Cornering the revamped BMV model with neutrino oscillation data

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### Present status of oscillation parameters

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

| Oscillation parameter | Best fit value | $3\sigma$ range |
|-----------------------|----------------|-----------------|
| $\theta_{12}/^\circ$  | $34.5^{+1.1}_{-1.0}$ | $31.5 \rightarrow 38.0$ |
| $\theta_{23}/^\circ$ (NH) | $41.0 \pm 1.1$ | $38.3 \rightarrow 52.8$ |
| $\theta_{23}/^\circ$ (IH) | $50.5 \pm 1.0$ | $38.5 \rightarrow 53.0$ |
| $\theta_{13}/^\circ$ (NH) | $8.44^{+0.18}_{-0.15}$ | $7.9 \rightarrow 8.9$ |
| $\theta_{13}/^\circ$ (IH) | $8.41^{+0.16}_{-0.17}$ | $7.9 \rightarrow 8.9$ |
| $\delta_{CP}/^\circ$ (NH) | $252^{+56}_{-36}$ | $0 \rightarrow 360$ |
| $\delta_{CP}/^\circ$ (IH) | $259^{+47}_{-41}$ | $0 \rightarrow 31 \& 142 \rightarrow 360$ |
| $\Delta m_{21}^2/10^{-5}\text{eV}^2$ | $7.50^{+0.19}_{-0.17}$ | $7.03 \rightarrow 8.09$ |
| $\Delta m_{31}^2/10^{-3}\text{eV}^2$ (NH) | $+2.55 \pm +0.04$ | $+2.43 \rightarrow +2.67$ |
| $\Delta m_{31}^2/10^{-3}\text{eV}^2$ (IH) | $-2.49 \pm +0.04$ | $-2.61 \rightarrow -2.37$ |
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 $1.47 \times 10^{21}$. 
Brief information about T2HK

K. Abe et. al.(HK Collaboration): 1502.05199

- 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 assumes.
A4 symmetry and BMV model: brief overview

Babu, Ma, Valle: Phys. Lett. B552, 207 (2003)

- 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,

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

- 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,

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

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,

$$U_\nu(\theta) \to K(\theta, \beta) = U_\delta^\dagger(\beta)U_\nu(\theta)$$

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.

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

\(\chi^2_{\text{total}}\) is minimized over the free oscillation parameters (\(\theta_{23}, \theta_{13}, \theta_{12}, \) and \(\delta_{\text{CP}}\)) 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 (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.
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 $4\sigma$. 
Conclusion

- 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.