



Unveiling the Majorana nature of neutrinos via precision measurement of the CP violation

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NuCo 2021: Neutrinos en Colombia

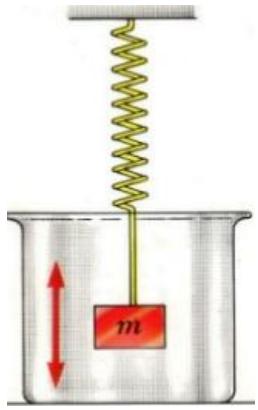
Universidad del Atlántico

Outline

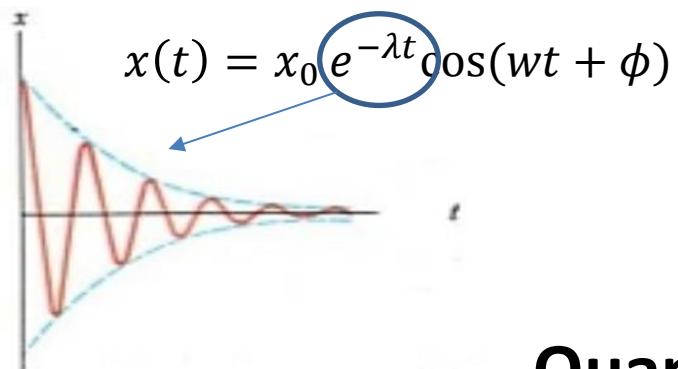
- **Introduction**
- **Quantum Decoherence Neutrinos**
- **Neutrino Oscillation Probabilites**
- **Simulation and Analysis details**
- **Results**
- **Summary**

Decoherence-Examples

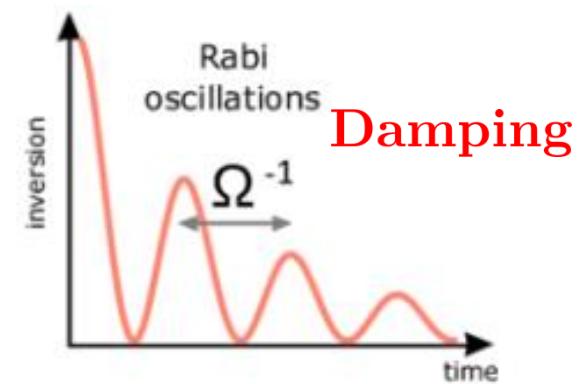
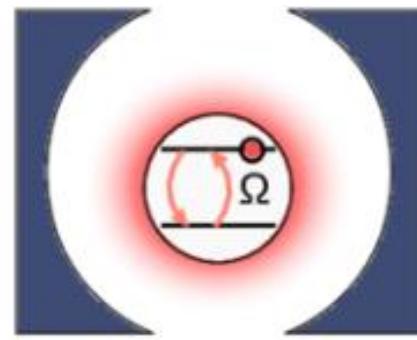
Classical



Damping



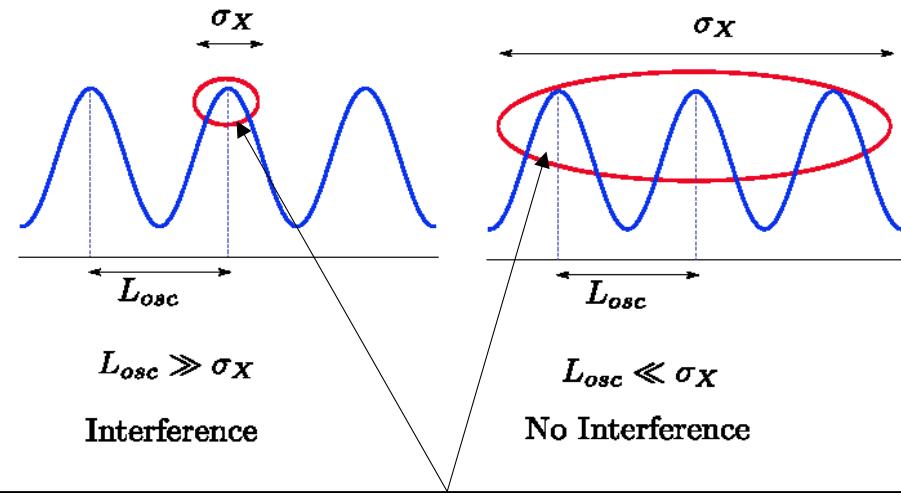
Quantum Optics



Damping signature of decoherence

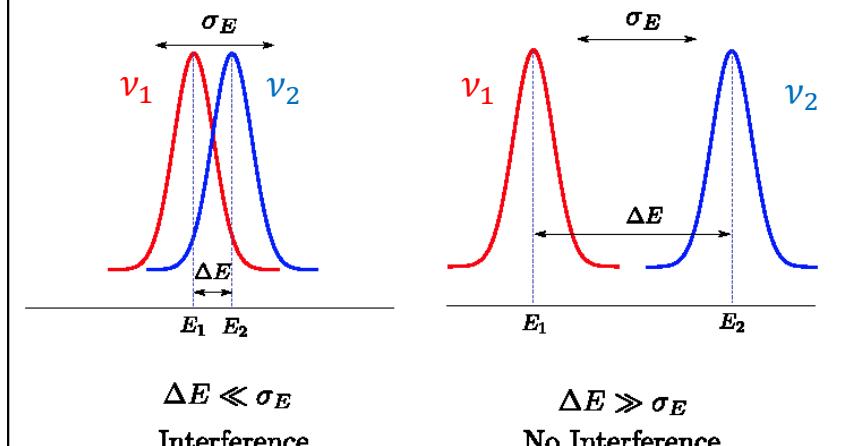
“Standard” decoherence – neutrino oscillation

