EXPLORING THE IMPACT OF QUANTUM DECOHERENCE ON PRECISION MEASUREMENTS IN DUNE AND T2HK

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ABSTRACT

This study delves into how quantum decoherence in neutrinos could influence the precision of standard oscillation parameter measurements in the DUNE and T2HK experiments. Our analysis suggests that the measurements of δ_{CP}, $\sin^2\theta_{13}$, and $\sin^2\theta_{23}$ are notably affected in DUNE, more so than in T2HK. Conversely, DUNE exhibits a higher sensitivity to detecting decoherence effects compared to T2HK. By combining data from both experiments, we demonstrate the potential for achieving robust measurements of standard parameters, which may not be feasible with DUNE data alone.

NEUTRINO OSCILLATION AND QUANTUM DECOHERENCE

The neutrino system with quantum decoherence is an open quantum system which can be interaction with the environment, following the The Lindblad master equation:

$$\frac{d\rho(t)}{dt} = -i\left[H,\rho(t)\right] + L\left[\rho(t)\right] \text{ , where } L\left[\rho(t)\right] = -\frac{1}{2}\sum_j \left\{A_j^\dagger A_j \rho(t) + \rho(t) A_j^\dagger A_j\right\} + \sum_j A_j \rho(t) A_j^\dagger \quad (1)$$

and H is the neutrino system Hamiltonian, $\rho(t)$ is the neutrino density matrix, and $L\left[\rho(t)\right]$ is the term that encloses the dissipative effects described by the $\{A_j\}$ operators. However, a simple way to transform (1) and resolve the system is rewriting everything in terms of Gell-Mann matrices λ_i. Thus, we have $\rho = \sum_i \rho_i \lambda_i$ and

$$\frac{d\rho(t)}{dt} = -i\left[H,\rho(t)\right] + \sum_i \sum_j \rho_i (M_D)_{ij} \lambda_j \text{ , where } M_D = -\text{Diag}(\Gamma_1,\Gamma_2,\Gamma_1,\Gamma_1,\Gamma_2,\Gamma_1,\Gamma_2,\Gamma_1) \quad (2)$$

and $\frac{1}{3}\Gamma_1 \leq \Gamma_2 \leq \frac{5}{3}\Gamma_1$. We choose M_D as (2) because the form of M_D is the same in vacuum and constant density matter. If $\delta_{CP} = 180°$ we can approximately calculate the $\nu_\mu \to \nu_e$ probability

$$\begin{aligned} P_{\nu_\mu\to\nu_e}(L) = P^{osc}_{\nu_\mu\to\nu_e}(L) &- \left(\frac{1}{3} + 2D_m\right)\left(e^{-\Gamma_1 L} - 1\right) \\ &+ \left(\frac{\tilde{J}_m}{4}\left(\cos\left(\bar{\Delta}_{31} - 2aL\right) - \cos\left(\bar{\Delta}_{31} - \bar{\Delta}_{21}\cos^2\theta_{12}\right)\right) + 2D_m \cos\left(2aL\right)\right)\left(e^{-\frac{1}{2}\Sigma_{12}L} - 1\right) \quad (3) \\ &+ \Delta\Gamma_{12}\left(\frac{\tilde{J}_m}{8}\left(\frac{\sin\left(\bar{\Delta}_{31} - 2aL\right)}{\left(\Delta_{31} - 2aL\right)} - \frac{\sin\left(\bar{\Delta}_{31} - \bar{\Delta}_{21}\cos^2\theta_{12}\right)}{\left(\Delta_{31} - \Delta_{21}\cos^2\theta_{12}\right)}\right) + D_m \frac{\sin\left(2aL\right)}{2a}\right) e^{-\frac{1}{2}\Sigma_{12}L}, \end{aligned}$$

where $\bar{\Delta}_{ij} = \Delta_{ij}L$, $\Delta_{ij} = \frac{\Delta m^2_{ij}}{2E}$, $\Delta\Gamma_{12} = \Gamma_2 - \Gamma_1$, $\Sigma_{12} = \Gamma_2 + \Gamma_1$, $\{m_i\}$ are the mass eigenstates, $\{\theta_{ij}\}$ are the mixing angles, E is the neutrino energy, L is the baseline,

$$\tilde{J}_m = -\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{13}\sin 2\theta_{23}\left(\frac{\bar{\Delta}_{21}}{2aL}\right)\left(\frac{\bar{\Delta}_{31}}{\bar{\Delta}_{31} - 2aL}\right) = -\tilde{J}\left(\frac{\bar{\Delta}_{21}}{2aL}\right)\left(\frac{\bar{\Delta}_{31}}{\bar{\Delta}_{31} - 2aL}\right) \quad (4)$$

