PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

SILAFAE 2018

Visible neutrino decay and matter effects at future long-base line experiments

Anthony Calatayud

Based on EPJC 78:809

In collaboration with:
M. V. Ascencio Sosa, A. M. C. C., A. M. Gago, J. Jones Pérez

Pontificia Universidad Católica del Perú

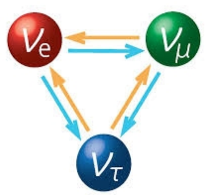
High Energy Group – PUCP

Lima - November 2018

XII Latin American Symposium of High Energy Physics (SILAFAE)

Introduction

Beyond Standard Model:



Standard Nuetrino Oscillation (vacuum and matter) ⟷ Neutrino Decay (invisible and visible)

Majoron Model:

Scalar — Pseudo-scalar

$$\mathcal{L}_{\text{int}} = \frac{(g_s)_{ij}}{2}\bar{\nu}_i \nu_j J + i\frac{(g_p)_{ij}}{2}\bar{\nu}_i \gamma_5 \nu_j J$$

There are two modes:

$$\nu_i \rightarrow \nu_j + J$$

or

$$\nu_i \rightarrow \bar{\nu}_j + J$$

If the neutrino resulting from decay is sterile we have **invisible decay**, but if the resulting neutrino is active we have **visible decay**.

PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

SILAFAE 2018

Neutrino oscillation including effects of matter and decay

Hamiltonian:

$$H = \frac{1}{2E} U_0 \begin{pmatrix} m_1^2 & & \\ & m_2^2 - i\,\alpha_2 & \\ & & m_3^3 - i\,\alpha_3 \end{pmatrix} U_0^\dagger + \begin{pmatrix} \sqrt{2} G_F N_e & & \\ & 0 & \\ & & 0 \end{pmatrix}$$

Decay parameter → $\alpha_i = E\,\Gamma_i$ ← Decay width

Decay parameteres are define in the mass basis.

Diagonalize H: $\tilde{U}^{-1} H\, \tilde{U} = H^{\text{diag}}$

Where $\tilde{U}_{\alpha I}$ combines the basis of interaction and matter.

$\tilde{U}_{\alpha I}$ {
- Interaction (flavor, $\alpha = e, \mu, \tau$)
- Matter $\bigoplus$ decay (where the effective Hamiltonian is diagonal, $\mathrm{I} = \tilde{1}, \tilde{2}, \tilde{3}$)

PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

SILAFAE 2018

Neutrino oscillation including effects of matter and decay

Hamiltonian eigenvalues: $\tilde{m}_I^2 - i\,\tilde{\alpha}_I = 2E\,(H^{\text{diag}})_{II}$

If $\alpha_3 \neq 0$ → $\tilde{\alpha}_1, \tilde{\alpha}_2$ are not necessarily zero, $\tilde{\alpha}_3$ as well.

Probability function:

Invisible Decay Probability (ID)

$$P_{\text{dec}}\left(\nu_\alpha^{(r)} \to \nu_\beta^{(s)}\right) = \left|\sum_{I=1}^{3} \left(\tilde{U}^{(r)}\right)^{-1}_{I\alpha} \exp\left[-i\frac{\tilde{m}_I^2 L}{2E_\alpha}\right] \exp\left[-\frac{\tilde{\alpha}_I L}{2E_\alpha}\right] \tilde{U}^{(s)}_{\beta I}\right|^2 \delta_{rs}\,\delta(E_\alpha - E_\beta) + P_{\text{vis}}(E_\alpha,\, E_\beta)$$

Energy Conservation

Helicity Conservation

Visible Decay Probability (VD)

Flux in the far detector:

$$\frac{d\Phi_\beta^{(s)}}{dE_\beta} = \int P_{\text{dec}}\left(\nu_\alpha^{(r)} \to \nu_\beta^{(s)}\right) \frac{d\Phi_\alpha^{(r)}}{dE_\alpha} dE_\alpha$$

Helicity: $r, s = (+, -)$

PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

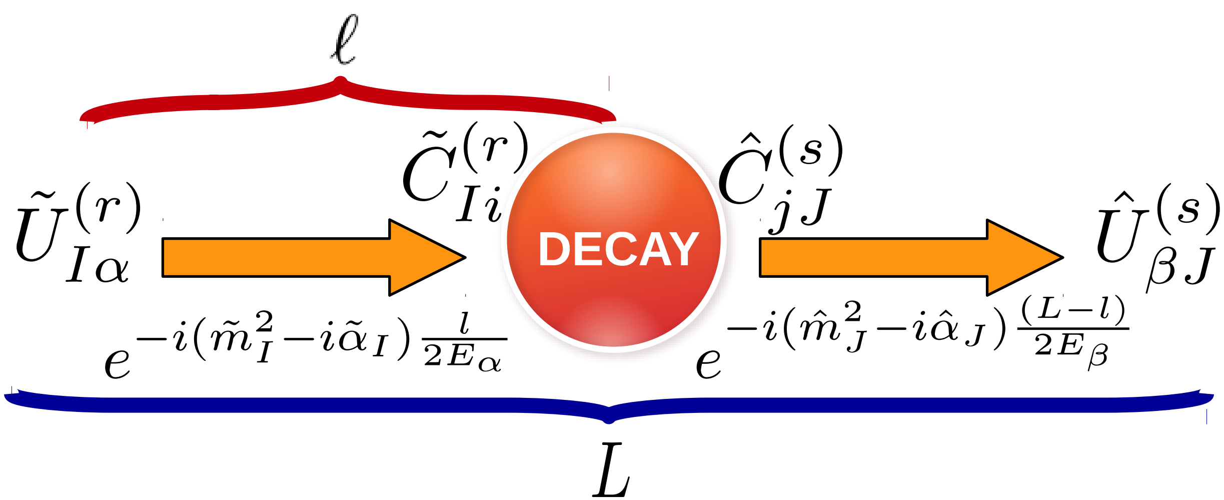
SILAFAE 2018

Neutrino oscillation including effects of matter and decay

Visible Decay Probability:

$$P_{\rm vis}(E_\alpha, E_\beta) = \int d\ell \left| \sum_{I=\tilde{1}}^{\tilde{3}} \left(\tilde{U}^{(r)}\right)^{-1}_{I\alpha} \exp\left[-i\frac{\tilde{m}_I^2\,\ell}{2E_\alpha}\right] \exp\left[-\frac{\tilde{\alpha}_I\,\ell}{2E_\alpha}\right] \sum_{i=2}^{3}\sum_{j=1}^{i-1} \tilde{C}^{(r)}_{Ii} \sqrt{\frac{d}{dE_\beta}\Gamma_{\nu_i^r\to\nu_j^s}(E_\alpha)} \right.$$

$$\left. \times \sum_{J=\hat{1}}^{\hat{3}} \left(\hat{C}^{(s)}\right)^{-1}_{jJ} \exp\left[-i\frac{\hat{m}_J^2(L-\ell)}{2E_\beta}\right] \exp\left[-\frac{\hat{\alpha}_J(L-\ell)}{2E_\beta}\right] \hat{U}^{(s)}_{\beta J} \right|^2$$



