Breaking of CPT due to quantum decoherence tested at DUNE

Félix N. Díaz Desposorio

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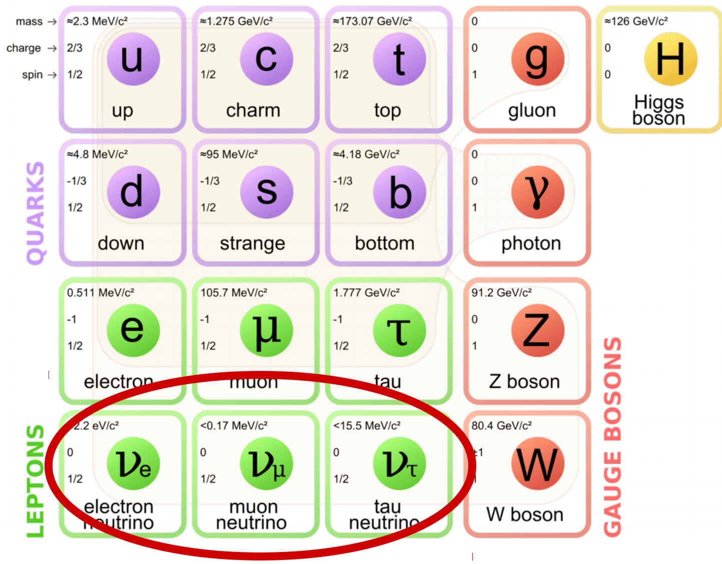
Corpus Christi - 2019

Outline

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

Introduction



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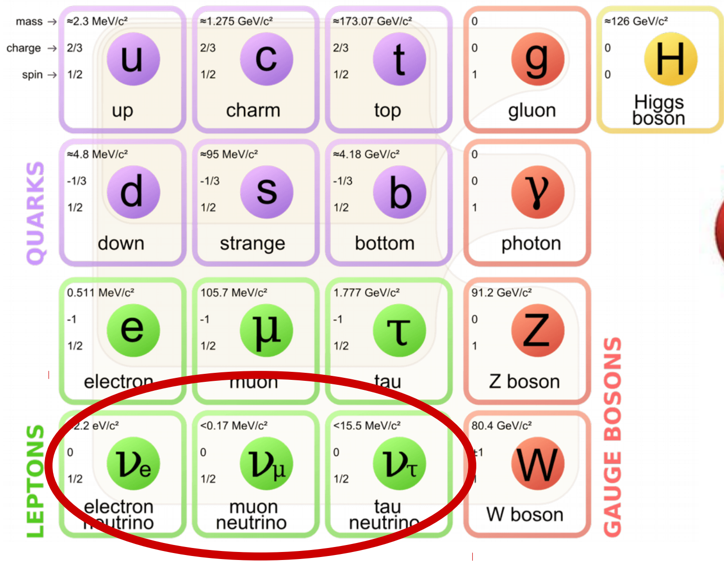
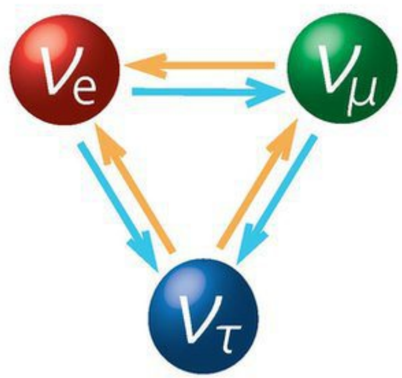


Oscillation



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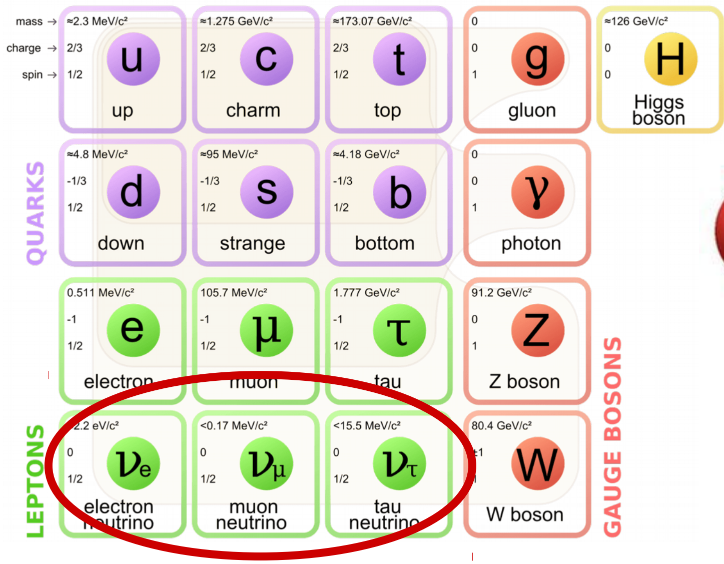

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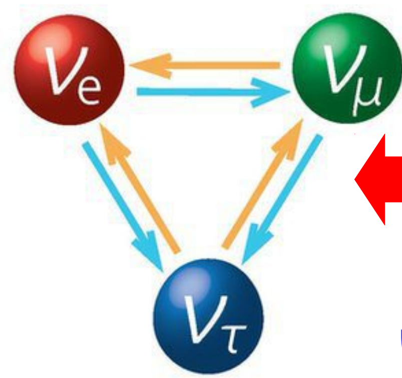
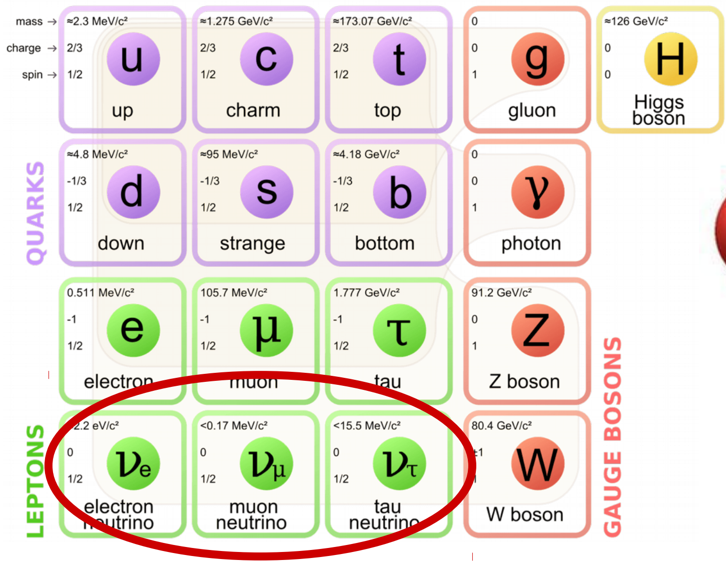


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor Eigenstates

Mass Eigenstates

Introduction



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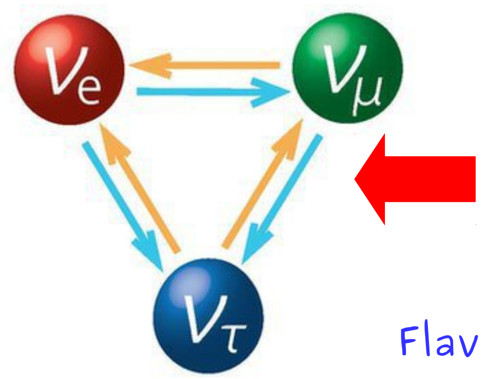

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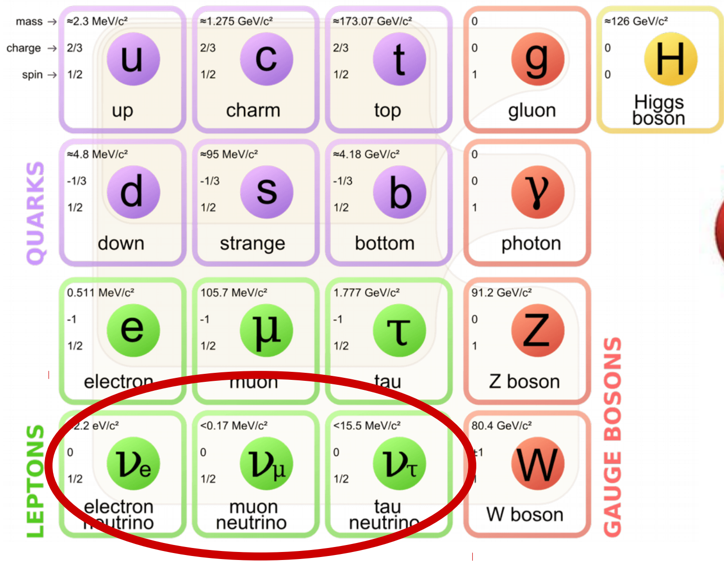
Mass Eigenstates

Oscillation Parameters

$$U = U_{PMNS} = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{atms \& acelerador}} \times \underbrace{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13}\end{pmatrix}}_{\text{atms \& reactor \& acelerador}} \times \underbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{solar \& reactor}}$$

