

# Modular Invariance Approach to Flavor, CP Violation and Fermion Mass Hierarchies

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S.T. Petcov, MQFT; In memory of I. Todorov, 27/05/2026

I was lucky and privileged to have been in the late 1970ies and 1980ies a member of the Theoretical Physics Group led by Acad. Todorov at the Institute for Nuclear Research and Nuclear of the Bulgarian Academy of Sciences in Sofia. I continued to consider myself a member of the Group even after I formally left INRNE.

As a consequence of Acad. Todorov scientific authority, high research standards, as well as of his personal qualities - Ivan Todorov was a man of remarkable moral integrity, there was a very healthy working atmosphere in the Group, which at the same time was very stimulating scientifically. Prof. Todorov enthusiasm for and stile of doing research - working almost incessantly, were contagious. It was a real pleasure to work in the Group.

The regular seminar of Acad. Todorov, which was held on Thursday at 1:15 PM in seminar room 300 at INRNE and run for 50 years, had also extremely important positive impact on my and my junior colleagues development as scientists.

It played crucial role in the development of our Theoretical Physics Group at INRNE into a leader in the research in field theory and theoretical particle physics in Bulgaria, and in certain fields also internationally.

The Seminar had many other important effects: in particular, it was “uniting” us; from “outside” we probably looked something like members of a “peculiar sect” fully devoted to the scientific research we were involved with.

The scientifically highly successful international conferences and schools organized in Bulgaria during the Cold War period under the guidance of Prof. Todorov served, in particular, as a meeting ground for the leading Russian and East European theoretical physicists and their West European and American colleagues. They were crucial also for the development of theoretical physics in Bulgaria.

Through all these “ingredients” Acad. Todorov succeeded in creating an internationally renown School in Theoretical Physics in Bulgaria.

Prof. Todorov was also a man with vast cultural interests. It was always interesting and very stimulating intellectually to be in his company during his leisure time (he particularly enjoyed walks and excursions in Vitosha mountain), and to be exposed to his literature or historical “treasures”. On certain specific occasions this included also wine “treasures” .

# The Flavour Problem

Understanding the origins of flavour in both quark and lepton sectors, i.e., of the patterns of quark masses and mixing, and of the charged lepton and neutrino masses and of neutrino mixing and of CP violation in the quark and lepton sectors, is one of the most challenging still unresolved fundamental problem in contemporary particle physics.

“Asked what single mystery, if he could choose, he would like to see solved in his lifetime, Weinberg doesn’t have to think for long: he wants to be able to explain the observed pattern of quark and lepton masses.”

From “Model Physicist”, CERN Courier, 13 October 2017.

The renewed attempts to seek new better solutions of the flavour problem than those already proposed were stimulated primarily by the remarkable progress made in the studies of neutrino oscillations, which began 25 years ago with the discovery of oscillations of atmospheric  $\nu_\mu$  and  $\bar{\nu}_\mu$  by SuperKamiokande experiment. This lead, in particular, to the determination of the pattern of the 3-neutrino mixing, which turn out to consist of two large and one small mixing angles.

In what follows we will discuss a new approach to the flavour problem within the three family framework.

# The Lepton Flavour Problem

Consists of three basic elements (sub-problems), namely, understanding:

- Why  $m_{\nu_j} \lll m_{e,\mu,\tau}, m_q$ ,  $q = u, c, t, d, s, b$  ( $m_{\nu_j} \lesssim 0.5$  eV,  $m_l \geq 0.511$  MeV,  $m_q \gtrsim 2$  MeV);
- The origins of the patterns of
  - i) neutrino mixing of 2 large and 1 small angles ( $\theta_{12}^l = 33.65^\circ$ ,  $\theta_{23}^l = 47.1^\circ$ ,  $\theta_{13}^l = 8.49^\circ$ ), and of ii)  $\Delta m_{ij}^2$ , i.e., of  $\Delta m_{21}^2 \ll |\Delta m_{31}^2|$ ,  $\Delta m_{21}^2/|\Delta m_{31}^2| \cong 1/30$ .
- The origin of the hierarchical pattern of charged lepton masses:  $m_e \ll m_\mu \ll m_\tau$ ,  $m_e/m_\mu \cong 1/200$ ,  $m_\mu/m_\tau \cong 1/17$ .

The first two added new important aspects to the flavour problem.

$$m_{\nu_j} \lll m_{e,\mu,\tau}, m_q, q = u, c, t, d, s, b:$$

seesaw mechanism(s), Weinberg operator, radiative  $\nu$  mass generation, extra dimensions. However, additional input (symmetries) needed to explain the pattern of lepton mixing and to get specific testable predictions.

# The quark Flavour Problem

Consists of three basic elements (sub-problems), namely, understanding:

- The origin(s) of the observed patterns of up- and down-type quark masses characterized by strong hierarchies.

$$m_d \ll m_s \ll m_b, \quad \frac{m_d}{m_s} = 5.02 \times 10^{-2}, \quad \frac{m_s}{m_b} = 2.22 \times 10^{-2}, \quad m_b = 4.18 \text{ GeV};$$

$$m_u \ll m_c \ll m_t, \quad \frac{m_u}{m_c} = 1.7 \times 10^{-3}, \quad \frac{m_c}{m_t} = 7.3 \times 10^{-3}, \quad m_t = 172.9 \text{ GeV};$$

- The origin of the pattern of the quark mixing: the three quark mixing angles are small and hierarchical,  $\sin \theta_{13}^q \ll \sin \theta_{23}^q \ll \sin \theta_{12}^q \ll 1$ ,  $\sin \theta_{12}^q \cong 0.22$ ,  $\sin \theta_{12}^q \cong 0.22$ ,  $\sin \theta_{23}^q \cong 0.042$ ,  $\sin \theta_{13}^q \cong 0.0038$  ( $\theta_{12}^q = 12.96^\circ$ ,  $\theta_{23}^q = 2.42^\circ$ ,  $\theta_{13}^q = 0.22^\circ$ ).

- The origin and magnitude of CP violation in the quark sector.

Each of the considered sub-problems of the lepton and quark flavour problems is by itself a formidable problem. As a consequence, solutions to each individual problem have been proposed. However, a universal "elegant and convincing" solution, i.e., solution without significant "drawbacks", to the lepton and quark flavour problems is still lacking. I will describe a novel approach to the flavour problem that seems promising.

# Considered Solutions to the Lepton and Quark Flavour Problems

- $m_{\nu_j} \ll \ll m_{e,\mu,\tau}, m_q, q = u, c, t, d, s, b$ :

seesaw mechanism, Weinberg operator, radiative  $\nu$  mass generation, extra dimensions.

However, additional input (symmetries) needed to explain the pattern of lepton mixing and to get specific testable predictions.

- **The origin of the hierarchical pattern of charged lepton and quark masses.**

The best qualitative explanation is arguably provided by the Froggatt-Nielsen mechanism based on  $U(1)_{FN}$  flavour symmetry and its generalisations.

Problems: predictions suffer from large uncertainties; most naturally accommodates small mixing angles, while two lepton mixing angles are large.

- **The origins of the patterns of neutrino mixing of 2 large and 1 small angles.**

Arguably the most elegant and natural explanation is obtained within the non-Abelian discrete flavour symmetry approach to the problem.

However, the symmetry breaking in the lepton and quark flavour models based on non-Abelian discrete symmetries is impressively cumbersome: it requires the introduction of a plethora of “flavon” scalar fields having elaborate potentials, which in turn require the introduction of a number of “driving fields” and large shaping symmetries to ensure the requisite breaking of the symmetry leading to correct mass and mixing patterns.

To give an example, in the lepton flavour model based on the  $T'$  symmetry constructed in I. Girardi et al., arXiv:1312.1966, there are 3 doublets, 4 triplets and 7 singlets of flavon fields and the scalar potential has a  $Z_8 \times Z_4 \times Z_4 \times Z_3 \times Z_3 \times Z_2$  shaping symmetry.

**Combining the proposed individual “solutions” of the related sub-problems it is difficult, if not impossible, to avoid the drawbacks of each of the “ingredient” sub-problem “solutions”. In some cases this can be achieved at the cost of severe fine-tuning.**

# The Flavour Problem: Modular Invariance Approach

Modular invariance approach to the flavour problem was proposed in F. Feruglio, arXiv:1706.08749 and has been intensively developed in the last seven years.

In this approach the flavour (modular) symmetry is broken by the vacuum expectation value (VEV) of a single scalar field - the modulus  $\tau$ . The VEV of  $\tau$  can also be the only source of violation of the CP symmetry.

Many (if not all) of the drawbacks of the widely studied alternative approaches are absent in the modular invariance approach to the flavour problem.

The first phenomenologically viable “minimal” (in terms of fields, i.e., without flavons) lepton flavour model based on modular symmetry appeared in June of 2018 (J.T. Penedo, STP, arXiv:1806.11040). Later it was shown that one of the flavon-less models considered in F. Feruglio, arXiv:1706.08749 is also phenomenologically viable. Since then various aspects of this approach were and continue to be extensively studied – the number of publications on the topic currently exceeds 395.

The talk is based on some of the following articles.

1. S. T. Petcov and M. Tanimoto, “ $S'_4$  Quark Flavour Model in the Vicinity of the Fixed Point  $= i\infty$ ”, [arXiv:2601.04529 [hep-ph]].
2. A. Granelli, D. Meloni, M. Parriciatu, J. T. Penedo and S. T. Petcov, “Modular-symmetry-protected seesaw,” JHEP 12 (2025) 035 [arXiv:2505.21405 [hep-ph]].
3. G. J. Ding, E. Lisi, A. Marrone and S. T. Petcov, “Interplay and correlations between quark and lepton observables in modular symmetry models,” Phys. Rev. D 111 (2025) 075024 [arXiv:2409.15823 [hep-ph]].
4. G. J. Ding, J. N. Lu, S. T. Petcov and B. Y. Qu, “Non-holomorphic modular  $S_4$  lepton flavour models,” JHEP 01 (2025) 191 [arXiv:2408.15988 [hep-ph]].
5. J. T. Penedo and S. T. Petcov, “Finite modular symmetries and the strong CP problem,” JHEP 10 (2024) 172 [arXiv:2404.08032 [hep-ph]].
6. S. T. Petcov and M. Tanimoto, “ $A_4$  modular invariance and the strong CP problem,” Eur. Phys. J. C 84 (2024) 914 [arXiv:2404.00858 [hep-ph]].
7. S. T. Petcov, “On the normalisation of the modular forms in modular invariant theories of flavour,” Phys. Lett. B 850 (2024) 138540 [arXiv:2311.04185 [hep-ph]].
8. I. de Medeiros Varzielas, M. Levy, J. T. Penedo and S. T. Petcov, “Quarks at the Modular  $S_4$  Cusp”, JHEP 09 (2023) 196 [arXiv:2307.14410].
9. S.T. Petcov and M. Tanimoto, “ $A_4$  Modular Flavour Model of Quark Mass Hierarchies Close to the Fixed Point  $\tau = i\infty$ ”, JHEP 08 (2023) 086 [arXiv:2306.05730].
10. S.T. Petcov and M. Tanimoto, “ $A_4$  Modular Flavour Model of Quark Mass Hierarchies Close to the Fixed Point  $\tau = \omega$ ”, EPJ C 83 (2023) 579 [arXiv:2212.13336].

11. P.P. Novichkov, J.T. Penedo and S.T. Petcov, “Modular Symmetries and Modulus stabilisation”, JHEP 03 (2022) 149 [arXiv:2201.02020].
12. P.P. Novichkov, J.T. Penedo and S.T. Petcov, “Fermion Mass Hierarchies, Large Lepton Mixing and Residual Modular Symmetries”, JHEP 2104 (2021) 206 [arXiv:2102.07488].
13. P.P. Novichkov, J.T. Penedo and S.T. Petcov, “Modular Flavour Symmetries and Modulus Stabilisation”, JHEP 2203 (2022) 149 [arXiv:2201.02020].
14. P.P. Novichkov, J.T. Penedo and S.T. Petcov, “Double cover of modular  $S_4$  for flavour model building”, Nucl. Phys. B 963 (2021) 115301 [arXiv:2006.03058].
15. P.P. Novichkov, J.T. Penedo and S.T. Petcov, A.V. Titov, “Generalised CP Symmetry in Modular-Invariant Models of Flavour”, JHEP 1907 (2019) 165 [arXiv:1905.11970].
16. P.P. Novichkov, S.T. Petcov and M. Tanimoto, “Trimaximal Neutrino Mixing from Modular  $A_4$  Invariance with Residual Symmetries,” Phys. Lett. B 793 (2019) 247 [arXiv:1812.11289].
17. P.P. Novichkov, J.T. Penedo and S.T. Petcov, A.V. Titov, “Modular  $A_5$  symmetry for flavour model building,” JHEP 1904 (2019) 174 [arXiv:1812.02158].
18. P.P. Novichkov, J.T. Penedo and S.T. Petcov, A.V. Titov, “Modular  $S_4$  models of lepton masses and mixing,” JHEP 1904 (2019) 005 [arXiv:1811.04933].
19. 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].

# Matter Fields and Modular Forms

The matter(super)fields (charged lepton, neutrino, quark) transform under  $\bar{\Gamma} \simeq PSL(2, \mathbb{Z}) = SL(2, \mathbb{Z})/\mathbb{Z}_2$ ,  $\mathbb{Z}_2 = \{I, -I\}$  ( $\Gamma \simeq SL(2, \mathbb{Z})$ ) as "weighted" multiplets:

$$\psi_i \xrightarrow{\gamma} (c\tau + d)^{-k_\psi} \rho_{ij}(\tilde{\gamma}) \psi_j, \tilde{\gamma} \in \Gamma_N (\gamma \in \Gamma(N)),$$

$$\left( \gamma\tau = \frac{a\tau + b}{c\tau + d}, \gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix}, a, b, c, d \in \mathbb{Z}, ad - bc = 1, \text{Im}\tau > 0 \right)$$

$k_\psi$  is the weight of  $\psi$ ;  $k_\psi \in \mathbb{Z}$  (or rational number).

$\Gamma(N)$  - principal congruence (normal) subgroup of  $SL(2, \mathbb{Z})$ .

$\rho(\tilde{\gamma})$  is a unitary representation of the inhomogeneous (homogeneous) finite modular group  $\Gamma_N = \bar{\Gamma}/\bar{\Gamma}(N)$  ( $\Gamma'_N = \Gamma/\Gamma(N)$ ),  $\tilde{\gamma}$  - representation of  $\gamma$  in  $\Gamma_N$  ( $\Gamma'_N$ )

F. Feruglio, arXiv:1706.08749; S. Ferrara et al., Phys.Lett. B233 (1989) 147, B225 (1989) 363

As we have indicated in brackets, one can consider also the case of  $\Gamma$  and  $\gamma \in \Gamma(N)$ . Then  $\rho(\gamma)$  will be a unitary representation of the homogeneous finite modular group  $\Gamma'_N$ .

**The group  $\Gamma \equiv SL(2, \mathbb{Z})$  is generated by the matrices**

$$S = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}, \quad T = \begin{pmatrix} 1 & 1 \\ 0 & 1 \end{pmatrix}, \quad R = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix},$$

**obeying  $S^2 = R$ ,  $(ST)^3 = R^2 = \mathbf{I}$ , and  $RT = TR$ .**

**Thus,**

$$S\tau = -\frac{1}{\tau} \quad T\tau = \tau + 1.$$

**Remarkably, for  $N \leq 5$ , the inhomogeneous finite modular groups  $\Gamma_N$  are isomorphic to non-Abelian discrete groups widely used in flavour model building:**

$\Gamma_2 \simeq S_3$ ,  $\Gamma_3 \simeq A_4$ ,  $\Gamma_4 \simeq S_4$  and  $\Gamma_5 \simeq A_5$ .

$\Gamma_N$  is presented by two generators  $S$  and  $T$  satisfying:

$$S^2 = (ST)^3 = T^N = I.$$

The group theory of  $\Gamma_2 \simeq S_3$ ,  $\Gamma_3 \simeq A_4$ ,  $\Gamma_4 \simeq S_4$  and  $\Gamma_5 \simeq A_5$  is summarized, e.g., in P.P. Novichkov *et al.*, **JHEP 07 (2019) 165**, [arXiv:1905.11970](https://arxiv.org/abs/1905.11970).

$\Gamma \simeq SL(2, \mathbb{Z})$  – homogeneous modular group,  $\Gamma(N)$  and the quotient groups  $\Gamma'_N \equiv \Gamma/\Gamma(N)$  – homogeneous finite modular groups. For  $N = 3, 4, 5$ ,  $\Gamma'_N$  are isomorphic to the double covers of the corresponding non-Abelian discrete groups:

$\Gamma'_3 \simeq A'_4 \equiv T'$ ,  $\Gamma'_4 \simeq S'_4$  and  $\Gamma'_5 \simeq A'_5$ .

$\Gamma'_N$  is presented by two generators  $S$  and  $T$  satisfying:

$$S^4 = (ST)^3 = T^N = I, \quad S^2 T = T S^2 \quad (S^2 = R).$$

The group theory of  $\Gamma'_3 \simeq A'_4$ ,  $\Gamma'_4 \simeq S'_4$  and  $\Gamma'_5 \simeq A'_5$  for flavour model building was developed in X.-G. Liu, G.-J. Ding, [arXiv:1907.01488](https://arxiv.org/abs/1907.01488) ( $A'_4$ );

P.P. Novichkov *et al.*, [arXiv:2006.03058](https://arxiv.org/abs/2006.03058) ( $S'_4$ ); C.-Y. Yao *et al.*, [arXiv:2011.03501](https://arxiv.org/abs/2011.03501) ( $A'_5$ ).



## Relevant sub-groups of $\Gamma_N$ and $\Gamma'_N$ :

$$\mathbb{Z}_3^{ST} = \{I, ST, (ST)^2\}$$

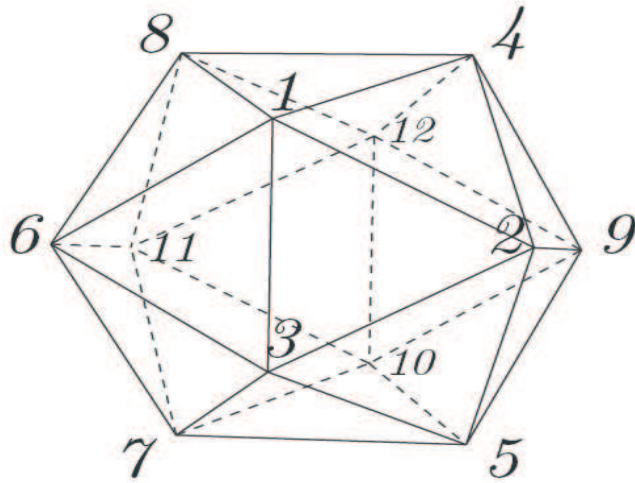
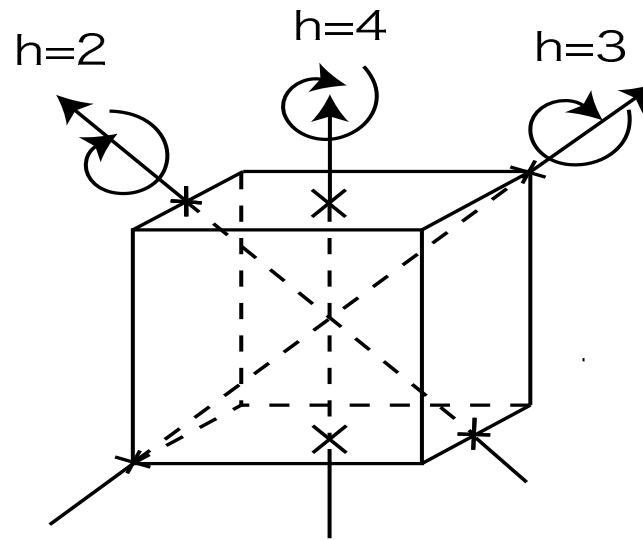
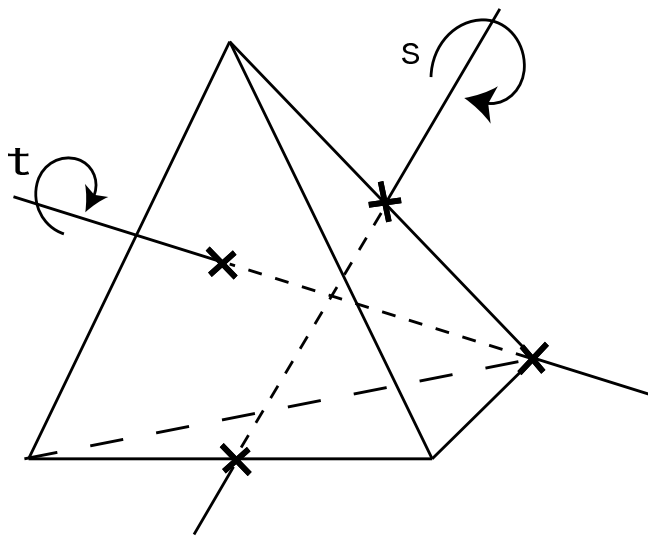
$$\mathbb{Z}_N^T = \{I, T, (T)^2, \dots, T^{N-1}\}$$

$$\Gamma_N: \mathbb{Z}_2^S = \{I, S\}$$

$$\Gamma'_N: \mathbb{Z}_4^S = \{I, S, S^2, S^3\} \quad (R^2 = I, \mathbb{Z}_2^R = \{I, R\}, R\tau = \tau)$$

Group	Number of elements	Generators	Irreducible representations
$S_4$	24	$S, T (U)$	$1, 1', 2, 3, 3'$
$S'_4$	48	$S, T (R)$	$1, 1', 2, 3, 3', \hat{1}, \hat{1}', \hat{2}, \hat{3}, \hat{3}'$
$A_4$	12	$S, T$	$1, 1', 1'', 3$
$T'$	24	$S, T (R)$	$1, 1', 1'', 2, 2', 2'', 3$
$A_5$	60	$\tilde{S}, \tilde{T}$	$1, 3, 3', 4, 5$
$A'_5$	120	$\tilde{S}, \tilde{T}$	$1, 3, 3', 4, 5, \hat{2}, \hat{2}', \hat{4}, \hat{6}$ .

