

Unravelling Non-standard Physics via Neutrino Oscillations

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Equity (SWPNIOE-2026)

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Outline

- Introduction:
 - Neutrinos, Oscillations and Matter Effects
- New Physics Effects in Neutrino Oscillations
 - Idea & Formalism
 - Some results
- Concluding Remarks

The Neutrino

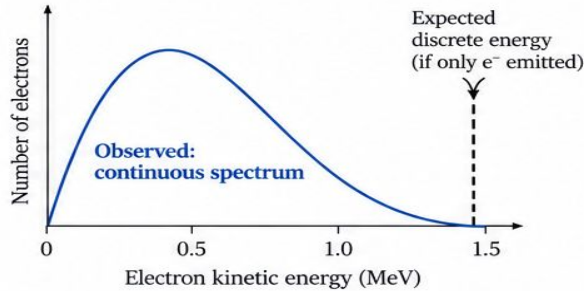
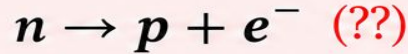
Born from a puzzle, essential to the Universe

*"I have done a terrible thing.
I have postulated a particle
that cannot be detected."*

— Wolfgang Pauli, 1930

1 A puzzle in β decay

In nuclear β decay, a neutron transforms into a proton, emitting an electron. The observed electron energy spectrum is continuous, not a mono-energetic line, implying missing energy and momentum.



*A missing piece in a simple decay
led to a new fundamental particle
and a new window to the Universe.*

2 Pauli's postulation (1930)



Wolfgang Pauli
(1900 – 1958)

*"I propose that there
exists in the nuclei
electrically neutral
particles, that I wish
to call neutrons ..."*

W. Pauli, 1930

To preserve conservation of energy, momentum and angular momentum, Pauli proposed the existence of a new, electrically neutral particle — the neutron (later named neutrino).

3 Fermi's theory (1934)



Enrico Fermi
(1901 – 1954)

Enrico Fermi developed a quantitative theory of β decay with the neutrino, introducing the four-fermion weak interaction.

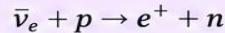


4 Experimental discovery (1956)



Clyde Cowan & Frederic Reines
(1956)

Clyde Cowan and Frederic Reines observed (anti)neutrinos from a nuclear reactor using inverse beta decay.



*First direct detection
of the (anti)neutrino!*

5 Basic properties

Neutrinos are fundamental fermions with unique properties.

Electric charge

Q

$Q = 0$
Electrically neutral

Spin



$s = \frac{1}{2}$
Fermions

Mass

m_ν

$m_\nu \neq 0$ (very small)
 $\approx$ eV scale

Interactions

W / Z

Only weak (and gravitational)
No electromagnetic or
strong interactions

Flavours

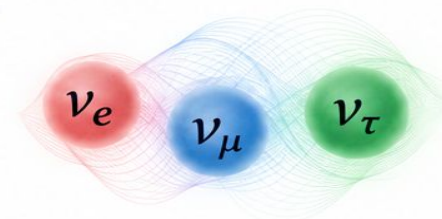
$\nu_e \quad \nu_\mu \quad \nu_\tau$

Three known flavours
(gauge eigenstates)

Helicity



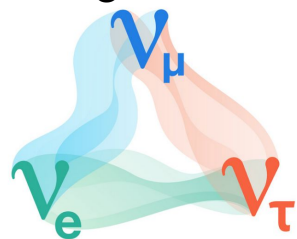
Left-handed (neutrinos)
Right-handed (antineutrinos)
(for relativistic neutrinos)



*Tiny.
Neutral.
Elusive.
But profoundly important.*

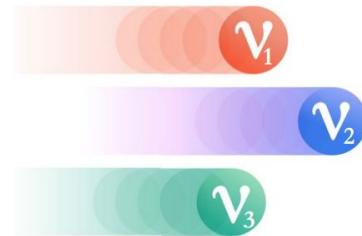
Neutrino Flavor Mixing and Oscillations

- Neutrino flavor states are overlapping combinations of distinct mass states:
Mixing.



flavor eigenstates

$$\left| \nu_\alpha \right\rangle = \sum_{i=1}^3 U_{\alpha i} \left| \nu_i \right\rangle$$



mass eigenstates

- Neutrinos change flavor while propagating: Neutrino Oscillations
- Two Flavor vacuum oscillations probability:

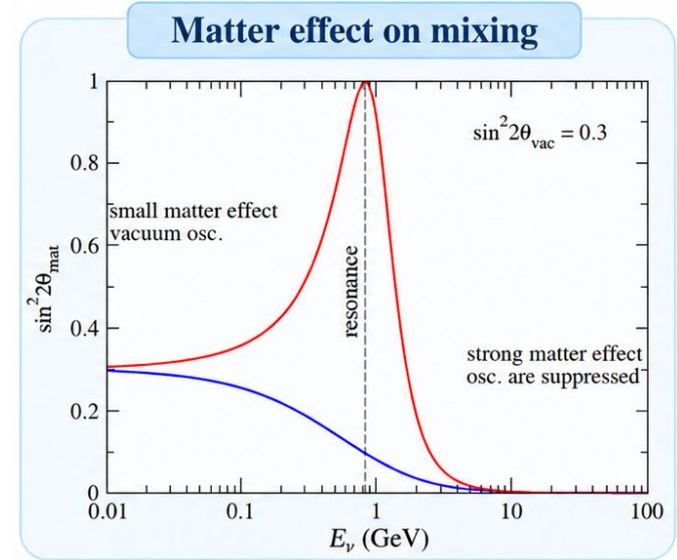
$$P_{\alpha \rightarrow \beta} = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 [eV^2] L [km]}{E [GeV]} \right).$$

Matter Effect in Oscillations

- ν_e interacts with electrons via CC interactions, giving rise to effective matter potential, $V_{CC} = \sqrt{2}G_F n_e$
- This modifies effective **masses** and **mixing**,

$$\sin 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\sqrt{(\Delta m^2 \cos 2\theta - 2E_\nu V_{CC})^2 + (\Delta m^2 \sin 2\theta)^2}},$$
$$\Delta m_m^2 = \sqrt{(\Delta m^2 \cos 2\theta - 2E_\nu V_{CC})^2 + (\Delta m^2 \sin 2\theta)^2}$$

- At resonance, $\theta_m = 45^\circ$, and $\Delta m^2 \cos 2\theta = 2E_\nu V_{CC}$, maximal mixing leading to the possibility of total transition $\Rightarrow$ **MSW effect**
- Resonance occurs for **neutrinos (anti-neutrinos)** if Δm^2 is **positive (negative)**
- Matter term changes sign for **neutrinos (anti-neutrinos)**: fake CP asymmetry



Non Standard Neutrino Interactions

- The neutrino Hamiltonian for MSW matter effect:

