The Singly-Charged Scalar Singlet as the Origin of Neutrino Masses

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XIV International Workshop on Interconnections between Particle Physics and Cosmology - 19 May 2021
Based on e-Print 2102.09898

UNSW SYDNEY

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Add singly-charged scalar singlet $h \sim (1,1,1)$ to the SM.

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$$\mathcal{L} = \mathcal{L}_{\text{SM}} - h^*(D^\mu D_\mu + M_h)h - (y_h^{ij} L_i L_j h + \text{h.c.})$$

Continuous global $U(1)$ symmetry: Lepton number. $L_i \sim 1$, $\bar{e}_i \sim -1$, $h \sim -2$.

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Antisymmetric coupling matrix: $$y_h = \begin{pmatrix} 0 & y_h^{e\mu} & y_h^{e\tau} \\ -y_h^{e\mu} & 0 & y_h^{\mu\tau} \\ -y_h^{e\tau} & -y_h^{\mu\tau} & 0 \end{pmatrix}$$

$\rightarrow$ Eigenvector $v_h = (y_h^{\mu\tau}, -y_h^{e\tau}, y_h^{e\mu})^T$ with eigenvalue zero, $y_h v_h = 0$.

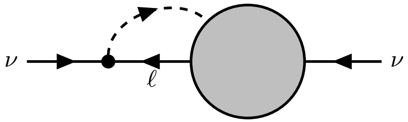
Singly-Charged Scalar Singlet

Assumption: *At least one of the external neutrinos couples via y_h when the main contribution to neutrino masses is generated.*

- One external neutrino: **Linear case**.
- Both external neutrinos: **Quadratic case**.

Neutrino Mass Matrix: Linear Case

Eigenvector $v_h = (y_h^{\mu\tau}, -y_h^{e\tau}, y_h^{e\mu})^T$ with eigenvalue zero, $y_h v_h = 0$.



Most general form of neutrino mass matrix: $M_\nu = U^* m_{\text{diag}} U^\dagger = X y_h - y_h X^T$

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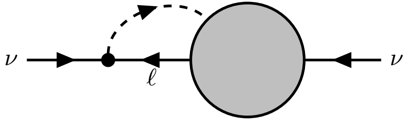


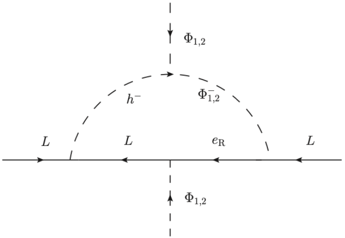
Most general form of neutrino mass matrix: $M_\nu = U^* m_{\text{diag}} U^\dagger = X y_h - y_h X^T$
$\rightarrow$ All three neutrinos in general massive.

$$\Rightarrow \quad \mathbf{v_h^T U^* m_{\text{diag}} U^\dagger v_h = 0}$$

Neutrino Mass Matrix: Linear Case

Example: Effective dim-5 operator $\frac{c^{ij}}{\Lambda} h^* \bar{e}_i L_j H + \text{h.c.}$ which violates LN

$\Rightarrow M_\nu \approx \frac{v^2}{(4\pi)^2\Lambda} \left(c\, y_e\, y_h - y_h y_e\, c^T\right)$



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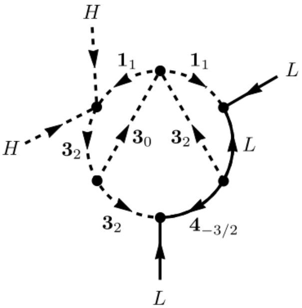
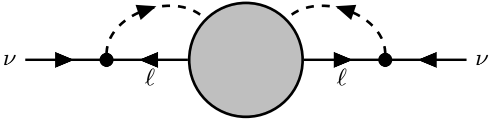


Cepedello, Hirsch, Helo, JHEP 07, 079 (2017)

Neutrino Mass Matrix: Quadratic Case

Eigenvector $v_h = (y_h^{\mu\tau}, -y_h^{e\tau}, y_h^{e\mu})^T$ with eigenvalue zero, $y_h v_h = 0$.



