Neutrino Non-standard interactions

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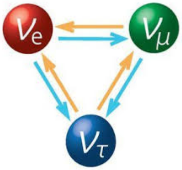
Neutrino Oscillations:

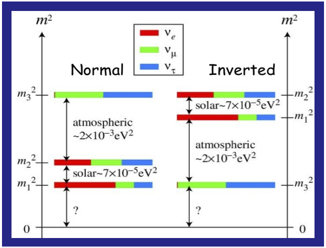


Three flavor neutrino oscillation involves six-oscillation parameters

* **The atmospheric mass squared difference:** $|\Delta m^2_{31}|$
* **The solar mass squared difference:** Δm^2_{21}
* **The atmospheric mixing angle:** θ_{23}
* **The reactor mixing angle:** θ_{13}
* **The solar mixing angle:** θ_{12}
* **The CP-violating phase:** δ

Unknowns

- Mass Hierarchy



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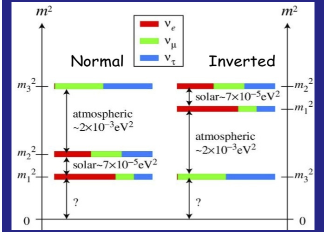

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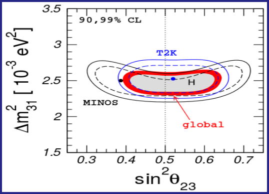
$\theta_{23} < 45^\circ \Rightarrow$ Lower Octant (LO).



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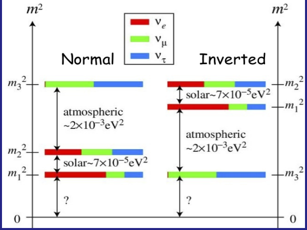

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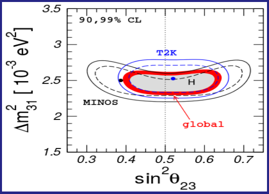

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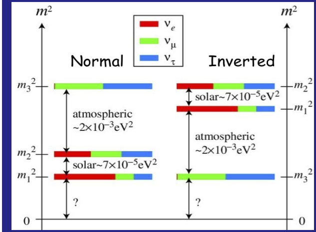

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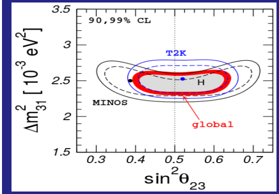
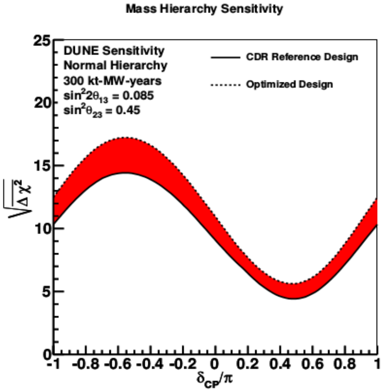
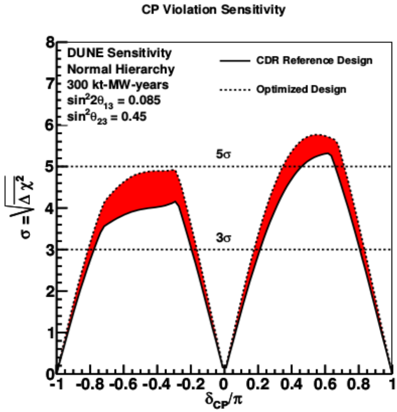


- *$\delta \neq 0^o, \pm 180^o \Rightarrow$ CP violation.*
- **Goals: T2K, NOνA (ongoing), DUNE, JUNO, T2HK, ESSnuSB (upcoming), etc... experiments.**

DUNE's sensitivity

- Mass hierarchy sensitivity (left panel), CPV-sensitivity (right panel).





DUNE CDR, 1512.06147

Obstacles

Various **'new-physics'** can spoil the determination of these unknowns.

'New-physics':

- **non-standard interactions (NSIs),**
- non-unitarity,
- sterile neutrino,
- large extra-dimension, etc...

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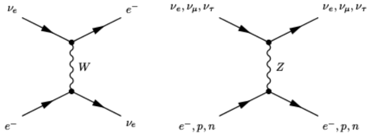
Focus will be on NSIs

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

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

Credits: Giunti and Kim

Non-standard interactions:

- **The effective Lagrangian:**

$$\mathcal{L}^{eff} = \mathcal{L}_{SM} + \underbrace{\frac{1}{\Lambda}\delta\mathcal{L}^{d=5}} + \underbrace{\frac{1}{\Lambda^2}\delta\mathcal{L}^{d=6}} + \ldots$$

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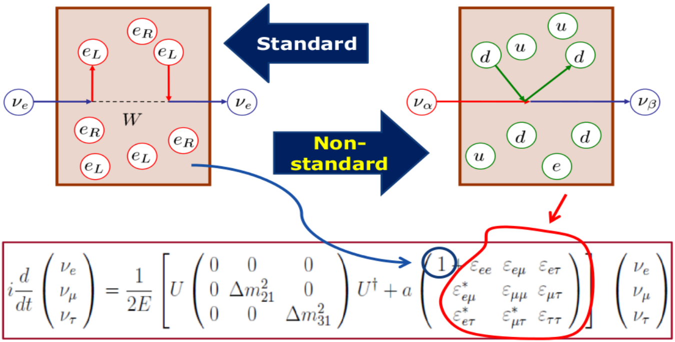
- The effective dimension-6 term: $\supset (\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{f}\gamma_\rho P_C f')2\sqrt{2}G_F \epsilon^{fC}_{\alpha\beta} + \textbf{h.c.}$

[Wolfenstein, '78, Valle '87]

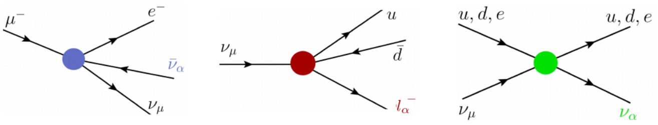


Credits: T. Ohlsson, MPIK'09

Cont...