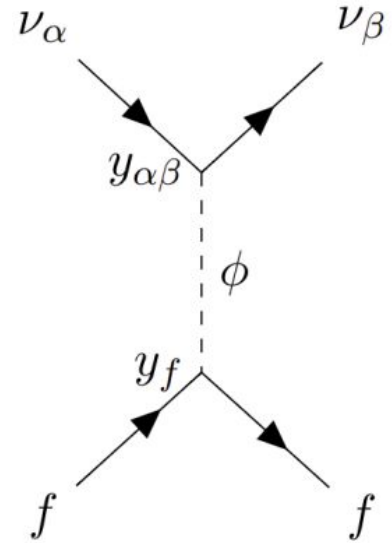
$$\mathcal{H}_{SI} \equiv \frac{MM^\dagger}{2E_\nu} \pm V_{SI}$$

- BSM theories suggest new interactions: **Non-standard interactions**
- **Vector NSI** formalism: introduces an extra vector mediator
- It contributes to the $\bar{\nu}\gamma^0\nu$ term: appears as a **modified potential**
- Effective Hamiltonian for vector NSI:

$$\mathcal{H}_{\text{matter}} \approx E_\nu + \frac{MM^\dagger}{2E_\nu} \pm (V_{SI} + V_{\text{NSI}})$$

Scalar Non Standard Interactions

- Interaction of neutrinos with environmental fermions mediated by a scalar
- Scalar NSI appears as a density dependent correction to the neutrino mass term in the Hamiltonian
- **Relates absolute neutrino mass to oscillation probabilities**
- Unique possibility to constrain absolute neutrino mass through oscillation experiments
- Scalar NSI depends on matter density, long baseline experiments are an excellent tool to explore
- Current bounds on the parameters from Solar+KamLAND and JUNO



Formalism of Scalar NSI

- Interaction of neutrinos with environmental fermions, mediated by a scalar.

Effective Lagrangian

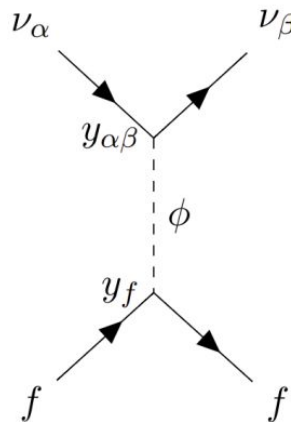
$$\mathcal{L}_{\text{SNSI}} = \frac{y_f Y_{\alpha\beta}}{m_\phi^2} [\bar{\nu}_\alpha(p_3) \nu_\beta(p_2)] [\bar{f}(p_1) f(p_4)].$$

Modification in Hamiltonian

$$\mathcal{H}_{\text{SNSI}} \approx E_\nu + \frac{(M + \delta M)(M + \delta M)^\dagger}{2E_\nu} \pm V_{\text{SI}} \quad \delta M = \sum_f \frac{n_f y_f Y_{\alpha\beta}}{m_\phi^2}$$

Parameterization of scalar NSI

$$\delta M = S_m \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{e\mu}^* & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{e\tau}^* & \eta_{\mu\tau}^* & \eta_{\tau\tau} \end{pmatrix}$$



S_m : scaling term, typical mass squared difference
 $\eta_{\alpha\beta}$: strength of scalar NSI

Dark Non Standard Interactions

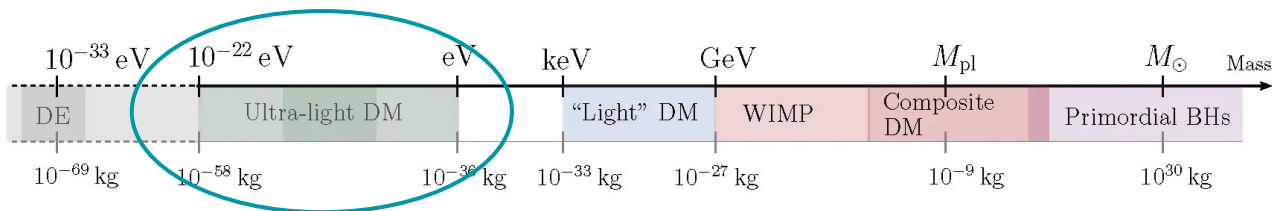
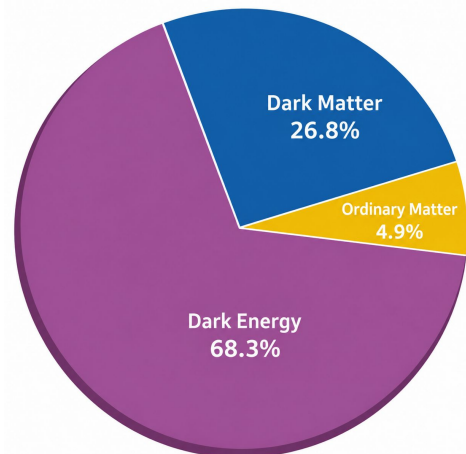


Image credit: arXiv:2005.03254

- Astrophysical and cosmological evidence suggests Universe is vastly composed of dark matter.
- There are models suggesting dark matter mass can vary over a large scale.
- When neutrinos propagate, they may interact with ultra light dark matter particles in the environment
- **The scattering of neutrinos with dark matter background: dark non standard interactions**



Formalism of dark NSI

- Interaction of neutrinos with ultra-light scalar dark matter particles.

Modified Lagrangian

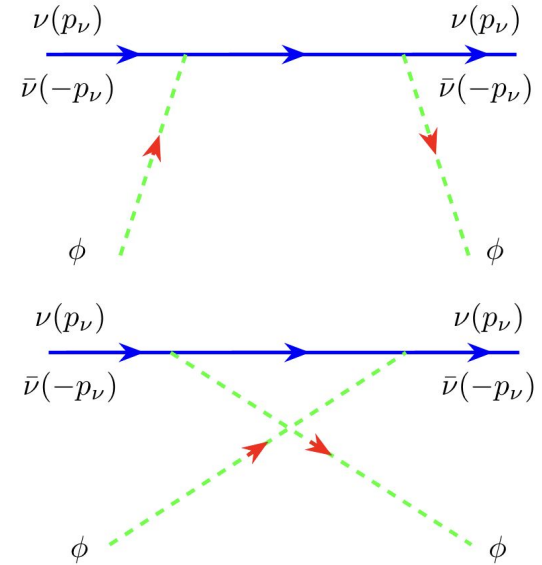
$$-\mathcal{L} = \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}M_{\alpha\beta}\bar{\nu}_\beta\nu_\alpha + y_{\alpha\beta}\phi\bar{\nu}_\alpha\nu_\beta + h.c.$$

