Beyond the Standard Model: Probing Modular Symmetries in Neutrino Oscillations with DUNE, T2HK, and JUNO

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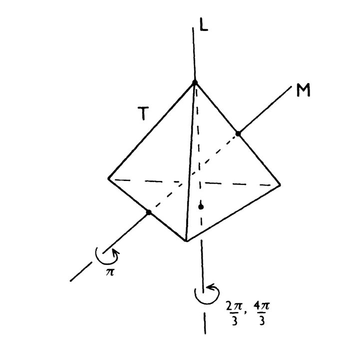
Introduction

- The evidence of neutrino mass originates from neutrino Oscillations.
- The Standard Model (SM), fails to explain neutrino mass as it has no right handed neutrino.
- To, explain neutrino mass we need to extend SM and for this we utilize seesaw mechanism.
- To explain the mixing pattern in leptonic sector, the extension in symmetry sector is carried out by continuous or discrete symmetry.

What is A_4 discrete Symmetry ???

A_4 is the group of even permutations of four objects. It has $\frac{4!}{2} = 12$ elements. Geometrically, it can be seen as the invariance group of a tetrahedron.



Drawbacks:

- Tri-bimaximal mixing pattern can be derived by A_4 discrete symmetry and it leads to the zero reactor mixing angle (θ_{13}).
- Discrete symmetry mechanism is that we need to handle VeV alignment of several number of flavon fields.

A_4 Modular Symmetry

- Modular group:

$$\Gamma(3) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2,\mathbb{Z}),\ \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \right\}.$$

- A_4 can also be defined as the group generated by the two elements S and T obeying the relations.

$$S^2 = (ST)^3 = T^3 = 1$$

- Representation of S and T,

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

$$S : \tau \rightarrow \frac{-1}{\tau}, T : \tau \rightarrow \tau + 1$$

- Modularity Condition:

$$\tau \rightarrow \frac{a\tau + b}{c\tau + d}, \quad f\left(\frac{a\tau + b}{c\tau + d}\right) = (c\tau + d)^{2k} f(\tau),$$

- The Yukawa couplings transform as modular forms in this symmetry.

We consider three models, all based on A_4 modular symmetry.

Model-A: Linear seesaw

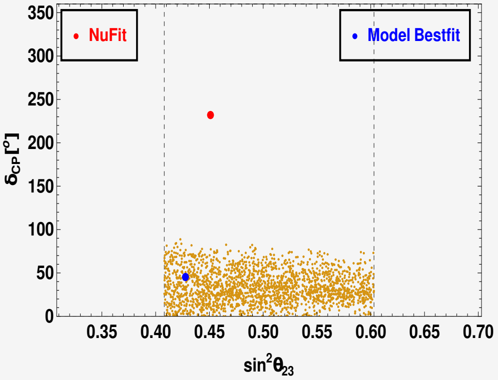
- The superpotential giving neutrino mass terms: [arXiv : 2007.00545]

$$W_D = G_D L_{\wp L} H_u \, (Y N_R)_{1,1'',1'} + G'_D \left[L_{\wp L} H_u \, (Y S_L^c)_{1,1',1''} \right] \frac{\rho_a^3}{\Lambda_a^3}$$
$$+ \left[\alpha_{NS} Y (S_L^c N_R)_{\rm sym} + \beta_{NS} Y (S_L^c N_R)_{\rm Anti-sym} \right] \rho_a$$

- neutrino mass matrix:

$$m_\nu = -M_D M_{RS}^{-1} M_{LS}^T$$

- Model-A predicts normal hierarchy and constraints the $\delta_{\rm CP}$ value.



Range obtained for $\delta_{\rm CP} \in [0^\circ, 89^\circ]$

Model-B: Type-I seesaw

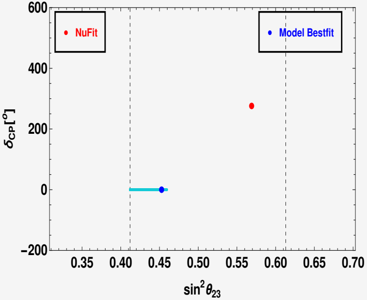
- The particles added to the Standard Model (SM) are three right handed neutrinos. $[arXiv: 1706.08749]$
- The invariant superpotential terms giving neutrino mass are:

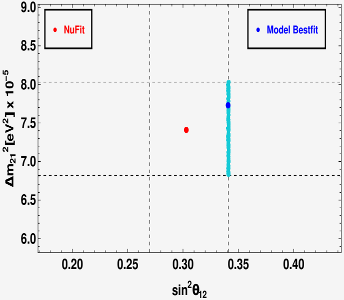
$$W_\nu = g(N_R^c H_u L Y)_1 + M_b(N_R^c N_R^c Y)_1$$

