

Behind!
~~Beyond~~ the
Standard Model

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SUSY and Naturalness

Recall the Naturalness argument:

$$\begin{aligned} m_H^2 &= \int_0^\infty dE \frac{dm_H^2}{dE}(E; p_{\text{FT}}) = \int_0^{\tilde{\Sigma}^{\Lambda_{\text{SM}}}} dE(\dots) + \int_{\tilde{\Sigma}^{\Lambda_{\text{SM}}}}^\infty dE(\dots) \\ &= \delta_{\text{SM}} m_H^2 + \delta_{\text{BSM}} m_H^2 \end{aligned}$$

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

SUSY and Naturalness

Recall the Naturalness argument:

$$\begin{aligned} m_H^2 &= \int_0^\infty dE \frac{dm_H^2}{dE}(E; p_{\text{FT}}) = \int_0^{\lesssim \Lambda_{\text{SM}}} dE(\dots) + \int_{\gtrsim \Lambda_{\text{SM}}}^\infty dE(\dots) \\ &= \delta_{\text{SM}} m_H^2 + \delta_{\text{BSM}} m_H^2 \end{aligned}$$

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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:

$$y = \int_0^\infty dE \frac{dy}{dE}(E; p_{\text{FT}}) = \int_0^{\lesssim \Lambda_{\text{SM}}} dE(\dots) + \int_{\gtrsim \Lambda_{\text{SM}}}^\infty dE(\dots)$$
$$= \delta_{\text{SM}} y + \delta_{\text{BSM}} y$$

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Moreover, Yukawas are **also protected** by a symmetry:
SM gains Flavor symmetry if $y = 0$



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$\delta_{\text{SM}} y_f \simeq \frac{y_f g^2}{16\pi^2} \log(\Lambda_{\text{SM}}/M_{\text{EW}})$ → $y_{d,e,\dots} \ll y_t$ **is Natural**
 that's why flavor origin might be at $\Lambda_{\text{SM}} \gg \text{TeV}$

SUSY and Naturalness

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

$$m_F = \int_0^\infty dE \frac{dm_F}{dE}(E; p_{\text{FT}}) = \int_0^{\tilde{\Lambda}} dE(\dots) + \int_{\tilde{\Lambda}}^\infty dE(\dots)$$
$$= \delta_{\text{IR}} m_F + \delta_{\text{UV}} m_F$$

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

Problem? $\delta_{\text{IR}} m_F \stackrel{?}{\simeq} \frac{g^2}{16\pi^2} \Lambda$ **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** $\rightarrow m_H^{\text{SUSY}} = m_F$



SUSY scalars can be Naturally light

Let us see how this works, focusing on top contribution

SM fields:

h

t_L

t_R



Chiral SFs:

$\Phi_h = \{h, \tilde{h} \text{ (Higgsino)}\}$

$\Phi_{t_L} = \{t_L, \tilde{t}_L \text{ (stop Left)}\}$

$\Phi_{t_R} = \{t_R^c, \tilde{t}_R^\dagger \text{ (stop Right)}\}$

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

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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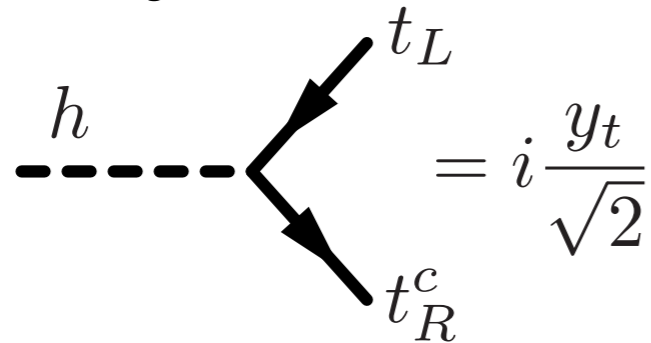
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F-term potential:

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

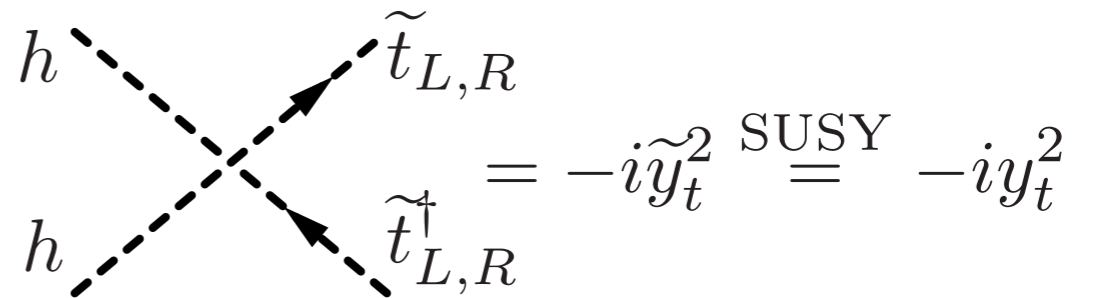
SUSY and Naturalness

The Feynman rules are:



A Feynman diagram showing a dashed line labeled h on the left, which splits into two solid lines with arrows pointing right. The top line is labeled t_L and the bottom line is labeled t_R^c . To the right of the vertex, the expression $= i \frac{y_t}{\sqrt{2}}$ is written.

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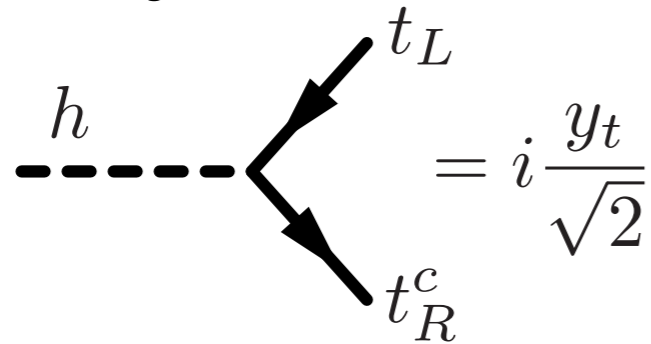


A Feynman diagram showing two dashed lines labeled h on the left, which cross each other and then split into two dashed lines with arrows pointing right. The top line is labeled $\tilde{t}_{L,R}$ and the bottom line is labeled $\tilde{t}_{L,R}^\dagger$. To the right of the vertex, the expression $= -i\tilde{y}_t^2 \stackrel{\text{SUSY}}{=} -iy_t^2$ is written.

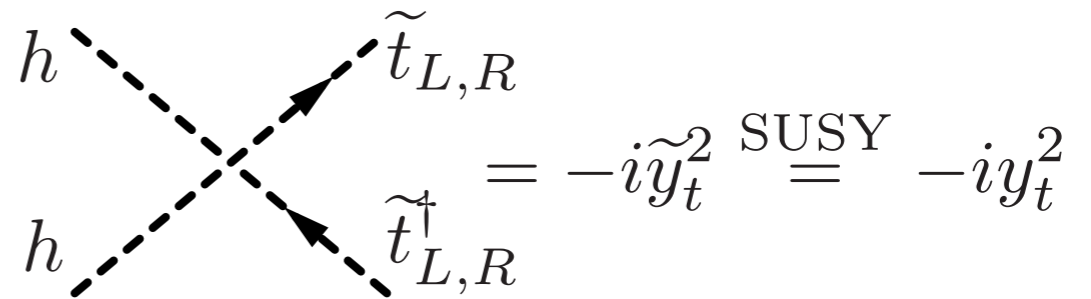
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SUSY and Naturalness

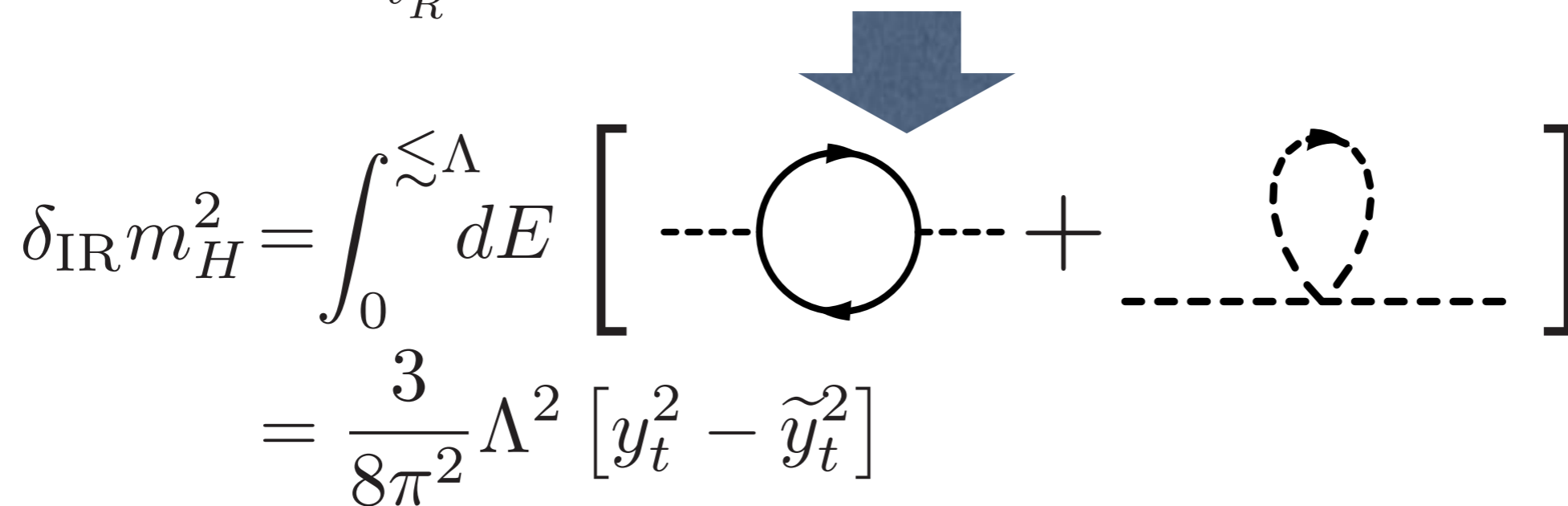
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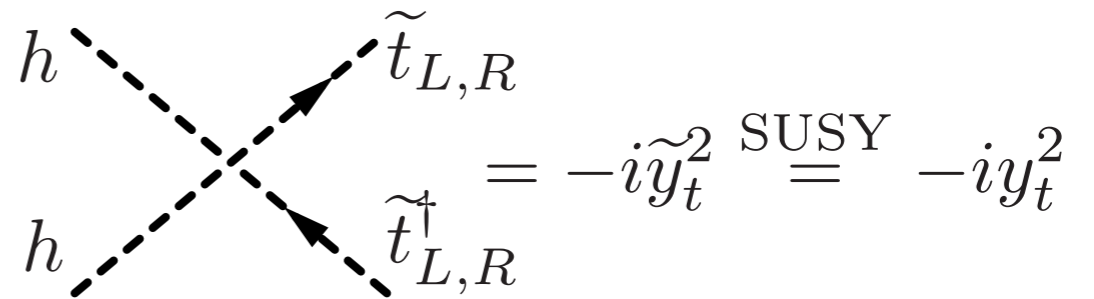
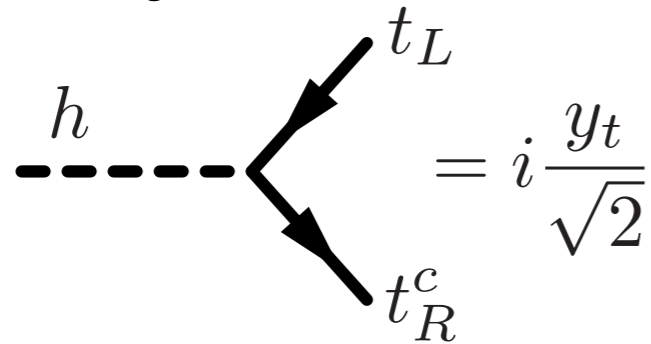
A large blue arrow points downwards from the Feynman rules to a diagrammatic representation of a loop integral. The diagram shows a dashed line entering a circle from the left, with a solid line loop inside the circle, and a dashed line exiting the circle to the right. This is followed by a plus sign and another diagram where a dashed line enters a circle from the left, with a dashed line loop inside the circle, and a dashed line exiting the circle to the right. The entire expression is enclosed in large square brackets.

$$\delta_{\text{IR}} m_H^2 = \int_0^{\tilde{\Lambda}} dE \left[\text{---} \bigcirc \text{---} + \text{---} \bigcirc \text{---} \right]$$

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

SUSY and Naturalness

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time to celebrate?

