

# DeepCore sensitivity to Non Standard neutrino Interactions in the Earth

Samyak Jain<sup>[1]</sup>, Veronika Palusova<sup>[2]</sup>, Thomas Ehrhardt<sup>[2]</sup>,  
Sebastian Böser<sup>[2]</sup>, and Francis Halzen<sup>[1]</sup>

University of Wisconsin-Madison<sup>[1]</sup>  
Johannes Gutenberg University of Mainz<sup>[2]</sup>



## Introduction

- The existence of neutrino masses is a clear indication of physics beyond the SM. One needs to introduce either right handed neutrinos or physics at higher energy scales
- NSI refer to modification of neutrino interactions in matter due to any new neutrino physics. This can be done by many neutrino mass models or by introducing new mediators
- For long-baseline oscillation experiments, NSI effects can accumulate along the propagation path by perturbing oscillation probabilities
- IceCube DeepCore instruments the Antarctic ice to detect atmospheric neutrinos, which traverse large baselines through the Earth before detection. The ongoing analysis uses 9 years of DeepCore data to constrain NSI

## Matter effects (within SM)

- The time evolution of the flavor states is governed by the Hamiltonian induced by the PMNS matrix
- This 'vacuum' Hamiltonian is further perturbed by the MSW effect in the Earth - CC scattering of  $\nu_e$  with  $e^-$  and equal NC scattering of all flavors in matter ( $e^-, u, d$ )

$$\mathcal{H}_{\text{mat}} = \text{diag}(V_{CC}(x), 0, 0) = \sqrt{2}G_F N_e \text{diag}(1, 0, 0) \quad (0.1)$$

where the identical NC potentials can be subtracted out without affecting oscillation probabilities

## NSI formalism

- For coherent forward scattering with NSI, we can similarly add up the corresponding Hamiltonian density.
- Similar to the NC current in the SM, the simplest terms NC NSI can introduce from coherent forward scattering are of the form

$$\mathcal{L} = -2\sqrt{2}G_F\varepsilon_{\alpha\beta}^{fC} (\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta) (\bar{f}\gamma_\mu P_C f) \quad (0.2)$$

- One can again convert this to a Hamiltonian density by averaging over the propagation medium, and obtain

$$H_{\text{mat}} = V_{CC}(x) \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \sum_f V_f(x) \begin{pmatrix} \varepsilon_{ee}^f & \varepsilon_{e\mu}^f & \varepsilon_{e\tau}^f \\ \varepsilon_{e\mu}^{f*} & \varepsilon_{\mu\mu}^f & \varepsilon_{\mu\tau}^f \\ \varepsilon_{e\tau}^{f*} & \varepsilon_{\mu\tau}^{f*} & \varepsilon_{\tau\tau}^f \end{pmatrix} \quad (0.3)$$

## NSI formalism

- Normalize everything to the  $e^-$  number density:

$$H_{\text{mat}} = V_{CC}(x) \begin{pmatrix} 1 + \varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon_{e\mu}^* & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon_{e\tau}^* & \varepsilon_{\mu\tau}^* & \varepsilon_{\tau\tau} \end{pmatrix} \quad (0.4)$$

where

$$\varepsilon_{\alpha\beta} = \sum_f \frac{N_f(x)}{N_e(x)} \varepsilon_{\alpha\beta}^f \approx \text{nearly uniform in the Earth} \quad (0.5)$$

## NSI formalism

- Oscillation experiments sensitive to  $\mathcal{H}_{mat}$  up to an overall multiple of  $\mathbb{I}$ : subtract  $\epsilon_{\mu\mu}\mathbb{I}$  to obtain the most general NSI parameterization

$$H_{mat} = V_{CC}(x) \begin{pmatrix} 1 + \epsilon_{ee} - \epsilon_{\mu\mu} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon_{e\mu}^* & 0 & \epsilon_{\mu\tau} \\ \epsilon_{e\tau}^* & \epsilon_{\mu\tau}^* & \epsilon_{\tau\tau} - \epsilon_{\mu\mu} \end{pmatrix} \quad (0.6)$$

$\Rightarrow$  2 real parameters and 3 complex parameters: 8 independent real parameters.

