Recent development in non-standard neutrino interactions

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FOURTH BULLETIN

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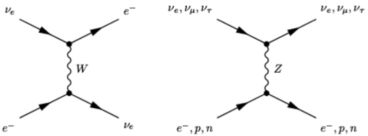
Neutrino interactions in matter:

- In Standard Model:



- Schrodinger equation:

$$i \frac{\mathrm{d}}{\mathrm{d}x} \Psi_\alpha = \mathcal{H}_\mathrm{F} \Psi_\alpha . \tag{9.54}$$

This equation has the structure of a Schrödinger equation with the effective Hamiltonian matrix $\mathcal{H}_\mathrm{F}$ in the flavor basis given by

$$\mathcal{H}_\mathrm{F} = \frac{1}{2E} \left(U \mathbb{M}^2 U^\dagger + \mathbb{A} \right) . \tag{9.55}$$

In the case of three-neutrino mixing, we have

$$\Psi_\alpha = \begin{pmatrix} \psi_{\alpha e} \\ \psi_{\alpha \mu} \\ \psi_{\alpha \tau} \end{pmatrix} , \qquad \mathbb{M}^2 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} , \qquad \mathbb{A} = \begin{pmatrix} A_\mathrm{CC} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} , \tag{9.56}$$

where

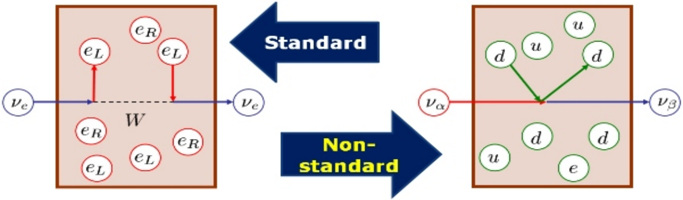
$$A_\mathrm{CC} \equiv 2 E V_\mathrm{CC} = 2\sqrt{2} E G_\mathrm{F} N_e . \tag{9.57}$$

Non-standard interactions

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

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

Wolfenstein, '78, Valle '87



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

- The Hamiltonian in presence of NSI:

$$H = \frac{1}{2E}\left[U \text{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U^\dagger + \text{diag}(A,0,0) + A\epsilon_{\alpha\beta}\right]$$

- Model-independent bounds:

$|\varepsilon_{ee}| < 4.2$, $|\varepsilon_{e\mu}|, |\varepsilon_{\mu\tau}| < 0.33$, $|\varepsilon_{e\tau}| < 3.0$, $|\varepsilon_{\mu\mu}| < 0.07$, $|\varepsilon_{\tau\tau}| < 21$

[Biggio, Blennow, Martinez 0907.0097, Ohlsson 1209.2710]

- Recent status report: Dev, et. al., 1907.00991

Three-flavor ν-oscillation parameters:

- Six parameters: 3-mixing angles (θ_{12}, θ_{23}, θ_{13}), 2 mass-squared differences (Δm^2_{21}, Δm^2_{31}) and a CP phase δ.

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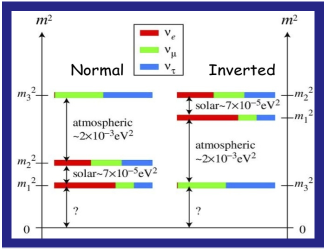

- The sign of Δm^2_{31} i.e.
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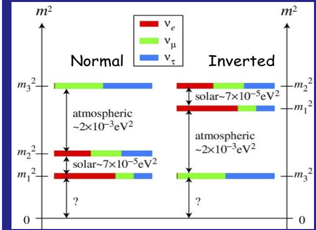

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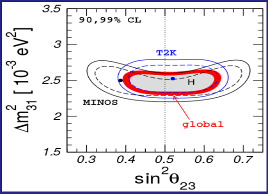
- **The octant of θ_{23} i.e.**
  $\theta_{23} > 45^\circ \Rightarrow$ Higher Octant (HO) or
  $\theta_{23} < 45^\circ \Rightarrow$ Lower Octant (LO).



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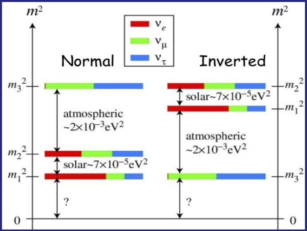

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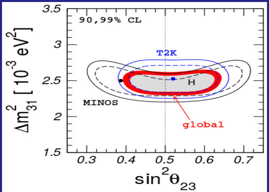
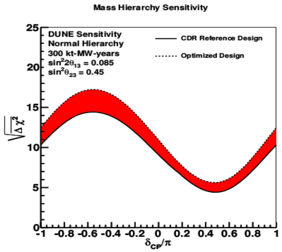


- *$\delta \neq 0^o, \pm 180^o \Rightarrow$ CP violation.*

Neutrino Mass Hierarchy:

- Focus is on neutrino mass hierarchy.
- Deep Underground Neutrino Experiment (DUNE)(L=1300 km) will be able to resolve mass hierarchy.