SUSY and Naturalness

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not yet ...

where is SUSY?

time to celebrate?

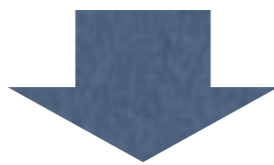


SUSY and Naturalness

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We must break SUSY, easy to do it preserving Naturalness

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

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

SUSY and Naturalness

SOFT BREAKING

all terms that break SUSY preserving Naturalness

- scalar mass terms $-m_{\phi_i}^2 |\phi_i|^2$, 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
- linear terms $-C_i\phi_i$.

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only $d > 0$ ~~SUSY~~ parameters (not all $d > 0$)

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

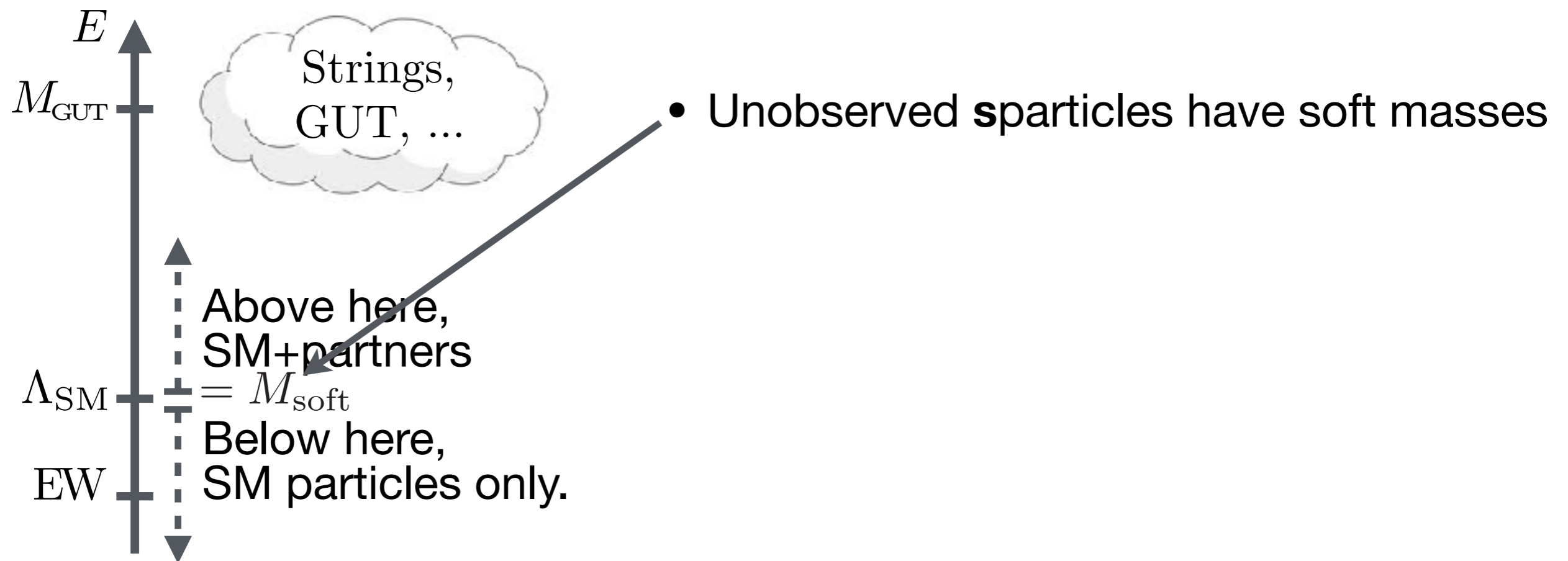
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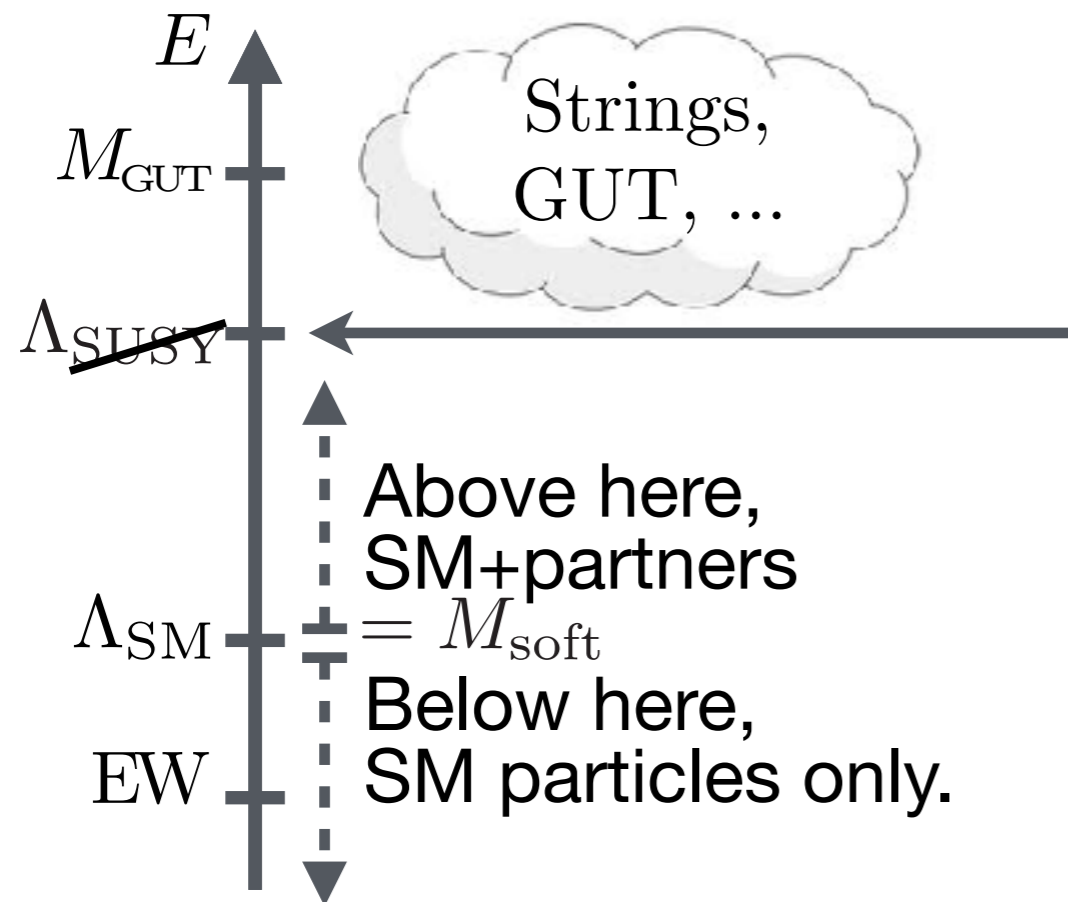
SUSY and Naturalness

The “**low-energy SUSY**” picture for high energy physics



SUSY and Naturalness

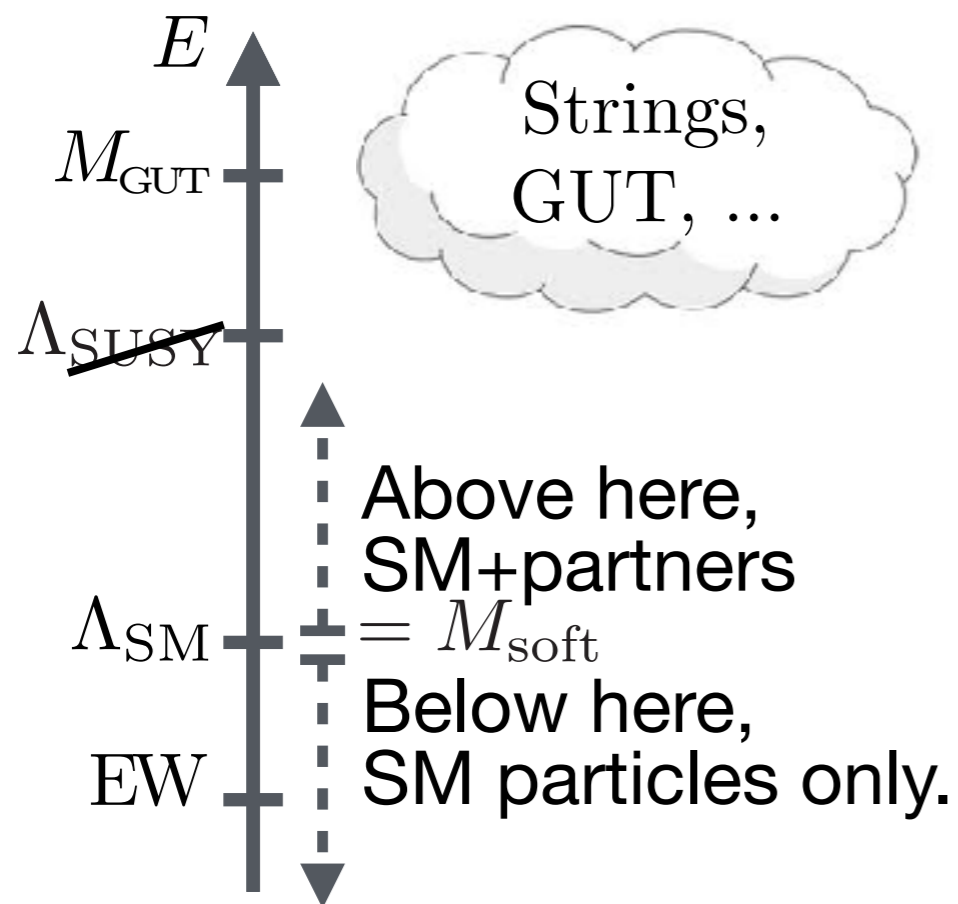
The “**low-energy SUSY**” picture for high energy physics



