A systematic approach to neutrino masses and their phenomenology

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based on work in collaboration with
Juan Herrero-García 1903.10552 [Eur.Phys.J. C79 (2019) no.11, 938]
+ Tobias Felkl 2102.09898

Majorana neutrino masses

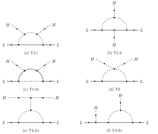
Tree-level. Seesaw models Minkowski;Yanagida; Glashow; Gell-Mann, Ramond, Slansky; Mohapatra, Senjanovic; Magg, Wetterich; Lazarides,Shafi, Wetterich; Schechter, Valle; Foot, Lew, He, Joshi

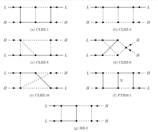
simple, GUT connection, leptogenesis, but huge scales
→ very hard to test and hierarchy problem

Radiative. In principle more testable, but hundreds of them.

Classified by

1. Topologies
   Bonnet, Hernandez, Ota, Winter 0907.3143; Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629; . . .
2. $\Delta L = 2$ EFT operators
   Babu, Leung hep-ph/0106054; deGouvea, Jenkins 0708.1344; Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas 2009.13537; . . .





$$O_1 = L^i L^j H^k H^l \epsilon_{ik}\epsilon_{jl} \qquad O_2 = L^i L^j L^k \bar{e} H^l \epsilon_{ij}\epsilon_{kl}$$

$$O_{3a} = L^i L^j Q^k \bar{d} H^l \epsilon_{ij}\epsilon_{kl} \qquad O_{3b} = L^i L^j Q^k \bar{d} H^l \epsilon_{ik}\epsilon_{jl}$$

see review Cai, Herrero-García, MS, Vicente, Volkas: "From the Trees to the Forest: a review of radiative neutrino mass models" 1706.08524

Can we do better? ⟶ Hybrid approach using simplified models

Main idea

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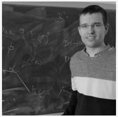
1. m_ν requires at least one new particle X (mass M) coupled to SM lepton(s), carrying L (and maybe B).
2. QFT: L is violated (by two units) via new operators at scale Λ which encode the (model-dependent) UV physics.
3. Majorana neutrino masses, $m_\nu \propto 1/\Lambda$, are generated.
4. $m_\nu > 0.05\text{eV}$ & $M \leq \Lambda \Rightarrow$ 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.

Juan Herrero-García



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, $m_\nu = y^2v^2/M$, are generated.
4. $m_\nu > 0.05\text{eV}$ & $y \leq 1 \Rightarrow$ conservative upper bound $M \leq 10^{15}\text{GeV}$

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Possible new particles

$$LH \longrightarrow N\,(\text{SSI}),\, \Sigma\,(\text{SSIII})$$

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

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

$$LH^\dagger \longrightarrow \dots$$

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

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

$$\dots$$

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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
	$L_1 \sim (1, 2, -1/2)_F^{1,0}$	$m\,\bar{L}_1 L$	$\frac{c}{\Lambda}L_1 HLH$		$\mathcal{O}_1$	0	$\frac{c\,m}{M}\,\frac{v^2}{\Lambda}$ c	$M \lesssim 10^{15}$ GeV

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Particles generating loop level neutrino masses

Zee-Babu

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

Zee

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

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

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Phenomenology

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- Driven by non-renormalizable part:
  1. $\Delta L = 2$ processes, like neutrino-less double beta decay.
  2. Washout of BAU
- Driven by renormalizable interaction:
  1. Violation of lepton flavor, universality, PMNS unitarity.
  2. Direct searches at colliders
  3. B violation, like nucleon decays

B violation (LQ) [Weinberg, Weldon, Nath, Barr, Babu, Arnold, Dorsner,...]

e.g. tree-level nucleon decays: $S_1 = (\bar{3}, 1, 1/3) : y_1 S_1^\dagger \bar{u}\bar{e} + y_2 S_1 \bar{u}\bar{d}$

$$\Gamma(p \to \pi^0 e^+) \simeq \frac{|y_1|^2 |y_2|^2}{8\pi} \frac{m_p^5}{M_{S_1}^4} < \frac{1}{10^{33}\mathrm{y}} \qquad \Rightarrow M_{S_1} \gtrsim 10^{16}\mathrm{GeV}$$

S_1 cannot generate neutrino masses without imposing B conservation.

