Model-independent upper limits on lepton number violating states from neutrino mass

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Problem: How are neutrino masses generated?

- Neutrino oscillations imply that neutrinos are massive.
- At least one neutrino has a mass larger or equal to 0.05 eV.
- However in the SM neutrinos are massless: need BSM physics.
- Hint: lowest dimension effective operator $O_W = LLHH$ (D=5, Weinberg) violates lepton number (L) in 2 units.
- After EWSB, naturally light Majorana neutrino masses.
- Which is the UV completion of O_W chosen by Nature?

Contents

I- Mechanisms for neutrino masses

Mechanisms

- Tree level. Only a few: seesaws I/II/III. Simple, GUT connection, leptogenesis, but huge scales imply very hard to test and hierarchy problem.

- Radiative. In principle more testable, but hundreds of them. Classified by:

1. Topologies at a loop order (up to 3 loops)

2. L=2 EFT operators beyond Weinberg operator.

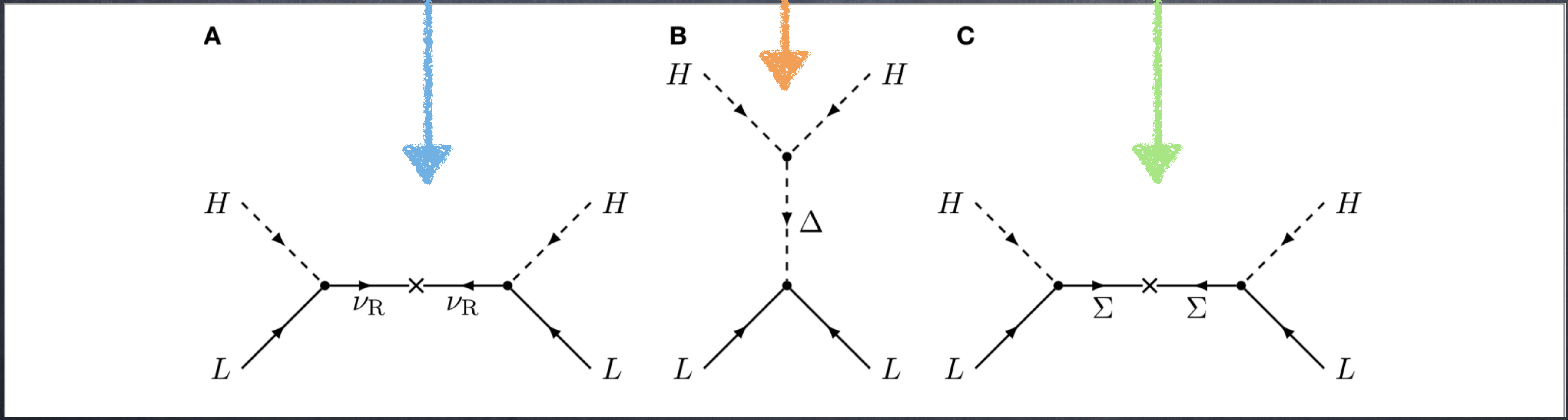
Tree level: seesaws

Minkowski, Yanagida, Gell-Mann, Mohapatra, Glashow...

