# Future leptonic $\delta_{CP}$-phase determination in the presence of NSI

L.A.D. and O.G.M. arXiv: 2304.05545

Luis A. Delgadillo

ESFM-IPN

June 2023

Instituto Politécnico Nacional

# Outline

- Introduction
- Framework
- Simulation
- Results
- Conclusions

# Neutrino Oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- Mixing matrix $U$ (PMNS):

Particle Data Group Parametrization

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

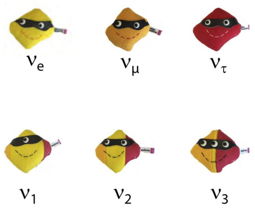
Particle Data Group `https://pdg.lbl.gov/`

Oscillation Probability

- $P(\nu_\alpha \to \nu_\beta) = \left| \langle \nu_\beta(L) | \nu_\alpha \rangle \right|^2 = \left| \sum_j U^*_{\alpha j} U_{\beta j} \exp\left( -i \frac{m_j^2 L}{2E_\nu} \right) \right|^2 .$

# Oscillation Parameters

- 2 flavors: $P(\nu_e \to \nu_\mu) = \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m^2_{21} L}{4E_\nu}\right)$.
- 3-$\nu$ mixing:
  - $\theta_{12} \approx 34^\circ \quad \theta_{13} \approx 9^\circ \quad \theta_{23} \approx 45^\circ$.
  - $\Delta m^2_{21} \approx 7.5\times10^{-5}$ eV$^2$ $\quad |\Delta m^2_{31}| \approx 2.5\times10^{-3}$ eV$^2$.

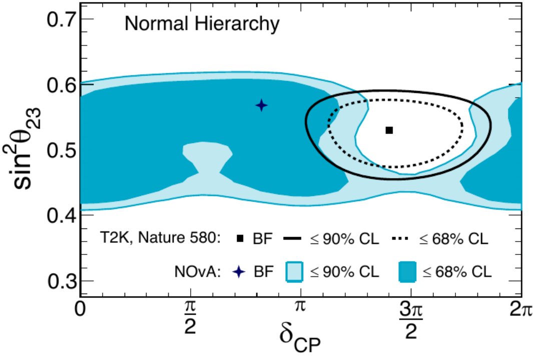



- Indications: $\delta_{CP}$ and sign of $\Delta m^2_{31}$.

Salas et al. JHEP02, 071 (2021).

# Leptonic $\delta_{CP}$-phase determination

- Neutrino 2020: ($\sim 2\sigma$) discrepancy on $\delta_{\rm CP}$ measurement among T2K and NOvA.




A. Himmel `https://zenodo.org/record/3959581#.ZBjbiNLMIso`.

- Systematic errors, statistical fluctuations?
- Neutrino non-standard interactions (NSI)?
- Sterile neutrino? ...

# Neutral Curent (NC) NSI

NC-NSI parameterized by dimension 6 operators

$$\mathcal{L} = -2\sqrt{2}G_F \epsilon_{\alpha\beta}^{fC}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_C f).^1$$

Neutrino propagation trough the Earth:

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \epsilon_{\alpha\beta}^{f} \frac{N_f}{N_e} := \sum_{f=e,u,d} (\epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}) \frac{N_f}{N_e},$$

$N_f$: number density of the fermion $f$. At Earth, $N_n \simeq N_p = N_e$, where $N_u \simeq N_d \simeq 3N_e$.

$$\epsilon_{\alpha\beta} \simeq \epsilon_{\alpha\beta}^{e} + 3\epsilon_{\alpha\beta}^{u} + 3\epsilon_{\alpha\beta}^{d}.$$

[1] $C=(L,R)$; $P_C = (1 \mp \gamma^5)/2$.

# Effective Hamiltonian

Effective Hamiltonian in the flavor base

$$H_f = \frac{1}{2E_\nu}\left[U^\dagger M^2 U + a\begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix}\right],$$

$E_\nu$ neutrino energy, $U = R_{23}(\theta_{23})U_{13}(\theta_{13},\delta_{CP})R_{12}(\theta_{12})$ mixing matrix PMNS, $M^2 = \mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})$ mass matrix, $a = 2\sqrt{2}G_F N_e E_\nu$ matter potential.

We consider complex NSI, where $\epsilon_{\alpha\beta} = |\epsilon_{\alpha\beta}|e^{i\phi_{\alpha\beta}}$. For $\alpha \neq \beta$, the phases $(\phi_{\alpha\beta})$ could contribute to $CP$-violation in the lepton sector.

