Neutrino mass models: New classification and upper limits on their scale

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Hot Topics in Neutrino Physics

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SISSA
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Which is the UV completion of LLHH?

- Tree level. Only seesaws I/II/III. Minimal, GUT connection, leptogenesis, but huge scales imply very hard to test and problem of hierarchies.

- Radiative. No hierarchy problem, and in principle more testable… but hundreds of them! Classified by:

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

2. $\Delta\mathscr{L} = 2$ EFT operators beyond the Weinberg operator.

Contents

I- Mechanisms for m_ν

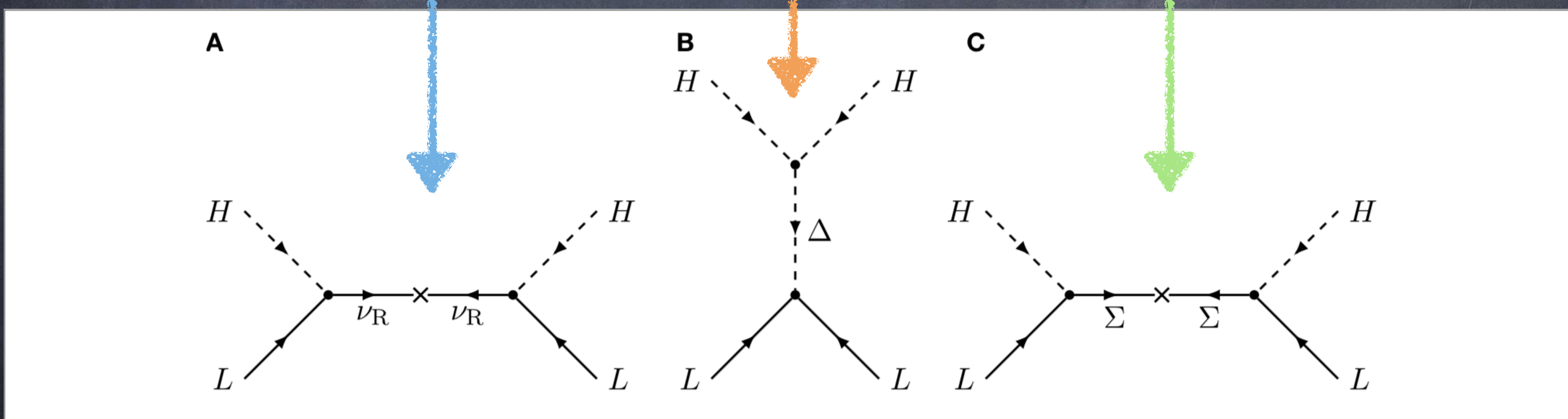
Tree level: seesaws

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

$yLHN, mNN$

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

$yLH\Sigma, m\Sigma\Sigma$



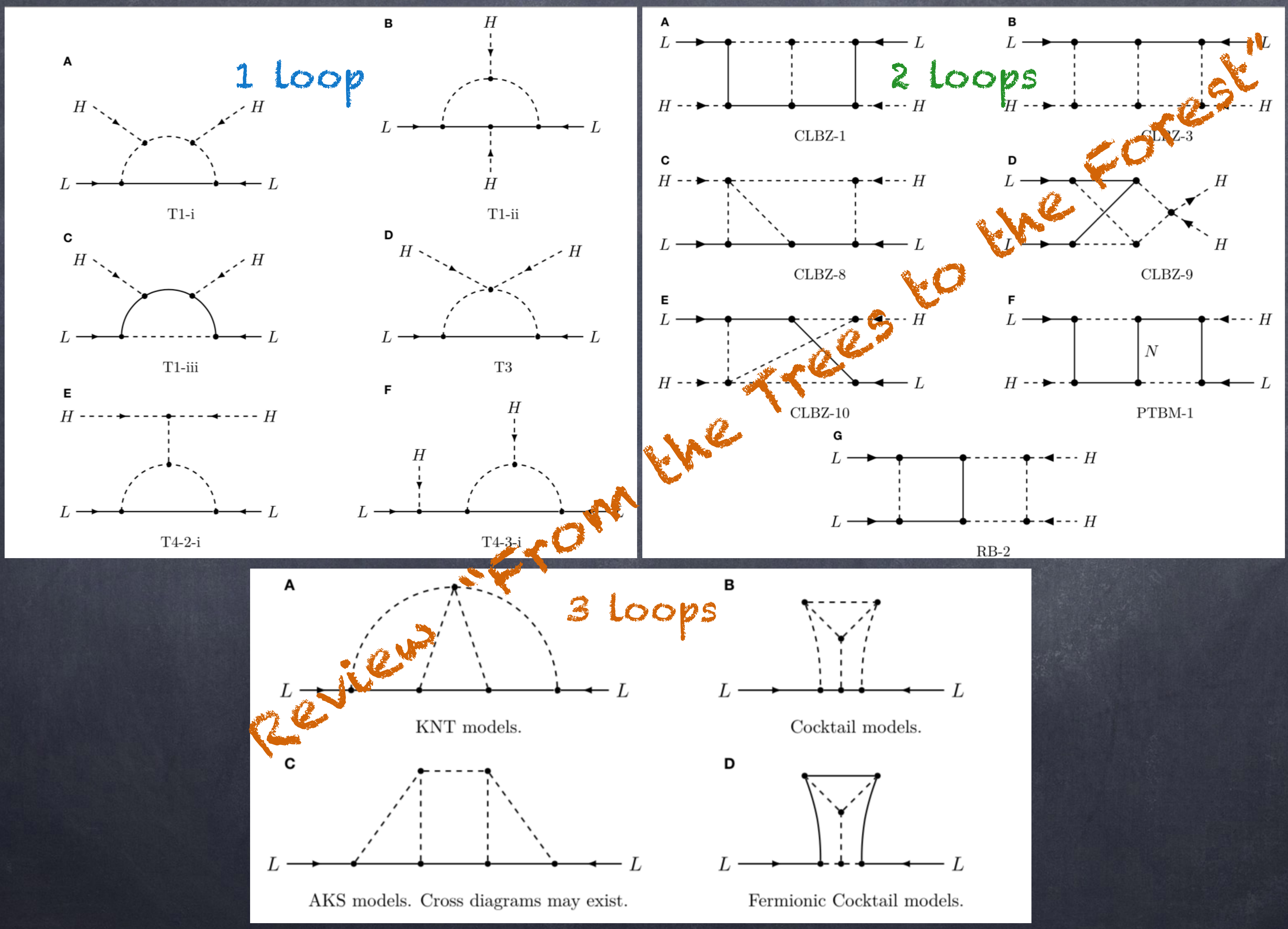
SS I

SS II

SS III

Loop-level models