Coherence (Decoherence) @Production/Detection

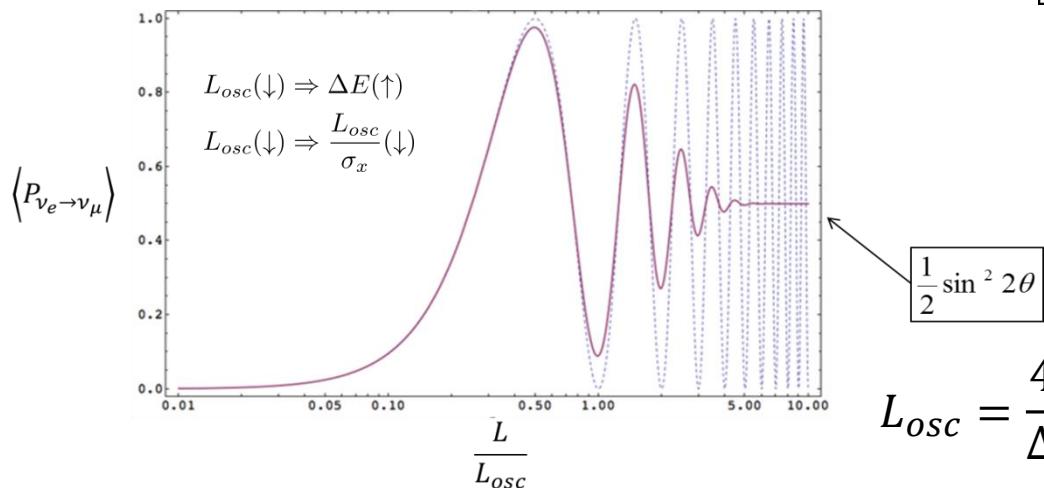


σ_x = size of the detection/production region

σ_E = QM energy uncertainty of the neutrino state



Decoherence destroys interference



Coherence (Decoherence) @Propagation

$L_{coh} \gg L$ coherence

$L_{coh} \ll L$ decoherence

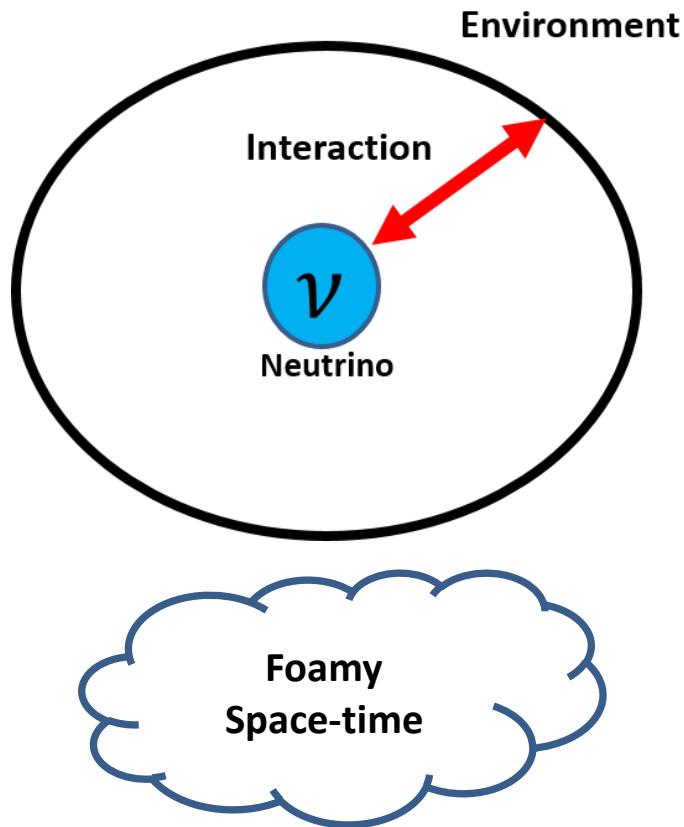
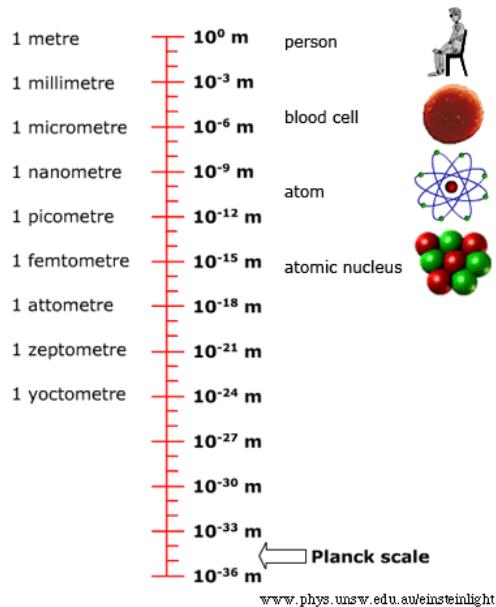
$$L_{osc} = \frac{4\pi E}{\Delta m^2}$$

$$L_{coh} \simeq \frac{2E^2}{|\Delta m^2|} \sigma_x^P$$

Quantum decoherence

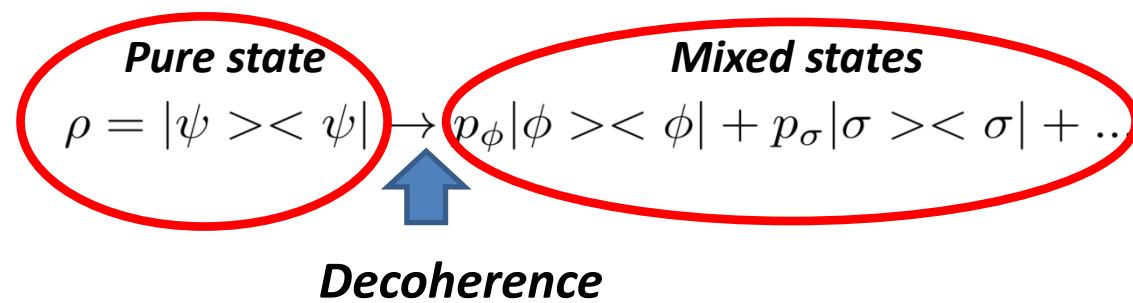
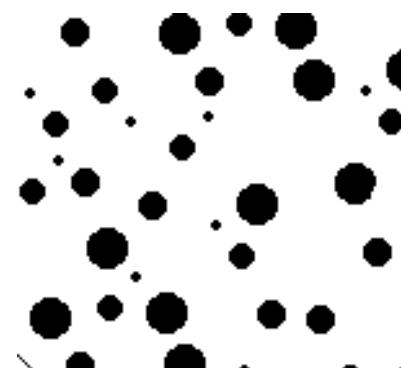
F. Benatti and R. Floreanini,
JHEP 0002 (2000) 032

logarithmic scale



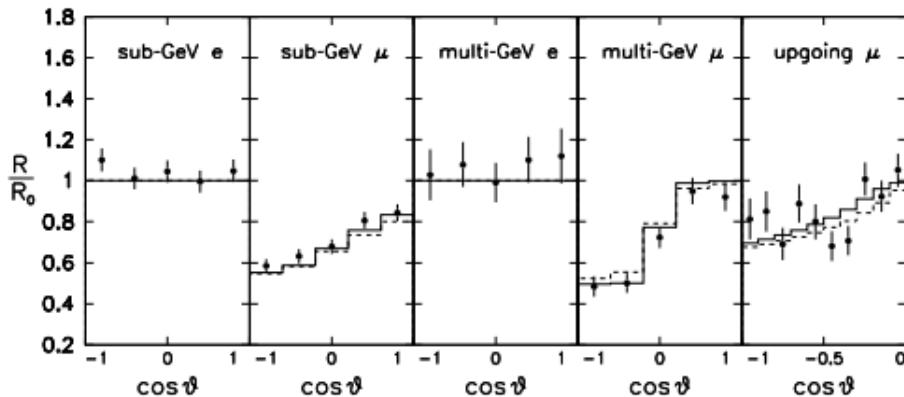
J. Ellis, et al., NPB241 (1984)
J. Ellis, N. E. Mavromatos,
D. V. Nanopoulos PLB293
(1992)

Virtual Black -Holes



Quantum decoherence as solution of ν data

Super-Kamiokande (atmospheric ν)



E. Lisi, A. Marrone, and D. Montanino, PRL 85, 1166 (2000).

$$\Gamma_\nu \neq \Gamma_{\bar{\nu}} \equiv \cancel{\text{CPT}}$$

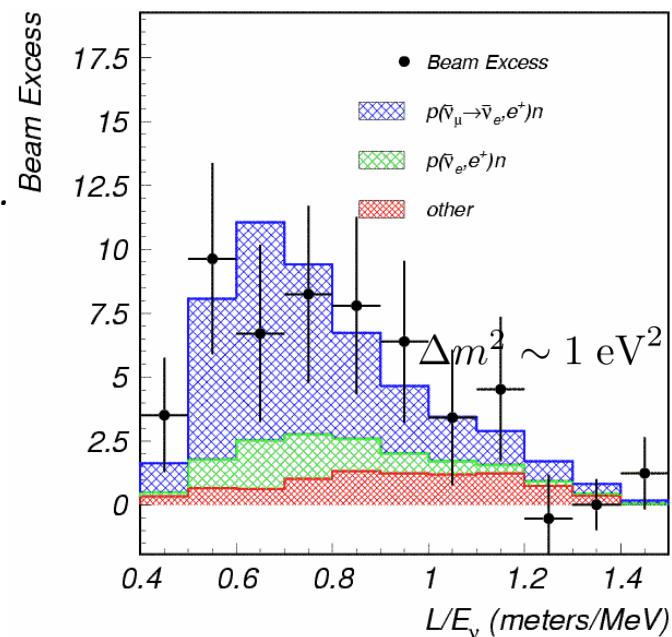
$$m_\nu = m_{\bar{\nu}}$$

$$\theta_\nu = \theta_{\bar{\nu}}$$

$$P_{\nu_\mu \rightarrow \nu_\mu} = \frac{1}{2} \left(1 - e^{-\Gamma_0 \left(\frac{G_e V}{E_\nu} \right) L} \right)$$