- Dimension-6 term:

NSI affecting production | NSI affecting detection | NSI affecting propagation



$\varepsilon^{e\mu,P}_{\mu\alpha} \left(\bar{e}\gamma^\rho P \mu\right)\left(\bar{\nu}_\mu \gamma_\rho P_L \nu_\alpha\right)$ $\quad \varepsilon^{ud,P}_{\mu\alpha} \left(\bar{d}\gamma^\rho P u\right)\left(\bar{\nu}_\mu \gamma_\rho P_L l_\alpha\right)$ $\quad \varepsilon^{f,P}_{\mu\alpha} \left(\bar{f}\gamma^\rho P f\right)\left(\bar{\nu}_\mu \gamma_\rho P_L \nu_\alpha\right)$

Credits: P. Coloma, Fermilab'17

- Model independent bounds:

Source/detector **Matter**

$$|\varepsilon^{s/d}_{\alpha\beta}| < \begin{bmatrix} 0.041 & 0.025 & 0.041 \\ 0.026 & 0.078 & 0.013 \\ 0.12 & 0.018 & 0.13 \end{bmatrix} \; ; \; |\varepsilon^{m}_{\alpha\beta}| < \begin{bmatrix} 4.2 & 0.33 & 3.0 \\ & 0.068 & 0.33 \\ & & 21 \end{bmatrix}$$

[Davidson, Pea-Garay, Rius, Santamaria, JHEP03 (2003) 011, Biggio, Blennow, Fernandez-Martinez, JHEP08 (2009) 090, Ohlsson, RPP76 (2013) 044201]

Cont...

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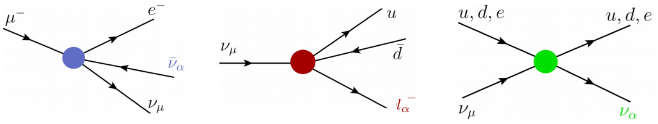

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Focus on matter-NSIs

An effective 2×2 model:

- The Hamiltonian:

$$\begin{pmatrix} -\frac{\Delta m^2}{4E}\cos 2\theta + \sqrt{2}\, G_F N_e & \frac{\Delta m^2}{4E}\sin 2\theta \\ \frac{\Delta m^2}{4E}\sin 2\theta & \frac{\Delta m^2}{4E}\cos 2\theta \end{pmatrix} + \sqrt{2} G_F N_d \begin{pmatrix} 0 & \varepsilon \\ \varepsilon & \varepsilon' \end{pmatrix}$$

- The survival probability for solar neutrinos:

$$P_{ee} = \frac{1}{2}\left[1 + \cos 2\theta \cos 2\theta_m\right]; \qquad [\mathit{Parke}, \mathit{PRL}57, 1275(1986)]$$

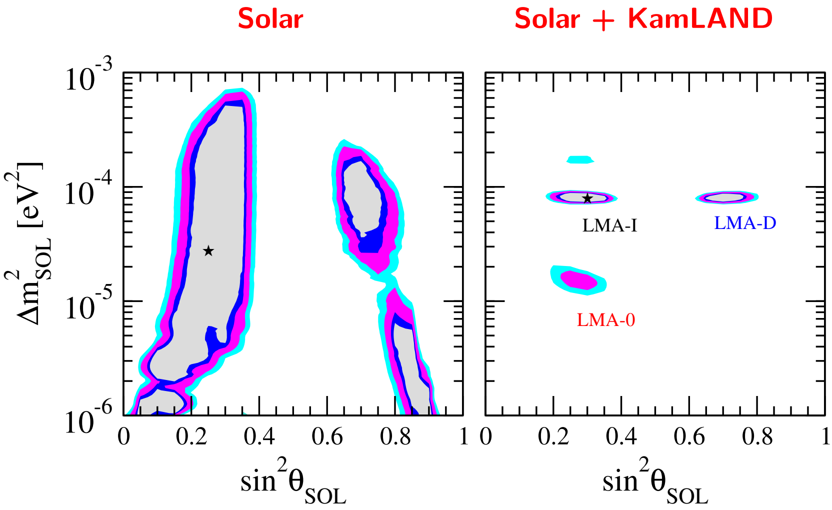
- The mixing angle in matter is given by

$$\cos 2\theta_m = \frac{\Delta m^2 \cos 2\theta - 2\sqrt{2}\, E G_F (N_e - \varepsilon' \mathbf{N_d})}{[\Delta m^2]^2_{matter}}$$

- To explain solar neutrinos deficit, $P_{ee} < 0.5$ (required) and $\cos 2\theta < 0$ (not allowed) for $\varepsilon' = 0$
- **Note: Thanks to $\varepsilon' \neq 0$, one can have $P_{ee} < 0.5$ for $\cos 2\theta < 0$ i.e., $\theta > \frac{\pi}{4}$**
- **Thus, solar mixing angle can lie in the HO, also called as 'LMA-D' solution**

[Miranda, Tortola, Valle, JHEP10 (2006) 008]

Cont...



