SILAFAE

Breaking of CPT due to quantum decoherence tested at DUNE

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J.C. Carrasco, F.N. Díaz, A.M. Gago arXiv:1811.04982

Pontificia Universidad Católica del Perú

XII Latin American Symposium on High Energy Physics

Lima - 2018

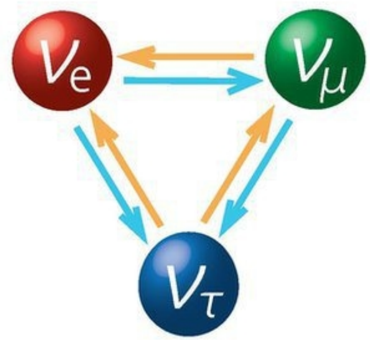
Outline

1. Introduction.
2. Theoretical Approach.
3. DUNE and Simulation Details.
4. Results.
5. Conclusions.

Introduction

Neutrino Oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & \text{PMNS} & \\ & \text{matrix} & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow$$



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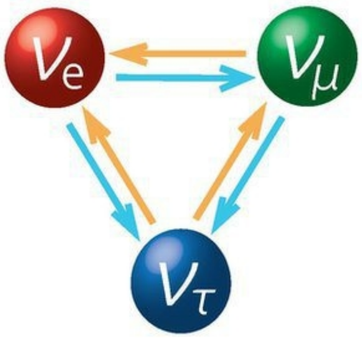

Neutrino Decay

Non Standard Interaction

Quantum Decoherence

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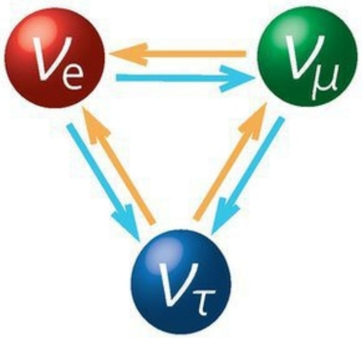

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~~CPT~~

$$P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$$

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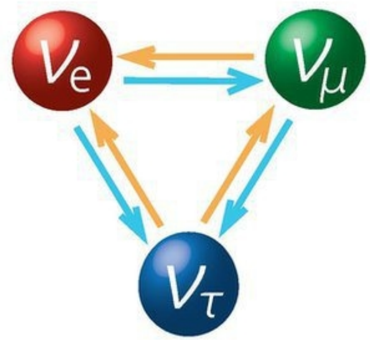

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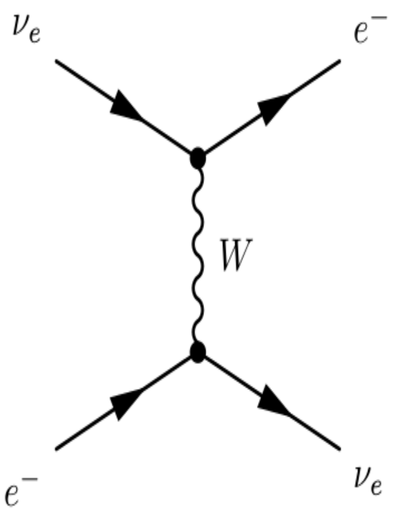
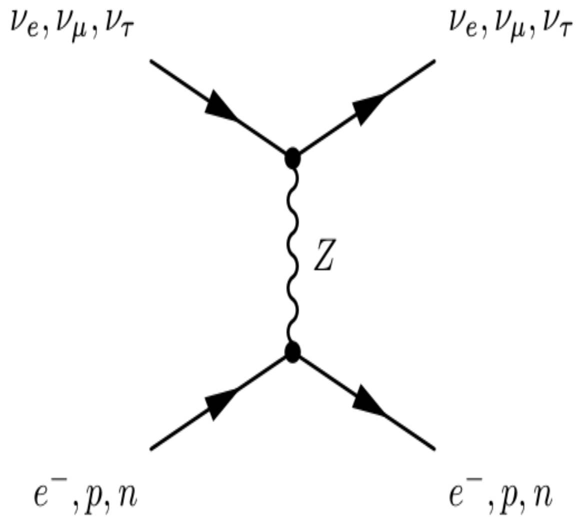
Intrinsic CPTV





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Matter interaction

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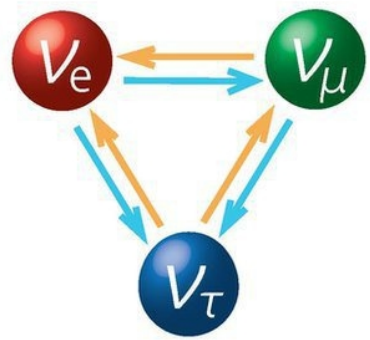

- **Neutrino Decay**
- **Non Standard Interaction**
- **Quantum Decoherence**

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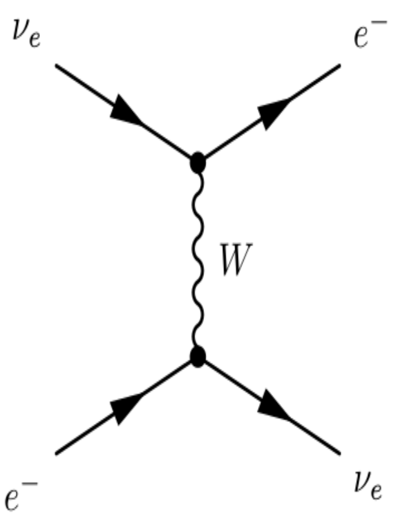
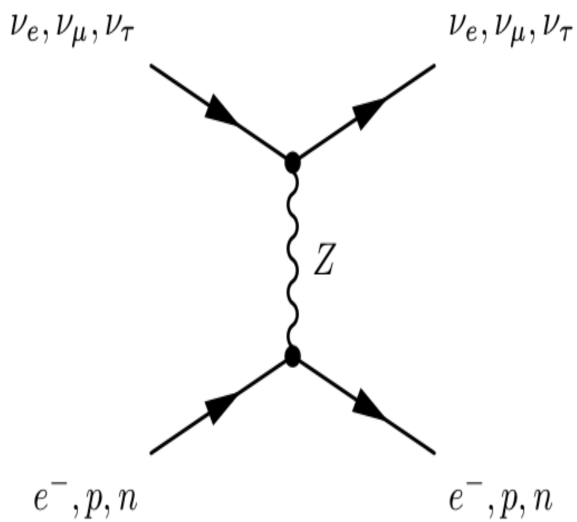
Measurement

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Intrinsic CPTV





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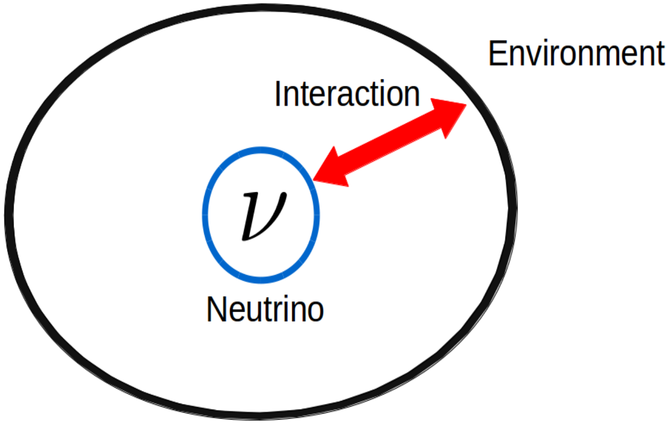
Matter interaction

Theoretical Approach

Considering the neutrino like an open quantum system.