- Unobserved sparticles have soft masses
- Soft breaking generated at Λ_{SUSY}

SUSY and Naturalness

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- Soft breaking generated at Λ_{SUSY}
- Corrections to m_H^2 below Λ_{SUSY} :

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

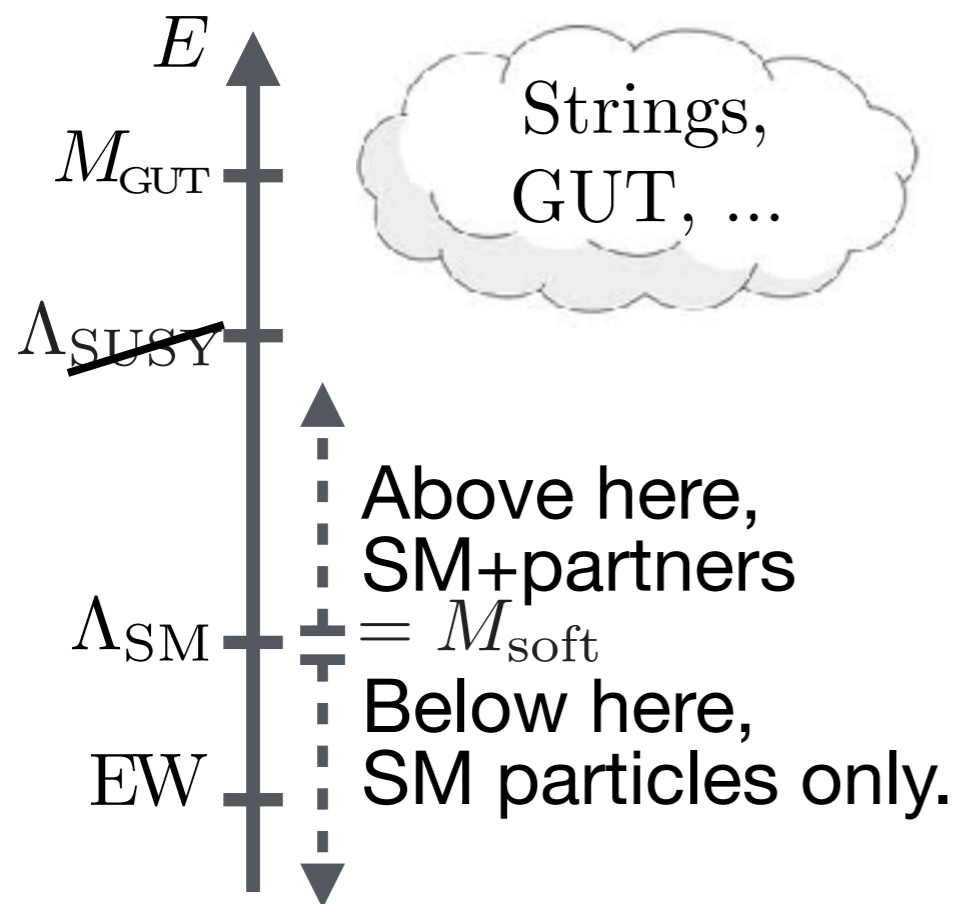
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$$\Delta \geq \frac{\delta m_H^2}{m_H^2} \simeq \left(\frac{125 \text{ GeV}}{m_H} \right)^2 \left(\frac{M_{\text{soft}}}{500 \text{ GeV}} \right)^2 \log(\Lambda_{\text{SUSY}}/M_{\text{EW}})$$

Natural SUSY cannot hide above the TeV scale.

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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. $SU(3)_c \times SU(2)_L \times U(1)_Y \subset SU(5)$
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GUT miracle: SM matter fits in GUT group multiplets

Three Generations of Matter (Fermions)

	I	II	III	
mass	2.4 MeV	1.27 GeV	171.2 GeV	0
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name	u up	c charm	t top	γ photon
	4.8 MeV	104 MeV	1.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Quarks	d down	s strange	b bottom	g gluon
	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
Leptons	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z weak force
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	±1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e electron	μ muon	τ tau	W weak force
				Bosons (Forces)

SU(5)

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

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

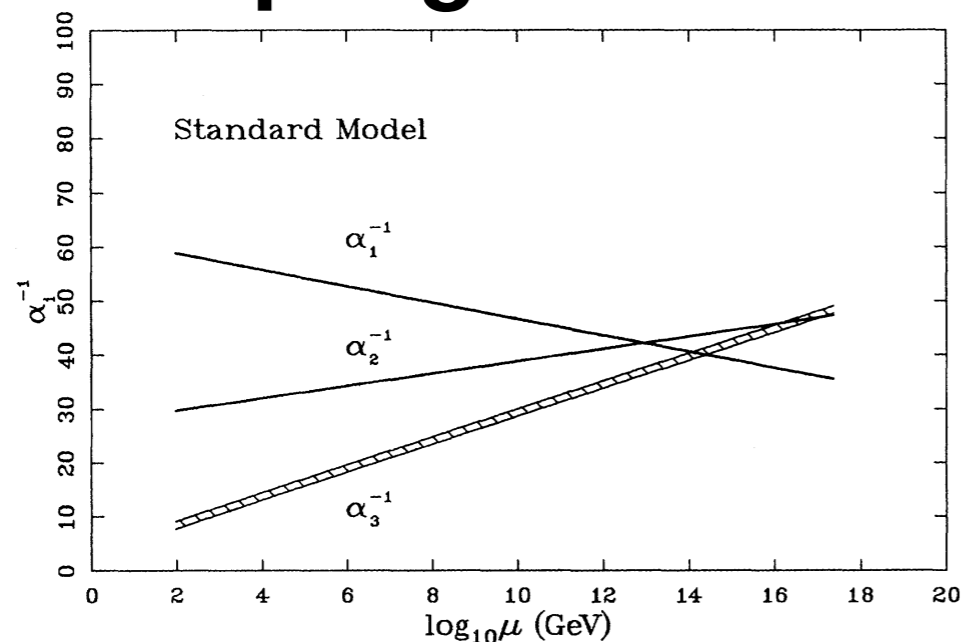
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For this being true:

1. **Couplings must unify:**

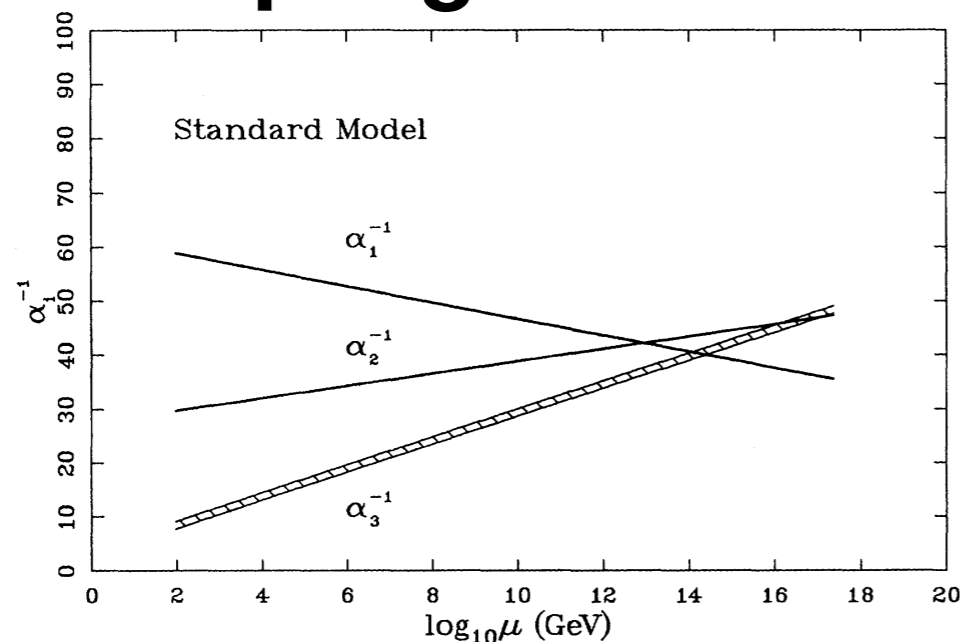


“almost” meet (not quite)
at $M_{\text{GUT}} \sim 10^{14} \text{ GeV}$

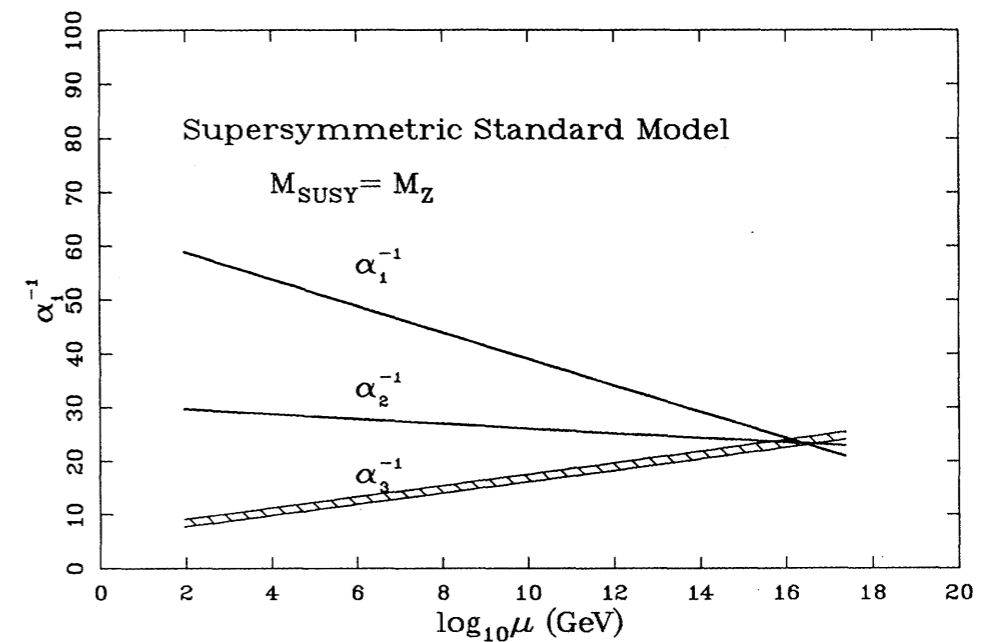
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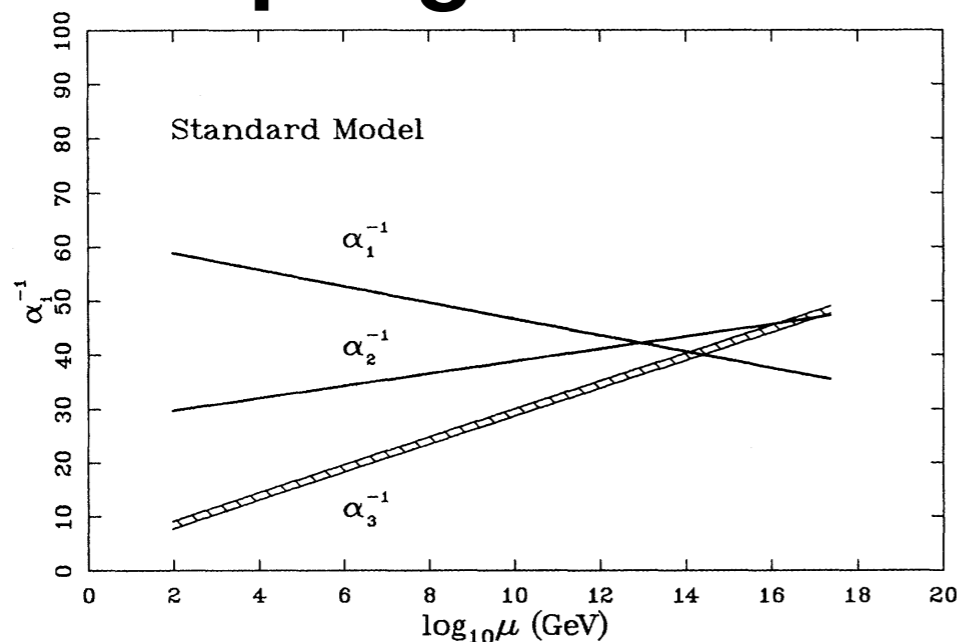