**Number of elements, generators and irreducible representations of  $S_4, S'_4, A_4, A'_4 \equiv T', A_5$  and  $A'_5$  discrete groups.**



Examples of symmetries:  $A_4$ ,  $S_4$ ,  $A_5$ .

From M. Tanimoto et al., arXiv:1003.3552

# Modular Forms

Within the considered framework the elements of the Yukawa coupling and fermion mass matrices in the Lagrangian of the theory are expressed in terms of modular forms of a certain level  $N$  and weight  $k_f$ .

**The modular forms are functions of a single complex scalar field – the modulus  $\tau$  – and have specific transformation properties under the action of the modular group.**

Both the Yukawa couplings and the matter fields (supermultiplets) are assumed to transform in representations of an inhomogeneous (homogeneous) finite modular group  $\Gamma_N^{(\prime)}$ . Once  $\tau$  acquires a VEV, the modular forms and thus the Yukawa couplings and the form of the mass matrices get fixed, and a certain flavour structure arises.

**Quantitatively and barring fine-tuning, the magnitude of the values of the non-zero elements of the fermion mass matrices and therefore the fermion mass ratios are determined by the modular form values (which in turn are functions of the  $\tau$ 's VEV).**

# Modular Forms (contd.)

The key elements of the considered framework are modular forms  $f(\tau)$  of weight  $k_f$  and level  $N$  – holomorphic functions of  $\tau$ , which transform under  $\bar{\Gamma}(\Gamma)$  as follows:

$$F(\gamma\tau) = (c\tau + d)^{k_F} \rho_{\mathbf{r}}(\tilde{\gamma}) F(\tau), \quad \tilde{\gamma} \in \Gamma_N (\gamma \in \Gamma(N)),$$

F. Feruglio, arXiv:1706.08749

$\rho_{\mathbf{r}}$  is a unitary representation of the finite modular group  $\Gamma_N (\Gamma'_N)$ .

In the case of  $\bar{\Gamma}(\Gamma)$  non-trivial modular forms exist only for **positive even integer (positive integer)** weight  $k_F$ .

For given  $k, N$  ( $N$  is a natural number), the modular forms span a linear space of finite dimension:

of weight  $k$  and level 3,  $\mathcal{M}_k(\Gamma_3^{(\prime)} \simeq A_4^{(\prime)})$ , is  $k + 1$ ;

of weight  $k$  and level 4,  $\mathcal{M}_k(\Gamma_4^{(\prime)} \simeq S_4^{(\prime)})$ , is  $2k + 1$ ;

of weight  $k$  and level 5,  $\mathcal{M}_k(\Gamma_5^{(\prime)} \simeq A_5^{(\prime)})$ , is  $5k + 1$ .

Thus,  $\dim \mathcal{M}_1(\Gamma'_3 \simeq A'_4) = 2$ ,  $\dim \mathcal{M}_1(\Gamma'_4 \simeq S'_4) = 3$ ,  $\dim \mathcal{M}_1(\Gamma'_5 \simeq A'_5) = 6$ .

Multiplets of  $\Gamma_N (\Gamma'_N)$  of higher weight modular forms can be constructed from tensor products of the lowest weight 2 (weigh 1) multiplets (they represent homogeneous polynomials of the lowest weight modular forms).

Following arXiv:1706.08749, it was of highest priority and of crucial importance for model building to find the basis of modular forms of the **lowest weight 2 (weight 1)** transforming in irreps of  $\Gamma_N$  ( $\Gamma'_N$ ).

**It took about two years to find the requisite bases for  $\Gamma_N$  ( $\Gamma'_N$ ),  $N = 2, 3, 4, 5$ .**

F. Feruglio, 1706.08749 ( $\Gamma_3 \simeq A_4$ ,  $k_f = 2$ : the 3 mod. forms form a 3 of  $A_4$ );

T. Kobayashi et al., 1803.10391 ( $\Gamma_2 \simeq S_3$ ,  $k_f = 2$ : the 2 mod. forms form a 2 of  $S_3$ );

J. Penedo, STP, 1806.11040 ( $\Gamma_4 \simeq S_4$ ,  $k_f = 2$ : the 5 mod. forms form a 2 and 3' of  $S_4$ );

P.P. Novichkov et al., 1812.02158; G.-J. Ding et al., 1903.12588 ( $\Gamma_5 \simeq A_5$ ),  $k_f = 2$ : the 11 basis modular forms were shown to form a 3, a 3' and a 5 of  $A_5$ ).

**More elegant construction: modular forms for  $A'_4$ ,  $S'_4$ ,  $A'_5$  (and  $A_4$ ,  $S_4$ ,  $A_5$ ).**

The weight 1 modular forms

i) of  $A'_4$  form a 2 of  $A'_4$ , ii) of  $S'_4$  form a  $\hat{3}$  of  $S'_4$ , iii) of  $A'_5$  form a 5 of  $A'_5$ ,

as was proven respectively in X.-G. Liu, G.-J. Ding, 1907.01488, P.P. Novichkov et al., 2006.03058 and C.-Y. Yao et al., 2011.03501.

In each of the cases of  $A'_4$ ,  $S'_4$  and  $A'_5$  the lowest weight 1 modular forms, and thus all higher weight modular forms, including those (of even weight) associated with  $A_4$ ,  $S_4$  and  $A_5$ , constructed from tensor products of the weight 1 multiplets, were shown in the three quoted articles to be **expressed in terms of only two independent functions of  $\tau$** .

These pairs of functions are different for the three different groups; but they all are related (in different ways) to the Dedekind  $\eta$ -function (in the case of  $A'_5$  ( $A_5$ ) - to two Jacobi theta constants also) and have similar (fastly converging)  $q$ -expansions, i.e., power series expansions in  $q = e^{2\pi i\tau}$ .

Thus, in the case of a flavour symmetry described by a finite modular group  $\Gamma_N^{(l)}$ ,  $N = 2, 3, 4, 5$ , the elements of the matrices of the Yukawa couplings in the considered approach represent homogeneous polynomials of various degree of only two (holomorphic) functions of  $\tau$ . They include also a limited (relatively small) number of constant parameters.

The modular forms of level  $N = 2, 3, 4, 5$  for  $\Gamma_{2,3,4,5}^{(\iota)} \simeq S_3, A_4^{(\iota)}, S_4^{(\iota)}, A_5^{(\iota)}$  have been constructed by use of the Dedekind eta function,  $\eta(\tau)$ :

$$\eta(\tau) = q^{\frac{1}{24}} \prod_{n=1}^{\infty} (1 - q^n) = q^{\frac{1}{24}} \sum_{n=-\infty}^{\infty} (-1)^n q^{\frac{n(3n-1)}{2}}, \quad q = e^{i2\pi\tau}.$$

In the cases of  $\Gamma_5^{(\iota)} \simeq A_5^{(\iota)}$  two “Jacobi theta constants” are also used.

**Modular forms of level  $N = 4$  for  $\Gamma'_4 \simeq S'_4$  ( $\Gamma_4 \simeq S_4$ ) – in terms of  $\theta(\tau)$ ,  $\varepsilon(\tau)$ :**

$$\theta(\tau) \equiv \frac{\eta^5(2\tau)}{\eta^2(\tau)\eta^2(4\tau)} = \Theta_3(2\tau), \quad \varepsilon(\tau) \equiv \frac{2\eta^2(4\tau)}{\eta(2\tau)} = \Theta_2(2\tau).$$

$\Theta_2(\tau)$  and  $\Theta_3(\tau)$  are the Jacobi theta constants,  $\eta(a\tau)$ ,  $a = 1, 2, 4$ , is the Dedekind eta.

**Modular forms of level  $N = 3$  for  $\Gamma'_3 \simeq A'_4$  ( $\Gamma_3 \simeq A_4$ ) – in terms of  $\hat{e}_1$  and  $\hat{e}_2$ :**

$$\hat{e}_1 = \frac{\eta^3(3\tau)}{\eta(\tau)}, \quad \hat{e}_2 = \frac{\eta^3(\tau/3)}{\eta(\tau)}.$$

**Modular forms of level  $N = 5$  for  $\Gamma'_5 \simeq A'_5$  ( $\Gamma_5 \simeq A_5$ ) – in terms of  $\theta_5(\tau)$  and  $\varepsilon_5(\tau)$ :**

$$\theta_5(\tau) = \exp(-i\pi/10) \Theta_{\frac{1}{10}, \frac{1}{2}}(5\tau) \eta^{-3/5}(\tau), \quad \varepsilon_5(\tau) = \exp(-i3\pi/10) \Theta_{\frac{3}{10}, \frac{1}{2}}(5\tau) \eta^{-3/5}(\tau).$$

# Example: $S'_4$

P.P. Novichkov, J.T. Penedo. S.T.P., arXiv:2006.03058

**Weight 1 modular forms furnishing a  $\hat{3}$  of  $S'_4$ :**

$$Y_{\hat{3}}^{(1)}(\tau) = \begin{pmatrix} \sqrt{2}\varepsilon\theta \\ \varepsilon^2 \\ -\theta^2 \end{pmatrix}$$

**Modular  $S_4$  lowest-weight 2 multiplets furnish a 2 and a 3' irreducible representations of  $S_4$  ( $S'_4$ ) and are given by :**

$$Y_2^{(2)}(\tau) = \begin{pmatrix} \frac{1}{\sqrt{2}}(\theta^4 + \varepsilon^4) \\ -\sqrt{6}\varepsilon^2\theta^2 \end{pmatrix} = \begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix}, \quad Y_{3'}^{(2)}(\tau) = \begin{pmatrix} \frac{1}{\sqrt{2}}(\theta^4 - \varepsilon^4) \\ -2\varepsilon\theta^3 \\ -2\varepsilon^3\theta \end{pmatrix} = \begin{pmatrix} Y_3 \\ Y_4 \\ Y_5 \end{pmatrix}.$$

**At weight  $k = 3$ , a non-trivial singlet and two triplets exclusive to  $S'_4$  arise:**

$$Y_{\hat{1}'}^{(3)}(\tau) = \sqrt{3}(\varepsilon\theta^5 - \varepsilon^5\theta),$$

$$Y_{\hat{3}}^{(3)}(\tau) = \begin{pmatrix} \varepsilon^5\theta + \varepsilon\theta^5 \\ \frac{1}{2\sqrt{2}}(5\varepsilon^2\theta^4 - \varepsilon^6) \\ \frac{1}{2\sqrt{2}}(\theta^6 - 5\varepsilon^4\theta^2) \end{pmatrix}, \quad Y_{\hat{3}'}^{(3)}(\tau) = \frac{1}{2} \begin{pmatrix} -4\sqrt{2}\varepsilon^3\theta^3 \\ \theta^6 + 3\varepsilon^4\theta^2 \\ -3\varepsilon^2\theta^4 - \varepsilon^6 \end{pmatrix}.$$

**At weight  $k = 4$  one again recovers the  $S_4$  result: the modular forms furnish a 1, 2, 3 and 3' irreducible representations of  $S_4$  ( $S'_4$ ).**

$$Y_1^{(4)}(\tau) = \frac{1}{2\sqrt{3}}(\theta^8 + 14\varepsilon^4\theta^4 + \varepsilon^8), \quad Y_2^{(4)}(\tau) = \begin{pmatrix} \frac{1}{4}(\theta^8 - 10\varepsilon^4\theta^4 + \varepsilon^8) \\ \sqrt{3}(\varepsilon^2\theta^6 + \varepsilon^6\theta^2) \end{pmatrix},$$

$$Y_3^{(4)}(\tau) = \frac{3}{2\sqrt{2}} \begin{pmatrix} \sqrt{2}(\varepsilon^2\theta^6 - \varepsilon^6\theta^2) \\ \varepsilon^3\theta^5 - \varepsilon^7\theta \\ -\varepsilon\theta^7 + \varepsilon^5\theta^3 \end{pmatrix}, \quad Y_{3'}^{(4)}(\tau) = \begin{pmatrix} \frac{1}{4}(\theta^8 - \varepsilon^8) \\ \frac{1}{2\sqrt{2}}(\varepsilon\theta^7 + 7\varepsilon^5\theta^3) \\ \frac{1}{2\sqrt{2}}(7\varepsilon^3\theta^5 + \varepsilon^7\theta) \end{pmatrix},$$

The functions  $\theta(\tau)$  and  $\varepsilon(\tau)$  are given by:

$$\theta(\tau) \equiv \frac{\eta^5(2\tau)}{\eta^2(\tau)\eta^2(4\tau)} = \Theta_3(2\tau), \quad \varepsilon(\tau) \equiv \frac{2\eta^2(4\tau)}{\eta(2\tau)} = \Theta_2(2\tau).$$

$\Theta_2(\tau)$  and  $\Theta_3(\tau)$  are the Jacobi theta constants,  $\eta(a\tau)$ ,  $a = 1, 2, 4$ , is the Dedekind eta function.

The functions  $\theta(\tau)$  and  $\varepsilon(\tau)$  admit the following  $q$ -expansions - power series expansions in  $q_4 \equiv \exp(i\pi\tau/2)$  ( $\text{Im}(\tau) \geq \sqrt{3}/2$ ,  $|q_4| \lesssim 0.26$ ) :

$$\theta(\tau) = 1 + 2 \sum_{k=1}^{\infty} q_4^{(2k)^2} = 1 + 2q_4^4 + 2q_4^{16} + \dots,$$

$$\varepsilon(\tau) = 2 \sum_{k=1}^{\infty} q_4^{(2k-1)^2} = 2q_4 + 2q_4^9 + 2q_4^{25} + \dots$$

In the “large volume” limit  $\text{Im}\tau \rightarrow \infty$ ,  $\theta \rightarrow 1$ ,  $\varepsilon \rightarrow 0$ .

In this limit  $\varepsilon \sim 2q_4$  and  $\mathcal{E}$  can be used as an expansion parameter instead of  $q_4$ .

Due to quadratic dependence in the exponents of  $q_4$ , the  $q$ -expansion series converge rapidly in the fundamental domain of the modular group, where  $\text{Im}(\tau) \geq \sqrt{3}/2$  and  $|q_4| \leq \exp(-\pi\sqrt{3}/4) \simeq 0.26$ .

Similar conclusions are valid for the pair of functions in terms of which the lowest weight 1 modular forms, and thus all higher weight modular forms of  $A'_4$  and  $A'_5$  are expressed.

## Example: $A'_5$

C.-Y. Yao et al., arXiv:2011.03501

Weight 1 modular forms furnishing a  $\hat{6}$  of  $A'_5$ :

$$Y_{\hat{6}}^{(1)}(\tau) = \left( 2\varepsilon_5^5 + \theta_5^5, 2\theta_5^5 - \varepsilon_5^5, 5\varepsilon_5\theta_5^4, 5\sqrt{2}\varepsilon_5^2\theta_5^3, -5\sqrt{2}\varepsilon_5^3\theta_5^2, 5\varepsilon_5^4\theta_5 \right)^T.$$

The functions  $\theta_5(\tau)$  and  $\varepsilon_5(\tau)$  are related to the Dedekind eta function and the Jacobi theta constants and have the following  $q$ -expansions:

$$\begin{aligned} \theta_5(\tau) &= 1 + \frac{3}{5}q_5^5 + \frac{2}{25}q_5^{10} - \frac{28}{125}q_5^{15} + \dots, \\ \varepsilon_5(\tau) &= q_5 \left( 1 - \frac{2}{5}q_5^5 + \frac{12}{25}q_5^{10} + \frac{37}{125}q_5^{15} + \dots \right), \quad q_5 \equiv \exp(i2\pi\tau/5). \end{aligned}$$

In the “large volume” limit  $\text{Im}\tau \rightarrow \infty$ , similar to the  $S'_4$  two functions,  $\theta_5 \rightarrow 1$ ,  $\varepsilon_5 \rightarrow 0$ .

In this limit  $\varepsilon_5 \sim q_5$  and  $\varepsilon_5$  can be used as an expansion parameter instead of  $q_5$ . The  $q_5$ -expansion series converge rapidly in the fundamental domain of the modular group, where  $\text{Im}(\tau) \geq \sqrt{3}/2$  and  $|q_5| \leq \exp(-\pi\sqrt{3}/5) \simeq 0.34$ .

# The Framework

$\mathcal{N} = 1$  rigid (global) SUSY, the matter action  $\mathcal{S}$  reads:

$$\mathcal{S} = \int d^4x d^2\theta d^2\bar{\theta} K(\tau, \bar{\tau}, \psi, \bar{\psi}) + \left( \int d^4x d^2\theta W(\tau, \psi) + \text{h.c.} \right),$$

$K$  is the Kähler potential,  $W$  is the superpotential,  $\psi$  denotes a set of chiral supermultiplets  $\psi_i$ ,  $\theta$  and  $\bar{\theta}$  are Grassmann variables;

$\tau$  is the modulus chiral superfield, whose lowest component is the complex scalar field acquiring a VEV (we use in what follows the same notation  $\tau$  for the lowest complex scalar component of the modulus superfield and call this component also “modulus”).

$\tau$  and  $\psi_i$  transform under the action of  $\bar{\Gamma}$  ( $\Gamma$ ) in a certain way (S. Ferrara et al., PL B225 (1989) 363 and B233 (1989) 147). Assuming that  $\psi_i = \psi_i(x)$  transform in a certain irrep  $\mathbf{r}_i$  of  $\Gamma_N$  ( $\Gamma'_N$ ), the transformations read:

$$\gamma = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in \bar{\Gamma} (\Gamma) : \begin{cases} \tau \rightarrow \frac{a\tau + b}{c\tau + d}, \\ \psi_i \rightarrow (c\tau + d)^{-k_i} \rho_{\mathbf{r}_i}(\gamma) \psi_i. \end{cases}$$

$\psi_i$  is not a modular form multiplet, the integer  $(-k_i)$  can be  $> 0$ ,  $< 0$ ,  $0$ .

