Cornering the revamped BMV model with neutrino oscillation data

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Motivation: A4 symmetry and BMV model

Result: Constraining parameter space by the BMV model

Result: Reconstruction of parameter value

Result: Exclusion of the BMV model by experiments

Summary
## Present status of oscillation parameters

**Table:** de Salas, Forero, Ternes, Tortola, Valle: 1708.01186

<table>
<thead>
<tr>
<th>Oscillation parameter</th>
<th>Best fit value</th>
<th>$3\sigma$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$34.5^{+1.1}_{-1.0}$</td>
<td>$31.5 \rightarrow 38.0$</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$ (NH)</td>
<td>$41.0 \pm 1.1$</td>
<td>$38.3 \rightarrow 52.8$</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$ (IH)</td>
<td>$50.5 \pm 1.0$</td>
<td>$38.5 \rightarrow 53.0$</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$ (NH)</td>
<td>$8.44^{+0.18}_{-0.15}$</td>
<td>$7.9 \rightarrow 8.9$</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$ (IH)</td>
<td>$8.41^{+0.16}_{-0.17}$</td>
<td>$7.9 \rightarrow 8.9$</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$ (NH)</td>
<td>$252^{+56}_{-36}$</td>
<td>$0 \rightarrow 360$</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$ (IH)</td>
<td>$259^{+47}_{-41}$</td>
<td>$0 \rightarrow 31 &amp; 142 \rightarrow 360$</td>
</tr>
<tr>
<td>$\Delta m_{21}^2/10^{-5} \text{eV}^2$</td>
<td>$7.50^{+0.19}_{-0.17}$</td>
<td>$7.03 \rightarrow 8.09$</td>
</tr>
<tr>
<td>$\Delta m_{31}^2/10^{-3} \text{eV}^2$ (NH)</td>
<td>$+2.55 \pm +0.04$</td>
<td>$+2.43 \rightarrow +2.67$</td>
</tr>
<tr>
<td>$\Delta m_{31}^2/10^{-3} \text{eV}^2$ (IH)</td>
<td>$-2.49 \pm +0.04$</td>
<td>$-2.61 \rightarrow -2.37$</td>
</tr>
</tbody>
</table>
What is DUNE (Deep Underground Neutrino Experiment)?

R. Acciarri et al. (DUNE Collaboration): 1512.06148

- A proposed long baseline experiment (the erstwhile LBNE) with 1300 km baseline

- likely to have a 40 kt FD with 3.5 yrs. of $\nu$ and 3.5 yrs. of $\bar{\nu}$ run.

- The incident $\nu_\mu$ beam is generated by 80 GeV proton beam delivered at 1.07 MW with a POT of $1.47 \times 10^{21}$. 
Upscaled version of T2K with the same baseline of 295 km but with a much larger detector of 560 kt fiducial mass.

A beam of 7.5 MW corresponding to a POT of $1.53 \times 10^{22}$

1 year of $\nu$ and 3 yrs. of $\bar{\nu}$ run was assumed.
A4 symmetry and BMV model: brief overview


- Requires the existence of extra heavy fermions and three scalars $\chi_i, i = 1, 2, 3$, all of them belonging to $A_4$ triplets representation and coupled through standard Yukawa interactions.

- After breaking the $A_4$ at high energy,

$$M_{eE}M_{eE}^\dagger = \begin{pmatrix} (f_1v_1)^2I & (f_1v_1)M_EL \\ (f_1v_1)M_EL & U_\omega \text{Diag}[3(h_i^e u)^2]U_\omega^\dagger + M_E^2I \end{pmatrix}$$

- Translates into zero-th order neutrino mixing matrix,

$$U_\nu(\theta) = \begin{pmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta/\sqrt{2} & \cos \theta/\sqrt{2} & -1/\sqrt{2} \\ \sin \theta/\sqrt{2} & \cos \theta/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$
A single flavon scalar $\xi$ is added to break the remnant symmetry in A4 and the charged fermion mass matrix is changed slightly,

\[
M_{eE}M_{eE}^\dagger = \begin{pmatrix}
(f_e v_1)^2 I & (f_e v_1) Y_D^\dagger \\
(f_e v_1) Y_D & U_\omega \text{Diag}[3(h_i^e u)^2] U_\omega^\dagger + Y_D Y_D^\dagger
\end{pmatrix}
\]  

(1)

where $Y_D = M_E (I + \beta \text{Diag}[1, \omega, \omega^2])$, and $\beta$ is a small complex parameter.