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



Examples of loop models

Zee, Cheng-Li, Babu

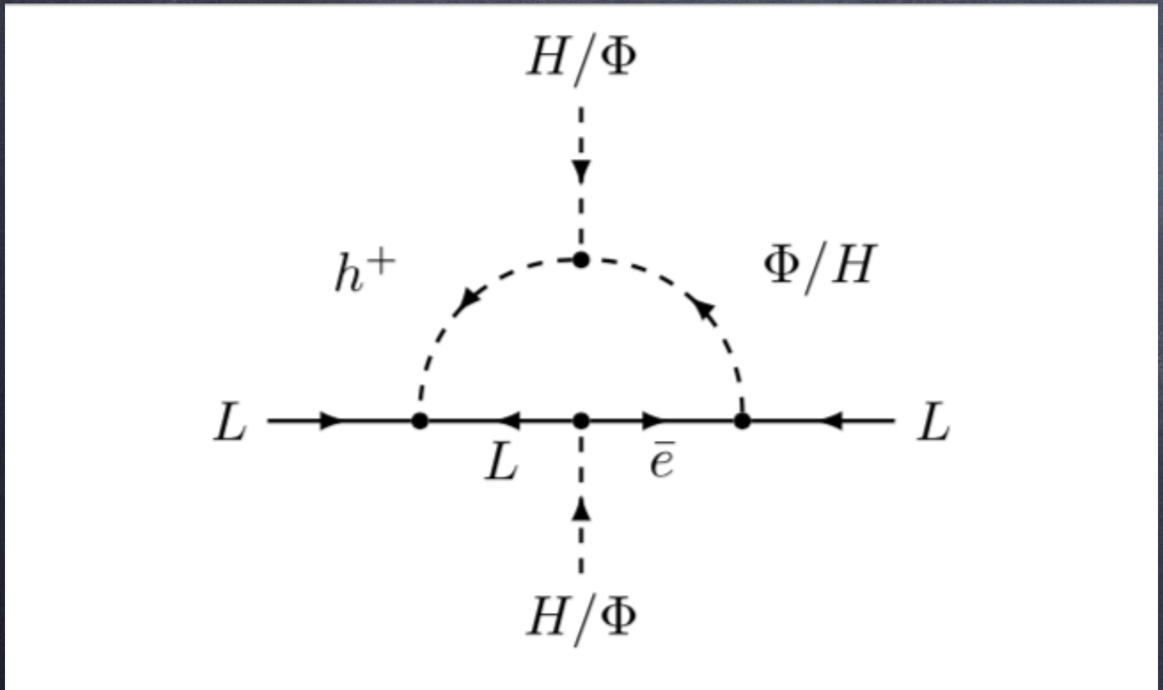
Singly-charged scalar h^+: $LfLh^+$

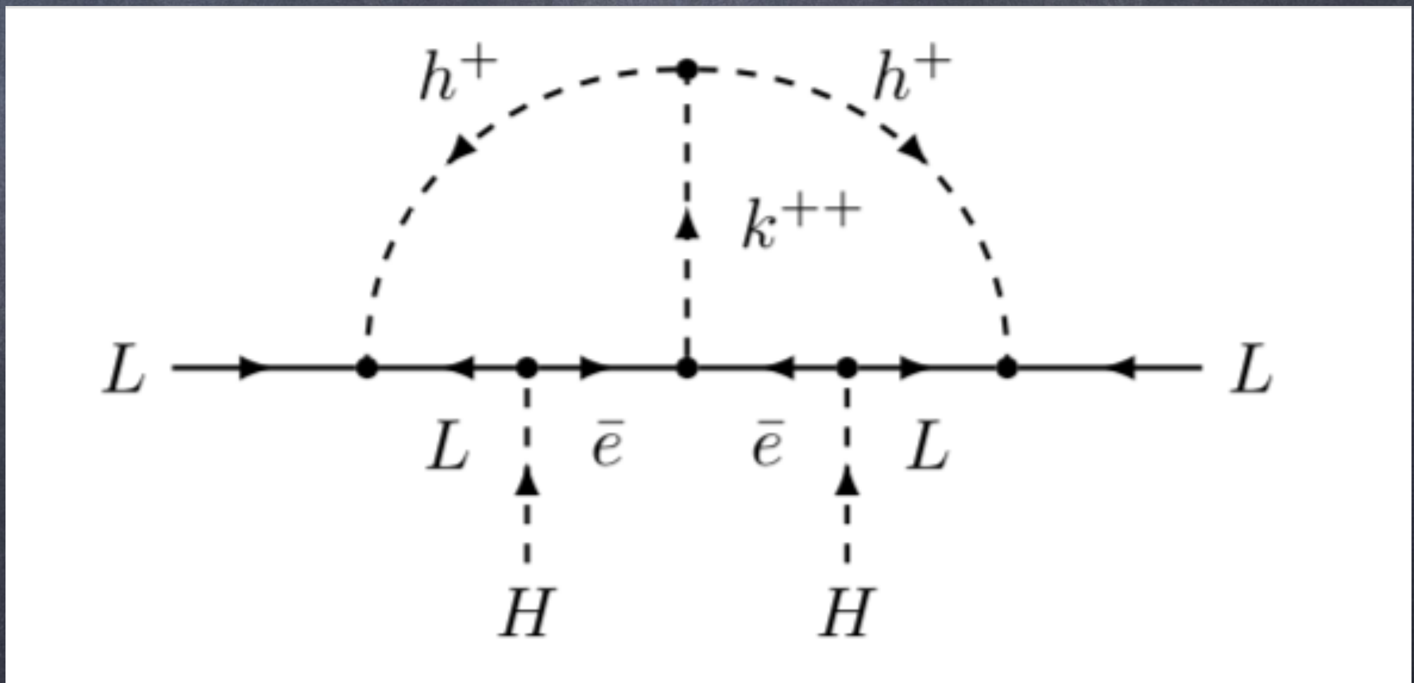
1 loop: Zee model

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

2 loops: Zee-Babu model

$$+\bar{e}g\bar{e}k^{--} + \mu k^{++}h^-h^-$$





$\Delta\mathscr{L} = 2$ operators

Babu-Leung, De Gouvea-Jenkins

Zee model → O_2 Zee-Babu model → O_9

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

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

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

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

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

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

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

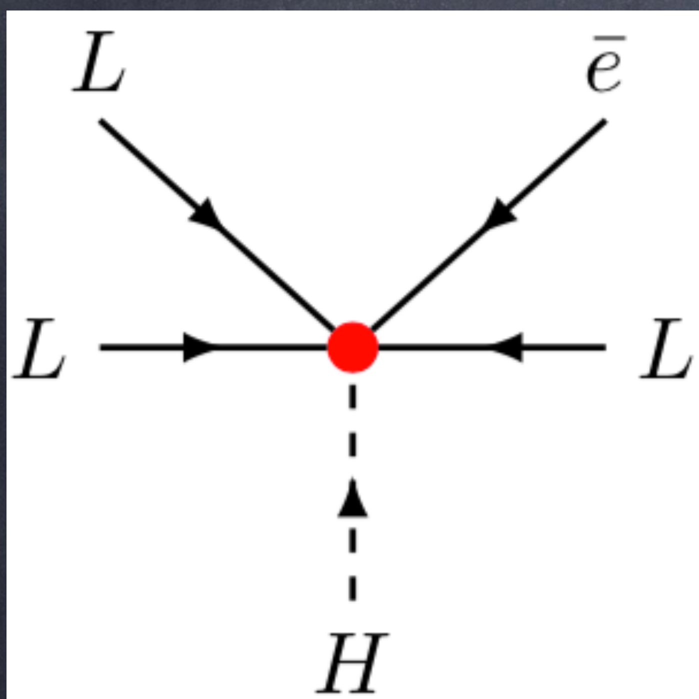
$$O_{17} = L^i L^j d^c d^c \bar{d}^c \bar{u}^c \epsilon_{ij}, \qquad O_{18} = L^i L^j d^c u^c \bar{u}^c \bar{u}^c \epsilon_{ij},$$