Pure decoherence

Liquid Scintillator Neutrino Detector (LSND)



Solution LSND: Decoherence \oplus Oscillation

Quantum decoherence - Neutrinos

Many other interesting work:

**Eur. Phys. J. C (2010) 69: 493–502
DOI 10.1140/epjc/s10052-010-1388-1**

Regular Article - Theoretical Physics

Quantum dissipation in vacuum neutrino oscillation

R.L.N. Oliveira^a, M.M. Guzzo^b
Instituto de Física Gleb Wataghin, Universidade Estadual de Campinas, Brazil

PRL 118, 221801 (2017)

THE EUROPEAN PHYSICAL JOURNAL C

PHYSICAL REVIEW LETTERS

João A. B. Coelho,^{1,2,*} W. Anthony Mann,^{1,†} and Saqib S. Bashar¹
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(Received 26 February 2017; published 30 May 2017)

Nonmaximal θ_{23} Mixing at NOvA from Neutrino Decoherence

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week ending 2 JUNE 2017

PHYSICAL REVIEW D 97, 115017 (2018)

Revisiting quantum decoherence for neutrino oscillations in matter with constant density

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PHYSICAL REVIEW D 102, 115003 (2020)

Neutrino decoherence from quantum gravitational stochastic perturbations

Niels Bohr Institute, University of Copenhagen, DK-2100 Copenhagen, Denmark
Thomas Stattard¹ and Mikkel Jensen

PHYSICAL REVIEW D 100, 055023 (2019)

Decoherence in neutrino propagation through matter, and bounds from IceCube/DeepCore

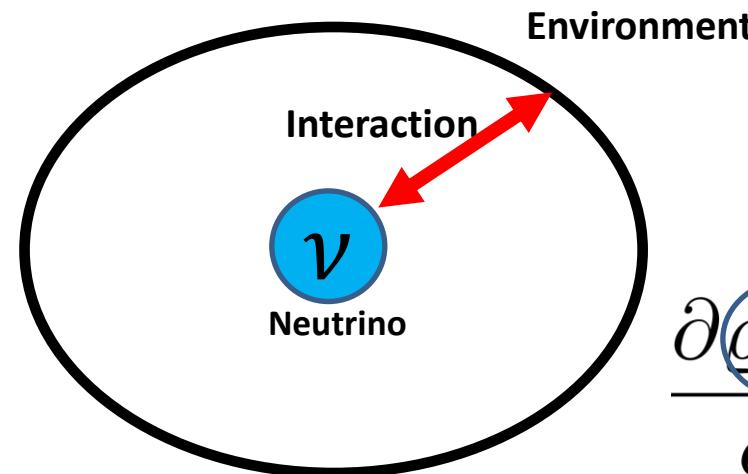
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Quantum decoherence effects in neutrino oscillations at DUNE

G. Balieiro Gomes^{1,2,*}, D. V. Forero,^{1,3,†} M. M. Guzzo,^{1,‡} P. C. de Holanda,^{1,§} and R. L. N. Oliveira^{1,||}
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Quantum decoherence - Neutrinos

F. Benatti and R. Floreanini, JHEP 0002 (2000) 032



Lindblad Master Equation

$$\frac{\partial \varrho'(t)}{\partial t} = -i[H, \varrho'(t)] + \mathcal{D}[\varrho'(t)]$$

Density matrix *Dissipative term*

Unitary Evolution

$$H = \frac{1}{2E} (\Delta M^2 + U^\dagger \mathbb{A} U)$$

$$\Delta M^2 = \text{Diag}(0, \Delta m_{21}^2, \Delta m_{31}^2) \quad \mathbb{A} = \text{Diag}(2E\sqrt{2}G_F n_e, 0, 0)$$

Non-Unitary Evolution (irreversible)

$$\mathcal{D}[\varrho'(t)] = \frac{1}{2} \sum_j \left([A_j, \varrho'(t) A_j^\dagger] + [A_j \varrho'(t), A_j^\dagger] \right)$$

Irreversibility

$A_j = A_j^\dagger \Rightarrow S = \text{Tr}[\rho \ln \rho]$ increases

Trace Conservation

$$d\text{Tr}[\rho(t)]/dt = 0$$

Complete Positivity

Positivity of probabilities

Quantum decoherence - Neutrinos

Expanding on $SU(3)$

$$\mathbf{D} \equiv D_{kj} \text{ symmetric}$$

$$\hat{O} = O_0 \mathbb{I} + O_k \lambda_k$$

$$\hat{O} \equiv \rho', H, A_j$$

$$D_{kj} = \frac{1}{2} \sum_{l,m,n} (\vec{a}_n \cdot \vec{a}_l) f_{knm} f_{mlj}$$

λ_k Gell-Mann matrices (1...8)

$$D_{\mu 0} = D_{0\mu} = 0 \quad \vec{a}_r = \{a_r^1, a_r^2, \dots, a_r^8\}$$

$$\dot{\rho'_0} = 0, \quad \dot{\rho'_k} = (H_{kj} + D_{kj}) \rho'_j = M_{kj} \rho'_j$$

$$H_{kj} = \sum_i h_i f_{ijk}$$

$$\varrho'(t) = e^{\mathbf{M}t} \varrho'(0)$$

Solving Neutrino Oscillation Probabilities: Standard Mechanism (SO) \oplus Decoherence (DE)

$$\dot{\varrho}^{\alpha} = \overbrace{(\mathbf{H}_m + \mathbf{D}_m)}^{\mathbf{M}} \varrho'^{\alpha} \Rightarrow \varrho'^{\alpha}(t) = e^{\mathbf{M}t} \varrho'^{\alpha}(0)$$

Decoherence Matrix $\mathbf{D}_m = \mathbf{D}_m^d + \mathbf{D}_m^{nd}$ with $\mathbf{D}_m^d = -\Gamma \times \mathbb{I}$

$$\varrho'^{\alpha}(t) = e^{\mathbf{M}t} \varrho'^{\alpha}(0) = e^{-\Gamma t} e^{(\mathbf{H}_m + \mathbf{D}_m^{nd})t} \varrho'^{\alpha}(0) = e^{-\Gamma t} \varrho^{\alpha}(t)$$

$$\begin{aligned} \tilde{\varrho}^{\alpha} &= \tilde{\varrho}^{(0)} + \theta_{13} \tilde{\varrho}^{(\theta)} + \alpha_{\Delta} \tilde{\varrho}^{(\alpha_{\Delta})} + \alpha_{\Delta} \theta_{13} \tilde{\varrho}^{(\alpha_{\Delta} \theta_{13})} + \dots \\ &\quad + \Gamma_{ij} \tilde{\varrho}^{(\Gamma_{ij})} + \Gamma_{ij} \theta_{13} \tilde{\varrho}^{(\Gamma_{ij} \theta_{13})} + \Gamma_{ij} \alpha_{\Delta} \tilde{\varrho}^{(\Gamma_{ij} \alpha_{\Delta})} + \dots \end{aligned} \quad \varrho^{\alpha}(t) = e^{\mathbf{H}_m t} \tilde{\varrho}^{\alpha}(t),$$

in terms of a single
non-diagonal element
 Γ_{ij} ($\bar{\Gamma}_{ij} = \Gamma_{ij} t$)

Power series expansion in: $\Gamma_{ij}, \theta_{13}, \alpha_{\Delta} = \Delta m_{12}^2 / \Delta m_{13}^2$

$$\varrho^{\alpha}(t) = e^{\mathbf{H}_m t} (\varrho^{\alpha}(0) + \bar{\Gamma}_{ij}(\dots))$$

$$P_{\nu_{\alpha} \rightarrow \nu_{\beta}}^{\text{SO} \oplus \text{DE}} = \frac{1}{3} + \frac{1}{2} (\varrho'^{\beta}(0))^T \varrho'^{\alpha}(t)$$

