DUNE sensitivity for observing/discriminating theories beyond standard neutrino oscillation

A. Calatayud Cadenillas, A. Pérez García, A. M. Gago
anthony.calatayud@pucp.edu.pe, aperezg@pucp.edu.pe, agagomed@gmail.com

DOCTORADO EN FÍSICA PUCP
TAUP VIENNA 2023

Abstract

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 invisible decay (ID) and full decay (FD), non-standard interactions (NSI), violation of the equivalence principle (VEP), and quantum decoherence (QD). The CP-violating phase parameter, δ_{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 δ_{CP} can be very different from the value used in the theoretical hypothesis.

Theoretical framework

The BSO models in our work can be described from the Hamiltonian formalism following the following equation:

$$H_T = H + H_{BSO},$$

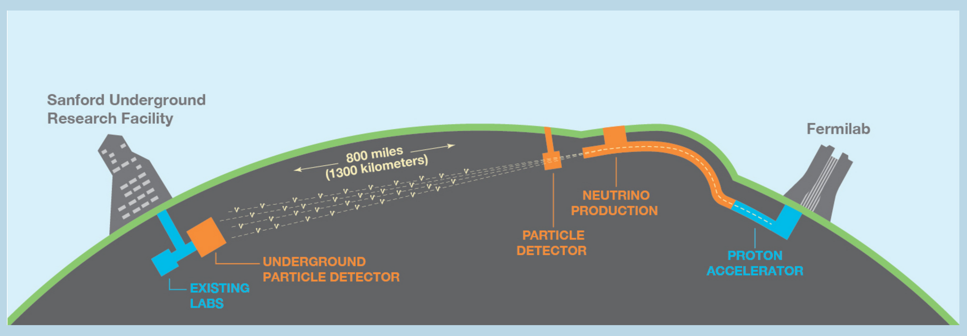
where H is the standard oscillation Hamiltonian

$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \mathrm{diag}\,(A_{CC}, 0, 0)\,,$$

E is the neutrino energy, $\Delta m^2_{ij} = m_i^2 - m_j^2$, m_i is the $i{-}th$ mass eigenstate, A_{CC} is the potential in matter, H_{BSO} depends on the model and U is the PMNS matrix. In addition, we assume in all cases Normal Ordering.

Experimental Setup and Data Analysis

Deep Underground Neutrino Experiment (DUNE) will be an experiment with the following specifications: baseline $L = 1300$ Km, average matter density $\rho = 2.96\mathrm{g/cm}^3$, 3.5 years in neutrino mode (FHC) and 3.5 years in antineutrino mode (RHC), beam power is 1.07 MW and average energy $E_m = 2.6$GeV.



We use GLoBES for the computational simulation, only δ_{CP} and BSO parameter are free in the fitting. We define

$$\chi^2 = \sum_i \frac{(N_i^{\text{true}} - N_i^{\text{test}})^2}{N_i^{\text{true}}}\ ,\ i \in \text{Number of bins},$$

where N_i is the number of events. We consider $\nu_e, \bar{\nu}_e$ appearance and $\nu_\mu, \bar{\nu}_\mu$ disappearance.

Conclusions

We observe how the various BSO models can produce deviations greater than 3 sigma in δ_{CP} despite not being distinguishable from each other. On the other hand, we also find that even by increasing the intensity of the BSO parameter and achieving a separation greater than 5 sigma between the true and test models, δ_{CP} fit cannot be distinguished from δ_{CP} true.

Acknowledgements

This research was supported by HUIRACOCHA Scholarship 2020 from PUCP and partially supported by CONCYTEC (FONDECYT contract 060-2021). The supports are gratefully acknowledged.

BSO Models

In our work it is useful to define ξ as the intensity of each of the BSO models.

Invisible Decay: The mass eigenstates m_3 decay to a sterile neutrino ν_s by coupling with a Majoron J, i.e., $\nu_3 \to \nu_s + J$. So

$$H_{BSO} = \frac{1}{2E} U \mathrm{diag}\,(0, 0, -i\alpha_3)\, U^\dagger\ ,\ \xi = \alpha_3 L/E_m,$$

where α_3 is the decay parameter of m_3.

Full Decay: Here we consider Invisible Decay and the Visible Decay case where the decay is given by $m_3 \to m_1 + J$ by the scalar coupling with J. Furthermore, we assume $m_1 = 0.05$eV.

VEP: We consider that the universal gravitational constant depends linearly on m_i, this leads to a new gravitational potential $\Phi'_N = \gamma_i \Phi_N$ which breaks Einstein's Equivalence Principle . We take the case $\gamma_1 = \gamma_3 \neq \gamma_2$. then

$$H_{BSO} = 2EU\mathrm{diag}\,(0, \gamma, 0)\, U^\dagger\ ,\ \xi = E_m L \gamma,$$

where $\gamma = \gamma_2 - \gamma_1$.

NSI: The different flavors of neutrinos interact in a non-standard way with matter and this can be described by

$$H_{BSO} = A_{CC} \begin{pmatrix} 0 & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & 0 & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & 0 \end{pmatrix}\ ,\ \xi = 2\|\epsilon_{\alpha\beta}\| A_{CC} L,$$

where $\epsilon_{\alpha\beta}$ are the NSI interaction parameters with $\alpha, \beta \in \{e, \mu, \tau\}$.

