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Cornering the revamped BMV model with neutrino oscillation data

Sabya Sachi Chatterjee [a,b], Mehedi Masud [c], Pedro Pasquini [d], J.W.F. Valle [c,*]

[a] Institute of Physics, Sachivalaya Marg, Sainik School Post, Bhubaneswar 751005, India
[b] Homi Bhabha National Institute, Training School Complex, Anushakti Nagar, Mumbai 400085, India
[c] AHEP Group, Institut de Física Corpuscular – C.S.I.C./Universitat de València, Parc Cientific de Paterna, C/Catedratico José Beltrán, 2, E-46980, Paterna, València, Spain
[d] Instituto de Física Gleb Wataghin – UNICAMP, 13083-859, Campinas, SP, Brazil

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A B S T R A C T

Using the latest global determination of neutrino oscillation parameters from [1] we examine the status of the simplest revamped version of the BMV (Babu–Ma–Valle) model, proposed in [2]. The model predicts a striking correlation between the "poorly determined" atmospheric angle θ_{23} and CP phase δ_{CP}, leading to either maximal CP violation or none, depending on the preferred θ_{23} octants. We determine the allowed BMV parameter regions and compare with the general three-neutrino oscillation scenario. We show that in the BMV model the higher octant is possible only at 99% C. L., a stronger rejection than found in the general case. By performing quantitative simulations of forthcoming DUNE and T2HK experiments, using only the four "well-measured" oscillation parameters and the indication for normal mass ordering, we also map out the potential of these experiments to corner the model. The resulting global sensitivities are given in a robust form, that holds irrespective of the true values of the oscillation parameters.

1. Introduction

The observed flavor structure of quarks and leptons is unlikely to be an accident. Specially puzzling are the neutrino oscillation parameters [1], featuring two large angles with no counterpart in the quark sector [3], as well as a smaller mixing parameter measured at reactors, and which lies suspiciously close in magnitude to the Cabbibo angle [4,5]. While the standard model gives an incredibly good description of "vertical" or intrafamily gauge interactions, it gives no guidance concerning "horizontal" interfamily interactions. A reasonable attempt to shed light on the pattern of fermion masses and mixings is the idea of flavor symmetry [6–8]. Over the last years many models have been proposed in order to account for the pattern of neutrino oscillations [7,9] and most of them make well-defined predictions for the "poorly determined" oscillation parameters $\sin^2\theta_{23}$ and δ_{CP} [10–13].

In this paper we consider, for definiteness, on the model suggested in [2], i.e. the simplest flavon generalization of the A_4-symmetry-based BMV model [14]. This revamped model predicts a sharp correlation between the CP phase and the atmospheric angle θ_{23}, which implies either maximal CP violation or none, depending on the preferred octants of the atmospheric angle θ_{23}. We focus on the capability of future experiments DUNE [15] and T2HK [16] to test the predictions of the simplest realistic A_4 model presented in [2] given the current measurements of the oscillation parameters. We also perform quantitative simulations of the future DUNE and T2HK experiments in order to illustrate their potential in testing the model. To this endeavor we use only the four "well-measured" oscillation parameters plus the indication in favor of normal mass ordering and lower octant. We determine their increased sensitivity in probing the BMV model compared to the general unconstrained case. We present the results as robust, global model-testing criteria that hold for any choice of the true values of the oscillation parameters.

2. Theoretical preliminaries

The model is a minimal extension of the BMV model [14], which assembles the $SU(2)_L$ doublet fermions into an A_4 triplet within a supersymmetric framework. It 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 stan-

* Corresponding author.
E-mail addresses: sabya@iopb.res.in (S.S. Chatterjee), masud@ific.uv.es (M. Masud), pasquini@ifi.unicamp.br (P. Pasquini), valle@ific.uv.es (J.W.F. Valle).
URL: http://astroparticles.es/ (J.W.F. Valle).