Where:

- Before decay

$$\tilde{C}^{(r)}_{Ii} = \sum_{\rho=e,\mu,\tau} \tilde{U}^{(r)}_{\rho I} (U_0)^{(r)*}_{\rho i}$$

- After decay

$$\hat{C}^{(s)}_{jJ} = \sum_{\rho=e,\mu,\tau} \hat{U}^{(s)}_{\rho J} (U_0)^{(s)*}_{\rho j}$$

A. M. Gago, R. A. Gomes, A. L. G. Gomes, et al., JHEP **11**, 022 (2017), 1705.03074

PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

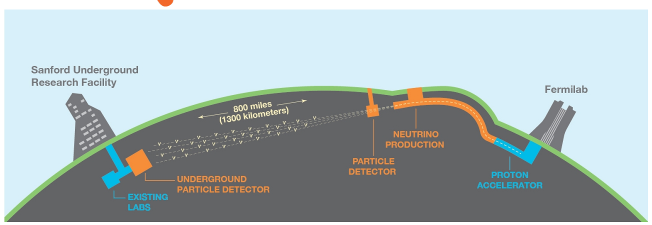
SILAFAE 2018

Setting and parameters values

Long base-line experiments:

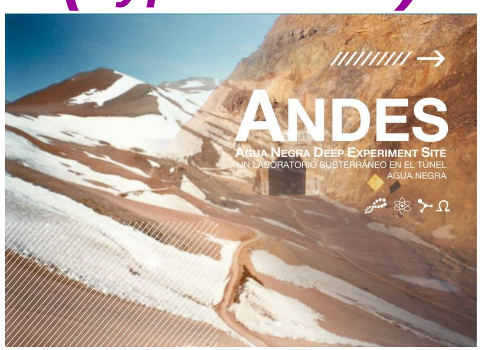
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Baseline: 1300 km
Matter density: 2.96 g/cm³



(hypothetical)

Baseline: 7650 km
Matter density: 4.7 g/cm³



Power: 1.47 MW (Main Injector)
Far Detector: (LArTPC), 40kt
POT: 1.1 x 10^{21}
Mode: Forward Horn Current – FHC (ν)
Reverse Horn Current – RHC $(\bar{\nu})$
Time: 3.5 years in each mode (7 years in total)

Parameter	Value	Parameter	Value
$\theta_{12}/^\circ$	33.56	$\delta_{CP}/^\circ$	-90
$\theta_{23}/^\circ$	41.6	$\frac{\Delta m^2_{12}}{10^{-5}\mathrm{eV}^2}$	7.50
$\theta_{13}/^\circ$	8.46	$\frac{\Delta m^2_{13}}{10^{-3}\mathrm{eV}^2}$	2.524

JHEP 01 (2017) 087 [arXiv:1611.01514]

Flux x Cross Section:

$$(\Phi \times \sigma)_\beta \equiv \sum_s \sigma_\beta^{s,\,\mathrm{CC}}(E_\beta)\frac{d\Phi_\beta^{(s)}}{dE_\beta}$$

Define:

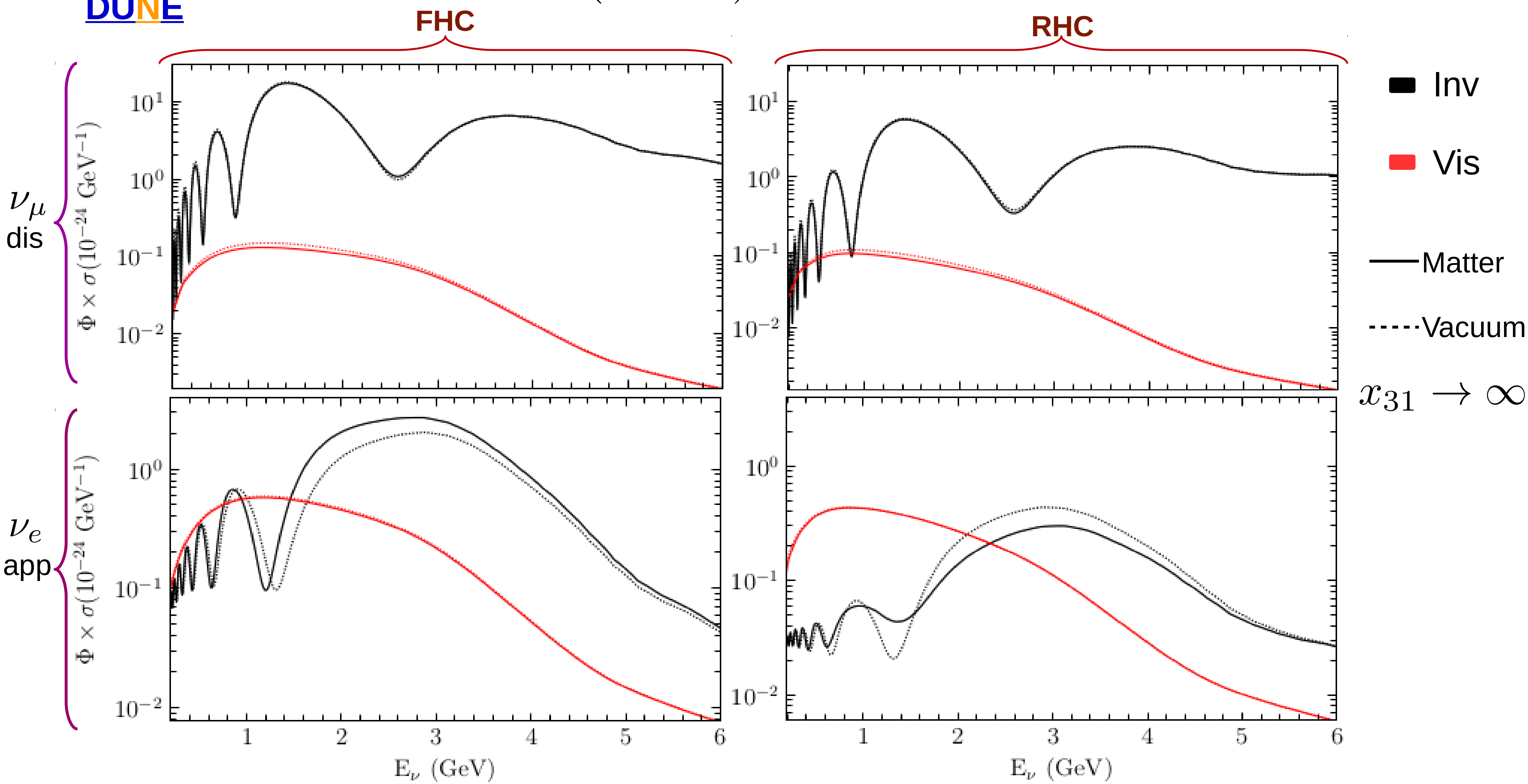
$$x_{31} = \frac{m_3}{m_1} = \frac{m_3}{m_{lightest}}$$