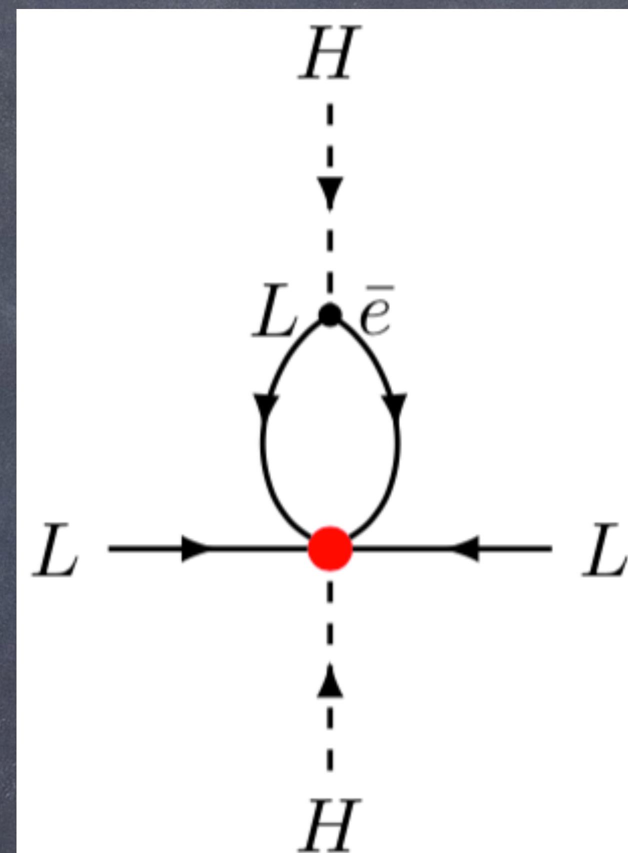
$$O_{19} = L^i Q^j d^c d^c \bar{e}^c \bar{u}^c \epsilon_{ij}, \qquad O_{20} = L^i d^c \bar{Q}_i \bar{u}^c \bar{e}^c \bar{u}^c.$$

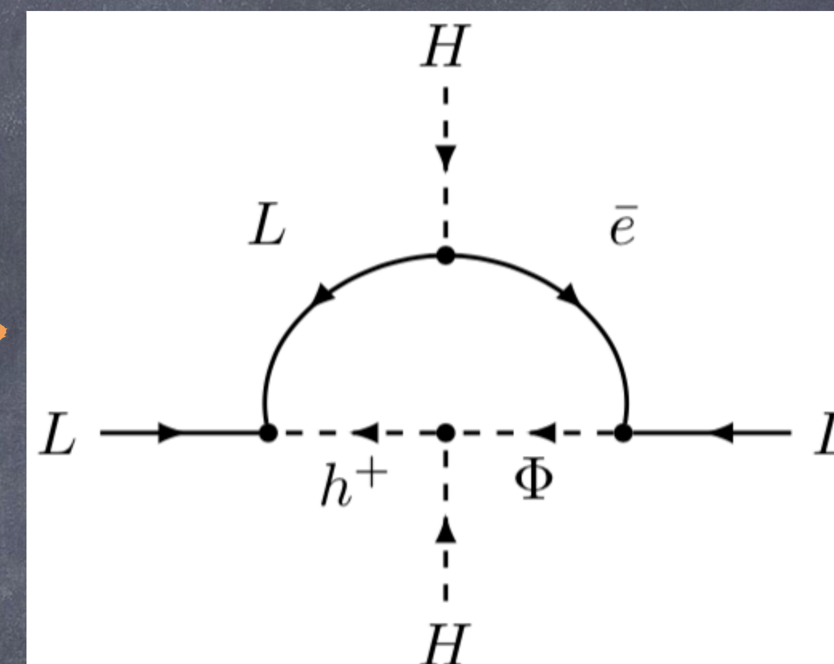
...

Estimate

De Gouvea-Jenkins







Operator

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

Estimate

Chirality flip

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

Loop factor

Model: Zee

c_2

$$m_\nu \simeq \frac{f_{\mu\tau} y_\tau \mu}{m_{h^+}} \frac{y_\tau v^2}{16\pi^2 m_{h^+}}$$

Parametrisation

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

Loop factor

μ/Λ

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

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

Can we do better? Hybrid approach

II - Upper Limits

Main idea

1. Observation: m_ν requires at least one new particle X (mass M) coupled to SM lepton/s, carrying $\mathscr{L}$.

2. QFT: $\Delta\mathscr{L} = 2$ by new operators at Λ, which encode the model-dependent UV physics.

3. $m_\nu \propto 1/\Lambda$ is 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.

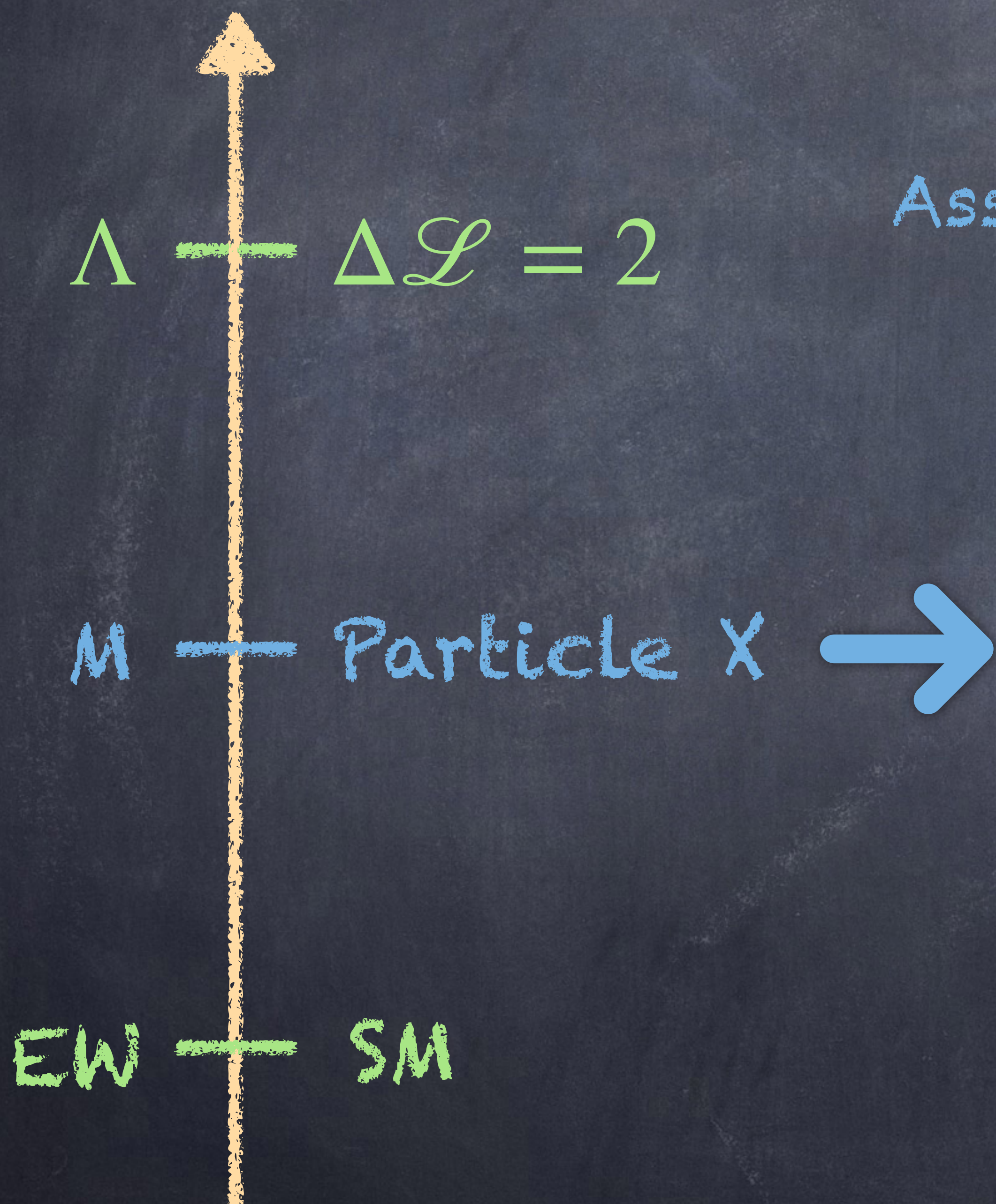
Example at tree level

- SM bilinear LH (SS I):

