MSc Promotional Presentation: Fitting NOvA and T2K data with the revamped A_4 symmetry model for the poorly constrained neutrino oscillation parameters

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What are Neutrinos?

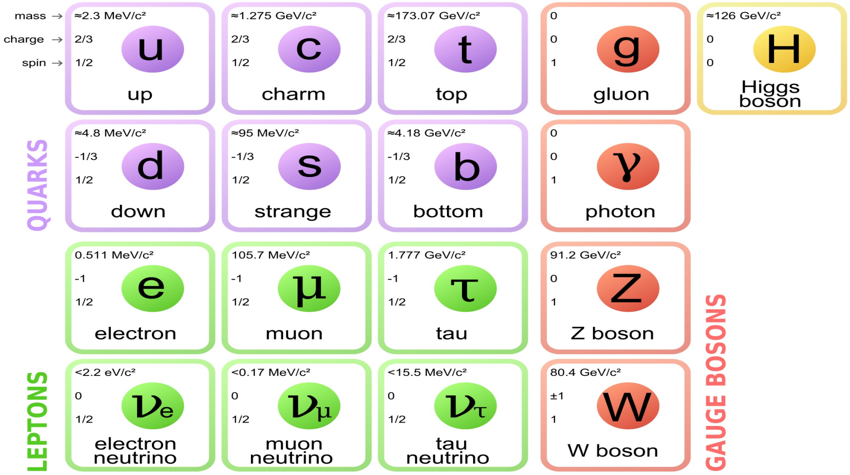

Figure: Standard Model of Elementary Particles.
source: *https://en.wikipedia.org/wiki/StandardModel*

Oscillation Parameters

1. Known Parameters and their measurements
   - The bestfit values of $\sin^2\theta_{12}$ and Δm^2_{12} are known with good accuracy from solar neutrino experiments, with O(MeV) energy.
   - $|\Delta m^2_{32}|$ is measured from atmospheric neutrino experiments and accelerator neutrino experiments, with O(GeV) energy. Its bestfit values are known but a degeneracy results mainly due to the mass Hierarchy Problem.
   - $\sin^2\theta_{13}$ is known to good accuracy from reactor neutrino experiments, with O(MeV) energy.
2. Poorly known Parameters
   - $\sin^2\theta_{23}$ is also measured from accelerator neutrino experiments, however the octancy (i.e. $\sin^2\theta_{23} < 0.5$ vs $\sin^2\theta_{23} > 0.5$) remains unknown.
   - δ_{CP} is poorly determined. The violation of CP implies $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$.
   - Mass Hierarchy: Although $|\Delta m^2_{23}|$ is known with good accuracy, the exact mass order remains unknown. The two possibilities being Normal ($m_1 < m_2 < m_3$) and Inverted ($m_3 < m_1 < m_2$).

NOvA Experiments

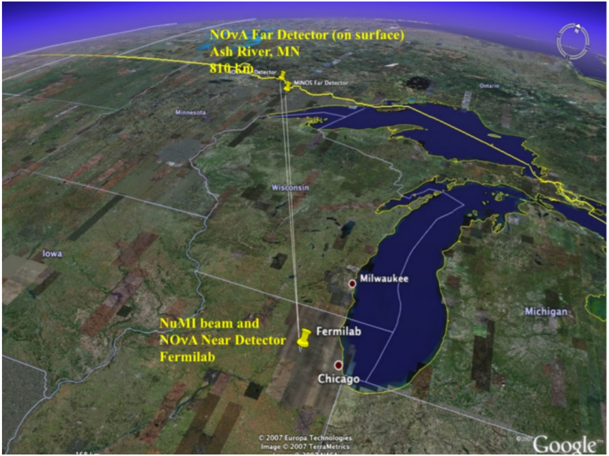

Figure: The NOvA Experiment google map view. *Taken from J. Bian et al (2013)*/arXiv:1309.7898v1

T2K Experiments

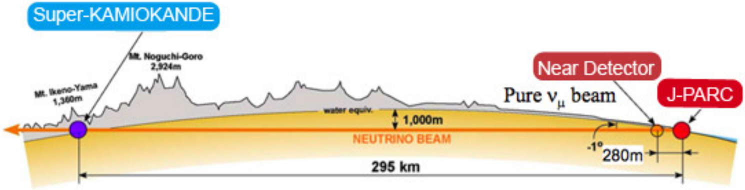

Figure: Schematic view of the T2K experiment from the J-PARC accelerator (red dot) and near detectors (orange dot) in Tokai to Super-Kamiokande (purple dot). *Taken from Abe K et al (2011)* /arXiv:1106.1238v2

