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

Tobias Felkl - Based on *JHEP 05 (2021) 122*; arXiv: 2102.09898

School of Physics, The University of New South Wales, Sydney, NSW 2052, Australia
Sydney Consortium for Particle Physics and Cosmology

Theory Lagrangian and Conventions

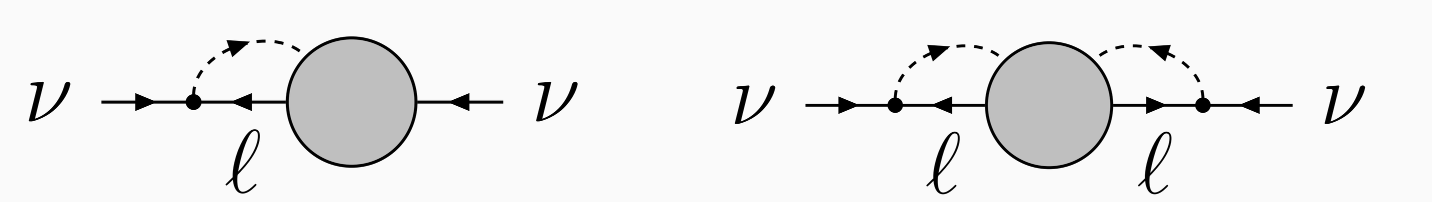
We extend the particle content of the Standard Model (SM) by a singly-charged scalar particle h which is a singlet under the strong interactions and the weak interactions. On the renormalisable level, the theory is defined as in

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

where further operators contributing to the scalar potential are omitted. The (3×3) coupling matrix y_h is antisymmetric in flavour space and therefore always features a non-trivial eigenvector $v_h = (y_h^{\mu\tau}, -y_h^{e\tau}, y_h^{e\mu})^T$ with a vanishing eigenvalue, $y_h v_h = 0$. We relate neutrino mass eigenstates ν_i and flavour eigenstates ν_α via $\nu_\alpha = \sum_{i=1}^3 U_{\alpha i}\nu_i$ with the unitary PMNS matrix U, and thus $m_{\text{diag}} \equiv U^T M_\nu U$. Since three generations of active neutrinos are assumed, $m_{\text{diag}} = \text{diag}(m_1, m_2, m_3)$ contains two or three non-vanishing eigenvalues.

Neutrino-Mass Matrix and Constraints

In the following it is assumed that either one (**Linear Case**, **LC**, below on the **left**) or both (**Quadratic Case**, **QC**, below on the **right**) of the neutrinos on the external lines couple via y_h to the Feynman diagram associated with the generation of neutrino masses:



The black dot stands for the coupling y_h and the dashed line is the h propagator. Since we only consider Majorana neutrino masses, there also need to be at least two insertions of the SM Higgs VEV, and lepton-number conservation must be violated. As we remain agnostic about further details of the physics at play, the rest of the Feynman diagram is depicted by the gray blob. Explicitly, the neutrino mass matrix is given by

$$M_\nu \equiv U^* m_{\text{diag}} U^\dagger = X y_h - y_h X^T \tag{1}$$

with a general complex (3×3) matrix X in the LC, and by

$$M_\nu \equiv U^* m_{\text{diag}} U^\dagger = y_h S y_h \tag{2}$$

with a symmetric complex (3×3) matrix S in the QC, where X and S formally carry information about the physics underlying the gray blob in the respective Feynman diagram. From this, one may straightforwardly derive the constraint

$$v_h^T U^* m_{\text{diag}} U^\dagger v_h = 0 \tag{3}$$

for the LC, and

$$m_{\text{diag}} U^\dagger v_h = 0 \tag{4}$$

for the QC. These directly relate the couplings y_h^{ij} contained in v_h to measured active-neutrino data contained in m_{diag} and U. We interpret them as **necessary conditions** for the correct description of neutrino masses in the SM extended by h and some source of lepton-number breaking in the LC and the QC, respectively. The constraints are not sensitive to the details of how this breaking is achieved, since the matrices X and S which were introduced to parametrise it have dropped out, and thus (3) and (4) are model-independent.

