Neutrino mass ordering sensitivities at DUNE, HK and KNO in presence of scalar NSI

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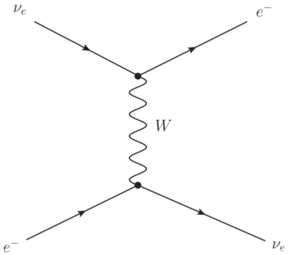
Outline

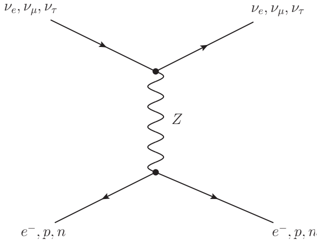
- Introduction: ν interactions, Matter effects & ν Oscillations
- Scalar Non-standard Interactions
  - Idea
  - Formalism
  - Our methodology
  - Impact of Scalar NSI in long baseline sector: mass ordering sensitivities
- Concluding Remarks & Outlook

Neutrino interactions with matter

- Neutrinos interact with matter via charged-current (CC) or neutral-current (NC) interactions.



(a)



(b)

- Only ν_e participate in CC interactions.
- NC interactions are flavour blind.

Neutrino interactions in standard model

- Elastic ν–electron scattering.
- The neutrino matter effects come from the forward scattering of neutrinos, considering zero momentum transfer between initial and final states.
- The effective Lagrangian for these interactions is given by

$$\mathcal{L}_{\rm cc}^{\rm eff} = -\frac{4G_F}{\sqrt{2}} \left[\overline{\nu_e}(p_3)\gamma_\mu P_L \nu_e(p_2)\right] \left[\overline{e}(p_1)\gamma^\mu P_L e(p_4)\right],$$

- P_L and P_R: left and right chiral projection operators respectively, with $P_L = (1-\gamma_5)/2$ and $P_R = (1+\gamma_5)/2)$
- p_i's: momentum of incoming and outgoing states
- G_F: the Fermi constant.

The effective Hamiltonian for ν–oscillations in matter

- These effects appear as matter potentials in the neutrino Hamiltonian $V_{\rm CC} = \pm\sqrt{2}G_F n_e$ and $V_{\rm NC} = -\dfrac{G_F n_n}{\sqrt{2}}$.
- The effective Hamiltonian ($\mathcal{H}_{matter}$) :

$$\mathcal{H}_{matter} \approx E_\nu + \frac{MM^\dagger}{2E_\nu} \pm V_{\rm SI} \,,$$

- The neutrino mass matrix M in flavour basis: $\mathcal{U}D_\nu\mathcal{U}^\dagger$, where $D_\nu \equiv$ diag(m_1, m_2, m_3).
- The simplified effective Hamiltonian ($\mathcal{H}_{\rm matter}$):

$$\mathcal{H}_{\rm matter} = E_\nu + \frac{1}{2E_\nu}\mathcal{U}{\rm diag}(0, \Delta m^2_{21}, \Delta m^2_{31})\mathcal{U}^\dagger + {\rm diag}(V_{\rm CC}, 0, 0)$$

Vector mediated NSI

- Vector NSI formalism: introduces an extra vector mediator
- The vector NSI effect contributes to the $\bar{\nu}\gamma^0\nu$ term: a modified potential

Effective Hamiltonian for a typical vector NSI

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

Scalar Non Standard Interactions

- Coupling of neutrinos with a scalar → interesting possibility

Effective Lagrangian for a typical scalar NSI

$$\mathcal{L}_{\rm eff}^{\rm S} = \frac{y_f y_{\alpha\beta}}{m_\phi^2} (\bar{\nu}_\alpha(p_3)\nu_\beta(p_2))(\bar{f}(p_1)f(p_4)), \tag{1}$$

where,

- α, β refer to the neutrino flavors e, μ, τ,
- f = e, u, d indicate the matter fermions, (e: electron, u: up-quark, d: down-quark),
- $\bar{f}$ is for corresponding anti fermions,
- $y_{\alpha\beta}$ is the Yukawa couplings of the neutrinos with the scalar mediator ϕ,
- y_f is the Yukawa coupling of ϕ with f,
- m_ϕ is the mass of the scalar mediator ϕ.