The BMV model

The BMV (Babu-Ma-Valle) model [arXiv:hep-ph/0206292v1] makes use of the A_4 symmetric group, requiring the existence of extra (heavy) fermions plus 3 scalars fields (χ_1, χ_2, χ_3). This results in the charged lepton mass matrix taking the form:

$$M = \begin{pmatrix} (f_e v_1)^2 I & M_E f_e v_1 I \\ M_E f_e v_1 I & U_\omega(Diag\{3(h_i^e u)^2\})U_\omega^\dagger + M_E^2 I \end{pmatrix} = \begin{pmatrix} m_1^2 & m_2^2 \\ m_2^{2\dagger} & m_3^2 \end{pmatrix} \quad (1)$$

where f_e couples the standard fermions to the Higgs field and h_i^e couples the new scalars. v_1 and u are the vacuum expectation values of the Higgs field and new scalars respectfully. U_ω with $\omega = e^{\frac{2\pi i}{3}}$ is termed the magic matrix and the recovered mixing matrix U_ν take the form :

$$U_\omega = \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix}, U_\nu = \begin{pmatrix} cos\theta & -sin\theta & 0 \\ \frac{sin\theta}{\sqrt{2}} & \frac{cos\theta}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ \frac{sin\theta}{\sqrt{2}} & \frac{cos\theta}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \quad (2)$$

The Revamped BMV model

The resulting neutrino mixing matrix implies an exclusive θ_{12} depends with $\theta_{13} \equiv 0$, $\theta_{23} \equiv \frac{\pi}{4}$ and no Dirac phase.This conflicts with the discovery from Daya Bay [arXiv:1501.04991v1], Double CHOOZ [arXiv:1501.04991v1] and RENO [arXiv:1003.1391v1] Collaborations. The Revamped BMV model [arXiv:1305.6774v1] restores the non-vanishing θ_{13} by the addition of an additional scalar flavon. The selected parameter for $\langle\zeta\rangle$ scales M_E by β and the charged lepton mass matrix is modified to:

$$M' = \begin{pmatrix} (f_e v_1)^2 I & f_e v_1 Y_D^\dagger \\ f_e v_1 Y_D & U_\omega(Diag\{3(h_i^e u)^2\})U_\omega^\dagger + Y_D Y_D^\dagger \end{pmatrix} \quad (3)$$

where $Y_D = M_E I + \beta M_E Diag\{1, \omega, \omega^2\}$.

The Revamped BMV model

We obtain expressions for the standard parameters w.r.t the new parameters as follows.

$$\tan\theta_{12} = \big|[U'_\nu]_{12}|/|[U'_\nu]_{11}\big| \quad (4)$$
$$\sin\theta_{13} = |[U'_\nu]_{13}| \quad (5)$$
$$\tan\theta_{23} = |[U'_\nu]_{23}|/|[U'_\nu]_{33}| \quad (6)$$
$$\delta_{CP} = Arg[(\cos\theta_{12}\cos\theta_{23})/(|[U'_\nu]_{22}|e^{i\phi_\beta} + \sin\theta_{12}\sin\theta_{13}\sin\theta_{23})] \quad (7)$$

where $\phi_\beta = Arg[[U'_\nu]_{22}] - Arg[[U'_\nu]_{12}] + Arg[[U'_\nu]_{13}] - Arg[[U'_\nu]_{23}]$ is the argument of the new parameter β.
We perform the diagonalization numerically by ranging the new parameters as $|\beta| \leq 1$, $10^4 \leq M_E \leq 10^5$ [GeV], $1 \leq f_e v_1 \leq 100$ [GeV], $-\pi \leq \theta \leq \pi$ and $-\pi \leq \phi_\beta \leq \pi$.

Aims and Objective of Study

- Probe the Revamped BMV model using data NOvA and T2K long-baseline experiments
- Perform a comparative analysis between the revamped BMV model and the SM.
- Test the capability of the new model in constraining the poorly determined parameters.

