: both Higgses take VEV

$$\langle |H_{\rm u}|^2 \rangle = \frac{v_{\rm u}^2}{2} \qquad \langle |H_{\rm d}|^2 \rangle = \frac{v_{\rm d}^2}{2}$$

2 sources of EWSB $\Longrightarrow$ $v_{\rm u}^2 + v_{\rm d}^2 = v^2 = (246 \mathrm{GeV})^2$

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Abbreviations:
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Both Higgses **must** take VEV, for u and d-type masses:

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For $y_\mathrm{u,d} < 4\pi$ (perturbative): $0.08 \simeq \frac{y_\mathrm{top}^\mathrm{SM}}{4\pi} \lesssim t_\beta \lesssim \frac{4\pi}{y_\mathrm{bot}^\mathrm{SM}} \simeq 500$

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #2: **many scalars** around

In Unitary Gauge

$$H_{\mathrm{u}} = \begin{bmatrix} 0 \\ \frac{v_{\mathrm{u}} + h_{\mathrm{u}}}{\sqrt{2}} \end{bmatrix} + \begin{bmatrix} c_\beta H_+ \\ c_\beta \frac{iA}{\sqrt{2}} \end{bmatrix} \qquad H_{\mathrm{d}} = \begin{bmatrix} \frac{v_{\mathrm{d}} + h_{\mathrm{d}}}{\sqrt{2}} \\ 0 \end{bmatrix} + \begin{bmatrix} s_\beta \frac{iA}{\sqrt{2}} \\ s_\beta H_- \end{bmatrix}$$

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$H_+=(H_-)^*$**:** one **charged** scalar

A **:** one **neutral** pseudo-scalar (CP-odd)

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$h_{\rm u,d}$: two **neutral** scalars

$$\begin{bmatrix} h_{\rm u} \\ h_{\rm d} \end{bmatrix} = \begin{bmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} h \\ H \end{bmatrix}$$

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The Higgs we saw
$m_h = 125\,\mathrm{GeV}$

The Other Higgs
(maybe heavier)

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #3: **modified Higgs couplings**

$$\kappa_{\mathrm{u}} = \frac{g_{h\mathrm{uu}}}{g_{h\mathrm{uu}}^{\mathrm{SM}}} = \frac{\sin(\alpha + \pi/2)}{\sin\beta}$$

$$\kappa_{\mathrm{d}} = \frac{g_{h\mathrm{dd}}}{g_{h\mathrm{dd}}^{\mathrm{SM}}} = \frac{\cos(\alpha + \pi/2)}{\cos\beta}$$

$$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{\mathrm{SM}}} = \sin(\beta - \alpha)$$

The form of the potential allows us to express α in terms of β and of the pseudo-scalar A mass:

$$\tan\alpha = \frac{(m_A^2 + m_Z^2)t_\beta}{m_h^2(1 + t_\beta^2) - m_Z^2 - m_A^2 t_\beta^2}$$

The SUSY Higgs

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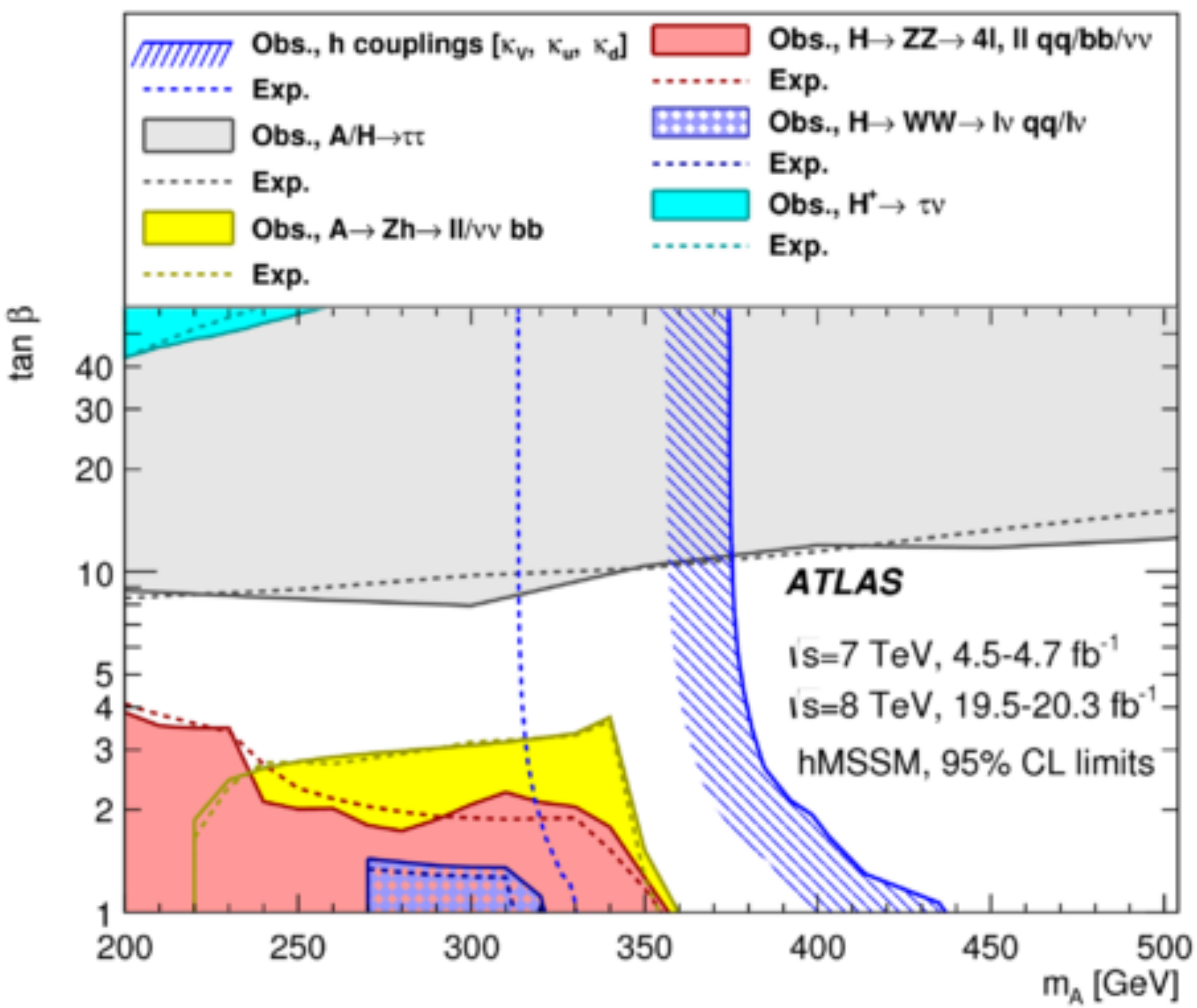

ATLAS arXiv:1509.00672

Direct scalar searches play an important role in this plane.