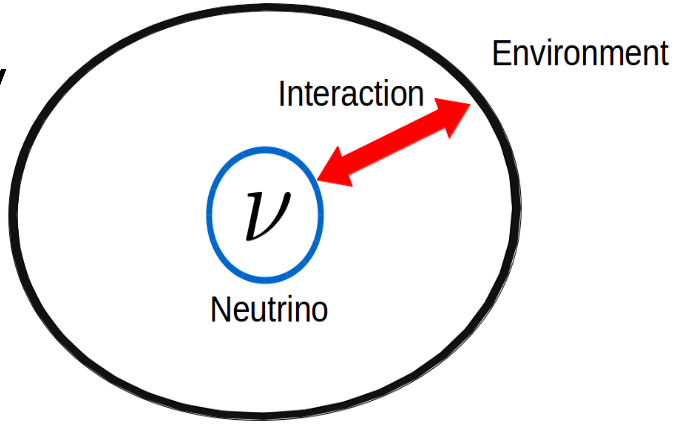
Theoretical Approach

Considering the neutrino like an open quantum system.

The time evolution of our quantum system is given by

$$\frac{\partial \hat{\rho}(t)}{\partial t} = -i[\hat{H}, \hat{\rho}(t)] + \mathcal{D}[\hat{\rho}(t)]$$

Dissipative term



A. Gago et al arXiv:hep-ph/0208166

J.A. Carpio et al Phys. Rev. D 97, 115017

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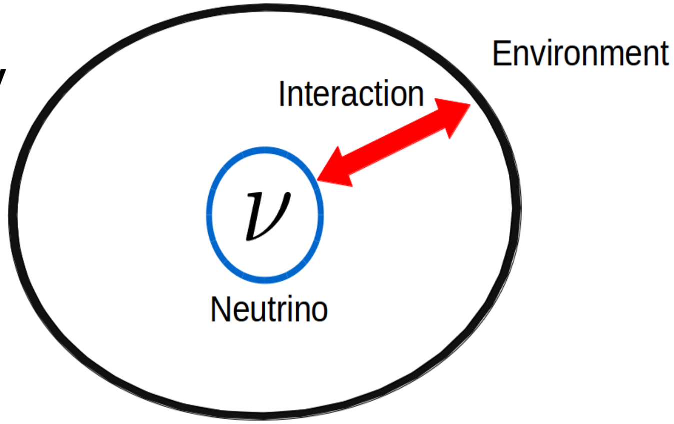

For 3 generations, the probability is given by

$$P_{\nu_\alpha\rightarrow\nu_\beta} = \frac{1}{3} + \frac{1}{2}\left(\sum_{i,j}\rho_i^\beta\rho_j^\alpha[e^{Mt}]_{ij}\right)$$

Where $M = H + D$

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Theoretical Approach

- **CPT Asymmetry**

We use the difference of survival probability to refer the CPT violation

$$\Delta P_{\not{\text{CPT}}} = P_{\nu_\alpha \to \nu_\alpha} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}$$

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Diagonal elements equal to Γ

Same for neutrinos and antineutrinos

One β_{ij} at a time.

$$\mathbf{D} = \begin{pmatrix} \Gamma & \beta_{12} & 0 & 0 & 0 & 0 & 0 & 0 \\ \beta_{12} & \Gamma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Gamma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \Gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Gamma & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \Gamma & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Gamma \end{pmatrix}$$

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$$\Delta P_{\not{\mathrm{CPT}}} = \beta_{ij} \frac{\left(e^{\Omega_{\beta_{ij}} t} - e^{-\Omega_{\beta_{ij}} t}\right)}{\Omega_{\beta_{ij}}} \rho_i^\alpha \rho_j^\alpha \; e^{-\Gamma t}$$

Where: $\Omega_{\beta_{ij}} = \sqrt{\Delta_{\beta_{ij}}{}^2 - \beta_{ij}^2}$ $\qquad \Delta_{\beta_{ij}} = \dfrac{\Delta m_{ij}^2}{2p}, \quad i, j = 1, 2, 3$

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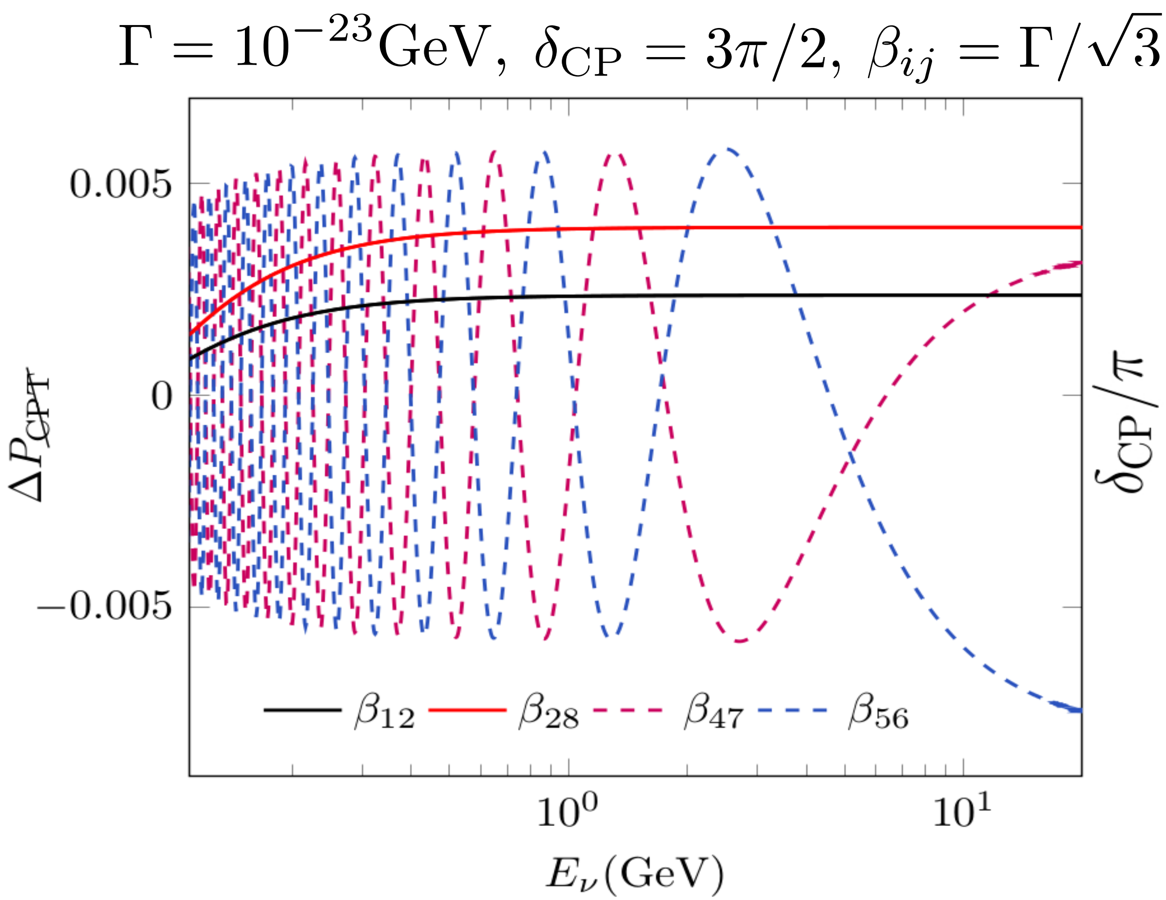
Damping