then,

- If $m_1 = 0.07$ eV: $x_{31} \to 1$
- If $m_1 \to 0$ eV: $x_{31} \to \infty$

Impact on $(\Phi \times \sigma)$ at DUNE and ANDES

DUNE

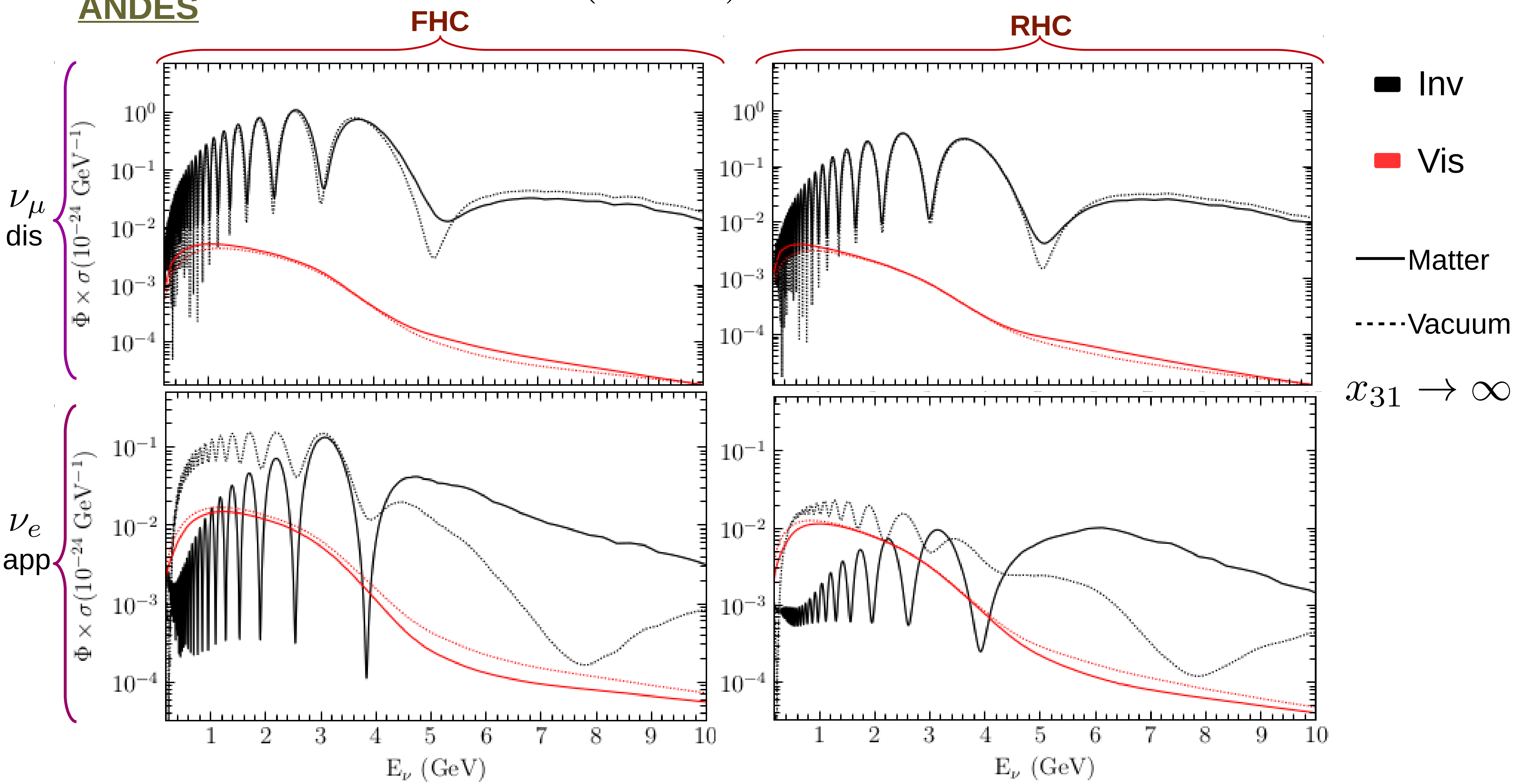


$\delta_{CP} = -90°, \alpha_3 = 4 \times 10^{-5} \mathrm{eV}^2$

SILAFAE 2018

Impact on $(\Phi \times \sigma)$ at DUNE and ANDES

ANDES

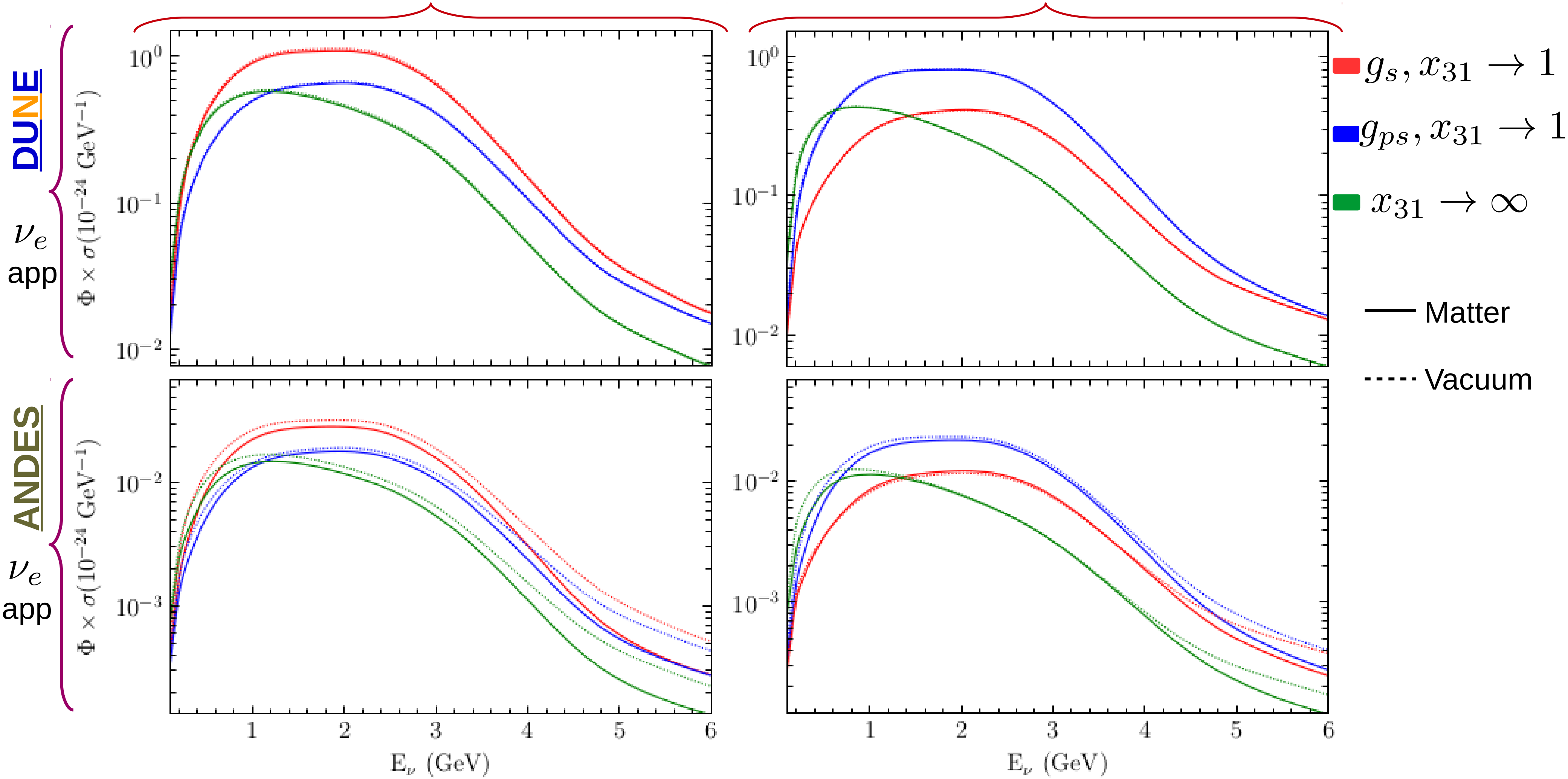


$\delta_{CP} = -90°, \alpha_3 = 8 \times 10^{-6} \mathrm{eV}^2$

SILAFAE 2018

Impact on $(\Phi \times \sigma)$ at DUNE and ANDES

Visible Decay



Sensitivity and Parameter Fits at DUNE

Chi-square definition

$$\chi^2(\theta_{23},\, \delta_{\rm CP},\, \alpha_3,\, \theta_{23}^{\rm true},\, \delta_{\rm CP}^{\rm true},\, \alpha_3^{\rm true}) = \sum_i^{\rm bins} \frac{\left(N_i\left(\theta_{23}, \delta_{\rm