Most general form of neutrino mass matrix: $M_\nu = U^* m_{\text{diag}} U^\dagger = y_h S y_h$

Neutrino Mass Matrix: Quadratic Case

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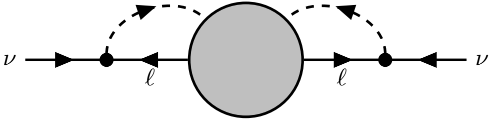


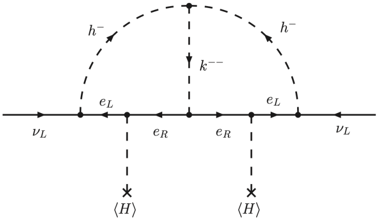
Most general form of neutrino mass matrix: $M_\nu = U^* m_{\text{diag}} U^\dagger = y_h S y_h$
$\rightarrow$ One neutrino remains massless.

$$\Rightarrow \quad \mathbf{m}_{\text{diag}} \mathbf{U}^\dagger \mathbf{v_h} = \mathbf{0}$$

Neutrino Mass Matrix: Quadratic Case

Example: Effective dim-5 operator $\frac{d^{ij}}{\Lambda}(h^*)^2 \bar{e}_i \bar{e}_j + \text{h.c.}$ which violates LN

$\Rightarrow M_\nu \approx \frac{v^2}{(4\pi)^4 \Lambda} y_h \, y_e \, d \, y_e \, y_h$



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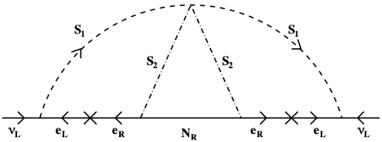

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Neutrino-Mass Constraint

Eigenvector $v_h = (y_h^{\mu\tau}, -y_h^{e\tau}, y_h^{e\mu})^T$ with eigenvalue zero, $y_h v_h = 0$.

Derived constraints:

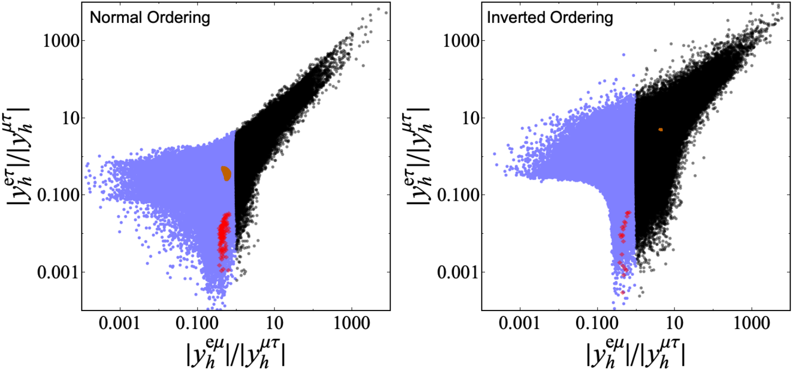
$$\mathbf{v_h^T U^* m_{diag} U^\dagger v_h = 0}, \quad \text{Linear case. (One complex expression)}$$

$$\mathbf{m_{diag} U^\dagger v_h = 0}, \quad \text{Quadratic case. (Two complex expressions)}$$

They ...

- ... directly relate the couplings y_h^{ij} to measured neutrino data.
- ... provide a *necessary condition* for the correct description of neutrino masses in the SM extended by h.
- ... are independent of the mechanism of lepton-number breaking.

Solution to the Neutrino-Mass Constraints



Neutrino-mass constraints shape available parameter space for y_h^{ij} non-trivially.

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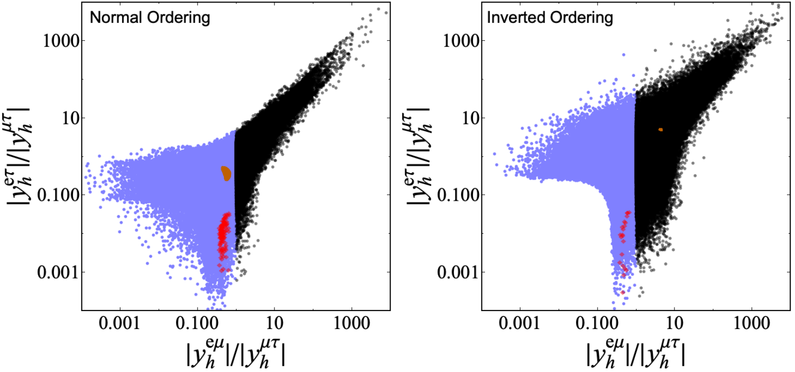

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- Quadratic case (brown): **Very predictive**, stringently constrained.