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Summary plot

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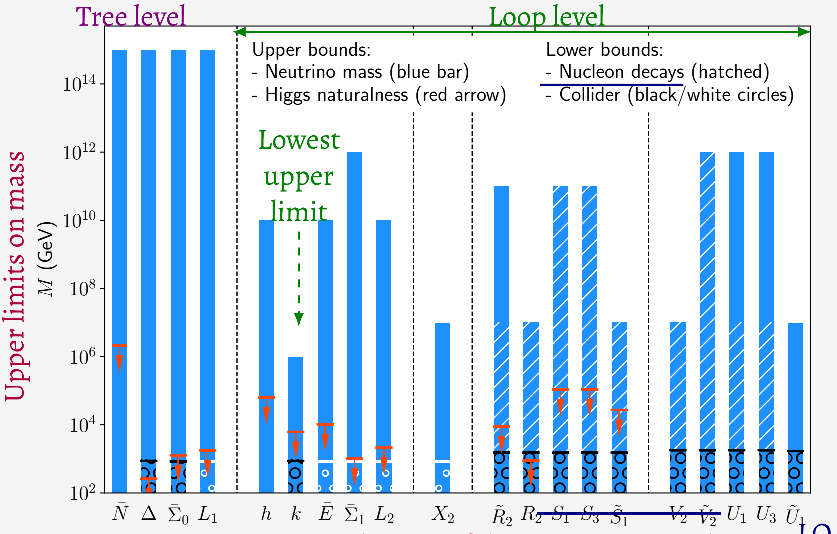

Neutrino masses involve one of these 20 new particles.

Singly-charged scalar singlet $h \sim (1, 1, 1)$


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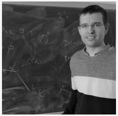
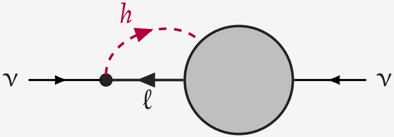

Juan Herrero-García

- Relevant Yukawa interaction $y_h^{ij} L_i L_j h$
- y_h is antisymmetric $y_h = -y_h^T$

→ non-trivial eigenvector v_h with eigenvalue zero, $y_h\, v_h = 0$

linear case

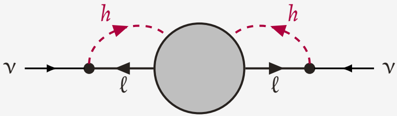


$$M_\nu = X y_h - y_h X^T$$

⇒ 1 complex condition

$$0 = v_h^T M_\nu v_h = v_h^T U^* m_{\text{diag}} U v_h$$

quadratic case



$$M_\nu = y_h S y_h \quad \text{with } S = S^T$$

⇒ 2 complex conditions
previously discussed in Zee-Babu model 0711.0483

$$0 = m_{\text{diag}} U^\dagger v_h$$

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Yukawa couplings

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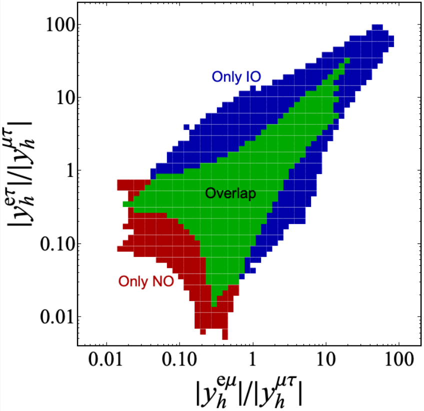

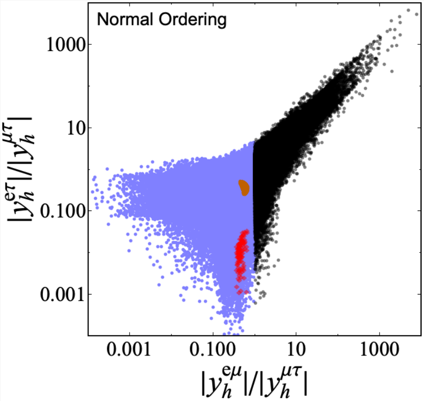

- Linear case: blue (2σ), black (3σ)
- Quadratic case: brown
- Anomalies ($\frac{g_{\mu,\tau}}{g_e}$, Cabibbo angle): red

see 2012.09845

Lepton flavour universality

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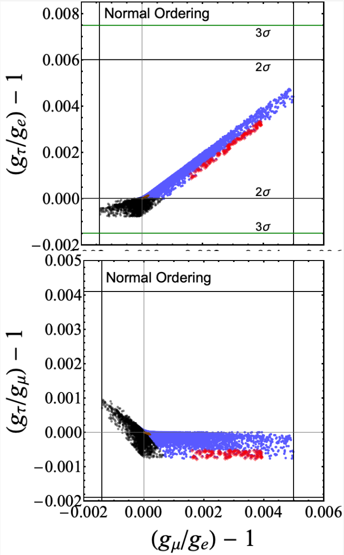