CP}, \alpha_3\right) - N_i\left(\theta_{23}^{\rm true}, \delta_{\rm CP}^{\rm true}, \alpha_3^{\rm true}\right)\right)^2}{N_i\left(\theta_{23}^{\rm true}, \delta_{\rm CP}^{\rm true}, \alpha_3^{\rm true}\right)}$$

Sensitivity of α_3, we make $\theta_{23} = \theta_{23}^{\rm true},\ \delta_{CP} = \delta_{CP}^{\rm true}$ and $\alpha_3^{\rm true} = 0\ {\rm eV}^2$.

Marginalization:

$$\chi^2(\theta_{23}^{\rm true},\, \delta_{\rm CP}^{\rm true},\, \alpha_3,\, \theta_{23}^{\rm true},\, \delta_{\rm CP}^{\rm true},\, 0)\Big|_{\min \delta_{\rm CP}^{\rm true}}$$

and

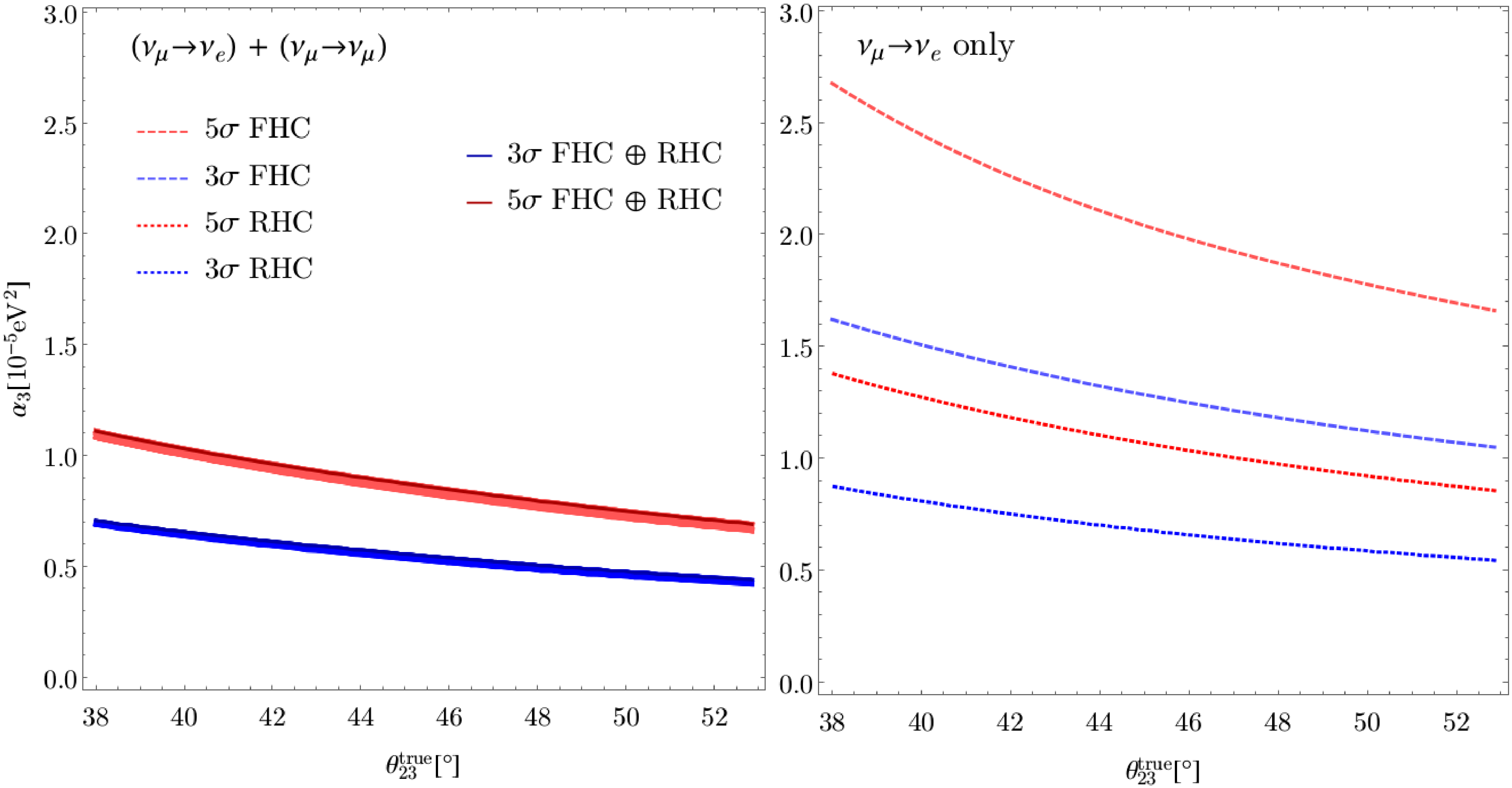
$$\chi^2(\theta_{23}^{\rm true},\, \delta_{\rm CP}^{\rm true},\, \alpha_3,\, \theta_{23}^{\rm true},\, \delta_{\rm CP}^{\rm true},\, 0)\Big|_{\min \theta_{23}^{\rm true}}$$

PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

Sensitivity and Parameter Fits at DUNE

SILAFAE 2018

Sensivity Plots

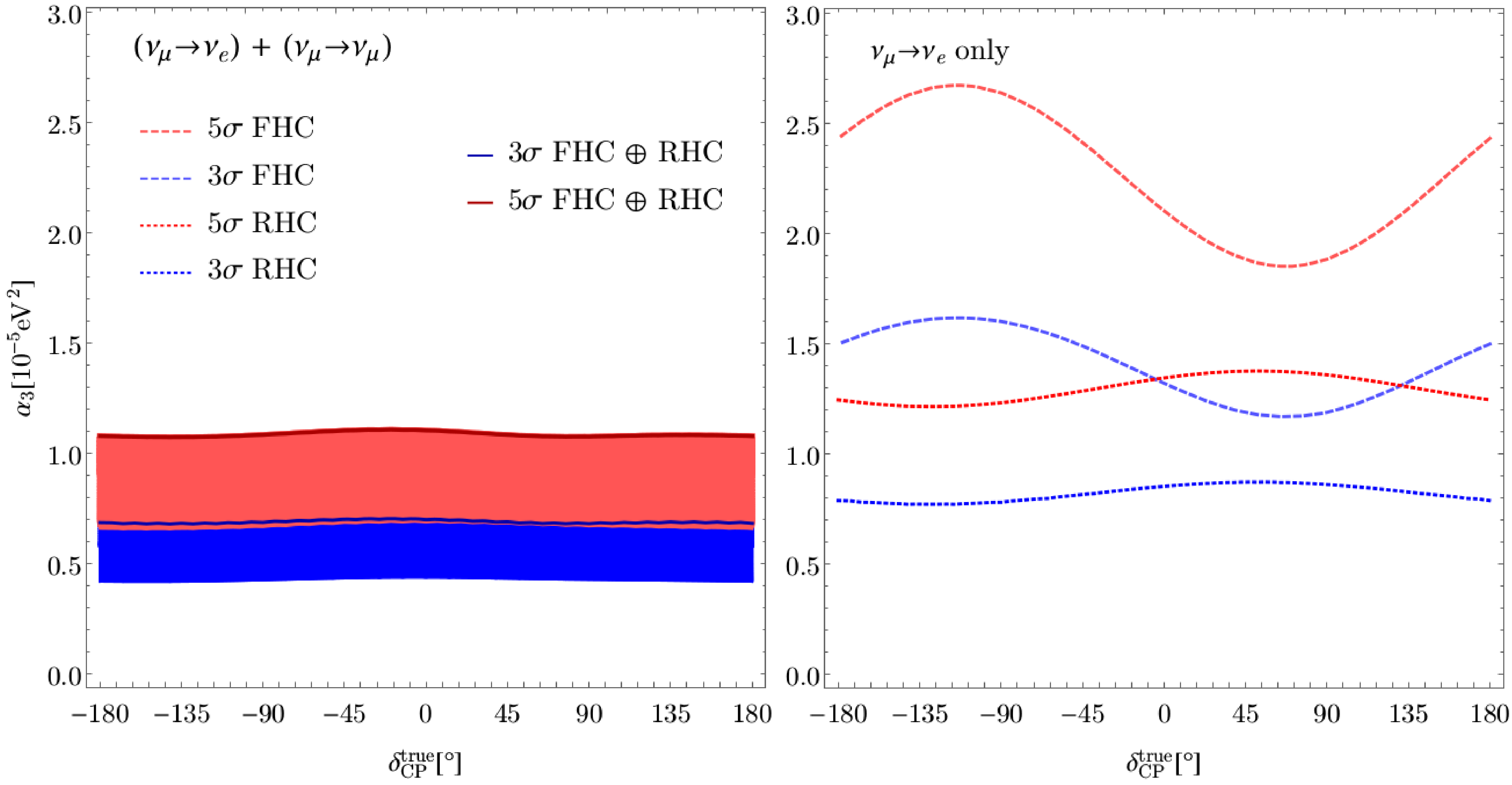


PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

Sensitivity and Parameter Fits at DUNE

SILAFAE 2018

Sensivity Plots



PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

SILAFAE 2018

Sensitivity and Parameter Fits at DUNE

Sensivity Plots