The SUSY Higgs

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Decoupling limit: $m_{\rm d}^2 \to \infty$ (technically natural)

$$m_A^2 = m_{\rm d}^2 + \ldots \to \infty \Rightarrow \tan\alpha \simeq -\frac{1}{t_\beta}$$

The SUSY Higgs

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$m_A^2 = m_{\rm d}^2 + \ldots \to \infty$ ➡ $\tan\alpha \simeq -\dfrac{1}{t_\beta}$ ➡ $\alpha \simeq \beta - \pi/2$ ➡ **SM Higgs**

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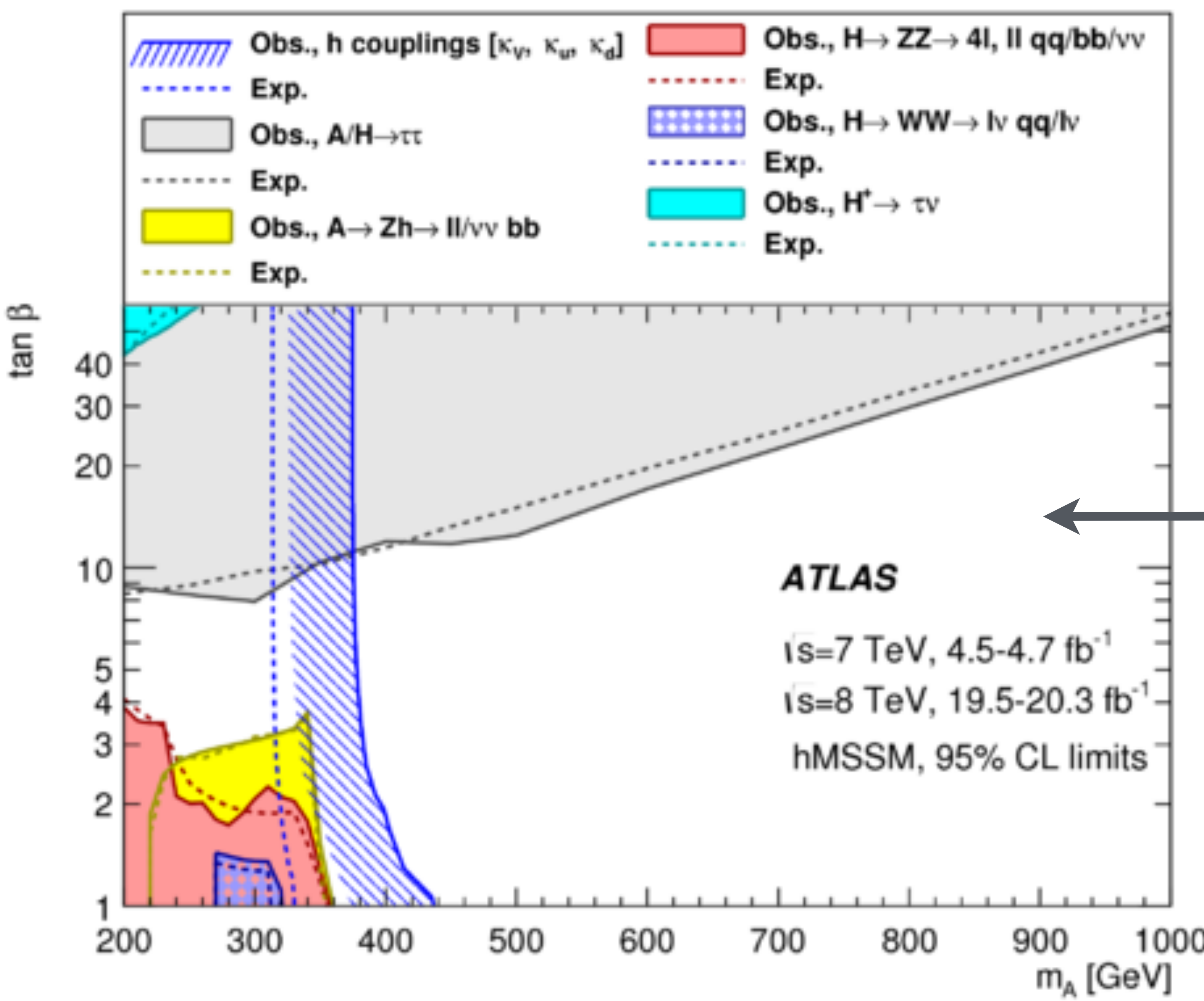
In the limit we also have: $\sin 2\beta = \dfrac{2B}{m_A^2} \Rightarrow t_\beta \simeq \dfrac{m_A^2}{B} \to \infty$

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #3: **modified Higgs couplings**



ATLAS arXiv:1509.00672

Huge decoupling limit region is **technically natural**.

The SUSY Higgs

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Problem: λ is too small. **Solution:** increase λ.

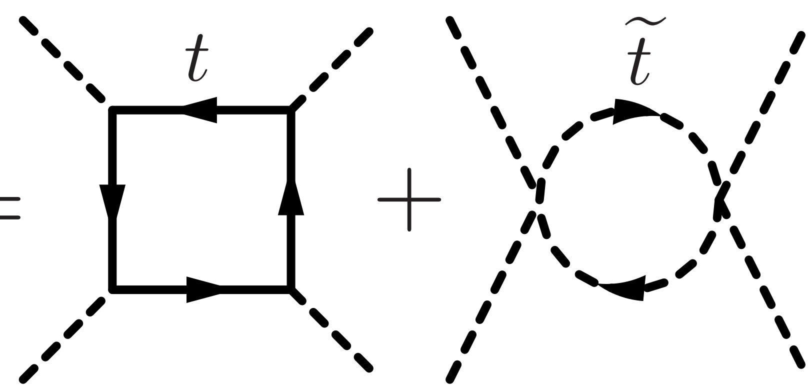
$$\lambda \to \lambda + \delta\lambda \qquad \delta\lambda = \frac{m_H^2 - m_Z^2}{2v^2} \simeq 0.06$$

The SUSY Higgs

Two ways to increase λ :

