Deviations to Tri-Bi-Maximal mixing in the limit of $\mu \leftrightarrow \tau$ symmetry

Diana Carolina Rivera Agudelo

in collaboration with A. Pérez-Lorenzana and Sergio Tostado

3rd COMHEP
USC, Cali, Colombia

December 4, 2018

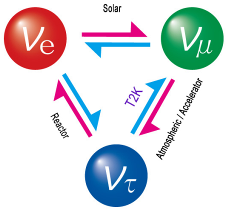
Outline

Introduction: Neutrino mixing

Standard parametrization: $c_{ij} \equiv \cos\theta_{ij}, s_{ij} \equiv \sin\theta_{ij}$

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - c_{23}s_{12}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix} P_\nu .$$

- $P_\nu = \mathrm{diag}\left[1, e^{-i\frac{\beta_1}{2}}, e^{-i\frac{\beta_2}{2}}\right]$
- Global analysis (1σ):
  $\theta_{12}/^\circ = 34.5^{+1.2}_{-1.0}$, $\theta_{13}/^\circ = 8.45^{+0.16}_{-0.14}$,
  $\theta_{23}/^\circ = 47.7^{+1.2}_{-1.7}$, $\delta_{cp}/\pi = 1.32^{+0.21}_{-0.15}$
- Majorana nature $\Longleftrightarrow 0\nu\beta\beta$



Credits T2K coll.

[1]

[1] P.F. de Salas *et al.*, PLB 782, 633 2018

$\mu - \tau$ symmetry and TBM pattern

- If $\theta_{13} = 0, \quad \theta_{23} = \pi/4$

$$U_{\mu-\tau} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ \frac{-s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & \frac{-1}{\sqrt{2}} \\ \frac{-s_{12}}{\sqrt{2}} & \frac{c_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix},$$

- $c_{12}(s_{12})$ stands for $\sin\theta_{12}(\cos\theta_{12})$
- When $\sin^2\theta_{12} = 1/3 \rightarrow$ Tri-Bi-Maximal[2] (TBM) mixing

TBM main features

Null reactor angle, no CP violation, solar angle $\theta_{12} = 30^\circ$

Disfavored by experiments

Maximal atmospheric angle $\theta_{23} = 45^\circ$ is still allowed

Credits nobelprize.org

[2] T. Fukuyama and H. Nishiura, arXiv:hep-ph/9702253 [hep-ph].

Deviations from TBM pattern

However, small deviations from $\mu \leftrightarrow \tau$ symmetry can be adopted. Let us consider

- $U_{PMNS} = U_{TBM} U_{\mathrm{Corr}}$, where

Correction matrix

$$U_{\mathrm{Corr}} = U_{ij}(\phi, \sigma)\ \mathrm{Diag}\left(1, \mathrm{e}^{-\mathrm{i}\frac{\alpha_1}{2}}, \mathrm{e}^{-\mathrm{i}\frac{\alpha_2}{2}}\right) \ ,$$

Two possibilities since U_{12} is trivial:

$$U_{13} = \begin{pmatrix} \cos\phi & 0 & \sin\phi\ e^{-i\sigma} \\ 0 & 1 & 0 \\ -\sin\phi\ e^{i\sigma} & 0 & \cos\phi \end{pmatrix}, \quad U_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & \sin\phi\ e^{-i\sigma} \\ 0 & -\sin\phi\ e^{i\sigma} & \cos\phi \end{pmatrix}$$

ϕ and σ encode the deviation from TBM mixing. α_1 and α_2 are aimed to account for the Majorana nature.