Dark NSI induced correction

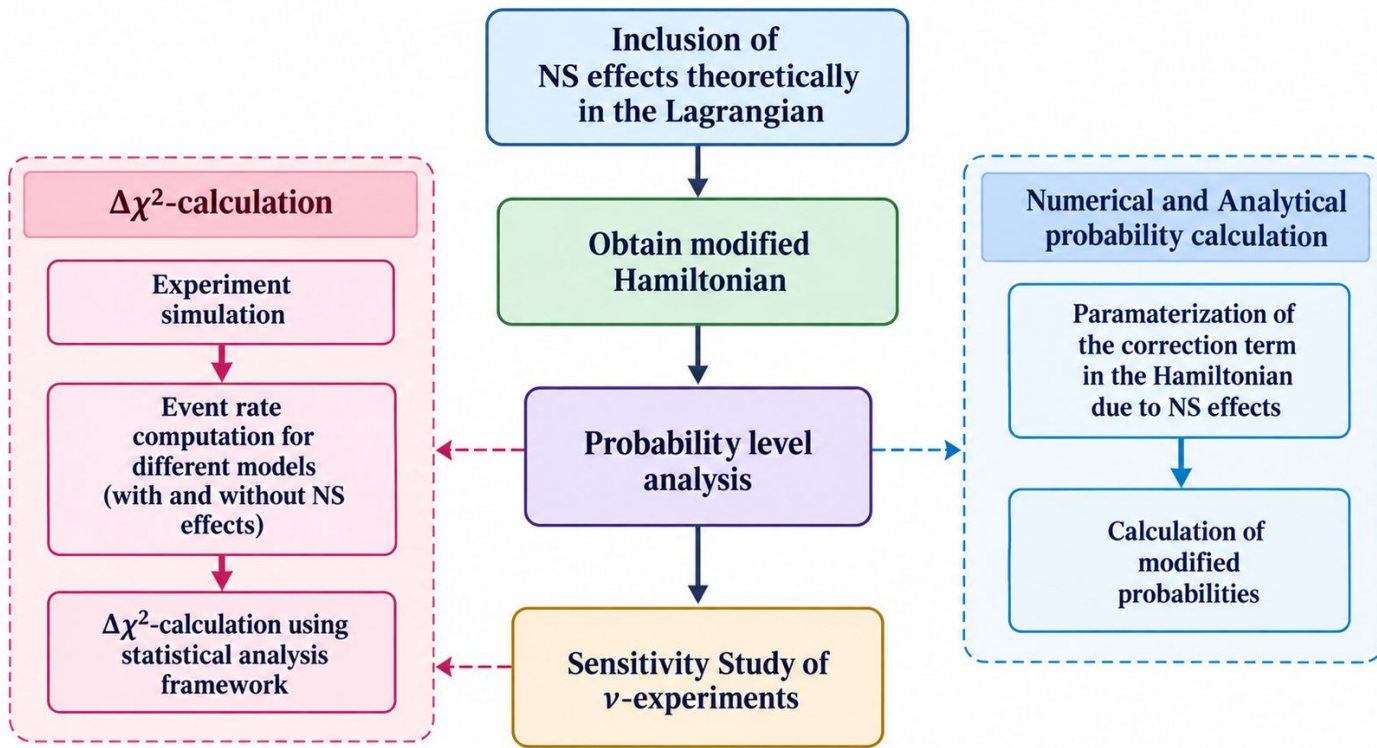
$$\delta\Gamma_{\alpha\beta} \approx \pm \sum_j y_{\alpha j} y_{j\beta}^* \rho_\chi \gamma_0$$

Modified Hamiltonian

$$H_{DNSI} = \frac{M^2 + \delta M^2}{2E_\nu} \pm V_{SI}$$



General Formalism to study Non-standard interactions



Lorentz Invariance Violation

- Lorentz Invariance Violation (LIV): Violation of the space time symmetry.
- Physics laws are invariant under Lorentz transformation
- Neutrino oscillations is a way to probe LIV
- Effect of LIV can be treated as a perturbation to the standard description of neutrino oscillations
- Generally studied using Standard Model extension framework (SME)

Lorentz Invariance violation

- In the SME framework, LIV originates from additional terms in the neutrino-sector Lagrangian:

$$\mathcal{L}_{\text{LIV}} \supset -(a_L)_{\alpha\beta}^{\mu} \bar{\nu}_{\alpha} \gamma_{\mu} \nu_{\beta} + i(c_L)_{\alpha\beta}^{\mu\nu} \bar{\nu}_{\alpha} \gamma_{\mu} \partial_{\nu} \nu_{\beta}.$$

$$\begin{aligned} H_{\text{eff}} &= H_{\text{vacuum}} + H_{\text{matter}} + H_{\text{LIV}} \\ &= \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix} U^{\dagger} + V_{cc} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ &\quad + \begin{pmatrix} a_{ee} & a_{e\mu} & a_{e\tau} \\ a_{e\mu}^* & a_{\mu\mu} & a_{\mu\tau} \\ a_{e\tau}^* & a_{\mu\tau}^* & a_{\tau\tau} \end{pmatrix} - \frac{4}{3} E \begin{pmatrix} c_{ee} & c_{e\mu} & c_{e\tau} \\ c_{e\mu}^* & c_{\mu\mu} & c_{\mu\tau} \\ c_{e\tau}^* & c_{\mu\tau}^* & c_{\tau\tau} \end{pmatrix} \end{aligned}$$