Invariance of  $\mathcal{S}$  under these transformations implies (global SUSY):

$$\begin{cases} W(\tau, \psi) \rightarrow W(\tau, \psi), \\ K(\tau, \bar{\tau}, \psi, \bar{\psi}) \rightarrow K(\tau, \bar{\tau}, \psi, \bar{\psi}) + f_K(\tau, \psi) + \overline{f_K}(\bar{\tau}, \bar{\psi}). \end{cases}$$

The second line represents a Kähler transformation.

An example Kähler potential that is widely used in model building reads:

$$K(\tau, \bar{\tau}, \psi, \bar{\psi}) = -\Lambda_0^2 \log(-i\tau + i\bar{\tau}) + \sum_i \frac{|\psi_i|^2}{(-i\tau + i\bar{\tau})^{k_i}},$$

$\Lambda_0 > 0$  having mass dimension one.

More general  $K(\tau, \bar{\tau}, \psi, \bar{\psi})$  and the possible consequences they can have for flavour model building are discussed in

Mu-Chun Chen et al., arXiv:1909.06910 and 2108.02240; Y. Almumin et al., arXiv:2102.11286.

$$W(\tau, \psi) \rightarrow W(\tau, \psi),$$

The superpotential can be expanded in powers of  $\psi_i$ :

$$W(\tau, \psi) = \sum_n \sum_{\{i_1, \dots, i_n\}} \sum_s g_{i_1 \dots i_n, s} (Y_{i_1 \dots i_n, s}(\tau) \psi_{i_1} \dots \psi_{i_n})_{\mathbf{1}, s},$$

$\mathbf{1}$  stands for an invariant singlet of  $\Gamma_N$  ( $\Gamma'_N$ ). For each set of  $n$  fields  $\{\psi_{i_1}, \dots, \psi_{i_n}\}$ , the index  $s$  labels the independent singlets. Each of these is accompanied by a coupling constant  $g_{i_1 \dots i_n, s}$  and is obtained using a modular multiplet  $Y_{i_1 \dots i_n, s}$  of the requisite weight. To ensure invariance of  $W$  under  $\Gamma_N$  ( $\Gamma'_N$ ),  $Y_{i_1 \dots i_n, s}(\tau)$  must transform as:

$$Y(\tau) \xrightarrow{\gamma} (c\tau + d)^{k_Y} \rho_{\mathbf{r}_Y}(\gamma) Y(\tau),$$

$\mathbf{r}_Y$  is a representation of  $\Gamma_N$  ( $\Gamma'_N$ ), and  $k_Y$  and  $\mathbf{r}_Y$  are such that

$$k_Y = k_{i_1} + \dots + k_{i_n}, \quad (1)$$

$$\mathbf{r}_Y \otimes \mathbf{r}_{i_1} \otimes \dots \otimes \mathbf{r}_{i_n} \supset \mathbf{1}. \quad (2)$$

Thus,  $Y_{i_1 \dots i_n, s}(\tau)$  represents a multiplet of weight  $k_Y$  and level  $N$  modular forms transforming in the representation  $\mathbf{r}_Y$  of  $\Gamma_N$  ( $\Gamma'_N$ ).

# Mass Matrices

Consider the bilinear (i.e., mass term)

$$\psi_i^c M(\tau)_{ij} \psi_j,$$

where the superfields  $\psi$  and  $\psi^c$  transform as

$$\begin{aligned} \psi &\xrightarrow{\gamma} (c\tau + d)^{-k} \rho_r(\gamma) \psi \quad (\rho(\gamma), \Gamma_N^{(l)}, N = 2, 3, 4, 5), \\ \psi^c &\xrightarrow{\gamma} (c\tau + d)^{-k^c} \rho_{r^c}^c(\gamma) \psi^c, \quad (\rho^c(\gamma), \Gamma_N^{(l)}). \end{aligned}$$

**Modular invariance:**  $M(\tau)_{ij}$  must be modular form of level  $N$  and weight  $K \equiv k + k^c$ ,

$$M(\tau) \xrightarrow{\gamma} M(\gamma\tau) = (c\tau + d)^K \rho^c(\gamma)^* M(\tau) \rho(\gamma)^\dagger.$$

# Inputs in the Analyses

## Lepton sector: reference 3- $\nu$ mixing scheme

$$\nu_{lL} = \sum_{j=1}^3 U_{lj} \nu_{jL} \quad l = e, \mu, \tau.$$

**Data: 3  $\nu$ s are light:  $\nu_{1,2,3}$ ,  $m_{1,2,3} \lesssim 0.5$  eV;**

**KATRIN:  $m_{\bar{\nu}_e} < 0.45$  eV ( $m_{1,2,3} < 0.45$  eV);**

**Cosmology:  $\sum_j m_j < 0.065\text{--}0.616$  eV (95% CL; 2503.07752).**

**The value of  $\min(m_j)$  and “mass ordering” unknown.**

**$\Delta m_{21}^2$ ,  $|\Delta m_{31}^2|$  - known ( $\text{sgn}(\Delta m_{31}^2)$  - unknown).**

**$\nu_j$ ,  $m_j \neq 0$ : nature - Dirac or Majorana - unknown.**

**The PMNS matrix  $U$  -  $3 \times 3$  unitary:  $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$  - known; **CPV phases  $\delta$ ,  $\alpha_{21}$ ,  $\alpha_{31}$  - unknown.****

**Thus, 5 known + 4 unknown parameters + MO.**

“Known” = measured; “unknown” = not measured.

**$m_e$ ,  $m_\mu$ ,  $m_\tau$  also known - used as input.**

( $\nu$  MO:  $m_1 < m_2 < m_3$  (NO),  $m_3 < m_1 < m_2$  (IO))

# PMNS Matrix: Standard Parametrization

$$U = V P, \quad P = \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\frac{\alpha_{21}}{2}} & 0 \\ 0 & 0 & e^{i\frac{\alpha_{31}}{2}} \end{pmatrix},$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- $s_{ij} \equiv \sin \theta_{ij}$ ,  $c_{ij} \equiv \cos \theta_{ij}$ ,  $\theta_{ij} = [0, \frac{\pi}{2}]$ ,
- $\delta$  - Dirac CPV phase,  $\delta = [0, 2\pi]$ ; CP inv.:  $\delta = 0, \pi, 2\pi$ ;
- $\alpha_{21}, \alpha_{31}$  - Majorana CPV phases; CP inv.:  $\alpha_{21(31)} = k(k')\pi$ ,  $k(k') = 0, 1, 2, \dots$   
S.M. Bilenky et al., 1980
- $\Delta m_{\odot}^2 \equiv \Delta m_{21}^2 \cong 7.34 \times 10^{-5} \text{ eV}^2 > 0$ ,  $\sin^2 \theta_{12} \cong 0.305$ ,  $\cos 2\theta_{12} \gtrsim 0.306$  ( $3\sigma$ ),
- $|\Delta m_{31(32)}^2| \cong 2.448$  (2.502)  $\times 10^{-3} \text{ eV}^2$ ,  $\sin^2 \theta_{23} \cong 0.545$  (0.551), NO (IO) ,
- $\theta_{13}$  - the CHOOZ angle:  $\sin^2 \theta_{13} = 0.0222$  (0.0223)  
F. Capozzi et al. (Bari Group), arXiv:2003.08511.

Parameter	Ordering	Best fit	1 $\sigma$ range	2 $\sigma$ range	3 $\sigma$ range	"1 $\sigma$ " (%)
$\Delta m_{21}^2/10^{-5} \text{ eV}^2$	NO, IO	$7.49^{+0.19}_{-0.19}$	–	–	6.92 – 8.05	–
$\sin^2 \theta_{12}/10^{-1}$	NO, IO	$3.08^{+0.012}_{-0.011}$	–	–	2.75 – 3.45	–
$\Delta m_{31}^2/10^{-3} \text{ eV}^2$	NO	$2.513^{+0.021}_{-0.019}$	–	–	2.451 – 2.578	–
$\Delta m_{32}^2/10^{-3} \text{ eV}^2$	IO	$-2.484 \pm 0.020$	–	–	-2.547 – (-2.421)	–
$\sin^2 \theta_{13}/10^{-2}$	NO	$2.215^{+0.056}_{-0.058}$	–	–	2.0300 – 2.388	–
	IO	$2.231 \pm 0.056$	–	–	2.060 – 2.409	–
$\sin^2 \theta_{23}/10^{-1}$	NO	$4.70^{+0.017}_{-0.013}$	–	–	<b>4.35 – 5.85</b>	–
	IO	$5.50^{+0.012}_{-0.015}$	–	–	<b>4.40 – 5.84</b>	–
$\delta$	NO	$212^{+26}_{-41}$	–	–	124 – 364	–
	IO	$274^{+22}_{-25}$	–	–	<b>201 – 335</b>	–

$$\Delta\chi_{\text{IO-NO}}^2 \quad \text{IO-NO} \quad +6.1 (2.45\sigma)$$

Global  $3\nu$  analysis of oscillation parameters: best-fit values and allowed ranges at  $N_\sigma = 3$  for either NO or IO, including all data (also the SK atmospheric neutrino data). The last row reports the difference between the  $\chi^2$  minima in IO and NO. The results on the NO and CPV due to  $\delta$  are inconclusive.

I. Esteban et al., arXiv:2410.05380 (NuFit-6.0 results).

$\sin^2 \theta_{23}$  - relatively large uncertainty;  $\Delta m_{21}^2 / |\Delta m_{31}^2| \cong 1/30$ .

Future: JUNO (in China), T2HK (in Japan), DUNE (in USA),...

JUNO: started 26/09/2025; first data 11/11/2025:

$\sin^2 \theta_{12} = 0.3092 \pm 0.0087$ , factor of 1.4 improvement.

Program of research in neutrino physics extends beyond 2040.

# Example: Lepton Flavour Models Based on $S_4$ (Seesaw Models without Flavons)

P.P. Novichkov et al., arXiv:1811.04933

We assume that neutrino masses originate from the (supersymmetric) type I seesaw mechanism.

The fields involved:

- two Higgs doublets  $H_u$  and  $H_d$ ; transform trivially under  $\Gamma_4$ ,  $\rho_u = \rho_d \sim 1$ ,  $k_u = k_d = 0$ ;
- three lepton  $SU(2)$  doublets  $L_1, L_2, L_3$ ; furnish a 3-dim. irrep of  $S_4$ , i.e.,  $\rho_L \sim 3$  or  $3'$ , and carry weight  $k_L = 2$ ;
- three neutral lepton gauge singlets  $N_1^c, N_2^c, N_3^c$ ; transform as a triplet of  $\Gamma_4$ ,  $\rho_N \sim 3$  or  $3'$ , and carry weight  $k_N = 0$ ;
- three charged lepton  $SU(2)$  singlets  $E_1^c, E_2^c, E_3^c$ ; transform as singlets of  $\Gamma_4$ ,  $\rho_{1,2,3} \sim 1', 1, 1'$  and carry weights  $k_{1,2,3} = 0, 2, 2$ .

With these assumptions, the superpotential has the form:

$$W = \sum_{i=1}^3 \alpha_i (E_i^c L f_{E_i}(Y))_1 H_d + g (N^c L f_N(Y))_1 H_u + \Lambda (N^c N^c f_M(Y))_1$$

$\alpha_{1,2,3}, g, g', \Lambda$  are constants.

---

We work in the basis of  $S$  and  $T$  generators employed in arXiv:1806.11040. We give below the triplet irreps of the generators  $S$  and  $T$  in this basis, which will be used in our further analysis:

$$S = \pm \frac{1}{3} \begin{pmatrix} -1 & 2\omega^2 & 2\omega \\ 2\omega & 2 & -\omega^2 \\ 2\omega^2 & -\omega & 2 \end{pmatrix}, \quad T = \pm \frac{1}{3} \begin{pmatrix} -1 & 2\omega & 2\omega^2 \\ 2\omega & 2\omega^2 & -1 \\ 2\omega^2 & -1 & 2\omega \end{pmatrix},$$

$\omega = e^{i2\pi\tau/3}$ . The plus (minus) corresponds to the irrep 3 (3') of  $S_4$ .

In the employed basis we have:

$$ST = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega^2 & 0 \\ 0 & 0 & \omega \end{pmatrix}.$$

By specifying the weights of the matter fields one obtains the weights of the relevant modular forms.

After modular symmetry breaking, the matrices of charged lepton and neutrino Yukawa couplings,  $\lambda$  and  $\mathcal{Y}$ , as well as the Majorana mass matrix  $M$  for heavy neutrinos, are generated:

$$W = \lambda_{ij} E_i^c L_j H_d + \mathcal{Y}_{ij} N_i^c L_j H_u + \frac{1}{2} M_{ij} N_i^c N_j^c,$$

a sum over  $i, j = 1, 2, 3$  is assumed. After integrating out  $N^c$  and after EWS breaking, the charged lepton mass matrix  $M_e$  and the light neutrino Majorana mass matrix  $M_\nu$  are generated (we work in the L-R convention for the charged lepton mass term and the R-L convention for the light and heavy neutrino Majorana mass terms):

$$M_e = v_d \lambda^\dagger, \quad v_d \equiv \text{vev}(H_d^0),$$
$$M_\nu = -v_u^2 \mathcal{Y}^T M^{-1} \mathcal{Y}, \quad v_u \equiv \text{vev}(H_u^0).$$

# The Majorana mass term for heavy neutrinos

Assume  $k_\Lambda = 0$ , i.e., no non-trivial modular forms are present in  $\Lambda(N^c N^c f_M(Y))_1$ ,  $k_N = 0$ , and for both  $\rho_N \sim 3$  or  $\rho_N \sim 3'$

$$(N^c N^c)_1 = N_1^c N_1^c + N_2^c N_3^c + N_3^c N_2^c,$$

leading to the following mass matrix for heavy neutrinos:

$$M = 2\Lambda \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \quad \text{for } k_\Lambda = 0.$$

The spectrum of heavy neutrino masses is degenerate; the only free parameter is the overall scale  $\Lambda$ , which can be rendered real. The Majorana mass term conserves a “non-standard” lepton charge and two of the three heavy Majorana neutrinos with definite mass form a Dirac pair.

C.N. Leung, STP, 1983

# The neutrino Yukawa couplings

The lowest non-trivial weight,  $k_L = 2$ , leads to

$$g \left( N^c L Y_2^{(2)} \right)_1 H_u + g' \left( N^c L Y_{3'}^{(2)} \right)_1 H_u.$$

There are 4 possible assignments of  $\rho_N$  and  $\rho_L$  we consider. Two of them, namely  $\rho_N = \rho_L \sim \mathbf{3}$  and  $\rho_N = \rho_L \sim \mathbf{3}'$  give the following form of  $\mathcal{Y}$ :

$$\mathcal{Y} = g \left[ \begin{pmatrix} 0 & Y_1 & Y_2 \\ Y_1 & Y_2 & 0 \\ Y_2 & 0 & Y_1 \end{pmatrix} + \frac{g'}{g} \begin{pmatrix} 0 & Y_5 & -Y_4 \\ -Y_5 & 0 & Y_3 \\ Y_4 & -Y_3 & 0 \end{pmatrix} \right], \quad \text{for } k_L + k_N = 2 \quad \text{and} \quad \rho_N = \rho_L.$$

The two remaining combinations,  $(\rho_N, \rho_L) \sim (\mathbf{3}, \mathbf{3}')$  and  $(\mathbf{3}', \mathbf{3})$ , lead to:

$$\mathcal{Y} = g \left[ \begin{pmatrix} 0 & -Y_1 & Y_2 \\ -Y_1 & Y_2 & 0 \\ Y_2 & 0 & -Y_1 \end{pmatrix} + \frac{g'}{g} \begin{pmatrix} 2Y_3 & -Y_5 & -Y_4 \\ -Y_5 & 2Y_4 & -Y_3 \\ -Y_4 & -Y_3 & 2Y_5 \end{pmatrix} \right], \quad \text{for } k_L + k_N = 2 \quad \text{and} \quad \rho_N \neq \rho_L.$$

In both cases, up to an overall factor, the matrix  $\mathcal{Y}$  depends on one complex parameter  $g'/g$  and the VEV of  $\tau$ ,  $\text{vev}(\tau)$ .

$$Y_2^{(2)}(\tau) = \begin{pmatrix} \frac{1}{\sqrt{2}} (\theta^4 + \varepsilon^4) \\ -\sqrt{6} \varepsilon^2 \theta^2 \end{pmatrix} = \begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix}, \quad Y_{3'}^{(2)}(\tau) = \begin{pmatrix} \frac{1}{\sqrt{2}} (\theta^4 - \varepsilon^4) \\ -2 \varepsilon \theta^3 \\ -2 \varepsilon^3 \theta \end{pmatrix} = \begin{pmatrix} Y_3 \\ Y_4 \\ Y_5 \end{pmatrix}.$$

# The charged lepton Yukawa couplings

In the minimal (in terms of weights) viable possibility for  $L_{1,2,3}$  furnishing a 3-dim. irrep of  $S_4$ , i.e.,  $\rho_L \sim 3$  or  $3'$ , and carrying a weight  $k_L = 2$ , and  $E_{1,2,3}^c$  transforming as singlets of  $\Gamma_4$ ,  $\rho_{1,2,3} \sim 1', 1, 1'$  (up to permutations) and carrying weights  $k_{1,2,3} = 0, 2, 2$ , the relevant part of  $W$ ,  $W_e$ , can take 6 different forms which lead to the same matrix  $U_e$  diagonalising  $M_e M_e^\dagger = v_d^2 \lambda^\dagger \lambda$ , and thus do not lead to new results for the PMNS matrix. We give just one of these 6 forms corresponding to  $\rho_L = 3$ ,  $\rho_1 = 1'$ ,  $\rho_2 = 1$ ,  $\rho_3 = 1'$ :

$$\alpha \left( E_1^c L Y_{3'}^{(2)} \right)_1 H_d + \beta \left( E_2^c L Y_3^{(4)} \right)_1 H_d + \gamma \left( E_3^c L Y_{3'}^{(4)} \right)_1 H_d.$$

This leads leads to

$$\lambda = \begin{pmatrix} \alpha Y_3 & \alpha Y_5 & \alpha Y_4 \\ \beta (Y_1 Y_4 - Y_2 Y_5) & \beta (Y_1 Y_3 - Y_2 Y_4) & \beta (Y_1 Y_5 - Y_2 Y_3) \\ \gamma (Y_1 Y_4 + Y_2 Y_5) & \gamma (Y_1 Y_3 + Y_2 Y_4) & \gamma (Y_1 Y_5 + Y_2 Y_3) \end{pmatrix},$$

In this “minimal” example the matrix  $\lambda$  depends on 3 free parameters,  $\alpha$ ,  $\beta$  and  $\gamma$ , which can be rendered real by re-phasing of the charged lepton fields.

We recall that

$$M_e = v_d \lambda^\dagger, \quad v_d \equiv \text{vev}(H_d^0), \\ M_\nu = -v_u^2 \mathcal{Y}^T M^{-1} \mathcal{Y}, \quad v_u \equiv \text{vev}(H_u^0).$$

Parameters of the model:  $\alpha, \beta, \gamma, g^2/\Lambda$  – real;  $g'$  and VEV of  $\tau$  – complex, i.e., 6 real parameters + 2 phases for description of 12 observables (3 charged lepton masses, 3 neutrino masses, 3 mixing angles and 3 CPV phases). Excellent description of the data is obtained also for real  $g'$  (i.e., 6 real parameters + 1 phase, employing  $gCP$ ).

The 3 real parameters  $v_d\alpha, \beta/\alpha, \gamma/\alpha$  – fixed by fitting  $m_e, m_\mu$  and  $m_\tau$ . The remaining 3 real parameters and 2 (1) phases –  $v_u^2 g^2/\Lambda, |g'/g|, |\tau|$  and  $\arg(g'/g), \arg \tau$  ( $\arg \tau$ ) – describe the 9  $\nu$  observables, 3  $\nu$  masses, 3 mixing angles and 3 CPV phases.

