Atmospheric neutrinos at ESSnuSB far detectors

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KTH Royal Institute of Technology

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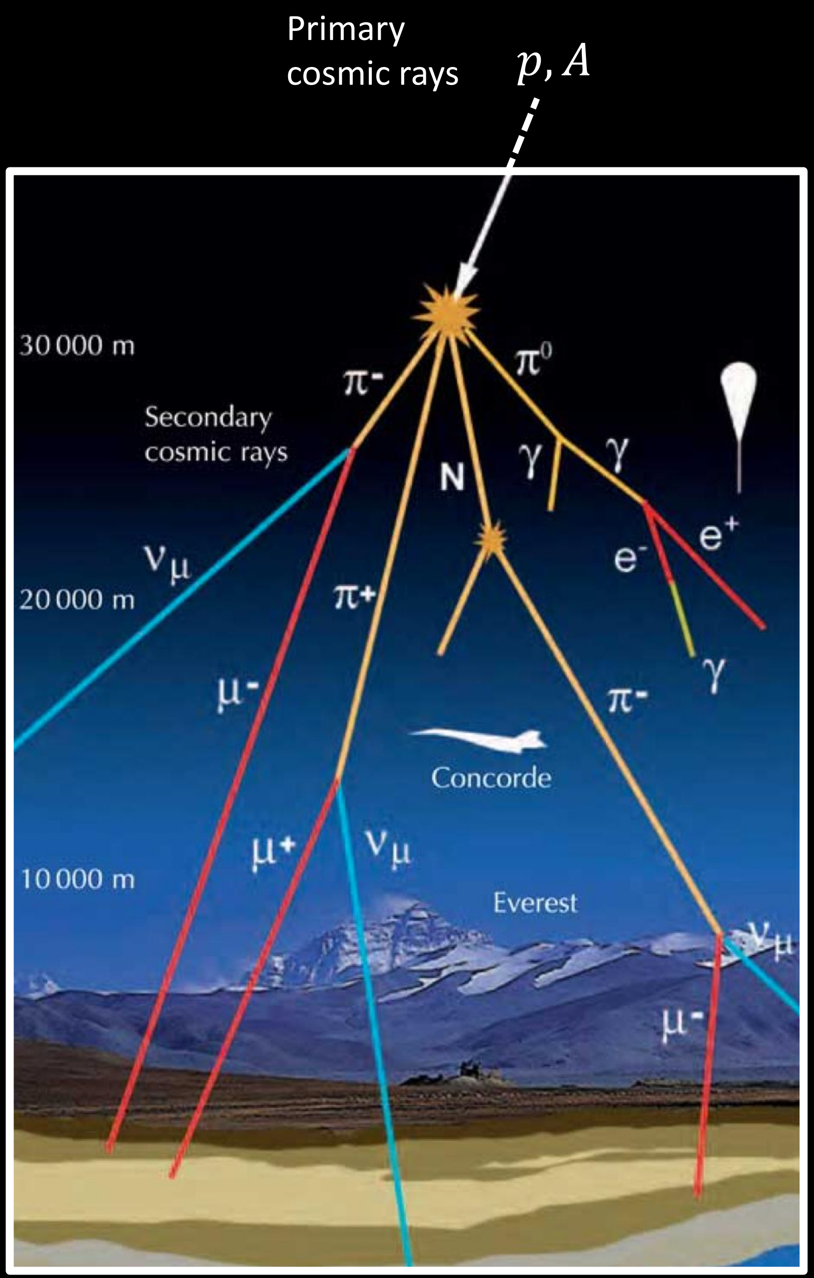


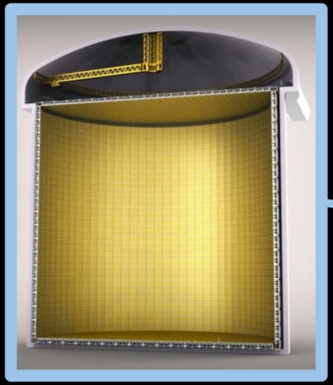
What are atmospheric neutrinos?

- **Originate in CR-interactions inside the atmosphere**
- **Energies from 0.1 GeV to PeV and beyond**
- **Common production processes:**

