A SYSTEMATIC APPROACH TO NEUTRINO MASSES AND THEIR PHENOMENOLOGY

Michael A. Schmidt

TeV Particle Astrophysics 2019

5 December 2019

UNSW SYDNEY

based on work in collaboration with
Juan Herrero-Garcia 1903.10552 [Eur.Phys.J. C79 (2019) no.11, 938]

- The Standard Model is very successful…
- …but incomplete
  In particular neutrinos are massive
- Hint: lowest dimensional effective operator $O_1 = LLHH$ ($d = 5$, Weinberg) violates lepton number by 2 units
- After EWSB, naturally light Majorana neutrino masses
- What is the underlying theory of neutrino masses?

Overview

Mechanisms for neutrino masses

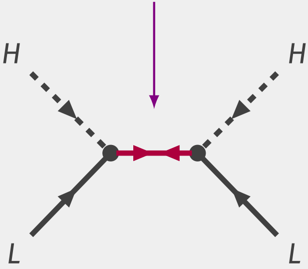
Majorana neutrino masses

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

- Radiative. In principle more testable, but hundreds of them.
  Classified by
  1. Topologies at a given loop order (up to 3 loops)
  2. $\Delta L = 2$ EFT operators beyond Weinberg operator

SS I: $\bar{N} \sim (1, 1, 0)$

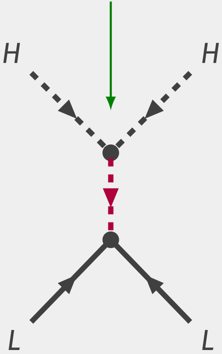
$yLH\bar{N} + m\bar{N}\bar{N}$



Minkowski; Yanagida; Glashow;
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic.

SS II: $\Delta \sim (1, 2, 1)$

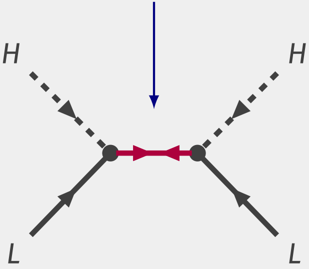
$yL\Delta L + \mu H\Delta^\dagger H$



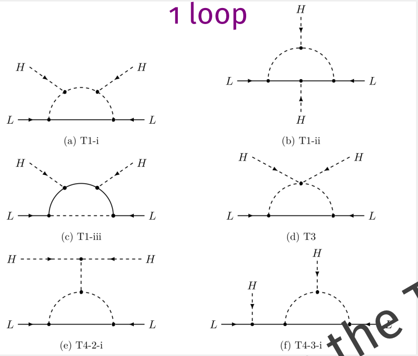
Mohapatra, Senjanovic;
Magg, Wetterich;
Lazarides, Shafi, Wetterich;
Schechter, Valle.

SS III: $\bar{\Sigma} \sim (1, 3, 0)$

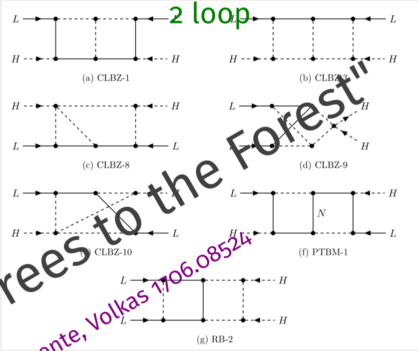
$yLH\bar{\Sigma} + m\bar{\Sigma}\bar{\Sigma}$



Foot, Lew, He, Joshi.



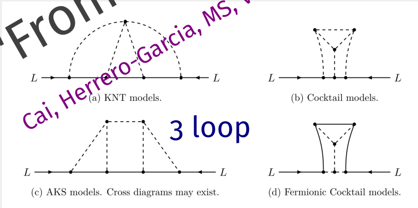
(a) T1-i (b) T1-ii (c) T1-iii (d) T3 (e) T4-2-i (f) T4-3-i



(a) CLBZ-1 (b) CLBZ-3 (c) CLBZ-8 (d) CLBZ-9 (e) CLBZ-10 (f) PTBM-1 (g) RB-2

Review: "From the Trees to the Forest"

Cai, Herrero-Garcia, MS, Vicente, Volkas 1706.08524

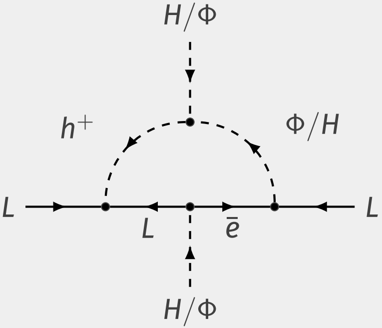


(a) KNT models. (b) Cocktail models. (c) AKS models. Cross diagrams may exist. (d) Fermionic Cocktail models.

