

Imprints of scalar mediated NSI on long baseline experiments



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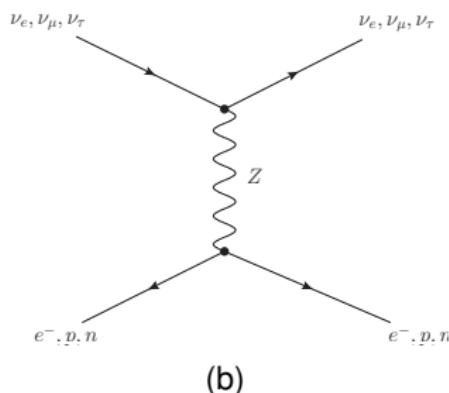
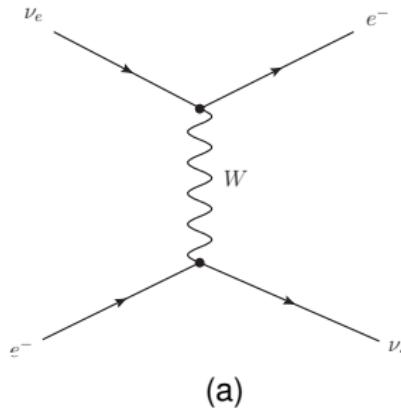
**31st International Symposium on Lepton Photon Interactions at High Energies,
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Outline

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

Neutrino interactions with matter

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



- 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

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

- 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

$$V_{\text{CC}} = \pm \sqrt{2} G_F n_e \quad \text{and} \quad V_{\text{NC}} = - \frac{G_F n_n}{\sqrt{2}}$$

- The effective Hamiltonian ($\mathcal{H}_{\text{matter}}$) :

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

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

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

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

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

Scalar Non Standard Interactions

- coupling of neutrinos with a scalar → interesting possibility

Effective Lagrangian for a typical scalar NSI

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

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

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

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

Scalar NSI

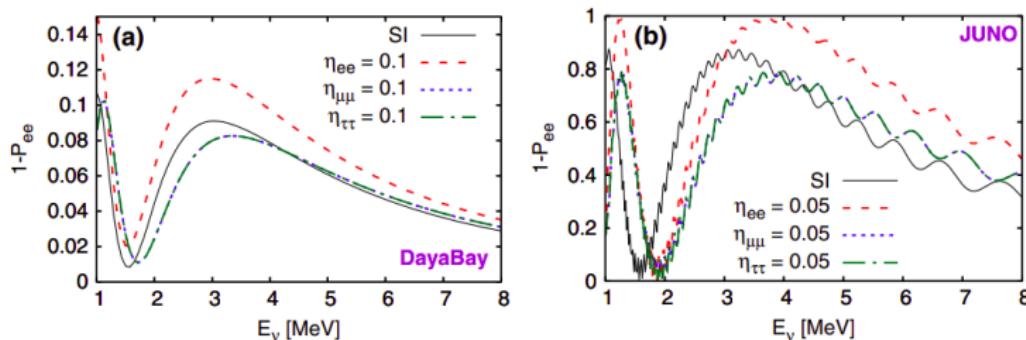
- M_{eff} ($\equiv \mathcal{U}' D_\nu \mathcal{U}'^\dagger$) can be diagonalized by a mixing matrix $\mathcal{U}' \equiv P \mathcal{U} Q^\dagger$
- Q: a Majorana rephasing matrix, can be absorbed as $Q D_\nu Q^\dagger = D_\nu$
- P: unphysical diagonal rephasing matrix, rotated into the scalar NSI contribution

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

- 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

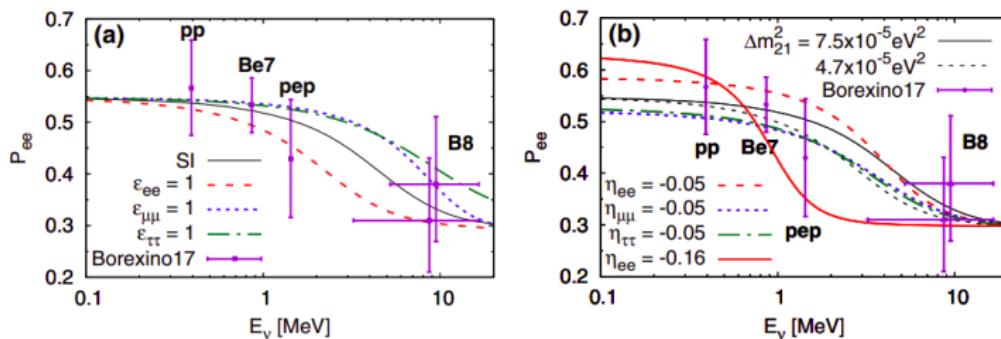
- The variation in the matter density is negligible.
- One combination of M and δM : redefined as the effectively measured mass matrix.
- The matter density subtraction at their typical matter density $\rho_s = 2.6 \text{ g/cm}^3$ is implemented as $M + \delta M(\rho) \equiv M_{re} + \delta M(\rho_s) \frac{\rho - \rho_s}{\rho}$.
- 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