First way: **rely on large loop corrections** (only way in MSSM)

$$\delta\lambda =$$



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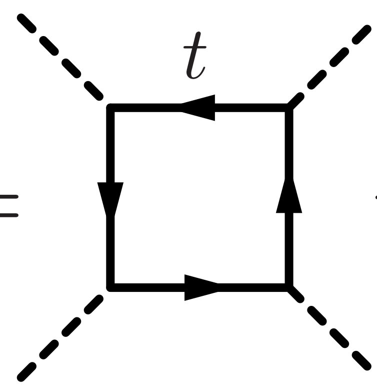
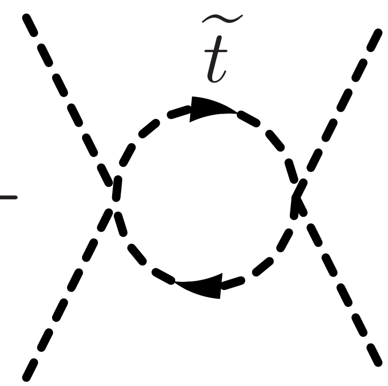
$\delta\lambda =$  $+$  $\sim \dfrac{3y_t^4}{8\pi^2} \log \dfrac{M_{\tilde{t}}}{m_t}$

Need **exponentially heavy stops …** (use $y_t \simeq 0.94$)

$$M_{\tilde{t}} \sim m_t e^{\frac{8\pi^2 \delta\lambda}{3y_t^2}} \sim 1.3\ \text{TeV}$$

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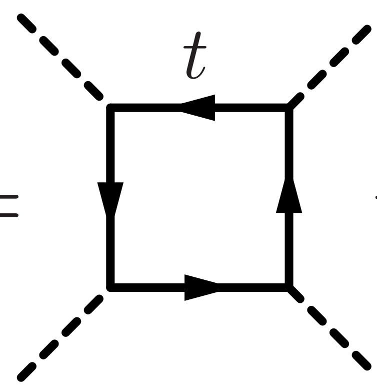

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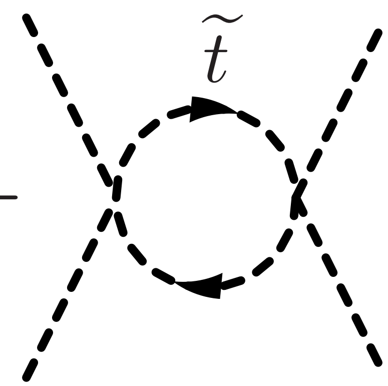

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… which is **exponentially bad for tuning:**

$$\Delta \geq \left(\frac{M_{\rm soft}}{500\ \mathrm{GeV}}\right)^2 \log(\Lambda_{\cancel{\rm SUSY}}/M_{\rm EW})$$

low $\Lambda_{\cancel{\rm SUSY}}$ = 10 TeV

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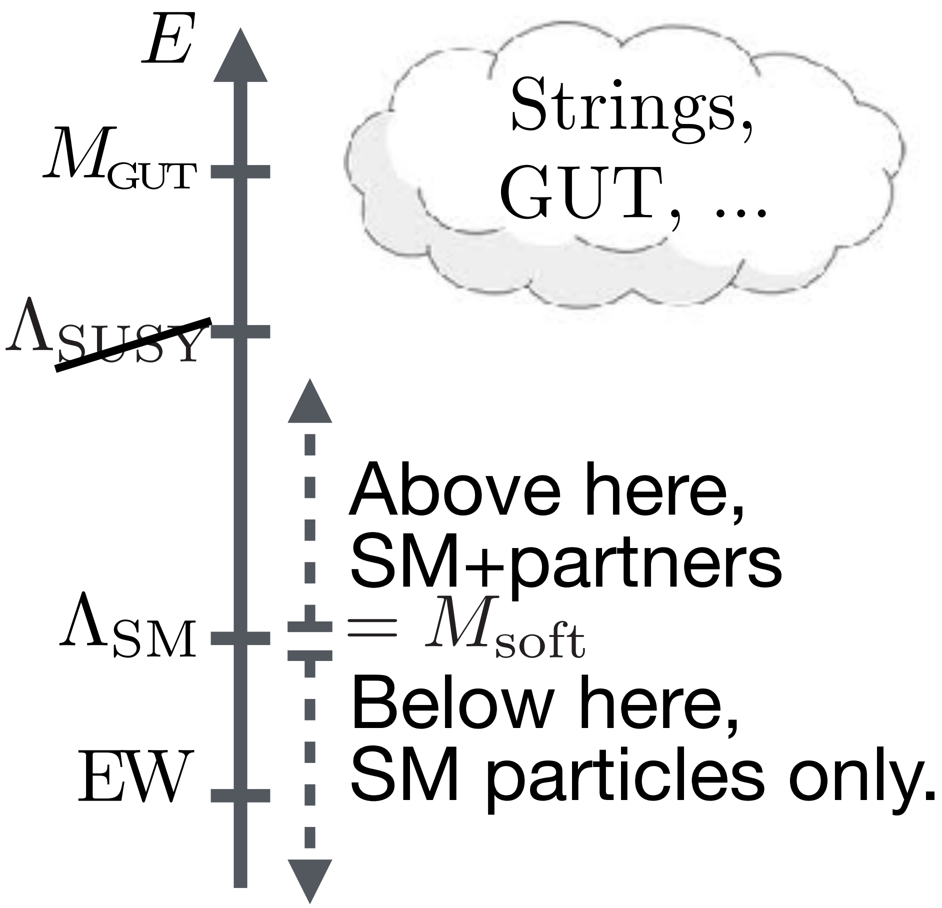
SUSY and Naturalness

