Quantum decoherence and CP violation at Protvino to ORCA

Chinmay Bera

Department of Physics,
École Centrale School of Engineering
Mahindra University, Hyderabad,
Telangana, 500043, India

Working with
Dr. Deepthi K N

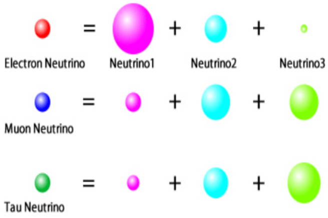
May 27, 2024

Overview

Neutrino oscillation

- Neutrino flavor (ν_α) oscillations are generated by the quantum interference of neutrino mass states (ν_j),
$$|\nu_\alpha\rangle = \sum_j U_{\alpha j} |\nu_j\rangle \ .$$

- Coherence between ν_j is essential for neutrino oscillations.
- Neutrino system behaves as a closed system.



- Time evolution of ρ represented by Liouville-Von Neumann equation
$$\frac{d\rho(t)}{dt} = -i[H, \rho(t)] \ .$$

- $P_{\alpha\beta}(t) = Tr[\rho_\alpha(t)\rho_\beta(0)]$.

Motivation

- $P_{\alpha\beta}(t \approx L) = P_{\alpha\beta}(\Delta m^2_{21}, |\Delta m^2_{31}|, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}; E, L, V(x))$.
- Significant opportunity to probe new physics (NP) phenomenon with upcoming high-precision neutrino oscillation experiments.
- One such interesting phenomenon is the environmentally induced decoherence.
- This effect arises in the oscillation probabilities through the damping term $e^{-\Gamma L}$.

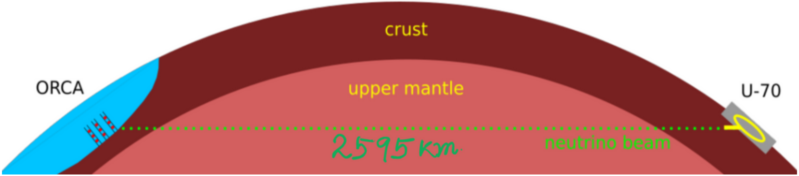


Fig 1. Protvino to ORCA.

Decoherence

- Neutrino system interacts with the stochastic environment.
- $\frac{d\tilde{\rho}_m(t)}{dt} = -i\left[H, \tilde{\rho}_m(t)\right] + \mathcal{D}\left[\tilde{\rho}_m(t)\right]$.
- **Assumptions:**
  (a) complete positivity,
  (b) trace preserving conditions,
  (c) increasing von Neumann entropy,
  (d) average energy conservation of the system.

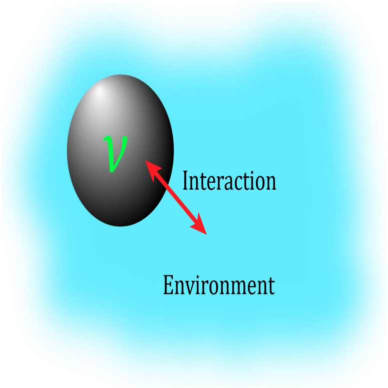


Fig 2. Neutrino system as an open quantum system.

Oscillation probability in presence of decoherence

- $P_{\alpha\beta}(t) = Tr[\tilde{\rho}_\alpha(t)\tilde{\rho}_\beta(0)]$.
- $$P_{\alpha\beta}(L) = \delta_{\alpha\beta} - 2\sum_{j>k} Re\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{V}^*_{\beta k}\right)$$
$$+ 2\sum_{j>k} Re\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\beta k}\right)\exp(-\Gamma_{jk}L)\cos\left(\frac{\tilde{\Delta}m^2_{jk}}{2E}L\right)$$
$$+ 2\sum_{j>k} Im\left(\tilde{U}_{\beta j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\beta k}\right)\exp(-\Gamma_{jk}L)\sin\left(\frac{\tilde{\Delta}m^2_{jk}}{2E}L\right) .$$
- Damping of interference terms by a factor $e^{-\Gamma L}$ in the oscillation probability.
- Energy dependency on Γ :

$$\Gamma_{jk}(E_\nu) = \Gamma_0\left(\frac{E_\nu}{GeV}\right)^n \; ; \; n = 0, \pm 1, \pm 2 .$$