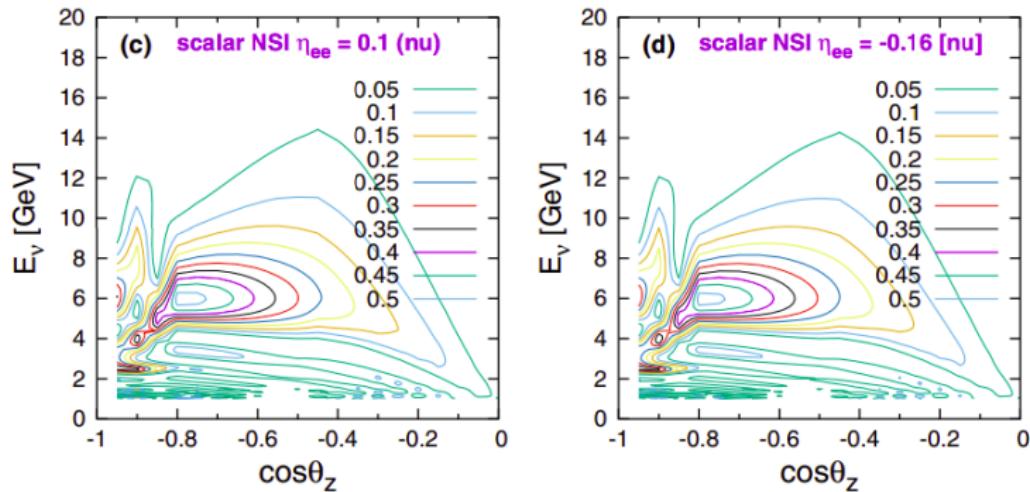
- The scalar NSI is not energy dependent: not suppressed at low energies



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., PRD 101(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: $\nu_\mu \rightarrow \nu_e$ (appearance) and $\nu_\mu \rightarrow \nu_\mu$ (disappearance)

Medhi A., MMD, Dutta D.; JHEP06(2022)129, JHEP01(2023)079

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 :

$$\delta M \equiv \sqrt{|\Delta m_{31}^2|} \begin{pmatrix} \eta_{ee} & \eta_{e\mu} & \eta_{e\tau} \\ \eta_{\mu e} & \eta_{\mu\mu} & \eta_{\mu\tau} \\ \eta_{\tau e} & \eta_{\tau\mu} & \eta_{\tau\tau} \end{pmatrix}.$$

- $\sqrt{|\Delta m_{31}^2|}$: a characteristic scale.
- $\eta_{\alpha\beta}$: 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

$$\eta_{\alpha\beta} = |\eta_{\alpha\beta}| e^{i\phi_{\alpha\beta}}; \quad \alpha \neq \beta. \quad (2)$$

- 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

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

Case-II

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

Case-III

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

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

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

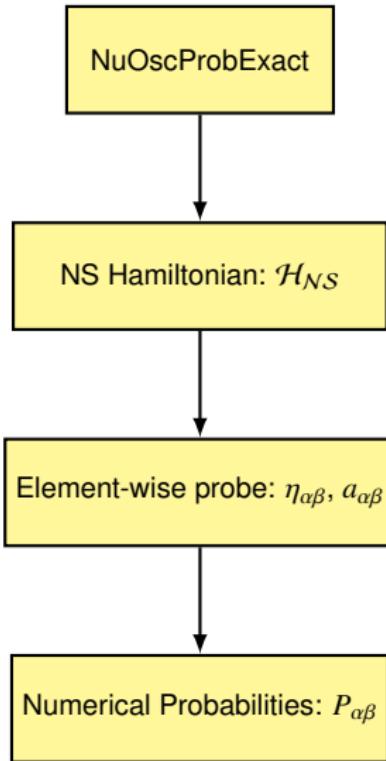
- A statistical framework that includes a hypothesis testing to test different cases.
- SI-case and various SNSI cases.

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.

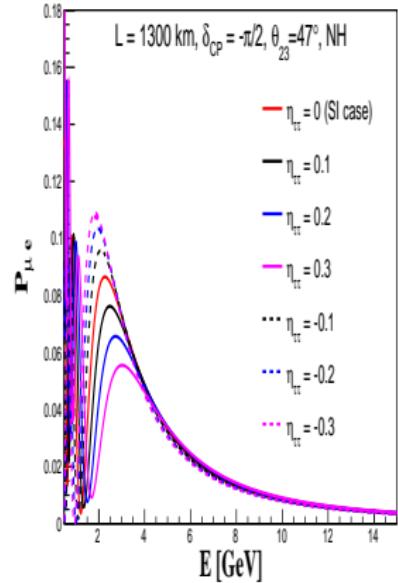
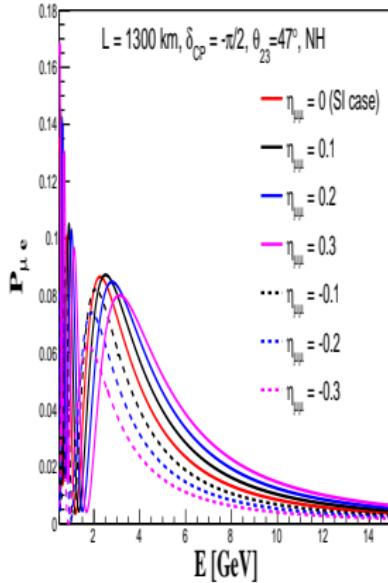
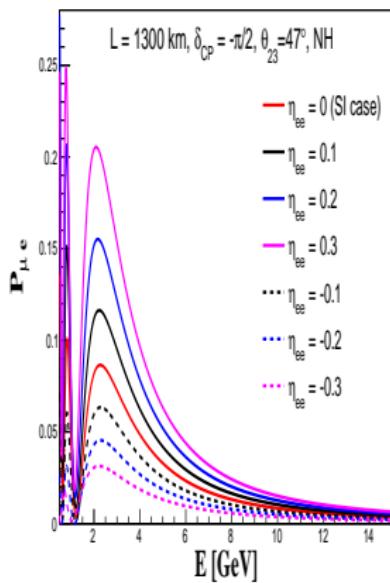
Oscillation Probabilities in presence of SNSI