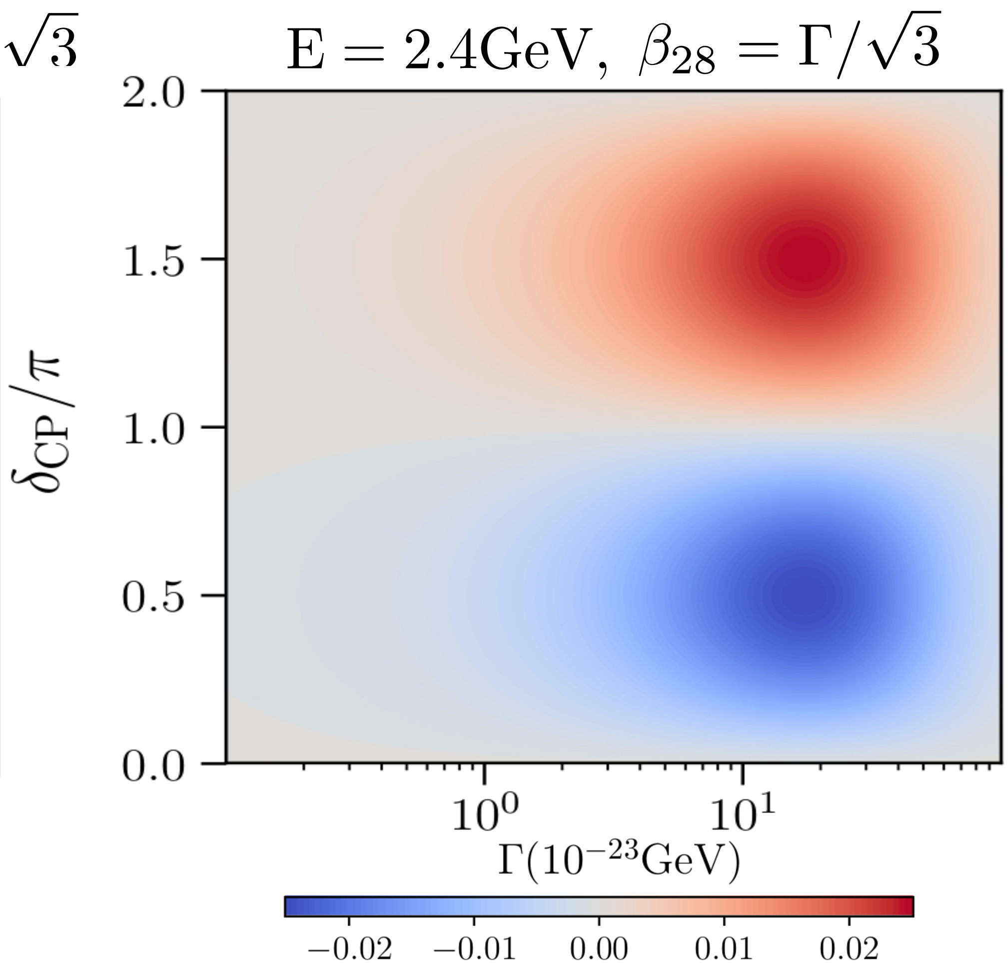
Where: $\Omega_{\beta_{ij}} = \sqrt{\Delta_{\beta_{ij}}{}^2 - \beta_{ij}^2}$ $\qquad \Delta_{\beta_{ij}} = \frac{\Delta m_{ij}^2}{2p}, \quad i, j = 1, 2, 3$

Theoretical Approach

Considering the muon dissapearance channel and the DUNE baseline

$$\Delta P_{\not{\text{CPT}}} = P_{\nu_\mu \to \nu_\mu} - P_{\bar{\nu}_\mu \to \bar{\nu}_\mu} \qquad L = 1300\text{Km}$$





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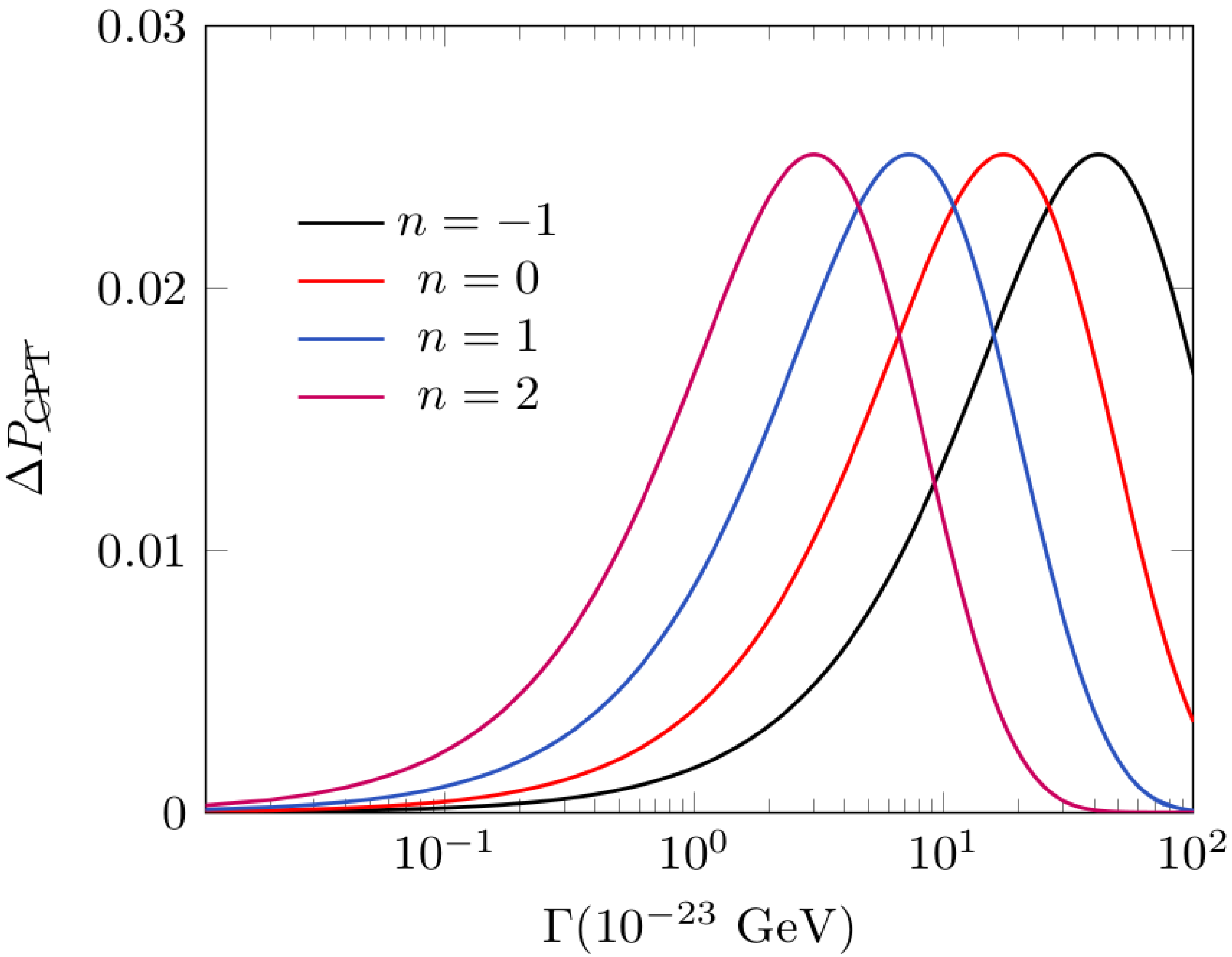