Lepton-Flavour Universality

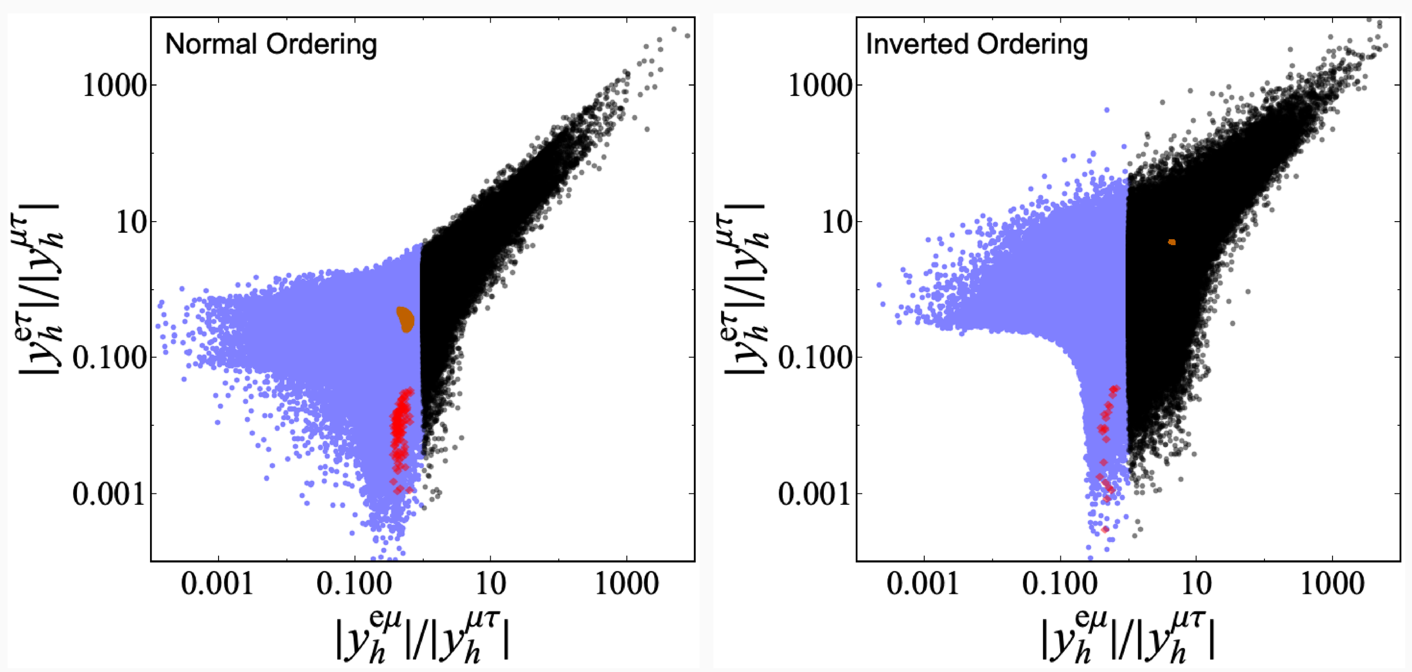
The decays of a charged lepton into another lighter charged lepton and and a neutrino-antineutrino pair ($l_i \to l_j\bar{\nu}\nu$) can be formally described in terms of three ratios of effective gauge couplings, the so-called universality ratios g_μ/g_e, g_τ/g_e and g_τ/g_μ. In the SM, they are all equal to 1 due to lepton-flavour universality. Nonetheless, current global fits [3] indicate a slight deviation from that,

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

with the uncertainties given at 2σ. In the presence of h, the anomalies in g_μ/g_e and g_τ/g_e as well as discrepancies in the results of direct and indirect determinations of the CKM-matrix element V_{us} ("Cabibbo Angle Anomaly", CAA) can be accommodated [1]. We were interested in the question whether an explanation of these phenomena, collectively dubbed the "**flavour anomalies**" henceforth, via h is compatible with this particle also inducing neutrino masses.

Solving the Neutrino-Mass Constraints

We employ (3) to determine two of the magnitudes $|y_h^{ij}|$ in terms of the third one, the phases $\arg(y_h^{ij})$ and the active-neutrino parameters in the LC. In the QC, (4) also determines two of the phases $\arg(y_h^{ij})$. We use the latest fit results provided by NuFIT in 2020 [2] to vary the leptonic mixing angles θ_{ij}, neutrino-mass-squared differences $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ and the CP-violating phase δ, assuming Gaussian distributions. The coupling magnitudes $|y_h^{ij}|$ and the smallest neutrino mass m_0 are sampled over with a log-flat prior, the phases $\arg(y_h^{ij})$ and Majorana phases $\eta_{1,2}$ with a flat prior.