- Neutrino mass matrix:

$$m_\nu = -M_D M_R^{-1} M_D^T \, .$$

- Model-B giving rise to inverted hierarchy.
- Predictions from model-B are:





Obtained values for $\delta_{CP} = 0^\circ$, $\sin^2\theta_{23} < 0.495$, $\sin^2\theta_{12} \simeq 0.34$

Model-C: Type-III seesaw

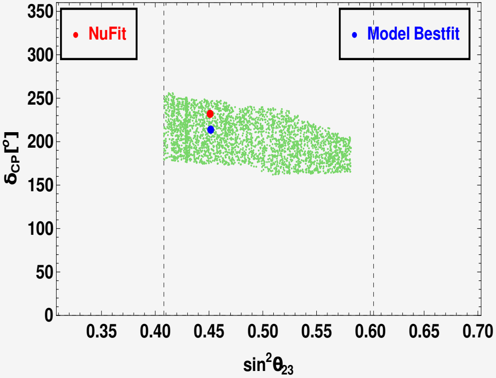
- Three right handed fermionic triplets are added to the model with an additional $U(1)_{B-L}$ symmetry. $[arXiv : 2204.08338]$
- The superpotential for neutrino sector is:

$$W_\nu = \ (\alpha_\Sigma)_{ij} \left[H_u \Sigma^c_{R_i} \sqrt{2} \mathbf{Y} L_j \right] + \frac{M'_\Sigma}{2} \left(\beta_\Sigma \mathrm{Tr} \left[\Sigma^c_{R_i} \mathbf{Y} \Sigma^c_{R_i} \right]_{\mathrm{s}} + \gamma'_\Sigma \mathrm{Tr} \left[\Sigma^c_{R_i} \mathbf{Y} \Sigma^c_{R_i} \right]_{\mathrm{a}} \right) \frac{\rho_c}{\Lambda_c}$$

- Neutrino mass matrix:

$$m_\nu = -M_D M_R^{-1} M_D^T \ .$$

- The oscillation parameters constrained by the model:



- Predictions from model-C: Normal Hierarchy and $162^\circ < \delta_{CP} < 256^\circ$.

- We test these models in DUNE, T2HK and JUNO.

Experimental details

	DUNE	T2HK
Detector position	40 kton LArTPC	374 kton water
Baseline	1300 km	296 km
Beam angle	on axis	2.5° off-axis
Energy Peak	2.5 GeV	600 MeV
Run-Time	5:5	5:5

JUNO: Baseline: 53 km with 20-kton liquid scintillator detector located 700 m underground. We consider run time to be 6 years and energy resolution of 3 $\%/\sqrt{E\ (Mev)}$

Analysis

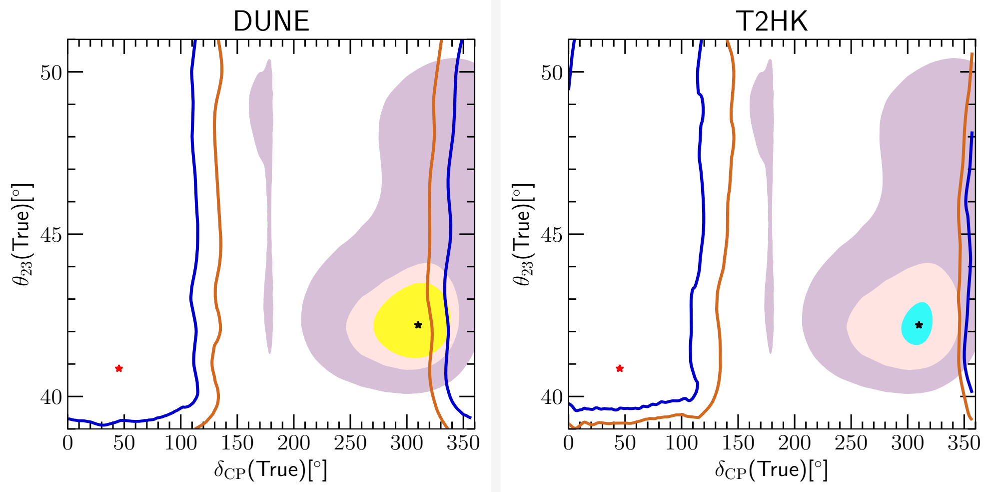
- Our results are statistically analyzed using the GLoBES χ^2 function:

$$\chi^2 = 2\sum_j \left[N_j^{\rm th} - N_j^{\rm true} - N_j^{\rm true} \ln\left(\frac{N_j^{\rm th}}{N_j^{\rm true}}\right)\right], \tag{1}$$

