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# DUNE sensitivity for observing/discriminating theories beyond standard neutrino oscillation

**A. Calatayud-Cadenillas,**[a,*] **A. Pérez García**[a] **and A. M. Gago**[a]

[a] *Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Apartado 1761, Lima, Perú*

*E-mail:* anthony.calatayud@pucp.edu.pe, aperezg@pucp.edu.pe, agagomed@gmail.com

Effects beyond-standard oscillation (BSO) are being studied as they can modify the framework of the standard oscillation due to second-order contributions. In this work, we investigate the sensitivity of the DUNE experiment to observe such BSO effects as we increase their intensity, for which we include different BSO hypotheses. The BSO hypotheses considered in this work are: neutrino decay (invisible and visible), non-standard interactions, violation of the equivalence principle, and quantum decoherence. We systematically evaluate DUNE's ability to distinguish between different BSO hypotheses, assigning one of them as the true signal and another as the test signal. The CP-violating phase parameter, $\delta_{CP}$, may have potential distortions with respect to the measured value using an incorrect BSM hypothesis. Even when the BSO scenarios are almost indistinguishable from each other, the measured value of $\delta_{CP}$ can be very different from the value used in the theoretical hypothesis.

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*Speaker

## 1. Introduction

Long-standing experimental evidence strongly supports flavor neutrino oscillation induced by non-zero neutrino mass, referred to as standard neutrino oscillation. Despite these observations, it cannot be denied that the possibility of another beyond-standard phenomenon, as yet unnoticed experimentally, may introduce distortions in the measurement of standard neutrino oscillation parameters. With improved sensitivities, the DUNE experiment [1] is poised to test this BSO hypothesis. Assuming a BSO hypothesis, this contribution examines the DUNE experiment's ability to discriminate between the true BSO hypothesis and an incorrect choice for the theoretical hypothesis.

## 2. Theoretical Formalism and Analysis details

The four BSOs selected for our analysis are: The Violation of the Equivalence Principle (VEP), Non-Standard Interactions (NSI), Neutrino decay, invisible (ID), full decay (FD) (which includes visible decay), and Quantum Decoherence (QD). The general approach for working with VEP, NSI, and ID is to augment the standard oscillation (SO) Hamiltonian in the flavor basis ($H_{\text{SO}}$) with the corresponding new $H_{\text{BSO}}$ term: $H_{\text{TOT}} = H_{\text{SO}} + H_{\text{BSO}}$, noting that for ID, the added term is anti-Hermitian. All the motivation and theoretical details for VEP and NSI, can be reviewed in [2] and [3], respectively. Meanwhile, for FD (and ID), and QD, the approach differs; the details can be found in [4] and [5] for FD and QD, respectively.

### 2.1 Parameter of Intensity of the BSOs

We introduce the parameter $\xi$ to measure the impact of different BSO hypotheses. For VEP, $\xi$ is expressed as: $\xi = \langle E_\nu \rangle \Phi \Delta\gamma_{21} L$, where $\Phi$ denotes the gravitational potential, $\Delta\gamma_{21} = \gamma_2 - \gamma_1$ represents the disparity between the neutrino couplings to the gravitational potential [2]. For VEP the mixing matrix, which connects the gravitational eigenstates with the flavor eigenstates, is equal to the Pontecorvo-Maki-Nakagawa-Sakata matrix. Here, $\langle E_\nu \rangle$ signifies the average neutrino energy, while $L$ denotes the source-detector neutrino distance. For NSI, $\xi$ takes the form $\xi = \epsilon_{\alpha\beta} A_{CC} L / \langle E_\nu \rangle$, where $\epsilon_{\alpha\beta}$ is a the module of the effective parameter quantifying NSI, with $\alpha\beta = e\mu, e\tau$, and $\mu\tau$, while $A_{CC}$ represents the matter potential [3]. For ID and FD scenarios, we have $\xi = \alpha_3 L / \langle E_\nu \rangle$, where $\alpha_3 = \Gamma_3 \langle E_\nu \rangle$. Here, $\Gamma_3$ denotes the decay rate of $\nu_3 \to \nu_x$, with $\nu_x$ being a sterile (active) neutrino for ID (FD) [4]. In the case of QD, $\xi$ simplifies to $\xi = \Gamma L$, where $\Gamma$ represents the decoherence parameter [5]. In Table 1 we display the upper limits of the different BSO hypotheses and their corresponding $\xi$.