Singly-charged scalar: $fLLh^+$

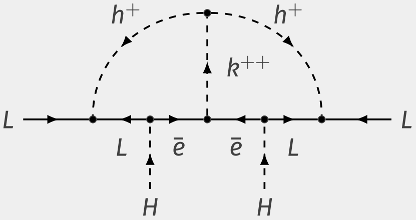
Zee model

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



Zee-Babu model

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



Zee model Zee-Babu model

$$\mathcal{O}_2 = L^i L^j L^k \bar{e} H^l \epsilon_{ij}\epsilon_{kl} \qquad \mathcal{O}_{3a} = L^i L^j Q^k \bar{d} H^l \epsilon_{ij}\epsilon_{kl} \qquad \mathcal{O}_{3a} = L^i L^j Q^k \bar{d} H^l \epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{4a} = L^i L^j Q^\dagger_i \bar{u}^\dagger H^k \epsilon_{jk} \qquad \mathcal{O}_{4b} = L^i L^j Q^\dagger_k \bar{u}^\dagger H^k \epsilon_{ij} \qquad \mathcal{O}_8 = L^i \bar{d} \bar{e}^\dagger \bar{u}^\dagger H^j \epsilon_{ij}$$

$$\mathcal{O}_9 = L^i L^j L^k \bar{e} L^l \bar{e} \epsilon_{ij}\epsilon_{kl} \qquad \mathcal{O}_{10} = L^i L^j L^k \bar{e} Q^l \bar{d} \epsilon_{ij}\epsilon_{kl}$$

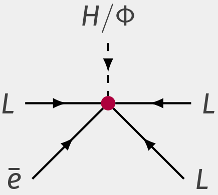
$$\mathcal{O}_{11a} = L^i L^j Q^k \bar{d} Q^l \bar{d} \epsilon_{ij}\epsilon_{kl} \qquad \mathcal{O}_{11b} = L^i L^j Q^k \bar{d} Q^l \bar{d} \epsilon_{ik}\epsilon_{jl}$$

$$\mathcal{O}_{12a} = L^i L^j Q^\dagger_i \bar{u}^\dagger Q^\dagger_j \bar{u}^\dagger \qquad \mathcal{O}_{12b} = L^i L^j Q^\dagger_k \bar{u}^\dagger Q^\dagger_l \bar{u}^\dagger \epsilon_{ij}\epsilon^{kl}$$

$$\ldots$$

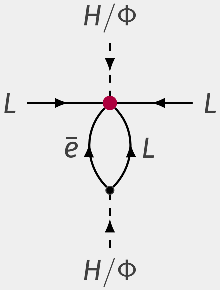
$$\mathcal{O}_{59} = L^i Q^j \bar{d} \bar{d} \bar{e}^\dagger \bar{u}^\dagger H^k H^\dagger_i \epsilon_{jk} \qquad \mathcal{O}_{60} = L^i \bar{d} Q^\dagger_j \bar{u}^\dagger \bar{e}^\dagger \bar{u}^\dagger H^j H^\dagger_i$$

operators up to dimension 11 classified



Operator

$O_2 = LLL\bar{e}H$

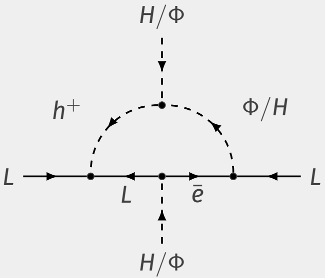


Estimate

chirality flip y_τ

$$m_\nu \simeq \frac{1}{16\pi^2} y_\tau \frac{c_2 v^2}{\Lambda}$$

loop factor $\frac{1}{16\pi^2}$



UV model: Zee

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

Neutrino masses

Classification in terms of effective $\Delta L = 2$ operators

Babu, Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344 Bonnet, Hernandez, Ota, Winter 0907.3143

$$m_\nu \simeq \frac{c_R v^2}{(16\pi^2)^l \Lambda}\ \text{, with} \qquad c_R \simeq \prod_i g_i \times \epsilon \times \left(\frac{v^2}{\Lambda^2}\right)^n$$