# NC-NSI to explain ($\delta_{CP}$) discrepancy among T2K&NOvA

T2K: $L = 295$ km, (practically vacuum oscillation experiment), $\langle E_\nu \rangle \sim 0.6$ GeV, prefers $\delta_{\text{CP}} \sim 1.5\ \pi$.

NOvA: $L = 810$ km (more matter interaction) $\langle E_\nu \rangle \sim 1.9$ GeV, prefers $\delta_{\text{CP}} \sim \pi$.

In presence of NSI: $\delta_{\text{NOvA}} = \delta_{\text{T2K}} + \phi$, extra $CP$-phases: $\phi = \{\phi_{e\mu}\ ,\ \phi_{e\tau}\} \sim 3/2\pi$ y $|\epsilon_{e\mu}| \sim |\epsilon_{e\tau}| \sim 0.2$.

At the probability level:

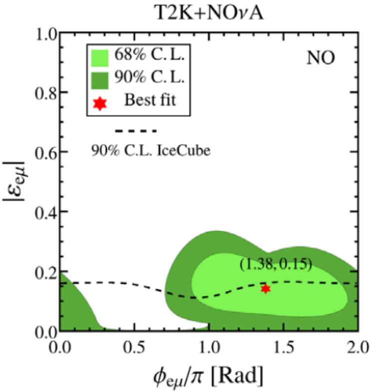
$$P(\epsilon = 0, \delta_{\text{measured}}) \simeq P(\epsilon, \delta_{\text{true}}).$$

Chatterjee, Palazzo PRL 126, 051802 (2021).
Denton et al. PRL 126, 051801 (2021).

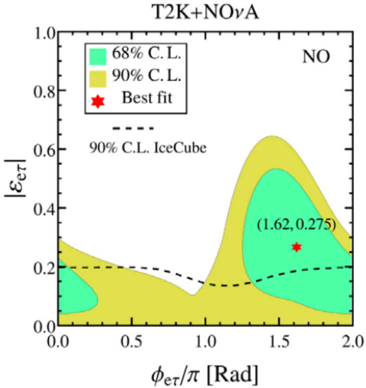
# Electron neutrino appearance (one parameter at a time)

$$P(\nu_\mu \rightarrow \nu_e) \propto \epsilon_{e\mu}, \epsilon_{e\tau}.$$

- NSI $\epsilon_{e\mu}$




- NSI $\epsilon_{e\tau}$




Chatterjee, Palazzo PRL 126, 051802 (2021).

# Numerical fit: T2K+NOvA (one parameter at a time)

TABLE I. Best fit values and $\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm SM+NSI}$ for the two choices of the NMO.

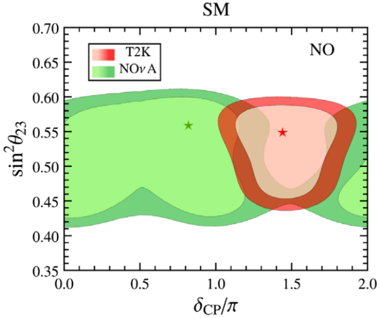
| NMO | NSI | $\lvert\varepsilon_{\alpha\beta}\rvert$ | $\phi_{\alpha\beta}/\pi$ | $\delta_{\rm CP}/\pi$ | $\Delta\chi^2$ |
|---|---|---|---|---|---|
| NO | $\varepsilon_{e\mu}$ | 0.15 | 1.38 | 1.48 | 4.50 |
| | $\varepsilon_{e\tau}$ | 0.27 | 1.62 | 1.46 | 3.75 |
| IO | $\varepsilon_{e\mu}$ | 0.02 | 0.96 | 1.50 | 0.07 |
| | $\varepsilon_{e\tau}$ | 0.15 | 1.58 | 1.52 | 1.01 |

Chatterjee, Palazzo PRL 126, 051802 (2021).

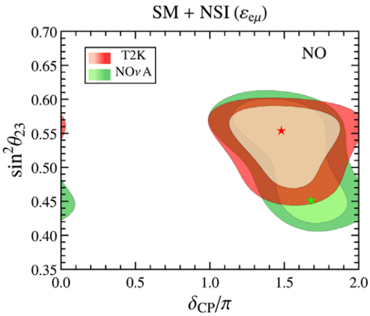
Similar results: Denton et al. PRL 126, 051801 (2021).