Ge & Parke, PRL.122(2019)211801; Babu et al., PRD101(2020)095029

Scalar NSI

- The effective Lagrangian: can not be converted into vector currents
- The scalar NSI: will not appear as a contribution to the matter potential
- It may appear as a medium-dependent perturbation to the neutrino mass term
- The corresponding Dirac equation incorporating the new scalar interactions:

$$\bar{\nu}_\beta \left[i\partial_\mu \gamma^\mu + \left(M_{\beta\alpha} + \frac{\sum_f n_f y_f y_{\alpha\beta}}{m_\phi^2} \right) \right] \nu_\alpha = 0\,,$$

The effective Hamiltonian with scalar NSI

$$\mathcal{H}_{\rm SNSI} \approx E_\nu + \frac{M_{\rm eff} M_{\rm eff}^\dagger}{2E_\nu} \pm V_{\rm SI}$$

- $M_{\rm eff} = M + M_{\rm SNSI}$

Scalar NSI

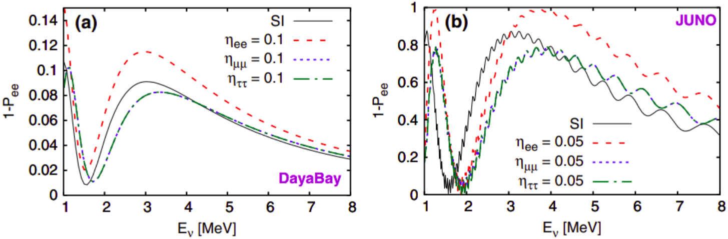
- M_{eff} $(\equiv \mathcal{U}' D_\nu \mathcal{U}'^\dagger)$ can be diagonalized by a mixing matrix $\mathcal{U}' \equiv P\mathcal{U}Q^\dagger$
- Q: a Majorana rephasing matrix, can be absorbed as $QD_\nu Q^\dagger = D_\nu$
- P: unphysical diagonal rephasing matrix, rotated into the scalar NSI contribution

$$M_{eff} \equiv \mathcal{U}D_\nu\mathcal{U}^\dagger + P^\dagger M_{SNSI}P \equiv M + \delta M.$$

- The scalar NSI contribution δM scales with the matter density.
- The oscillation probability would feel the matter density variations along the baseline.

Scalar NSI in short baseline terrestrial experiments

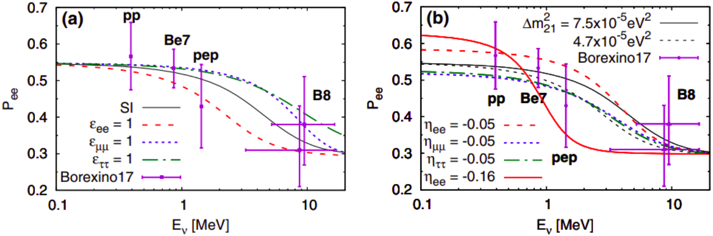
- The variation in the matter density is negligible.
- One combination of M and δM: redefined as the effectively measured mass matrix.
- The matter density subtraction at their typical matter density ρ_s = 2.6 g/cm3 is implemented as $M + \delta M(\rho) \equiv M_{re} + \delta M(\rho_s)\dfrac{\rho - \rho_s}{\rho}$.
- At $\rho = \rho_s$: the effective mass matrix is $M_{re} \equiv M + \delta M(\rho_s) = U_\nu D_\nu U_\nu^\dagger$.