Loop factor

μ/Λ

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

$$m_\nu \gtrsim 0.05\text{eV} \Rightarrow \begin{cases} l = 1 \rightarrow \Lambda < 10^{12}\text{GeV} \\ l = 2 \rightarrow \Lambda < 10^{10}\text{GeV} \\ l = 3 \rightarrow \Lambda < 10^{8}\text{GeV} \end{cases}$$

$\rightarrow$ no information on $\Delta L = 0$ processes

Systematic construction of models

Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas (in prep)

Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629

Volkas (NuFact 2019): "exploding! $\Delta L = 2$ operators" ... "1000s of models"

$\rightarrow$ too many models!

Neutrino masses

Classification in terms of effective $\Delta L = 2$ operators

Babu, Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344 Bonnet, Hernandez, Ota, Winter 0907.3143

$$m_\nu \simeq \underbrace{\frac{c_R v^2}{(16\pi^2)^l \Lambda}}_{\text{Loop factor}}, \text{with} \qquad c_R \simeq \prod_i g_i \times \underbrace{\epsilon}_{\mu/\Lambda} \times \underbrace{\left(\frac{v^2}{\Lambda^2}\right)^n}_{LLHH(H^\dagger H)^n}$$

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

$\to$ no information on $\Delta L = 0$ processes

Systematic construction of models

Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas (in prep)

Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629

Volkas (NuFact 2019): "exploding! $\Delta L = 2$ operators" ..."1000s of models"

$\to$ too many models!

Neutrino masses

Classification in terms of effective $\Delta L = 2$ operators

Babu, Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344 Bonnet, Hernandez, Ota, Winter 0907.3143

$$m_\nu \simeq \frac{c_R v^2}{(16\pi^2)^l \Lambda}, \text{with} \qquad c_R \simeq \prod_i g_i \times \epsilon \times \left(\frac{v^2}{\Lambda^2}\right)^n$$

Loop factor $\qquad \mu/\Lambda \qquad LLHH(H^\dagger H)^n$

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

$\to$ no information on $\Delta L = 0$ processes

Systematic construction of models

Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas (in prep)

Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629

Volkas (NuFact 2019): "exploding! $\Delta L = 2$ operators" ..."1000s of models"

$\to$ too many models!

Can we do better? → Hybrid approach

Can we do better? → Hybrid approach

Questions

1. How can we classify the plethora of models?
2. What are the most testable ones, with the lightest particles?
3. Is any class of models already ruled-out?
4. Can we study the phenomenology without going to a particular model?

Upper limits

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 scale Λ which encode the (model-dependent) UV physics.

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

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

5. L-conserving pheno mostly determined by renormalizable $\Delta L = 0$ operator

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

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. $m_\nu > 0.05\mathrm{eV}$ & $y \leq 1 \Rightarrow$ conservative upper bound

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

Possible new particles

$$
\begin{aligned}
LH &\to N\,(\text{SSI}), \Sigma\,(\text{SSIII}) \\
LL &\to \Delta\,(\text{SSII}), h\,(\text{Zee}) \\
\bar{e}\bar{e} &\to k\,(\text{Zee-Babu}) \\
LH^\dagger &\to \dots \\
\bar{e}H^\dagger &\to \dots \\
\bar{e}\sigma_\mu L^\dagger &\to \dots \\
\dots &
\end{aligned}
$$

Particles generating tree level neutrino masses

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

$\Delta L = 2$ operators

Seesaw type

	Particle	$\Delta\mathcal{L}=0$	$\lvert\Delta\mathcal{L}\rvert=2$		BL	ℓ	m_ν	Upper bound
Seesaws	$\bar{N} \sim (1,1,0)_F^{-1,0}$	$y\,\bar{N}HL$	$M\,\bar{N}\bar{N}$	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
	$\bar{\Sigma}_0 \sim (1,3,0)_F^{-1,0}$	$y\,\bar{\Sigma}_0 LH$	$M\,\bar{\Sigma}_0\bar{\Sigma}_0$	III	$\mathcal{O}_1$	0	$\frac{y^2\,v^2}{M}$	$M \lesssim 10^{15}$ GeV
	$L_1 \sim (1,2,-1/2)_F^{1,0}$	$m\,\bar{L}_1 L$	$\frac{c}{\Lambda}L_1HLH$		$\mathcal{O}_1$	0	$\frac{c\,m}{M}\,\frac{v^2}{\Lambda}$ c	$M \lesssim 10^{15}$ GeV