The **"low-energy SUSY"** picture for high energy physics



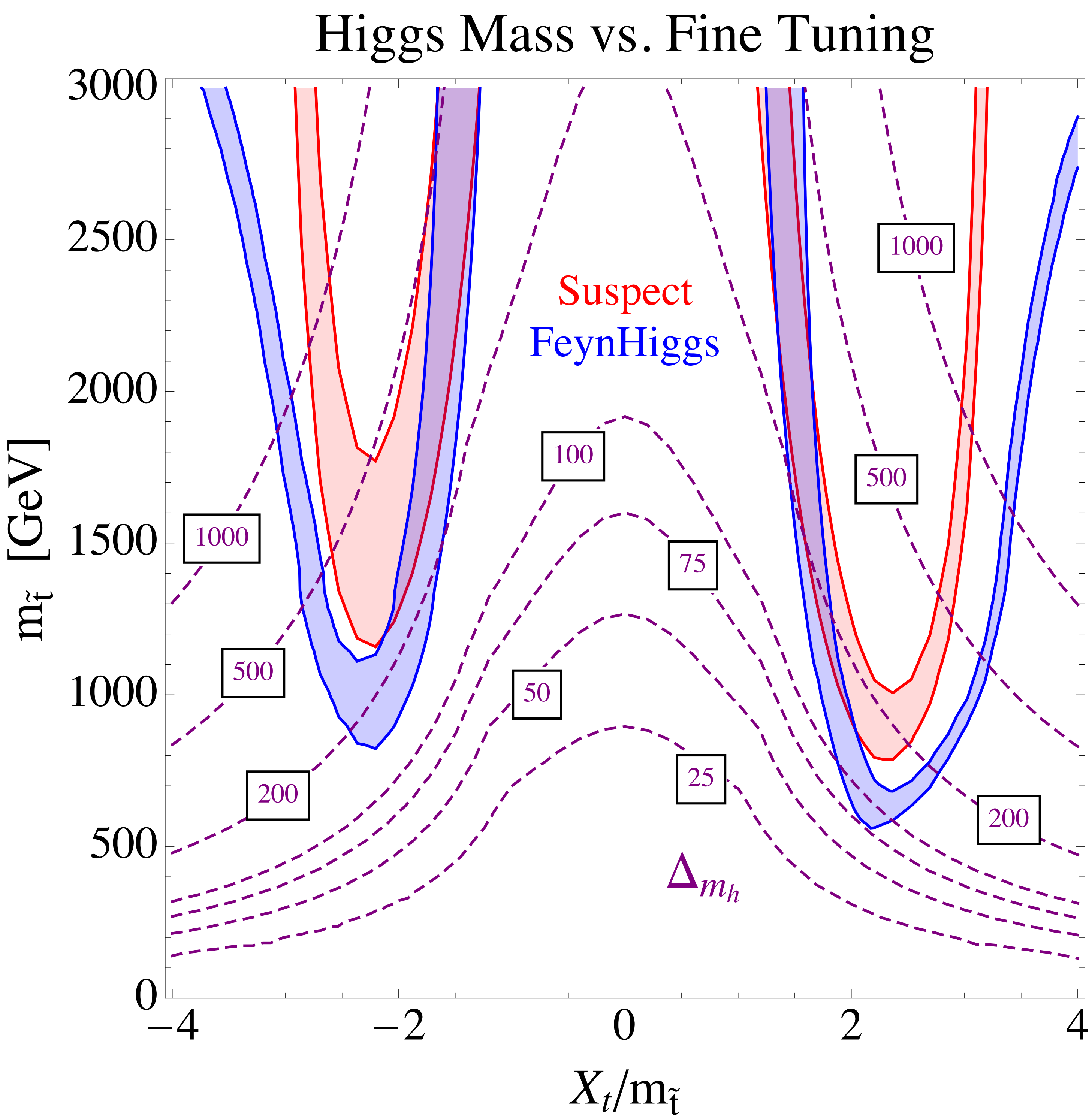
- Unobserved **s**particles have soft masses
- Soft breaking generated at $\Lambda_{\cancel{\text{SUSY}}}$
- Corrections to m_H^2 below $\Lambda_{\cancel{\text{SUSY}}}$:

$$\delta m_H^2 \sim \frac{3y_t^2}{8\pi^2} M_{\text{soft}}^2 \log(\Lambda_{\cancel{\text{SUSY}}}/M_{\text{EW}})$$

$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125\,\text{GeV}}{m_H}\right)^2 \left(\frac{M_{\text{soft}}}{500\,\text{GeV}}\right)^2 \log(\Lambda_{\cancel{\text{SUSY}}}/M_{\text{EW}})$$

Natural SUSY cannot hide above the TeV scale.
General tuning estimate **worsened** by the log term.

The SUSY Higgs



from arXiv:1112.2703

$$\Delta \gtrsim 100$$

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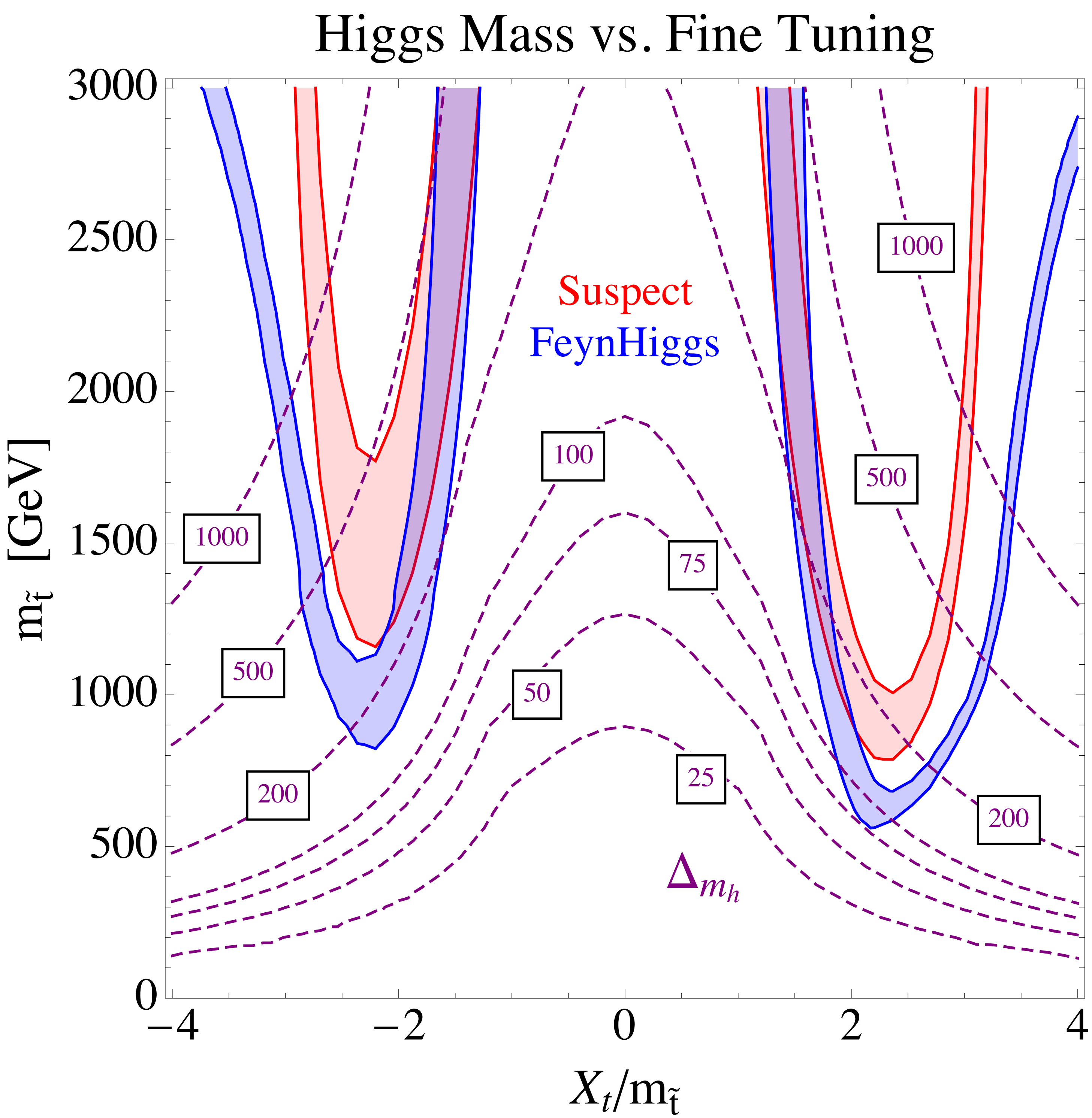

