Some Compelling Aspects of Neutrino Physics

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Personal Details

- Obtained my **Bachelor of Science** (B.Sc.) degree in Physics (Honours) with 70.75% marks from Assam University, Silchar, Assam, India during 2007 - 2010.
- Obtained my **Master of Science** (M.Sc.) with a specialization in Particle Physics with 9.51 CGPA from University of Hyderabad, Hyderabad, India during 2010 - 2012.
- Completed my **Doctor of Philosophy** (Ph.D.) degree in *Neutrino Physics* under the supervision of Prof. Srubabati Goswami from Physical Research Laboratory, Ahmedabad, India during 2012 - 2017.
- Currently (2017 -) working as a **Post-Doctoral Fellow** (PDF) in *Neutrino Physics* with Prof. Zhi-zhong Xing at Institute of High Energy Physics, Beijing, China.

Publication List

- **Newton Nath**, Zhi-zhong Xing, Jue Zhang : $\mu - \tau$ Reflection Symmetry Embedded in Minimal Seesaw, **Eur. Phys. J. C (2018)**, arXiv:1801.09931 [hep-ph].
- K. N. Deepthi, Srubabati Goswami, **Newton Nath** : Can nonstandard interactions jeopardize the hierarchy sensitivity of DUNE?, **Phys. Rev. D 96, 075023 (2017)**, arXiv:1612.00784 [hep-ph].
- **Newton Nath**, Monojit Ghosh, Srubabati Goswami, Shivani Gupta : Phenomenological study of extended seesaw model for light sterile neutrino, **JHEP03(2017)075**, arXiv:1610.09090 [hep-ph].
- Anjan S. Joshipura, **Newton Nath** : Neutrino masses and mixing in A_5 with flavour antisymmetry, **Phys.Rev. D94, 036008 (2016)**, arXiv:1606.01697[hep-ph].
- **Newton Nath**, Monojit Ghosh, Shivani Gupta : Light Sterile Neutrino Mass Matrix with Texture Zero and a Vanishing Mass, **Int. J. Mod. Phys. A 31, 1650132 (2016)**, arXiv:1512.00635[hep-ph].
- **Newton Nath**, Monojit Ghosh, Srubabati Goswami :The Physics of antineutrinos in DUNE and resolution of octant degeneracy, **Nucl.Phys. B913 (2016) 381-404**, arXiv:1511.07496[hep-ph].
- Monojit Ghosh, Pomita Ghoshal, Srubabati Goswami, **Newton Nath**, Sushant K. Raut :A new look to the degeneracies in the neutrino oscillation parameters and their resolution by T2K, NOνA and ICAL, **Phys. Rev. D93, 013013 (2016)** , arXiv :1504.06283[hep-ph].

Conference Proceedings[1]

- N.D. Kuchibhatla†, S. Goswami, **N. Nath** : Effect of non-standard neutrino interactions on the sensitivities of DUNE, **NuFact2017**, **PoS(NuFact2017)162**.
- **Newton Nath**†, Srubabati Goswami and K. N. Deepthi: Generalized degeneracies and their resolution in neutrino oscillation experiments, **XXII DAE-BRNS SYMPOSIUM 2016**, **Springer Proceedings in Physics 203**, arXiv:1703.00245 [hep-ph].
- **Newton Nath**†, Monojit Ghosh and Srubabati Goswami: What antineutrinos can tell about octant and δ_{CP} in DUNE?, **ICHEP2016**, **PoS(ICHEP2016)979**, arXiv:1611.03635 [hep-ph].
- **Newton Nath**†, Monojit Ghosh and Srubabati Goswami: The Physics of antineutrinos in DUNE and resolution of octant degeneracy, **Neutrino2016**, **J. Phys.: Conf. Ser. 888 012261**, arXiv:1610.01183 [hep-ex].

