DEEP UNDERGROUND NEUTRINO EXPERIMENT

Sterile neutrino search with atmospheric neutrinos in DUNE

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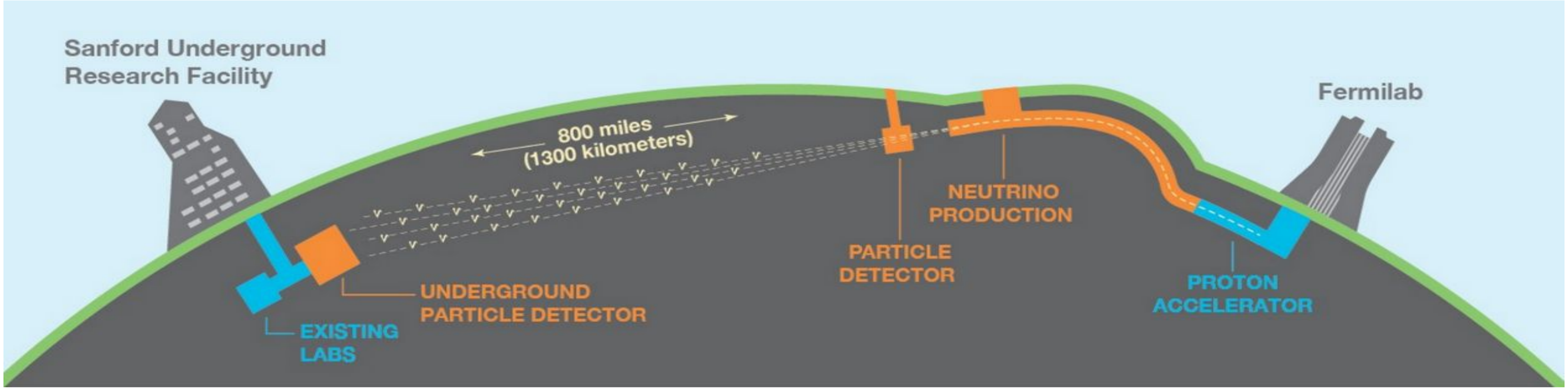
Presentation of DUNE

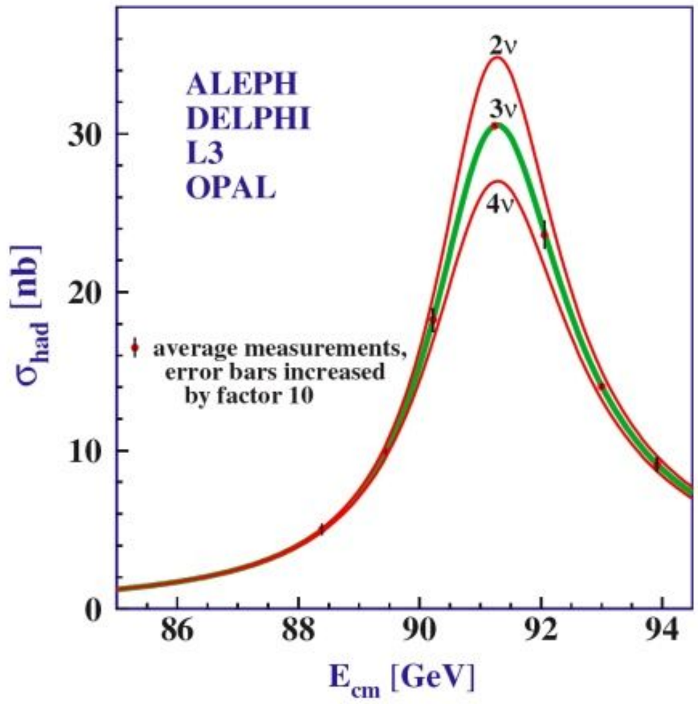


Goals

- Charge parity violation phase
- Neutrino mixing angles
- Neutrino mass hierarchy
- Search for proton decay
- Study of supernovae neutrinos