The model considered leads to testable predictions for  $\min(m_j)$  ( $\sum_i m_i$ ), type of the  $\nu$  mass spectrum (NO or IO), the CPV Dirac and Majorana phases,  $|\langle m \rangle|$ , the range of  $\theta_{23}$ , as well as of correlations between different observables.

Seven real parameters (5 real couplings + the complex VEV of  $\tau$ ) – is the minimal number of parameters in the constructed so far phenomenologically viable lepton flavour models with massive Majorana neutrinos based on modular invariance.

## Numerical Analysis

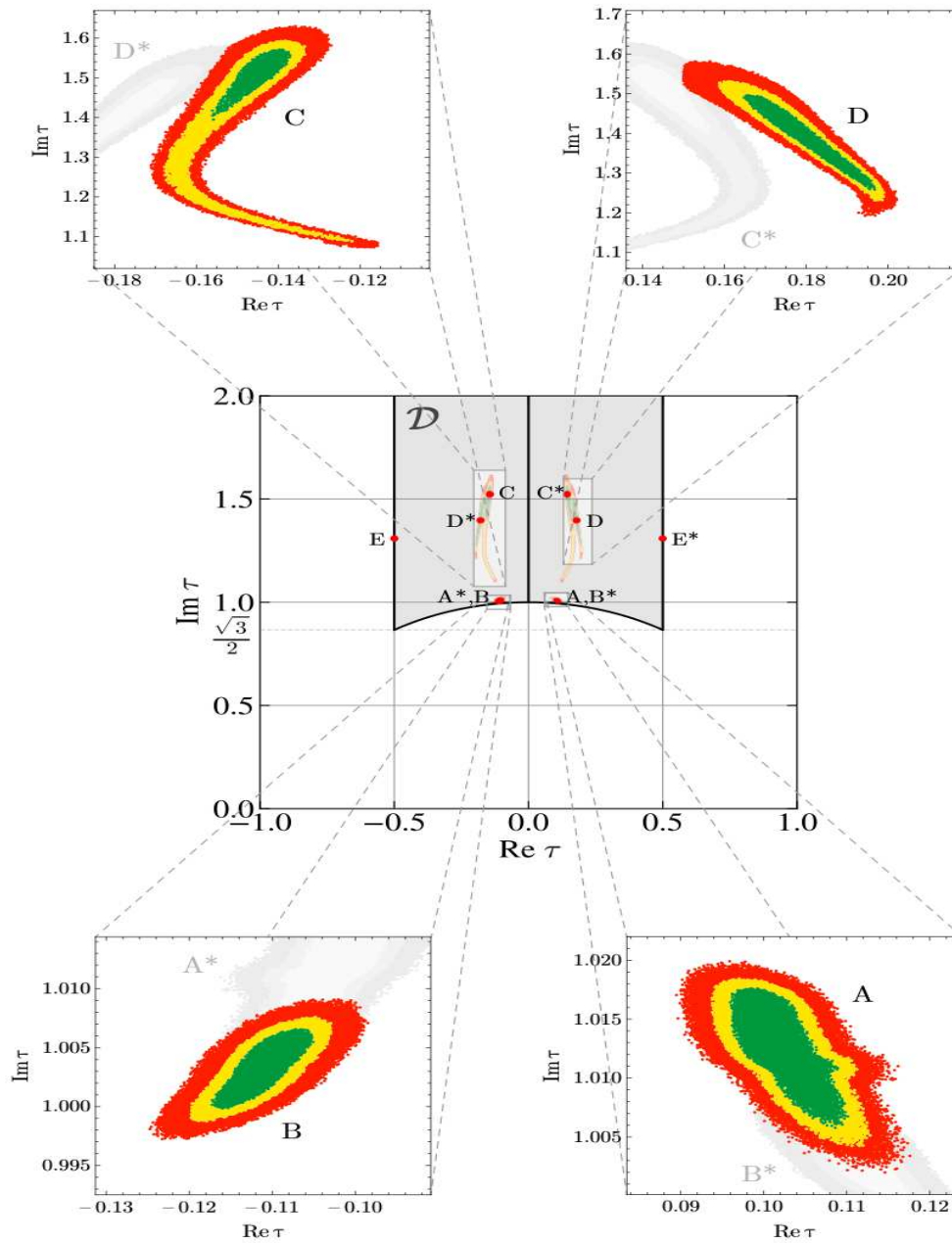
Each model depends on a set of dimensionless parameters

$$p_i = (\tau, \beta/\alpha, \gamma/\alpha, g'/g, \dots, \Lambda'/\Lambda, \dots),$$

which determine dimensionless observables (mass ratios, mixing angles and phases), and two overall mass scales:  $v_d \alpha$  for  $M_e$  and  $v_u^2 g^2 / \Lambda$  for  $M_\nu$ . Phenomenologically viable models are those that lead to values of observables which are in close agreement with the experimental results summarized in the Table below. We assume also to be in a regime in which the running of neutrino parameters is negligible.

Observable	Best fit value and $1\sigma$ range	
$m_e/m_\mu$	$0.0048 \pm 0.0002$	
$m_\mu/m_\tau$	$0.0565 \pm 0.0045$	
	NO	IO
$\delta m^2/(10^{-5} \text{ eV}^2)$	$7.34^{+0.17}_{-0.14}$	
$ \Delta m^2 /(10^{-3} \text{ eV}^2)$	$2.455^{+0.035}_{-0.032}$	$2.441^{+0.033}_{-0.035}$
$r \equiv \delta m^2/ \Delta m^2 $	$0.0299 \pm 0.0008$	$0.0301 \pm 0.0008$
$\sin^2 \theta_{12}$	$0.304^{+0.014}_{-0.013}$	$0.303^{+0.014}_{-0.013}$
$\sin^2 \theta_{13}$	$0.0214^{+0.0009}_{-0.0007}$	$0.0218^{+0.0008}_{-0.0007}$
$\sin^2 \theta_{23}$	$0.551^{+0.019}_{-0.070}$	$0.557^{+0.017}_{-0.024}$
$\delta/\pi$	$1.32^{+0.23}_{-0.18}$	$1.52^{+0.14}_{-0.15}$

**Best fit values and  $1\sigma$  ranges for neutrino oscillation parameters, obtained in the global analysis of F. Capozzi et al., arXiv:1804.09678, and for charged-lepton mass ratios, given at the scale  $2 \times 10^{16}$  GeV with the  $\tan\beta$  averaging described in F. Feruglio, arXiv:1706.08749 obtained from G.G. Ross and M. Serna, arXiv:0704.1248. The parameters entering the definition of  $r$  are  $\delta m^2 \equiv m_2^2 - m_1^2$  and  $\Delta m^2 \equiv m_3^2 - (m_1^2 + m_2^2)/2$ . The best fit value and  $1\sigma$  range of  $\delta$  did not drive the numerical searches here reported.**



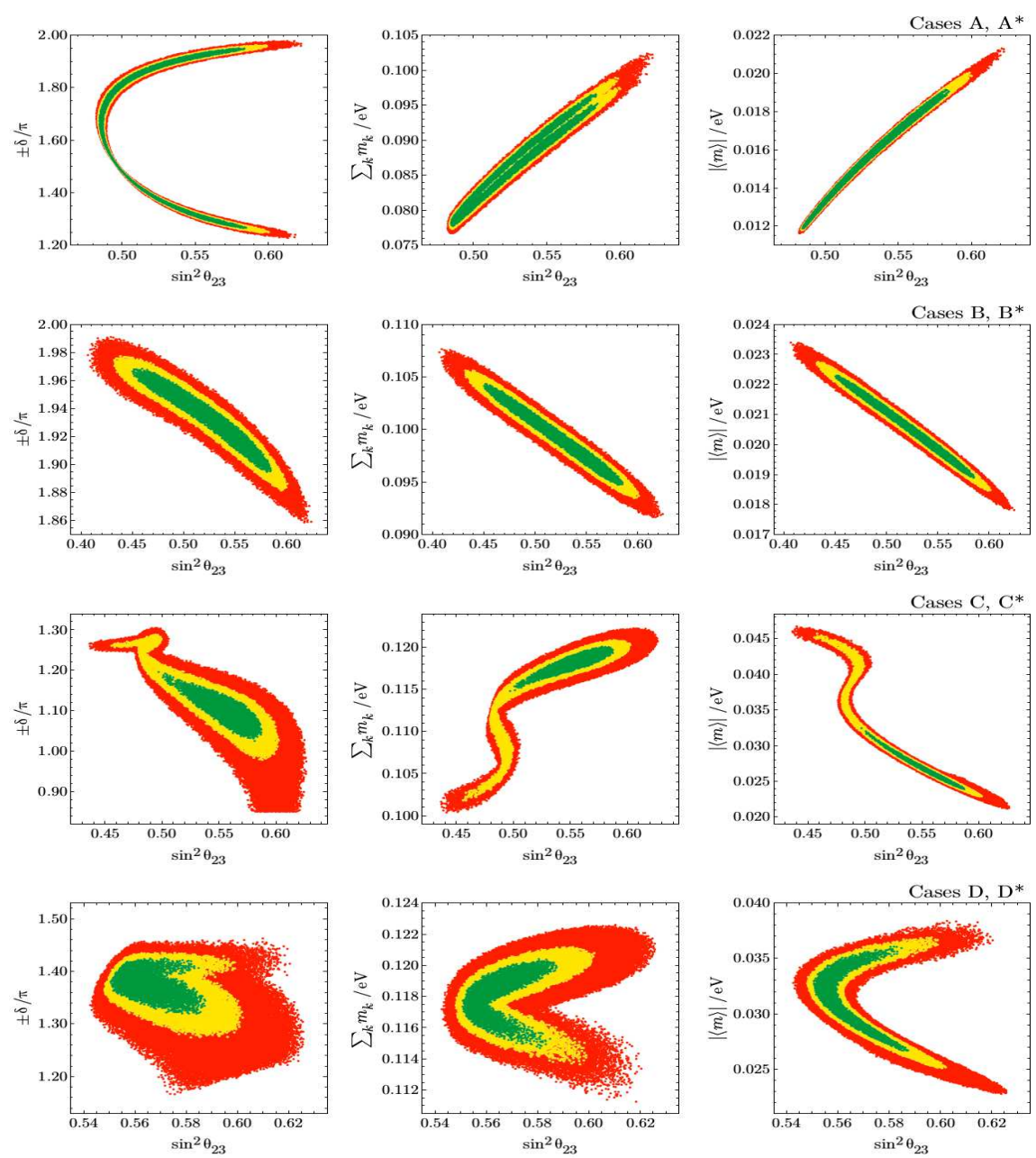
P.P. Novichkov, J.T. Penedo, STP, A.V. Titov, arXiv:1811.04933

	Best fit value	$2\sigma$ range	$3\sigma$ range
$\text{Re } \tau$	$\pm 0.1045$	$\pm(0.09597 - 0.1101)$	$\pm(0.09378 - 0.1128)$
$\text{Im } \tau$	1.01	1.006 – 1.018	1.004 – 1.018
$\beta/\alpha$	9.465	8.247 – 11.14	7.693 – 12.39
$\gamma/\alpha$	0.002205	0.002032 – 0.002382	0.001941 – 0.002472
$\text{Re } g'/g$	0.233	$(-0.02383) - 0.387$	$(-0.02544) - 0.4417$
$\text{Im } g'/g$	$\pm 0.4924$	$\pm((-0.592) - 0.5587)$	$\pm((-0.6046) - 0.5751)$
$v_d \alpha$ [MeV]	53.19		
$v_u^2 g^2/\Lambda$ [eV]	0.00933		
$m_e/m_\mu$	0.004802	0.004418 – 0.005178	0.00422 – 0.005383
$m_\mu/m_\tau$	0.0565	0.048 – 0.06494	0.04317 – 0.06961
$r$	0.02989	0.02836 – 0.03148	0.02759 – 0.03224
$\delta m^2$ [ $10^{-5}$ eV <sup>2</sup> ]	7.339	7.074 – 7.596	6.935 – 7.712
$ \Delta m^2 $ [ $10^{-3}$ eV <sup>2</sup> ]	2.455	2.413 – 2.494	2.392 – 2.513
$\sin^2 \theta_{12}$	0.305	0.2795 – 0.3313	0.2656 – 0.3449
$\sin^2 \theta_{13}$	0.02125	0.01988 – 0.02298	0.01912 – 0.02383
$\sin^2 \theta_{23}$	0.551	0.4846 – 0.5846	0.4838 – 0.5999
Ordering	NO		
$m_1$ [eV]	0.01746	0.01196 – 0.02045	0.01185 – 0.02143
$m_2$ [eV]	0.01945	0.01477 – 0.02216	0.01473 – 0.02307
$m_3$ [eV]	0.05288	0.05099 – 0.05405	0.05075 – 0.05452
$\sum_i m_i$ [eV]	0.0898	0.07774 – 0.09661	0.07735 – 0.09887
$ \langle m \rangle $ [eV]	0.01699	0.01188 – 0.01917	0.01177 – 0.02002
$\delta/\pi$	$\pm 1.314$	$\pm(1.266 - 1.95)$	$\pm(1.249 - 1.961)$
$\alpha_{21}/\pi$	$\pm 0.302$	$\pm(0.2821 - 0.3612)$	$\pm(0.2748 - 0.3708)$
$\alpha_{31}/\pi$	$\pm 0.8716$	$\pm(0.8162 - 1.617)$	$\pm(0.7973 - 1.635)$
$N\sigma$	0.02005		

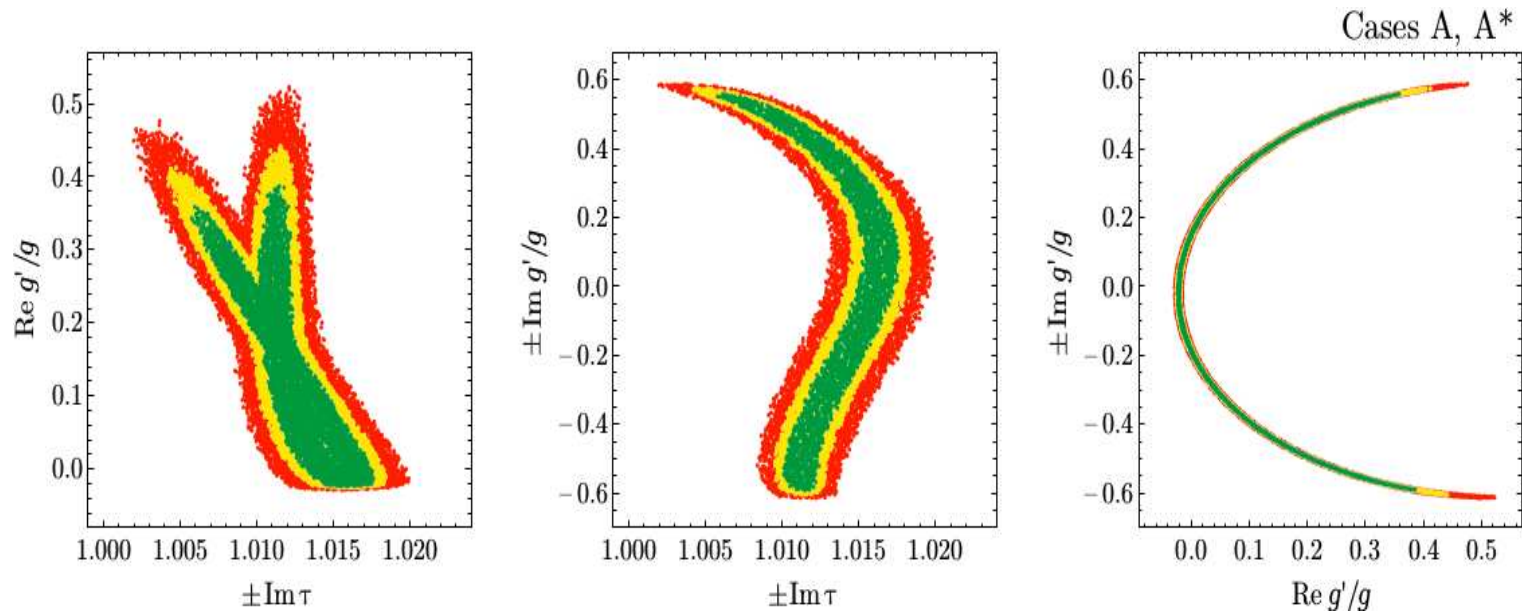
Best fit values along with  $2\sigma$  and  $3\sigma$  ranges of the parameters and observables in cases A and A\*, (which refer to  $(k_\Lambda, k_g) = (0, 2)$  and  $\tau = \pm 0.1045 + i 1.01$ ).

	Best fit value	$2\sigma$ range	$3\sigma$ range
$\text{Re } \tau$	$\mp 0.109$	$\mp(0.1051 - 0.1172)$	$\mp(0.103 - 0.1197)$
$\text{Im } \tau$	1.005	0.9998 – 1.007	0.9988 – 1.008
$\beta/\alpha$	0.03306	0.02799 – 0.03811	0.02529 – 0.04074
$\gamma/\alpha$	0.0001307	0.0001091 – 0.0001538	0.0000982 – 0.0001663
$\text{Re } g'/g$	0.4097	0.3513 – 0.5714	0.3241 – 0.5989
$\text{Im } g'/g$	$\mp 0.5745$	$\mp(0.5557 - 0.5932)$	$\mp(0.5436 - 0.5944)$
$v_d \alpha$ [MeV]	893.2		
$v_u^2 g^2/\Lambda$ [eV]	0.008028		
$m_e/m_\mu$	0.004802	0.004425 – 0.005175	0.004211 – 0.005384
$m_\mu/m_\tau$	0.05649	0.04785 – 0.06506	0.04318 – 0.06962
$r$	0.0299	0.02838 – 0.03144	0.02757 – 0.03223
$\delta m^2$ [ $10^{-5}$ eV <sup>2</sup> ]	7.34	7.078 – 7.59	6.932 – 7.71
$ \Delta m^2 $ [ $10^{-3}$ eV <sup>2</sup> ]	2.455	2.414 – 2.494	2.393 – 2.514
$\sin^2 \theta_{12}$	0.305	0.2795 – 0.3314	0.2662 – 0.3455
$\sin^2 \theta_{13}$	0.02125	0.0199 – 0.02302	0.01914 – 0.02383
$\sin^2 \theta_{23}$	0.551	0.4503 – 0.5852	0.4322 – 0.601
Ordering	NO		
$m_1$ [eV]	0.02074	0.01969 – 0.02374	0.01918 – 0.02428
$m_2$ [eV]	0.02244	0.02148 – 0.02522	0.02101 – 0.02574
$m_3$ [eV]	0.05406	0.05345 – 0.05541	0.05314 – 0.05577
$\sum_i m_i$ [eV]	0.09724	0.09473 – 0.1043	0.0935 – 0.1056
$ \langle m \rangle $ [eV]	0.01983	0.01889 – 0.02229	0.01847 – 0.02275
$\delta/\pi$	$\pm 1.919$	$\pm(1.895 - 1.968)$	$\pm(1.882 - 1.977)$
$\alpha_{21}/\pi$	$\pm 1.704$	$\pm(1.689 - 1.716)$	$\pm(1.681 - 1.722)$
$\alpha_{31}/\pi$	$\pm 1.539$	$\pm(1.502 - 1.605)$	$\pm(1.484 - 1.618)$
$N\sigma$	0.02435		

Best fit values along with  $2\sigma$  and  $3\sigma$  ranges of the parameters and observables in cases B and B\*, (which refer to  $(k_\Lambda, k_g) = (0, 2)$  and  $\tau = \pm 0.109 + i 1.005$ ).



P.P. Novichkov et al., arXiv:1811.04933



P.P. Novichkov et al., arXiv:1811.04933

## Success led to Ambitious Program

The charged lepton mass hierarchy is described correctly by the model due to a fine-tuning of the constants  $\beta/\alpha$  and  $\gamma/\alpha$ .

This is a common problem of the numerous proposed lepton and quark flavour models based on modular invariance and constructed prior 2021.

**Idea: the fermion mass hierarchies should arise as a consequence of the properties of the modular forms rather than by fine-tuning the constants present in the fermion mass matrices.**

A possible solution to the fine-tuning problem in modular invariant models of flavour was proposed in

P.P. Novichkov, J.T. Penedo, STP, arXiv:2102.07488.