## Generalized Matter Potential (GMP)

- As in the PMNS, one can decompose this into rotation matrices - arXiv:1103.4365

$$H_{\text{mat}} = Q_{\text{rel}} U_{\text{mat}} D_{\text{mat}} U_{\text{mat}}^\dagger Q_{\text{rel}}^\dagger \quad \text{with} \quad \begin{cases} Q_{\text{rel}} = \text{diag}(e^{i\alpha_1}, e^{i\alpha_2}, e^{-i\alpha_1 - i\alpha_2}) \\ U_{\text{mat}} = R_{12}(\phi_{12})R_{13}(\varphi_{13})\tilde{R}_{23}(\varphi_{23}, \delta_{NS}) \\ D_{\text{mat}} = V_{CC}(x) \text{diag}(\varepsilon, \varepsilon', 0) \end{cases} \quad (0.7)$$

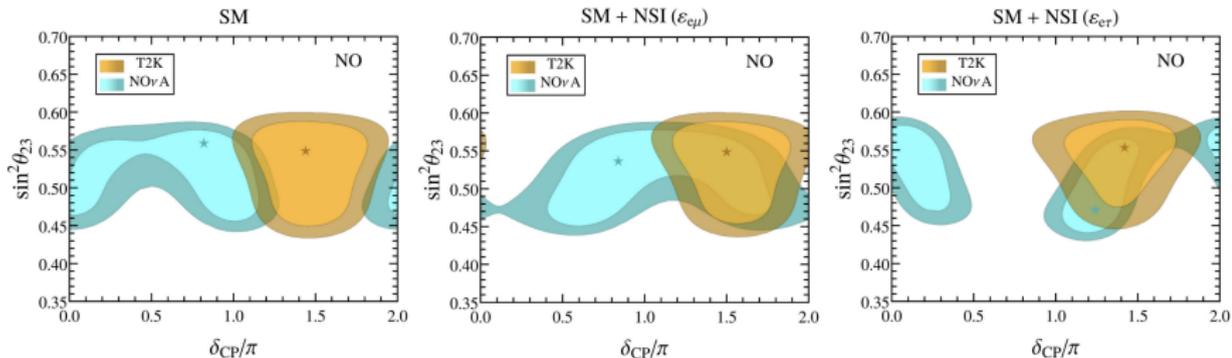
- It has been shown that if  $\varepsilon' = 0$ , there is a strong cancellation of NSI effects.  $\implies$  Weakest possible NSI constraints in this regime.  $\delta_{NS}, \varphi_{23}$  become unphysical
- Little sensitivity to CP violating effects: excluded
- Left with  $\varepsilon, R(\varphi_{12}), R(\varphi_{13})$  - Generalized Matter Potential (GMP)
- Non-zero  $\varphi_{12}$  and  $\varphi_{13}$  imply  $e - \mu$  and  $e - \tau$  oscillations due to NSI, while departures from  $\varepsilon = 1$  govern the overall NSI strength compared to weak interactions

## Existing constraints

- The SM case is recovered for  $\varepsilon = 1, \varphi_{12} = \varphi_{13} = 0$
- Oscillation probabilities invariant under  $\mathcal{H} \Rightarrow -\mathcal{H}^*$  [5]  $\Rightarrow$  Oscillations depend only on overall sign of  $\varepsilon \cdot \Delta m_{31}^2 \Rightarrow$  we can investigate both mass orderings by allowing  $\varepsilon < 0$  as well
- Existing constraints:
  - IceCube 3 yr analysis (arXiv:2106.07755): Obtained 90% CL constraints
$$\varepsilon : (-1.2, -0.3), (0.2, 1.4) \quad \varphi_{12} : (-9^\circ, 8^\circ) \quad \varphi_{13} : (-14^\circ, 9^\circ) \quad (0.8)$$
  - Constraints on the individual coupling strengths have been obtained by IceCube and other experiments

## T2K - NOvA tension (Possible sign of NSI?)

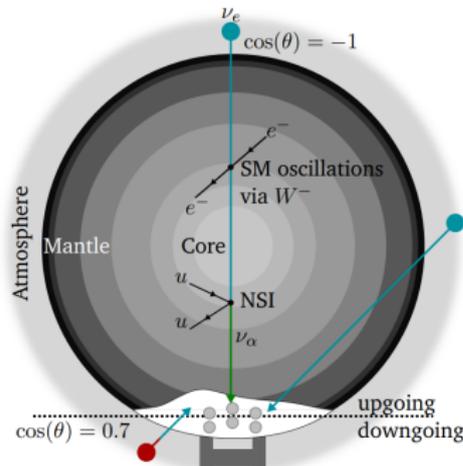
- T2K and NOvA, two long baseline oscillation experiments, have reported a rising tension between their preferred  $\delta_{CP}$  values
- NOvA has a longer baseline through the Earth - matter effects are stronger
- arXiv:2409.10599 - tension can be resolved by a non-zero  $\epsilon_{e\mu}$  or  $\epsilon_{e\tau}$
- Apart from the GMP, we also plan to constrain these couplings individually