$yLHN, mNN$

$yL\Delta L, \mu H\Delta^\dagger H$

$yLH\Sigma, m\Sigma\Sigma$



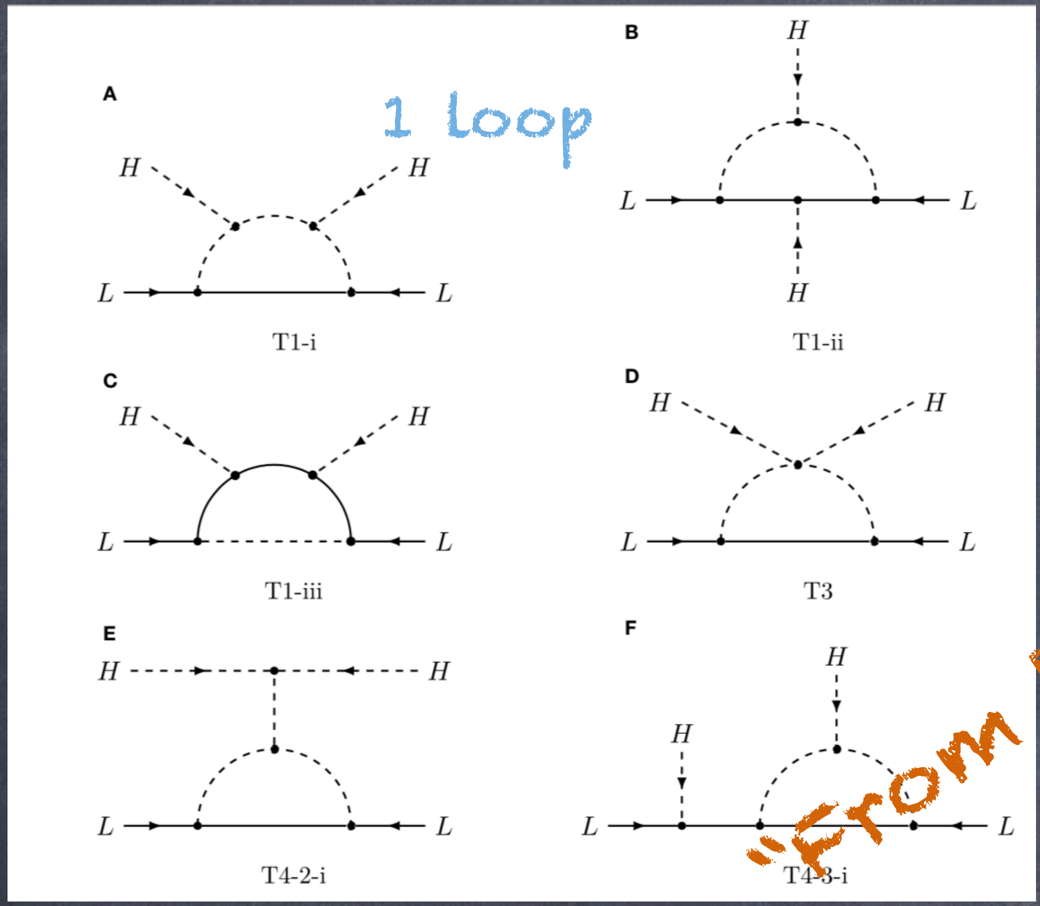
SS I

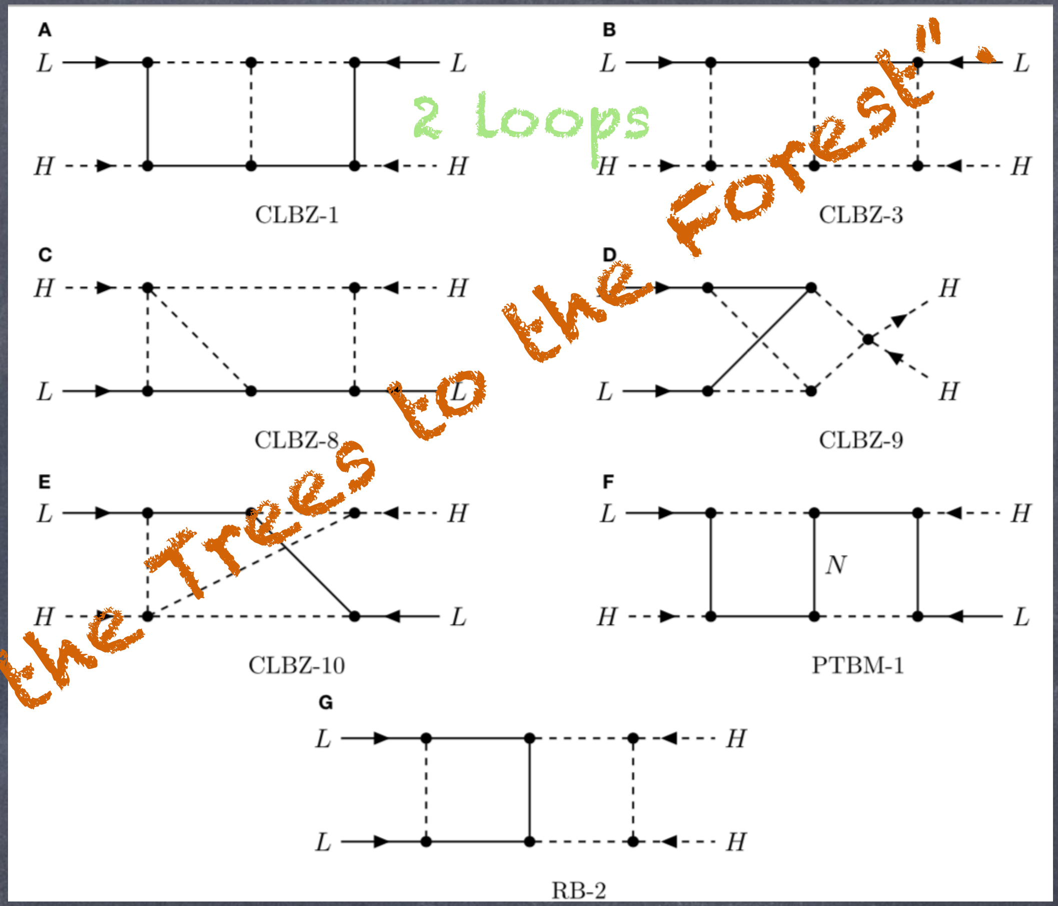
SS II

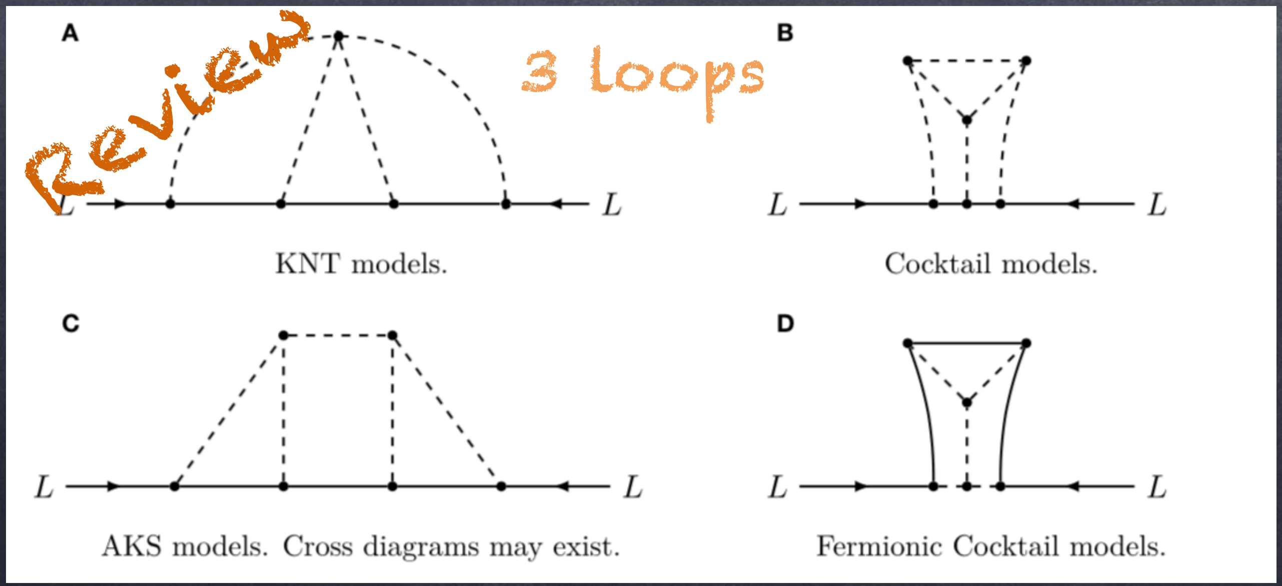
SS III

Loop level models

Zee, Cheng-Li, Babu, Ma, Bonnet, Cepedello, Aristizabal-Sierra, Krauss, Aoki…





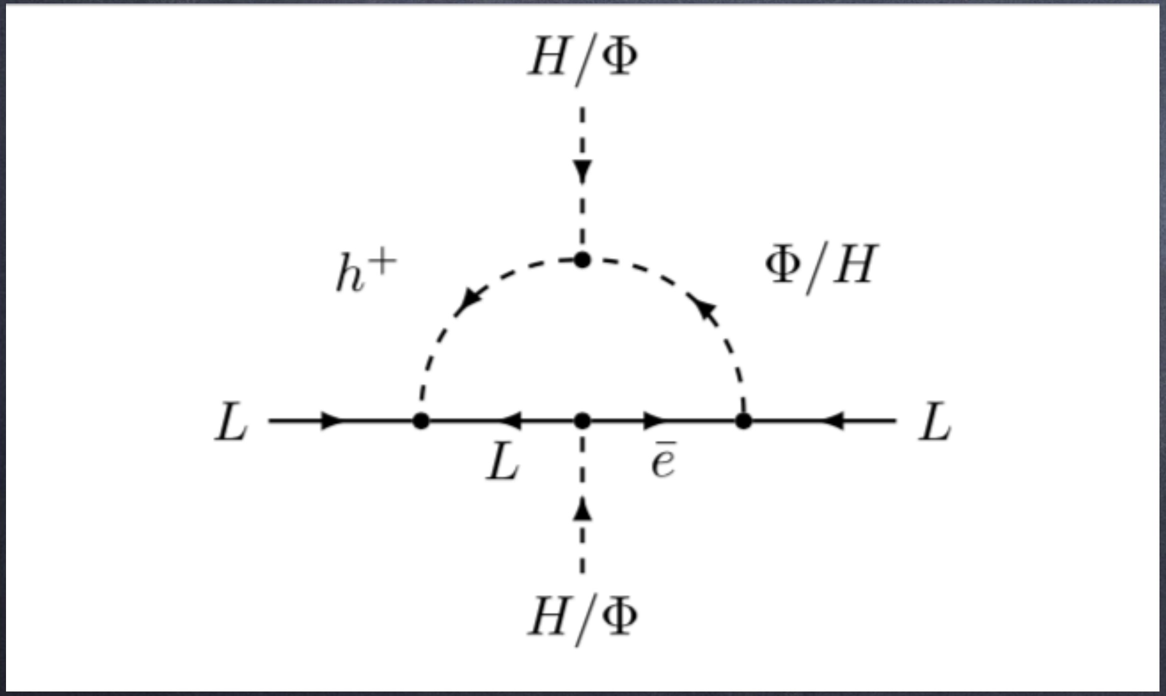


Examples

Zee, Cheng-Li, Babu

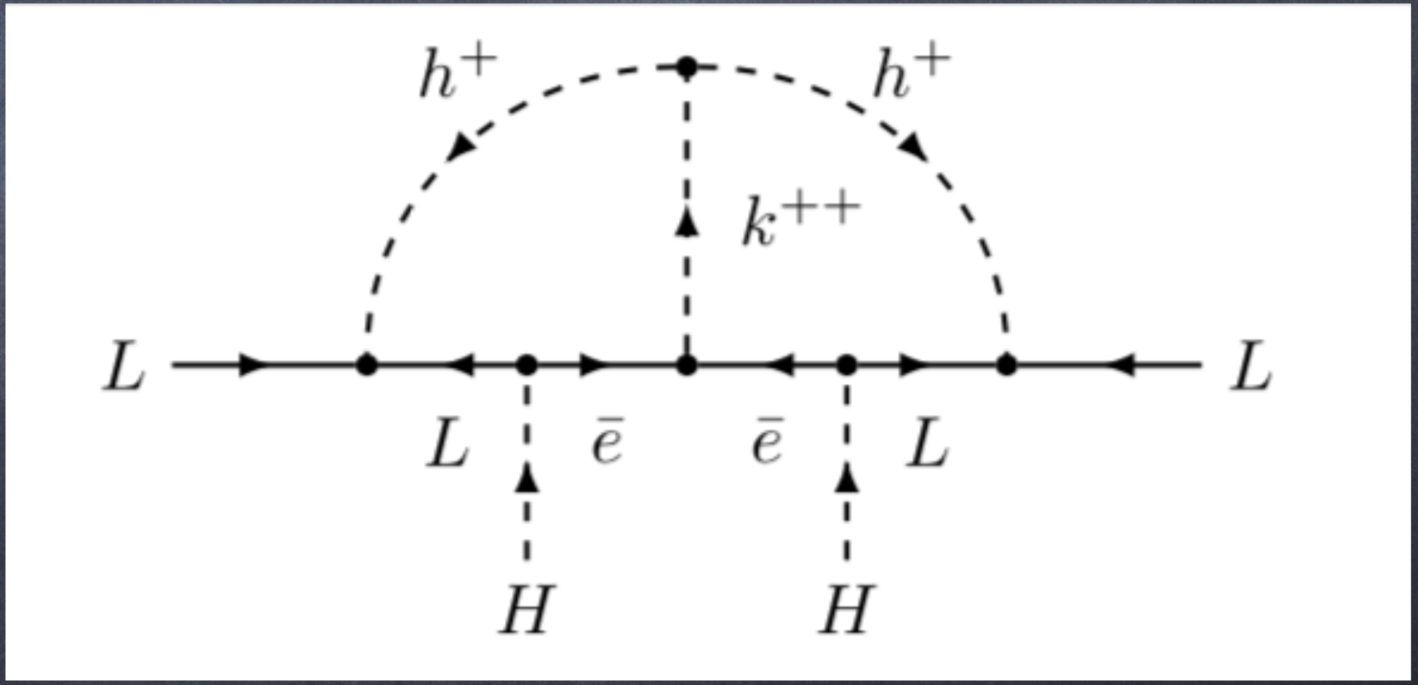
Zee model

$fLLh^+, y\bar{e}\Phi^\dagger L, \mu h^- H\Phi$



Zee-Babu model

$geek^{++}, fLLh^+, \mu k^{++}h^-h^-$



L=2 EFT operators

Babu-Leung, De Gouvea-Jenkins

Zee model

Zee-Babu model

$$O_2 = L^i L^j L^k e^c H^l \epsilon_{ij}\epsilon_{kl}, \quad O_{3a} = L^i L^j Q^k d^c H^l \epsilon_{ij}\epsilon_{kl}, \quad O_{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl},$$

$$O_{4a} = L^i L^j \bar{Q}_i \bar{u}^c H^k \epsilon_{jk}, \quad O_{4b} = L^i L^j \bar{Q}_k \bar{u}^c H^k \epsilon_{ij}, \quad O_8 = L^i \bar{e}^c \bar{u}^c d^c H^j \epsilon_{ij}.$$