[Miranda, Tortola, Valle, JHEP10 (2006) 008]

Three-flavor formalism:

Generalized mass hierarchy degeneracy

In the SM, the matter potential can break the sign degeneracy:

$$H = H_0 + H_{\rm mat}$$

However, in presence of NSI:

$$H_{\rm mat} = \sqrt{2} G_F N_e(x) \begin{pmatrix} 1 + (\epsilon_{ee} - \epsilon_{\mu\mu}) & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & (\epsilon_{\tau\tau} - \epsilon_{\mu\mu}) \end{pmatrix}$$

$$\Delta m^2_{31} \to -\Delta m^2_{31} + \Delta m^2_{21}$$
$$\sin\theta_{12} \leftrightarrow \cos\theta_{12}$$
$$\delta \to \pi - \delta$$

$$\epsilon_{ee} - \epsilon_{\mu\mu} \to -(\epsilon_{ee} - \epsilon_{\mu\mu}) - 2$$
$$\epsilon_{\tau\tau} - \epsilon_{\mu\mu} \to -(\epsilon_{\tau\tau} - \epsilon_{\mu\mu})$$
$$\epsilon_{\alpha\beta} \to -\epsilon^*_{\alpha\beta} \quad (\alpha \neq \beta)$$

$$H \to -H^*$$

The LMA-dark solution reappears here

PC and Schwetz, 1604.05772
Bakhti and Farzan, 1403.0744

Credits: P. Coloma, Fermilab'17

[Gonzalez-Garcia, Maltoni, Salvado, JHEP05 (2011) 075]

Oscillation probability in presence of NSIs:

- The Hamiltonian in the flavor basis:

$$H = \frac{1}{2E}\left[U\mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U^\dagger + A\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu}e^{i\phi_{e\mu}} & \epsilon_{e\tau}e^{i\phi_{e\tau}} \\ \epsilon_{e\mu}e^{-i\phi_{e\mu}} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau}e^{i\phi_{\mu\tau}} \\ \epsilon_{e\tau}e^{-i\phi_{e\tau}} & \epsilon_{\mu\tau}e^{-i\phi_{\mu\tau}} & \epsilon_{\tau\tau} \end{pmatrix}\right],$$

  where U is the PMNS mixing matrix

- Assumptions: Small parameters (e.g., s_{13}, $r = \Delta m^2_{21}/\Delta m^2_{31}$, and $\epsilon_{\alpha\beta}$)
- The appearance channel probability:

$$\begin{aligned} P_{\mu e} &= x^2 f^2 + 2xyfg\cos(\Delta + \delta_{CP}) + y^2 g^2 + \mathcal{O}(\epsilon_{e\mu}) \\ &+ 4\hat{A}\epsilon_{e\tau}s_{23}c_{23}\left\{xf[f\cos(\phi_{e\tau}+\delta) - g\cos(\Delta+\delta+\phi_{e\tau})] - yg[g\cos\phi_{e\tau} - f\cos(\Delta-\phi_{e\tau})]\right\} \\ &+ 4\hat{A}^2 g^2 c^2_{23}|s_{23}\epsilon_{e\tau}|^2 + 4\hat{A}^2 f^2 s^2_{23}|c_{23}\epsilon_{e\tau}|^2 - 8\hat{A}^2 fgs^2_{23}c^2_{23}\epsilon^2_{e\tau}\cos\Delta + \mathcal{O}(s^2_{13}\epsilon_{e\tau}, s_{13}\epsilon^2_{e\tau}, \epsilon^3_{e\tau}), \end{aligned}$$

  where,

$$x = 2s_{13}s_{23},\ \ y = rc_{23}\sin 2\theta_{12},\ \ \Delta = \frac{\Delta m^2_{31}L}{4E},\ \ \hat{A} = \frac{A}{\Delta m^2_{31}},$$

$$f, \bar{f} = \frac{\sin[\Delta(1 \mp \hat{A}(1+\epsilon_{ee}))]}{(1 \mp \hat{A}(1+\epsilon_{ee}))},\ \ g = \frac{\sin[\hat{A}(1+\epsilon_{ee})\Delta]}{\hat{A}(1+\epsilon_{ee})}$$

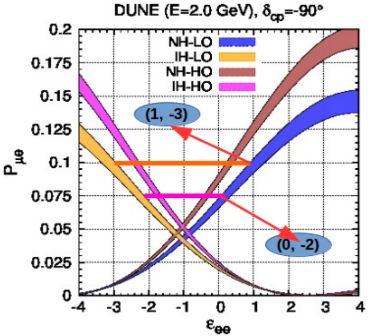
Kikuchi, Minakata, Uchinami, JHEP03 (2009) 114, Liao, Marfatia, Whisnant, PRD93, 093016 (2016)

At DUNE:

- $P_{\mu e}$ for $\epsilon_{ee} = -1, \epsilon_{\alpha\beta} = 0$:

$$P_{\mu e} = \underbrace{x^2 f^2 + 2xyg \sin\Delta\cos(\Delta + \delta_{CP}) + y^2 g^2}_{Standard\ \ Matter}$$

- **For** $\epsilon_{ee} \neq 0$, **and** $\delta_{CP} = -90^\circ$,



$\rightsquigarrow$

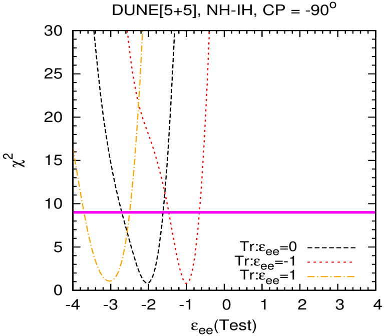
- $\epsilon_{ee} \to -\epsilon_{ee} - 2 \Rightarrow$ WH-RO-RCP.
- For $\epsilon_{ee} > 2 \Rightarrow$ no WH-RO-RCP solution.
- $\epsilon_{ee} = -1 \Rightarrow$ *"region of confusion"* since same ϵ_{ee} for both NH & IH.

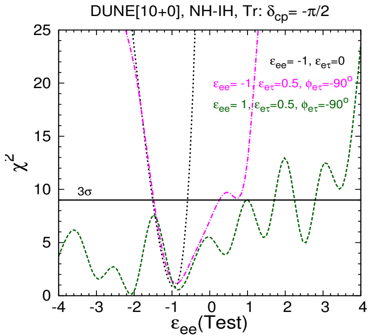
  [Deepthi, Goswami, NN PRD96(2017)]

[Liao, Marfatia, Whisnant 1601.00927, Coloma, Schwetz 1604.05772, Masud, Mehta 1606.05662, Dutta, Ghoshal, Roy 1609.07094, Flores, Garces, Miranda 1806.07951]

Cont...