1. New particle: fermion singlet $\bar{N}$ with $Y = 0$ and $\mathscr{L} = -1$.
2. $\Delta\mathscr{L} = 2$ by $y\bar{N}LH + M\bar{N}\bar{N}$.
3. $m_\nu = y^2 v^2 / M$ is generated.
4. $m_\nu > 0.05\,\mathrm{eV}$ & $\mathrm{y} \leq 1 \Longrightarrow$ conservative upper bound:

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

New particles X



Assuming no extra BSM symmetries:

$$\left\{\begin{array}{lcl} LH & \longrightarrow & \bar{N}\,(\text{SS I}),\ \bar{\Sigma}_0\,(\text{SS III}) \\ LL & \longrightarrow & \Delta\,(\text{SS II}),\, h\,(\text{Zee}) \\ ee & \longrightarrow & k\,(\text{Zee} - \text{Babu}) \\ LH^{\dagger} & \longrightarrow & \ldots \end{array}\right.$$

m_ν at tree level

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

Seesaws

Particle	$\Delta\mathcal{L}=0$	$\lvert\Delta\mathcal{L}\rvert=2$	BL	ℓ	m_ν	Upper bound
$\bar{N} \sim (1,1,0)_F^{-1,0}$	$y\,\bar{N}HL$	$M\,\bar{N}\bar{N}$	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
$\Delta \sim (1,3,1)_S^{-2,0}$	$y\,L\Delta L$	$\mu\,H\Delta^\dagger H$	$\mathcal{O}_1$	0	$\frac{y\,\mu\,v^2}{M^2}$	$M \lesssim 10^{15}$ GeV
$\bar{\Sigma}_0 \sim (1,3,0)_F^{-1,0}$	$y\,\bar{\Sigma}_0 LH$	$M\,\bar{\Sigma}_0\bar{\Sigma}_0$	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV

m_ν at loop level

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

Zee   Loop order   Zee-Babu

	Particle	$\Delta\mathcal{L} = 0$	$\lvert\Delta\mathcal{L}\rvert = 2$	BL	ℓ	m_ν	Upper bound
Seesaws	$\bar{N} \sim (1,1,0)_F^{-1,0}$	$y\,\bar{N}HL$	$M\,\bar{N}\bar{N}$	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
	$\Delta \sim (1,3,1)_S^{-2,0}$	$y\,L\Delta L$	$\mu\,H\Delta^\dagger H$	$\mathcal{O}_1$	0	$\frac{y\,\mu\,v^2}{M^2}$	$M \lesssim 10^{15}$ GeV
	$\bar{\Sigma}_0 \sim (1,3,0)_F^{-1,0}$	$y\,\bar{\Sigma}_0 LH$	$M\,\bar{\Sigma}_0\bar{\Sigma}_0$	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
	$L_1 \sim (1,2,-1/2)_F^{1,0}$	$m\,\bar{L}_1 L$	$\frac{c}{\Lambda} L_1 HLH$	$\mathcal{O}_1$	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	$h \sim (1,1,1)_S^{-2,0}$	$y\,LLh$	$\frac{c}{\Lambda} h^\dagger \bar{e} LH$	$\mathcal{O}_2$	1	$\frac{c\,y\,y_l}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{10}$ GeV
	$k \sim (1,1,2)_S^{-2,0}$	$y\,\bar{e}^\dagger \bar{e}^\dagger k$	$\frac{c}{\Lambda^3} k^\dagger L^\dagger L^\dagger L^\dagger L^\dagger$	$\mathcal{O}_9^\dagger$	2	$\frac{c\,y\,y_l^2}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{6}$ GeV
	$\bar{E} \sim (1,1,1)_F^{-1,0}$	$y\,\bar{E}LH^\dagger$	$\frac{c}{\Lambda^4} LEHQ^\dagger \bar{u}^\dagger H$	$\mathcal{O}_6$	2	$\frac{c\,y\,y_u}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{10}$ GeV
		$m\,\bar{e}E$	$\frac{c}{\Lambda^3} \bar{E}LLLH$	$\mathcal{O}_2$	1	$\frac{c\,m}{M}\,\frac{y_l}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{10}$ GeV
	$\bar{\Sigma}_1 \sim (1,3,1)_F^{-1,0}$	$y\,H^\dagger \bar{\Sigma}_1 L$	$\frac{c}{\Lambda^2} LHH\Sigma_1 H$	$\mathcal{O}_1'^{1}$	1	$\frac{c\,y}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{12}$ GeV
	$L_2 \sim (1,2,-3/2)_F^{1,0}$	$y\,H\bar{e}L_2$	$\frac{c}{\Lambda^2} \bar{L}_2 LLL$	$\mathcal{O}_2$	1	$\frac{c\,y\,y_l}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{11}$ GeV
	$X_2 \sim (1,2,3/2)_V^{-2,0}$	$y\,\bar{e}^\dagger \bar{\sigma}^\mu L X_{2\mu}$	$\frac{c}{\Lambda}\,\bar{u}^\dagger \bar{\sigma}^\mu \bar{d} X_{2\mu}^\dagger H$	$\mathcal{O}_8$	2	$\frac{cy\,y_u y_d y_e}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{7}$ GeV

Particles with B (LQ)

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

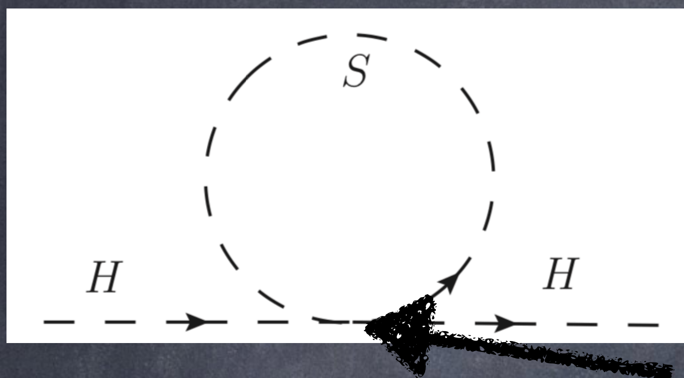
$\Delta \mathscr{L} = 2$

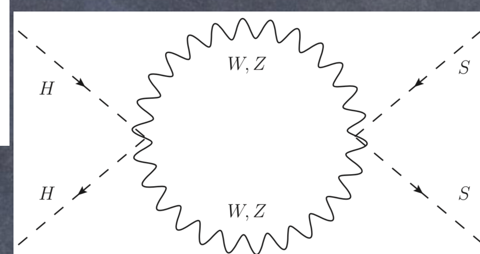
Loop order

Radiative

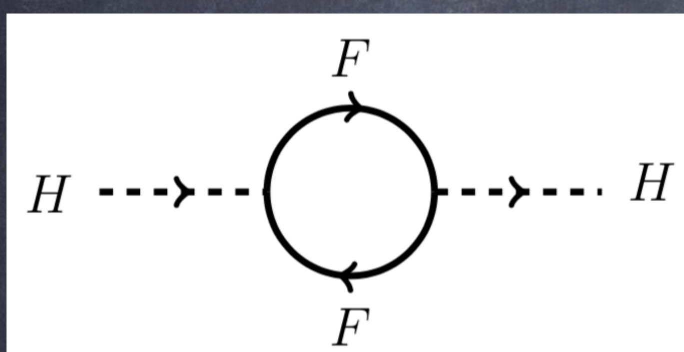
Particle	$\Delta\mathcal{L}=0$	$\lvert\Delta\mathcal{L}\rvert=2$	BL	ℓ	m_ν	Upper bound
$\tilde{R}_2 \sim (3,2,1/6)_S^{-1,1}$	$y\,\bar{d}L\tilde{R}_2$	$\frac{c}{\Lambda}\tilde{R}_2^\dagger QLH$	$\mathcal{O}_{3_b}$	1	$\frac{c\,y\,y_d}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{11}$ GeV
$R_2 \sim (3,2,7/6)_S^{-1,1}$	$y\,\bar{e}^\dagger Q^\dagger R_2$	$\frac{c}{\Lambda^3}R_2^\dagger L^\dagger L^\dagger L^\dagger \bar{d}^\dagger$	$\mathcal{O}_{10}^\dagger$	2	$\frac{c\,y\,y_d\,y_l}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{7}$ GeV
	$y\,\bar{u}LR_2$	$\frac{c}{\Lambda^3}R_2^\dagger L^\dagger L^\dagger L^\dagger \bar{d}^\dagger$	$\mathcal{O}_{15}^\dagger$	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