The mixing matrix gets modified to,

\[
U_\nu(\theta) \rightarrow K(\theta, \beta) = U_\delta^\dagger (\beta) U_\nu(\theta)
\]

where the pre-factor $U_\delta^\dagger (\beta)$ characterizes the revamping and generates a nonzero reactor mixing angle.

The mixing angles are extracted from this modified mixing matrix and the phase of the complex coupling of flavon $\beta$ becomes the source of CP violation.
The revamped model shows the theoretical correlation between the flavon coupling ($\beta$) and the solar angle $\theta_{13}$ and also between the CP phase and the atmospheric angle $\theta_{23}$.

We wanted to extend on this study by testing the model in DUNE and T2HK and doing a $\chi^2$ level analysis for excluding the model.
Numerical procedure (using GLoBES)

\[ \chi^2 = \min \{ \xi_a, \xi_b \} \left[ 2 \sum_{i=1}^{n} (y_i - x_i - x_i \ln \frac{y_i}{x_i}) + \xi_a^2 + \xi_b^2 \right]. \] (2)

\( n \) is the total number of bins and \( \xi_a \) and \( \xi_b \) denote the pulls due to systematic errors.

We simulate the true dataset \( x_i \) using GLoBES (by considering the present BF parameters) and get the test dataset from the value of oscillation parameters predicted by the model.

\[ \chi^2_{\text{total}} = \chi^2_{\nu_\mu \to \nu_e} + \chi^2_{\bar{\nu}_\mu \to \bar{\nu}_e} + \chi^2_{\nu_\mu \to \nu_\mu} + \chi^2_{\bar{\nu}_\mu \to \bar{\nu}_\mu}. \] (3)

\( \chi^2_{\text{total}} \) is minimized over the free oscillation parameters (\( \theta_{23}, \theta_{13}, \theta_{12}, \) and \( \delta_{CP} \)) predicted by the model.
Allowed region in $\delta_{CP}(test)$-$\sin^2 \theta_{23}(test)$ plane

- Dark blue (90%) and light blue (99%) corresponds to present bound for unconstrained $3\nu$ scenario \cite{de Salas et. al.:1708.01186}.

- Green: Allowed by the model and consistent with the global fit.
Normal ordering is preferred and inverted ordering is only allowed at 99% C.L.

For normal ordering, preferred solution indicates to the lower octant and maximal CP violation.
Capability to reconstruct the CP phase

- Left column: Standard 3ν scenario. Right column: Model prediction
- Top row: DUNE. Bottom Row: T2HK
T2HK is more capable to reconstruct the values of $\delta_{CP}$.

The model has a significant impact on the ability of the experiment to reconstruct the CP phase.
For $\delta_{CP}(\text{true}) = -\pi/2$, the minima (cyan patch) indicates to a lower octant

For CP conservation, the minima indicates to a higher octant

These observations are consistent with the earlier results.
For each $\delta_{CP}(\text{true})$-$\sin^2 \theta_{23}(\text{true})$, all the test parameters were marginalized over their allowed range.

Regions within the black contour correspond to 90% CL of the present best fit.
Sensitivity of DUNE, T2HK to the model: a fit-independent approach...(cont.)

At $4\sigma$ DUNE can exclude, the regions corresponding to $\sin^2 \theta_{23} \gtrsim 0.59$ and $\lesssim 0.44$ without much dependence on $\delta_{CP}$.

T2HK can exclude more regions for its higher statistics.

Current BF values of $\theta_{23}$ and $\delta_{CP}$ are also discarded at $4\sigma$.
We have focused on the sharp correlation between $\theta_{23}$ and $\delta_{CP}$ predicted in the model.

We showed the allowed regions in this parameter space and compare it with the standard global fits.

We showed how the ability to reconstruct the CP phase and the atmospheric angle gets significantly affected.

Finally we have also presented the capability of the experiment to exclude the model in a fit independent way.