Consequences of mixed $\mu\tau$ flavored twisted Friedberg-Lee invariance of neutrinos

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Current experimental status of neutrino physics

- The oscillation data, the bounds on $\sum_i m_{\nu_i}$ and $0\nu\beta\beta$ decay experiments severely constrain the flavor structures of the light neutrino mass matrix.
- Despite spectacular developments, there exists several unsettled issues and open questions:

  (i) *What is the nature of light neutrinos, Dirac or Majorana?*
  (ii) *What is the ordering of neutrino masses, normal or inverted?*
  (iii) *What is the absolute scale of neutrino masses?*
  (iv) *In which octant does the atmospheric mixing angle θ_{23} lie?*

- The current best-fit values of θ_{23} are reported as[1] 49.6° for *Normal Ordering* (NO) and 49.8° for *Inverted Ordering* (IO).

  (v) *What is the value of the Dirac CP phase δ?*

- The possibility of CP conservation ($\sin\delta = 0$) is allowed at slightly above 1σ. One of the CP violating value $\delta = \pi/2$ is disfavored at 99% CL. Therefore, $\delta = 3\pi/2$ and slight departures from it remain as the most tantalizing possbilities.
- The current trend of data is in tension with many popular neutrino mass models that predict co-bimaximal mixing $(\theta_{23} = \pi/4, \delta = \pi/2, 3\pi/2)$.
- If a non-maximal δ or θ_{23} is established in future, these models will be ruled out.

[1] Esteban, Gonzalez-Garcia, Alvaro Hernandez-Cabezudo, Maltoni, Schwetz. arXiv:1811.05487 [hep-ph].

Statement of $\mu\tau$-flavored CP symmetry with a twisted Friedberg-Lee invariance

- We propose that the low-energy neutrino Lagrangian enjoys invariances under
  (i) a generalized $\mu\tau$-flavored CP transformation ($\mathrm{CP}^{\mu\tau\theta}$), and
  (ii)a generalized Friedberg-Lee (FL) transformation on the left-chiral fields $\nu_{\ell L}$:

$$\nu_{L\ell} \to iG^{\mu\tau\theta}_{\ell m}\gamma^0\nu^C_{Lm} + \eta_\ell\xi$$

- It leads to two simultaneous constraints on the light neutrino Majorana mass matrix M_ν:

$$(a) \quad M^\nu \boldsymbol{\eta} = 0, \quad \text{and} \quad (b) \quad (G^{\mu\tau\theta})^T M_\nu G^{\mu\tau\theta} = M_\nu^*.$$

  where

$$G^{\mu\tau\theta} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & -\cos\theta & \sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}, \quad \theta \in [0, \pi].$$

- (a) is satisfied for a nontrivial eigenvector $\boldsymbol{\eta}$ if:

$$\det M_\nu = 0 \quad \Rightarrow \quad \text{at least one vanishing light neutrino mass.}$$

- Thus, the model *predicts the absolute scale* of light neutrino masses.
- We'll show that existence of (b) i.e., $\mathrm{CP}^{\mu\tau\theta}$ alone, allows a large departure of δ from maximality.
- However, the additionally imposed FL symmetry only allows a tiny deviation from the maximality of δ in this model.

Consequences of $\mu\tau$ flavored CP symmetry

- Now $G^T M_\nu G = M_\nu^*$ and $U^T M_\nu U = \mathrm{diag}(m_1, m_2, m_3)$ together imply an identity[2]:

$$G^\theta U^* = Ud, \quad d_{ij} = \pm\delta_{ij}.$$

Prediction of Majorana phases

- (i) either $\alpha = 0$ or $\alpha = \pi$, and (ii) $\beta = 2\delta$ or $\beta = 2\delta - \pi$

Prediction of the atmospheric mixing angle

- $\cot 2\theta_{23} = \cot\theta \cos(\phi_2 - \phi_3)$.

Correlation between the Dirac CP phase δ and θ_{23}

- $\sin\delta = \pm \sin\theta / \sin 2\theta_{23}$

- In the $\mu\tau$-interchange limit, $\theta \to \pi/2$, $\theta_{23} \to \pi/4$ and $\cos\delta = 0$.
- In general, both θ_{23} and δ can deviate largely from their maximal values.
- All these relations hold irrespective of the neutrino mass ordering!

[2] Grimus,Lavoura Phys.Lett. B579 (2004).