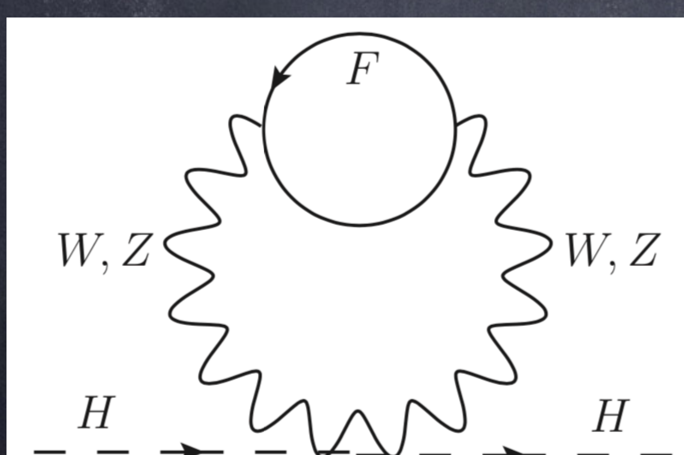


$$\Longrightarrow M \lesssim \frac{16\pi^2 |\delta m_H^2|_{\max}^{1/2}}{\sqrt{6N_c(3Dg^4 + N_w Y^2 g'^4)}}$$



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

SS I; Vissani, Casas



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

SS III (II)
Farina

Naturalness limits much stronger, but less robust.

III - lower limits

Phenomenology controlled by:

A. Renormalizable interaction

1. Violation of: $\mathscr{L}_\alpha$, universality, U_{PMNS} unitarity, NSIs.

2. Collider searches.

B. Non-renormalizable $\Delta\mathscr{L} = 2$ operator

1. $0\nu\beta\beta$.

2. Washout of BAU.

$0\nu\beta\beta$

Ibarra, De Gouvea, Blennow, Rodejohann, Bonnet, Deppisch...

- New contributions may be significant for:

1. SS I, if $M_{\bar{N}} \sim \mathcal{O}(\text{GeV})$
2. New D=7 operators, if $\Lambda \lesssim \mathcal{O}(100)$ TeV

   Like $\mathcal{O}_8 = ueL\bar{d}H$, for L_1, X_2, S_1, U_1

B violation (LQ)

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

Di-quark couplings generate tree-level nucleon decays:

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

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

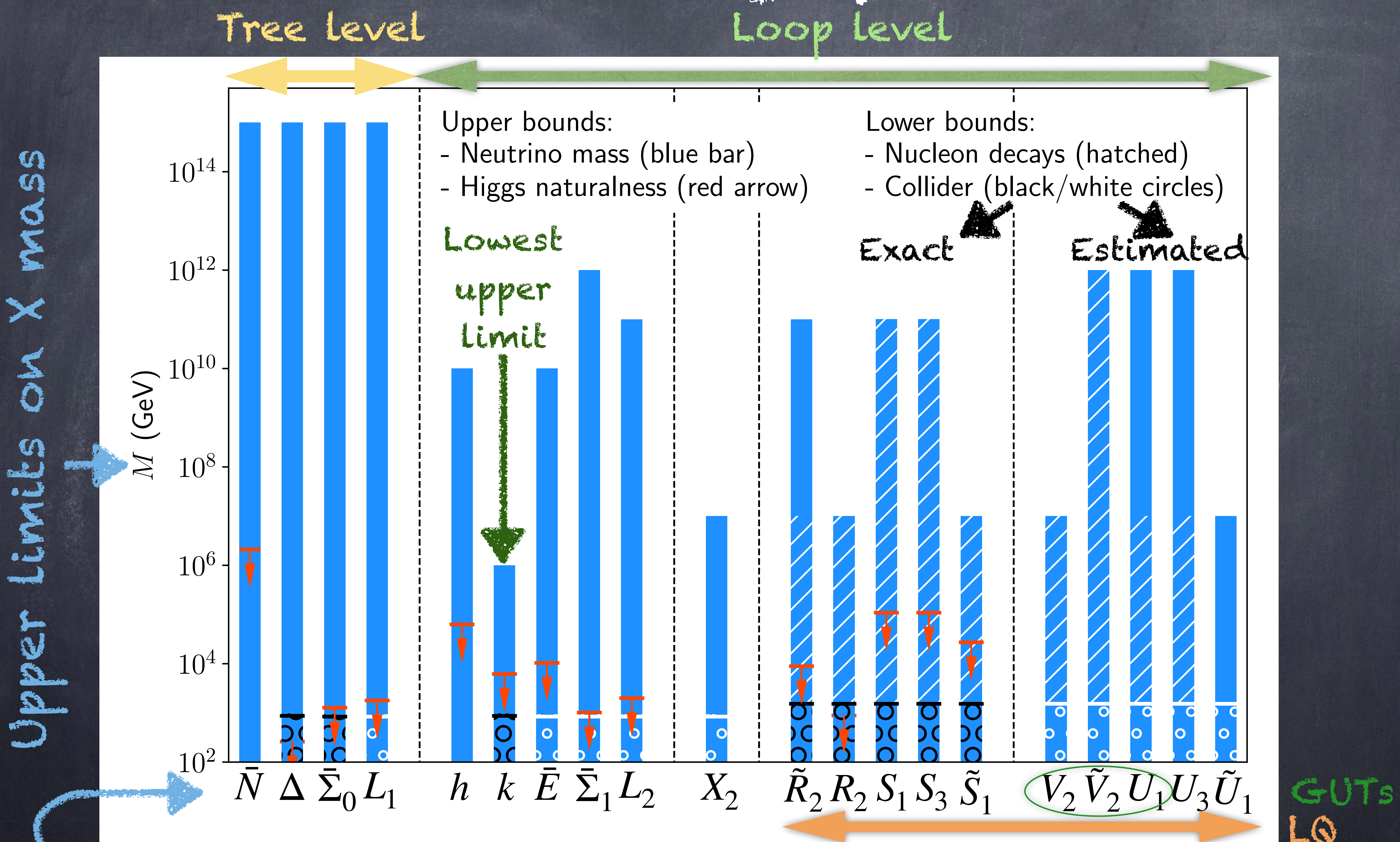
$$\Delta(\mathscr{B} - \mathscr{L}) = 0 \implies M_{S_1} \gtrsim 10^{16}\ \mathrm{GeV}$$

Therefore, S_1 cannot generate m_ν.

[In some cases, $\Delta(\mathscr{B}) = -\Delta(\mathscr{L}) = 1$ decays.]

