Quantum Decoherence and CPT Violation at DUNE

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Juan Carlos Carrasco, Alberto M. Gago Medina

Pontificia Universidad Católica del Perú

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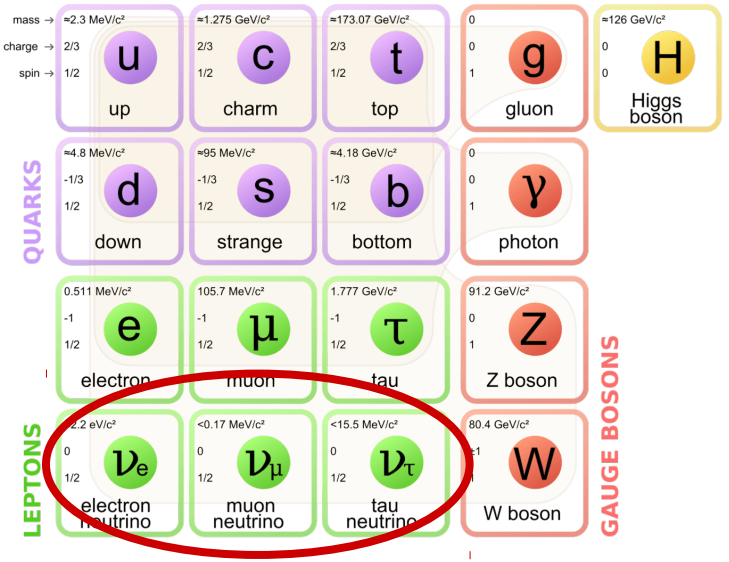
São Paulo - 2018

Outline

1. Introduction.
2. Quantum Decoherence.
3. DUNE and Simulation Details.
4. Preliminary Results.
5. Conclusions.

Introduction



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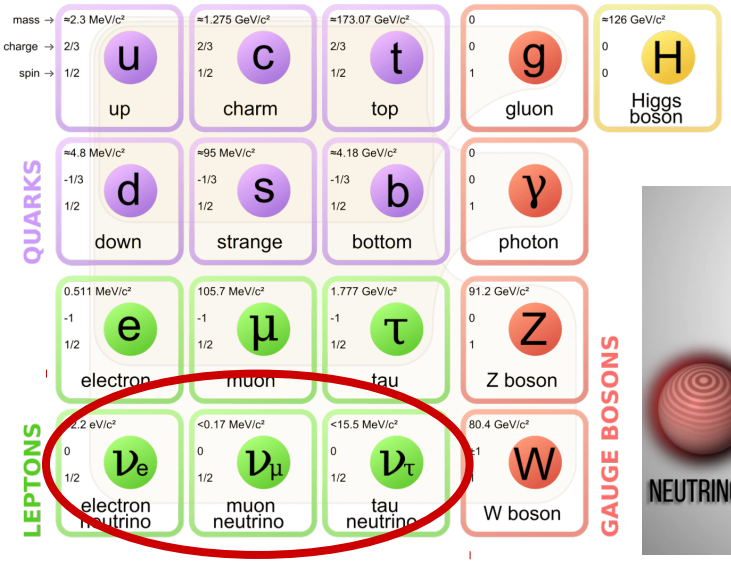

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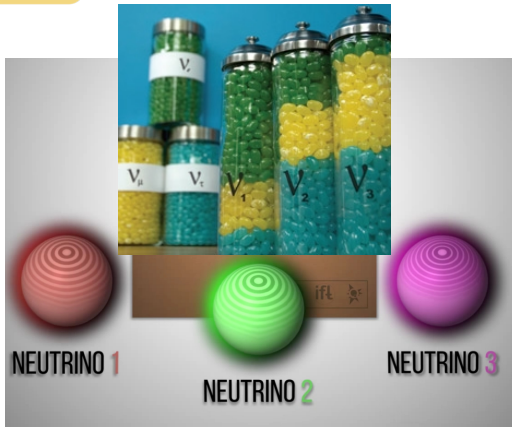

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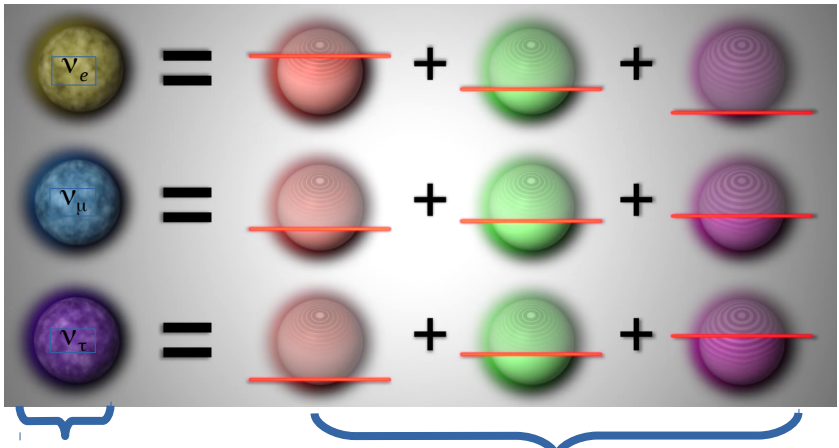

Flavor Eigenstates

Mass Eigenstates

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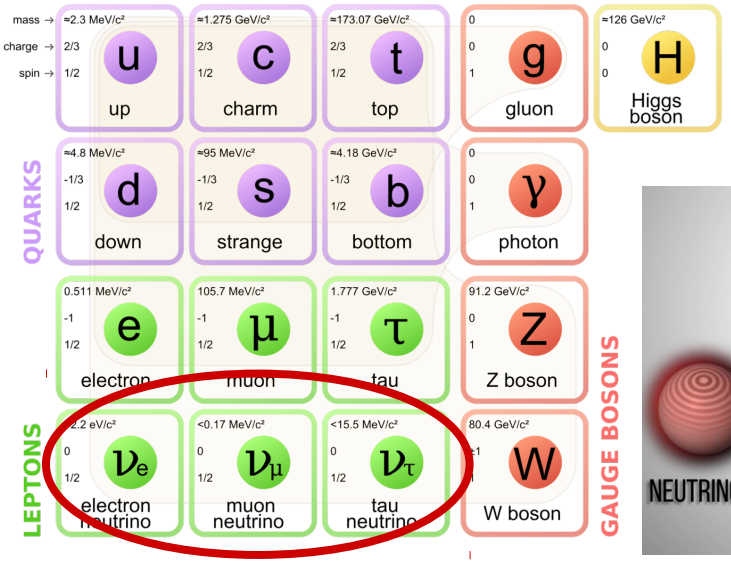

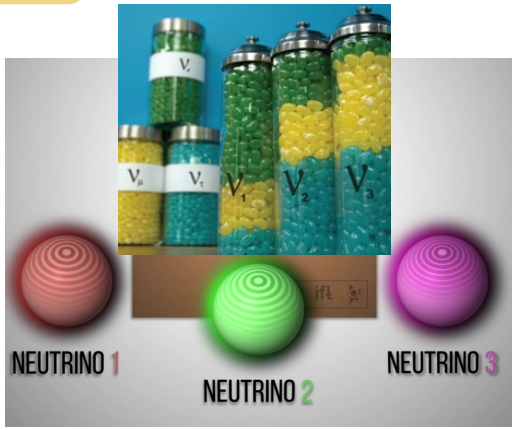

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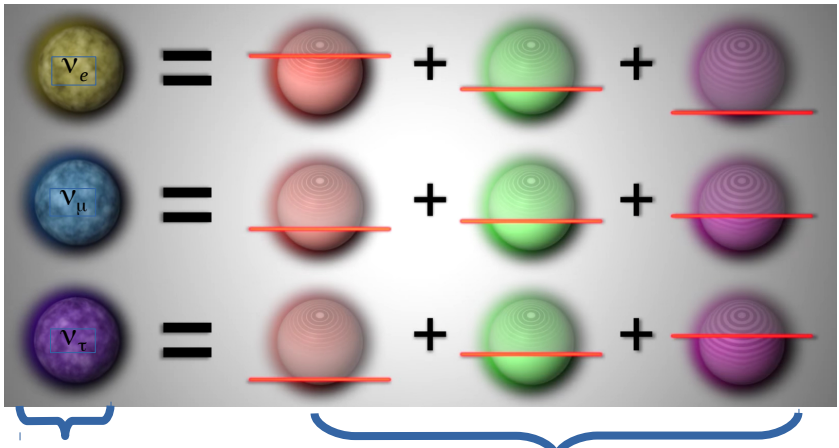

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Oscillation Parameters

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

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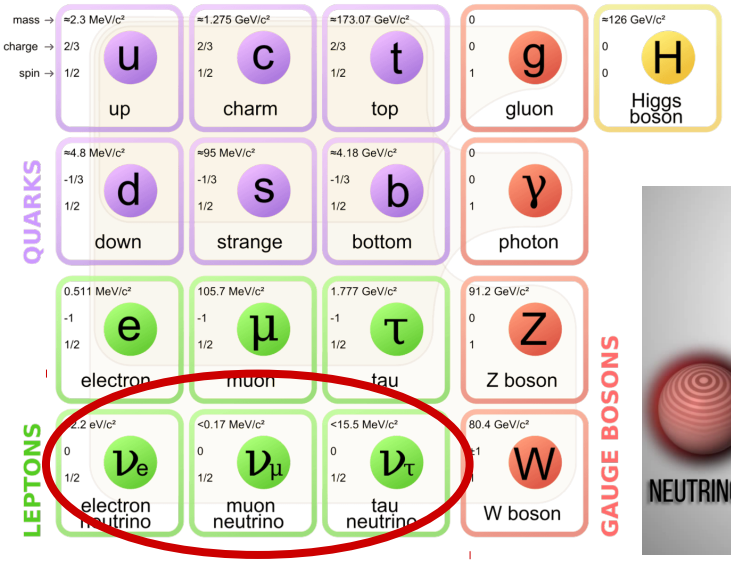

