New physics from oscillations at the DUNE near detector and the role of systematic uncertainties

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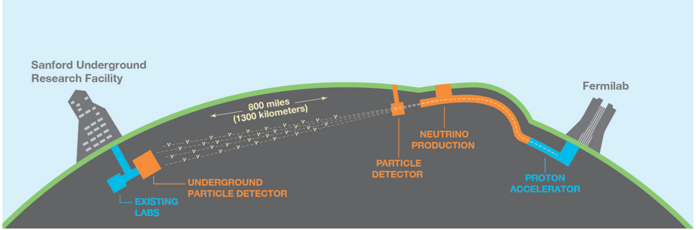
DUNE will test the robustness of the three-neutrino picture.



Sources of systematics

- Cross sections
- ν flux

Far detector vs near detector

- Near detector measurements reduce the far detector systematic uncertainties.
- New physics at the near detector (heavily affected by systematics)

Overview

1. Theoretical scenarios: non-unitarity and sterile neutrinos

2. New sensitivity analysis at DUNE near detector

Non-unitarity and sterile neutrinos

More than 3 massive neutrinos

$$\mathcal{U} = \begin{pmatrix} N_{3\times 3} & \Theta_{3\times(n-3)} \\ R_{(n-3)\times 3} & S_{(n-3)\times(n-3)} \end{pmatrix}$$

Non-unitarity

$$m > \text{EW}$$

- Strong constraints from EW and flavor precision data. (Enrique Fernandez-Martinez, et al. arXiv:1605.08774; Stefan Antusch et al. arXiv:1407.6607)
- Not produced at neutrino beams as DUNE.

Sterile neutrinos

$$m \ll \text{EW}$$

- We recover unitarity at EW processes.
- Produced at neutrino beams as DUNE.
- Bounds from oscillations. (Mattias Blennow, Pilar Coloma, et al. arXiv:1609.08637)

Non-unitarity

Non-unitary mixing matrix

$$P_{\alpha\beta} = \left| \left(N S^0 N^\dagger \right)_{\beta\alpha} \right|^2, \; S^0 = \exp(-iHL)$$

Common parametrization of N

$$\mathbf{N} = \begin{pmatrix} 1-\alpha_{ee} & 0 & 0 \\ -\alpha_{\mu e} & 1-\alpha_{\mu\mu} & 0 \\ -\alpha_{\tau e} & -\alpha_{\tau\mu} & 1-\alpha_{\tau\tau} \end{pmatrix} U_{\text{PMNS}}$$

(Zhi-zhong Xing, arXiv:0709.2220; Zhi-zhong Xing, arXiv:1110.0083; F. J. Escrihuela, D. V. Forero et al. arXiv:1503.08879)

Non-unitarity at near detector

Standard unitary case

$$\mathrm{P}_{\gamma\beta}^{\text{Standard}} = \left|\left(UU^{\dagger}\right)_{\beta\gamma}\right|^{2} = \delta_{\gamma\beta}$$

Non-unitarity appearance

$$\gamma \neq \beta$$

$$P_{\gamma\beta}^{\text{Non-unitarity}} = \left|\left(NN^{\dagger}\right)_{\beta\gamma}\right|^{2} = |\alpha_{\gamma\beta}|^{2}$$

Non-unitarity disappearance

$$\gamma = \beta$$

$$P_{\beta\beta}^{\text{Non-unitarity}} = \left|\left(NN^{\dagger}\right)_{\beta\beta}\right|^{2} = 1 - 4\alpha_{\beta\beta}$$

Sterile neutrinos 3+1

4×4 unitary matrix

$$\mathcal{U} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} = \begin{pmatrix} N_{3\times 3} & \Theta_{3\times 1} \\ R_{1\times 3} & S_{1\times 1} \end{pmatrix}$$

4×4 unitary matrix

$$P^{\text{Steriles}}_{\alpha\beta} = \left| \left(\mathcal{U}\mathcal{S}\mathcal{U}^\dagger \right)_{\beta\alpha} \right|^2 , \mathcal{S} = \text{diag}\left(\exp\left(-i\Delta m^2_{j1} L/2E \right) \right)$$

Sterile neutrino 3+1 at near detectors

Sterile neutrino appearance

$$\mathbf{P}_{\alpha\beta}^{\text{SBL}} = 4\,|U_{\alpha 4}|^2\,|U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

