Weak interactions and Higgs Theory, 3 HCPSS lectures

(M. Schmaltz, Boston University)

1. SM Lagrangian, predictions
2. Higgs Physics
3. SM effective field theory

(Un)Natural ness

} see also TASI lectures 2013 Heather Logan

The Standard Model is an $SU(3)_{color} \times SU(2)_{weak} \times U(1)_{Hypercharge}$ gauge theory.

$$\mathcal{L}_{gauge} = \underbrace{-\frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu}}_{\text{gluons}} \underbrace{- \frac{1}{4} W^a_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}}_{W, Z, \gamma}$$

e.g. $W^a_{\mu\nu} \equiv \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g\, \epsilon^{abc} W^b_\mu W^c_\nu$

$\Longrightarrow$ 

massless propagator

interactions

Fermions:

Lorentz group

Dirac

QED: 4-component spinors $e = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$ $\qquad e_L \equiv P_L e = \begin{pmatrix} e_L \\ 0 \end{pmatrix}$
$e_R \equiv P_R e = \begin{pmatrix} 0 \\ e_R \end{pmatrix}$

"+ γ_0"

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

charge -1

$$\sim (e_L^+ \; e_R) \begin{pmatrix} \text{"}i\not{D}\text{"} & -m \\ -m & \text{"}i\not{D}\text{"} \end{pmatrix} \begin{pmatrix} e_L \\ e_R \end{pmatrix}$$

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

$e_L \to e^{i\alpha_L} e_L$

$e_R \to e^{i\alpha_R} e_R$

the SM does <u>NOT</u> work this way!

SM field	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$Q = T_3 + Y$
e_R	1	1	-1	Leptons
$L_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	1	2	$-1/2$	
u_R	3	1	$2/3$	Quarks
d_R	3	1	$-1/3$	
$Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	3	2	$1/6$	
H	1	2	$1/2$	Higgs
$\tilde{H} \equiv i\sigma_2 H^*$	1	2	$-1/2$	

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!

<u>But</u>

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

not a mass

Higgs doublet :

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

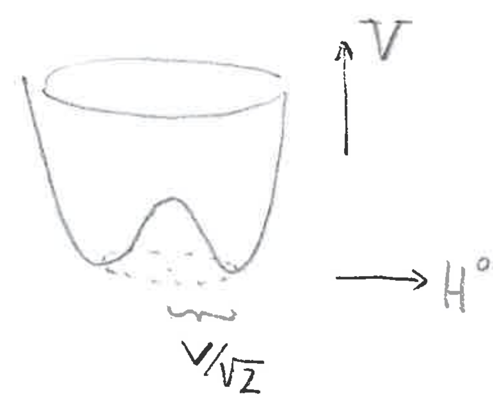
$$H(x) = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix} = \frac{1}{\sqrt{2}} e^{i\theta^a(x)\sigma^a} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

complex

real

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

"unitary gauge"



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

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

hard to observe

impossible to see

Higgs mechanism for $W^\pm, Z$ masses

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

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

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

$Z = c_W W_3 - s_W B$ real , $A = s_W W_3 + c_W B$ massless

$s_W = \sin\theta_W = \dfrac{g'}{\sqrt{g^2+g'^2}}$

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

Fermion masses:

$$y_e \overline{\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} e_R \quad \rightarrow \quad m_e = y_e \frac{v}{\sqrt{2}}$$

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

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

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

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

Z: $\frac{e}{c_W s_W} \bar{q}_i \cancel{Z} (T_i^3 - s_W^2 Q_i) q_i$

photon: $e \, \bar{q}_i \cancel{A} Q_i q_i$

$\Big\}$ flavor preserving

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

$$v \simeq 246 \text{ GeV} \qquad (G_F \text{ in } \mu\text{-decay})$$

$$\frac{m_W}{m_Z} = \frac{g}{\sqrt{g^2+g'^2}} = c_W \qquad m_W = \frac{gv}{2}$$

$$m_f = y_f \frac{v}{\sqrt{2}} \qquad m_h = \sqrt{2\lambda}\, v$$

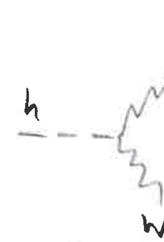
• all gauge couplings determined by $g, g' \Longleftrightarrow e, \sin^2\theta_W$

lecture 1.