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\epsilon_{ij}^{kl}\left(\nu_i^\dagger\bar{\sigma}^\mu\nu_j\right)\left(\ell_k^\dagger\bar{\sigma}_\mu\ell_l\right)$$

$$\epsilon_{ij}^{kl} = -\frac{1}{\sqrt{2}G_F}\frac{(y_h^{ik})^* y_h^{jl}}{M_h^2}$$

Effective leptonic gauge couplings

$$\frac{g_\mu}{g_e} \simeq 1+\epsilon_{ee}^{\tau\tau}-\epsilon_{\mu\mu}^{\tau\tau},$$
$$\frac{g_\tau}{g_e} \simeq 1+\epsilon_{ee}^{\mu\mu}-\epsilon_{\mu\mu}^{\tau\tau},$$
$$\frac{g_\tau}{g_\mu} \simeq 1+\epsilon_{ee}^{\mu\mu}-\epsilon_{ee}^{\tau\tau}\,.$$

- Linear case: blue (2σ), black (3σ)
- Quadratic case: brown
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see 2012.09845

Conclusions

- Useful framework to organize the plethora of neutrino models and to study their phenomenology
    - Robust upper limits on all possible new particles involved in m_ν
    - Nucleon decays rule out some scenarios.
- Model-inpedendent results for neutrino masses from singly-charged scalar singlet $h \sim (1, 1, 1)$

Summary plot

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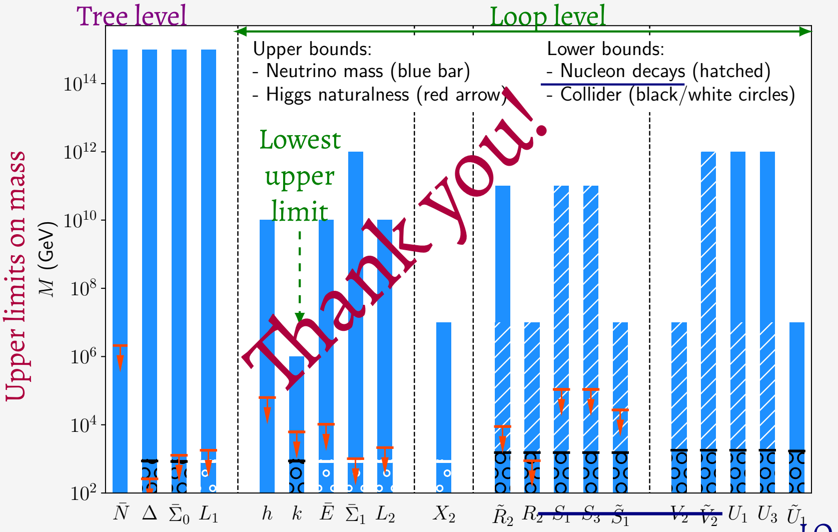


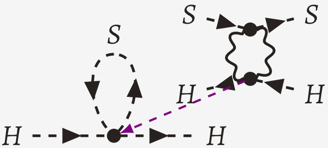
Thank you!

Neutrino masses involve one of these 20 new particles.

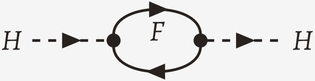
Backup slides

Higgs naturalness

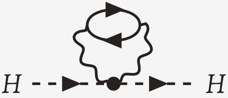
See also: SSI: Vissani hep-ph/9709409; SSII(III) 1303.7244



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



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



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

Naturalness limits much stronger, but less robust

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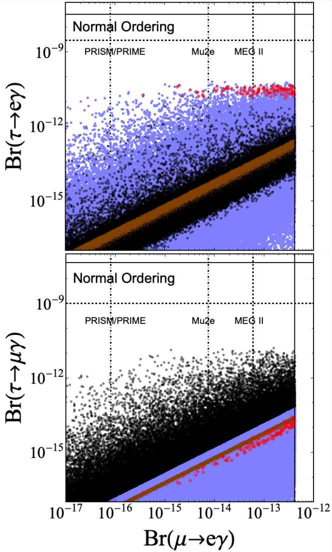
Neutrinoless double β decay [Ibarra, De Gouvea, Blennow, Rodejohann, Bonnet, …]

New contributions may be significant for:

1. SSI/III, if new fermion singlets $M_R \sim \mathcal{O}(\text{GeV})$
2. New $D = 7$ operators, if $\Lambda \lesssim \mathcal{O}(100\text{TeV})$
   Like $O_8 = \bar{u}^\dagger \bar{e}^\dagger L \bar{d} H$, generated by L_1, X_2, S_1, U_1