Particles generating loop level neutrino masses

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

Zee

Zee-Babu

Loop order

	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	$\frac{c\,m}{M}\,\frac{v^2}{\Lambda}$ c	$M \lesssim 10^{15}$ 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	$\frac{c\,yy_u\,y_d\,y_l}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{7}$ 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
	$X_2 \sim (1,2,3/2)_V^{-2,0}$	$y\,\bar{e}^\dagger\bar{\sigma}^\mu LX_{2\mu}$	$\frac{c}{\Lambda}\,\bar{u}^\dagger\bar{\sigma}^\mu\bar{d}X_{2\mu}^\dagger H$	$\mathcal{O}_8$	2	$\frac{cy\,y_u y_d y_e}{(4\pi)^4}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{7}$ GeV

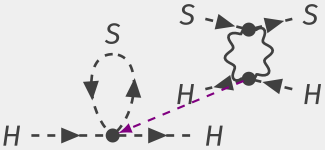
Particles with B (leptoquarks)

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

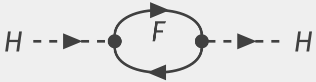
Radiative

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	$\frac{c\,y\,y_d}{(4\pi)^2}\,\frac{v^2}{\Lambda}$	$M \lesssim 10^{11}$ 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

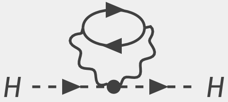
See also: SSI: Vissani hep-ph/9709409; SSII(III) 1303.7244



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



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



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

Naturalness limits much stronger, but less robust

Lower limits

- Driven by renormalizable interaction:
  1. Violation of lepton flavor, universality, PMNS unitarity.
  2. Direct searches at colliders

- Driven by non-renormalizable part:
  1. $\Delta L = 2$ processes, like neutrino-less double beta decay.
  2. B violation, like nucleon decays
  3. Washout of BAU

Di-quark couplings generate tree-level nucleon decays:

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

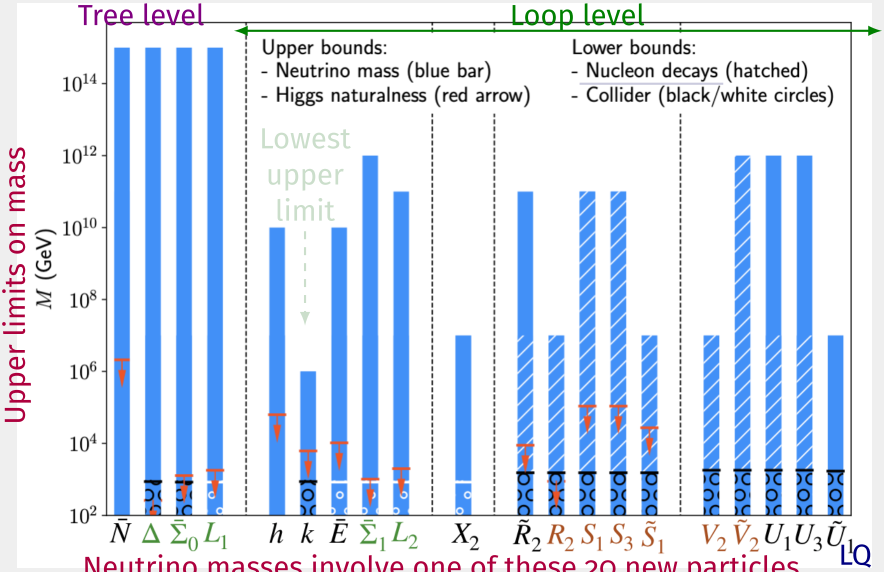
$$\Gamma(p \to \pi^0 e^+) \simeq \frac{|y_1|^2 |y_2|^2}{8\pi} \frac{m_p^5}{M_{S_1}^4} < \frac{1}{10^{33}\mathrm{y}}$$

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

Therefore, S_1 cannot generate neutrino masses without imposing B conservation by hand.

