Addressing flavor symmetries of neutrinos at DUNE

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In collaboration/Based on,

1805.05823/hep-ph, NN

1811.07040/hep-ph, NN, R. Srivastava & J.W.F. Valle

1904.05632/hep-ph, G.-J. Ding, NN, R. Srivastava & J.W.F. Valle

FLASY-2019 @ TDLi (Shanghai) & USTC (Hefei)

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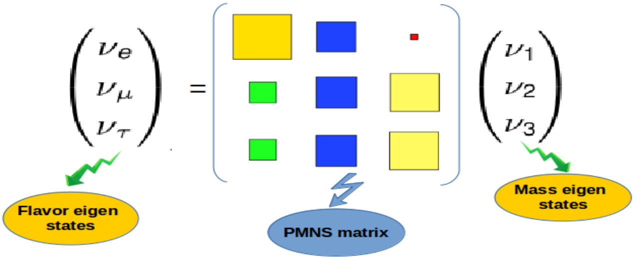
Neutrino oscillation:

- Standard 3-flavour ν-oscillation framework:



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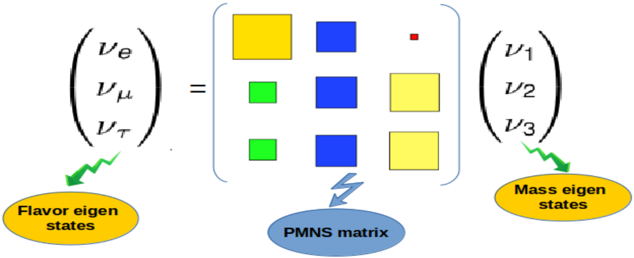

PMNS matrix :

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric, K2K, MINOS, T2K, etc. — Reactor Accelerator — Solar KamLAND

- **3-mixing angles, 1 CP-phase.**

Neutrino oscillation in 3 generation

- The transition probability $\nu_\alpha \to \nu_\beta$:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

where α, β are e, μ or τ

Full 3-flavour vacuum probability formula:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j} Re[U^*_{\alpha i} U^*_{\beta j} U_{\beta i} U_{\alpha j}] sin^2 \frac{\Delta_{ij} L}{4E} + 2\sum_{i<j} Im[U^*_{\alpha i} U^*_{\beta j} U_{\beta i} U_{\alpha j}] sin2 \frac{\Delta_{ij} L}{4E}$$

$$\Delta_{ij} = m_j^2 - m_i^2$$

Parameters of neutrino oscillation:

- Elements of U: **3-mixing ∠'s (θ_{12}, θ_{23}, θ_{13}) and 1-Dirac phase(δ_{CP})**
- **2-independent** $(mass)^2$ **differences,** $\Delta_{21} = m_2^2 - m_1^2$, $\Delta_{31} = |m_3^2 - m_1^2|$

Current Status:

de Salas, Forero, Ternes, Valle, arXiv:1708.01186, PLB782 (2018)

Parameter	Best fit $\pm$ 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.03	2.44–2.57	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.42^{+0.03}_{-0.04}$	2.34–2.47	2.31–2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/°$	$34.5^{+1.2}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.67–5.83	4.45–5.99
$\theta_{23}/°$	$47.7^{+1.2}_{-1.7}$	43.1–49.8	41.8–50.7
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$\theta_{23}/°$	$47.9^{+1.0}_{-1.7}$	44.5–48.9	42.3–50.7
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	2.03–2.34	1.96–2.41
$\theta_{13}/°$	$8.45^{+0.16}_{-0.14}$	8.2–8.8	8.0–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	2.07–2.36	1.99–2.44
$\theta_{13}/°$	$8.53^{+0.14}_{-0.15}$	8.3–8.8	8.1–9.0
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	1.01–1.75	0.87–1.94
$\delta/°$	238^{+38}_{-27}	182–315	157–349
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.27–1.82	1.12–1.94
$\delta/°$	281^{+23}_{-27}	229–328	202–349

NO or IO ?

LO or HO ?

