Quantum Decoherence and CPT Violation at DUNE

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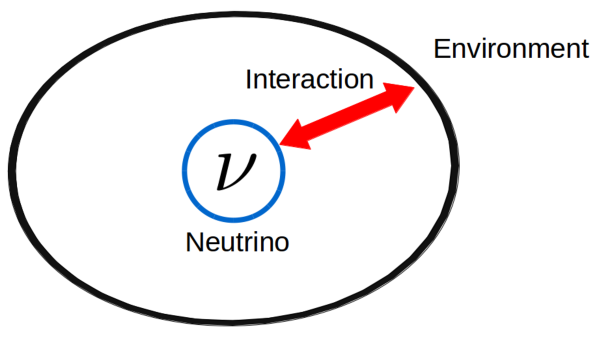
Abstract

We study the posibility to measure CPT violation effects due to quantum decoherence within the contex of the neutrino system. Considering the previous, we develop analytical formulas for oscillation probabilities, in vacuum and matter, for long-baseline experiments valid up to $\Gamma \sim 10^{-23}$GeV. We evaluate these CPTV efects using the ν_μ and $\overline{\nu}_\mu$ disappearance channels, in the framework of the DUNE experiment. For the optimal case, we find 5 σ of confidence for $\Gamma \sim 4 \times 10^{-23}$GeV and $\delta_{\rm CP} \approx 3\pi/2$.

Theoretical Formalism

We consider the neutrino state like a quantum system that loses coherence due to the interaction with the environment. This phenomenon can modify the interference between the neutrino mass eigenstates and therefore alter the oscillation frequencies. The time evolution of our neutrino open quantum system is given by Lindblad Master equation,



$$\frac{\partial \hat{\rho}(t)}{\partial t} = -i[\hat{H}, \hat{\rho}(t)] + \mathcal{D}[\hat{\rho}(t)] \qquad \text{basis SU(3)} \qquad D = \begin{bmatrix} -\gamma_1 & \beta_{12} & \beta_{13} & \beta_{14} & \beta_{15} & \beta_{16} & \beta_{17} & \beta_{18} \\ \beta_{12} & -\gamma_2 & \beta_{23} & \beta_{24} & \beta_{25} & \beta_{26} & \beta_{27} & \beta_{28} \\ \beta_{13} & \beta_{23} & -\gamma_3 & \beta_{34} & \beta_{35} & \beta_{36} & \beta_{37} & \beta_{38} \\ \beta_{14} & \beta_{24} & \beta_{34} & -\gamma_4 & \beta_{45} & \beta_{46} & \beta_{47} & \beta_{48} \\ \beta_{15} & \beta_{25} & \beta_{35} & \beta_{45} & -\gamma_5 & \beta_{56} & \beta_{57} & \beta_{58} \\ \beta_{16} & \beta_{26} & \beta_{36} & \beta_{46} & \beta_{56} & -\gamma_6 & \beta_{67} & \beta_{68} \\ \beta_{17} & \beta_{27} & \beta_{37} & \beta_{47} & \beta_{57} & \beta_{67} & -\gamma_7 & \beta_{78} \\ \beta_{18} & \beta_{28} & \beta_{38} & \beta_{48} & \beta_{58} & \beta_{68} & \beta_{78} & -\gamma_8 \end{bmatrix} \tag{1}$$

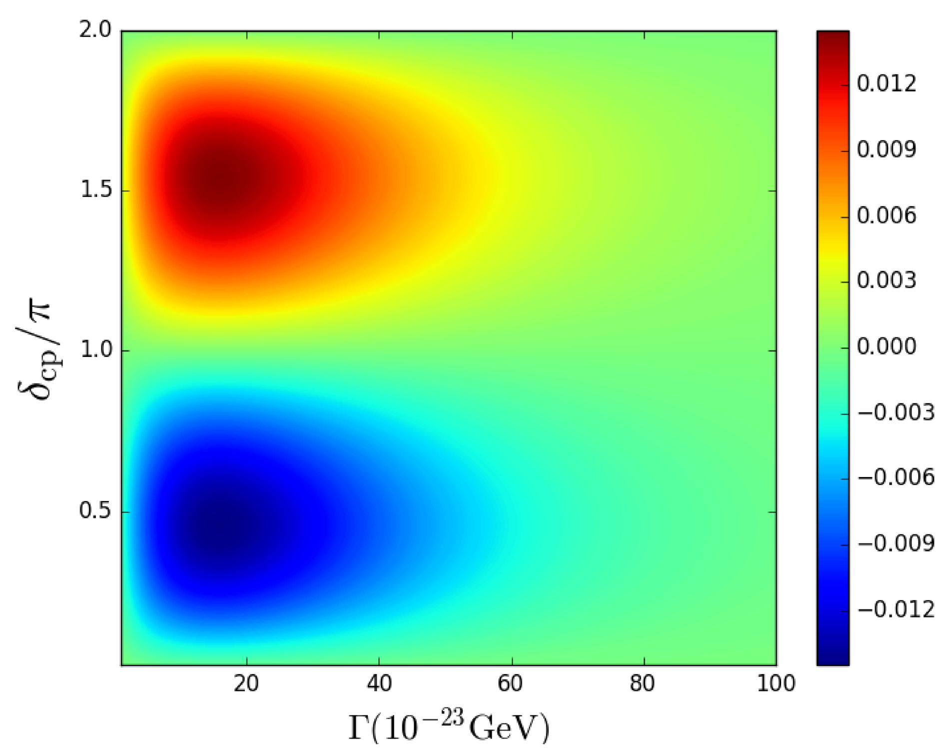
We found 15 elements that violate CPT in the dissipative term D , highlighted elements [1]. If we consider all the diagonal elements equal to γ, we obtain:

$$P_{\alpha\alpha}^{\rm Vac-Dec} = \frac{1}{3}(1 - e^{-\gamma t}) + e^{-\gamma t} P_{\alpha\alpha}^{\rm Vac} + P_{\not{\rm CPT}}^{\rm Dec} \tag{2}$$

For $\alpha = \mu$ and Γ up to $\sim 10^{-23}$GeV, we can approximate

$$P_{\mu\mu}^{\rm Matt-Dec} \approx \frac{1}{3}(1 - e^{-\gamma t}) + e^{-\gamma t} P_{\mu\mu}^{\rm Matt} + \frac{P_{\not{\rm CPT}}^{\rm Dec}}{2(\Delta_{13} - V_{cc})} \left(\Delta_{13} \frac{\sin V_{cc} t}{V_{cc}} - V_{cc} \frac{\sin \Delta_{13} t}{\Delta_{13}} \right). \tag{3}$$

To evaluate CPT symmetry violation, we use $\Delta_{\not{\rm CPT}} = P_{\alpha\alpha} - P_{\overline{\alpha\alpha}}$. Then, replacing $P_{\alpha\alpha} = P_{\mu\mu}^{\rm Matt-Dec}$,



$$\Delta_{\not{\rm CPT}}^{\rm Matt-Dec} = \Delta_{\not{\rm CPT}}^{\rm Matt} e^{-\gamma t} + \frac{\Delta_{\not{\rm CPT}}^{\rm Dec}}{2(\Delta_{13} - V_{cc})} \left(\Delta_{13} \frac{\sin V_{cc} t}{V_{cc}} - V_{cc} \frac{\sin \Delta_{13} t}{\Delta_{13}} \right) \tag{4}$$

where $\Delta_{\not{\rm CPT}}^{\rm Dec} = 2 \sum_{i,j} \beta_{ij} \frac{\sin[\Omega_{ij} t]}{\Omega_{ij}} \rho_i^\alpha \rho_j^\alpha e^{-\gamma t}$, with $\Omega_{ij} = \sqrt{\Delta_{ij}{}^2 - \beta^2}$ and $\Delta_{ij} = \Delta m_{ij}^2 / 2p$.

Figure 1: Dependence of $\Delta_{\not{\rm CPT}}^{\rm Dec}$ with respect to δ_{CP} and Γ. We consider $\beta_{12} = \Gamma/3$.

DUNE and Simulation Details

DUNE is an upcoming experiment with a baseline of 1300Km from Fermilab to SURF.

To simulated the experiment was used nuSQuIDS package and GLoBES software [2][3]. We configure the simulation with 80 GeV beam, 1.07 MW beam power and 5 years exposure for neutrino and antineutrino mode [4].

We define the observable of CPT asymmetry depending of the number of events of neutrinos and antineutrinos