At Chi-square level:



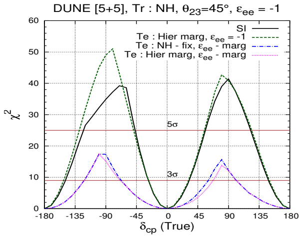


$$\epsilon_{ee} \rightarrow -\epsilon_{ee} - 2$$

Deepthi, Goswami, NN PRD96(2017)

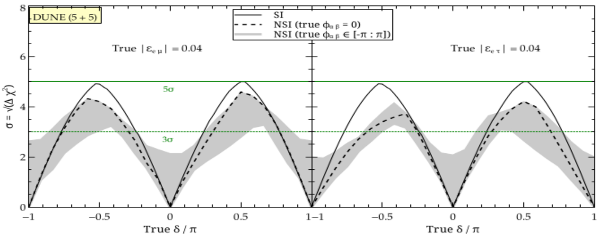
CPV sensitivity at DUNE

- For $\epsilon_{ee} \neq 0$.



Deepthi, Goswami, NN NPB936 (2018)

- For $\epsilon_{\alpha\beta} \neq 0$.



Masud, Chatterjee, Mehta, J. Phys. G: Nucl. Part. Phys. 43 (2016)

Cont...

How to resolve the degeneracy?

How to reduce # of NSIs?

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

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Constrain NSIs parameter space

and/or,

Model based analysis

Cont...

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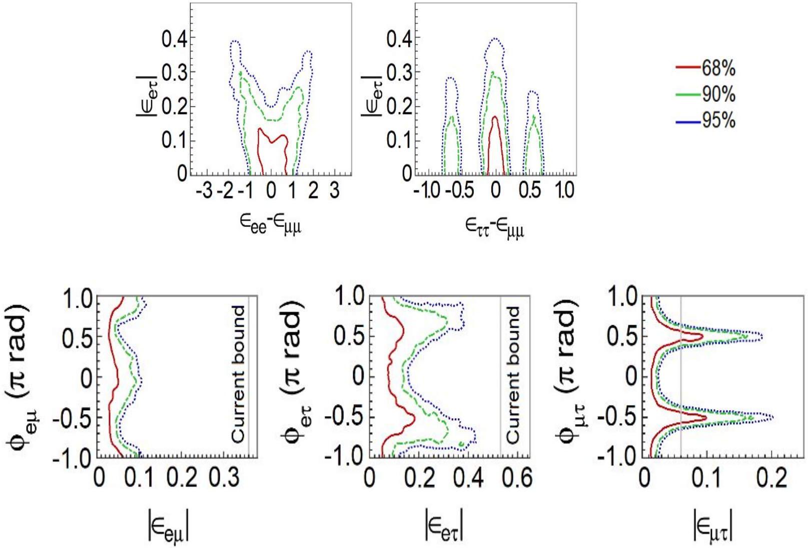
Constrain NSIs parameter space

and/or,

Model based analysis

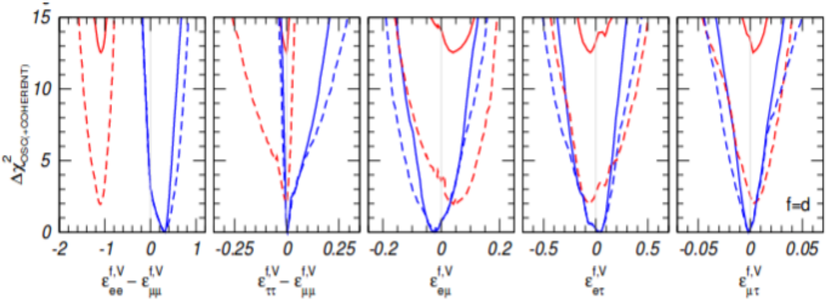
(*reduces # of free parameters*)

DUNE's sensitivity:



DUNE Collaboration: 2008.12769 [hep-ex]

Combining Oscillation+Scattering data



- Here $\theta_{12} < \pi/4$, (blue) $\theta_{12} > \pi/4$ (red), oscillation data (dashed), and oscillation+COHERENT (solid) curves.

Colama, Gonzalez-Garcia, Maltoni, Schwetz, PRD'96(2017)

Global-fit:

	OSC			+COHERENT	
	LMA	LMA ⊕ LMA-D		LMA	LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	[−0.020, +0.456]	⊕[−1.192, −0.802]	ε^u_{ee}	[−0.008, +0.618]	[−0.008, +0.618]
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	[−0.005, +0.130]	[−0.152, +0.130]	$\varepsilon^u_{\mu\mu}$	[−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, +0.067]	$\varepsilon^u_{e\mu}$	[−0.060, +0.049]	[−0.060, +0.049]
$\varepsilon^u_{e\tau}$	[−0.292, +0.119]	[−0.292, +0.336]	$\varepsilon^u_{e\tau}$	[−0.248, +0.116]	[−0.248, +0.116]
$\varepsilon^u_{\mu\tau}$	[−0.013, +0.010]	[−0.013, +0.014]	$\varepsilon^u_{\mu\tau}$	[−0.012, +0.009]	[−0.012, +0.009]
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	[−0.027, +0.474]	⊕[−1.232, −1.111]	ε^d_{ee}	[−0.012, +0.565]	[−0.012, +0.565]
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	[−0.005, +0.095]	[−0.013, +0.095]	$\varepsilon^d_{\mu\mu}$	[−0.103, +0.361]	[−0.103, +0.361]
			$\varepsilon^d_{\tau\tau}$	[−0.102, +0.361]	[−0.102, +0.361]
$\varepsilon^d_{e\mu}$	[−0.061, +0.049]	[−0.061, +0.073]	$\varepsilon^d_{e\mu}$	[−0.058, +0.049]	[−0.058, +0.049]
$\varepsilon^d_{e\tau}$	[−0.247, +0.119]	[−0.247, +0.119]	$\varepsilon^d_{e\tau}$	[−0.206, +0.110]	[−0.206, +0.110]
$\varepsilon^d_{\mu\tau}$	[−0.012, +0.009]	[−0.012, +0.009]	$\varepsilon^d_{\mu\tau}$	[−0.011, +0.009]	[−0.011, +0.009]
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	[−0.041, +1.312]	⊕[−3.328, −1.958]	ε^p_{ee}	[−0.010, +2.039]	[−0.010, +2.039]
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	[−0.015, +0.426]	[−0.424, +0.426]	$\varepsilon^p_{\mu\mu}$	[−0.364, +1.387]	[−0.364, +1.387]
			$\varepsilon^p_{\tau\tau}$	[−0.350, +1.400]	[−0.350, +1.400]
$\varepsilon^p_{e\mu}$	[−0.178, +0.147]	[−0.178, +0.178]	$\varepsilon^p_{e\mu}$	[−0.179, +0.146]	[−0.179, +0.146]
$\varepsilon^p_{e\tau}$	[−0.954, +0.356]	[−0.954, +0.949]	$\varepsilon^p_{e\tau}$	[−0.860, +0.350]	[−0.860, +0.350]
$\varepsilon^p_{\mu\tau}$	[−0.035, +0.027]	[−0.035, +0.035]	$\varepsilon^p_{\mu\tau}$	[−0.035, +0.028]	[−0.035, +0.028]

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

NSIs from models

- NSIs:

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

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

NSIs from models

- NSIs:

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

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

Two scenarios: $\epsilon \sim 1$

- $m_X \sim 10$ MeV $\Rightarrow g_X \sim 10^{-5} - 10^{-4}$ (light mediator)

  [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]

- $m_X \sim 100$ 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

Light mediator

- Adopted Z' mediated $U(1)'$ extended gauge model to study NSIs
  [Barranco, Miranda, Rashba: 0508299, Scholberg:: 0511042, Denton, Farzan, Shoemaker: 1804.03660, Heeck, Lindner, Rodejohann, Vogl: 1812.04067, Han, Liao, Liu, Marfatia: 1910.03272]
- An effective Lagrangian for the neutrino-fermion interactions with the Z' boson,

$$\mathcal{L}_{\rm eff} = -\frac{g'^2}{Q^2 + M_{Z'}^2}\left[\sum_\alpha x_\alpha \bar{\nu}_\alpha \gamma^\mu P_L \nu_\alpha\right]\left[\sum_f x_f \bar{f}\gamma_\mu f\right]$$

- Comparing with $\mathcal{L}^{\rm NC} \supset \epsilon^{fC}_{\alpha\beta}(\overline{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_L f)$ leads to

$$\varepsilon^{fV}_{\alpha\alpha} = \frac{g'^2 x_\alpha x_f}{\sqrt{2} G_F (Q^2 + M_{Z'}^2)}$$

- Considered model $U(1)' = U(1)_{B-2L_\alpha - L_\beta}$ and charges are:

	L_e	L_μ	L_τ	l_e	l_μ	l_τ	N_1	N_2	N_3	H	ϕ_1	ϕ_2
$SU(2)_L$	2	2	2	1	1	1	1	1	1	2	1	1
$U(1)'$	x_e	x_μ	x_τ	x_e	x_μ	x_τ	x_e	x_μ	x_τ	0	1	2

with $x_\alpha = 0, -1, -2$ for $\alpha = e, \mu, \tau$

Flores, NN, Peinado, JHEP 06 (2020) 045

- **Possible NSIs are** $\epsilon_{ee}, \epsilon_{\mu\mu}, \epsilon_{\tau\tau}$

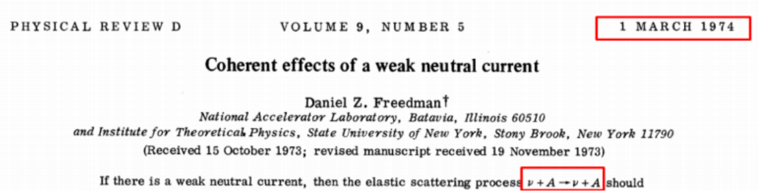
COHERENT collaboration

- It measures CEνNS (Coherent Elastic Neutrino-Nucleus Scattering) processes
- Uses the high-quality pion-decay-at-rest neutrino source at the Spallation Neutron Source (SNS) in Oak Ridge National Laboratory (ORNL), Tennessee.

$Internal - Wiki$

- Source to detectors distance are $\sim 20 - 30$ m and detector masses varies $\sim 10 - 2000$ kg

CEνNS:



PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

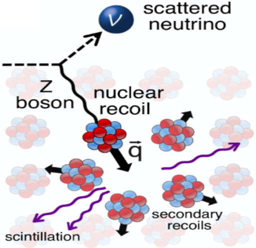
Daniel Z. Freedman†

National Accelerator Laboratory, Batavia, Illinois 60510

and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\boxed{\nu + A \to \nu + A}$ should



$$E_\nu \lesssim 50 \text{ MeV}$$
$$qR \ll 1$$

- Primary goals: to study coherent elastic neutrino-nucleus scattering, weak mixing angle measurements, **NSIs**
- Subsequent goals: neutrino magnetic moment searches, neutron distribution measurements, dark matter, etc.

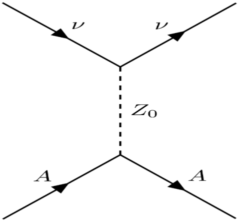
Cont...