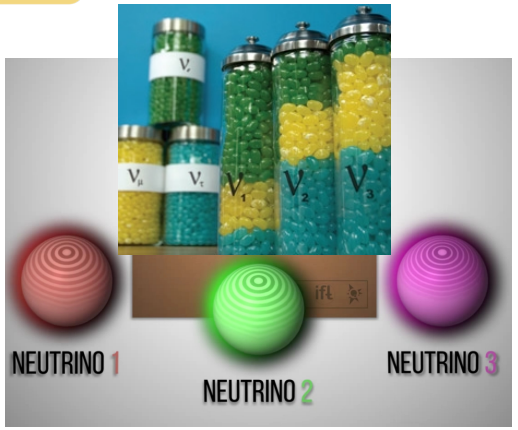

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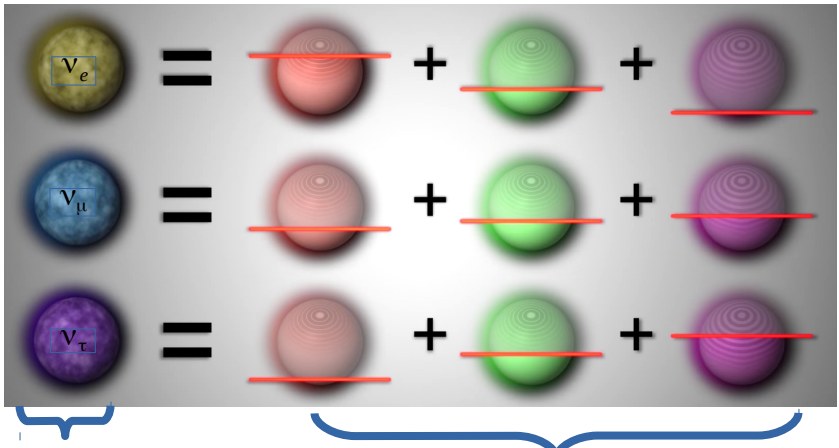

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- Dirac Phase
- P. Degeneracy

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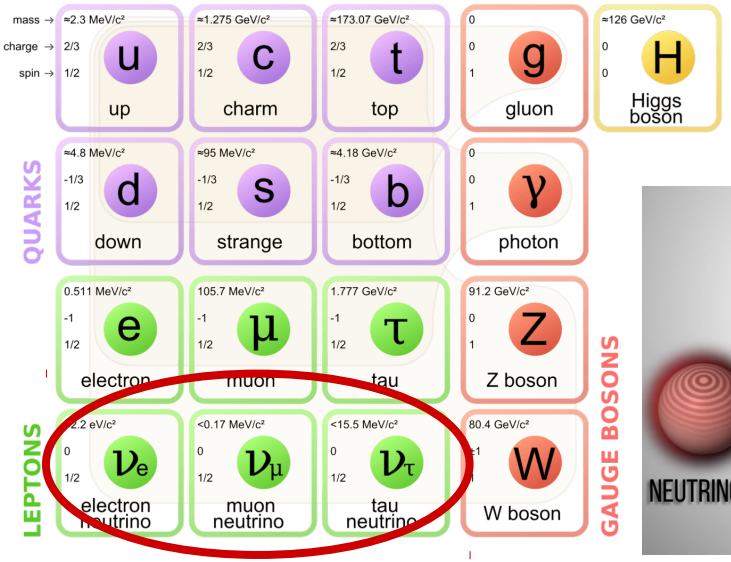

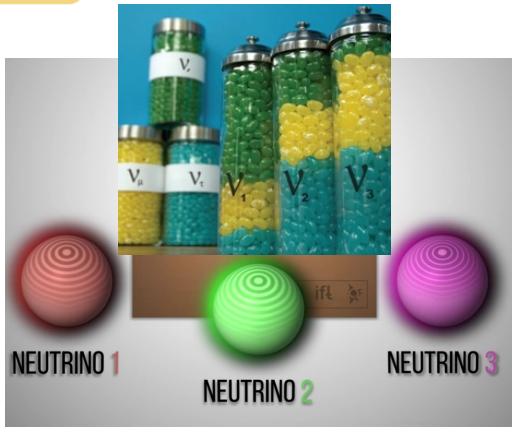

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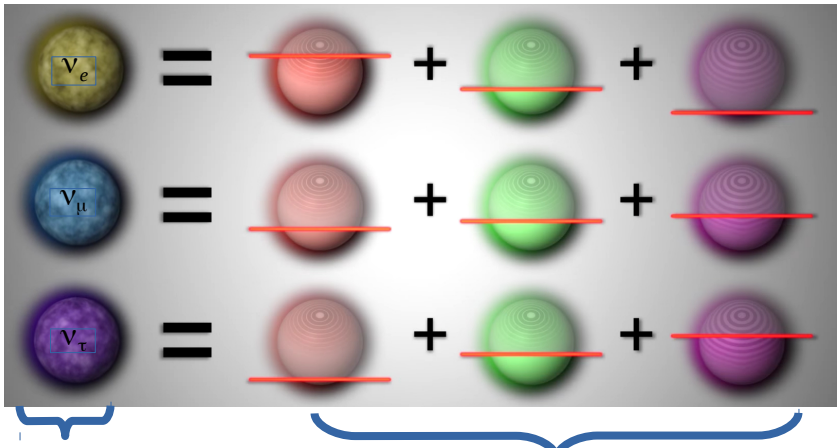

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- Neutrino Decay
- Non Standard Interaction
- Quantum Decoherence

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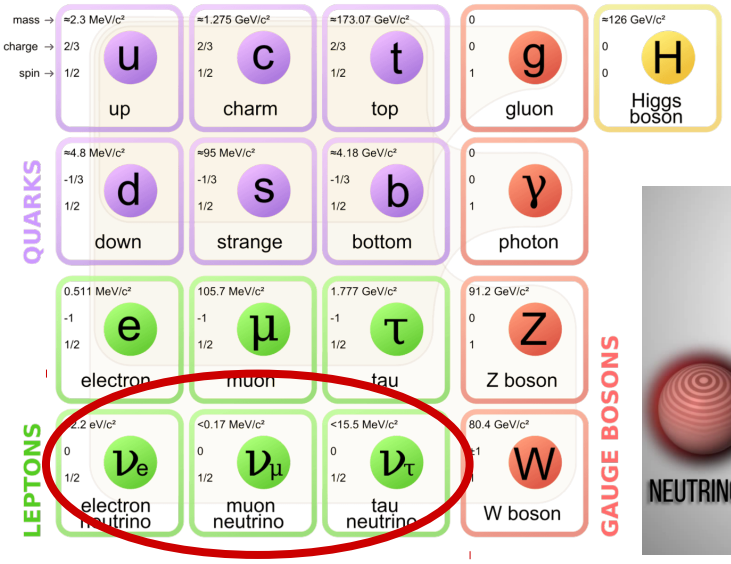

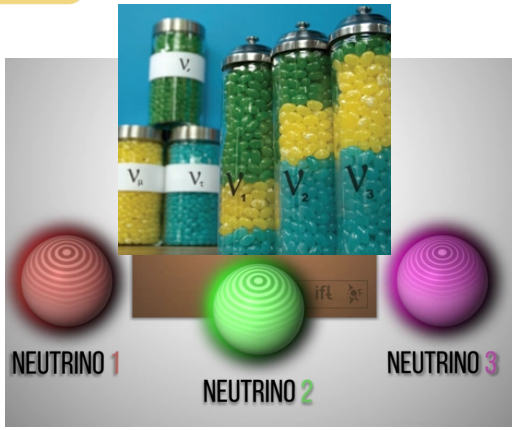

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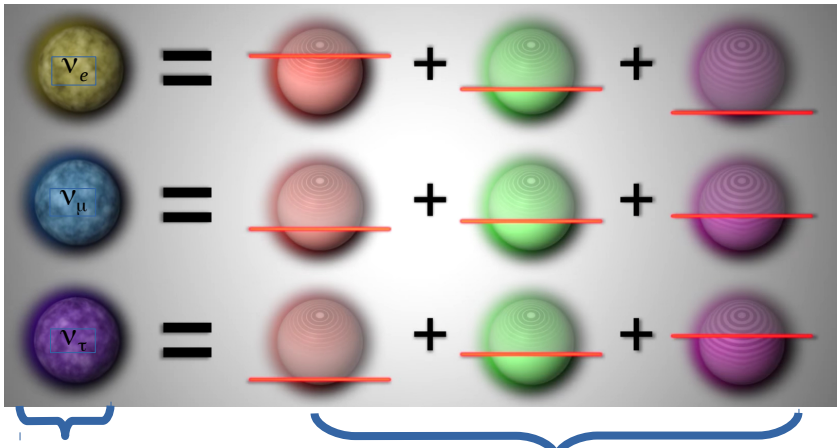

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DEEP UNDERGROUND NEUTRINO EXPERIMENT

- Neutrino Decay
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Introduction

On the other hand...