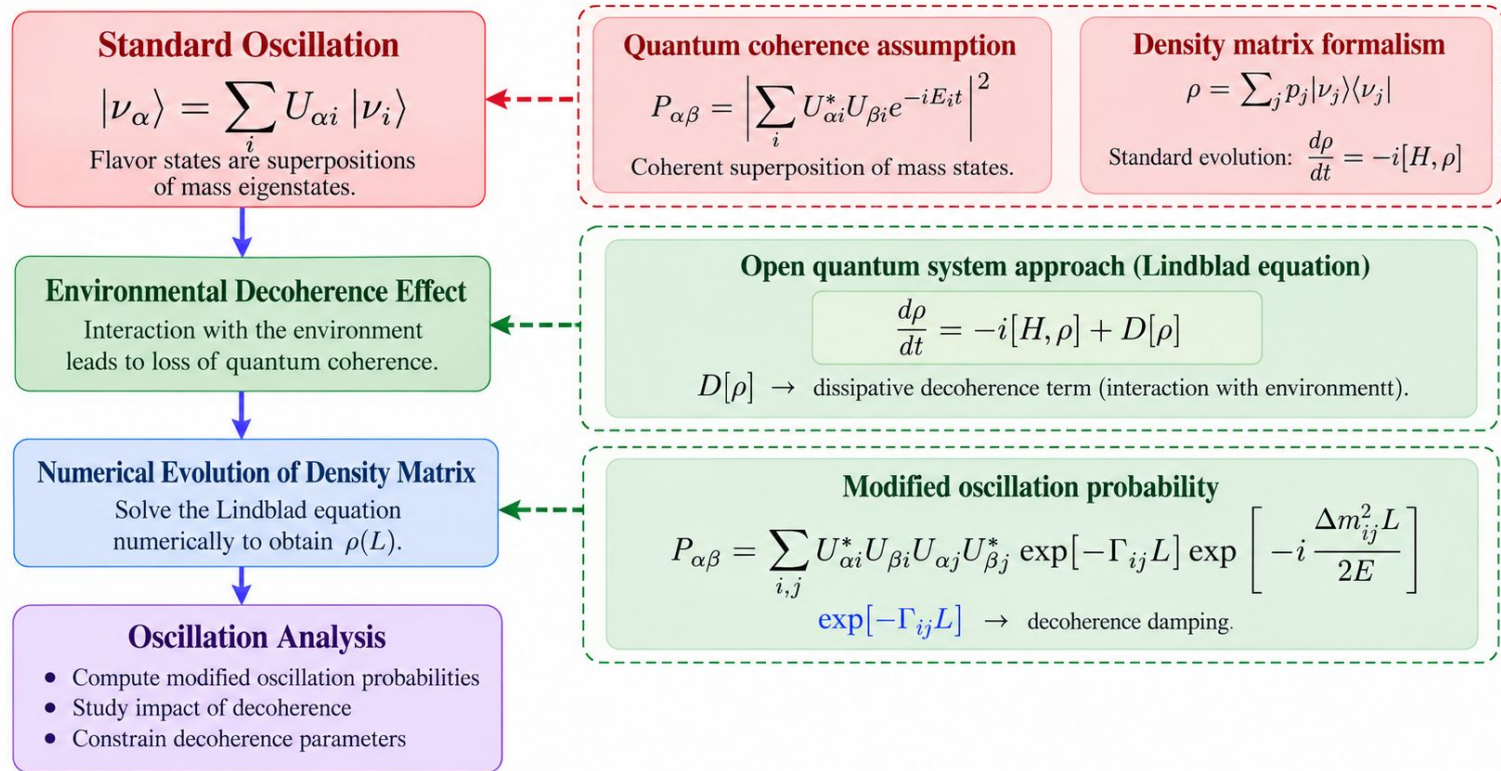
where

- $a_{\alpha\beta} \equiv |a_{\alpha\beta}| e^{i\phi_{\alpha\beta}^a}$ are CPT violating LIV terms
- $c_{\alpha\beta} \equiv |c_{\alpha\beta}| e^{i\phi_{\alpha\beta}^c}$ are CPT conserving LIV terms

Quantum Decoherence in neutrinos

- Decoherence: loss of coherence between two or more superposing states due to system's dissipative interaction with the environment.
- Neutrinos propagating through matter : open quantum system.
- Loss of coherence between neutrino mass eigenstates.
- Open quantum system time evolution : Lindblad Master Equation.
- Neutrino oscillations receives modification due to Environmental decoherence.

Formalism of quantum decoherence



Analytic Neutrino Oscillations Probability : Scalar NSI

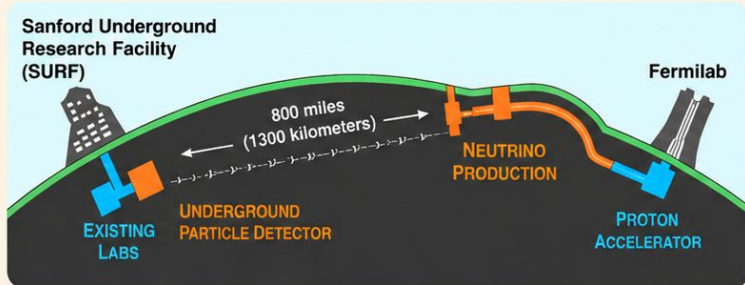
$$P_{\mu e} = P_{\mu e}^{SI} + P_{\mu e}^{(\eta_{\alpha\beta})}$$

$$P_{\mu e}^{(\eta_{ee})} = \left[2s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \cos(\delta_{CP} + \Delta) \frac{\sin[(A_e - 1)\Delta]}{A_e - 1} \frac{\sin[A_e\Delta]}{A_e} (\mathbf{m}_2 - \mathbf{m}_1) \right. \\ + 2\alpha c_{23}^2 \sin^2(2\theta_{12}) \frac{\sin^2[A_e\Delta]}{A_e^2} (\mathbf{m}_2 - \mathbf{m}_1) + 8s_{13}^2 s_{23}^2 \frac{\sin[(A_e - 1)\Delta]}{A_e - 1} \left(\frac{\sin[(A_e - 1)\Delta]}{A_e - 1} \mathbf{m}_3 \right. \\ + \frac{1}{A_e - 1} \left[2\Delta \cos[(A_e - 1)\Delta] - (A_e + 1) \frac{\sin[(A_e - 1)\Delta]}{A_e - 1} \right] \times (\mathbf{m}_1 c_{12}^2 + \mathbf{m}_2 s_{12}^2) \Big) \\ + \alpha s_{13} \sin(2\theta_{23}) \sin(2\theta_{12}) \cos(\delta_{CP} + \Delta) \left(2 \frac{\sin[A_e\Delta]}{A_e} \frac{\sin[(A_e - 1)\Delta]}{A_e - 1} m_3 - \frac{1}{A_e - 1} \right. \\ \left. \left. \times \left[\frac{2}{A_e} \left(\sin[(A_e - 1)\Delta] \frac{\sin[A_e\Delta]}{A_e} - \Delta \sin[(2A_e - 1)\Delta] \right) + (A_e + 1) \frac{\sin[A_e\Delta]}{A_e} \frac{\sin[(A_e - 1)\Delta]}{A_e - 1} \right] (m_1 + m_2) \right) \right] \times \left(\frac{S_m}{\Delta m_{31}^2} \right) \eta_{ee} .$$

- Explicit dependence on absolute neutrino mass.
 - mass summation term : $m_1 + m_2, m_1 c_{12}^2 + m_2 s_{12}^2$
 - mass difference term: $m_2 - m_1$
 - m_3 term

Long baseline neutrino experiments

Deep Underground Neutrino Experiment (DUNE)



- **Baseline** : 1300 km
- **Neutrino beam** : ν -beam at Fermilab
- **Far detector** : at SURF
- **Fiducial volume** : 40 kt (LArTPC)
- **Runtime** : 6.5 yr ν + 6.5 yr $\bar{\nu}$