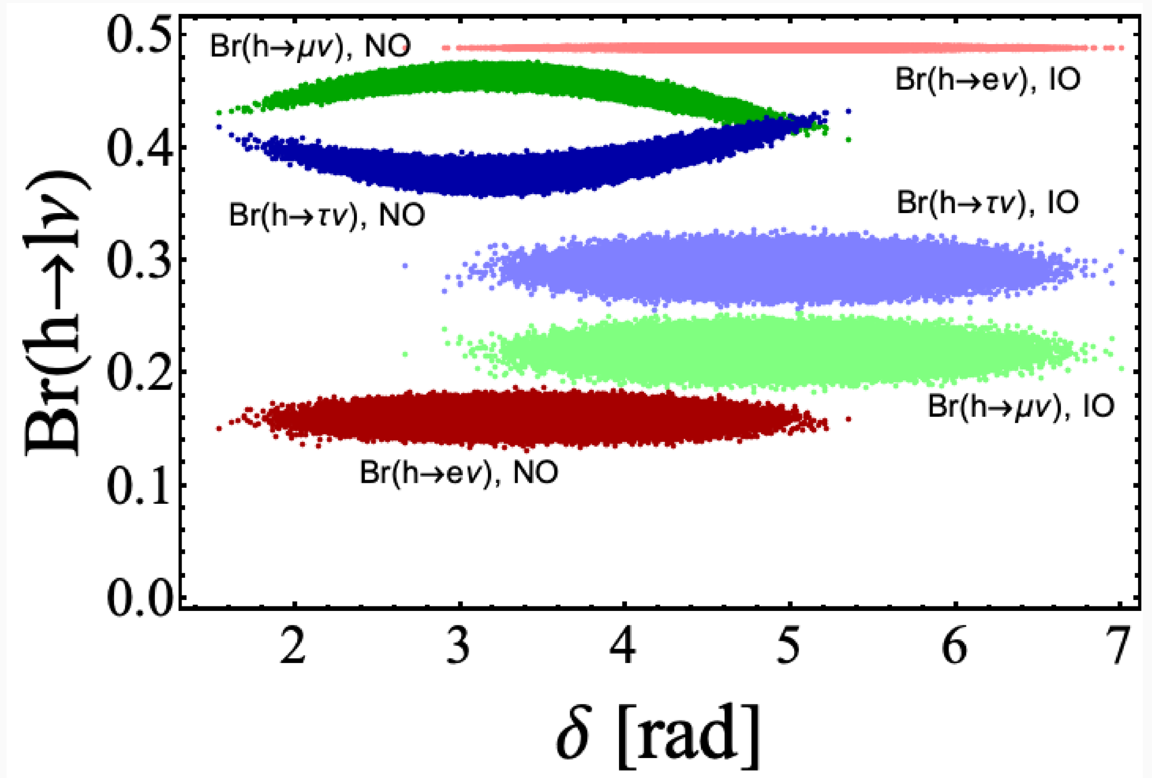


The results of solving the constraints are shown in the plots above. The following colour code is used:

- Brown: Viable solutions to the constraint in the QC.
- Blue and **Black**: Viable solutions to the constraint in the LC with the colours distinguishing if the deviation of $|g_\tau/g_e|$ from its current best-fit value is predicted to be at 2σ (= blue) or 3σ (= black).
- Red: Flavour anomalies explained at 1σ. Compatible with the simultaneous explanation of neutrino masses only in the LC.