- **Neutrino beam** energy: 0.5 to 8 GeV
- **Near Detector** at 575m from the source
- **Far Detector (FD)** 1.5 km underground
- 4 LArTPCs modules of **17.5 kt each**

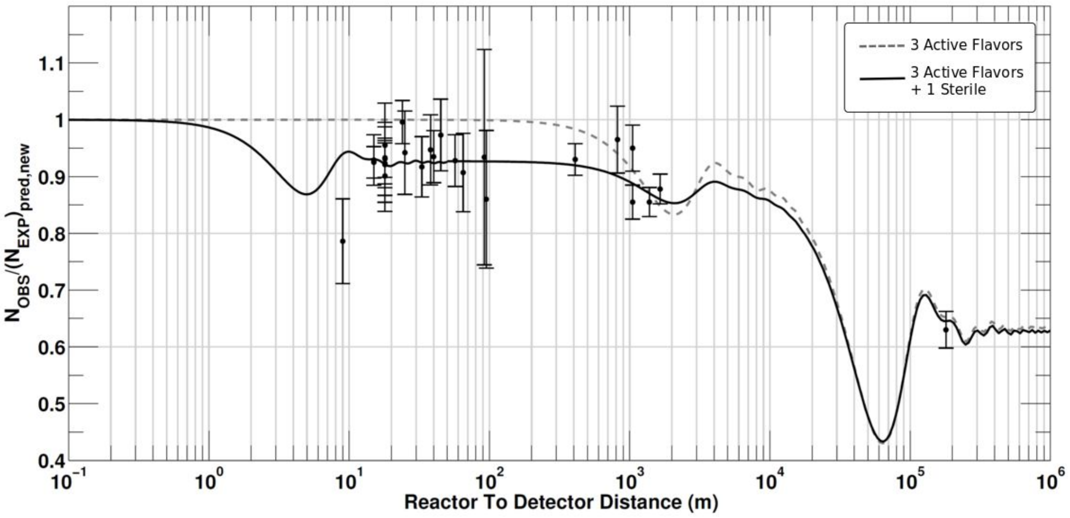
Sterile neutrinos



While the 3 neutrino model is a good fit to most measurements, multiple anomalies have been detected by different experiments

If we add a new neutrino to the model, it has to be sterile i.e. interacting only through gravitational interaction and neutrino oscillation

Sterile neutrinos



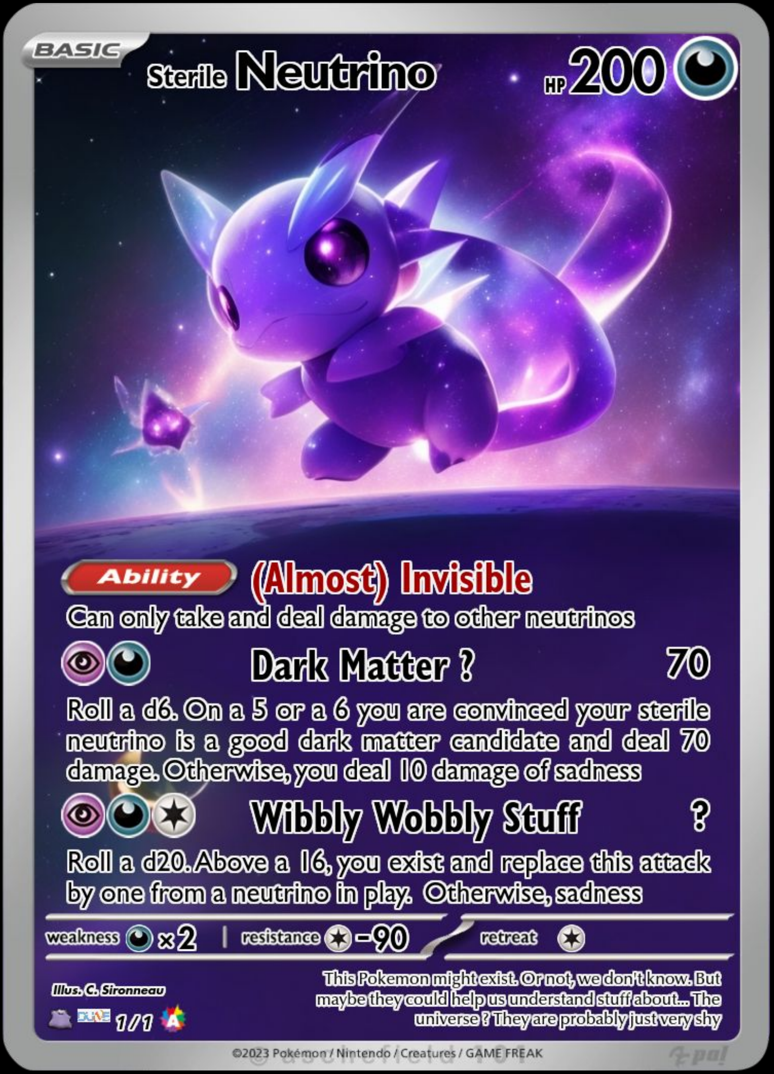
RAA: anomalies measured by multiple experiments in the total flux and energy spectrum of reactor anti neutrinos