do meet (quite well)
at $M_{\text{GUT}} \sim 10^{16}$ GeV

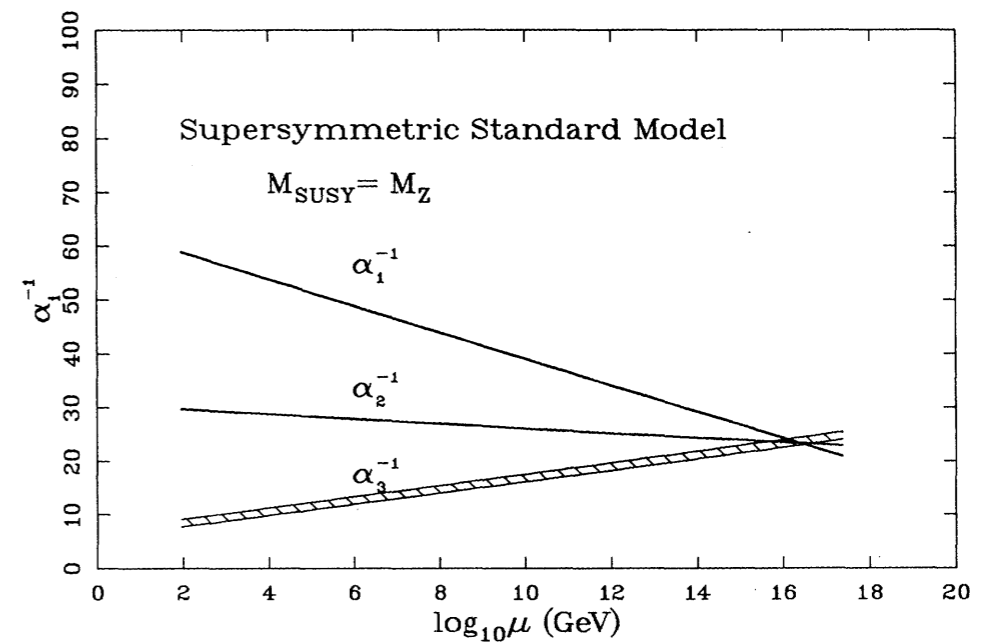
Other virtues of SUSY

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

1. Couplings must unify:

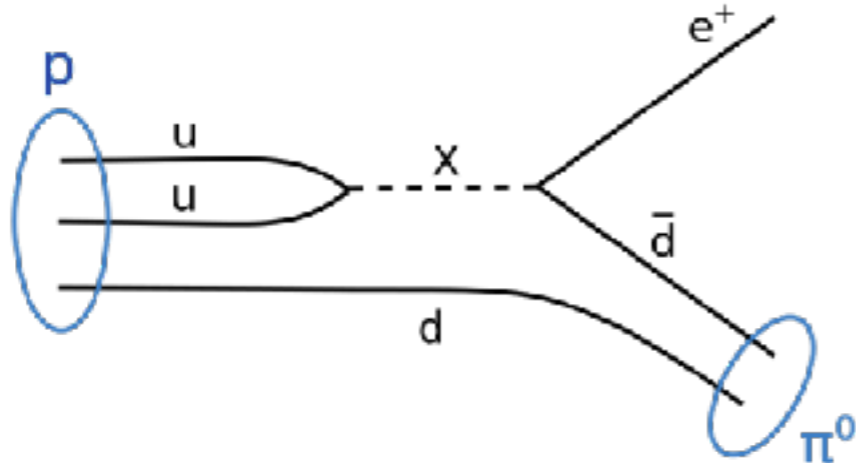


“almost” meet (not quite)
at $M_{GUT} \sim 10^{14} \text{ GeV}$



do meet (quite well)
at $M_{GUT} \sim 10^{16} \text{ GeV}$

2. Proton must decay:



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

GUT excluded in SM.
Viable in SUSY-SM

Other virtues of SUSY

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

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(unlike in SM, no Accidental Symmetries)

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$$\theta \rightarrow -\theta$$

$$\text{SF}_{\text{matter}} \rightarrow -\text{SF}_{\text{matter}} \quad \text{SF}_{\text{Higgs,gauge}} \rightarrow +\text{SF}_{\text{Higgs,gauge}}$$

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

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



SM particles are EVEN
Associated Sparticles are ODD

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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

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



SUSY Higgs SF

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

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$$\mathcal{L}_Y^u = y_u q_L H u_R^c$$

$$\mathbf{2}_{1/6} \otimes \mathbf{2}_{1/2} \otimes \mathbf{1}_{-2/3} \supset \mathbf{1}_0$$

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The SUSY Higgses scalar potential:

$$\begin{aligned} V[H_u, H_d] = & \mu^2 [|H_u|^2 + |H_d|^2] \\ & + \frac{g^2 + g'^2}{8} [|H_u|^2 - |H_d|^2]^2 + \frac{g^2}{2} |H_u^\dagger H_d|^2 \\ & + m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + B [H_u H_d + H_u^* H_d^*] \end{aligned}$$

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only masses can
break SUSY

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Particular case of generic 2 Higgs doublet model

The SUSY Higgs

Four implications of the SUSY Higgs sector structure

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

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

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #1: both Higgses take VEV

$$\langle |H_u|^2 \rangle = \frac{v_u^2}{2} \qquad \langle |H_d|^2 \rangle = \frac{v_d^2}{2}$$

2 sources of EWSB  $v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$

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2 sources of EWSB



$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$

define: $v_u/v_d = \tan \beta$



$$\begin{cases} v_u = v \sin \beta \\ v_d = v \cos \beta \end{cases}$$

Abbreviations:

$$s_\beta = \sin \beta \quad t_\beta = \frac{s_\beta}{c_\beta}$$
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Both Higgses **must** take VEV, for u and d-type masses:

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

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #2: **many scalars** around

In Unitary Gauge

$$H_u = \begin{bmatrix} 0 \\ \frac{v_u + h_u}{\sqrt{2}} \end{bmatrix} + \begin{bmatrix} c_\beta H_+ \\ c_\beta \frac{iA}{\sqrt{2}} \end{bmatrix} \quad H_d = \begin{bmatrix} \frac{v_d + h_d}{\sqrt{2}} \\ 0 \end{bmatrix} + \begin{bmatrix} s_\beta \frac{iA}{\sqrt{2}} \\ s_\beta H_- \end{bmatrix}$$

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

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

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$$\begin{bmatrix} h_u \\ h_d \end{bmatrix} = \begin{bmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{bmatrix} \begin{bmatrix} h \\ H \end{bmatrix}$$

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

The Other Higgs
(maybe heavier)

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #3: modified Higgs couplings

$$\kappa_u = \frac{g_{h_{uu}}}{g_{h_{uu}}^{\text{SM}}} = \frac{\sin(\alpha + \pi/2)}{\sin \beta}$$

$$\kappa_d = \frac{g_{h_{dd}}}{g_{h_{dd}}^{\text{SM}}} = \frac{\cos(\alpha + \pi/2)}{\cos \beta}$$

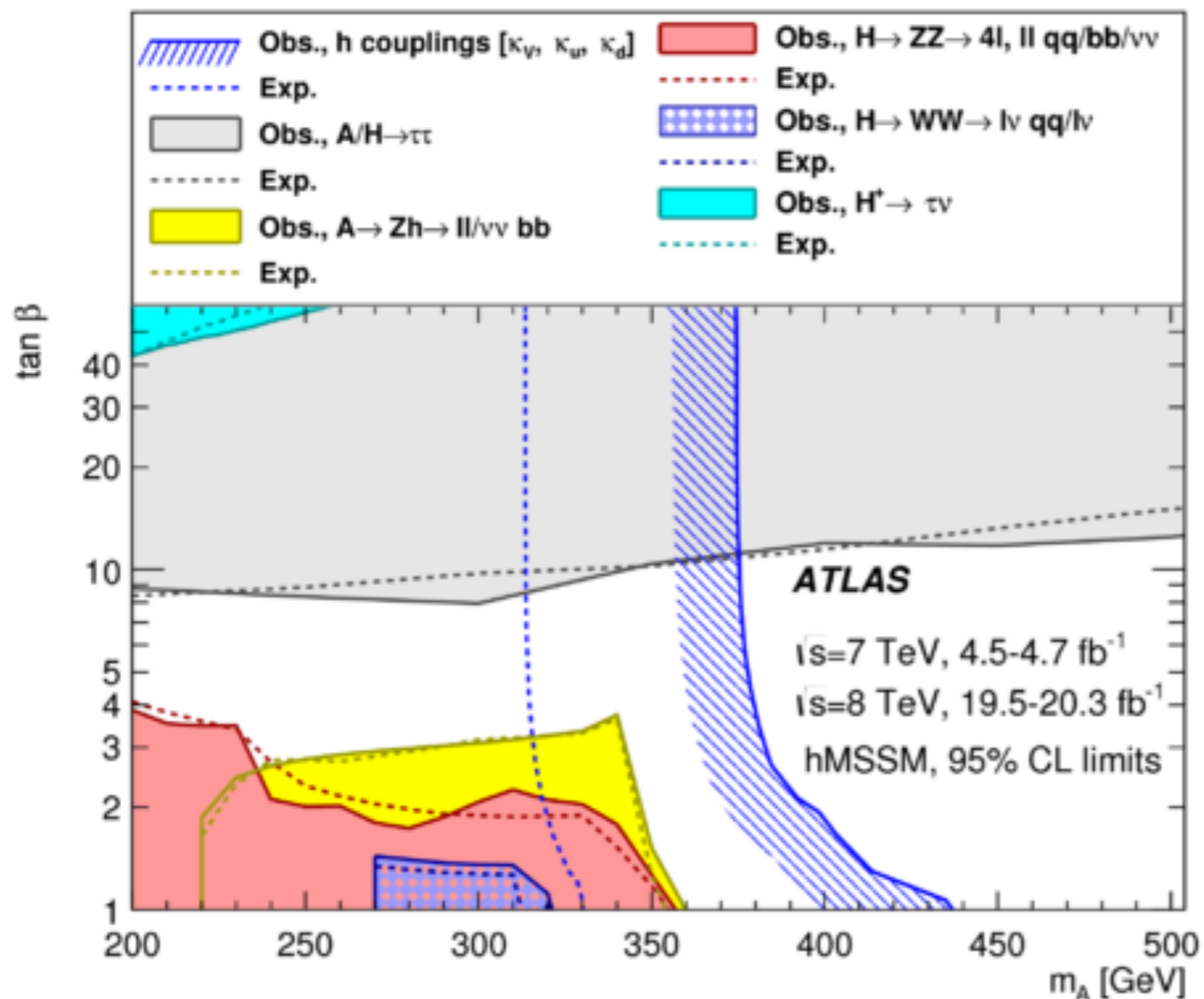
$$\kappa_V = \frac{g_{h_{VV}}}{g_{h_{VV}}^{\text{SM}}} = \sin(\beta - \alpha)$$