Current upper bounds on decoherence parameters

Bounds on Γ by IceCube experiments

Article https://doi.org/10.1038/s41567-024-02436-w

Search for decoherence from quantum gravity with atmospheric neutrinos

Received: 25 July 2023

Accepted: 8 February 2024

Published online: 26 March 2024

Check for updates

The IceCube Collaboration*

Neutrino oscillations at the highest energies and longest baselines can be used to study the structure of spacetime and test the fundamental principles of quantum mechanics. If the metric of spacetime has a quantum mechanical description, its fluctuations at the Planck scale are expected to introduce non-unitary effects that are inconsistent with the standard unitary time evolution of quantum mechanics. Neutrinos interacting with such fluctuations would lose their quantum coherence, deviating from the expected oscillatory flavour composition at long distances and high energies. Here we use atmospheric neutrinos detected by the IceCube South Pole Neutrino Observatory in the energy range of 0.5–10.0 TeV to search for coherence loss in neutrino propagation. We find no evidence of anomalous neutrino decoherence and determine limits on neutrino–quantum gravity interactions. The constraint on the effective decoherence strength parameter within an energy-independent decoherence model improves on previous limits by a factor of 30. For decoherence effects scaling as E^2, our limits are advanced by more than six orders of magnitude beyond past measurements compared with the state of the art.

Bounds on Γ by IceCube experiments

Article https://doi.org/10.1038/s41567-024-02436-w

Search for decoherence from quantum gravity with atmospheric neutrinos

Received: 25 July 2023

The IceCube Collaboration*

Table 1 | Summary of constraints on decoherence models obtained in this analysis

n	Phase perturbation Γ_{90}	State selection Γ_{90}
0	1.18×10^{-15} eV	1.17×10^{-15} eV
1	6.89×10^{-16} eV	6.67×10^{-16} eV
2	9.80×10^{-18} eV	9.48×10^{-18} eV
3	1.58×10^{-19} eV	1.77×10^{-19} eV

The 90% CL upper limits on decoherence strength parameter Γ_0 (which we name Γ_{90}) are reported for each power-law index n with power-law pivot energy E_0=1TeV in the state selection and phase perturbation models.

Bounds by reactor and accelerator experiments

Neutrino oscillation bounds on quantum decoherence

JHEP09(2023)097

Valentina De Romeri,[a] Carlo Giunti,[b] Thomas Stuttard[c] and Christoph A. Ternes[b,d]

[a]*Instituto de Física Corpuscular (CSIC-Universitat de València), Parc Científic UV C/ Catedrático José Beltrán, 2 E-46980 Paterna (Valencia) - Spain*

[b]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy*

[c]*Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark*

[d]*Dipartimento di Fisica, Università di Torino, via P. Giuria 1, I-10125 Torino, Italy*

E-mail: deromeri@ific.uv.es, carlo.giunti@to.infn.it, thomas.stuttard@nbi.ku.dk, ternes@to.infn.it

Abstract: We consider quantum-decoherence effects in neutrino oscillation data. Working in the open quantum system framework we adopt a phenomenological approach that allows to parameterize the energy dependence of the decoherence effects. We consider several phenomenological models. We analyze data from the reactor experiments RENO, Daya Bay and KamLAND and from the accelerator experiments NOvA, MINOS/MINOS+ and T2K. We obtain updated constraints on the decoherence parameters quantifying the strength of damping effects, which can be as low as $\Gamma_{ij} \lesssim 8 \times 10^{-27}$ GeV at 90% confidence level in some cases. We also present sensitivities for the future facilities DUNE and JUNO.