# CP Symmetry in Modular Invariant Flavour Models

The formalism of combined finite modular and generalised CP (gCP) symmetries for theories of flavour was developed in P.P. Novichkov et al., arXiv:1905.11970.

gCP invariance was shown to imply that the constants  $g$ , which accompany each invariant singlet in the superpotential, must be real (in a symmetric basis of  $S$  and  $T$  and at least for  $\Gamma_N^{(\prime)}$ ,  $N \leq 5$ ). Thus, the number of free parameters in modular-invariant models which also enjoy a gCP symmetry gets reduced, leading to “minimal” models which have higher predictive power.

In these models, the only source of both modular symmetry breaking and CP violation is the VEV of the modulus  $\tau$ .

The “minimal” phenomenologically viable modular-invariant flavour models with gCP symmetry constructed so far

- of the lepton sector with massive Majorana neutrinos (12 observables) contain  $\geq 7$  (6) real parameters – 5 (4) real couplings + the complex  $\tau$  (6 (5) real constants + 1 phase);
- of the quark sector contain  $\geq 9$  real parameters – 7 real couplings + the complex  $\tau$ ;
- while the models of lepton and quark flavours (22 observables) have  $\geq 14$  real parameters – 12 real couplings + the complex  $\tau$ .

See, e.g., B.-Y. Qu et al., arXiv:2106.11659

Under the CP transformation,

$$\tau \xrightarrow{\text{CP}} -\tau^* .$$

P.P. Novichkov et al., 1905.11970; A. Baur et al., 1901.03251 and 1908.00805

It was further demonstrated that **CP is conserved** for

$$\text{Re}\tau = \pm 1/2; \quad \tau = e^{i\theta}, \quad \theta = [\pi/3, 2\pi/3]; \quad \text{Re}\tau = 0, \quad \text{Im}\tau \geq 1 .$$

i.e., for the values of  $\tau$ 's VEV at the boundary of the fundamental domain and on the imaginary axis.

# Residual Symmetries

The breakdown of modular symmetry is parameterised by the VEV of  $\tau$ . There is no value of  $\tau$ 's VEV which preserves the full symmetry  $\Gamma^{(l)}$  ( $\Gamma_N^{(l)}$ ). At certain “symmetric points”  $\tau = \tau_{\text{sym}}$ ,  $\Gamma^{(l)}$  ( $\Gamma_N^{(l)}$ ) is only partially broken, with the unbroken generators giving rise to **residual symmetries**. The  $R = S^2$  generator ( $\Gamma_N^{(l)}$ ) is unbroken for any value of  $\tau$ , thus a  $\mathbb{Z}_2^R$  symmetry is always preserved.

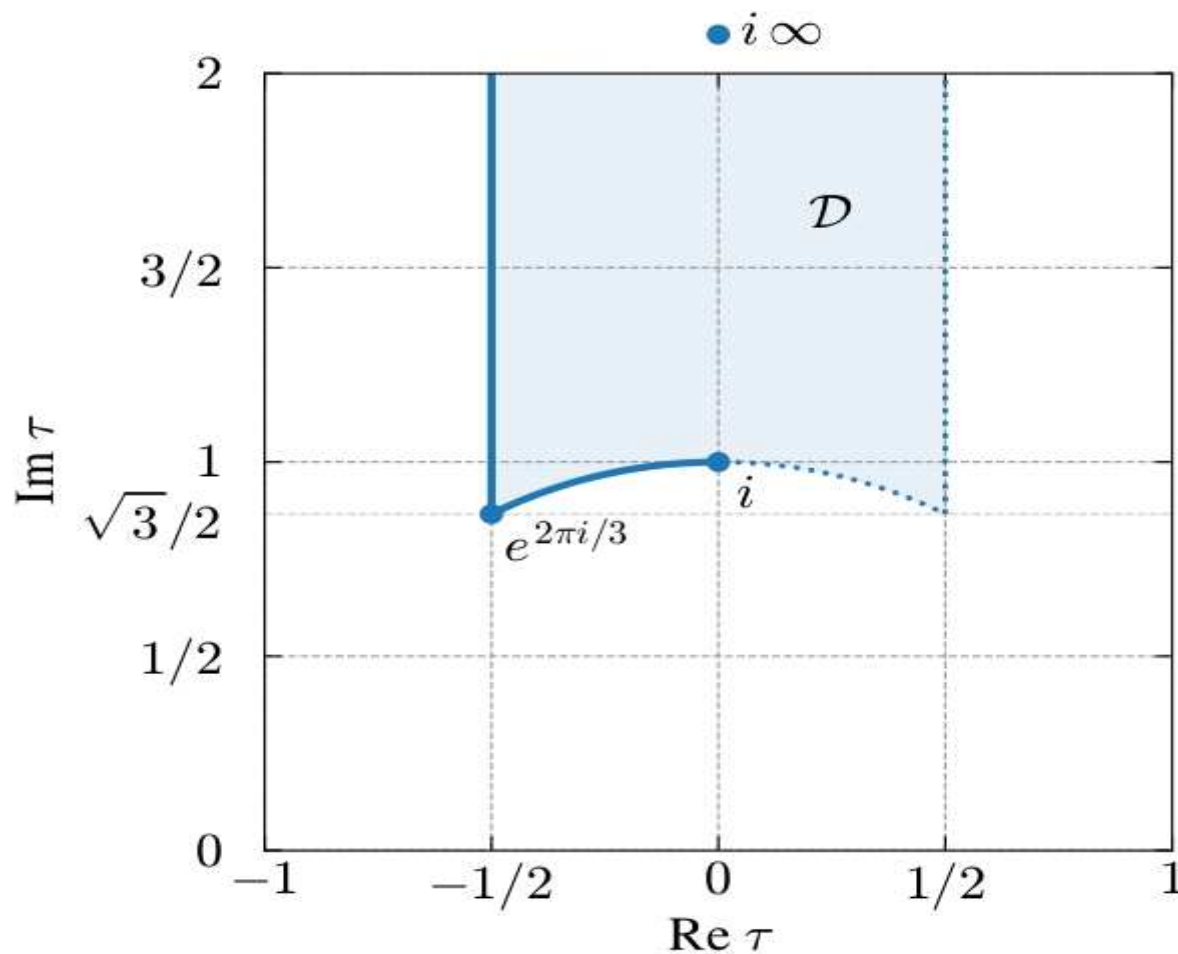
**There are only 3 inequivalent symmetric points in  $\mathcal{D}$ :**

- $\tau_{\text{sym}} = i\infty$ , invariant under  $T$ , preserving  $\mathbb{Z}_N^T$ ;
  - $\tau_{\text{sym}} = i$ , invariant under  $S$ , preserving  $\mathbb{Z}_2^S$  ( $\mathbb{Z}_4^S$ ,  $S^2 = R$ );
  - $\tau_{\text{sym}} = \omega \equiv \exp(2\pi i/3)$ , invariant under  $ST$ , preserving  $\mathbb{Z}_3^{ST}$ .
- P.P. Novichkov et al., arXiv:1811.04933 and arXiv:2006.03058

These symmetric values of  $\tau$  preserve the CP ( $\mathbb{Z}_2^{\text{CP}}$ ) symmetry of a CP- and modular-invariant theory (e.g. a modular theory where the couplings satisfy a reality condition).

P.P. Novichkov et al., arXiv:1911.04933 and arXiv:2006.03058

The CP ( $\mathbb{Z}_2^{\text{CP}}$ ) symmetry is preserved for  $\text{Re}\tau = 0$  or for  $\tau$  lying on the border of the fundamental domain  $\mathcal{D}$ , but is broken at generic values of  $\tau$ .



The fundamental domain  $\mathcal{D}$  of the modular group  $\Gamma$  and its three symmetric points  $\tau_{\text{sym}} = i\infty, i, \omega$ . At the solid and dotted lines (which include the three points) CP is also preserved. The value of  $\tau$  can always be restricted to  $\mathcal{D}$  by a suitable modular transformation.

Figure from P.P. Novichkov et al., arXiv:2006.03058

# Fermion Mass Hierarchies without Fine-Tuning

The  $l$ - and  $q$ - mass hierarchies in practically all modular flavour models proposed in the literature before arXiv:2102.07488 – **obtained with fine-tuning.**

**Fine-tuning:**

- i) **unjustified hierarchies between model's parameters, and/or**
- ii) **high sensitivity of observables to model parameters.**

The flavour structure of the fermion mass matrices  $M_F$  can be severely constrained by the residual symmetries present at each of the 3 symmetry points,

$$\tau_{\text{sym}} = i, \mathbb{Z}_2^S,$$

$$\tau_{\text{sym}} = \omega \equiv \exp(i 2\pi/3) = -1/2 + i\sqrt{3}/2, \mathbb{Z}_3^{ST}, \text{ and}$$

$$\tau_{\text{sym}} = i\infty, \mathbb{Z}_N^T:$$

**residual symmetries may enforce the presence of multiple zeros in  $M_F$ .**

The possibility to build viable flavour models with observed charged lepton (quark) mass hierarchies in the vicinity of the symmetry points was studied in H. Okada, M. Tanimoto, 2009.14242, 2012.0188; F. Feruglio et al., 2101.08718 (see also G-J. Ding et al., 1910.03460).

**As  $\tau$  moves away from  $\tau_{\text{sym}}$ , the zero entries in  $M_F$  will become non-zero. Their magnitude will be controlled by the size of the departure  $\epsilon$**

from  $\tau_{\text{sym}}$  and by the field transformation properties under the residual symmetry group.

Thus, fine-tuning might be avoided in the vicinity of  $\tau_{\text{sym}}$  as  $l-$  and  $q-$  mass hierarchies would follow from the properties of the modular forms present in the corresponding  $M_F$  rather than being determined by the values of the accompanying constants also present in  $M_F$ .

P.P. Novichkov, J.T. Penedo, STP, arXiv:2102.07488.

# Mass Matrices

Consider the bilinear (i.e., mass term)

$$\psi_i^c M(\tau)_{ij} \psi_j,$$

where the superfields  $\psi$  and  $\psi^c$  transform as

$$\psi \xrightarrow{\gamma} (c\tau + d)^{-k} \rho_r(\gamma) \psi \quad (\rho(\gamma), \Gamma_N^{(l)}, N = 2, 3, 4, 5),$$

$$\psi^c \xrightarrow{\gamma} (c\tau + d)^{-k^c} \rho_{r^c}^c(\gamma) \psi^c, \quad (\rho^c(\gamma), \Gamma_N^{(l)}).$$

**Modular invariance:**  $M(\tau)_{ij}$  must be modular form of level  $N$  and weight  $K \equiv k + k^c$ ,

$$M(\tau) \xrightarrow{\gamma} M(\gamma\tau) = (c\tau + d)^K \rho^c(\gamma)^* M(\tau) \rho(\gamma)^\dagger.$$

**Choose  $\gamma$ :** **S** ( $Z_2^S$ ); **ST** ( $Z_3^{ST}$ ); **T** ( $Z_N^T$ ); work in a diagonal basis of the corresponding generator:  $\rho(\gamma), \rho^c(\gamma)$  - diagonal.

**Consider:** i)  $\tau_{\text{sym}} = i, s = \frac{\tau - i}{\tau + i}, |s| \ll 1$  ;

ii)  $\tau_{\text{sym}} = \omega, u = \frac{\tau - \omega}{\tau - \omega^2}, |u| \ll 1$  ;

iii)  $\tau_{\text{sym}} = i\infty, \epsilon = |q_N| = e^{-2\pi \text{Im} \tau / N} \ll 1$  ( $N = 2, 3, 4, 5$ , models:  $\text{Im} \tau \sim 2.5$ ).

**Expand  $M(\gamma\tau)$  and  $M(\tau)$  in the vicinity of the symmetric point.**

---

$$\tau_{\text{sym}} = i\infty$$

At  $\tau_{\text{sym}} = i\infty$  we have  $\mathbb{Z}_N^T$  symmetry ( $\tau_{\text{sym}} = i\infty$  is invariant under  $T$ ).

Consider  $T$ -diagonal basis for the group generators  $S$  and  $T$ .

In this basis  $\rho^{(c)}(T) = \text{diag}(\rho_i^{(c)})$ .

By setting  $\gamma = T$  in the equation for  $M(\gamma\tau)$  one finds

$$M_{ij}(T\tau) = (\rho_i^c \rho_j)^* M_{ij}(\tau).$$

$M_{ij}$  is a function of  $q \equiv \exp(2\pi i\tau/N)$  (recall the  $q$ -expansions) and

$$\epsilon \equiv |q| = e^{-2\pi \text{Im} \tau/N}$$

parameterises the deviation of  $\tau$  from the symmetric point.

The entries  $M_{ij}(q)$  depend analytically on  $q$ . Further,

$q \xrightarrow{T} \zeta q$  ( $T\tau = \tau + 1$ ), with  $\zeta \equiv \exp(2\pi i/N)$ . Thus, in terms of  $q$ ,

$$M_{ij}(\zeta q) = (\rho_i^c \rho_j)^* M_{ij}(q).$$

Expanding both sides in powers of  $q$ , one finds

$$\zeta^n M_{ij}^{(n)}(0) = (\rho_i^c \rho_j)^* M_{ij}^{(n)}(0), \quad (3)$$

$M_{ij}^{(n)}$  is the  $n$ -th derivative of  $M_{ij}$  with respect to  $q$ . This means that  $M_{ij}^{(n)}(0)$  can only be non-zero for values of  $n$  such that  $(\rho_i^c \rho_j)^* = \zeta^n$ .

In the symmetric limit  $q \rightarrow 0$ , e.g.,  $M_{ij} = M_{ij}^{(0)}(0) \neq 0$  only if  $\rho_i^c \rho_j = 1$ .

More generally, if  $(\rho_i^c \rho_j)^* = \zeta^l$  with  $0 \leq l < N$ ,

$$M_{ij}(q) = a_0 q^l + a_1 q^{N+l} + a_2 q^{2N+l} + \dots$$

in the vicinity of the symmetric point.

Thus, the entry  $M_{ij}$  is expected to be  $\mathcal{O}(\epsilon^l)$  whenever  $\text{Im } \tau$  is “large”.  
The power  $l$  only depends on how the representations of  $\psi$  and  $\psi^c$  decompose under the residual symmetry group  $\mathbb{Z}_N^T$ .

Thus, the entry  $M_{ij}$  is expected to be  $\mathcal{O}(\epsilon^l)$  whenever  $\text{Im } \tau$  is “large”.  
 The power  $l$  only depends on how the representations of  $\psi$  and  $c$  decompose under the residual symmetry group  $\mathbb{Z}_N^T$ .

**Example:**  $S'_4$  ( $N = 4$ ), residual symmetry is  $\mathbb{Z}_4^T$ .

$\mathbb{Z}_4^T$  has 4 inequivalent 1-dimensional irreducible representations  $1_k$ ,  $k = 0, 1, 2, 3$  ( $k$ -charge).

The group generator in the  $1_k$  representation:  $\exp(i2\pi k/4)$ .

**Assume:**  $\psi_i^c \sim 1'$ ,  $i = 1, 2, 3$ , and  $\psi_{1,2,3} \sim 3$  of  $S'_4$ .

**$T$ -diagonal basis:**

$$\rho_i^c(\mathbf{T}) = -1 = \exp(i\frac{2\pi}{4}\mathbf{2}) = \zeta^2, \quad \psi_i^c \sim \mathbf{1}_2, \quad i = 1, 2, 3;$$

$$\rho_{1,2,3}(\mathbf{T}) = \text{diag}(-1, -i, i) = \text{diag}(\exp(i\frac{2\pi}{4}\mathbf{2}), \exp(i\frac{2\pi}{4}\mathbf{3}), \exp(i\frac{2\pi}{4}\mathbf{1})) = \text{diag}(\zeta^2, \zeta^3, \zeta);$$

$$\psi \sim \mathbf{1}_2 \oplus \mathbf{1}_3 \oplus \mathbf{1}_1$$

Thus, we have:

$$(\rho_i^c \rho_j)^* = \begin{pmatrix} 1 & \zeta^3 & \zeta \\ 1 & \zeta^3 & \zeta \\ 1 & \zeta^3 & \zeta \end{pmatrix}$$

Correspondingly,

$$M \sim v \begin{pmatrix} 1 & \epsilon^3 & \epsilon \\ 1 & \epsilon^3 & \epsilon \\ 1 & \epsilon^3 & \epsilon \end{pmatrix}$$

$$\text{Det } M \sim \epsilon^4: \quad m_1 \ll m_2 \ll m_3; \quad \text{Tr } M \cong m_3 \sim 1; \quad m_2 m_3 \sim \epsilon$$

$$m_3 : m_2 : m_1 \sim m_3 (1 : \epsilon : \epsilon^3)$$

# Summary

$\mathcal{T}\text{sym} = i\infty$ ,  $\mathbb{Z}_N^T$  symmetry: for  $(\rho_i^c \rho_j)^* = \zeta^l$  with  $0 \leq l < N$ ,  $\zeta \equiv \exp(2\pi i/N)$

$$M_{ij}(q) = a_0 q^l + a_1 q^{N+l} + a_2 q^{2N+l} + \dots, \quad |q_N| = e^{-2\pi \text{Im} \tau / N} \equiv \epsilon, \text{ e.g. } |q_4| \leq 0.26,$$

in the vicinity of the symmetric point.

**The entry  $M_{ij} \sim \mathcal{O}(\epsilon^l)$  whenever  $\text{Im} \tau$  is large (models:  $\text{Im} \tau \sim 2.5$ );**

**$l = 0, 1, 2; 3; 4$  for  $A_4^{(l)}$ ;  $S_4^{(l)}$ ;  $A_5^{(l)}$ .**

**The power  $l$  only depends on how the representations of  $\psi$  and  $\psi^c$  decompose under the residual symmetry group  $\mathbb{Z}_N^T$ , it is not a new independent parameter. Thus, we can have, for example:**

$$m_\tau : m_\mu : m_e \sim (1, \epsilon, \epsilon^2) \text{ for } A_4^{(l)}; \quad m_\tau : m_\mu : m_e \sim (1, \epsilon, \epsilon^3) \text{ or } (1, \epsilon^2, \epsilon^3) \text{ for } S_4^{(l)};$$

**more varieties for  $A_5^{(l)}$ , e.g.,  $m_\tau : m_\mu : m_e \sim (1, \epsilon^2, \epsilon^4)$ .**

$\mathcal{T}\text{sym} = i$ ,  $\mathbb{Z}_2^S$  symmetry: for  $(i^{k^c} i^k \rho_i^c \rho_j)^* = (-1)^n$ ,  $n = 0, 1, 2, \dots$ ,

$$M_{ij}^n(0) \neq 0, \quad M_{ij} \sim \mathcal{O}(\epsilon^m), \quad m = 0, 1, \quad \epsilon \equiv |s|, \quad s \equiv (\tau - i)/(\tau + i).$$

**Not sufficient to reproduce the  $l$ - and  $q$ - mass hierarchies!**

**The power  $m = 0, 1$  depends on how the representations of  $\psi$  and  $\psi^c$  decompose under  $\mathbb{Z}_4^S$  and on their respective weights  $k^c$  and  $k^c$ .**

$\mathcal{T}\text{sym} = \omega$ ,  $\omega \equiv \exp(i2\pi/3)$ ,  $\mathbb{Z}_3^{ST}$  symmetry: for  $(\omega^{k^c} \rho_i^c \omega^k \rho_j)^* = \omega^{2n}$ ,  $\omega^3 = 1$ ,

$$M_{ij}^n(0) \neq 0, \quad M_{ij} \sim \mathcal{O}(\epsilon^m), \quad m = 0, 1, 2, \quad \epsilon \equiv |u|, \quad u \equiv (\tau - \omega)/(\tau - \omega^2).$$

**The power  $m = 0, 1, 2$  depends on how the representations of  $\psi$  and  $\psi^c$  decompose under  $\mathbb{Z}_3^{ST}$  and on their respective weights  $k^c$  and  $k^c$ . In this case we can have:  $m_\tau : m_\mu : m_e \sim (1, \epsilon, \epsilon^2)$  for  $A_4^{(l)}$ ,  $S_4^{(l)}$  and  $A_5^{(l)}$ .**

# Decomposition under Residual Symmetries

As  $\tau$  departs from  $\tau_{\text{sym}}$ , the entries  $M_{ij}$  of  $M_F$  are of  $\mathcal{O}(\epsilon^l)$ , where  $\epsilon$  parameterises the deviation of  $\tau$  from  $\tau_{\text{sym}}$ .