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

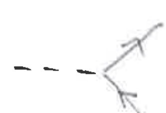
$\Rightarrow$ replace $v \to v(1+\frac{h}{v})$ in masses

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



$\propto \frac{m_W^2}{v}$

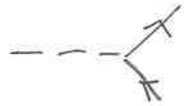
$m_b \bar{b}_L b_R \to m_b (1+\frac{h}{v}) \bar{b}_L b_R$



$\frac{m_b}{v}$

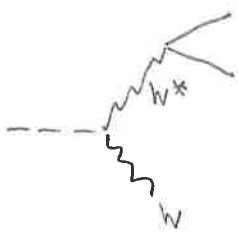
no new parameters $\Rightarrow$ Higgs couplings predicted

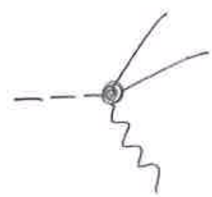
Higgs decays

- $h \longrightarrow b\bar{b}$  $A \sim \frac{m_b}{v} \sim 10^{-2}$

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

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

- $h \longrightarrow WW^*$ 

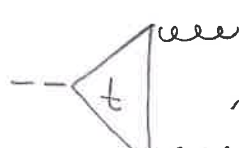
$\overset{\sim}{\Longrightarrow}$  $\sim \frac{m_W^2}{v}\frac{g}{m_W^2} = \frac{g}{v}$

rough

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

3 body final state

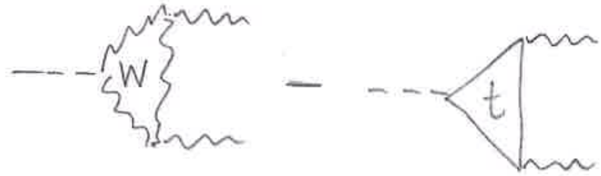
dimensional analysis

- $h \rightarrow gg$ loop process 

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

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

• $h \to \gamma\gamma$



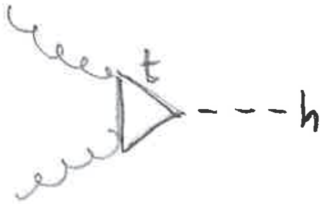
$\sim \frac{\alpha}{4\pi}\frac{1}{v}$

partially cancel

BR predictions (@125.5 GeV HXSWG)

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

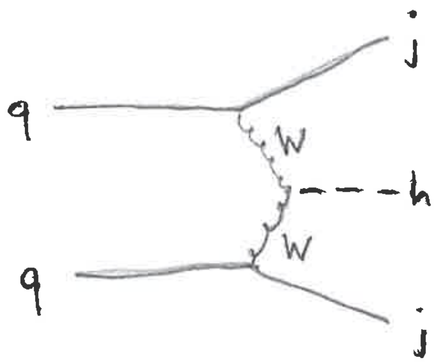
Higgs production (@ 125.5 GeV, 8 TeV HXSWG)

gg 

$\sigma = 19$ pb $\pm 10\%$ ← pdfs, scale

most important

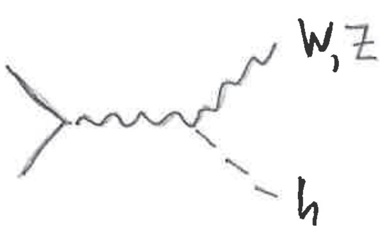
VBF



$\sigma = 1.6 \pm 3\%$

forward jet tags, "seen" in $\gamma\gamma$

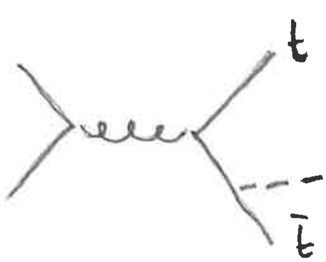
Associated



0.7 + 0.4 pb

Tevatron, LEP, LC

$t\bar{t}h$



0.1 pb

measure tth coupling

Invisible decays? ($h \to$ dark matter, ν's, $aa \to 4j$)

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

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

$\Rightarrow$ uniform decrease of signal in all channels

1. current data allow $\sim 20\%$ $Br_{inv.}$
2. flat direction: $Br_{inv.} \uparrow$ $\sigma \uparrow$

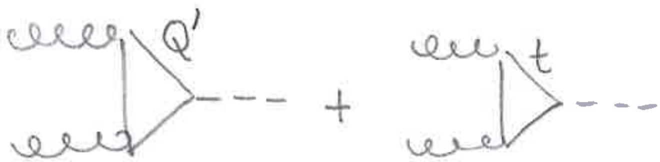
Q: reasonable?

