Modular Invariant Neutrino Masses

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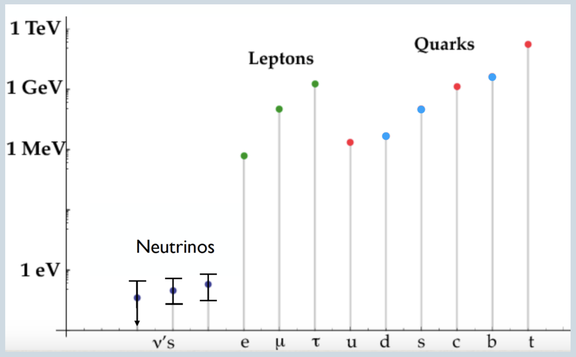
Summary

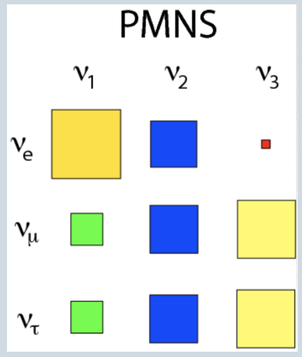
Finding models to explain the observed pattern of neutrino masses and mixing remains an interesting problem. Recent works have opened up an entirely new framework to find models, inspired from string theory, called "modular symmetry" [1].

In this work, we explore the possibility to explain these observed parameters within this framework, focussing on a particular structure which requires invariance under the discrete group S_4.

Neutrino Masses

Neutrino masses are significantly smaller than in the other fermion sectors, but with large mixings.





There are several possibilities to explain such small masses with more natural couplings, such as the type-I Seesaw mechanism, or the dimension-5 Weinberg operator.

$$w_\nu = -y_0(N^c H_u L)_1 + \Lambda(N^c N^c Y)_1$$

$$w_\nu = -\frac{1}{\Lambda}(H_u H_u \; LL \; Y)_1$$

Neutrino Observables

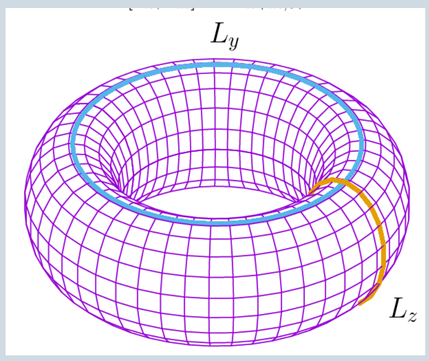
From defining the neutrino (and charged lepton) mass matrix, one may extract all parameters related to the lepton sector.

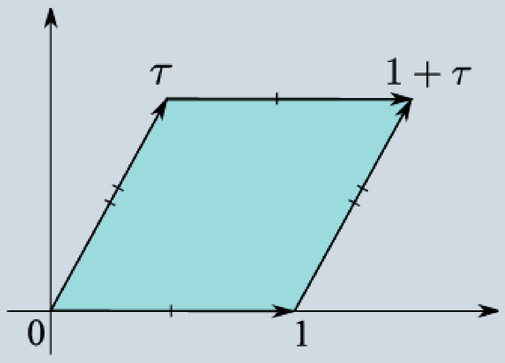
	IO	NO
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.39(21)$	$7.39(21)$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$-2.512(33)$	$+2.525(32)$
$\sin^2\theta_{12}$	$0.310(13)$	$0.310(13)$
$\sin^2\theta_{13}$	$0.02263(66)$	$0.02240(66)$
$\sin^2\theta_{23}$	$0.582(17)$	$0.582(17)$
δ/π	$1.56(15)$	$1.21(19)$

A successful model should reproduce well the six observed neutrino parameters, which are shown above for the two mass orderings.

Modular Symmetry

To go from a string theory in 10 dimensions, to the 4 spacetime dimensions we live in requires compactification, most simply, along a torus. The shape of this torus affects our low energy effective theory.