Ge & Parke, PRL.122(2019)211801; Babu et al., PRD101(2020)095029

Scalar NSI in Solar sector

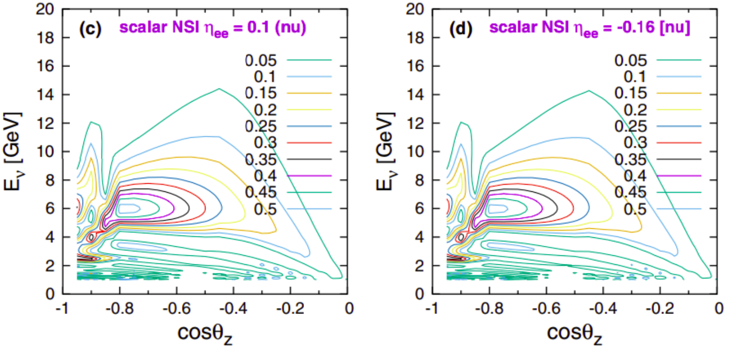
- The scalar NSI is not energy dependent: not suppressed at low energies



Ge & Parke, PRL.122(2019)211801; Babu et al., PRD101(2020)095029

Scalar NSI in Atmospheric sector

- The atmospheric neutrino oscillation: experiences matter density variation.
- Neutrinos crossing the Earth core: the most significant matter density variation.
- A binned analysis, mainly in the ν–zenith angle may identify the scalar NSI effects.



Ge & Parke, PRL.122(2019)211801; Babu et al., PRD101(2020)095029

Scalar NSI in Long Baseline sector

- The effective mass matrix may get modified by the scalar NSI: It can impact δ_{CP} measurements.
- Most relevant neutrino oscillation channels: $\nu_\mu \to \nu_e$ (appearance) and $\nu_\mu \to \nu_\mu$ (disappearance)

[Our work: JHEP06(2022)129, JHEP01(2023)079, JHEP06(2024)128, arXiv:2406.15307, arXiv:2307.05348]

Parameterization

Parametrization of Scalar NSI effect

- δM: the perturbative term (scalar NSI in which the unphysical rephasing matrix P is rotated into)
- An effective and general form of δM:

$$\delta M \equiv S_m \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix}.$$

- Scaling $S_m \equiv \sqrt{2.55 \times 10^{-3} eV^2}$, corresponds to a typical $\sqrt{|\Delta m^2_{31}|}$
- $\eta_{\alpha\beta}$: dimensionless, quantify the effects of the scalar NSI

Choices of Scalar NSI matrix

- The Hermicity of the neutrino Hamiltonian: diagonal elements are real and the off-diagonal elements are complex

$$\eta_{\alpha\beta} = |\eta_{\alpha\beta}| e^{i\phi_{\alpha\beta}}; \qquad \alpha \neq \beta. \tag{2}$$

- Our choice: a diagonal δM which preserves the Hermicity of the Hamiltonian
- Exploration of the scalar NSI elements through different probability channels.
- No definite bounds yet on $\eta_{\alpha\beta}$

Choices of SNSI matrix

Case-I

$$M_{\text{eff}} = \mathcal{U}\text{diag}\,(m_1, m_2, m_3)\,\mathcal{U}^\dagger + \sqrt{|\Delta m^2_{31}|}\;\text{diag}\,(\eta_{ee}, 0, 0)\,. \quad (3)$$

Case-II

$$M_{\text{eff}} = \mathcal{U}\text{diag}\,(m_1, m_2, m_3)\,\mathcal{U}^\dagger + \sqrt{|\Delta m^2_{31}|}\;\text{diag}\left(0, \eta_{\mu\mu}, 0\right). \quad (4)$$

Case-III

$$M_{\text{eff}} = \mathcal{U}\text{diag}\,(m_1, m_2, m_3)\,\mathcal{U}^\dagger + \sqrt{|\Delta m^2_{31}|}\;\text{diag}\,(0, 0, \eta_{\tau\tau})\,. \quad (5)$$

- Scalar NSI brings in a direct dependence of Neutrino Oscillations to the Absolute Neutrino masses!

Density dependence of SNSI

- The effect of SNSI scales linearly with matter density, upcoming experiments with longer baselines would observe a more dominant contribution.
- We define the $\eta_{\alpha\beta}$ parameters as for an experiment e.g. DUNE as,

$$\eta_{\alpha\beta} = \eta_{\alpha\beta}^{(\text{true})} \left(\frac{\rho_{\text{DUNE}} - \rho_0}{\rho_0} \right).$$

- $\eta_{\alpha\beta}^{(\text{true})}$ is the true value of the SNSI parameter.
- ρ_{DUNE} is the average matter density experienced in DUNE.
- ρ_0 is the average matter density for reactor and LBL experiments from which the neutrino mixing parameters are currently determined.