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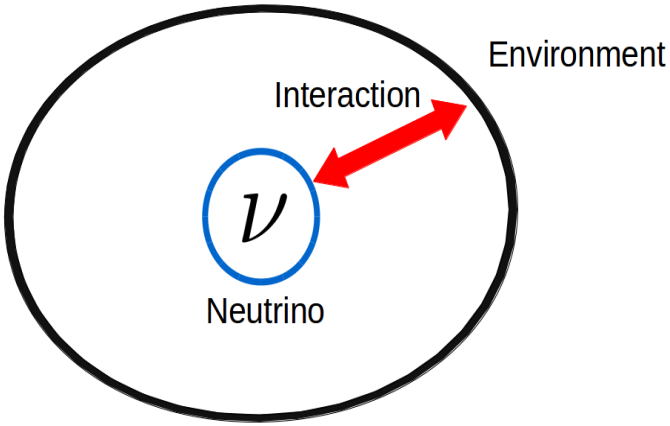
CPT symmetry and neutrino oscillation $P_{\nu_\alpha \to \nu_\beta} = P_{\bar{\nu}_\beta \to \bar{\nu}_\alpha}$

Quantum Decoherence

Quantum Decoherence

Considering the neutrino like an open quantum system.



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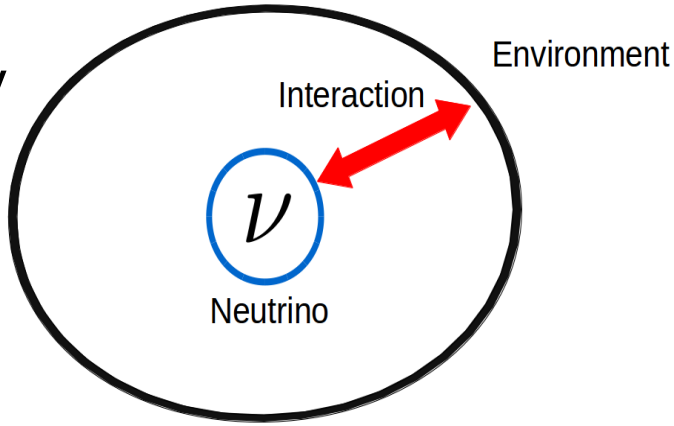
Considering the neutrino like an open quantum system.

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



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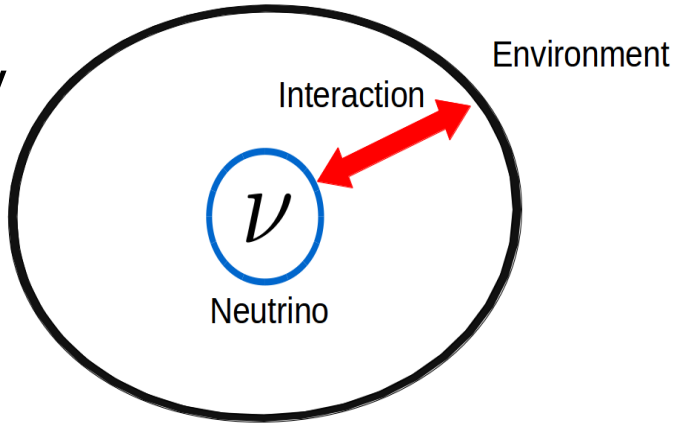

Assuming positivity, the most general expression for the dissipative term is:

$$\mathcal{D}[\hat{\rho}(t)] = \frac{1}{2}\sum_j \left([\hat{A}_j, \hat{\rho}(t)\hat{A}_j^\dagger] + [\hat{A}_j \hat{\rho}(t), \hat{A}_j^\dagger] \right)$$

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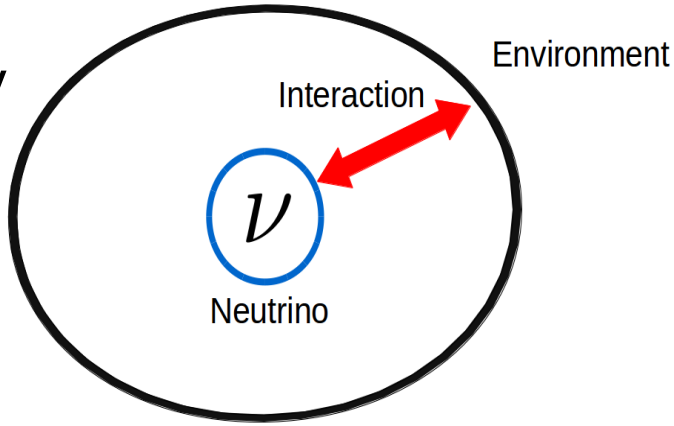

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Hermitian

For N neutrinos generations, $j = 1, 2 \ldots N^2 - 1$

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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 $M = H + D$

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

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

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

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

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

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

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

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

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

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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.

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

$$\mathcal{A}_{\mathrm{CPT}} = P_{\nu_\alpha \to \nu_\alpha} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}$$

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$$\mathcal{A}_{\mathrm{CPT}} = P_{\nu_\alpha \to \nu_\alpha} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\alpha}$$

- The diagonal elements of the dissipative matrix equal to Γ
- The same dissipative matrix for neutrinos and antineutrinos
- The dissipative matrix is containing a single one non-diagonal elements β_{ij} at a time.

Quantum Decoherence

The expression of the CPT asymmetry

$$\mathcal{A}_{\rm CPT} = 2\beta_{ij}\,\frac{\sin[\Omega_{\beta_{ij}}t]}{\Omega_{\beta_{ij}}}\,\rho_i^\alpha\,\rho_j^\alpha\;\; e^{-\Gamma t}$$

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

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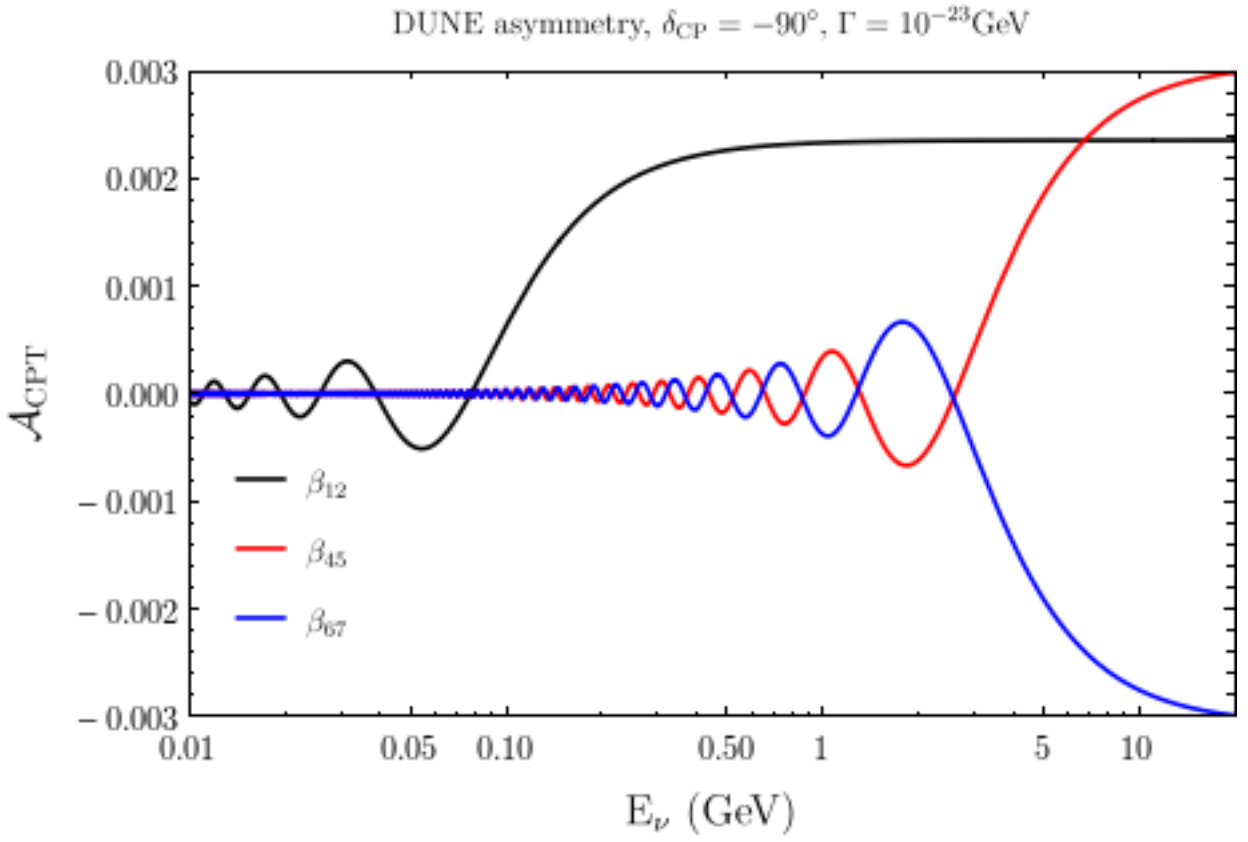
$\alpha = \mu$

