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HIDDeN
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

IJCLab
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Laboratoire de Physique des 2 Infinis

New Physics from Oscillations at the DUNE Near Detector

In collaboration with P. Coloma, J. López-Pavón & S. Urrea, based on JHEP 08 (2021) 065

Salvador Rosauro-Alcaraz 02/06/2023

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Introduction

Standard neutrino oscillations

What we know (at 1σ)

I. Esteban *et al.* 2007.14792 www.nu-fit.org

$$\text{Solar sector} \begin{cases} \sin^2\theta_{12} = 0.304^{+0.012}_{-0.012} \\ \Delta m^2_{21} = 7.42^{+0.21}_{-0.20} \cdot 10^{-5} eV^2 \end{cases}$$

$$\text{Atm. sector} \begin{cases} \sin^2\theta_{23} = 0.573^{+0.016}_{-0.020} \\ |\Delta m^2_{31}| = 2.517^{+0.026}_{-0.028} \cdot 10^{-3} eV^2 \end{cases}$$

$$\sin^2\theta_{13} = 0.02219^{+0.00062}_{-0.00063}$$

Introduction

Standard neutrino oscillations

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I. Esteban *et*

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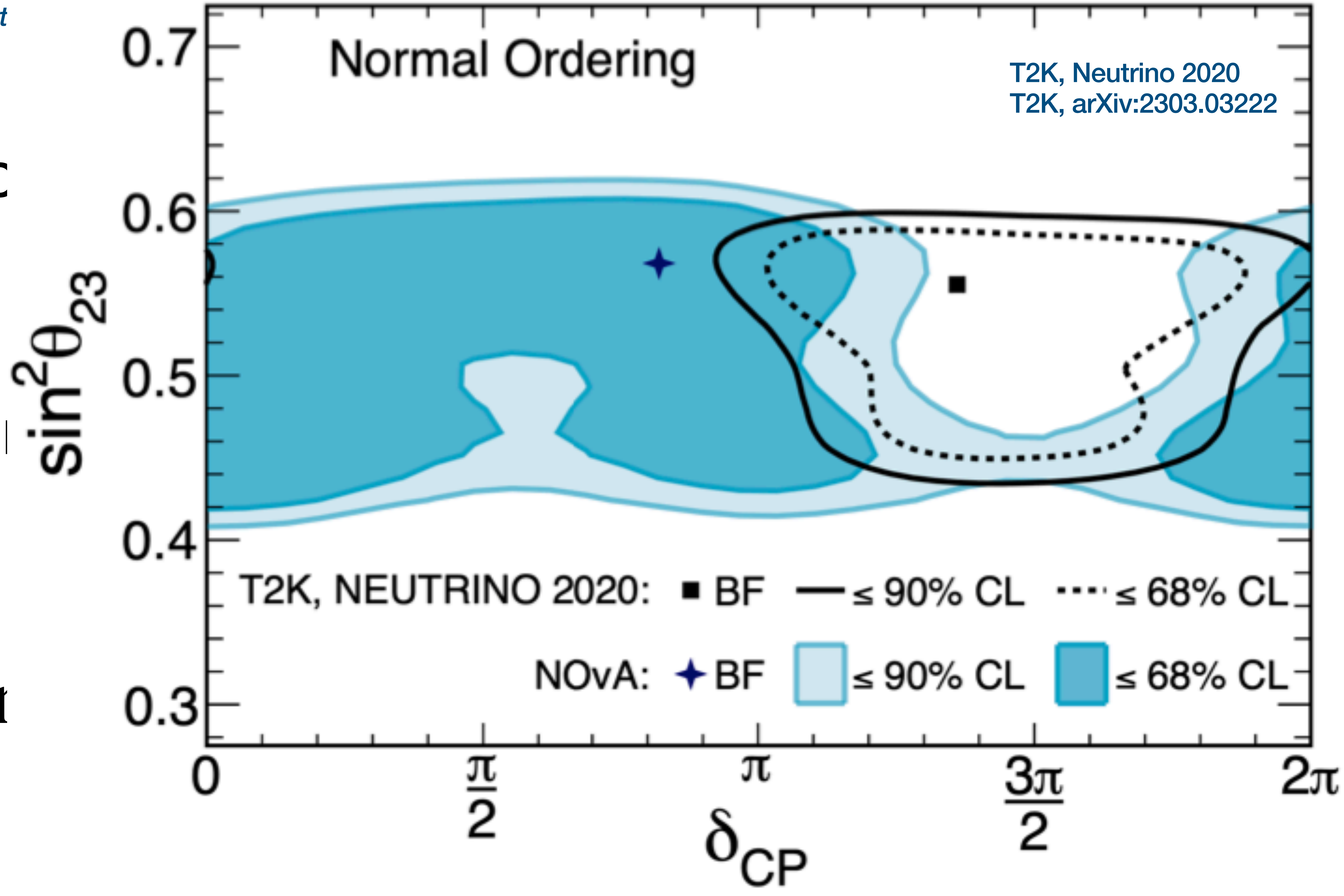
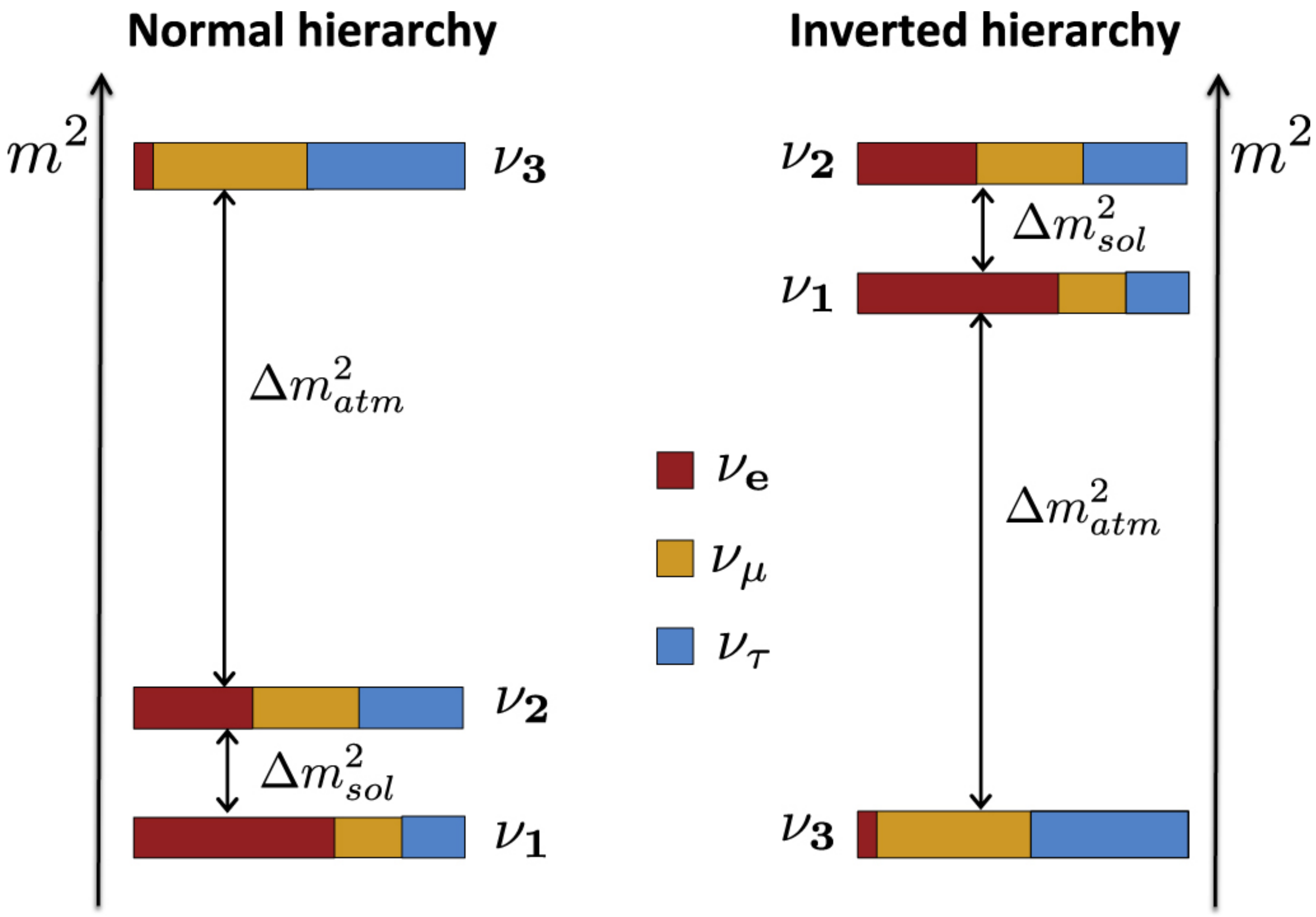

T2K, Neutrino 2020
T2K, arXiv:2303.03222

What we **do not** know (yet)

Is there leptonic
CP violation, i.e., $\delta \neq 0,\, \pi$?