∗ The SM differential cross section:

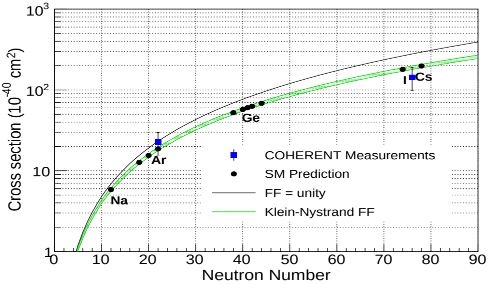
$$\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right),$$

where weak nuclear charge,

$$Q_w^2 = \left[Z g_p^V F_Z(Q^2) + N g_n^V F_N(Q^2)\right]^2$$



$$\frac{d\sigma}{dT} \propto N^2$$



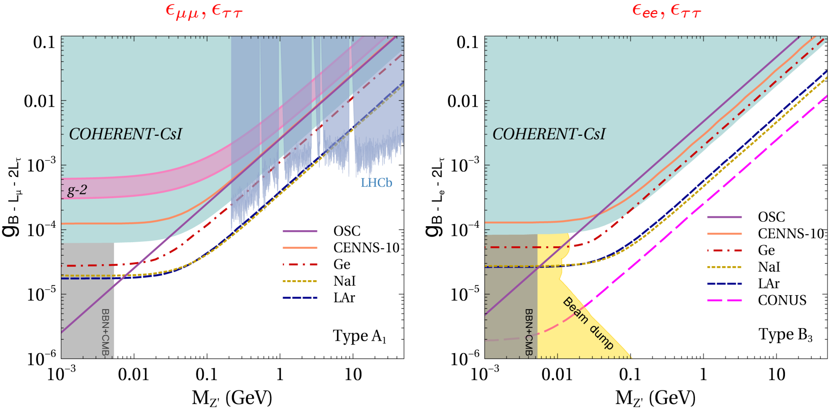
[COHERENT Collab., Akimov et. al., PRL126, 012002 (2021)]

∗ **In presence of NSIs:**

$$Q_{w\,\alpha}^2 = \left[Z(g_p^V + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV})F_Z(q^2) + N(g_n^V + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})F_N(q^2)\right]^2$$

Cont...

- Exclusion regions in the $(M_{Z'}, g')$ plane for possible NSIs



- Left panel: one explores 7 MeV $\leq M_{Z'} \leq$ 3 GeV for $0.8 \times 10^{-5} \leq g' \leq 10^{-3}$.
- Right panel: CONUS can explore the most of the parameter space

Flores, NN, Peinado, JHEP 06 (2020) 045

Heavy mediator

- NSIs in modified ν2HDM:

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

$\boxed{e_R \text{ is odd and } \Phi_2, \nu_R \text{ are even under global } U(1)}$

- The first term leads to $\supset y_e \bar{\nu}_{eL} H^+ e_R + h.c.$
- The effective Lagrangian:

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

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

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

- Other possible terms:

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

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

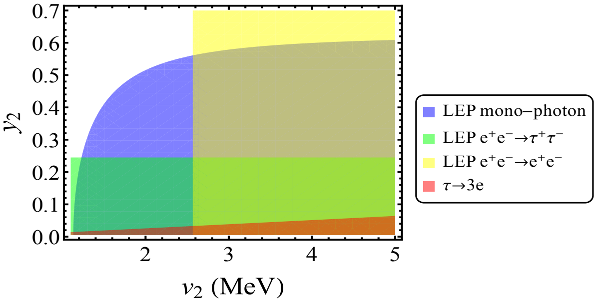
Cont...

- Other NSIs:

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

$$\epsilon_{\mu\tau} = \frac{1}{2\sqrt{2}G_F}\frac{y_1 y_2}{4m^2_{H^\pm}}\,, \qquad \epsilon_{\tau\tau} = \frac{1}{2\sqrt{2}G_F}\frac{y_2^2}{4m^2_{H^\pm}} \quad \text{(not studied)}$$

- LFV decay $\mu \to 3e$ forces $y_1 \sim 10^{-6} \Rightarrow$ very small $\epsilon_{e\mu}, \epsilon_{\mu\mu(\tau)}$
- LEP constraints:

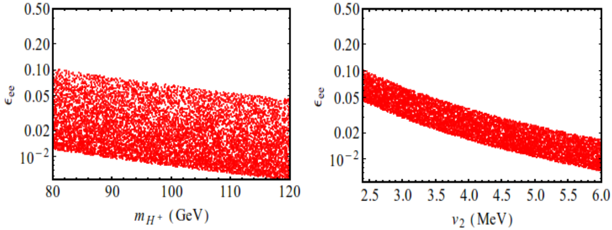


- Sizable NSIs in this model: $\boxed{\epsilon_{ee}, \epsilon_{e\tau}}$

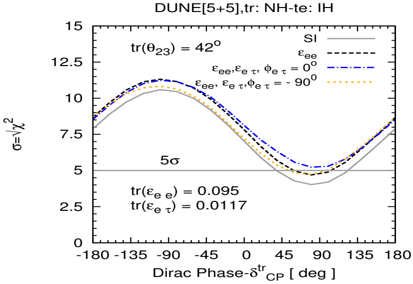
[Dey, **NN**, Sadhukhan, PRD98 (2018)]

Cont...