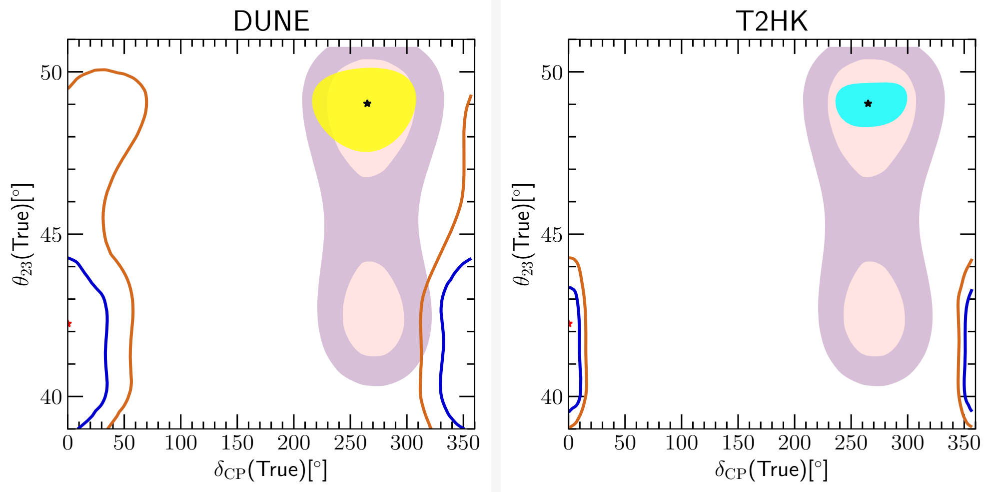
- The true values of oscillation parameters are taken from NuFIT-5.2.

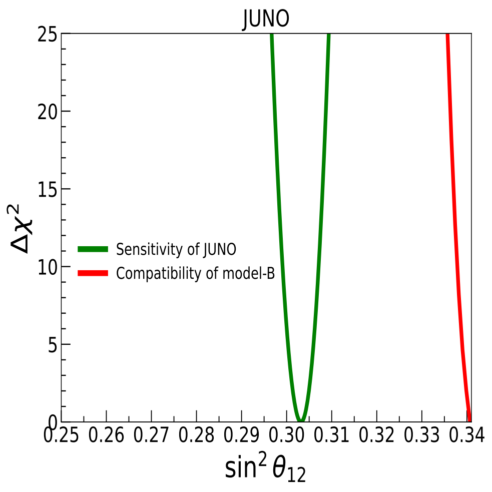
$$\Delta\chi^2 = \chi^2 - \chi^2_{min} \tag{2}$$

Results from Model-A

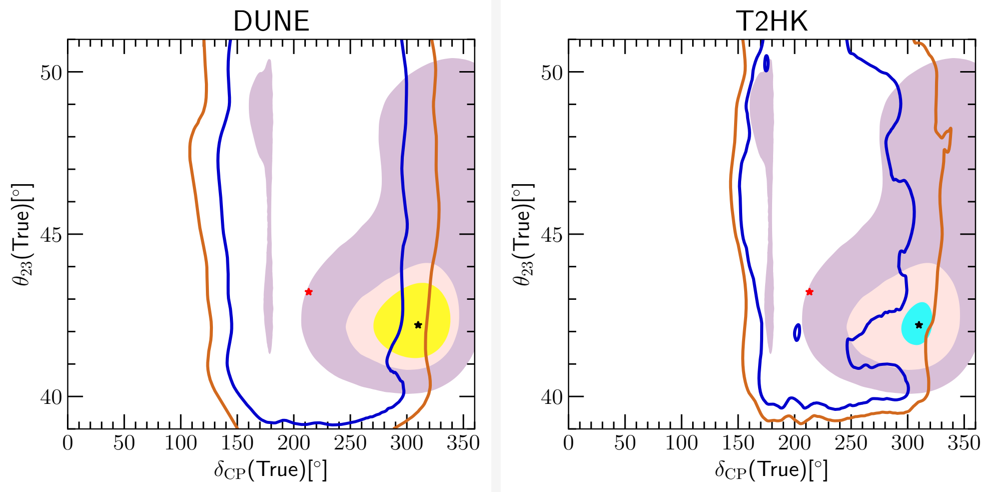


Results from Model-B



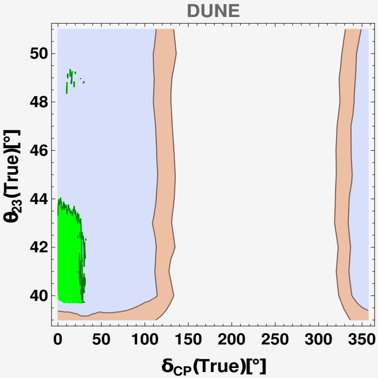

JUNO
25
20
15
10
5
0
$\Delta\chi^2$
Sensitivity of JUNO
Compatibility of model-B
0.25 0.26 0.27 0.28 0.29 0.30 0.31 0.32 0.33 0.34
$\sin^2\theta_{12}$