Introduction



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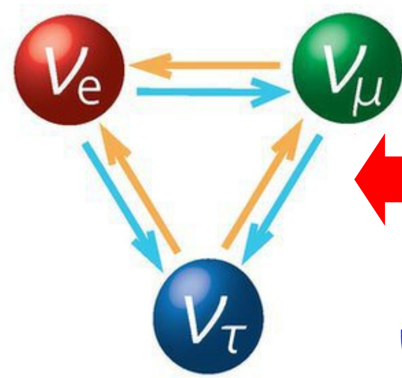

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Oscillation Parameters

Mass Hierarchies

Dirac Phase

P. Degeneracy

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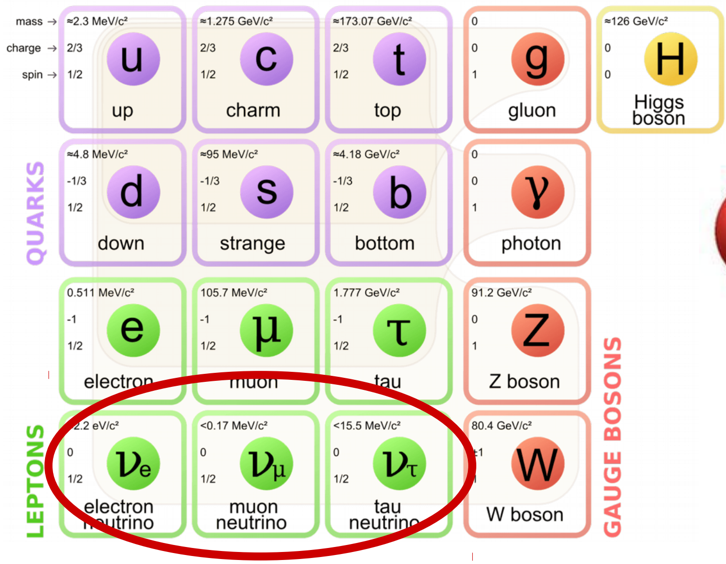

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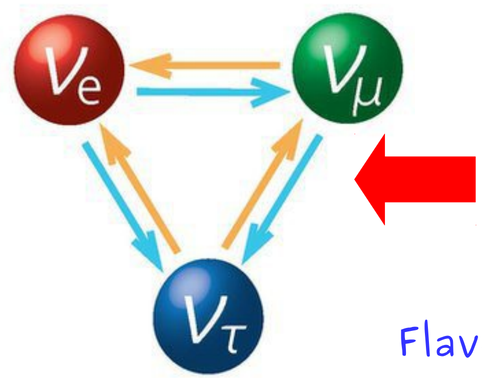

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Flavor Eigenstates Mass Eigenstates

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Neutrino Decay

Non Standard Interaction

Quantum Decoherence

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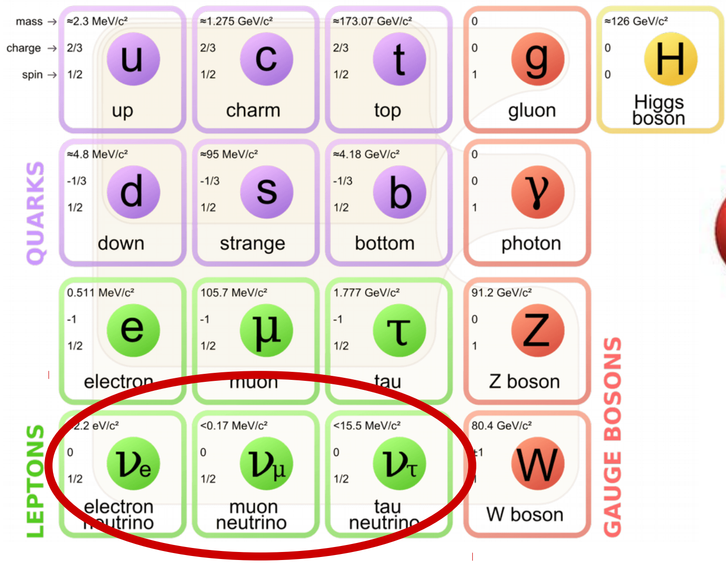

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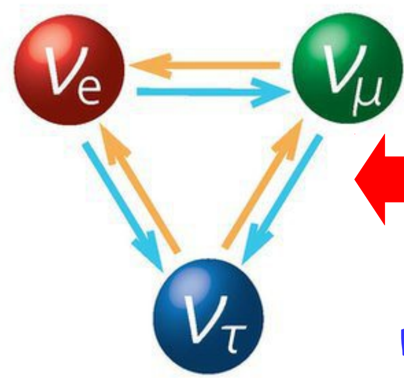

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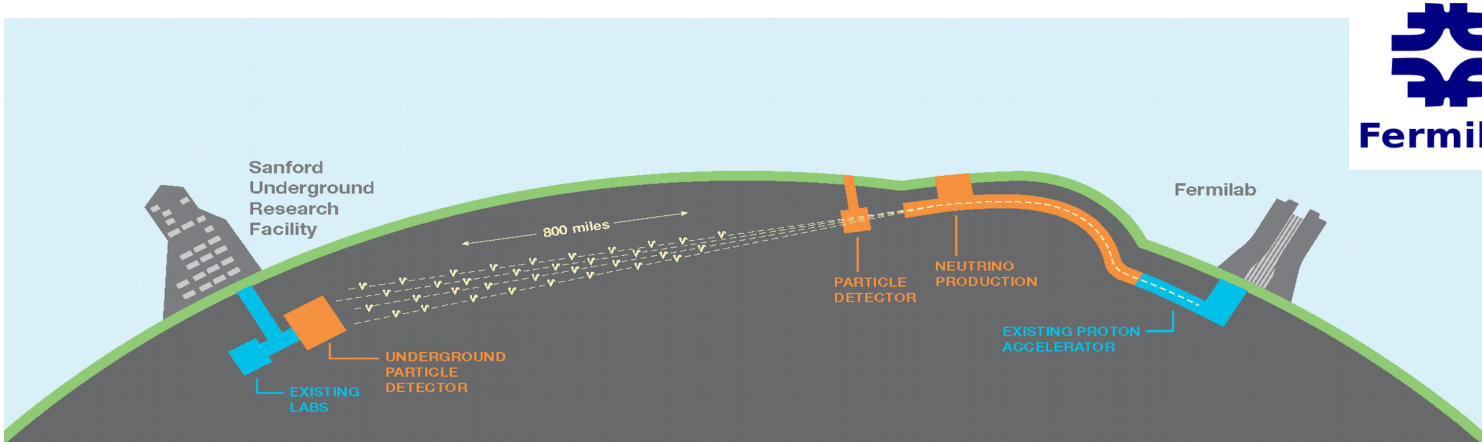

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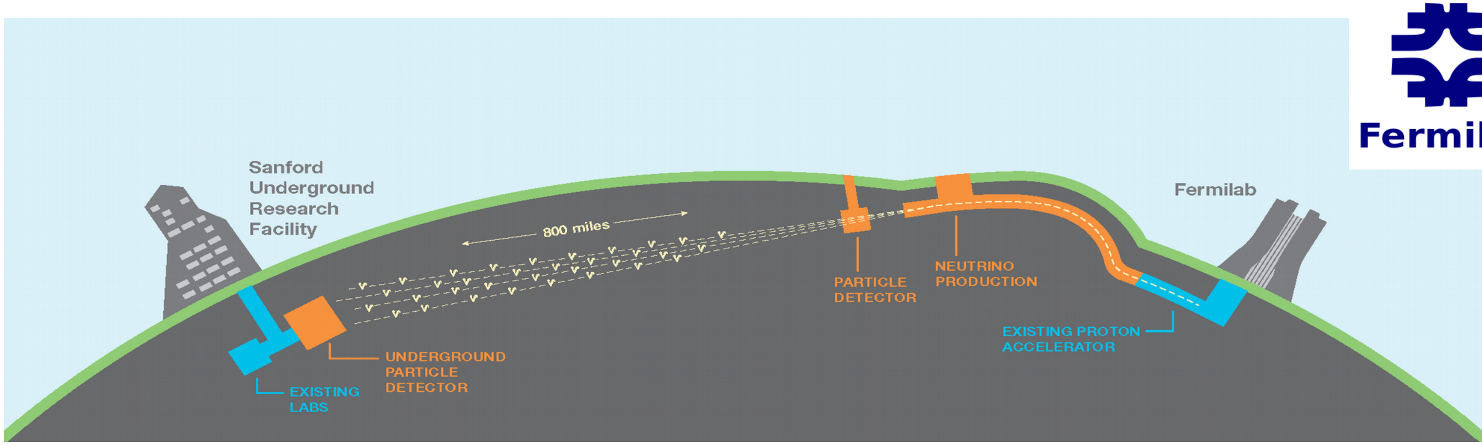
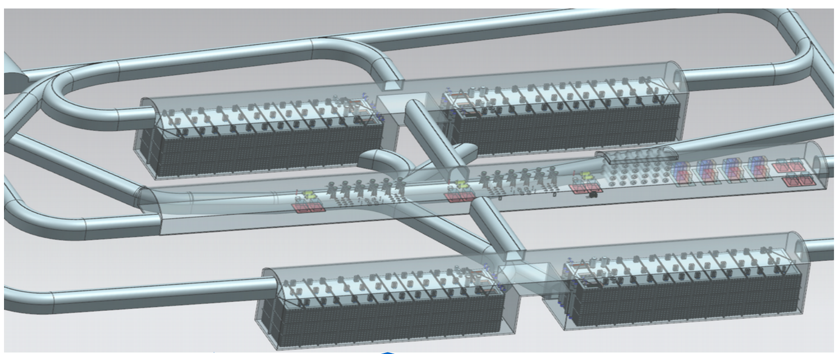
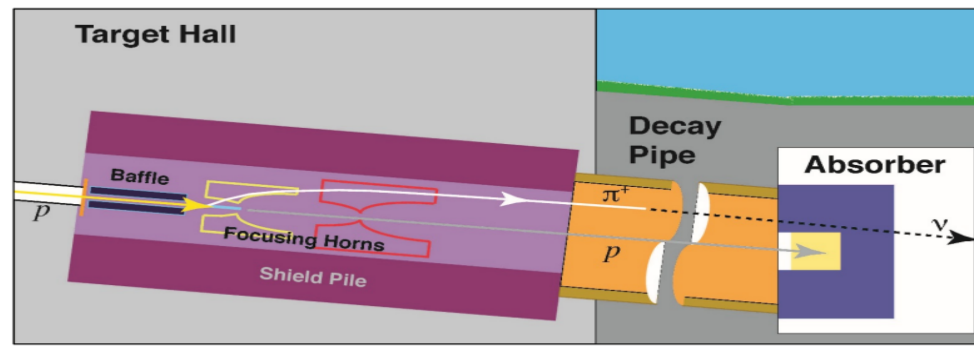