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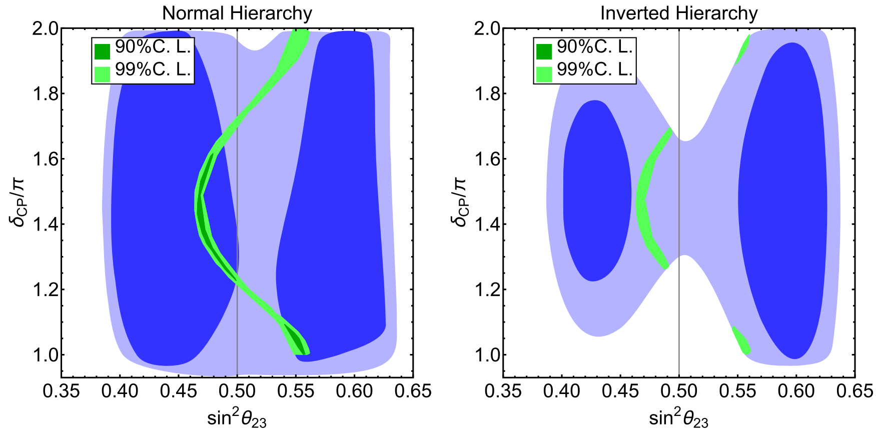

Fig. 1. Regions of three-neutrino oscillation parameters allowed at 90% and 99% of C. L. in the unconstrained global fit [1] (dark and light blue, respectively) and within the BMV scenario (dark and light green respectively). The left and right panels correspond to normal and inverted mass ordering, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dard Yukawa interactions. Both standard Higgs fields H_i and the three new scalars χ_i acquire vacuum expectation values (vev) v_i and u respectively, breaking the A_4 symmetry at higher energies, and resulting in the charged lepton mass matrix given as,

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

where f_e and h_i^e are the Yukawa constants coupling the standard-model fermions to the standard Higgs field and the new scalars respectively. Here I is a 3×3 unity matrix and U_ω is the magic matrix,

$$U_\omega = \begin{pmatrix} 1 & 1 & 1 \\ 1 & \omega & \omega^2 \\ 1 & \omega^2 & \omega \end{pmatrix} \quad (2)$$

with $\omega = e^{2i\pi/3}$ and we assume $v_i \ll u \ll M_E$. With such hierarchy we have a "universal" see-saw scheme for generating the standard-model charged and neutral lepton masses, that translates into a zero-th order neutrino mixing matrix,

$$U_\nu(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta/\sqrt{2} & \cos\theta/\sqrt{2} & -1/\sqrt{2} \\ \sin\theta/\sqrt{2} & \cos\theta/\sqrt{2} & 1/\sqrt{2} \end{pmatrix} \quad (3)$$

With the discovery of nonzero θ_{13} by Daya Bay such simple form is now excluded by experimental data, as it leads zero reactor mixing angle due to a remnant symmetry of A_4.

In this letter we focus on the generalized version of the model proposed in [2], by adding to it a single flavon scalar ξ that breaks this remnant symmetry present in the original version of the model [14], and slightly changes the charged fermion mass matrix to,

$$M_{eE}M_{eE}^{\dagger} = \begin{pmatrix} (f_e v_1)^2 I & (f_e v_1) Y_D^\dagger \\ (f_e v_1) Y_D & U_\omega \text{Diag}[3(h_i^e u)^2] U_\omega^\dagger + Y_D Y_D^\dagger \end{pmatrix} \quad (4)$$

where $Y_D = M_E(I + \beta\text{Diag}[1,\omega,\omega^2])$, and β is a small complex parameter. This equation modifies the neutrino mixing matrix to,

$$U_\nu(\theta) \to K(\theta,\beta) = U_\delta^\dagger(\beta) U_\nu(\theta) \quad (5)$$

where the pre-factor $U_\delta^\dagger(\beta)$ characterizes the revamping and generates a nonzero reactor mixing angle as a result of the breaking of the remnant $\mu-\tau$ symmetry in A_4. Within this revamped scenario $|\beta|$ correlates linearly with θ_{13} and the phase of β induces CP violation in oscillations. Both arise from the breaking of $\mu-\tau$ invariance. In addition to generating these phenomenologically required parameters, the model also predicts a correlation between the two parameters in the lepton mixing matrix that are currently "poorly determined" in neutrino oscillation studies, namely θ_{23} and δ_{CP}.