Introduction

Standard neutrino oscillations



What we do not know (yet)

Is there leptonic CP violation, i.e., $\delta \neq 0, \pi$?

Mass ordering: $sign(\Delta m^2_{31})$

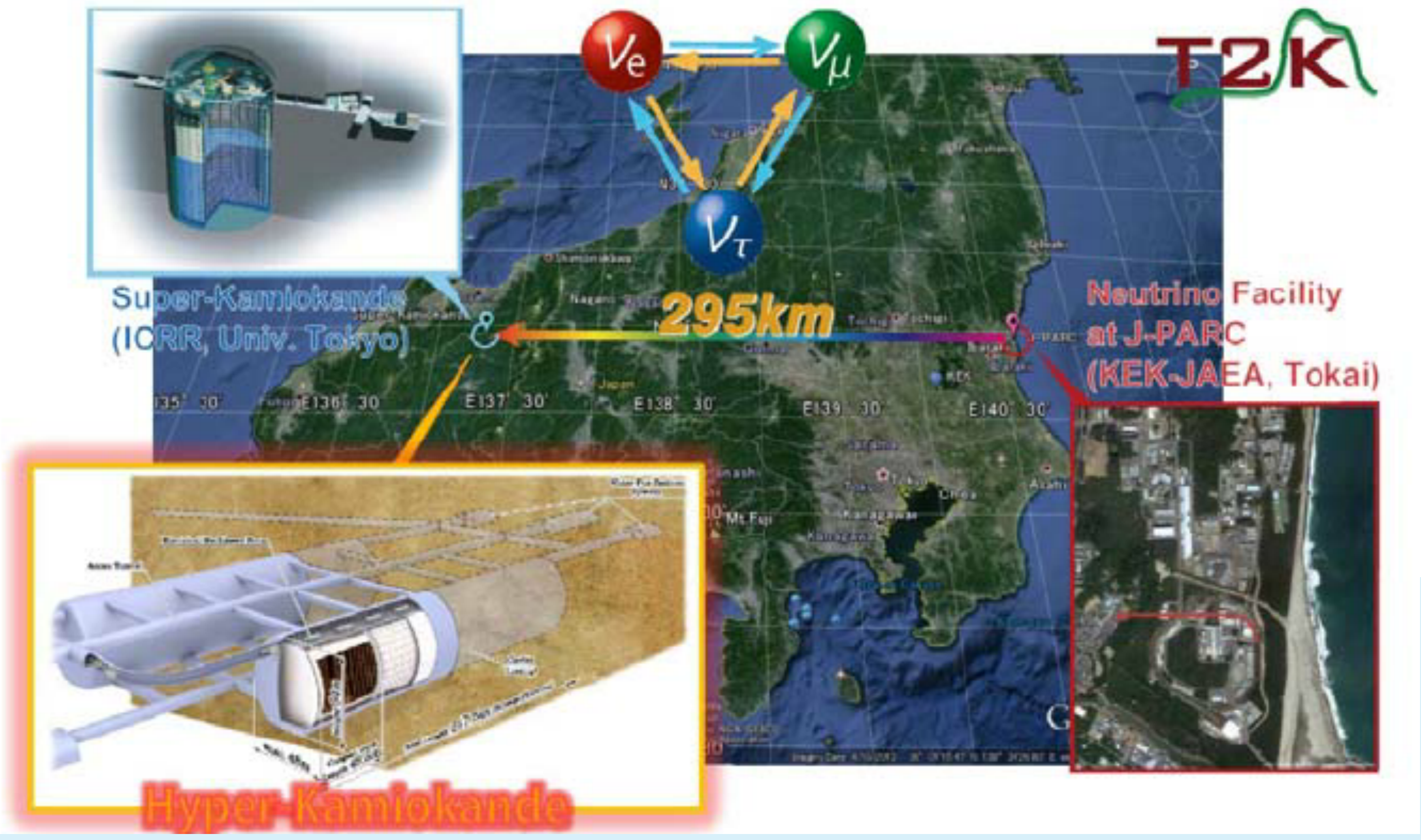
Octant of θ_{23}

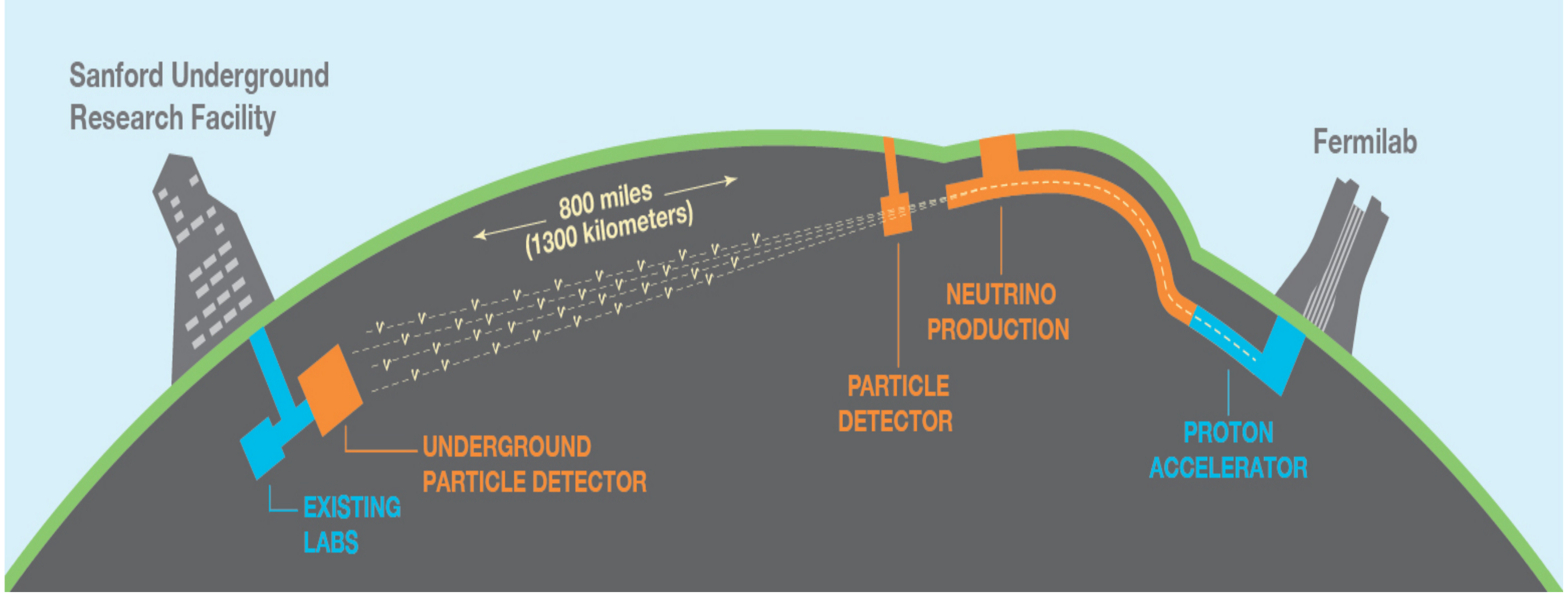
Introduction

Future facilities

DUNE & T2HK

DUNE Collaboration, arXiv:2006.16043
T2HK Collaboration, arXiv:1412.4673





What we do not know (yet)