IV- Summary and conclusions

Summary plot

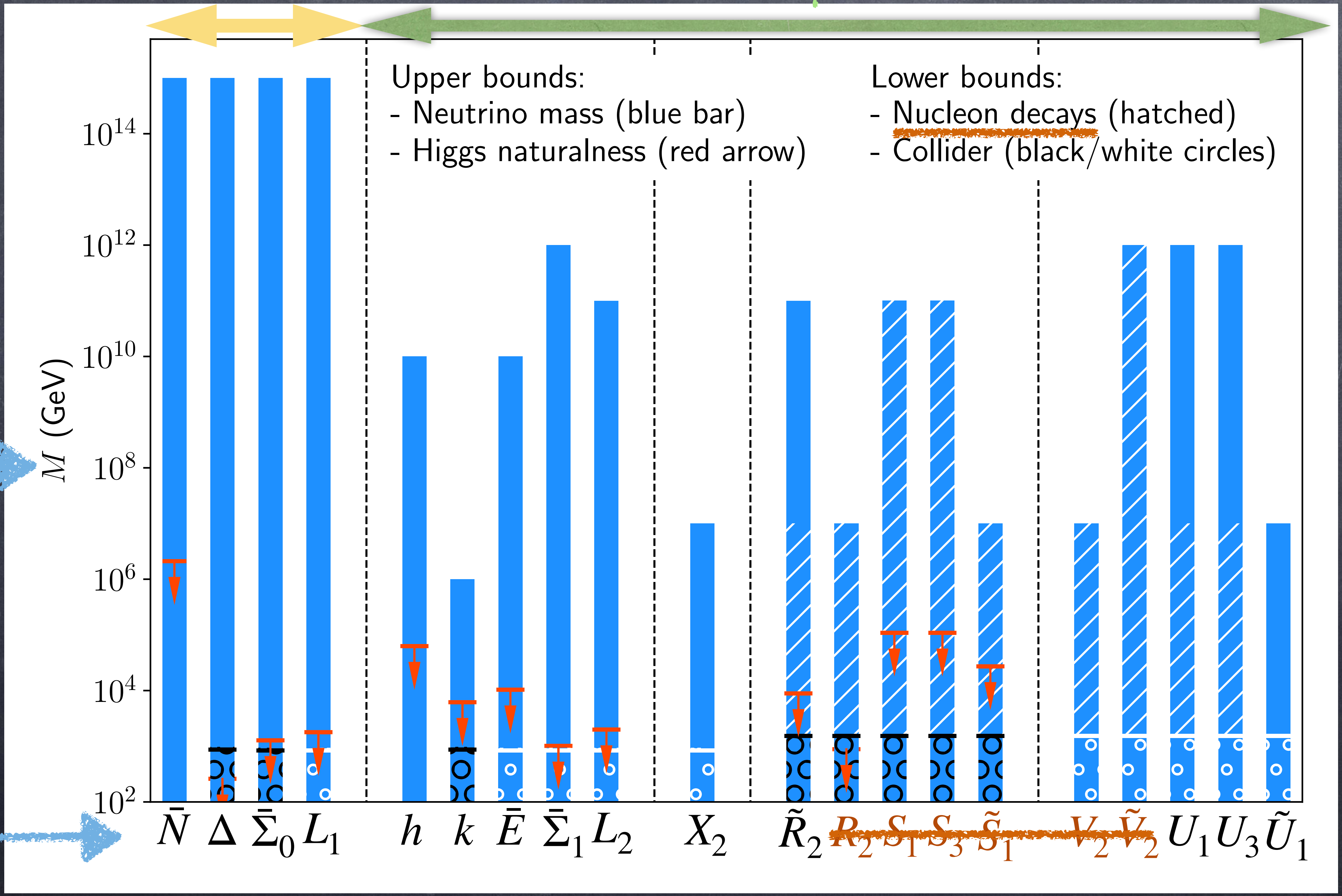


m_ν involve one of these 20 new particles

Summary plot

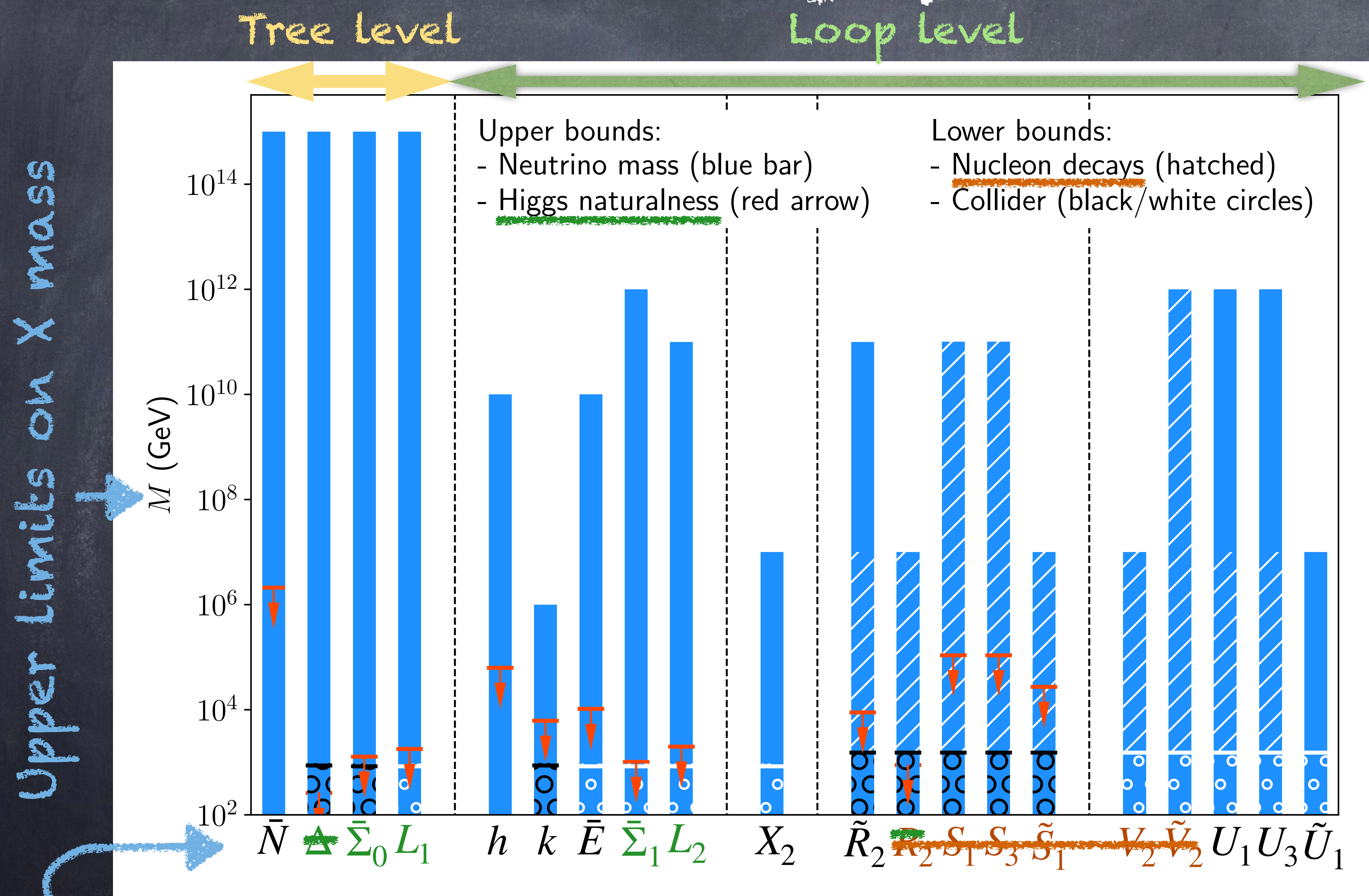
Tree level   Loop level

Upper limits on X mass



Nucleon decays exclude 6 particles (in red)