Relations between experimental parameters and PMNS entries

Mixing angles:

$$\sin^2\theta_{12} = \frac{\mid U_{e2} \mid^2}{1 - \mid U_{e3} \mid^2}, \qquad \sin^2\theta_{23} = \frac{\mid U_{\mu 3} \mid^2}{1 - \mid U_{e3} \mid^2}, \qquad \sin^2\theta_{13} = \mid U_{e3} \mid^2,$$

CP is obtained from Jarlskog invariant

$$\begin{aligned} J_{CP} &= \mathrm{Im}\left[U_{e1}U_{\mu 2}U^*_{e2}U^*_{\mu 1}\right] \\ &= (1 - s^2\theta_{13})\sqrt{s^2\theta_{13}s^2\theta_{12}s^2\theta_{23}(1 - s^2\theta_{12})(1 - s^2\theta_{23})}\,\sin\delta_{CP}. \end{aligned}$$

Case I: 1-3 Rotation

$$U_{PMNS} = U_{TBM}U_{13}(\phi,\sigma)\ \mathrm{Diag}\left(1, e^{-i\frac{\alpha_1}{2}}, e^{-i\frac{\alpha_2}{2}}\right)$$

$$\sin^2\theta_{12} = \frac{1}{3-2\sin^2\phi},$$
$$\sin^2\theta_{23} = \frac{1}{2}\left(1+\frac{\sqrt{3}\sin 2\phi\cos\sigma}{3-2\sin^2\phi}\right),$$
$$\sin^2\theta_{13} = \frac{2}{3}\sin^2\phi.$$

Dirac CP

$$\sin\delta_{CP} = -\frac{(2+\cos 2\phi)\sin\sigma}{\left[(2+\cos 2\phi)^2 - 3\sin^2 2\phi\cos^2\sigma\right]^{1/2}}.$$

Majorana phases

$$\beta_1 = \alpha_1, \qquad \beta_2 = \alpha_2 + 2(\sigma - \delta_{CP})$$

Case II: 2-3 Rotation

$$U_{PMNS} = U_{TBM} U_{23}(\phi, \sigma)\ \mathrm{Diag}\left(1, \mathrm{e}^{-\mathrm{i}\frac{\alpha_1}{2}}, \mathrm{e}^{-\mathrm{i}\frac{\alpha_2}{2}}\right)$$

$$\begin{aligned}
\sin^2\theta_{12} &= 1 - \frac{2}{3 - \sin^2\phi}, \\
\sin^2\theta_{23} &= \frac{1}{2}\left(1 - \frac{\sqrt{6}\sin 2\phi\cos\sigma}{3 - \sin^2\phi}\right), \\
\sin^2\theta_{13} &= \frac{1}{3}\sin^2\phi
\end{aligned}$$

Dirac CP

$$\sin\delta_{CP} = -\frac{(5 + \cos 2\phi)\sin\sigma}{\left[(5 + \cos 2\phi)^2 - 24\sin^2 2\phi\cos^2\sigma\right]^{1/2}}$$

Majorana phases

$$\beta_1 = \alpha_1, \qquad \beta_2 = \alpha_2 + 2(\sigma - \delta_{CP})$$

$\mu - \tau$ symmetric limit in the mass matrix

- Since $M_\nu = U_\nu \mathrm{diag}(m_1, m_2, m_3) U_\nu^{\mathrm{T}}$, $U_\nu = U_{TBM}$ implies