Fermilab

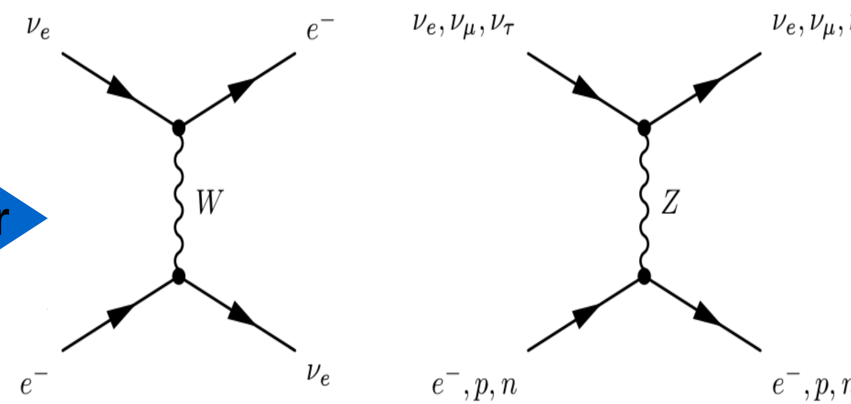


Beam



Liquid Argon

Interaction with matter



Ancillary files

Alion, T. et al - "Experiment Simulation Configurations Used in DUNE CDR"

Introduction

On the other hand...

Introduction

On the other hand...

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. Lee, *Columbia University, New York, New York*

AND

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(Received June 22, 1956)

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CPT symmetry and neutrino oscillation $P_{\nu_\alpha \rightarrow \nu_\beta} = P_{\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha}$

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Neutrino Oscillation

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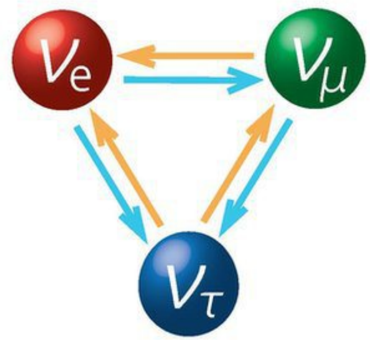


Neutrino Decay

Non Standard Interaction

Quantum Decoherence

some scenarios

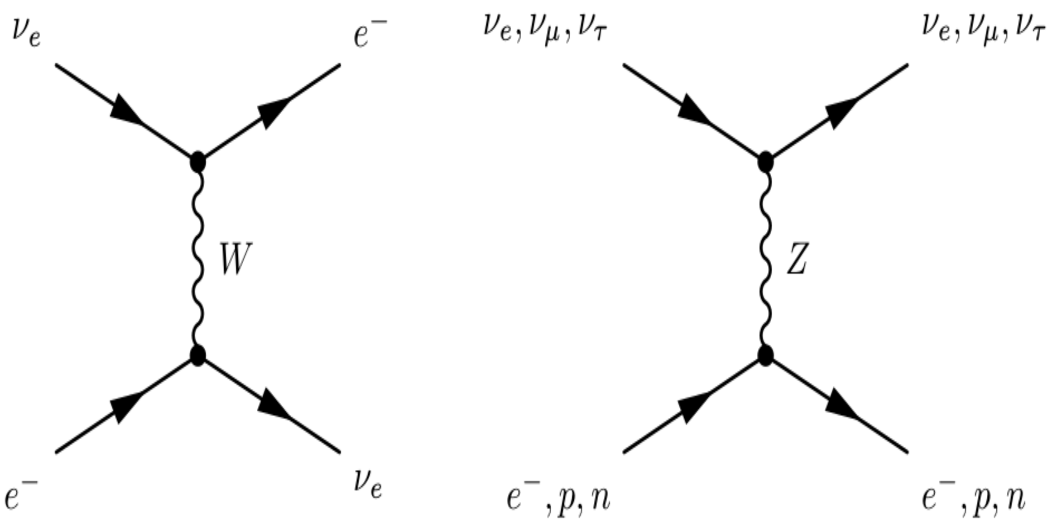
$\not{CPT}$

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

Measurement

DEEP UNDERGROUND NEUTRINO EXPERIMENT

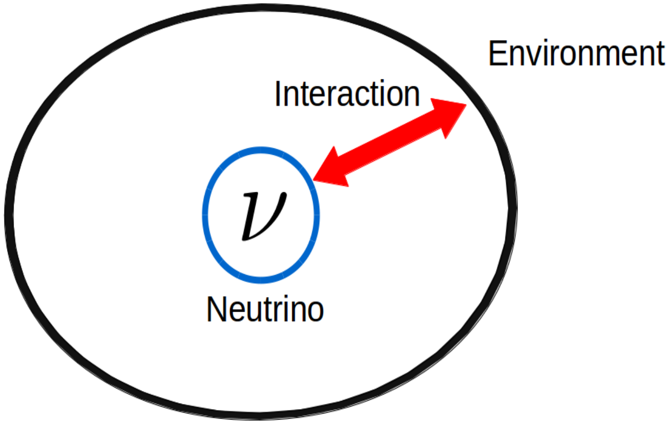
CPTV due to matter



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

Theoretical Approach

Considering the neutrino like an open quantum system.



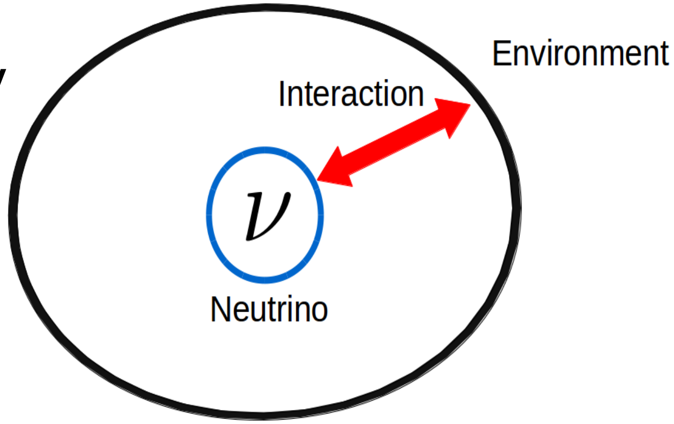
Theoretical Approach

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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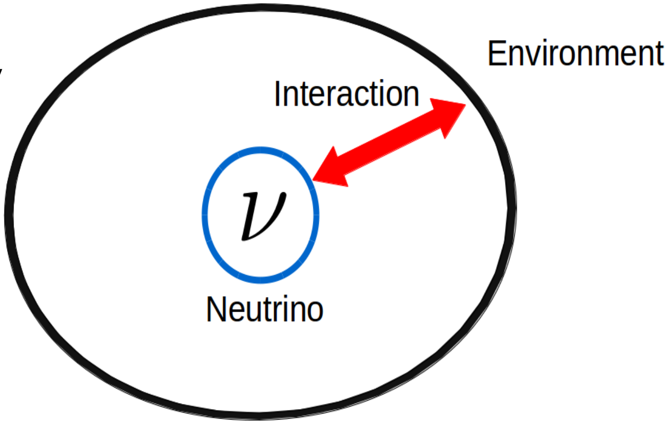

$$\frac{\partial \hat{\rho}(t)}{\partial t} = -i[\hat{H}, \hat{\rho}(t)] + \mathcal{D}[\hat{\rho}(t)]$$

Dissipative term

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 $M = H + D$

A. Gago et al arXiv:hep-ph/0208166 *J.A. Carpio et al Phys. Rev. D 97, 115017*

Theoretical Approach

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

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Where $M = H + D$

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

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

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

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

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

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

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

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

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

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

In a CPTV case one coefficient of the factor $\rho_i \rho_j$ must be ρ_2 or ρ_5 or ρ_7 and the other should be anyone of the others $\rho_1, \rho_3, \rho_4, \rho_6, \rho_8$ having in total fifteen cases.