[Acciarri (Fermilab) et al. 1512.06148]



- "**New-physics**" like NSI can impact mass hierarchy determination for DUNE.

  Liao, Marfatia, Whisnant 1601.00927, Coloma, Schwetz 1604.05772, Masud, Mehta 1606.05662, Dutta, Ghoshal, Roy 1609.07094, Deepthi, Goswami, **NN** 1612.00784, Flores, Garces, Miranda 1806.07951

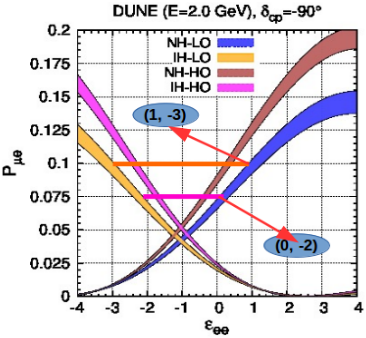
Cont...

- Generalized mass hierarchy degeneracy:

$$\Delta m^2_{31} \to -\Delta m^2_{32}, \quad \sin\theta_{12} \to \cos\theta_{12}, \quad \delta \to \pi - \delta,$$
$$\epsilon_{ee} \to -\epsilon_{ee} - 2, \quad \epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha\beta \neq ee)$$

Coloma, Schwetz 1604.05772

- For non-zero ϵ_{ee} (for $\delta_{CP} = -90^\circ$),

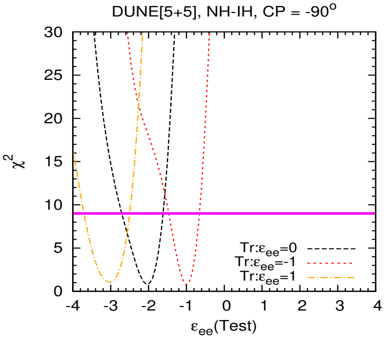


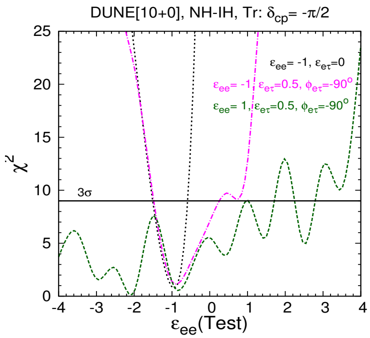
- $\epsilon_{ee} \to -\epsilon_{ee} - 2 \Rightarrow$ WH-RO-RCP.
- For $\epsilon_{ee} > 2 \Rightarrow$ no WH-RO-RCP solution.
- $\epsilon_{ee} = -1 \Rightarrow$ *"region of confusion"* since same ϵ_{ee} for both NH & IH.

  Deepthi, Goswami, NN PRD'96(2017)

Cont...

At Chi-square level:





$$\epsilon_{ee} \to -\epsilon_{ee} - 2$$

Deepthi, Goswami, NN PRD'96(2017)

Cont...

How to resolve the degeneracy?

How to reduce # of NSIs?

$$\begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}$$

Cont...

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Constrain NSI parameter space

and/or,

Model based analysis

Cont...

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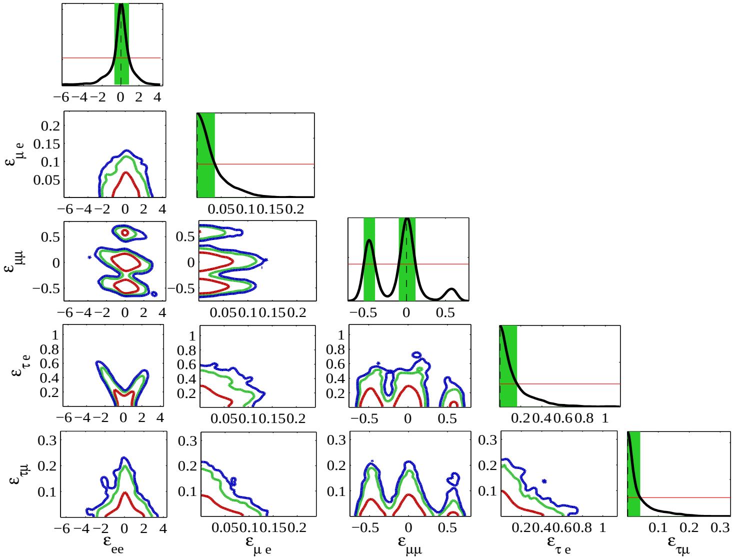
Constrain NSI parameter space

and/or,

Model based analysis

(*reduces # of free parameters*)