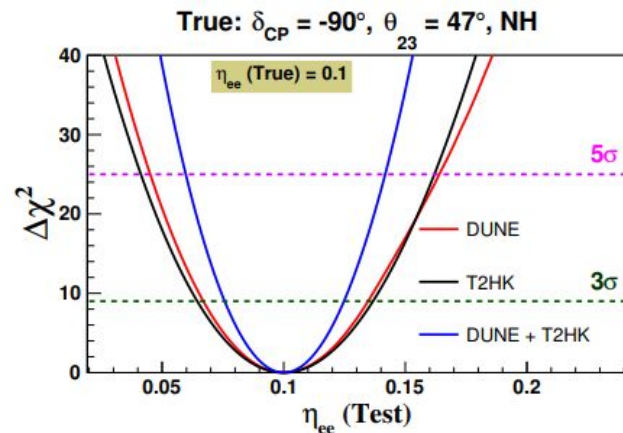
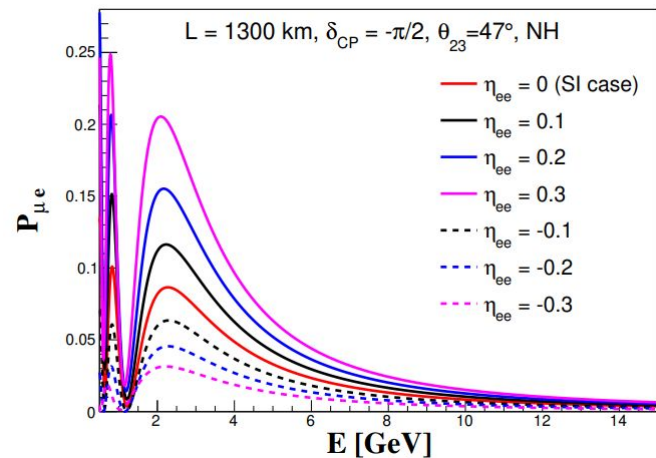
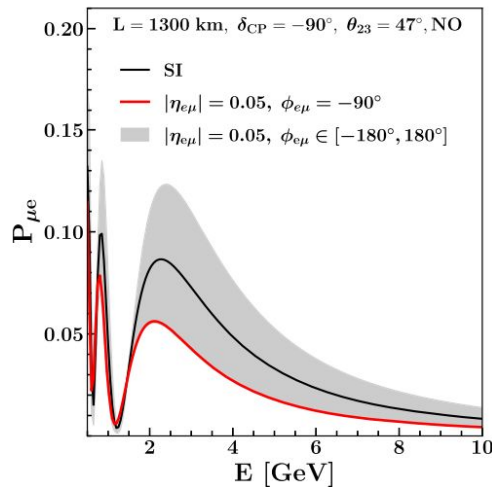
Tokai to HyperK (T2HK / HK)



- **Baseline** : 295 km
- **Neutrino beam** : ν -beam at JPARC
- **Far detector** : is HyperK
- **Fiducial volume** : 187 kt (WC)
- **Runtime** : 2.5 yr ν + 7.5 yr $\bar{\nu}$

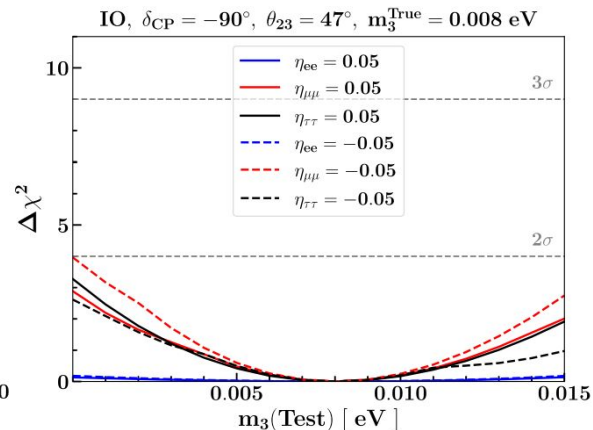
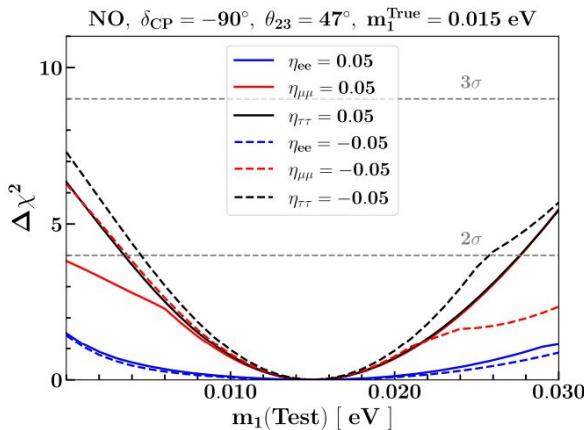
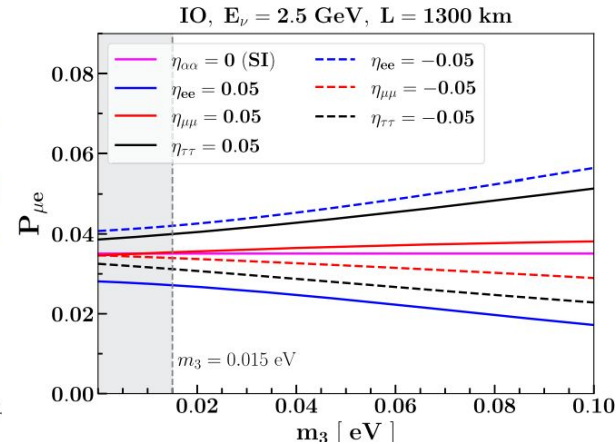
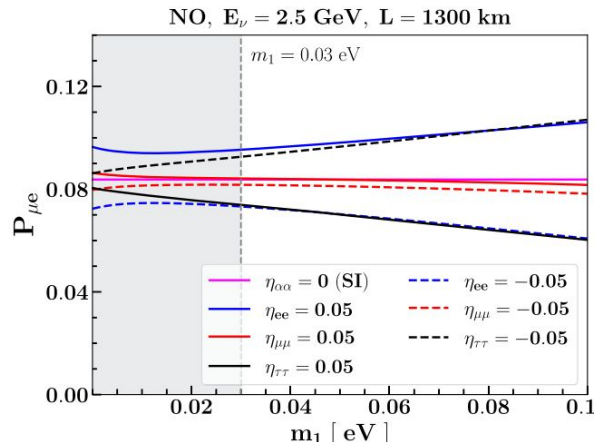
Impact of scalar NSI on neutrino oscillations

- Positive (negative) η_{ee} enhances (suppresses) oscillation probability.
- Presence of off-diagonal $\eta_{e\mu}$ suppresses probability. $\phi_{e\mu}$ has significant impact.
- DUNE and T2HK can constrain η_{ee} . Combining DUNE and T2HK significantly increase the result.

