

A systematic approach to neutrino masses and their phenomenology

Beyond Standard Model: From Theory to Experiment – 30 March 2021

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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



Neutrino masses

- 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

Simplified models

Singly-charged scalar singlet

Conclusions

Majorana neutrino masses

- **Tree-level.** Only a few: seesaws I/II/III
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** at a given loop order (up to 3 loops)
 2. $\Delta L = 2$ **EFT operators** beyond Weinberg operatorsee review

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

Zee model Zee-Babu model

$$\begin{aligned}
 O_2 &= L^i L^j L^k \bar{e} H^l \epsilon_{ij} \epsilon_{kl} & O_{3a} &= L^i L^j Q^k \bar{d} H^l \epsilon_{ij} \epsilon_{kl} & O_{3a} &= L^i L^j Q^k \bar{d} H^l \epsilon_{ik} \epsilon_{jl} \\
 O_{4a} &= L^i L^j Q_i^\dagger \bar{u}^\dagger H^k \epsilon_{jk} & O_{4b} &= L^i L^j Q_k^\dagger \bar{u}^\dagger H^k \epsilon_{ij} & O_8 &= L^i \bar{d} e^\dagger \bar{u}^\dagger H^j \epsilon_{ij} \\
 O_9 &= L^i L^j L^k \bar{e} L^l \bar{e} \epsilon_{ij} \epsilon_{kl} & O_{10} &= L^i L^j L^k \bar{e} Q^l \bar{d} \epsilon_{ij} \epsilon_{kl} \\
 O_{11a} &= L^i L^j Q^k \bar{d} Q^l \bar{d} \epsilon_{ij} \epsilon_{kl} & O_{11b} &= L^i L^j Q^k \bar{d} Q^l \bar{d} \epsilon_{ik} \epsilon_{jl} \\
 O_{12a} &= L^i L^j Q_i^\dagger \bar{u}^\dagger Q_j^\dagger \bar{u}^\dagger & O_{12b} &= L^i L^j Q_k^\dagger \bar{u}^\dagger Q_l^\dagger \bar{u}^\dagger \epsilon_{ij} \epsilon^{kl} \\
 &\dots & & & & \\
 O_{59} &= L^i Q^j \bar{d} \bar{d} e^\dagger \bar{u}^\dagger H^k H_i^\dagger \epsilon_{jk} & O_{60} &= L^i \bar{d} Q_j^\dagger \bar{u}^\dagger e^\dagger \bar{u}^\dagger H^j H_i^\dagger
 \end{aligned}$$

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

$$m_\nu \simeq \frac{c_R v^2}{(16\pi^2)^l \Lambda}, \text{ with}$$

Loop factor

$$c_R \simeq \prod_i g_i \times \epsilon \times \left(\frac{v^2}{\Lambda^2} \right)^n$$

μ/Λ

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

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

→ 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"

→ a large number of models!

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MECHANISMS FOR NEUTRINO MASSES
○○●

SIMPLIFIED MODELS
○○○○○○○○

SINGLY-CHARGED SCALAR SINGLET
○○○○○

CONCLUSIONS
○○





Can we do better? → Hybrid approach using simplified models

Main idea

Juan Herrero-García, MS 1903.10552 [Eur.Phys.J. C79 (2019) no.11, 938]

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

Possible new particles

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

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

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

$$LH^\dagger \rightarrow \dots$$

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

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

...

Particles generating tree level neutrino masses

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

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

Seesaw type

	Particle	$\Delta\mathcal{L} = 0$	$ \Delta\mathcal{L} = 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	○	$\frac{y^2 v^2}{M}$	$M \lesssim 10^{15} \text{ GeV}$
	$\Delta \sim (1, 3, 1)_S^{-2,0}$	$y L\Delta L$	$\mu H\Delta^\dagger H$	II	\mathcal{O}_1	○	$\frac{y \mu v^2}{M^2}$	$M \lesssim 10^{15} \text{ GeV}$
	$\bar{\Sigma}_0 \sim (1, 3, 0)_F^{-1,0}$	$y \bar{\Sigma}_0 LH$	$M \bar{\Sigma}_0 \bar{\Sigma}_0$	III	\mathcal{O}_1	○	$\frac{y^2 v^2}{M}$	$M \lesssim 10^{15} \text{ GeV}$
	$L_1 \sim (1, 2, -1/2)_F^{1,0}$	$m \bar{L}_1 L$	$\frac{c}{\Lambda} L_1 HLH$		\mathcal{O}_1	○	$\frac{c m}{M} \frac{v^2}{\Lambda} \mathbf{c}$	$M \lesssim 10^{15} \text{ GeV}$