$$|m_{e\mu}| = |m_{e\tau}| \quad \text{and} \quad m_{\mu\mu} = m_{\tau\tau}$$

Deviations can be accommodated in a correction matrix *via*

$$M_\nu = M_{\mu-\tau} + \delta M \left(\hat{\delta}, \hat{\epsilon}\right).$$

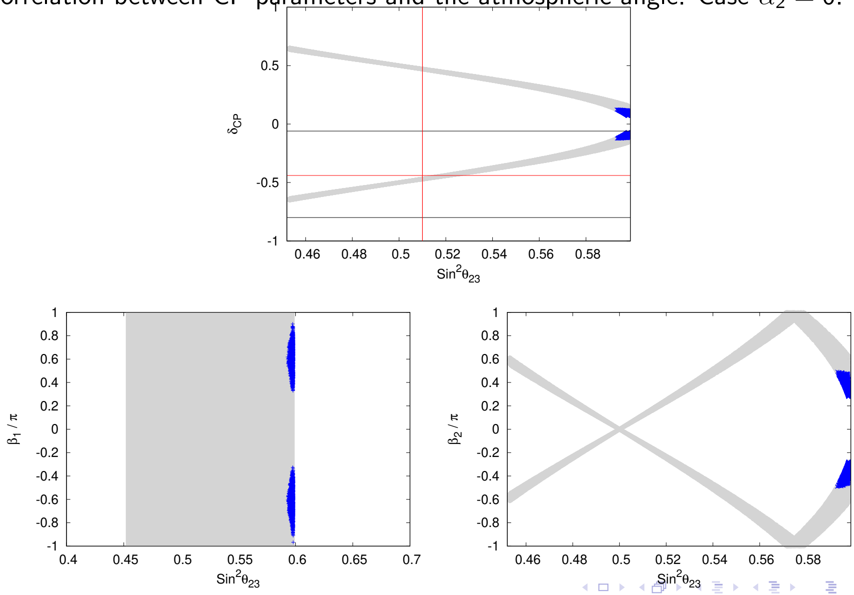
Breaking parameters

$$\hat{\delta} = \frac{\sum_i (U_{ei} U_{\tau i} - U_{ei} U_{\mu i}) m_i}{\sum_i U_{ei} U_{\mu i} m_i},$$

$$\hat{\epsilon} = \frac{\sum_i (U_{\tau i} U_{\tau i} - U_{\mu i} U_{\mu i}) m_i}{\sum_i U_{\mu i} U_{\mu i} m_i}.$$

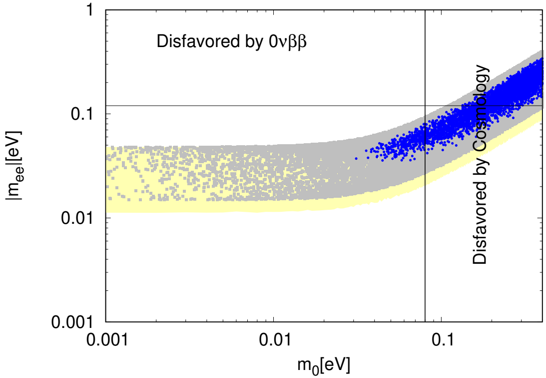
Results Case I (U_{13})

Correlation between CP parameters and the atmospheric angle. Case $\alpha_2 = 0$.



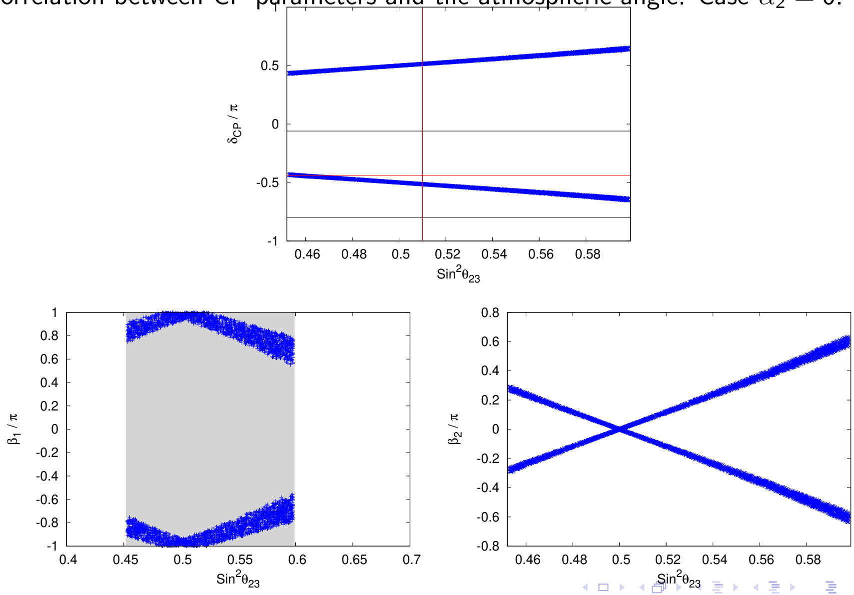
Results Case I (U_{13})

Neutrinoless double beta decay. Case $\alpha_2 = 0$.