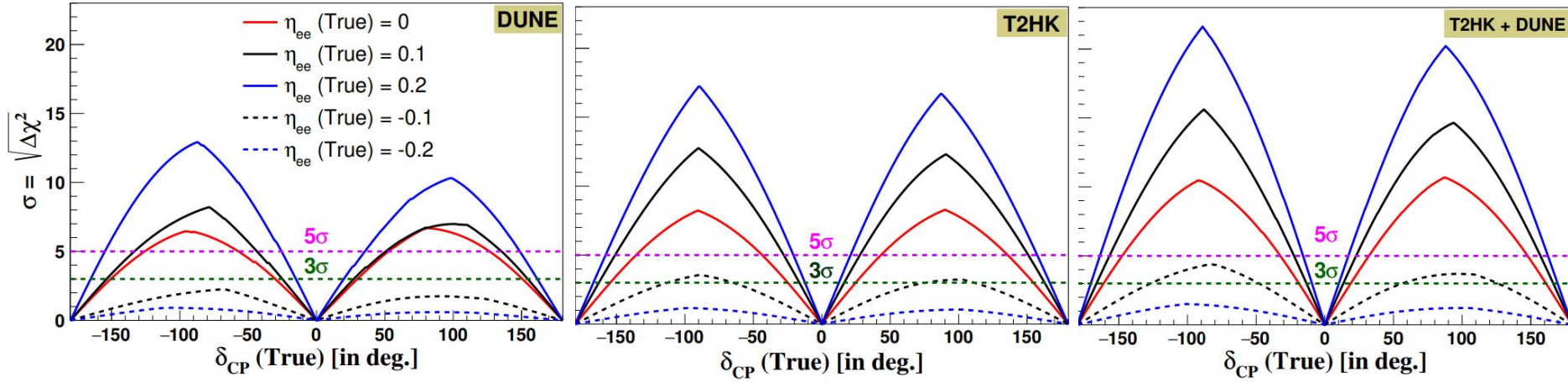


Absolute neutrino mass dependence

- With increase in the strength of SNSI parameter dependency on the neutrino masses becomes more prominent for both NO and IO.
- NO: m_l constrained at 3σ for positive and negative $\eta_{\mu\mu}, \eta_{\tau\tau}$; weak for η_{ee} .
- IO: Constraints at 2σ for for positive and negative $\eta_{\mu\mu}$, $\eta_{\tau\tau}$; weaker for η_{ee} .



Scalar NSI: CPV sensitivity



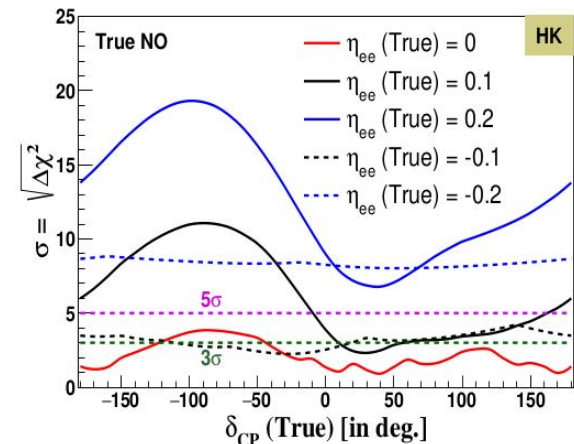
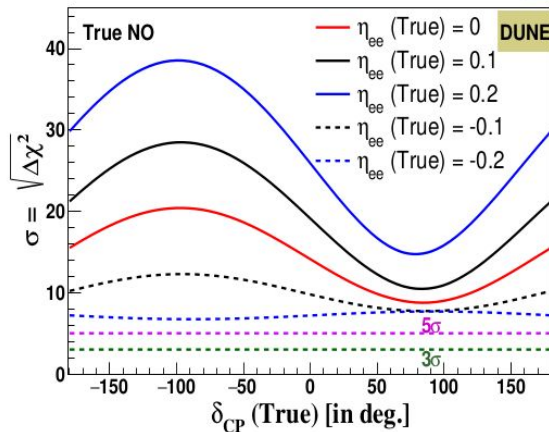
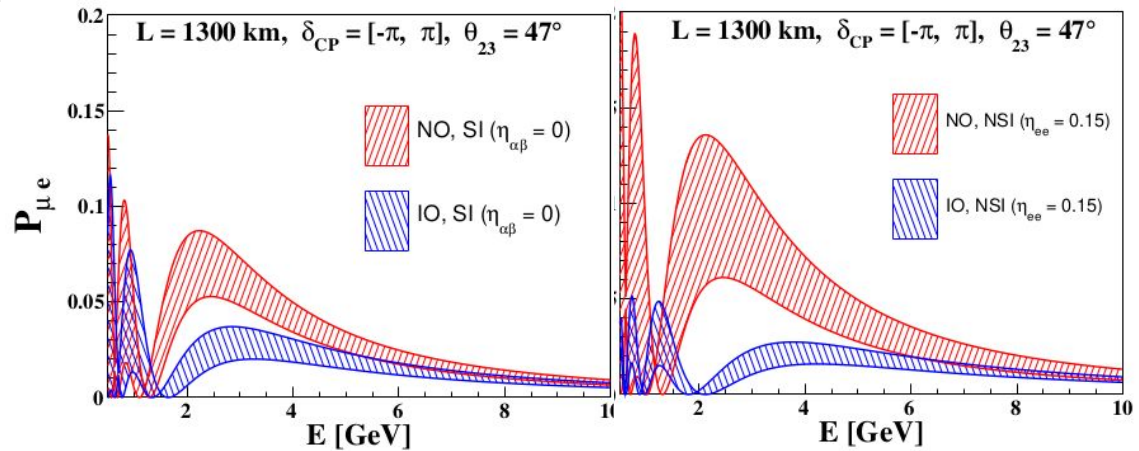
$$\Delta\chi_{\text{CPV}}^2(\delta_{\text{CP}}^{\text{true}}) = \min \left[\chi^2(\delta_{\text{CP}}^{\text{true}}, \delta_{\text{CP}}^{\text{test}} = 0), \chi^2(\delta_{\text{CP}}^{\text{true}}, \delta_{\text{CP}}^{\text{test}} = \pm\pi) \right]$$

- A positive (negative) η_{ee} enhances (suppresses) CPV sensitivity at DUNE and T2HK.
- Synergy between DUNE and T2HK significantly enhances the CPV sensitivity.