CPV

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- **NO preferred over IO by** 3.4σ

Questions?

Theory behind the origin of ν masses & mixings?

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- Seesaw mechanism $\Rightarrow$ tiny ν-masses.
- Symmetry based studies $\Rightarrow$ ν-mixings.

$\mu - \tau$ symmetry:

First seed:

- Fukuyama, Nishiura proposed $\mu - \tau$ symmetry in the M_ν,

$$M_\nu = \begin{pmatrix} 0 & A & \pm A \\ A & B & C \\ \pm A & C & B \end{pmatrix} . \qquad (1)$$

where $A, B, C \in \mathcal{R}$.

arXiv:hep-ph/9702253 & 1701.04985, (PTEP 2017)

- Leads to $\theta_{23} = \mp 45^\circ$ and $\theta_{13} = 0^\circ$.
- (1,1)-entry $= 0 \Rightarrow$ small θ_{12}.

Cont...

- Easy generalization,

$$M_\nu = \begin{pmatrix} D & A & \pm A \\ A & B & C \\ \pm A & C & B \end{pmatrix} . \quad (2)$$

- Leads to,

$$\tan 2\theta_{12} = \frac{2\sqrt{2}A}{B \pm C - D} . \quad (3)$$

- For $B \pm C - D = A$, we get,

$$U_{HPS} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/3} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/3} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix} . \quad (4)$$

  - **U_{HPS} was 1st proposed by Harrison, Perkins & Scott** **arXiv:hep-ph/0202074, PLB530 (2002)**
- Also, famously called 'Tri-Bi-Maximal' leptonic mixing pattern.
- $U_{HPS} \Rightarrow$ $\sin\theta_{12} = \frac{1}{\sqrt{3}} \Rightarrow$ 'trimaximal mixing',
  $\sin\theta_{23} = \frac{1}{\sqrt{2}} \Rightarrow$ 'bimaximal mixing'
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  $\sin\theta_{23} = \frac{1}{\sqrt{2}} \Rightarrow$ 'bimaximal mixing'
  and $\theta_{13} = 0^\circ$.
- M_ν **is unchanged under:** $\nu_e \leftrightarrow \nu_e, \nu_\mu \leftrightarrow \pm\nu_\tau$ **($\mu - \tau$ permutation symmetry).**

$\mu - \tau$ reflection symmetry

Originally proposed by Harrison & Scott, PLB547 (2002)

- At present $\theta_{13} = 0^\circ$ is excluded at more than 5σ.
- **Many discrete flavor groups are rule out now.**

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- Extend the '$\mu - \tau$ permutation symmetric' matrix to a complex matrix as

$$M_\nu = \begin{pmatrix} D & A & \pm A^* \\ A & B & C \\ \pm A^* & C & B^* \end{pmatrix} ; \quad \mathrm{C, D} \in \mathbb{R} \ \& \ \mathrm{A, B} \in \mathbb{C}. \tag{5}$$

- One finds, $X^T M_\nu X = M_\nu^*$ with

$$X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} . \tag{6}$$

- M_ν can be diagonalized by the unitary matrix

$$U = \begin{pmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ \pm v_1^* & \pm v_2^* & \pm v_3^* \end{pmatrix} . \tag{7}$$

- One finds two well known predictions: $\theta_{23} = 45^\circ, s_{13} \cos\delta = 0$.
- Allows $\theta_{13} \neq 0$ and $\delta = \pm 90^\circ$ (**...wow**).
- M_ν is unchanged under:

$$\nu_e \leftrightarrow \nu_e^c, \quad \nu_\mu \leftrightarrow \pm \nu_\tau^c . \tag{8}$$

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- Excellent agreement with the latest data.