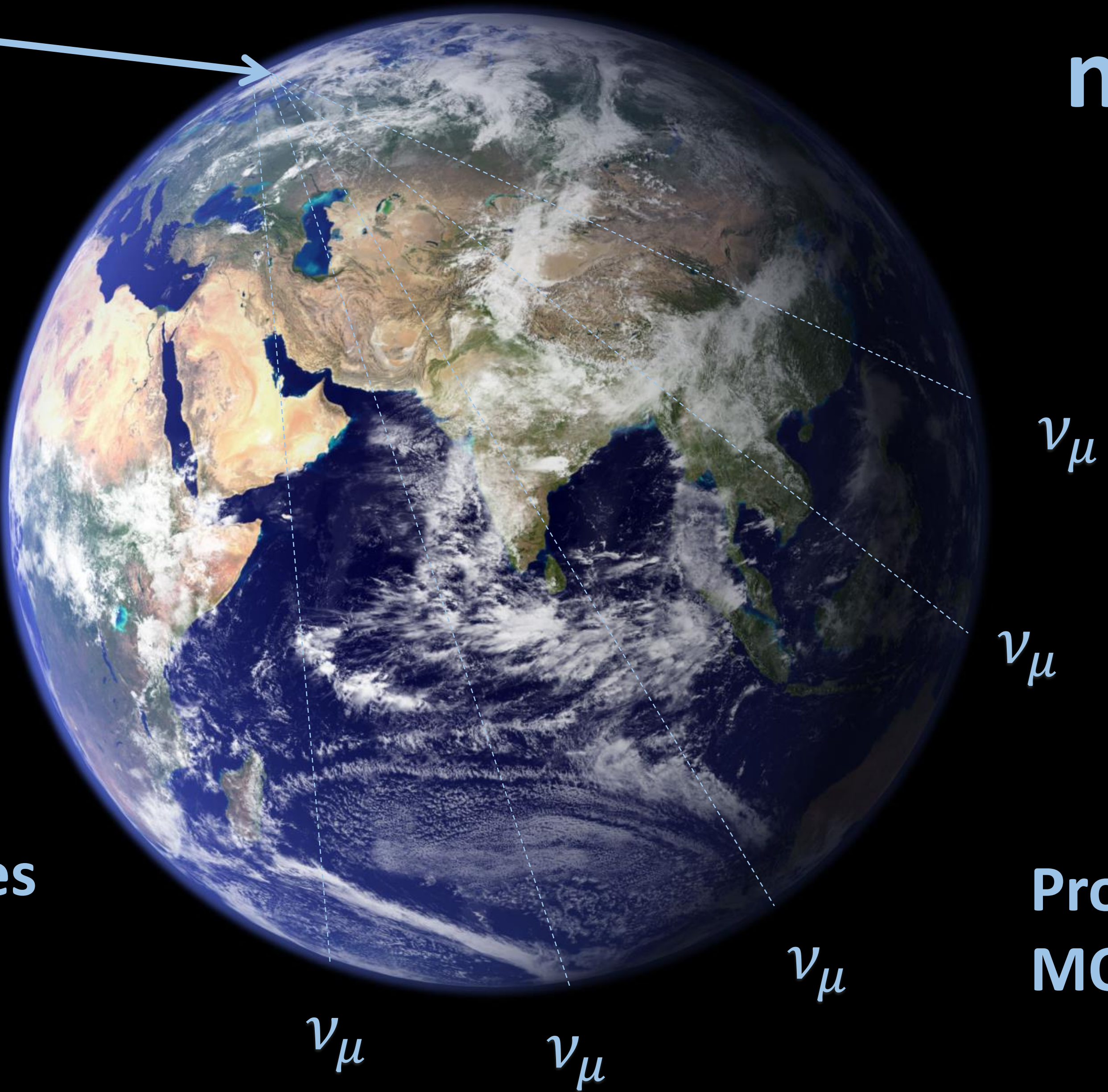
$$\boldsymbol{p}, \boldsymbol{A} + \text{air}$$
$$\rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}$$
$$\rightarrow \mu^{\pm}, \nu_{\mu}, \bar{\nu}_{\mu}$$
$$\rightarrow e^{\pm}, \nu_{e}, \bar{\nu}_{e}, \nu_{\mu}, \bar{\nu}_{\mu}$$

$$\pi^{+} \rightarrow \mu^{+}\nu_{\mu}$$
$$\mu^{+} \rightarrow e^{+}\bar{\nu}_{\mu}\nu_{e}$$

What are atmospheric neutrinos?