$$\text{E} = 2.4\text{GeV},\ \beta_{28} = \Gamma/\sqrt{3}$$
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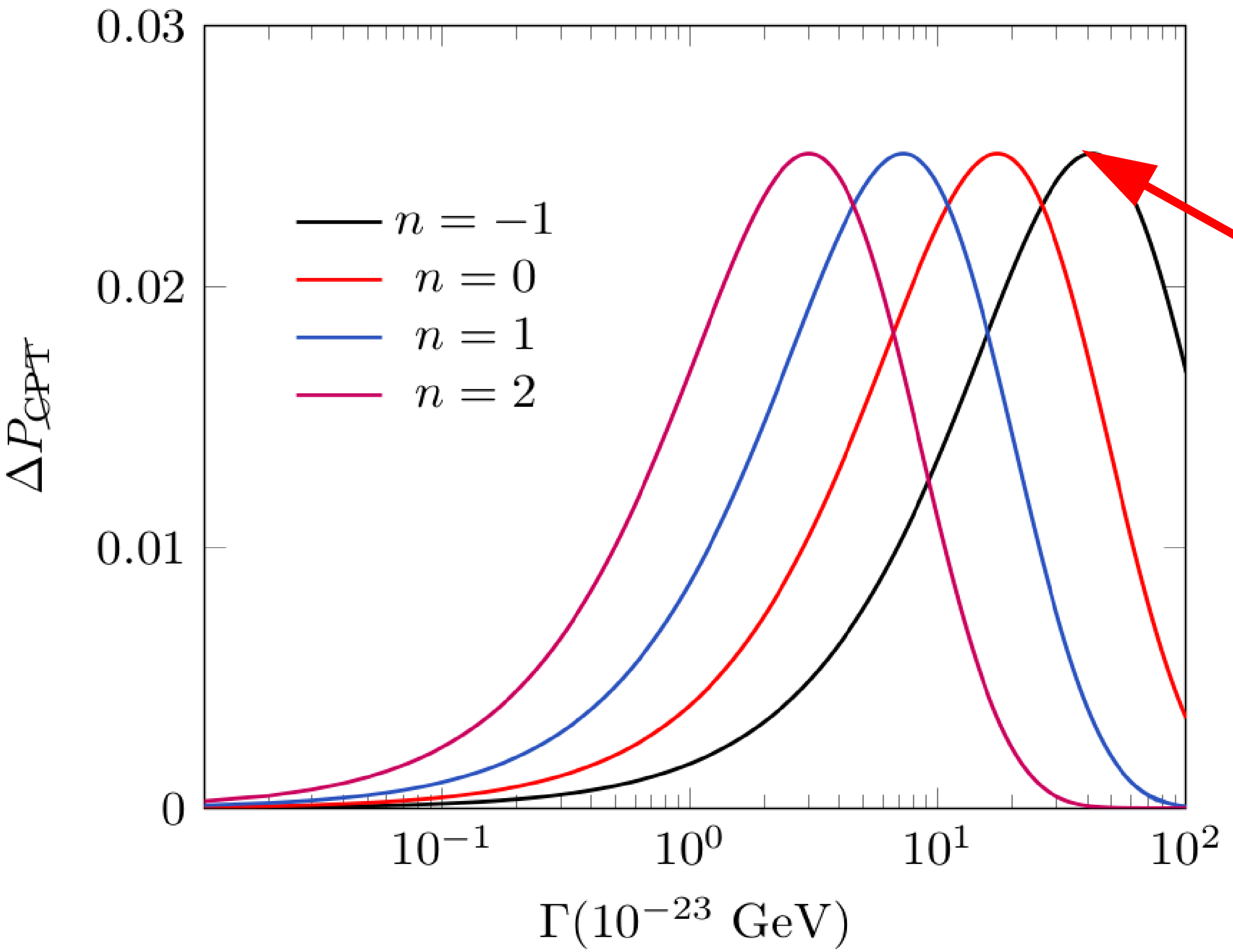

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Change the value but not the amplitude

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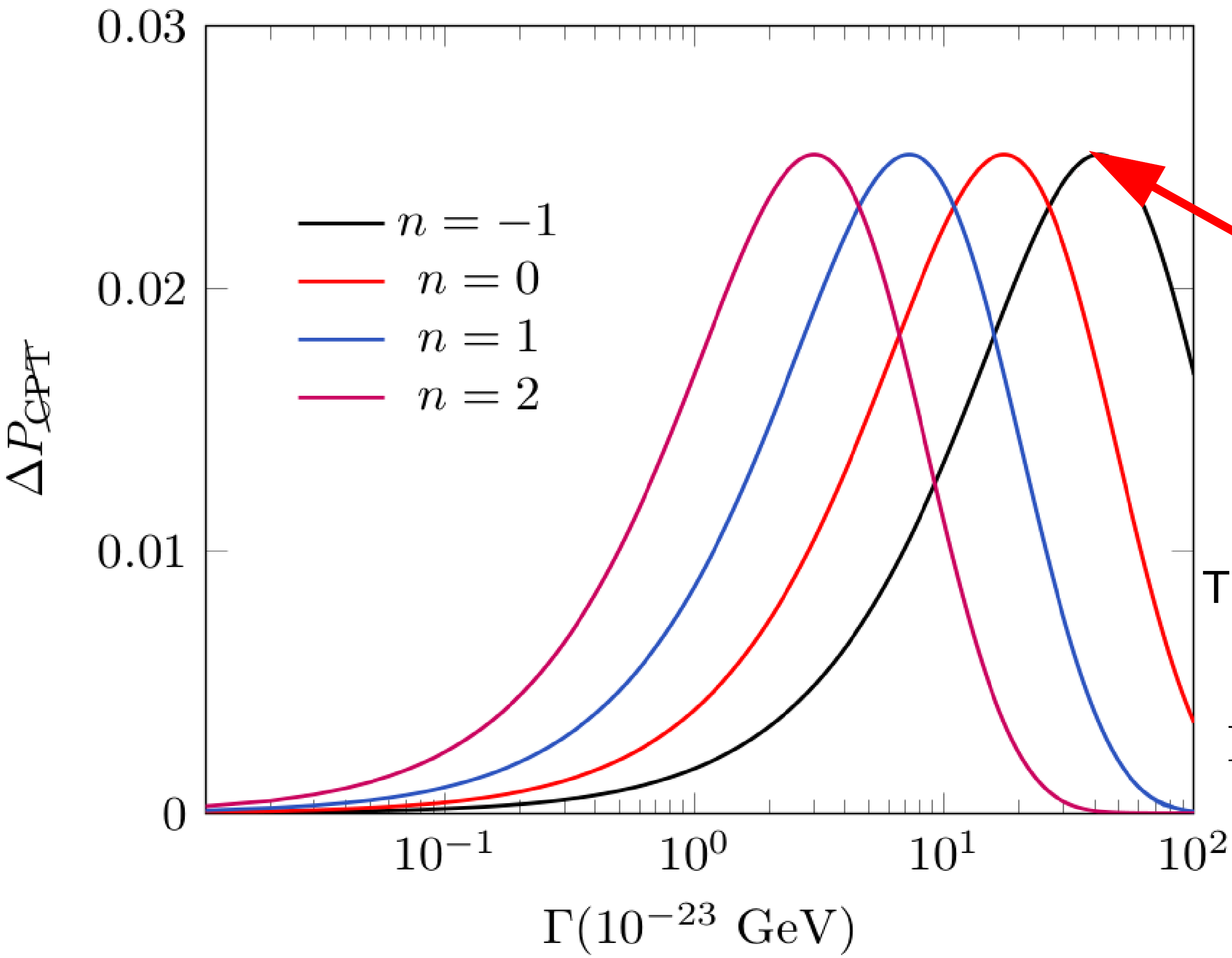