Implications

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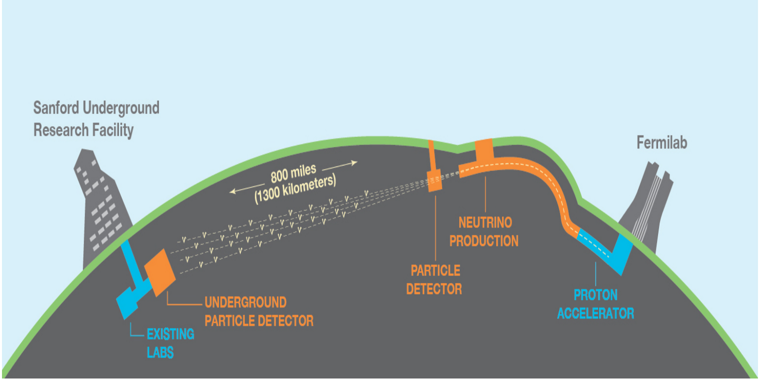
- DUNE (Deep Underground Neutrino Experiment), a proposed long baseline experiment at Fermilab, USA.

- DUNE will improve the precision of θ_{23} and play a key role to probe δ. [Acciarri et al.(DUNE), arXiv:1512.06148].

DUNE



- DUNE : Neutrinos travel from Fermilab to Sanford Underground Research Facility (SURF), 1300 km, 2.3 GeV, 1.07 MW, 4×10 kt-LArTPC detector.
  [Alio et al.(DUNE), arXiv:1601.09550].
- Their first 2-modules are expected to be completed in 2024, with the beam operational in 2026.
- To simulate the data we use GLoBES package.
  arXiv:hep-ph/0407333, 0701187.

Framework:

- We consider,

$$M_D = \begin{pmatrix} ae^{i\phi_a} & ae^{-i\phi_a} \\ be^{i\phi_b} & ce^{i\phi_c} \\ ce^{-i\phi_c} & be^{-i\phi_b} \end{pmatrix}, M_R = diag(M_1, M_1)\ . \tag{9}$$

- Within type-I seesaw:

$$\begin{aligned} -M_\nu &= M_D M_R^{-1} M_D^T, \\ &= \frac{1}{M_1}\begin{pmatrix} 2a^2\cos 2\phi_a & abe^{i(\phi_a+\phi_b)} + ace^{-i(\phi_a-\phi_c)} & abe^{-i(\phi_a+\phi_b)} + ace^{i(\phi_a-\phi_c)} \\ - & b^2e^{2i\phi_b} + c^2e^{2i\phi_c} & 2bc\cos(\phi_b-\phi_c) \\ - & - & b^2e^{-2i\phi_b} + c^2e^{-2i\phi_c} \end{pmatrix}. \end{aligned}$$

- $M_{ee} = M_{ee}^*\ , \quad M_{\mu\tau} = M_{\mu\tau}^*\ , \quad M_{e\mu} = M_{e\tau}^*\ , \quad M_{\mu\mu} = M_{\tau\tau}^*$

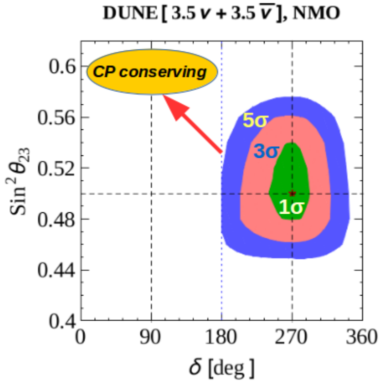
- Predicts non-zero θ_{13} with,

$$\theta_{23} = 45^\circ, \quad \delta = \pm 90^\circ. \tag{10}$$

NN, arXiv: 1805.05823, PRD98 (2018)

Cont...

- DUNE's Potential:



- **CP-conservation (CPC) hypothesis can be ruled out at $> 3\sigma$.**

NN, arXiv: 1805.05823, PRD98 (2018)

Cont...