# NSI solution to the T2K and NOvA discrepancy on $\delta_{CP}$

- $3\nu$-oscillations (SM)



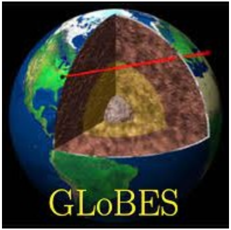

- SM+NSI $\epsilon_{e\mu}$




Chatterjee, Palazzo PRL 126, 051802 (2021).

# Simulation

- We use the General Long Baseline Experiment Simulator (GLoBES) software https://www.mpi-hd.mpg.de/personalhomes/globes/.




- n-years of exposure: n/2 ($\nu$ mode) and n/2 ($\bar{\nu}$ mode).
- Electron neutrino appearance $P(\nu_\mu \to \nu_e)$ and muon neutrino disappearance $P(\nu_\mu \to \nu_\mu)$ events.
- Sensitivity and allowed regions, $\chi^2$-statistics.

# Experimental configurations

## DUNE

- Baseline: 1300 km.
- Neutrino energy: $\langle E_\nu \rangle \sim 3$ GeV.
- Data: 13 years total, 6.5 and (6.5) $\nu$ ($\bar{\nu}$).

## ESSnuSB

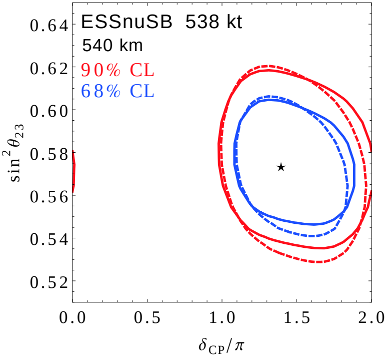
- Baseline: 540 km, 360 km.
- Neutrino energy: $\langle E_\nu \rangle \sim 0.3$ GeV.
- Data: 10 years total, 5 and (5) $\nu$ ($\bar{\nu}$).

## T2HKK

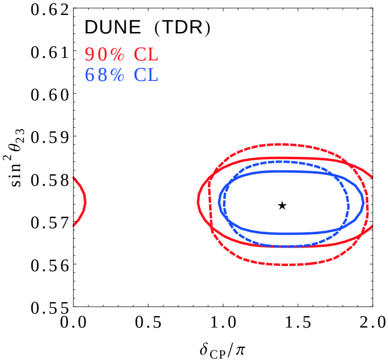
- Two-baseline: 295$-$(1100) km.
- Neutrino energy: $\langle E_\nu \rangle \sim 0.6-(0.8)$ GeV.
- Data: 10 years total, 5 and (5) $\nu$ ($\bar{\nu}$).

# ESSnuSB and DUNE (one parameter at a time)

- NSI effect ($\epsilon_{e\mu}$) at ESS




- NSI effect ($\epsilon_{e\mu}$): DUNE

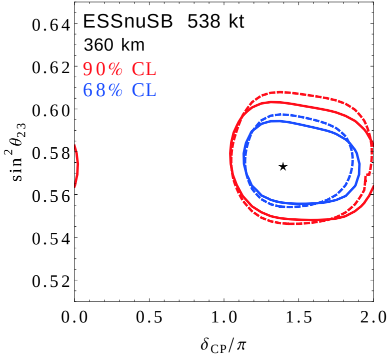



Solid lines $3\nu$-osc. (SM), dashed lines SM+NSI ($\epsilon_{e\mu}$).

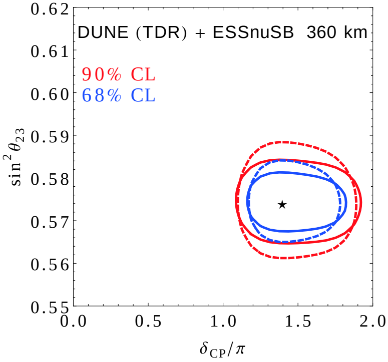
LAD, OGM arXiv:2304.05545 [hep-ph].

# ESSnuSB and DUNE (one parameter at a time)

- SM+NSI ($\epsilon_{e\tau}$) at ESS




- SM+NSI ($\epsilon_{e\tau}$): DUNE+ESS



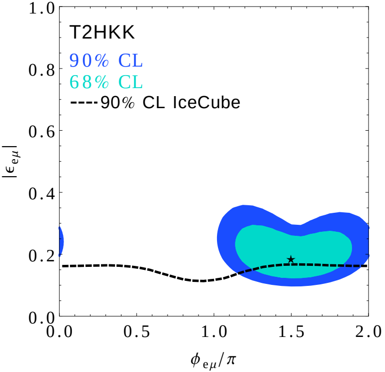

Solid lines $3\nu$-osc. (SM), dashed lines SM+NSI ($\epsilon_{e\tau}$).

