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

JHEP 05 (2021) 122; e-Print 2102.09898

Tobias Felkl

Sydney Consortium of Particle Physics & Cosmology
School of Physics, University of New South Wales, Sydney, Australia

2021 Meeting of the Division of Particles and Fields of the American Physical Society (DPF21)

UNSW SYDNEY

Singly-Charged Scalar Singlet

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

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

Singly-Charged Scalar Singlet

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

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

How to model-independently study the generation of Majorana neutrino masses and their phenomenology?

Singly-Charged Scalar Singlet

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

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

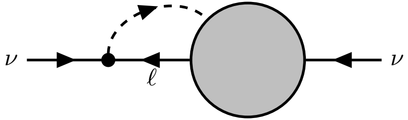
How to model-independently study the generation of Majorana neutrino masses and their phenomenology?

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, $y_h v_h = 0$.

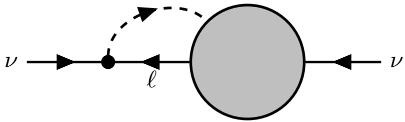
Neutrino Mass Matrix: Linear Case

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: $M_\nu = U^* m_{\text{diag}} U^\dagger = X y_h - y_h X^T$

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

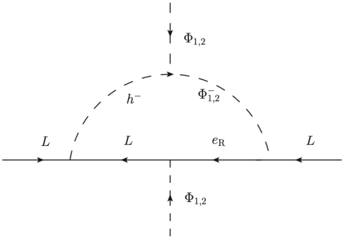


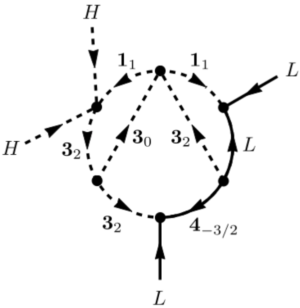
Most general form of neutrino mass matrix: $M_\nu = U^* m_{\text{diag}} U^\dagger = X y_h - y_h X^T$
$\rightarrow$ All three neutrinos in general massive.

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

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

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





Zee, Phys. Lett. B93 389 (1980)

Cheng, Li, Phys,. Rev. D22 2860 (1980)

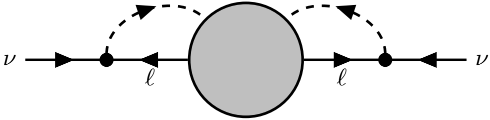
Wolfenstein, Nucl. Phys. B175 93 (1980)

HG, Ohlsson, Riad, Wiren, JHEP 04, 130 (2017)

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

Neutrino Mass Matrix: Quadratic Case

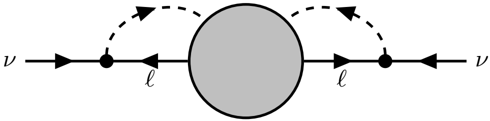
Eigenvector $v_h = (y_h^{\mu\tau}, -y_h^{e\tau}, y_h^{e\mu})^T$ with eigenvalue zero, $y_h v_h = 0$.



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

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



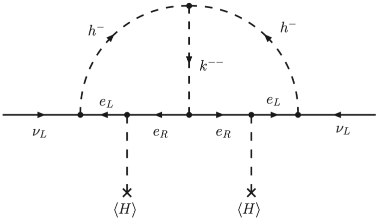
Most general form of neutrino mass matrix: $M_\nu = U^* m_{\text{diag}} U^\dagger = y_h S y_h$
$\rightarrow$ One neutrino remains massless.