ESSnuSB

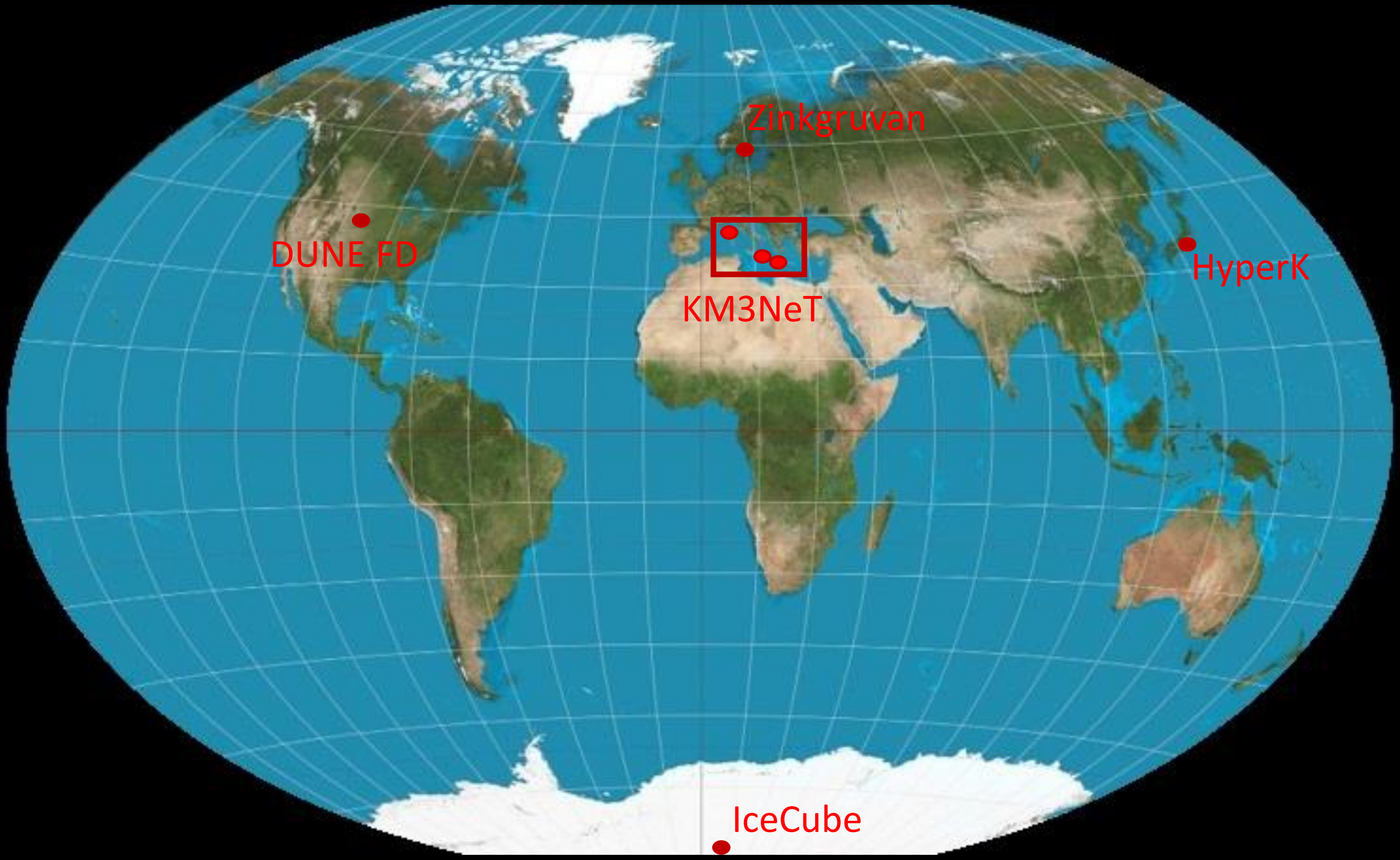


Propagation distances
$\sim$ 15km to 12700km

Prospects to study
MO, NSI, LIV *etc*

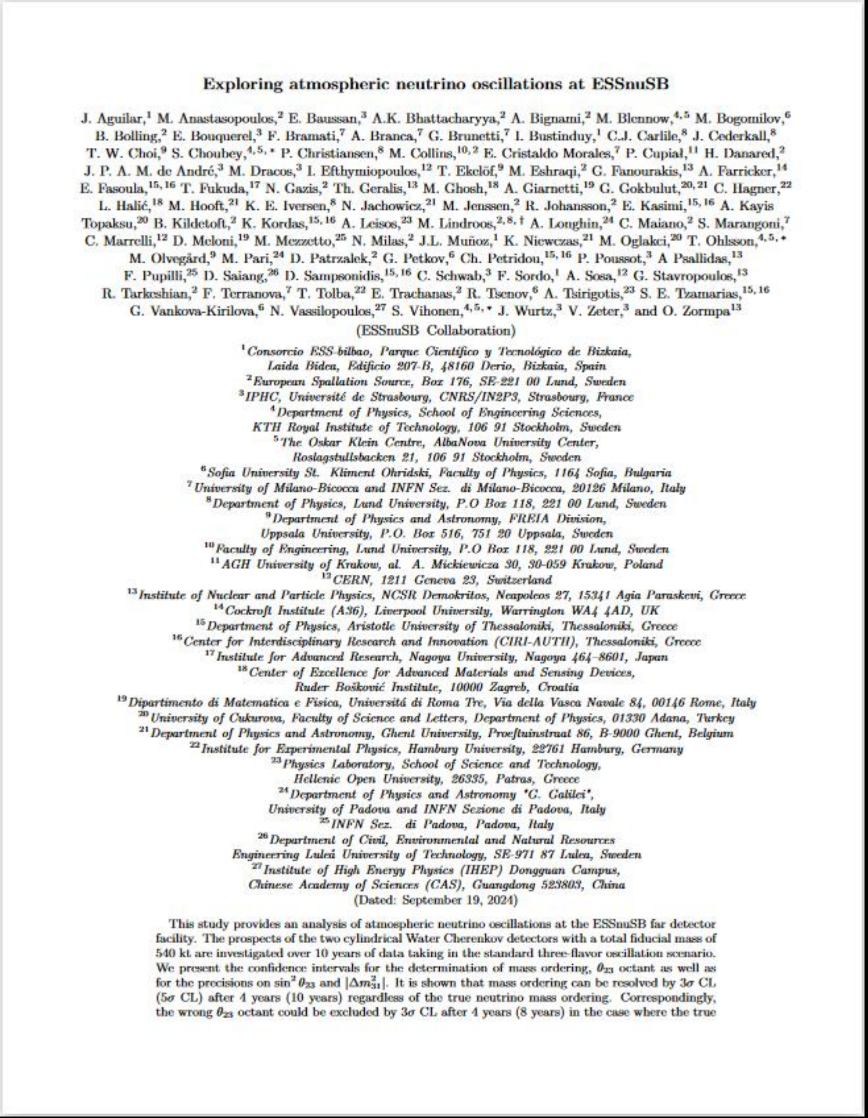
Advantages of ESSnuSB FD

- **Geographical location:** fluxes are stronger near the polar regions
- **Large fiducial mass:** ESSnuSB FD expected to have 540 kt
- **Complementarity:** synergies with the long-baseline program



Atmospheric neutrino research at KTH

- First atmospheric neutrino paper was finalized and submitted to arXiv in July 2024
- The paper discusses prospects of atmospheric neutrinos in the standard phenomenology
- Received a positive Referee report from JHEP, resubmission planned for Sep 30th, 2024
- New research has been started for studying NSI with atmospheric neutrinos from ESSnuSB



Exploring atmospheric neutrino oscillations at ESSnuSB

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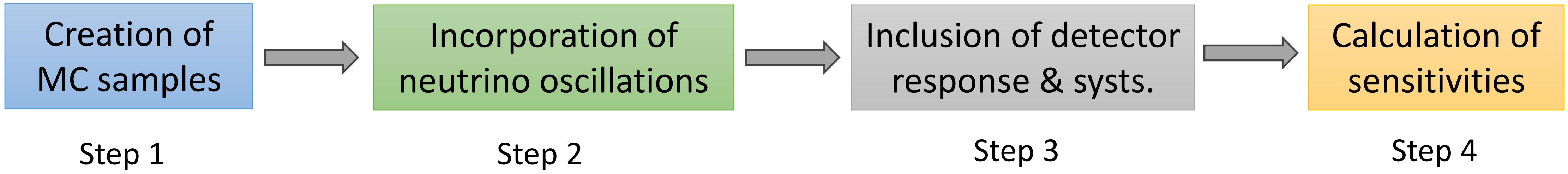
(Dated: September 19, 2024)

This study provides an analysis of atmospheric neutrino oscillations at the ESSnuSB far detector facility. The prospects of the two cylindrical Water Cherenkov detectors with a total fiducial mass of 540 kt are investigated over 10 years of data taking in the standard three-flavor oscillation scenario. We present the confidence intervals for the determination of mass ordering, θ_{23} octant as well as for the precisions on $\sin^2\theta_{23}$ and $|\Delta m^2_{31}|$. It is shown that mass ordering can be resolved by 3σ CL (5σ CL) after 4 years (10 years) regardless of the true neutrino mass ordering. Correspondingly, the wrong θ_{23} octant could be excluded by 3σ CL after 4 years (8 years) in the case where the true

Simulating atmospheric neutrinos for ESSnuSB FD

How?