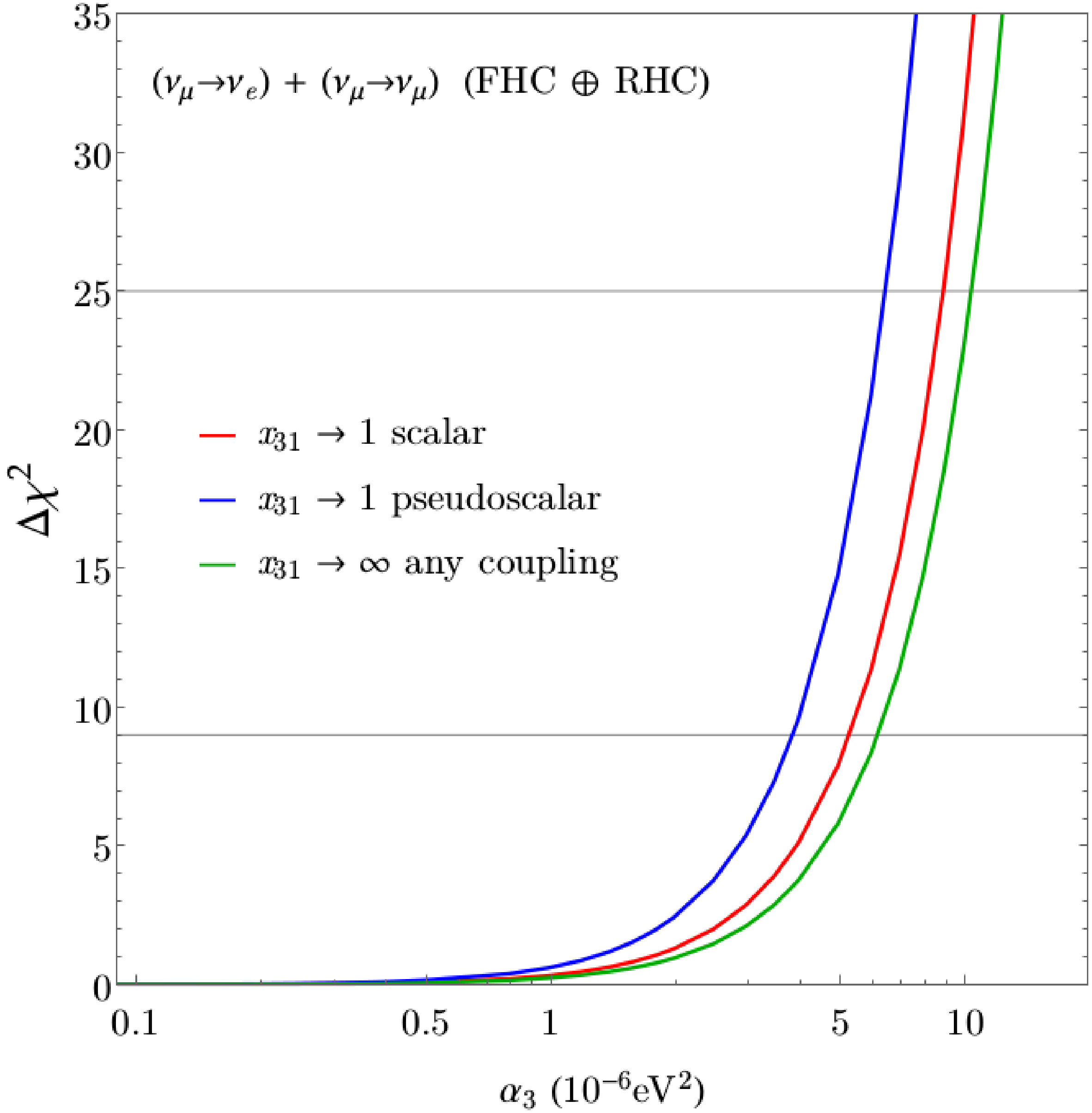
PSEUDOSCALAR

<u>3σ:</u>

$$\alpha_3 = 3.8 \times 10^{-6}\ \mathrm{eV}^2$$

<u>5σ:</u>

$$\alpha_3 = 6.4 \times 10^{-6}\ \mathrm{eV}^2$$



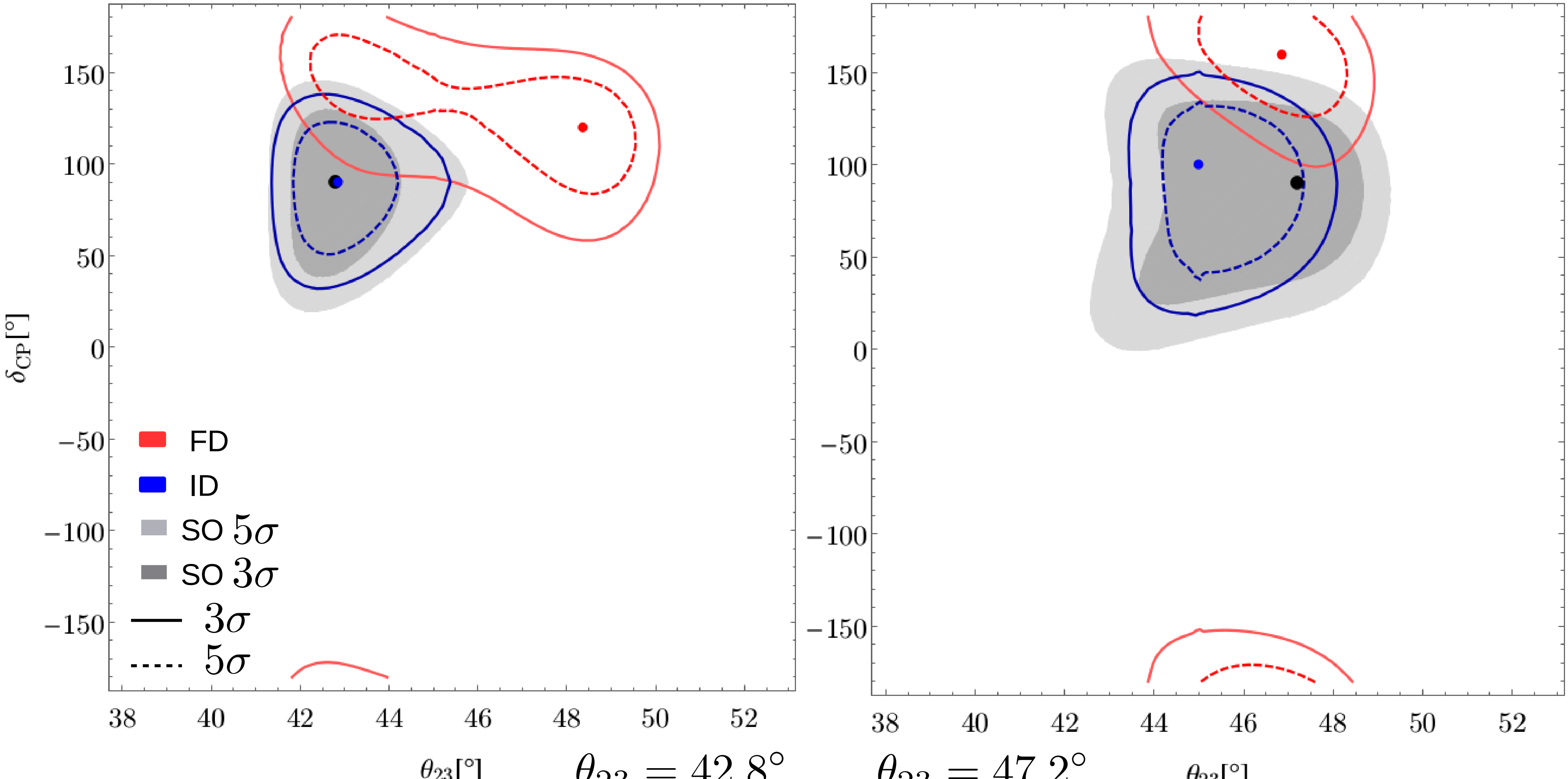
PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

Sensitivity and Parameter Fits at DUNE

SILAFAE 2018

Parameter Fits Plots

$\alpha_3^{\text{true}} = 4 \times 10^{-5}\ \text{eV}^2\ ,\ \delta_{CP} = 90^\circ$