[1] '†' Corresponding Author

Neutrino oscillations

- Neutrino oscillation $\Rightarrow$ Transition from one flavor to another

time=0; time=t;
ν_e; $\longrightarrow$ distance=L; $\longrightarrow$ ν_e, ν_μ, ν_τ;

The 3-flavor ν-oscillation probability can be written as:

$$\begin{aligned} P_{\alpha\beta} = \quad & \delta_{\alpha\beta} - 4\sum_{i<j} Re[U^*_{\alpha i} U^*_{\beta j} U_{\beta i} U_{\alpha j}] sin^2 \frac{\Delta_{ij} L}{4E} \\ & +2\sum_{i<j} Im[U^*_{\alpha i} U^*_{\beta j} U_{\beta i} U_{\alpha j}] sin2 \frac{\Delta_{ij} L}{4E} \end{aligned} \quad (1)$$

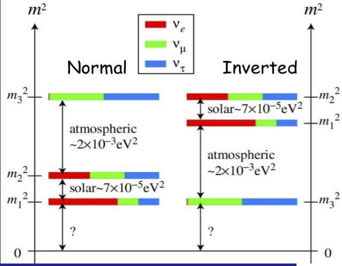
where, $\Delta_{ij} = m_i^2 - m_j^2$

Parameters of neutrino oscillation:

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

Unknowns:

- Various ν-oscillations experiments have measured these parameters.
- Unknowns in Neutrino Physics.



- The sign of Δm^2_{31} i.e.
  $\Delta m^2_{31} > 0 \Rightarrow$ Normal Hierarchy (NH)
  or
  $\Delta m^2_{31} < 0 \Rightarrow$ Inverted Hierarchy (IH).

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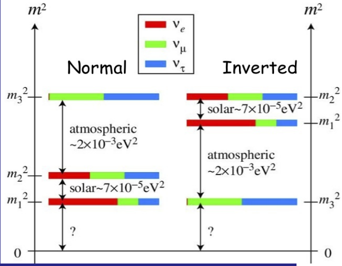

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- The octant of θ_{23} i.e.
  $\theta_{23} > 45^\circ \Rightarrow$ Higher Octant (HO) or
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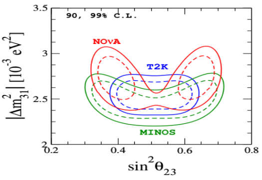

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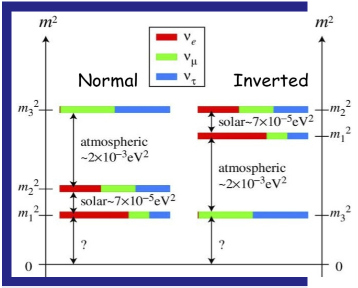

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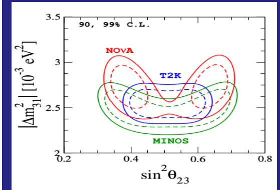


- The Dirac CP phase δ_{CP}, where $\delta_{CP} \neq 0^o, \pm180^o \Rightarrow$ *CP violation*. There already exists hints that CP phase may be nearly maximal. [Salas et.al., arXiv:1708.01186]

Current status of the oscillation parameters[2]

Parameter	best fit	3σ range
$\Delta m^2_{21}[10^{-5}eV^2]$	7.56	7.05–8.14
$\|\Delta m^2_{31}\|[10^{-3}eV^2]$ (NH)	2.55	2.43–2.67
$\|\Delta m^2_{31}\|[10^{-3}eV^2]$ (IH)	2.49	2.37–2.61
$\theta_{12}(deg)$	34.5	31.5–38
$\theta_{23}(deg)(NH)$	41.0	38.3–52.8
$\theta_{23}(deg)(IH)$	50.5	38.5–53.0
$\theta_{13}(deg)$ (NH)	8.44	7.9–8.9
$\theta_{13}(deg)$ (IH)	8.41	7.9–8.9
δ/π (NH)	1.40	0.0–2.0
δ/π (IH)	1.44	0.0–2.0