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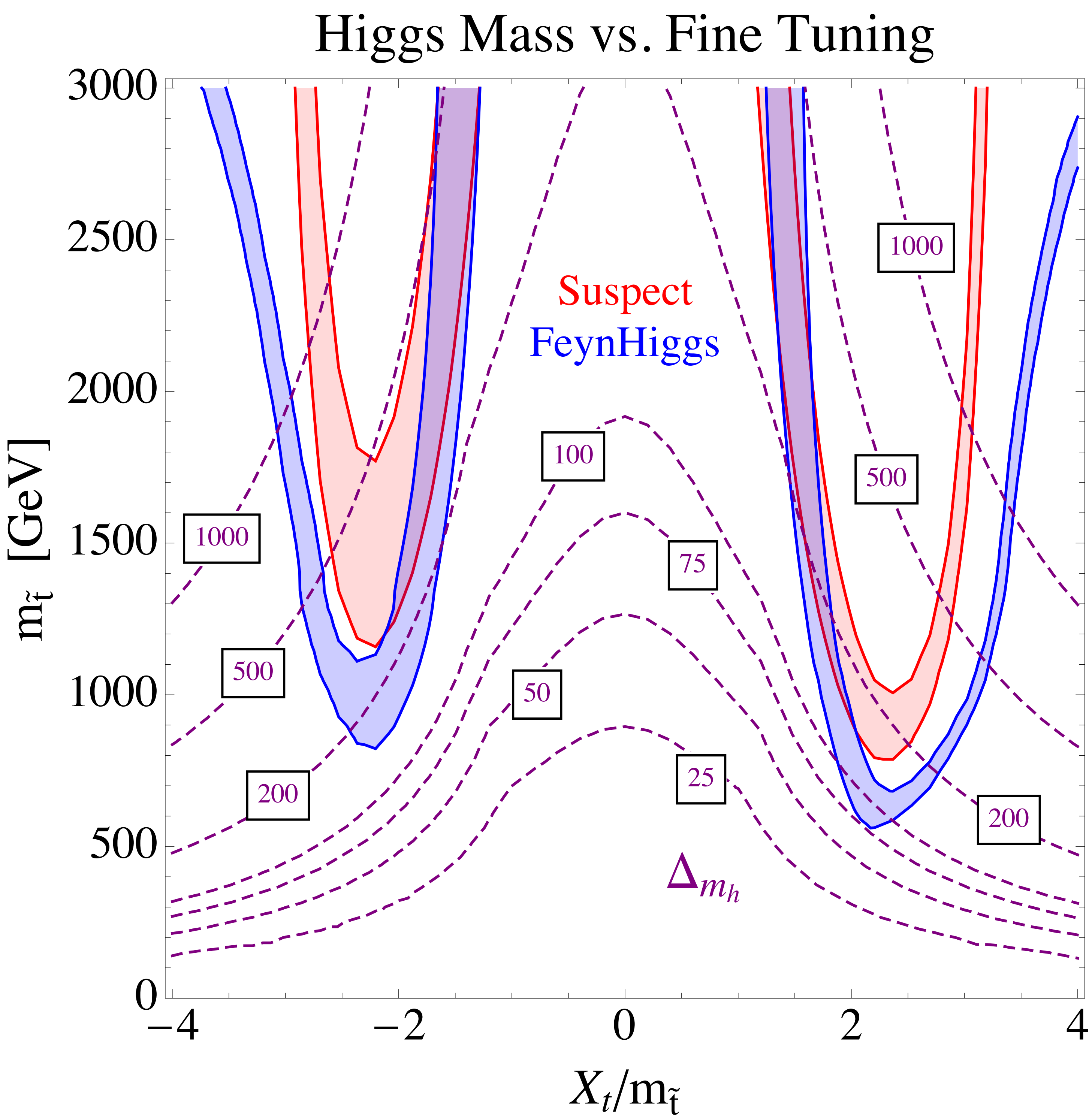