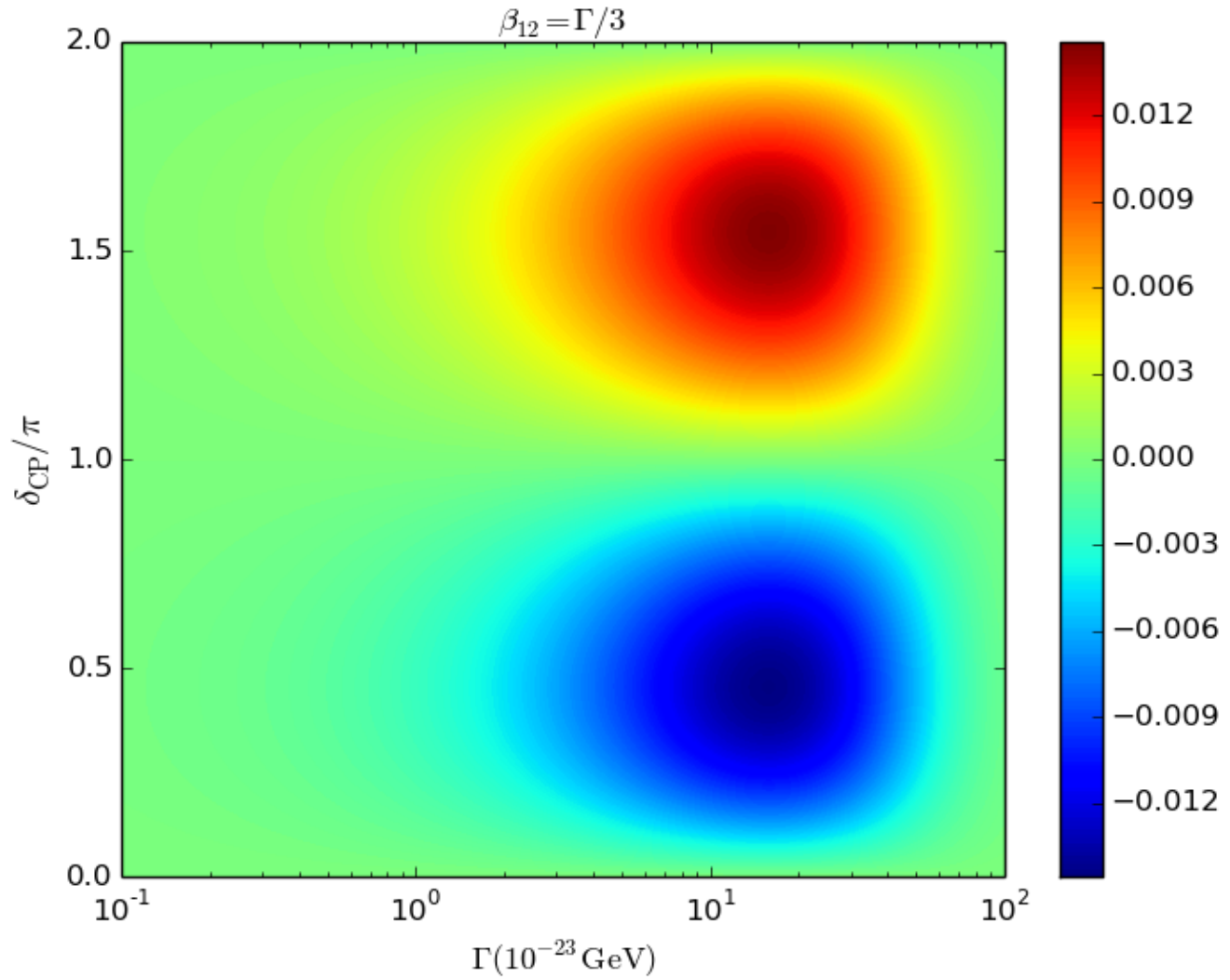
$L = 1300\text{Km}$

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



Quantum Decoherence

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



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For different energy dependence

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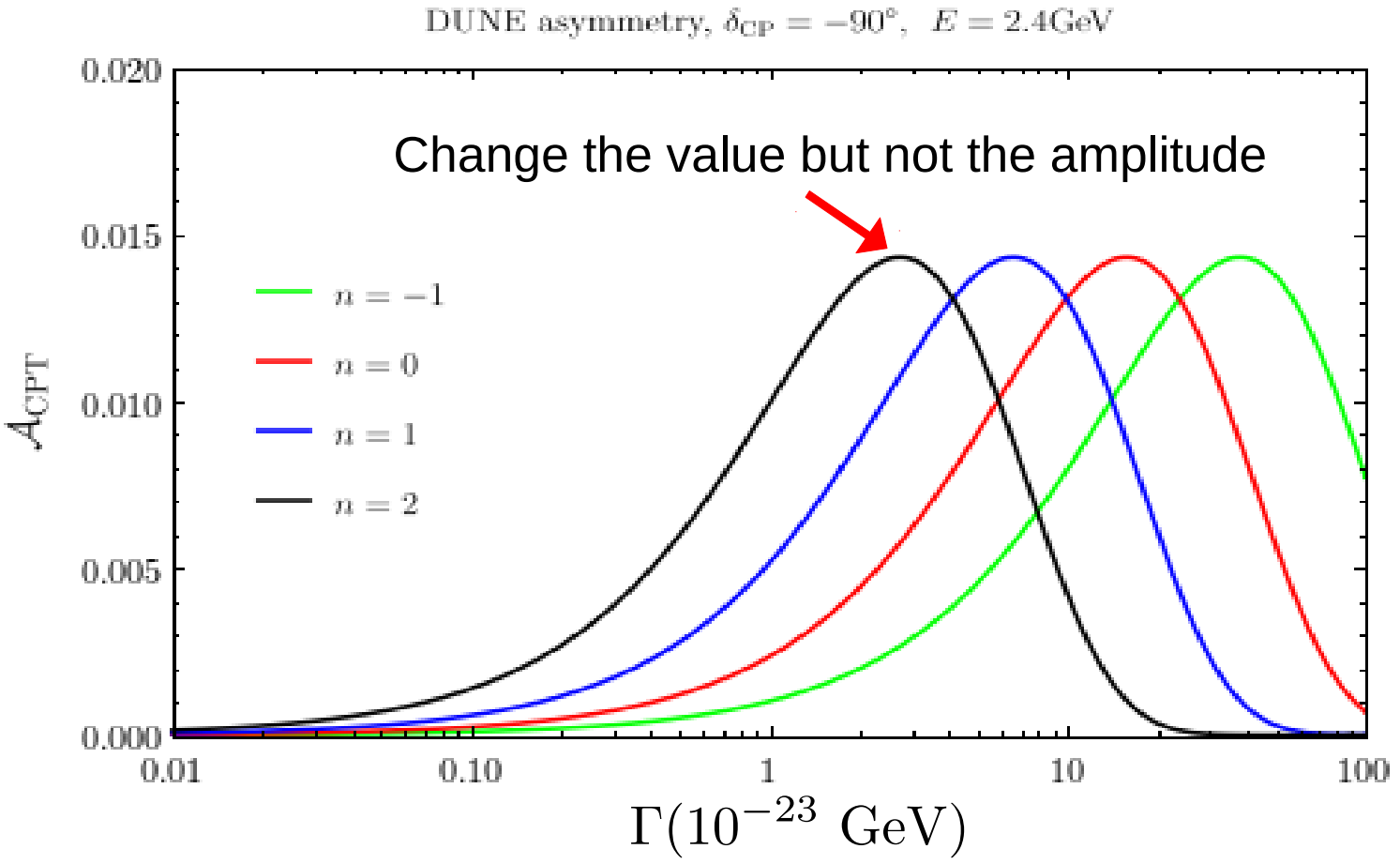

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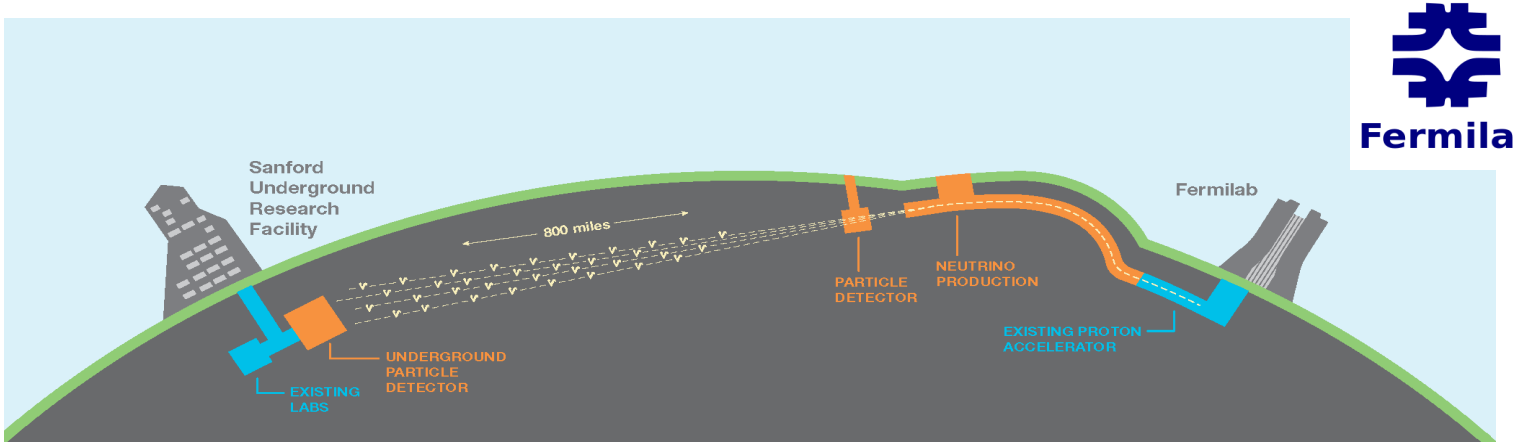

