3 ways of thinking beyond the SM

- NP from well motivated experimental evidence (DM)
- dimensionless parameters (neutrino Yukawas)
- dimensional parameters (naturalness)

has the first run of the LHC given the lie to naturalness?

<u>Naturalness</u> is a problem of <u>decoupling</u> in a theory with two widely separated energy scales

We want the low-energy parameters
not to depend on those at high-energy
(i.e., no fine-tuning in the effective theory)

scalar particles tend not to decouple

there will be no problem
if there is only one scale

SM by itself is OK

there will be no problem
if we do not compute the correction

quantum gravity and Landau poles
are (probably) OK

Can we do a loop integral?

$$\int \frac{d^4k}{(2\pi)^4} \frac{1}{(k-p)^2 - m^2} \frac{1}{k^2 - m^2}$$

integration to infinity probes quantum gravity
but what we do not know how to compute
is swept under the rug of renormalisation

the cutoff in effective field theories refers to the external momenta (not the loop's!)

used in a momentum-dependent regularisation leads to potentially misleading results

e.g., Veltman formula

$$m^2 = \frac{\Lambda^2}{8\pi^2}\left[3\lambda^2 + 3g'^2 + 6g^2 - 12\lambda_t^2\right]$$

Assume there is a large scale:
how does the correction to the Higgs mass go?

it is finite and proportional to

- the coupling to heavy states
- the mass squared of heavy states

it is not proportional
to SM couplings or cutoff!

the top quark is not special

its contribution to the Higgs mass is natural aside

naturalness in
parametric fits of SUSY models

it depends on the NP

New physics above the SM
does give a problem

but it is a problem that can be solved
by making the new physics
supersymmetric

(making the whole SM SUSY works but is an overkill)

Naturalness redux

How much SUSY
does the Higgs boson need?

take the SM (not SUSY)
and add new physics (SUSY)

does the explicit breaking of SUSY
spoil naturalness?

(not too different from usual soft SUSY breaking)

an important example: the neutrino seesaw mechanism

$$\frac{\Lambda^2}{16\pi^2}\lambda_t^2 \qquad \Lambda \simeq M < 10^3 \text{ GeV}$$

$$\frac{M^2}{16\pi^2}y_\nu^2 \qquad M \leq 10^7 \text{ GeV}$$

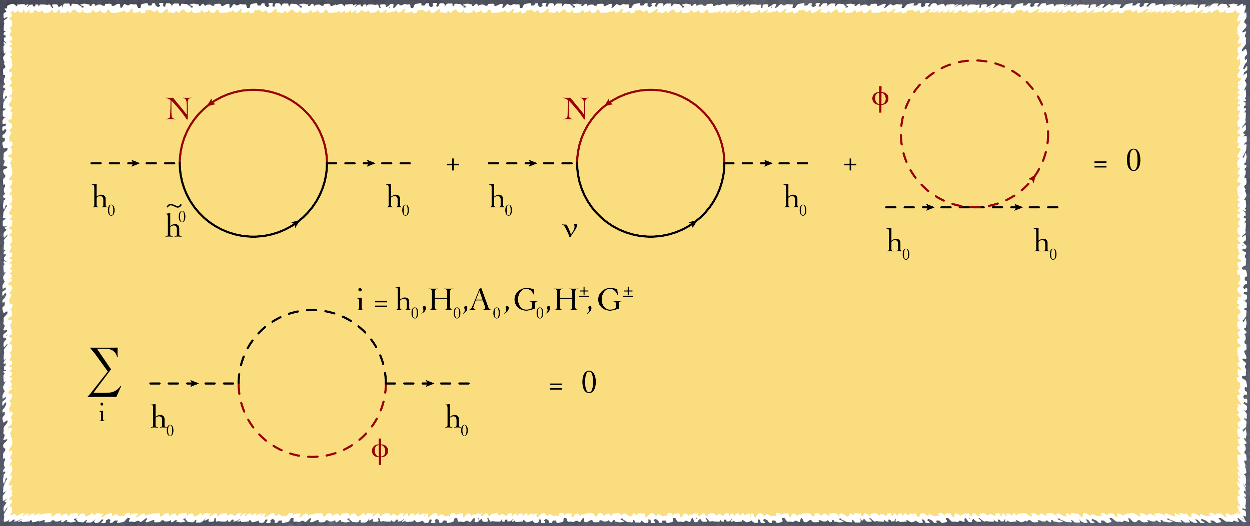
toy model: 1 generation

$$\begin{aligned}
\Phi^1_\alpha &= H^u_\alpha + \theta \cdot L_\alpha + \theta^2 F^u_\alpha \\
\Phi^2_\alpha &= H^d_\alpha + \theta \cdot \tilde{h}^d_\alpha + \theta^2 F^d_\alpha \\
\Phi_{\mathrm{NP}} &= \phi + \theta \cdot N + \theta^2 F
\end{aligned}$$