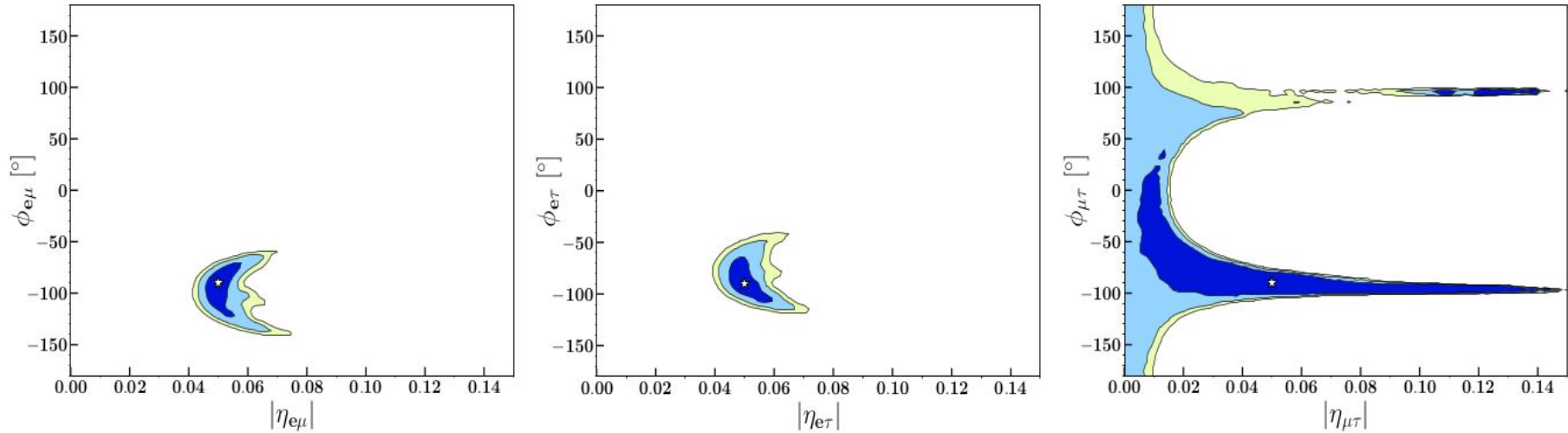
MO Sensitivity in presence of SNSI

$$\Delta\chi^2_{\text{MO}} = \chi^2_{\text{NO}} - \chi^2_{\text{IO}} \text{ (for true NO)}$$

- In presence of η_{ee} , the separation between NO and IO increases.
- MO sensitivity enhances for chosen values of η_{ee} for both DUNE and HK.



Correlation between off-diagonal SNSI parameters

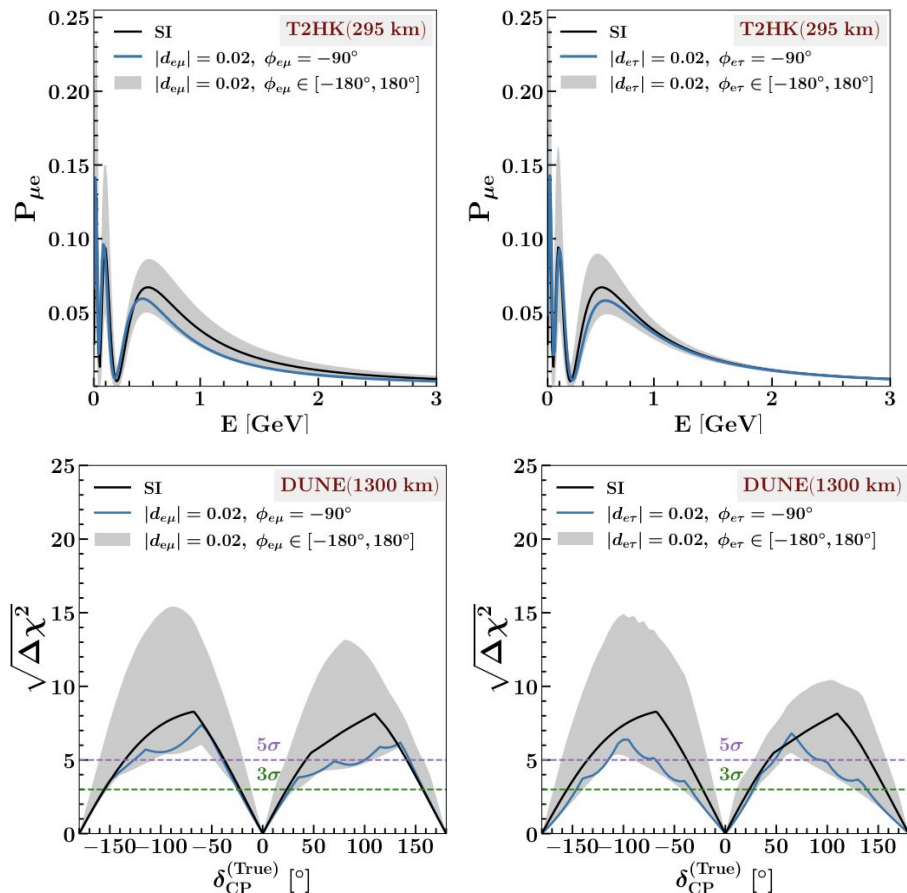


- For the combined scenario of $\eta_{\mu\tau}$ and $\phi_{\mu\tau}$, a degeneracy is observed for $\phi_{\mu\tau} = 90^\circ$.
- NO significant correlation is observed for $\eta_{e\mu}$ - $\phi_{e\mu}$ and $\eta_{e\tau}$ - $\phi_{e\tau}$.

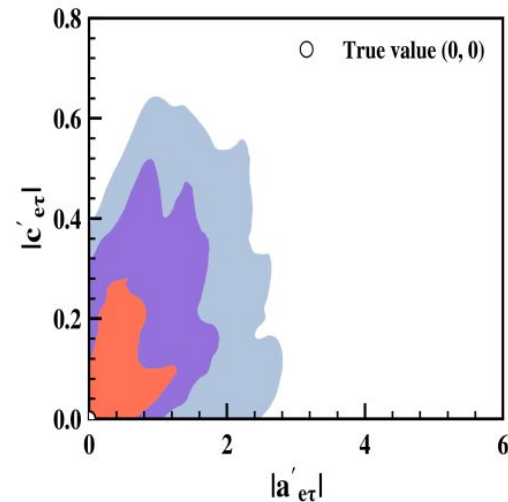
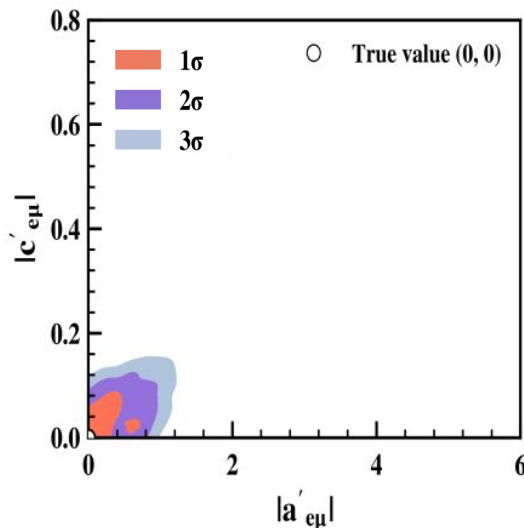
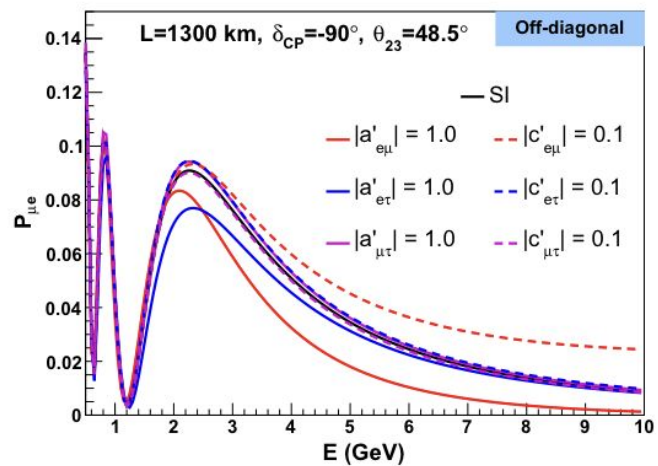
Dark NSI in Neutrino Oscillations