$$O_9 = L^i L^j L^k e^c L^l e^c \epsilon_{ij}\epsilon_{kl}, \quad O_{10} = L^i L^j L^k e^c Q^l d^c \epsilon_{ij}\epsilon_{kl},$$

$$O_{11a} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ij}\epsilon_{kl}, \quad O_{11b} = L^i L^j Q^k d^c Q^l d^c \epsilon_{ik}\epsilon_{jl},$$

$$O_{12a} = L^i L^j \bar{Q}_i \bar{u}^c \bar{Q}_j \bar{u}^c, \quad O_{12b} = L^i L^j \bar{Q}_k \bar{u}^c \bar{Q}_l \epsilon_{ij}\epsilon^{kl},$$

$$O_{13} = L^i L^j \bar{Q}_i \bar{u}^c L^k e^c \epsilon_{jk}, \quad O_{14a} = L^i L^j \bar{Q}_k \bar{u}^c Q^k d^c \epsilon_{ij},$$

$$O_{15} = L^i L^j L^k d^c \bar{L}_i \bar{u}^c \epsilon_{jk}, \quad O_{16} = L^i L^j \bar{e}^c d^c \bar{e}^c u^c \epsilon_{ij},$$

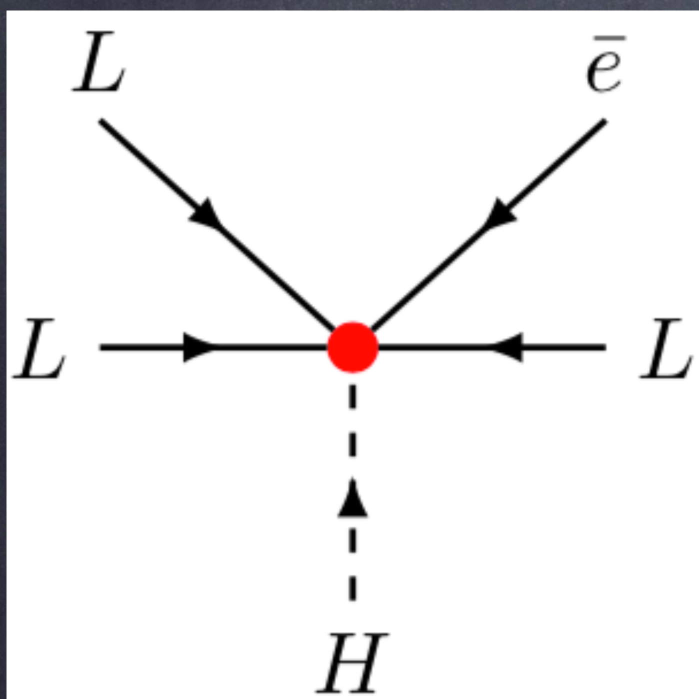
$$O_{17} = L^i L^j d^c d^c \bar{d}^c \bar{u}^c \epsilon_{ij}, \quad O_{18} = L^i L^j d^c u^c \bar{u}^c \bar{u}^c \epsilon_{ij},$$

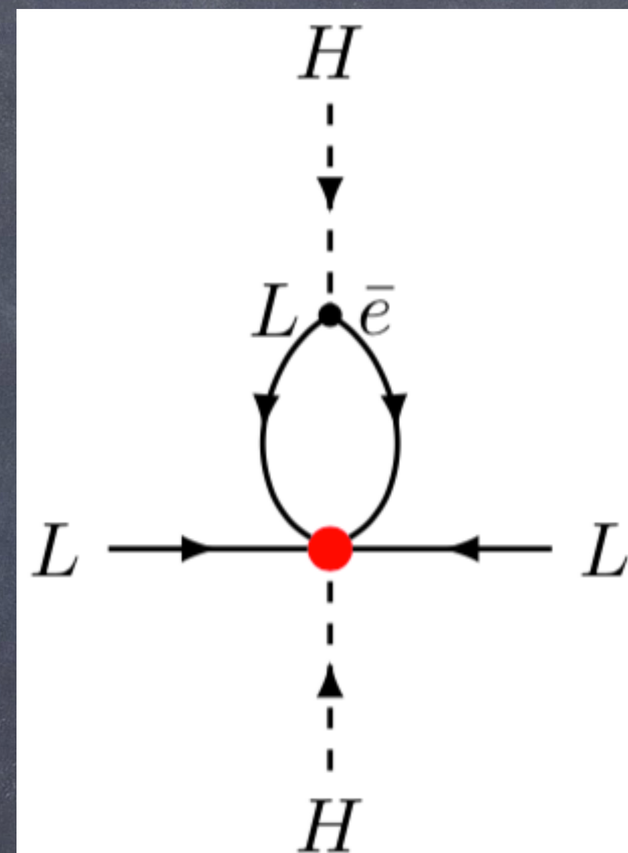
$$O_{19} = L^i Q^j d^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij}, \quad O_{20} = L^i d^c \bar{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c.$$

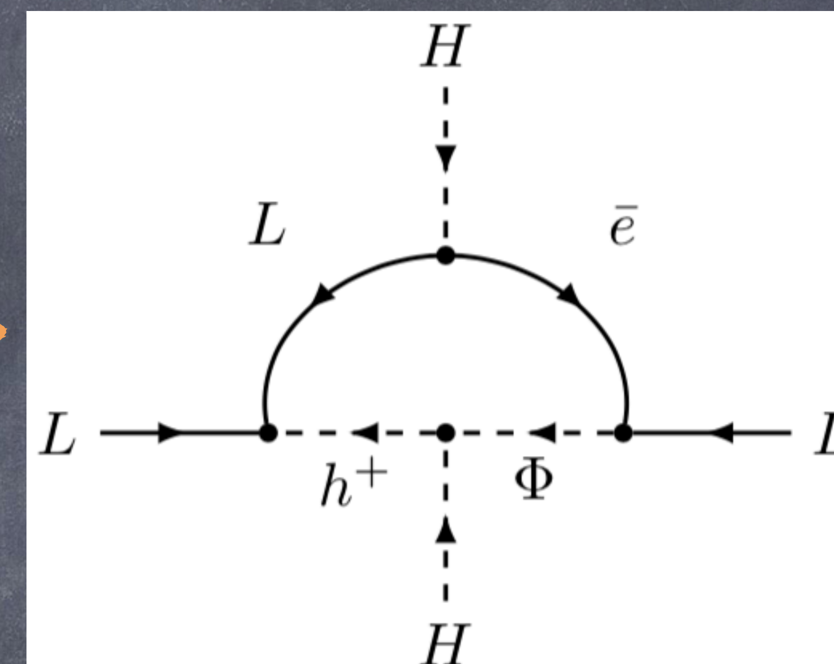
...