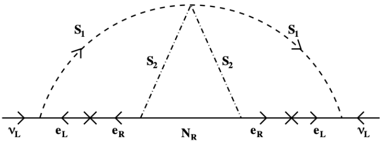
$$\Rightarrow \quad \mathbf{m}_{\text{diag}} \mathbf{U}^\dagger \mathbf{v_h} = \mathbf{0}$$

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

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





Zee, Phys. Lett. B161 141 (1985)

Zee, Nucl. Phys. B264 99 (1986)

Babu, Phys. Lett. B203 132 (1988)

Nebot, Oliver, Palao, Santamaria, Phys. Rev. D77, 093013 (2008)

Krauss, Nasri, Trodden, Phys. Rev. D67, 085002 (2003)

Neutrino-Mass Constraints

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:

$$\mathbf{v_h^T U^* m_{\mathrm{diag}} U^\dagger v_h = 0}, \qquad \text{Linear case.}$$

$$\mathbf{m_{\mathrm{diag}} U^\dagger v_h = 0}, \qquad \text{Quadratic case.}$$

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.

How to solve the constraint? Example: Quadratic case

Constraints yield four real conditions for both neutrino-mass orderings:

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

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

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

- RHS: Assign pseudo-random variates from normal distributions. (NuFIT)
  Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, JHEP 09, 178 (2020)
- LHS: Assign random values to one magnitude and one phase
  $\rightarrow$ Rest fixed by constraint.
- Mass $M_h \in [350\,\text{GeV}, 100\,\text{TeV}]$

Linear case: One very lengthy complex expression, see next slide ...

Constraint in the Linear Case

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

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

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

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

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

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

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

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

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

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

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

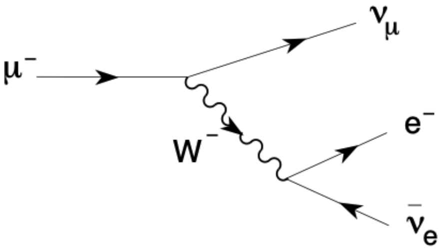
$$-\left(m_3 - e^{-2i(\delta+\eta_2)} m_2 s_{12}^2\right) s_{13} s_{23}\Big) y_h^{e\tau} + \left(e^{-2i\eta_2} m_2 s_{12}^2 c_{13}^2 + e^{-2i\eta_1} c_{12}^2 m_1 c_{13}^2 + e^{2i\delta} m_3 s_{13}^2\right) y_h^{\mu\tau}\Bigg) y_h^{\mu\tau} = 0$$

Lepton-Flavour Non-Universality

Define the ratios of effective leptonic gauge couplings inferred from $l_i \to l_j \bar{\nu}\nu$:

$$\sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\tau\to e}}} \propto \frac{G_{\tau\mu}}{G_{\tau e}} = \frac{g_\mu}{g_e}, \quad \sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau\mu}}{G_{\mu e}} = \frac{g_\tau}{g_e}, \quad \sqrt[4]{\frac{\Gamma_{\tau\to e}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau e}}{G_{\mu e}} = \frac{g_\tau}{g_\mu}$$

They are all equal to one in the SM (LFU).



Pich, Prog.Part.Nucl.Phys. 75 (2014) 41-85

Lepton-Flavour Non-Universality

Define the ratios of effective leptonic gauge couplings inferred from $l_i \to l_j \bar{\nu}\nu$:

$$\sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\tau\to e}}} \propto \frac{G_{\tau\mu}}{G_{\tau e}} = \frac{g_\mu}{g_e}, \quad \sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau\mu}}{G_{\mu e}} = \frac{g_\tau}{g_e}, \quad \sqrt[4]{\frac{\Gamma_{\tau\to e}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau e}}{G_{\mu e}} = \frac{g_\tau}{g_\mu}$$

They are all equal to one in the SM (LFU). Current best-fit values:

$$\left|\frac{g_\mu}{g_e}\right| = 1.0018 \pm 0.0032, \quad \left|\frac{g_\tau}{g_e}\right| = 1.0030 \pm 0.0030, \quad \left|\frac{g_\tau}{g_\mu}\right| = 1.0011 \pm 0.0030$$

Gersabeck, Pich, Comptes Rendus Physique 21 (2020) 75

Lepton-Flavour Non-Universality

Define the ratios of effective leptonic gauge couplings inferred from $l_i \to l_j \bar{\nu}\nu$:

$$\sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\tau\to e}}} \propto \frac{G_{\tau\mu}}{G_{\tau e}} = \frac{g_\mu}{g_e}, \quad \sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau\mu}}{G_{\mu e}} = \frac{g_\tau}{g_e}, \quad \sqrt[4]{\frac{\Gamma_{\tau\to e}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau e}}{G_{\mu e}} = \frac{g_\tau}{g_\mu}$$