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Change the value but not the amplitude

The value of Γ at the peak, $\Gamma \sim 1/L$

$\Gamma \sim 1/(LE^n)$

$\Gamma \sim \{4.0, 1.5, 0.6, 0.3\} \times 10^{-22}\text{GeV}$

Theoretical Approach

- **Optimal case**

$$\beta_{28} = \Gamma/\sqrt{3} \qquad \beta_{12} = (\sqrt{2/3})\Gamma/3 \qquad \beta_{56} = -\beta_{47} = \Gamma/3$$

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Intrinsic CPTV in Standard Oscillation (SO)

$P^{\mathrm{SO}}_{\nu_\alpha \to \nu_\beta} \neq P^{\mathrm{SO}}_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$ **Matter interaction**

$\Rightarrow \Delta P^{\mathrm{SO}}_{\not{\mathrm{CPT}}} \neq 0$

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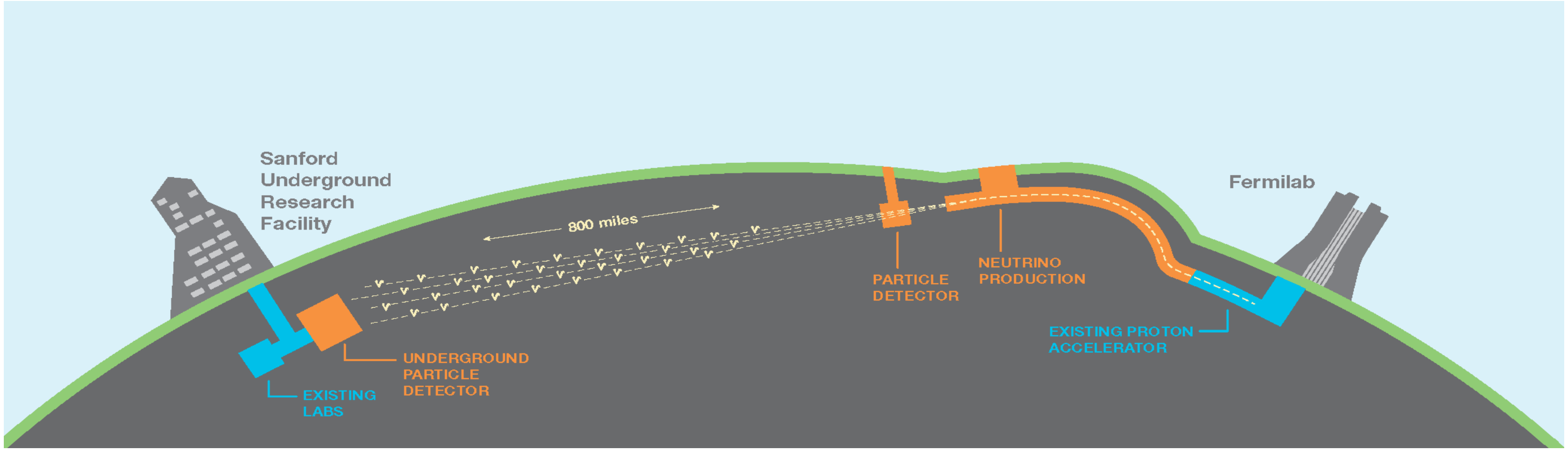
$$\Delta P^{\mathrm{SO}\bigoplus\mathrm{DDM}}_{\not{\mathrm{CPT}}} = e^{-\Gamma t} \Delta P^{\mathrm{SO}}_{\not{\mathrm{CPT}}}$$

DUNE and Simulation Details



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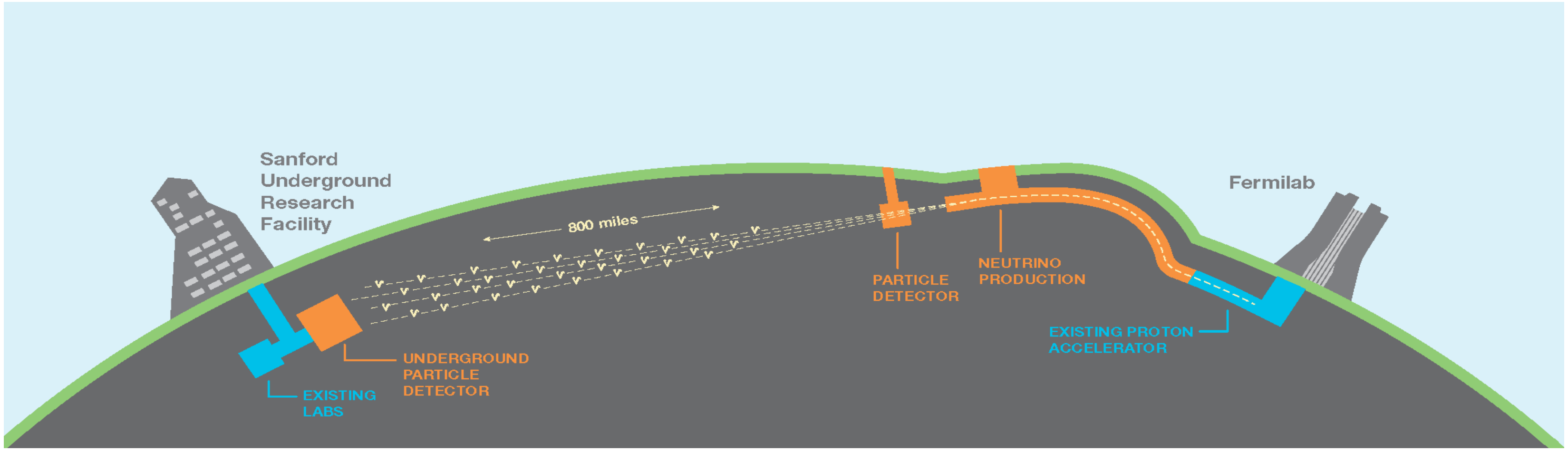