Also :

- excess of anti (electron neutrinos) in anti (muon neutrinos) beam was shown in LSND
- anomaly confirmed by MiniBooNE
- neutrino rate deficit in calibration runs in the Gallium solar nu experiments

→ Anomalies studied (and confirmed) by multiple experiments but the best fit point for 4nu model is usually ruled out (i.e. STEREO)

Looking for this little guy



Recent sterile studies

- **Reactor experiments :**

→ **Double Chooz**, explores $\Delta m^2 \sim 0.1\ ev^2$

→ **PROSPECT** and **STEREO** study the Reactor Antineutrino Anomaly (RAA) and have both excluded the best fit of RAA sterile nu with $\Delta m^2 \sim 1\ ev^2$ (papers from 2021 and 2023)

→ Future : **JUNO** with **RENO 50** sensitive to "super light sterile neutrino" ($\Delta m^2 \sim 10^{-5}\ ev^2$)

- **Accelerator experiments :**

→ **LSND**, low energy beam of anti numu, look for excess in nue events

→ **MiniBooNE**, higher energies but same L/E

→ **T2K**, no evidence of sterile mixing in "3+1" model (2019 paper)

- **Atmospherics / cosmic rays :**

→ **IceCube**, sensitive to high energy events

→ **KM3NeT**, no analysis yet but expected sensitivity

→ **SuperK**, set limit on sterile mixing to tau and mu (no delta sensitivity)

- **Gallium based solar nu experiments :**

→ **GALLEX**, **SAGE**, **BEST** : anomalies could be explained with $\Delta m^2 \sim 1\ ev^2$

Sterile neutrinos in DUNE

- We can use **beam neutrinos and higher L/E** to constrain more the sterile mixing parameters → ongoing work
- **Atmospheric neutrinos** can nicely complement the studies with beam neutrinos:

  → **wider range of L/E**

  → extra probe for sterile neutrinos with a **different source**

  → easier **comparison** with other ongoing or future experiments detecting atmospherics (KM3NeT, IceCube, Super-K, Hyper-K)

  → explore whether DUNE **energy and angular resolution** can be of advantage

(myself included)

Preliminary study

- Focus on **atmospheric neutrinos**
- The addition of a neutrino in the model changes oscillation probabilities
  → produce **appearance or disappearance** of neutrino flavours depending on energy/angle
- Compare expected number of events assuming Standard Model and “3+1” model with one sterile neutrino
- Example of calculation done for **numu** (everything is **also done for nue**)
- Focus on **CC interactions and NO** at first

$$N_{exp,ev} = [(\phi_{\nu_\mu} P_{\mu\mu} + \phi_{\nu_e} P_{e\mu})\sigma_{\nu_\mu} + (\phi_{\overline{\nu_\mu}} P_{\overline{\mu\mu}} + \phi_{\overline{\nu_e}} P_{\overline{e\mu}})\sigma_{\overline{\nu_\mu}}] \cdot N_{Ar} \cdot \Delta E \cdot \Delta\theta_z \cdot \Delta t$$