- Recent T2K result favors : NH, $\delta_{CP} = -\pi/2, \theta_{23} \backsim 45^\circ$. [PRL, 118(2017), 151801]
- NOνA favors : NH-HO with 0.2σ and disfavors : maximal θ_{23} with 0.8σ and IH-$\delta_{CP} = \pi/2$ with more than 3σ. [NOνA Collaboration, 2018]

[2]Salas et.al., arXiv:1708.01186

Definition of Degeneracy

Problem: Existence of parameter degeneracy

Degeneracy: Two different sets of neutrino oscillation parameters giving rise to same oscillation probability i.e.,

$$P_{\alpha\beta}(x) = P_{\alpha\beta}(y)$$

x, y: different sets of oscillation parameters i.e.,
$x = x(\theta_{ij}, \delta_{CP}, \Delta_{ij})$, $y = y(\theta'_{ij}, \delta'_{CP}, \Delta'_{ij})$

Conclusion:

Extraction of x will be confused with extraction of y

Probability Channels

The relevant probability channels:

- Appearance Channel:

$$P_{\mu e} = 4 s_{13}^2 s_{23}^2 \frac{\sin^2 (A-1)\Delta}{(A-1)^2} + \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2 A\Delta}{A^2} \tag{2}$$

$$+ \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\Delta + \delta_{cp}) \frac{\sin(A-1)\Delta}{(A-1)} \frac{\sin A\Delta}{A} \tag{3}$$

where, $s_{ij} = \sin\theta_{ij},\ \ i < j = 1, 2, 3$

- Disappearance Channel:

$$P_{\mu\mu} = 1 - \sin^2 2\theta_{23} \sin^2 \Delta + \mathcal{O}(\alpha, s_{13})$$

- $\Delta = \dfrac{\Delta_{31} L}{4E}$ and $\alpha = \Delta_{21}/\Delta_{31}$ are +ve(-ve) for NH (IH)
  $A = 2EV/\Delta_{31} =$ +ve (-ve) for $\nu(\overline{\nu})$, V is matter potential.

Generalized Degeneracy

- For unknown hierarchy, octant and δ_{CP}:

$$P_{\mu e}(\theta_{23}, \Delta, \delta_{CP}) = P_{\mu e}(\theta'_{23}, -\Delta', \delta'_{CP})$$

$\Rightarrow$ generalized (hierarchy-θ_{23}-δ_{CP}) degeneracy.[3]

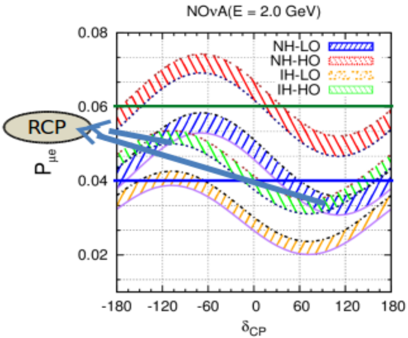
- Eight possibilities:

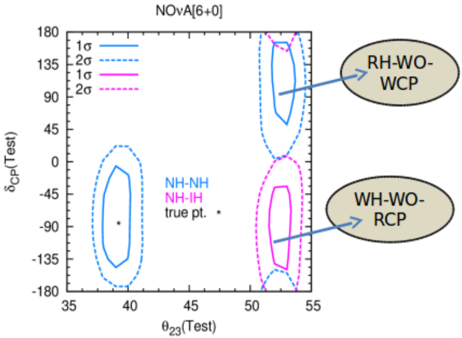
Solution with (right δ_{CP})	Solution with (wrong δ_{CP})
1) RH-RO-Rδ_{CP}	5) WH-WO-Wδ_{CP}
2) RH-WO-Rδ_{CP}	6) RH-RO-Wδ_{CP}
3) WH-RO-Rδ_{CP}	7) RH-WO-Wδ_{CP}
4) WH-WO-Rδ_{CP}	8) WH-RO-Wδ_{CP}

here, R=Right, W=Wrong

[3] Ghosh, Ghoshal, Goswami, NN and Raut,PRD93,013013 (2016)