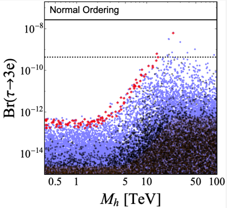
Lepton flavour violation

Tobias Felkl, Juan Herrero-García, MS 2102.09898



$$\frac{Br(\ell \to \ell'\gamma)}{Br(\ell \to \ell'\nu\bar{\nu})} = \frac{\alpha}{48\pi}\frac{|y_h^{\ell\alpha} y_h^{\ell'\alpha}|^2}{G_F^2 M_h^4}$$

- Photon penguin dominance
- Box diagrams important for $M_h \gtrsim 5$ TeV



- Linear case: blue (2σ), black (3σ)
- Quadratic case: brown
- Anomalies ($\frac{g_{\mu,\tau}}{g_e}$, Cabibbo angle): red

see 2012.09845

Branching ratios

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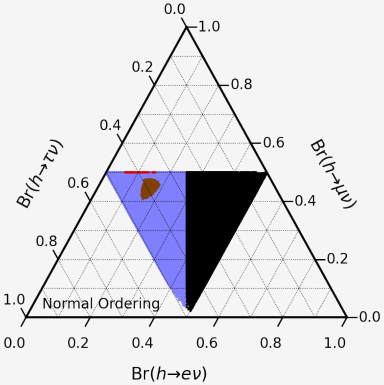
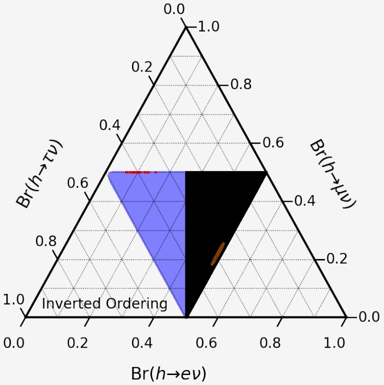




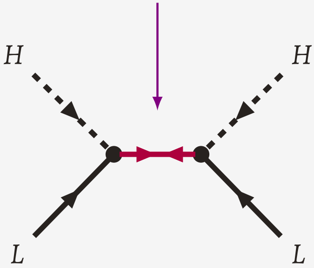
$$\mathrm{Br}(h \to \ell_a \nu) = \frac{\sum_{b\neq a} |y_h^{ab}|^2}{2(|y_h^{e\mu}|^2 + |y_h^{e\tau}|^2 + |y_h^{\mu\tau}|^2)}$$

- Linear case: blue (2σ), black (3σ)
- Quadratic case: brown
- Anomalies ($\frac{g_{\mu,\tau}}{g_e}$, Cabibbo angle): red see 2012.09845

Tree level: seesaws

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

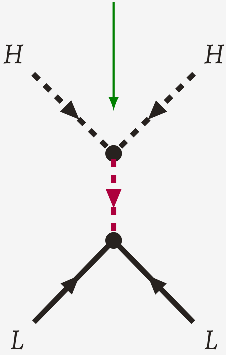
$y L H \bar{N} + m \bar{N} \bar{N}$



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

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

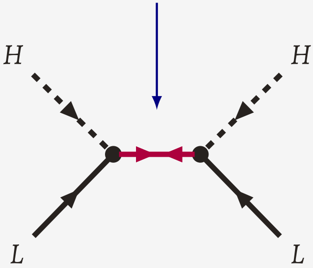
$y L \Delta L + \mu H \Delta^{\dagger} H$



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

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

$y L H \bar{\Sigma} + m \bar{\Sigma} \bar{\Sigma}$



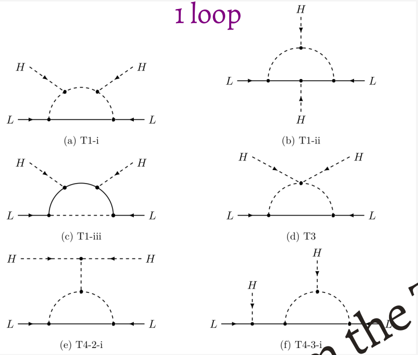
Foot, Lew, He, Joshi.