Sterile neutrino disappearance

$$\mathbf{P}_{\beta\beta}^{\text{SBL}} = 1 - 4\,|U_{\beta 4}|^2\left(1 - |U_{\beta 4}|^2\right)\sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

Averaged-out limit $\frac{\Delta m_{14}^2 L}{4E} \gg 1$

$$\left\langle \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)\right\rangle = \frac{1}{2}$$

$$\left\langle \mathbf{P}_{\alpha\beta}^{\text{SBL}} \right\rangle = 2\,|U_{\alpha 4}|^2\,|U_{\beta 4}|^2, \qquad \left\langle \mathbf{P}_{\beta\beta}^{\text{SBL}} \right\rangle = 1 - 2\,|U_{\beta 4}|^2\left(1 - |U_{\beta 4}|^2\right)$$

From 3+1 sterile neutrino scenario to α parametrization

Mapping

$$\begin{pmatrix} |\alpha_{ee}| & 0 & 0 \\ |\alpha_{\mu e}| & |\alpha_{\mu\mu}| & 0 \\ |\alpha_{\tau e}| & |\alpha_{\tau\mu}| & |\alpha_{\tau\tau}| \end{pmatrix} = \begin{pmatrix} \frac{1}{2}\,|U_{e4}|^2 & 0 & 0 \\ |U_{\mu 4}|\,|U_{e4}| & \frac{1}{2}\,|U_{\mu 4}|^2 & 0 \\ |U_{\tau 4}|\,|U_{e4}| & |U_{\tau 4}|\,|U_{\mu 4}| & \frac{1}{2}\,|U_{\tau 4}|^2 \end{pmatrix}$$

Sterile neutrino 3+1 averaged-out limit vs non-unitarity

Non-unitarity $m >$ EW

$$P^{\text{App}}_{\gamma\beta} = |\alpha_{\gamma\beta}|^2$$

$$P^{\text{Dis}}_{\beta\beta} = 1 - 4\alpha_{\beta\beta}$$

Averaged-out limit $EW \gg \Delta m^2 \geq 100\text{eV}^2$

$$P^{\text{App}}_{\gamma\beta} = 2\,|\alpha_{\gamma\beta}|^2$$

$$P^{\text{Dis}}_{\beta\beta} = 1 - 4\alpha_{\beta\beta}$$

DUNE set-up

Globes files

DUNE Collaboration, arXiv:2103.04797 [hep] 8 Mar 2021.

Flux configuration

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

What has been done in the literature?

- Sterile neutrinos sensitivity analysis for ν_e appearance and disappearance and ν_μ disappearance at both near and far detectors. **(Only considering global normalization systematics).**(DUNE Collaboration, arXiv:2008.12769v1)
- ν_τ appearance channel **in the far detector.**(André de Gouvêa, Kevin J. Kelly, G. V. Stenico, Pedro Pasquini, arXiv:1904.07265)
- Analysis for non-unitarity and sterile neutrinos including energy shape uncertainties in other set-ups. (Without including ν_τ)(F. J. Escrihuela, D. V. Forero, O. G. Miranda, M. Tortola, J. W. F. Valle, arXiv:1503.08879)

What is new?

- We have included **spectral shape uncertainty** in all channels for steriles neutrinos, the averaged out limit and non-unitarity at DUNE near detector.
- We have explored the ν_τ **appearance** channel at the DUNE **near detector.**
- We have explored the sensitivity for NSI in detection and production including shape uncertainties.

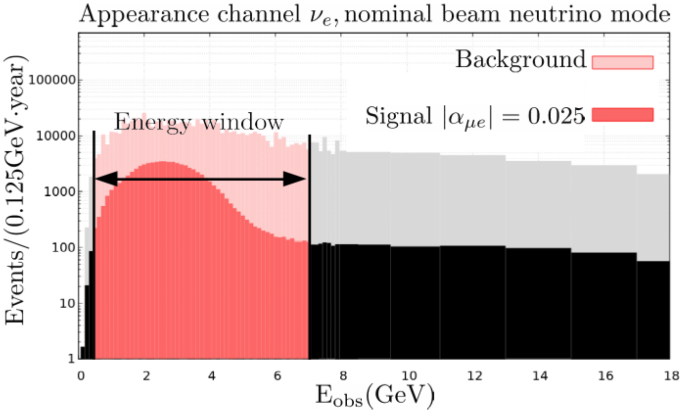
Challenges and assumptions

ν_τ appearance

Detection difficulties:

- Energy threshold of τ production 3.2 GeV.
- Short lifetime of τ, indirect measurement via hadronic decays($\sim 65\%$ branching ratio).
- NC background, we have considered a sample in which 30% of the hadronic events are identified keeping 0.5% of NC background.(André de Gouvêa, Kevin J. Kelly, G. V. Stenico, Pedro Pasquini, arXiv:1904.07265v1)

Why is the shape uncertainty very important for the near detector?

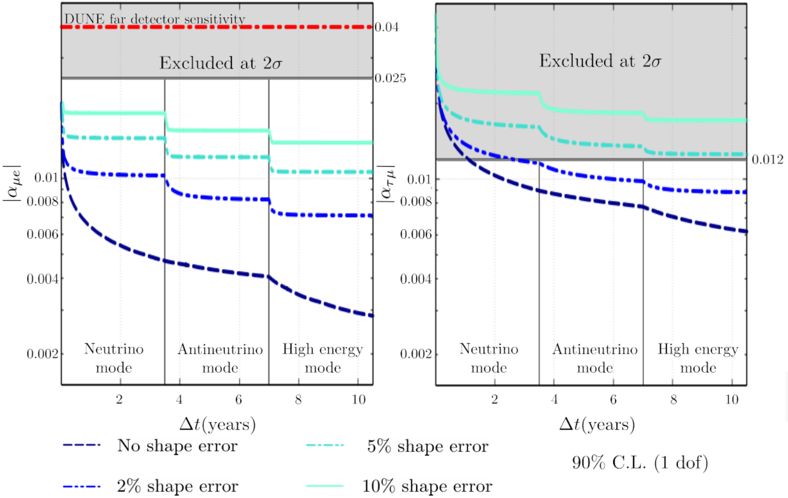


The sensitivity comes from the spectral information.

Type of systematics

- Global normalization error. Marginal impact on the sensitivity.
- **Shape uncertainty**: a normalization error in each energy beam. High impact on the sensitivity.

Appearance averaged-out results



Sterile neutrinos

ν_e appearance

$$P_{\mu e} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

ν_τ appearance

$$P_{\mu\tau} = 4|U_{\tau 4}|^2|U_{\mu 4}|^2 \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

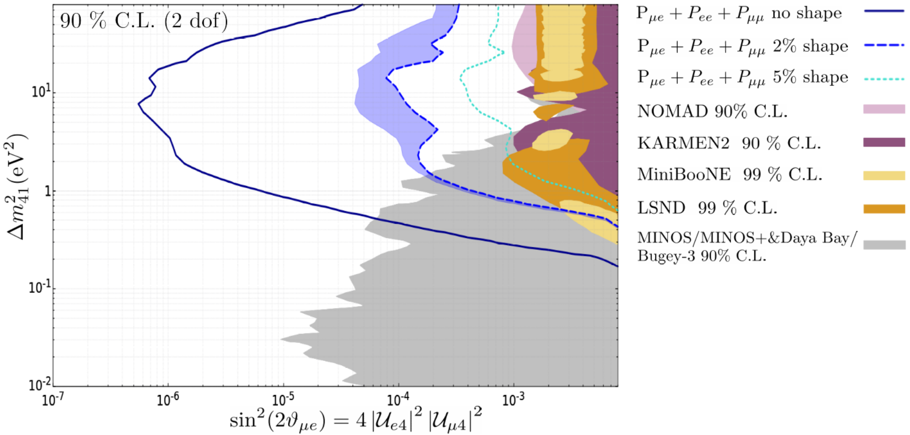
ν_e disappearance

$$P_{ee} = 1 - 4|U_{e4}|^2\left(1 - |U_{e4}|^2\right) \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