Particles generating loop level neutrino masses

Zee-Babu

Zee **Loop order**

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

Particles with B (leptoquarks)

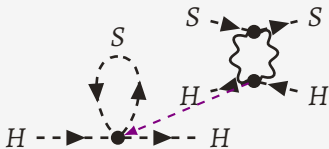
$X \sim (SU(3)_c, SU(2)_L, U(1)_Y)_{S/F/V}^{L,3B} \quad \Delta L = 2 \text{ operators} \quad \text{Loop order}$

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

Radiative

Higgs naturalness

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



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



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



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

Naturalness limits much stronger, but less robust

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

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

S_1 cannot generate neutrino masses without imposing B conservation.

Phenomenology

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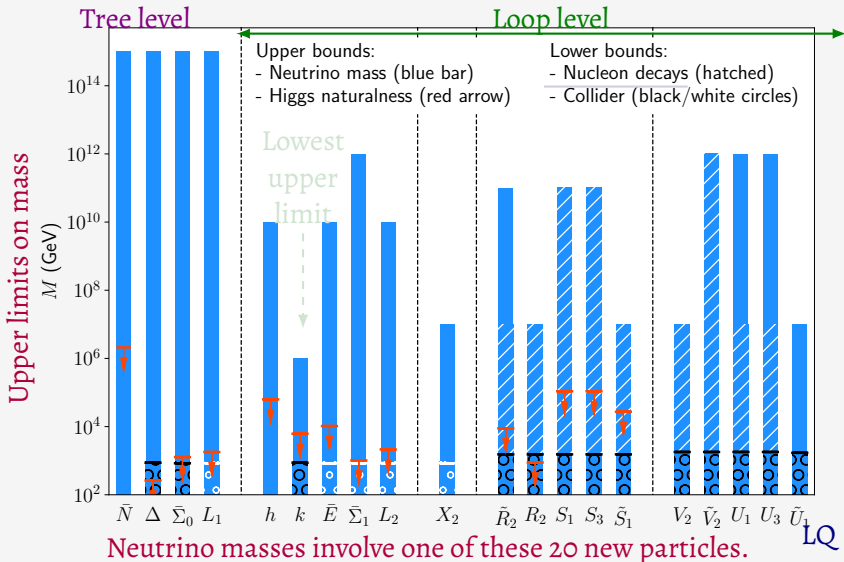
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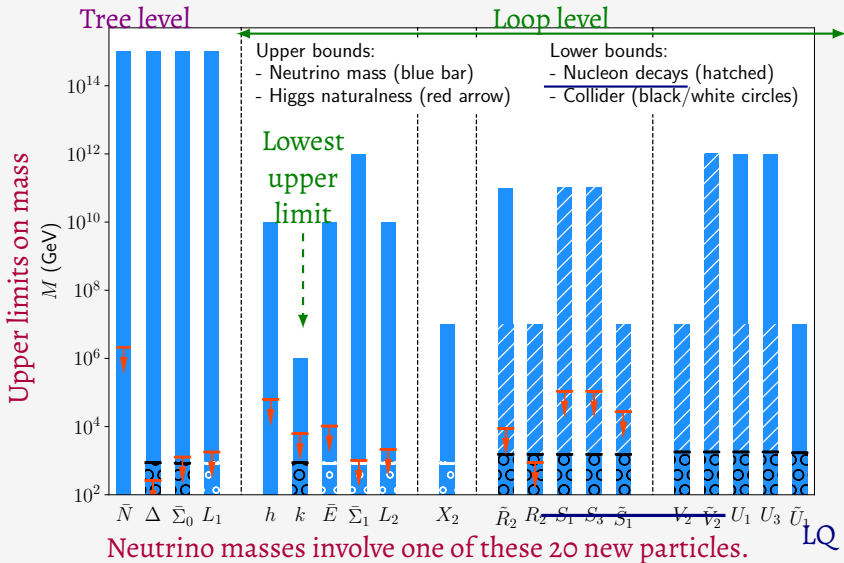
Summary plot