- 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



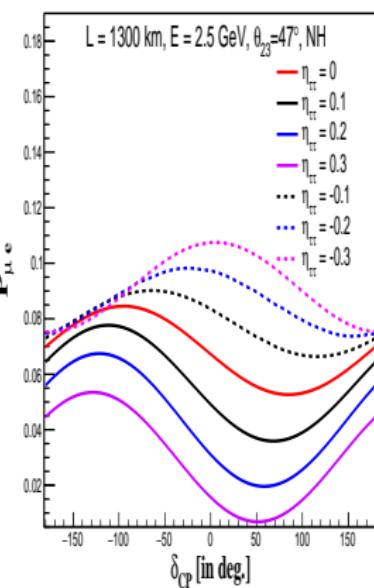
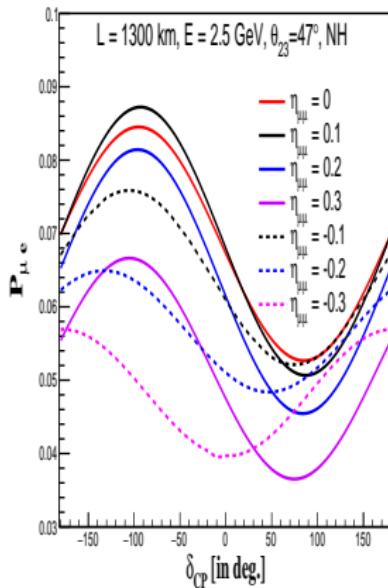
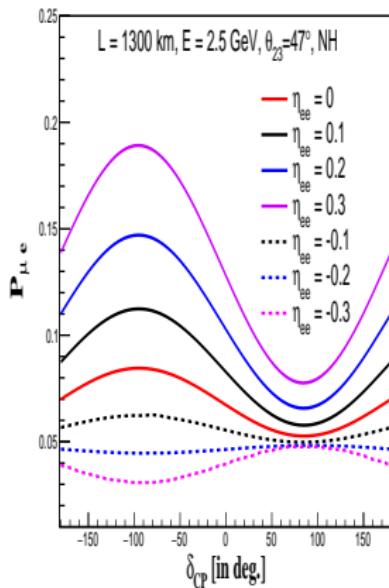
<https://github.com/mbustama/NuOscProbExact>

Results: $P_{\mu e}$ vs E



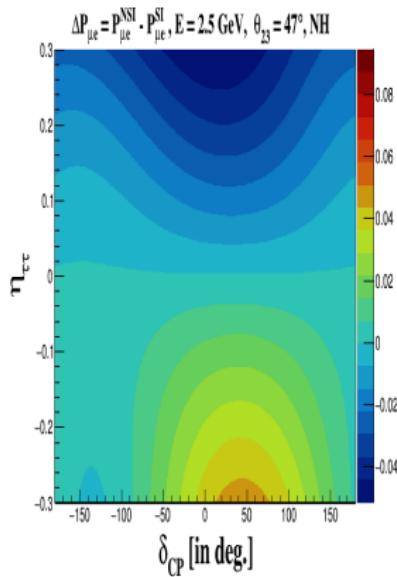
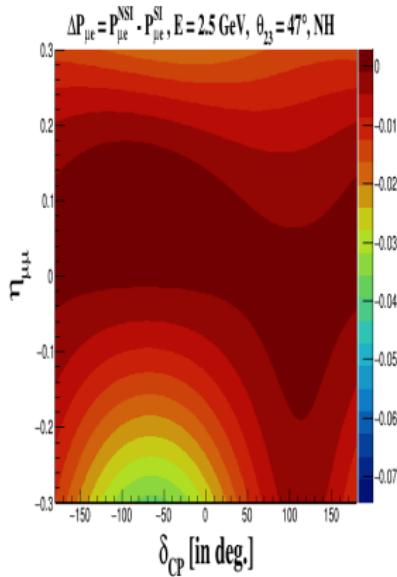
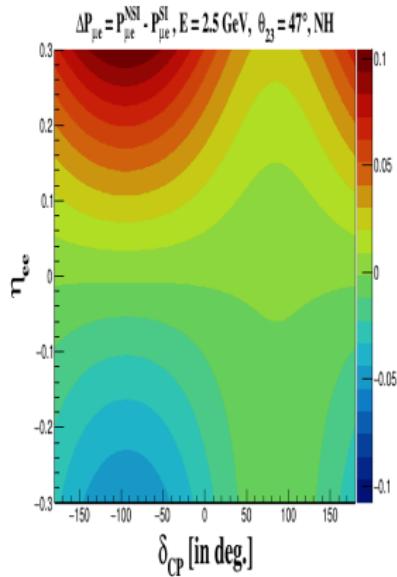
- η_{ee} and $\eta_{\tau\tau}$: amplitude
- $\eta_{\mu\mu}$: peak shift.