Degeneracies at NOνA are [4] ,





At Probability

- Overlapping region around $-120^o, +90^o \Rightarrow$ WH-WO-Rδ_{CP}.
- Same probability value for NH-LO and IH-LO $\Rightarrow$ WH-RO-Wδ_{CP}.
- Same probability value for NH-HO and NH-LO $\Rightarrow$ RH-WO-Wδ_{CP}.
- For NH-HO at $(48^o, -180^o)$ and $(48^o, 45^o) \Rightarrow$ RH-RO-Wδ_{CP}.
- For NH-LO $(39^o, -180^o)$ and IH-HO $(51^o, 0^o) \Rightarrow$ WH-WO-Wδ_{CP}.

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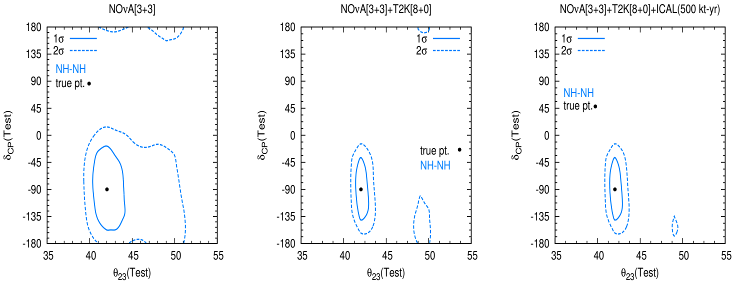
[4] Ghosh, Ghoshal, Goswami, NN and Raut, PRD93,013013 (2016)

Resolution of various degeneracies

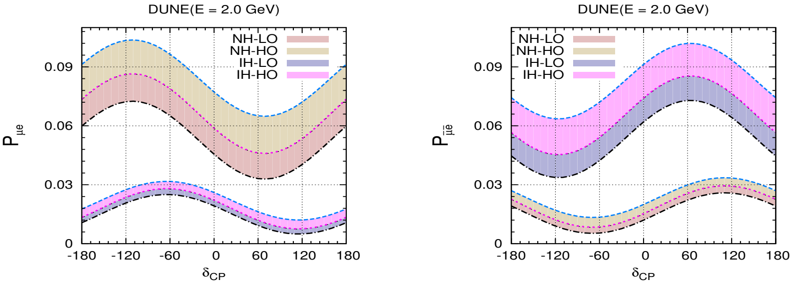
- Resolution of degeneracies with NOνA, T2K, ICAL ,



- Addition of $\overline{\nu}$ removes WO-WH solution.
- Addition of more data provides better precision on θ_{23}.

[Ghosh, Ghoshal, Goswami, NN and Raut,PRD93,013013 (2016)]

- Probability level study at DUNE [5] :



- No overlapping between NH and IH bands ⇒ no hierarchy degeneracy.
- Same probability at different δ_{CP} ⇒ degeneracy occurring for $W\delta_{CP}$.

Octant Degeneracy	ν	$\overline{\nu}$
LHP, LO	degenerate with UHP, HO	no degeneracy
UHP, LO	no degeneracy	degenerate with LHP,HO
LHP, HO	no degeneracy	degenerate with UHP, LO
UHP, HO	degenerate with LHP,LO	no degeneracy

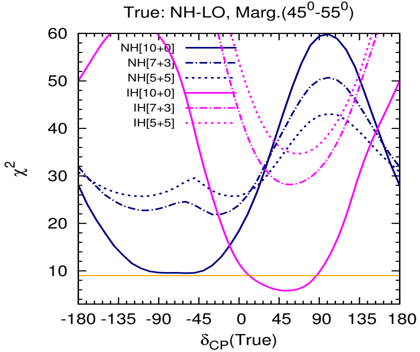
Table: The octant degenerate parameter space for neutrinos and antineutrinos.