The predicted correlation between θ_{23} and δ_{CP} can be determined numerically by varying $|\beta| < 1$, $0 \le \text{Arg}[\beta], \theta \le 2\pi$, $1 \le f_e v_1 \le 100$ GeV and $10^4 \le M_E \le 10^5$ GeV. The results obtained are summarized in Fig. 1, where the dark green region indicates the predicted parameter correlation at 90% C. L., while the light green region is at 99% CL. This is a very important correlation between δ_{CP} and the atmospheric angle which allows the model to be directly probed by experiment. It is obtained by varying the model parameters as above and by taking only the points consistent with the current global determination of neutrino oscillation parameters at the corresponding confidence level. The regions corresponding to the general unconstrained scenario given by the latest neutrino oscillation global fit [1] are indicated in dark and light blue, for the same confidence level.

In contrast with the general three-neutrino oscillation picture, we find that, taking into account the most recent global fit of neutrino oscillation parameters [1], the inverted mass ordering is only allowed at the 99% of C. L., an enhanced rejection than in the general unconstrained scenario. This is partly due to the fact that the preferred values of θ_{23} in the BMV case lie closer to maximality than in the general three-neutrino oscillation picture.

On the other hand, the strongly preferred normal ordering case has two solutions, one in each octant of θ_{23}. Of these, one notices that there is only a small region in the higher octant, close to a *CP-conserving* value of the phase, $\delta_{CP} = \pi$. Although disfavored, this region is still allowed at 90% of C. L., as seen by the dark green region. In contrast, the preferred solution lies in the left octant, close to *maximal* CP violation. By comparing the dark green and dark blue regions one sees how the global analysis of the oscillation parameters within this model leads to an improved determination of θ_{23} and δ_{CP} when compared with the generic three-neutrino oscillation scenario. We now turn to the prospects of testing this model at future experimental setups.

3. Numerical analysis and new experiments

In order to determine the sensitivity of each experiment through numerical simulation, we use the GLoBES software as described in [17,18]. Unless told otherwise, the true values of the

Table 1
General three-neutrino oscillation parameters taken from the most recent global fit [1].

Parameters	[1]
s^2_{12}	$0.321^{+0.18}_{-0.16}$
$\theta_{12}(^\circ)$	$34.5^{+1.1}_{-1.0}$
s^2_{13}	$0.0216^{+0.090}_{-0.075}$
$\theta_{13}(^\circ)$	$8.44^{+0.18}_{-0.15}$
$\Delta m^2_{31}/10^{-3}(\text{eV}^2)$	2.55 ± 0.04
$\Delta m^2_{21}/10^{-5}(\text{eV}^2)$	7.56 ± 0.19
s^2_{23}	$0.43^{+0.20}_{-0.18}$
$\theta_{23}(^\circ)$	41.0 ± 1.1
δ_{CP}/π	$1.40^{+0.31}_{-0.20}$

oscillation parameters are assumed to be the best fit values obtained in [1], see Table 1. In accordance to recent global fit results, normal ordering has been assumed fixed throughout the simulation.

The sensitivity is calculated, at certain confidence levels, by using a Poissionian χ^2 function [19,20] between the true dataset x_i and the test dataset y_i,

$$\chi^2 = \min_{\{\xi_a,\xi_b\}} \left[2\sum_{i=1}^{n} (y_i - x_i - x_i \ln \frac{y_i}{x_i}) + \xi_a^2 + \xi_b^2 \right], \tag{6}$$

where n is the total number of bins and ξ_a and ξ_b denote the pulls due to systematic errors. The test dataset is given by

$$y_i(\tilde{f}, \xi_a, \xi_b) = N_i^{pre}(\tilde{f}) \left[1 + \pi^a \xi_a\right] + N_i^b(\tilde{f}) \left[1 + \pi^b \xi_b\right], \tag{7}$$

where $\tilde{f}$ is the set of oscillation parameters predicted by the model and π^a, π^b are the systematic errors on signal and background respectively, assumed to be uncorrelated.