Bounds by reactor and accelerator experiments

Neutrino oscillation bounds on quantum decoherence

Valentina De Romeri,[a] Carlo Giunti,[b] Thomas Stuttard[c] and Christoph A. Ternes[b,d]

[a] *Instituto de Física Corpuscular (CSIC-Universitat de València), Parc Científic UV C/ Catedrático José Beltrán, 2 E-46980 Paterna (Valencia) - Spain*

[b] *Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino,*

Decoherence Model	n = −2	n = −1	n = 0	n = +1	n = +2
A: $\Gamma_{21} = \Gamma_{31} = \Gamma_{32}$	7.8×10^{-27} (KL)	1.8×10^{-24} (KL)	5.1×10^{-24} (M)	3.0×10^{-25} (M)	1.3×10^{-26} (M)
B: $\Gamma_{21} = \Gamma_{31}, \Gamma_{32} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	2.4×10^{-23} (N)	2.3×10^{-24} (M)	1.0×10^{-25} (M)
C: $\Gamma_{21} = \Gamma_{32}, \Gamma_{31} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	9.4×10^{-24} (M)	5.7×10^{-25} (M)	2.5×10^{-26} (M)
D: $\Gamma_{31} = \Gamma_{32}, \Gamma_{21} = 0$	6.9×10^{-25} (R)	2.1×10^{-23} (T2K)	5.6×10^{-24} (M)	3.3×10^{-25} (M)	1.5×10^{-26} (M)
E: $\Gamma_{21}, \Gamma_{31} = \Gamma_{32} = 0$	7.9×10^{-27} (KL)	1.8×10^{-24} (KL)	3.2×10^{-23} (M)	2.2×10^{-24} (M)	1.0×10^{-25} (M)
F: $\Gamma_{31}, \Gamma_{21} = \Gamma_{32} = 0$	1.0×10^{-24} (R)	1.9×10^{-23} (T2K)	2.3×10^{-23} (N)	2.2×10^{-24} (M)	1.0×10^{-25} (M)
G: $\Gamma_{32}, \Gamma_{21} = \Gamma_{31} = 0$	4.0×10^{-23} (T2K)	6.5×10^{-23} (T2K)	1.1×10^{-23} (M)	6.6×10^{-25} (M)	3.0×10^{-26} (M)

TABLE III: Summary of results: each column shows the most constraining upper limit on Γ_{ij}, in GeV, for each model (A to G) and value of n. We also clarify, within parenthesis, which experiment sets the bound (KL = KamLAND, R = RENO, M = MINOS/MINOS+, N = NOvA).

Bounds on Γ by MINOS and T2K experiments

Quantum decoherence and relaxation in long-baseline neutrino data

A.L.G. Gomes,[a] **R.A. Gomes**[a] **and O.L.G. Peres**[b]

[a] *Instituto de Física, Universidade Federal de Goiás, 74690-900, Goiânia, GO, Brazil*

[b] *Instituto de Física Gleb Wataghin, UNICAMP, 13083-859, Campinas, SP, Brazil*

E-mail: abnergomes@ufg.br, ragomes@ufg.br, orlandop@unicamp.br

ABSTRACT: We investigate the effect of quantum decoherence and relaxation in neutrino oscillations using MINOS and T2K data. The formalism of open quantum systems is used to describe the interaction of a neutrino system with the environment, where the strength of the interaction is regulated by a decoherence parameter Γ. We assume an energy dependence parameterized by $\Gamma = \gamma_0 (E/\mathrm{GeV})^n$, with $n = -2, 0, +2$, and consider three different scenarios, allowing the investigation of the effect of relaxation and of constraining the solar and atmospheric sectors to the same decoherence parameter. The MINOS and T2K data present a complementary behavior, with regard to our theoretical model, resulting in a better sensitivity for $n = +2$ and $n = -2$, respectively. We perform a combined analyses of both experimental data, which also include a reactor constraint on $\sin^2\theta_{13}$, and observe an independence of the results to the scenarios we investigate. Our analyses obtain limits on γ_0 based on long-baseline data for scenarios allowing or not relaxation. We improve some previous bounds on γ_0 and outline which data (solar, reactor, atmospheric, long-baseline) determine the more stringent constraints for different scenarios and energy dependencies.