**Table 1: Upper limits and $\xi$ parameter**

| BSO | ID ($\alpha_3$) | FD ($\alpha_3$) | QD ($\Gamma$) | VEP ($\Phi\Delta\gamma_{21}$) | NSI$e\mu$($\epsilon_{e\mu}$) | NSI$e\tau$ ($\epsilon_{e\tau}$) | NSI$\mu\tau$ ($\epsilon_{\mu\tau}$) |
|---|---|---|---|---|---|---|---|
| Bounds | $2.4x10^{-4}$eV$^2$ | $7.8x10^{-5}$eV$^2$ | $4.8x10^{-23}$GeV | $2.94x10^{-23}$ | $3.6x10^{-2}$ | $1.67x10^{-1}$ | $3.3x10^{-2}$ |
| $\xi$ | 0.608 | 0.198 | 0.316 | 0.504 | 0.053 | 0.248 | 0.049 |

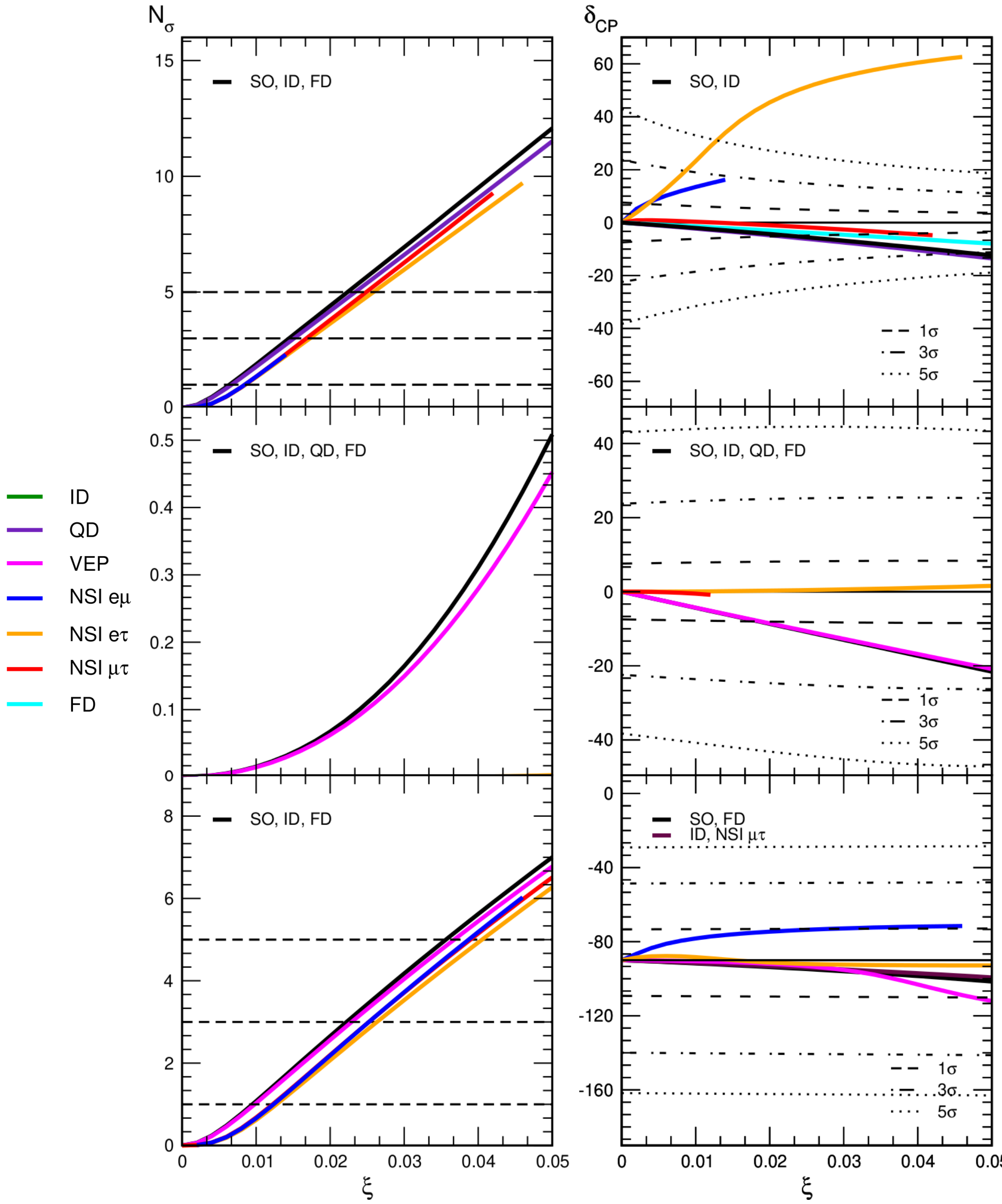


**Figure 1:** The black line represents SO and some BSO hypotheses that cannot be differentiated because the curves are closely overlapped. The left panel is $N_\sigma$ vs $\xi$, and the right panel is $\delta_{\rm CP}^{\rm fit}$ vs $\xi$. In the top panel, it has $\delta_{\rm CP}^{\rm true} = 0°$ assuming VEP as true data. The middle panel has $\delta_{\rm CP}^{\rm true} = 0°$ assuming $\text{NSI}_{\epsilon\mu}$ as true data. Finally, the bottom panel has $\delta_{\rm CP}^{\rm true} = -90°$ assuming QD as true data.

## 3. Experimental Setup and Analysis Method

Our experimental setup is the Deep Underground Neutrino Experiment (DUNE) with the following parameters: $L = 1300$ km, average neutrino energy $\langle E_\nu \rangle = 2.6$ GeV, and an average matter density of $\rho = 2.96$ g/cm$^3$. Simulations are conducted using GLoBES [6], considering $\nu_e, \bar{\nu}e$ appearance, and $\nu_\mu, \bar{\nu}_\mu$ disappearance events for 3.5 years in neutrino (antineutrino) mode (FHC

(RHC)). The $\chi^2$ definition follows the prescription given in [2]. Our analysis involves generating true data based on a specific BSO hypothesis (for the true NSI data, the complex phase was fixed at $-\pi/2$) and fitting it with another BSO hypothesis. The parameters of the