N_i^{pre} and N_i^b represent the number of predicted signal events and the background events in the ith energy bin, respectively. The true or observed data assumption from an experiment enter in Eq. (6) through

$$x_i(f) = N_i^{obs}(f) + N_i^b(f). \tag{8}$$

Now the total χ^2 is calculated by combining various relevant channels,

$$\chi^2_{\text{total}} = \chi^2_{\nu_\mu\to\nu_e} + \chi^2_{\bar{\nu}_\mu\to\bar{\nu}_e} + \chi^2_{\nu_\mu\to\nu_\mu} + \chi^2_{\bar{\nu}_\mu\to\bar{\nu}_\mu} . \tag{9}$$

Finally this χ^2_{total} is minimized over the free oscillation parameters ($\theta_{23}, \theta_{13}, \theta_{12}$, and δ_{CP})[1] predicted by the model to get $\Delta\chi^2_{min}$. In order to map out the expectations for the octant and/or CP preference we assume only the four "well-measured" oscillation parameters (upper rows in Table 1) plus the indication in favor of normal mass ordering. Indeed, as seen above, the inverted mass ordering is only allowed at the 99% of C. L. In the next section we consider the case of a fit-independent global approach in the plane of $\sin^2\theta_{23}$(true)–δ_{CP}(true) (following [21]). We focus on two forthcoming experiments: the DUNE [15] and T2HK experiments [16], basing ourselves on their CDR report as briefly described below.

DUNE: The proposed DUNE experiment has a baseline of 1300 km and the far detector (FD) is placed at an on-axis location. In our simulation, a 40 kt liquid argon FD with 3.5 yr of ν run and 3.5 yr of $\bar{\nu}$ run was considered. The ν_μ beam is generated by a 80 GeV proton beam delivered at 1.07 MW with a POT (protons on target) of 1.47×10^{21}. The simulation for DUNE was done according to [15].

T2HK: The proposed T2HK experiment has a baseline of 295 km and the detector is placed at the same off-axis (0.8 degrees) location as in T2K. The idea is to upgrade the T2K experiment, with a much larger detector (560 kton fiducial mass) located in Kamioka, so that much larger statistics is ensured. We assume an integrated beam with power 7.5 MW $\times 10^7$ sec which corresponds to 1.53×10^{22} POT. The ratio of the runtimes of ν and $\bar{\nu}$ mode was taken as $1:3$. The simulation for T2HK was performed according to [16].

4. DUNE and T2HK sensitivities

As seen in [1], the atmospheric angle θ_{23} and the CP phase δ_{CP} are the two most uncertain of the fundamental oscillation parameters. This is in agreement with other recent global fits of neutrino oscillations [22–24]. Theoretical scenarios, such as the BMV model, imply correlations between them. Thus, we now answer the very general and interesting questions: *To what extent model correlations, such as the one predicted by the BMV model, can be tested by experimental data? Can one exhibit the rejection power of future experiments independently of any arbitrarily given choice for the parameters θ_{23} and δ_{CP} eventually made by nature?*

Performing this exercise enables us to establish robust quantitative criteria capable of probing the model of interest, independently of any given input from neutrino oscillation fits. Fig. 2 answers the questions above, giving quantitative model-testing criteria valid irrespective of any assumed global neutrino oscillation fits.

Our simulation procedure has been set up as follows. In order to calculate the oscillation parameters predicted by the model and then fit them to the true data set, we have marginalized over the model parameters within their allowed range, for each true data set. Finally, we calculate the minimum $\Delta\chi^2$ at various confidence levels, as shown by the different color combinations in Fig. 2. The cyan, blue, green, and orange bands correspond to the 1σ, 2σ, 3σ, and 4σ confidence level of compatibility, at 1 degree of freedom, that is, $\Delta\chi^2 = 1$, 4, 9, and 16 respectively. The left panel gives the result for DUNE, while the right panel corresponds to T2HK. From this global-fit-independent sensitivity plot, one sees that DUNE can exclude, at 4σ statistical significance, the regions corresponding to $\sin^2\theta_{23} \gtrsim 0.59$ and $\sin^2\theta_{23} \lesssim 0.44$ without significant dependence on the value of δ_{CP} (TRUE). On the other hand, thanks to its higher statistics, T2HK has better sensitivity than DUNE and consequently can exclude even larger regions of parameter space. Notice that, as indicated in both panels, the best fit point obtained in [1] lies outside the corresponding 4σ sensitivity regions at DUNE and T2HK, indicating how severely such parameter choice would be rejected by these experiments. We stress that these are robust model-testing criteria valid for any assumed global choice of neutrino oscillation parameters.

