

# Electroweak Symmetry Breaking Theory

(for experimenters and theorists)

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- 1. The SM Lagrangian  $\Rightarrow$  predictions
- 2. Higgs physics
- 3. the SM as an effective theory  $\Rightarrow$  BSM
- 4. Relaxion?

excellent lectures on web:

1-2:	Heather Logan, TASI 2013 school	1406.1786
1-3):	Michael Peskin, CERN-JINR 2016 school	1708.09043
4:	Graham, Kaplan, Rajendran, "Cosmological Relaxion of the EW scale"	1504.07551 + citations e.g. 1708.00010

The Standard Model is an

$$SU(3)_{\text{color}} \times SU(2)_{\text{weak}} \times U(1)_{\text{Hypercharge}}$$

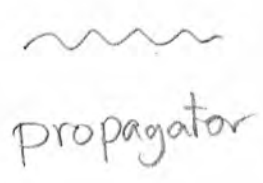
gauge theory.

$$L_{\text{gauge}} = -\frac{1}{4} G_{\mu\nu}^a G^{a\mu\nu} - \frac{1}{4} W_{\mu\nu}^a W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

8 gluons  $W, Z, \gamma$

e.g.  $W_{\mu\nu}^a \equiv \partial_\mu W_\nu^a - \partial_\nu W_\mu^a + g \epsilon^{abc} W_\mu^b W_\nu^c$

without EW symmetry breaking:



interactions

Fermions:

QED: 4-component spinors  $\swarrow$  Lorentz group  $\swarrow$  Dirac

$$e = \begin{pmatrix} e_L \\ e_R \end{pmatrix} \quad e_L \equiv P_L e = \begin{pmatrix} e_L \\ 0 \end{pmatrix}$$

$$e_R \equiv P_R e = \begin{pmatrix} 0 \\ e_R \end{pmatrix}$$

$\swarrow$  " +  $\gamma_0$ "  $\swarrow$  charge -1

$$\mathcal{L}_e = \bar{e} (i \gamma^\mu D_\mu - m) e \quad D_\mu = \partial_\mu - i e A_\mu Q$$

$$\sim (\bar{e}_L^+ \bar{e}_R) \begin{pmatrix} "i \not{\partial}" & -m \\ -m & "i \not{\partial}" \end{pmatrix} \begin{pmatrix} e_L \\ e_R \end{pmatrix}$$

$$= \underbrace{\bar{e}_L i \not{\partial} e_L + \bar{e}_R i \not{\partial} e_R}_{\text{independent kinetic terms, gauge couplings}} - m \underbrace{(\bar{e}_L e_R + \bar{e}_R e_L)}_{\text{breaks chiral symmetry}}$$

independent kinetic terms,  
gauge couplings

breaks chiral symmetry  
 $e_L \rightarrow e^{i\alpha_L} e_L$   
 $e_R \rightarrow e^{i\alpha_R} e_R$

the SM does NOT work this way!

SM field	$SU(3)_c$	$SU(2)_w$	$U(1)_y$	$Q = T_3 + Y$	
$e_R$	1	1	-1		} determines couplings to gauge bosons
$L_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	1	2	$-\frac{1}{2}$		
$u_R$	3	1	$\frac{2}{3}$		
$d_R$	3	1	$-\frac{1}{3}$		
$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	3	2	$\frac{1}{6}$		
$H$	1	2	$\frac{1}{2}$		} Higgs
$\tilde{H} \equiv i\sigma_2 H^*$	1	2	$-\frac{1}{2}$		

Notation:  $e_R \equiv P_R e = \begin{pmatrix} 0 \\ e_R \end{pmatrix}$

2-component spinors in 4-component notation.

$e_L = \begin{pmatrix} e_L \\ 0 \end{pmatrix}$

- $m \bar{e}_L e_R$  not gauge invariant
  - $m e_R^+ e_R$  not Lorentz invariant ( $\bar{e}_R e_R = 0$ )
- } massless fermions!