Neutrino Oscillation Probabilities SO \oplus DE Phenomenology

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SO} \oplus \text{DE}} = \frac{1}{3} + \frac{1}{2} \sum_{k,l} e^{-\Gamma t} \varrho_k^\beta(0) (\varrho_l^\alpha(0) + \bar{\Gamma}_{ij}(\dots)_l) [e^{\mathbf{H}_m t}]_{kl}$$

Decoherence Matrix

$$\mathbf{D} = \begin{pmatrix} -\Gamma & \Gamma_{12} & \Gamma_{13} & \Gamma_{14} & \Gamma_{15} & \Gamma_{16} & \Gamma_{17} & \Gamma_{18} \\ \Gamma_{12} & -\Gamma & \Gamma_{23} & \Gamma_{24} & \Gamma_{25} & \Gamma_{26} & \Gamma_{27} & \Gamma_{28} \\ \Gamma_{13} & \Gamma_{23} & -\Gamma & \Gamma_{34} & \Gamma_{35} & \Gamma_{36} & \Gamma_{37} & \Gamma_{38} \\ \Gamma_{14} & \Gamma_{24} & \Gamma_{34} & -\Gamma & \Gamma_{45} & \Gamma_{46} & \Gamma_{47} & \Gamma_{48} \\ \Gamma_{15} & \Gamma_{25} & \Gamma_{35} & \Gamma_{45} & -\Gamma & \Gamma_{56} & \Gamma_{57} & \Gamma_{58} \\ \Gamma_{16} & \Gamma_{26} & \Gamma_{36} & \Gamma_{46} & \Gamma_{56} & -\Gamma & \Gamma_{67} & \Gamma_{68} \\ \Gamma_{17} & \Gamma_{27} & \Gamma_{37} & \Gamma_{47} & \Gamma_{57} & \Gamma_{67} & -\Gamma & \Gamma_{78} \\ \Gamma_{18} & \Gamma_{28} & \Gamma_{38} & \Gamma_{48} & \Gamma_{58} & \Gamma_{68} & \Gamma_{78} & -\Gamma \end{pmatrix}.$$

Rich Phenomenology

CP and CPT violated symmetries:

$\delta_{\text{CP}} \neq 0$, or $\phi_1 \neq 0$ or $\phi_2 \neq 0$ or $\phi_2 - \phi_1 \neq 0$

Related work (two generations SO \oplus DE Majorana phases):

F. Benatti and R. Floreanini, PRD **64**, 085015(2001).

R.L. N. De Oliveira, M.M. Guzzo, P.C. De Holanda, PRD **89**, 053002(2014).

A. Capolupo, S. M. Giampaolo and G. Lambiase, PLB **792**, 298 (2019).

$$U = U_{PMNS}$$

$$\rho_0^\alpha = \sqrt{2/3}$$

$$\rho_1^\alpha = 2\text{Re}(U_{\alpha 1}^* U_{\alpha 2})$$

$$\rho_2^\alpha = -2\text{Im}(U_{\alpha 1}^* U_{\alpha 2})$$

$$\rho_3^\alpha = |U_{\alpha 1}|^2 - |U_{\alpha 2}|^2$$

$$\rho_4^\alpha = 2\text{Re}(U_{\alpha 1}^* U_{\alpha 3})$$

$$\rho_5^\alpha = -2\text{Im}(U_{\alpha 1}^* U_{\alpha 3})$$

$$\rho_6^\alpha = 2\text{Re}(U_{\alpha 2}^* U_{\alpha 3})$$

$$\rho_7^\alpha = -2\text{Im}(U_{\alpha 2}^* U_{\alpha 3})$$

$$\rho_8^\alpha = \frac{1}{\sqrt{3}}(|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2 - 2|U_{\alpha 3}|^2)$$

$$U_{\text{Majorana}} = U_{PMNS} \cdot \text{diag}(1, \exp -i\phi_1, \exp -i\phi_2)$$

Non-diagonal element	CPV	CPTV
$\Gamma_{12}, \Gamma_{23}, \Gamma_{24}, \Gamma_{26}, \Gamma_{28}$		
$\Gamma_{15}, \Gamma_{35}, \Gamma_{45}, \Gamma_{56}, \Gamma_{58}$	✓	✓
$\Gamma_{17}, \Gamma_{37}, \Gamma_{47}, \Gamma_{67}, \Gamma_{78}$		
$\Gamma_{13}, \Gamma_{14}, \Gamma_{16}, \Gamma_{18}$		
$\Gamma_{25}, \Gamma_{27}, \Gamma_{34}, \Gamma_{36}$	✓	✗
$\Gamma_{46}, \Gamma_{48}, \Gamma_{57}, \Gamma_{68}$		
Γ_{38}	✗	✗

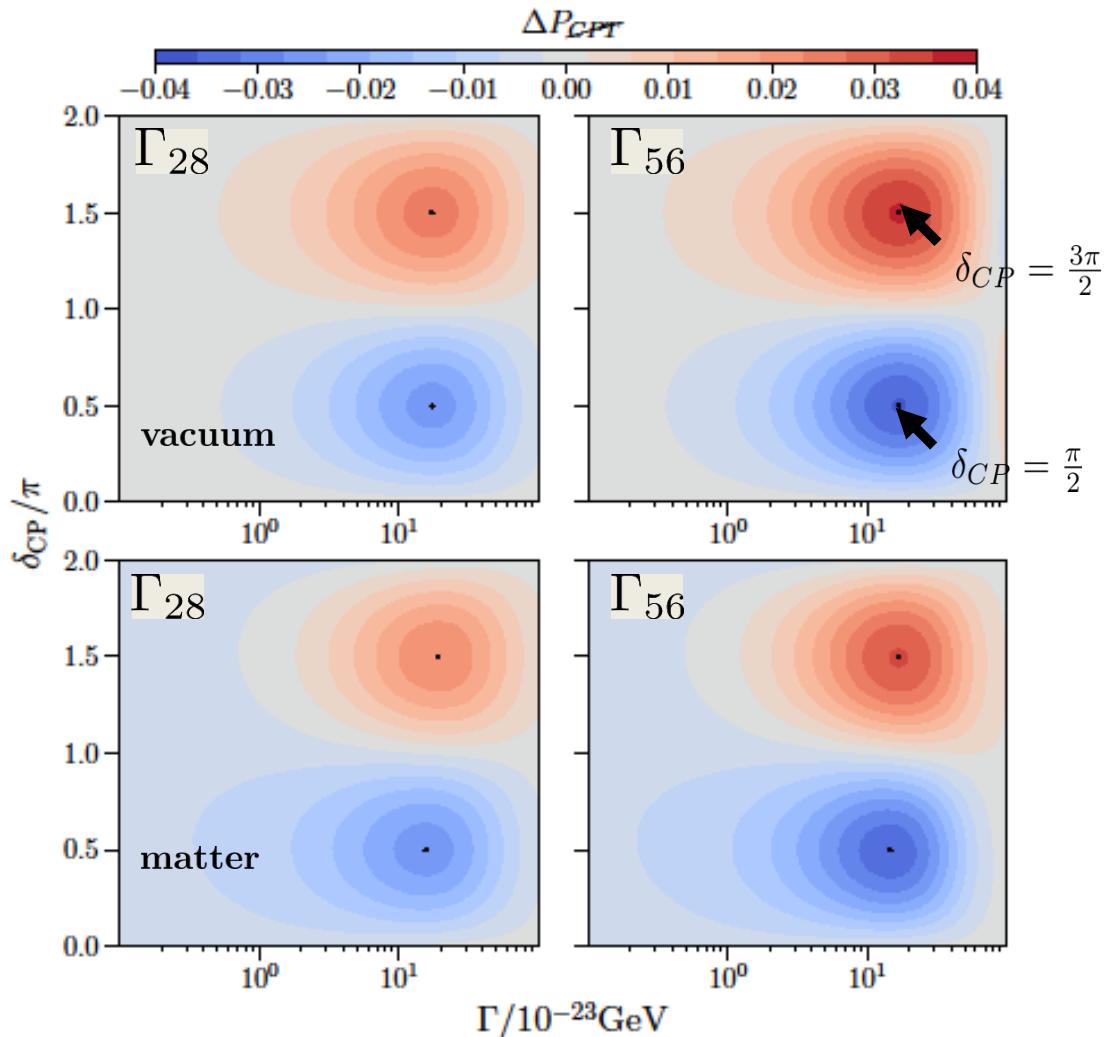
Neutrino Oscillation Probabilities SO \oplus DE