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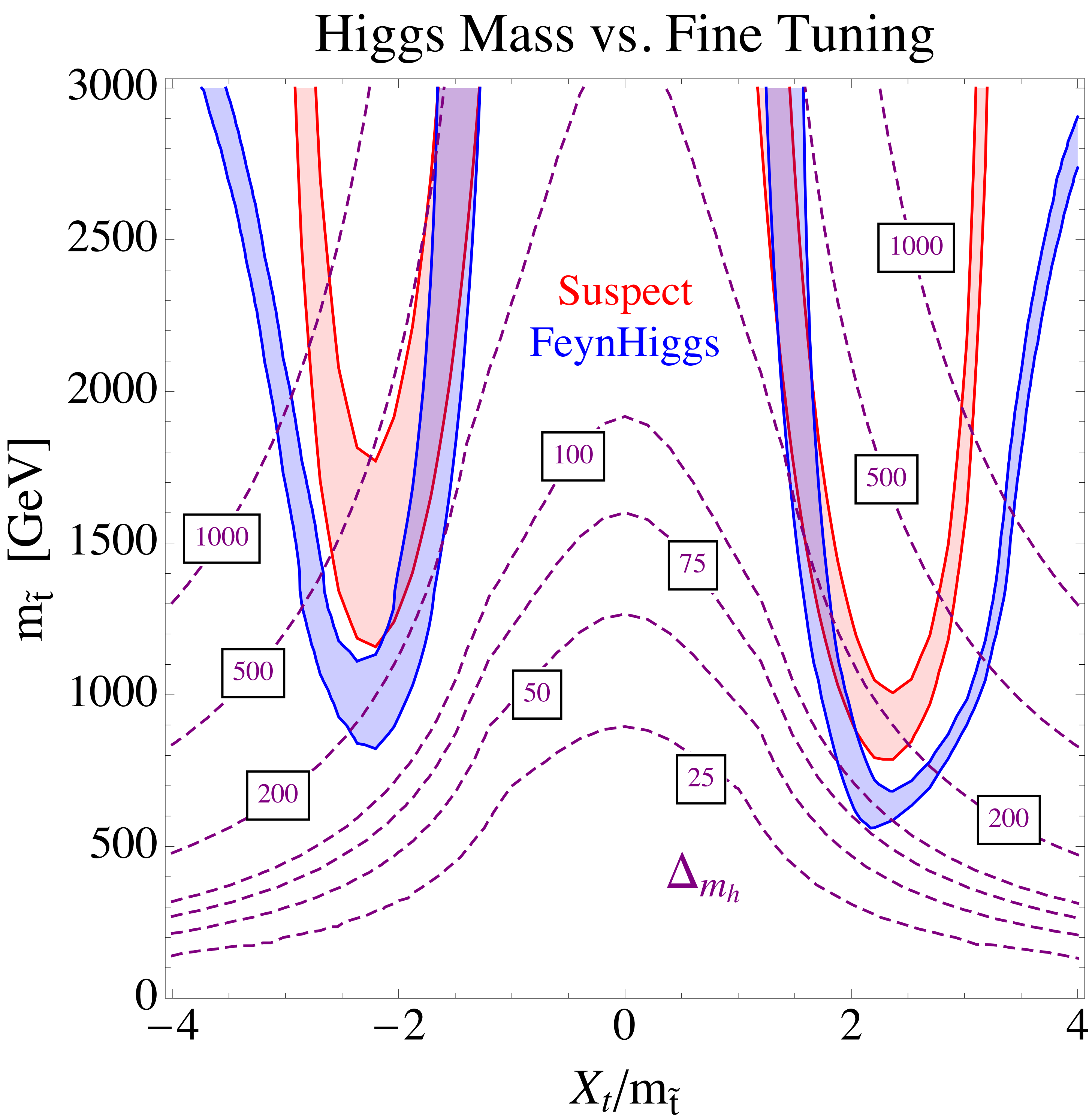

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Add an extra singlet SF. (NMSSM or $\lambda\mathrm{SUSY}$)

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Caveat: needed values of $\lambda_S \sim 1$ give **~10 TeV cutoff.**

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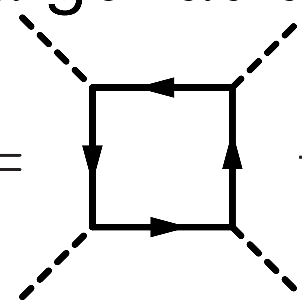
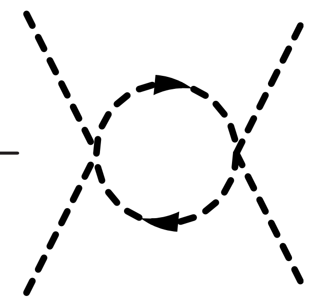
$\delta\lambda =$  $+$  $\sim \dfrac{3y_t^4}{8\pi^2} \log \dfrac{M_{\tilde{t}}}{m_t}$

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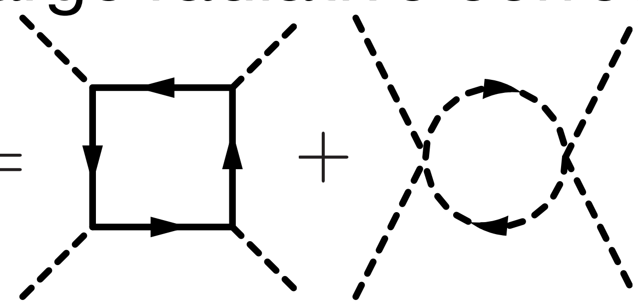
$\delta\lambda =$  $\sim \dfrac{3y_t^4}{8\pi^2} \log \dfrac{M_{\tilde{t}}}{m_t}$

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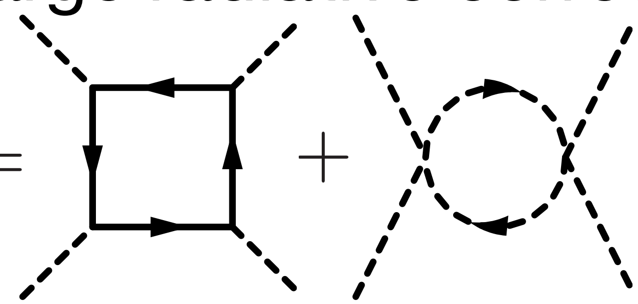
$\delta\lambda =$  $\sim \dfrac{3y_t^4}{8\pi^2} \log \dfrac{M_{\tilde{t}}}{m_t}$