JHEP10(2023)035

Bounds on Γ by MINOS and T2K experiments

Quantum decoherence and relaxation in long-baseline neutrino data

A.L.G. Gomes,[a] R.A. Gomes[a] and O.L.G. Peres[b]

[a] *Instituto de Física, Universidade Federal de Goiás, 74690-900, Goiânia, GO, Brazil*

[b] *Instituto de Física Gleb Wataghin, UNICAMP,*

JHEP10(2

	$n=-2$	$n=0$	$n=2$
MINOS (this work)			
Case 1 ($\Gamma_{31}=\Gamma_{32}=\Gamma_{21}$, with relaxation)	$(0.33-37.0)\times10^{-23}$	6.8×10^{-23}	1.7×10^{-25}
Case 2 ($\Gamma_{31}=\Gamma_{32}=\Gamma_{21}$, no relaxation)	30.0×10^{-23}	6.5×10^{-23}	2.4×10^{-25}
Case 3 ($\Gamma_{31}=\Gamma_{32}$, $\Gamma_{21}=0$, no relaxation)	19.0×10^{-23}	5.9×10^{-23}	2.5×10^{-25}
T2K (this work)			
Case 1	2.8×10^{-23}	6.2×10^{-23}	3.1×10^{-23}
Case 2	2.9×10^{-23}	5.2×10^{-23}	3.3×10^{-23}
Case 3	1.7×10^{-23}	3.9×10^{-23}	4.1×10^{-23}
MINOS+T2K (this work)			
Case 1	2.9×10^{-23}	6.6×10^{-23}	2.3×10^{-25}
Case 2	3.4×10^{-23}	6.1×10^{-23}	2.9×10^{-25}
Case 3	2.0×10^{-23}	5.0×10^{-23}	3.3×10^{-25}

Our work:
arXiv:2405.03286

Phenomenological models

- Case 1: $\Gamma_{21} = \Gamma_{31} = \Gamma_{32} \neq 0$
- Case 2: $\Gamma_{21} = \Gamma_{31} \ , \ \Gamma_{32} = 0$
- Case 3: $\Gamma_{21} = \Gamma_{32} \ , \ \Gamma_{31} = 0$
- Case 4: $\Gamma_{31} = \Gamma_{32} \ , \ \Gamma_{21} = 0$

$$\Gamma_{jk}(E_\nu) = \Gamma_0 \left(\frac{E_\nu}{GeV} \right)^n \ ; \ n = 0, \pm 1, \pm 2 \ .$$

Objectives: To study

- the effects of Γ on different oscillation channels.
- the bounds on decoherence parameters in P2O considering $\Gamma \propto E_\nu^n$.
- MH and CPV sensitivity considering 3σ value of Γ.

Simulation details

Baseline	2595 km
Exposure	0.8×10^{20} POT/year
Beam power	90 kW (modest) and 450 kW (upgradable)
Run time	6 years $(3(\nu) + 3(\bar{\nu}))$
Detector mass	8 Mton (Water Cherenkov)
Matter density	3.25 gm/cm^3

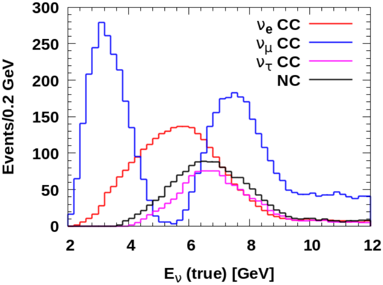


Fig 3. Events rate considering standard interaction in the presence of earth matter.
[1] Eur. Phys. J. C (2019) 79: 758