Atmospheric neutrino flux for different flavors → Honda flux for Homestake

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Oscillation probabilities to numu or numu_bar

Preliminary study

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Interaction cross section with Ar40

Preliminary study

- Focus on **atmospheric neutrinos**
- The addition of a neutrino in the model changes oscillation probabilities
  → produce **appearance or disappearance** of neutrino flavours depending on energy/angle
- Compare expected number of events assuming Standard Model and "3+1" model with one sterile neutrino
- Example of calculation done for **numu** (everything is **also done for nue**)
- Focus on **CC interactions and NO** at first

$$N_{exp,ev} = [(\phi_{\nu_\mu} P_{\mu\mu} + \phi_{\nu_e} P_{e\mu})\sigma_{\nu_\mu} + (\phi_{\overline{\nu_\mu}} P_{\overline{\mu\mu}} + \phi_{\overline{\nu_e}} P_{\overline{e\mu}})\sigma_{\overline{\nu_\mu}}] \cdot N_{Ar} \cdot \Delta E \cdot \Delta\theta_z \cdot \Delta t$$

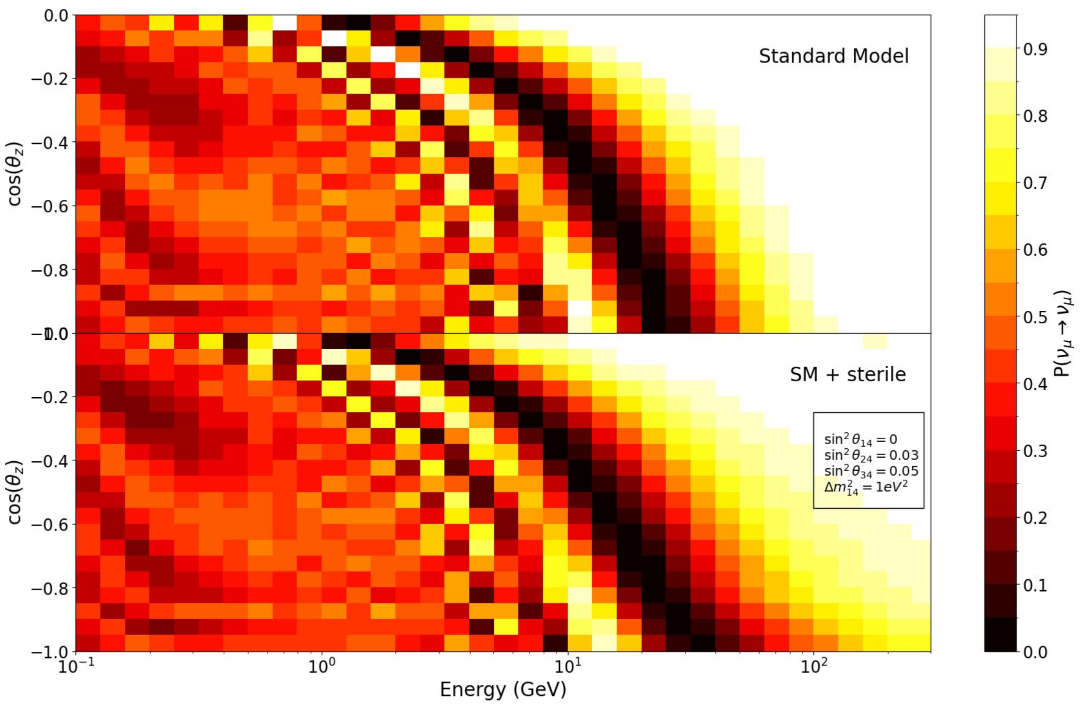
$$N_{Ar} = \frac{m_{det}}{m_{Ar40}}$$

Number of target atoms

Δt : time of data taking in seconds

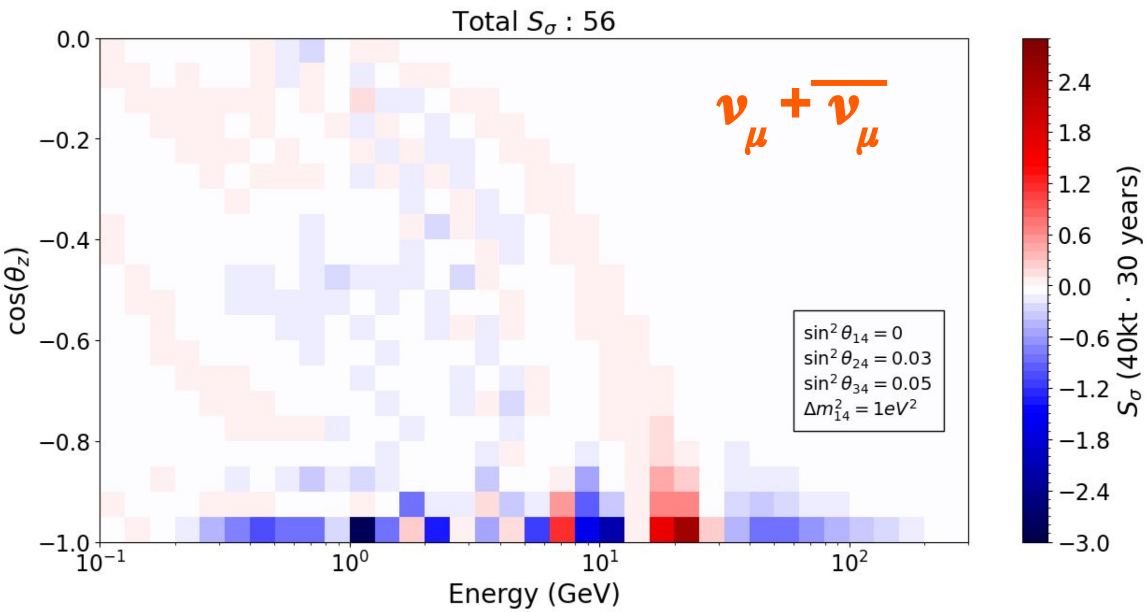
$\Delta E \,, \Delta\theta_z$: width of the bins used for the histograms (binning is based on the flux histograms)

Probability computation



- The **oscillation probabilities** are calculated using the OscProb code available on GitHub: https://github.com/joaoabcoelho/OscProb
- Here show survival probability of numu for SM and "3+1" model assuming NO
- Put sterile CP violating phases to 0
- Probability averaged on each energy bin
- Active mixing angles from **nuFit v5.2** with Kamiokande atmospherics data (http://arxiv.org/abs/2007.14792, http://www.nu-fit.org)

Sensitivity estimator



Use a quick estimator of the sensitivity as a **preliminary probe** to compare with the results from a KM3NeT/ORCA paper (https://arxiv.org/pdf/2107.00344.pdf)