- Note: $(\nu + \bar{\nu})$ runs are help full to resolve octant-δ_{CP} degeneracy.

[5] NN, Ghosh and Goswami, PLB913 (2016) 381-404

Octant discovery χ^2:

- NH-LO ($\theta_{23}^{\rm true} = 39°$):



$$\mapsto \chi^2 = \left(\frac{\theta_{23}^{true} - \theta_{23}^{test}}{\sigma(\theta_{23}^{true})}\right)^2$$

- Known hierarchy $\Rightarrow$ 3σ octant discovery χ^2 for all values of δ_{CP} for DUNE in ν mode.
- Unknown hierarchy $\Rightarrow$ octant degeneracy at 3σ in UHP but not at 2σ for all δ_{CP} for [10+0].
- (7+3) runs $\Rightarrow$ octant discovery at more than 4σ for any value of δ_{CP}.

Impact of New Physics

- DUNE(L=1300 km) has large matter effect ⇒ able to resolve hierarchy (if there is no new-physics).

  [Acciarri (Fermilab) et al. 1512.06148]

- "**New-physics**" effect at DUNE can ruin mass hierarchy determination.

  Liao, Marfatia, Whisnant 1601.00927, Coloma, Schwetz 1604.05772, Masud, Mehta 1606.05662, Dutta, Ghoshal, Roy 1609.07094

- Various possible **new-physics** are non-standard interactions (NSIs), non-unitarity, sterile neutrino, large extra-dimension, etc...

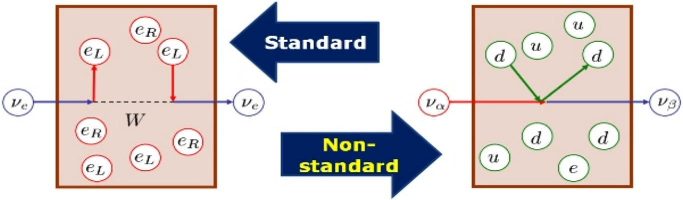
  Blennow, Coloma, Martinez, Garcia, Pavon 1609.08637, Tang, Zhang, Li, 1708.04909, Berryman, Gouvea, Kelly,Peres, Tabrizi, 1603.00018.

Non-standard interactions

- Dimension 6, exotic couplings involving ν's can affect neutrinos propagation through matter,

$$\mathcal{L}_{\rm NSI}^{NC} = (\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{f}\gamma_\rho P_C f) 2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fC} + \text{h.c.} \qquad (4)$$

Wolfenstein, '78, Valle '87



where,

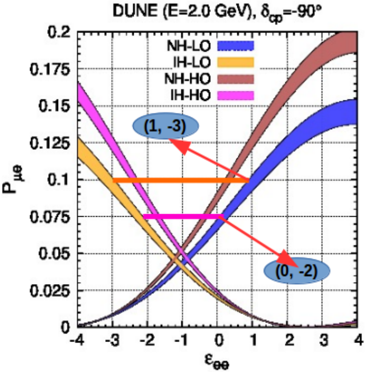
$$\epsilon_{\alpha\beta} e^{i\phi_{\alpha\beta}} = A \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}. \qquad (5)$$

- Model-independent bounds, $|\varepsilon_{ee}| < 4.2, |\varepsilon_{e\tau}| < 3.0$

[Biggio, Blennow, Martinez 0907.0097, Ohlsson 1209.2710]

Probabality level

- Considering only ϵ_{ee} (for $\delta_{CP} = -90^\circ$),



$\rightsquigarrow$

- $\epsilon_{ee} \to -\epsilon_{ee} - 2 \Rightarrow$ WH-RO-RCP.
- For $\epsilon_{ee} > 2 \Rightarrow$ no WH-RO-RCP solution.
- $\epsilon_{ee} = -1 \Rightarrow$ *"region of confusion"* since same ϵ_{ee} for both NH & IH.