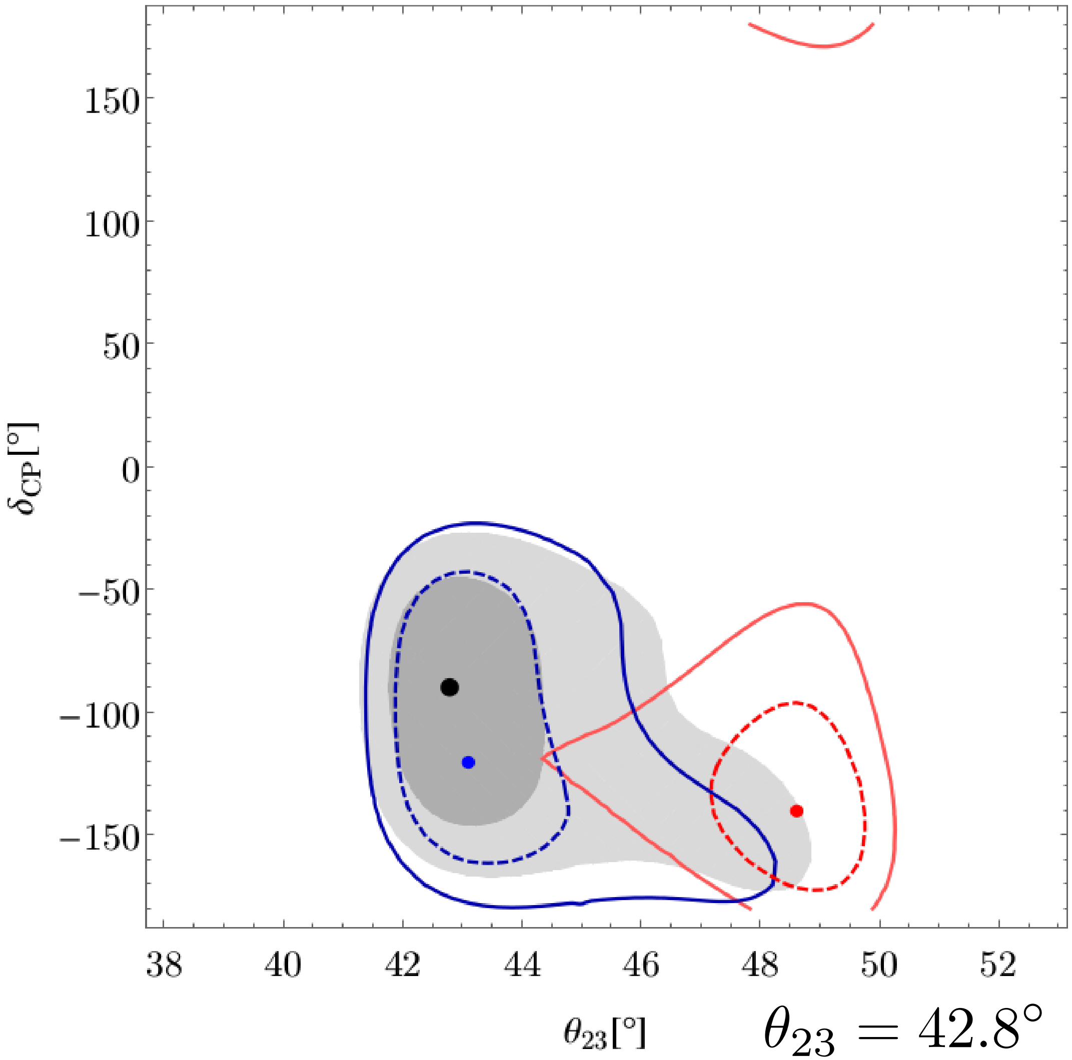
$\theta_{23} = 42.8^\circ$ $\theta_{23} = 47.2^\circ$

Sensitivity and Parameter Fits at DUNE

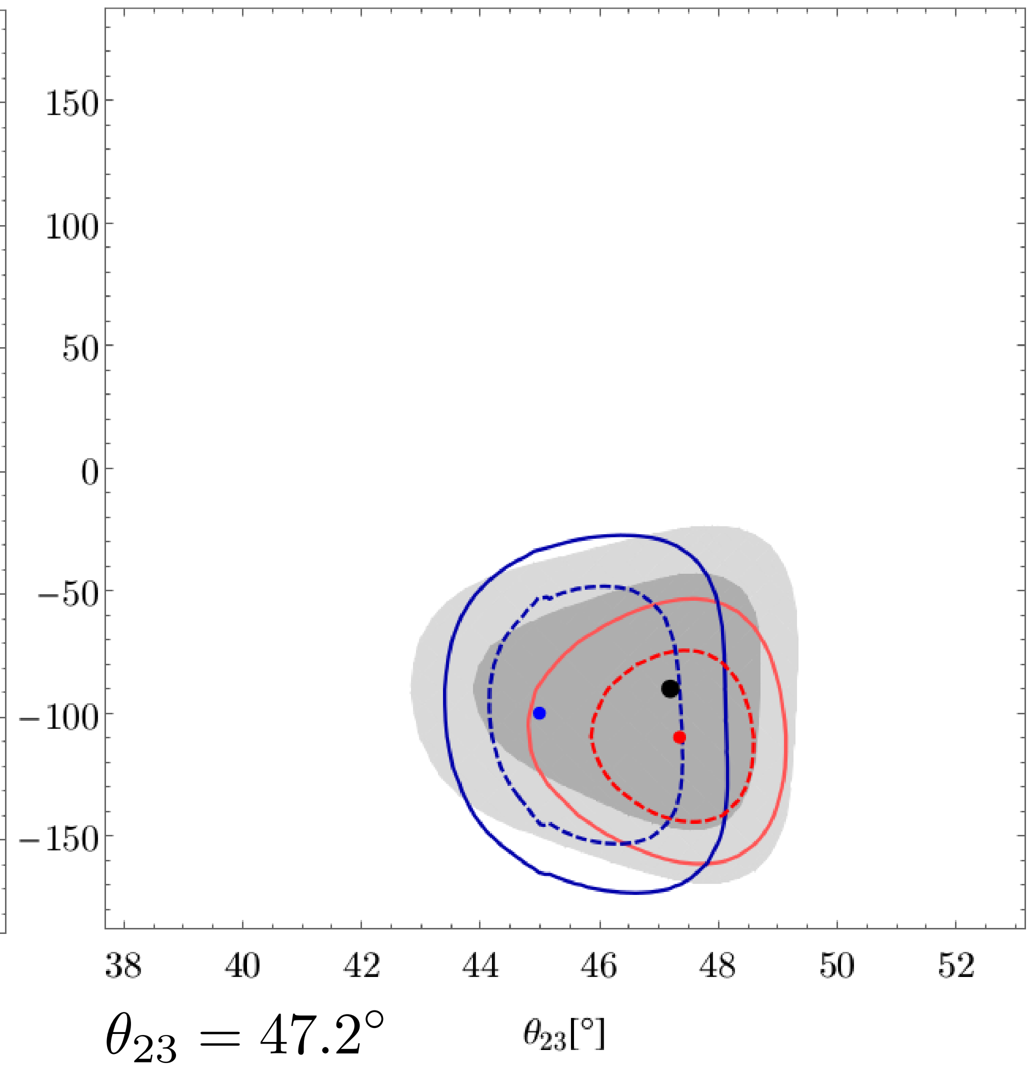
SILAFAE 2018

Parameter Fits Plots

$\alpha_3^{\text{true}} = 4 \times 10^{-5}\ \text{eV}^2\ ,\ \delta_{CP} = -90°$



$\theta_{23} = 42.8°$



$\theta_{23} = 47.2°$

PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

SILAFAE 2018

Conclusions

- The study of $\Phi \times \sigma$ show:

DUNE → ν_e app { Invisible Decay

ANDES → ν_e app { Invisible Decay, Visible Decay

ANDES → ν_μ diss

- We found the sensitivity of DUNE depends on $m_{lightest}$ in the following scenarios:

$$x_{31} \to 1 \begin{cases} \alpha_3^{(s)} < 2.8 \times 10^{-6}\ \mathrm{eV}^2 \\ \alpha_3^{(p)} < 2.0 \times 10^{-6}\ \mathrm{eV}^2 \end{cases}$$

$$x_{31} \to \infty \left\{ \alpha_3^{(s,p)} < 3.2 \times 10^{-6}\ \mathrm{eV}^2 \right.$$

- The fit of θ_{23} and δ_{CP}, assuming SO, with data generated for FD, it is found that the allowed regions will change towards larger values of θ_{23}, and toward conservation CP-values of δ_{CP} .