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

Four implications of the SUSY Higgs sector structure.
Implication #3: **modified Higgs couplings**



ATLAS arXiv:1509.00672

Direct scalar searches play an important role in this plane.

The SUSY Higgs

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Decoupling limit: $m_d^2 \rightarrow \infty$ (technically natural)

$$m_A^2 = m_d^2 + \dots \rightarrow \infty \rightarrow \tan \alpha \simeq -\frac{1}{t_\beta}$$

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$$m_A^2 = m_d^2 + \dots \rightarrow \infty \rightarrow \tan \alpha \simeq -\frac{1}{t_\beta} \rightarrow \alpha \simeq \beta - \pi/2 \rightarrow \text{SM Higgs}$$

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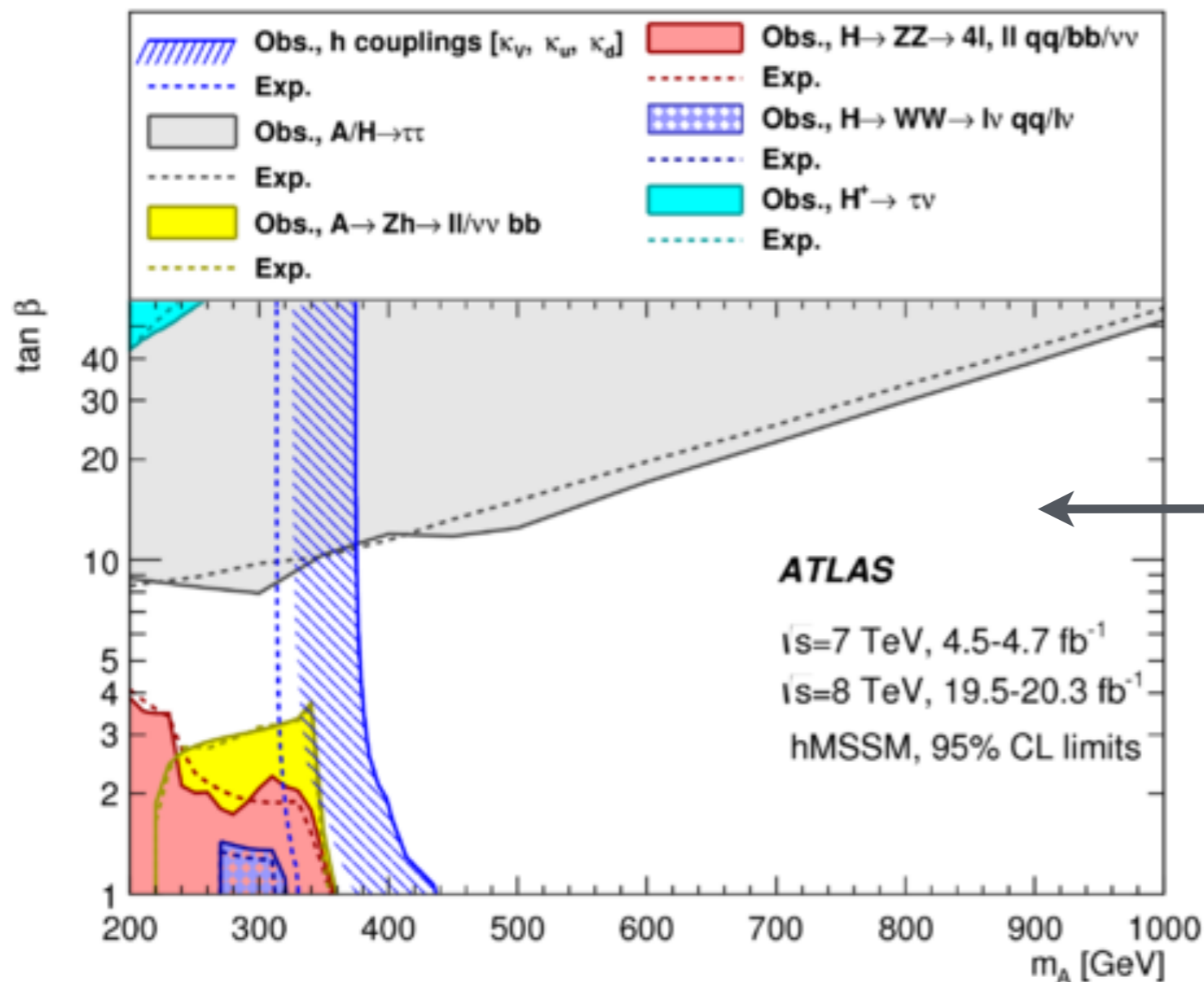
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In the limit we also have: $\sin 2\beta = \frac{2B}{m_A^2} \Rightarrow t_\beta \simeq \frac{m_A^2}{B} \rightarrow \infty$

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

Four implications of the SUSY Higgs sector structure.

Implication #4: **wrong Higgs mass !!**

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

Implication #4: **wrong Higgs mass !!**

In the decoupling limit, H_d can be **ignored** (set to zero)

$$V[H_u, H_d] \rightarrow V_{\text{SM}} = \mu_{\text{SM}}^2 |H_u|^2 + \lambda |H_u|^4$$

$$\mu_{\text{SM}}^2 = \mu^2 + m_u^2$$
$$\lambda = \frac{g^2 + g'^2}{8}$$

The SUSY Higgs

Four implications of the SUSY Higgs sector structure.

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Habitual SM formula gives:

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Beyond decoupling limit: $m_H \leq |\cos 2\beta| m_Z$. Even worse

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Problem: λ is too small.

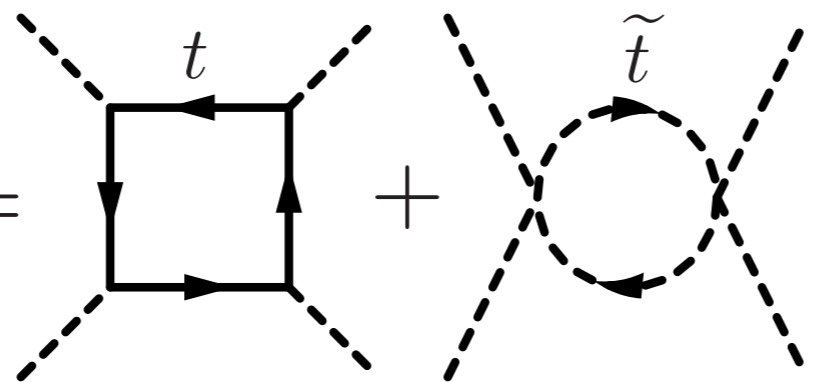
Solution: increase λ .

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

The SUSY Higgs

Two ways to increase λ :

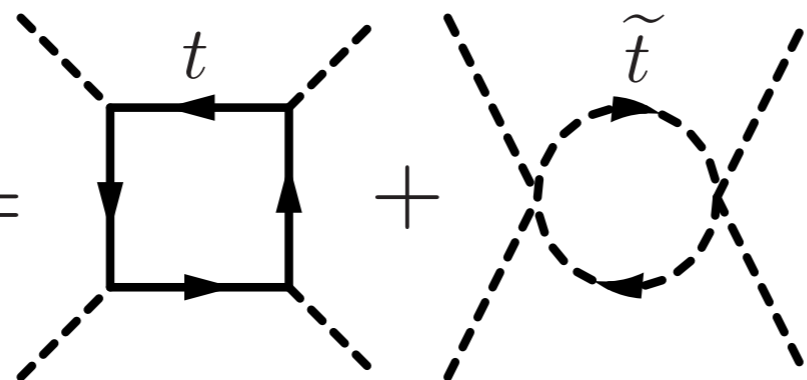
First way: **rely on large loop corrections** (only way in MSSM)

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The SUSY Higgs

Two ways to increase λ :

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

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

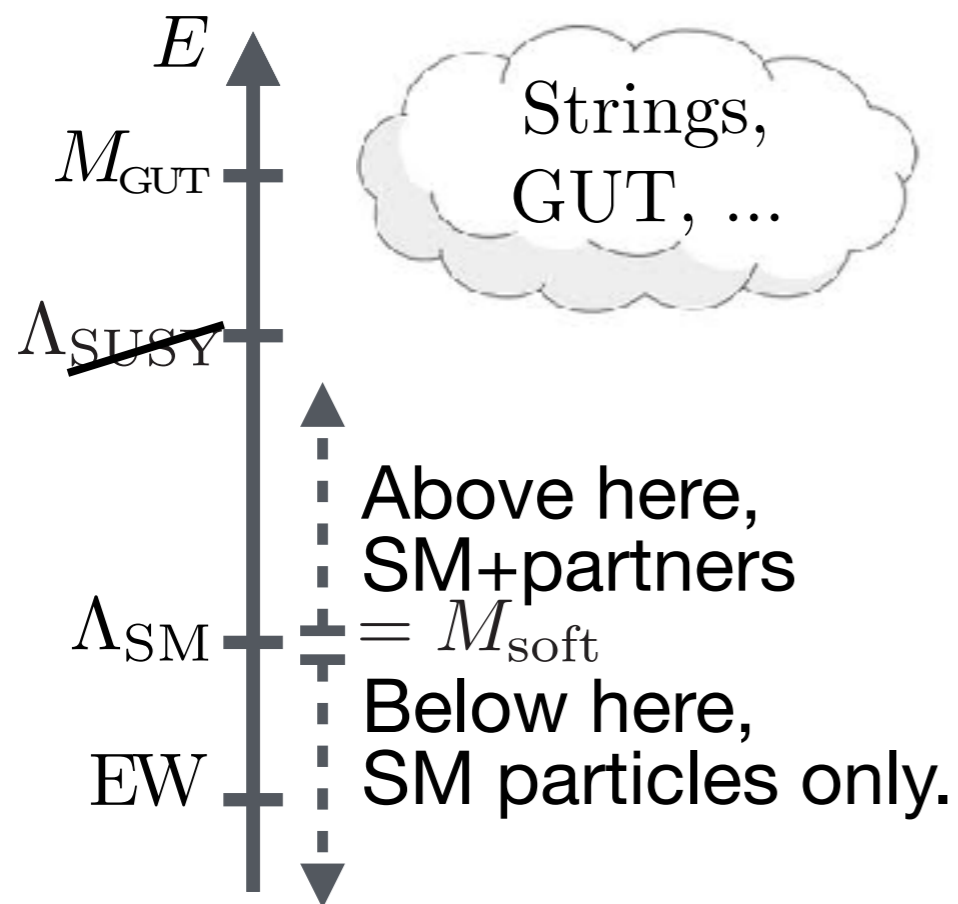
$$\Delta \geq \left(\frac{M_{\text{soft}}}{500 \text{ GeV}} \right)^2 \log(\Lambda_{\text{SUSY}} / M_{\text{EW}})$$