EFT estimate

De Gouvea-Jenkins







Operator

$$\mathcal{O}_2 = LLL\bar{e}H$$

Estimate

Chirality flip

$$m_\nu \simeq \frac{c_2 y_\tau v^2}{16\pi^2 \Lambda}$$

Loop factor

UV model: Zee

$$m_\nu \simeq \frac{f\, m_\tau^2\, \mu}{16\pi^2 m_{h^+}^2}$$

Neutrino mass parametrisation

$$m_\nu \simeq \frac{c_{\rm R} v^2}{(16\pi^2)^\ell \Lambda}\,, \text{with} \quad c_{\rm R} \simeq \prod_i g_i \times \epsilon \times \left(\frac{v^2}{\Lambda^2}\right)^n$$

Loop factor

μ/Λ

$LLHH(H^\dagger H)^n$

$$m_\nu \gtrsim 0.05\,\text{eV} \implies \begin{array}{l} l = 1 \to \Lambda < 10^{12}\,\text{GeV} \\ l = 2 \to \Lambda < 10^{10}\,\text{GeV} \\ l = 3 \to \Lambda < 10^{8}\,\text{GeV} \end{array}$$

Can we do better? Hybrid approach

Questions

A. How can we classify the plethora of models?

B. What are the most testable ones, with the lightest states?

C. Is any one already ruled-out?

II- Upper limits on scale of new particles

Main idea

1. m_ν requires at least one new particle X (mass M) coupled to SM lepton/s, carrying L (and maybe B).

2. QFT: L is violated (by two units) via new operators at Λ, which encode the (model-dependent) UV physics.

3. Majorana neutrino masses, $m_\nu \propto 1/\Lambda$, are generated.

4. $m_\nu > 0.05\,\mathrm{eV}\ \&\ \mathrm{M} \leq \Lambda \Longrightarrow$ conservative upper bound on M.

Bounds apply to all models where X is the lightest state.

Example at tree level

- SM bilinear LH (seesaw type I):

1. New particle: fermion singlet N with Y=0 and L=-1.
2. L is violated (by two units) via MNN (+ yLHN).
3. Neutrino masses, $m_\nu = y^2 v^2/M$, are generated.
4. $m_\nu > 0.05\,\mathrm{eV}\ \&\ \mathrm{y} \leq 1 \Longrightarrow$ conservative upper bound:

$$M \leq 10^{15}\,\mathrm{GeV}$$

Possible new particles

$$LH \longrightarrow N\,(\text{SS I}),\ \Sigma\,(\text{SS IIII})$$

$$LL \longrightarrow \Delta\,(\text{SS II}), h\,(\text{Zee})$$

$$ee \longrightarrow k\,(\text{Zee} - \text{Babu})$$

$$LH^\dagger \longrightarrow \ldots$$

$$\bar{e}H^\dagger \longrightarrow \ldots$$

$$\bar{e}\sigma_\mu L^\dagger \longrightarrow \ldots$$

…

Particles generating tree level neutrino masses

$X \sim (SU(3)_c, SU(2)_L, U(1)_Y)^{L,3B}_{S/F/V}$

Seesaw type

L=2 operators

Seesaws

Particle	$\Delta\mathcal{L}=0$	$\lvert\Delta\mathcal{L}\rvert=2$		BL	ℓ	m_ν	Upper bound
$\bar N \sim (1,1,0)_F^{-1,0}$	$y\,\bar N H L$	$M\,\bar N \bar N$	I	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
$\Delta \sim (1,3,1)_S^{-2,0}$	$y\,L\Delta L$	$\mu\,H\Delta^\dagger H$	II	$\mathcal{O}_1$	0	$\frac{y\,\mu\,v^2}{M^2}$	$M \lesssim 10^{15}$ GeV
$\bar\Sigma_0 \sim (1,3,0)_F^{-1,0}$	$y\,\bar\Sigma_0 L H$	$M\,\bar\Sigma_0\bar\Sigma_0$	III	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
$L_1 \sim (1,2,-1/2)_F^{1,0}$	$m\,\bar L_1 L$	$\frac{c}{\Lambda} L_1 H L H$		$\mathcal{O}_1$	0	$\frac{c\,m}{M}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{15}$ GeV

Particles generating loop level neutrino masses

$X \sim (SU(3)_c, SU(2)_L, U(1)_Y)^{L,\,3B}_{S/F/V}$

Zee

Loop order

Zee-Babu

	Particle	$\Delta\mathcal{L}=0$	$\lvert\Delta\mathcal{L}\rvert=2$	BL	ℓ	m_ν	Upper bound
Seesaws	$\bar{N} \sim (1,1,0)^{-1,0}_F$	$y\,\bar{N}HL$	$M\,\bar{N}\bar{N}$	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
	$\Delta \sim (1,3,1)^{-2,0}_S$	$y\,L\Delta L$	$\mu\,H\Delta^\dagger H$	$\mathcal{O}_1$	0	$\frac{y\,\mu\,v^2}{M^2}$	$M \lesssim 10^{15}$ GeV
	$\bar{\Sigma}_0 \sim (1,3,0)^{-1,0}_F$	$y\,\bar{\Sigma}_0 LH$	$M\,\bar{\Sigma}_0\bar{\Sigma}_0$	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
	$L_1 \sim (1,2,-1/2)^{1,0}_F$	$m\,\bar{L}_1 L$	$\frac{c}{\Lambda}L_1HLH$	$\mathcal{O}_1$	0	$\frac{c\,m}{M}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{15}$ GeV
		$y\,H^\dagger\bar{e}L_1$	$\frac{c}{\Lambda^2}\bar{L}_1\bar{u}\bar{d}^\dagger L^\dagger$	$\mathcal{O}_8^\dagger$	2	$\frac{c\,y y_u\,y_d\,y_l}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{7}$ GeV
Radiative	$h \sim (1,1,1)^{-2,0}_S$	$y\,LLh$	$\frac{c}{\Lambda}h^\dagger\bar{e}LH$	$\mathcal{O}_2$	1	$\frac{c\,y\,y_l}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{10}$ GeV
	$k \sim (1,1,2)^{-2,0}_S$	$y\,\bar{e}^\dagger\bar{e}^\dagger k$	$\frac{c}{\Lambda^3}k^\dagger L^\dagger L^\dagger L^\dagger L^\dagger$	$\mathcal{O}_9^\dagger$	2	$\frac{c\,y\,y_l^2}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{6}$ GeV
	$\bar{E} \sim (1,1,1)^{-1,0}_F$	$y\,\bar{E}LH^\dagger$	$\frac{c}{\Lambda^4}LEHQ^\dagger\bar{u}^\dagger H$	$\mathcal{O}_6$	2	$\frac{c\,y\,y_u}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{10}$ GeV
		$m\,\bar{E}e$	$\frac{c}{\Lambda^3}EL^\dagger L^\dagger L^\dagger H^\dagger$	$\mathcal{O}_2^\dagger$	1	$\frac{c\,m}{M}\,\frac{y_l}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{10}$ GeV
	$\bar{\Sigma}_1 \sim (1,3,1)^{-1,0}_F$	$y\,H^\dagger\bar{\Sigma}_1 L$	$\frac{c}{\Lambda^2}LHH\Sigma_1 H$	$\mathcal{O}_1'^{1}$	2	$\frac{c\,y}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{10}$ GeV
	$L_2 \sim (1,2,-3/2)^{1,0}_F$	$y\,H\bar{e}L_2$	$\frac{c}{\Lambda^2}\bar{L}_2LLL$	$\mathcal{O}_2$	1	$\frac{c\,y\,y_l}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{11}$ GeV
	$X_2 \sim (1,2,3/2)^{-2,0}_V$	$y\,\bar{e}^\dagger\bar{\sigma}^\mu LX_{2\mu}$	$\frac{c}{\Lambda}\,\bar{u}^\dagger\bar{\sigma}^\mu\bar{d}X^\dagger_{2\mu}H$	$\mathcal{O}_8$	2	$\frac{cy\,y_u y_d y_e}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{7}$ GeV