**The powers  $l$  are extracted from products of factors which, correspond to representations of the residual symmetry group.**

One can systematically identify these residual symmetry representations for the different possible choices of  $\Gamma'_N$  representations of matter fields. This knowledge can be exploited to construct hierarchical  $M_F$  via controlled corrections to entries which are zero in the symmetric limit.

The matter fields  $\psi$  furnish ‘weighted’ representations  $(r, k)$  of  $\Gamma'_N$ .

When a residual symmetry is preserved by the value of  $\tau$ ,

**$\psi$  decompose into unitary representations of the residual symmetry group.**

Modulo a possible  $\mathbb{Z}_2^R$  factor, these groups are  $\mathbb{Z}_N^T$ ,  $\mathbb{Z}_4^S$ , and  $\mathbb{Z}_3^{ST}$ .

A cyclic group  $\mathbb{Z}_n \equiv \langle a \mid a^n = 1 \rangle$  has  $n$  inequivalent 1-dimensional irreps  $1_k$ ,  $k = 0, \dots, n-1$  is sometimes referred to as a “charge”. The group generator  $a$  is represented by one of the  $n$ -th roots of unity,

$$1_k : \quad \rho(a) = \exp\left(2\pi i \frac{k}{n}\right).$$

For odd  $n$ , the only real irrep of  $\mathbb{Z}_n$  is the trivial one,  $1_0$ ; for even  $n$ , there is one more real irrep,  $1_{n/2}$ . All other irreps are complex, and split into pairs of conjugated irreps:  $(1_k)^* = 1_{n-k}$ .

**Second example:**  $\tau = \omega$ ,  $\mathbb{Z}_3^{ST}$  symmetry. Assume  $\psi$  is a triplet  $(\mathbf{3}, k)$  of  $S'_4$ . It transforms under the unbroken  $\gamma = ST$  at  $\tau = \omega$  as

$$\psi_i \xrightarrow{ST} (-\omega - 1)^{-k} \rho_3(ST)_{ij} \psi_j = \omega^k \rho_3(ST)_{ij} \psi_j.$$

The eigenvalues of  $\rho_3(ST)$  are 1,  $\omega$  and  $\omega^2$ .

So, in a  $ST$ -diagonal basis the transformation rule explicitly reads

$$\psi \xrightarrow{ST} \omega^k \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix} \psi = \begin{pmatrix} \omega^k & 0 & 0 \\ 0 & \omega^{k+1} & 0 \\ 0 & 0 & \omega^{k+2} \end{pmatrix} \psi,$$

**Thus,  $\psi$  decomposes as  $\psi \rightsquigarrow \mathbf{1}_k \oplus \mathbf{1}_{k+1} \oplus \mathbf{1}_{k+2}$  under  $\mathbb{Z}_3^{ST}$ .**

One can find the residual symmetry representations for any other multiplet of a finite modular group in a similar way. For a given level  $N$ , the decompositions of fields under a certain residual symmetry group only depend on the pair  $(r, k)$ .

The decompositions of the weighted representations of  $\Gamma'_N$  ( $N \leq 5$ ) under the three residual symmetry groups, i.e. the residual decompositions of the irreps of  $\Gamma'_2 \simeq S_3$ ,  $\Gamma'_3 \simeq A'_4 = T'$ ,  $\Gamma'_4 \simeq S'_4 = SL(2, \mathbb{Z}_4)$ , and  $\Gamma'_5 \simeq A'_5 = SL(2, \mathbb{Z}_5)$  are listed in Tables 6–9 of Appendix A in P.P. Novichkov et al., arXiv:2102.07488.

$N$	$\Gamma'_N$	Pattern	Sym. point	Viable $\mathbf{r} \otimes \mathbf{r}^c$
2	$S_3$	$(1, \epsilon, \epsilon^2)$	$\tau \simeq \omega$	$[2 \oplus 1^{(\prime)}] \otimes [1 \oplus 1^{(\prime)} \oplus 1']$
3	$A'_4$	$(1, \epsilon, \epsilon^2)$	$\tau \simeq \omega$	$[1_a \oplus 1_a \oplus 1'_a] \otimes [1_b \oplus 1_b \oplus 1''_b]$
			$\tau \simeq i\infty$	$[1_a \oplus 1_a \oplus 1'_a] \otimes [1_b \oplus 1_b \oplus 1''_b]$ with $1_a \neq (1_b)^*$
4	$S'_4$	$(1, \epsilon, \epsilon^2)$	$\tau \simeq \omega$	$[3_a, \text{ or } 2 \oplus 1^{(\prime)}, \text{ or } \hat{2} \oplus \hat{1}^{(\prime)}] \otimes [1_b \oplus 1_b \oplus 1'_b]$
		$(1, \epsilon, \epsilon^3)$	$\tau \simeq i\infty$	$\mathbf{3} \otimes [2 \oplus 1, \text{ or } 1 \oplus 1 \oplus 1'], \mathbf{3}' \otimes [2 \oplus 1', \text{ or } 1 \oplus 1' \oplus 1'],$ $\hat{\mathbf{3}}' \otimes [\hat{2} \oplus \hat{1}, \text{ or } \hat{1} \oplus \hat{1} \oplus \hat{1}'], \hat{\mathbf{3}} \otimes [\hat{2} \oplus \hat{1}', \text{ or } \hat{1} \oplus \hat{1}' \oplus \hat{1}']$
5	$A'_5$	$(1, \epsilon, \epsilon^4)$	$\tau \simeq i\infty$	$\mathbf{3} \otimes \mathbf{3}'$

**Hierarchical mass patterns which can be realised in the vicinity of symmetric points. These patterns are unaffected by the exchange  $\mathbf{r} \leftrightarrow \mathbf{r}^c$  and may only be viable for certain weights. Subscripts run over irreps of a certain dimension. Primes in parenthesis are uncorrelated.**

**Leading-order mass spectra patterns of bilinears  $\psi^c\psi$  in the vicinity of the symmetric points  $\omega$  and  $i\infty$ , for 3d multiplets  $\psi \sim (r, k)$  and  $\psi^c \sim (r^c, k^c)$  of the finite modular groups  $\Gamma'_N$ ,  $N = 2, 3, 4, 5$ , i.e., for  $S_3$ ,  $A'_4$ ,  $S'_4$  and  $A'_5$  are given in Tables 10 - 13 of Appendix B in P.P. Novichkov et al., arXiv:2102.07488.**

**The number of cases which can lead to viable hierarchical charged lepton or quark mass patterns is extremely limited.**

**Table 10.** Leading-order mass spectra patterns of bilinears  $\psi^c\psi$  in the vicinity of the symmetric point  $\omega$  for 3d multiplets  $\psi \sim (r, k)$  and  $\psi^c \sim (r^c, k^c)$  of the finite modular group  $\Gamma_3 \simeq S_3$ . Spectra are insensitive to transposition, i.e. to the exchange  $\psi \leftrightarrow \psi^c$ . Congruence relations for  $k + k^c$  are modulo 3 (“flavour blind”  $k, k^c$  considered).

r	r <sup>c</sup>	$\tau \simeq \omega$		
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$
$2 \oplus 1$	$2 \oplus 1$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$2 \oplus 1$	$2 \oplus 1'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$2 \oplus 1'$	$2 \oplus 1'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$2 \oplus 1$	$1' \oplus 1 \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$2 \oplus 1$	$1' \oplus 1' \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$2 \oplus 1'$	$1' \oplus 1 \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$2 \oplus 1'$	$1' \oplus 1' \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$2 \oplus 1$	$1 \oplus 1 \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$2 \oplus 1$	$1' \oplus 1' \oplus 1'$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$2 \oplus 1'$	$1 \oplus 1 \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$2 \oplus 1'$	$1' \oplus 1' \oplus 1'$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$1' \oplus 1 \oplus 1$	$1' \oplus 1 \oplus 1$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1' \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1' \oplus 1' \oplus 1$	$1' \oplus 1' \oplus 1$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1 \oplus 1 \oplus 1$	$1' \oplus 1 \oplus 1$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1 \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1' \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1'$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1' \oplus 1' \oplus 1$	$1' \oplus 1' \oplus 1'$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1 \oplus 1 \oplus 1$	$1 \oplus 1 \oplus 1$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1 \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1'$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$1' \oplus 1' \oplus 1'$	$1' \oplus 1' \oplus 1'$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )

**Table 11.** Leading-order mass spectra patterns of bilinears  $\psi^c\psi$  in the vicinity of the symmetric points  $\omega$  and  $i\infty$ , for 3d multiplets  $\psi \sim (r, k)$  and  $\psi^c \sim (r^c, k^c)$  of the finite modular group  $\Gamma'_5 \simeq A'_4$ . Spectra are insensitive to transposition, i.e. to the exchange  $\psi \leftrightarrow \psi^c$ . Congruence relations for  $k + k^c$  are modulo 3.

$r$	$r^c$	$\tau \simeq \omega$			$\tau \simeq i\infty$
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$	
<b>3</b>	<b>3</b>	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
<b>3</b>	$1'' \oplus 1' \oplus 1$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
<b>3</b>	$1' \oplus 1 \oplus 1$	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )
<b>3</b>	$1'' \oplus 1 \oplus 1$	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )
<b>3</b>	$1' \oplus 1' \oplus 1$	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )
<b>3</b>	$1'' \oplus 1'' \oplus 1$	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )
<b>3</b>	$1'' \oplus 1' \oplus 1'$	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )
<b>3</b>	$1'' \oplus 1'' \oplus 1'$	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )
<b>3</b>	$1 \oplus 1 \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
<b>3</b>	$1' \oplus 1' \oplus 1'$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
<b>3</b>	$1'' \oplus 1'' \oplus 1''$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$1'' \oplus 1' \oplus 1$	$1'' \oplus 1' \oplus 1$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$1' \oplus 1 \oplus 1$	$1'' \oplus 1' \oplus 1$	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )
$1'' \oplus 1 \oplus 1$	$1'' \oplus 1' \oplus 1$	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )
$1' \oplus 1' \oplus 1$	$1'' \oplus 1' \oplus 1$	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )
$1'' \oplus 1' \oplus 1$	$1'' \oplus 1'' \oplus 1$	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )
$1'' \oplus 1' \oplus 1$	$1'' \oplus 1' \oplus 1'$	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )	(1, 1, $\epsilon^2$ )
$1'' \oplus 1' \oplus 1$	$1'' \oplus 1'' \oplus 1'$	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )
$1 \oplus 1 \oplus 1$	$1'' \oplus 1' \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$1' \oplus 1 \oplus 1$	$1' \oplus 1 \oplus 1$	(1, 1, $\epsilon$ )	(1, $\epsilon^2$ , $\epsilon^2$ )	(1, 1, $\epsilon$ )	(1, 1, $\epsilon$ )
$1' \oplus 1 \oplus 1$	$1'' \oplus 1 \oplus 1$	(1, 1, 1)	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, 1, 1)

$\mathbf{r}$	$\mathbf{r}^c$	$\tau \simeq \omega$			$\tau \simeq i\infty$
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$	
$1' \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$
$1' \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1$	$(1, 1, \epsilon)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(1, 1, \epsilon)$
$1' \oplus 1 \oplus 1$	$1'' \oplus 1' \oplus 1'$	$(1, \epsilon^2, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$
$1' \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1'$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$
$1'' \oplus 1 \oplus 1$	$1'' \oplus 1 \oplus 1$	$(1, 1, \epsilon^2)$	$(1, 1, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$1' \oplus 1' \oplus 1$	$1'' \oplus 1 \oplus 1$	$(1, 1, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(1, 1, \epsilon^2)$
$1'' \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$
$1'' \oplus 1 \oplus 1$	$1'' \oplus 1' \oplus 1'$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$
$1'' \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1'$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(1, 1, \epsilon^2)$	$(1, \epsilon, \epsilon)$
$1' \oplus 1' \oplus 1$	$1' \oplus 1' \oplus 1$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(1, 1, \epsilon^2)$	$(1, \epsilon, \epsilon)$
$1' \oplus 1' \oplus 1$	$1'' \oplus 1'' \oplus 1$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$
$1' \oplus 1' \oplus 1$	$1'' \oplus 1' \oplus 1'$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$
$1' \oplus 1' \oplus 1$	$1'' \oplus 1'' \oplus 1'$	$(1, 1, \epsilon^2)$	$(1, 1, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$1' \oplus 1' \oplus 1'$	$1'' \oplus 1' \oplus 1$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$
$1'' \oplus 1' \oplus 1$	$1'' \oplus 1'' \oplus 1''$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$
$1'' \oplus 1'' \oplus 1$	$1'' \oplus 1'' \oplus 1$	$(1, \epsilon^2, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$
$1'' \oplus 1' \oplus 1'$	$1'' \oplus 1'' \oplus 1$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, 1, \epsilon)$
$1'' \oplus 1'' \oplus 1$	$1'' \oplus 1'' \oplus 1'$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$
$1'' \oplus 1' \oplus 1'$	$1'' \oplus 1' \oplus 1'$	$(1, 1, \epsilon)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(1, 1, \epsilon)$
$1'' \oplus 1' \oplus 1'$	$1'' \oplus 1'' \oplus 1'$	$(1, 1, 1)$	$(1, \epsilon, \epsilon^2)$	$(1, \epsilon, \epsilon^2)$	$(1, 1, 1)$
$1'' \oplus 1'' \oplus 1'$	$1'' \oplus 1'' \oplus 1'$	$(1, 1, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(1, 1, \epsilon^2)$
$1 \oplus 1 \oplus 1$	$1' \oplus 1 \oplus 1$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$1 \oplus 1 \oplus 1$	$1'' \oplus 1 \oplus 1$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$
$1 \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$
$1 \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$
$1 \oplus 1 \oplus 1$	$1'' \oplus 1' \oplus 1'$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$
$1 \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1'$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$

$\mathbf{r}$	$\mathbf{r}^c$	$\tau \simeq \omega$			$\tau \simeq i\infty$
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$	
$1' \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1'$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$
$1' \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1''$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$
$1' \oplus 1' \oplus 1'$	$1'' \oplus 1 \oplus 1$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$
$1'' \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1''$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$
$1' \oplus 1' \oplus 1$	$1' \oplus 1' \oplus 1'$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$
$1' \oplus 1' \oplus 1$	$1'' \oplus 1'' \oplus 1''$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$
$1' \oplus 1' \oplus 1'$	$1'' \oplus 1'' \oplus 1$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$1'' \oplus 1'' \oplus 1$	$1'' \oplus 1'' \oplus 1''$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$
$1' \oplus 1' \oplus 1'$	$1'' \oplus 1' \oplus 1'$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$
$1' \oplus 1' \oplus 1'$	$1'' \oplus 1'' \oplus 1'$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$
$1'' \oplus 1' \oplus 1'$	$1'' \oplus 1'' \oplus 1''$	$(1, 1, \epsilon^2)$	$(\epsilon, \epsilon^2, \epsilon^2)$	$(1, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$1'' \oplus 1'' \oplus 1'$	$1'' \oplus 1'' \oplus 1''$	$(1, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon^2)$	$(1, 1, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$
$1 \oplus 1 \oplus 1$	$1 \oplus 1 \oplus 1$	$(1, 1, 1)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, 1)$
$1 \oplus 1 \oplus 1$	$1' \oplus 1' \oplus 1'$	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, 1)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$
$1 \oplus 1 \oplus 1$	$1'' \oplus 1'' \oplus 1''$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, 1)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$
$1' \oplus 1' \oplus 1'$	$1' \oplus 1' \oplus 1'$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, 1)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$
$1' \oplus 1' \oplus 1'$	$1'' \oplus 1'' \oplus 1''$	$(1, 1, 1)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, 1)$
$1'' \oplus 1'' \oplus 1''$	$1'' \oplus 1'' \oplus 1''$	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, 1)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$

**Table 12.** Leading-order mass spectra patterns of bilinears  $\psi^c\psi$  in the vicinity of the symmetric points  $\omega$  and  $i\infty$ , for 3d multiplets  $\psi \sim (r, k)$  and  $\psi^c \sim (r^c, k^c)$  of the finite modular group  $\Gamma'_4 \simeq S'_4$ . Spectra are insensitive to transposition, i.e. to the exchange  $\psi \leftrightarrow \psi^c$ . Congruence relations for  $k + k^c$  are modulo 3.

$r$	$r^c$	$\tau \simeq \omega$			$\tau \simeq i\infty$
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$	
$\mathbf{3}$	$\mathbf{3}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$\mathbf{3}$	$\mathbf{3}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^2$ )
$\mathbf{3}$	$\hat{\mathbf{3}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^3$ )
$\mathbf{3}$	$\hat{\mathbf{3}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon$ )
$\mathbf{3}'$	$\mathbf{3}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$\mathbf{3}'$	$\hat{\mathbf{3}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^3$ )
$\hat{\mathbf{3}}$	$\mathbf{3}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon$ )
$\hat{\mathbf{3}}$	$\hat{\mathbf{3}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^2$ )
$\hat{\mathbf{3}}$	$\hat{\mathbf{3}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$\hat{\mathbf{3}}'$	$\hat{\mathbf{3}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^2$ )
$\mathbf{3}$	$\mathbf{2} \oplus \mathbf{1}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon^3$ )
$\mathbf{3}$	$\mathbf{2} \oplus \mathbf{1}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon$ )
$\mathbf{3}$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^3$ )
$\mathbf{3}$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon$ )
$\mathbf{3}'$	$\mathbf{2} \oplus \mathbf{1}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon$ )
$\mathbf{3}'$	$\mathbf{2} \oplus \mathbf{1}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon^3$ )
$\mathbf{3}'$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon$ )
$\mathbf{3}'$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^3$ )
$\hat{\mathbf{3}}$	$\mathbf{2} \oplus \mathbf{1}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^3$ )
$\hat{\mathbf{3}}$	$\mathbf{2} \oplus \mathbf{1}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon$ )

$\mathbf{r}$	$\mathbf{r}^c$	$\tau \simeq \omega$			$\tau \simeq i\infty$
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$	
$\hat{\mathbf{3}}$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon$ )
$\hat{\mathbf{3}}$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon^3$ )
$\hat{\mathbf{3}}'$	$\mathbf{2} \oplus \mathbf{1}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon$ )
$\hat{\mathbf{3}}'$	$\mathbf{2} \oplus \mathbf{1}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^3$ )
$\hat{\mathbf{3}}'$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon^3$ )
$\hat{\mathbf{3}}'$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon$ )
$\mathbf{2} \oplus \mathbf{1}$	$\mathbf{2} \oplus \mathbf{1}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$\mathbf{2} \oplus \mathbf{1}$	$\mathbf{2} \oplus \mathbf{1}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, $\epsilon^2$ )
$\mathbf{2} \oplus \mathbf{1}$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$\mathbf{2} \oplus \mathbf{1}$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	( $\epsilon$ , $\epsilon$ , $\epsilon^3$ )
$\mathbf{2} \oplus \mathbf{1}'$	$\mathbf{2} \oplus \mathbf{1}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
$\mathbf{2} \oplus \mathbf{1}'$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	( $\epsilon$ , $\epsilon$ , $\epsilon^3$ )
$\mathbf{2} \oplus \mathbf{1}'$	$\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	( $\epsilon$ , $\epsilon$ , $\epsilon$ )
$\mathbf{3}$	$\mathbf{1}' \oplus \mathbf{1} \oplus \mathbf{1}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^3$ )
$\mathbf{3}$	$\mathbf{1}' \oplus \mathbf{1}' \oplus \mathbf{1}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon$ )
$\mathbf{3}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, 1, $\epsilon^3$ )
$\mathbf{3}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, 1, $\epsilon$ )
$\mathbf{3}'$	$\mathbf{1}' \oplus \mathbf{1} \oplus \mathbf{1}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon$ )
$\mathbf{3}'$	$\mathbf{1}' \oplus \mathbf{1}' \oplus \mathbf{1}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^3$ )
$\mathbf{3}'$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, 1, $\epsilon$ )
$\mathbf{3}'$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, 1, $\epsilon^3$ )
$\mathbf{3}$	$\mathbf{1} \oplus \mathbf{1} \oplus \mathbf{1}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon^2$ , $\epsilon^3$ )
$\mathbf{3}$	$\mathbf{1}' \oplus \mathbf{1}' \oplus \mathbf{1}'$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^3$ )
$\mathbf{3}$	$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon^2$ , $\epsilon^3$ )
$\mathbf{3}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}'$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )
$\mathbf{3}'$	$\mathbf{1} \oplus \mathbf{1} \oplus \mathbf{1}$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^3$ )







$\mathbf{r}$	$\mathbf{r}^c$	$\tau \simeq \omega$			$\tau \simeq i\infty$
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$	
$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	(1, 1, 1)
$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\mathbf{1}' \oplus \mathbf{1} \oplus \mathbf{1}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(\epsilon, \epsilon, \epsilon^3)$
$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\mathbf{1}' \oplus \mathbf{1}' \oplus \mathbf{1}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(\epsilon, \epsilon^3, \epsilon^3)$
$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$
$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, 1, \epsilon^2)$
$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(1, \epsilon^2, \epsilon^2)$
$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\mathbf{1}' \oplus \mathbf{1}' \oplus \mathbf{1}'$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(\epsilon^3, \epsilon^3, \epsilon^3)$
$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$
$\hat{\mathbf{1}} \oplus \hat{\mathbf{1}} \oplus \hat{\mathbf{1}}$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	(1, 1, 1)
$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}'$	$\hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}' \oplus \hat{\mathbf{1}}'$	(1, 1, 1)	$(\epsilon^2, \epsilon^2, \epsilon^2)$	$(\epsilon, \epsilon, \epsilon)$	$(\epsilon^2, \epsilon^2, \epsilon^2)$

**Table 13.** Leading-order mass spectra patterns of bilinears  $\psi^c\psi$  in the vicinity of the symmetric points  $\omega$  and  $i\infty$ , for 3d multiplets  $\psi \sim (r, k)$  and  $\psi^c \sim (r^c, k^c)$  of the finite modular group  $\Gamma'_5 \simeq A'_5$ . Spectra are insensitive to transposition, i.e. to the exchange  $\psi \leftrightarrow \psi^c$ . Congruence relations for  $k + k^c$  are modulo 3.

