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

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Synopsis

We consider the generation of Majorana neutrino masses via a singly-charged scalar singlet h. Its only renormalisable coupling to SM fermions is given by $y_h LLh$. In the minimal case of extending the SM by one copy of h and requiring that at least one external neutrino couples via y_h when neutrino masses are generated, one finds only two distinct structures for the neutrino mass matrix. These two categories, dubbed the **linear case** and the **quadratic case**, apply to many different models, among them the *Zee model* [7, 2, 6] which is an example of the linear case, and the *Zee-Babu model* [8, 9, 1] and the *KNT model* [5] which are examples of the quadratic case. For both cases we identify a constraint for the couplings y_h^{ij} in terms of measured neutrino data which is independent of how the breaking of lepton-number conservation is achieved. Furthermore, we find that h explaining both the Cabibbo Angle Anomaly and experimental deviations of the effective leptonic gauge couplings from universality at 1σ [3] is compatible with the simultaneous generation of neutrino masses in the linear case, but not in the quadratic case.

Theory Lagrangian and Conventions

We extend the particle content of the Standard Model 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

$$\mathcal{L} = \mathcal{L}_{\rm SM} - h^*(D^\mu D_\mu + M_h)h - (y_h^{ij} L_i L_j h + \text{h.c.}) \tag{1}$$

where further operators contributing to the scalar potential are omitted. The coupling matrix

$$y_h = \begin{pmatrix} 0 & y_h^{e\mu} & y_h^{e\tau} \\ -y_h^{e\mu} & 0 & y_h^{\mu\tau} \\ -y_h^{e\tau} & -y_h^{\mu\tau} & 0 \end{pmatrix} \tag{2}$$

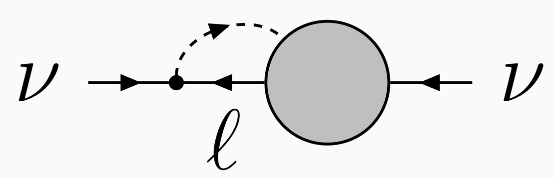
is antisymmetric in flavour space and therefore always features a non-trivial eigenvector $v_h = (y_h^{\mu\tau}, -y_h^{e\tau}, y_h^{e\mu})^T$ with a vanishing eigenvalue, $y_h v_h = 0$. We relate neutrino mass eigenstates ν_i and flavour eigenstates ν_α via

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

with the unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix U, and thus $m_{\rm diag} \equiv U^T M_\nu U$. Since three generations of active neutrinos are assumed, $m_{\rm diag} = \text{diag}(m_1, m_2, m_3)$ contains two or three non-vanishing eigenvalues. In the following, we distinguish between two scenarios of neutrino-mass generation which result in different general structures for the neutrino-mass matrix, the *linear case* and the *quadratic case*.

Linear Case

In the linear case, one of the neutrinos on the external lines couples via y_h to the rest of the Feynman diagram associated to neutrino-mass generation, while the other neutrino couples differently:



The black dot symbolises the coupling y_h and the dashed line is the h propagator. The most general form of the neutrino mass matrix is given by

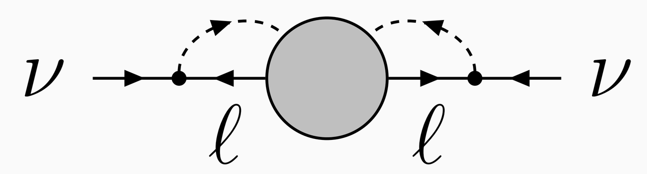
$$M_\nu \equiv U^* m_{\rm diag} U^\dagger = X y_h - y_h X^T \tag{4}$$

with the matrix X encoding the physics symbolised by the gray blob which has to involve a source of lepton-number breaking and at least two insertions of the SM Higgs VEV. Since X is not specified further, the determinant of M_ν does in general not vanish and hence all three active neutrinos receive masses in the linear case. Multiplying the above equation by the eigenvector v_h from both the left-hand side and the right-hand side, one obtains

$$v_h^T U^* m_{\rm diag} U^\dagger v_h = 0. \tag{5}$$

Quadratic Case

In the quadratic case, both neutrinos on the external lines couple via y_h to the rest of the Feynman diagram associated to neutrino-mass generation:



The black dot symbolises the coupling y_h and the dashed line is the h propagator. The most general form of the neutrino mass matrix is given by

$$M_\nu \equiv U^* m_{\rm diag} U^\dagger = y_h S y_h \tag{6}$$

with the symmetric matrix S encoding the physics symbolised by the gray blob which has to involve a source of lepton-number breaking and at least two insertions of the SM Higgs VEV. Due to the antisymmetry of y_h, the determinant of M_ν vanishes by construction and hence one neutrino will remain massless at leading order in the quadratic case. Multiplying the above equation by the eigenvector v_h from the right-hand side, one obtains

$$m_{\rm diag} U^\dagger v_h = 0. \tag{7}$$

Explicitly spelt out, this implies

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

$$\frac{y_h^{e\mu}}{y_h^{\mu\tau}} = \tan(\theta_{12}) \frac{\sin(\theta_{23})}{\cos(\theta_{13})} - \tan(\theta_{13}) \cos(\theta_{23}) e^{i\delta} \tag{9}$$

