Status and prospects of $\mu - \tau$ symmetry

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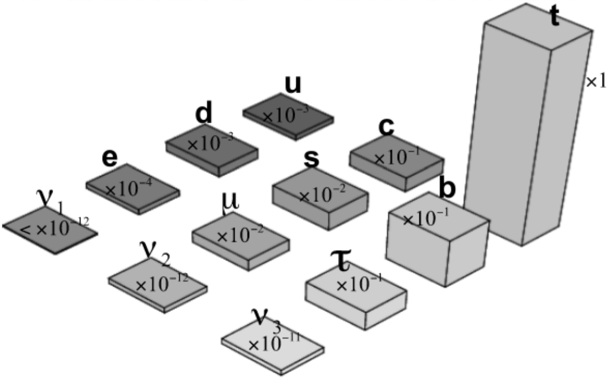
Neutrino Mass:

Tiny Neutrino mass: a long standing issue.



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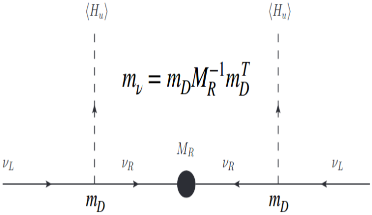
Type-I seesaw



[Minkowski'77, Yanagida'79, Gell-Mann/Slansky/Ramond'79, Mohapatra/Senjanovic'80, Schecter/Valle'80]

Neutrino Mixing

Standard 3-flavour ν-mixing patterns:

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

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

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

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- **3-mixing angles, 1 CP-phase.**
- **2-additional Majorana phases.**

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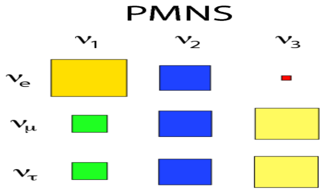

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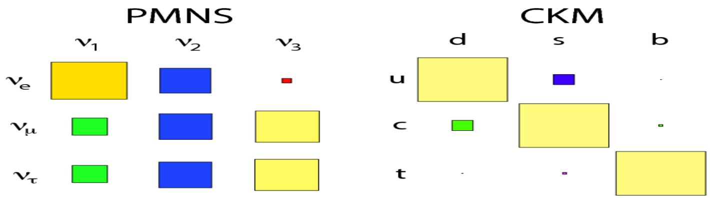


Why this form ?

Tri-Bi-Maximal Mixing:

- **Before Daya-Bay results, [PRL'13]:**

$$\mathbf{U_{TBM}} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/3} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/3} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix} .$$

  - U_{TBM} **was 1st proposed by Harrison, Perkins & Scott** arXiv:hep-ph/0202074, PLB530 (2002)

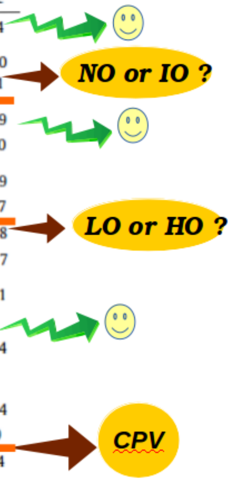
- $U_{TBM} \Rightarrow$ $\sin\theta_{12} = \frac{1}{\sqrt{3}} \Rightarrow$ 'trimaximal mixing',

  $\sin\theta_{23} = \frac{1}{\sqrt{2}} \Rightarrow$ 'bimaximal mixing'

  and $\theta_{13} = 0^\circ$.

Current Status:

Parameter	Best fit ± 1σ	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.20–7.94	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50 ± 0.03	2.44–2.57	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}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
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.91–5.84	4.53–5.98
$\theta_{23}/°$	$47.9^{+1.0}_{-1.7}$	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



- **At present $\theta_{13} = 0$ is excluded at more than 5σ.**

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

$\mu - \tau$ reflection symmetry

Originally proposed by Harrison & Scott, PLB547 (2002)

- M_ν is unchanged under:

$$\nu_e \leftrightarrow \nu_e^c, \quad \nu_\mu \leftrightarrow \pm\nu_\tau^c \quad \nu_\tau \leftrightarrow \pm\nu_\mu^c \ .$$

where,

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

- M_ν can be diagonalized by

$$U = \begin{pmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ \pm v_1^* & \pm v_2^* & \pm v_3^* \end{pmatrix} \Rightarrow |U_{\mu i}| = |U_{\tau i}|, i = 1, 2, 3$$

- 2-well known predictions: $\theta_{23} = 45^\circ, s_{13} \cos\delta = 0$.
- Allows non-zero θ_{13} for $\delta = \pm 90^\circ$ (**...wow**).
- Also predicts trivial Majorana phases, $\rho, \sigma = 0^\circ, 90^\circ$.