  [Deepthi, Goswami, NN PRD, 96, 075023 (2017)]

  see also, Liao, Marfatia Whisnant, PRD 93, 093016 (2016), Coloma, Schwetz, PRD 94, 055005 (2016)

- We extend similar study on the determination of δ_{CP},

  [Deepthi, Goswami, NN arXiv:1711.04840 [hep-ph]]

Existence of light sterile neutrino

- Understanding the masses and mixings of one-zero textures in $3+1$ scenario
  [NN, Ghosh and Gupta, IJMPA 31, 1650132 (2016)]

- Phenomenological study of extended seesaw model for light sterile neutrino [NN, Ghosh, Goswami and Gupta, JHEP 1703 (2017) 075]

Flavor Symmetry

Theoretical framework

- One should have theoretical understanding also to understand this beautiful mixing pattern.
- Flavor symmetries provide concrete framework to do this.
- We assume Majorana neutrino mass matrix M_ν obey flavor anti-symmetry instead of flavor symmetry [6],

$$S_\nu^T M_\nu S_\nu = -M_\nu \tag{6}$$

[6] Grimus, Kaneko, Lavoura, Sawanaka and Tanimoto, JHEP 01 (2006) 110, Joshipura, JHEP 1511 (2015) 186.

A_5 group

- Alternating group A_5 is the even permutations of 5 distinct objects.
- It has 60 different elements and 5 conjugacy classes:

$$1C_1, 15C_2, 20C_3, 12C_5^1 \ and \ 12C_5^2. \tag{7}$$

- It has 5-irreducible representations: 1, 3, 3′, 4 and 5.
- All representations except singlet are faithful.
- The Abelian subgroups are $\mathbf{Z}_2$ (15 elements), $\mathbf{Z}_3$ (20 elements) and $\mathbf{Z}_5$ (24 elements).
- 15 elements of $\mathbf{Z}_2$ contain 5 distinct $\mathbf{Z}_2 \times \mathbf{Z}_2$ subgroups.
- Generators in 3-dimensional representations are,

$$H = \frac{1}{2}\begin{bmatrix} -1 & \mu_- & \mu_+ \\ \mu_- & \mu_+ & -1 \\ \mu_+ & -1 & \mu_- \end{bmatrix}; \ E = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}; \ F = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

here $\mu_\pm = (-1 \pm \sqrt{5})/2$

Case I: $S_\nu = Z_2$ and $T_l = Z_5$

$\theta \neq 0,\ \beta = 0$ $\qquad\qquad$ $\theta \neq 0,\ \beta \neq 0$

$$|U_{PMNS}| = \begin{bmatrix} 0.2181 & 0.9616 & 0.1644 \\ 0.6901 & 0.1940 & 0.6972 \\ 0.6901 & 0.1940 & 0.6972 \end{bmatrix} ; \begin{bmatrix} 0.2196 & 0.9603 & 0.1716 \\ 0.7118 & 0.1883 & 0.6766 \\ 0.6671 & 0.2055 & 0.7160 \end{bmatrix}$$

[Joshipura and NN, PRD 94 (2016) 036008]

- L.H.S. $|U_{PMNS}| \Rightarrow |U_{\mu 3}| = |U_{\tau 3}| \Rightarrow$ maximal θ_{23} and correct θ_{13} but not correct θ_{12}.
- R.H.S $|U_{PMNS}| \Rightarrow$ non-maximal θ_{23} and δ_{CP} with correct θ_{13}.
- Both of these are for a massless ν and a pair of degenerate νs.
- A small perturbation in the ν-mass matrix M_ν leads to correct mass ratio and mixing $\angle' s$
- Similar results also obtain for $T_l = Z_3$

$\mu - \tau$ Reflection Symmetry[7]