- The most generally parameterized 3×3 symmetric mass matrix M_ν subjected to (a) and (b):

$$M_\nu = \begin{pmatrix} -\frac{2a_1}{(1+c_\theta)}\frac{\eta_2}{\eta_1} & a_1 + ia_2 & -a_1 t_{\frac{\theta}{2}} + ia_2 t_{\frac{\theta}{2}}^{-1} \\ a_1 + ia_2 & c_1 t_{\frac{\theta}{2}} - a_1 \frac{\eta_1}{\eta_2} - ia_2(1+c_\theta)\frac{\eta_1}{\eta_2} & c_1 - ia_2 t_{\frac{\theta}{2}}^{-1} c_\theta \frac{\eta_1}{\eta_2} \\ -a_1 t_{\frac{\theta}{2}} + ia_2 t_{\frac{\theta}{2}}^{-1} & c_1 - ia_2 t_{\frac{\theta}{2}}^{-1} c_\theta \frac{\eta_1}{\eta_2} & c_1 t_{\frac{\theta}{2}}^{-1} - a_1 \frac{\eta_1}{\eta_2} + ia_2(1+c_\theta)\frac{\eta_1}{\eta_2} \end{pmatrix},$$

- The normalized eigenvector corresponding to the vanishing mass eigenvalue:

$$\mathbf{v} = N^{-1} \begin{pmatrix} -\frac{\eta_1}{\eta_2}\cot\frac{\theta}{2} \\ -\cot\frac{\theta}{2} \\ 1 \end{pmatrix} e^{i\gamma}, \quad \text{with} \quad N = \left[\left(1 + \frac{\eta_1^2}{\eta_2^2}\right)\cot^2\frac{\theta}{2} + 1\right]^{1/2}.$$

- If the zero eigenvalue is associated with $m_1 = 0$ ($m_3 = 0$), we discover additional conditions for the NO (IO).

Normal ordering: v is associated with first column of PMNS matrix U

$$\cos\delta = \pm \frac{\sin 2\theta_{12} s_{13} \cos\theta}{\sqrt{\sin^2 2\theta_{12} s_{13}^2 \cos^2\theta + 4\left[1 + (1 + \frac{\eta_1^2}{\eta_2^2})\cot^2\frac{\theta}{2}\right]^2 \cot^2\frac{\theta}{2}}},$$

$$\cos^2\theta_{23} = \frac{\left[\left\{1 + (1 + \frac{\eta_1^2}{\eta_2^2})\cot^2\frac{\theta}{2}\right\} s_{12}^2 - 1\right]\cot\theta + \cot\frac{\theta}{2}}{(\cot^2\frac{\theta}{2} - 1)\cot\theta + 2\cot\frac{\theta}{2}}.$$

- Although, $\cos\delta \neq 0$ for NO, numerically δ is very close to $3\pi/2$, lying in the narrow interval $269.4^\circ - 270.6^\circ$. $\cos\delta$ is naturally small due to supression by a factor s_{13} in the numerator and the accompanying coefficient $\mathcal{O}(1)$.

Inverted ordering: v is associated with third column of PMNS matrix U

$$\cos\delta = 0,$$
$$\tan\theta_{23} = \cot\frac{\theta}{2} \Rightarrow \theta_{23} = (\pi-\theta)/2.$$

- Clearly, for both types of mass ordering, whilst θ_{23} is in general nonmaximal ($\theta_{23} \neq \pi/4$), but δ is exactly maximal ($\delta = \pi/2, 3\pi/2$) for IO and deviates slightly from its maximal value for NO.
- Hence, any large deviation of δ from maximality, will exclude the scenario: $(\mathrm{CP}^{\mu\tau\theta} + \mathrm{FL})$.
- For the NO, δ can deviate slightly from $3\pi/2$. But the devition so tiny that this scenario essentially predicts vanishing Majorana CP violation.
- If we sacrifice FL, there will be substantial Majorana *CP* violation.