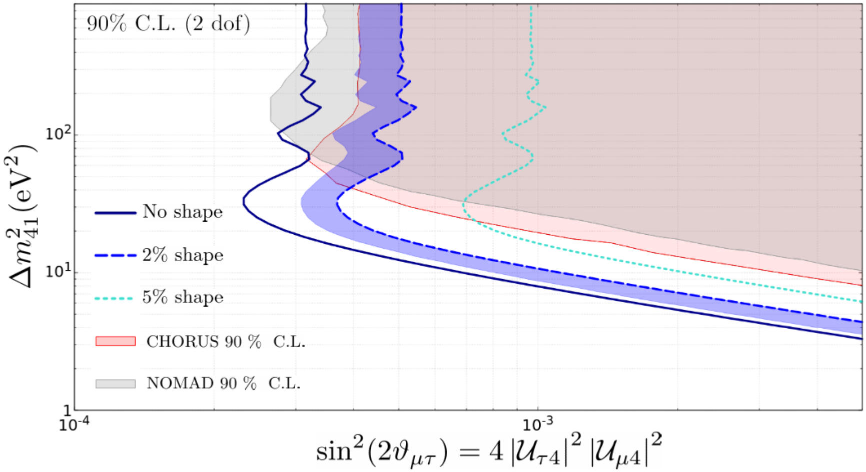
ν_μ disappearance

$$P_{\mu\mu} = 1 - 4|U_{\mu 4}|^2\left(1 - |U_{\mu 4}|^2\right) \sin^2\left(\frac{\Delta m_{14}^2 L}{4E}\right)$$

Combined analysis of the three channels $P_{\mu e} + P_{ee} + P_{\mu\mu}$



ν_τ appearance



Prospects and conclusions

- For the rest of the results, ν_e and ν_μ disappearance and NSI in production and detection check our paper arXiv:2105.11466.
- Whenever ratio signal background is very small and we obtain most of our information from the spectra, the energy shape uncertainty plays a dominant role.
- Efforts must be made to try to reduce the shape uncertainty as much as possible if we wish to have good sensitivity at this type of new physics measurements.
- Independent measurements of the cross sections can be made to improve on how well we know their energy dependence.
- Even with our more conservative and realistic implementation of systematic uncertainties, our results indicate that an improvement over current bounds is generally expected.

Thank you

Back-up

Fluxes and ν_τ cross section

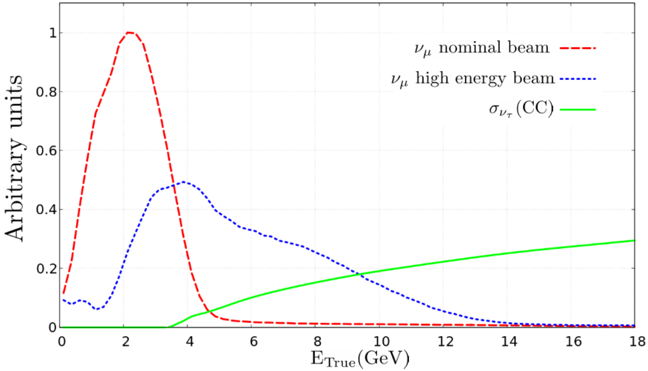


Figure: Comparison between the nominal ν_μ flux and the HE flux as a function of the neutrino energy, in arbitrary units. Both curves are shown for neutrino mode only; the comparison is qualitatively similar for the antineutrino running mode fluxes. For comparison, the ν_τ CC cross section is also shown.