**Figure:** arXiv:2409.10599 - Allowed regions in the  $\theta_{23}$  and  $\delta_{CP}$  plane for the no-NSI and best fit NSI hypotheses -  $\epsilon_{e\mu} = 0.125e^{1.35i\pi}$  and  $\epsilon_{e\tau} = 0.22e^{1.7i\pi}$  respectively

## Neutrino events in IceCube

- Events are detected via Cherenkov radiation emitted by products of neutrino interactions in the ice
- Events can be binned in interaction energy  $E$ , incoming angle  $\theta$ , and event morphologies - tracks, cascades, or mixed



## Neutrino events in IceCube

- For the relevant energies (few GeVs to  $\sim 100$  GeV), Neutrino NC interactions in the ice produces cascades for all flavors, and CC interactions produces cascades for  $\nu_e, \nu_\tau$
- In contrast, muons from  $\nu_\mu$  CC interactions can travel for many meters in the ice  $\Rightarrow$  track like signature

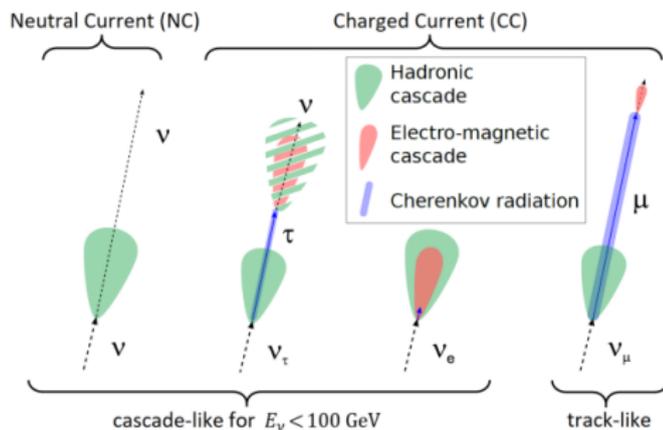
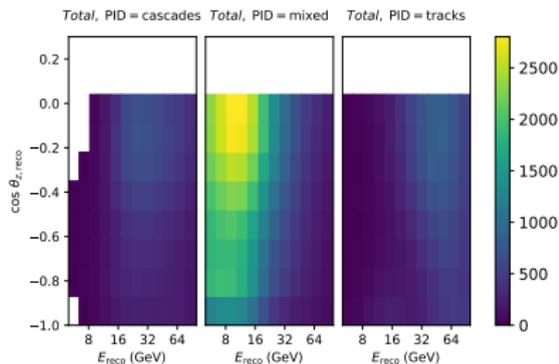


Figure: Event morphologies for different flavors - DOI: [10.25358/openscience-9288](https://doi.org/10.25358/openscience-9288)

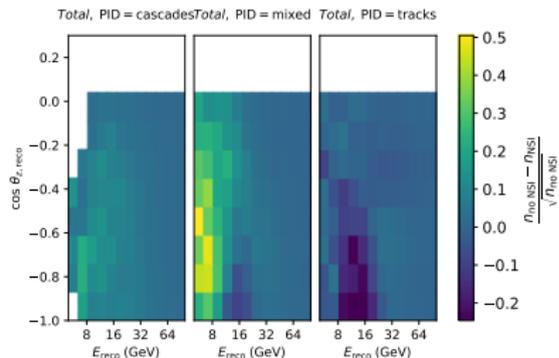
# NSI impact (event counts)

**IceCube Preliminary**  
 Counts ( $\epsilon = 1, \varphi_{12} = \varphi_{13} = 0$ )



(a)  $\epsilon = 1, \varphi_{12} = \varphi_{13} = 0$

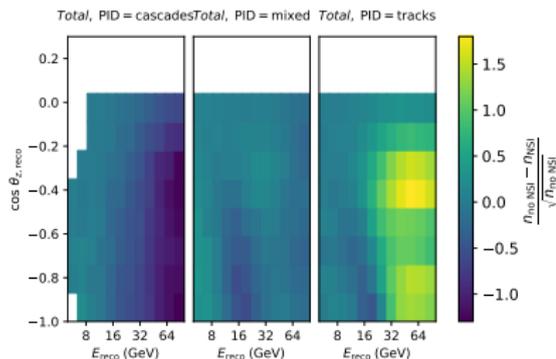
**IceCube Preliminary**  
 Counts impact ( $\epsilon = 2$ )