$$\mathcal{W}(\Phi_i) = \epsilon_{\alpha\beta}\Phi_1^\alpha \Phi_2^\beta \Phi_{\rm NP} + \frac{M}{2}\Phi_{\rm NP}^2$$

$$\begin{aligned}\mathcal{L}_{\rm int} = \quad & -\eta^2(\epsilon_{\alpha\beta}H^u_\alpha H^d_\beta)(\epsilon_{\alpha'\beta'}H^{u\,*}_{\alpha'}H^{d\,*}_{\beta'}) - \eta^2|\phi|^2 H^d_\alpha H^{d\,*}_\alpha - \eta^2|\phi|^2 H^u_\alpha H^{u\,*}_\alpha \\ & -\eta\epsilon_{\alpha\beta}\left(M\phi^* H^u_\alpha H^d_\beta + L_\alpha\cdot\tilde{h}^d_\beta\phi + \tilde{h}^d_\beta\cdot N H^u_\alpha + \underline{L_\alpha\cdot N H^d_\beta} + h.c.\right)\end{aligned}$$

+ SM

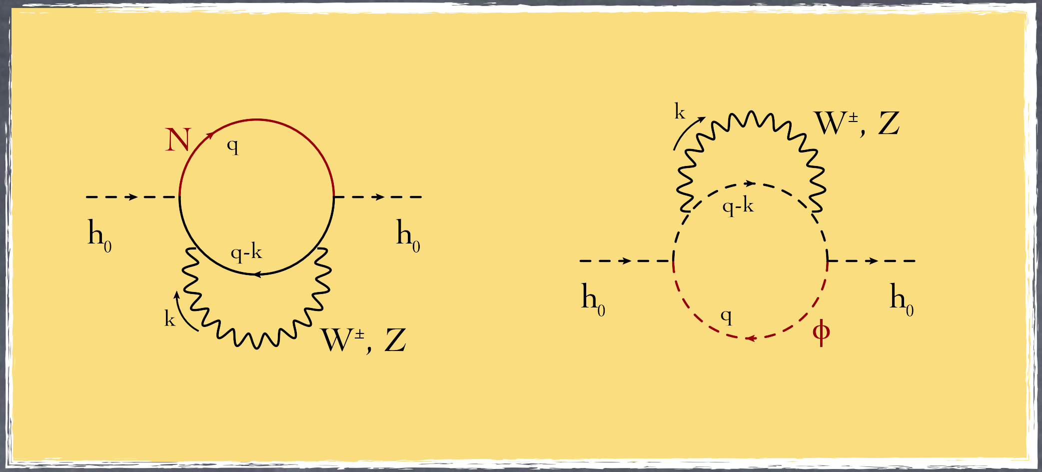


Higgs mass safe at the 1 loop

→ little hierarchy solved

SM hard SUSY breaking

it starts at 2-loop level



only NP SUSY

$$\delta m_H^2 \simeq \frac{\alpha}{4\pi}\frac{y_\nu^2}{16\pi^2}M^2$$

$$M \simeq 10^8 \text{ GeV}$$

3-loop level

NP + weak gauge bosons SUSY

$$\delta m_H^2 \simeq \left(\frac{\alpha}{4\pi}\right)^2 \frac{y_\nu^2}{16\pi^2}M^2$$

$$M \simeq 10^9 \text{ GeV}$$

the usual type-1 seesaw cannot
give rise to baryogengesis via leptogenisis

$M \leq 10^7$ $M \geq 10^8$

the model provides
the missing order of magnitude

you decide the scale,
the scale decides
the degree of SUSY required

telescoping models:

↓

- only extra sleptons and higgsinos
- also weak gauginos
- also squarks
- also gluinos

potentially interesting phenomenology

- 2HDM + sleptons (STU, DY slepton pair production at the LHC, $\tilde{L}^{\pm} \to \pi^{\pm} \tilde{L}_0$)
- no large flavor changing
- DM candidate (higgsino)