Results: $P_{\mu e}$ vs δ_{CP}



- The degeneracies in $\eta_{\alpha\beta} - \delta_{CP}$ space: will impact the δ_{CP} measurements at this baseline

Results: $\Delta P_{\alpha\beta} = P_{\alpha\beta}(\text{with SNSI}) - P_{\alpha\beta}(\text{w/o SNSI})$



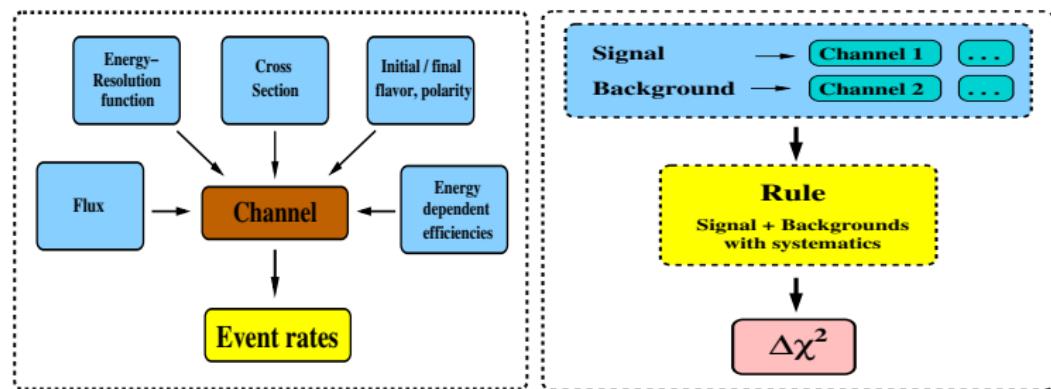
Statistical framework (using GLoBES package)

Statistical framework for Hypothesis Testing

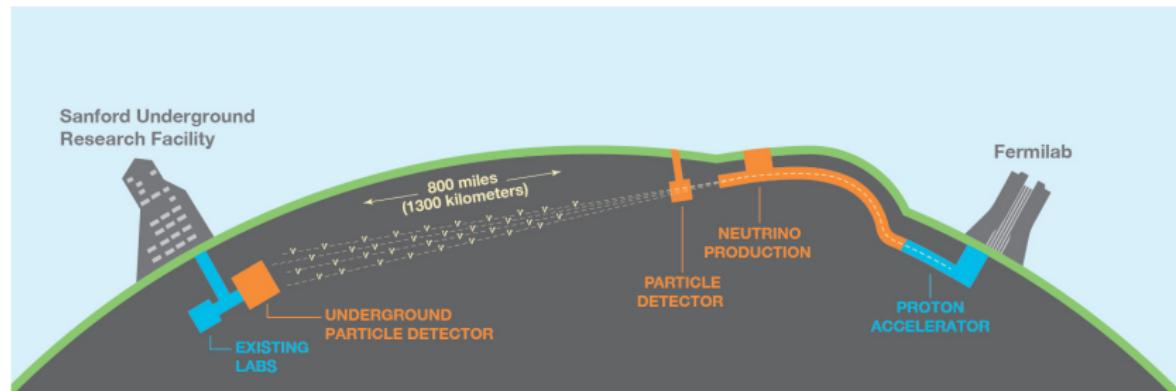
- A statistical framework that includes a hypothesis testing to test different cases.

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

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

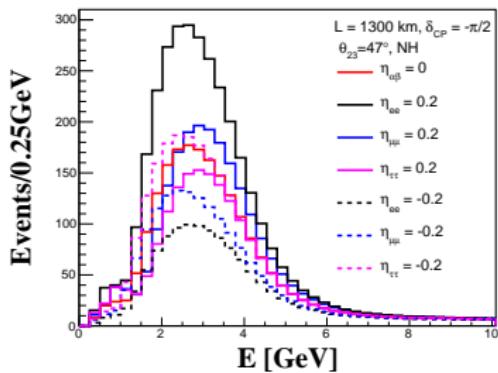


DUNE: Deep Underground Neutrino Experiment: Upcoming superbeam neutrino experiment



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

Results: Simulated Event Rates at DUNE



- Binned events: in good agreement with the probabilities
- For positive (negative) η_{ee} : number of events increases (decreases) compared to the ‘no scalar NSI’ case in each bin.
- For positive (negative) values of $\eta_{\mu\mu}$ and $\eta_{\tau\tau}$: peaks shift
- For positive (negative) values of $\eta_{\mu\mu}, \eta_{\tau\tau}$: the number of events increases (decreases) around the oscillation maxima

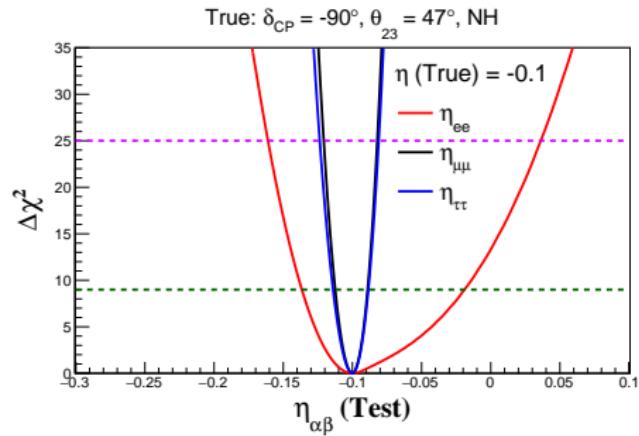
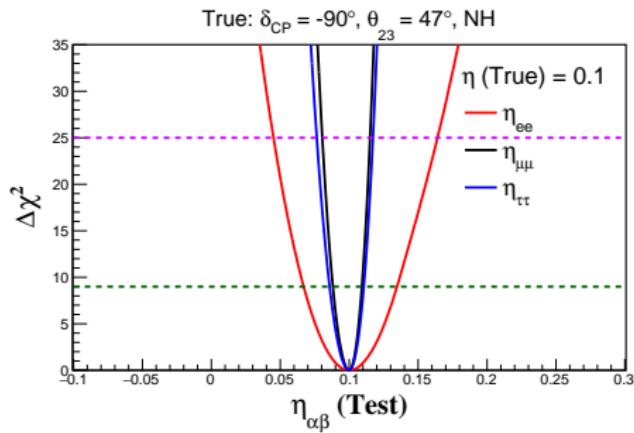
χ^2 – Analysis