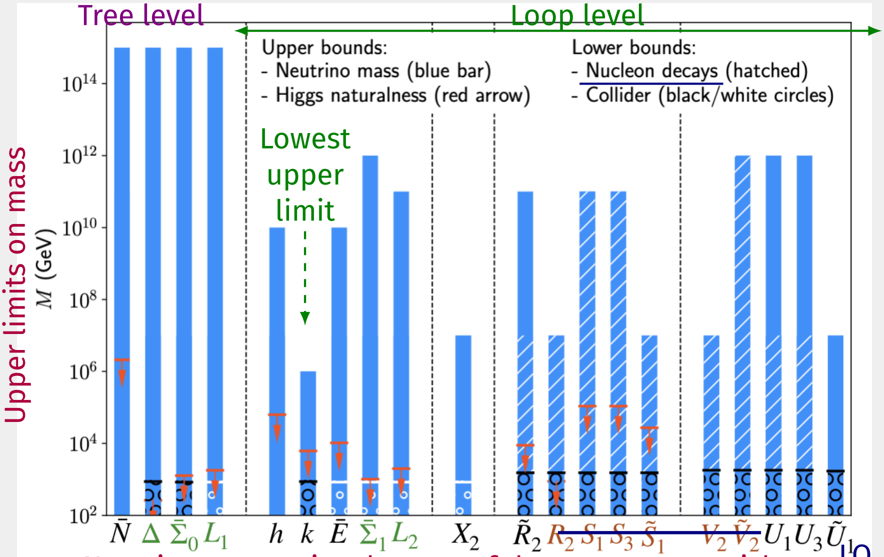
Summary and conclusions

Summary plot



Neutrino masses involve one of these 20 new particles.

Summary plot



Neutrino masses involve one of these 20 new particles.

Conclusions

- Simple way of organizing the plethora of neutrino models in a small number of categories

- Robust limits on all possible new particles involved in m_ν

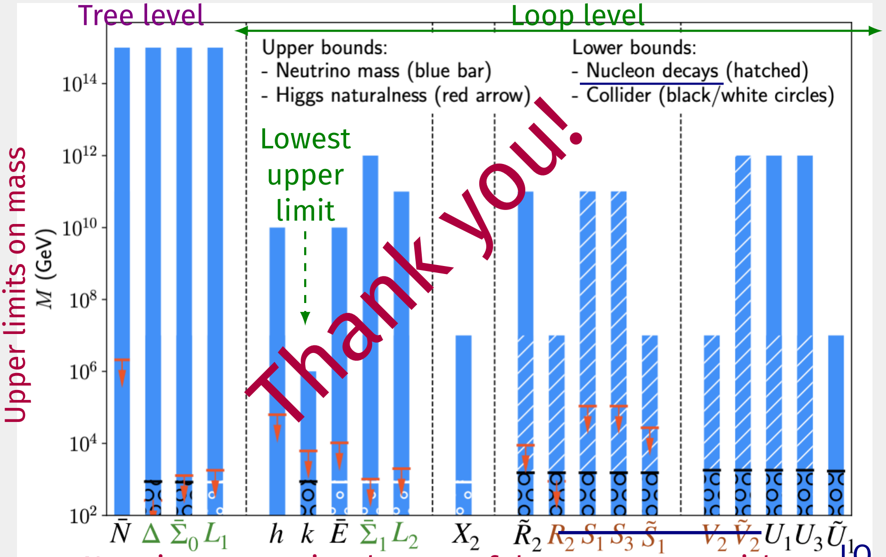
- Useful framework to study phenomenology

- Nucleon decays rule out some scenarios.

Postdoc position in flavour physics available at UNSW

– quark, neutrino, charged-lepton flavour –

Contact me
if you are interested



Neutrino masses involve one of these 20 new particles.

Backup slides

Neutrinoless double β decay [Ibarra, De Gouvea, Blennow, Rodejohann, Bonnet, ...]

New contributions may be significant for:

1. SSI/III, if new fermion singlets $M_R \sim \mathcal{O}(\mathrm{GeV})$

2. New $D = 7$ operators, if $\Lambda \lesssim \mathcal{O}(100\,\mathrm{TeV})$
   Like $O_8 = \bar{u}^\dagger \bar{e}^\dagger L \bar{d} H$, generated by L_1, X_2, S_1, U_1