INVESTIGATING BEYOND STANDARD NEUTRINO OSCILLATION THEORIES AT DUNE

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ABSTRACT

While the conventional neutrino oscillation process, driven by neutrino mass, is firmly established, there exist potential secondary influences on this phenomenon stemming from physical mechanisms beyond neutrino mass. These additional mechanisms could potentially alter the established framework. This investigation systematically examines the capabilities of the DUNE experiment to detect and characterize such beyond-standard oscillation (BSO) effects. We assess DUNE's capacity to differentiate between various BSO hypotheses by varying the magnitude of these effects. The BSO hypotheses under scrutiny encompass neutrino decay (both visible and invisible), non-standard interactions, violations of the equivalence principle, and quantum decoherence. Additionally, our analysis quantifies the potential distortions that may affect the measured value of the CP-violating phase parameter, δ_{CP}, when fitted with an incorrect BSO hypothesis. It's worth noting that such distortions could occur even in scenarios where distinguishing between different BSO mechanisms proves challenging, blurring the line between the true underlying mechanism and the theoretical hypothesis.

THEORETICAL FRAMEWORK

The standard neutrino Hamiltonian is given by:

$$H^{fv}_{\text{osc}} = \frac{1}{2E_\nu}\left(\mathbf{U}\Delta\mathbf{M}^2\mathbf{U}^\dagger + \mathbf{A}\right), \tag{1}$$

where E_ν is the neutrino energy, $\mathbf{U}$ is the PMNS mixing matrix, $\Delta\mathbf{M}^2$ is the diagonal mass matrix Diag $(0, \Delta m^2_{21}, \Delta m^2_{31})$, with $\Delta m^2_{ij} = m^2_i - m^2_j$. The diagonal matrix $\mathbf{A}$ is given by Diag $(\mathrm{A_{CC}}, 0, 0)$, encompassing the matter potential $\mathrm{A_{CC}} = 2\sqrt{2}G_F n_e$.

As subleading effects, we considered the following BSO hypotheses separately: Violation of the Equivalence Principle (VEP), Non-Standard Interactions (NSI), Neutrino decay, invisible (ID), full decay (FD), and Quantum Decoherence (QD). For the first three, it is useful to note they can be added as:

$$H^{\text{tot}}_{\text{osc}} = H^{fv}_{\text{osc}} + H_{\text{BSO}} \tag{2}$$

INCLUDING BSO

1. **VEP:** We consider a mass-dependent gravitational potential $\Phi' = \gamma_i \Phi$, where γ_i is a parameter that depends on the mass of the ith particle, leading to:

$$H_{\text{BSO}} = 2E_\nu \Phi \mathbf{U_g} \boldsymbol{\Delta\gamma_{ij}} \mathbf{U_g}^\dagger, \tag{3}$$

where $\boldsymbol{\Delta\gamma_{ij}} = $ Diag $(0, \Delta\gamma_{21}, \Delta\gamma_{31})$. For our analysis we assume $\mathbf{U_g} = \mathbf{U}$, $\Delta\gamma_{21} \neq 0$, and $\Delta\gamma_{31} = 0$.

2. **NSI:** These allow different neutrino flavor transitions due to its interaction with matter, described by $\mathcal{L}^{\text{NSI}}_{eff} = -2\sqrt{2}\epsilon^{fP}_{\alpha\beta} G_F (\bar\nu_\alpha \gamma_\mu P_L \nu_\beta)(\bar f \gamma_\mu P f)$. This modifies the hamiltonian as:

$$H_{\text{BSO}} = \sqrt{2}G_F n_e \begin{pmatrix} \epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{pmatrix} \tag{4}$$

We have worked with all parameters set to zero, except for a single non-diagonal parameter (either NSI$_{e\mu}$ or NSI$_{e\tau}$) and its complex conjugate.

3. **Neutrino decay:** Light neutrinos are allowed to decay due to their interaction with a massless scalar particle called the Majoron ($\nu_j \to \nu_i + J$). Depending on the observation of the final state neutrinos, we have:
   1. **ID:** The parent neutrino can decay either into a sterile neutrino or into an active neutrino that is not observable, modifying the hamiltonian as:

   $$H_{BSO} = -\frac{i}{2}\mathbf{U}\Gamma\mathbf{U}^\dagger \tag{5}$$

   We consiered $\mathbf{\Gamma} = $ Diag $(0, 0, \alpha_3/E_\nu)$, where α_3 is the decay constant of $\nu_3 \to \nu_x$.
   2. **FD:** In addition to invisible decay, neutrino may also decay into observable active neutrinos (visible decay). The effect of VD in distorting the SO formula is expressed through an exponential decay factor $e^{-\alpha_3^{vis} L/E_\nu}$.

4. **QD:** The neutrino system can be envisioned as an open quantum system subjected to the effects of its interaction with the environment, following the The Lindblad master equation:

$$\frac{d\rho(t)}{dt} = -i\left[H, \rho(t)\right] + L\left[\rho(t)\right] \tag{6}$$

where H is the neutrino system Hamiltonian, $\rho(t)$ is the neutrino density matrix, and $L[\rho(t)]$ is the term that encloses the dissipative effects. QD disrupts the coherence pattern, resulting in damping factors as $e^{-\Gamma L}$ multiplying the oscillatory terms contained in the neutrino flavor transition probability.

METHOD AND ANALYSIS

We have established the parameter ξ to measure the impact of different BSO hypotheses. Its definition varies according to the way each hypotheses distorts oscillations, as seen in Table 1.

BSO scenario	ξ
VEP	$\langle E_\nu \rangle \Phi \Delta\gamma_{21} L$
NSI	$2\sqrt{2}G_F n_e \lvert\epsilon_{ex}\rvert L$
ID/FD	$\alpha_3 L/\langle E_\nu \rangle$
QD	ΓL

Table 1 – Definition of BSO strength parameter, ξ.