They are all equal to one in the SM (LFU). Current best-fit values:

$$\left|\frac{g_\mu}{g_e}\right| = 1.0018 \pm 0.0032, \quad \left|\frac{g_\tau}{g_e}\right| = 1.0030 \pm 0.0030, \quad \left|\frac{g_\tau}{g_\mu}\right| = 1.0011 \pm 0.0030$$

Gersabeck, Pich, Comptes Rendus Physique 21 (2020) 75

- h contributes to g_i/g_j at tree level
- 1σ ranges of $|y_h^{e\mu}|/M_h$, $|y_h^{\mu\tau}|/M_h$ determined in 2012.09845
- Effect in $\mu \to e$ explains CAA (indirectly: $G_F \to |V_{us}^{CKM}|$)

Crivellin, Kirk, Manzari, Panizzi,

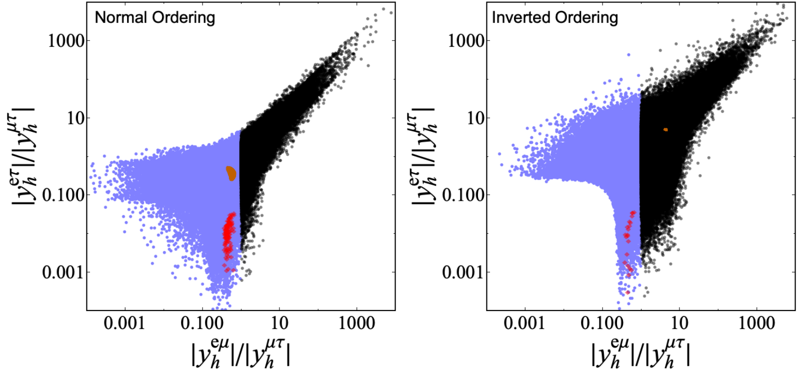
Phys. Rev. D. 103, 073002 (2021)

$$\frac{g_\mu}{g_e} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{\mu\tau}|^2 - |y_h^{e\tau}|^2}{M_h^2}$$

$$\frac{g_\tau}{g_e} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{\mu\tau}|^2 - |y_h^{e\mu}|^2}{M_h^2}$$

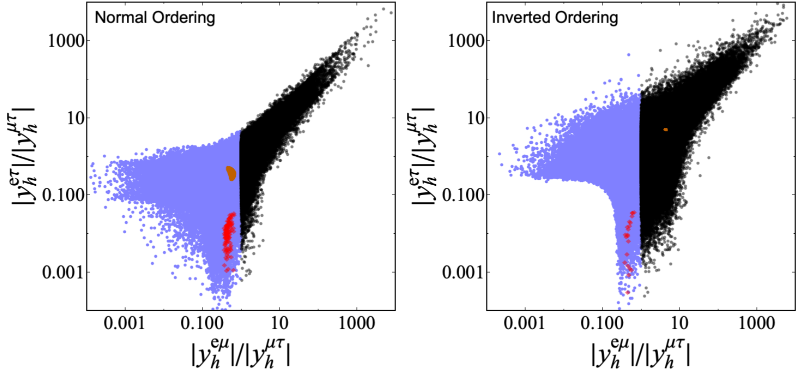
$$\frac{g_\tau}{g_\mu} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{e\tau}|^2 - |y_h^{e\mu}|^2}{M_h^2}$$