But:

$\mathcal{L}_{Yukawa} = -y_e \bar{L}_L H e_R - y_d \bar{Q}_L H d_R - y_u \bar{Q}_L \tilde{H} u_R + h.c.$



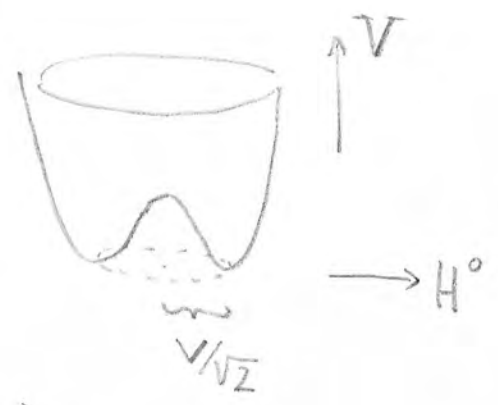
not a mass

Higgs doublet:

$$\mathcal{L}_H = D_\mu H^\dagger D^\mu H - \lambda \overbrace{\left( H^\dagger H - \frac{v^2}{2} \right)^2}^{V(H)}$$

$$H(x) = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \frac{1}{\sqrt{2}} e^{i\theta(x)} \begin{pmatrix} 0 \\ v+h(x) \end{pmatrix}$$

↑ complex
↑
↑ real



remove from  $\mathcal{L}$  by gauge transformation

"unitary gauge"

$$V \rightarrow +\lambda v^2 h^2 + \lambda v h^3 + \frac{\lambda}{4} h^4$$

$$m_h^2 = 2\lambda v^2$$



# Higgs mechanism for $W, Z$ masses

$$D_\mu H = \left( \partial_\mu - ig' \frac{1}{2} B_\mu - ig \frac{\sigma^a}{2} W_\mu^a \right) H$$

$$\Rightarrow (D_\mu H)^\dagger D^\mu H \xrightarrow{H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}} \underbrace{\frac{g^2 v^2}{4}}_{m_W^2} W_\mu^+ W^{-\mu} + \underbrace{\frac{(g^2 + g'^2) v^2}{4}}_{m_Z^2} \frac{1}{2} Z_\mu Z^\mu$$

$$W^\pm = \frac{W_1 \mp i W_2}{\sqrt{2}} \text{ complex}$$

$$Z = c_w W_3 - s_w B \text{ real}, \quad A = s_w W_3 + c_w B \text{ massless}$$

$$s_w = \sin \theta_w = \frac{g'}{\sqrt{g^2 + g'^2}}$$

$W, Z$  have "eaten"  $\theta^a$  Nambu-Goldstone-Bosons.

Fermion masses:

$$y_e \begin{pmatrix} \bar{\nu}_L \\ e_L \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix} e_R \rightarrow m_e = y_e \frac{v}{\sqrt{2}}$$

3 generations  $\rightarrow \frac{v}{\sqrt{2}} y_e^{ij} \bar{e}_L^i e_R^j$ , mass matrix  $m_e^{ij} = \frac{v}{\sqrt{2}} y_e^{ij}$

rotate fields:  $e_L \rightarrow U_{eL} e_L$  to diagonalize  $y_e/m_e \Rightarrow 3$  masses  
 $e_R \rightarrow U_{eR} e_R$

quarks:  $m_d = y_d \frac{v}{\sqrt{2}}$  diagonalize  $\Rightarrow 6$  masses

$$m_u = y_u \frac{v}{\sqrt{2}}$$

mismatch of bases:  $V_{CKM} = U_{uL}^\dagger U_{dL}$  3 angles, 1 phase

$W^\pm$  coupling:  $g \overline{(u c t)}_L W^\pm V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L + h.c.$  flavor violating

Z:  $\left. \begin{matrix} \frac{e}{c_w s_w} \bar{q}_i \not{=} (T_i^3 - s_w^2 Q_i) q_i \end{matrix} \right\}$  flavor preserving

photon:  $e \bar{q}_i \not{=} Q_i q_i$

summary: •  $W^\pm, Z$ , fermion masses from Higgs VEV

$$V \approx 246 \text{ GeV} \quad (G_F \text{ in } \mu\text{-decay})$$

$$\frac{m_W}{m_Z} = \frac{g}{\sqrt{g^2 + g'^2}} = c_w \quad m_W = \frac{gV}{2}$$

$$m_f = y_f \frac{V}{\sqrt{2}} \quad m_h = \sqrt{2\lambda} V$$

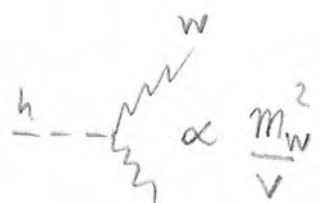
• all gauge couplings determined by  $g, g' \Leftrightarrow e, \sin^2 \theta_w$

lecture 1.