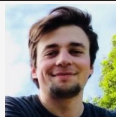
Juan Herrero-García, MS 1903.10552 [Eur.Phys.J. C79 (2019) no.11, 938]



Summary plot

Juan Herrero-García, MS 1903.10552 [Eur.Phys.J. C79 (2019) no.11, 938]



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

Tobias Felkl



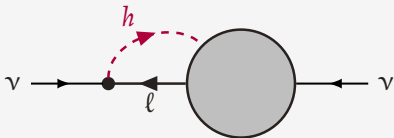
Juan Herrero-García

- 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

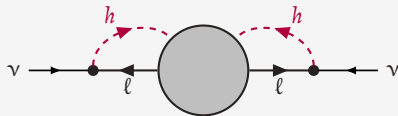


$$M_\nu = X y_h - y_h X^T$$

⇒ 1 complex condition

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

quadratic case



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

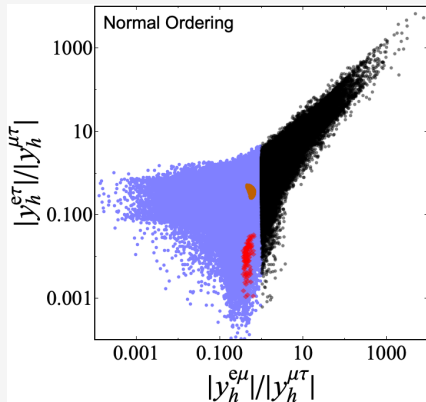
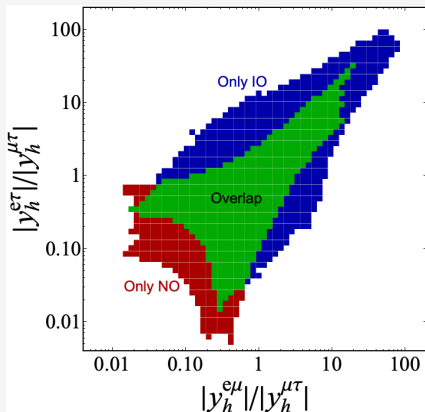
⇒ 2 complex conditions

previously discussed in Zee-Babu model 0711.0483

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

Yukawa couplings

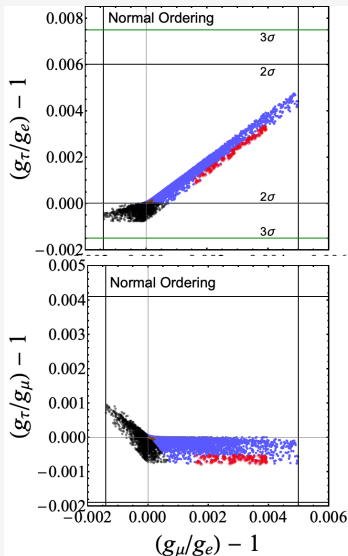
Tobias Felkl, Juan Herrero-García, MS 2102.09898



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

Lepton flavour universality

Tobias Felkl, Juan Herrero-García, MS 2102.09898



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

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

Effective leptonic gauge couplings

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

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

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

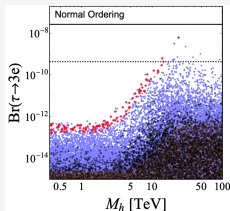
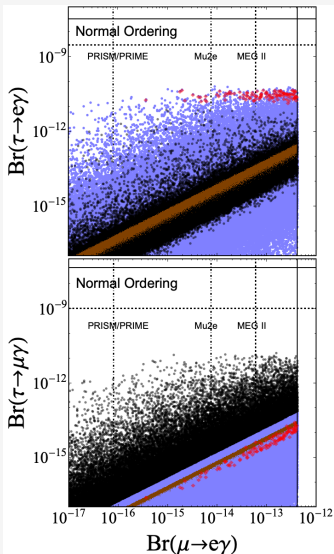
- Linear case: blue (2σ), black (3σ)
- Quadratic case: brown
- Anomalies ($\frac{g_{\mu,\tau}}{g_e}$, Cabibbo angle): red