LAD, OGM arXiv:2304.05545 [hep-ph].

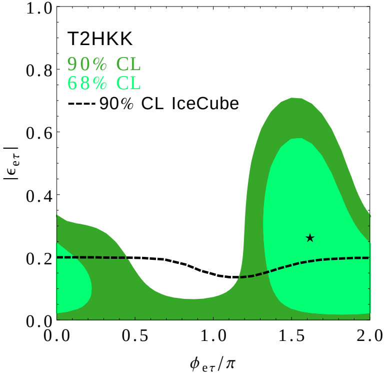
# NC-NSI at T2HKK (one parameter at a time)

Expected allowed regions : $\Delta\chi^2_{\mathrm{SM+NSI}}(\epsilon_{e\mu}$ or $\epsilon_{e\tau})$.

- NSI $\epsilon_{e\mu}$ at T2HKK




- NSI $\epsilon_{e\tau}$ at T2HKK




LAD, OGM arXiv:2304.05545 [hep-ph]

# Conclusions

- NSI as an explanation to ($\delta_{CP}$) discrepancy T2K/NOvA.
- Combination (ESSnuSB+DUNE): beneficial to obtain a reliable value of $\delta_{CP}$ (even in presence of NSI).
- T2HKK: useful to determine the NSI parameters ($\epsilon_{e\mu}$, $\epsilon_{e\tau}$).

# THANK YOU

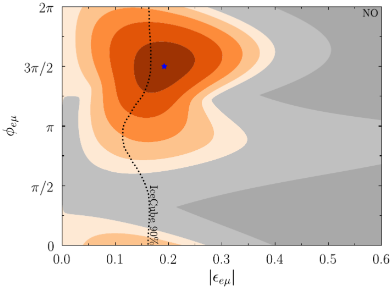
# BACK UP

Any Questions?

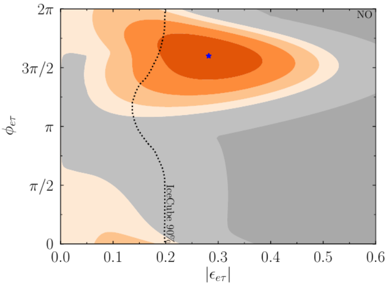
# Electron neutrino appearance channel (one parameter at a time)

$$P(\nu_\mu \to \nu_e) \propto \epsilon_{e\mu}, \epsilon_{e\tau}.$$

- Matter NSI $\epsilon_{e\mu}$




- Matter NSI $\epsilon_{e\tau}$




Denton et al. PRL 126, 051801 (2021).

# Electron neutrino appearance channel (one parameter at a time)

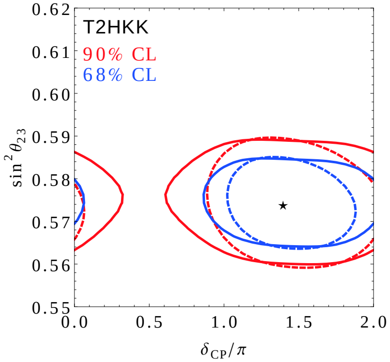
TABLE I. Best fit values and $\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm NSI}$ for a fixed MO considering one complex NSI parameter at a time. (For the SM, $\chi^2_{\rm NO} - \chi^2_{\rm IO} = 2.3$.)

| MO | NSI | $\lvert\epsilon_{\alpha\beta}\rvert$ | $\phi_{\alpha\beta}/\pi$ | $\delta/\pi$ | $\Delta\chi^2$ |
|---|---|---|---|---|---|
| NO | $\epsilon_{e\mu}$ | 0.19 | 1.50 | 1.46 | 4.44 |
| | $\epsilon_{e\tau}$ | 0.28 | 1.60 | 1.46 | 3.65 |
| | $\epsilon_{\mu\tau}$ | 0.35 | 0.60 | 1.83 | 0.90 |
| IO | $\epsilon_{e\mu}$ | 0.04 | 1.50 | 1.52 | 0.23 |
| | $\epsilon_{e\tau}$ | 0.15 | 1.46 | 1.59 | 0.69 |
| | $\epsilon_{\mu\tau}$ | 0.17 | 0.14 | 1.51 | 1.03 |

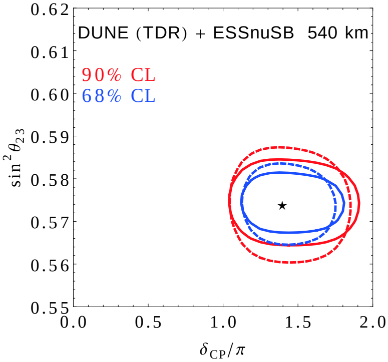
Denton et al. PRL 126, 051801 (2021).