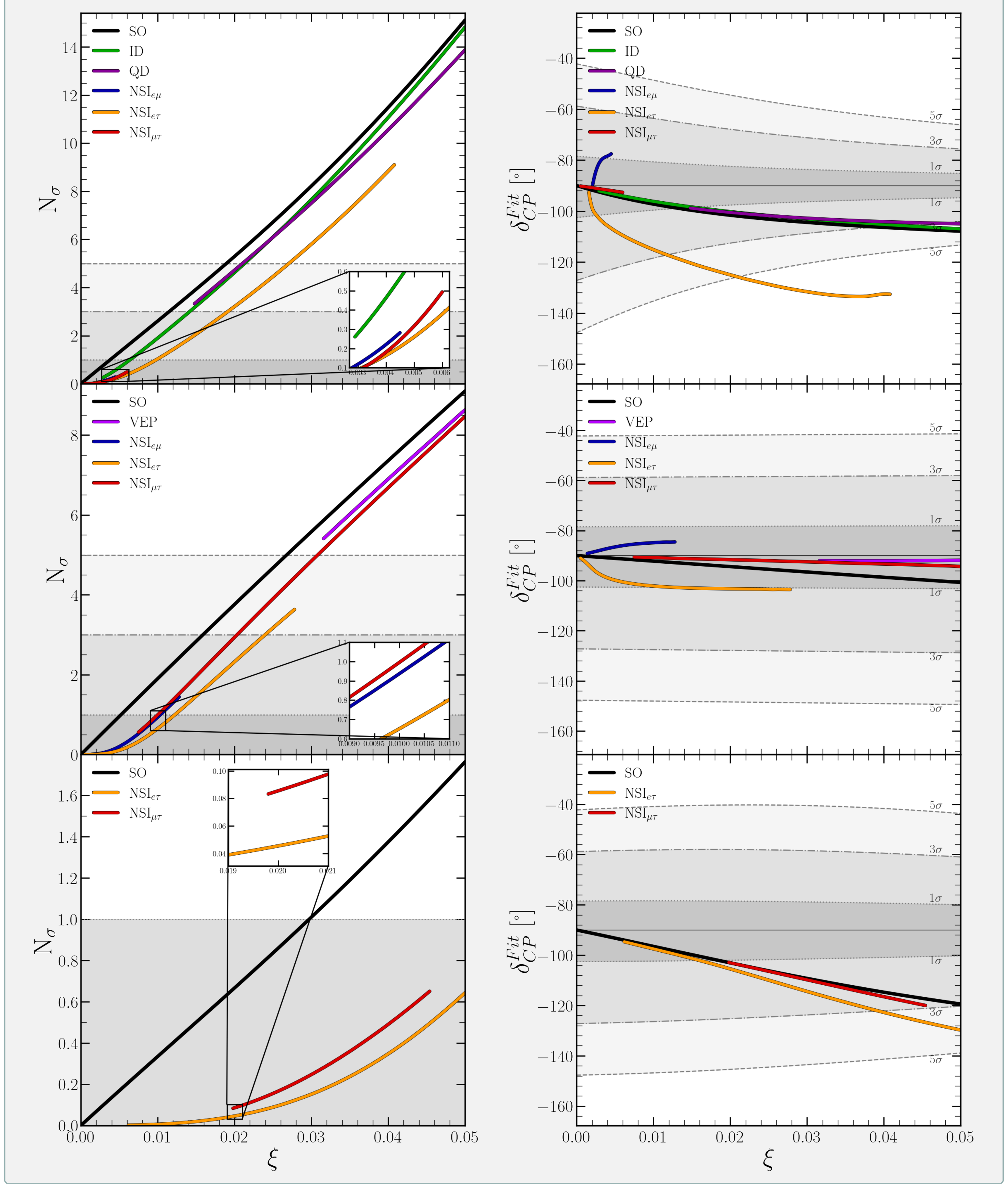
The Deep Underground Neutrino Experiment (DUNE) will be an experiment with a baseline of 1284.9 Km, average matter density of 2.848 g/cm^3, 6.5 years in both neutrino (FHC) and antineutrino (RHC) modes, and beam power of 1.2 MW. The computational simulation for this was done with GLoBES, using priors on θ_{13}, and δ_{CP} and BSO parameter free in the fitting. We also define

$$\chi^2 = \min_{\vec\alpha}\left\{2\sum_i\left[N_i^{test}(\vec\alpha) - N_i^{true} + N_i^{true}\ln\left(\frac{N_i^{true}}{N_i^{test}(\vec\alpha)}\right)\right] + \sum_j\left(\frac{\alpha_j}{\sigma_j}\right)^2\right\} + \left(\frac{\theta_{13}^{true} - \theta_{13}^{test}}{\sigma_{\theta_{13}}}\right)^2, \tag{7}$$

where i is the number of bins, $\vec\alpha$ is the systematic uncertainties, $\{\sigma_j\}$ are the systematic errors and $\sigma_{\theta_{13}}$ is the θ_{13} error.

RESULTS

Representative plots of found cases are shown. We define the deviation between true and test model in terms of number of sigmas as N$_\sigma$. Plots correspond to true VEP (top), QD (middle) and NSI electron-muon (middle) with $\delta_{CP}^{true} = -90°$ and normal hierarchy.



CONCLUSIONS

If certain BSO effects occur in nature, DUNE will possess the capability to distinguish the true model from other BSO alternatives. Even if that were not the case, there could be significant deviations in the corresponding δ^{fit}_{CP} compared to the true value, thus hinting at BSO physics.

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