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	3σ range
$\theta_{12}/^\circ$	$34.5^{+1.1}_{-1.0}$	$31.5 \to 38.0$
$\theta_{23}/^\circ$ (NH)	41.0 ± 1.1	$38.3 \to 52.8$
$\theta_{23}/^\circ$ (IH)	50.5 ± 1.0	$38.5 \to 53.0$
$\theta_{13}/^\circ$ (NH)	$8.44^{+0.18}_{-0.15}$	$7.9 \to 8.9$
$\theta_{13}/^\circ$ (IH)	$8.41^{+0.16}_{-0.17}$	$7.9 \to 8.9$
$\delta_{\rm CP}/^\circ$ (NH)	252^{+56}_{-36}	$0 \to 360$
$\delta_{\rm CP}/^\circ$ (IH)	259^{+47}_{-41}	$0 \to 31$ & $142 \to 360$
$\Delta m^2_{21}/10^{-5} eV^2$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$
$\Delta m^2_{31}/10^{-3} eV^2$ (NH)	$+2.55 \pm +0.04$	$+2.43 \to +2.67$
$\Delta m^2_{31}/10^{-3} eV^2$ (IH)	$-2.49 \pm +0.04$	$-2.61 \to -2.37$

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 ν and 3.5 yrs. of $\bar{\nu}$ run.
- The incident ν_μ beam is generated by 80 GeV proton beam delivered at 1.07 MW with a POT of 1.47×10^{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 1.53×10^{22}
- 1 year of ν 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 χ_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,

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

- Translates into zero-th order neutrino mixing matrix,

$$U_\nu(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta/\sqrt{2} & \cos\theta/\sqrt{2} & -1/\sqrt{2} \\ \sin\theta/\sqrt{2} & \cos\theta/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Revamped A4 symmetry and BMV model: brief overview

Morisi, Forero, Romao, and Valle: PRD88, 016003 (2013)

- A single flavon scalar ξ is added to break the remnant symmetry in A4 and the charged fermion mass matrix is changed slightly,

$$M_{eE}M_{eE}^{\dagger} = \begin{pmatrix} (f_e v_1)^2 I & (f_e v_1) Y_D^{\dagger} \\ (f_e v_1) Y_D & U_{\omega}\mathrm{Diag}[3(h_i^e u)^2]U_{\omega}^{\dagger} + Y_D Y_D^{\dagger} \end{pmatrix} \qquad (1)$$

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

- The mixing matrix gets modified to,

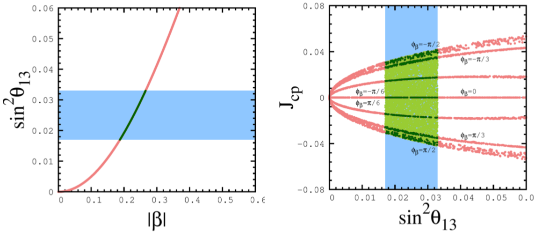
$$U_{\nu}(\theta) \rightarrow K(\theta, \beta) = U_{\delta}^{\dagger}(\beta)U_{\nu}(\theta)$$

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

- The mixing angles are extracted from from this modified mixing matrix and the phase of the complex coupling of flavon β becomes the source of CP violation.

Revamped A4 symmetry and BMV model: brief overview...(cont.)

Morisi, Forero, Romao, and Valle: PRD88, 016003 (2013)



- The revamped model shows the theoretical correlation between the flavon coupling (β) and the solar angle θ_{13} and also between the CP phase and the atmospheric angle θ_{23}.
- We wanted to extend on this study by testing the model in DUNE and T2HK and doing a χ^2 level analysis for excluding the model.

Numerical procedure (using GLoBES)

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

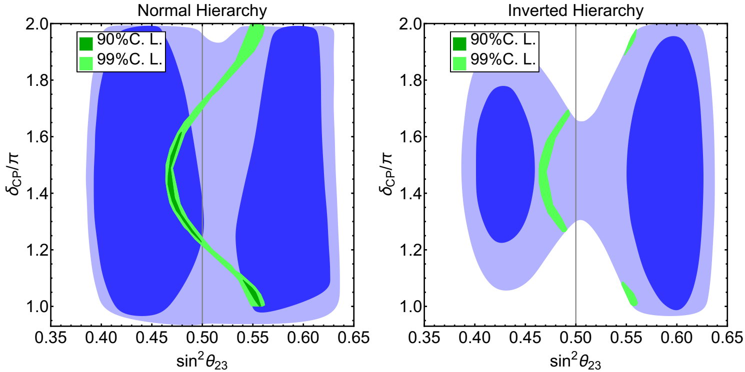
  n is the total number of bins and ξ_a and ξ_b denote the pulls due to systematic errors.

- 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.