$\downarrow \sim 7$ $\downarrow \sim 5$

low $\Lambda_{\text{SUSY}} = 10 \text{ TeV}$

SUSY and Naturalness

The “**low-energy SUSY**” picture for high energy physics



- Unobserved sparticles have soft masses
- Soft breaking generated at Λ_{SUSY}
- Corrections to m_H^2 below Λ_{SUSY} :

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

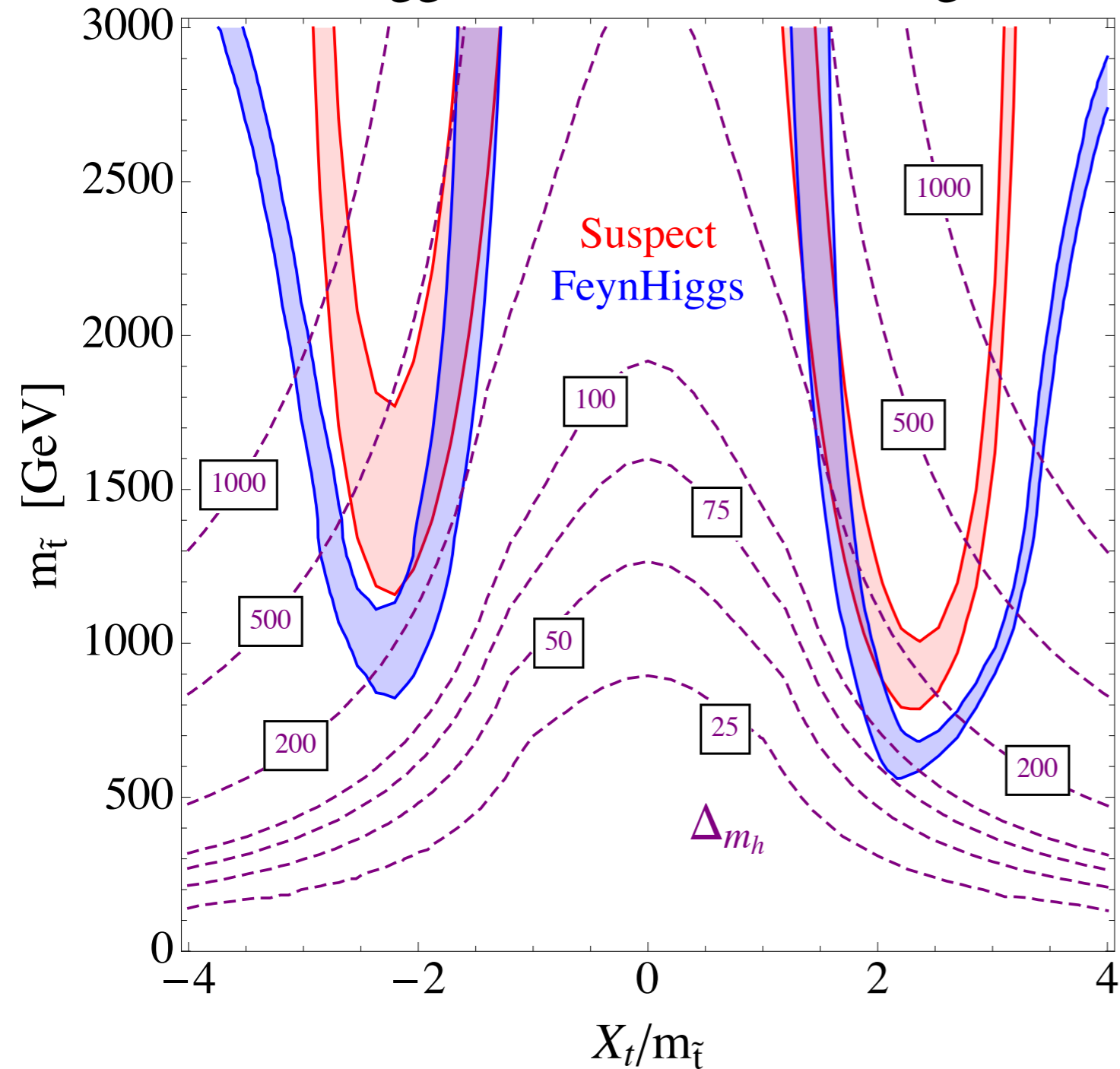
↓

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

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

The SUSY Higgs

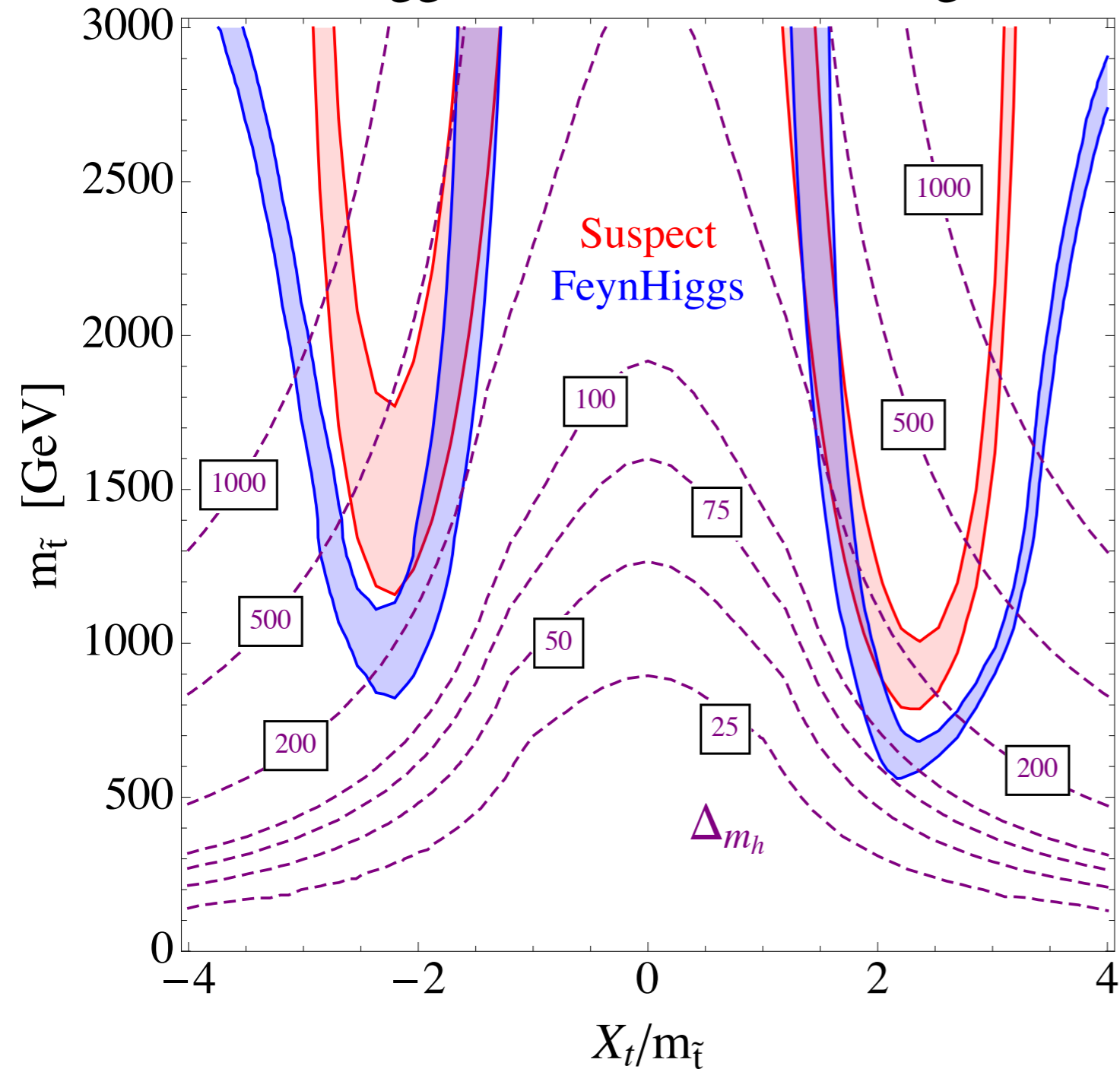
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from arXiv:1112.2703