Higgs couplings:  $H = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$

$\Rightarrow$  replace  $V \rightarrow v(1 + \frac{h}{v})$  in masses

e.g.  $m_W^2 W^+ W^- \rightarrow m_W^2 (1 + \frac{h}{v})^2 W^+ W^-$



$$m_b \bar{b}_L b_R \rightarrow m_b (1 + \frac{h}{v}) \bar{b}_L b_R$$



no new parameters  $\Rightarrow$  Higgs couplings predicted



# Higgs decays

•  $h \rightarrow b\bar{b}$

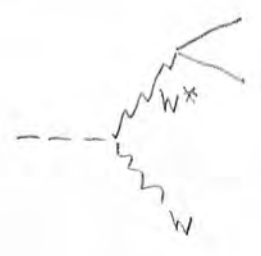


$$A \sim \frac{m_b}{v} \sim 10^{-2}$$

$$\Rightarrow \frac{\Gamma_{b\bar{b}}}{m_h} = \frac{1}{8\pi} \left(\frac{m_b}{v}\right)^2 N_c \left(1 - \frac{(2m_b)^2}{m_h^2}\right)^{3/2} \approx 10^{-5}$$

$\uparrow$   
 actually,  $\frac{\lambda_b[m_h]}{\sqrt{2}}$

•  $h \rightarrow WW^*$



$$\sim \frac{m_W^2}{v} \frac{g}{m_W^2} = \frac{g}{v}$$

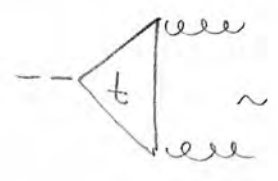
rough

$$\frac{\Gamma_{WW^*}}{\Gamma_{b\bar{b}}} \sim \frac{g^2/v^2}{m_b^2/v^2} \frac{1}{16\pi^2} m_h^2 \sim \mathcal{O}(1)$$

$\uparrow$  3 body final state       $\uparrow$  dimensional analysis

•  $h \rightarrow gg$

loop process



$$\sim \frac{g_s^2}{16\pi^2} \frac{\lambda_t}{m_t} = \frac{\alpha_s}{4\pi} \frac{1}{v}$$

$$\frac{\Gamma_{gg}}{m_h} < 10^{-5}$$

•  $h \rightarrow \gamma\gamma$




$$\sim \frac{\alpha}{4\pi} \frac{1}{V}$$

BR predictions (@125.5 GeV HXSWG)

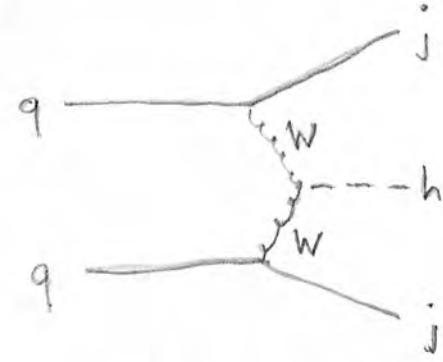
$b\bar{b}$	57%	$\sim 2\sigma$
$WW^*$	22%	$4\sigma$
$gg$	8.5%	
$\tau\tau$	6.2%	$1-2\sigma$
$c\bar{c}$	2.9%	
$ZZ^*$	2.8%	$>5\sigma$
$\gamma\gamma$	0.23%	$>5\sigma$
$\gamma Z$	0.16%	
$\mu^+\mu^-$	0.02%	

# Higgs production ( @ 125.5 GeV , 8 TeV HXSWG )


gg   $\sigma = 19 \text{ pb} \pm 10\%$

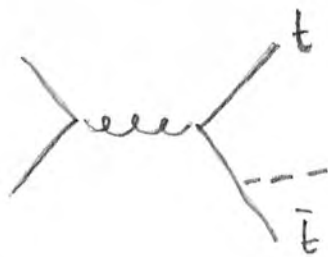
← pdfs, scale

most important

VBF   $\sigma = 1.6 \pm 3\%$

forward jet tags, "seen" in 88

Associated   $0.7 + 0.4 \text{ pb}$  Tevatron, LEP, LC

$t\bar{t}h$    $0.1 \text{ pb}$  measure  $t\bar{t}h$  coupling

Invisible decays? ( $h \rightarrow \text{dark matter}, \nu\text{'s}, a.a. \rightarrow 4j$ )