Neutrinoless double beta ($0\nu\beta\beta$) decay process

- For certain nuclei (e.g. Ge-76), it is energetically favourable to undergo a $2\nu\beta\beta$ instead of a singular $\beta-$decay emitting two e^-s and two ν_e.
- Horeover, if the neutrino is a Majorana particle, two (anti)neutrinos in the final state can annihilate each other to give rise to a $0\nu\beta\beta$ decay:

$$(A, Z) \longrightarrow (A, Z+2) + 2e^- .$$

- Observation of $0\nu\beta\beta$ decay signal will firmly establish the Majorana nature of the neutrinos.
- The half-life $T_{1/2}$ for $0\nu\beta\beta$ decay process

$$T_{1/2}^{-1} = G_{0\nu} |\mathcal{M}|^2 |M_{ee}|^2 m_e^{-2}$$

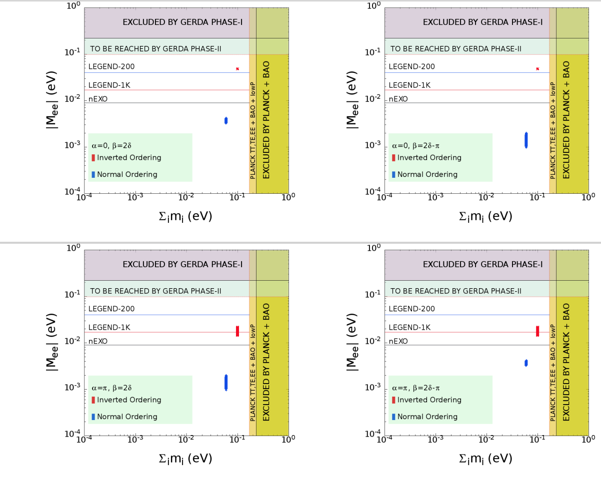
$G_{0\nu}$ $\rightarrow$ two-body phase space factor,
$\mathcal{M}$ $\rightarrow$ the nuclear matrix element (NME),
m_e $\rightarrow$ electron mass,
M_{ee} $\rightarrow$ (1,1) element of M_ν.

- Using the PDG convention for U_{PMNS},

$$M_{ee} = c_{12}^2 c_{13}^2 m_1 + s_{12}^2 c_{13}^2 m_2 e^{i\alpha} + s_{13}^2 m_3 e^{i(\beta - 2\delta)}.$$

- For four pairs of values of α and $\beta - 2\delta$, there can be four possible M_{ee} for both IO and NO. Using the experimental bound on the $T_{1/2}$, there exists upper bounds on $|M_{ee}|$.

- The plots of $|M_{ee}|$ versus the sum of the light neutrino masses $\sum_i m_i$ for both NO and IO are displayed.



Effect of CP asymmetry in neutrino oscillations

- Next consider the effect of leptonic Dirac CP violation.
- Dirac CP violation is expected to show up in neutrino oscillation experiments.
- In $\nu_\mu \to \nu_e$ oscillation the Dirac CP phase δ makes its appearence through the CP asymmetry parameter

$$A_{\mu e} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)} = \frac{2\sqrt{P_{atm}}\sqrt{P_{sol}}\sin\Delta_{32}\sin\delta}{P_{atm} + 2\sqrt{P_{atm}}\sqrt{P_{sol}}\cos\Delta_{32}\cos\delta + P_{sol}}$$

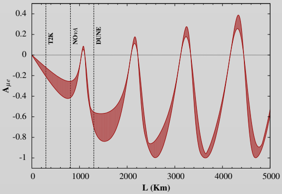
where

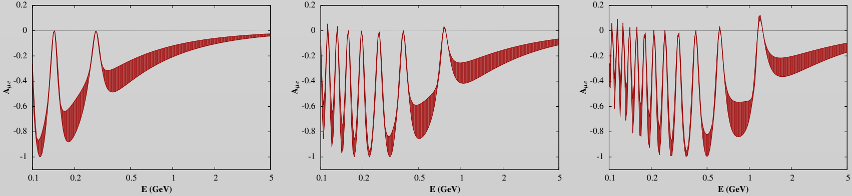
$$\sqrt{P_{atm}} = \sin\theta_{23}\sin\theta_{13}\frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)}\Delta_{31},$$

$$\sqrt{P_{sol}} = \cos\theta_{23}\cos\theta_{13}\sin 2\theta_{12}\frac{\sin aL}{aL}\sin\Delta_{21}.$$

- Here $\Delta_{ij} = \Delta m_{ij}^2 L/4E$ and the factor $a = G_F N_e/\sqrt{2}$ takes into account the matter effects in neutrino propagation through the earth.