Theoretical Approach

- **CPT Asymmetry**

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

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

Theoretical Approach

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Diagonal elements equal to Γ

Same for neutrinos and antineutrinos ⟵

One β_{ij} at a time.

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

Theoretical Approach

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

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

Theoretical Approach

- **CPT Asymmetry**

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

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

Diagonal elements equal to Γ

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One β_{ij} at a time.

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Damping

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

Theoretical Approach

Considering the muon dissapearance channel and the DUNE baseline

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

Theoretical Approach

Considering the muon dissapearance channel and the DUNE baseline

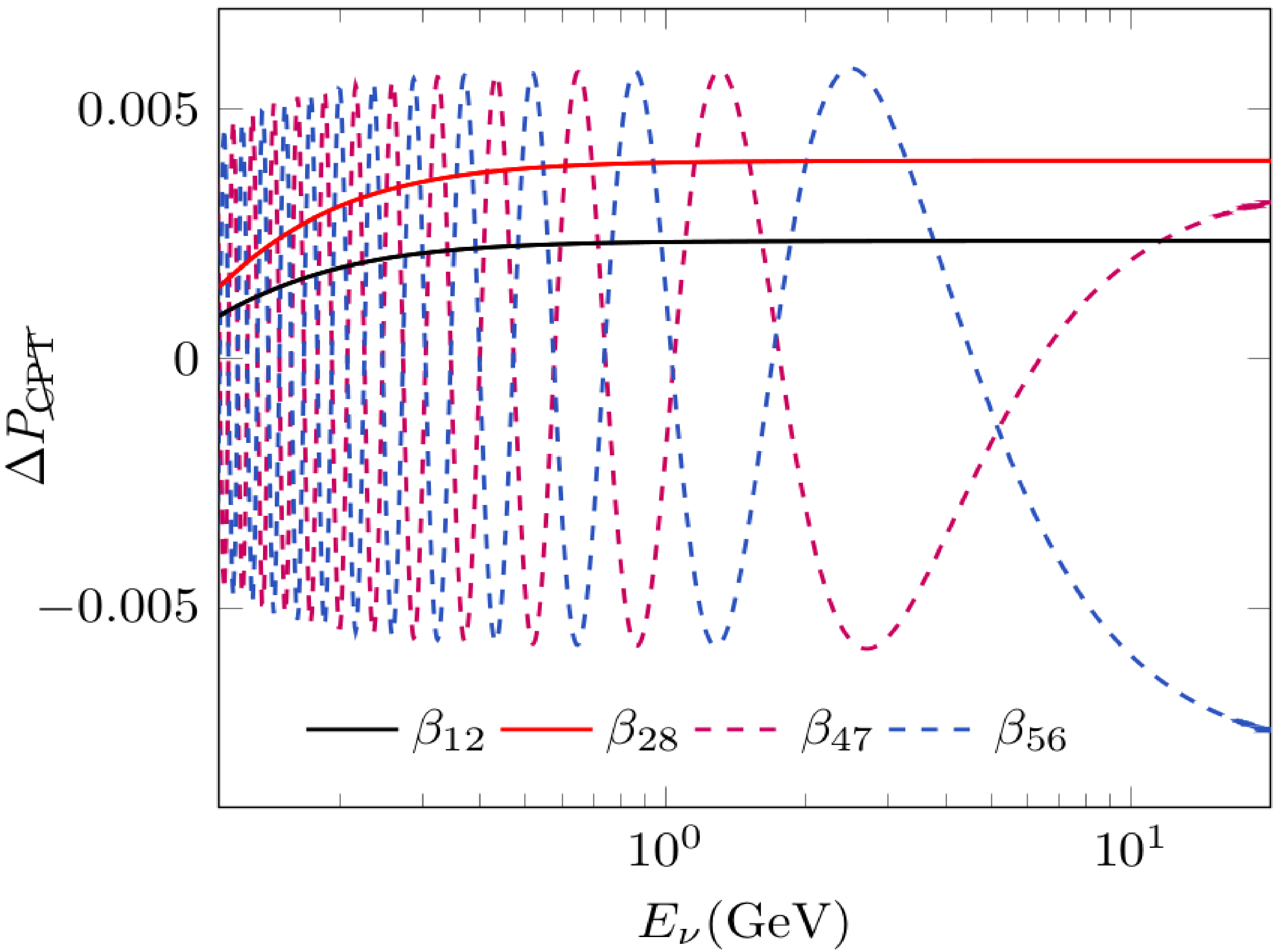
$$\Delta P_{\not{CPT}} = P_{\nu_\mu \to \nu_\mu} - P_{\bar{\nu}_\mu \to \bar{\nu}_\mu}$$

$\Gamma = 10^{-23}\text{GeV}$

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

$\beta_{ij} = \Gamma/\sqrt{3}$

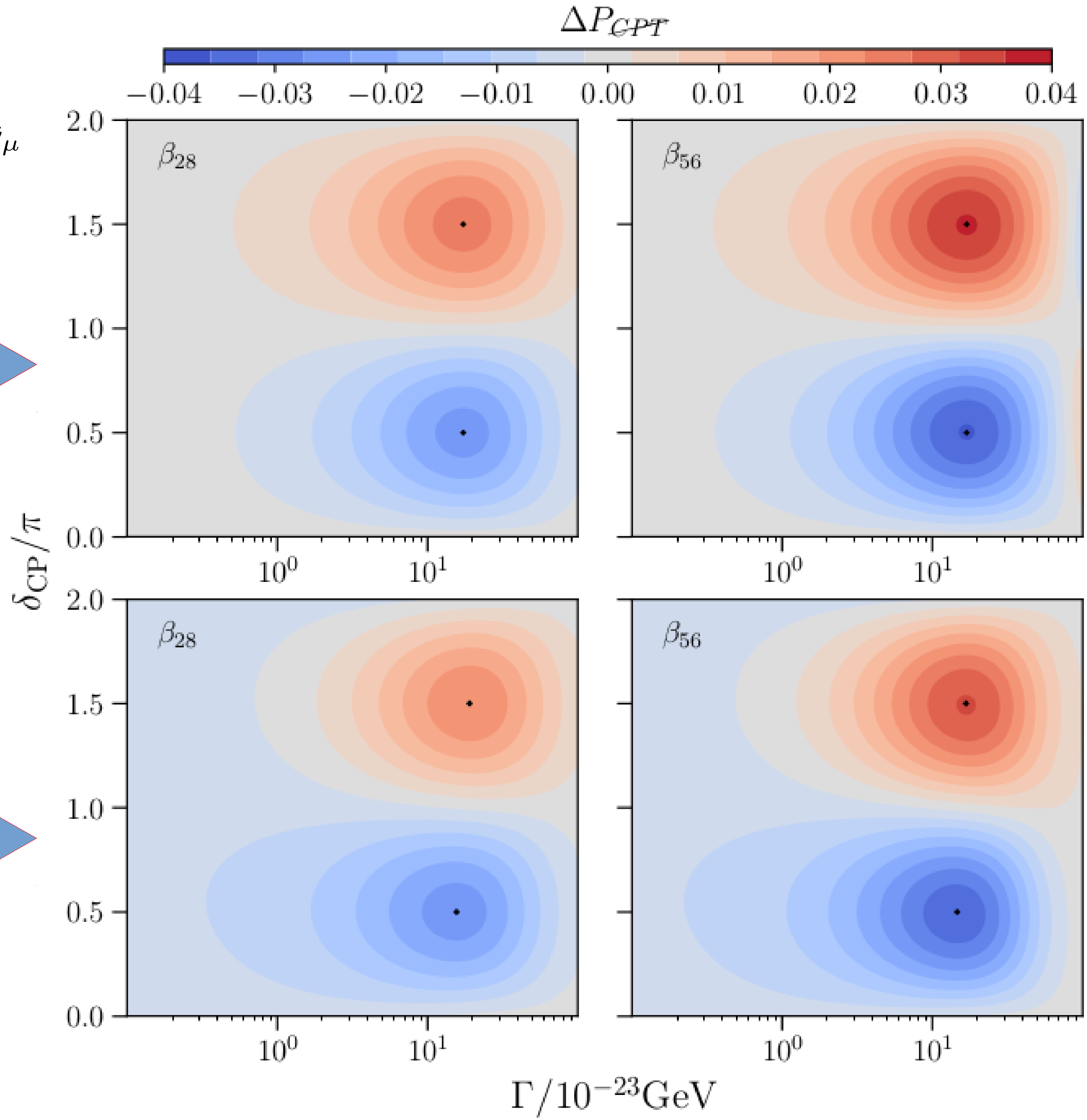
$L = 1300\text{Km}$



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

Vacuum

Matter



$$\beta_{28} = \Gamma/\sqrt{3}$$
$$\beta_{56} = \Gamma/\sqrt{3}$$
$$E_\nu = 2.4 \text{ GeV}$$