- The statistical χ^2 to probe whether an experiment can distinguish between CP-conserving ($\delta_{CP} = 0, \pm \pi$) and CP-violating values ($\delta_{CP} \neq 0, \pm \pi$):

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

- $N_{true}^{i,j}$ and $N_{test}^{i,j}$: numbers of true and test events in the $\{i, j\}$ -th bin
- Significance: denoted by $n\sigma$, where $n \equiv \sqrt{\Delta\chi^2}$

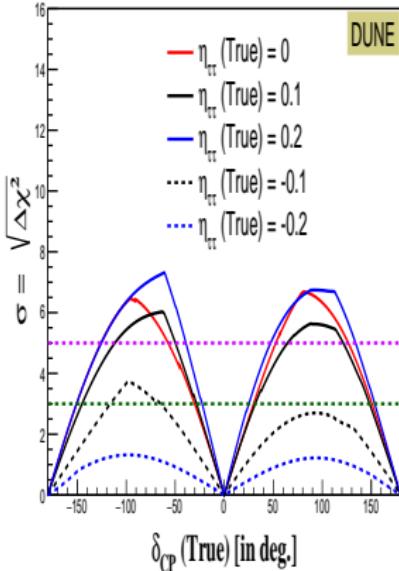
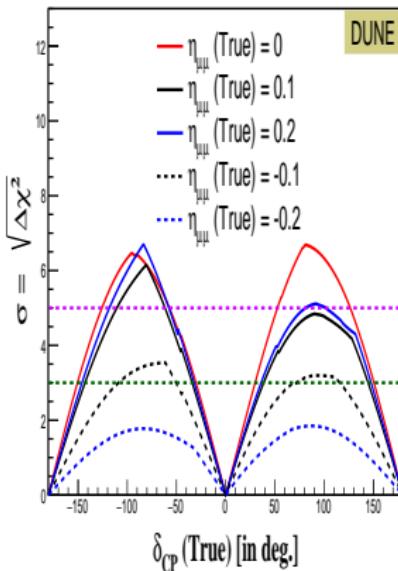
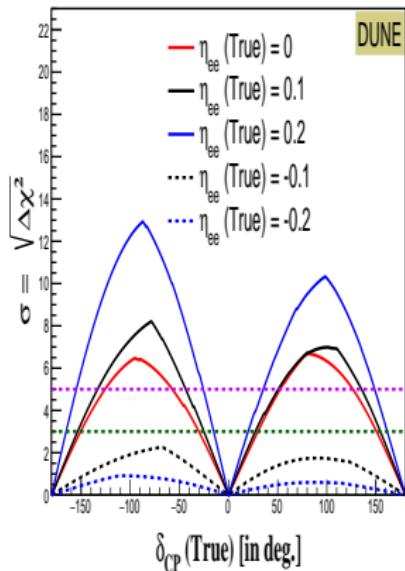
Results: Sensitivity of DUNE to $\eta_{\alpha\beta}$



Results: CP Violation sensitivity of DUNE

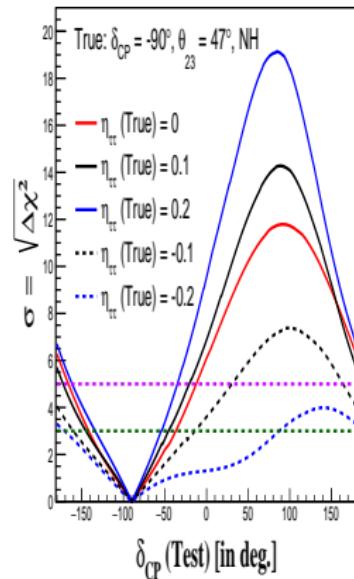
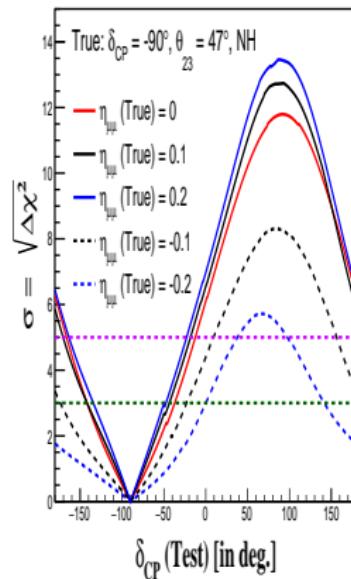
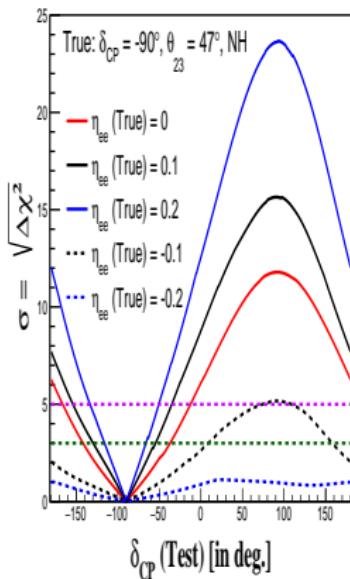
$$\Delta\chi^2_{\text{CPV}}(\delta_{\text{CP}}^{\text{true}}) = \min \left[\chi^2(\delta_{\text{CP}}^{\text{true}}, \delta_{\text{CP}}^{\text{test}} = 0), \chi^2(\delta_{\text{CP}}^{\text{true}}, \delta_{\text{CP}}^{\text{test}} = \pm\pi) \right].$$

DUNE [5 (ν) + 5 ($\bar{\nu}$)]



- Negative η deteriorates CP Violation sensitivity.