Summary plot

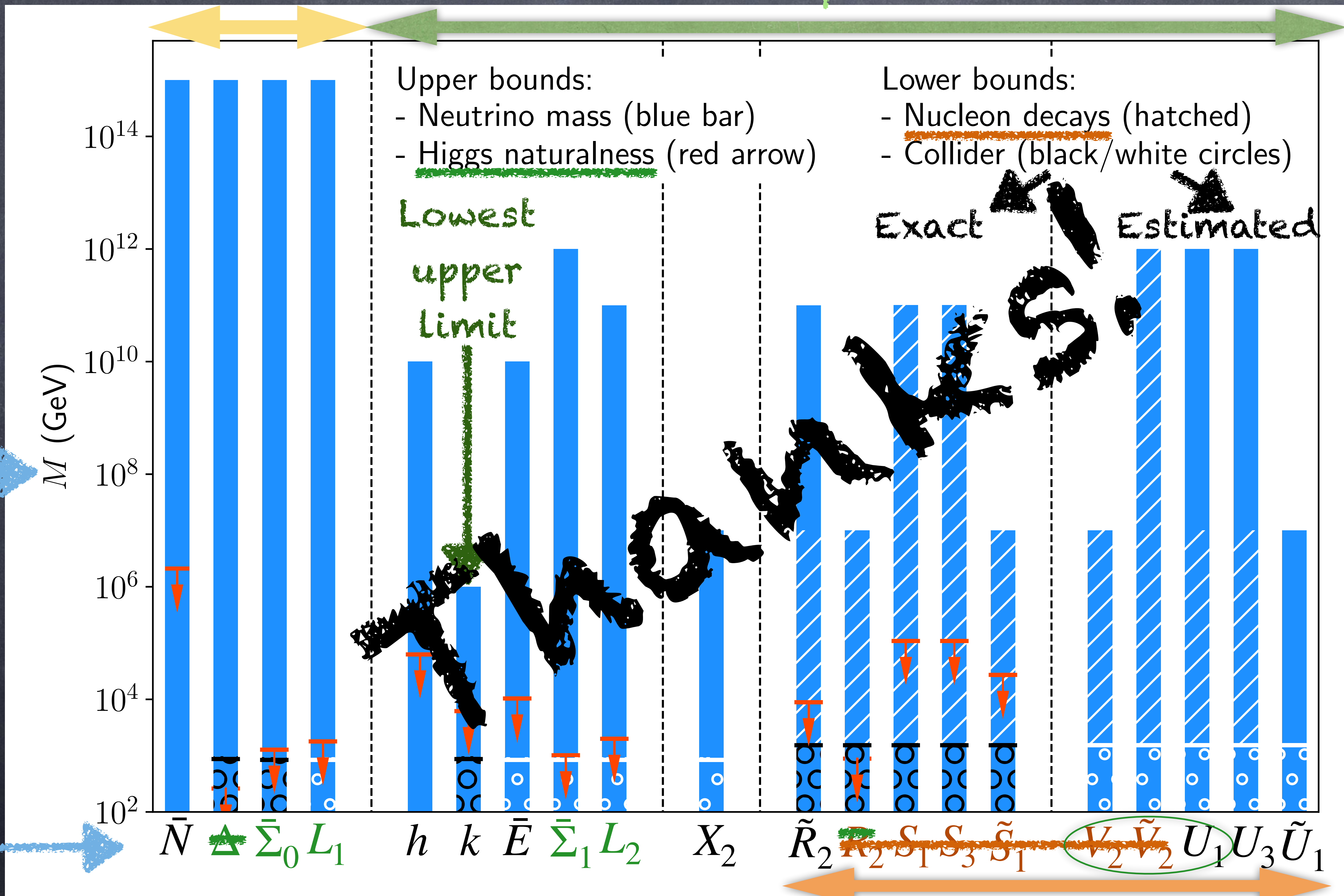


Higgs naturalness disfavours 1 to 5 more (in green)

Conclusions

- New simple classification of m_ν models in "just" 20 categories.
- Robust model-independent upper limits on all possible new states involved in m_ν.
- Hybrid approach useful to study phenomenology.
- 14 allowed categories by nucleon decays.
- Collider searches + Higgs naturalness further disfavour 1 to 5 more, leaving 9 to 13 allowed categories.
- Most promising states: doubly-charged scalars (<1000 TeV).

The Big Picture of m_ν



Upper limits on X mass

m_ν involve one of these 9 to 13 new particles

Back-up

Questions

A. How can we classify the plethora of models?

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

C. Is any class of models already ruled-out?

D. How to study phenomenology of classes of models?

How is m_ν generated?

- ν oscillations imply that ν are massive.
- At least one ν has a mass larger or equal to 0.05 eV.
- However, in the SM ν are massless: need BSM physics.
- Hint: lowest dimension EFT O_W = LLHH has $\Delta\mathscr{L} = 2$.
- After EWSB, naturally light Majorana m_ν.
- Which is the UV completion of O_W = LLHH?

Loop level m_ν estimate

De Gouvea

- Weinberg operator induced via $\Delta\mathscr{L} = 2$ operators.
- Estimate of the matching at loop level:

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

B violation (LQ)

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

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

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

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

B+L

$$\downarrow$$

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

Washout of BAU

Harvey, Turner

- $\Delta\mathscr{L} = 2$ operators + sphalerons may erase the BAU, unless:

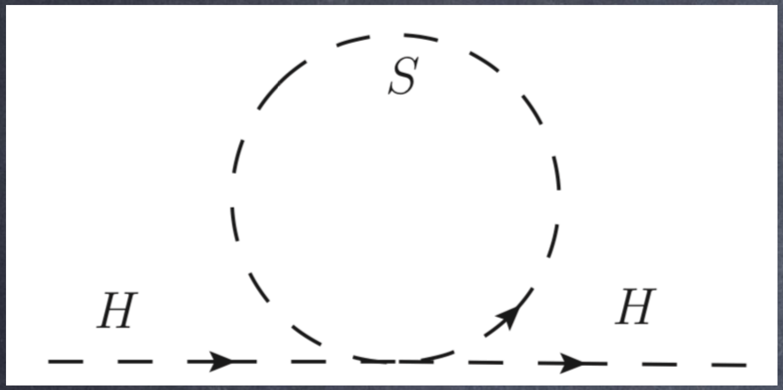
$$\Gamma(T_{\mathscr{B}-\mathscr{L}}) \leq H(T_{\mathscr{B}-\mathscr{L}})$$

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

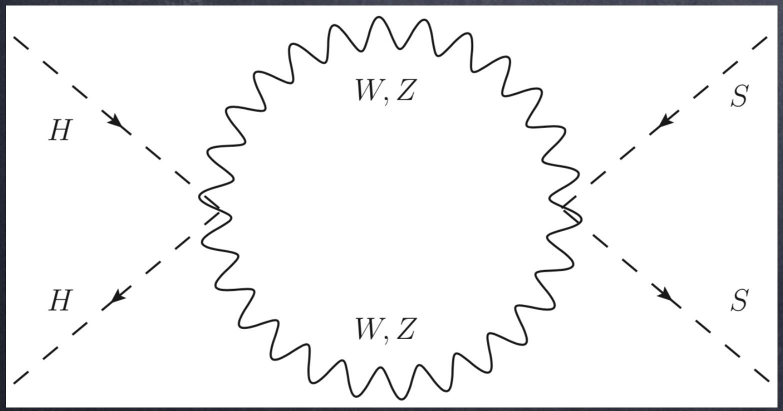
$$T_{\mathscr{B}-\mathscr{L}} = 10^6, 10^{10}, 10^{12}\ \mathrm{GeV} \Longrightarrow \begin{cases} \Lambda_{d=5} \gtrsim 10^{11}, 10^{13}, 10^{14}\,\mathrm{GeV} \\ \Lambda_{d>5} \gtrsim 10^{7}, 10^{10}, 10^{13}\,\mathrm{GeV} \end{cases}$$

Strong limits on Λ, dependent on $\mathscr{B} - \mathscr{L}$ scale.