$r$	$r^c$	$\tau \simeq \omega$			$\tau \simeq i\infty$
		$k + k^c \equiv 0$	$k + k^c \equiv 1$	$k + k^c \equiv 2$	
<b>3</b>	<b>3</b>	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
<b>3</b>	<b>3'</b>	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, $\epsilon$ , $\epsilon^4$ )
<b>3'</b>	<b>3'</b>	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)	(1, 1, 1)
<b>3</b>	$1 \oplus 1 \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^4$ )
<b>3'</b>	$1 \oplus 1 \oplus 1$	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon$ , $\epsilon^2$ )	(1, $\epsilon^2$ , $\epsilon^3$ )
$1 \oplus 1 \oplus 1$	$1 \oplus 1 \oplus 1$	(1, 1, 1)	( $\epsilon^2$ , $\epsilon^2$ , $\epsilon^2$ )	( $\epsilon$ , $\epsilon$ , $\epsilon$ )	(1, 1, 1)

# $A'_5$ Model with $L \sim \mathbf{3}$ , $E^c \sim \mathbf{3}'$ , $N^c \sim \hat{\mathbf{2}}'$

$L \sim (\mathbf{3}, k_L = 3)$ ,  $E^c \sim (\mathbf{3}', k_E = 1)$ ,  $N^c \sim (\hat{\mathbf{2}}', k_N = 2)$ ; vicinity of  $\tau = i\infty$ .

We consider first the most 'structured' series of hierarchical models, i.e. the case with both fields  $L$ ,  $E^c$  furnishing complete irreps of the finite modular group.

At level  $N = 5$  the only such possibility arises in the vicinity of  $\tau = i\infty$  when  $L$  and  $E^c$  are different triplets of  $A'_5$ .

For neutrino masses generated via a type I seesaw, we have considered gauge-singlets  $N^c$  furnishing a complete irrep of dimension 2 or 3.

We performed a detailed search for a model which

- i) is phenomenologically viable in the regime of interest,
- ii) produces a charged-lepton spectrum which is not fine-tuned,
- iii) involves at most 8 effective parameters (including  $\tau$ ).

**An observable  $O$  is typically considered fine-tuned with respect to some parameter  $p$  if  $\mathbf{BG} \equiv |\partial \ln O / \partial \ln p| \gtrsim 10$ .**

G. Giudice and R. Barbieri, 1987

Found one model satisfying these requirements:

$L \sim (\mathbf{3}, k_L = 3)$ ,  $E^c \sim (\mathbf{3}', k_E = 1)$ ,  $N^c \sim (\hat{\mathbf{2}}', k_N = 2)$ .

The charged-lepton mass matrix has the following structure:

$$M_e^\dagger \sim \begin{pmatrix} 1 & \epsilon^4 & \epsilon \\ \epsilon^3 & \epsilon^2 & \epsilon^4 \\ \epsilon^2 & \epsilon & \epsilon^3 \end{pmatrix}, \quad \epsilon \simeq q_5, \quad q_5 = \exp(i2\pi\tau/5).$$

**The predicted charged-lepton mass pattern is  $(m_\tau, m_\mu, m_e) \sim (1, \epsilon, \epsilon^4)$ .**

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# $S'_4$ Model with $L \sim \hat{\mathbf{2}} \oplus \hat{\mathbf{1}}$ , $E^c \sim \hat{\mathbf{3}}'$ , $N^c \sim \mathbf{3}$

$L \sim (\hat{\mathbf{2}} \oplus \hat{\mathbf{1}}, k_L = 2)$ ,  $E^c \sim (\hat{\mathbf{3}}', k_E = 2)$ ,  $N^c \sim (\mathbf{3}, k_N = 1)$ ; vicinity of  $\tau = i\infty$ .

In the second most 'structured' case, one of the fields  $L$ ,  $E^c$  is an irreducible triplet, while the other decomposes into a doublet and a singlet of the finite modular group.

This possibility is realised at level  $N = 4$  in the vicinity of  $\tau = i\infty$ .

For definiteness, we take  $L = L_{12} \oplus L_3$  with  $L_{12} \sim (\hat{\mathbf{2}}, k_L)$ ,  $L_3 \sim (\hat{\mathbf{1}}, k_L)$ , and  $E^c \sim (\hat{\mathbf{3}}', k_E)$ .

We have performed a systematic scan restricting ourselves to models involving at most 8 effective parameters (including  $\tau$ ) with no limit on modular form weights.

Models predicting  $m_e = 0$  are rejected.

$N^c$  (when present) furnish a complete irrep of dimension 2 or 3.

Out of the 60 models thus identified, we have selected the only one which

i) is viable in the regime of interest and

ii) produces a charged-lepton spectrum which is not fine-tuned.

This model turns out to be consistent with the experimental bound on the Dirac CPV phase. It corresponds to  $k_L = k_E = 2$  and  $N^c \sim (\mathbf{3}, 1)$ .

Using as expansion parameter  $\epsilon \equiv \varepsilon/\theta \simeq 2q$ ,  $q = \exp(i\pi\tau/2)$ ,  $M_e^\dagger$  is approximately given by:

$$M_e^\dagger \sim v_d \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon^3 \\ 1 & \epsilon^3 & \epsilon \\ \epsilon^2 & \epsilon & \epsilon^3 \end{pmatrix}; \quad M_e^\dagger \simeq \frac{\sqrt{3}}{2} v_d \alpha_1 \theta^8 \begin{pmatrix} \epsilon^2 & \frac{(\tilde{\alpha}_2 + \sqrt{3})}{2\sqrt{6}} \epsilon & \frac{(7\tilde{\alpha}_2 - \sqrt{3})}{2\sqrt{6}} \epsilon^3 \\ -\frac{\tilde{\alpha}_2}{6} & \frac{(7\sqrt{3}\tilde{\alpha}_2 + 9)}{6\sqrt{6}} \epsilon^3 & \frac{(\sqrt{3}\tilde{\alpha}_2 - 9)}{6\sqrt{6}} \epsilon \\ \tilde{\alpha}_3 \epsilon^2 & -\frac{\tilde{\alpha}_3}{\sqrt{2}} \epsilon & \frac{\tilde{\alpha}_3}{\sqrt{2}} \epsilon^3 \end{pmatrix}, \quad \tilde{\alpha}_{2(3)} \equiv \alpha_{2(3)}/\alpha_1.$$

**The charged-lepton mass pattern is predicted to be  $(m_\tau, m_\mu, m_e) \sim (1, \epsilon, \epsilon^3)$ .**

One can also find approximate expressions for the charged-lepton mass ratios:

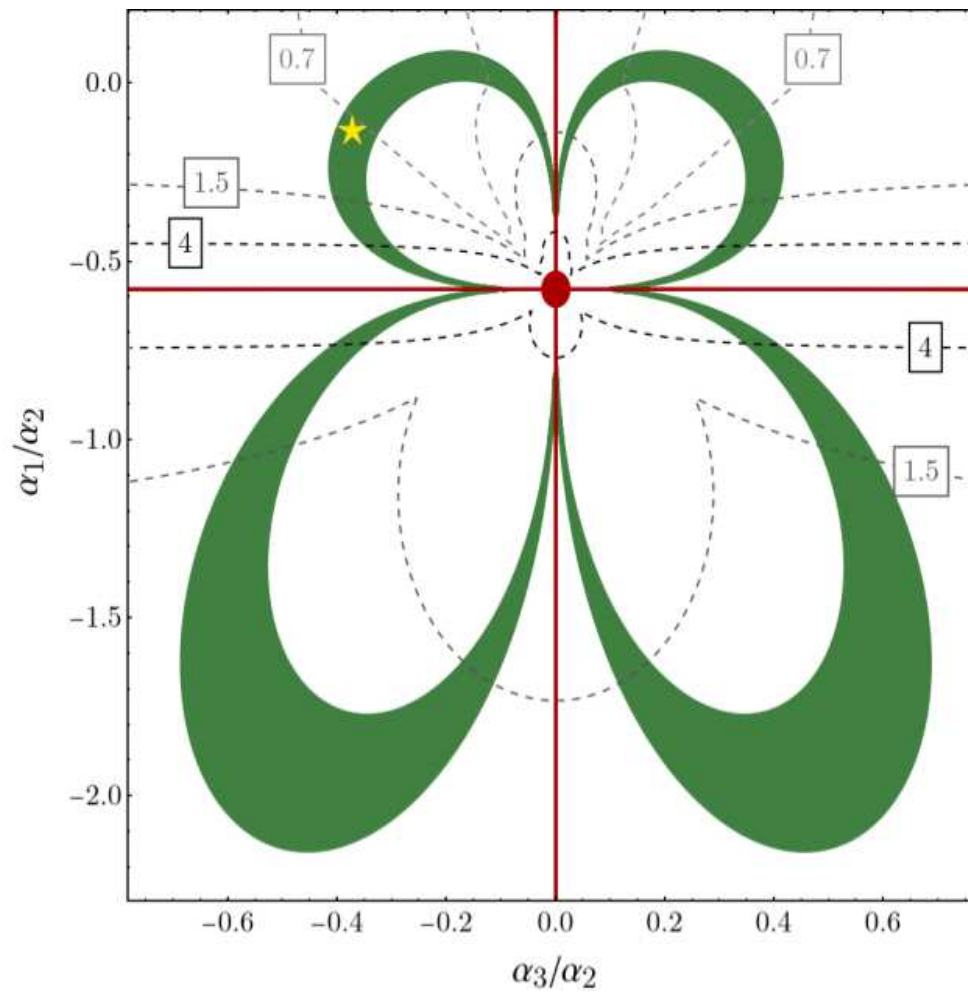
$$\frac{m_e}{m_\mu} \simeq 18\sqrt{3} \frac{|\tilde{\alpha}_3(\tilde{\alpha}_2^2 - 3)|}{|\tilde{\alpha}_2| \left( (\tilde{\alpha}_2 + \sqrt{3})^2 + 12\tilde{\alpha}_3^2 \right)} |\epsilon|^2,$$

$$\frac{m_\mu}{m_\tau} \simeq \sqrt{\frac{3}{2}} \frac{\sqrt{(\tilde{\alpha}_2 + \sqrt{3})^2 + 12\tilde{\alpha}_3^2}}{|\tilde{\alpha}_2|} |\epsilon|.$$

These expressions isolate viable ( $\epsilon$ -independent) regions in the plane of  $\tilde{\alpha}_2^{-1} = \alpha_1/\alpha_2$  and  $\tilde{\alpha}_3/\tilde{\alpha}_2 = \alpha_3/\alpha_2$ .

These regions are shown in the next figure including contours quantifying the degree of fine-tuning involved in the relation between  $l$ - mass ratios and constant parameters.

The model best-fit point corresponds to a small value of  $\max(\mathbf{BG}) \simeq 0.74$ .



Values of the charged-lepton Yukawa couplings of the  $S'_4$  model with “large”  $\text{Im}(\tau)$  which allow to reproduce charged-lepton mass ratios at  $1\sigma$  C.L. (green). The red regions are not accessible due to an upper limit on  $|\epsilon|$  within the fundamental domain. Contours refer to the Barbieri-Giudice measure of fine-tuning. The yellow star shows the location of the best-fit point for this model.

Model	$A'_5$	$S'_4$	$S'_4$
$\text{Re } \tau$	$-0.47^{+0.037}_{-0.096}$	$0.0235^{+0.0019}_{-0.002}$	$-0.496^{+0.009}_{-0.016}$
$\text{Im } \tau$	$3.11^{+0.26}_{-0.19}$	$2.65^{+0.05}_{-0.04}$	$0.877^{+0.0023}_{-0.024}$
$\alpha_2/\alpha_1$	$1.33^{+0.20}_{-0.18}$	$-7.43^{+2.76}_{-12.2}$	—
$\alpha_3/\alpha_1$	$3.07^{+0.21}_{-0.15}$	$2.76^{+5.27}_{-1.33}$	$2.45^{+0.44}_{-0.42}$
$\alpha_4/\alpha_1$	—	—	$-2.37^{+0.36}_{-0.3}$
$\alpha_5/\alpha_1$	—	—	$1.01^{+0.06}_{-0.06}$
$g_2/g_1$	$-0.0781^{+0.0228}_{-0.0346}$	$-0.407^{+0.0002}_{-0.0003}$	$1.5^{+0.15}_{-0.14}$
$g_3/g_1$	$0.57^{+0.0023}_{-0.0017}$	$0.321^{+0.02}_{-0.043}$	$2.22^{+0.17}_{-0.15}$
$v_d \alpha_1, \text{ GeV}$	$0.404^{+0.303}_{-0.149}$	$1.73^{+1.8}_{-1.15}$	$4.61^{+1.32}_{-1.33}$
$v_u^2 g_1/\Lambda, \text{ eV}$	$0.778^{+1.13}_{-0.477}$	$42.5^{+9.88}_{-5.2}$	$0.268^{+0.057}_{-0.063}$
$\epsilon(\tau)$	$0.0998^{+0.0267}_{-0.0274}$	$0.0313^{+0.0021}_{-0.0022}$	$0.0186^{+0.0028}_{-0.0023}$
CL mass pattern	$(1, \epsilon, \epsilon^4)$	$(1, \epsilon, \epsilon^3)$	$(1, \epsilon, \epsilon^2)$
max(BG)	5.579	0.738	0.848
$m_e/m_\mu$	$0.00474^{+0.00062}_{-0.0005}$	$0.00479^{+0.00058}_{-0.00056}$	$0.00475^{+0.00061}_{-0.00052}$
$m_\mu/m_\tau$	$0.0573^{+0.0111}_{-0.0137}$	$0.0574^{+0.0117}_{-0.013}$	$0.0556^{+0.0136}_{-0.0116}$
$r$	$0.0297^{+0.0021}_{-0.0021}$	$0.0298^{+0.0019}_{-0.0023}$	$0.0298^{+0.00196}_{-0.0023}$
$\delta m^2, 10^{-5} \text{ eV}^2$	$7.33^{+0.39}_{-0.4}$	$7.38^{+0.34}_{-0.44}$	$7.38^{+0.35}_{-0.44}$
$ \Delta m^2 , 10^{-3} \text{ eV}^2$	$2.47^{+0.04}_{-0.04}$	$2.48^{+0.05}_{-0.04}$	$2.48^{+0.05}_{-0.04}$
$\sin^2 \theta_{12}$	$0.306^{+0.036}_{-0.028}$	$0.301^{+0.044}_{-0.034}$	$0.304^{+0.039}_{-0.036}$
$\sin^2 \theta_{13}$	$0.0222^{+0.0021}_{-0.0018}$	$0.0223^{+0.0017}_{-0.0022}$	$0.0221^{+0.0019}_{-0.002}$
$\sin^2 \theta_{23}$	$0.55^{+0.044}_{-0.097}$	$0.548^{+0.045}_{-0.107}$	$0.539^{+0.0522}_{-0.099}$
$m_1, \text{ eV}$	$0.0493^{+0.00041}_{-0.00046}$	$0.0204^{+0.00042}_{-0.00035}$	0
$m_2, \text{ eV}$	$0.05^{+0.00037}_{-0.00042}$	$0.0221^{+0.0003}_{-0.00028}$	$0.0086^{+0.0002}_{-0.00026}$
$m_3, \text{ eV}$	0	$0.0542^{+0.00054}_{-0.00046}$	$0.0502^{+0.00046}_{-0.00043}$
$\Sigma_i m_i, \text{ eV}$	$0.0993^{+0.0008}_{-0.0009}$	$0.0967^{+0.0013}_{-0.001}$	$0.0588^{+0.0002}_{-0.0002}$
$ \langle m \rangle , \text{ eV}$	$0.0197^{+0.002}_{-0.0031}$	$0.0181^{+0.0004}_{-0.0003}$	$0.00144^{+0.00035}_{-0.00033}$
$\delta/\pi$	$1.88^{+0.37}_{-0.13}$	$1.44^{+0.01}_{-0.01}$	$1 \pm \mathcal{O}(10^{-6})$
$\alpha_{21}/\pi$	$0.91^{+0.28}_{-0.09}$	$1.77^{+0.01}_{-0.01}$	0
$\alpha_{31}/\pi$	0	$1.86^{+0.02}_{-0.02}$	$1 \pm \mathcal{O}(10^{-5})$
$N\sigma$	0.431	0.649	0.563

S.T. Petcov, MQFT; In memory of I. Todorov, 27/05/2026

# Large Mixing Angles without Fine-tuning Viable PMNS matrix in the symmetric limit

Modular-symmetric model of lepton flavour with hierarchical charged-lepton masses is expected to be free of fine-tuning, i.e., it is possible to have a PMNS matrix which is close to the observed one even in the symmetric limit, i.e., such that either none of its entries vanish, or only the (13) entry vanishes as  $\epsilon \rightarrow 0$ , if it satisfies at least one of the four conditions:

1.  $L \sim 1 \oplus 1 \oplus 1$ ,  $E^c \sim 1 \oplus r$ , where  $1$  is some real singlet of the flavour symmetry, and  $r$  is some (possibly reducible) representation such that  $r \not\supset 1$ ;
2.  $L \sim 1 \oplus 1 \oplus 1^*$ ,  $E^c \sim 1^* \oplus r$ , where  $1$  is some complex singlet of the flavour symmetry,  $1^*$  is its conjugate, and  $r$  is some (possibly reducible) representation such that  $r \not\supset 1, 1^*$ .
3. all charged-lepton masses vanish in the symmetric limit, i.e. the corresponding hierarchical pattern involves only positive powers of  $\epsilon$ , e.g.  $(\epsilon, \epsilon^2, \epsilon^3)$ ;
4. all light neutrino masses vanish in the symmetric limit, i.e.  $L$  decomposes into three (possibly identical) complex singlets none of which are conjugated to each other.