Reminder: Best-fit preferences $\theta_{23}, \delta \Rightarrow$

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Looking for more realistic model

- **Break $\mu - \tau$ reflection symmetry.**
- **Generalized CP symmetry.**
- **Bi-large ansatze.**

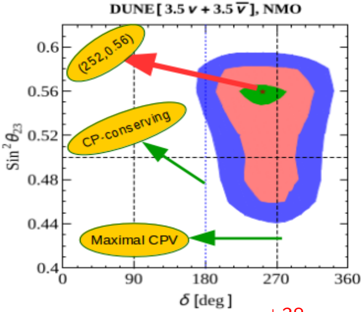
Recent topics: **Modular symmetries, tri-direct CP approaches etc...**

Cont...

Break M_D:

$$\widehat{M}_D = \begin{pmatrix} ae^{i\phi_a} & ae^{-i\phi_a} \\ be^{i\phi_b} & ce^{i\phi_c} \\ ce^{-i\phi_c} & b(1+\epsilon)e^{-i\phi_b} \end{pmatrix} .$$

$$\widehat{M}_\nu \simeq M_\nu - \epsilon \frac{be^{-i\phi_b}}{M_1} \begin{pmatrix} 0 & 0 & ae^{-i\phi_a} \\ 0 & 0 & ce^{i\phi_c} \\ be^{-i\phi_a} & ce^{i\phi_c} & 2be^{-2i\phi_b} \end{pmatrix} + \mathcal{O}(\epsilon^2) .$$



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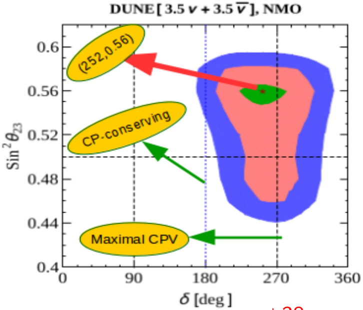

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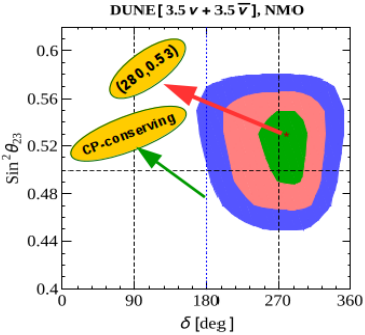
- **Predicted** δ, θ_{23} **are well within** 1σ, - **Maximal** θ_{23} **is ruled at** $> 1\sigma$

Cont...

Break M_R:

$$\widehat{M}_R = \begin{pmatrix} M_1 & 0 \\ 0 & M_1(1+\epsilon) \end{pmatrix} .$$

$$\widehat{M}_\nu \simeq M_\nu - \frac{\epsilon}{M_1} \begin{pmatrix} a^2 e^{-2i\phi_a} & ace^{-i(\phi_a - \phi_c)} & abe^{-i(\phi_a+\phi_b)} \\ - & b^2 e^{-2i\phi_b} & bce^{-i(\phi_b-\phi_c)} \\ - & - & c^2 e^{-2i\phi_c} \end{pmatrix} + \mathcal{O}(\epsilon^2) .$$



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Generalized CP (gCP) symmetry

- Reminder:

$$\psi \to X\psi \ ; \ \mu - \tau \ \textbf{permutation symmetry} \ ,$$

$$\psi \to X\psi^c \ ; \mu - \tau \ \textbf{reflection symmetry} \ ,$$

  where

$$X = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \ . \tag{11}$$

- In gCP, one assumes

$$\psi \xrightarrow{CP} iX_\psi \gamma^0 \psi^c \tag{12}$$

  X_ψ are the generalized CP transformation matrices

  [Feruglioa, Hagedorna, Ziegler, arXiv:1211.5560, Chen, Li, Ding, arXiv:1412.8352, Chen, Ding, Gonzalez-Canales, Valle, arXiv:1512.01551]

  with

$$X_\psi^T m_\psi X_\psi = m_\psi^* \ , \quad (\text{Majorana fields})$$

$$X_\psi^\dagger M_\psi^2 X_\psi = M_\psi^{2*} \ , \quad (\text{Dirac fields}) \ . \tag{13}$$

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X_ψ ?