Creation of the MC samples

- MC samples generated for 100 years
- Atmospheric fluxes based on Honda simulations for Pyhäsalmi
- A ROOT geometry of two cylindrical WC vessels used for ESSnuSB FD
- MC samples normalized for desired exposures (default: 10 years)

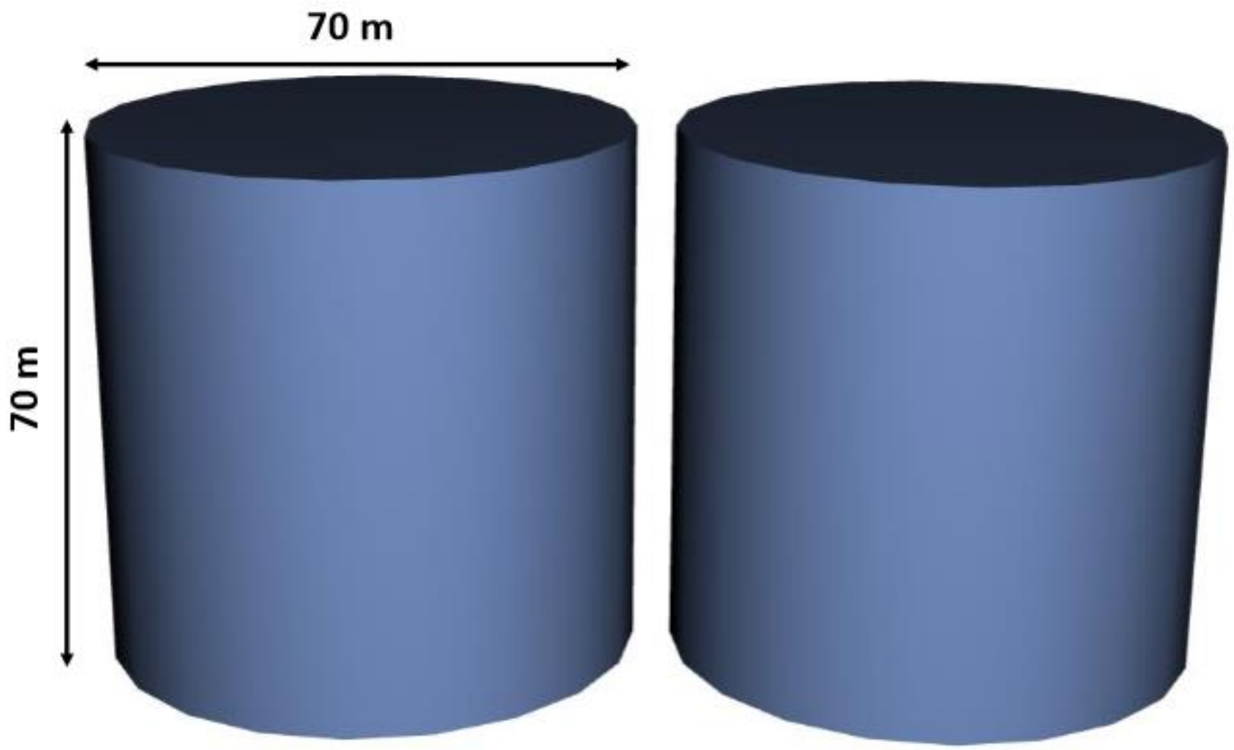


Illustration of the ROOT geometry

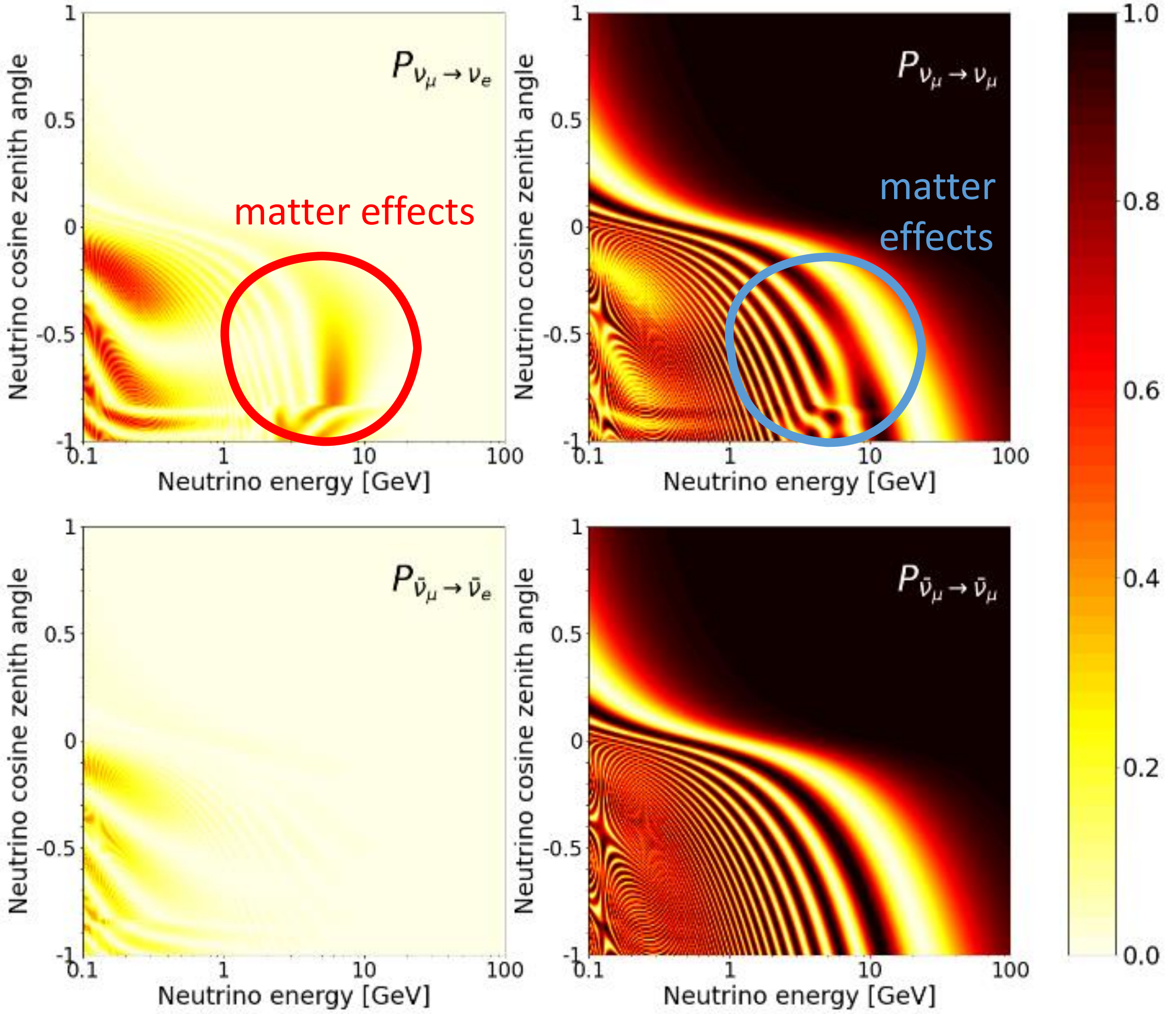
Neutrino oscillations

- Probabilities computed with GLoBES
- Baseline lengths calculated from neutrino cosine zenith angles:

$$L = \sqrt{(R+h)^2 - (R-d)^2 \sin^2\theta_z} - (R-d)\cos\theta_z \,,$$

R = Earth's radius,
h = neutrino creation height,
d = depth of neutrino detector.

Our configuration: R = 6371 km, h = 15 km and d = 1 km.



Probabilities for normal ordering (NO)

Detector response

In absence of the full detector simulation, a bin-based approach is adopted to model the detector response.

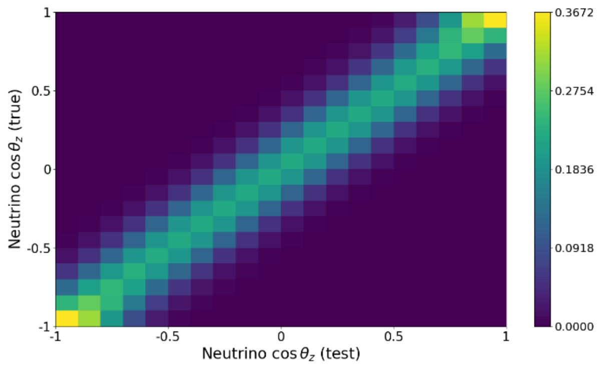
Detector response consists of three parts:

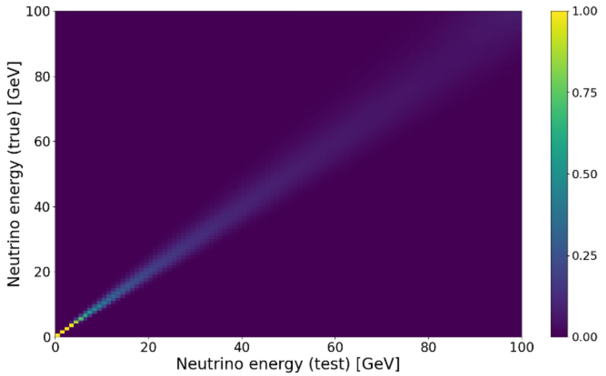
- Bin-based Gaussian smearing
- Detector efficiencies
- Systematic uncertainties

Event folding:

$$E_{ij} = \underbrace{N_{\text{norm}}}_{\text{Norm. factor}} \sum_{k=1}^{100} \sum_{l=1}^{20} \underbrace{K_i^k(E,E')}_{\text{Energy smearing}} \underbrace{M_j^l(\theta_z,\theta_z')}_{\text{Angular smearing}} \left[\underbrace{\epsilon_{ij}}_{\text{Detector efficiencies}} \overbrace{n_{ij}}^{\text{Raw events }(\nu)} + \underbrace{\bar{\epsilon}_{ij}}_{\text{Detector efficiencies}} \overbrace{n_{ij}}^{\text{Raw events }(\bar{\nu})} \right]$$

Gaussian smearing:





Systematic uncertainties:

Systematic error	Uncertainty
Flux normalization	20%
Cross-section normalization	10%
Zenith angle dependence	varies
Energy tilt	varies
Detector	5%

References for systematics:

1. M.C. Gonzalez-Garcia and M. Maltoni, Phys. Rev. D 70 (2004) 033010
2. A. Ghosh, T. Thakore and S. Choubey, JHEP 04 (2013) 009

Numerical analysis of the MC events

Analysis method:

$$\chi^2 = 2\sum_{n=1}^{2000}\left(E_n - O_n + O_n \log\frac{O_n}{E_n}\right) + \sum_{i=1}^{5}\left(\frac{\zeta_i}{\sigma_i}\right)^2$$

$$E_n = E_{n,0}\left(1 + \sum_{i=1}^{5} f_{n,i}\zeta_i\right)$$

Scan ranges:

Scan parameter	True value	Scan range	Scan points
$\sin^2\theta_{12}$	0.303	0.303	fixed
$\sin^2\theta_{13}$	0.02225	0.02225	fixed
$\sin^2\theta_{23}$	0.451	[0.4, 0.6]	50 points
δ_{CP}	1.29π	$[0, 2\pi)$	4 points
Δm^2_{21}	7.41×10^{-5} eV	7.41×10^{-5} eV	fixed
$\lvert\Delta m^2_{31}\rvert$	$2.507\times10^{-3}\mathrm{eV}^2$	$[2.40, 2.60]\times10^{-3}$ eV^2	50 points