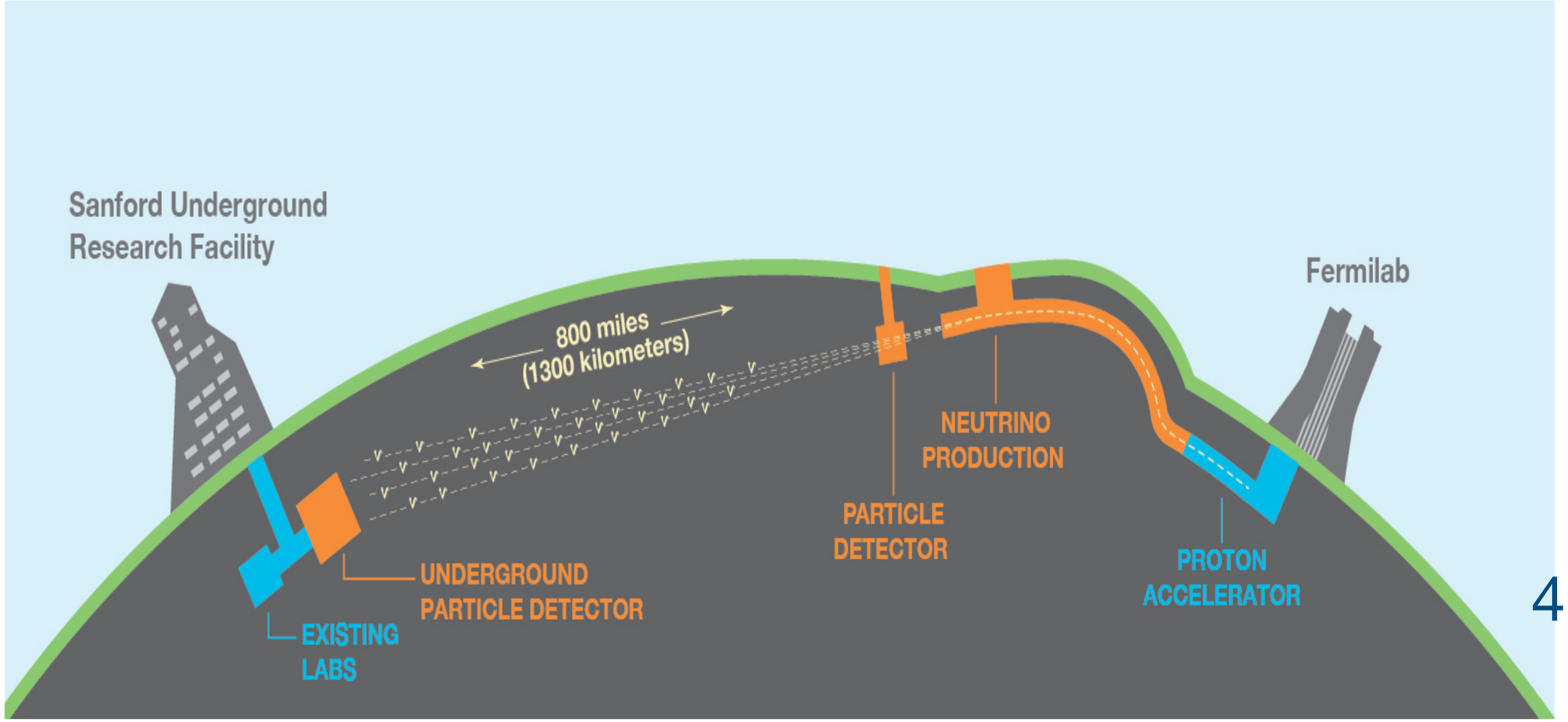
Is there leptonic CP violation, i.e., $\delta \neq 0, \pi$?

Mass ordering: $sign(\Delta m^2_{31})$

Octant of θ_{23}

Recipe for good measurements

$\vec{\sigma}_{FD}$ correlated with $\vec{\sigma}_{ND}$



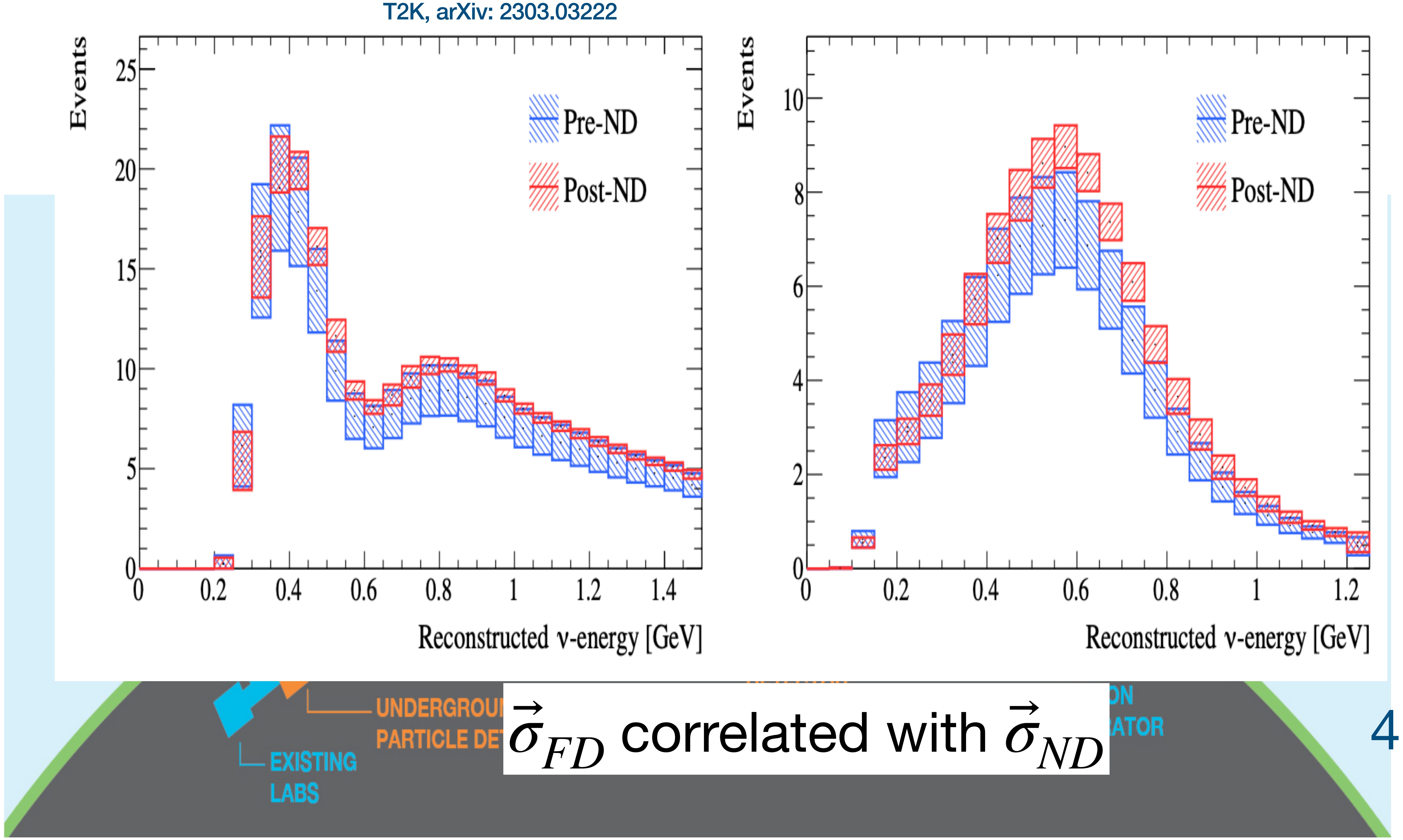
1 Measure events in ND, $N_{\mu}^{ND}(\vec{\sigma}_{ND})$

2 Measure events in FD, $N_{e}^{FD}(\vec{\theta}, \vec{\sigma}_{FD})$

3 Find ratio $R_{e\mu} = \dfrac{N_e^{FD}}{N_\mu^{ND}}$

4 Extract $\vec{\theta}$ from comparing it with the extrapolation of N_μ^{ND}

Recipe for good measurements


T2K, arXiv: 2303.03222

$\vec{\sigma}_{FD}$ correlated with $\vec{\sigma}_{ND}$

1. Measure events in ND, $N_\mu^{ND}(\vec{\sigma}_{ND})$
2. Measure events in FD, $N_e^{FD}(\vec{\theta}, \vec{\sigma}_{FD})$
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Physics at a ND

Beyond 3ν oscillations

Need right-handed neutrinos to explain light neutrino masses

$$\nu_\alpha = \sum_i^{3+N_s} \mathcal{U}_{\alpha i} n_i \qquad \mathcal{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

PMNS mixing matrix

Physics at a ND

Beyond 3ν oscillations

Need right-handed neutrinos to explain light neutrino masses

$$\boxed{\nu_\alpha = \sum_{i=1}^{3} N_{\alpha i} n_i + \sum_{i=4}^{N_s} \Theta_{\alpha i} n_i}$$

$$\mathscr{U} = \begin{pmatrix} N & \Theta \\ R & S \end{pmatrix}$$

$$N = (I - T)U$$

$$T = \begin{pmatrix} \alpha_{ee} & 0 & 0 \\ \alpha_{\mu e} & \alpha_{\mu\mu} & 0 \\ \alpha_{\tau e} & \alpha_{\tau\mu} & \alpha_{\tau\tau} \end{pmatrix}$$

Physics at a ND

Beyond 3ν oscillations

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$$\boxed{\nu_\alpha = \sum_{i=1}^{3} N_{\alpha i} n_i + \sum_{i=4}^{N_s} \Theta_{\alpha i} n_i}$$

Two regimes for non-unitarity:

- n_i not produced in neutrino oscillation experiments
- n_i participating in neutrino oscillations

Physics at a ND

Beyond 3ν oscillations

Need right-handed neutrinos to explain light neutrino masses

$$\nu_\alpha = \sum_{i=1}^{3} N_{\alpha i} n_i + \sum_{i=}^{N}$$

Two regimes for non-unitarity:

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- n_i participating in neutrino oscillations