- Dark NSI parameters, $\eta_{e\mu}$ and $\eta_{e\tau}$ suppresses oscillation probability.
- CPV sensitivity suppresses in presence of $\eta_{e\tau}$ and $\eta_{e\mu}$.
- $\phi_{e\mu}$ and $\phi_{e\tau}$ has significant impact.

$$\Delta\chi^2_{\text{CPV}}(\delta_{\text{CP}}^{\text{true}}) = \min \left[\chi^2(\delta_{\text{CP}}^{\text{true}}, \delta_{\text{CP}}^{\text{test}} = 0), \chi^2(\delta_{\text{CP}}^{\text{true}}, \delta_{\text{CP}}^{\text{test}} = \pm\pi) \right]$$



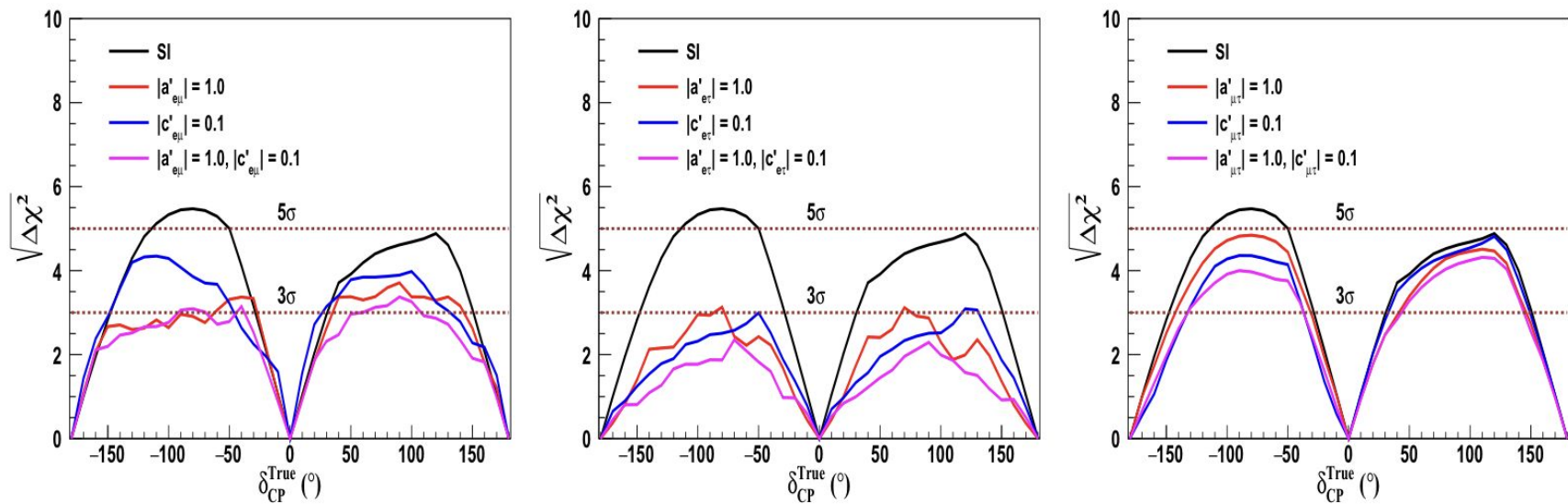
Lorentz Invariance Violation in neutrino oscillations



- The off-diagonal elements have a noticeable impact on probability for energies $E \gtrsim 1.5$ GeV.
- Stronger bound from DUNE on $a_{e\mu}$ and $a_{e\tau}$.

Experiments	Parameters [Unit]	Limits at 95% CL
SK	$a_{e\mu}$ [10^{-23} GeV]	$ \text{Re}(a_{e\mu}) < 1.8, \text{Im}(a_{e\mu}) < 1.8$
	$a_{e\tau}$ [10^{-23} GeV]	$ \text{Re}(a_{e\tau}) < 4.1, \text{Im}(a_{e\tau}) < 2.8$
KM3NeT	$a_{e\mu}$ [10^{-23} GeV]	< 2.53
	$a_{e\tau}$ [10^{-23} GeV]	< 4.70
DUNE (This Work)	$a_{e\mu}$ [10^{-23} GeV]	< 0.95
	$a_{e\tau}$ [10^{-23} GeV]	< 1.86

CP violation sensitivity in presence of LIV



- $a_{e\mu}$ suppresses sensitivity below 3σ for positive δ_{CP} plane, $a_{e\tau}$ suppresses over the entire δ_{CP} range, $a_{e\tau}$ milder effect
- Combining $a_{\alpha\beta}$ and $c_{\alpha\beta}$, further suppresses sensitivity.

APP (Neutrino and Astro-Particle Physics) Laboratory

Department of Physics, Tezpur University

Research Interests:

- Neutrino Physics (Non standard effects, sterile neutrinos)
- Detector Simulation & Instrumentation
- Cosmic Rays & Extensive Air Showers
- Deep learning and other Machine Learning algorithms for Reconstruction in HEP Experiments

Experimental Collaborations:

- Hyper-Kamiokande
- WCTE, IWCD
- GRAPES-3
- INO-ICAL

Current Grants:

CRG/2021/002961; DST-JSPS Indo
Japan Collaborative grant 2021



Abinash
PhD Completed,
Assistant Prof. at GL
College



Arnab
PhD Completed,
Post-doc at IACS



Dharitree
PhD student
(NS physics effects in
neutrinos, ML)



Priyankush
PhD student
(NS physics effects
in neutrinos, ML)



Abinash
PhD student
(NS effects in
neutrinos, ML)

Concluding remarks

- Neutrino oscillations: excellent tool for probing non-standard effects
- A caution!
Precision in measuring the standard oscillation parameters is important



***Thank you for the
kind attention!***