(b) Count difference from no-NSI scaled to errors for  $\epsilon = 2, \varphi_{12} = \varphi_{13} = 0$

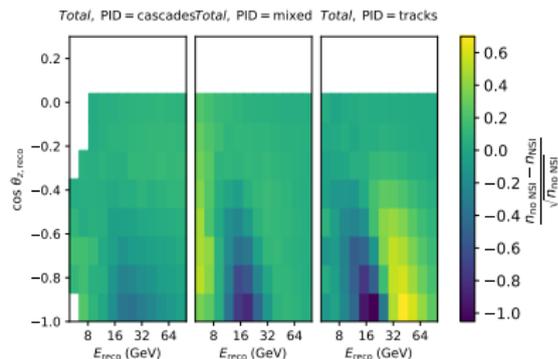
# NSI impact (event counts)

**IceCube Preliminary**  
Counts impact ( $\varphi_{12} = 10^\circ$ )



(a) Counts difference from no-NSI scaled to errors for  $\varepsilon = 1$ ,  $\varphi_{12} = 10^\circ$ ,  $\varphi_{13} = 0$

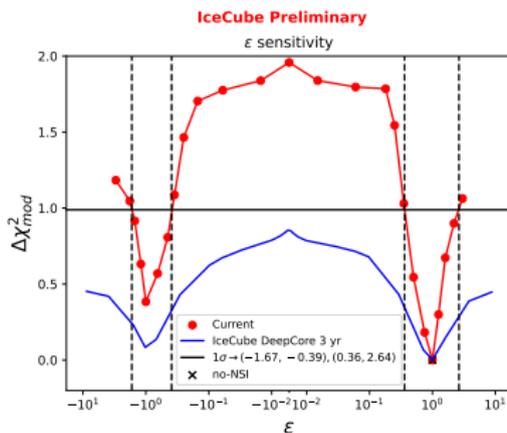
**IceCube Preliminary**  
Counts impact ( $\varphi_{13} = 10^\circ$ )



(b) Count difference from no-NSI scaled to errors for  $\varepsilon = 1$ ,  $\varphi_{12} = 0$ ,  $\varphi_{13} = 10^\circ$

## Sensitivity to NSI: $\varepsilon$

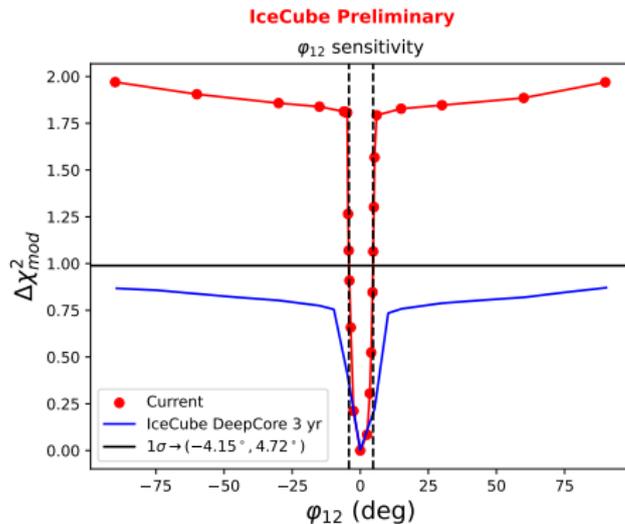
- Note: IceCube has very low sensitivity to CP violating effects, hence  $\delta_{CP}$  is not marginalized over for the GMP sensitivities



**Figure:** Sensitivity to  $\varepsilon$ , in comparison to the sensitivity of the previous IceCube analysis with 3 years of data

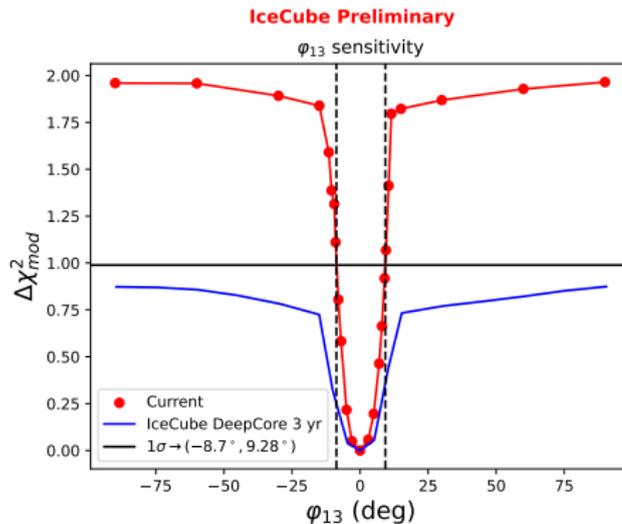
- Note the local minimum signifying the no-NSI case with the inverted mass ordering.