Stronger bounds elsewhere

Physics at a ND

Beyond 3ν oscillations

Need right-handed neutrinos to explain light neutrino masses

$$\boxed{\nu_\alpha = \sum_{i=1}^{3} N_{\alpha i} n_i + \sum_{i=4}^{N_s} \Theta_{\alpha i} n_i}$$

Two regimes for non-unitarity:

- n_i not produced in neutrino oscillation experiments
- n_i participating in neutrino oscillations

$$\Delta m^2_{41} \gg \left| \Delta m^2_{31} \right|$$

Study effects at ND

Physics at a ND

Sterile neutrino oscillations

$$P_{\gamma\beta} = \sin^2 2\theta_{\gamma\beta} \sin^2\left(\frac{\Delta m_{41}^2 L}{4E}\right), \quad \sin^2\theta_{\gamma\beta} \equiv 4\left|\mathcal{U}_{\gamma 4}\right|^2 \left|\mathcal{U}_{\beta 4}\right|^2$$

Physics at a ND

Sterile neutrino oscillations

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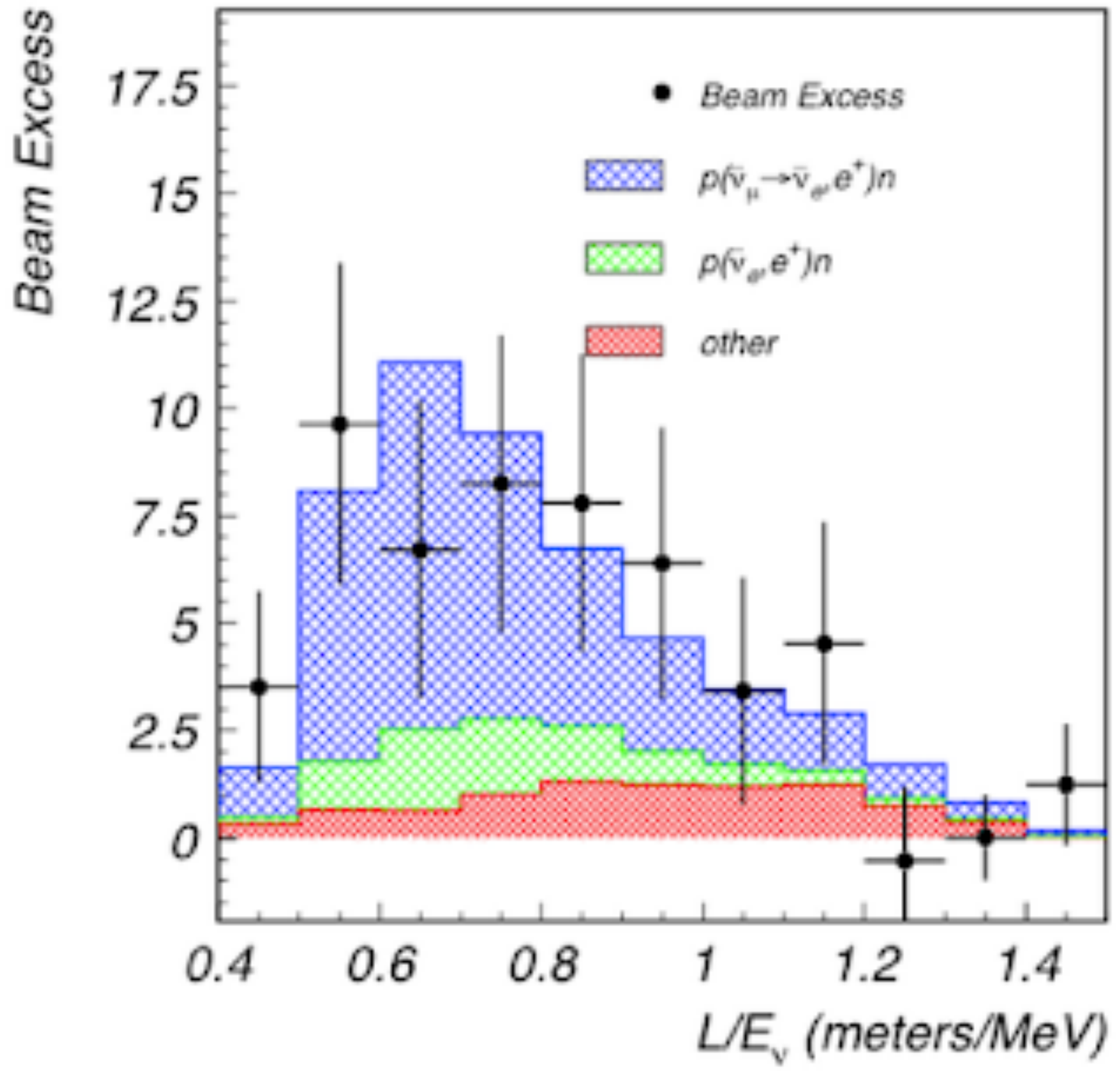
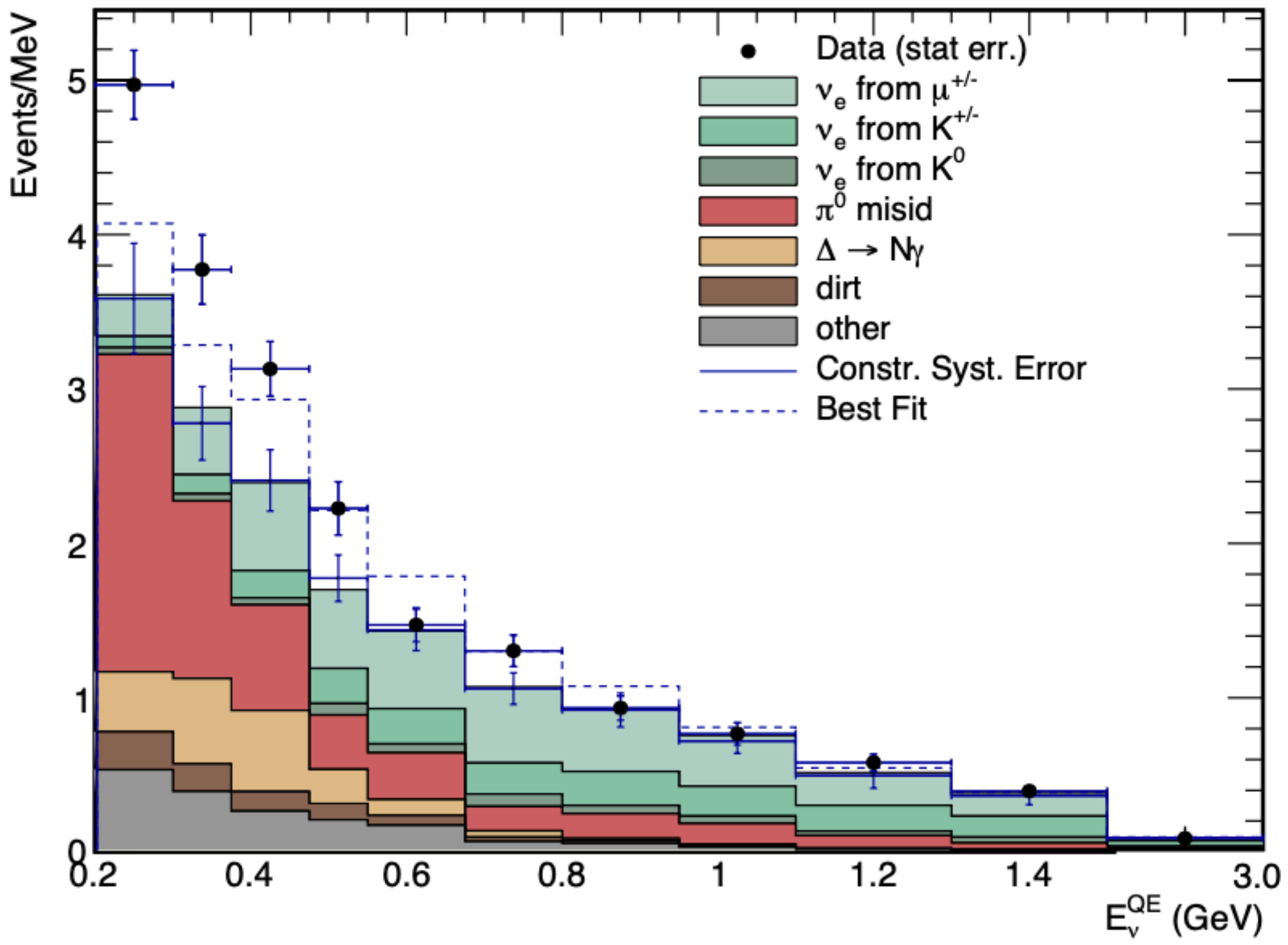
LSND Collaboration, arXiv: hep-ex/0104049