P.P. Novichkov et al., arXiv:2102.07488

The first two of the conditions were formulated earlier in Y. Reyimuaji and A. Romanino, arXiv:1801.10530 (JHEP 03 (2018) 067) for arbitrary flavour symmetry groups.

**One of the main conclusions: only a limited number of flavour symmetry representation choices for  $L$  and  $E^c$  give rise to a PMNS matrix which is viable in the symmetric limit (as defined above).**

## $S'_4$ Models with $\tau \simeq \omega$

The most 'structured' lepton flavour models without fine-tuning: these arise at level  $N = 4$  in the vicinity of  $\tau = \omega$  and correspond to  $E^c$  and  $L$  being a triplet (of weight 4) and the direct sum of three singlets (of weights 2) of the finite modular group  $S'_4$ , respectively. The charged-lepton mass pattern is  $(m_\tau, m_\mu, m_e) \sim (1, \epsilon, \epsilon^2)$ .

$M_\nu$ : seesaw,  $N^c \sim (\mathbf{3}', 1)$ ;  $m_1 = 0$ .

The model: 7 real coupling constants +  $\tau$ .

P.P. Novichkov et al., arXiv:2102.07488

In this model the b.f.v. and  $3\sigma$  ranges of  $\mathcal{T}$  read:

$$\tau = -0.496^{+0.009}_{-0.016} + i 0.877^{+0.0023}_{-0.024}; \quad u = \frac{\tau - \omega}{\tau - \omega^2}$$

# Modulus Stabilisation

In P.P. Novichkov, J.T. Penedo, STP, arXiv:2201.02020, we have studied the problem of modulus stabilisation (considered also by many authors, e.g., T. Kobayashi et al.).

SUGRA potential:  $V_{m,n}(\tau, \bar{\tau})$ ,  $n, m \geq 0$  integers, modular- and CP- invariant.

M. Cvetič et al., Nucl. Phys. B361 (1991) 194; E. Gonzalo et al., arXiv:1812.06520; J.M. Leedom et al., arXiv:2212.03876; G.-J. Ding et al. (arXiv:2405.06497)

M. Cvetič et al. conjectured: the minima of  $V_{m,n}(\tau, \bar{\tau})$  lie on the border of, or imaginary axis in,  $D$  (thus are CP-conserving); considered  $V_{0,0}(\tau, \bar{\tau})$ ,  $V_{1,1}(\tau, \bar{\tau})$  and  $V_{0,3}(\tau, \bar{\tau})$ .

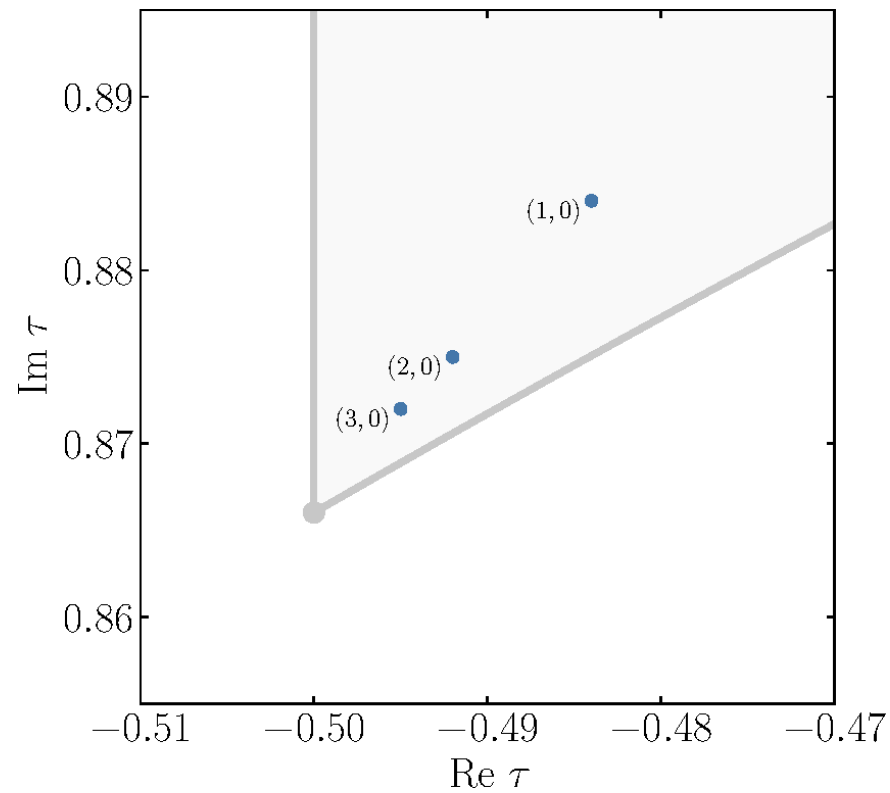
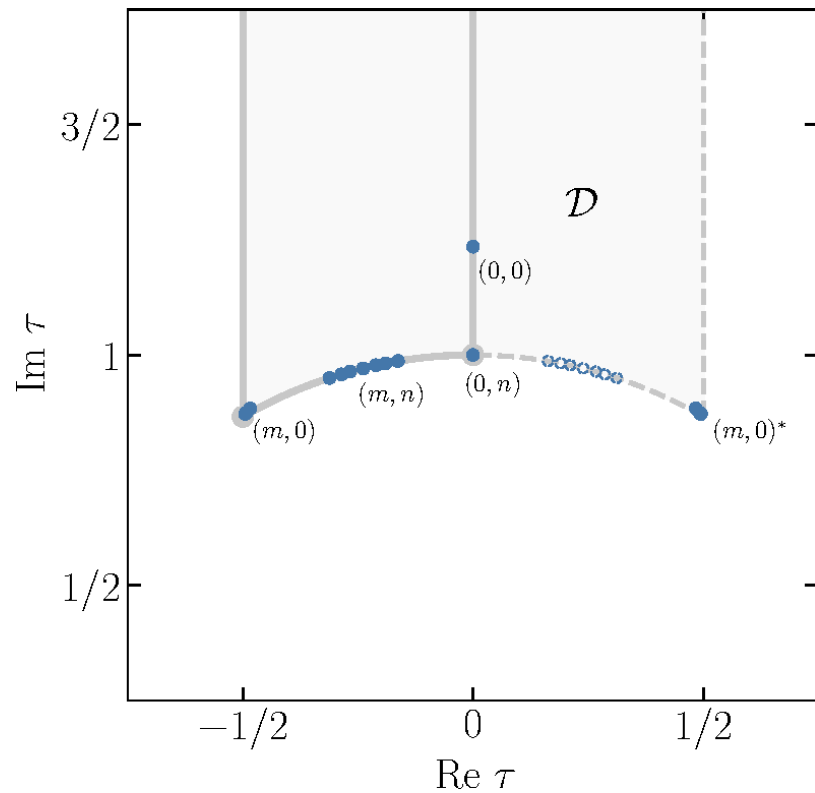
31 years later,  $V_{m,0}$ :  $u_{\min} \cong \frac{0.0145}{m + 0.0625} e^{-i2\pi/9}$  – breaks modular and CP symmetries;  $|u_{\min}|$  – from “Mexican hat”-like potential (similar to the Higgs field in the SM).

P.P. Novichkov, J.T. Penedo, STP, arXiv:2201.02020

$$V_{2,0} : u_{\min} \cong \frac{0.0145}{2 + 0.0625} e^{-i2\pi/9} \leftrightarrow \tau_{\min} = -0.492 + i0.875$$

In the  $S'_4$  model the b.f.v. and  $3\sigma$  ranges of  $\tau$  read:

$$\tau = -0.496^{+0.009}_{-0.016} + i0.877^{+0.0023}_{-0.024}; \quad u = \frac{\tau - \omega}{\tau - \omega^2}$$



**Global minima of the potentials  $V(\tau, \bar{\tau})_{m,n}$ . Note that points on the right half of the unit arc, which are CP-conjugates of the  $(m,n)$  minima, are excluded as they lie outside the fundamental domain. The right panel shows the series  $(m,0)$  in the vicinity of the left cusp in more detail.**

P.P. Novichkov et al., arXiv:2201.02020

	$n = 0$	$n = 1$	$n = 2$	$n = 3$
$m = 0$	$0.000 + 1.235i$	$0.000 + 1.000i$	$0.000 + 1.000i$	$0.000 + 1.000i$
$m = 1$	$\mp 0.484 + 0.884i$	$-0.238 + 0.971i$	$-0.190 + 0.982i$	$-0.163 + 0.987i$
$m = 2$	$\mp 0.492 + 0.875i$	$-0.286 + 0.958i$	$-0.239 + 0.971i$	$-0.211 + 0.978i$
$m = 3$	$\mp 0.495 + 0.872i$	$-0.312 + 0.950i$	$-0.267 + 0.964i$	$-0.239 + 0.971i$

Values of the modulus  $\tau$  at the global minima of the potential  $V_{m,n}(\tau, \bar{\tau})$  for various  $m$  and  $n$ . The values of  $\tau$  in red are CP-violating, those in blue are CP-conserving.

The minima of  $V_{0,0}(\tau, \bar{\tau})$ ,  $V_{1,1}(\tau, \bar{\tau})$  and  $V_{0,3}(\tau, \bar{\tau})$  – considered in M. Cvetič et al., Nucl. Phys. B361 (1991) 194 are CP-conserving.

M. Cvetič et al. conjectured: all minima of  $V_{m,n}(\tau, \bar{\tau})$  lie on the border of  $D$  or on the imaginary axis in  $D$  (thus are CP-conserving).

Not the case for  $V_{m,0}(\tau, \bar{\tau})$ .

P.P. Novichkov et al., arXiv:2201.02020

The presence of minima of  $V_{m,n}(\tau, \bar{\tau})$  not lying on the border of  $D$  or on the imaginary axis in  $D$ , and thus breaking the CP-symmetry, found in P.P. Novichkov et al., arXiv:2201.02020, was confirmed in J.M. Leedom et al., arXiv:2212.03876.

The minima of  $V_{m,0}(\tau, \bar{\tau})$  were found to break also the supersymmetry (P.P. Novichkov et al., PoS DISCRETE2022 (2024), 012 (doi:10.22323/1.431.0012)).

$$G(\tau, \bar{\tau}) = -\kappa^2 \Lambda_K^2 \log(2 \operatorname{Im} \tau) + \log \left| \kappa^3 W(\tau) \right|^2,$$

$\kappa^2 = 8\pi/M_P^2$ ,  $M_P$  being the Planck mass,  $\Lambda_K$  is a scale (mass dimension one),

$$W(\tau) = \Lambda_W^3 \frac{H(\tau)}{\eta(\tau)^{2n}},$$

$\Lambda_W$  is a mass scale so that  $H(\tau)$  is dimensionless.

Following M. Cvetič et al., Nucl. Phys. B361 (1991) 194 and E. Gonzalo et al., arXiv:1812.06520 (the most general  $H$  without singularities in the fundamental domain),

$$H(\tau) = (j(\tau) - 1728)^{m/2} j(\tau)^{n/3},$$

The Klein  $j$  function is invariant under the action of the modular group  $SL(2, \mathbb{Z})$ . Here,  $m$  and  $n$  are non-negative integers.

$$V(\tau, \bar{\tau}) = \frac{\Lambda_V^4}{(2 \operatorname{Im} \tau)^n |\eta(\tau)|^{4n}} \left[ \left| iH'(\tau) + \frac{n}{2\pi} H(\tau) \hat{G}_2(\tau, \bar{\tau}) \right|^2 \frac{(2 \operatorname{Im} \tau)^2}{n} - 3|H(\tau)|^2 \right], \quad n = 3,$$

$\Lambda_V = (\kappa^2 \Lambda_W^6)^{1/4}$  is the mass scale of the potential, and  $\hat{G}_2$  is the non-holomorphic Eisenstein function of weight 2 given by

$$\hat{G}_2(\tau, \bar{\tau}) = G_2(\tau) - \frac{\pi}{\operatorname{Im} \tau},$$

where  $G_2$  is its holomorphic counterpart.  $G_2$  can be related to the Dedekind function via

$$\frac{\eta'(\tau)}{\eta(\tau)} = \frac{i}{4\pi} G_2(\tau).$$

**The potential  $V(\tau, \bar{\tau})$  is modular- and CP- invariant.**

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Bottom-up modular invariance approaches to the lepton flavour problem have been exploited first using the finite modular groups

$\Gamma_3 \simeq A_4$  (F. Feruglio, 1706.08479; J.C. Criado, F. Feruglio, 1807.01125);

$\Gamma_2 \simeq S_3$  (T. Kobayashi et al., 1803.10391);

$\Gamma_4 \simeq S_4$  (J.T. Penedo, S.T. Petcov, 1806.11040, minimal, no flavons).

After these first studies, the interest in the approach grew significantly and models based on these and other groups have been constructed and extensively studied:

$\Gamma_4 \simeq S_4$

(Novichkov:2018ovf, Kobayashi:2019mna, Okada:2019lzv, Kobayashi:2019xvz, Gui-JunDing:2019wap, Wang:2019ovr, Wang:2020dbp, Gehrlein:2020jnr);

$\Gamma_5 \simeq A_5$

(P.P. Novichkov et al., 1812.02158; Ding:2019xna, Gehrlein:2020jnr);

$\Gamma_3 \simeq A_4$

(Kobayashi:2018scp, Novichkov:2018yse, Nomura:2019jxj, Nomura:2019yft, Ding:2019zxc, Okada:2019mjf, Nomura:2019lnr, Asaka:2019vev, Gui-JunDing:2019wap, Zhang:2019ngf, Nomura:2019xsb, Kobayashi:2019gtp, Wang:2019xbo, Abbas:2020vuy, Okada:2020dmb, Ding:2020yen, Behera:2020sfe, Nomura:2020opk, Nomura:2020cog, Behera:2020lpd, Asaka:2020tmo, Nagao:2020snm, Hutaurok:2020xtk);

$\Gamma_2 \simeq S_3$  (Okada:2019xqk, Mishra:2020gxx);

$\Gamma_7 \simeq PSL(2, \mathbb{Z}_7)$  (G.-J. Ding et al., 2004.12662).

Similarly, attempts have been made to construct viable models of **quark flavour and of quark-lepton unification (including based on GUTs)**:

(H.Okada, M. Tanimoto, 1812.09677, 1905.13421; T. Kobayashi et al., 1906.10341; Kobayashi:2018wkl, Lu:2019vgm, Abbas:2020qzc, Okada:2020rjb, Du:2020yly, Zhao:2021jxg, Chen:2021zty, Ding:2021eva, Ding:2021zbg).

The formalism of the **interplay of modular and gCP symmetries** has been developed and first applications made

(P.P. Novichkov et al., 1905.11970);

it was further extensively explored

(Kobayashi:2019uyt, Okada:2020brs, Yao:2020qyy, Wang:2021mkw, Qu:2021jdy),

as was **the possibility of coexistence of multiple moduli**

(P.P. Novichkov et al., 1811.04933 and 1812.11289 (pheno); deMedeiros-Varzielas:2019cyj, King:2019vhv, deMedeirosVarzielas:2020kji, Ding:2020zwx).

Modular invariant theories of flavour **with more than one modulus, based on symplectic modular groups** were also developed

(G.-J. Ding et al., 2010.07952 and 2102.06716).

The formalism of **double covers**  $\Gamma'_N$  has been developed and viable flavour models constructed for the cases of

$\Gamma'_3 \simeq T'$ ,  $\Gamma'_4 \simeq S'_4$  and  $\Gamma'_5 \simeq A'_5$

(X.-G. Liu, G.-J. Ding, 1907.01488 ( $T'$ ); P.P. Novichkov et al., 2006.03058 ( $S'_4$ ); X. Wang et al., 2010.10159 ( $A'_5$ ); Liu:2020akv, Yao:2020zml);

the formalism of **metaplectic (two-fold) cover group of the modular group**  $SL(2, \mathbb{Z})$ , involving half-integral (rational) weight modular forms, has also been developed (X.-G. Liu et al., 2007.13706).

It was also realised that there exist **three fixed (symmetry) points of the VEV of  $\tau$** ,  $\tau_{\text{sym}} = \omega (= -1/2 + i\sqrt{3}/2)$ ,  $i\infty$ ,  $i$  (in the mod. group fund. domain), at which the flavour (=finite modular) symmetry  $\Gamma_N$  ( $\Gamma'_N$ ) is broken to non-trivial **residual symmetries**,  $\mathbb{Z}_3^{ST}$ ,  $\mathbb{Z}_N^T$  and  $\mathbb{Z}_2^S$  ( $\mathbb{Z}_4^S \times \mathbb{Z}_2^R$ )

(P.P. Novichkov et al., 1811.04933 (2006.03058));  
this fact was further exploited in flavour model building  
(Novichkov:2018yse,Novichkov:2018nkm,Okada:2020brs)  
and especially in connection with the possibility to build viable flavour models with observed  
charged lepton (quark) mass hierarchies in the vicinity of the symmetry points  
(H. Okada, M. Tanimoto, 2009.14242, 2012.0188; F. Feruglio et al., 2101.08718)  
**even without fine-tuning** (P.P. Novichkov et al., 2102.07488).

It was shown also that **one can have successful leptogenesis** in theories with modular  
flavour symmetries  
(T. Asaka et al., 1909.06520; X. Wnag, S. Zhou, 1910.09473; H. Okada et al.,  
2105.14292).

The bottom-up analyses are expected to eventually connect with the results of the **top-  
down approach** based on ultraviolet-complete theories  
(Kobayashi:2018rad,Kobayashi:2018bff,deAnda:2018ecu,Baur:2019kwi,  
Kariyazono:2019ehj,Baur:2019iai,Nilles:2020nnc,Kobayashi:2020hoc,  
Abe:2020vmv,Ohki:2020bpo,Kobayashi:2020uaj,Nilles:2020kgo,Kikuchi:2020frp,  
Nilles:2020tdp,Kikuchi:2020nxn,Baur:2020jwc,Ishiguro:2020nuf,Nilles:2020gvu,  
Ishiguro:2020tmo,Hoshiya:2020hki,Baur:2020yjl,Kikuchi:2021ogn).

**More recent developments.**

### **Quark Mass Hierarchies in Modular Approach to Flavour**

I. de Medeiros Varzielas et al. (deMedeirosVarzielas:2023crv); S.T.P. and M. Tanimoto (Pet-  
cov:2023vws; Petcov:2022fjf); T. Kobayashi et al. (Higaki:2024ueb,Abe:2023qmr,Abe:2023ilq).

### **Modular Invariant Axion-less Solution to the Strong CP Problem**

F. Feruglio et al. (Feruglio:2024ytl,Feruglio:2023uof); J. Penedo and S.T.P. (Penedo:2024gtb);  
S.T.P. and M. Tanimoto (Petcov:2024vph).

### **The Modulus as Inflaton.**

G.-J. Ding et al. (Ding:2024neh,Ding:2024euc); S.F. King and Xin Wang (King:2024ssx). Y. Abe et al. (Abe:2023ylh)

### **Modular Invariance Approach to Flavour without SUSY**

G.-J. Ding et al. (Qu:2024rns,Ding:2024inn,Li:2024svh).

### **Baryogenesis from cosmological CP breaking**

M. Duch, A. Strumia, A.V. Titov, arXiv:2504.03506.

### **Modular-Symmetry-Protected Seesaw Mechanism**

A. Granelli, D. Meloni, M. Parriciatu, J.T. Penedo, S.T.P., arXiv:2505.21405.

**The presented list of publications is not exhaustive.**

## Instead of Conclusions

To summarise, there is still very important work to be done in the field of the modular invariance approach to the flavour problem. The stakes are high and worth the efforts: we are trying to develop The Theory of Flavour using the power and the beauty of the modular invariance.