$$\Delta N = N(\nu_\mu) - N(\overline{\nu}_\mu). \tag{5}$$

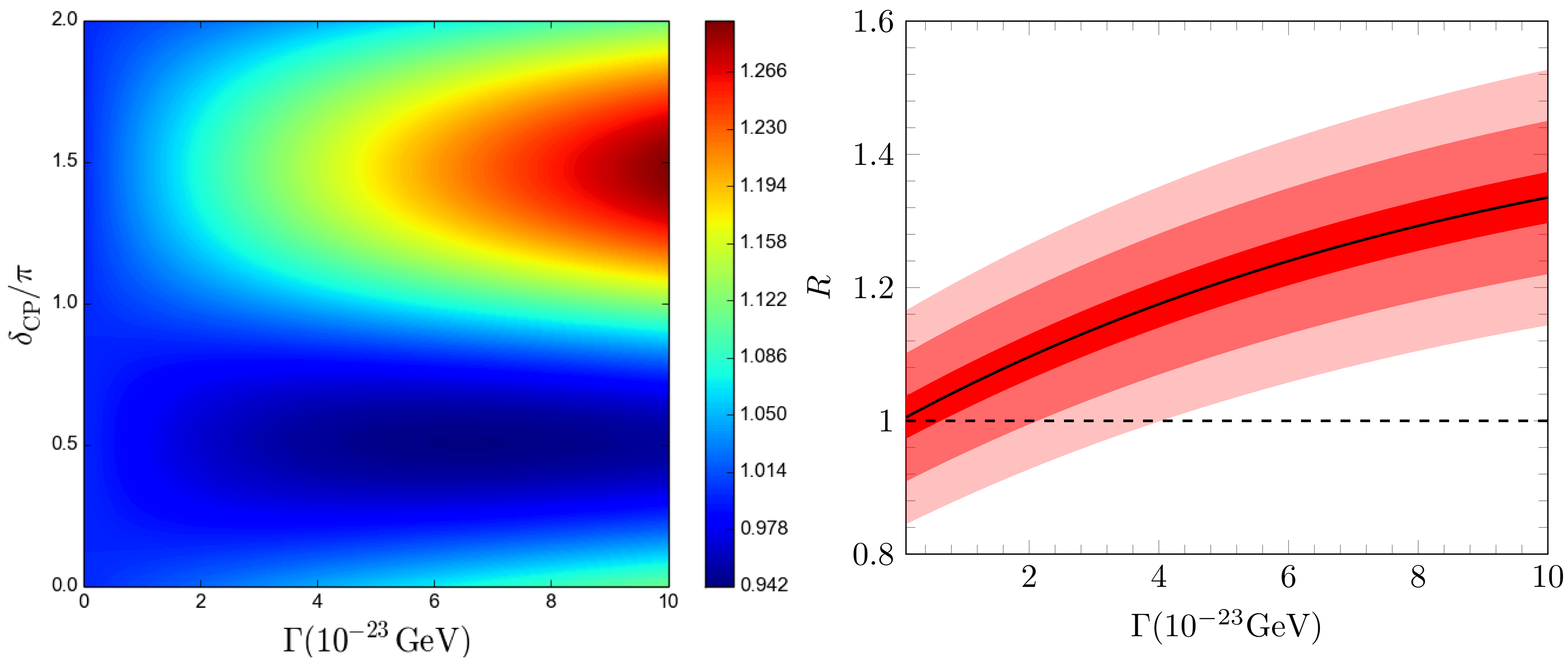
To differentiate the CPTV due to the effect of quantum decoherence from the CPTV due to the matter effect, we define the ratio R to normalize with respect the standard oscillation.

$$R = \frac{\Delta N^{\rm Matt-Dec}}{\Delta N^{\rm Matt}}. \tag{6}$$

We integrate the event rate from 0.5 to 20 GeV using the following rules:

Neutrino mode	Antineutrino mode
Signal	Signal
$\nu_\mu \to \nu_\mu$ CC	$\overline{\nu}_\mu \to \overline{\nu}_\mu$ CC
$\overline{\nu}_\mu \to \overline{\nu}_\mu$ CC	$\nu_\mu \to \nu_\mu$ CC
Background	Background
$\nu_\mu \to \nu_\tau$ CC	$\nu_\mu \to \nu_\tau$ CC
$\overline{\nu}_\mu \to \overline{\nu}_\tau$ CC	$\overline{\nu}_\mu \to \overline{\nu}_\tau$ CC
No Osc. $\nu_\mu \to \nu_\mu$ NC	No Osc. $\nu_\mu \to \nu_\mu$ NC
No Osc. $\overline{\nu}_\mu \to \overline{\nu}_\mu$ NC	No Osc. $\overline{\nu}_\mu \to \overline{\nu}_\mu$ NC

Results



The best case has the following configuration: $\beta_{12} = \beta_{23} = \beta_{45} = -\beta_{67} = \frac{1}{3}\Gamma$, $\beta_{28} = \frac{1}{\sqrt{3}}\Gamma$ and $\beta_{47} = -\beta_{56} = \left(\frac{1}{2\sqrt{3}} - \frac{1}{6}\right)\Gamma$. Considering normal hierarchy and $\delta_{\rm CP} \approx 3\pi/2$, this case presents 5σ of confidence for $\Gamma \sim 4 \times 10^{-23}$GeV.

Figure 2 : *Left*: R from Eq. (6) and its dependence on Γ and $\delta_{\rm CP}$. *Right*: The dashed line is the expected in the standard neutrino oscillation, the solid black line shows the effect of our diagonal dissipative factor. The red fringes (small, medium and large) represent the statistical error 1σ, 3σ and 5σ (respectively).

References

[1] A. M. Gago, E. M. Santos, W. J. C. Teves, and R. Zukanovich Funchal. A Study on quantum decoherence phenomena with three generations of neutrinos. 2002.
[2] Carlos A. Argüelles Delgado, Jordi Salvado, and Christopher N. Weaver. A Simple Quantum Integro-Differential Solver (SQuIDS). *Comput. Phys. Commun.*, 196:569–591, 2015.
[3] Patrick Huber, M. Lindner, and W. Winter. Simulation of long-baseline neutrino oscillation experiments with GLoBES (General Long Baseline Experiment Simulator). *Comput. Phys. Commun.*, 167:195, 2005.
[4] T. Alion et al. Experiment Simulation Configurations Used in DUNE CDR. 2016.