MiniBooNE Collaboration, arXiv:1805.12028



Anomalous $\nu_\mu \to \nu_e$

Physics at a ND

Non-unitarity from low-scale physics

$$P_{\gamma\beta} = \sin^2 2\theta_{\gamma\beta} \sin^2\left(\frac{\Delta m^2_{41} L}{4E}\right), \quad \sin^2\theta_{\gamma\beta} \equiv 4\left|\mathcal{U}_{\gamma 4}\right|^2 \left|\mathcal{U}_{\beta 4}\right|^2$$

Averaged-out regime $\Delta m^2_{41} L/E \gg 1$

$$\boxed{P_{\gamma\beta} = 2\left|\alpha_{\gamma\beta}\right|^2 = 2|\mathcal{U}_{\gamma 4}|^2|\mathcal{U}_{\beta 4}|^2}$$

Similar to NU at high scales

Physics at a ND

Non-standard neutrino interactions

General 4-fermion effective operator $\mathscr{L}_{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta\right)\left(\bar{f}\gamma^\mu P_{L(R)}f\right)$

Used to “reconcile” NOvA and T2K results

P. Denton, J, Gherlein & R. Pestes, arXiv: 2008.01110
S. Chartterjee & A. Palazzo, arXiv: 2008.04161

Physics at a ND

Non-standard neutrino interactions

General 4-fermion effective operator $\mathscr{L}_{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta\right)\left(\bar{f}\gamma^\mu P_{L(R)}f\right)$

$$P_{\gamma\beta} = \left|\epsilon^d_{\gamma\beta}\right|^2 + \left|\epsilon^s_{\gamma\beta}\right|^2 + 2\left|\epsilon^d_{\gamma\beta}\right|\left|\epsilon^s_{\gamma\beta}\right|\cos\left(\Delta\Phi_{\gamma\beta}\right)$$

Physics at a ND

Non-standard neutrino interactions

General 4-fermion effective operator $\mathscr{L}_{NSI} = -2\sqrt{2}G_F\epsilon_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta\right)\left(\bar{f}\gamma^\mu P_{L(R)}f\right)$

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Averaged-out regime $\Delta m^2_{41}L/E \gg 1$

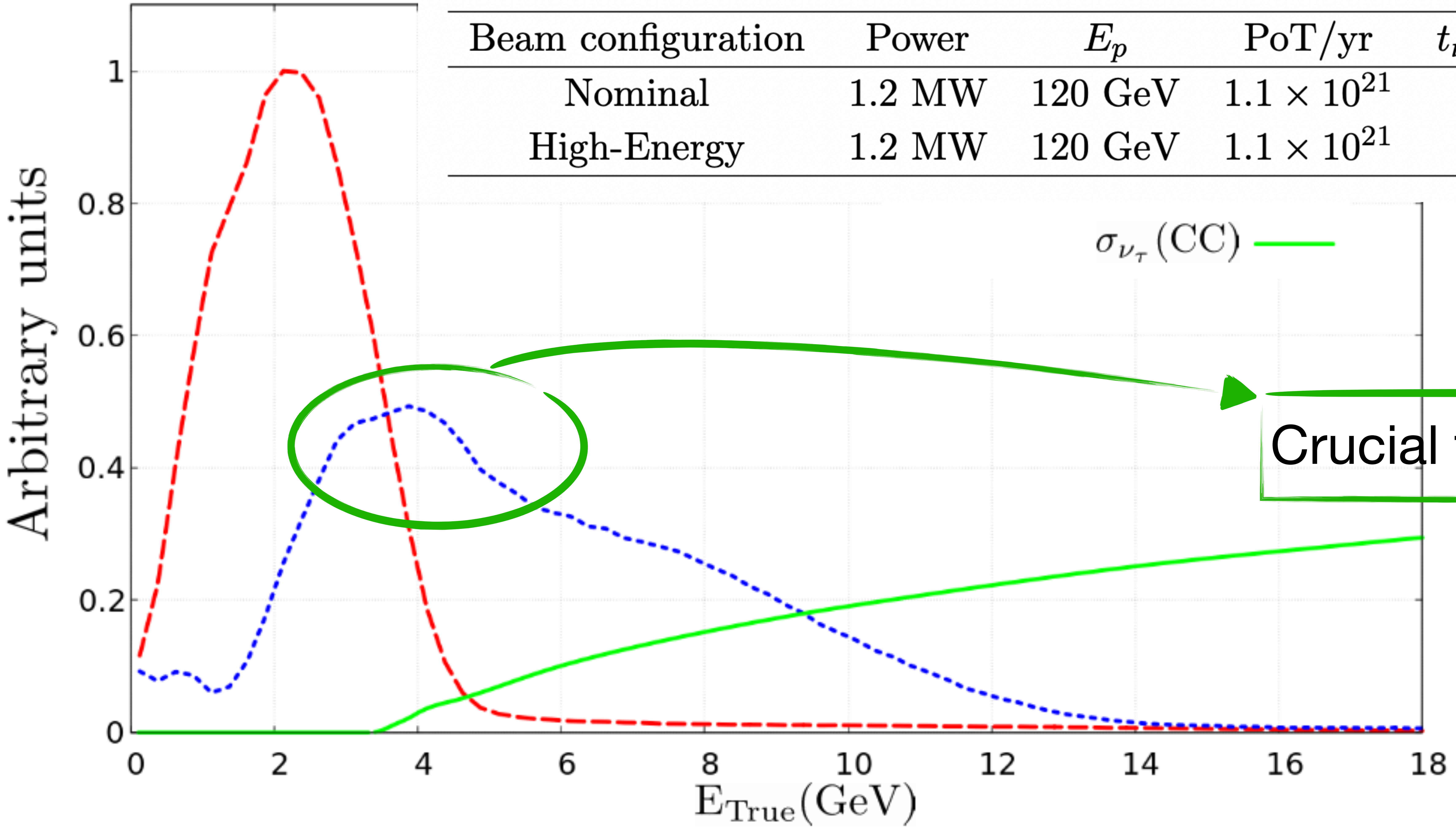
$$P_{\gamma\beta} = 2\left|\alpha_{\gamma\beta}\right|^2$$

Translate bounds from $\alpha_{\gamma\beta}$ to $\epsilon_{\gamma\beta}$

Simulation details

DUNE flux & detector simulation

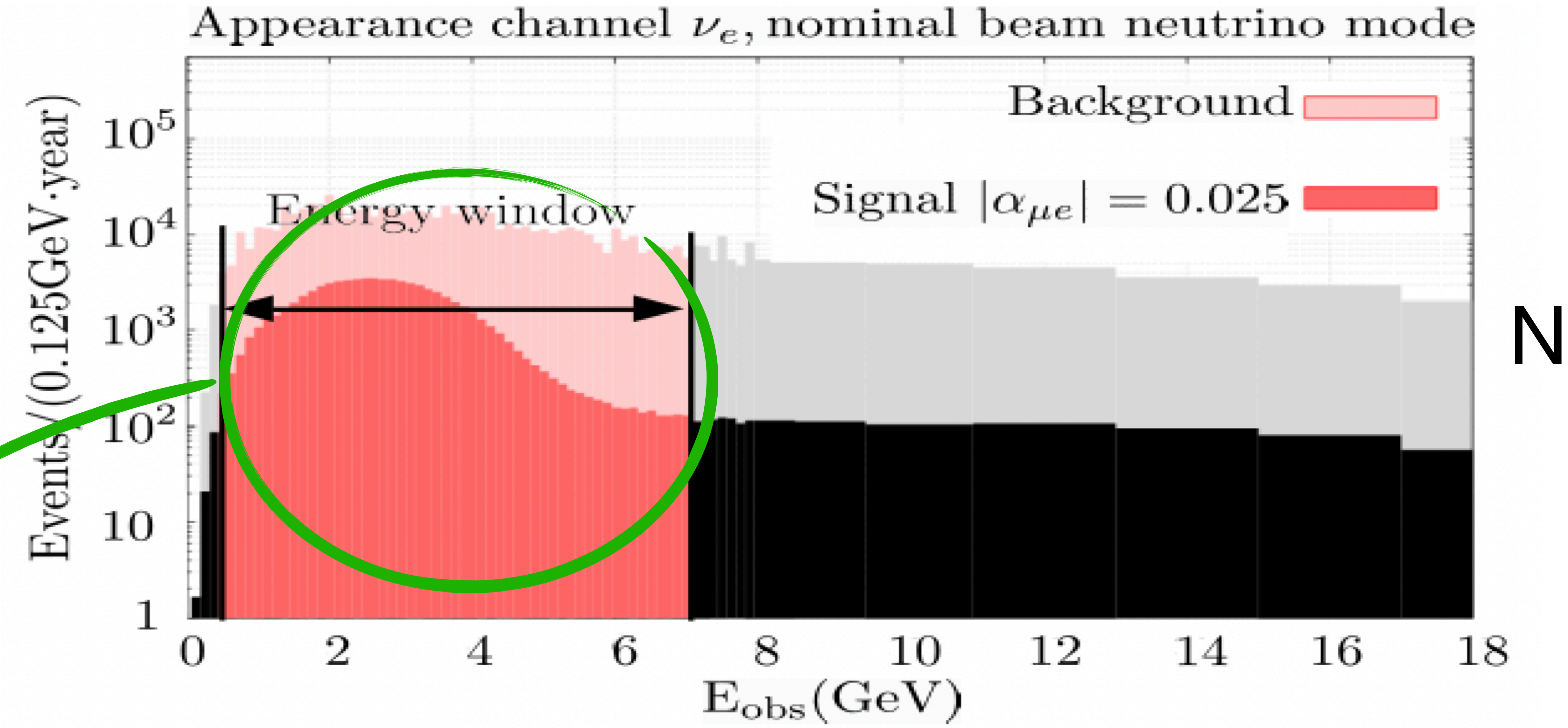
Beam configuration	Power	E_p	PoT/yr	t_ν (yr)	$t_{\bar{\nu}}$ (yr)	M_{det}
Nominal	1.2 MW	120 GeV	1.1×10^{21}	3.5	3.5	67.2 tons
High-Energy	1.2 MW	120 GeV	1.1×10^{21}	3.5	–	67.2 tons