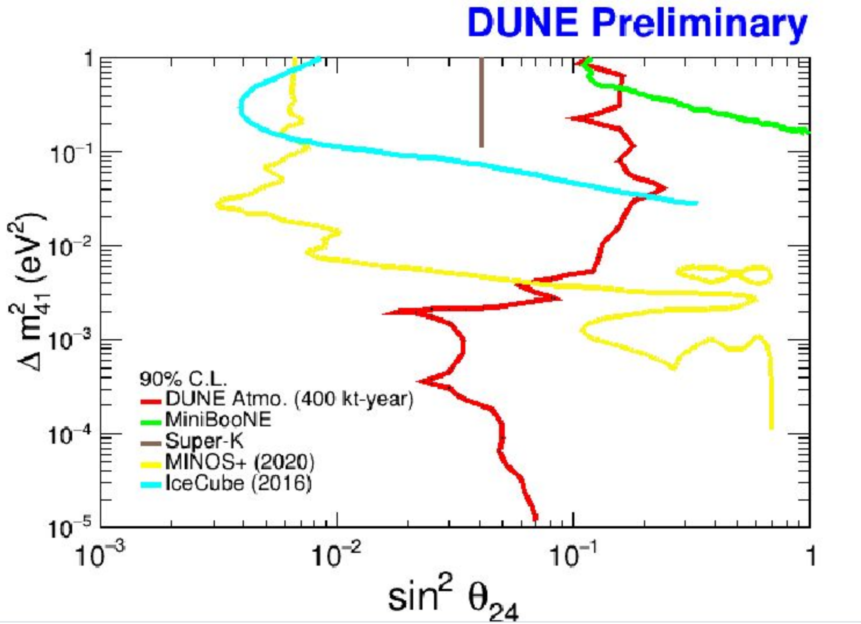
→ **the results seem to be coherent, encouraging**

Reminder : detector effects not included yet so we can compare without too many issues

$$S_\sigma = \frac{(N_{sterile} - N_{standard}) \mid N_{sterile} - N_{standard} \mid}{N_{sterile}}$$