Lepton flavour violation

Tobias Felkl, Juan Herrero-García, MS 2102.09898

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

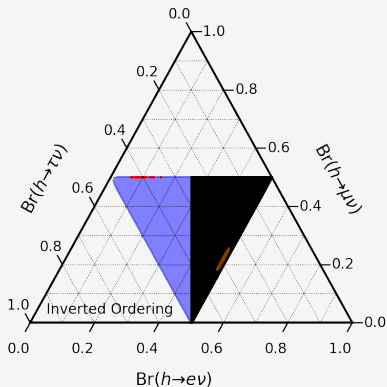
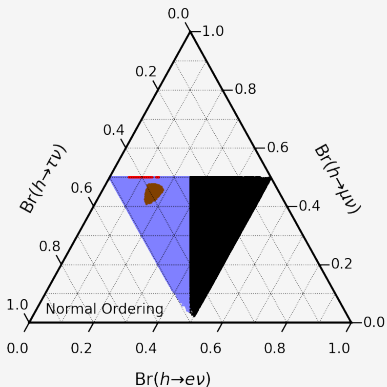
- Photon penguin dominance
- Box diagrams important for $M_h \gtrsim 5$ TeV



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

Branching ratios

Tobias Felkl, Juan Herrero-García, MS 2102.09898



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

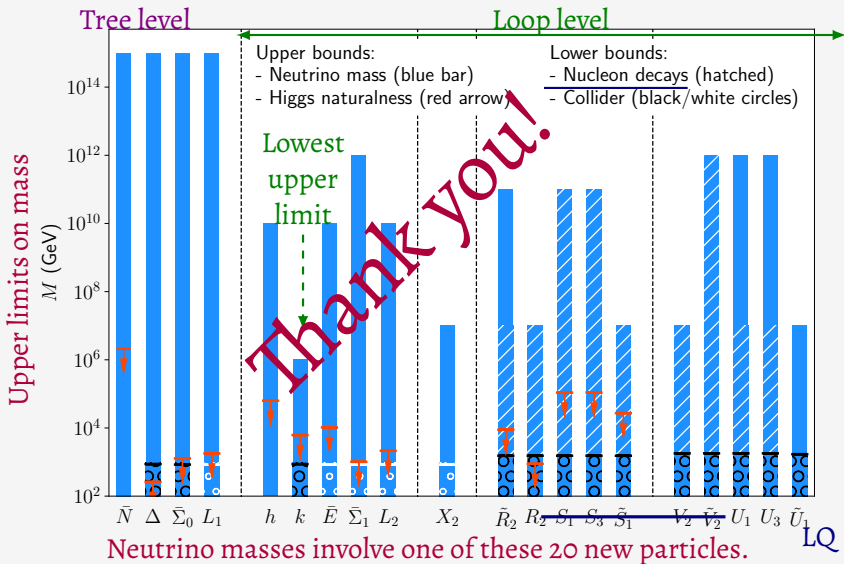
- Linear case: blue (2σ), black (3σ)
- Quadratic case: brown
- Anomalies ($\frac{g^{\mu,\tau}}{g_e}$, Cabibbo angle): red

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.
- **Model-independent results** for neutrino masses from singly-charged scalar singlet $h \sim (1, 1, 1)$

Summary plot

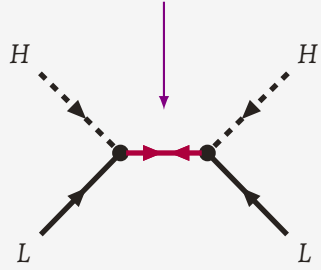
Juan Herrero-García, MS 1903.10552 [Eur.Phys.J. C79 (2019) no.11, 938]



Backup slides

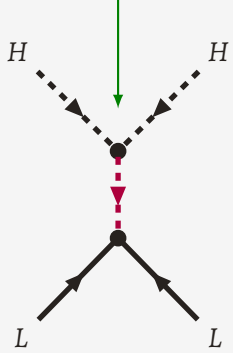
Tree level: seesaws

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



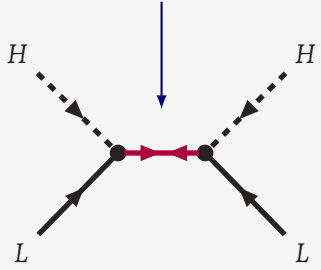
Minkowski; Yanagida; Glashow;
 Gell-Mann, Ramond, Slansky;
 Mohapatra, Senjanovic.