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X_ψ **?** U_{PMNS} **?**

Recent studies: **Chen, Ding, Gonzalez-Canales, Valle, arXiv:1604.03510, Chen, Chulia, Ding, Srivastava, Valle, arXiv:1802.04275, Joshipura, Patel , arXiv : 1805.02002, Lu, Ding, arXiv: 1806.02301, Barreiros, Felipe, Joaquim, arXiv:1810.05454**

Cont...

- **Steps to find U_{PMNS}:** [Chen, Chulia, Ding, Srivastava, Valle, arXiv:1802.04275]

$$U_\psi^T m_\psi U_\psi = diag(m_1, m_2, m_3)\ , \quad (\text{Majorana fields})$$
$$U_\psi^\dagger M_\psi^2 U_\psi = diag(m_1^2, m_2^2, m_3^2)\ , \quad (\text{Dirac fields})\ . \qquad (14)$$

- U_ψ satisfies the following constraint

$$U_\psi^\dagger X_\psi U_\psi^* \equiv P = \begin{cases} \text{diag}(\pm 1, \pm 1, \pm 1), & \text{for Majorana fields,} \\ \text{diag}(e^{i\delta_1}, e^{i\delta_2}, e^{i\delta_3}), & \text{for Dirac fields}\,, \end{cases} \qquad (15)$$

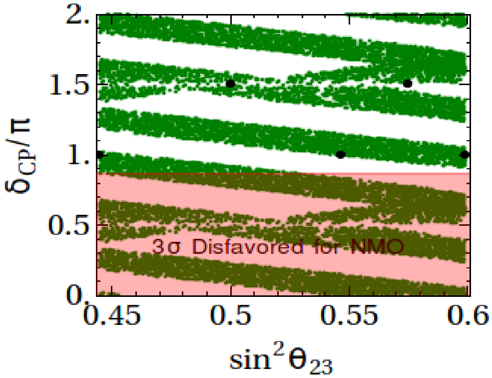
- **Unitary-symmetric matrix X_ψ can be decomposed as $X_\psi = \Sigma \cdot \Sigma^T$.**
- Subsequently, $P^{-\frac{1}{2}}\, U_\psi^\dagger\, \Sigma \;\equiv\; O_3\,, \Rightarrow U_\psi \;=\; \Sigma O_3^T\, P^{-\frac{1}{2}}$,
  where O_3,

$$O_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{\theta_1} & s_{\theta_1} \\ 0 & -s_{\theta_1} & c_{\theta_1} \end{pmatrix} \begin{pmatrix} c_{\theta_2} & 0 & s_{\theta_2} \\ 0 & 1 & 0 \\ -s_{\theta_2} & 0 & c_{\theta_2} \end{pmatrix} \begin{pmatrix} c_{\theta_3} & s_{\theta_3} & 0 \\ -s_{\theta_3} & c_{\theta_3} & 0 \\ 0 & 0 & 1 \end{pmatrix}.$$

- Maximum possible zeros in X_ψ: 4 ; [Chen, Ding, Gonzalez-Canales, Valle, arXiv:1604.03510]
- X_ψ : 11 possibilities, 8 are compatible with latest data.

Cont...

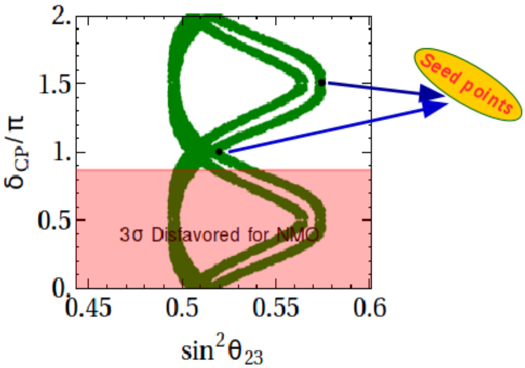
- No-Zeros in X : $\frac{1}{\sqrt{3}}\begin{pmatrix} e^{i\alpha} & e^{i(\frac{\alpha+\beta}{2}+\frac{2\pi}{3})} & e^{i(\frac{\alpha+\gamma}{2}+\frac{2\pi}{3})} \\ e^{i(\frac{\alpha+\beta}{2}+\frac{2\pi}{3})} & e^{i\beta} & e^{i(\frac{\beta+\gamma}{2}+\frac{2\pi}{3})} \\ e^{i(\frac{\alpha+\gamma}{2}+\frac{2\pi}{3})} & e^{i(\frac{\beta+\gamma}{2}+\frac{2\pi}{3})} & e^{i\gamma} \end{pmatrix}$
- This leads,



NN, Srivastava, Valle, arXiv:1811.07040, PRD99 (2019)

Cont...