← **similar to gaussian signed chi2**

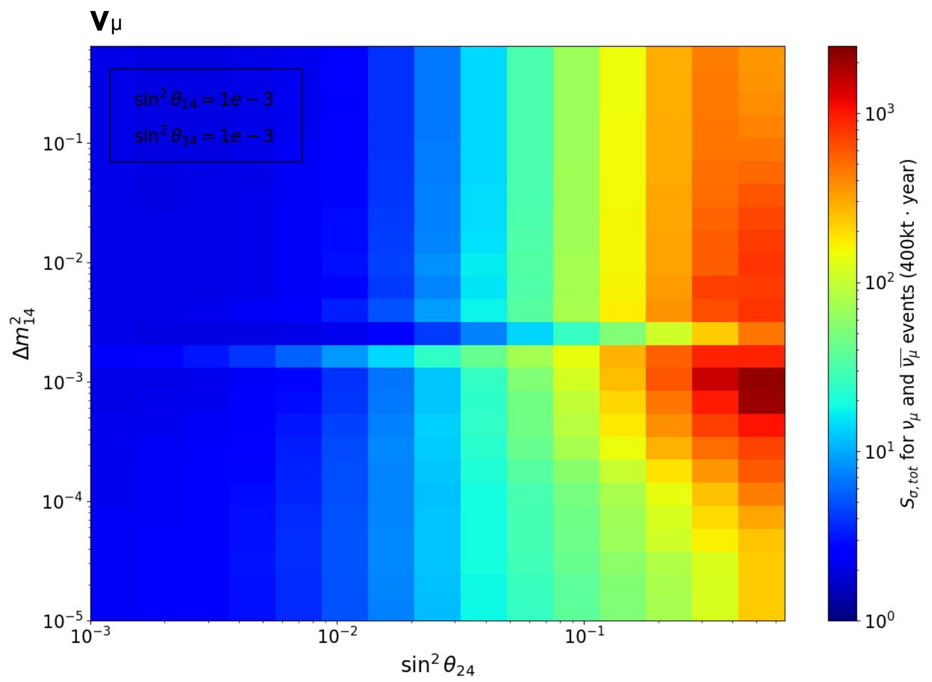
Sensitivity estimator

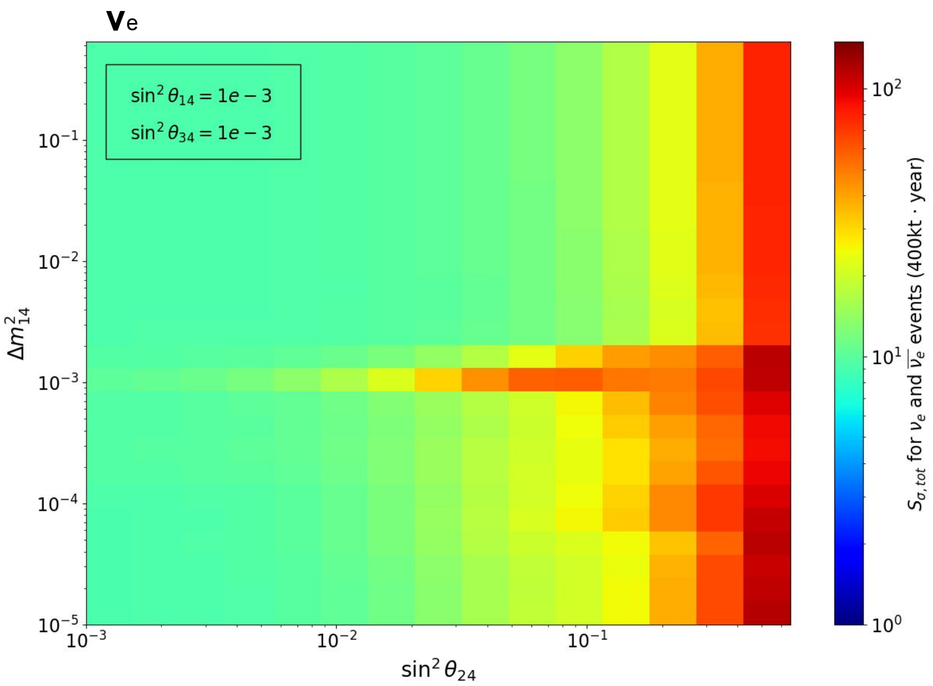


Tarak Thakore: *"Sensitivity to Neutrino Mass Ordering and sterile neutrino model parameters with atmospheric neutrinos measurements at DUNE"*

- Taking S_σ as an intermediate step towards a sensitivity estimation
- Goal: compare with previous simple DUNE study → https://indico.kps.or.kr/event/30/contributions/503/
- Need to fix values of other mixing parameters: $\sin^2\theta_{14}$ and $\sin^2\theta_{34}$ —> chose minimum value for simplicity → **10^{-3} for both $\sin^2\theta_{14}$ and $\sin^2\theta_{34}$**
- Effect of variations under study
- See if we get something somewhat close to this distribution with our S_σ estimator summed over all the bins
- Also change exposure to **400kt . year** → more realistic value