SS II: $\Delta \sim (1, 2, 1)$
 $yL\Delta L + \mu H\Delta^\dagger H$



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

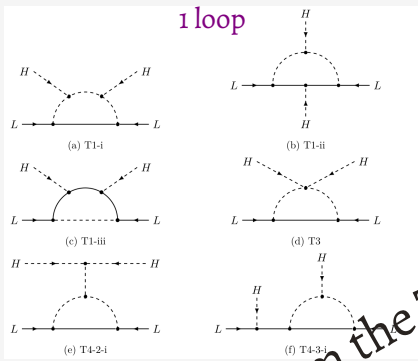
SS III: $\bar{\Sigma} \sim (1, 3, 0)$
 $yLH\bar{\Sigma} + m\bar{\Sigma}\bar{\Sigma}$



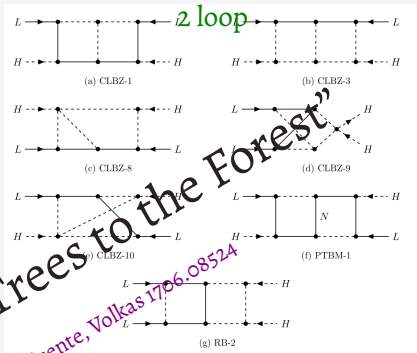
Foot, Lew, He, Joshi.

Loop level models

1 loop

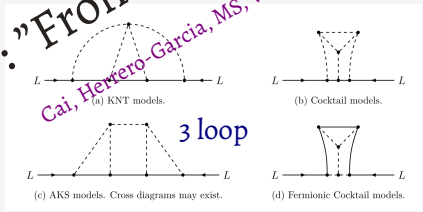


2 loop



Review: "From the Trees to the Forest"
 Cai, Herrero-Garcia, MS, Vicente, Volkas 1706.08524

3 loop



(c) AKS models. Cross diagrams may exist.

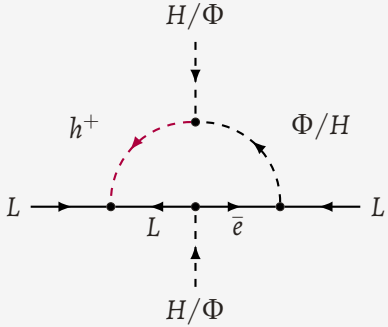
(d) Fermionic Cocktail models.

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

Singly-charged scalar: $fLLh^+$

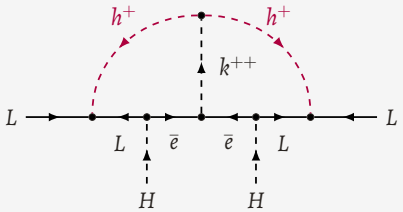
Zee model

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

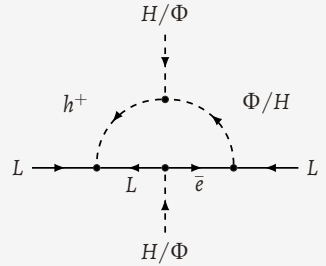
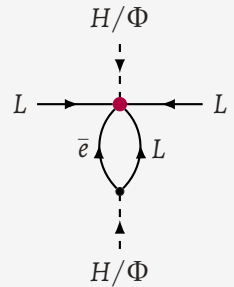
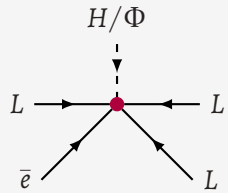


Zee-Babu model

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



EFT estimate for \mathcal{O}_2



Operator

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

Estimate

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

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

UV model: Zee

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

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 **phenomenology** without going to a specific model?