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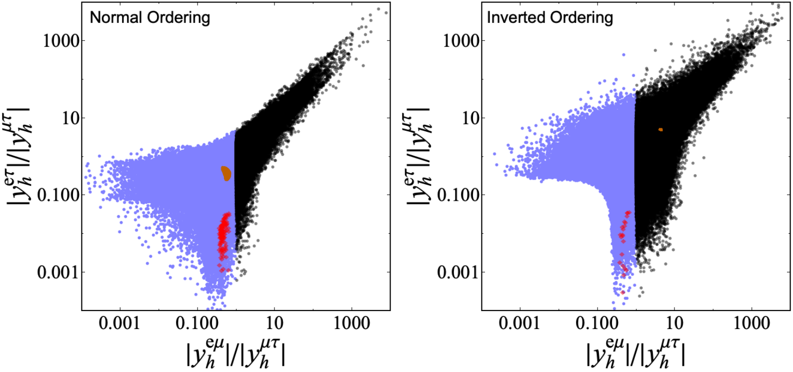

Neutrino-mass constraints shape available parameter space for y_h^{ij} non-trivially.

- Quadratic case (brown): **Very predictive**, stringently constrained.
- Linear case (blue, black): **Less predictive**, but **simultaneous explanation of LFU anomalies** (V_{us}^{CKM}, $\Gamma(l_i \to l_j \bar{\nu}\nu)$; in red) at 1σ possible.

Conclusions

Assumption: Neutrino masses generated via a singly-charged scalar singlet.
$\rightarrow$ **Model-independent constraints** for couplings y_h^{ij} in terms of neutrino data.

Discussion of *two distinct structures* of the neutrino mass matrix:

- *Linear case*: **Zee Model** and variants, ...
- *Quadratic case*: **Zee-Babu Model**, **Krauss-Nasri-Trodden Model** and their variants, ...

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The singly-charged scalar singlet as the origin of neutrino masses.
J. High Energ. Phys. 2021, 122 (2021). arxiv: e-Print 2102.09898

Thank you for attending the talk!

Back-Up

Conventions for the Neutrino Sector

Neutrino mass eigenstates ν_i and flavour eigenstates related ν_α via

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i} \nu_i . \tag{1}$$

PMNS matrix:

$$U = P U_{23} U_{13} U_{12} U_{\text{Maj}} \tag{2}$$

with

$$U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}, \quad U_{13} = \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix}, \tag{3}$$

$$U_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{4}$$

$U_{\text{Maj}} \equiv \text{diag}(e^{i\eta_1}, e^{i\eta_2}, 1)$ and $P = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, e^{i\alpha_3})$.

Conventions for the Neutrino Sector

Squared-mass differences $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$:

$$m_1 = m_0, \quad m_2 = \sqrt{\Delta m_{21}^2 + m_0^2}, \quad m_3 = \sqrt{\Delta m_{31}^2 + m_0^2} \tag{5}$$

in the case of Normal Ordering (NO) $m_1 < m_2 \ll m_3$, and

$$m_1 = \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2}, \quad m_2 = \sqrt{|\Delta m_{32}^2| + m_0^2}, \quad m_3 = m_0 \tag{6}$$

in the case of Inverted Ordering (IO) $m_3 \ll m_1 < m_2$.

Constraint in the Linear Case

$$\Bigg(\Big(c_{13}^2 m_3 c_{23}^2 + e^{-2i\eta_2} m_2 \left(e^{-i\delta} c_{23} s_{12} s_{13} + c_{12} s_{23}\right)^2 + e^{-2i\eta_1} m_1 \left(e^{-i\delta} c_{12} c_{23} s_{13} - s_{12} s_{23}\right)^2 \Big) y_h^{e\mu}$$

$$- \Big(c_{23} m_3 s_{23} c_{13}^2 + e^{-2i\eta_1} m_1 \left(e^{-i\delta} c_{12} c_{23} s_{13} - s_{12} s_{23}\right) \left(c_{23} s_{12} + e^{-i\delta} c_{12} s_{13} s_{23}\right)$$

$$- e^{-2i\eta_2} m_2 \left(e^{-i\delta} c_{23} s_{12} s_{13} + c_{12} s_{23}\right) \left(c_{12} c_{23} - e^{-i\delta} s_{12} s_{13} s_{23}\right) \Big) y_h^{e\tau}$$

$$+ c_{13} \Big(e^{i\delta} c_{23} m_3 s_{13} - e^{-2i\eta_2} m_2 s_{12} \left(e^{-i\delta} c_{23} s_{12} s_{13} + c_{12} s_{23}\right)$$

$$+ e^{-2i\eta_1} c_{12} m_1 \left(s_{12} s_{23} - e^{-i\delta} c_{12} c_{23} s_{13}\right) \Big) y_h^{\mu\tau} \Bigg) y_h^{e\mu}$$

$$- \Bigg(\Big(c_{23} m_3 s_{23} c_{13}^2 + e^{-2i\eta_1} m_1 \left(e^{-i\delta} c_{12} c_{23} s_{13} - s_{12} s_{23}\right) \left(c_{23} s_{12} + e^{-i\delta} c_{12} s_{13} s_{23}\right)$$