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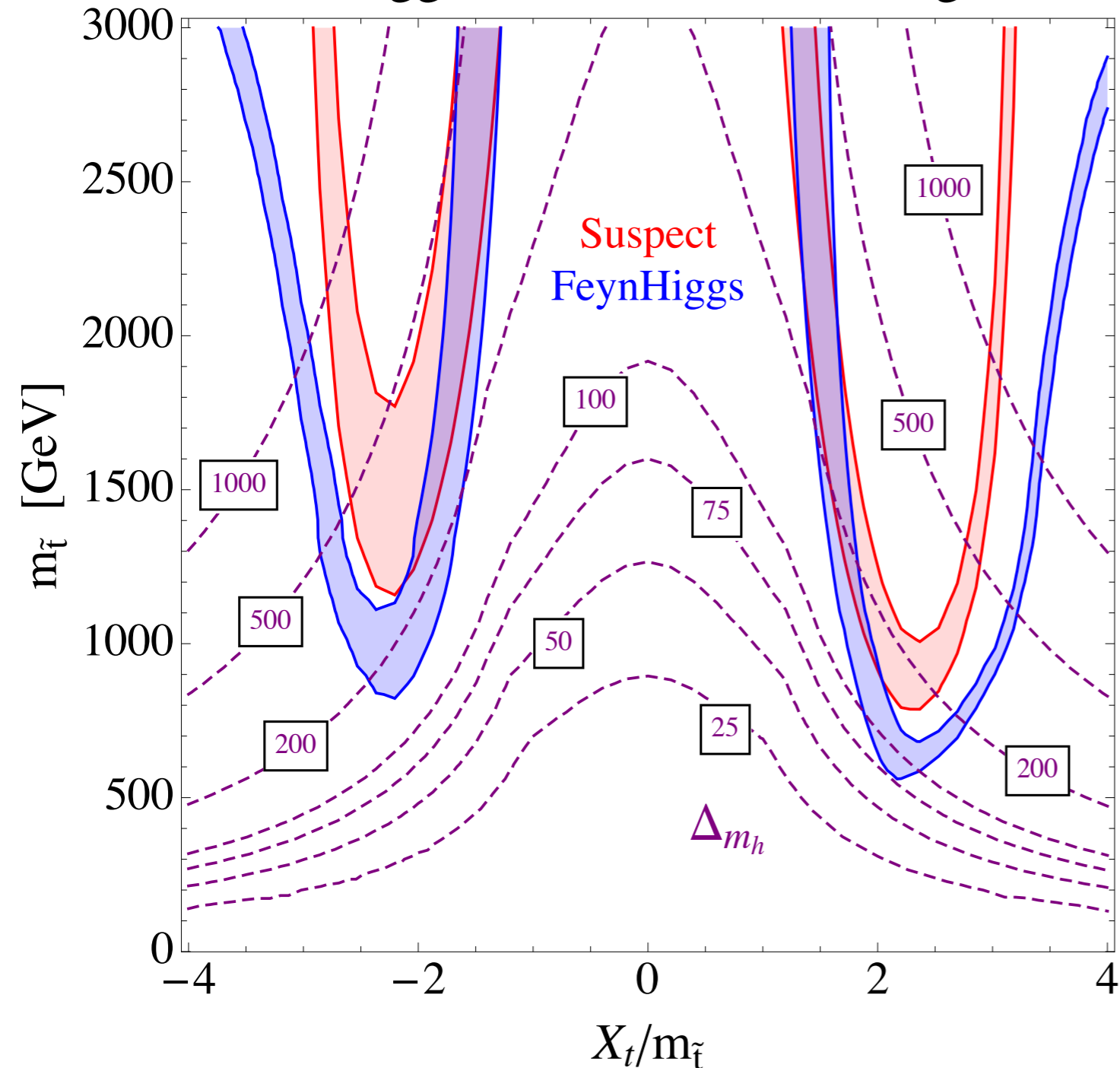
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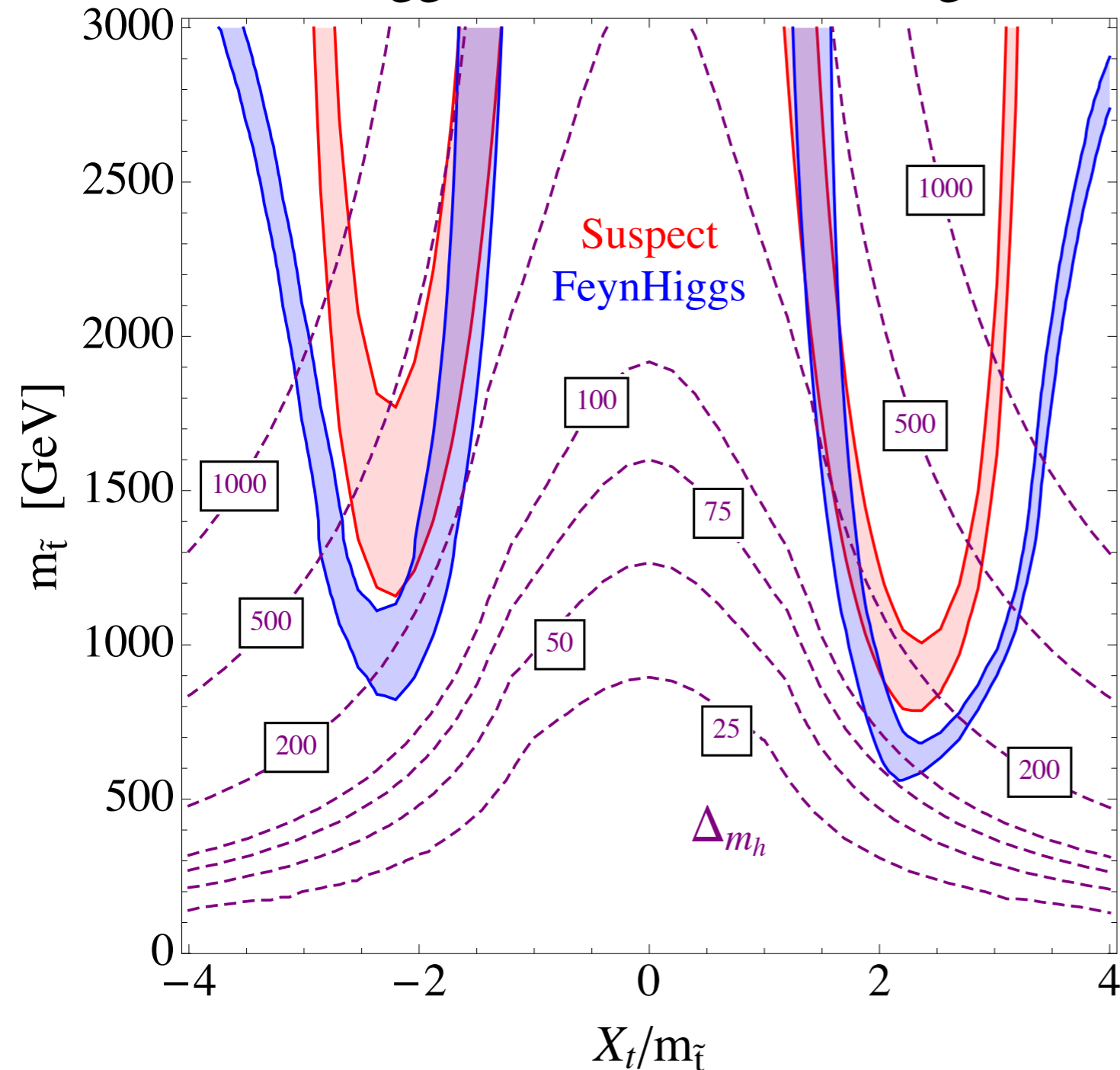
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Second way to make m_H right:

Add an extra singlet SF. (NMSSM or λ SUSY)

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

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Due to peculiar structure of Higgs potential, at tree-level: $\lambda = \frac{g^2 + g'^2}{8}$

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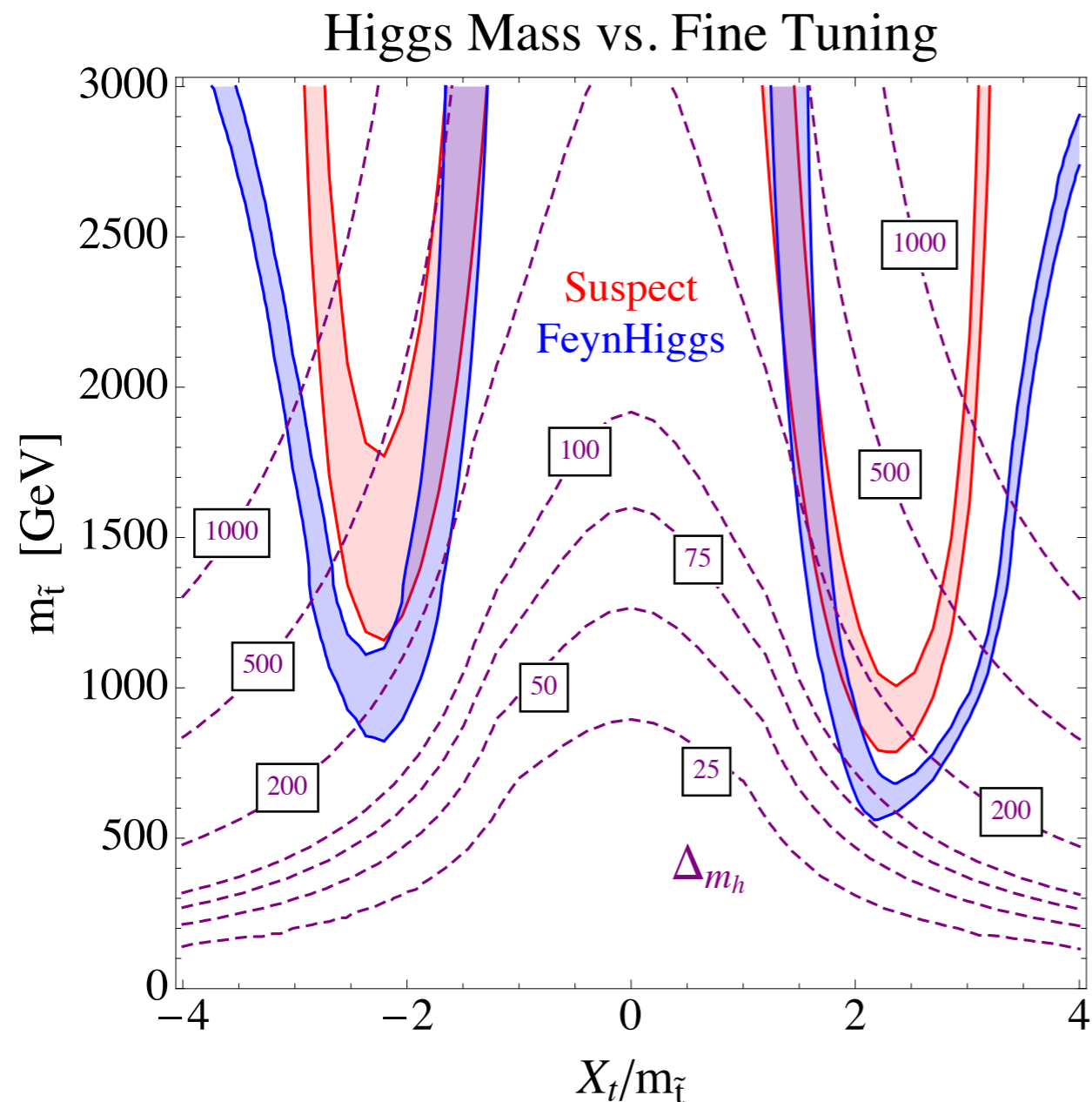
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MSSM is **Un-Natural** with 125 GeV Higgs!