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

Constraints for quadratic case

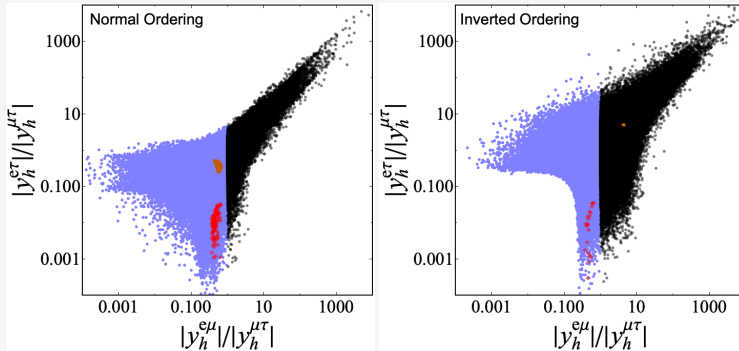
Normal ordering

$$\frac{y_h^{e\tau}}{y_h^{\mu\tau}} = \tan(\theta_{12}) \frac{\cos(\theta_{23})}{\cos(\theta_{13})} + \tan(\theta_{13}) \sin(\theta_{23}) e^{i\delta},$$
$$\frac{y_h^{e\mu}}{y_h^{\mu\tau}} = \tan(\theta_{12}) \frac{\sin(\theta_{23})}{\cos(\theta_{13})} - \tan(\theta_{13}) \cos(\theta_{23}) e^{i\delta}$$

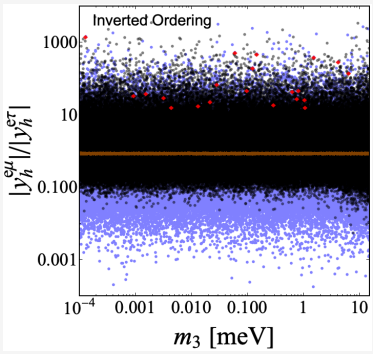
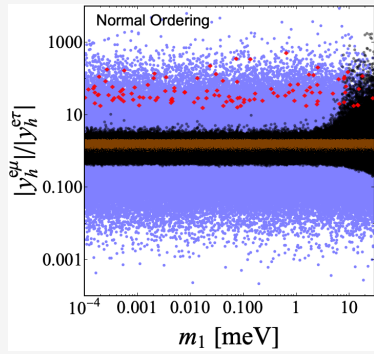
Inverted ordering

$$\frac{y_h^{e\tau}}{y_h^{\mu\tau}} = -\frac{\sin(\theta_{23})}{\tan(\theta_{13})} e^{i\delta},$$
$$\frac{y_h^{e\mu}}{y_h^{\mu\tau}} = \frac{\cos(\theta_{23})}{\tan(\theta_{13})} e^{i\delta}$$

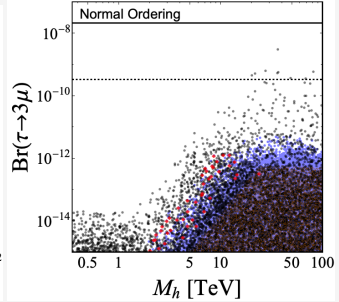
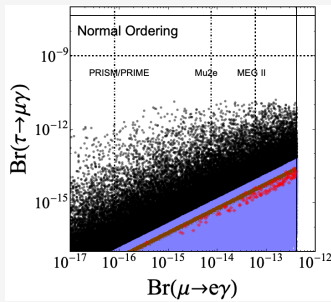
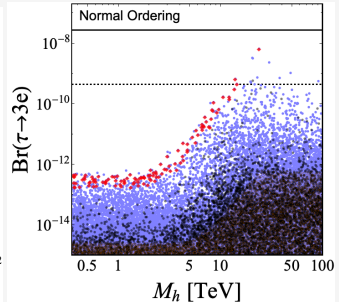
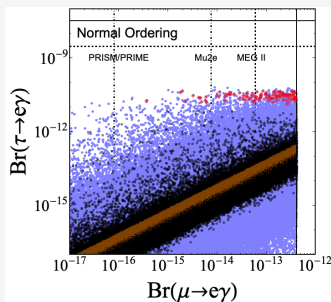
Yukawa couplings