5. Summary and conclusion

Taking advantage of the latest global determination of neutrino oscillation parameters given in [1] we have investigated the status of the simplest revamped version of the BMV model for neutrino oscillation, proposed in [2], as well as the chances of testing it further at future long-baseline neutrino experiments. To perform this task we have focussed on the sharp correlation between the "poorly determined" oscillation parameters θ_{23} and the phase δ_{CP}

[1] Two mass squared differences have been kept fixed at their best fit values in Table 1 since they are very well measured and also are not predicted by the model.

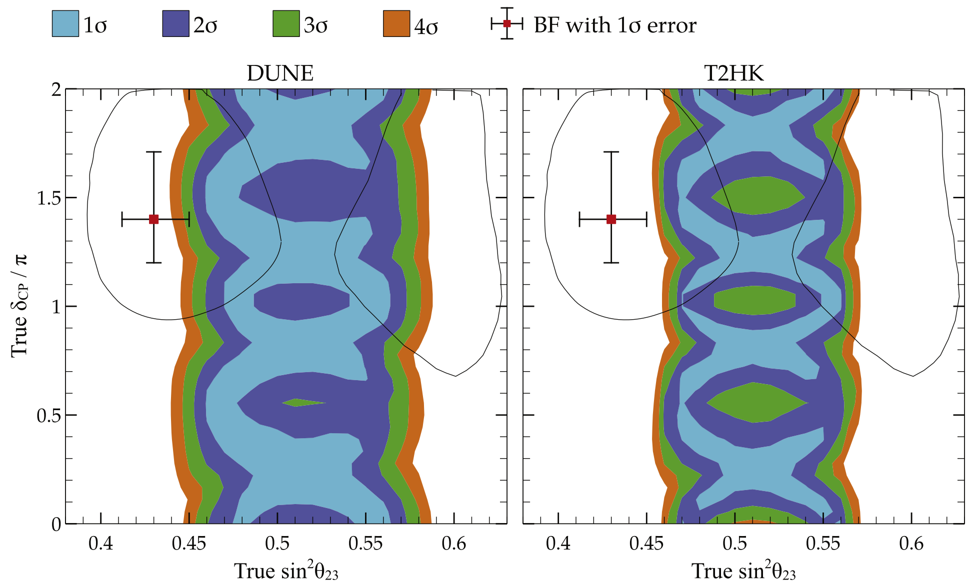

Fig. 2. Expected sensitivity regions at various confidence levels at which DUNE (left) or T2HK (right) would test the revamped BMV model. The regions within the black bordered contours correspond to 90% C. L. and the red square is the current best fit value [1]. The full parameter scan of true values of $\sin^2\theta_{23}$ and δ_{CP} assumes normal neutrino mass ordering. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

predicted in the model. We have determined the region of these oscillation parameters allowed within the BMV model, and compared it with what holds in the general three-neutrino oscillation scenario. We have found for this case a higher degree of rejection against the higher octant of θ_{23} than in the general unconstrained case. Through quantitative simulations of forthcoming experiments DUNE and T2HK, according to their technical proposals, we have also determined their potential for testing the BMV model. We have mapped out their sensitivity regions using only the values of the "well-measured" solar and atmospheric neutrino squared mass splittings, as well as the solar and reactor angle, plus the relatively strong preference for normal mass ordering that holds in the BMV scenario. We have also presented these results within a robust global approach valid for whatever the choice of θ_{23} and δ_{CP} is finally chosen by nature.

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