Particles with B (leptoquarks)

$X \sim (SU(3)_c, SU(2)_L, U(1)_Y)^{L,\,3B}_{S/F/V}$

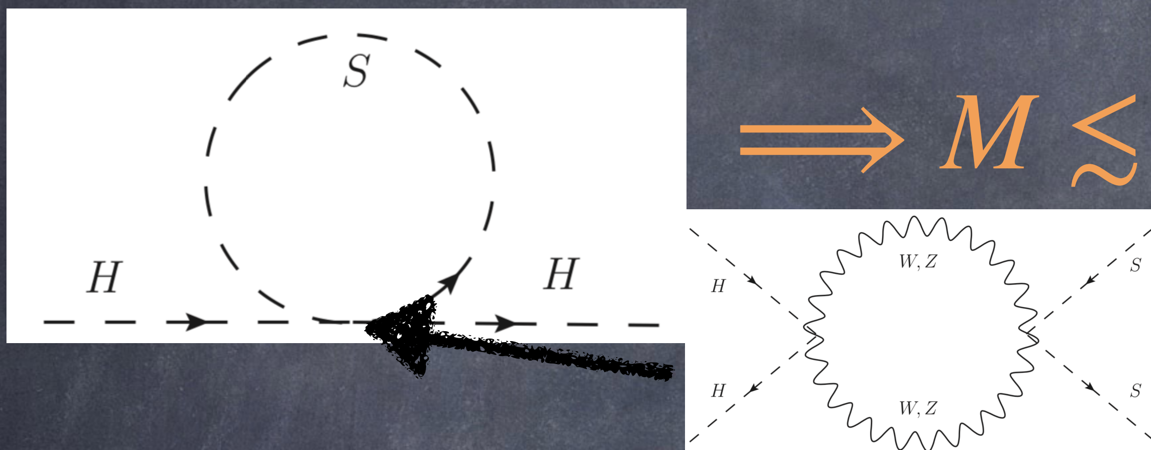
L=2 operators

Loop order

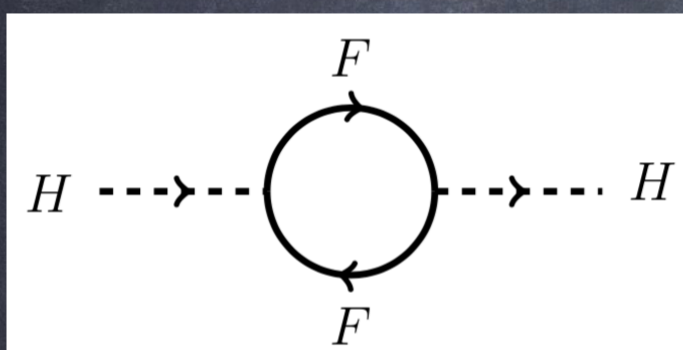
Radiative

Particle	$\Delta\mathcal{L}=0$	$\lvert\Delta\mathcal{L}\rvert=2$	BL	ℓ	m_ν	Upper bound
$\tilde{R}_2 \sim (3,2,1/6)_S^{-1,1}$	$y\,\bar{d}L\tilde{R}_2$	$\frac{c}{\Lambda}\tilde{R}_2^\dagger QLH$	$\mathcal{O}_{3_b}$	1	$\frac{c\,y\,y_d}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^9$ GeV
$R_2 \sim (3,2,7/6)_S^{-1,1}$	$y\,\bar{e}^\dagger Q^\dagger R_2$	$\frac{c}{\Lambda^3}R_2^\dagger L^\dagger LL\bar{d}^\dagger$	$\mathcal{O}_{10}^\dagger$	2	$\frac{c\,y\,y_d\,y_l}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^7$ GeV
	$y\,\bar{u}LR_2$	$\frac{c}{\Lambda^3}R_2^\dagger L^\dagger LL\bar{d}^\dagger$	$\mathcal{O}_{15}^\dagger$	3	$\frac{c\,y\,y_d\,y_u\,g^2}{2(4\pi)^6}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^6$ GeV
$S_1 \sim (\bar{3},1,1/3)_S^{-1,-1}$	$y\,LQS_1$	$\frac{c}{\Lambda}S_1^\dagger LH\bar{d}$	$\mathcal{O}_{3_b}$	1	$\frac{c\,y\,y_d}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{11}$ GeV
	$y\,\bar{u}^\dagger\bar{e}^\dagger S_1$	$\frac{c}{\Lambda}S_1^\dagger LH\bar{d}$	$\mathcal{O}_8$	2	$\frac{c\,y\,y_l\,y_u\,y_d}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^7$ GeV
$S_3 \sim (\bar{3},3,1/3)_S^{-1,-1}$	$y\,LS_3Q$	$\frac{c}{\Lambda}\bar{d}\,LS_3^\dagger H$	$\mathcal{O}_{3_b}$	1	$\frac{c\,y\,y_d}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{11}$ GeV
$\tilde{S}_1 \sim (\bar{3},1,4/3)_S^{-1,-1}$	$y\,\bar{e}^\dagger\bar{d}^\dagger\tilde{S}_1$	$\frac{c}{\Lambda^3}\tilde{S}_1^\dagger L^\dagger L^\dagger L^\dagger Q^\dagger$	$\mathcal{O}_{10}^\dagger$	2	$\frac{c\,y\,y_d\,y_l}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^7$ GeV
$V_2 \sim (\bar{3},2,5/6)_V^{-1,-1}$	$y\,\bar{d}^\dagger\bar{\sigma}^\mu V_{2\mu}L$	$\frac{c}{\Lambda^5}Q^\dagger\bar{\sigma}^\mu LV_{2\mu}^\dagger H\bar{e}LH$	$\mathcal{O}_{23}$	3	$\frac{c\,y\,y_d\,y_l}{(4\pi)^6}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^4$ GeV
	$y\,Q\sigma^\mu V_{2\mu}\bar{e}^\dagger$	$\frac{c}{\Lambda^5}Q^\dagger\bar{\sigma}^\mu LV_{2\mu}^\dagger H\bar{e}LH$	$\mathcal{O}_{44_{a,b,d}}$	3	$\frac{c\,y\,g^2}{2(4\pi)^6}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^7$ GeV
$\tilde{V}_2 \sim (\bar{3},2,-1/6)_V^{-1,-1}$	$y\,\bar{u}^\dagger\bar{\sigma}^\mu\tilde{V}_{2\mu}L$	$\frac{c}{\Lambda}Q^\dagger\bar{\sigma}^\mu LH\tilde{V}_{2\mu}^\dagger$	$\mathcal{O}_{4_a}$	1	$\frac{c\,y\,y_u}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{12}$ GeV
$U_1 \sim (3,1,2/3)_V^{-1,1}$	$y\,Q^\dagger\bar{\sigma}^\mu U_{1\mu}L$	$\frac{c}{\Lambda}\bar{u}^\dagger\bar{\sigma}^\mu LHU_{1\mu}^\dagger$	$\mathcal{O}_{4_a}$	1	$\frac{c\,y\,y_u}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{12}$ GeV
	$y\,\bar{d}\sigma^\mu U_{1\mu}\bar{e}^\dagger$	$\frac{c}{\Lambda}\bar{u}^\dagger\bar{\sigma}^\mu LHU_{1\mu}^\dagger$	$\mathcal{O}_8$	2	$\frac{c\,y\,y_u\,y_d\,y_l}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^7$ GeV
$U_3 \sim (3,3,2/3)_V^{-1,1}$	$y\,Q^\dagger\bar{\sigma}^\mu U_{3\mu}L$	$\frac{c}{\Lambda}\bar{u}^\dagger\bar{\sigma}^\mu LU_{3\mu}^\dagger H$	$\mathcal{O}_{4_a}$	1	$\frac{c\,y\,y_u}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{12}$ GeV
$\tilde{U}_1 \sim (3,1,5/3)_V^{-1,1}$	$y\,\bar{u}\sigma^\mu\bar{e}^\dagger\tilde{U}_{1\mu}$	$\frac{c}{\Lambda^5}\bar{u}^\dagger\bar{\sigma}^\mu LH\tilde{U}_{1\mu}^\dagger\bar{e}LH$	$\mathcal{O}_{46}$	3	$\frac{c\,y\,g^2}{2(4\pi)^6}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^7$ GeV