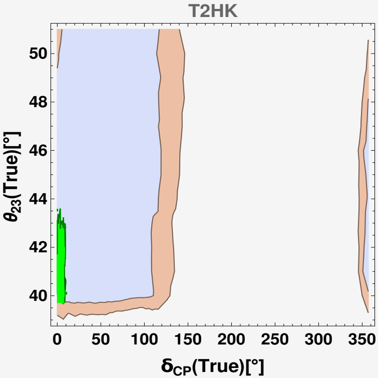
Results from Model-C



Capability of Experiments to separate two models

- Model-C can be separated from Model-A and B very easily, as they have different predictions for δ_{CP} value.
- Model-A and Model-B have common parameter space for δ_{CP}.



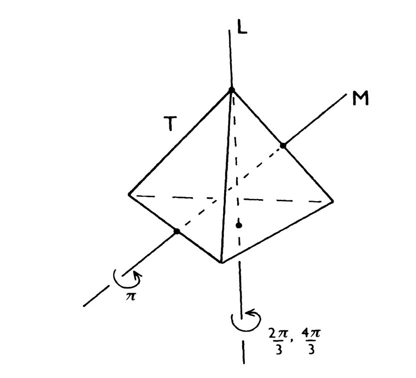


Conclusion

- Model-A can be tested in DUNE with better confidence level than T2HK.
- Model-B predicts stringent bound on CP phase (δ_{CP}) and $\sin^2\theta_{12}$, so it can be probed with JUNO if, true value of $\sin^2\theta_{12}$ shifts towards 0.34 in future.
- Model-C can be tested in DUNE, T2HK and, T2HKK experiments.
- T2HK experiment can distinguish model-A from model-B.

Thankyou

What is A_4 discrete Symmetry ???



Ma-Rajsekaran Basis:

- One dimension representation:

$$1 : S = 1, T = 1 \tag{3}$$

$$1' : S = 1, T = \omega \tag{4}$$

$$1'' : S = 1, T = \omega^2 \tag{5}$$

- Three dimensional represenation:

$$S = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{pmatrix}, T = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \tag{6}$$

Altarelli Feruglio Basis:

- One dimensional representaion is same like for Ma-Rajsekaran basis.
- Three dimensional representation:

$$T' = V^\dagger T V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix}, S' = V^\dagger S V = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix} \tag{7}$$

- and V is magic matrix and is defined as:

$$V = \frac{1}{\sqrt{3}}\begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix} \tag{8}$$

Yukawa:

$$
\begin{aligned}
y_1(\tau) &= \frac{i}{2\pi}\left(\frac{\eta'(\tau/3)}{\eta(\tau/3)} + \frac{\eta'((\tau+1)/3)}{\eta((\tau+1)/3)} + \frac{\eta'((\tau+2)/3)}{\eta((\tau+2)/3)} - \frac{27\eta'(3\tau)}{\eta(3\tau)}\right), \\
y_2(\tau) &= \frac{-i}{\pi}\left(\frac{\eta'(\tau/3)}{\eta(\tau/3)} + \omega^2\frac{\eta'((\tau+1)/3)}{\eta((\tau+1)/3)} + \omega\frac{\eta'((\tau+2)/3)}{\eta((\tau+2)/3)}\right), \\
y_3(\tau) &= \frac{-i}{\pi}\left(\frac{\eta'(\tau/3)}{\eta(\tau/3)} + \omega\frac{\eta'((\tau+1)/3)}{\eta((\tau+1)/3)} + \omega^2\frac{\eta'((\tau+2)/3)}{\eta((\tau+2)/3)}\right).
\end{aligned}
\tag{9}
$$

Product Rule:

$$1 \bigotimes 1 = 1$$
$$1' \bigotimes 1' = 1''$$
$$1' \bigotimes 1'' = 1$$
$$1'' \bigotimes 1'' = 1'$$
$$3 \bigotimes 3 = 1 \bigoplus 1' \bigoplus 1'' \bigoplus 3_a \bigoplus 3_s$$