-11-

$$\text{visible rate } i = \sigma \cdot \frac{\Gamma_i}{\Gamma_{\text{tot}}}$$

$$\Gamma_{\text{tot}} = \Gamma_{\text{SM}} + \Gamma_{\text{non-SM}}$$

$\Rightarrow$  uniform decrease of signal in all channels

1. current data allow  $\sim 20\%$   $\text{Br}_{\text{inv.}}$

2. flat direction:  $\text{Br}_{\text{inv.}} \uparrow \quad \sigma \uparrow$

Q: reasonable?

1.  $\Gamma_{\text{SM}} \sim \Gamma_{b\bar{b}} \propto \lambda_b^2 \sim (10^{-2})^2$  very small

$\Rightarrow \Gamma_{\text{non-SM}} \sim \Gamma_{\text{SM}}$  easy

example:  $h \rightarrow \chi\chi$  "Higgs portal" DM

$$\mathcal{L} \sim \frac{H^\dagger H}{M} \chi\chi \Rightarrow \lambda_\chi = \frac{v}{M} \quad \text{can probe } M \sim 10 \text{ TeV}$$



$$\sigma \sim \sigma_{SM} \left( 1 + \lambda_{Q'}^2 \frac{v^2}{m_{Q'}^2} \right)^2$$

20% easy ( $\lambda=1, m_Q \sim 750 \text{ GeV}$ )

does not enhance VBF  $\Rightarrow$  VBF already bounds  $Br_{inv} \lesssim 60\%$

precision measurements  $\rightarrow$  precision tests

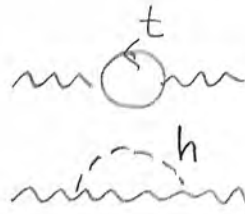
Example: Tevatron :  $M_W = 80.38 \pm 0.03$  GeV  
0.03 % accuracy !

by itself this is completely uninteresting.

BUT in SM :  $M_W = M_Z \cos \theta_W$  (tree level)  
 $\uparrow \quad \uparrow$   
LEP/SLC

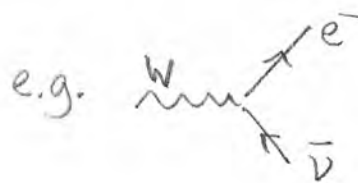
gitter predicts " $M_Z \cos \theta_W$ " =  $80.36 \pm 0.02$

requires:

- loop corrections e.g.   $\frac{\delta m^2}{m^2} \sim \frac{1}{16\pi^2} \sim 1\%$

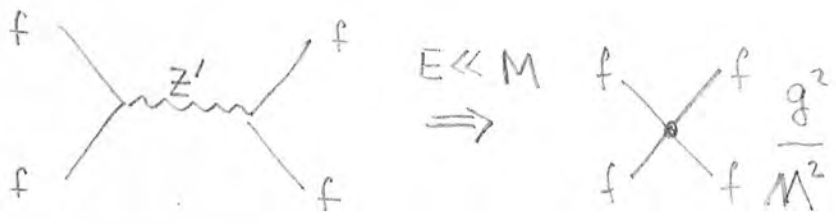
$\Rightarrow$  need 2 loop.

• careful definitions



# Precision tests and SM as effective theory

Example:  $Z'$  with mass  $M$ ,  $f = \text{SM field}$



$$\mathcal{L}_{\text{eff}} = \frac{\bar{f} \gamma_\mu f \bar{f} \gamma^\mu f}{\Lambda^2} \quad \Lambda = M/g$$

Lesson: Heavy new physics can be parameterized by effective couplings of SM fields suppressed by heavy scale.