Loop level models

Review: "From the Trees to the Forest"

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

1 loop



(a) T1-i

(b) T1-ii

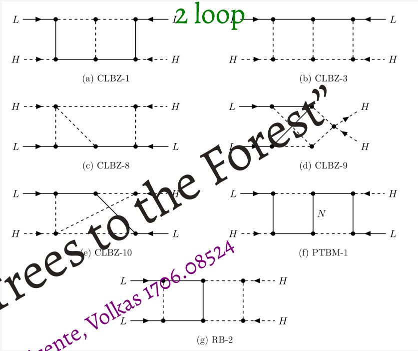
(c) T1-iii

(d) T3

(e) T4-2-i

(f) T4-3-i

2 loop



(a) CLBZ-1

(b) CLBZ-3

(c) CLBZ-8

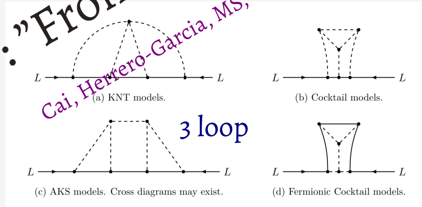
(d) CLBZ-9

(e) CLBZ-10

(f) PTBM-1

(g) RB-2

3 loop



(a) KNT models.

(b) Cocktail models.

(c) AKS models. Cross diagrams may exist.

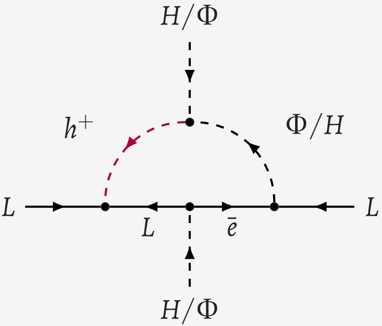
(d) Fermionic Cocktail models.

Loop level models: Examples [Zee, Cheng, Li, Babu]

Singly-charged scalar: $fLLh^+$

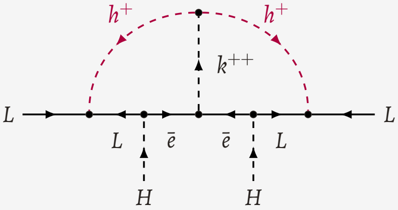
Zee model

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



Zee-Babu model

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



$\Delta L = 2$ EFT operators [Babu, Leung, De Gouvea, Jenkins]

Zee model Zee-Babu model

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

$$O_{4a} = L^i L^j Q_i^\dagger \bar{u}^\dagger H^k \epsilon_{jk} \qquad O_{4b} = L^i L^j Q_k^\dagger \bar{u}^\dagger H^k \epsilon_{ij} \qquad O_8 = L^i \bar{d} \bar{e}^\dagger \bar{u}^\dagger H^j \epsilon_{ij}$$

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

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

$$O_{12a} = L^i L^j Q_i^\dagger \bar{u}^\dagger Q_j^\dagger \bar{u}^\dagger \qquad O_{12b} = L^i L^j Q_k^\dagger \bar{u}^\dagger Q_l^\dagger \bar{u}^\dagger \epsilon_{ij} \epsilon^{kl}$$

$$\dots$$

$$O_{59} = L^i Q^j \bar{d} \bar{d} \bar{e}^\dagger \bar{u}^\dagger H^k H_i^\dagger \epsilon_{jk} \qquad O_{60} = L^i \bar{d} Q_j^\dagger \bar{u}^\dagger \bar{e}^\dagger \bar{u}^\dagger H^j H_i^\dagger$$

operators up to dimension 11 classified

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

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

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

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

Systematic construction of models

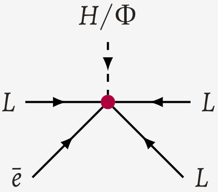
Angel, Rodd, Volkas 1212.5862; Cai, Clarke, MS, Volkas 1308.0463; Gargalionis, Volkas 2009.13537

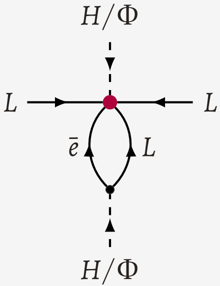
Bonnet, Hirsch, Ota, Winter 1204.5862; Aristizabal Sierra, Degee, Dorame, Hirsch 1411.7038; Cepedello, Fonseca, Hirsch 1807.00629

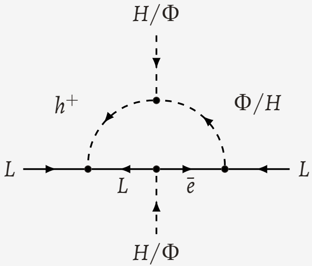
Gargalionis, Volkas 2009.13537: "exploding! $\Delta L = 2$ operators" ..."1000s of models"

$\longrightarrow$ a large number of models!

EFT estimate for $\mathcal{O}_2$







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

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