Fermilab

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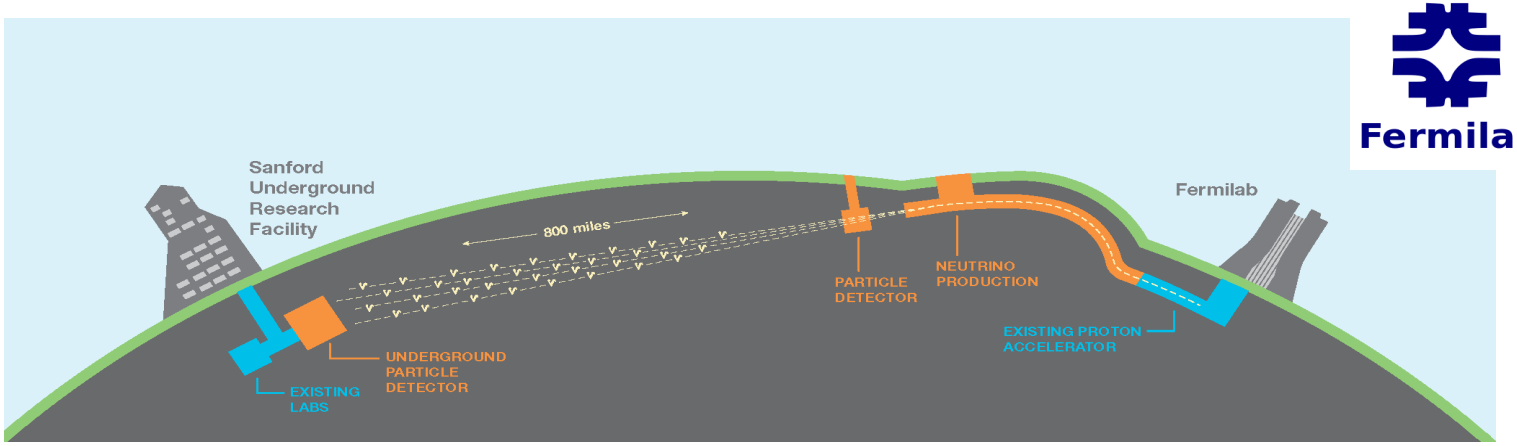

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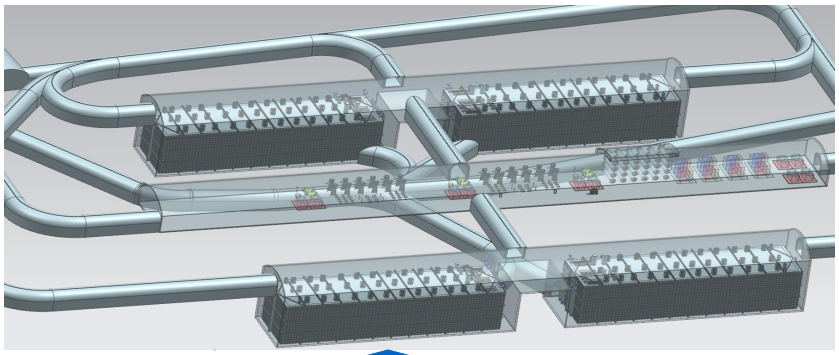
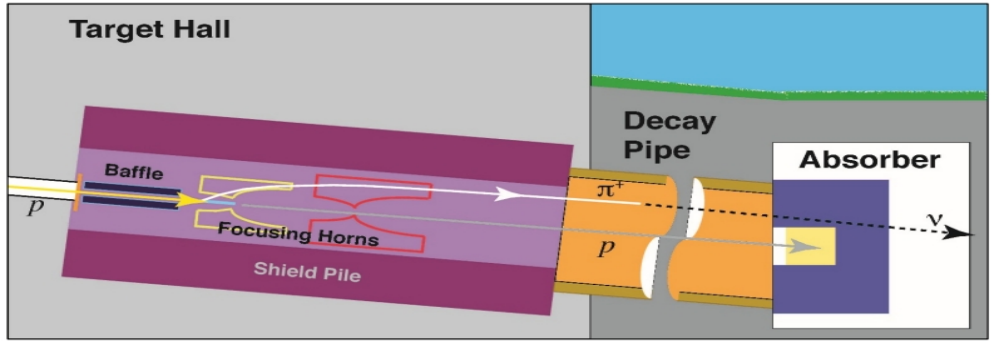
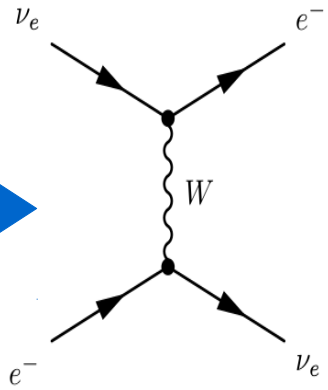


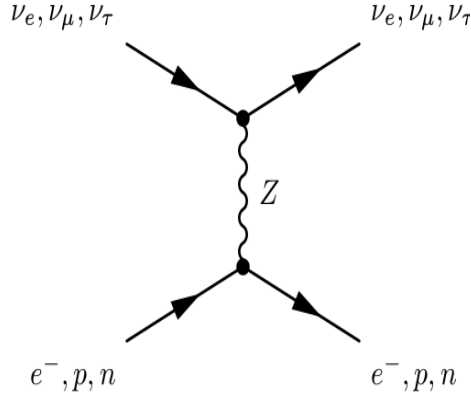
Liquid Argon

Beam



Interaction with matter





Ancillary files

Alion, T. and others - "Experiment Simulation Configurations Used in DUNE CDR"

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.

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

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.

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

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

$$\boxed{R = \frac{\Delta N^{\mathbf{std} \oplus \mathbf{deco}}}{\Delta N^{\mathbf{std}}}}$$

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

Preliminary Results

$$D_{\mu\nu} = \mathrm{diag}(\Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma, \Gamma)$$