Theoretical Approach

- **Energy Dependence**

$$\Gamma_{E_\nu} = \Gamma \left(\frac{E}{\text{GeV}} \right)^n$$

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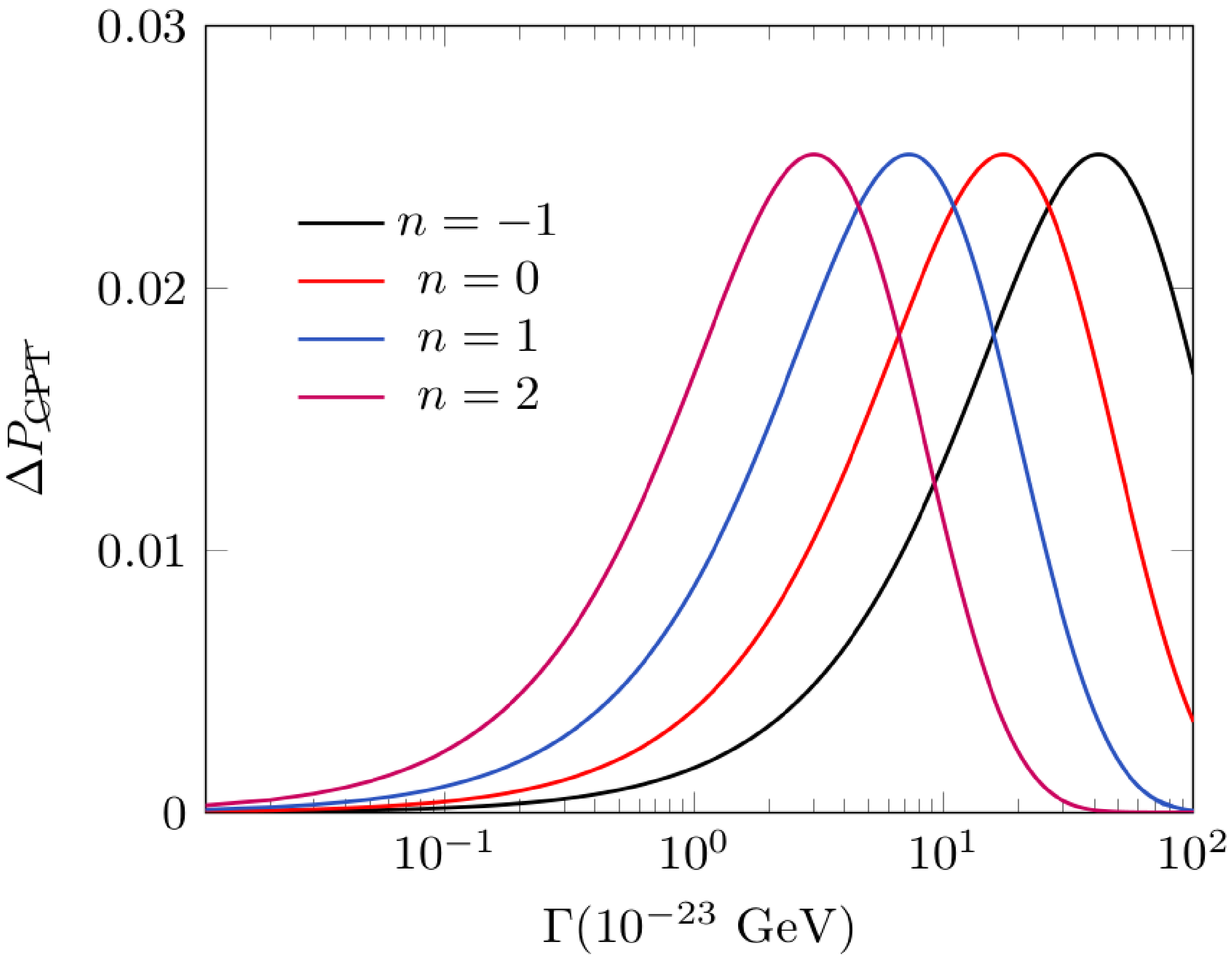

$$\mathrm{E} = 2.4\mathrm{GeV},\ \beta_{28} = \Gamma/\sqrt{3}$$
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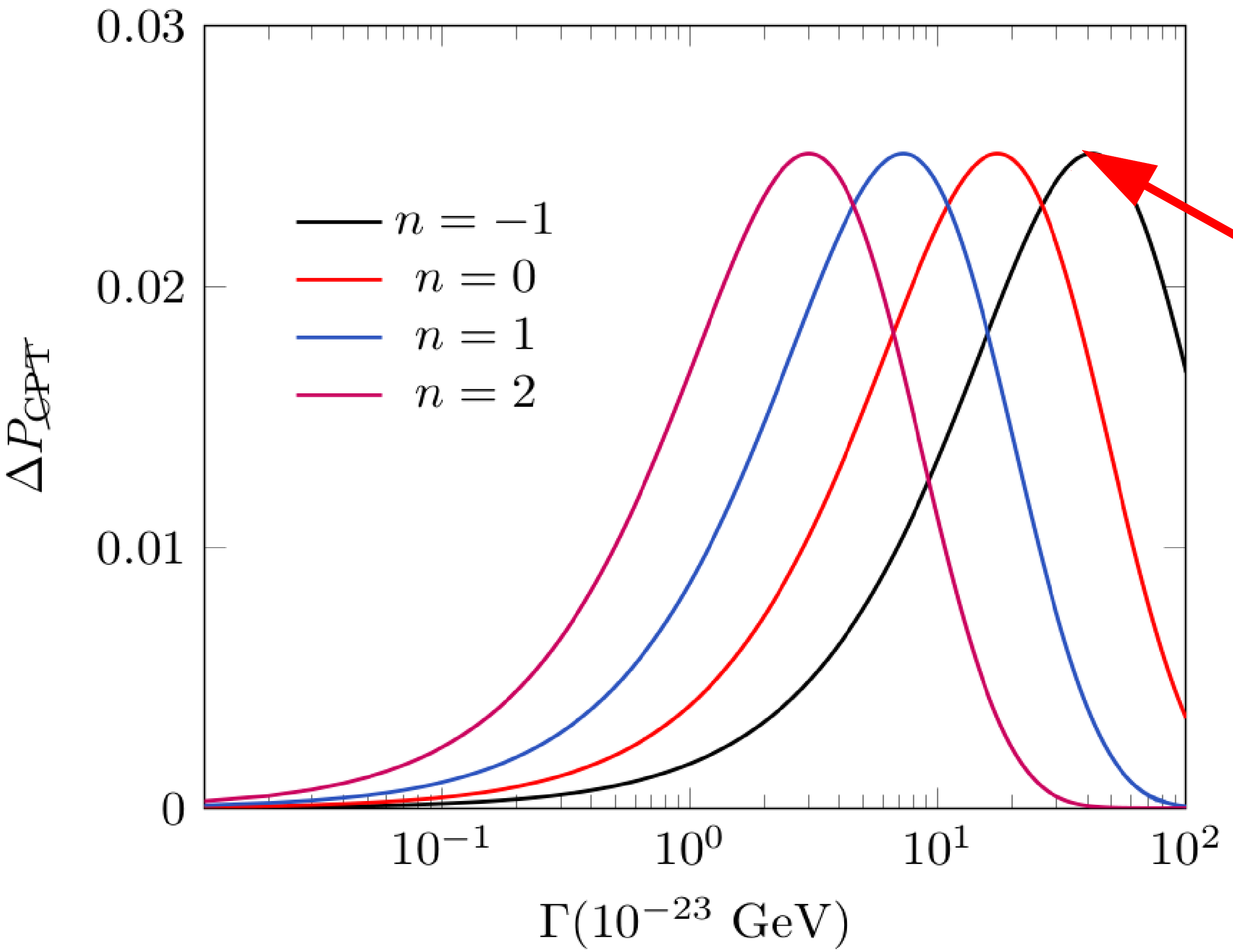

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Change the value but not the amplitude