latter and the CP-violation phase $\delta_{CP}$ are left free, while the remaining standard oscillation parameters are set according to [7]. This process is conducted by varying the intensity value of $\xi$ up to 0.05 for the true simulated data. The deviation between the true and the test BSO model will be measured in terms of $\sqrt{\chi^2} = N_\sigma$.

## 4. Results

The VEP is the true model in the top panels of Figure 1. We note significant $\sigma$ deviations between the VEP and the BSO test models at $\xi = 0.03$. Moreover, it's viable to achieve over a $5\sigma$ distortion in the fitted $\delta_{\rm CP}$ for $\text{NSI}_{e\tau}$ as BSO test hypothesis and $\xi = 0.02$. The $\text{NSI}_{e\mu}$ is the true model at the middle panel. In this case, distinguishing between the latter and other test BSO hypotheses is challenging, while the maximum $\delta_{\rm CP}$ deviation nearly reaches $3\sigma$ for VEP as the test model and at $\xi \sim 0.05$. Finally, the bottom panel represents QD as the true model. It's observable that differentiating it from the other BSO test hypotheses is feasible with a $5\sigma$ significance for $\xi > 0.04$. However, distinguishing the fitted $\delta_{\rm CP}$ from the true one is not possible.

## 5. Conclusion

We have discovered that if certain BSO proposals occur in nature, the DUNE experiment will possess the discriminating capability to distinguish the true model from other BSO alternatives. Interestingly, we have also observed that in scenarios where the true BSO model cannot be distinguished from others, there could be significant deviations in the corresponding fitted $\delta_{\rm CP}$ compared to the true value. This discrepancy could serve as a hint of BSO physics.

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PoS(TAUP2023)253