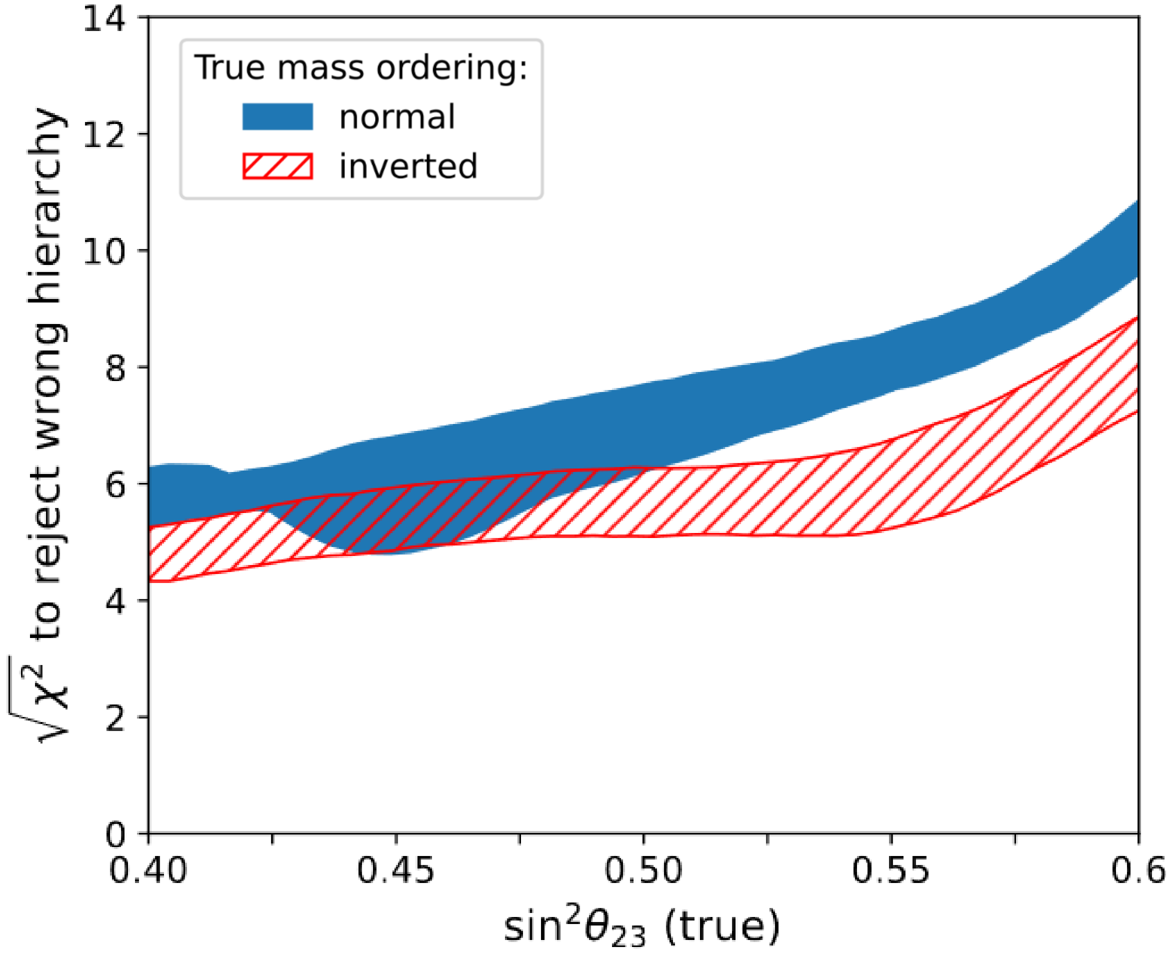
Sensitivities to MO and θ_{23} octant:

$\Delta\chi^2_{\mathrm{MO}} = \chi^2_{\mathrm{wrong-MO}} - \chi^2_{\mathrm{true-MO}}$, $\Delta\chi^2_{\mathrm{octant}} = \chi^2_{\mathrm{wrong-octant}} - \chi^2_{\mathrm{true-octant}}$

Example: $\Delta\chi^2_{\mathrm{MO}} = \chi^2_{\mathrm{IO}} - \chi^2_{\mathrm{NO}}$ when true mass ordering is NO

Main results

- **Sensitivity to neutrino mass ordering**
- Sensitivity to octant of θ_{23}
- Precisions on $\sin^2\theta_{23}$ and $|\Delta m^2_{31}|$
- Time-evolution of the sensitivities



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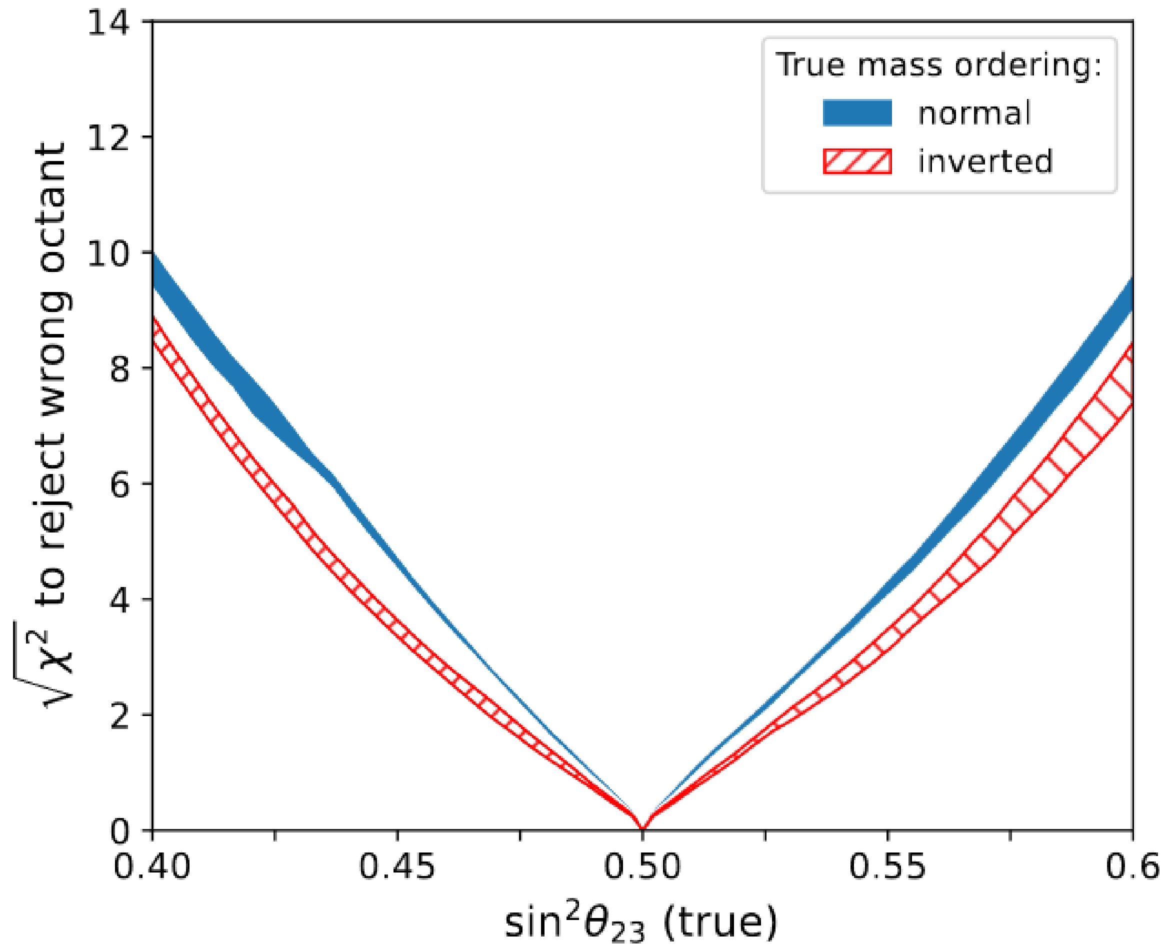