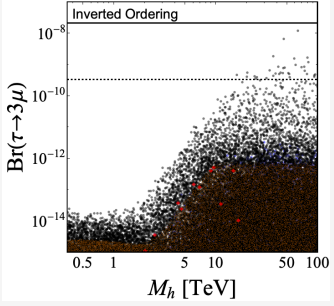
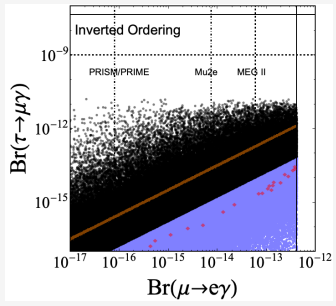
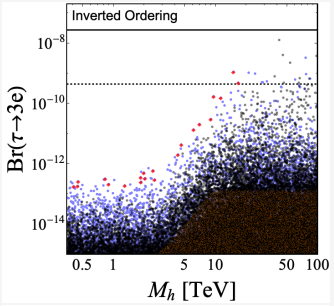
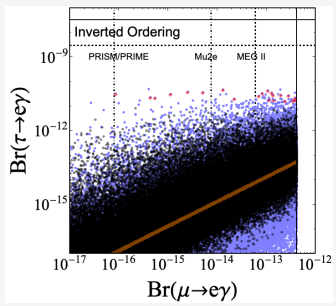
Yukawa couplings vs mass



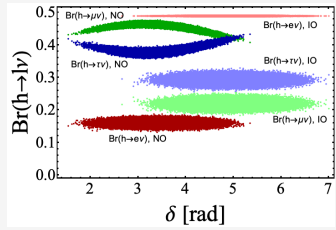
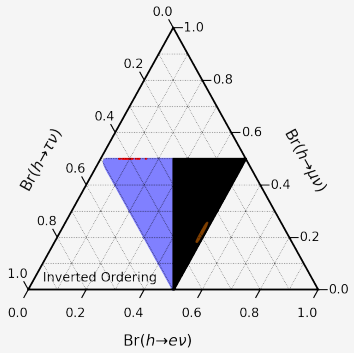
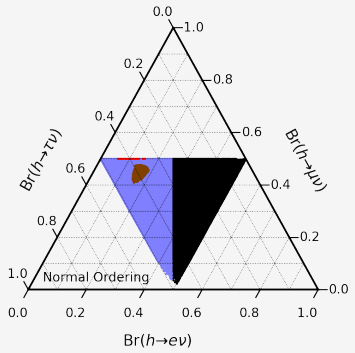
LFV – NO



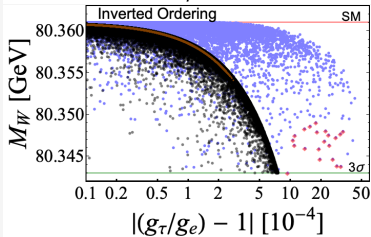
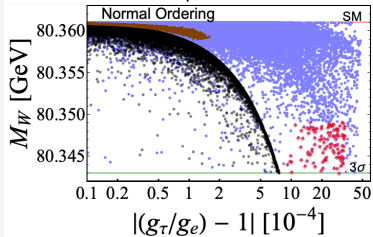
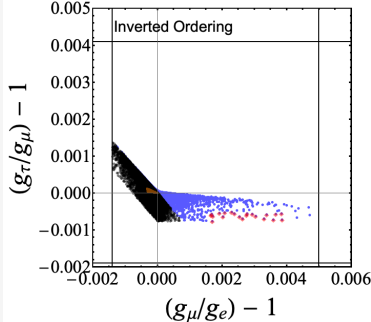
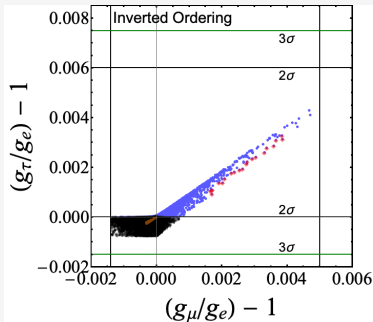
LFV – IO



Branching ratios



LFU - m_W



NSI