$\Rightarrow$  write all "possible" effective couplings of SM fields

("possible"  $\leftrightarrow$  gauge invariant, lorentz-invariant, ... )

systematically (ordered by mass-dimension of coefficient)

$$\mathcal{L} = \Lambda^4 + \Lambda^2 H^\dagger H + \underbrace{\lambda (H^\dagger H)^2 + \mathcal{L}_{\text{kinetic}} + \mathcal{L}_{\text{Yukawa}}}_{\text{dimensionless couplings } \mathcal{L}_{\text{SM}}}$$

$$+ \frac{(\overline{L_L H})^2}{\Lambda} \quad \text{"dimension 5"}$$

neutrino masses

"T": shifts Z mass

$$+ \frac{H^\dagger D_\mu H H^\dagger D^\mu H}{\Lambda^2}$$

shifts Z couplings

$$+ \frac{H^\dagger D_\mu H \bar{e}_R \gamma^\mu e_R}{\Lambda^2}$$

$$+ \frac{H^\dagger \sigma^a H W_{\mu\nu}^a B^{\mu\nu}}{\Lambda^2}$$

"dim 6"

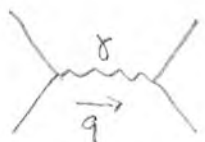
$$+ \frac{H^\dagger H B_{\mu\nu} B^{\mu\nu}}{\Lambda^2}$$

$$+ \frac{H^\dagger H W_{\mu\nu}^a W^{a\mu\nu}}{\Lambda^2}$$

+ ... (> 80 at dim 6!)

+ "dim 7" + "dim 8" + ...

example:



$$+ \frac{1}{\Lambda^2}$$

expansion parameter,

useful for  $q \ll \Lambda$

$$\sim \frac{1}{q^2} + \frac{1}{\Lambda^2} = \frac{1}{q^2} \left( 1 + \frac{q^2}{\Lambda^2} \right)$$




Examples:  $H^\dagger D_\mu H \rightarrow \frac{1}{2} (0 \nu) \left[ \cancel{\partial}_\mu - i g' \frac{1}{2} B_\mu - i g \frac{\sigma^a}{2} W_\mu^a \right] \begin{pmatrix} 0 \\ \nu \end{pmatrix}$

$$= \frac{v^2}{4} \sqrt{g^2 + g'^2} Z_\mu$$

"T"  $\frac{(H^\dagger D_\mu H)^2}{\Lambda^2} \rightarrow \frac{(g^2 + g'^2) v^4}{16 \Lambda^2} Z_\mu Z^\mu$

$$\Rightarrow \frac{\delta m_Z^2}{m_Z^2} = \frac{v^2}{2 \Lambda^2} \quad \text{LEP: } \Lambda \gtrsim 5 \text{ TeV}$$

•  $\frac{H^\dagger D_\mu H \bar{e}_R \gamma^\mu e_R}{\Lambda^2} \rightarrow \sim \frac{v^2}{\Lambda^2} Z_\mu \bar{e}_R \gamma^\mu e_R$  

$$\frac{\delta g}{g} \sim \frac{v^2}{\Lambda^2} \quad \text{LEP: } \Lambda \gtrsim \text{few TeV}$$

Example: 
$$+ S_1 g'^2 \frac{H^\dagger H B_{\mu\nu} B^{\mu\nu}}{\Lambda^2} + S_2 g^2 \frac{H^\dagger H W_{\mu\nu}^a W^{a\mu\nu}}{\Lambda^2} + S_{12} g g' \frac{H^\dagger \sigma^a H W_{\mu\nu}^a B^{\mu\nu}}{\Lambda^2}$$