Methodology of probing Scalar NSI effects at a detector

A model independent study of Scalar NSI effects at DUNE

Oscillation Probabilities

- Obtain Oscillation Probabilities by incorporating the modified NS Hamiltonian; Numerically

Statistical framework for Hypothesis Testing

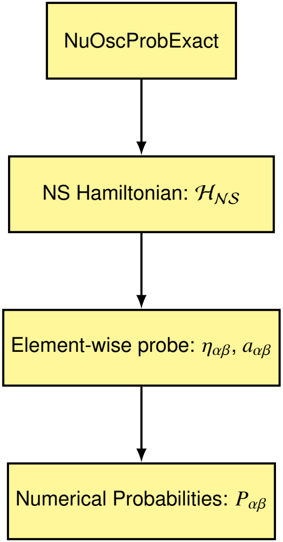
- A statistical framework that includes a hypothesis testing to test different cases.
- SI-case and various SNSI cases.

Quantifying Detector Potential for chosen Scalar NSI cases

- The statistical tests would give the sensitivity of different models and finally would give a confidence level to constrain the values of the chosen parameters.

Oscillation Probabilities in presence of SNSI

- Scalar NSI effects: implemented in a numerical probability calculator
- NuOscProbExact: A general purpose probability calculator, which employs expansions of quantum operators in terms of SU(2) and SU(3) matrices to calculate oscillation probabilities
- The Hamiltonian: accordingly modified for NS Effects.
- Element-wise probe of the NSI effects



https://github.com/mbustama/NuOscProbExact

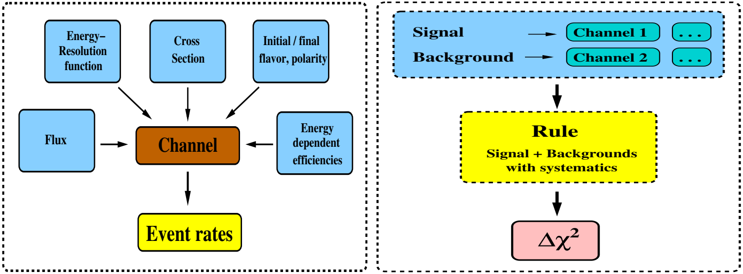
Statistical framework (using GLoBES package)

Statistical framework for Hypothesis Testing

- A statistical framework that includes a hypothesis testing to test different cases.

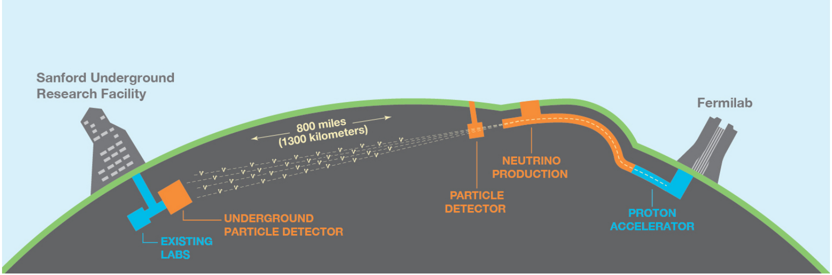
$$\Delta\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{\left[N^{i,j}_{true}(\eta) - N^{i,j}_{test}(\eta)\right]^2}{N^{i,j}_{true}(\eta)}$$

$N^{i,j}_{true}$ ($N^{i,j}_{test}$) : number of true (test) events in the $\{i, j\}$-th bin.