Higgs naturalness

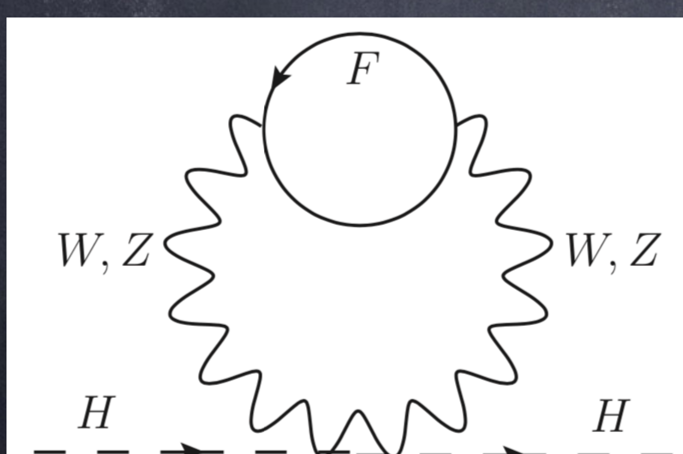


$$\Longrightarrow M \lesssim \frac{16\pi^2 |\delta m_H^2|^{1/2}_{\max}}{\sqrt{6N_c(3Dg^4 + N_w Y^2 g'^4)}}$$



$$\Longrightarrow M \lesssim \frac{2\pi |\delta m_H^2|^{1/2}_{\max}}{|y|\sqrt{2N_c}}$$

SSI
Vissani, Casas



$$\Longrightarrow M \lesssim \frac{4\pi^2 |\delta m_H^2|^{1/2}_{\max}}{\sqrt{N_c(3Dg^4 + N_w Y^2 g'^4)}}$$

SSII/III
Farina

Naturalness limits much stronger, but less robust.

III- lower limits on scale of new particles

Model-dependent lower limits

- Lepton flavor / universality / unitarity violation:
  $\mu \to e\gamma, \pi \to \mu\bar{\nu}_\mu / e\bar{\nu}_e, UU^\dagger \neq 1 \ldots$
- L=2 processes:
  $0\nu\beta\beta: \;\; 2n \to 2p + 2e$ (e.g., ^{136}Xe)
- Direct searches at colliders
- B violation (nucleon decays, $n - \bar{n}$ oscillations)
- Washout of BAU

B violation (LQ)

Weinberg, Weldon, Nath, Barr, Babu, Arnold, Dorsner...

Di-quark couplings generate tree-level nucleon decays:

$$S_1 = (\bar{3},1,1/3): \quad y_1 S_1\, ue + \; y_2 S_1^\dagger\, ud$$

$$\Gamma(p \to \pi^0 e^+) \simeq \frac{|y_1|^2 |y_2|^2}{8\pi} \frac{m_p^5}{M_{S_1}^4} < \frac{1}{10^{33}\,\mathrm{y}}$$

$$\Longrightarrow M_{S_1} \gtrsim 10^{16}\ \mathrm{GeV}$$

Therefore, S1 cannot generate neutrino masses.

Washout of BAU

Harvey, Turner

- L=2 operators + sphalerons may erase the BAU, unless:

$$\Gamma(T_{\mathscr{B}-\mathscr{L}}) \leq H(T_{\mathscr{B}-\mathscr{L}})$$

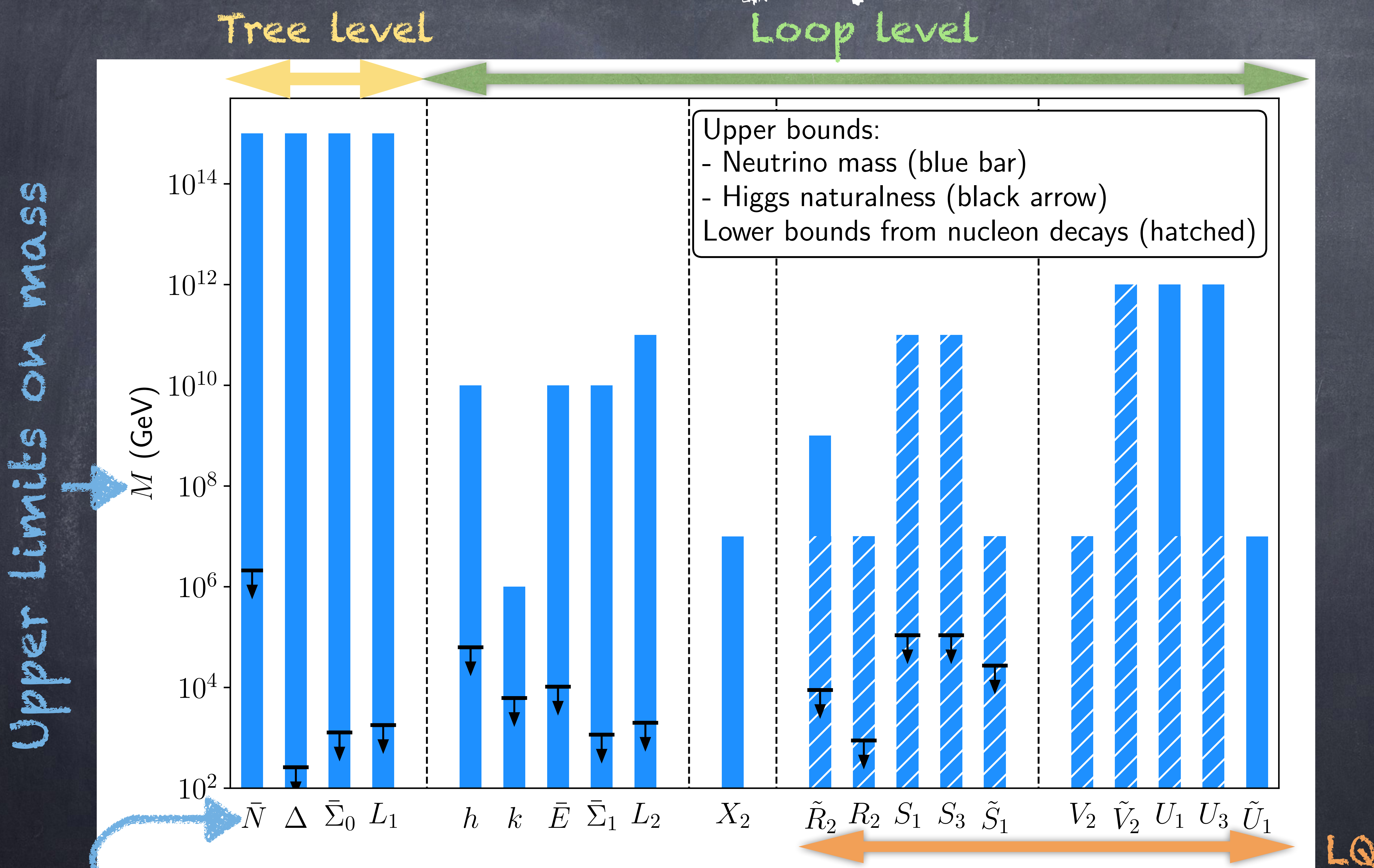
$$\Longrightarrow \Lambda \gtrsim [M_p\, T_{\mathscr{B}-\mathscr{L}}^{2d-9}/(20\,\mathrm{PS}_n)\,]^{1/(2d-8)}$$

$$T_{\mathscr{B}-\mathscr{L}} = 10^6, 10^{10}, 10^{13}\ \mathrm{GeV} \Longrightarrow \begin{array}{l} \Lambda_{d=5} \gtrsim 10^{11}, 10^{13}, 10^{14}\,\mathrm{GeV} \\ \Lambda_{d>5} \gtrsim 10^{7}, 10^{10}, 10^{13}\,\mathrm{GeV} \end{array}$$

Strong limits on scale Λ, dependent on B-L scale.