nuSQuIDS

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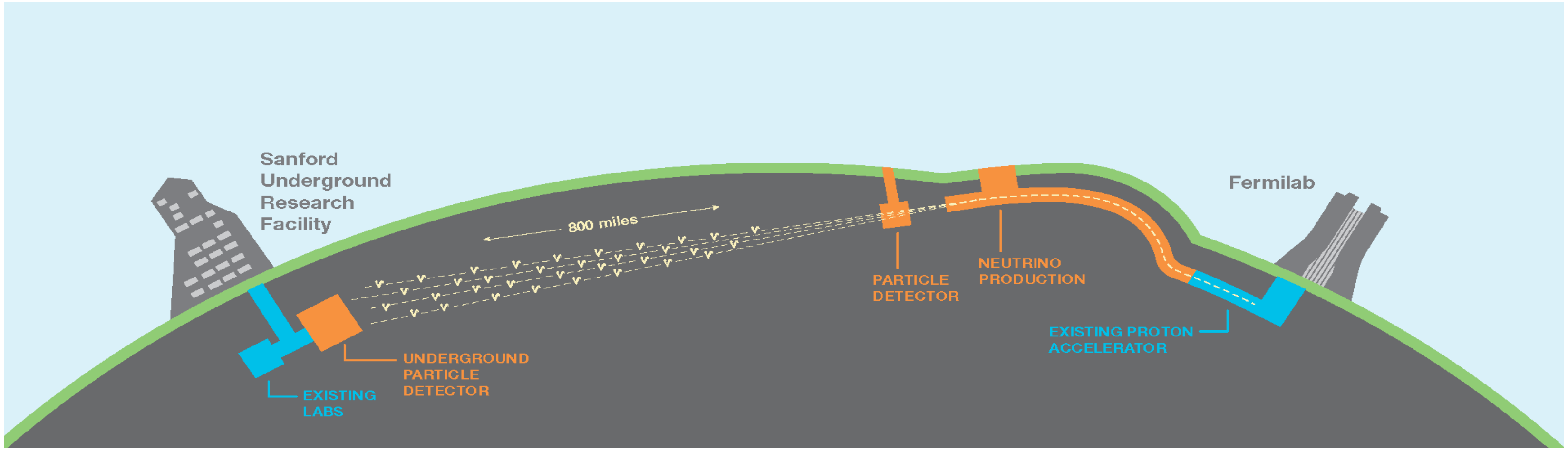


GLoBES

nuSQuIDS

Probability

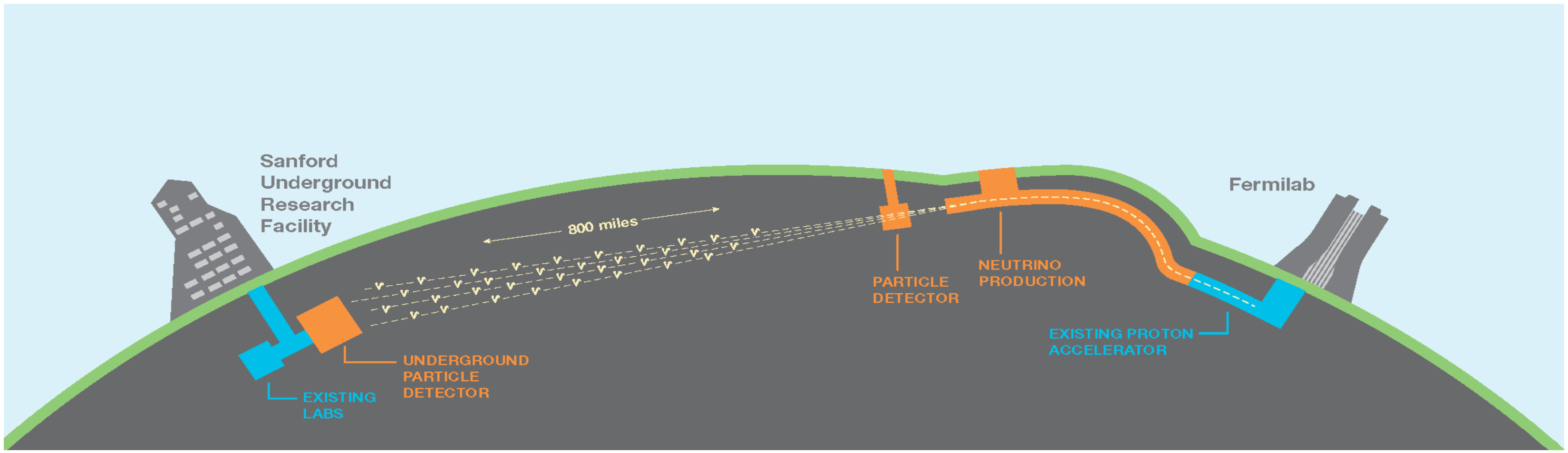
Efficiency **Fluxes** **Cross Section**

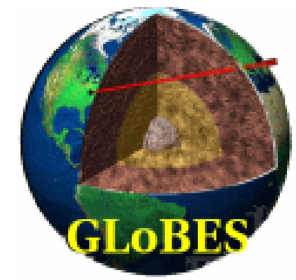
Smearing → Event Rate N

Ancillary files

Alion, T. et al - arXiv:1606.09550

DUNE and Simulation Details





nuSQuIDS

Probability

$\Gamma = 10^{-23}$ GeV	Std	$n=-1$	$n=0$	$n=1$	$n=2$
Neutrino mode					
ν_μ Signal	11025	11120	11263	11017	11524
$\bar{\nu}_\mu$ CC Background	724	721	702	556	408
NC Background	109	109	109	109	109
$\nu_\tau + \bar{\nu}_\tau$ CC Background	43	43	46	74	87
Antineutrino mode					
$\bar{\nu}_\mu$ Signal	3754	3752	3749	3557	3555
ν_μ CC Background	2149	2145	2097	1680	1261
NC Background	58	58	58	58	58
$\nu_\tau + \bar{\nu}_\tau$ CC Background	27	27	29	50	60

Efficiency **Fluxes** **Cross Section**

Smearing → Event Rate N

5 years neutrino mode (FHC)

5 years antineutrino mode (RHC)

Optimal case

Energy range $0.5 - 20$ GeV

$\delta_{\mathrm{CP}} = 3\pi/2$

Ancillary files

Alion, T. et al - arXiv:1606.09550

DUNE and Simulation Details

In order to show tangible results, we define the observable of CPT asymmetry depending of the number of events of neutrinos and antineutrinos.