Variation of $A_{\mu e}$ with L and E for both NO and IO





UHE Neutrino flavor fluxes at neutrino telescopes

- The dominant source of UHE cosmic neutrinos are *pp* collisions and $p\gamma$ collisions.
- In *pp* collisions, protons of TeV−PeV range produce neutrinos via the decays

$$\pi^+ \to \mu^+\nu_\mu, \pi^- \to \mu^-\bar{\nu}_\mu, \mu^+ \to e^+\nu_e\bar{\nu}_\mu, \mu^- \to e^-\bar{\nu}_e\nu_\mu.$$

Therefore, the normalized flux distributions over flavor at the source 'S' are

$$\{\phi^S_{\nu_e}, \phi^S_{\bar{\nu}_e}, \phi^S_{\nu_\mu}, \phi^S_{\bar{\nu}_\mu}, \phi^S_{\nu_\tau}, \phi^S_{\bar{\nu}_\tau}\} = \phi_0\left\{\frac{1}{6}, \frac{1}{6}, \frac{1}{3}, \frac{1}{3}, 0, 0\right\},$$

- Similar processes involving $p\gamma$ collisions lead to a flux distributions over flavor

$$\{\phi^S_{\nu_e}, \phi^S_{\bar{\nu}_e}, \phi^S_{\nu_\mu}, \phi^S_{\bar{\nu}_\mu}, \phi^S_{\nu_\tau}, \phi^S_{\bar{\nu}_\tau}\} = \phi_0\left\{\frac{1}{3}, 0, \frac{1}{3}, \frac{1}{3}, 0, 0\right\}.$$

- In either case, with $\phi^S_\ell = \phi^S_{\nu_\ell} + \phi^S_{\bar{\nu}_\ell}$ and $\ell = e, \mu, \tau$,

$$\{\phi^S_e, \phi^S_\mu, \phi^S_\tau\} = \phi_0\left\{\frac{1}{3}, \frac{2}{3}, 0\right\}.$$

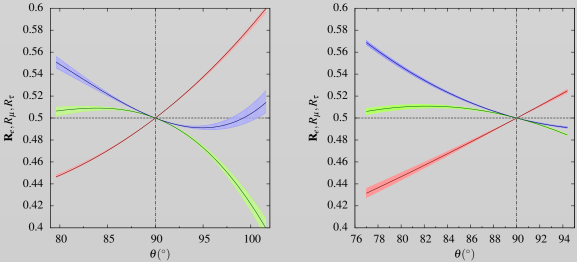
- As neutrino oscillations will change flavor, the flux reaching the telescope (T)

$$\phi^T_\ell = \phi^T_{\nu_\ell} + \phi^T_{\bar{\nu}_\ell} = \sum_m \left[\phi^S_{\nu_m} P(\nu_m \to \nu_\ell) + \phi^S_{\bar{\nu}_m} P(\bar{\nu}_m \to \bar{\nu}_\ell)\right].$$

- One can define certain flavor flux ratios R_ℓ ($\ell = e, \mu, \tau$) at the neutrino telescope as

$$R_\ell \equiv \frac{\phi_\ell^T}{\sum_m \phi_m^T - \phi_\ell^T} = \frac{1 + \sum_i |U_{\ell i}|^2 \Delta_i}{2 - \sum_i |U_{\ell i}|^2 \Delta_i}, \quad \Delta_i = |U_{\mu i}|^2 - |U_{\tau i}|^2.$$

- Each R_l depends on all three mixing angles θ_{ij} and $\cos\delta$.
- For both NO and IO, θ_{23} and $\cos\delta$ can be eliminated in favor of θ and η_1/η_2. θ_{12} and θ_{13} has been to vary in their current 3σ ranges.



- Variation of the flavor the flux ratios R_e (red), R_μ (blue) and R_τ (green) with θ for NO (left panel) and for IO (right panel).
- A future precision measurement of θ_{23}, will determine θ, and therefore predict the allowed ranges of $R_{e,\mu,\tau}$.

Conclusions

- A CP transformed $\mu\tau$-flavored twisted Friedberg-Lee symmetry has been proposed in the effective low-energy Lagrangian.
- While both types of mass ordering are allowed, the absolute scale of neutrino mass is fixed by the vanishing determinant of M_ν.
- The atmospheric mixing angle is in general nonmaximal ($\theta_{23} \neq \pi/4$), the Dirac CP phase δ is exactly maximal for IO and nearly maximal for NO since $\cos\delta \propto \sin\theta_{13}$.
- The model predicts practically vanishing Majorana CP violation.
- We compute the effect of leptonic Dirac CP violation in different long baseline experiments.
- From the flavor flux ratios at the neutrino telescopes, we comment on the possibility of determination of the octant of θ_{23}.

Thank You