- $$\chi^2_{\rm total} = \chi^2_{\nu_\mu \to \nu_e} + \chi^2_{\bar{\nu}_\mu \to \bar{\nu}_e} + \chi^2_{\nu_\mu \to \nu_\mu} + \chi^2_{\bar{\nu}_\mu \to \bar{\nu}_\mu} . \quad (3)$$

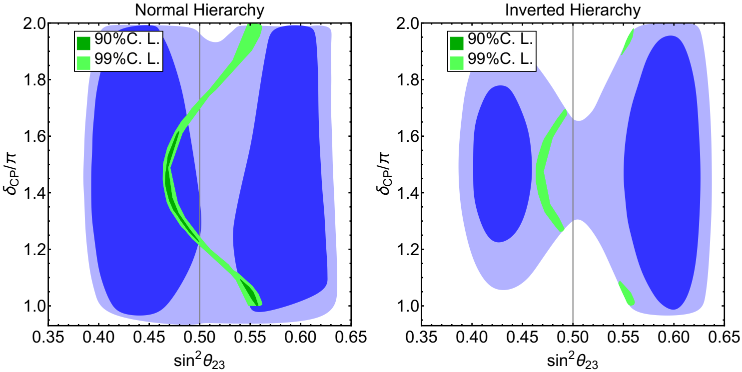
- $\chi^2_{\rm total}$ is minimized over the free oscillation parameters ($\theta_{23}, \theta_{13}, \theta_{12}$, and δ_{CP}) predicted by the model

Allowed region in δ_{CP}(test)-$\sin^2\theta_{23}$(test) plane



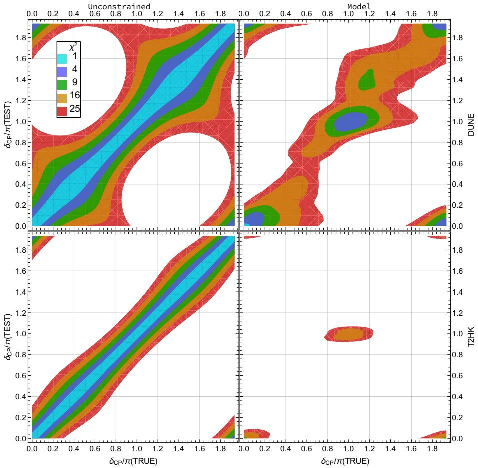
- Dark blue (90%) and light blue (99%) corresponds to present bound for unconstrained 3ν scenario (de Salas *et. al.*:1708.01186).
- Green: Allowed by the model and consistent with the global fit.

Allowed region in δ_{CP}(test)-$\sin^2\theta_{23}$(test) plane..(*cont.*)



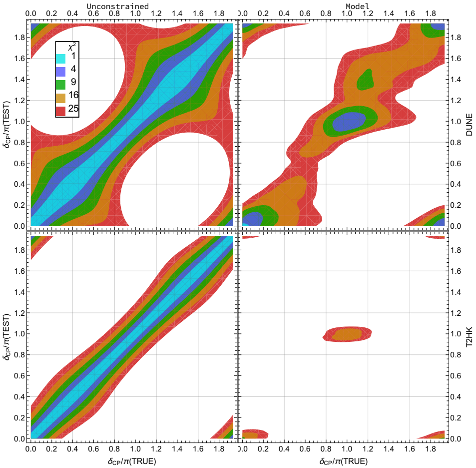
- Normal ordering is preferred and inverted ordering is only allowed at 99% C.L.
- For normal ordering, preferred solution indicates to the lower octant and maximal CP violation.

Capability to reconstruct the CP phase



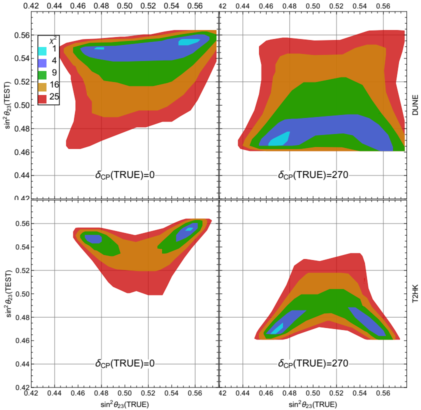
- Left column: Standard 3ν scenario. Right column : Model prediction
- Top row: DUNE. Bottom Row: T2HK

Capability to reconstruct the CP phase...(cont.)



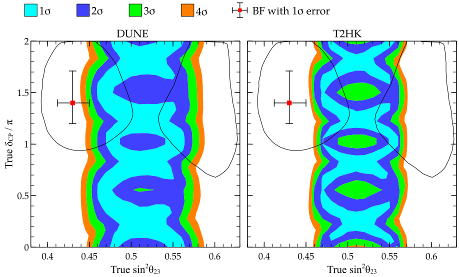
- T2HK is more capable to reconstruct the values of δ_{CP}.
- The model has a significant impact on the ability of the experiment to reconstruct the CP phase.

Capability to reconstruct θ_{23}



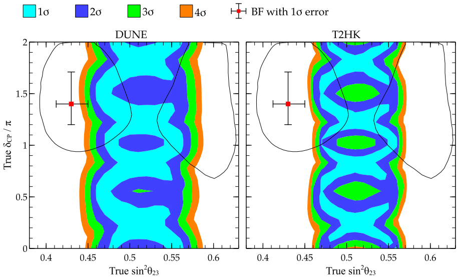
- For $\delta_{CP}(\text{true}) = -\pi/2$, the minima (cyan patch) indicates to a lower octant
- For CP conservation, the minima indicates to a higher octant
- These observations are consistent with the earlier results.

Sensitivity of DUNE, T2HK to the model: a *fit-independent* approach



- For each δ_{CP}(true)-$\sin^2\theta_{23}$(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 4σ DUNE can exclude, the regions corresponding to $\sin^2\theta_{23} \gtrsim 0.59$ and $\lesssim 0.44$ without much dependence on δ_{CP}
- T2HK can exclude more regions for its higher statistics.
- Current BF values of θ_{23} and δ_{CP} are also discarded at 4σ.

Conclusion

- We have focused on the sharp correlation between θ_{23} and δ_{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.