CPT violation symmetry

$$\begin{aligned}\Delta P_{CPTV} &= P_{\nu_\alpha \rightarrow \nu_\beta} - P_{\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha} \\ &= P_{\nu_\alpha \rightarrow \nu_\alpha} - P_{\bar{\nu}_\alpha \rightarrow \bar{\nu}_\alpha}\end{aligned}$$

$$\Delta P_{CPTV} = P_{\nu_\mu \rightarrow \nu_\mu} - P_{\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu}$$

CPT violation with Dirac Phase
Zero Majorana CP-phases



Neutrino Oscillation Probabilities SO \oplus DE Majorana phases

$$P_{\nu_\alpha \rightarrow \nu_\beta}^{\text{SO} \oplus \text{DE}} = \frac{1}{3} + \frac{1}{2} \sum_{k,l} e^{-\Gamma t} \varrho_k^\beta(0) (\varrho_l^\alpha(0) + \bar{\Gamma}_{ij}(\dots)_l) [e^{\mathbf{H}_m t}]_{kl}$$

$$P_{\nu_\mu \rightarrow \nu_e}^{\text{SO} \oplus \text{DE}} = \frac{(1 - e^{-\bar{\Gamma}})}{3} + P_{\nu_\mu \rightarrow \nu_e}^{\text{SO}} e^{-\bar{\Gamma}}$$

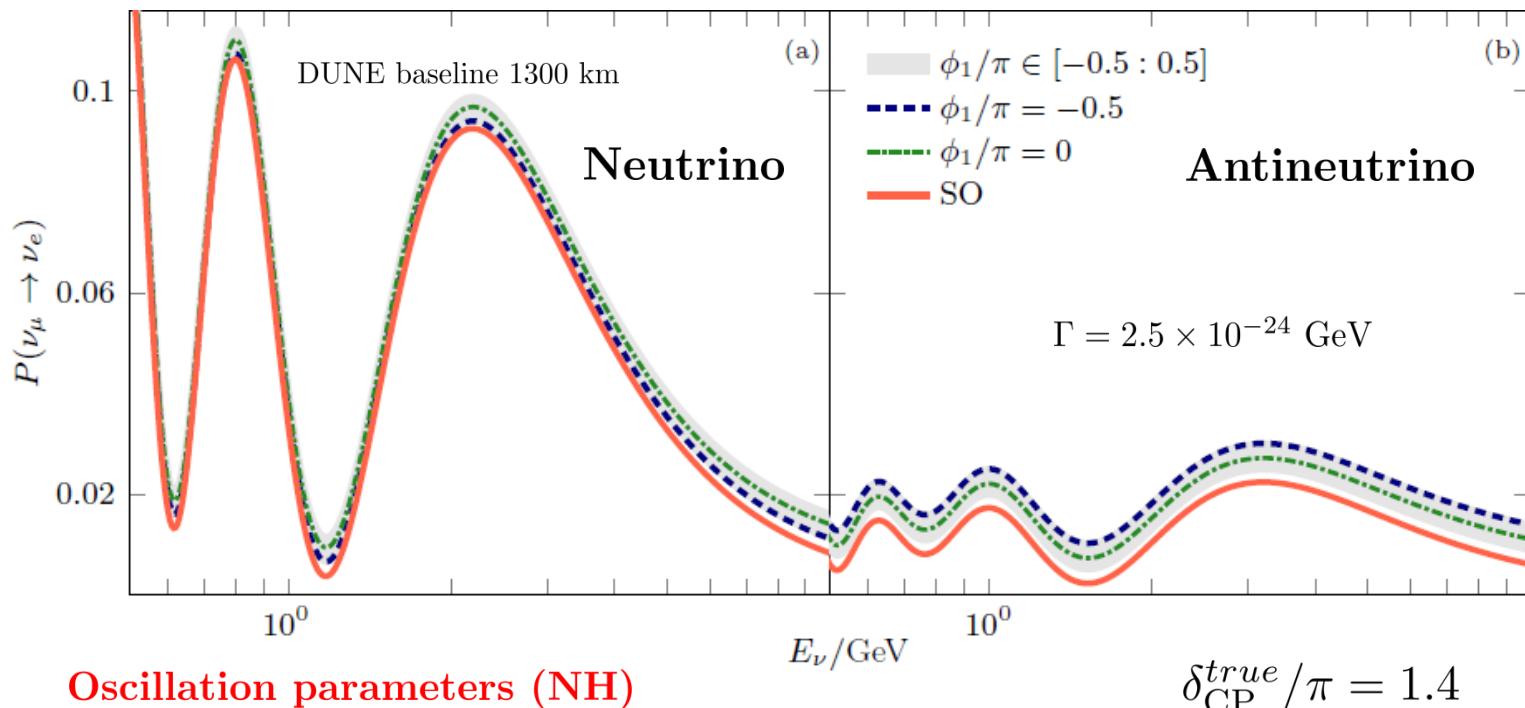
$$- \frac{\bar{\Gamma}_{28}}{\sqrt{3}} \sin 2\theta_{12} \sin^2 \theta_{23} \sin \phi_1 e^{-\bar{\Gamma}} + \mathcal{O}(\bar{\Gamma}_{28} \theta_{13}) + \dots$$

The $\Gamma_{28} = -\frac{\Gamma}{\sqrt{3}}$ produces the maximal CP violation effect

Neutrino Oscillation Probabilities: Standard Mechanism(SO) \oplus Quantum Decoherence (DE)

$$P_{\nu_\mu \rightarrow \nu_e}^{\text{SO} \oplus \text{DE}} = \frac{(1 - e^{-\bar{\Gamma}})}{3} + P_{\nu_\mu \rightarrow \nu_e}^{\text{SO}} e^{-\bar{\Gamma}} - \frac{\bar{\Gamma}_{28}}{\sqrt{3}} \sin 2\theta_{12} \sin^2 \theta_{23} \sin \phi_1 e^{-\bar{\Gamma}} + \mathcal{O}(\bar{\Gamma}_{28}\theta_{13}) + \dots$$