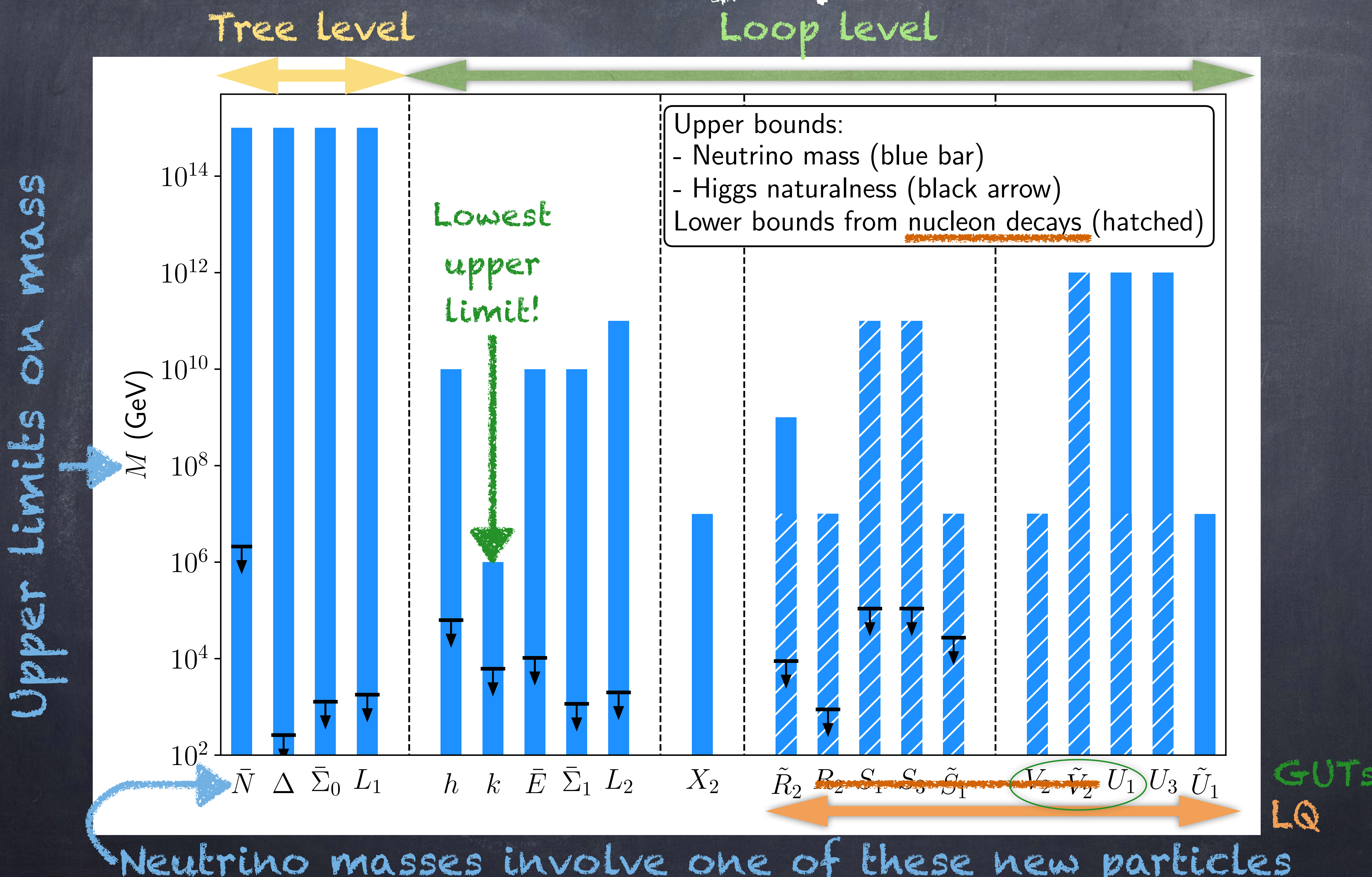
IV- Summary and conclusions

Summary plot



Neutrino masses involve one of these new particles

Summary plot



Conclusions

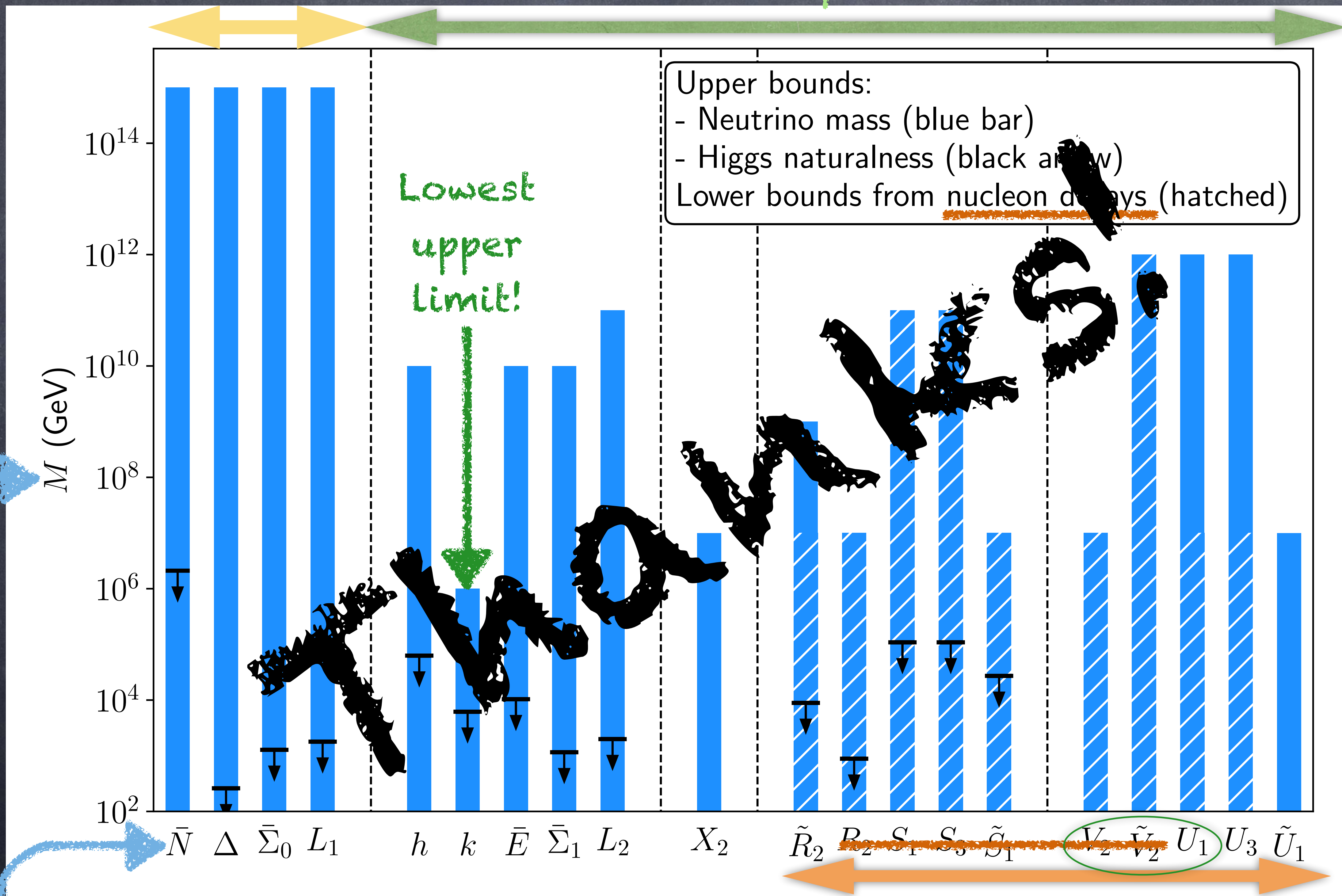
- Simple way of organising the plethora of neutrino models.
- Robust limits on all possible new states involved in m_ν.
- Useful framework to study phenomenology.
- Nucleon decays rule-out some scenarios.
- Most promising states: doubly-charged scalars (<1000 TeV).