Solution to the Neutrino-Mass Constraints



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

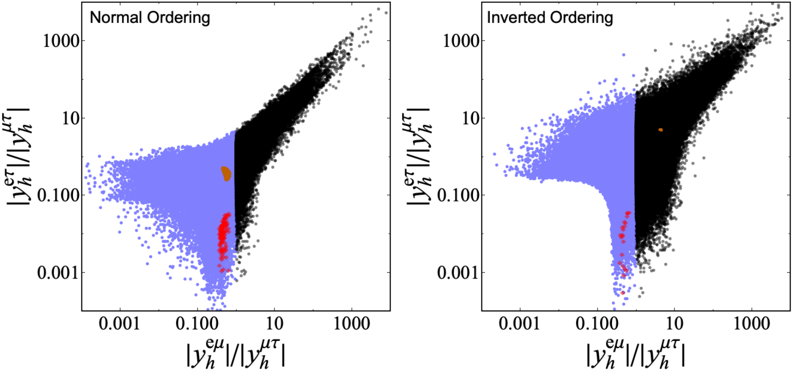
Solution to the Neutrino-Mass Constraints



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

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

Solution to the Neutrino-Mass Constraints

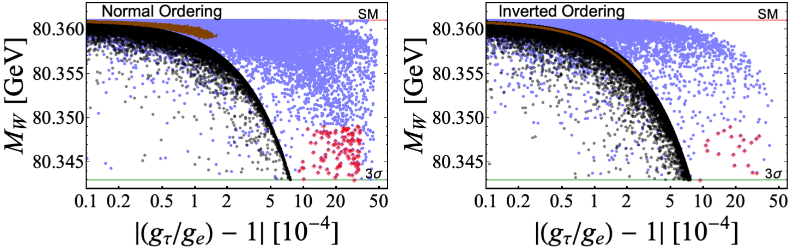


Neutrino-mass constraints shape available parameter space for y_h^{ij} non-trivially.

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

W-Boson Mass

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

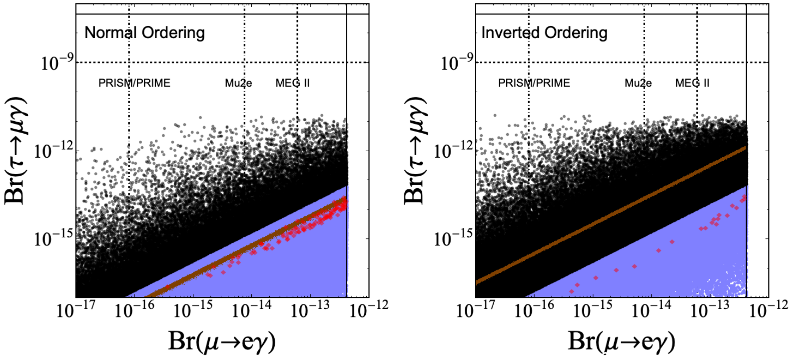


Radiative Charged-Lepton Decays

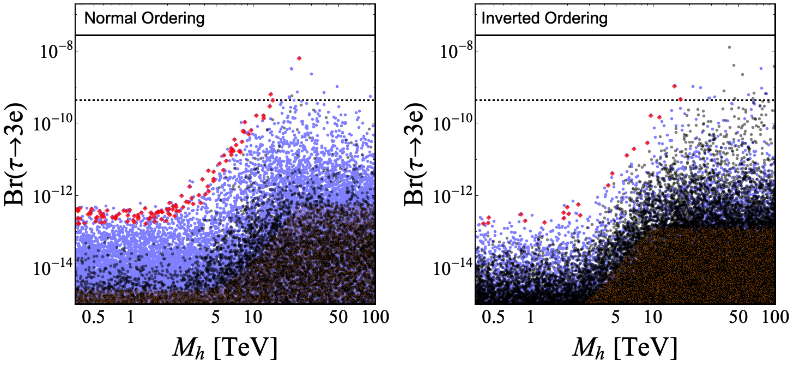
$$\mathrm{Br}(\mu \to e\gamma) = \mathrm{Br}(\mu \to e\nu\bar{\nu}) \frac{\alpha_{\mathrm{EM}}}{48\pi G_F^2} \frac{|y_h^{e\tau} y_h^{\mu\tau}|^2}{M_h^4},$$

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

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



Tri-Lepton Decays of Charged Leptons



Conclusions

Assumption: Neutrino masses generated via a singly-charged scalar singlet.
→ **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, ...