Crucial to study $\nu_\mu \to \nu_\tau$

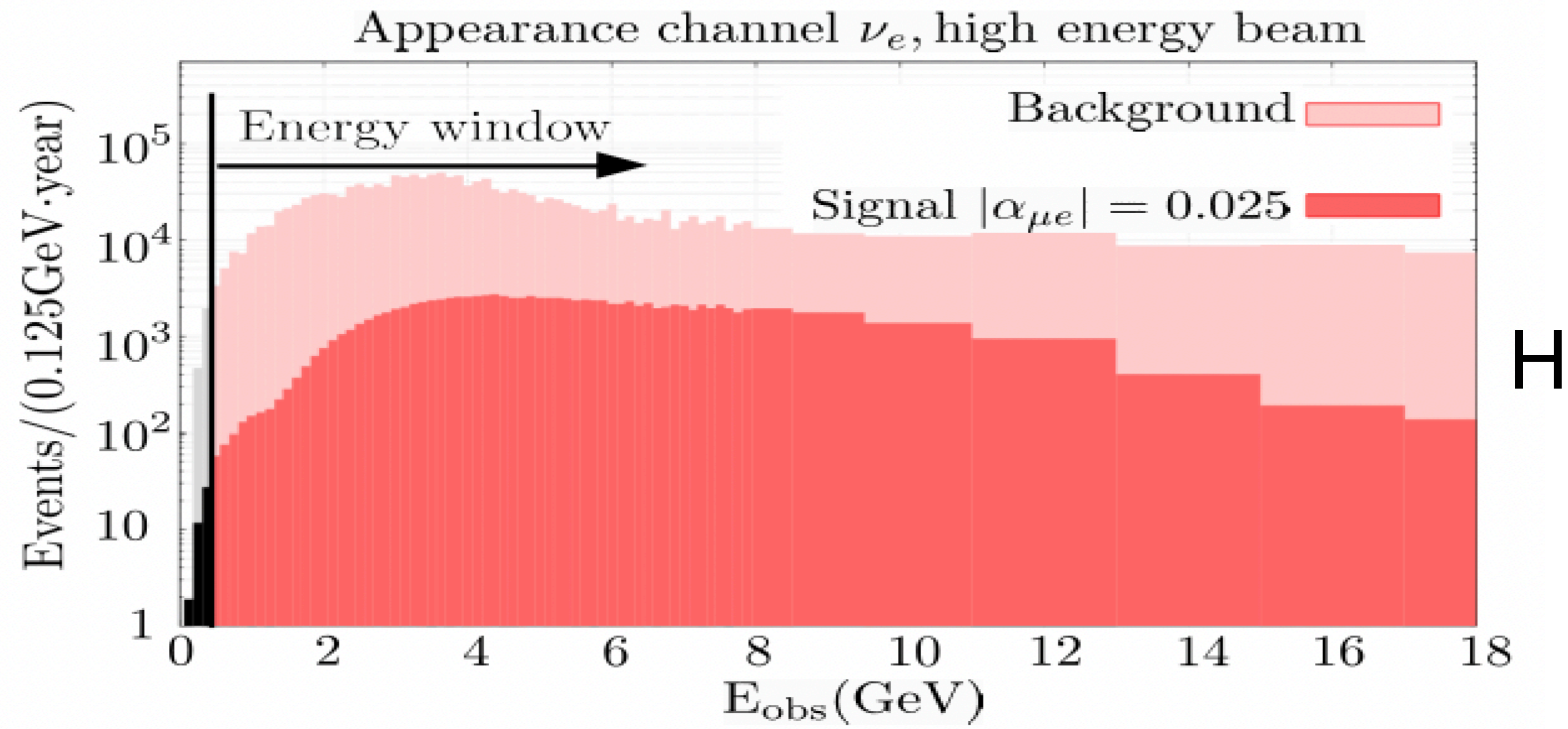
Simulation details

Event rates



Nominal beam

Events included in the analysis

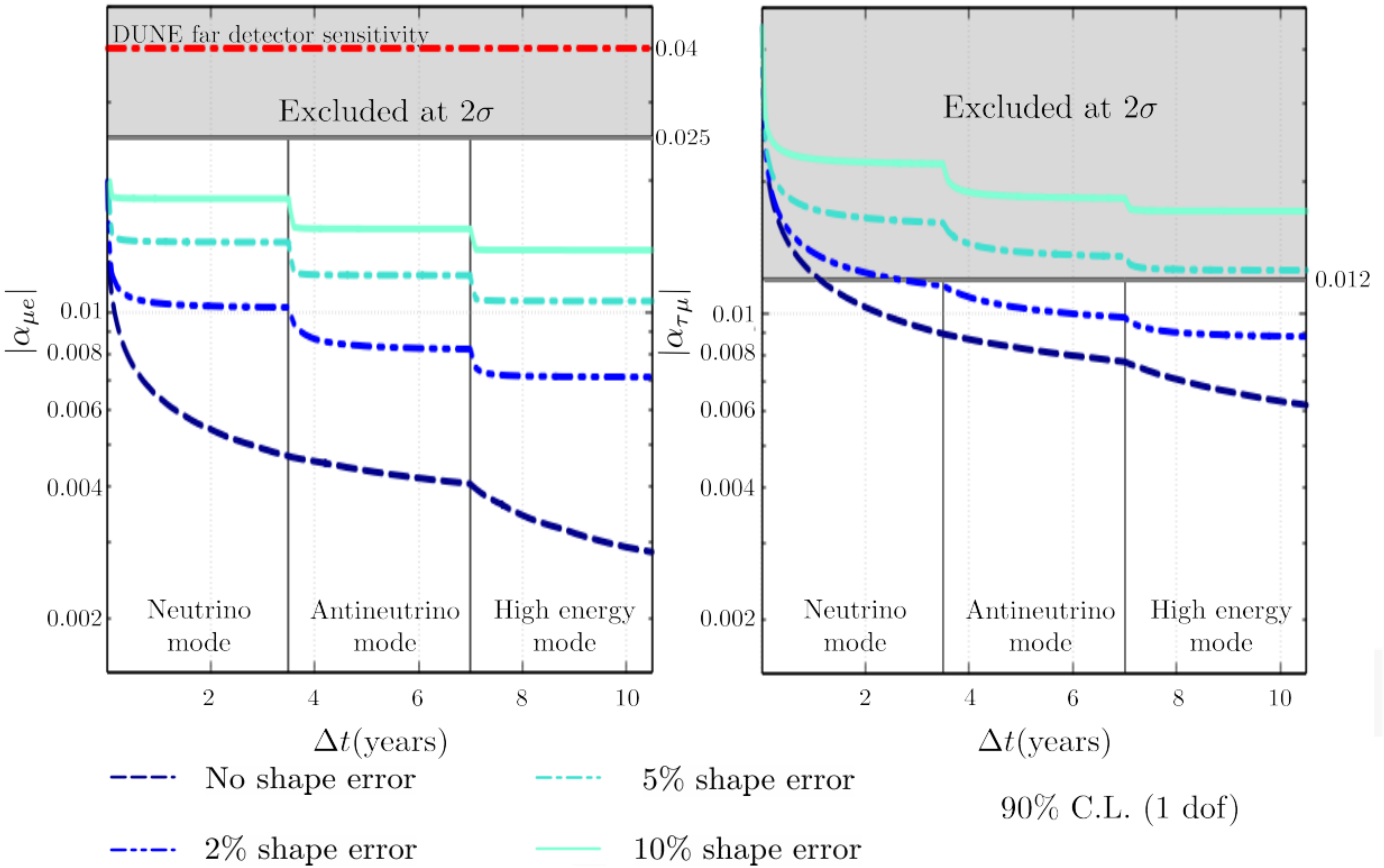


High energy beam

Results

Non-unitarity

$$\Delta m_{41}^2 L/E \gg 1$$

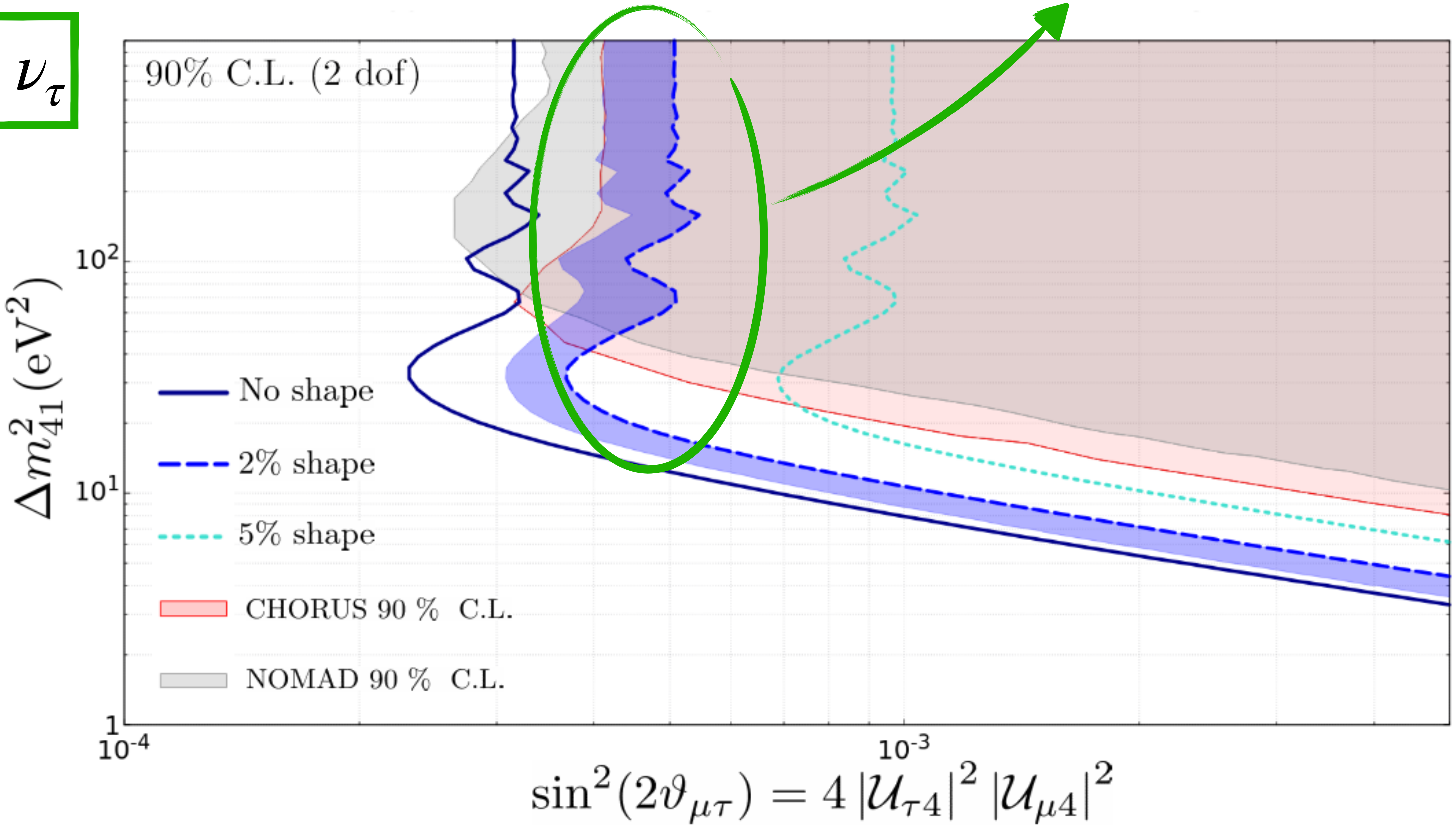


Results

Sterile oscillations

$\nu_\mu \rightarrow \nu_\tau$

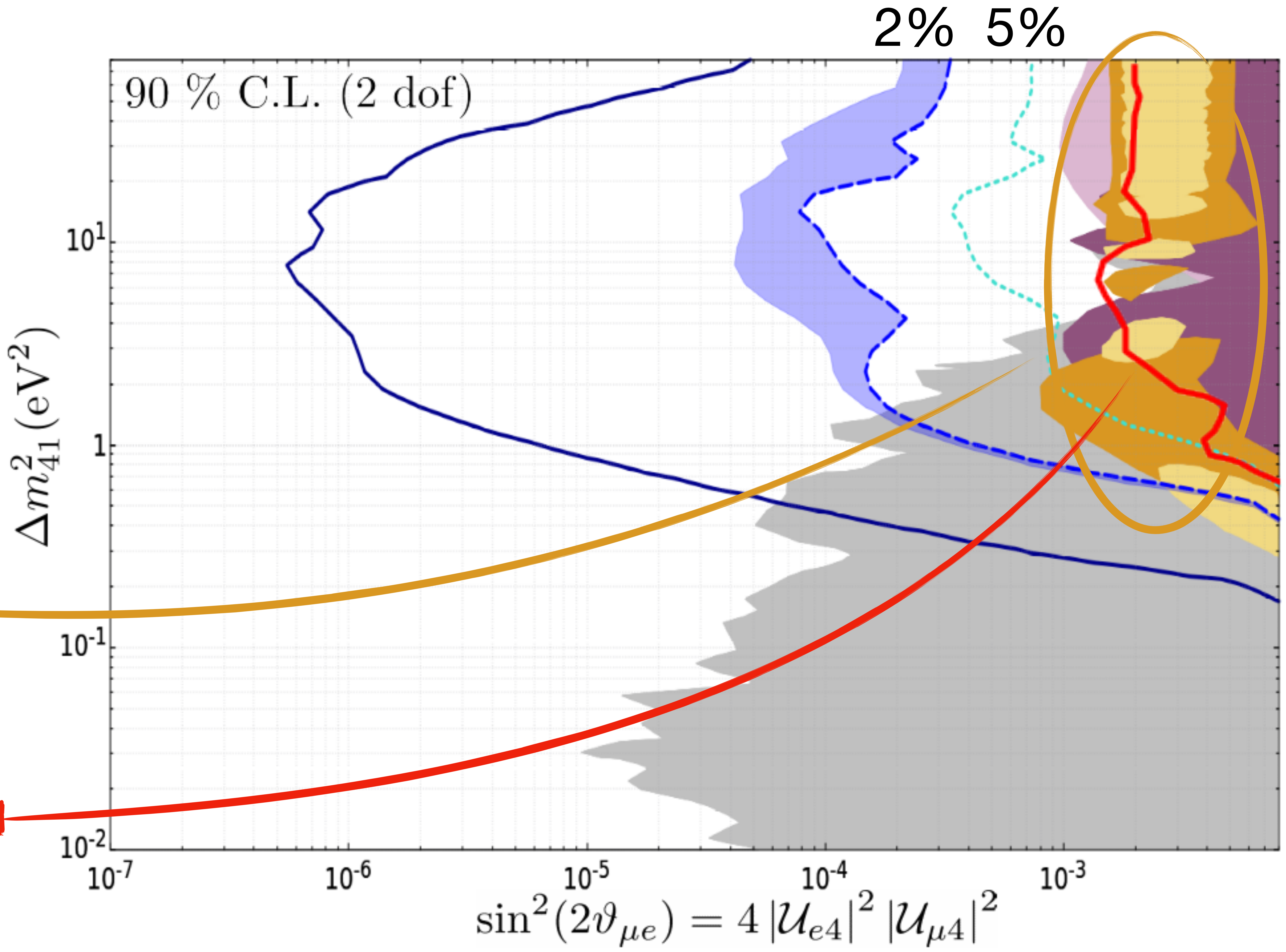
HE beam



Results

Sterile oscillations

$$\boxed{\nu_\mu \rightarrow \nu_e}$$



LSND & MiniBooNE
preferred region @ 99% CL

MicroBooNE @ 95% CL

MicroBooNE, arXiv: 2210.10216

Conclusions

Near detectors can be useful to study physics beyond 3ν oscillations

Systematic uncertainties play a crucial role

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Systematic uncertainties play a crucial role

Study ν_τ appearance in DUNE

Conclusions

Near detectors can be useful to study physics beyond 3ν oscillations

Systematic uncertainties play a crucial role

Study ν_τ appearance in DUNE

2% shape uncertainties:

- Reduce considerably the sensitivity to $\nu_\mu \to \nu_e$ around 2 orders of magnitude
- Reduce bound on NU parameters about a factor 2

Thank you!