$$\beta_{12} = \beta_{23} = \beta_{45} = \\ = -\beta_{67} = \Gamma/3$$

$$\beta_{47} = -\beta_{56} = \\ = (1/2\sqrt{3} - 1/6)\Gamma$$

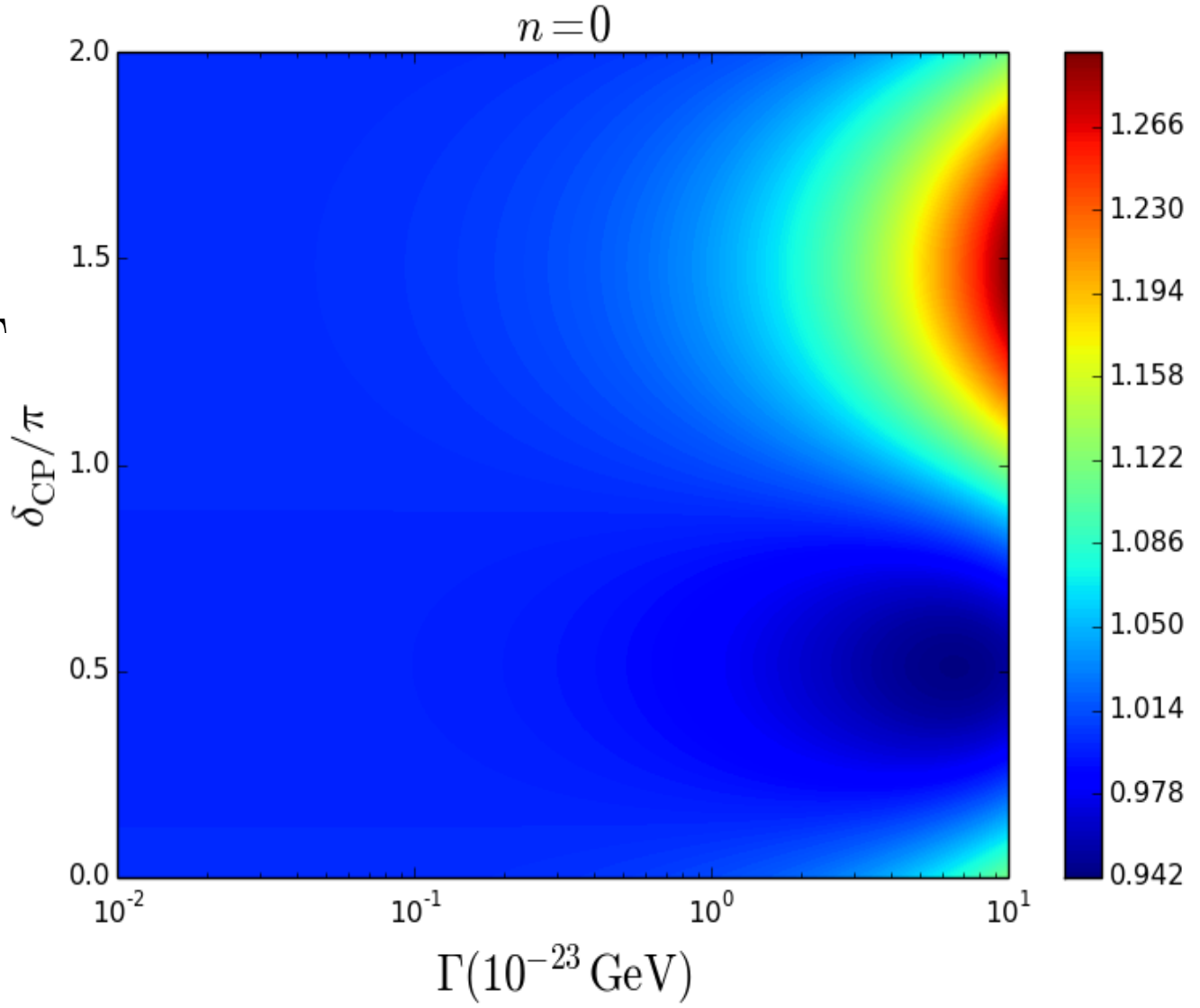
$$\beta_{28} = 1/\sqrt{3}$$

Energy range
$0.5 - 20\ \mathrm{GeV}$

5 years FHC

5 years RHC

Normal hierarchy



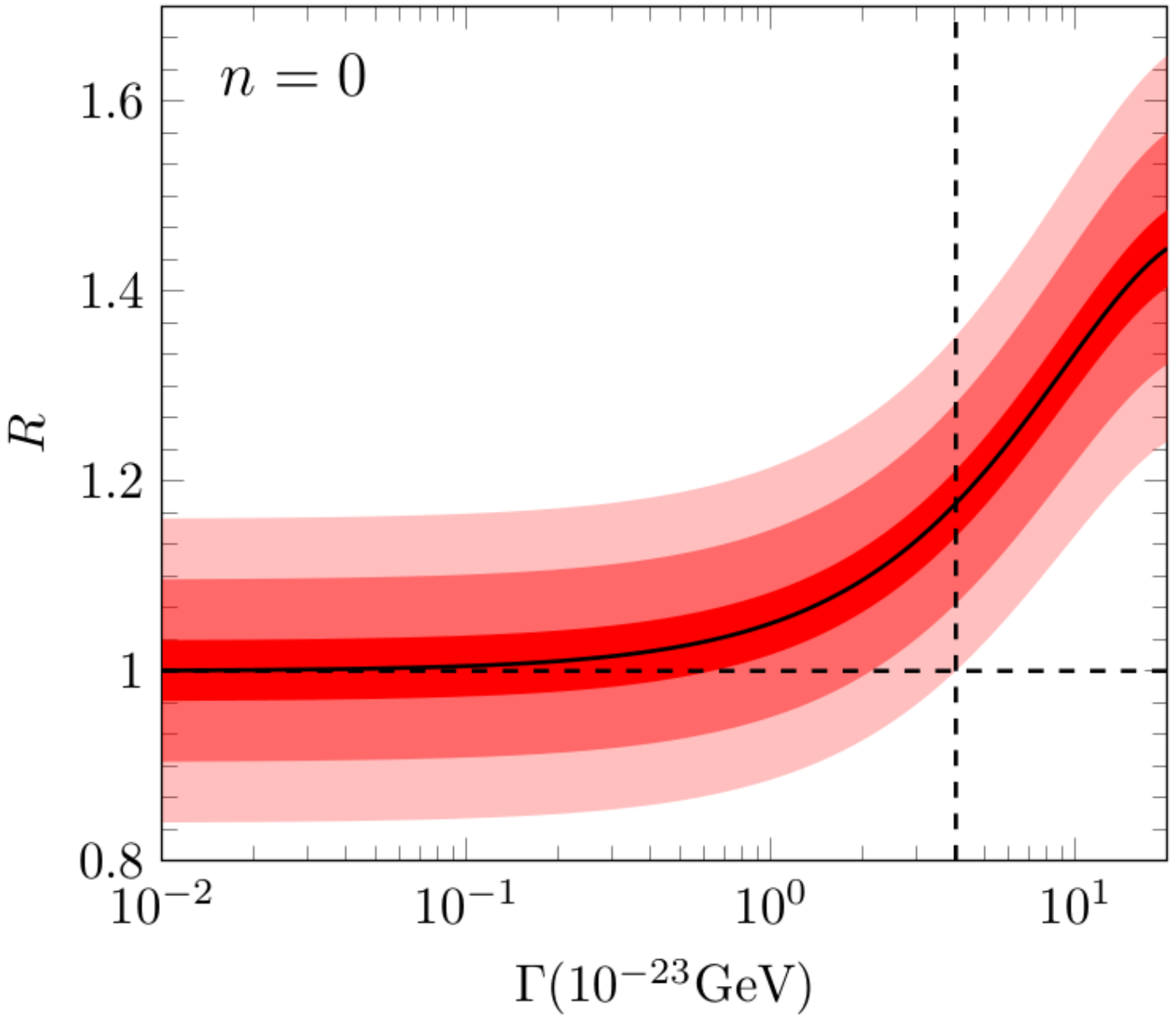
Preliminary Results

Energy range
$0.5 - 20$ GeV

5 years FHC

5 years RHC

Normal hierarchy
$\delta_{CP} \approx 3\pi/2$



Conclusions

- We revisit the theoretical framework for quantum decoherence phenomenon in the context of neutrino system.

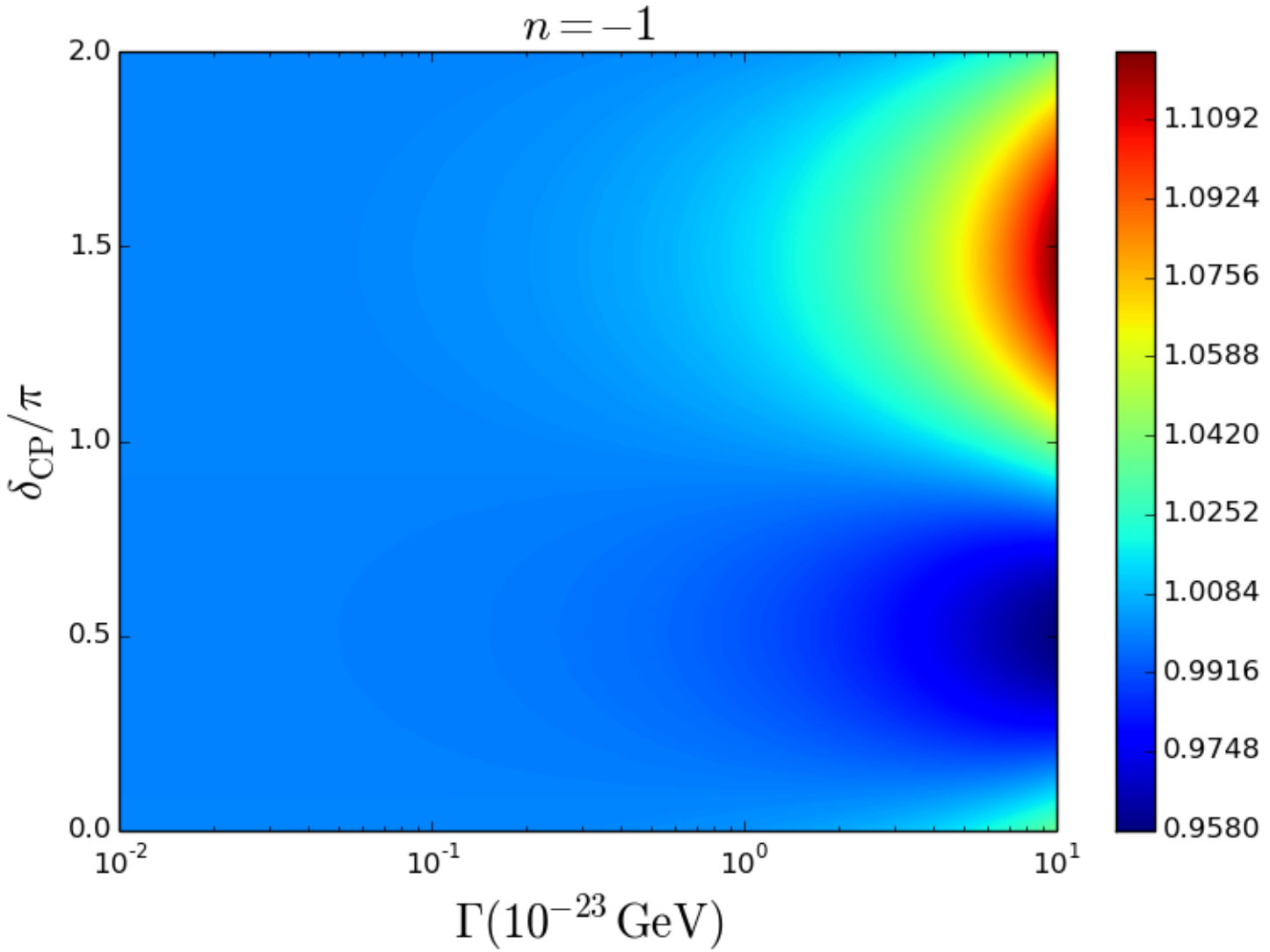
- In the 3-flavor framework, we identified 15 parameters of the decoherence matrix that produce a violation of the CPT symmetry.