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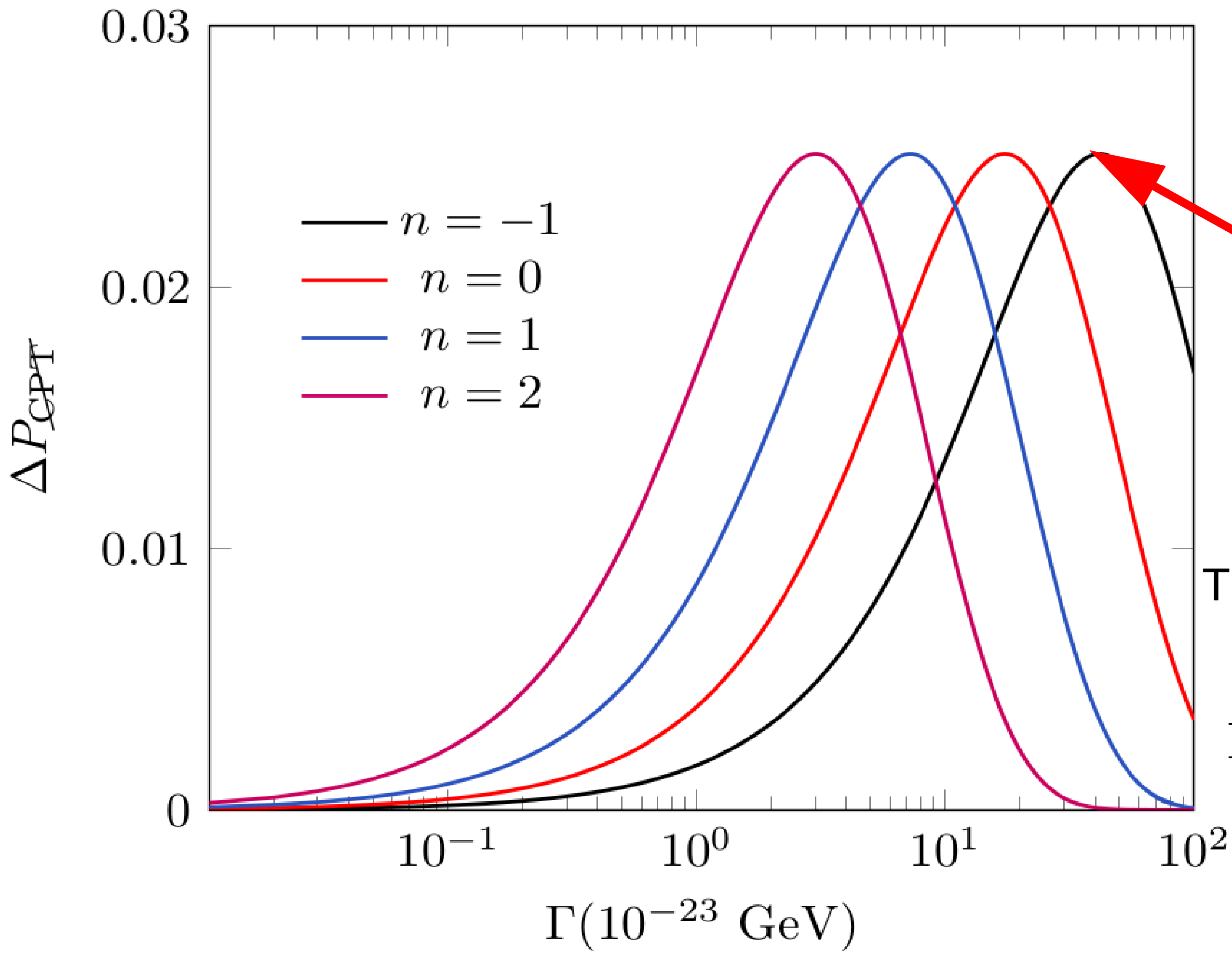

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Change the value but not the amplitude

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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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**

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

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$$P^{\mathrm{SO} \bigoplus \mathrm{DDM}}_{\nu_\alpha \nu_\beta} = \frac{1}{3}(1 - e^{-\Gamma t}) + e^{-\Gamma t} P^{\mathrm{SO}}_{\nu_\alpha \nu_\beta}$$

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Standard Oscillation and Diagonal Decoherence Matrix

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

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

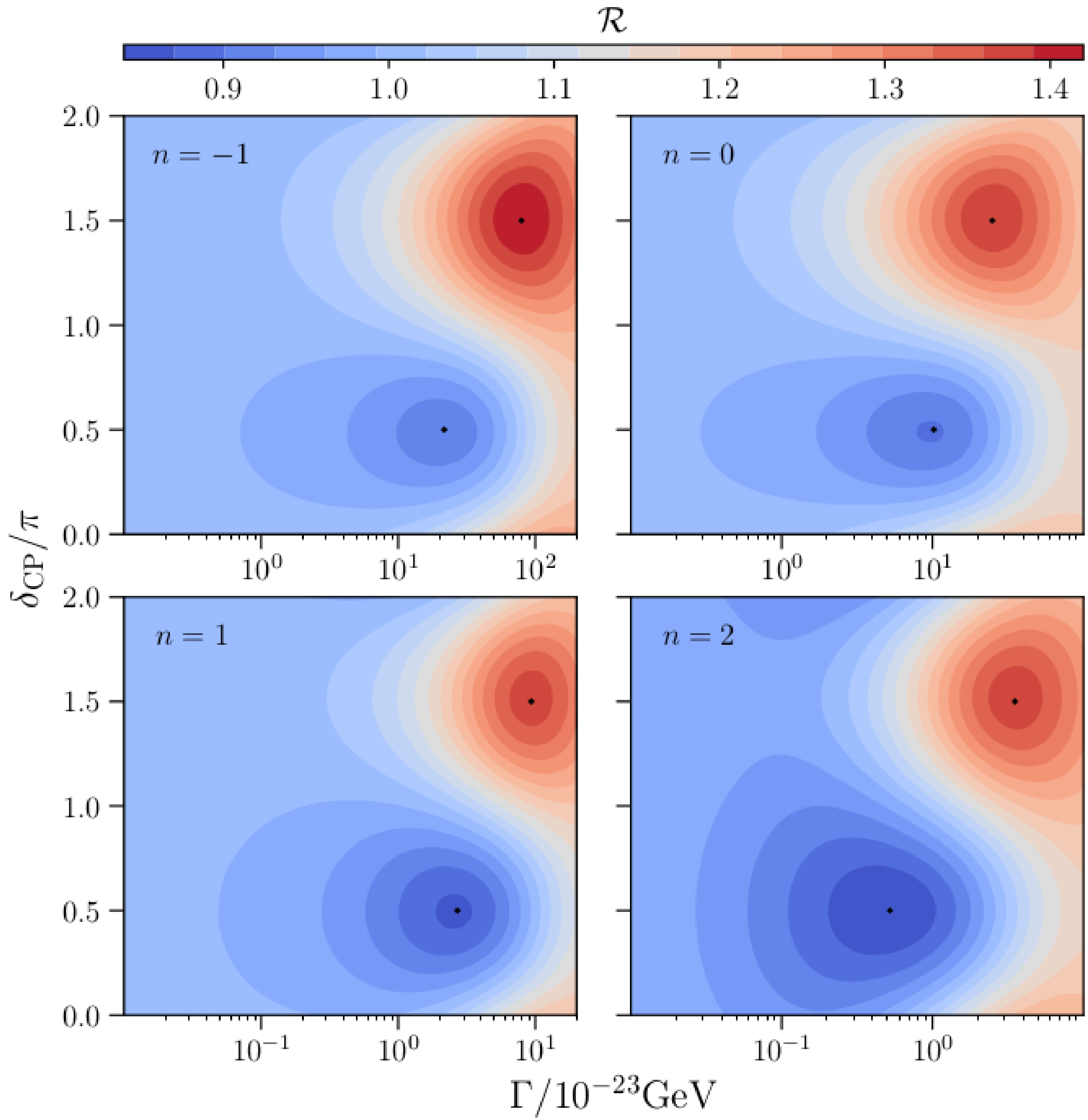
To study and differentiate the CPTV due to the effect of quantum decoherence from the CPTV due to the matter effect, we define the ratio