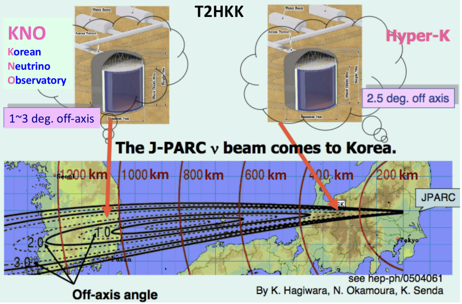
Huber, P., Lindner, M., Winter, W. Comput. Phys. Commun., (2005)

DUNE: Deep Underground Neutrino Experiment: Upcoming superbeam neutrino experiment



Detector details	Normalisation error		Energy calibration error	
	Signal	Background	Signal	Background
Baseline = 1300 km Runtime (yr) = 5 ν + 5 $\bar{\nu}$ 35 kton, LArTPC $\varepsilon_{app} = 80\%$, $\varepsilon_{dis} = 85\%$ $R_e = 0.15/\sqrt{E}$, $R_\mu = 0.20/\sqrt{E}$	$\nu_e : 5\%$ $\nu_\mu : 5\%$	$\nu_e : 10\%$ $\nu_\mu : 10\%$	$\nu_e : 5\%$ $\nu_\mu : 5\%$	$\nu_e : 5\%$ $\nu_\mu : 5\%$

Long Baseline Counterparts of HyperK (HK, KNO)



Experiment details	Channels	Normalization error: Signal	Normalization error: Background
HK Baseline = 295 km Fiducial mass =187 kt (WC) Runtime = 2.5 yr ν + 7.5 yr $\bar{\nu}$	$\nu_e(\bar{\nu}_e)$ appearance $\nu_\mu(\bar{\nu}_\mu)$ disappearance	3.2 % (3.9 %) 3.6 % (3.6 %)	10 % (10 %) 10 % (10 %)
HK+KNO Baseline = 295, 1100km Fiducial mass = 187, 187 kt(WC) Runtime = 2.5 yr ν + 7.5 yr $\bar{\nu}$	$\nu_e(\bar{\nu}_e)$ appearance $\nu_\mu(\bar{\nu}_\mu)$ disappearance	3.2 % (3.9 %) 3.6 % (3.6 %)	10 % (10 %) 10 % (10 %)

χ^2 – Analysis

- The statistical χ^2 to probe whether an experiment can distinguish between NO ($m_1 < m_2 < m_3$) and IO ($m_3 < m_1 < m_2$):

$$\chi^2 \equiv \min_{\eta} \sum_i \sum_j \frac{\left[N^{i,j}_{true} - N^{i,j}_{test}\right]^2}{N^{i,j}_{true}},$$

- $N^{i,j}_{true}$ and $N^{i,j}_{test}$: numbers of true and test events in the $\{i, j\}$-th bin
- Two cases are considered for the analysis to obtain $\Delta\chi^2$,
  - Considering NO as the true mass ordering,

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

  - Considering IO as the true mass ordering,

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

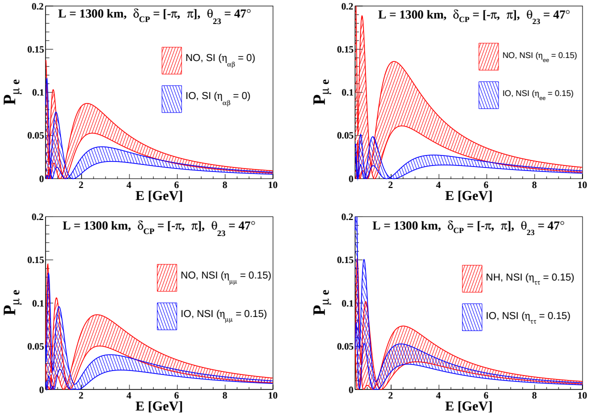
- Significance: denoted by $n\sigma$, where $n \equiv \sqrt{\Delta\chi^2}$

Synergy: DUNE, HK+KNO

- The combination of various experiments may help in determining the oscillation parameters unambiguously.
- Wider L–E space, increased statistics.