## Sensitivity to NSI: $\varphi_{12}$



**Figure:** Sensitivity to  $\varphi_{12}$ , in comparison to the sensitivity of the previous IceCube analysis with 3 years of data

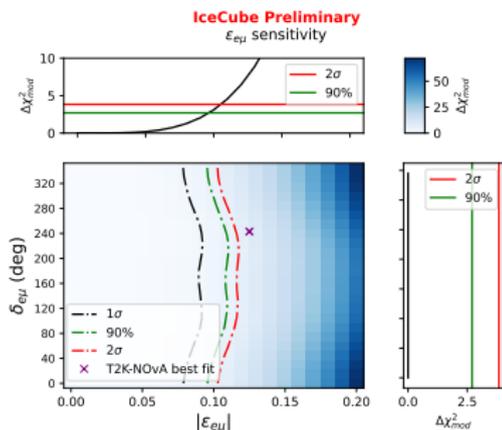
## Sensitivity to NSI: $\varphi_{13}$



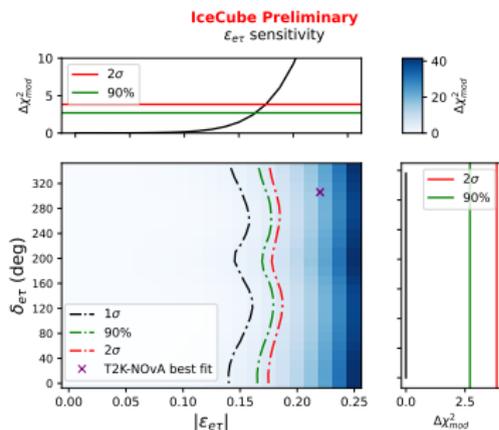
**Figure:** Sensitivity to  $\varphi_{13}$ , in comparison to the sensitivity of the previous IceCube analysis with 3 years of data

# IceCube's current sensitivity to $\varepsilon_{e\mu}$ , $\varepsilon_{e\tau}$

- Since this study is motivated by a  $\delta_{CP}$  discrepancy, we marginalize over it for these plots



(a) Sensitivity to  $\varepsilon_{e\mu}$  with a free  $\delta_{CP}$



(b) Sensitivity to  $\varepsilon_{e\tau}$  with a free  $\delta_{CP}$

## Summary

- NSI are a natural consequence of many neutrino mass / new neutrino physics models
- We adopt a model independent approach to constrain the *potentials* created due to NSI, which can be translated to physics models one is probing
- Adopting the Generalized Matter Potential parameterization allows us to constrain multiple NSI modes simultaneously, while our single NSI mode studies of  $\varepsilon_{e\mu}$  and  $\varepsilon_{e\tau}$  should allow us to comment on the T2K-NOvA  $\delta_{CP}$  tension.
- Assuming no-NSI, we should be able to rule out NSI being the cause of the tension at  $\sim 2\sigma$

## Acknowledgements and useful references

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## Appendix: Mapping between the standard NSI parameterization and the GMP [5]

$$\varepsilon_{ee} - \varepsilon_{\mu\mu} = \varepsilon \left( \cos^2 \phi_{12} - \sin^2 \phi_{12} \right) \cos^2 \phi_{13} - 1$$

$$\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu} = \varepsilon \left( \sin^2 \phi_{13} - \sin^2 \phi_{12} \cos^2 \phi_{13} \right)$$

$$\varepsilon_{e\mu} = -\varepsilon \cos \phi_{12} \sin \phi_{12} \cos^2 \phi_{13} e^{i(\alpha_1 - \alpha_2)}$$

$$\varepsilon_{e\tau} = -\varepsilon \cos \phi_{12} \cos \phi_{13} \sin \phi_{13} e^{i(2\alpha_1 + \alpha_2)}$$

$$\varepsilon_{\mu\tau} = \varepsilon \sin \phi_{12} \sin \phi_{12} \cos^2 \phi_{13} e^{i(\alpha_1 + 2\alpha_2)}$$