Higgs naturalness: scalars

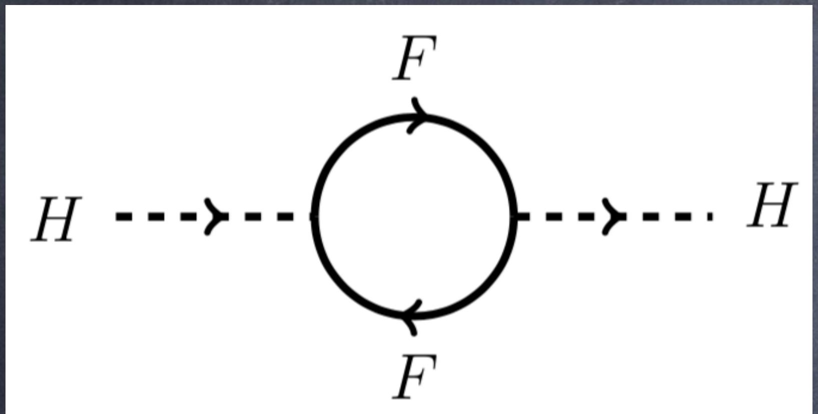


$$\delta m_H^2 \simeq -\left(\frac{\lambda}{16\pi^2}\right) N_w N_c\, M^2 \ln\left(\frac{M^2}{\Lambda^2}\right)$$



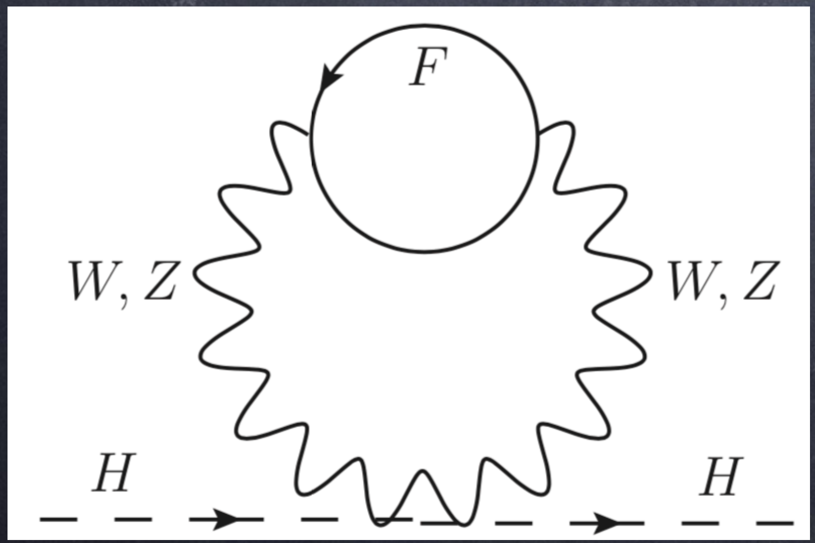
$$\delta\lambda \simeq \left(\frac{3}{32\pi^2}\right)(Y^2 g'^4 + C_2 g^4)\, \ln\left(\frac{M^2}{\Lambda^2}\right)$$

Higgs naturalness: fermions



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

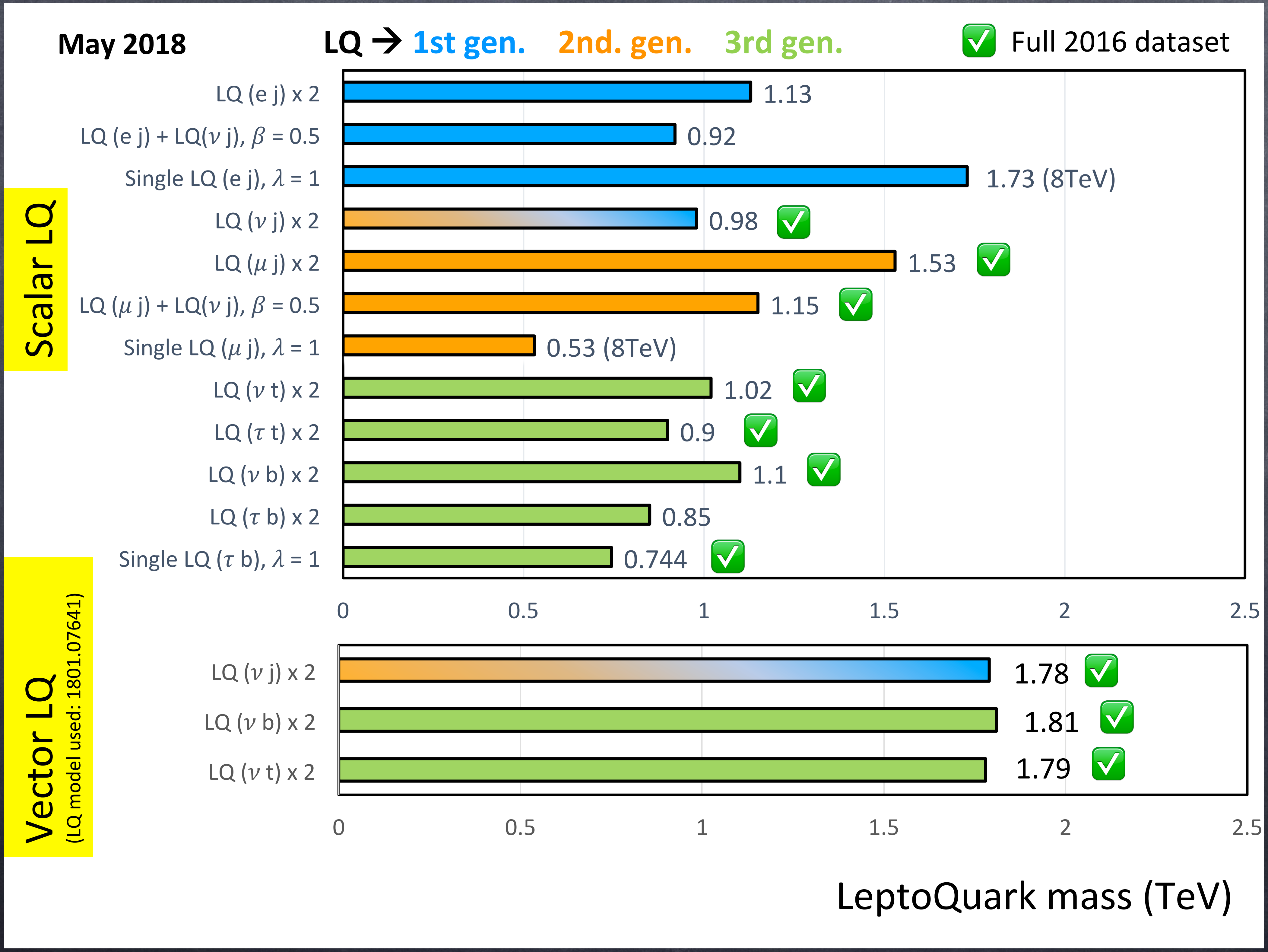
SS I. Vissani, Casas



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

SS III, Farina

CMS LQ Limits



Summary plot