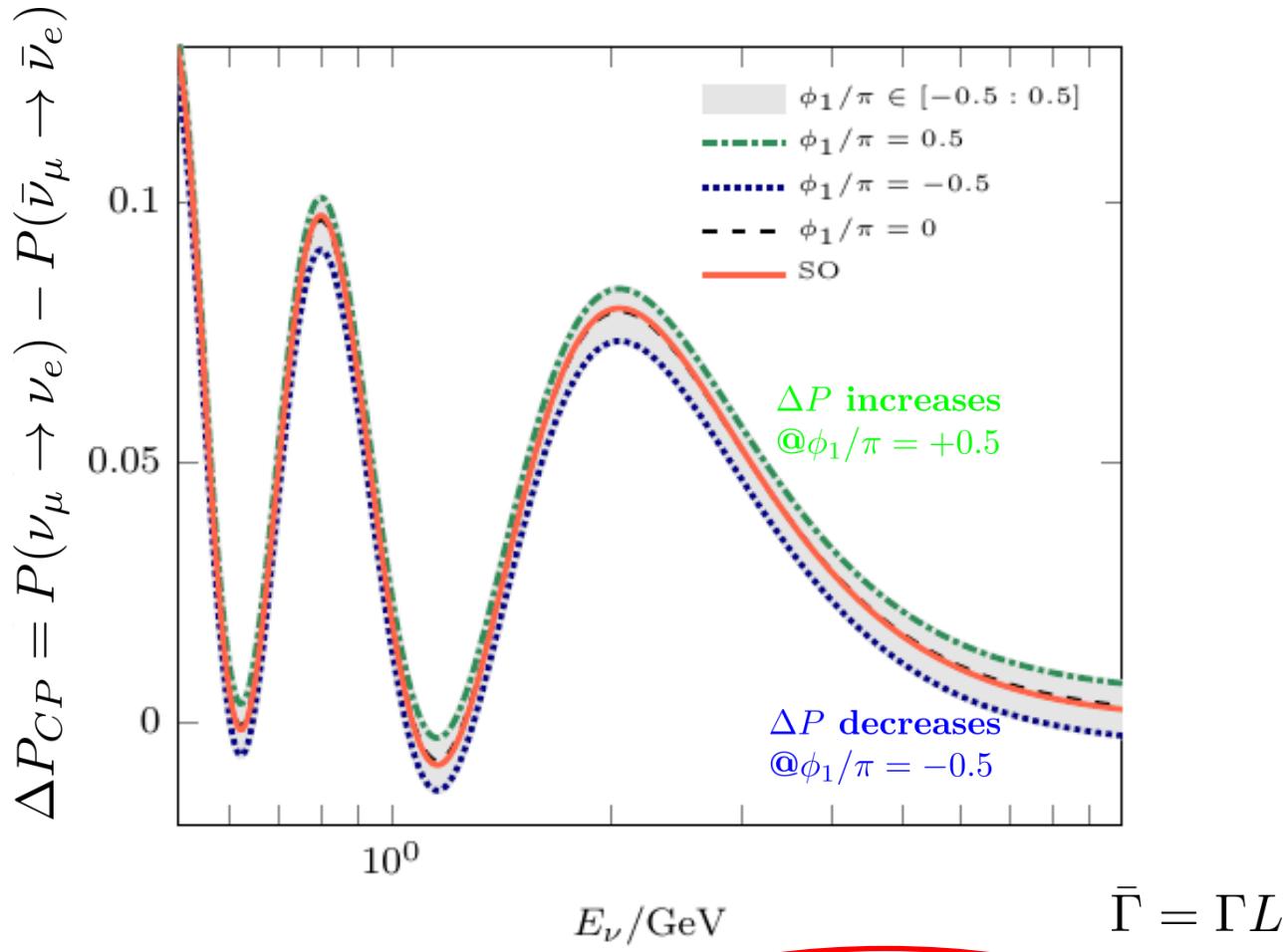
- Energy independent increment.
- The antineutrino(neutrino) probability for $\phi_1/\pi = -0.5$ ($\phi_1/\pi = +0.5$) grows much more than its neutrino(antineutrino) counterpart



$\theta_{12} = 33.82^\circ$, $\theta_{13} = 8.61^\circ$, $\theta_{23} = 48.3^\circ$,
 $\Delta m_{21}^2 = 7.39 \times 10^{-5}$ eV 2 , and $\Delta m_{31}^2 = 2.523 \times 10^{-3}$ eV 2

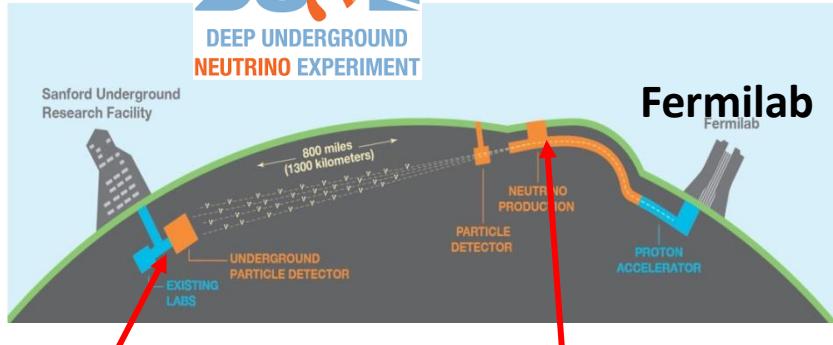
T2K hint
(unaffected by decoherence)

CP Violation Asymmetry



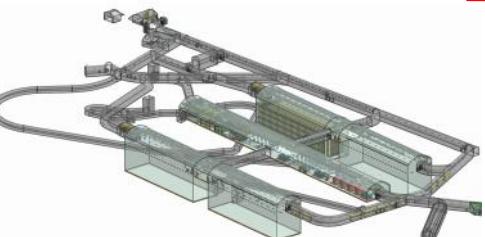
$$\Delta P^{\text{SO}} \oplus \text{DE} \simeq \Delta P^{\text{SO}} e^{-\bar{\Gamma}} + \frac{2\bar{\Gamma}}{3} \sin 2\theta_{12} \sin^2 \theta_{23} \sin \phi_1 e^{-\bar{\Gamma}} + \dots$$

Experimental Scenarios

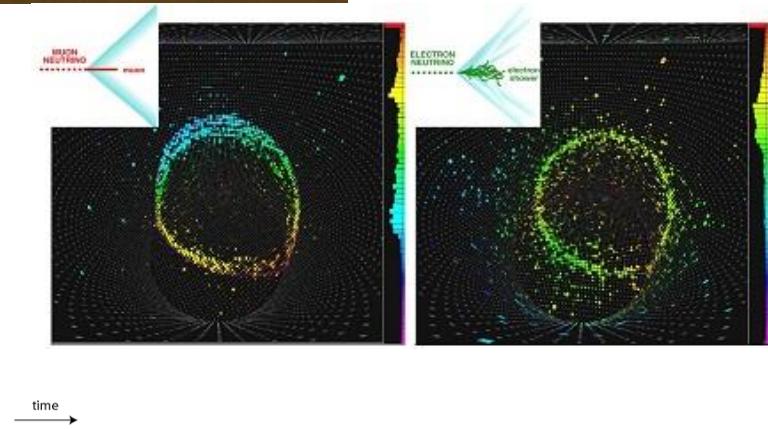
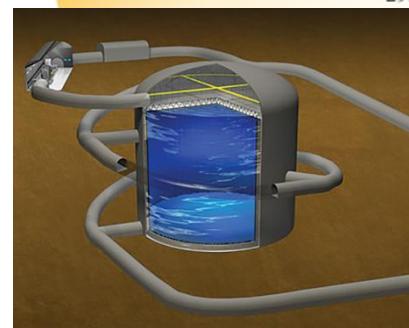
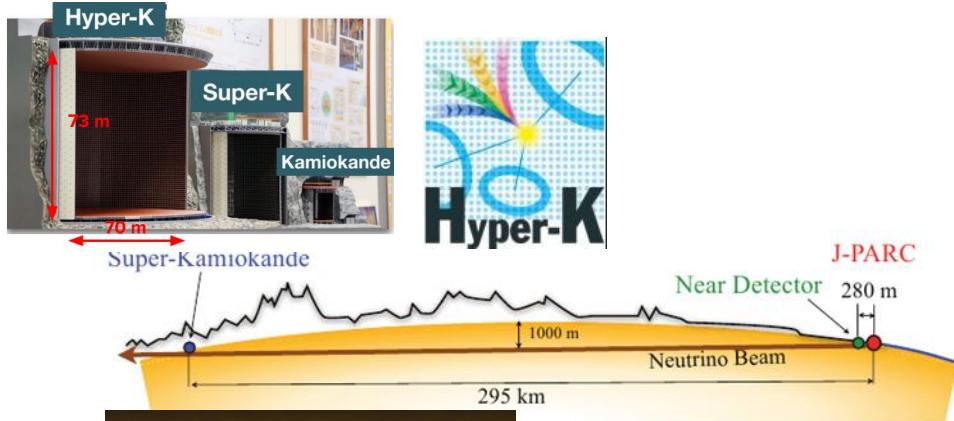
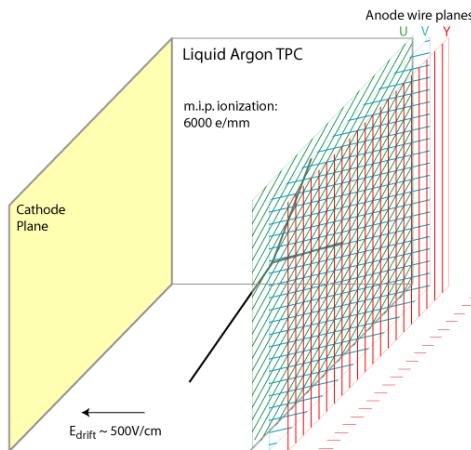
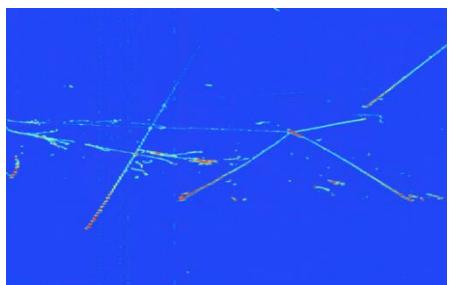