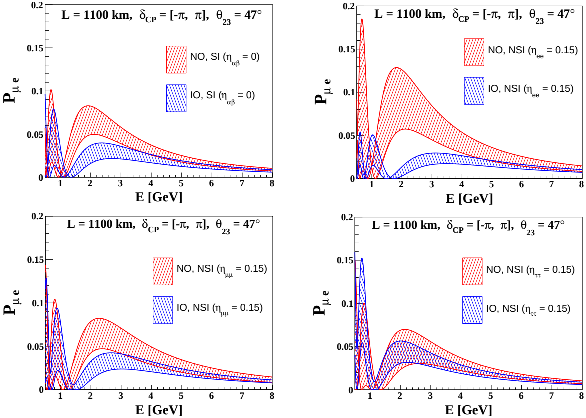
Experiment	Baseline (L in km)	Fiducial Volume (in kton)
HK+KNO	1100 km	187×2
DUNE	1300 km	40

Effects on Appearance Probability (DUNE, 1300 km)



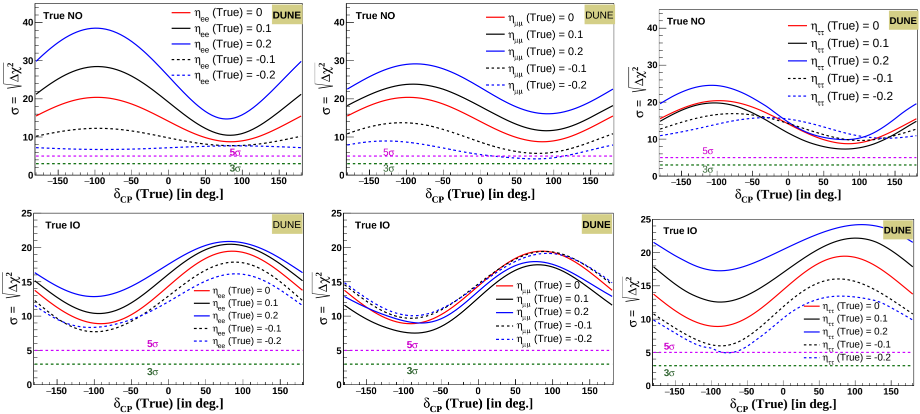
- In absence of NSI, DUNE baseline can separate between NO and IO
- Presence of η_{ee} widens the energy range and separation between the MOs
- $\eta_{\mu\mu}$ marginally reduces the separation; for $\eta_{\tau\tau}$ significant overlapping of bands

Effects on Appearance Probability (HK+KNO, 1100 km)



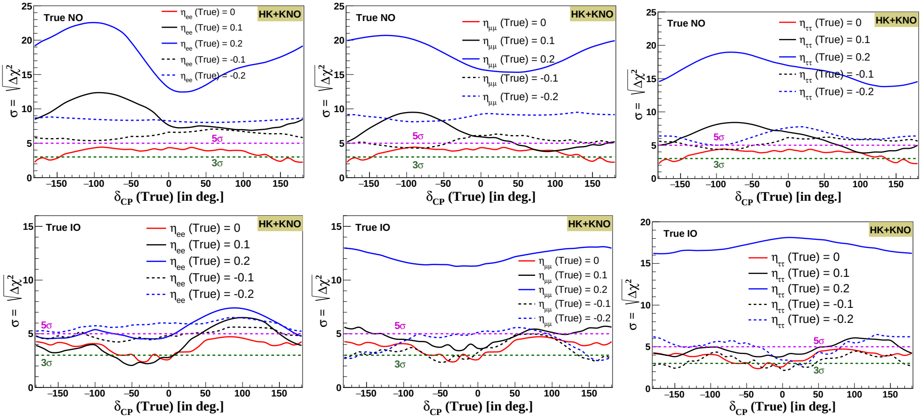
- In absence of NSI, HK+KNO baseline can separate between NO and IO
- Presence of η_{ee} widens the energy range and separation between the MOs
- $\eta_{\mu\mu}$ reduces the discriminating power of the neutrino MO
- For $\eta_{\tau\tau}$, both the NO and IO band are seen to completely overlap