DUNE's constraints:



Coloma, JHEP03(2016)016

Global-fit:

OSC		
	LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	[−0.020, +0.456]	⊕[−1.192, −0.802]
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	[−0.005, +0.130]	[−0.152, +0.130]
$\varepsilon^u_{e\mu}$	[−0.060, +0.049]	[−0.060, +0.067]
$\varepsilon^u_{e\tau}$	[−0.292, +0.119]	[−0.292, +0.336]
$\varepsilon^u_{\mu\tau}$	[−0.013, +0.010]	[−0.013, +0.014]
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	[−0.027, +0.474]	⊕[−1.232, −1.111]
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	[−0.005, +0.095]	[−0.013, +0.095]
$\varepsilon^d_{e\mu}$	[−0.061, +0.049]	[−0.061, +0.073]
$\varepsilon^d_{e\tau}$	[−0.247, +0.119]	[−0.247, +0.119]
$\varepsilon^d_{\mu\tau}$	[−0.012, +0.009]	[−0.012, +0.009]
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	[−0.041, +1.312]	⊕[−3.328, −1.958]
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	[−0.015, +0.426]	[−0.424, +0.426]
$\varepsilon^p_{e\mu}$	[−0.178, +0.147]	[−0.178, +0.178]
$\varepsilon^p_{e\tau}$	[−0.954, +0.356]	[−0.954, +0.949]
$\varepsilon^p_{\mu\tau}$	[−0.035, +0.027]	[−0.035, +0.035]

+COHERENT		
	LMA	LMA ⊕ LMA-D
ε^u_{ee}	[−0.008, +0.618]	[−0.008, +0.618]
$\varepsilon^u_{\mu\mu}$	[−0.111, +0.402]	[−0.111, +0.402]
$\varepsilon^u_{\tau\tau}$	[−0.110, +0.404]	[−0.110, +0.404]
$\varepsilon^u_{e\mu}$	[−0.060, +0.049]	[−0.060, +0.049]
$\varepsilon^u_{e\tau}$	[−0.248, +0.116]	[−0.248, +0.116]
$\varepsilon^u_{\mu\tau}$	[−0.012, +0.009]	[−0.012, +0.009]
ε^d_{ee}	[−0.012, +0.565]	[−0.012, +0.565]
$\varepsilon^d_{\mu\mu}$	[−0.103, +0.361]	[−0.103, +0.361]
$\varepsilon^d_{\tau\tau}$	[−0.102, +0.361]	[−0.102, +0.361]
$\varepsilon^d_{e\mu}$	[−0.058, +0.049]	[−0.058, +0.049]
$\varepsilon^d_{e\tau}$	[−0.206, +0.110]	[−0.206, +0.110]
$\varepsilon^d_{\mu\tau}$	[−0.011, +0.009]	[−0.011, +0.009]
ε^p_{ee}	[−0.010, +2.039]	[−0.010, +2.039]
$\varepsilon^p_{\mu\mu}$	[−0.364, +1.387]	[−0.364, +1.387]
$\varepsilon^p_{\tau\tau}$	[−0.350, +1.400]	[−0.350, +1.400]
$\varepsilon^p_{e\mu}$	[−0.179, +0.146]	[−0.179, +0.146]
$\varepsilon^p_{e\tau}$	[−0.860, +0.350]	[−0.860, +0.350]
$\varepsilon^p_{\mu\tau}$	[−0.035, +0.028]	[−0.035, +0.028]

Esteban, Gonzalez-Garcia, Maltoni, Martinez-Soler, Salvado, JHEP08(2018)180

For details about COHERENT, see Talk by L. Flores

NSIs from models

- NSIs:

$$\sim G_F \epsilon_{\alpha\beta}^{fC} (\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{f} \gamma_\rho P_C f)$$

$$\epsilon \propto \frac{1}{G_F} \frac{g_X^2}{m_X^2}$$

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Two scenarios: $\epsilon \sim 1$

- $m_X \sim 10$ MeV $\Rightarrow g_X \sim 10^{-5} - 10^{-4}$ (light mediator)
  Scattering experiments play a crucial role in this energy range

  Denton, Farzan, Shoemaker 1804.03660, Heeck, Lindner, Rodejohann, Vogl 1812.04067, Han, Liao, Liu, Marfatia 1910.03272, Babu, Chauhanb, Dev 1912.13488, Flores, **NN**, Peinado 2002.12342.