Oscillation probabilities

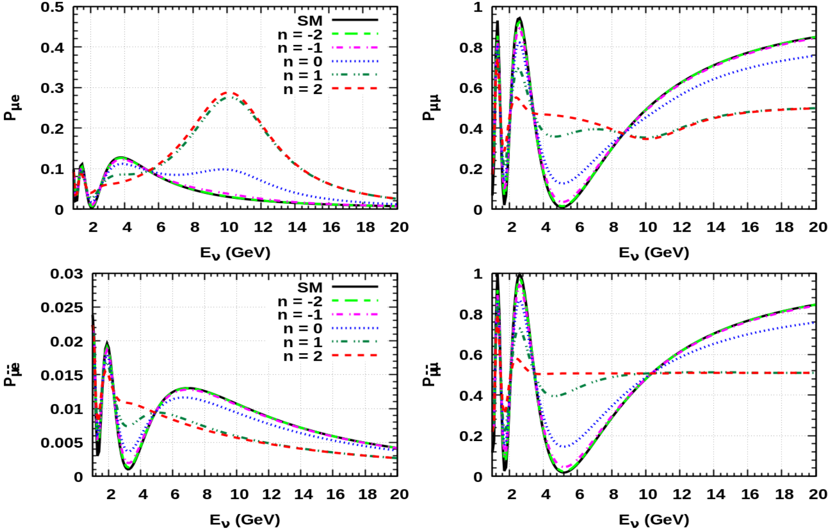


Fig 4. The left (right) plot in the upper panel represents ν_e appearance (ν_μ disappearance) probability and in the lower panel corresponding anti-neutrino probability. We consider a representative case $\Gamma_{21} = \Gamma_{31} = \Gamma_{32} = 2.3 \times 10^{-23}$ GeV.

Analysis

- We incorporated a new oscillation probability engine into GLoBES [2,3] by taking into account the effect of decoherence on neutrino propagation.
- $\Delta\chi^2_\Gamma = \chi^2(\Gamma(true) = 0, \Gamma(test) \neq 0)$.
  Marginalized over θ_{23} and δ_{CP}, $(\Delta m^2_{31})_{NH}$.
- $\Delta\chi^2_{MH} = \chi^2_{true}(\Gamma \neq 0, \Delta m^2_{31} > 0) - \chi^2_{test}(\Gamma = 0, \Delta m^2_{31} < 0)$.
  Marginalized over θ_{23} and δ_{CP}.
- $\Delta\chi^2_0 = \chi^2_{true}(\delta_{CP}(true), \Gamma \neq 0) - \chi^2_{test}(\delta_{CP} = 0, \Gamma = 0)$,
  $\Delta\chi^2_\pi = \chi^2_{true}(\delta_{CP}(true), \Gamma \neq 0) - \chi^2_{test}(\delta_{CP} = \pi, \Gamma = 0)$,
  $\Delta\chi^2_{CPV} = min[\Delta\chi^2_0, \Delta\chi^2_\pi]$.
  Marginalized over θ_{23}, $(\Delta m^2_{31})_{NH}$.

[2] Comput. Phys. Commun. 167 (2005) 195 , [3] Comput. Phys. Commun. 177 (2007) 432–438 .