- This symmetry predicts,

$$\theta_{23} = \pi/4, \delta = \pm\pi/2, \rho, \sigma = 0, \pi/2 \; . \tag{8}$$

- Demanding the left and right-handed neutrino fields transform under $\mu - \tau$ reflection symmetry we get,

$$M_D = \begin{pmatrix} b & b^* \\ c & d \\ d^* & c^* \end{pmatrix} ; \quad M_R = \begin{pmatrix} m_{22} & m_{23} \\ m_{23} & m_{22}^* \end{pmatrix} \tag{9}$$

[NN, Xing, Zhang, EPJC (2018), arXiv:1801.09931]

- In type - I seesaw formalism, this leads us to,

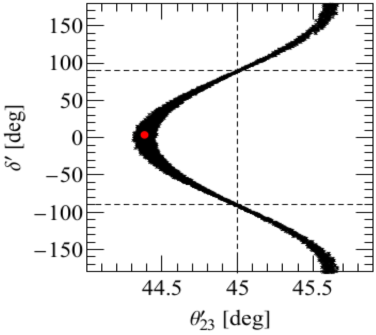
$$-M_\nu = M_D M_R^{-1} M_D^T = \begin{pmatrix} A & B & B^* \\ B & C & D \\ B^* & D & C^* \end{pmatrix} , \tag{10}$$

[7] Harrison and Scott, PLB547, 219 (2002)

Cont...

- Breaking of $\mu - \tau$ reflection symmetry,

$$M_D = \begin{pmatrix} b & b^*(1+\epsilon) \\ c & d \\ d^* & c^* \end{pmatrix} \quad (11)$$



[NN, Xing, Zhang, EPJC (2018), arXiv:1801.09931]

Ongoing works :

- Non-standard neutrino Interaction in modified ν2HDM, [with U.K. Dey, S. Sadhukhan]
- Testing of 'partial $\mu - \tau$ reflection' symmetry and its predictions with respect to DUNE, [with S. Goswami, A. Joshipura.]
- $\mu - \tau$ reflection symmetry and leptogenesis in littlest seesaw formalism, [with S. Zhou.]

Future plans:

- Implication of Gauge $L_\mu - L_\tau$ symmetry considering type-II seesaw formalism, [with S. Zhou.]
- Neutrino mixing patterns and leptogenesis considering A_4-flavor model, [with B. Karmakar.].
- Study of the effective Majorana neutrino mass in the $0\nu\beta\beta$ decay, [with Yu-feng Li.].
- Correlations of neutrino oscillation parameters from various flavor models and their testibility at neutrino oscillation experiments.
- Impact of new physics on the determination of neutrino oscillation parameters in neutrino oscillation experiments.

Summary and Conclusions

- We have introduced generalized "*hierarchy*-θ_{23}-δ_{CP}" degeneracy to observe different degenerate solutions.
- We discuss the combine effect of NOVA+T2K+ICAL@INO for the resolutions of various degeneracies.
- For DUNE, we emphasize on the importance of $\overline{\nu}$ run in resolving octant ambiguity and increasing CP sensitivity.
- We discuss the impact of digonal NSI on the determination of neutrino mass hierarchy considering DUNE.
- We introduce, $(\epsilon_{ee}, \delta_{cp}) \longrightarrow (-\epsilon_{ee} - 2, \delta'_{cp})$ generalized degeneracy in presence of NSI.

Cont...

- We also focus on the consequences of assuming Majorana neutrino mass matrix display flavor anti-symmetry property.
- In this respect, we have studied A_5 group and its various Abelian subgroups which lead to phenomenologically allowed neutrino mixing matrix.
- Demanding left as well as right-handed neutrino fields transform under $\mu - \tau$ reflection symmetry, we obtain low energy neutrino mass matrix which obey this symmetry.
- To investigate the low energy neutrino phenomenology, we study the breaking of such symmetry.

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Thank you