Impact on MO sensitivities: DUNE



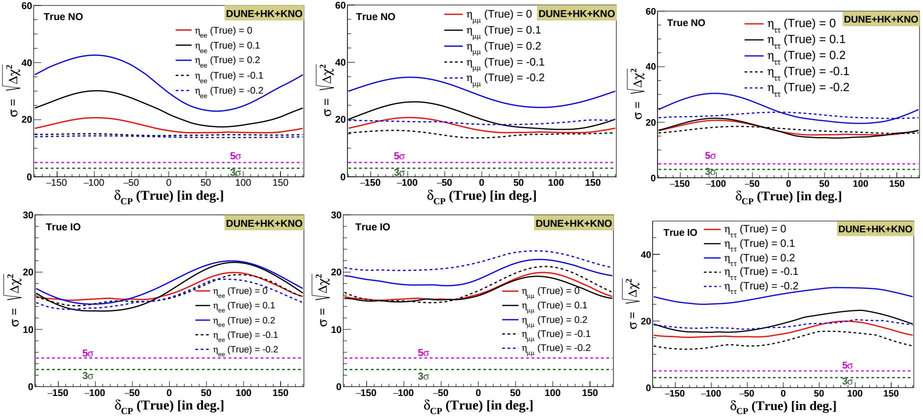
- True NO: +ve (-ve) values of $\eta_{ee}/\eta_{\mu\mu}$ enhance (suppress) the MO sensitivities.
- $\eta_{\tau\tau}$: Enhancement/suppression depending on the δ_{CP} value for true NO.
- For true IO, positive (negative) η_{ee} and $\eta_{\tau\tau}$, enhance (suppress) the MO sensitivities.
- For a +ve (-ve) $\eta_{\mu\mu}$ the sensitivities get mostly suppressed (enhanced), for true IO.

Impact on MO sensitivities: HK+KNO



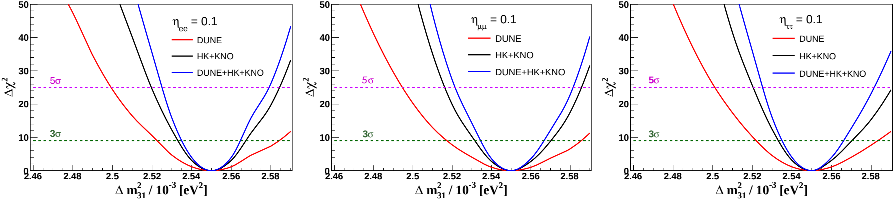
- We observe significant impact on MO–sensitivities at different δ_{CP}, for both the MOs

Impact on MO sensitivities: DUNE+HK+KNO



- The MO sensitivity is above 5σ CL for all values of δ_{CP}.
- For true NO, a positive (negative) η_{ee} and $\eta_{\mu\mu}$ enhances (suppresses) the MO sensitivities for most values of δ_{CP}.
- For true IO, the effect of $\eta_{\tau\tau}$ is prominent as compared to η_{ee}.

Precision Measurement of Δm^2_{31}



- The constraining capability of DUNE+HK+KNO configuration is better compared to DUNE, HK+KNO for all the cases of scalar NSI parameters. Synergy leads to better constraining.
- In presence of η_{ee} and $\eta_{\tau\tau}$, the constraining ofΔm^2_{31} is nominally better in comparison to $\eta_{\mu\mu}$.

Concluding Remarks & Outlook

- Identifying the subdominant effects like NSI in the neutrino experiments and their effects on the physics potential of different experiments are crucial.
- Scalar NSI may significantly impact on the determination of true MO.
- Scalar NSI & neutrino mass: dependence of neutrino oscillations on absolute neutrino masses.
- Scalar coupling models: parameterization of the scalar NSI effects.


Thank you for the kind attention!

Benchmark values of the oscillation parameters

Parameters	True Values	Marginalization range
θ_{12} [°]	34.51	fixed
θ_{23} [°]	47	$40 \rightarrow 50$
θ_{13} [°]	8.44	fixed
δ_{CP}	$-\pi/2$	$-\pi \rightarrow \pi$
Δm^2_{21} $[10^{-5} eV^2]$	7.56	$6.82 \rightarrow 8.04$
Δm^2_{31} (NO) $[10^{-3} eV^2]$	2.55	(2.25 - 2.65)
Δm^2_{31} (IO) $[10^{-3} eV^2]$	-2.49	- (2.25 - 2.65)

Table 1: Benchmark values of ν-oscillation parameters used.