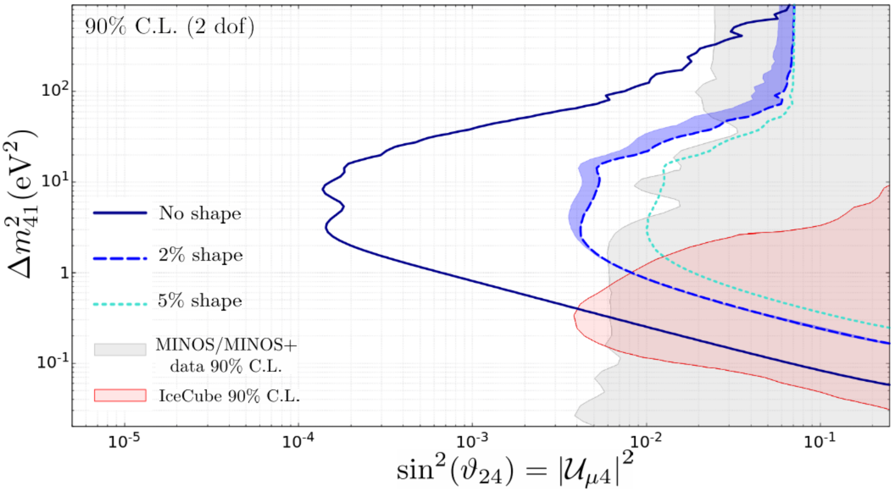
Present bounds

	"Non-Unitarity" $(m > \text{EW})$	"Light steriles" $\Delta m^2 \gtrsim 100\ \text{eV}^2$		"Light steriles" $\Delta m^2 \sim 0.1 - 1\ \text{eV}^2$	
α_{ee}	$1.3 \cdot 10^{-3}$	$2.4 \cdot 10^{-2}$	BUGEY	$1.0 \cdot 10^{-2}$	BUGEY
$\alpha_{\mu\mu}$	$2.2 \cdot 10^{-4}$	$2.2 \cdot 10^{-2}$	SK	$1.4 \cdot 10^{-2}$	MINOS
$\alpha_{\tau\tau}$	$2.8 \cdot 10^{-3}$	$1.0 \cdot 10^{-1}$	SK	$1.0 \cdot 10^{-1}$	SK
$\alpha_{\mu e}$	$6.8 \cdot 10^{-4}$ $(2.4 \cdot 10^{-5})$	$2.5 \cdot 10^{-2}$	NOMAD	$1.7 \cdot 10^{-2}$	
$\alpha_{\tau e}$	$2.7 \cdot 10^{-3}$	$6.9 \cdot 10^{-2}$		$4.5 \cdot 10^{-2}$	
$\alpha_{\tau\mu}$	$1.2 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$	NOMAD	$5.3 \cdot 10^{-2}$	

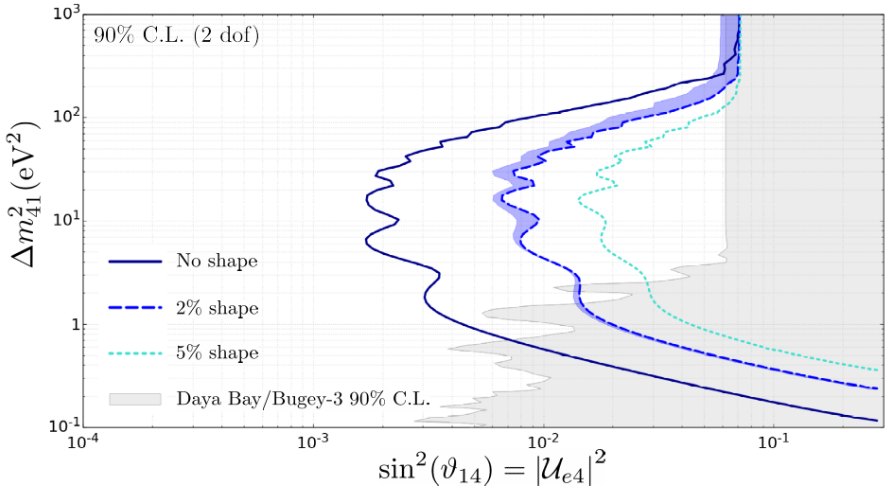
Fernandez-Martinez, Hernandez-Garcia, JLP
1605.08774
Blennow, Coloma, Fernandez-Martinez, Hernandez-Garcia, JLP
1609.08637