Results: CP Precision sensitivity of DUNE

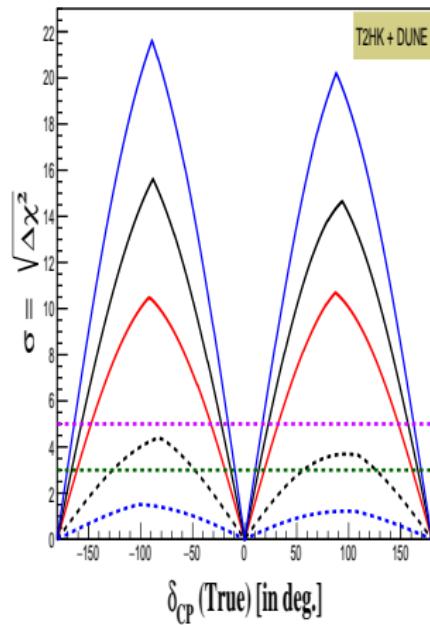
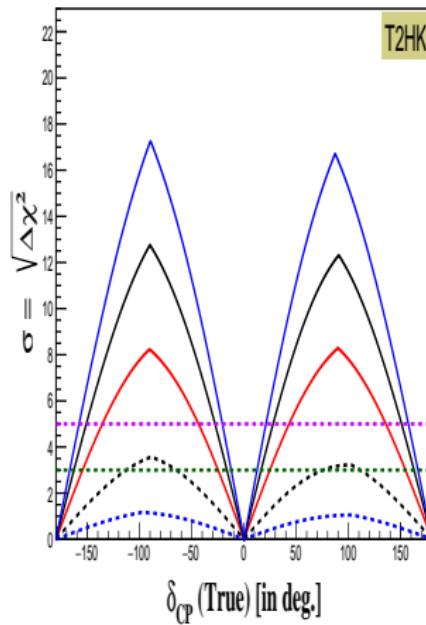
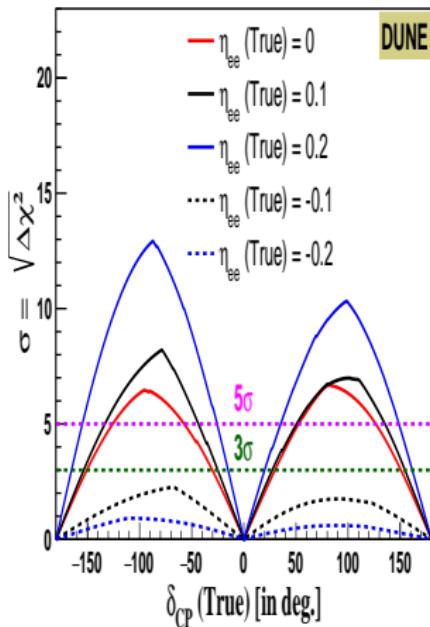


Synergy: DUNE, T2HK

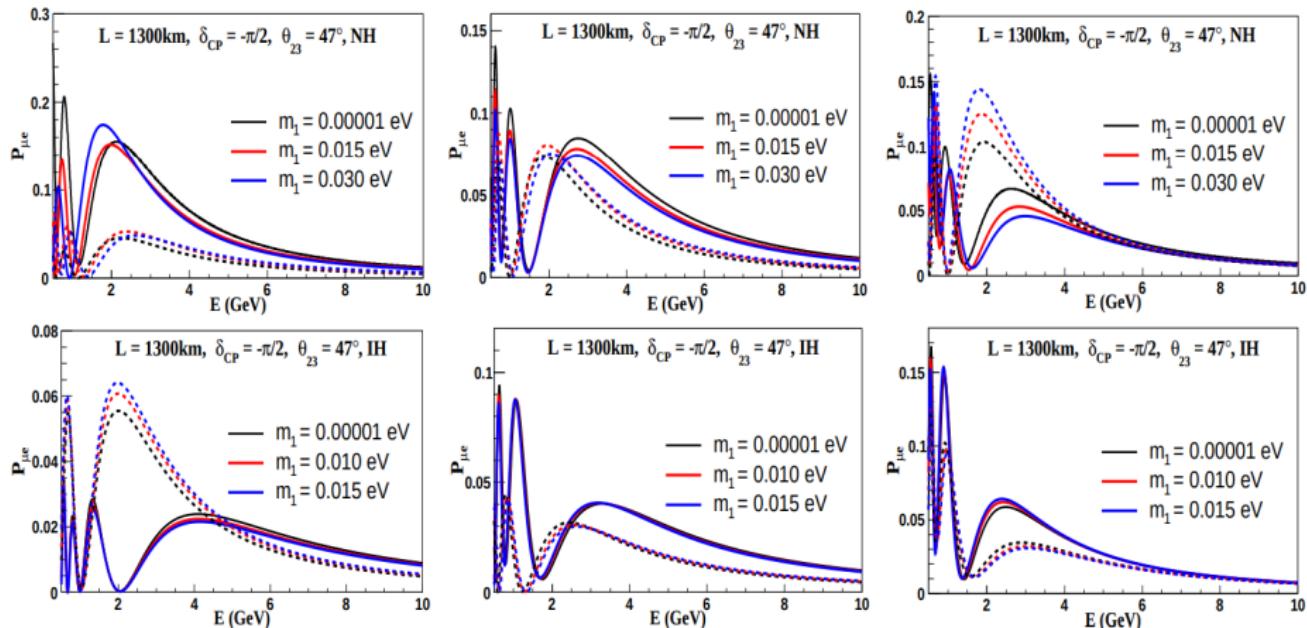
- The combination of various experiments may help in determining the oscillation parameters unambiguously.
- Wider L–E space, increased statistics.