Felkl, T., Herrero-García, J. & Schmidt, M. A.
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 watching 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) $m_3 \ll m_1 < m_2$.

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_{3l}^2 [10^{-3} eV^2]	Δm_{21}^2 [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)	$[0, \pi]$	$[350, 10^5]$

$\Delta m_{31}^2 > 0$ for NO, and $\Delta m_{32}^2 < 0$ 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)

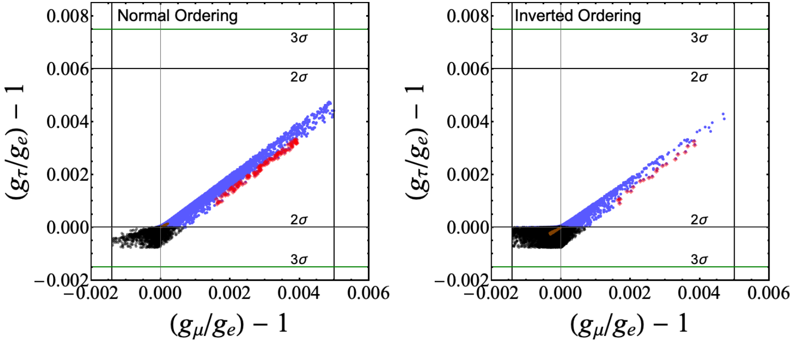
Zyla et al. (PDG), PTEP 2020, 083C01

Universality of Leptonic Gauge Couplings

$$\sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\tau\to e}}} \propto \frac{G_{\tau\mu}}{G_{\tau e}} = \frac{g_\mu}{g_e} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{\mu\tau}|^2 - |y_h^{e\tau}|^2}{M_h^2} \equiv 1 + \epsilon_{ee}^{\tau\tau} - \epsilon_{\mu\mu}^{\tau\tau}, \qquad (7)$$

$$\sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau\mu}}{G_{\mu e}} = \frac{g_\tau}{g_e} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{\mu\tau}|^2 - |y_h^{e\mu}|^2}{M_h^2} \equiv 1 + \epsilon_{ee}^{\mu\mu} - \epsilon_{\mu\mu}^{\tau\tau}, \qquad (8)$$

$$\sqrt[4]{\frac{\Gamma_{\tau\to e}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau e}}{G_{\mu e}} = \frac{g_\tau}{g_\mu} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{e\tau}|^2 - |y_h^{e\mu}|^2}{M_h^2} \equiv 1 + \epsilon_{ee}^{\mu\mu} - \epsilon_{ee}^{\tau\tau} \qquad (9)$$

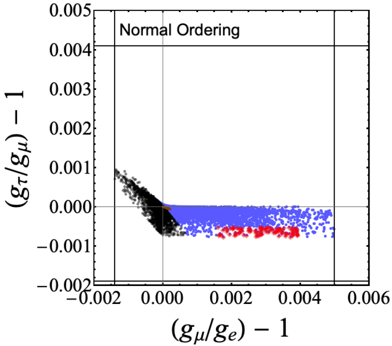


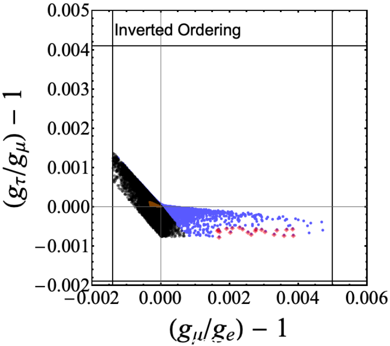
Universality of Leptonic Gauge Couplings

$$\sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\tau\to e}}} \propto \frac{G_{\tau\mu}}{G_{\tau e}} = \frac{g_\mu}{g_e} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{\mu\tau}|^2 - |y_h^{e\tau}|^2}{M_h^2} \equiv 1 + \epsilon_{ee}^{\tau\tau} - \epsilon_{\mu\mu}^{\tau\tau}, \quad (10)$$