Results

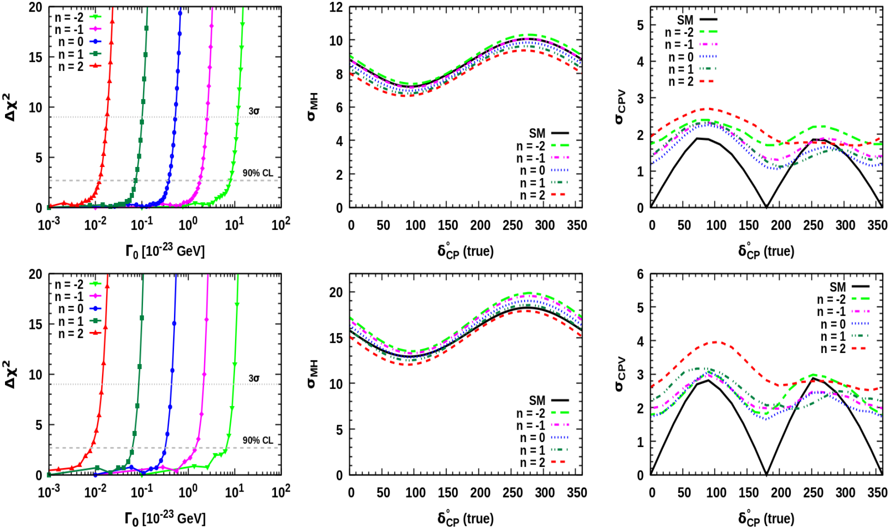


Fig 5. Case 1: $\Gamma_{21} = \Gamma_{31} = \Gamma_{32} \neq 0$. Upper and lower panel are the results of 90 kW and 450 kW beam respectively.

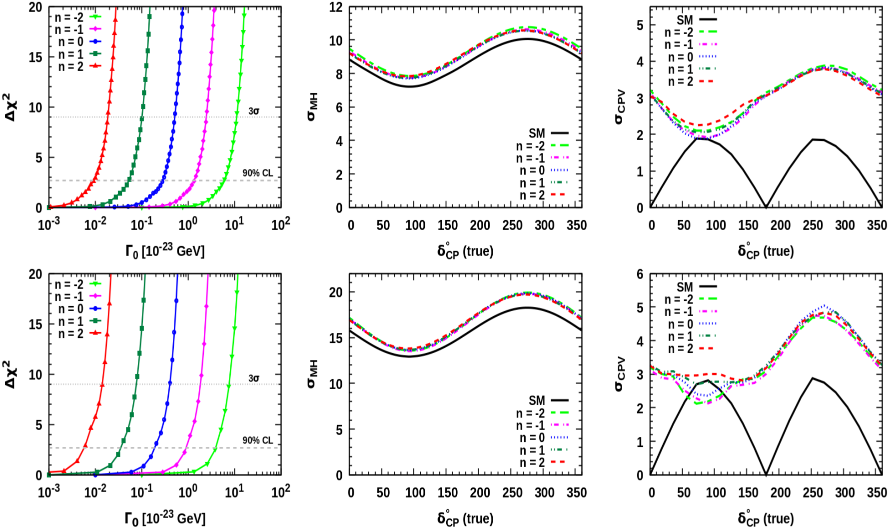


Fig 6. Case 2: $\Gamma_{21} = \Gamma_{31}$, $\Gamma_{32} = 0$. Upper and lower panel are the results of 90 kW and 450 kW beam respectively.

Summary table

n	CL	90 kW		450 kW	
		Case 1	Case 2	Case1	Case 2
$n=-2$	90% 3σ	8.06×10^{-23} 1.15×10^{-22}	6.0×10^{-23} 1.11×10^{-22}	6.4×10^{-23} 9.0×10^{-23}	3.9×10^{-23} 7.6×10^{-23}
$n=-1$	90% 3σ	1.8×10^{-23} 2.55×10^{-23}	1.36×10^{-23} 2.46×10^{-23}	1.4×10^{-23} 2.1×10^{-23}	8.5×10^{-24} 1.75×10^{-23}
$n=0$	90% 3σ	3.76×10^{-24} 5.3×10^{-24}	2.76×10^{-24} 5.18×10^{-24}	3.1×10^{-24} 4.2×10^{-24}	1.89×10^{-24} 4.0×10^{-24}
$n=1$	90% 3σ	7.4×10^{-25} 1.04×10^{-24}	5.4×10^{-25} 1.02×10^{-24}	6.2×10^{-25} 8.5×10^{-25}	3.6×10^{-25} 7.7×10^{-25}
$n=2$	90% 3σ	1.24×10^{-25} 1.79×10^{-25}	9.07×10^{-26} 1.87×10^{-25}	7.8×10^{-26} 1.5×10^{-25}	5.87×10^{-26} 1.4×10^{-25}

Table 1: Upper bounds on Γ_0 (GeV) obtained for different power law dependencies.