This torus may be defined explicitly by a single parameter, τ, and under certain transformations of this, the torus is invariant. Fixing the value of this parameter and representations of the fields in the theory fixes the neutrino mass matrix entirely.

S4

In this work, we consider invariance under the finite modular group $\Gamma_4 \simeq S_4$ [2].

The discrete group S_4 is isomorphic the rigid rotations of a cube.

For a superpotential which is modular invariant, if the superfields transform under the modular symmetry, then one requires Yukawa couplings, $Y(\tau)$, which also transform, to generate singlet terms. In our model, we also include additional flavons, φ, φ'.

$$w_\nu = -\frac{1}{\Lambda}\left[(\varphi' LL\ Y_{\mathbf{2}})_1 + \xi(\varphi' LL\ Y_{\mathbf{3'}})_1\right]$$

An example Weinberg term is written above, and one must ensure the representations of the fields under S_4 find singlet solutions.

The Model

We are free to determine the modular weights, k_I, and representations of the field content. Once this is fixed, the mass matrices are determined, and may be calculated with a given modular parameter τ.

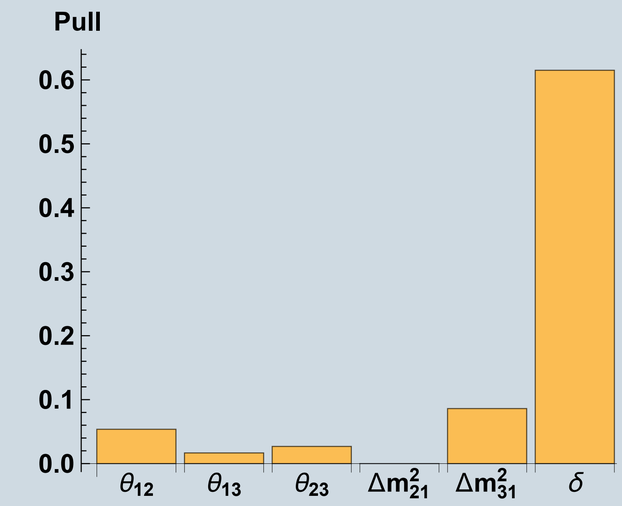
	E^c_1	E^c_2	E^c_3	N^c	L	$H_{u,d}$	φ	φ'
$\Gamma_4 \equiv S_4$	1	1	1	3	3	1	3	1′
k_I (Seesaw)	$-39/10$	$-31/10$	$-23/10$	$-3/2$	$+3/2$	0	$+4/5$	$+1$
k_I (Weinberg)	$-9/10$	$-1/10$	$+7/10$	–	$-3/2$	0	$+4/5$	$+1$

$$\mathcal{W}_W = \begin{pmatrix} 0 & Y_1 & -Y_2 \\ Y_1 & -Y_2 & 0 \\ -Y_2 & 0 & Y_1 \end{pmatrix} + \xi \begin{pmatrix} 2Y_3 & -Y_5 & -Y_4 \\ -Y_5 & 2Y_4 & -Y_3 \\ -Y_4 & -Y_3 & 2Y_5 \end{pmatrix}$$

The Weinberg mass matrix defined above is a function of two complex parameters, τ and ξ. We vary these inputs to extract the six observed parameters, as well as predictions for: the absolute neutrino mass scale, Majorana phases, mass ordering and the lifetime of neutrinoless double beta decay.

Results

We perform a χ^2 analysis over the parameter space in τ, ξ and find regions which can reproduce the experimental data with $\chi^2 \sim \mathcal{O}(1)$.



Above we show the pulls for each of our six neutrino observables. For this point, with inverted mass ordering, the largest pull is from the CP violating phase δ, but this is still within the 1σ experimental range.

[1] F. Feruglio, "Are neutrino masses modular forms?," arXiv:1706.08749 [hep-ph].

[2] J. T. Penedo and S. T. Petcov, "Lepton Masses and Mixing from Modular S_4 Symmetry," Nucl. Phys. B 939 (2019) 292 [arXiv:1806.11040 [hep-ph]].