- One-Zero in X : $\begin{pmatrix} e^{i\alpha} c_\Theta^2 & e^{i\gamma} c_\Theta s_\Theta & e^{i\beta} s_\Theta \\ e^{i\gamma} c_\Theta s_\Theta & e^{i(-\alpha+2\gamma)} s_\Theta^2 & -e^{i\alpha_1} c_\Theta \\ e^{i\beta} s_\Theta & -e^{i\alpha_1} c_\Theta & 0 \end{pmatrix}$
- This leads,



- **Seed points: $(0.575,\ 1.5\pi)$ & $(0.52,\ 1.0\pi)$**

[NN, Srivastava, Valle, arXiv:1811.07040, PRD99 (2019)]

Cont...

- Two-Zeros in X :

$$\begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta}c_\Theta & ie^{i(\beta+\gamma)/2}s_\Theta \\ 0 & ie^{i(\beta+\gamma)/2}s_\Theta & e^{i\gamma}c_\Theta \end{pmatrix} \tag{16}$$

- $\Rightarrow \sin^2\delta \sin^2 2\theta_{23} = \sin^2\Theta$, (Θ is the model parameter.)

  'Generalized $\mu - \tau$ reflection symmetry'

- $\Theta = \pm\pi/2 \Rightarrow$ 'exact $\mu - \tau$ reflection symmetry',

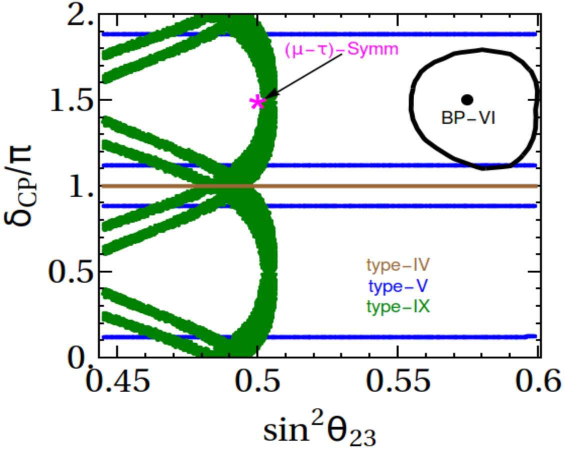
  i.e. $\boxed{\theta_{23} = 45^\circ, \delta = \pm 90^\circ}$

- $\Theta = 0 \Rightarrow$ **CP-conservation.**

- $\Theta \neq 0 \Rightarrow$ **deviations from $\mu - \tau$ reflection symmetry.**

Cont...

- DUNE's capability:



- **Precise measurement of θ_{23}, δ by DUNE can rule out various models.**

NN, Srivastava, Valle, arXiv:1811.07040, PRD99 (2019)

Bi-large ansatze

Motivation:

- Smallest leptonic-mixing angle $\simeq$ largest of the quark-mixing angle.
- Cabibbo angle (λ) may act as the universal seed for quark and lepton mixings.
- Bi-large patterns arise from the simplest GUTs model.