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

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

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

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

2. 

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

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

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

precision measurements $\longrightarrow$ precision tests

Example: Tevatron : $m_W = 80.38 \pm 0.03$ GeV

0.03 % accuracy !

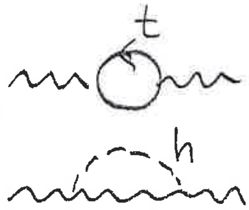
by itself this is completely uninteresting.

BUT in SM : $m_W = m_Z \cos\theta_W$ (tree level)

m_Z, $\cos\theta_W$ ← LEP/SLC

gfitter predicts "$m_Z \cos\theta_W$" $= 80.36 \pm 0.02$

requires: • loop corrections e.g.

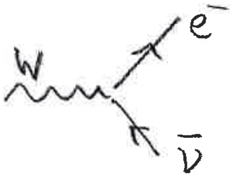


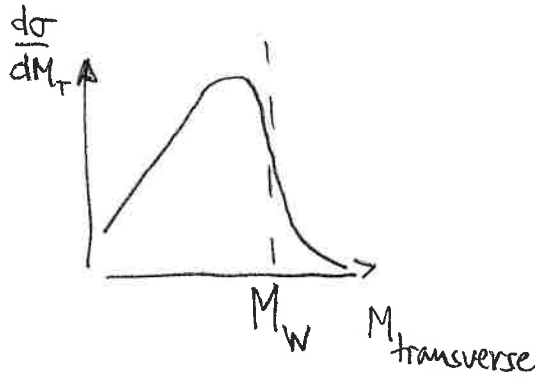
$\frac{\delta m^2}{m^2} \sim \frac{1}{16\pi^2} \sim 1\%$

$\Rightarrow$ need 2 loop.

• careful definitions

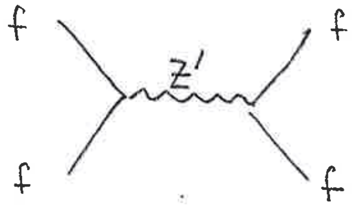
e.g.



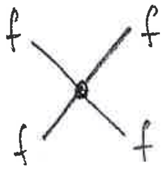


Precision tests and SM as effective theory

Example: Z' with mass M, f = SM field



$\xRightarrow{E \ll M}$



$\frac{g^2}{M^2}$

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

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, ...)

<u>systematically</u> (ordered by mass-dimension of coefficient)

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

$$+ \frac{(L_L H)^2}{\Lambda}$$

"dimension 5"

neutrino masses

"T": shifts Z mass

shifts Z couplings

$$+ \frac{H^\dagger D_\mu H \, H^\dagger D^\mu H}{\Lambda^2} + \frac{H^\dagger D_\mu H \, \bar{e}_R \gamma^\mu e_R}{\Lambda^2} + \frac{H^\dagger \sigma^a H \, W^a_{\mu\nu} B^{\mu\nu}}{\Lambda^2}$$

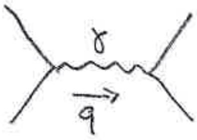
"dim 6"

$$+ \frac{H^\dagger H \, B_{\mu\nu} B^{\mu\nu}}{\Lambda^2} + \frac{H^\dagger H \, W^a_{\mu\nu} W^{a\mu\nu}}{\Lambda^2} + \ldots$$

(>80 at dim 6!)

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

<u>example</u>:



+

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

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: $H^\dagger D_\mu H \longrightarrow \frac{1}{2}(0\ v)\left[\cancel{\partial_\mu} - ig'\frac{1}{2}B_\mu - ig\frac{\sigma^a}{2}W_\mu^a\right]\begin{pmatrix}0\\ v\end{pmatrix}$

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

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

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

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

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

Example: $+ s_1 g'^2 \frac{H^\dagger H \, B_{\mu\nu}B^{\mu\nu}}{\Lambda^2} + s_2 g^2 \frac{H^\dagger H \, W^a_{\mu\nu} W^{a\mu\nu}}{\Lambda^2} + s_{12}\, g g' \frac{H^\dagger \sigma^a H \, W^a_{\mu\nu} B^{\mu\nu}}{\Lambda^2}$