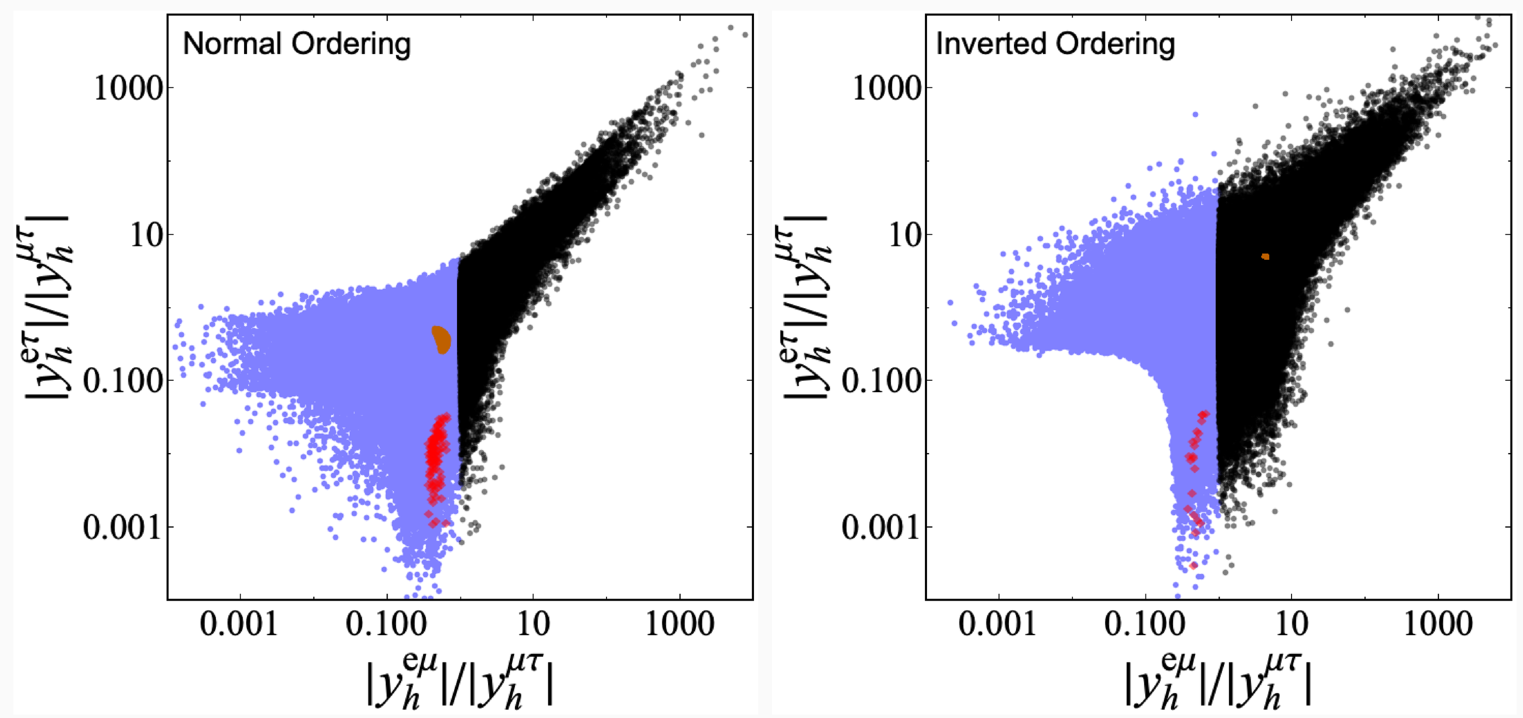
in the case of normal ordering of neutrino masses, and

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

for inverted ordering.

Solving the Neutrino-Mass Constraints

The derived constraints in (5) and (7) directly relate the couplings y_h^{ij} contained in v_h to measured active-neutrino data contained in $m_{\rm diag}$ and U. We interpret them as *necessary conditions* for the correct description of neutrino masses in the SM extended by h in the linear case and the quadratic case, respectively. The constraints are not sensitive to the details of the mechanism of lepton-number breaking, since the matrices X and S which parametrise this breaking have dropped out, and thus they are model-independent.
We employ (5) 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 linear case. In the quadratic case, (7) also determines two of the phases $\arg(y_h^{ij})$. We use the latest fit results provided by NuFIT in 2020 [4] to assign pseudo-random variates from normal distributions to 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. 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. Colour code:

- Brown: Viable solutions to the constraint in the quadratic case. This scenario is very predictive since the constraint is largely controlled by the leptonic mixing angles which are quite precisely determined by now.
- Blue and Black: Viable solutions to the constraint in the linear case with the colours distinguishing if $|y_h^{e\mu}|/|y_h^{\mu\tau}|$ is smaller or larger than one. This scenario is less predictive since here the constraint also depends on the smallest neutrino mass and the Majorana phases, the latter being completely unconstrained.
- Red: Explanation of the Cabibbo Angle Anomaly and experimental deviations of the effective leptonic gauge couplings from universality at 1σ via h [3], which is compatible with the simultaneous generation of neutrino masses by h only in the linear case. Here it is assumed that further exotic particles which are potentially involved in the generation of neutrino masses contribute only to a negligible extent, and thus the singly-charged scalar singlet is taken to be the sole driver of explaining the above anomalies.

It is distinctively visible that there is a slight sensitivity to the neutrino-mass ordering and that imposing (5) and (7) disfavours large hierarchies among the $|y_h^{ij}|$. One consequence is that the stringent bounds arising from $\mu \to e\gamma$ and $\mu \to 3e$ cannot be easily avoided in the minimal scenario of low-energy effects of new physics dominantly driven by just one singly-charged scalar singlet.

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