$$- e^{-2i\eta_2} m_2 \left(e^{-i\delta} c_{23} s_{12} s_{13} + c_{12} s_{23}\right) \left(c_{12} c_{23} - e^{-i\delta} s_{12} s_{13} s_{23}\right) \Big) y_h^{e\mu}$$

$$- \Big(c_{13}^2 m_3 s_{23}^2 + e^{-2i\eta_1} m_1 \left(c_{23} s_{12} + e^{-i\delta} c_{12} s_{13} s_{23}\right)^2 + e^{-2i\eta_2} m_2 \left(c_{12} c_{23} - e^{-i\delta} s_{12} s_{13} s_{23}\right)^2 \Big) y_h^{e\tau}$$

$$- e^{i\delta} c_{13} \Big(e^{-2i(\delta+\eta_1)} m_1 s_{13} s_{23} c_{12}^2 + e^{-i\delta} c_{23} \left(e^{-2i\eta_1} m_1 - e^{-2i\eta_2} m_2\right) s_{12} c_{12}$$

$$- \left(m_3 - e^{-2i(\delta+\eta_2)} m_2 s_{12}^2\right) s_{13} s_{23} \Big) y_h^{\mu\tau} \Bigg) y_h^{e\tau} + \Bigg(c_{13} \Big(e^{i\delta} c_{23} m_3 s_{13} - e^{-2i\eta_2} m_2 s_{12} \left(e^{-i\delta} c_{23} s_{12} s_{13} + c_{12} s_{23}\right)$$

$$+ e^{-2i\eta_1} c_{12} m_1 \left(s_{12} s_{23} - e^{-i\delta} c_{12} c_{23} s_{13}\right) \Big) y_h^{e\mu}$$

$$+ e^{i\delta} c_{13} \Big(e^{-2i(\delta+\eta_1)} m_1 s_{13} s_{23} c_{12}^2 + e^{-i\delta} c_{23} \left(e^{-2i\eta_1} m_1 - e^{-2i\eta_2} m_2\right) s_{12} c_{12}$$

$$- \left(m_3 - e^{-2i(\delta+\eta_2)} m_2 s_{12}^2\right) s_{13} s_{23} \Big) y_h^{e\tau} + \left(e^{-2i\eta_2} m_2 s_{12}^2 c_{13}^2 + e^{-2i\eta_1} c_{12}^2 m_1 c_{13}^2 + e^{2i\delta} m_3 s_{13}^2 \right) y_h^{\mu\tau} \Bigg) y_h^{\mu\tau} = 0$$

Constraint in the Quadratic Case

Normal Ordering:

$$\frac{y_h^{e\tau}}{y_h^{\mu\tau}} = \tan(\theta_{12})\frac{\cos(\theta_{23})}{\cos(\theta_{13})} + \tan(\theta_{13})\sin(\theta_{23})e^{i\delta}, \tag{7}$$

$$\frac{y_h^{e\mu}}{y_h^{\mu\tau}} = \tan(\theta_{12})\frac{\sin(\theta_{23})}{\cos(\theta_{13})} - \tan(\theta_{13})\cos(\theta_{23})e^{i\delta} \tag{8}$$

Inverted Ordering:

$$\frac{y_h^{e\tau}}{y_h^{\mu\tau}} = -\frac{\sin(\theta_{23})}{\tan(\theta_{13})}e^{i\delta}, \tag{9}$$

$$\frac{y_h^{e\mu}}{y_h^{\mu\tau}} = \frac{\cos(\theta_{23})}{\tan(\theta_{13})}e^{i\delta} \tag{10}$$

Input values

m_e [keV]	m_μ [MeV]	m_τ [GeV]	G_F [$\frac{1}{\text{GeV}^2}$]	α_{EM}^{-1}	M_Z [GeV]
510.9989	105.6584	1.777	$1.166\,38 \times 10^{-5}$	137.035999	91.1535

	Δm^2_{3l} [10^{-3} eV^2]	Δm^2_{21} [10^{-5} eV^2]	δ [rad]
NO	2.517 ± 0.026	7.42 ± 0.20	3.44 ± 0.42
IO	-2.498 ± 0.028	7.42 ± 0.20	4.92 ± 0.45
	$\sin^2(\theta_{12})$	$\sin^2(\theta_{13})$	$\sin^2(\theta_{23})$
NO	0.304 ± 0.012	$0.022\,19 \pm 0.000\,62$	0.573 ± 0.016
IO	0.304 ± 0.012	$0.022\,38 \pm 0.000\,62$	0.575 ± 0.016