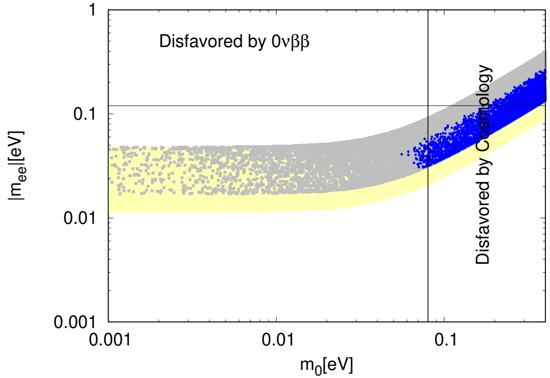
Results Case II (U_{23})

Correlation between CP parameters and the atmospheric angle. Case $\alpha_2 = 0$.



Results Case II (U_{23})

Neutrinoless double beta decay. Case $\alpha_2 = 0$.



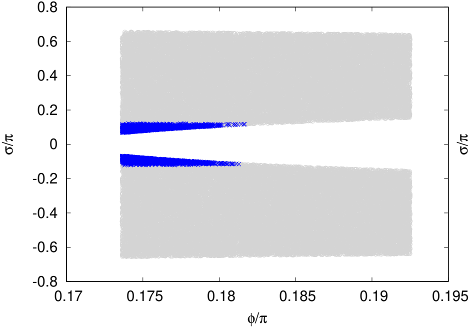
Concluding Remarks

- TBM pattern is actually disfavored by experiments
- Corrections to TBM matrix can predict current mixing angles
- Small $\mu - \tau$ symmetry breaking in the mass matrix could help bounding Majorana phases via a precise determination of the atmospheric angle
- Small breaking favors degenerate hierarchy and can be tested in future experiments

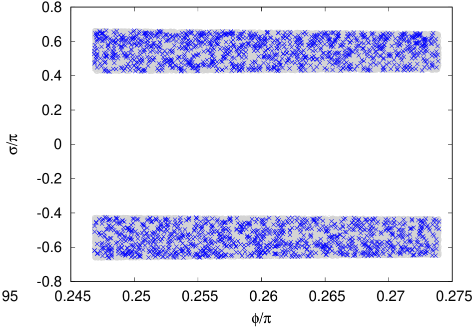
Thank you!!

Correction Parameters

Case I:



Case II:



- Better correlation is obtained for $\alpha_2 = 0$. Values of α_1 are the same of β_1.
- These regions are consistent with current 3σ ranges of the mixing angles

$\mu - \tau$ symmetric mass matrix

Mass matrix obtained from $U_{\mu-\tau}$

$$M_\nu^{\mu-\tau} = \begin{pmatrix} m_1 c_{12}^2 + m_2 s_{12}^2 & -\frac{s2_{12}}{\sqrt{8}}(m_1 - m_2) & \sigma \frac{s2_{12}}{\sqrt{8}}(m_1 - m_2) \\ -\frac{s2_{12}}{\sqrt{8}}(m_2 - m_1) & \frac{1}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 + m_3) & \frac{-\sigma}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 - m_3) \\ \sigma \frac{s2_{12}}{\sqrt{8}}(m_1 - m_2) & \frac{-\sigma}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 - m_3) & \frac{1}{2}(m_1 s_{12}^2 + m_2 c_{12}^2 + m_3) \end{pmatrix}$$