Summary plot

Tree level

Loop level

Upper limits on mass



GUTs

LQ

Neutrino masses involve one of these new particles

Back-up

Loop level estimate

De Gouvea

- Weinberg operator induced via L=2 operators.
- Matching at loop level. Estimate of m_ν:

1. Each loop: $1/(16\pi^2)$
2. SM chirality-flips: y_τ, y_t
3. W-bosons: g^2

B violation (LQ)

Weinberg, Weldon, Nath, Barr, Babu, Arnold, Dorsner...

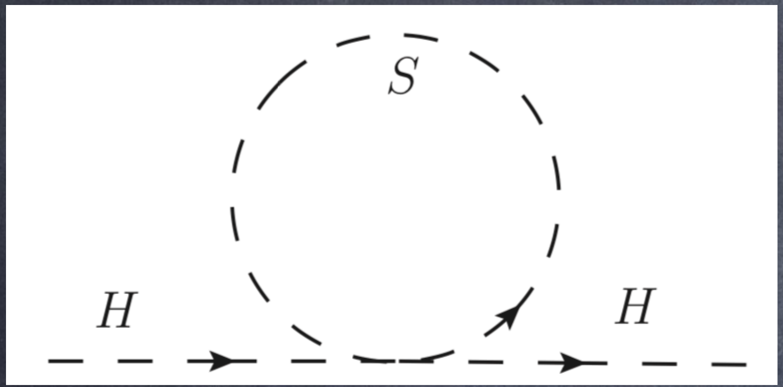
$$S_1\,\bar{d}\bar{u},\quad S_{1,3}\,Q^\dagger Q^\dagger,\quad \bar{u}\bar{\sigma}^\mu V_{2\mu} Q^\dagger,\quad \bar{d}\sigma^\mu \tilde{V}_{2\mu} Q^\dagger \Rightarrow M \gtrsim 10^{16}\ \mathrm{GeV}$$

$$\tilde{S}_1\,\bar{u}\bar{u} \quad \Rightarrow \quad p \to e^+ e^- \bar{\nu}_e \pi^+ \quad M \gtrsim 10^{11}\ \mathrm{GeV}$$

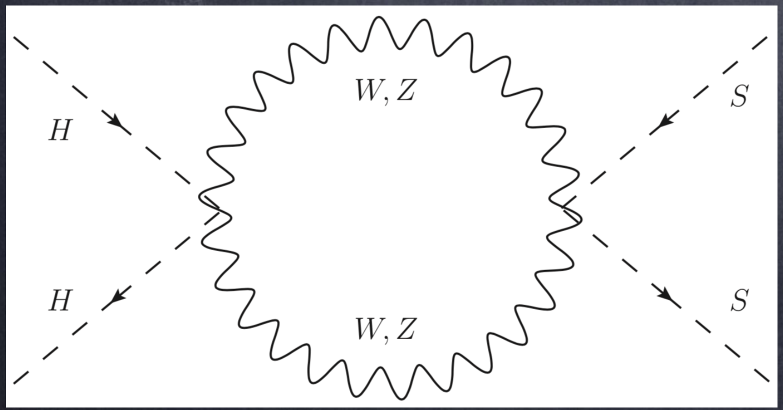
$$\tilde{R}_2 Q H^\dagger Q/\Lambda',\quad H^\dagger R_2 \bar{d}^\dagger \bar{d}^\dagger/\Lambda',\quad \bar{d}^\dagger \sigma_\mu H^\dagger Q U^\mu_{1,3}/\Lambda' \qquad \text{B+L}$$

$$p \to K^+ \nu \qquad \Lambda' = M_p \;\Rightarrow \qquad M \gtrsim 10^7\ \mathrm{GeV}$$

Higgs naturalness: scalars

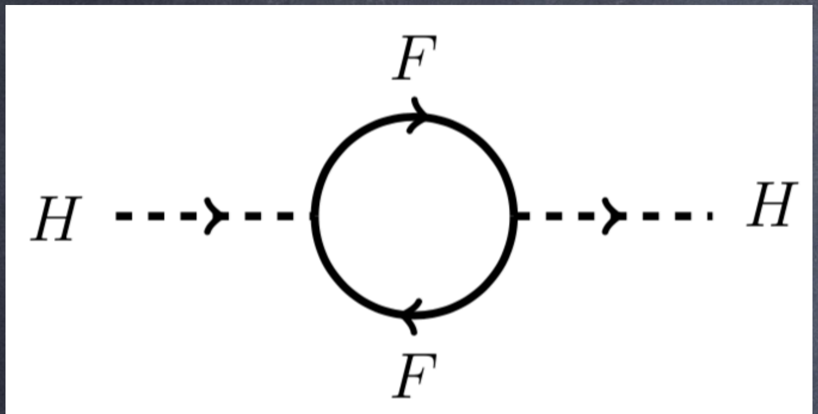


$$\delta m_H^2 \simeq -\left(\frac{\lambda}{16\pi^2}\right) N_w N_c\, M^2 \ln\left(\frac{M^2}{\Lambda^2}\right)$$



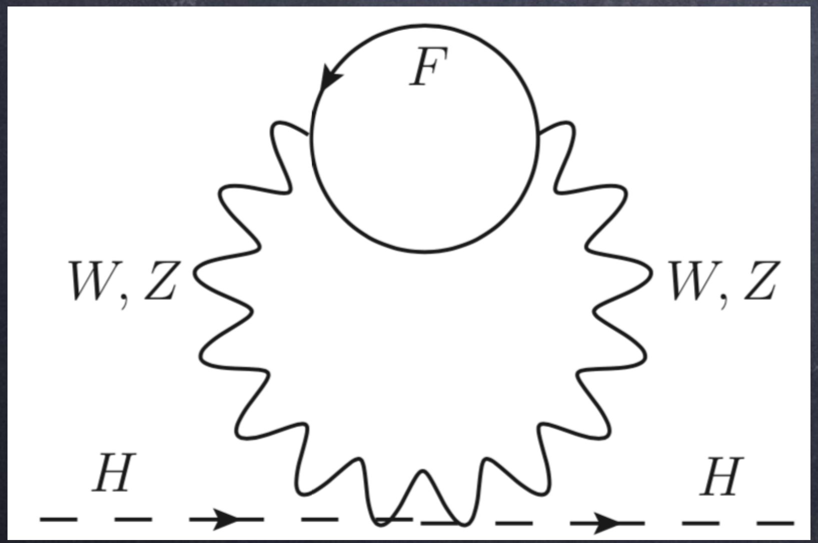
$$\delta\lambda \simeq \left(\frac{3}{32\pi^2}\right)(Y^2 g'^4 + C_2 g^4)\ \ln\left(\frac{M^2}{\Lambda^2}\right)$$

Higgs naturalness: fermions



$$\delta m_H^2 \simeq \left(\frac{1}{4\pi^2}\right) N_c |y|^2 M^2 \ln\left(\frac{M^2}{\Lambda^2}\right)$$

SSI. Vissani, Casas



$$\delta m_H^2 \simeq \left(\frac{M^2}{32\pi^4}\right) N_c (3Dg^4 + N_w Y^2 g'^4) \ln\left(\frac{M^2}{\Lambda^2}\right)$$

SSII/III, Farina