	$\lvert y_h^{ij} \rvert$	$\arg(y_h^{ei})$	$\arg(y_h^{\mu\tau})$	m_0 [meV]	$\eta_{1,2}$ [rad]	M_h [GeV]
Prior	Log-Flat	Flat	Fixed	Log-Flat	Flat	Log-Flat
Range	$[10^{-4}, 2\pi]$	$[0, 2\pi]$	0	$[10^{-4}, 30]$ (NO) $[10^{-4}, 15]$ (IO)	$[0, \pi]$	$[350, 10^5]$

$\Delta m^2_{31} > 0$ for NO, and $\Delta m^2_{32} < 0$ for IO.

Zyla et al. (PDG), PTEP 2020, 083C01 (2020)
Freitas, 2020

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2020

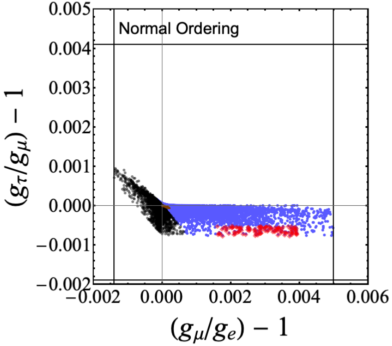
Observables

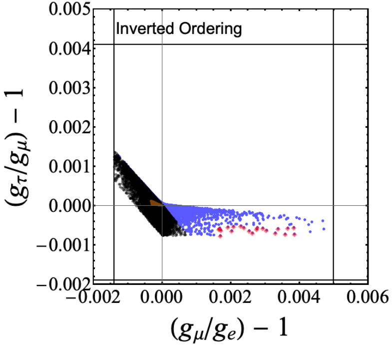
Observable	Experiment: Current Bound	Experiment: Future Sensitivity	Scan: Max. NO	Scan: Max. IO
$\mathrm{Br}(\mu \to e\gamma)$	4.2×10^{-13} (90% CL)	6×10^{-14}	4.2×10^{-13}	4.2×10^{-13}
$\mathrm{Br}(\tau \to e\gamma)$	3.3×10^{-8} (90% CL)	3×10^{-9}	6.4×10^{-11}	4.9×10^{-11}
$\mathrm{Br}(\tau \to \mu\gamma)$	4.4×10^{-8} (90% CL)	10^{-9}	1.6×10^{-11}	1.6×10^{-11}
$\mathrm{Br}(\mu \to 3e)$	10^{-12} (90% CL)	10^{-16}	10^{-12}	10^{-12}
$\mathrm{Br}(\tau \to 3e)$	2.7×10^{-8} (90% CL)	4.3×10^{-10}	6.6×10^{-9}	1.3×10^{-8}
$\mathrm{Br}(\tau \to 3\mu)$	2.1×10^{-8} (90% CL)	3.3×10^{-10}	3.0×10^{-9}	1.2×10^{-8}
$\lvert g_\mu / g_e \rvert$	[0.9986, 1.0050] (2σ)		1.0050	1.0047
$\lvert g_\tau / g_\mu \rvert$	[0.9981, 1.0041] (2σ)		1.0009	1.0014
$\lvert g_\tau / g_e \rvert$	[1.0000, 1.0060] (2σ) [0.9985, 1.0075] (3σ)		1.0048	1.0043
$\lvert \delta M_W \rvert$[GeV]	0.018 (3σ)		0.018	0.018

Baldini et al. (MEG), Eur. Phys. J. C 76, 434 (2016)
Baldini et al. (MEG II), Eur. Phys. J. C 78, 380 (2018)
Aubert et al. (BaBar), Phys. Rev. Lett. 104, 021802 (2010)
Altmannshofer et al. (Belle-II), PTEP 2019, 123C01 (2019)
Bellgardt et al. (SINDRUM), Nucl. Phys. B 299, 1-6 (1988)
Arndt et al. (Mu3e), 2020
Hayasaka et al., Phys. Lett. B 687, 139-143 (2010)
Gersabeck, Pich, Comptes Rendus Physique 21, 75-92 (2020)

Zyla et al. (PDG), PTEP 2020, 083C01

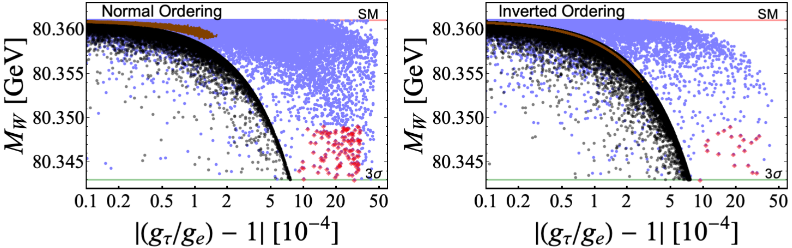
Universality of Leptonic Gauge Couplings