Recent review: Xing and Zhao, RPP79 (2016)

Cont...

- **Embedded $\mu-\tau$ reflection symmetry in minimal seesaw $\Rightarrow m_{light}=0$ (still allowed by latest data).**
- **To address both the ν-mass & mixing patterns.**
- **We assume,**

$$\nu_L \to \mathbf{S}\nu_L^c, \qquad \mathbf{N_R} \to \mathbf{S'}\mathbf{N_R^c}$$

where $\nu_L^c = C\overline{\nu_L}^T$ and $N_R^c = C\overline{N_R}^T$ and

$$\mathbf{S} = \begin{pmatrix} 1 & 0 \\ 0 & S' \end{pmatrix}, \quad \mathbf{S'} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}.$$

- M_D, M_R obey,

$$M_D = SM_D^* S', \qquad M_R = S' M_R^* S'.$$

- One gets,

$$M_D = \begin{pmatrix} |b|e^{i\phi_b} & |b|e^{-i\phi_b} \\ |c|e^{i\phi_c} & |d|e^{i\phi_d} \\ |d|e^{-i\phi_d} & |c|e^{-i\phi_c} \end{pmatrix}, M_R = \begin{pmatrix} |m_{22}|e^{i\phi_m} & m_{23} \\ m_{23} & |m_{22}|e^{-i\phi_m} \end{pmatrix},$$

NN, Xing & Zhang, 1801.09931/hep-ph, EPJC 78 (2018)

Cont...

- In type-I seesaw,

$$-\mathbf{M}_\nu = \mathbf{M_D}\mathbf{M_R}^{-1}\mathbf{M_D^T} = \begin{pmatrix} A & B & B^* \\ B & C & D \\ B^* & D & C^* \end{pmatrix} .$$

- M_ν can be diagonalized by,

$$V = P_l \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} P_\nu , \qquad (1)$$

where $P_l = diag(e^{i\phi_e}, e^{i\phi_\mu}, e^{i\phi_\tau})$ and $P_\nu = diag(1, e^{i\rho}, e^{i\sigma})$.

- **6-predictions:**

$$\phi_e = \mathbf{90}^\circ, \quad \phi_\mu \equiv -\phi_\tau = \phi, \quad \theta_{23} = \mathbf{45}^\circ, \quad \delta = \pm\mathbf{90}^\circ, \quad \rho,\ \sigma = \mathbf{0} \ \text{ or } \ \mathbf{90}^\circ.$$

- Also,

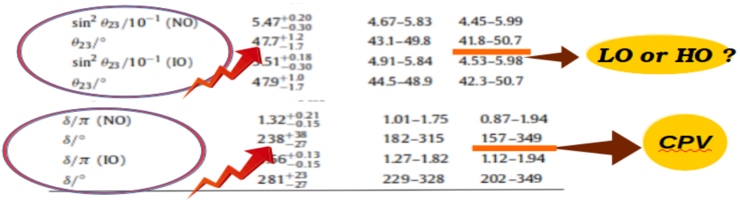
$$\tan\theta_{13} = \mp \frac{1}{\sqrt{2}} \frac{\mathrm{Im}\,(C')}{\mathrm{Im}\,(B')} \quad (C' = Ce^{-2i\phi}, B' = Be^{-i\phi}),$$

$$\tan 2\theta_{12} = \frac{2\sqrt{2}\cos 2\theta_{13}\mathrm{Im}\,(B')}{c_{13}\left[(\mathrm{Re}(C') - D)\cos 2\theta_{13} - (\mathrm{Re}(C') + D)s_{13}^2 + Ac_{13}^2\right]} \ ; \quad \text{for NH}$$

- Excellent agreement with the latest data.

Cont...