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

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

Results

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



Optimal Case

Energy range

$0.5 - 20\ \mathrm{GeV}$

5 years FHC

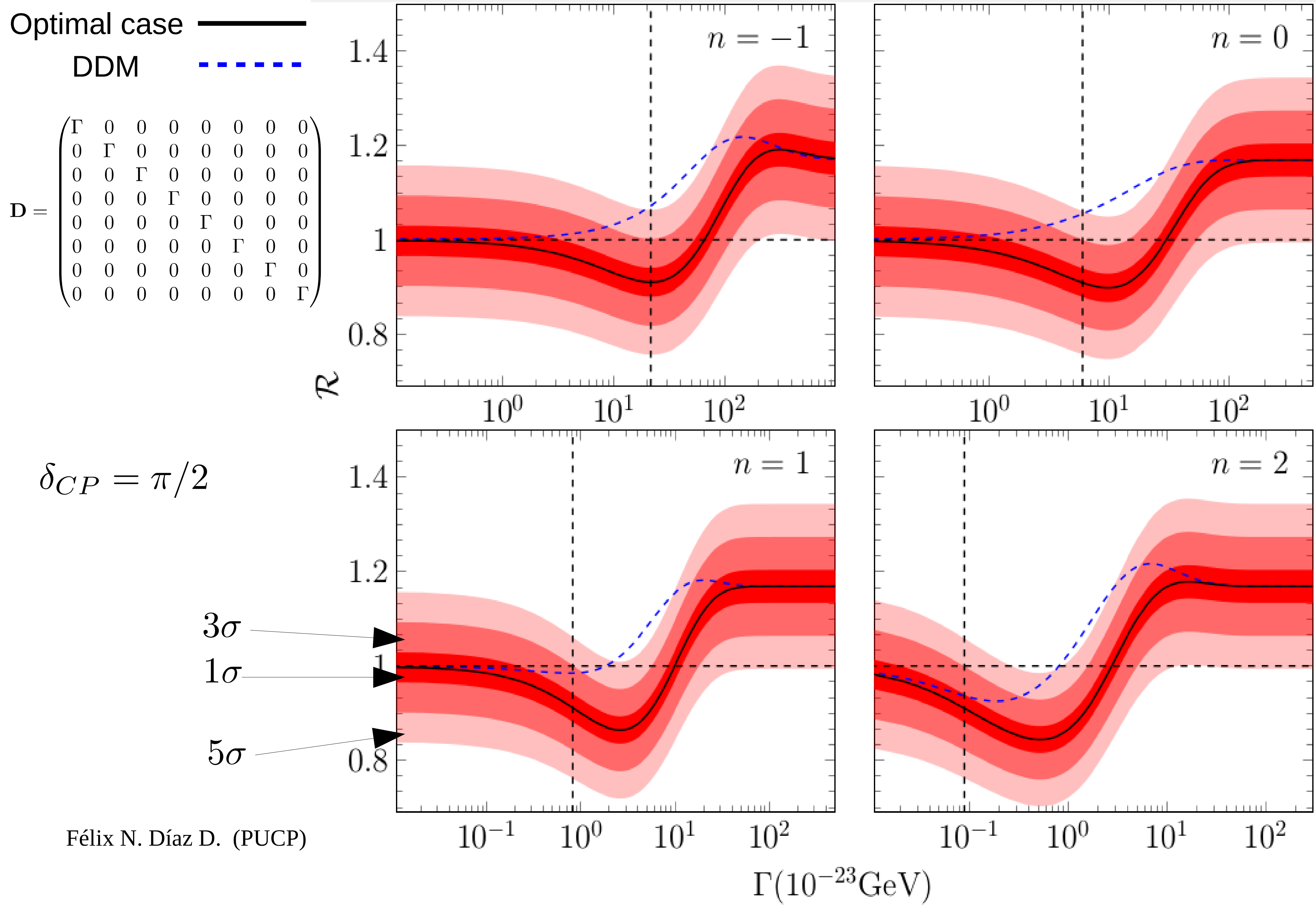
5 years RHC

Normal hierarchy

Results

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

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



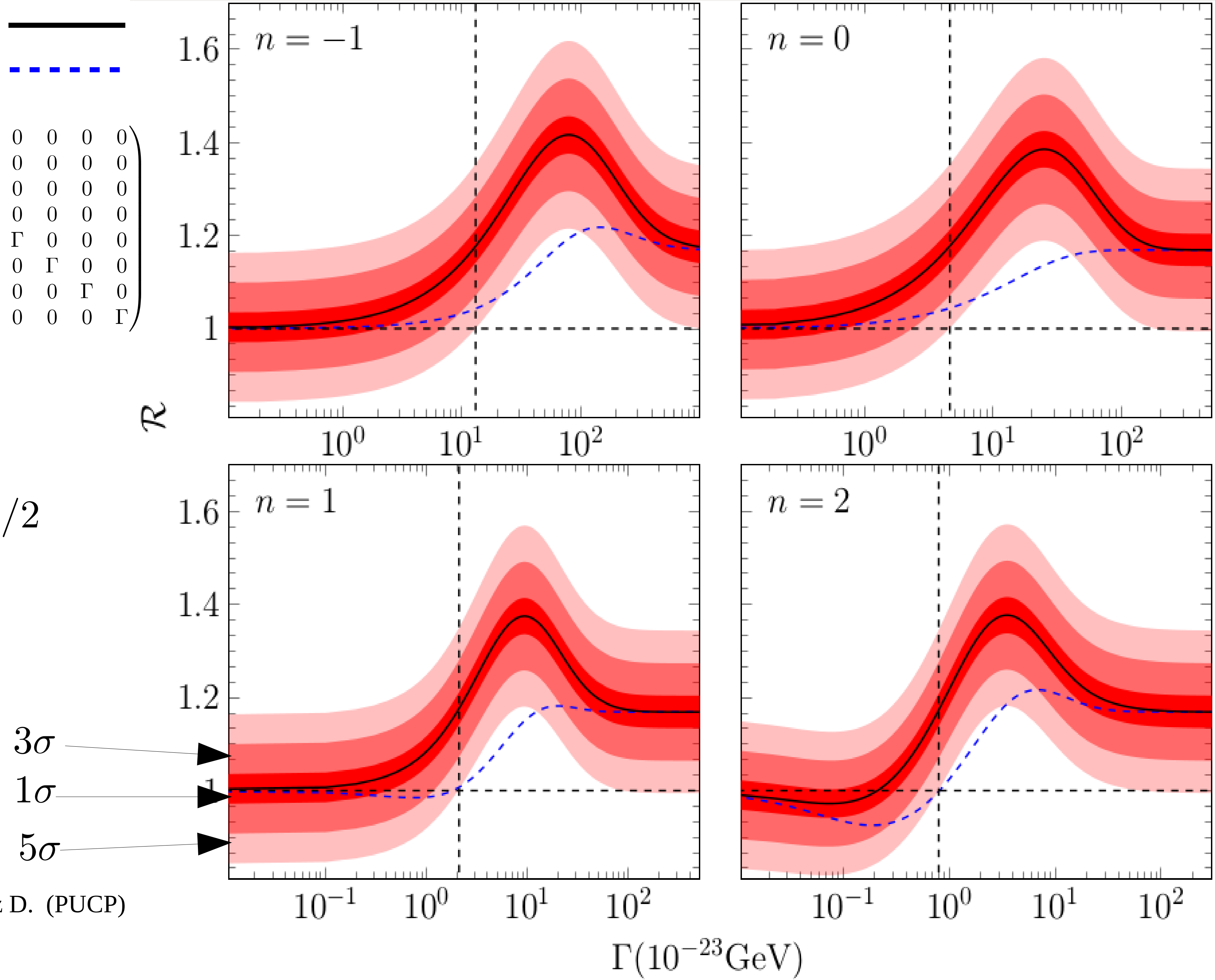
Results

Optimal case ——

DDM - - - - -

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

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



Conclusions

- We have shown that a breakdown of the 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.

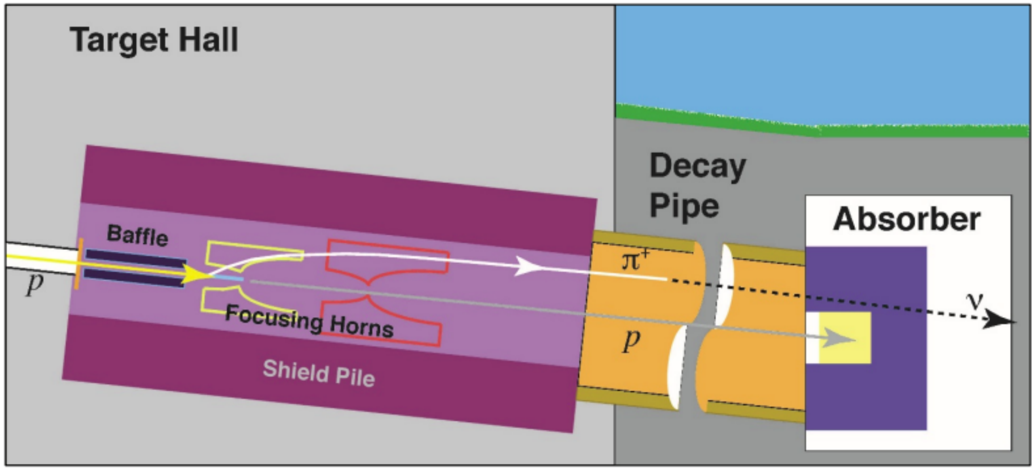
- The simulated measurements of $\mathcal{R}$ have been performed considering four hypothesis of energy dependence on the decoherence parameters. For $\delta_{CP} = 3\pi/2$ and a NDM, we achieve a 5σ for $\mathcal{R}$ with respect to its expectation value at the SO case, $\mathcal{R} = 1$, For $\delta_{CP} = \pi/2$, we reach discrepancies of the order of 3σ in our best case.

- The observations of CPTV appear when the neutrino system is treated as an open system. The latter means that it is likely that if we had access to the information of the environment, the overall CPT symmetry is conserved. For this reason, it deserves a more profound discussion to ascertain if this CPTV is a breaking at the fundamental level or it is only an apparent one, because of our lack of information from the environment.