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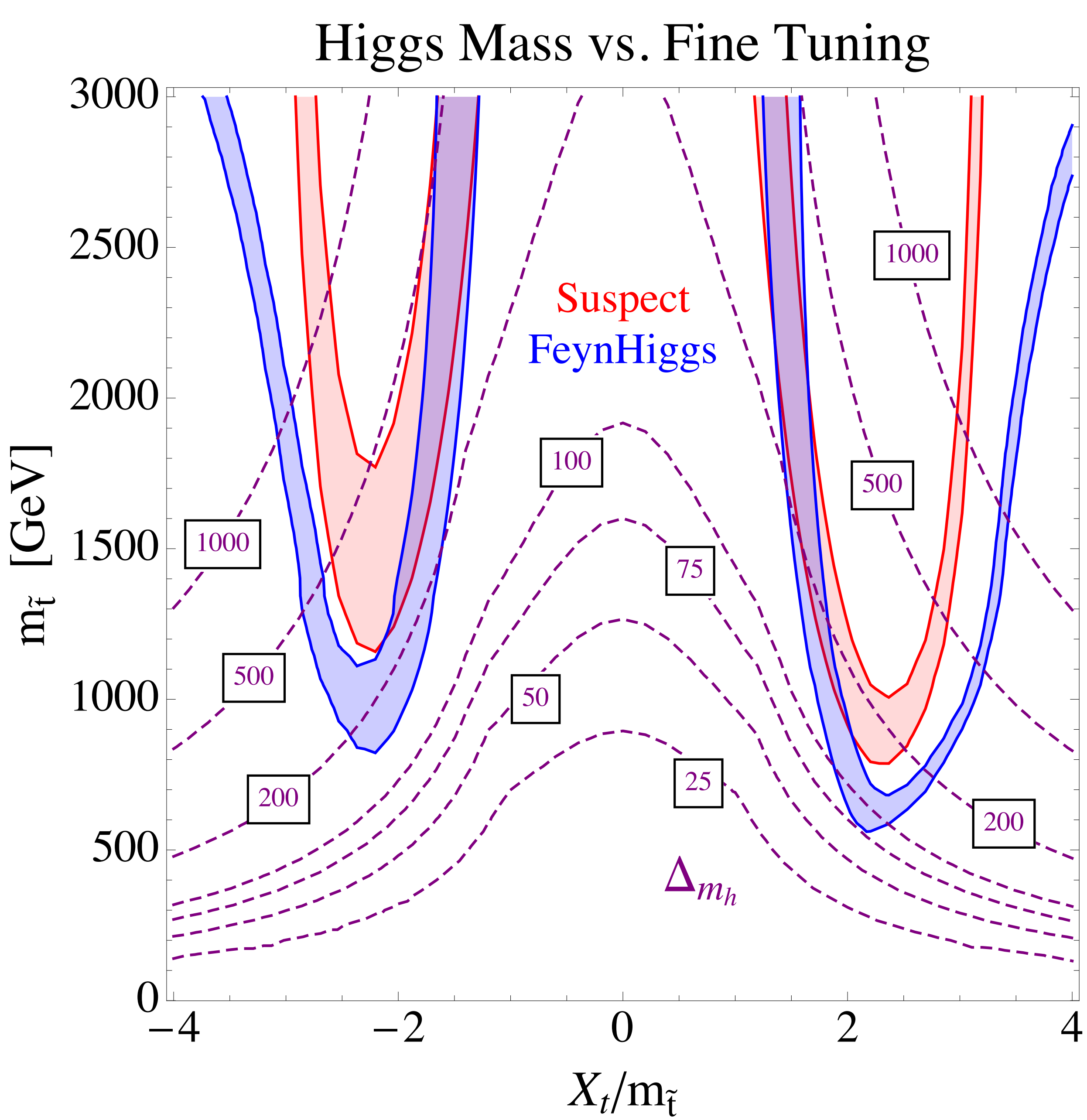

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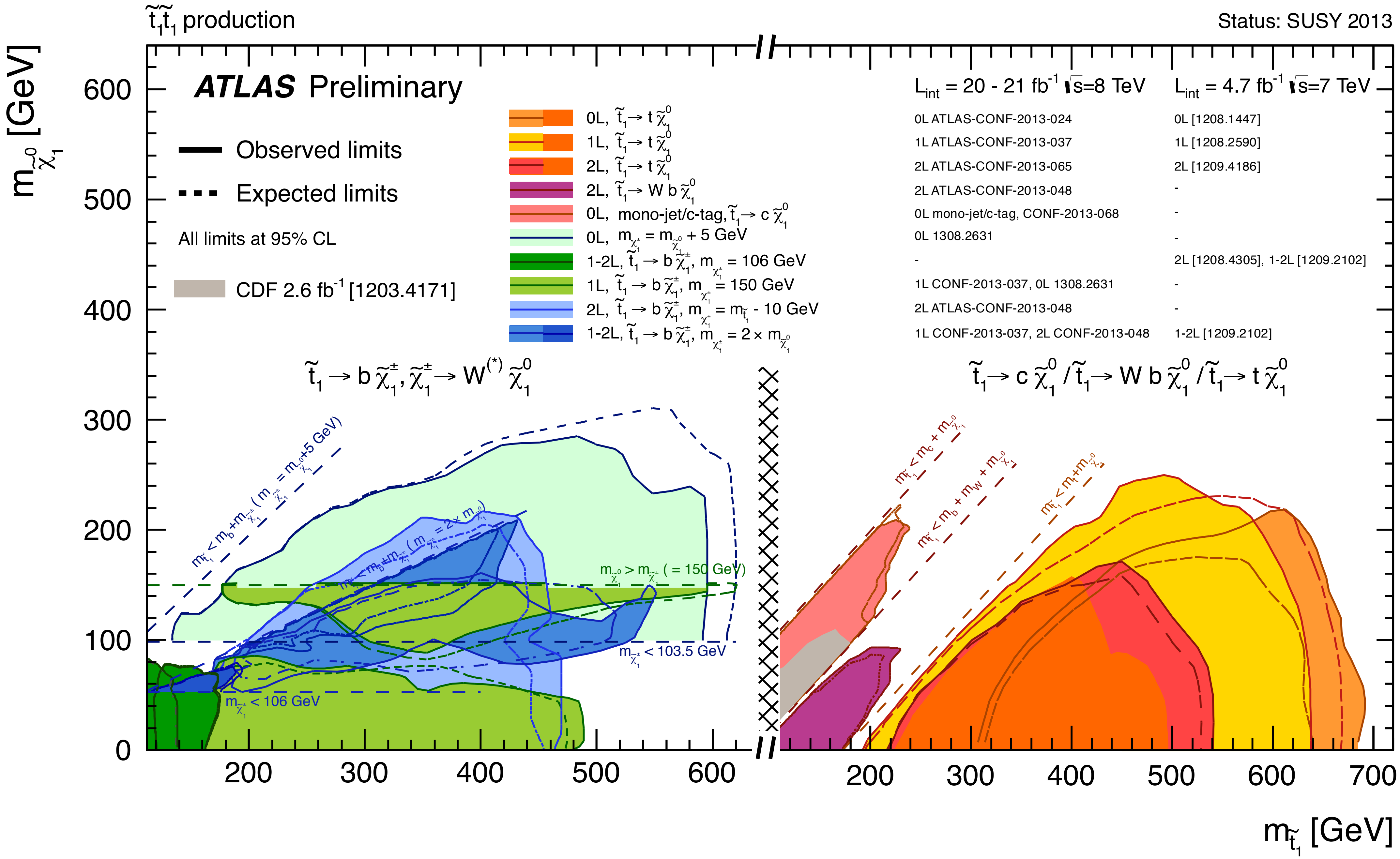