$$\alpha_{\alpha\beta} \leq 2\sqrt{\alpha_{\alpha\alpha}\alpha_{\beta\beta}}$$

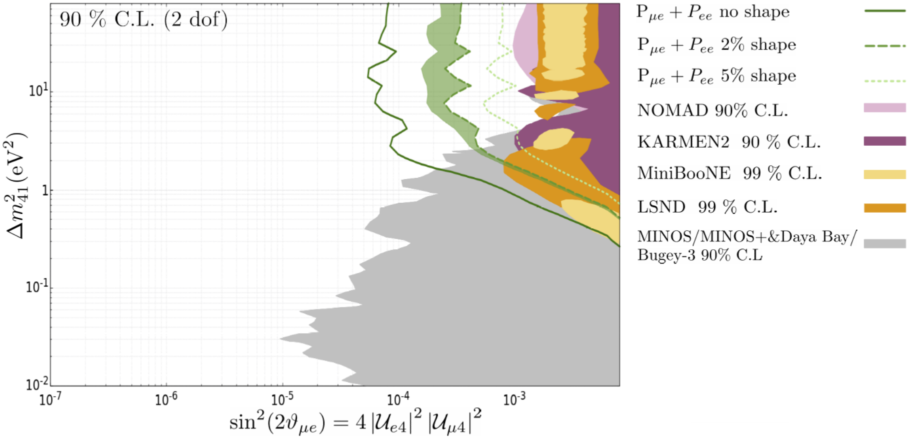
ν_μ disappearance



ν_e disappearance



$P_{\mu e} + P_{ee}$



90 % C.L. (2 dof)
10^{1}
1
10^{-1}
10^{-2}
$\Delta m^2_{41}\,(\mathrm{eV}^2)$
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
$\sin^2(2\vartheta_{\mu e}) = 4\,|\mathcal{U}_{e4}|^2\,|\mathcal{U}_{\mu 4}|^2$
$P_{\mu e} + P_{ee}$ no shape
$P_{\mu e} + P_{ee}$ 2% shape
$P_{\mu e} + P_{ee}$ 5% shape
NOMAD 90% C.L.
KARMEN2 90 % C.L.
MiniBooNE 99 % C.L.
LSND 99 % C.L.
MINOS/MINOS+&Daya Bay/
Bugey-3 90% C.L

NSI in detection and production(mapping)

Near detector probability

$$P_{\gamma\beta}(L=0) = \left|\left[\left(I+\epsilon^d\right)\left(I+\epsilon^s\right)\right]_{\beta\gamma}\right|^2 = |\epsilon^d_{\beta\gamma}|^2 + |\epsilon^s_{\beta\gamma}|^2 + 2|\epsilon^d_{\beta\gamma}||\epsilon^s_{\beta\gamma}|\cos(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma}),$$

Mapping with α parametrization

$$2|\alpha_{\beta\gamma}|^2 = |\epsilon^d_{\beta\gamma}|^2 + |\epsilon^s_{\beta\gamma}|^2 + 2|\epsilon^d_{\beta\gamma}||\epsilon^s_{\beta\gamma}|\cos(\Phi^s_{\beta\gamma} - \Phi^d_{\beta\gamma})\,.$$

NSI in detection and production(results)

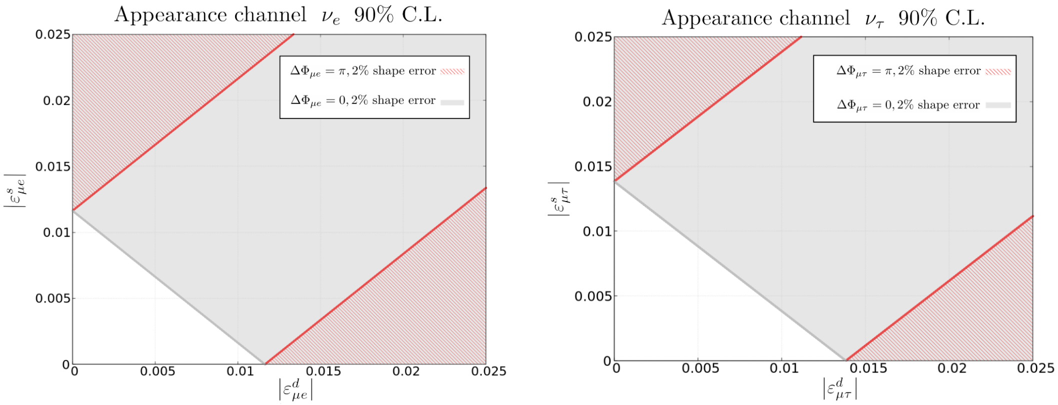


Figure: Sensitivity to NSI in production and detection. Results are shown for effects on the $P_{\mu e}$ (left panel) and $P_{\mu\tau}$ (right panel). In both panels the sensitivity is shown for the two limiting cases $\Delta\Phi = \pi, 0$, which lead to a destructive and constructive interference between production and detection NSI respectively.