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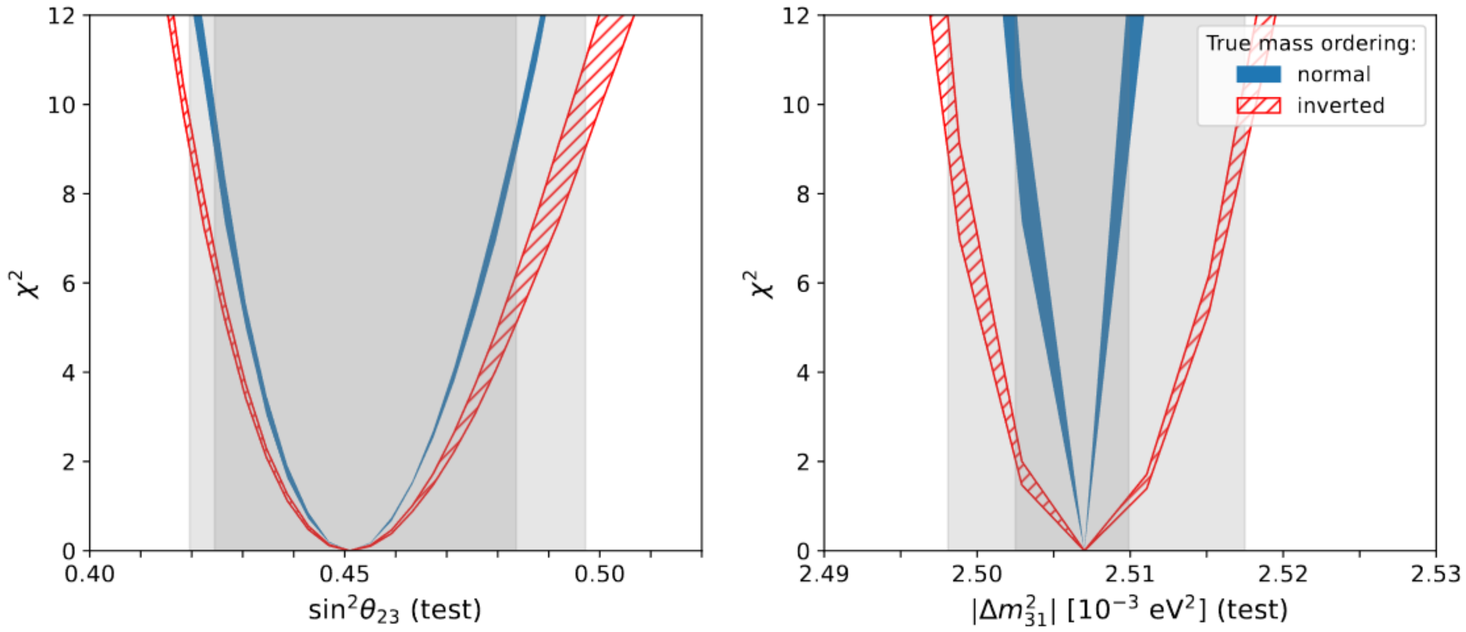

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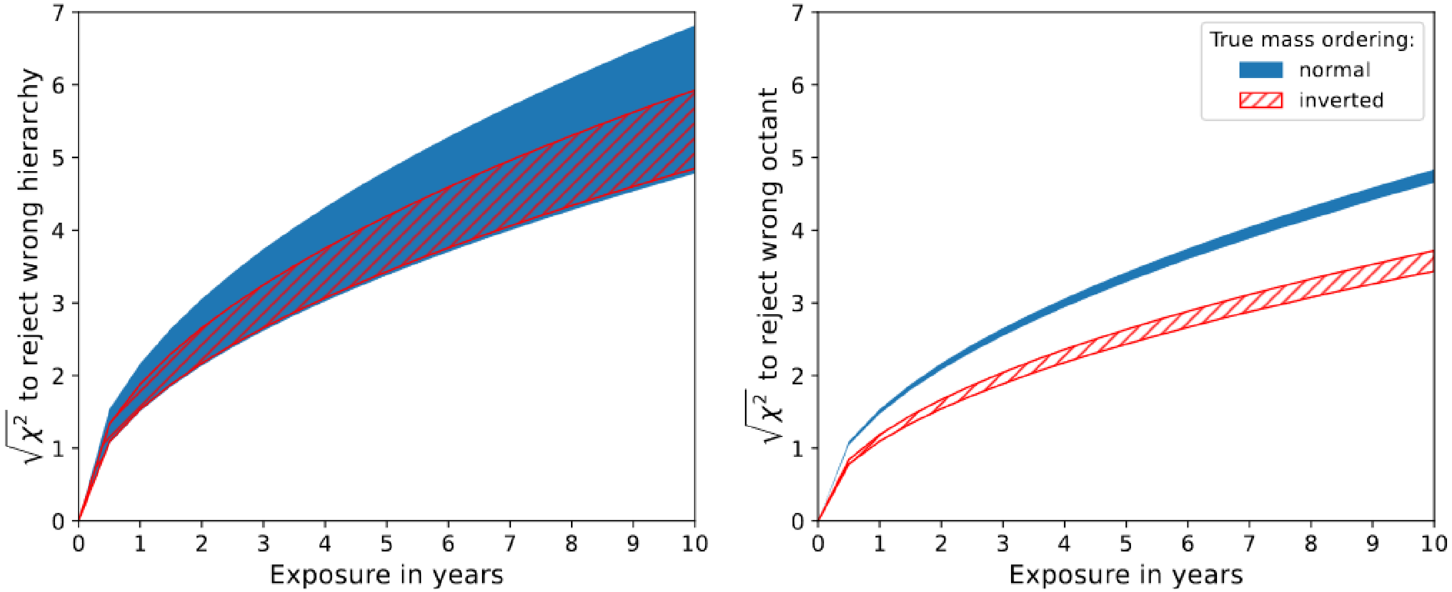