# T2HKK and DUNE+ESS $(\epsilon_{e\mu})$

- NSI $(\epsilon_{e\mu})$ at T2HKK




- NSI $(\epsilon_{e\mu})$: DUNE+ESS




Solid lines (SM), dashed lines SM+NSI $(\epsilon_{e\mu})$.

LAD, OGM arXiv:2304.05545 [hep-ph].

# Constraints from cLFV processes

Constraints on NC-NSI parameters from cLFV processes

| NSI | Explicit Form | Estimated Limit (**NO**) | Estimated Limit (**IO**) |
|---|---|---|---|
| $\lvert\epsilon_{ee}^{eL}\rvert$ | $(2\sqrt{2}G_F)^{-1}M_\Delta^{-2}\lvert Y_{\Delta ee}^* Y_{\Delta ee}\rvert$ | $< 8.0 \times 10^{-4}$ | $< 8.0 \times 10^{-4}$ |
| $\lvert\epsilon_{e\mu}^{eL}\rvert$ | $(2\sqrt{2}G_F)^{-1}M_\Delta^{-2}\lvert Y_{\Delta ee}^* Y_{\Delta \mu e}\rvert$ | $< 7.0 \times 10^{-7}$ | $< 7.0 \times 10^{-7}$ |
| $\lvert\epsilon_{e\tau}^{eL}\rvert$ | $(2\sqrt{2}G_F)^{-1}M_\Delta^{-2}\lvert Y_{\Delta ee}^* Y_{\Delta \tau e}\rvert$ | $< 2.0 \times 10^{-4}$ | $< 2.1 \times 10^{-4}$ |
| $\lvert\epsilon_{\mu\mu}^{eL}\rvert$ | $(2\sqrt{2}G_F)^{-1}M_\Delta^{-2}\lvert Y_{\Delta \mu e}^* Y_{\Delta \mu e}\rvert$ | $< 6.8 \times 10^{-6}$ | $< 2.5 \times 10^{-6}$ |
| $\lvert\epsilon_{\mu\tau}^{eL}\rvert$ | $(2\sqrt{2}G_F)^{-1}M_\Delta^{-2}\lvert Y_{\Delta \mu e}^* Y_{\Delta \tau e}\rvert$ | $< 4.8 \times 10^{-6}$ | $< 2.5 \times 10^{-6}$ |
| $\lvert\epsilon_{\tau\tau}^{eL}\rvert$ | $(2\sqrt{2}G_F)^{-1}M_\Delta^{-2}\lvert Y_{\Delta \tau e}^* Y_{\Delta \tau e}\rvert$ | $< 9.5 \times 10^{-5}$ | $< 9.9 \times 10^{-5}$ |

MANDAL, MIRANDA, GARCIA, VALLE, and XU PRD 105, 095020 (2022).

# Matter Neutral Current (NC)-NSIs

Neutrino NC-NSIs can be parameterized by a dimension six operator

$$\mathcal{L} = -2\sqrt{2} G_F \epsilon^{fC}_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_C f), \;\; G_F \sim 1/M_W^2, \;\; \epsilon^{fC}_{\alpha\beta} \sim M_W^2/M_{NSI}^2$$

Projector operators

$$P_C = P_{R,L} = \frac{1}{2}(1 \pm \gamma^5)$$

For the case of neutrinos propagating trough the Earth:

$$\epsilon_{\alpha\beta} = \sum_{f=e,u,d} \epsilon^f_{\alpha\beta} \frac{N_f}{N_e} := \sum_{f=e,u,d} (\epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}) \frac{N_f}{N_e},$$

$N_f = \bar{f}\gamma^0 f$ correspond to the number density of the $f$ fermion. Since $N_f$ is independent of the axial current, both possible Lorentz structures $P_C$ would have the same impact on the NSI matter effects.