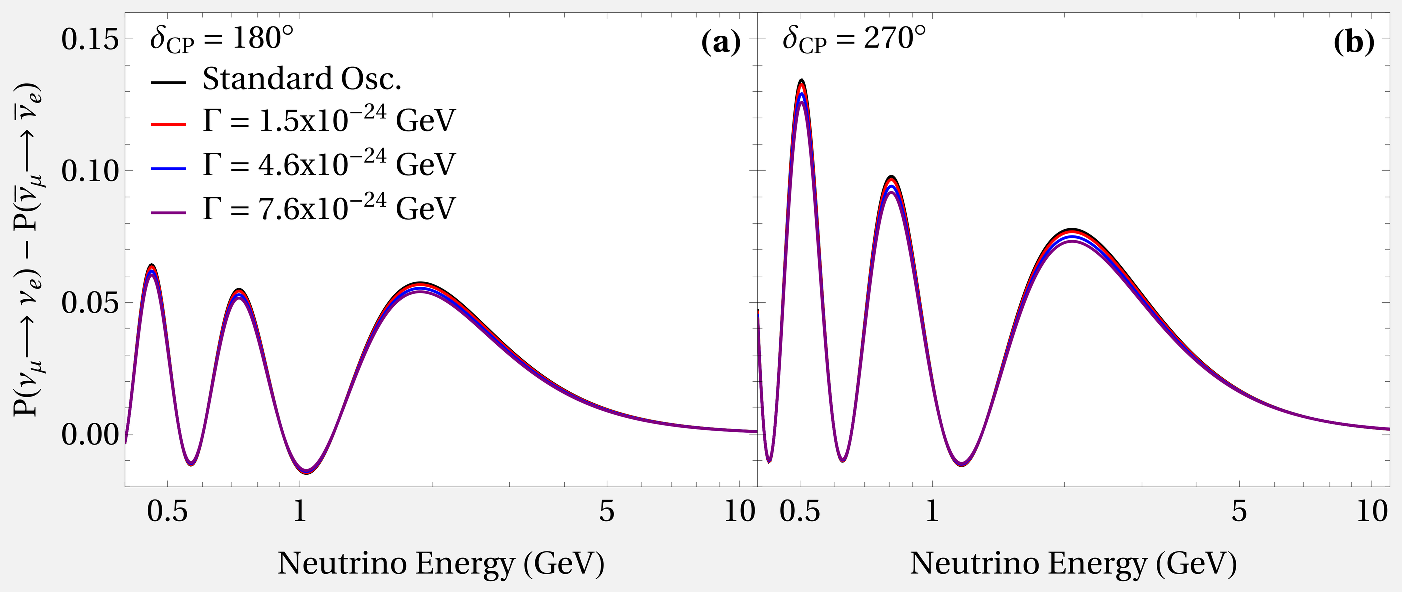
and

$$D_m = -\frac{\sin 2\theta_{12}}{4}\left(\left(\frac{\bar{\Delta}_{21}}{2aL}\right)^2 \sin 2\theta_{12}\cos^2\theta_{23} + \left(\frac{\bar{\Delta}_{21}}{2aL}\right)\left(\frac{\bar{\Delta}_{31}}{\bar{\Delta}_{31} - 2aL}\right)\sin\theta_{13}\sin 2\theta_{23}\right) \quad (5)$$

with $a = \frac{G_F N_e}{\sqrt{2}}$, where G_F is the Fermi constant and N_e is the electron number density.

We take $\Gamma_2 = \frac{5}{3}\Gamma_1$ and $\Gamma := \Gamma_1$ corresponding to maximum Γ_2 value. The standard oscillations parameters are:

Δm^2_{21}	7.50×10^{-5} eV^2
Δm^2_{31}	2.55×10^{-3} eV^2
$\sin^2\theta_{12}$	0.32
$\sin^2\theta_{13}$	0.022
$\sin^2\theta_{23}$	0.57
δ_{CP}	270°, 180°



DUNE & T2HK EXPERIMENTS

1. DUNE is a future experiment at Fermilab with a L = 1284.9 Km, density matter $\rho = 2.848$g/cm^3, 6.5 years in both neutrino (FHC) and antineutrino (RHC) modes, a far detector with 40 kt fiducial mass of liquid argon, and a beam from collisions of 120 GeV protons and 1.2 MW beam power (i.e. 624 kt-MW-years of exposure).
2. T2HK is a update version of T2K with L = 295 Km, $\rho = 2.6$g/cm^3, 7.5 years in antineutrino mode and 2.5 years in neutrino mode, a water Cherenkov detector with 186 kt fiducial mass and 1.3 MW beam power.

ANALYSIS

We use GLoBES for the simulations of DUNE and T2HK. Chi-squared analysis was performed for each experiment separately and for the combination of both experiments. The True events were simulated with different values of Γ and the Fit events were simulated with standard oscillation. For our analysis we define

$$\chi^2 = \min_{\vec{\alpha}}\left\{2\sum_i\left[N_i^{test}(\vec{\alpha}) - N_i^{true} + N_i^{true}\ln\left(\frac{N_i^{true}}{N_i^{test}(\vec{\alpha})}\right)\right] + \sum_j\left[\frac{\alpha_j}{\sigma_j}\right]^2\right\} + \chi^2_{\text{solar}}$$

where i is the number of bins, $\vec{\alpha}$ is the systematic uncertainties, $\{\sigma_j\}$ are the systematic errors and χ^2_{solar} is a penalty for the solar parameters.

CONCLUSIONS

The measurement of δ_{CP}, θ_{13}, and θ_{23} is more impacted in DUNE compared to T2HK when quantum decoherence effects are present. DUNE is expected to have greater sensitivity than T2HK in detecting decoherence effects. By combining data from DUNE and T2HK, it is possible to obtain a reliable measurement of oscillation parameters.

REFERENCES

- G. Barenboim, A.M. Calatayud-Cadenillas, A.M. Gago and C.A. Ternes *Quantum decoherence effects on precision measurements at DUNE and T2HK*, *Phys. Lett. B* **852** (2024) 138626.
- J. A. Carpio, E. Massoni and A.M. Gago, *Testing quantum decoherence at DUNE*, *Phys. Rev. D* **100** 015035.
- P.F. de Salas, et al., *2020 global reassessment of the neutrino oscillation picture*, *J. High Energy Phys.* **02** (2021) 071.

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RESULTS