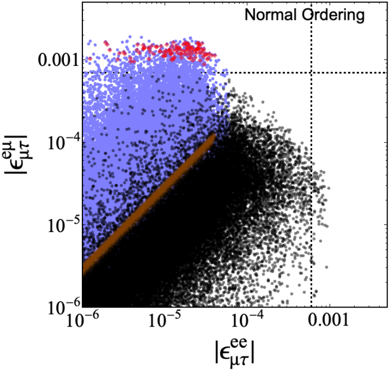
W-Boson Mass

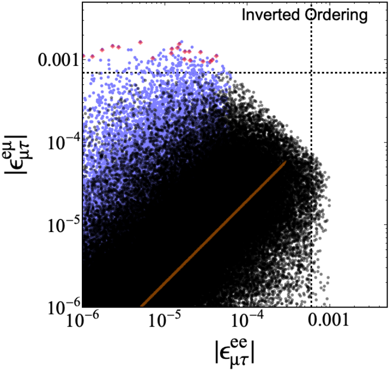
$$\delta M_W^2 = -\frac{M_W^2}{\sqrt{2}G_F}\left|1 - \frac{M_W M_Z}{2M_W^2 - M_Z^2}\right| \frac{|y_h^{e\mu}|^2}{M_h^2} \qquad (11)$$



Leptonic Non-Standard Interactions

$$\epsilon_{\tau e}^{e\mu} \equiv \frac{(y_h^{e\tau})^* y_h^{e\mu}}{\sqrt{2} G_F M_h^2} = -(\epsilon_{\mu\tau}^{ee})^*, \qquad \epsilon_{\mu\tau}^{e\mu} \equiv -\frac{(y_h^{e\mu})^* y_h^{\mu\tau}}{\sqrt{2} G_F M_h^2} \tag{12}$$



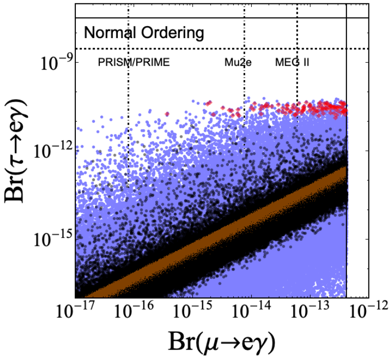


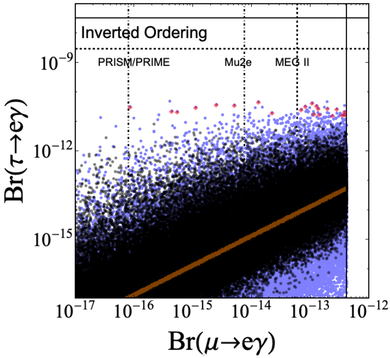
Radiative Charged-Lepton Decay

$$\text{Br}(\mu \to e\gamma) = \text{Br}(\mu \to e\nu\bar{\nu}) \frac{\alpha_{\text{EM}}}{48\pi G_F^2} \frac{|y_h^{e\tau} y_h^{\mu\tau}|^2}{M_h^4}, \quad (13)$$

$$\text{Br}(\tau \to e\gamma) = \text{Br}(\tau \to e\nu\bar{\nu}) \frac{\alpha_{\text{EM}}}{48\pi G_F^2} \frac{|y_h^{e\mu} y_h^{\mu\tau}|^2}{M_h^4}, \quad (14)$$

$$\text{Br}(\tau \to \mu\gamma) = \text{Br}(\tau \to \mu\nu\bar{\nu}) \frac{\alpha_{\text{EM}}}{48\pi G_F^2} \frac{|y_h^{e\mu} y_h^{e\tau}|^2}{M_h^4} \quad (15)$$





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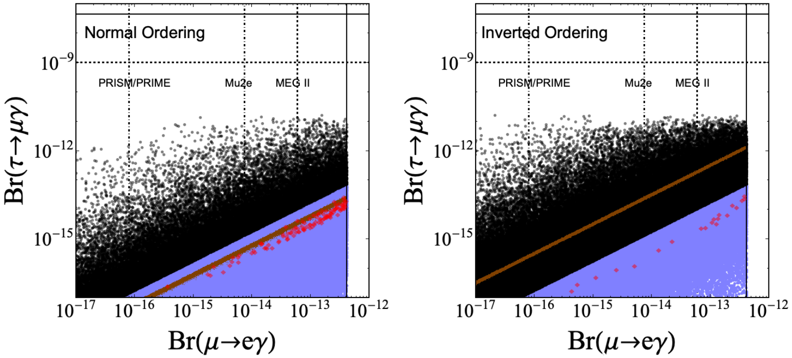
$$\mathrm{Br}(\tau \to e\gamma) = \mathrm{Br}(\tau \to e\nu\bar{\nu}) \frac{\alpha_{\mathrm{EM}}}{48\pi G_F^2} \frac{|y_h^{e\mu} y_h^{\mu\tau}|^2}{M_h^4}, \quad (17)$$