Boucenna, Morisi, Tortala, Valle: 1206.2555, Roy, Morisi, Singh, Valle: 1410.3658

- ν-mixing angles are related with λ,

$$\sin\theta_{23} = 1 - \lambda, \quad \sin\theta_{12} = 2\lambda, \quad \sin\theta_{13} = \lambda \text{ with } \lambda = 0.22453. \qquad (17)$$

- ν-part of mixing matrix U_{BL1} is given by

$$U_{BL1} \approx \begin{bmatrix} 1 - \frac{5\lambda^2}{2} & 2\lambda & -\lambda \\ \lambda - 2\sqrt{2}\lambda^{3/2} & \sqrt{2\lambda} - \frac{\lambda^{3/2}}{2\sqrt{2}} & 1 - \lambda - \frac{\lambda^2}{2} \\ 2\lambda + \sqrt{2}\lambda^{3/2} & -1 + \lambda & \sqrt{2\lambda} - \frac{\lambda^{3/2}}{2\sqrt{2}} \end{bmatrix} + h.o.$$

Ding, NN, Srivastava, Valle, arXiv:1904.05632, PLB796 (2019)

Cont...

- The $SO(10)$ GUT-motivated, CKM-type charged-lepton corrections,

$$U_{l_1} = R_{23}(\theta_{23}^{CKM})\Phi R_{12}(\theta_{12}^{CKM})\Phi^\dagger \simeq \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda\, e^{-i\phi} & 0 \\ -\lambda\, e^{i\phi} & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3 e^{i\phi} & -A\lambda^2 & 1 \end{bmatrix} ,$$

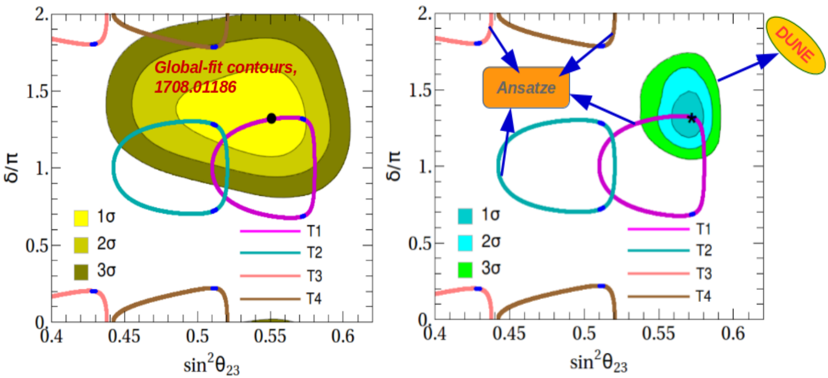
with $\sin\theta_{12}^{CKM} = \lambda$ and $\sin\theta_{23}^{CKM} = A\lambda^2$, where λ, A are the Wolfenstein parameters.

- The lepton mixing matrix is simply given by $U = U_{l_1}^\dagger U_{BL1} \Rightarrow$

$$\sin^2\theta_{13} \simeq 4\lambda^2(1-\lambda)\cos^2\frac{\phi}{2} ,$$
$$\sin^2\theta_{12} \simeq 2\lambda^2(2 - 2\sqrt{2\lambda}\cos\phi + \lambda) ,$$
$$\sin^2\theta_{23} \simeq (1-\lambda)^2 - 2\sqrt{2}A\lambda^{5/2} - 2\lambda^3(1+2\cos\phi) ,$$
$$J_{CP} \simeq -2\left(\sqrt{2}+\sqrt{\lambda}\right)\lambda^{5/2}\sin\phi .$$

Cont...

- Left panel ⇒ **Global-fit**, right panel ⇒ **DUNE analysis.**



Ding, NN, Srivastava, Valle, arXiv:1904.05632, PLB796 (2019)

- Types - 1, 2, 4 are compatible with latest data.
- Blue marks are obtained by requiring 1-3 mixing angle to lie within its current 3σ range.

Wrap-up

- Focus was to introduce the current status of different flavor symmetries to explain realistic leptonic mixing patterns.
- $\mu - \tau$ reflection symmetry, generalized CP symmetry, bi-large ansatze have been discussed.
- Impact of these symmetries on DUNE have been examined.
- DUNE with its high statistics and ability to measure (θ_{23}, δ) with high precision, will serve as an excellent experiment to test these different mixing patterns.

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thank you