Reminder: Best-fit preferences



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Looking for more realistic model

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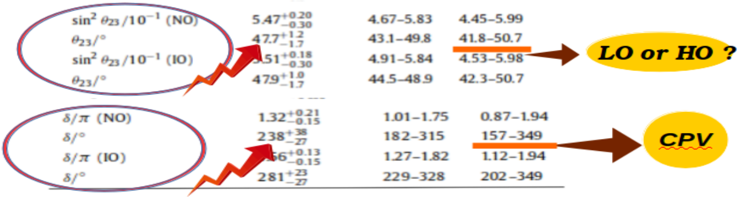

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- **Break $\mu - \tau$ reflection symmetry:**

RG-running

Cont...

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LO or HO ?

CPV

Looking for more realistic model

- **Break $\mu-\tau$ reflection symmetry:**

RG-running **or**

Cont...

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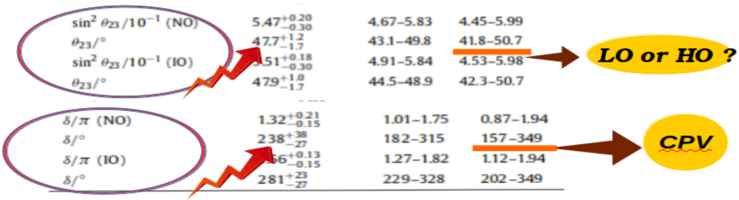

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Looking for more realistic model

- **Break $\mu - \tau$ reflection symmetry:**

RG-running **or** **Explicit**

Recent topics: **Generalized CP symmetry, Modular symmetry, Bi-large ansatze, Tri-direct CP approaches etc...**

RGE effect:

- **REG effect works as a bridge between the high-energy predictions and the low-energy measurements.**
- At the one-loop level, the energy dependence of M_ν is given by

$$16\pi^2 \frac{\mathrm{d}M_\nu}{\mathrm{d}t} = C\left(Y_l^\dagger Y_l\right)^T M_\nu + CM_\nu\left(Y_l^\dagger Y_l\right) + \alpha M_\nu \; .$$

[**Chankowski, Pluciennik, PLB316(1993)**]

- With

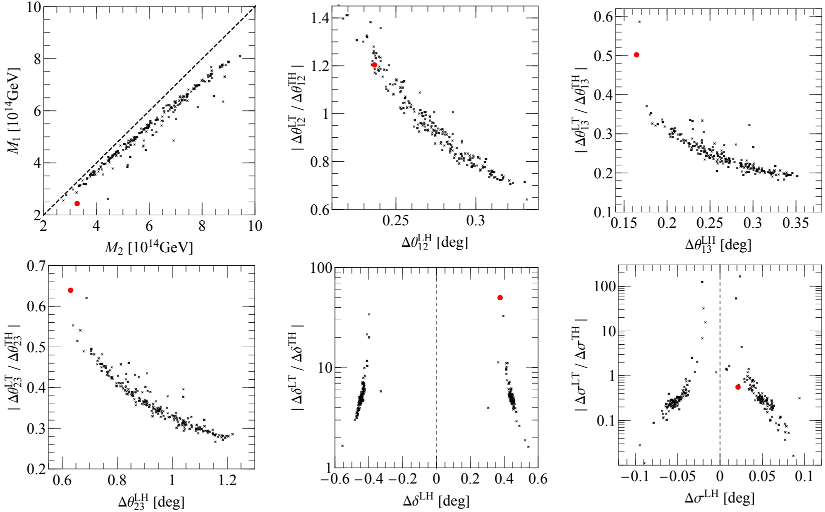
$$M_\nu(\Lambda_{\rm EW}) = I_\alpha I_\tau^\dagger M_\nu(\Lambda_{\mu\tau}) I_\tau^* \; ,$$

where one defines $I_\tau \simeq \mathrm{diag}\{1, 1, 1-\Delta_\tau\}$ along with

$$\mathbf{I}_\alpha = \exp\left(\frac{\mathbf{1}}{\mathbf{16}\pi^{\mathbf{2}}}\int_{\ln \boldsymbol{\Lambda}_{\mu\tau}}^{\ln \boldsymbol{\Lambda}_{\rm EW}} \alpha \;\mathrm{d}\mathbf{t}\right) , \qquad \boldsymbol{\Delta}_\tau = \frac{\mathbf{C}}{\mathbf{16}\pi^{\mathbf{2}}}\int_{\ln \boldsymbol{\Lambda}_{\rm EW}}^{\ln \boldsymbol{\Lambda}_{\mu\tau}} \mathbf{y}_\tau^{\mathbf{2}} \;\mathrm{d}\mathbf{t} \; .$$

Cont...