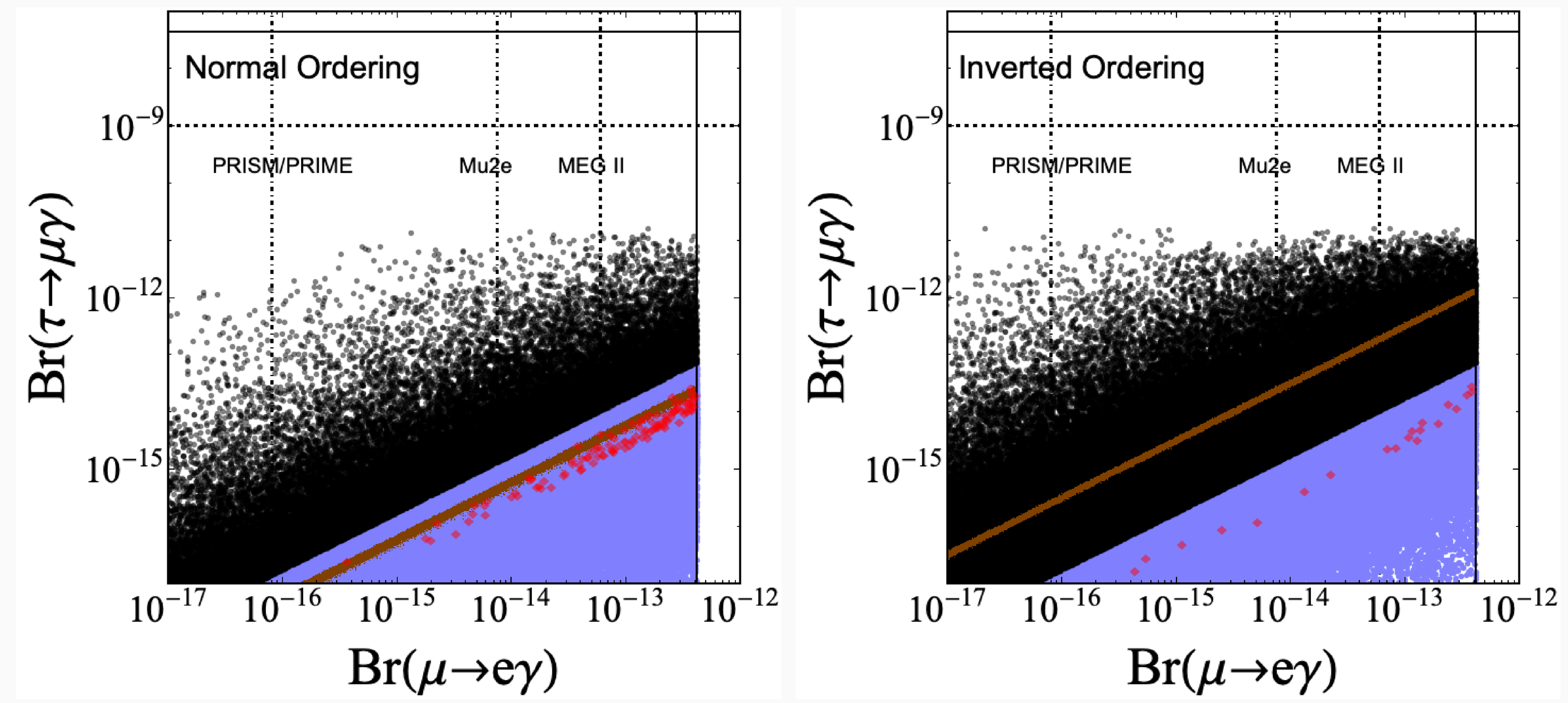
Quadratic Case: Branching Ratios

One consequence of the predictive power of the QC is the quite precise determination of the branching ratios of the different decay channels of h. Besides, the strict hierarchy among the channels is strongly dependent on the assumed neutrino-mass ordering: For instance, the BR of the electron channel $h \to e\nu$ is close to maximal (0.5) in the case of Inverted Ordering (IO), whereas it is the most suppressed one for Normal Ordering (NO).



Flavour-Violating Decays of Charged Leptons

Large parts of the parameter space which are currently compatible with (3) and (4) will be probed via future searches for the processes $\mu \to e\gamma$ and $\mu - e$ conversion in nuclei. In our scenario, the involved rates are strongly correlated. Both in the QC and for the combined explanation of the flavour anomalies and neutrino masses in the LC, there is also a tight correlation between flavour-violating muon decays and tau-lepton decays.



Contact: t.felkl@unsw.edu.au

References

[1] Andreas Crivellin et al. "Searching for lepton flavor universality violation and collider signals from a singly charged scalar singlet". In: *Phys. Rev. D* 103.7 (2021), p. 073002. DOI: 10.1103/PhysRevD.103.073002. arXiv: 2012.09845 [hep-ph].

[2] Ivan Esteban et al. "The fate of hints: updated global analysis of three-flavor neutrino oscillations". In: *JHEP* 09 (2020), p. 178. DOI: 10.1007/JHEP09(2020)178. arXiv: 2007.14792 [hep-ph].

[3] Evelina Gersabeck and Antonio Pich. "Tau and charm decays". In: *Comptes Rendus Physique* 21.1 (2020), pp. 75–92. DOI: 10.5802/crphys.14.