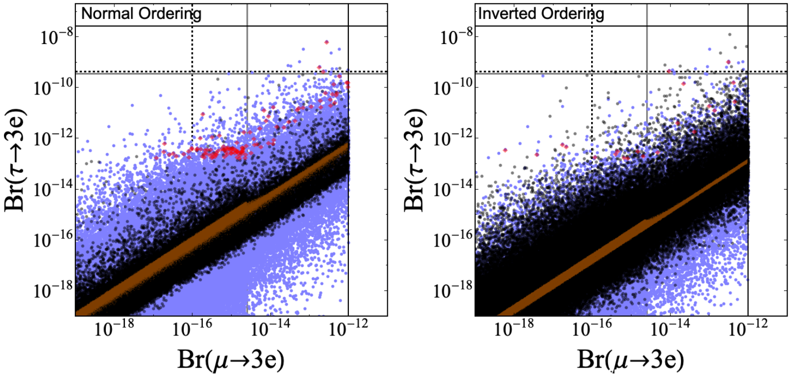
$$\mathrm{Br}(\tau \to \mu\gamma) = \mathrm{Br}(\tau \to \mu\nu\bar{\nu}) \frac{\alpha_{\mathrm{EM}}}{48\pi G_F^2} \frac{|y_h^{e\mu} y_h^{e\tau}|^2}{M_h^4} \quad (18)$$



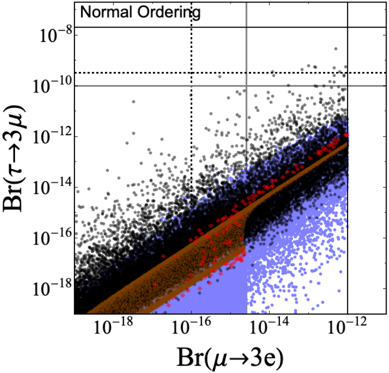
Tri-Lepton Decays of Charged Leptons

$$\mathrm{Br}(\tau \to 3e) = \frac{e^2\, m_\tau^3}{192\,\pi^3\,\Gamma_\tau}\,|c_R^{e\tau}|^2\left(4\log\left[\frac{m_\tau^2}{m_e^2}\right] - 11\right)$$
$$+ \frac{m_\tau^5}{3072\,\pi^3\,\Gamma_\tau}\left(\left|\left(|\xi_{12}|^2 + |\xi_{13}|^2\right)\frac{\xi_{12}^*\,\xi_{23}}{32\,\pi^2\,m_\phi^2} + \frac{e^2}{288\,\pi^2}\frac{\xi_{12}^*\,\xi_{23}}{m_\phi^2}\right|^2 + \left|\frac{e^2}{288\,\pi^2}\frac{\xi_{12}^*\,\xi_{23}}{m_\phi^2}\right|^2\right)$$
$$+ \frac{e\,m_\tau^4}{384\,\pi^3\,\Gamma_\tau}\left(2\left(|\xi_{12}|^2 + |\xi_{13}|^2\right)\frac{\mathrm{Re}\left(c_R^{e\tau}\,\xi_{12}\,\xi_{23}^*\right)}{32\,\pi^2\,m_\phi^2} + \frac{3e^2}{288\,\pi^2}\frac{\mathrm{Re}\left(c_R^{e\tau}\,\xi_{12}\,\xi_{23}^*\right)}{m_\phi^2}\right),$$