Methodology

Data simulation and analysis GLoBES

- GLoBES- General Long Baseline Experiment Simulator.
- c Programming Language ran on Linux or OS systems.
- NOvA and T2K experimental data input with AEDL files.
- Allows user input
- handles both standard and non-standard physics models
- User manual available on https://www.mpi-hd.mpg.de/personalhomes/globes/

Data analysis with $\Delta\chi^2$

- $\chi^2 = \sum_i 2[(N_i^{th} - N_i^{ex}) + N_i^{exp} ln(\frac{N_i^{exp}}{N_i^{th}})] + \left(\frac{sin^2 2\theta test_{13} - sin^2 2\theta_{13}^{true}}{0.05 sin^2 2\theta_{13}^{true}}\right)^2 + \left(\frac{sin^2 2\theta_{32}^{test} - sin^2 2\theta_{32}^{true}}{0.02 sin^2 2\theta_{32}^{true}}\right)^2 + \left(\frac{|\Delta m_{\mu\mu}^{test}|^2 - |\Delta m_{\mu\mu}^{true}|^2}{|\Delta m_{\mu\mu}^{true}|^2}\right)^2$
- $\Delta\chi^2 = \chi^2 - \chi^2_{min}$

$\Delta\chi^2$ Analysis of NOvA and T2K data with SM

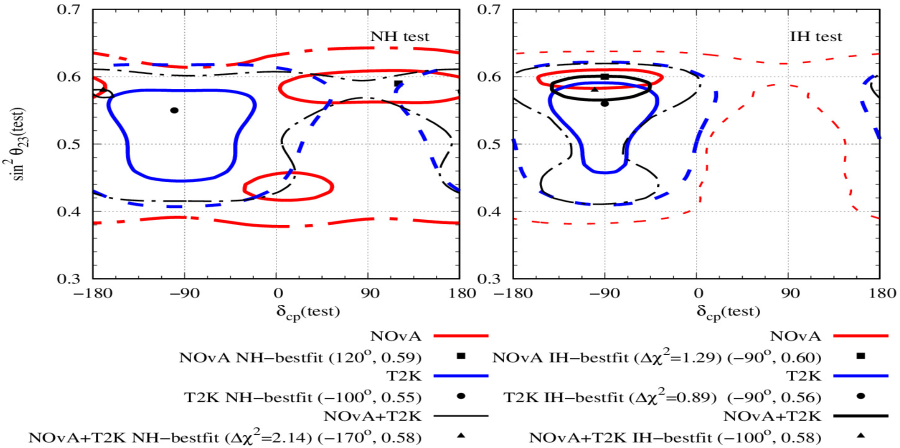

Figure: LEFT: NH test, dotted lines are within 3σ, solid lines within 1σ RIGHT: IH test.

$\Delta\chi^2$ Analysis of NOvA and T2K data with Revamped BMV model

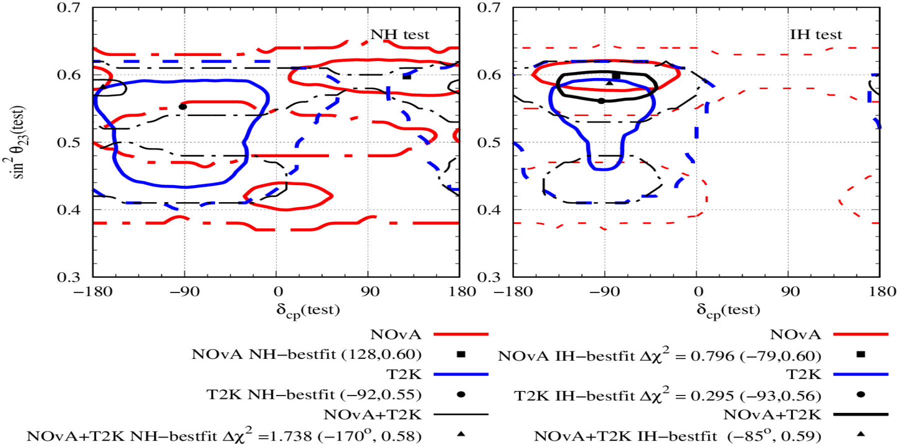

Figure: LEFT: NH test, the dotted lines are within 3σ, solid lines are within 1σ. RIGHT: IH test.

Conclusion

- The new model provides new constraints for NOvA none for T2K.
- The constraint is only on 3σ region.
- The apparent constraint on NOvA+T2K is a consequence of NOvA constrain.
- $\sin^2\theta_{23} = 0.5$ only if $\delta_{CP} \approx 170^o$ for NOvA
- ϕ_β has poor constrains on both poorly determined paramaters
- $\sin^2\theta_{23}$ does not depend on θ.
- the bestfit points favor higher octancy for $\sin^2\theta_{23}$

Questions

Questions??