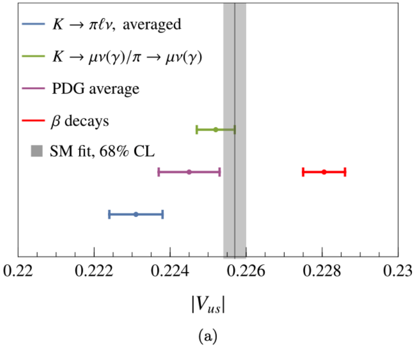
$$\sqrt[4]{\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau\mu}}{G_{\mu e}} = \frac{g_\tau}{g_e} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{\mu\tau}|^2 - |y_h^{e\mu}|^2}{M_h^2} \equiv 1 + \epsilon_{ee}^{\mu\mu} - \epsilon_{\mu\mu}^{\tau\tau}, \quad (11)$$

$$\sqrt[4]{\frac{\Gamma_{\tau\to e}}{\Gamma_{\mu\to e}}} \propto \frac{G_{\tau e}}{G_{\mu e}} = \frac{g_\tau}{g_\mu} \approx 1 + \frac{1}{\sqrt{2}G_F}\frac{|y_h^{e\tau}|^2 - |y_h^{e\mu}|^2}{M_h^2} \equiv 1 + \epsilon_{ee}^{\mu\mu} - \epsilon_{ee}^{\tau\tau} \quad (12)$$





Cabibbo Angle Anomaly



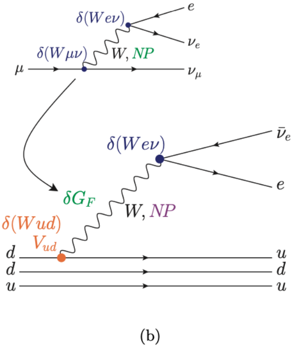
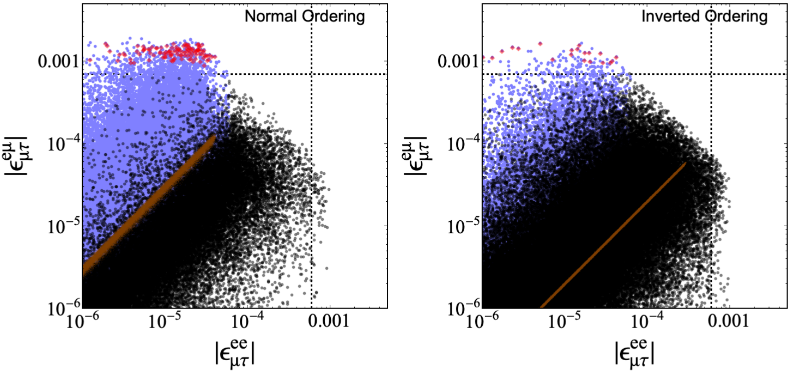


Figure 1: (a) Determinations of $|V_{us}|$ from different sources.[7,8,6] $|V_{us}| = 0.22805(64) \equiv |V_{us}^{\beta}|$, which was determined, using CKM unitarity from $|V_{ud}| = 0.97365(15)$,[9] is shown in red. (b) Possible NP interpretations leading to effects in β-decays (and $\mu \to e\bar{\nu}\nu$). Note that the contribution of $\delta(We\nu)$ to $\mu \to e\bar{\nu}\nu$ cancels against the direct contribution of $\delta(We\nu)$ to the β-decay. $\delta(W\mu\nu)$, however, leads to an effect in β-decays.