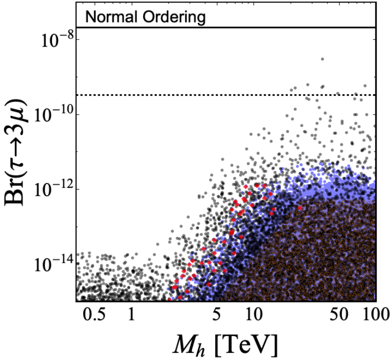
Crivellin, Kirk, Manzari, Panizzi, 2020

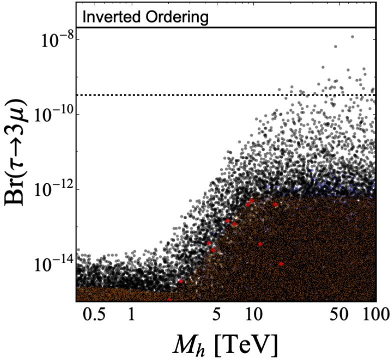


Tri-Lepton Decays of Charged Leptons

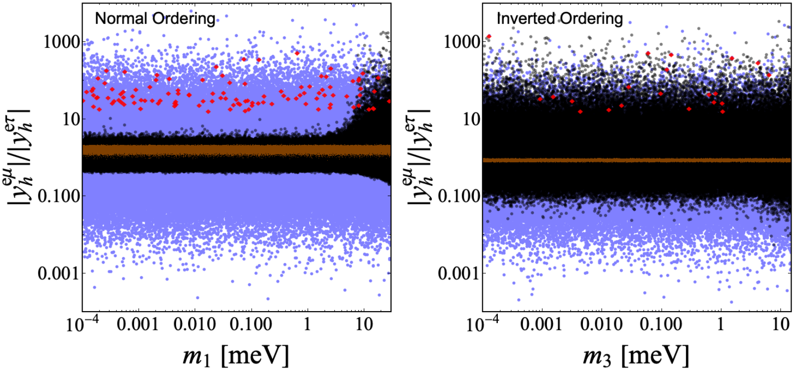


Tri-Lepton Decays of Charged Leptons





Coupling Magnitudes



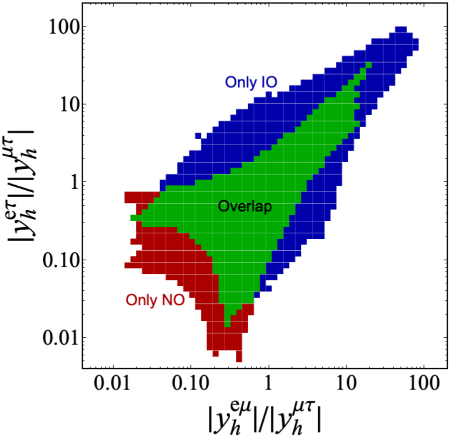
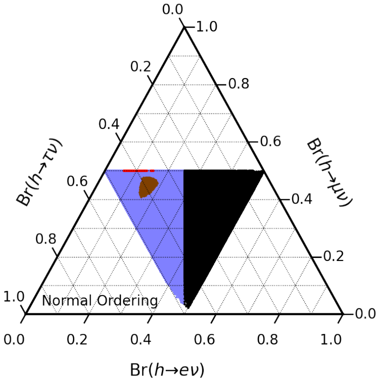
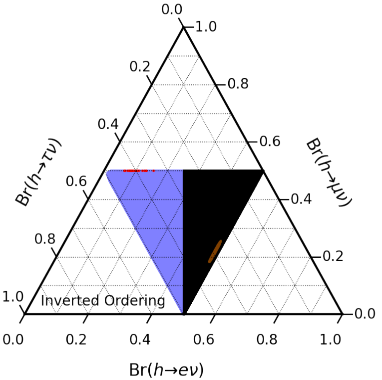


Figure: Plot of the coupling ratios $|y_h^{e\mu}|/|y_h^{\mu\tau}|$ and $|y_h^{e\tau}|/|y_h^{\mu\tau}|$ as obtained in the numerical scan if approximately 95.45 % of the overall number of 547 991 (542 287) sample points generated for NO (IO) are taken into account. Each square shown to be compatible with NO (IO) contains at least 97 (74) sample points.

$$\Gamma(h \to \ell_a \nu_b) = \Gamma(h \to \ell_b \nu_a) = \frac{|y_h^{ab}|^2}{4\pi} M_h \tag{19}$$

$$\mathrm{Br}(h \to \ell_a \nu) = \frac{\sum_{b \neq a} |y_h^{ab}|^2}{2(|y_h^{e\mu}|^2 + |y_h^{e\tau}|^2 + |y_h^{\mu\tau}|^2)} \tag{20}$$





Branching Ratios

$$\Gamma(h \to \ell_a \nu_b) = \Gamma(h \to \ell_b \nu_a) = \frac{|y_h^{ab}|^2}{4\pi} M_h \tag{21}$$

$$\text{Br}(h \to \ell_a \nu) = \frac{\sum_{b \neq a} |y_h^{ab}|^2}{2(|y_h^{e\mu}|^2 + |y_h^{e\tau}|^2 + |y_h^{\mu\tau}|^2)} \tag{22}$$