Back-up slides

Simulation details

ν_τ detection

PDG, P. A. Zayla *et al.*, PTEP 2020
GENIE Collaboration, J. Tena-Vidal *et al.*, arXiv:2104.09179
A. de Gouvêa *et al.*, arXiv:1904.07265

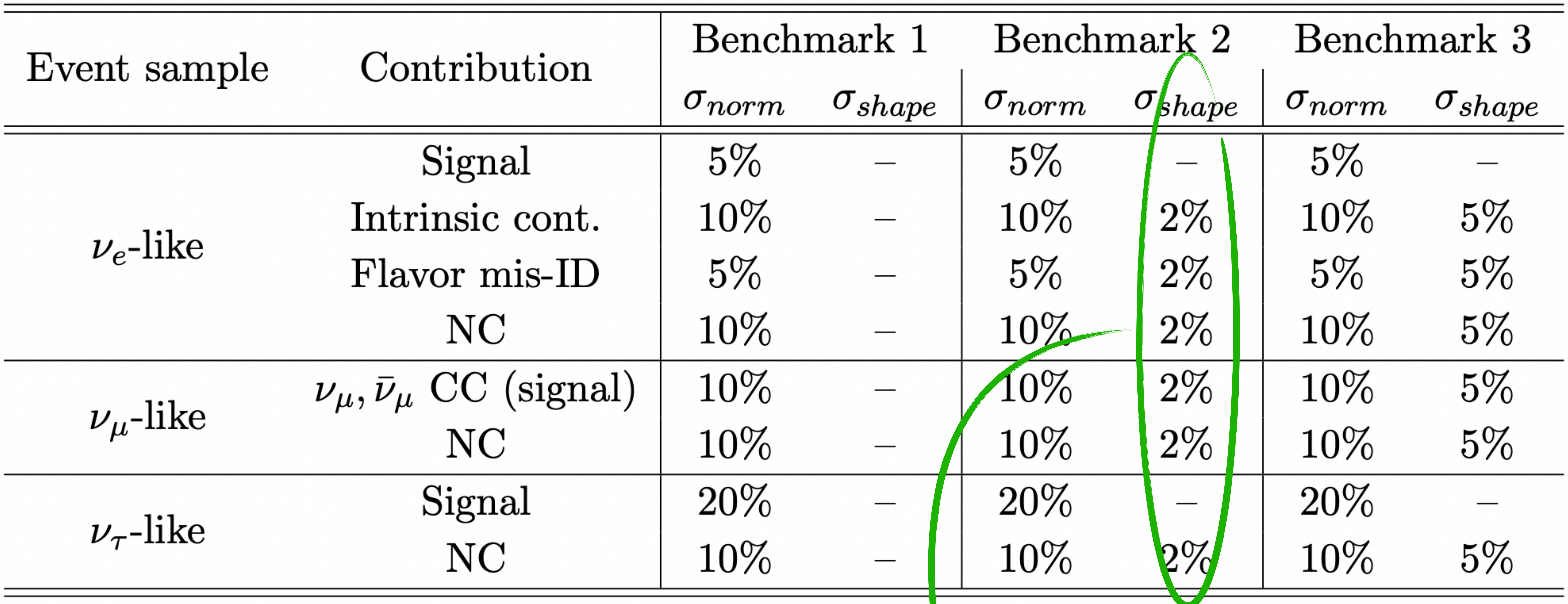
Produce τ through CC interactions

Consider only τ hadronic decay ($BR(\tau \to had) \sim 65\,\%$)

Main background due to NC

Simulation details

Systematic uncertainties



Event sample	Contribution	Benchmark 1		Benchmark 2		Benchmark 3	
		σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}	σ_{norm}	σ_{shape}
ν_e-like	Signal	5%	–	5%	–	5%	–
	Intrinsic cont.	10%	–	10%	2%	10%	5%
	Flavor mis-ID	5%	–	5%	2%	5%	5%
	NC	10%	–	10%	2%	10%	5%
ν_μ-like	$\nu_\mu, \bar{\nu}_\mu$ CC (signal)	10%	–	10%	2%	10%	5%
	NC	10%	–	10%	2%	10%	5%
ν_τ-like	Signal	20%	–	20%	–	20%	–
	NC	10%	–	10%	2%	10%	5%

Allows every bin to vary independently

Results

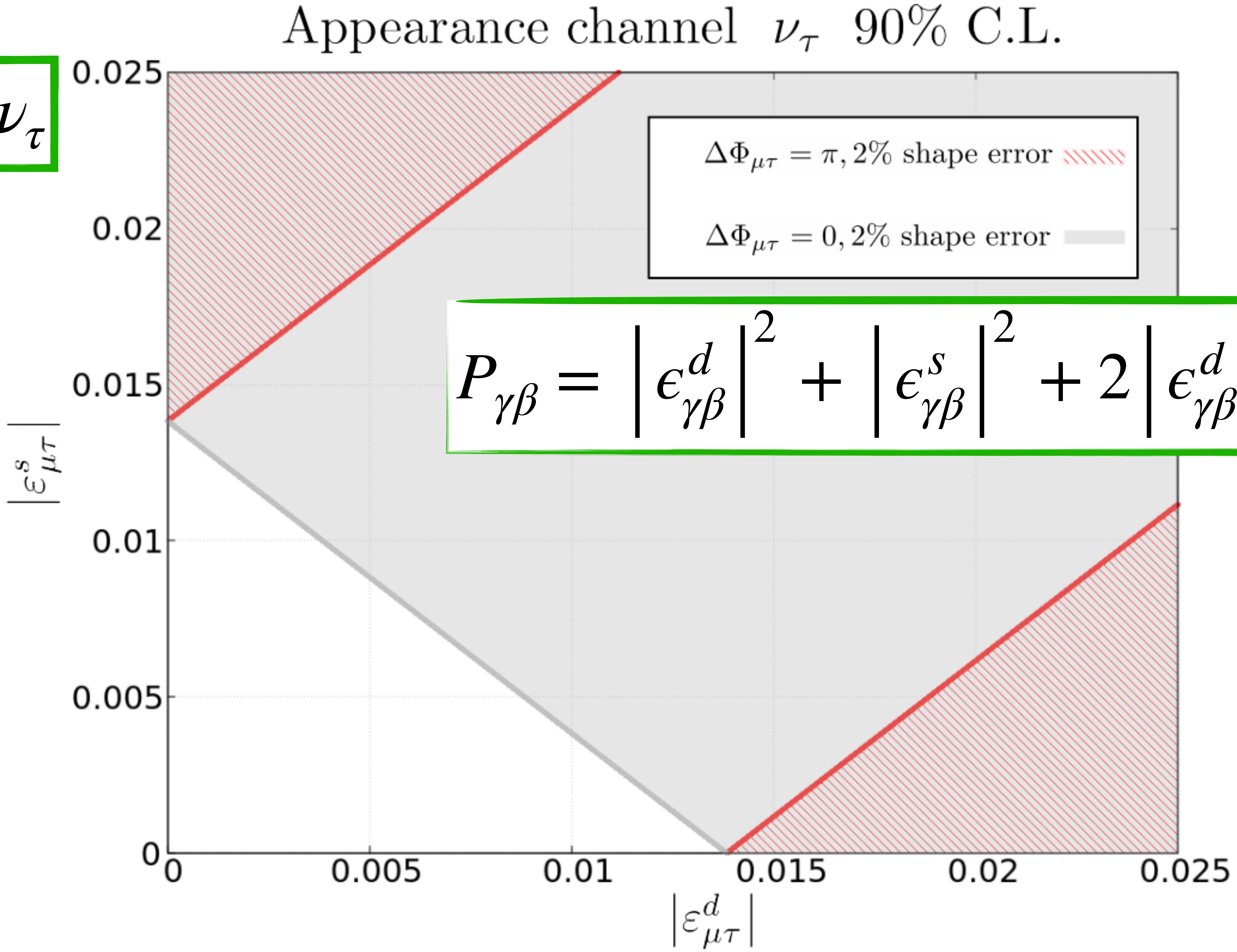
Non-standard neutrino interactions

$$\boxed{P_{\gamma\beta} = \left|\epsilon^{d}_{\gamma\beta}\right|^2 + \left|\epsilon^{s}_{\gamma\beta}\right|^2 + 2\left|\epsilon^{d}_{\gamma\beta}\right|\left|\epsilon^{s}_{\gamma\beta}\right|\cos\left(\Delta\Phi_{\gamma\beta}\right)}$$

Results

Non-standard neutrino interactions

$$\nu_\mu \to \nu_\tau$$



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