ν -detection

ν -production



Four detectors of Liquid Argon



time →

Signals and Backgrounds – Time exposure



Oscillation channels

$$\nu_\mu \rightarrow \nu_e \oplus \bar{\nu}_\mu \rightarrow \bar{\nu}_e \oplus \nu_\mu \rightarrow \nu_\mu \oplus \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

5 years of exposure per each mode

$$N_i \equiv \text{Signal} \oplus \text{Background}$$

$$\text{Signal} \equiv \nu_e(\bar{\nu}_e) \text{ CC}$$

$$\text{Background} \equiv \nu_e \text{CC} \oplus \text{NC} \oplus \nu_\tau + \bar{\nu}_\tau \text{ CC}$$

$$\nu_\mu \rightarrow \nu_\mu \oplus \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

$$\text{Signal} \equiv \nu_\mu(\bar{\nu}_\mu) \text{ CC}$$

$$\text{Background} \equiv \text{NC} \oplus \nu_\tau + \bar{\nu}_\tau \text{ CC}$$

Oscillation channels

$$\nu_\mu \rightarrow \nu_e \oplus \bar{\nu}_\mu \rightarrow \bar{\nu}_e \oplus \nu_\mu \rightarrow \nu_\mu \oplus \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

~ 3(9) years of exposure for neutrino(antineutrino)

$$N_i \equiv \text{Signal} \oplus \text{Background}$$

$$\text{Signal} \equiv \nu_e(\bar{\nu}_e) \text{ QE/NE}$$

$$\text{Background} \equiv \nu_e \text{CC} \oplus \text{NC} \oplus (\mu/e)$$

$$\nu_\mu \rightarrow \nu_\mu \oplus \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

$$\text{Signal} \equiv \nu_\mu(\bar{\nu}_\mu) \text{ QE/NE}$$

$$\text{Background} \equiv \text{NC}$$

Statistical Analysis

Theoretical Hypothesis

$$\chi^2(\xi, \xi^{\text{true}}) = \sum_i \frac{(N_i(\xi) - N_i(\xi^{\text{true}}))^2}{N_i(\xi^{\text{true}})}$$

Data

$\xi \rightarrow \text{Test values}$
 $\xi^{\text{true}} \rightarrow \text{True values}$

With priors (up to 3σ):

$$\chi^2 \rightarrow \chi^2 + \sum_j \frac{(\xi_j - \xi_j^{\text{true}})^2}{\sigma_j^2}$$

χ^2 -analysis for oscillation parameter distortion:

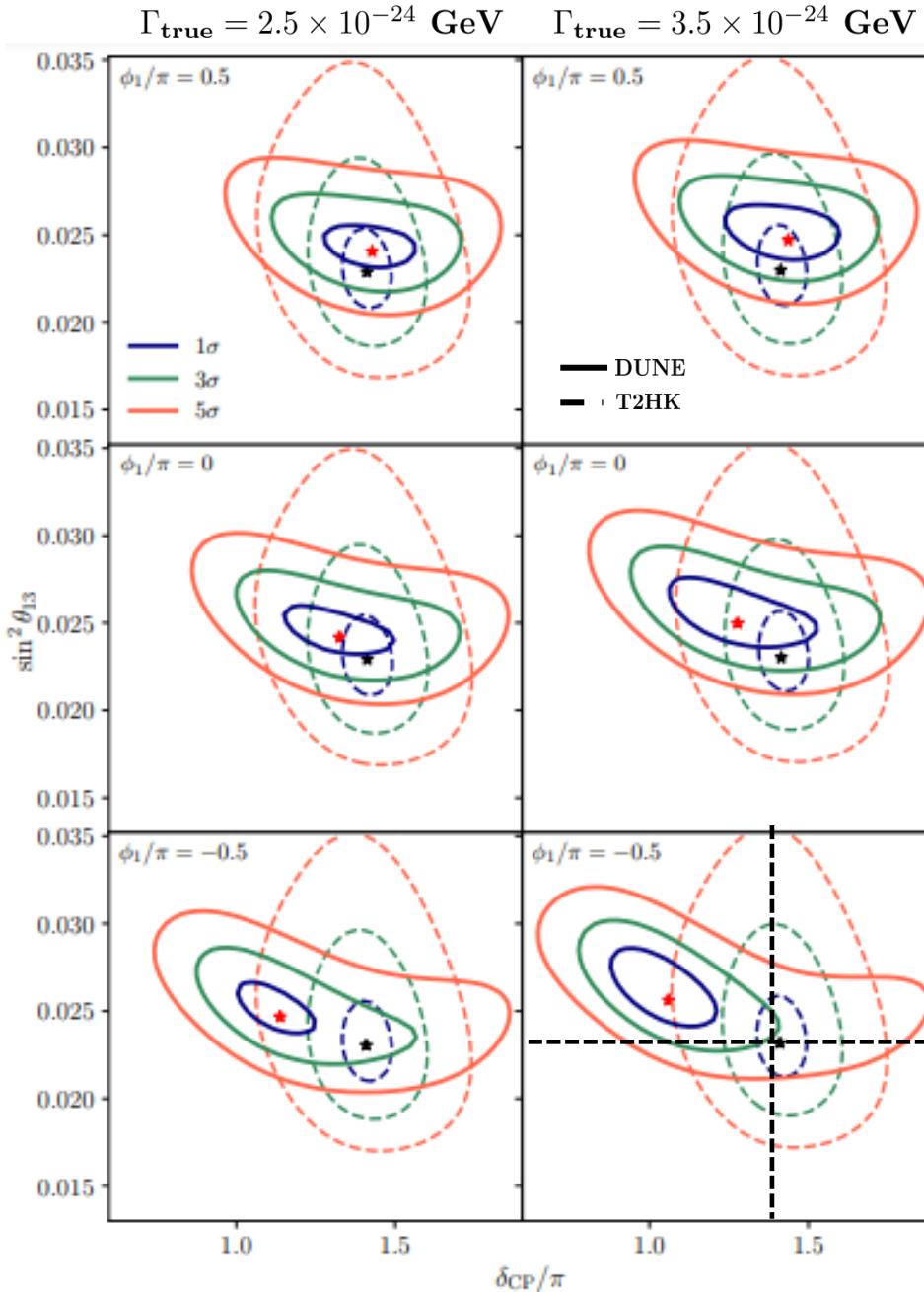
$$\Delta\chi^2 = \chi^2(\theta_{13}^{\text{test}}, \delta_{\text{CP}}^{\text{test}}; \theta_{13}^{\text{true}}, \delta_{\text{CP}}^{\text{true}}, \Gamma^{\text{true}}, \phi_1^{\text{true}})$$

$$- \chi^2_{\min}(\theta_{13}^{\text{fit}}, \delta_{\text{CP}}^{\text{fit}}; \theta_{13}^{\text{true}}, \delta_{\text{CP}}^{\text{true}}, \Gamma^{\text{true}}, \phi_1^{\text{true}})$$