Conclusions

1. The upper bounds on Γ are comparatively stronger for $n \geq 0$.
2. Similar conclusion can be drawn for upgraded 450 kW beam.
3. Case-2 ($\Gamma_{21} = \Gamma_{31}$, $\Gamma_{32} = 0$) poses strong constraints for $n = 0$ on $\Gamma \leq 2.76 \times 10^{-24}$ GeV for P2O and $\Gamma \leq 1.89 \times 10^{-24}$ GeV for P2O-upgrade.
4. MH sensitivity does not vary significantly w.r.t SM.
5. In the presence of decoherence, CP conserving values ($\delta_{CP} = 0, \pm\pi$) also show nonzero δ_{CP}

Thank you

chinmay20pphy014@mahindrauniversity.edu.in

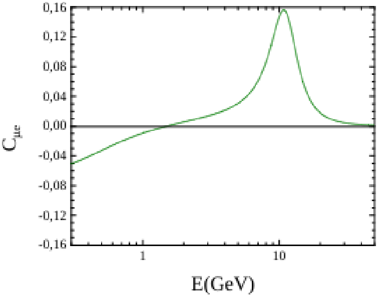
Peak explanation

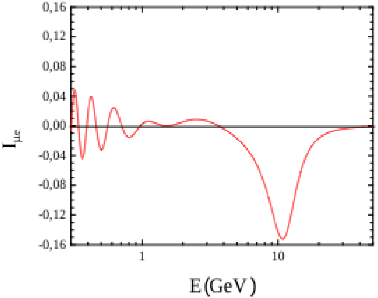
$$
\begin{aligned}
P_{\nu_\alpha \nu_{\alpha'}} =& \delta_{\alpha\alpha'} - 2\sum_{j>k} Re(\tilde{U}_{\alpha' j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\alpha' k}) \\
& + 2\sum_{j>k} Re(\tilde{U}_{\alpha' j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\alpha' k}) e^{-\Gamma_{jk} x} \cos\left(\frac{\tilde{\Delta}_{jk}}{2E} x\right) \\
& + 2\sum_{j>k} Im(\tilde{U}_{\alpha' j}\tilde{U}^*_{\alpha j}\tilde{U}_{\alpha k}\tilde{U}^*_{\alpha' k}) e^{-\Gamma_{jk} x} \sin\left(\frac{\tilde{\Delta}_{jk}}{2E} x\right)
\end{aligned}
$$

Cont...

$$C_{\mu e} = -2 \sum_{i<j} \text{Re}\left[\tilde{U}^*_{\mu i}\tilde{U}_{ei}\tilde{U}_{\mu j}\tilde{U}^*_{ej}\right]$$

$$I_{\mu e} = 2 \sum_{i<j} \text{Re}\left[\tilde{U}^*_{\mu i}\tilde{U}_{ei}\tilde{U}_{\mu j}\tilde{U}^*_{ej}\right] \cos\tilde{\Delta}_{ij}$$
$$-2 \sum_{i<j} \text{Im}\left[\tilde{U}^*_{\mu i}\tilde{U}_{ei}\tilde{U}_{\mu j}\tilde{U}^*_{ej}\right] \sin\tilde{\Delta}_{ij}$$





https://doi.org/10.1103/PhysRevD.100.055023

Events rate

- NH, $\delta_{CP} = \pi/2$; 90 kW beam power.

Signal events	ν_e	ν_μ	$\bar{\nu}_e$	$\bar{\nu}_\mu$
SM ($\Gamma = 0$)	2115	4746	160	1473
$\Gamma = 1.79 \times 10^{-25}$ GeV ($n = 2$)	2390	5160	154	1623
$\Gamma = 1.15 \times 10^{-22}$ GeV ($n = -2$)	2139	5039	159	1567

Bkg in ν_e app channel	ν_μ	NC	ν_τ
SM ($\Gamma = 0$)	2362	1190	876
$\Gamma = 1.79 \times 10^{-25}$ GeV ($n = 2$)	2596	1190	852
$\Gamma = 1.15 \times 10^{-22}$ GeV ($n = -2$)	2370	1190	868