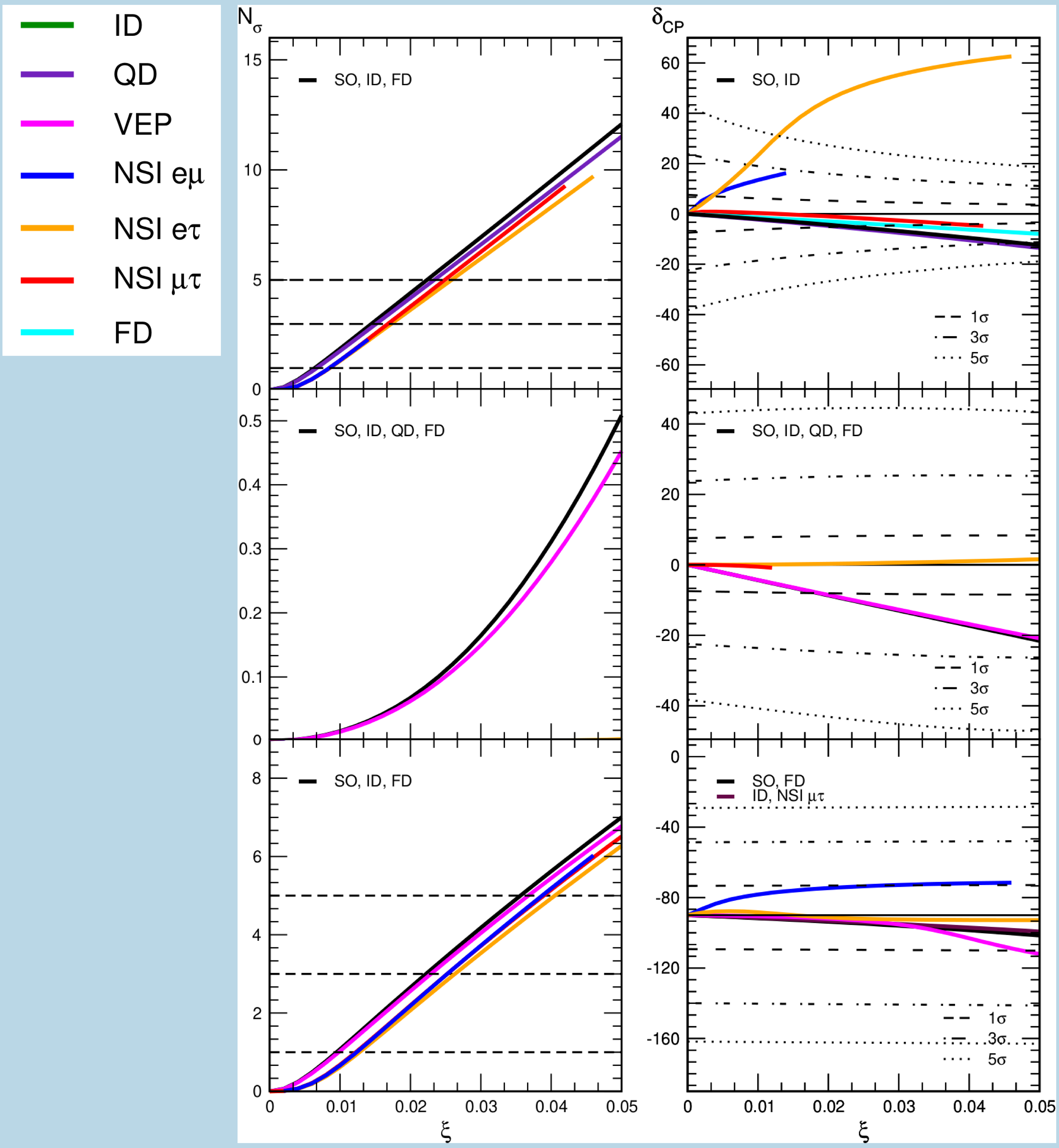
Q. Decoherence: Neutrinos interact with the environment in an open quantum system following the Lindblad equation,

$$\frac{\partial \rho}{\partial t} = -i\,[H_m, \rho] + \sum_{i,j} \mathcal{D}_{i,j} \rho_i \lambda_j\ ,\ \xi = \Gamma L,$$

where $\rho = \sum_i \rho_i \lambda_i$ is the neutrino density matrix, λ_i are the Gell-Mann matrices, H_m is the Hamiltonian in the mass eigenstate base and $\mathcal{D} = -\mathrm{diag}(0, 0, 0, 0, \Gamma, \Gamma, \Gamma, \Gamma, 0)$ y $\Gamma \geq 0$.

Results

Interesting cases are presented. We define the deviation between true and test model in terms of number of sigmas as N_σ. If we assume true VEP (top) and NSI electron-muon (middle) with $\delta_{CP}^{\text{true}} = 0°$ and QD (bottom) with $\delta_{CP}^{\text{true}} = -90°$ we obtain



References

[1] Ascencio-Sosa, M.V., Calatayud-Cadenillas, A.M., Gago, A.M. et al. *Matter effects in neutrino visible decay at future long-baseline experiments.* Eur. Phys. J. C 78, 809 (2018).

[2] Coloma, P. *Non-standard interactions in propagation at the Deep Underground Neutrino Experiment.* J. High Energ. Phys. 2016, 16 (2016).

[3] F. N. Díaz, J. Hoefken, and A. M. Gago. *Effects of the violation of the equivalence principle at DUNE.* Phys. Rev. D 102, 055020 (2020).

[4] J. A. Carpio, E. Massoni, and A. M. Gago. *Testing quantum decoherence at DUNE.* Phys. Rev. D 100, 015035 (2019).