  Also see Talk by L. Flores

- $m_X \sim 100$ GeV $\Rightarrow g_X \sim 1$ (heavy mediator)

  Forero, Huang 1608.04719, Dey, **NN**, Sadhukhan, 1804.05808, Liao, **NN**, Wang, Zhou 1911.00213

NSIs in radiative models: Babu, Dev, Jana, Thapaa 1907.09498

NSIs in ν2HDM

- In modified ν2HDM:

$$\mathcal{L}^{m}_{\nu 2\text{HDM}} \supset y_e \bar{L}_e \Phi_2 e_R + y_\nu \bar{L}_e \tilde{\Phi}_2 \nu_R + \text{h.c.}$$

- The effective Lagrnagian:

Φ_2, e_R, ν_R are odd under global $U(1)$

$$\mathcal{L}_{\text{eff}} \supset \frac{y_e^2}{4m^2_{H^\pm}} (\bar{\nu}_{eL}\gamma^\rho \nu_{eL}) \, (\bar{e}_R \gamma_\rho e_R) + \text{h.c.}$$

- Comparing $\mathcal{L}_{\text{eff}}$ with $\mathcal{L}_{\text{NSI}} \supset 2\sqrt{2} G_F \epsilon^{fC}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{f}\gamma_\rho P_C f) \Rightarrow$

$$\epsilon_{ee} = \frac{1}{2\sqrt{2}G_F} \frac{y_e^2}{4m^2_{H^\pm}}$$

- Other possible terms:

$$\mathcal{L}^{m}_{\nu 2\text{HDM}} \supset y_1 \bar{L}_\mu \Phi_2 e_R + y_2 \bar{L}_\tau \Phi_2 e_R + \textbf{h.c.}$$

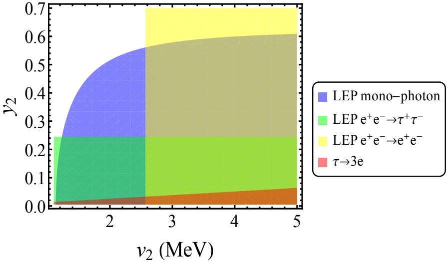
[Dey, **NN**, Sadhukhan, PRD98 (2018)]

Cont...

- Other NSIs:

$$\epsilon_{e\mu(\tau)} = \frac{1}{2\sqrt{2}G_F}\frac{y_e y_{1(2)}}{4m^2_{H^\pm}}, \quad \epsilon_{\mu\mu(\tau)} = \frac{1}{2\sqrt{2}G_F}\frac{y_1 y_{1(2)}}{4m^2_{H^\pm}}$$

- LFV decay $\mu \to 3e$ forces $y_1 \sim 10^{-6}$
- LEP constraints:

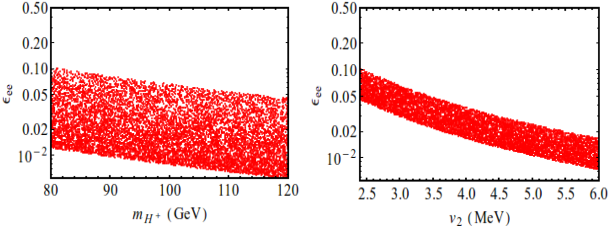


- Sizable NSIs in this model: $\epsilon_{ee}, \epsilon_{e\tau}$

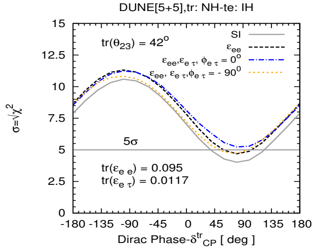
[Dey, **NN**, Sadhukhan, PRD98 (2018)]

Cont..

- Allowed range of ϵ_{ee} in $\nu 2HDM$:



- Also, $v_2 = 2.5$ MeV, $y_2 = 0.035 \Rightarrow \epsilon_{e\tau} \sim 0.01$
- **Mass hierarchy:** almost 5σ sensitivity has been observed for $\delta \in (-\pi, \pi)$



[Dey, **NN**, Sadhukhan, PRD98 (2018)]

NSI at IceCube (IC):

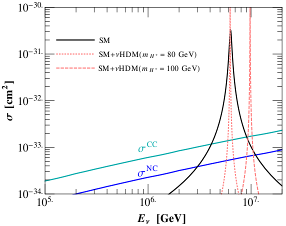
- To test the possibility of charged scalar ($\nu 2HDM$) resonances with NSIs
- In SM, IC is sensitive to Glashow resonance: $\overline{\nu}_e e^- \to W^- \to$ anything
- The resonance takes place at $E_\nu = m_W^2 / m_e = 6.3$ PeV
- Cross-section:

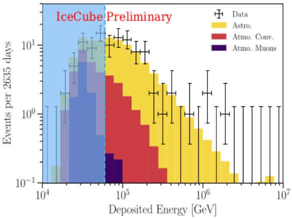
$$\sigma_{\rm Glashow}(s) = 24\pi\, \Gamma_W^2\, {\rm BR}(W^- \to \bar{\nu}_e e^-){\rm BR}(W^- \to {\rm had}) \frac{s/m_W^2}{(s - m_W^2)^2 + (m_W \Gamma_W)^2}$$

- New resonance:

$$\sigma_{\nu{\rm HDM}}(s) = 8\pi\, \Gamma_{H^-}^2\, {\rm BR}(H^- \to \bar{\nu}_\alpha e^-){\rm BR}(H^- \to {\rm all}) \frac{s/m_{H^-}^2}{(s - m_{H^-}^2)^2 + (m_{H^-} \Gamma_{H^-})^2}$$

[Babu, Dev, Jana, Sui PRL124(2020)]





[IceCube Collab. 1907.11266]

- Analyze $(y - m_{H^+})$ space for a given NSI to test IC sensitivity

[Dey, **NN**, Sadhukhan, (*in prep.*)]

NSIs from $\mu - \tau$ reflection symmetry:

Originally proposed by Harrison & Scott, PLB547 (2002)

- M_ν is unchanged under:

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

where,

$$M_\nu = \begin{pmatrix} D & A & A^* \\ A & B & C \\ A^* & C & B^* \end{pmatrix} \ \& \ M_\nu M_\nu^\dagger = \begin{pmatrix} z & w & w^* \\ w^* & x & y \\ w & y^* & x \end{pmatrix} .$$

where $\mathrm{C, D, x, z} \in \mathbb{R}$ & $\mathrm{A, B, w, y} \in \mathbb{C}$

- M_ν can be diagonalized by

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

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- Predictions: $\theta_{23} = \pi/4, \delta = \pm\pi/2$ **for** $\theta_{13} \neq 0$

Cont...

- NSI matrix:

$$\epsilon_{\alpha\beta} = \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} e^{i\phi_{e\mu}} & \epsilon_{e\tau} e^{i\phi_{e\tau}} \\ \epsilon_{e\mu} e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau} e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau} e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix},$$

- $\mu - \tau$ reflection symmetry helps to reduce # of parameters
- Flavor group $S_4 \times Z_4$ has been used

Fields	L	e_R	μ_R	τ_R	H	η	ϕ^+	φ	χ	ζ	ξ
$SU(2)_L$	**2**	**1**	**1**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	$-\frac{1}{2}$	-1	-1	-1	$+\frac{1}{2}$	$+\frac{1}{2}$	$+1$	0	0	0	0
S_4	**3**	**1**	**1**	**1**$'$	**1**	**3**	**1**	**3**$'$	**3**	**2**	**1**
Z_4	1	i	-1	$-i$	1	$-i$	$-i$	i	1	1	1
Z_2	$+$	$-$	$+$	$-$	$+$	$-$	$-$	$-$	$+$	$+$	$+$

- This leads:

$$M_\nu M_\nu^\dagger = \begin{pmatrix} \mathbf{a} & \mathbf{b} & \mathbf{b}^* \\ \mathbf{b}^* & \mathbf{c} & \mathbf{d} \\ \mathbf{b} & \mathbf{d}^* & \mathbf{c} \end{pmatrix}, \quad V = A \begin{pmatrix} 1+\tilde{\epsilon}_{ee} & \epsilon_{e\mu} & \epsilon_{e\mu}^* \\ \epsilon_{e\mu}^* & 0 & \epsilon_{\mu\tau} \\ \epsilon_{e\mu} & \epsilon_{\mu\tau}^* & 0 \end{pmatrix}. \quad (2)$$

[Liao, **NN**, Wang, Zhou, PRD101 (2020)]

Wrap-up Comments:

- Importance of NSI for the determination of neutrino mass hierarchy has been discussed
- Our main focus was to study NSI in a model (in)dependent way
- $\nu 2HDM$ model has been presented, which allows only two sizable NSIs ϵ_{ee} and $\epsilon_{e\tau}$
- We discuss $\nu 2HDM$ based NSI for DUNE as well as for IceCube
- Finally, NSIs within the formalism of $\mu - \tau$ reflection symmetry has also been presented.

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thank you