$H \rightarrow V$   

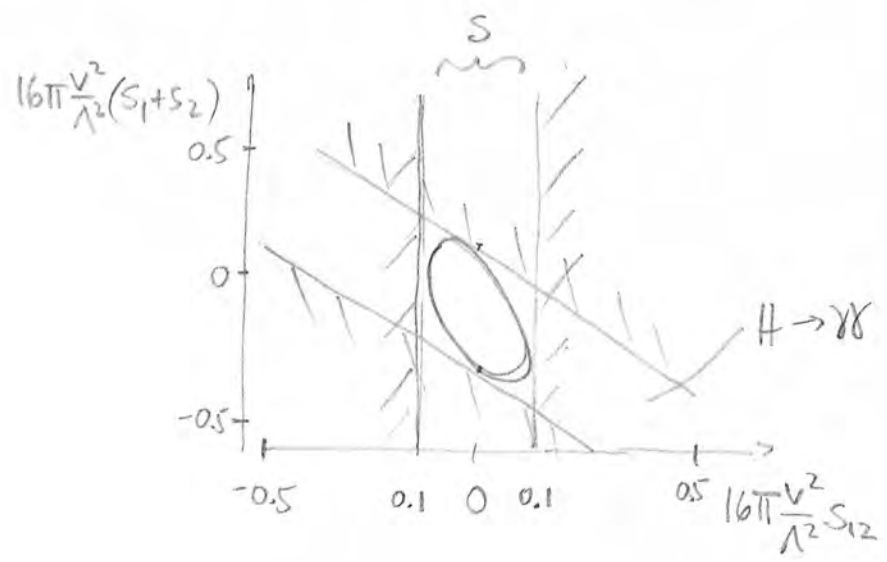
$$\hookrightarrow + S_1 g'^2 \frac{V^2}{2\Lambda^2} B_{\mu\nu} B^{\mu\nu} + S_2 g^2 \frac{V^2}{2\Lambda^2} W_{\mu\nu}^a W^{a\mu\nu} + S_{12} g g' \frac{V^2}{2\Lambda^2} W_{\mu\nu}^3 B^{\mu\nu}$$
  
 define away by rescaling gauge fields, unobservable "S" operator  $S = 16\pi S_{12} \frac{V^2}{\Lambda^2}$

$$+ S_1 g'^2 \frac{V}{\Lambda^2} h B_{\mu\nu} B^{\mu\nu} + S_2 g^2 \frac{V}{\Lambda^2} h W_{\mu\nu}^a W^{a\mu\nu} + S_{12} g g' \frac{V}{\Lambda^2} h W_{\mu\nu}^3 B^{\mu\nu}$$

$$\rightarrow \underbrace{4e^2 \frac{V^2}{\Lambda^2} (S_1 + S_2 + S_{12})}_{= -C_{\gamma\gamma}} \frac{1}{4V} h F_{\mu\nu} F^{\mu\nu} \left( + h F_{\mu\nu} Z^{\mu\nu} + h Z_{\mu\nu} Z^{\mu\nu} \right)$$

Precision electroweak:  $S = 0.0 \pm 0.1$  (95%) PDG

Higgs  $\rightarrow \gamma\gamma$  :  $C_{\gamma\gamma} = 0.001 \pm 0.002$  (95%) hep-ph 1303.1812v3  
 Falkowski-Riva-Urbano



$S_i = \frac{1}{16\pi^2} \Rightarrow \Lambda > 500 \text{ GeV}$

$S_i = 1 \Rightarrow \Lambda > 6 \text{ TeV}$

Note added: nice extension to  $h \rightarrow Z\gamma^*$  and  $h \rightarrow Z\gamma$  from these ops possible.

(un)naturalness:

$$V(H) = V_{\text{classical}} + V_{\text{loops}}$$

$$= + M_0^2 H^+ H + \text{---} \circ \text{---} + \dots + \text{quartic}$$

$$- \frac{3\lambda_t^2}{8\pi^2} \Lambda^2 H^+ H$$

↖ scale of new physics which cuts off loop. e.g. Superpartner masses

$$\Rightarrow M_0^2 - \frac{3\lambda_t^2}{8\pi^2} \Lambda^2 = -\frac{m_h^2}{2}$$

$$\Leftrightarrow M_0^2 - \frac{\Lambda^2}{25} = -\frac{\text{TeV}^2}{100}$$

no cancelation at all  $\Rightarrow \Lambda \approx \text{TeV}/2$

10% tuning

$$\Lambda \sim 1.5 \text{ TeV}$$

1% tuning

$$\Lambda \sim 5 \text{ TeV}$$

$m_{SUSY}:$   $M_0^2 - \frac{3\lambda_t^2}{8\pi^2} m_{\tilde{t}}^2 \underbrace{2 \log \frac{M_{mess}}{m_{\tilde{t}}}} = -\frac{m_h^2}{2}$

$\sim 2 \log 100 \sim 10$  "best case"

- $\Rightarrow$  no cancel  $m_{\tilde{t}} \leq 150$  GeV  
 10%  $\sim 500$  GeV  
 1%  $\sim 1.5$  TeV

Vanilla SUSY is already unnatural.

Similar story in other explicit models.

Conclusion? Maybe there is something very wrong with our understanding of the Higgs. I wish I knew what it was ...