¡Thank you!

PONTIFICIA UNIVERSIDAD CATÓLICA DEL PERÚ

SILAFAE 2018

Rules used in the Event Simulation

Rules for ν_e appearence

		ν_e **appearance**, FHC Flux	$\bar{\nu}_e$ **appearance**, RHC Flux
Signal	CC:	$(\nu_\mu \to \nu_e)_{ID} + (\nu_\mu \to \nu_e)_{VD} + (\bar{\nu}_\mu \to \nu_e)_{VD}$	$(\nu_\mu \to \nu_e)_{ID} + (\bar{\nu}_\mu \to \nu_e)_{VD} + (\nu_\mu \to \nu_e)_{VD}$
	CC:	$(\bar{\nu}_\mu \to \bar{\nu}_e)_{ID} + (\nu_\mu \to \bar{\nu}_e)_{VD} + (\bar{\nu}_\mu \to \bar{\nu}_e)_{VD}$	$(\bar{\nu}_\mu \to \bar{\nu}_e)_{ID} + (\bar{\nu}_\mu \to \bar{\nu}_e)_{VD} + (\nu_\mu \to \bar{\nu}_e)_{VD}$
Background	CC:	$(\nu_e \to \nu_e)_{ID}$	$(\nu_e \to \nu_e)_{ID}$
	CC:	$(\bar{\nu}_e \to \bar{\nu}_e)_{ID}$	$(\bar{\nu}_e \to \bar{\nu}_e)_{ID}$
	CC:	$(\nu_\mu \to \nu_\mu)_{ID} + (\nu_\mu \to \nu_\mu)_{VD}$	$(\nu_\mu \to \nu_\mu)_{ID} + (\bar{\nu}_\mu \to \nu_\mu)_{VD}$
	CC:	$(\bar{\nu}_\mu \to \bar{\nu}_\mu)_{ID} + (\nu_\mu \to \bar{\nu}_\mu)_{VD}$	$(\bar{\nu}_\mu \to \bar{\nu}_\mu)_{ID} + (\bar{\nu}_\mu \to \bar{\nu}_\mu)_{VD}$
	CC:	$(\nu_\mu \to \nu_\tau)_{ID} + (\nu_\mu \to \nu_\tau)_{VD}$	$(\nu_\mu \to \nu_\tau)_{ID} + (\bar{\nu}_\mu \to \nu_\tau)_{VD}$
	CC:	$(\bar{\nu}_\mu \to \bar{\nu}_\tau)_{ID} + (\nu_\mu \to \bar{\nu}_\tau)_{VD}$	$(\bar{\nu}_\mu \to \bar{\nu}_\tau)_{ID} + (\bar{\nu}_\mu \to \bar{\nu}_\tau)_{VD}$
	NC:	$(\nu_\mu \to \nu_\alpha)_{ID} + (\nu_\mu \to \nu_\alpha)_{VD}$	$(\nu_\mu \to \nu_\alpha)_{ID} + (\bar{\nu}_\mu \to \nu_\alpha)_{VD}$
	NC:	$(\bar{\nu}_\mu \to \bar{\nu}_\alpha)_{ID} + (\nu_\mu \to \bar{\nu}_\alpha)_{VD}$	$(\bar{\nu}_\mu \to \bar{\nu}_\alpha)_{ID} + (\bar{\nu}_\mu \to \bar{\nu}_\alpha)_{VD}$

Missing indentification

Rules for ν_μ disappearence

		ν_μ **disappearance**, FHC Flux	$\bar{\nu}_\mu$ **disappearance**, RHC Flux
Signal	CC:	$(\nu_\mu \to \nu_\mu)_{ID} + (\nu_\mu \to \nu_\mu)_{VD}$	$(\nu_\mu \to \nu_\mu)_{ID} + (\bar{\nu}_\mu \to \nu_\mu)_{VD}$
	CC:	$(\bar{\nu}_\mu \to \bar{\nu}_\mu)_{ID} + (\nu_\mu \to \bar{\nu}_\mu)_{VD}$	$(\bar{\nu}_\mu \to \bar{\nu}_\mu)_{ID} + (\bar{\nu}_\mu \to \bar{\nu}_\mu)_{VD}$
Background	CC:	$(\nu_\mu \to \nu_\tau)_{ID} + (\nu_\mu \to \nu_\tau)_{VD}$	$(\nu_\mu \to \nu_\tau)_{ID} + (\bar{\nu}_\mu \to \nu_\tau)_{VD}$
	CC:	$(\bar{\nu}_\mu \to \bar{\nu}_\tau)_{ID} + (\nu_\mu \to \bar{\nu}_\tau)_{VD}$	$(\bar{\nu}_\mu \to \bar{\nu}_\tau)_{ID} + (\bar{\nu}_\mu \to \bar{\nu}_\tau)_{VD}$
	NC:	$(\nu_\mu \to \nu_\alpha)_{ID} + (\nu_\mu \to \nu_\alpha)_{VD}$	$(\nu_\mu \to \nu_\alpha)_{ID} + (\bar{\nu}_\mu \to \nu_\alpha)_{VD}$
	NC:	$(\bar{\nu}_\mu \to \bar{\nu}_\alpha)_{ID} + (\nu_\mu \to \bar{\nu}_\alpha)_{VD}$	$(\bar{\nu}_\mu \to \bar{\nu}_\alpha)_{ID} + (\bar{\nu}_\mu \to \bar{\nu}_\alpha)_{VD}$

Missing indentification

Event Generation at DUNE

Events

Number of events of flavor β in the energy bin i, with helicity s and going through interaction $\mathrm{int} = \{CC, NC\}$, is obtained from:

$$N_{i,\beta}^{(s),\mathrm{int}} = \int dE_\beta \, K_i^{\mathrm{int}}(E_\beta) \, \sigma_\beta^{s,\mathrm{int}}(E_\beta) \frac{d\Phi_\beta^{(s)}}{dE_\beta}$$

where $\sigma_\beta^{s,\mathrm{int}}(E_\beta)$ is the cross section for the interaction int , and

$$K_i^{\mathrm{int}}(E_\beta) = \int_{E_{\mathrm{i,min}}}^{E_{\mathrm{i,max}}} dE_{\mathrm{bin}} \, \epsilon_\beta^{\mathrm{int}}(E_{\mathrm{bin}}) \, R^{\mathrm{int}}(E_{\mathrm{bin}} - E_\beta)$$

Detector efficiency: $\epsilon_\beta^{\mathrm{int}}(E_{\mathrm{bin}})$

Resolution function: $R^{\mathrm{int}}(E_{\mathrm{bin}} - E_\beta)$