THANK YOU VERY MUCH FOR YOUR ATTENTION

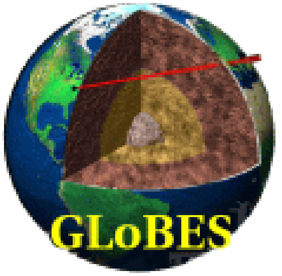
BACK UP

Simulation Details



$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\pi^- \to \mu^- + \bar{\nu}_\mu$$



nuSQuIDS

Probability

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

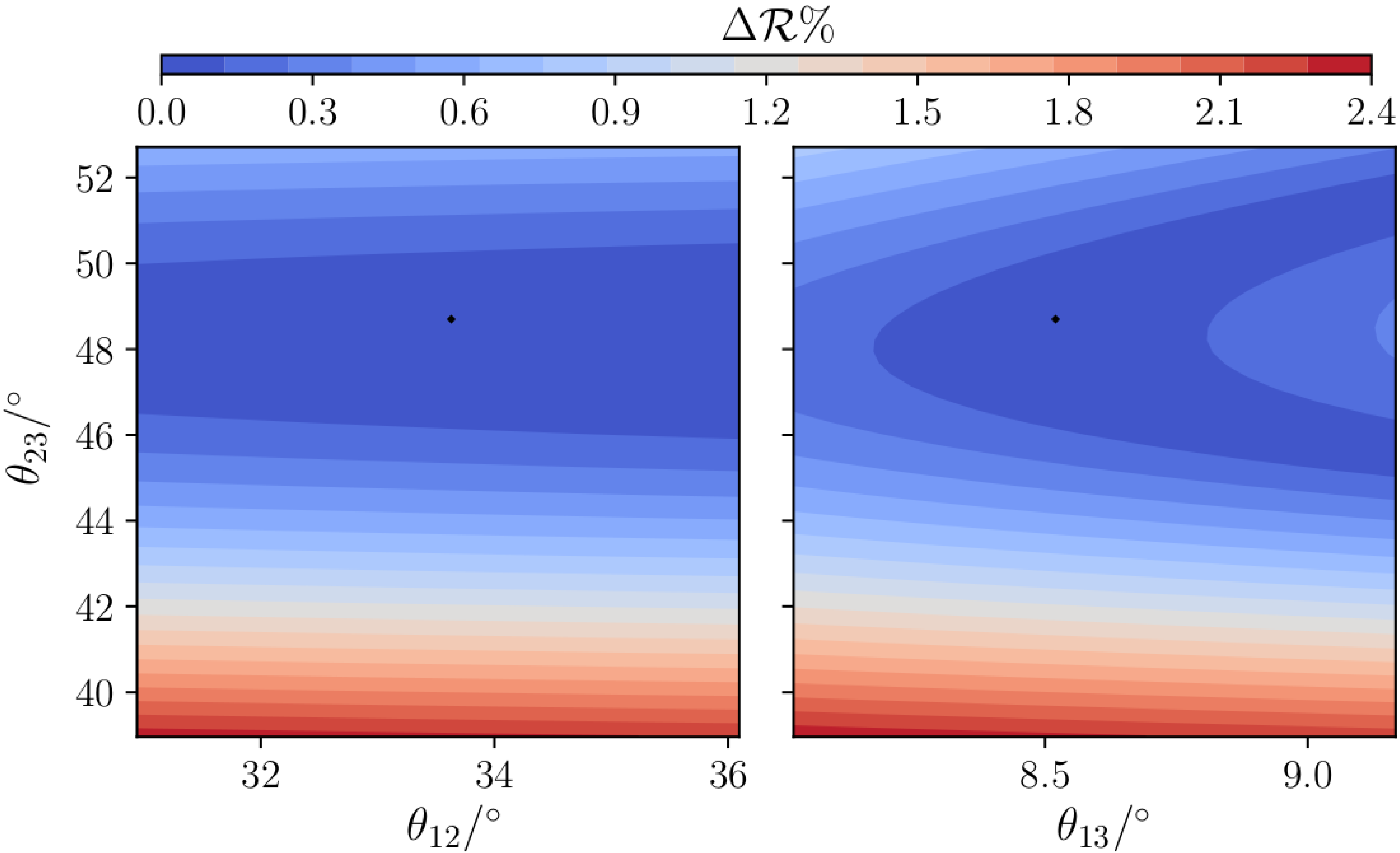
Smearing → Event Rate N

$\Gamma = 10^{-23}$ GeV	Std	$n=-1$	$n=0$	$n=1$	$n=2$
Neutrino mode					
$\nu_\mu + \bar{\nu}_\mu$ CC signal	11749	11841	11965	11573	11932
NC background	109	109	109	109	109
$\nu_\tau + \bar{\nu}_\tau$ CC background	43	43	46	74	87
Antineutrino mode					
$\bar{\nu}_\mu + \nu_\mu$ CC signal	5903	5897	5846	5237	4816
NC background	58	58	58	58	58
$\nu_\tau + \bar{\nu}_\tau$ CC background	27	27	29	50	60

5 years neutrino mode (FHC)
5 years antineutrino mode (RHC)
Optimal case
Energy range $0.5 - 20$ GeV
$\delta_{CP} = 3\pi/2$

Ancillary files

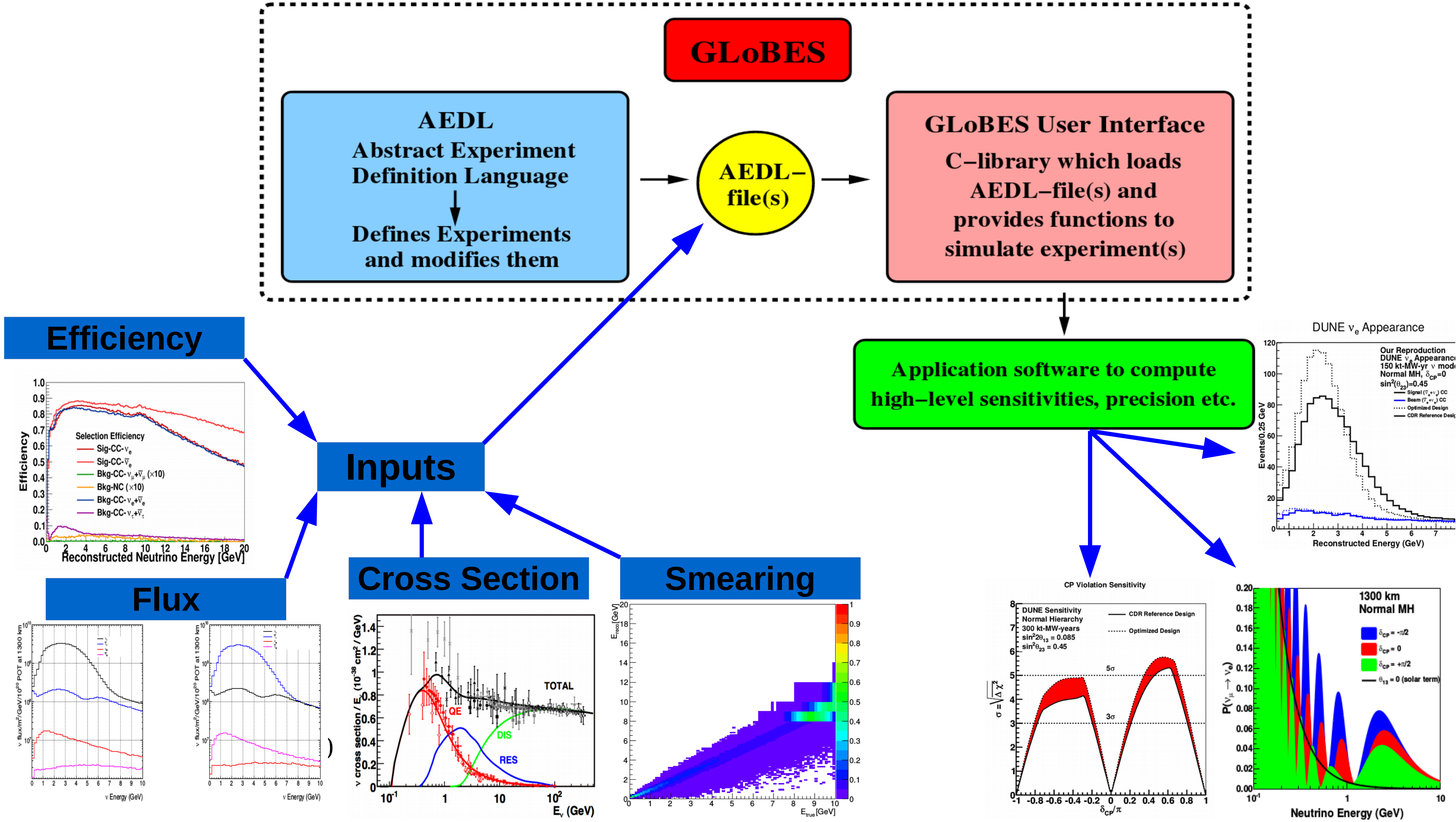
Alion, T. et al - arXiv:1606.09550



ΔR%
0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
52
50
48
46
44
42
40
θ23/°
32
34
36
θ12/°
8.5
9.0
θ13/°

General Long Baseline Experiment Simulator

GLoBES



nuSQuIDS

A Simple Quantum Integro-Differential Solver: SQuIDS

C++ → $\rho(t) \quad S(t)$

How it works?, Expresses all operators on the basis SU(N)

It allows us to add new terms to the right of the Lindblad equation.

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

Matter effect + **Decoherence effect**