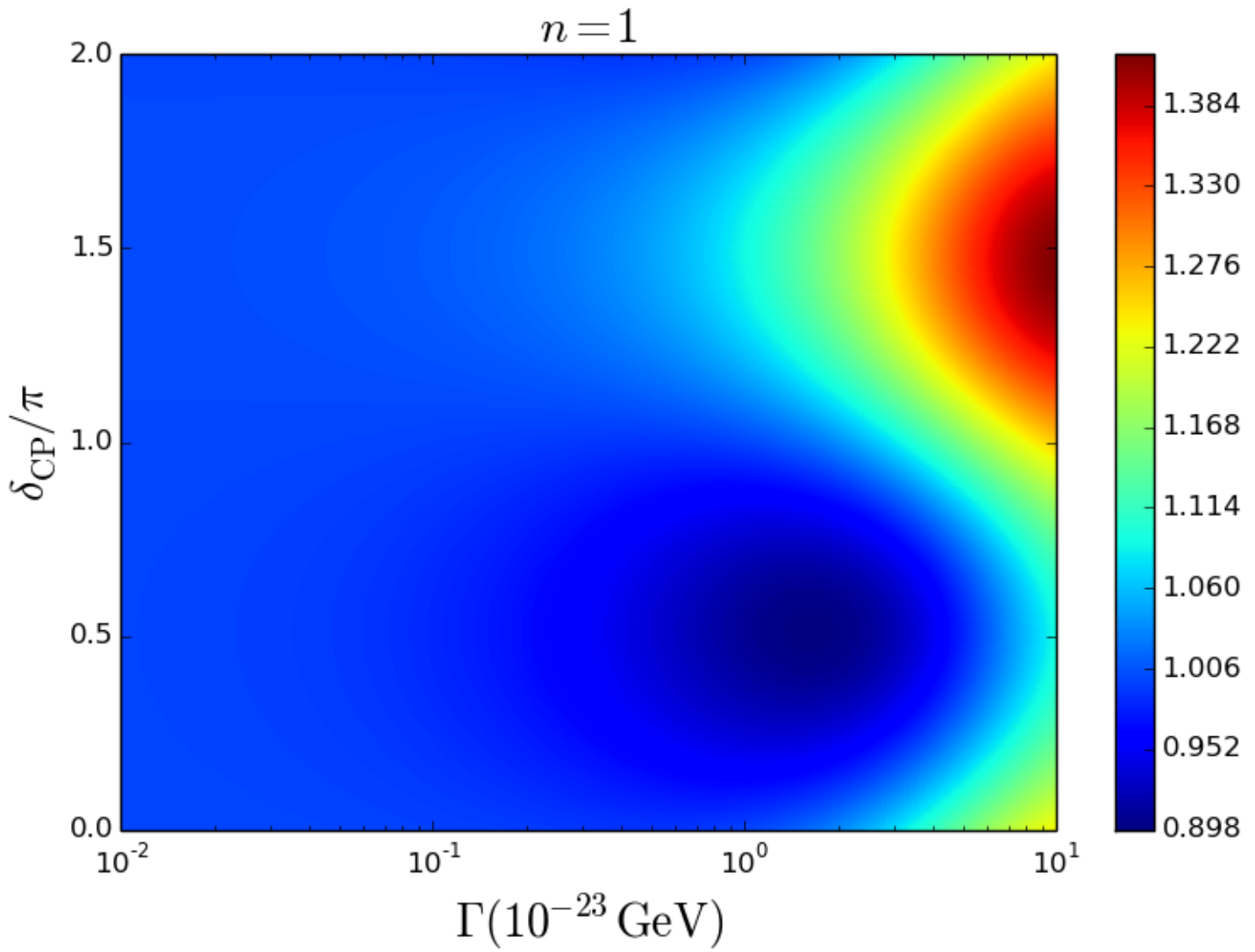
- We developed analitical expresions for the probability and the CPT asymmetry, in vacuum. We used the channels ν_μ and $\overline{\nu}_\mu$ dissapearance to analize the CPT asymmetry and its dependence of the decoherence parameter Γ , $\delta_{\rm CP}$ and the energy.

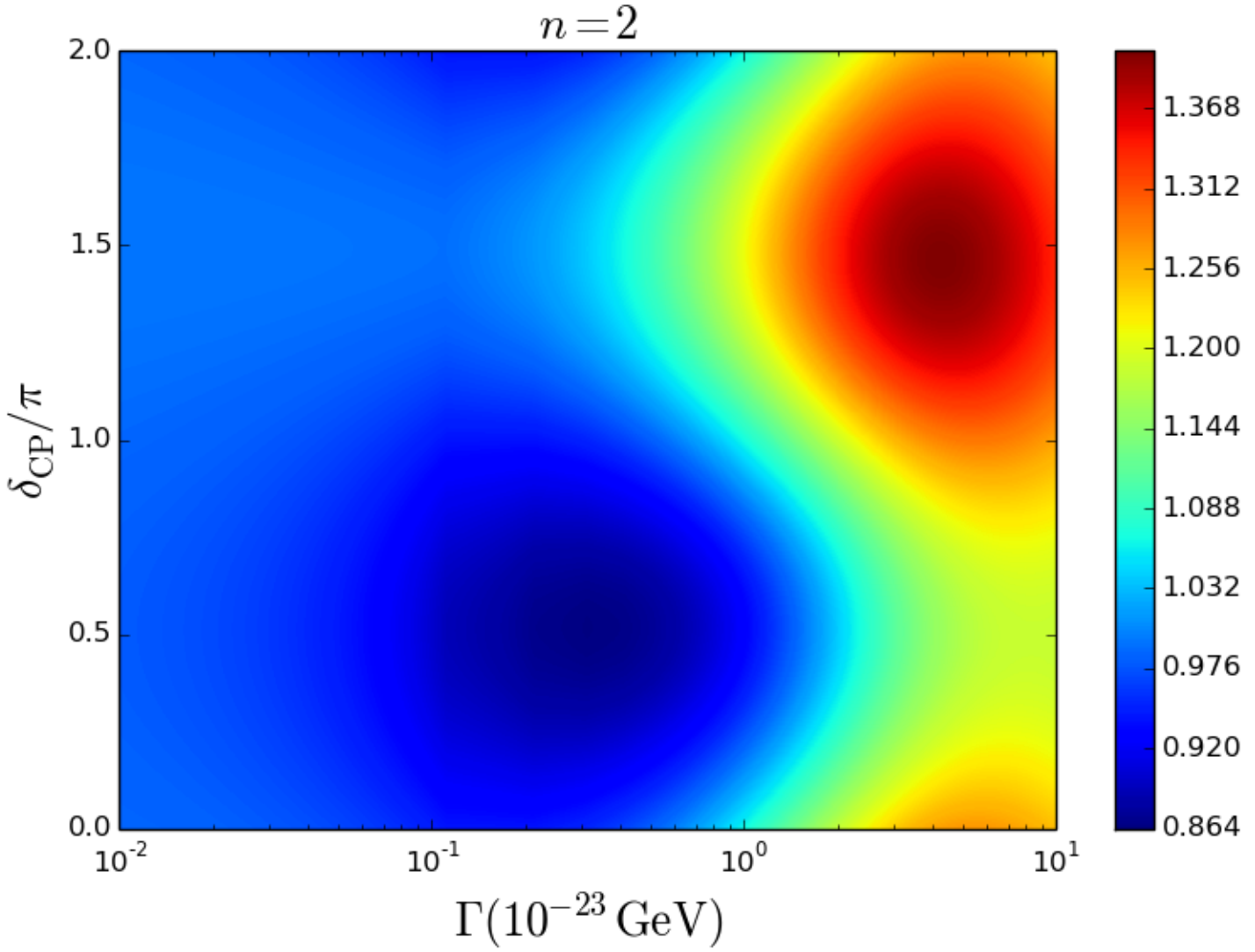
- We found a high impact in CPT asymmetry when we consider $\delta_{\rm CP} = 3\pi/2, \pi/2$ and normal hierarchy. In the context of DUNE, we found $5\ \sigma$ of confidence when $\Gamma(10^{-23}\ {\rm GeV}) \sim$ 12.1, 4, 1.7 and 0.7 for $n =$ -1, 0, 1 and 2 respectively.

THANK YOU VERY MUCH FOR YOUR ATTENTION

BACK UP


$n=-1$
2.0
1.5
1.0
0.5
0.0
$\delta_{\rm CP}/\pi$
10^{-2}
10^{-1}
10^{0}
10^{1}
$\Gamma(10^{-23}\,{\rm GeV})$
1.1092
1.0924
1.0756
1.0588
1.0420
1.0252
1.0084
0.9916
0.9748
0.9580


$n=1$
2.0
1.5
1.0
0.5
0.0
$\delta_{\rm CP}/\pi$
10^{-2}
10^{-1}
10^{0}
10^{1}
$\Gamma(10^{-23}\,{\rm GeV})$
1.384
1.330
1.276
1.222
1.168
1.114
1.060
1.006
0.952
0.898