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

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

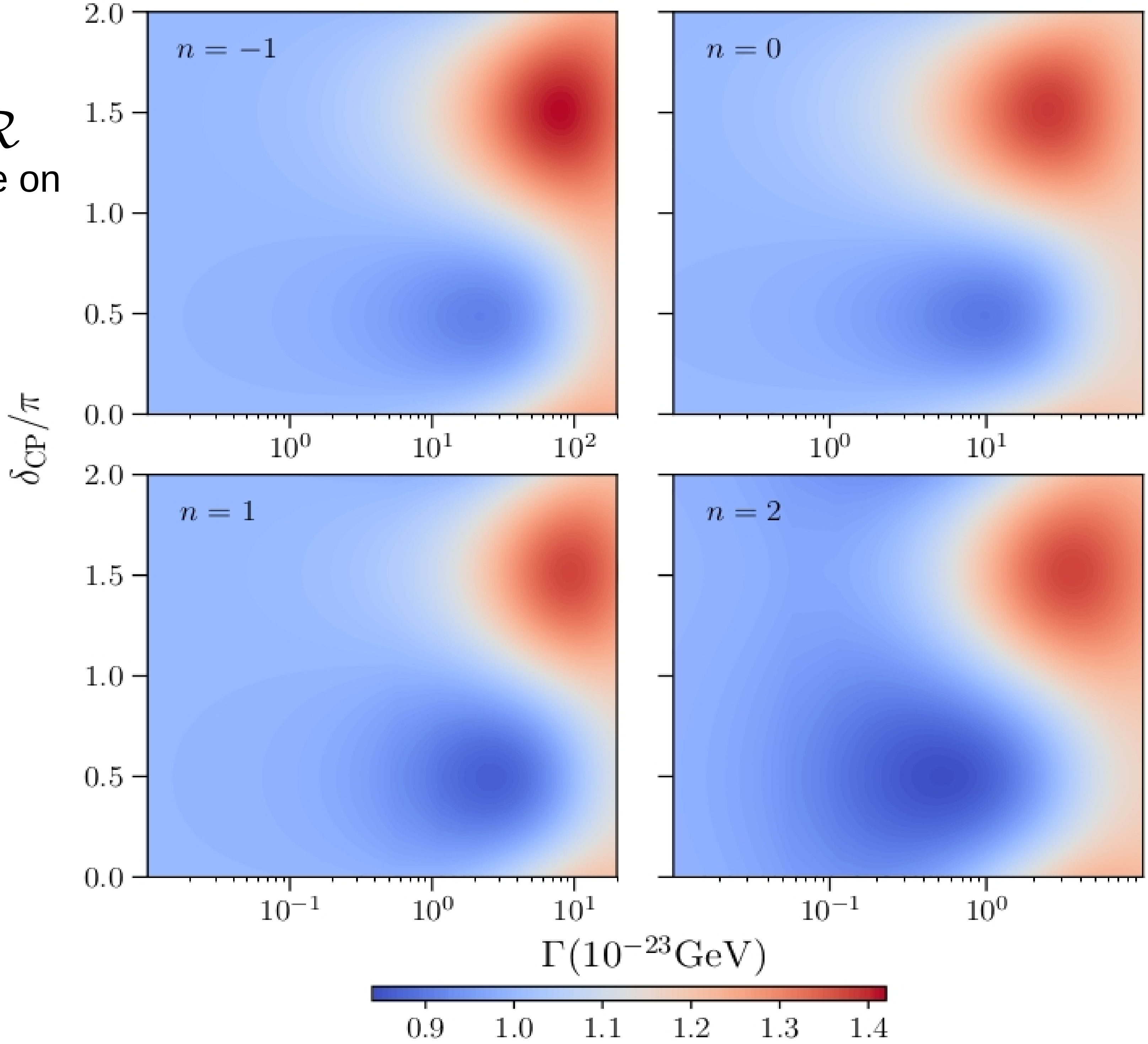
To study and differentiate the CPTV due to the effect of quantum decoherence from the CPTV due to the matter effect, we define the ratio

$$\mathcal{R} = \frac{\Delta N^{\mathrm{SO} \bigoplus \mathrm{DEC}}}{\Delta N^{\mathrm{SO}}}$$

The uncertainty for the event rate are considered as $\sqrt{N}$.