$H \to v$

$$\hookrightarrow \underbrace{+ s_1 g'^2 \frac{v^2}{2\Lambda^2} B_{\mu\nu}B^{\mu\nu} + s_2 g^2 \frac{v^2}{2\Lambda^2} W^a_{\mu\nu}W^{a\mu\nu}}_{\text{define away by rescaling gauge fields, unobservable}} + \underbrace{s_{12}\, g g' \frac{v^2}{2\Lambda^2} W^3_{\mu\nu} B^{\mu\nu}}_{\text{"S" operator } S = 16\pi s_{12} \frac{v^2}{\Lambda^2}}$$

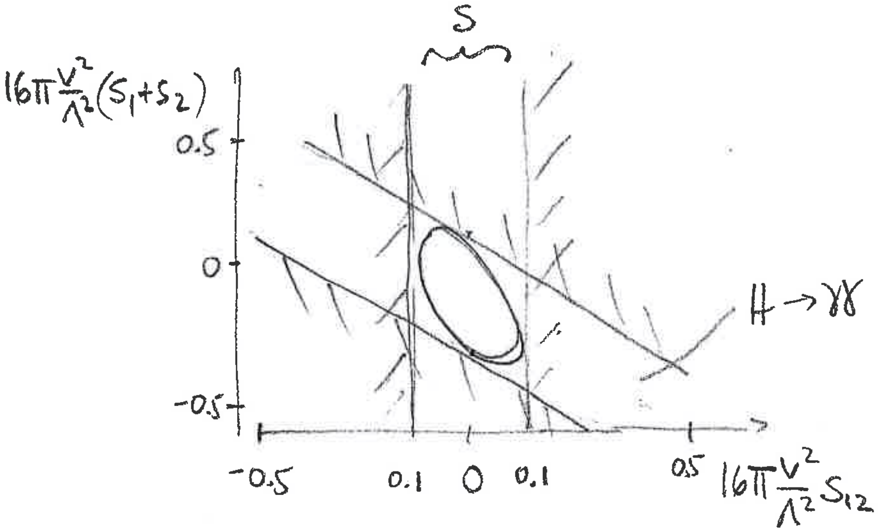
$$\underbrace{+ s_1 g'^2 \frac{v}{\Lambda^2} h B_{\mu\nu}B^{\mu\nu} + s_2 g^2 \frac{v}{\Lambda^2} h W^a_{\mu\nu} W^{a\mu\nu} + s_{12}\, g g' \frac{v}{\Lambda^2} h W^3_{\mu\nu} B^{\mu\nu}}$$

$$\to \underbrace{4e^2 \frac{v^2}{\Lambda^2}(s_1+s_2+s_{12})}_{= -c_{\gamma\gamma}} \frac{1}{4v} h F_{\mu\nu}F^{\mu\nu} \quad \left(+ \; h F_{\mu\nu} Z^{\mu\nu} + h Z_{\mu\nu} Z^{\mu\nu} \right.$$

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

Higgs $\to \gamma\gamma$: $c_{\gamma\gamma} = 0.001 \pm 0.002$ (95%) hep-ph 1303.1812v3

Falkowski-Riva-Urbano



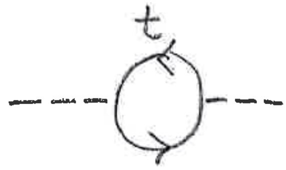
$s_i = \frac{1}{16\pi^2} \Rightarrow \Lambda > 500$ GeV

$s_i = 1 \Rightarrow \Lambda > 6$ TeV

(Un)naturalness:

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

$$= + M_0^2 H^\dagger H +$$



$$+ \cdots + \text{quartic}$$

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

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

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

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

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

10% tuning $\Lambda \sim 1.5$ TeV

1% tuning $\Lambda \sim 5$ TeV

in SUSY: $$M_0^2 - \frac{3\lambda_t^2}{8\pi^2} m_{\tilde{t}}^2 \underbrace{2\log\frac{M_{mess}}{m_{\tilde{t}}}}_{\sim 2\log 100 \,\sim\, 10 \text{ "best" case}} = -\frac{m_h^2}{2}$$

$\Rightarrow$ no cancel $\quad m_{\tilde{t}} \lesssim 150$ GeV

10% $\quad \sim 500$ GeV

1% $\quad \sim 1.5$ 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 ...