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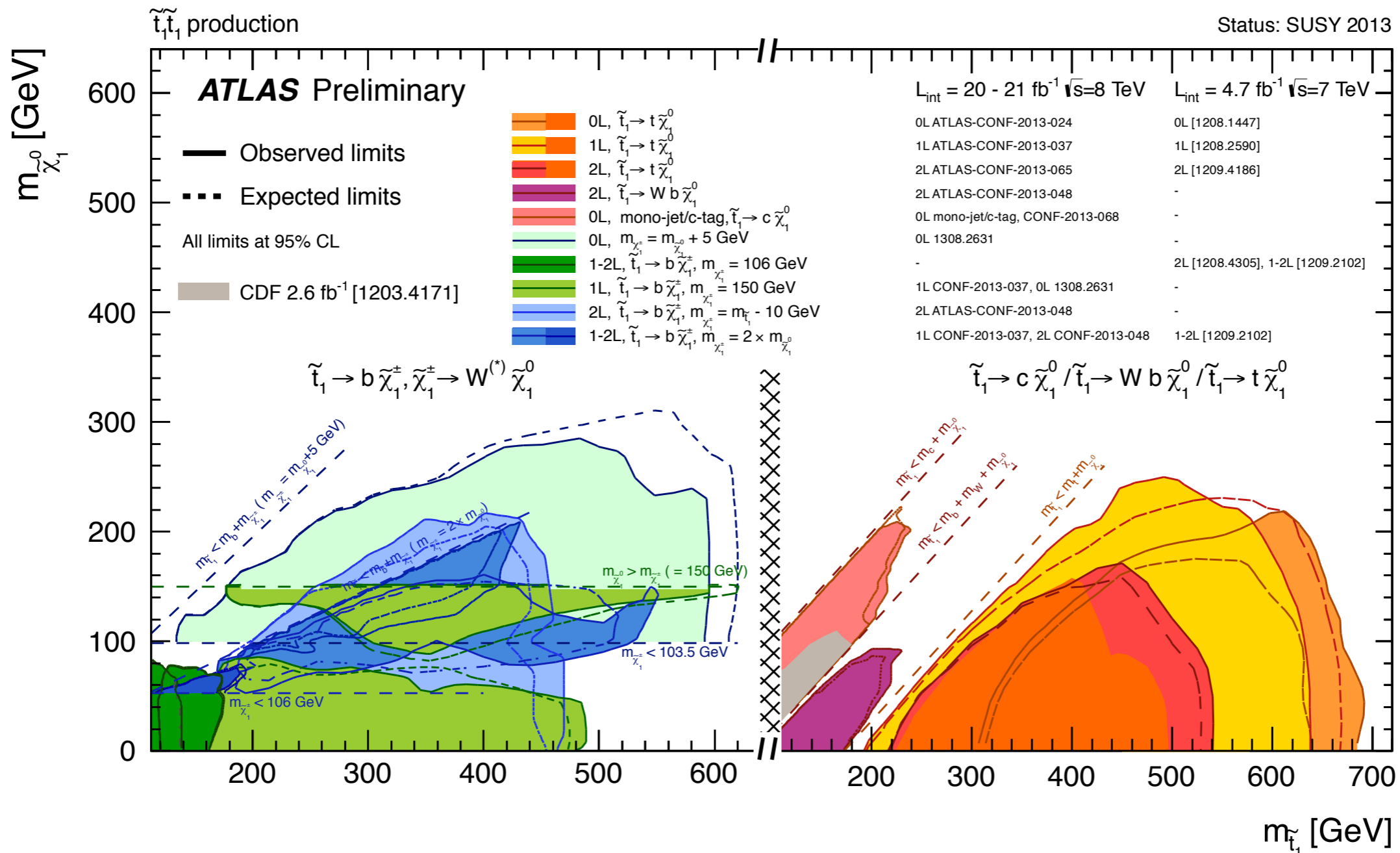


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Impressive search program

Quantitative illustration

Qualitative illustration

ATLAS SUSY Searches* - 95% CL Lower Limits
 Status: July 2015

ATLAS Preliminary
 $\sqrt{s} = 7, 8 \text{ TeV}$

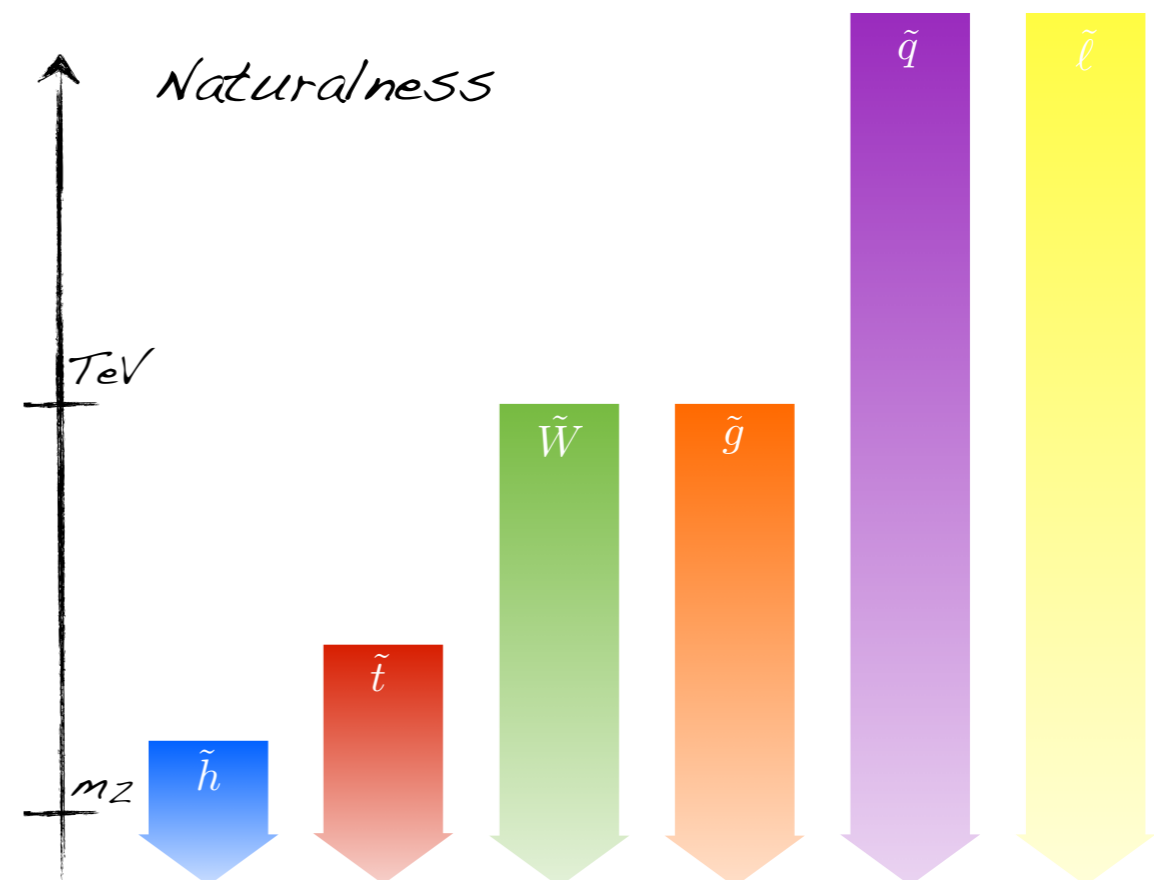
Model	Search	Model	Mass limit	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	Reference
GMSB	... (1)

GMSB

GMSB

Mass scale [TeV]

*Only a selection of the available lower limits on new states/correlations is shown. All limits shown are absolute unless for theoretical objects (e.g. \tilde{g} or \tilde{t}) where model uncertainties are indicated.



from arXiv:1309.0528

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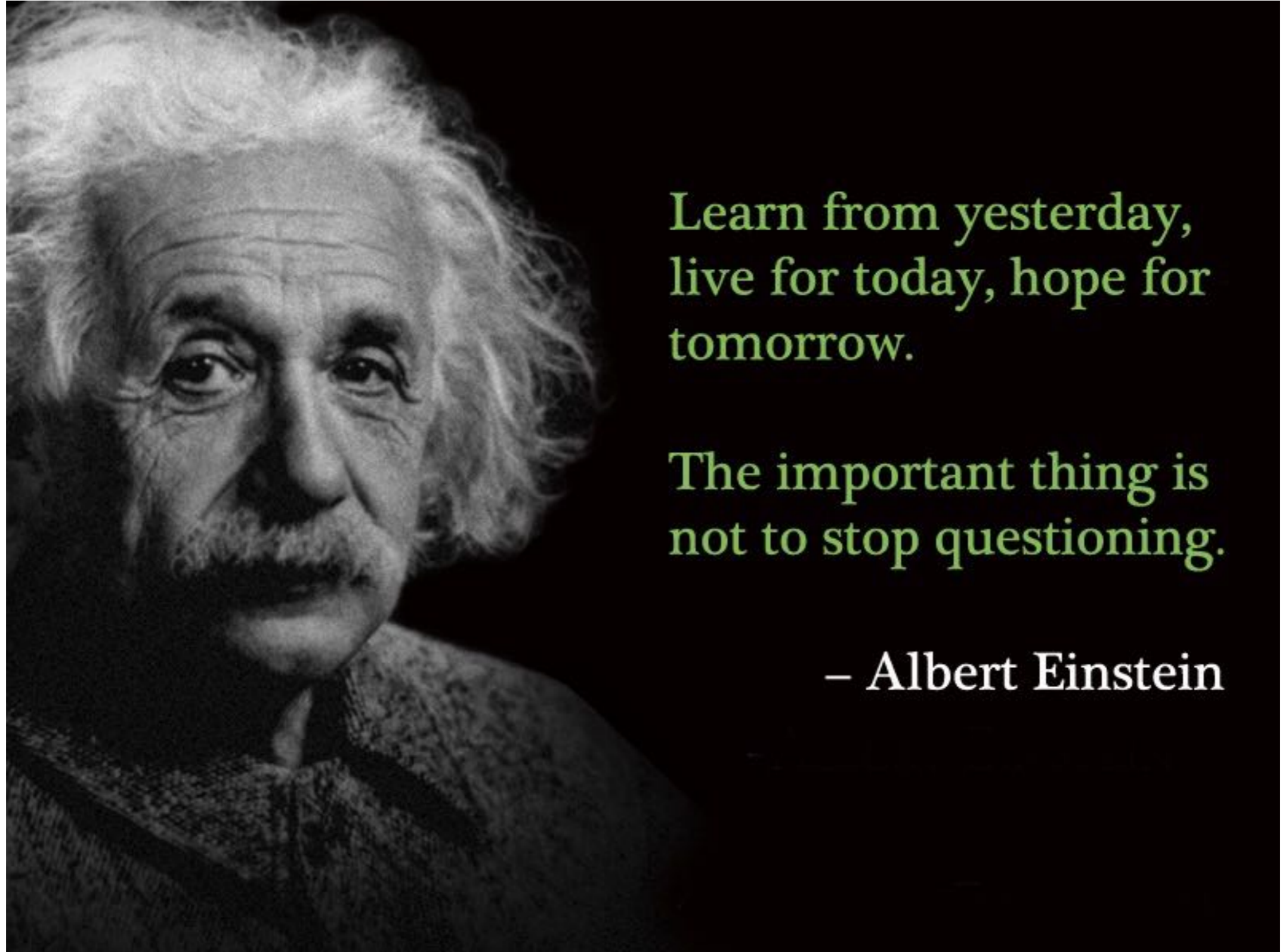
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Experimentalists should not **blindly trust** theorists.

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

Final Thoughts



Learn from yesterday,
live for today, hope for
tomorrow.

The important thing is
not to stop questioning.

– Albert Einstein