Kirk, Contribution to Moriond EW 2021

$$\epsilon^{e\mu}_{\tau e} \equiv \frac{(y_h^{e\tau})^* y_h^{e\mu}}{\sqrt{2} G_F M_h^2} = -(\epsilon^{ee}_{\mu\tau})^*, \qquad \epsilon^{e\mu}_{\mu\tau} \equiv -\frac{(y_h^{e\mu})^* y_h^{\mu\tau}}{\sqrt{2} G_F M_h^2} \tag{13}$$

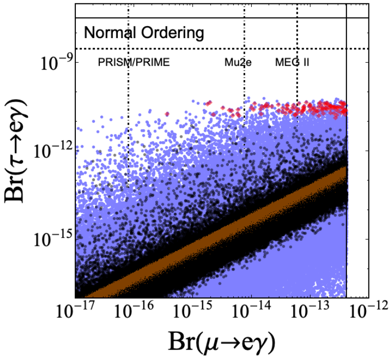


Radiative Charged-Lepton Decays

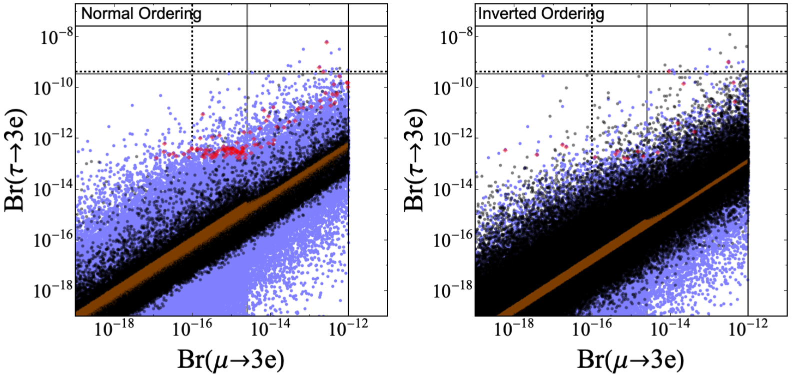
$$\mathrm{Br}(\mu \to e\gamma) = \mathrm{Br}(\mu \to e\nu\bar{\nu}) \frac{\alpha_{\mathrm{EM}}}{48\pi G_F^2} \frac{|y_h^{e\tau} y_h^{\mu\tau}|^2}{M_h^4}, \tag{14}$$

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

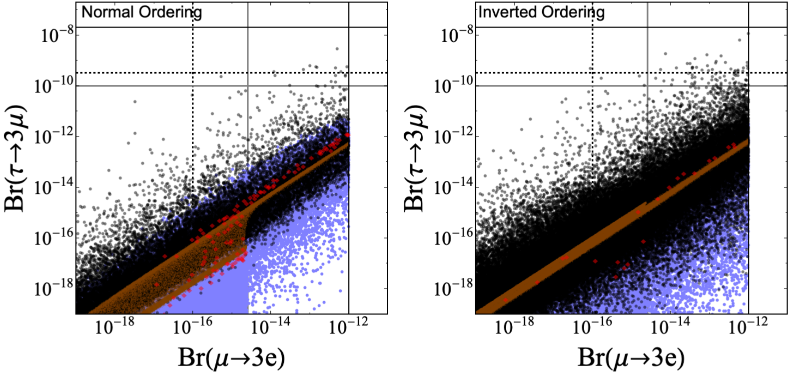
$$\mathrm{Br}(\tau \to \mu\gamma) = \mathrm{Br}(\tau \to \mu\nu\bar{\nu}) \frac{\alpha_{\mathrm{EM}}}{48\pi G_F^2} \frac{|y_h^{e\mu} y_h^{e\tau}|^2}{M_h^4} \tag{16}$$