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



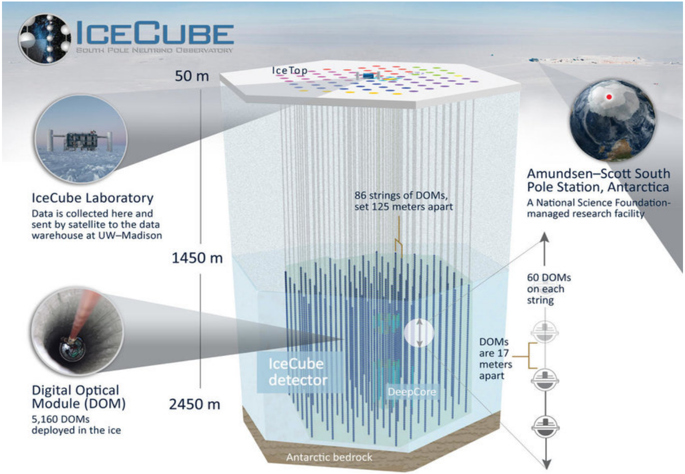
- Also, $v_2 = 2.5$ MeV, $y_2 = 0.035 \Rightarrow \epsilon_{e\tau} \sim 0.01$
- **Mass hierarchy:** almost 5σ sensitivity has been observed for $\delta \in (-\pi, \pi)$



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

IceCube

- The IceCube Neutrino Observatory, situated at Antarctica, designed to observe the cosmos from deep within the South Pole ice



- Research goals: High energy neutrinos, Gamma-ray bursts coincident with neutrinos, Indirect dark matter searches, Neutrino oscillations, Galactic supernovae, Sterile neutrinos.

NSI at IceCube (IC):

- To test the possibility of charged scalar ($\nu 2HDM$) based NSIs
- In SM, IC is sensitive to Glashow resonance: $\overline{\nu}_e e^- \to W^- \to$ anything
- Cross-section:

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

[Barger, Fu, Learned, Marfatia, Pakvasa, Weiler PRD90, 121301 (2014)]

- The resonance takes place at $E_\nu = m_W^2/m_e = 6.3$ PeV
- IC found one event at energy 6.05 ± 0.72 PeV

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Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

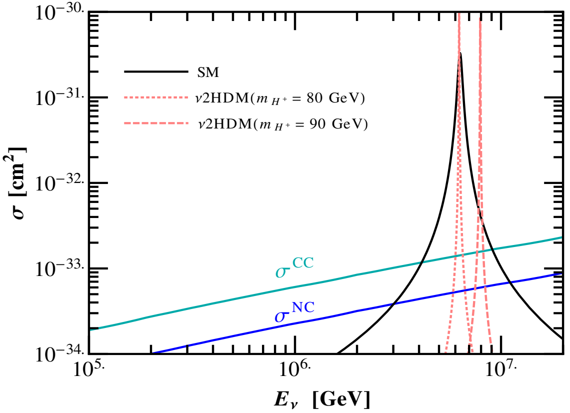
The IceCube Collaboration

Nature **591**, 220–224(2021) | Cite this article

Cont...

* Resonance due to charged-scalar:

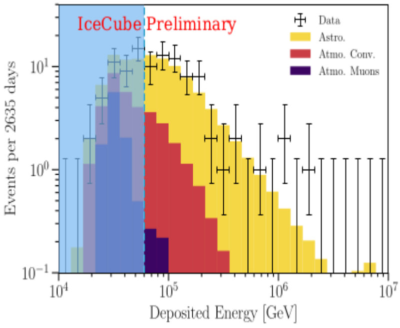
$$\sigma_{H^\pm}(E_\nu) = \frac{8\pi}{m^2_{H^\pm}} \left[\frac{2m_e E_\nu \mathrm{Br}(H^\pm \to e\nu_e)\mathrm{Br}(H^\pm \to \mathrm{all})\Gamma^2_{H^\pm}}{\left[(2m_e E_\nu - m^2_{H^\pm})^2 + \Gamma^2_{H^\pm} m^2_{H^\pm}\right]} \right],$$



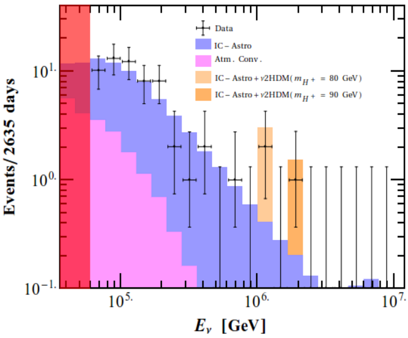
[Dey, **NN**, Sadhukhan, arXiv: 2010.05797]

Cont...

- Distributions of observed and expected events



[IceCube Collab. 1907.11266]

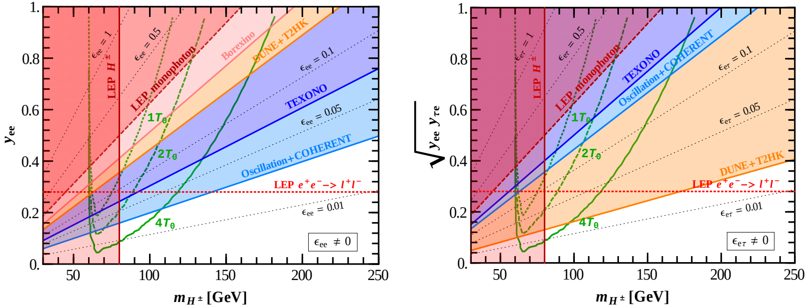


[Dey, **NN**, Sadhukhan, 2010.05797]

- With the benchmark charged Higgs masses of 80 and 90 GeV, one can explain the events in the first and third super-PeV IceCube bins (see light-orange and dark-orange bars)

NSIs signature at IceCube:

- Analyze $(y - m_{H^+})$ space to examine IC sensitivity to test NSIs $(\epsilon_{ee}, \epsilon_{e\tau})$



- Future IceCube data with $4T_0$ ($T_0 = 2635$ days) exposure time will be able to $\epsilon_{ee}, \epsilon_{e\tau} \sim 0.01$

[Dey, **NN**, Sadhukhan, arXiv: 2010.05797]

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:

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

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

Beyond NSIs

- **NSIs written in vector form:** $\mathcal{L}^{\rm NC} \supset \epsilon^{fC}_{\alpha\beta}(\overline{\nu}_\alpha \gamma^\rho P_L \nu_\beta)(\bar{f}\gamma_\rho P_L f)$
- **General Neutrino Interactions (GNIs):**

$$\mathcal{L}^{\rm NC} = -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,f} \right)^{\alpha\beta\gamma\delta} (\overline{\nu}_\alpha \mathcal{O}_j \nu_\beta) \left(\overline{f}_\gamma \mathcal{O}'_j f_\delta\right); f = e, u, d.$$

Bergmann, Grossman, Nardi, PRD'60(1999)

Beyond NSIs

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Bergmann, Grossman, Nardi, PRD'60(1999)

- $\mathcal{O}_j$ **and** $\mathcal{O}'_j$ **can extend to Lorentz structures** $\{S, P, V, A, T\}$

j	$\overset{(\sim)}{\epsilon}_j$	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ϵ_L	$\gamma_\mu(\mathbb{1} - \gamma^5)$	$\gamma^\mu(\mathbb{1} - \gamma^5)$
2	$\tilde{\epsilon}_L$	$\gamma_\mu(\mathbb{1} + \gamma^5)$	$\gamma^\mu(\mathbb{1} - \gamma^5)$
3	ϵ_R	$\gamma_\mu(\mathbb{1} - \gamma^5)$	$\gamma^\mu(\mathbb{1} + \gamma^5)$
4	$\tilde{\epsilon}_R$	$\gamma_\mu(\mathbb{1} + \gamma^5)$	$\gamma^\mu(\mathbb{1} + \gamma^5)$
5	ϵ_S	$(\mathbb{1} - \gamma^5)$	$\mathbb{1}$
6	$\tilde{\epsilon}_S$	$(\mathbb{1} + \gamma^5)$	$\mathbb{1}$
7	$-\epsilon_P$	$(\mathbb{1} - \gamma^5)$	γ^5
8	$-\tilde{\epsilon}_P$	$(\mathbb{1} + \gamma^5)$	γ^5
9	ϵ_T	$\sigma_{\mu\nu}(\mathbb{1} - \gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1} - \gamma^5)$
10	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(\mathbb{1} + \gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1} + \gamma^5)$

GNI at CEνNS

- **Reminder:**

  * The SM differential cross section: $\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right)$
  * Weak nuclear charge in SM: $Q_w^2 = \left[Z g_p^V F_Z(Q^2) + N g_n^V F_N(Q^2)\right]^2$
  * For NSI:

$$Q_{w\,\alpha}^2 = \left[Z(g_p^V + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV})F_Z(Q^2) + N(g_n^V + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})F_N(Q^2)\right]^2$$

GNI at CEνNS

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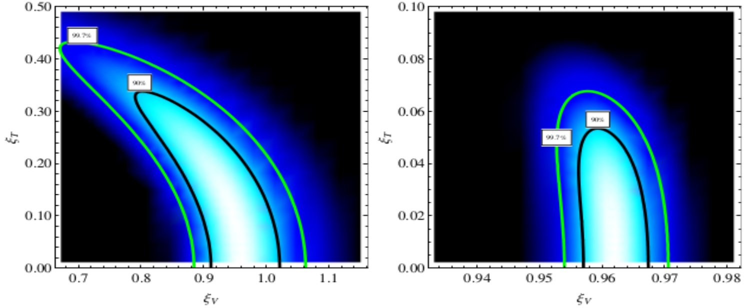
  * The SM differential cross section: $\frac{d\sigma}{dT} = \frac{G_F^2}{2\pi} M_N Q_w^2 \left(2 - \frac{M_N T}{E_\nu^2}\right)$
  * Weak nuclear charge in SM: $Q_w^2 = \left[Z g_p^V F_Z(Q^2) + N g_n^V F_N(Q^2)\right]^2$
  * For NSI:

$$Q_{w\,\alpha}^2 = \left[Z(g_p^V + 2\varepsilon_{\alpha\alpha}^{uV} + \varepsilon_{\alpha\alpha}^{dV})F_Z(Q^2) + N(g_n^V + \varepsilon_{\alpha\alpha}^{uV} + 2\varepsilon_{\alpha\alpha}^{dV})F_N(Q^2)\right]^2$$

- The differential cross section for GNI:

$$\begin{aligned}
\frac{d\sigma}{dT} \quad = \quad & \frac{{G_F}^2 M}{4\pi} N^2 \left[\xi_S^2 \frac{MT}{2{E_\nu}^2} + \xi_V^2 \left(1 - \frac{T}{T_{\max}}\right)\right. \\
& -2\xi_V \xi_A \frac{T}{E_\nu} + \xi_A^2 \left(1 - \frac{T}{T_{\max}} + \frac{MT}{{E_\nu}^2}\right) \\
& \left. +\xi_T^2 \left(1 - \frac{T}{T_{\max}} + \frac{MT}{4{E_\nu}^2}\right) - R\frac{T}{E_\nu} + \mathcal{O}\left(\frac{T^2}{E_\nu^2}\right)\right]
\end{aligned}$$

GNI at CEνNS with Ge detector



	ξ_S	ξ_V	ξ_A	ξ_T
Conservative	0.21	(0.893, 1.048)	0.14	0.25
Intermediate	0.11	(0.934, 0.993)	7.8×10^{-2}	0.14
Optimistic	4.4×10^{-2}	(0.955, 0.970)	3.1×10^{-2}	5.9×10^{-2}

Lindner, Rodejohann, Xu: 1612.04150

See also: Sierra, Romeri, Rojas: 1806.07424, Bischer, Rodejohann: 1905.08699, Khan, Rodejohann, Xu: 1906.12102, Han, Liao, Liu, Marfatia: 2004.13869

Wrap-up Comments:

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- **A light mediator ($U(1)'$) model and a heavy mediator ($\nu 2HDM$) model have been presented to study NSIs.**
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- **Finally, NSIs within the formalism of $\mu - \tau$ reflection symmetry has also been presented.**

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thank you