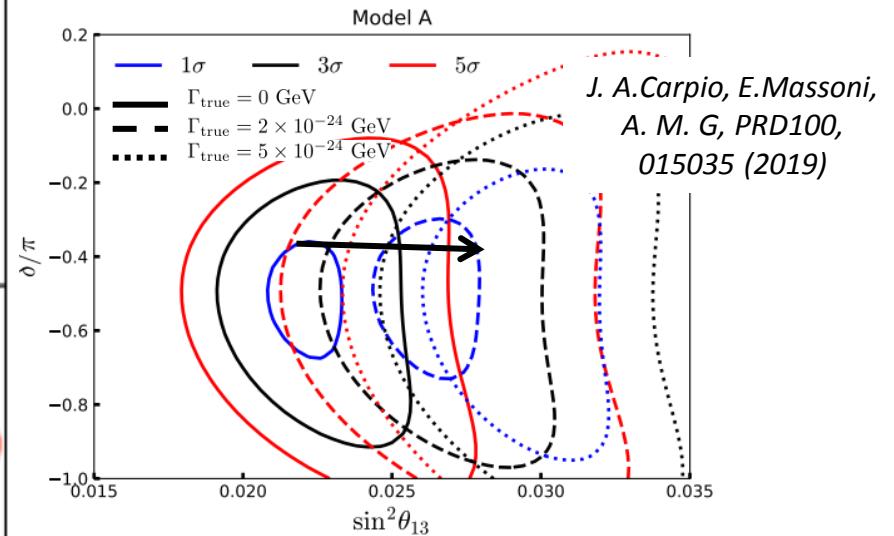
χ^2 -analysis for constraining Γ and ϕ_1 :

$$\chi^2(\Gamma^{\text{test}}, \phi_1^{\text{test}}; \Gamma^{\text{true}}, \phi_1^{\text{true}})$$

DUNE versus Tokai to HyperKamiokande (T2HK)



The theoretical hypothesis in the χ^2 -analysis is pure standard oscillation



Diagonal decoherence matrix

☞ only(main) dislocation on $\sin^2 \theta_{13}$

Non-Diagonal decoherence matrix $\Gamma_{28} \neq 0$

☞ dislocation on $\sin^2 \theta_{13}$ and δ_{CP}

DUNE versus Tokai to HyperKamiokande (T2HK)

$\Gamma = 2.5 \times 10^{-24}$ GeV	$\phi_1/\pi = 0.5$	$\phi_1/\pi = 0.0$	$\phi_1/\pi = -0.5$
$\sin^2 \theta_{13}^{fit}$	0.0241	0.0242	0.0247
N_σ	0.31σ	0.35σ	0.55σ
δ_{CP}^{fit}/π	1.43	1.33	1.13
N_σ	0.08σ	1.17σ	4.28σ
$\Gamma = 3.5 \times 10^{-24}$ GeV	$\phi_1/\pi = 0.5$	$\phi_1/\pi = 0.0$	$\phi_1/\pi = -0.5$
$\sin^2 \theta_{13}^{fit}$	0.0247	0.0250	0.0256
N_σ	0.54σ	0.69σ	0.87σ
δ_{CP}^{fit}/π	1.44	1.28	1.06
N_σ	0.13σ	2.34σ	5.39σ

$$\mathcal{R} = \frac{N_\sigma(\sin^2 \theta_{13}^{fit})}{N_\sigma(\delta_{CP}^{fit})}$$

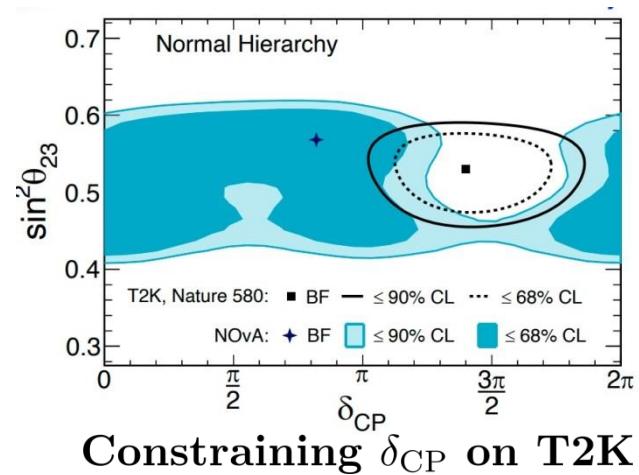
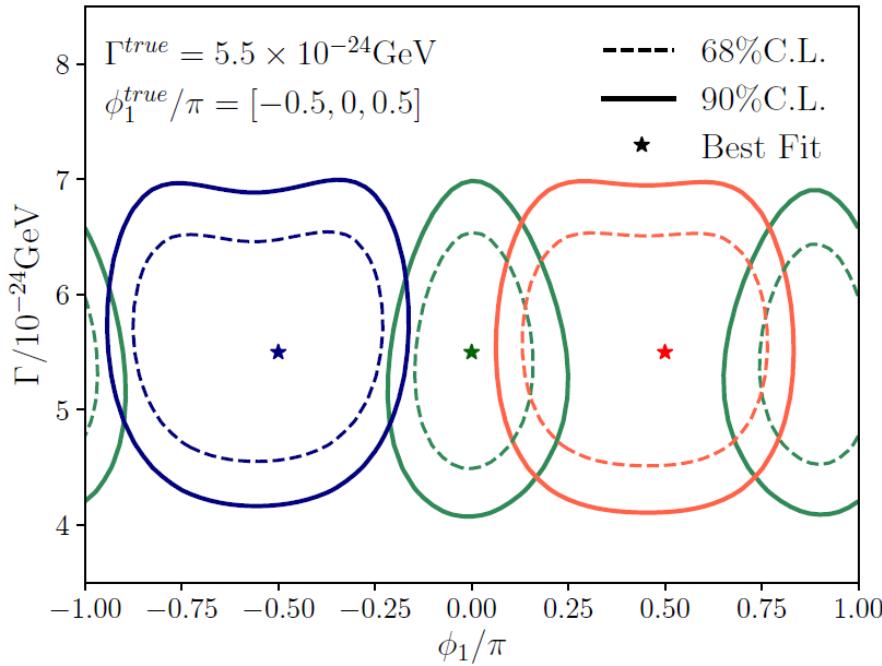
$$\boxed{\begin{aligned} & (3.9 - 4.2)_{\phi_1/\pi=+0.5} \\ & \mathcal{R} \sim (0.3)_{\phi_1/\pi=0.0} \\ & (0.13 - 0.16)_{\phi_1/\pi=-0.5} \end{aligned}}$$

$$\delta_{CP}/\pi = \overbrace{1.4}^{\text{true}} \rightarrow \overbrace{1.06}^{\text{fit}} @ \phi_1/\pi = -0.5 \quad \text{maximal dislocation on } \delta_{CP}$$

Constraining the Majorana phase at DUNE

Std. oscillation \oplus Decoherence Theo. Hyp.

For comparison:



*T2K collaboration,
Nature, 580, 339(2020).*

$$\phi_1/\pi = -0.50(+0.50) \pm 0.32 \text{ for } \Gamma = (5.50 \pm 1.42) \times 10^{-24} \text{ GeV}$$

☞ Non-zero Majorana CP-phase (+0.5/-0.5) can be differentiated from zero for more than 1σ .

☞ Similar precision for constraining $\phi_1/\pi = -0.5$ than the one reached by T2K for δ_{CP}

Summary

- **Decoherence and CP, CPT symmetries and Majorana phases:** Non-diagonal terms in the decoherence matrix would allow the existence of CP and CPT violating terms in the oscillation probability. These also could contain the Majorana CP-phases.
- **Distortion of oscillation parameters:** a signature of the presence of quantum decoherence, and non-null Majorana CP phase, in the data would be manifest through altered measurements of $\sin^2 \theta_{13}$ and/or the Dirac *CP* violation phase relative to the expected ones.
- **Constraining the Majorana CP-phase at DUNE:** Assuming decoherence(i.e. non-null elements in the decoherence matrix) there is a chance to constrain the Majorana CP phase $\phi_1/\pi = -0.5$ at DUNE with a precision similar that the one reached by T2K on δ_{CP} .

Muchas gracias