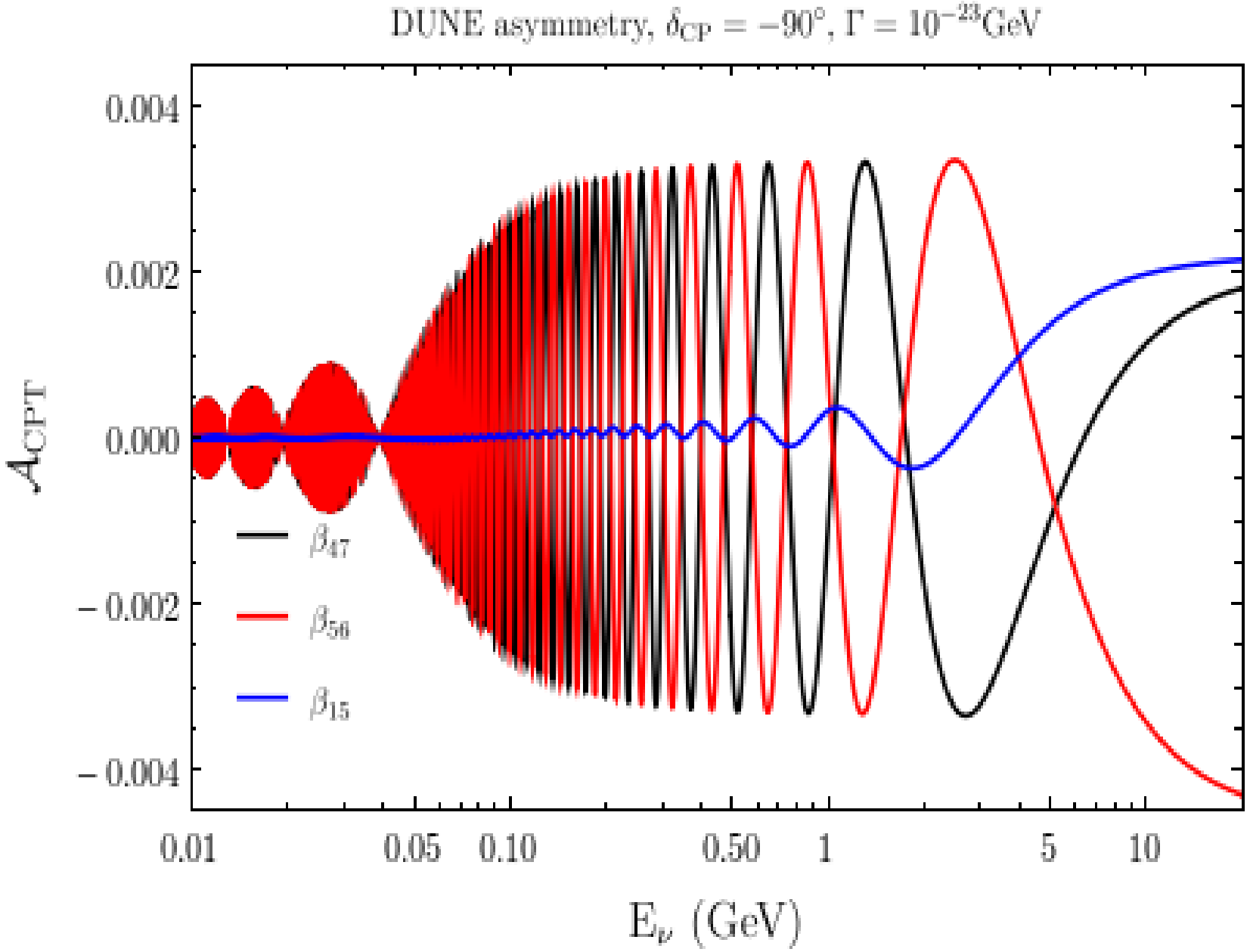

$n=2$
2.0
1.5
1.0
0.5
0.0
$\delta_{\rm CP}/\pi$
10^{-2}
10^{-1}
10^{0}
10^{1}
$\Gamma(10^{-23}\,{\rm GeV})$
1.368
1.312
1.256
1.200
1.144
1.088
1.032
0.976
0.920
0.864

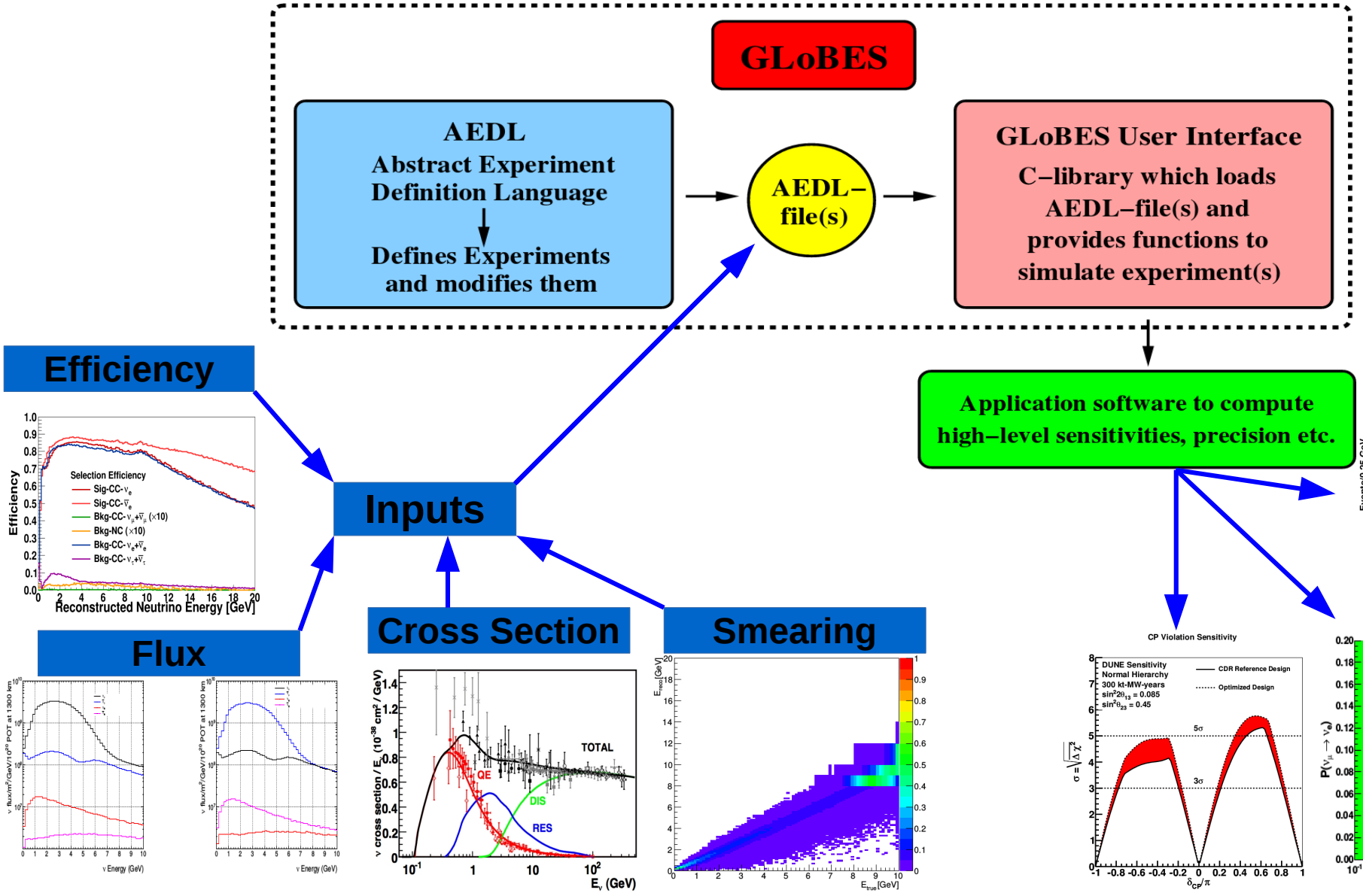
$$D_{\mu\nu} = \text{diag}(\Gamma,\Gamma,\Gamma,\Gamma,\Gamma,\Gamma,\Gamma,\Gamma) \quad \beta_{12} = \beta_{23} = \beta_{45} = -\beta_{67} = \Gamma/3$$
$$\beta_{47} = -\beta_{56} = (1/2\sqrt{3} - 1/6)\Gamma \quad \beta_{28} = 1/\sqrt{3}$$

5 years FHC

Energy range $0.5 - 20$ GeV $\delta_{CP} \approx 3\pi/2$ Normal hierarchy 5 years RHC

	Standard	$\Gamma = 10^{-23}$GeV	$\Gamma = 2 \times 10^{-23}$GeV	$\Gamma = 10^{-22}$GeV
Neutrino mode				
ν_μ Signal	11025	11260	11484	12876
$\overline{\nu}_\mu$ CC Background	724	699	677	562
NC Background	109	109	109	109
$\nu_\tau + \overline{\nu}_\tau$ CC Background	43	46	48	62
Antineutrino mode				
$\overline{\nu}_\mu$ Signal	3755	3758	3767	3967
ν_μ CC Background	2149	2112	2078	1876
NC Background	58	58	58	58
$\nu_\tau + \overline{\nu}_\tau$ CC Background	27	29	31	42


DUNE asymmetry, $\delta_{CP} = -90°$, $\Gamma = 10^{-23}$GeV
0.004
0.002
0.000
− 0.002
− 0.004
A_{CPT}
β_{47}
β_{56}
β_{15}
0.01
0.05
0.10
0.50
1
5
10
E_ν (GeV)


GLoBES
AEDL
Abstract Experiment
Definition Language
Defines Experiments
and modifies them
AEDL–
file(s)
GLoBES User Interface
C–library which loads
AEDL–file(s) and
provides functions to
simulate experiment(s)
Efficiency
Inputs
Flux
Cross Section
Smearing
Application software to compute
high–level sensitivities, precision etc.
Selection Efficiency
Sig-CC-ν_e
Sig-CC-$\bar{\nu}_e$
Bkg-CC-$\nu_\mu+\bar{\nu}_\mu$ (×10)
Bkg-NC (×10)
Bkg-CC-$\nu_e+\bar{\nu}_e$
Bkg-CC-$\nu_\tau+\bar{\nu}_\tau$
Efficiency
Reconstructed Neutrino Energy [GeV]
TOTAL
QE
DIS
RES
ν cross section / E_ν (10^{-38} cm^2 / GeV)
E_ν (GeV)
E_{reco} [GeV]
E_{true} [GeV]
DUNE ν_e Appearance
Our Reproduction
DUNE ν_e Appearance
150 kt-MW-yr ν mode
Normal MH, δ_{CP}=0
$\sin^2(\theta_{23})$=0.45
Signal (ν_e→ν_e) CC
Beam (ν_μ→ν_e) CC
Optimized Design
CDR Reference Design
Events/0.25 GeV
Reconstructed Energy (GeV)
CP Violation Sensitivity
DUNE Sensitivity
Normal Hierarchy
300 kt-MW-years
$\sin^2 2\theta_{13}$ = 0.085
$\sin^2\theta_{23}$ = 0.45
CDR Reference Design
Optimized Design
5σ
3σ
$\sigma = \sqrt{\Delta\chi^2}$
δ_{CP}/π
1300 km
Normal MH
δ_{CP} = -π/2
δ_{CP} = 0
δ_{CP} = +π/2
θ_{13} = 0 (solar term)
$P(\nu_\mu \rightarrow \nu_e)$
Neutrino Energy (GeV)