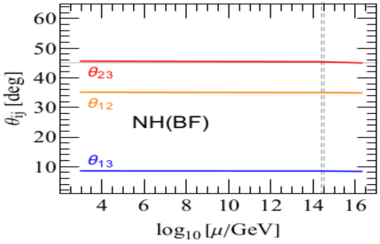
- **RGE predictions for NO (in MSSM with $\tan\beta = 30$):**

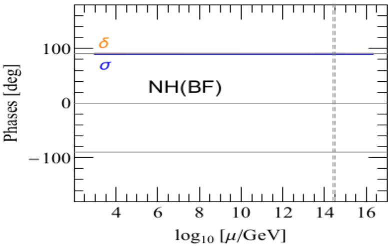


[NN, Xing & Zhang, 1801.09931/hep-phEPJC78 (2018).]

Cont...

- **Impact of RG running:**





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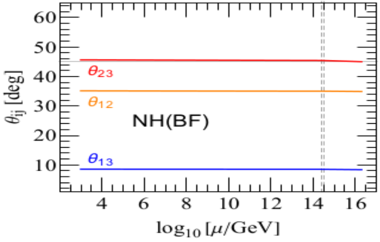

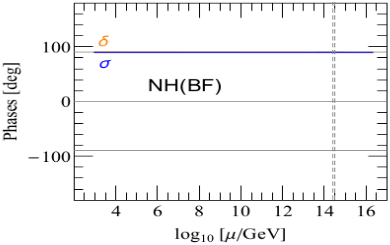

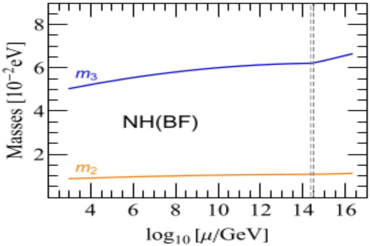

NN, Xing & Zhang, EPJC78 (2018).

Summarizing all explicit-breaking scenarios:

Breaking Scenarios	θ'_{23} [deg]	δ'_{CP} [deg]	$\Delta\theta'_{12}$ [deg]	$\Delta\theta'_{13}$ [deg]	$\sum m_\nu$ [eV]	m_{ee} [meV]
S1	$44.3 \to 45.7$	$-180 \to 180$	$-15 \to 10$	$-1 \to 9$	$0.0575 \to 0.061$	$1 \to 4.2$
S2	$35 \to 46$	$-100 \to -88$	$-18 \to 1$	$-0.1 \to 1.3$	$0.057 \to 0.061$	$3 \to 4.5$
	$40 \to 45$	$-90 \to -70$	$0 \to 9$	$0 \to 1.2$	–	–
S3	$37.5 \to 47$	$-98 \to -88$	$2 \to 7$	$-1.4 \to 0.2$	$0.057 \to 0.0615$	$3 \to 4.5$
	$46 \to 47$	$-94 \to -56$	$-20 \to 3$	$-1.7 \to 0.3$	–	–
S4	$43 \to 46$	$-100 \to -88$	$-0.2 \to 0.7$	$-3 \to 1$	$0.0575 \to 0.061$	$3.1 \to 4.4$
S5	$39 \to 46.5$	$-120 \to -84$	$-1 \to 2.6$	$-8 \to 8$	$0.057 \to 0.061$	$3 \to 4.5$

Scenarios $\Rightarrow$ $M_D(12) \to$ **S1**, $M_D(22) \to$ **S2**, $M_D(32) \to$ **S3**, $M_R(22) \to$ **S4**, $M_R(12) \to$ **S5**

NN, Xing & Zhang, EPJC78 (2018)

Minimal seesaw @ TeV Scale:

Xing & Zhou, PLB '07

- **2-N_R with highly degenerate masses of $\mathcal{O}(1)$ TeV are added.**
- **Along with ν-oscillation parameters, it also explains baryon number asymmetry through "resonant leptogenesis".** [Pilaftsis, Underwood '04]
- M_D has been parameterized as,

$$M_D = V_0 \begin{pmatrix} 0 & 0 \\ x & 0 \\ 0 & x \end{pmatrix} U \; ; \quad (\mathrm{M_l}, \mathrm{M_R} \quad \text{are} \quad \text{diag}).$$

where V_0, U are

$$V_0 = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/3} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/3} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}, \quad U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} e^{-i\alpha} & 0 \\ 0 & e^{+i\alpha} \end{pmatrix}$$

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TBM pattern

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$$M_D = V_0 \begin{pmatrix} 0 & 0 \\ x & 0 \\ 0 & x \end{pmatrix} U \; ; \quad (\mathrm{M_l}, \mathrm{M_R} \;\; \text{are} \;\; \text{diag}).$$

where V_0, U are

$$V_0 = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/3} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/3} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}, \quad U = \begin{pmatrix} \cos\vartheta & \sin\vartheta \\ -\sin\vartheta & \cos\vartheta \end{pmatrix} \begin{pmatrix} e^{-i\alpha} & 0 \\ 0 & e^{+i\alpha} \end{pmatrix}$$

TBM pattern

- **Note: α is the only phase, explains CPV in ν-oscillation & N_i decays.**
- **This model leads to nearly TBM pattern:**

$$\theta_{23} = \pi/4, \quad \delta = \pm\pi/2, \quad \sin^2\theta_{12} = (1 - 2\tan^2\theta_{13})/3.$$

Cont...

- The flavor-dependent CP-violating asymmetry $\varepsilon_{i\alpha}$:

$$\varepsilon_{ie} = \frac{\omega^2}{3(\omega^2-1)}\,\varepsilon_i\,, \qquad \varepsilon_{i\mu} = \varepsilon_{i\tau} = \frac{2\omega^2-3}{6(\omega^2-1)}\,\varepsilon_i$$

where ε_i is given by:

$$\varepsilon_i = \frac{-32\pi v^2 y^2 \left(1-\omega^2\right)^2}{\left(1+\omega^2\right)\left[1024\pi^2 v^4 r^2 + y^4\left(1+\omega^2\right)^2\right]}\; r \sin 4\alpha\,,$$

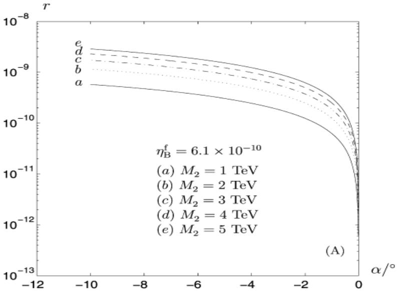
with $r = (M_2 - M_1)/M_2$.

- **Note: for $\varepsilon_i \neq 0$, r, α can't be zero.**
- **The final baryon number asymmetry η_B^f:**

$$\eta_B^f \approx -0.96\times 10^{-2}\sum_{i,\alpha}\left(\varepsilon_{i\alpha}\kappa_{i\alpha}\right);$$

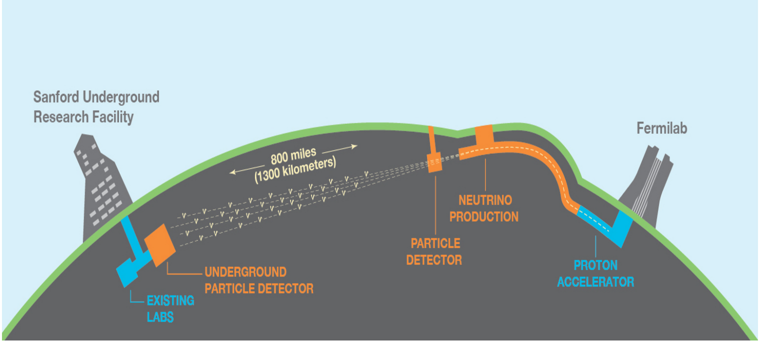
$\kappa_{i\alpha} \Rightarrow$ efficiency factor

$\Rightarrow$



Testing $\mu - \tau$ reflection symmetry @ DUNE:

- **DUNE : 'Deep Underground Neutrino Experiment' is a proposed long baseline experiment at Fermilab, USA.**



- DUNE: νs 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,

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

- Within type-I seesaw:

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

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

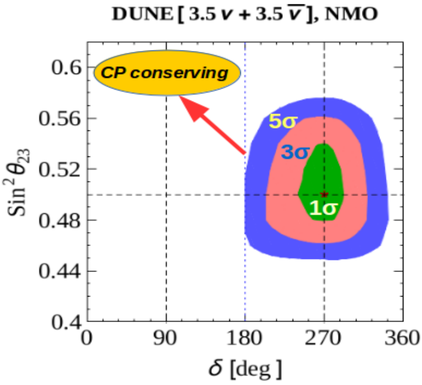
- Predicts non-zero θ_{13} with,

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

NN, arXiv: 1805.05823, PRD98 (2018)

Cont...

- **DUNE's Potential:**



- CP-conservation hypothesis can be ruled out around 5σ

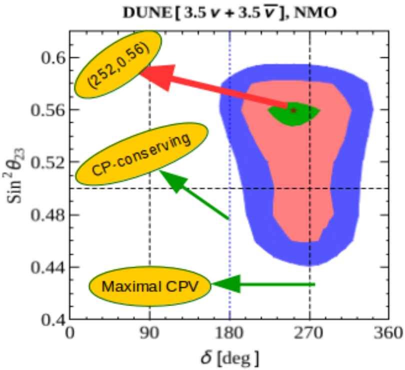
NN, arXiv: 1805.05823, PRD98 (2018)

Cont...

Break M_D:

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

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



- **Best fit: $(238^{+38}_{-27}, 0.547^{+0.02}_{-0.03})$**
- **Predicted δ, θ_{23} are well within 1σ**
- **Maximal θ_{23} is ruled at $> 1\sigma$**

Wrap-up Comments:

- At present, $\mu-\tau$ reflection symmetry has an excellent agreement with the latest data, it predicts $\theta_{23}=\pi/4$, $\delta=\pm\pi/2$ and $\theta_{13}\neq 0$ along with $\rho,\sigma=0,\pi/2$.
- We embed $\mu-\tau$ reflection symmetry in minimal seesaw to explain non-zero neutrino mass as well as their mixings.
- Considering RG-running equations, we discuss the breaking of the $\mu-\tau$ reflection symmetry
- Also, discuss a TeV scale minimal seesaw model which explains baryon asymmetry of the universe through the resonant leptogenesis.
- Impact of $\mu-\tau$ reflection symmetry on DUNE has 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.

Wrap-up Comments:

- **At present, $\mu - \tau$ reflection symmetry has an excellent agreement with the latest data, it predicts $\theta_{23} = \pi/4$, $\delta = \pm\pi/2$ and $\theta_{13} \neq 0$ along with $\rho, \sigma = 0, \pi/2$.**
- **We embed $\mu - \tau$ reflection symmetry in minimal seesaw to explain non-zero neutrino mass as well as their mixings.**
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- **Impact of $\mu - \tau$ reflection symmetry on DUNE has 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.**

thank you

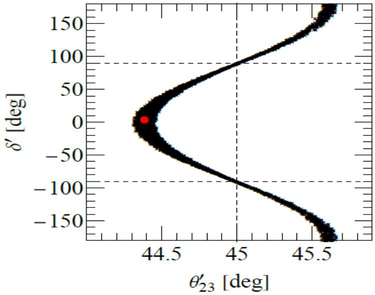
Back-Up

Explicit Breaking

- Modify (12)-position of M_D,

$$\textbf{S1}: \quad M'_D = \begin{pmatrix} b & b^*(1+\epsilon) \\ c & d \\ d^* & c^* \end{pmatrix}, \qquad (2)$$

"ϵ breaks $\mu - \tau$ Reflection Symmetry"



Cont...

- Modify (22)-position of M_R,

$$\textbf{S4}: \quad M_R' = \begin{pmatrix} m_{22} & m_{23} \\ m_{23} & m_{22}^*(1+\epsilon) \end{pmatrix} , \tag{3}$$

"ϵ breaks $\mu - \tau$ Reflection Symmetry"