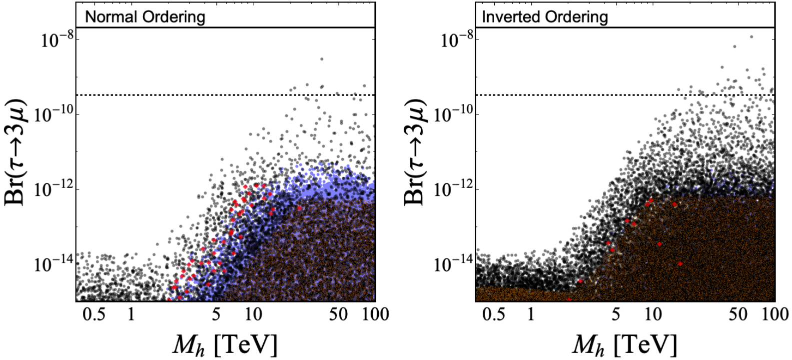
Tri-Lepton Decays of Charged Leptons



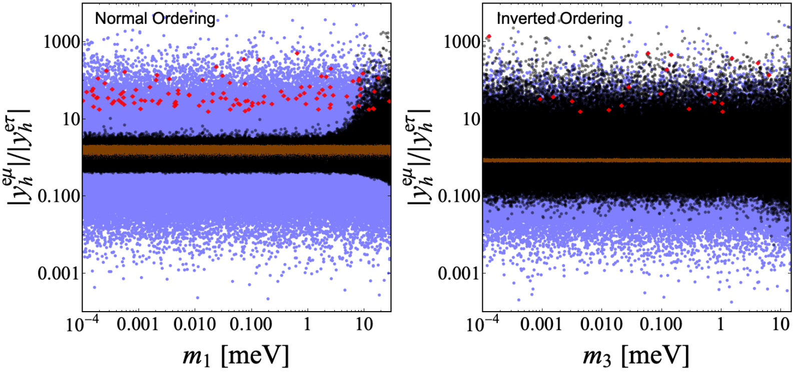
Tri-Lepton Decays of Charged Leptons



Tri-Lepton Decays of Charged Leptons



Coupling Magnitudes



Coupling Magnitudes

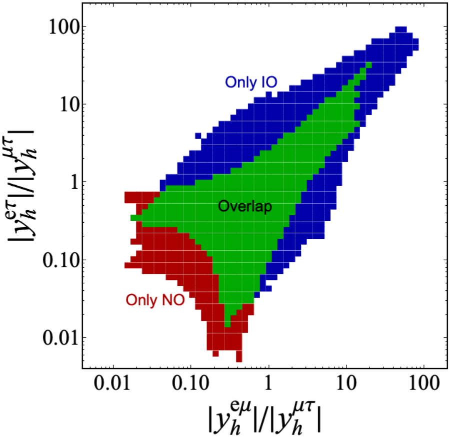
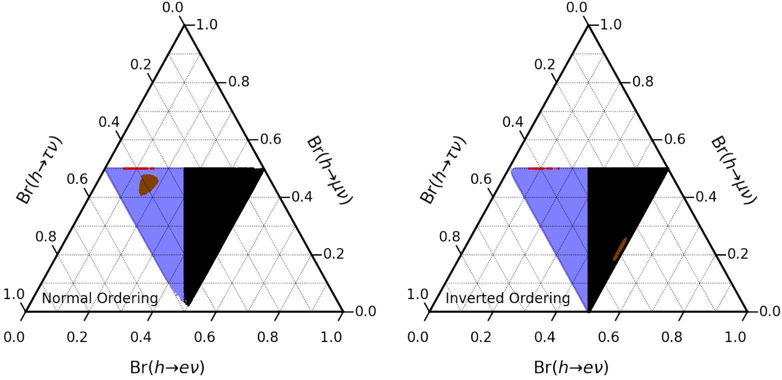


Figure: Plot of the coupling ratios $|y_h^{e\mu}|/|y_h^{\mu\tau}|$ and $|y_h^{e\tau}|/|y_h^{\mu\tau}|$ as obtained in the numerical scan if approximately 95.45 % of the overall number of 547 991 (542 287) sample points generated for NO (IO) are taken into account. Each square shown to be compatible with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

Branching Ratios

$$\Gamma(h \to \ell_a \nu_b) = \Gamma(h \to \ell_b \nu_a) = \frac{|y_h^{ab}|^2}{4\pi} M_h \quad (17)$$

$$\mathrm{Br}(h \to \ell_a \nu) = \frac{\sum_{b \neq a} |y_h^{ab}|^2}{2(|y_h^{e\mu}|^2 + |y_h^{e\tau}|^2 + |y_h^{\mu\tau}|^2)} \quad (18)$$



Branching Ratios

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

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