Experiment	Baseline (L in km)	Fiducial Volume (in kton)
T2HK	295 km	187×2
DUNE	1300 km	40

Results : Effects on CP Violation sensitivity



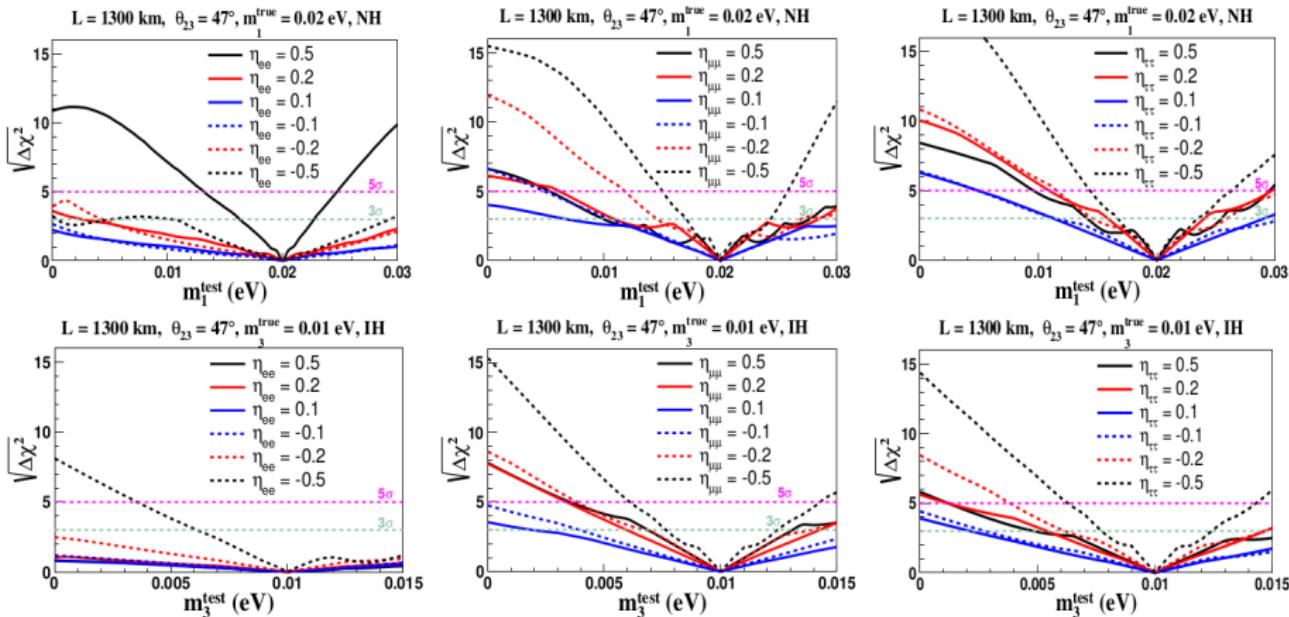
Neutrino mass measurements: Impact on oscillation probabilities



- $P_{\mu e}$: significant effect with varying ν -mass for both hierarchies.