Results

Our observable $\mathcal{R}$ and its dependence on δ_{CP} and Γ



Optimal Case

Energy range

$0.5 - 20\ \mathrm{GeV}$

5 years FHC

5 years RHC

Normal hierarchy

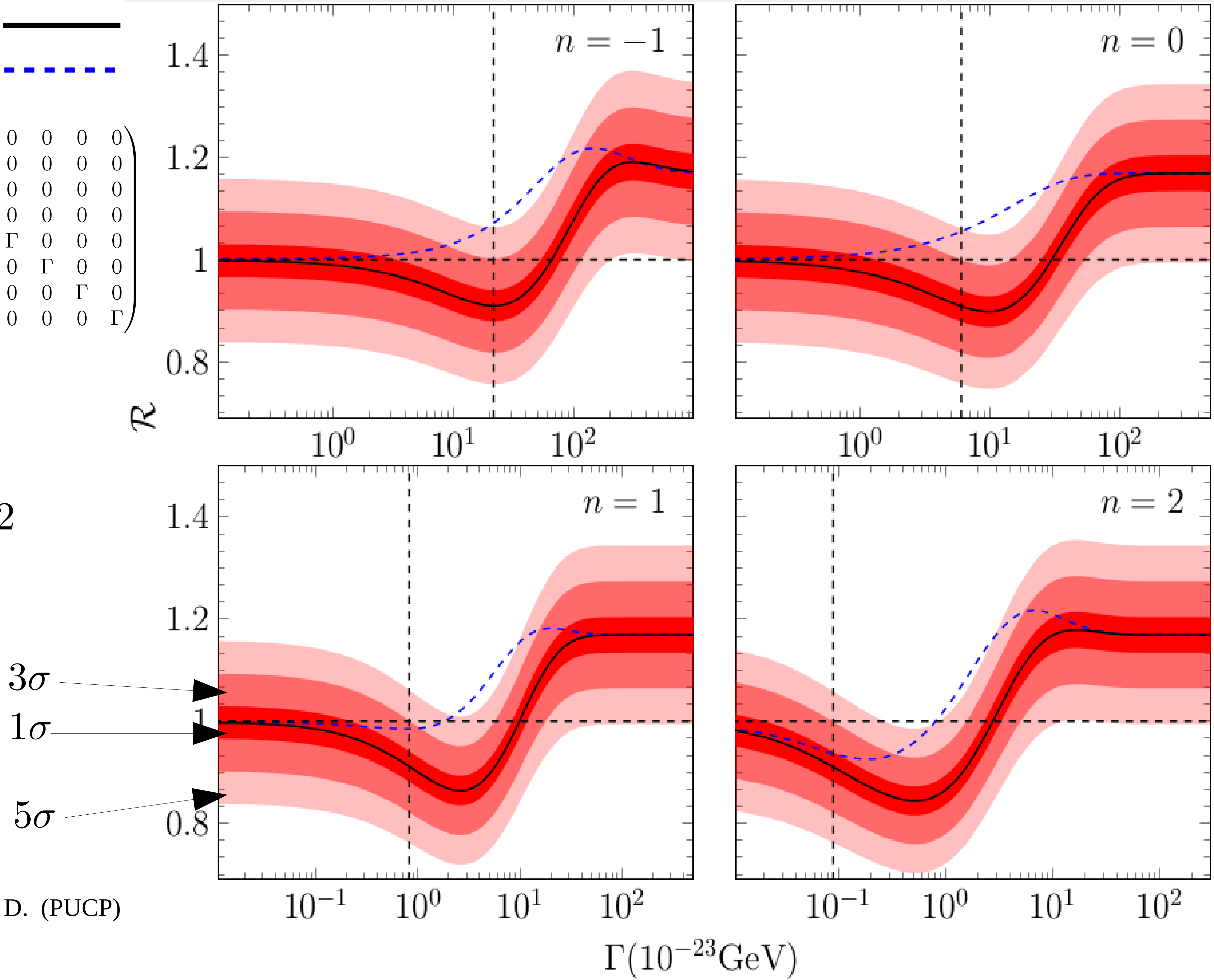
Results

Optimal case

DDM

$$\mathbf{D} = \begin{pmatrix} \Gamma & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Gamma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Gamma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \Gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Gamma & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \Gamma & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Gamma \end{pmatrix}$$

$$\delta_{CP} = \pi/2$$



Results

Optimal case (solid black line)

DDM (dashed blue line)

$$\mathbf{D} = \begin{pmatrix} \Gamma & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Gamma & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & \Gamma & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \Gamma & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \Gamma & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \Gamma & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & \Gamma & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & \Gamma \end{pmatrix}$$

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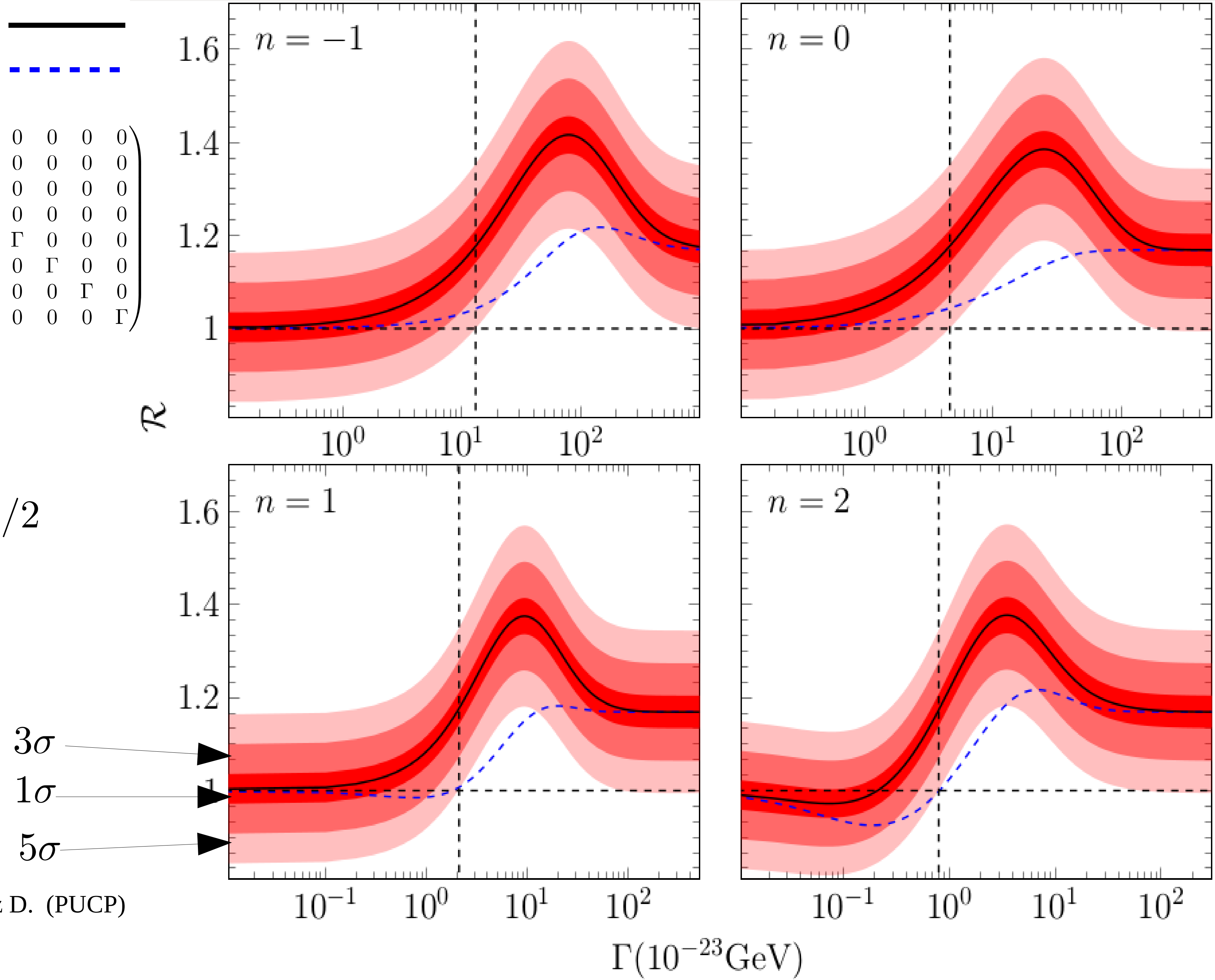

Conclusions

- We have shown that an apparent breakdown of the fundamental CPT symmetry can take place when the neutrino system is affected by the environment. we have quantified a possible measurement of this CPTV using the dissapearance channels $\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$, with their corresponding backgrounds, and an observable $\mathcal{R}$. All in the context of the DUNE experiment.

- The simulated measurements of $\mathcal{R}$ have been performed considering four hypothesis of energy dependence on the decoherence parameters. For $\delta_{CP} = 3\pi/2$ and a NDM, we achieve a 5σ for $\mathcal{R}$ with respect to its expectation value at the SO case, $\mathcal{R} = 1$, for the following Γ: $\{13.1, 4.6, 2.1, 0.8\} \times 10^{-23}\mathrm{GeV}$, for n=-1,0,1 and 2, respectively. At all these points, the DDM is compatible with the SO case. For $\delta_{CP} = \pi/2$, we reach discrepancies of the order of 3σ. In our best case for n=2 we have $\Gamma \simeq 10^{-24}\mathrm{GeV}$, but with the inability of discriminating from the DDM case.

THANK YOU VERY MUCH FOR YOUR ATTENTION

Quantum Decoherence

For 3 generations, the probability is given by

$$P_{\nu_\alpha \to \nu_\beta} = \frac{1}{3} + \frac{1}{2}\left(\sum_{i,j} \rho_i^\beta \rho_j^\alpha [e^{Mt}]_{ij}\right)$$

Where $M = H + D$

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

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

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

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

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

$$\rho_6^\alpha = 2\,\mathrm{Re}\,(U_{\alpha 1}^* U_{\alpha 3})$$

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

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

A. Gago - "A Study on quantum decoherence phenomena with three generations of neutrinos"

Quantum Decoherence

- **CPT Asymmetry**

The CPT assymetry grows with Γ until reaching a region where we have maximum amplitude then starts to decrease.