Future outlook

Non-Standard Interactions (NSI)

Effects on neutrino propagation:

$$H_{\text{eff}} = \frac{1}{2E_\nu}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger + 2\sqrt{2}E_\nu G_F N_e \underbrace{\begin{pmatrix}1+\epsilon^m_{ee} & \epsilon^m_{e\mu} & \epsilon^m_{e\tau}\\ \epsilon^{m\,*}_{e\mu} & \epsilon^m_{\mu\mu} & \epsilon^m_{\mu\tau}\\ \epsilon^{m\,*}_{e\tau} & \epsilon^{m\,*}_{\mu\tau} & \epsilon^m_{\tau\tau}\end{pmatrix}}_{\text{Standard + NSI matter potentials}}\right]$$

Effective Lagrangians:

$$\mathcal{L}^{CC}_{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{ff',C}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma^\mu P_C f')$$

$$\mathcal{L}^{NC}_{\text{NSI}} = -2\sqrt{2}G_F\epsilon^{f,C}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma^\mu P_C f)$$

Effective parametrization:

$$\epsilon^m_{\alpha\beta} = \left|\epsilon^m_{\alpha\beta}\right|e^{-i\phi^m_{\alpha\beta}}$$

3 + 3 new parameters (9 in total)

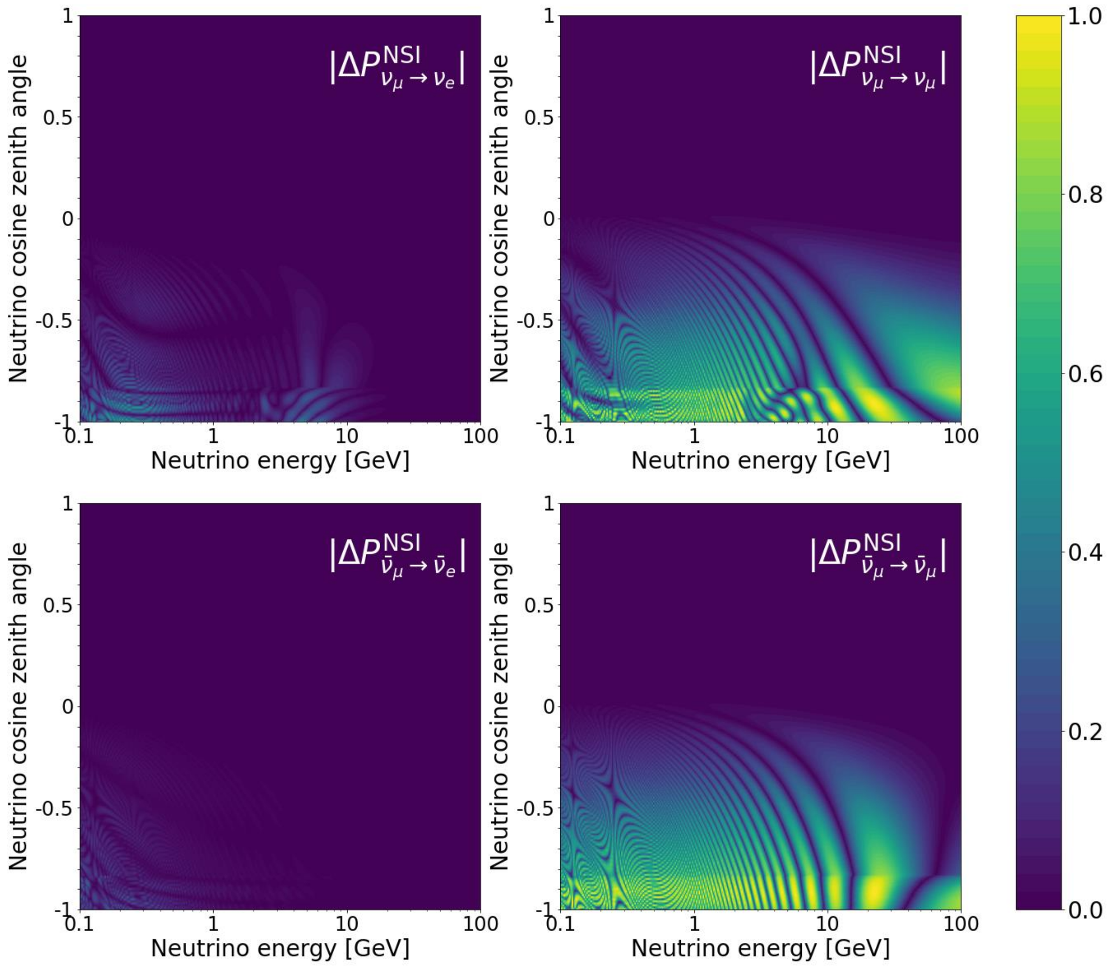
Future outlook

Non-Standard Interactions (NSI)

$$\Delta P^{\mathrm{NSI}}_{\nu_\alpha \to \nu_\beta} = P^{\mathrm{NSI}}_{\nu_\alpha \to \nu_\beta} - P^{\mathrm{SI}}_{\nu_\alpha \to \nu_\beta}$$

Probabilities computed with NSI effects

Standard probabilities obtained without NSI



Oscillograms for $|\epsilon^m_{\mu\tau}| = 0.1$ and $\phi^m_{\mu\tau} = 0$

Summary

- Atmospheric neutrinos are one of the most formidable natural neutrino sources
- We studied the physics prospects of detecting atmospheric neutrinos at ESSnuSB
- Our study found that MO can be resolved by 3σ (5σ) CL after 4 years (10 years)
- Next work investigates matter NSI in atmospheric neutrino oscillations (ongoing)