Medhi A., Sarker A., MMD; ArXiv: 2307.05348

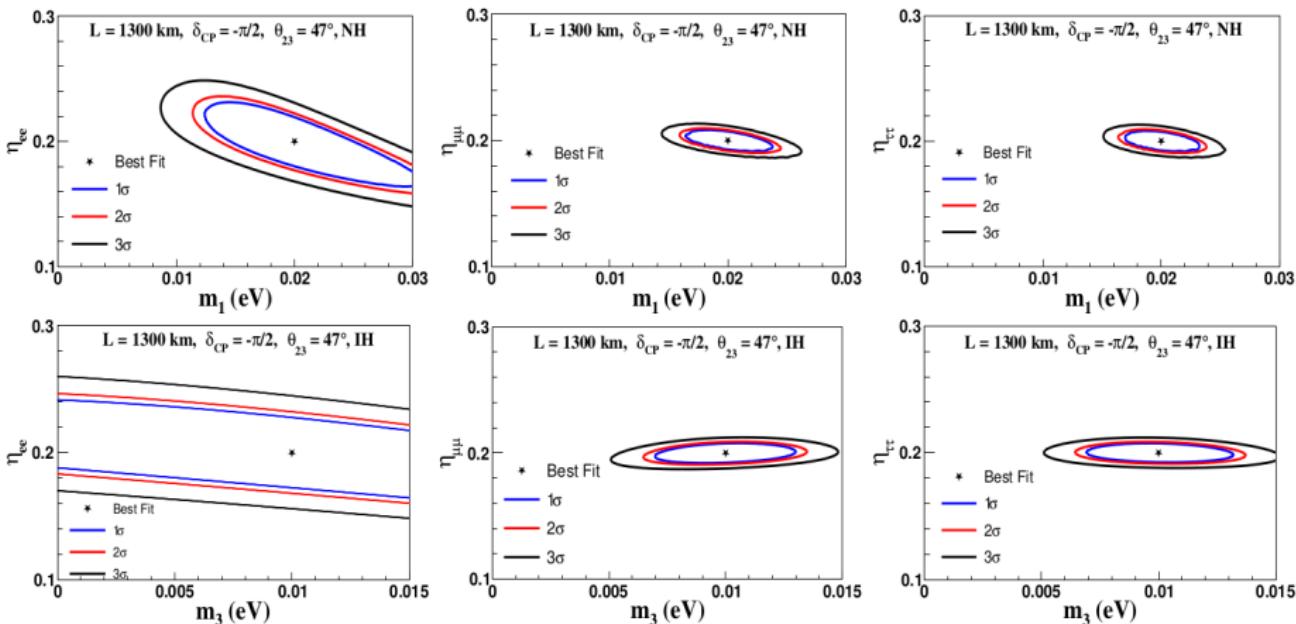
Precision measurement of neutrino mass



- For NH (top), a positive η_{ee} and a negative $\eta_{\mu\mu}$ or $\eta_{\tau\tau}$ enhances the sensitivity.
- For IH (bottom), a negative $\eta_{\alpha\beta}$ mostly enhances the constraining capability.

Medhi A., Sarker A., MMD; ArXiv: 2307.05348

Correlation in $(\eta_{\alpha\beta} - m)$ parameter space



- The constraint on the lightest mass in presence of η_{ee} worsens for IH.
- $\eta_{\tau\tau}$ or $\eta_{\mu\mu}$ makes the constraining capability better than that of η_{ee} for both hierarchies.

Medhi A., Sarker A., MMD; ArXiv: 2307.05348

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 δ_{CP} measurements.
- Scalar NSI & neutrino mass: dependence of neutrino oscillations on absolute neutrino masses.
- Scalar coupling models: parameterization of the scalar NSI effects.



"ONE HUNDRED MILLION NEUTRINOS ARE PASSING THROUGH
OUR BODIES EVERY SECOND, AND WE'RE WORRIED
ABOUT THE PRICE OF COFFEE." & GST"

Thank you for the kind attention!

Fundamental Building Blocks of Matter

Three generations of matter (fermions)			
	I	II	III
mass	2.4 MeV/c ²	1.27 GeV/c ²	171.2 GeV/c ²
charge	2/3	2/3	2/3
spin	1/2	1/2	1/2
name	u up	c charm	t top
Quarks			
mass	4.8 MeV/c ²	104 MeV/c ²	4.2 GeV/c ²
charge	-1/3	-1/3	-1/3
spin	1/2	1/2	1/2
name	d down	s strange	b bottom
Leptons			
mass	<2.2 eV/c ²	<0.17 MeV/c ²	<15.5 MeV/c ²
charge	0	0	0
spin	1/2	1/2	1/2
name	e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
Gauge bosons			
mass	0.511 MeV/c ²	105.7 MeV/c ²	1.777 GeV/c ²
charge	-1	-1	-1
spin	1/2	1/2	1/2
name	e electron	μ muon	τ tau
mass	80.4 GeV/c ²	80.4 GeV/c ²	80.4 GeV/c ²
charge	± 1	± 1	± 1
spin	1	1	1
name	W^+ W boson	Z^0 Z boson	Z^0 Z boson

Neutrino Oscillation

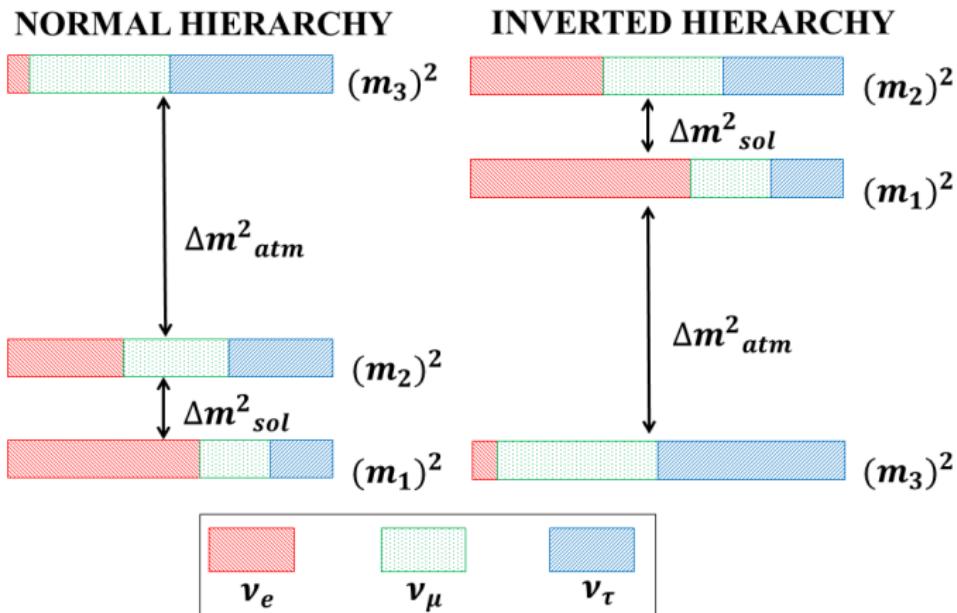
$$\nu_\alpha = \sum_j U_{\alpha j} \nu_j$$

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}, s_{ij} = \sin\theta_{ij}$

back

Neutrino Oscillation



back