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Impressive search program

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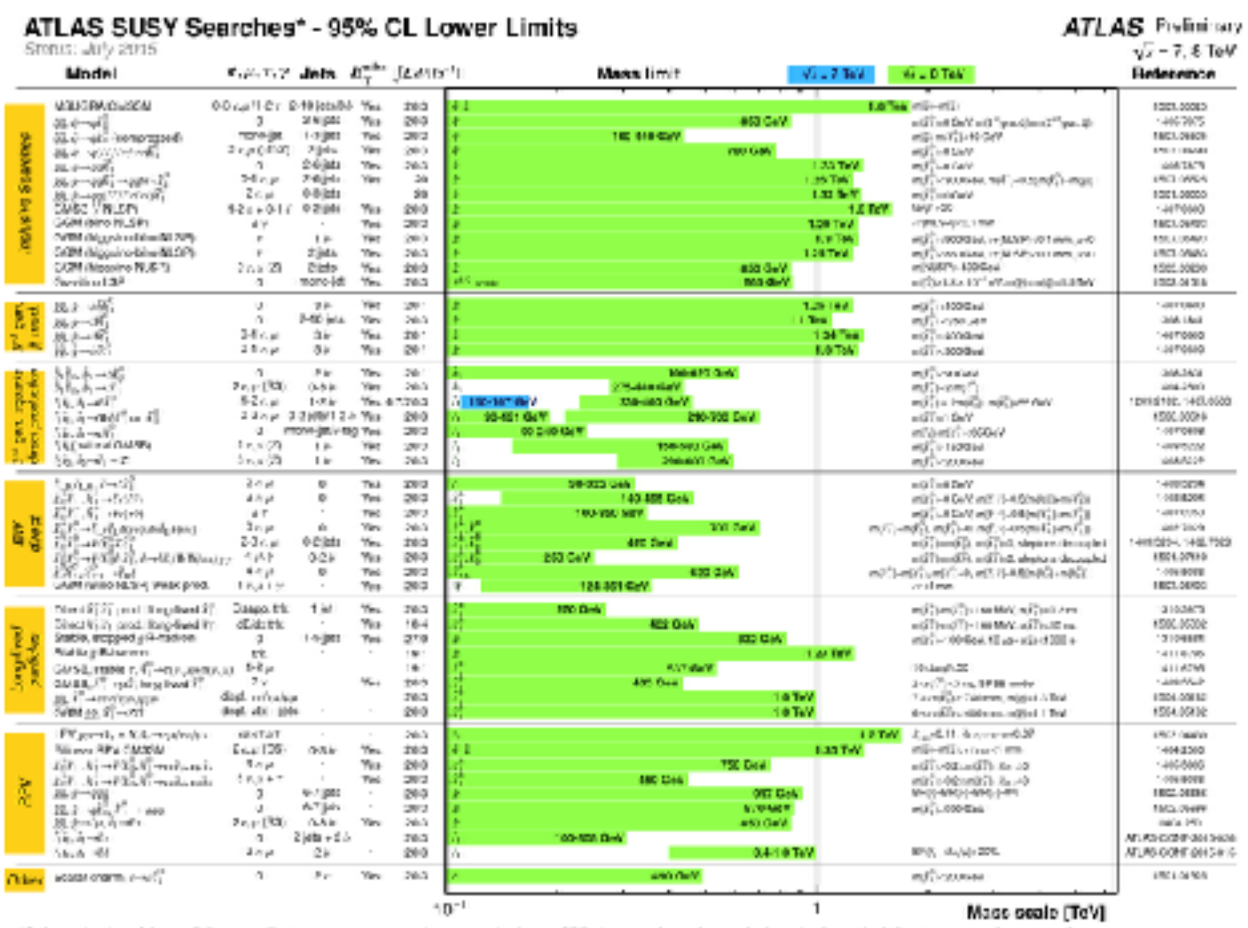

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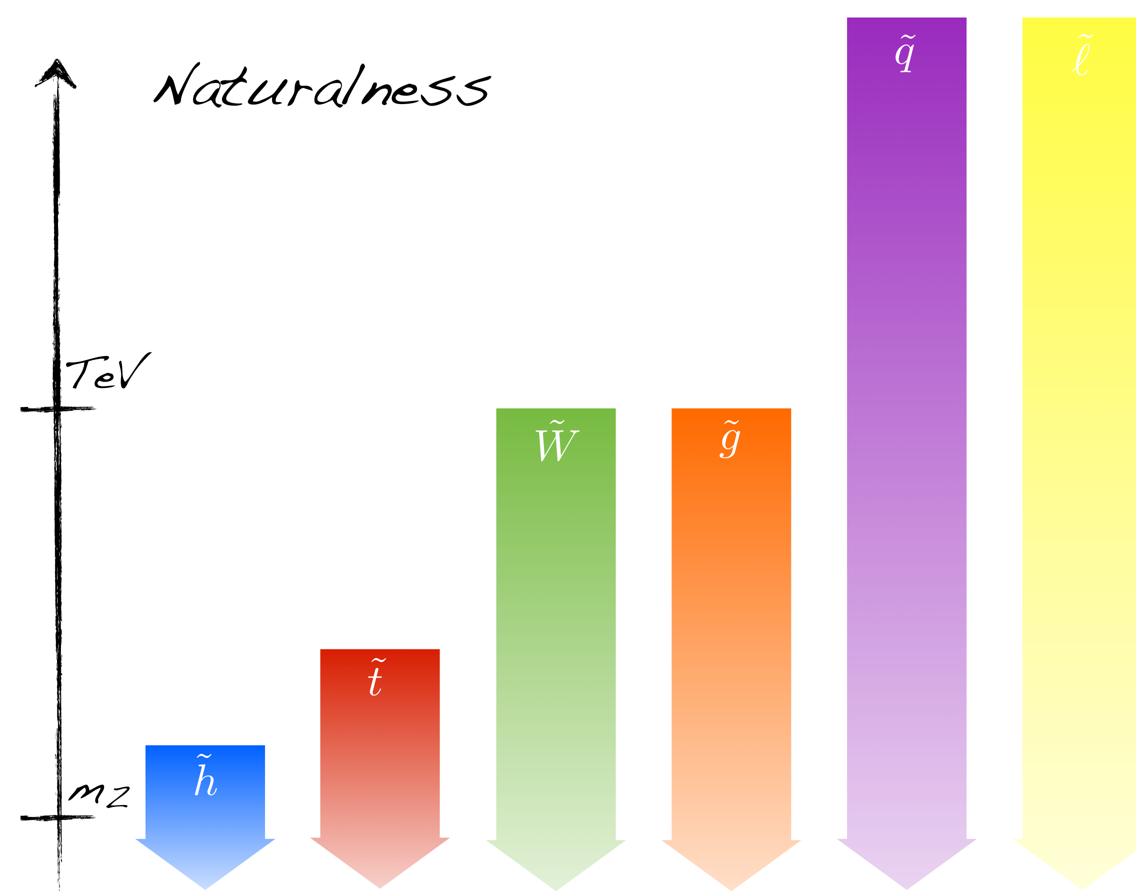

from arXiv:1309.0528

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Experimentalists should not **blindly trust** theorists.

They should **critically listen** to theorists. And get convinced (or not). Nobody has the truth.

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