Sensitivity estimator

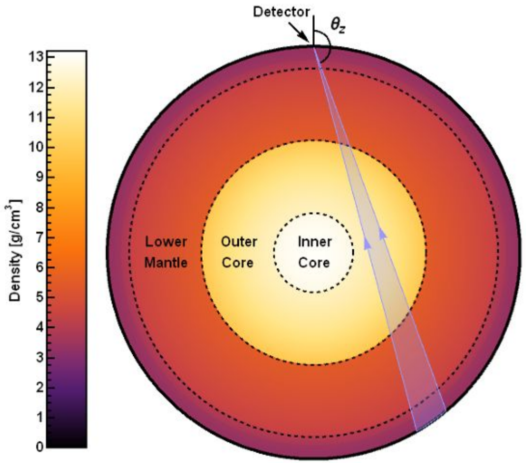




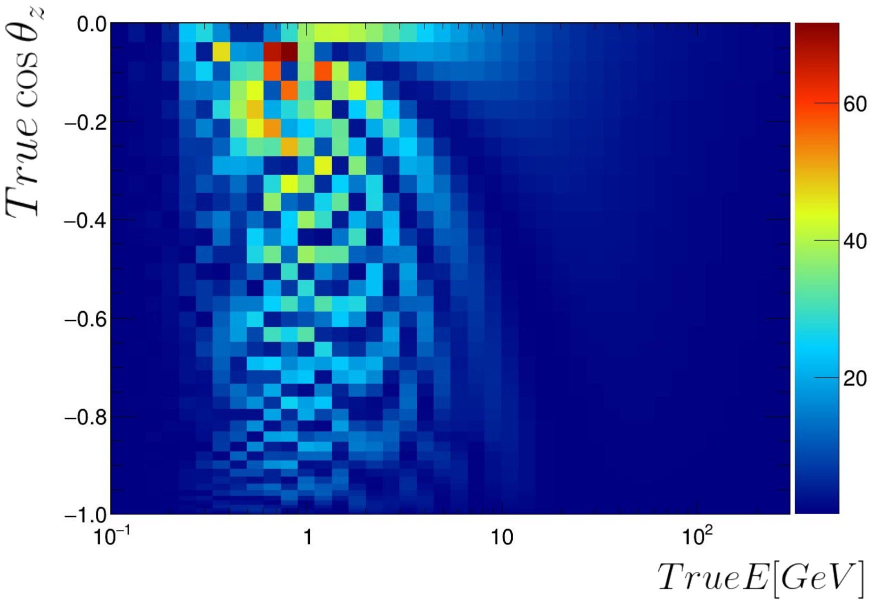
See semblance of the same shape so it's encouraging → **contour plots in the future** to confirm, as this is a rough estimator

EarthProbe

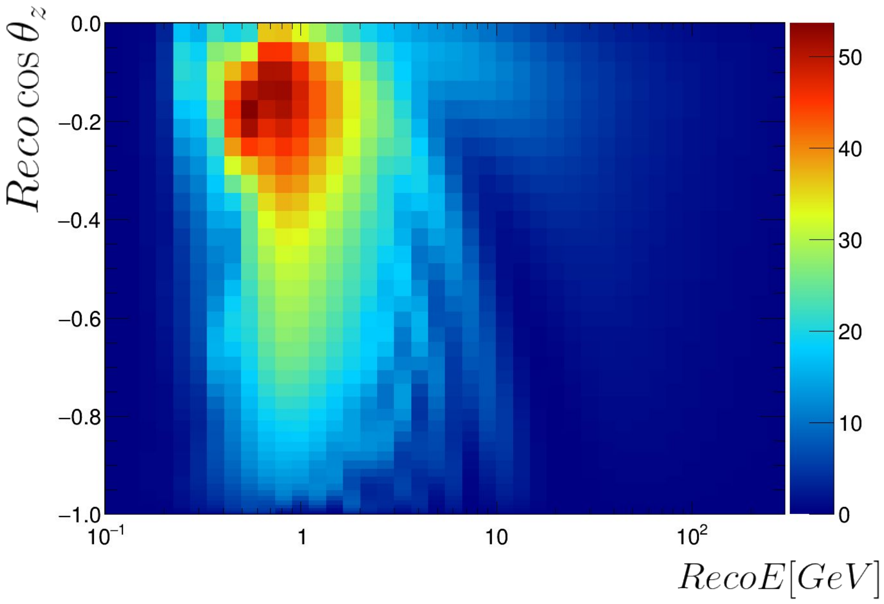
- Code co-written by Joao : **EarthProbe** (https://gitlab.in2p3.fr/apc-tomography/earthprobe)
- Initially designed to use atmospheric neutrino oscillations to study Earth's composition
- (My) **current work**: extend the code to do neutrino oscillation studies and **sterile neutrino search**
- EarthProbe includes **OscProb** and manages :
  - **flux and xsec** histograms
  - **detector** specificities
  - number of events computation
  - reconstruction **efficiency**
  - oscillation probabilities
  - analysis → likelihood computations and parameter fitting using **Minuit2**



EarthProbe



Number of **interacting (true) ν_μ events** expected for an exposure of 400kt . year in the SM hypothesis using a DUNE type detector



ν_μ events tagged as "tracks" after applying some energy, angle and PID **reconstruction efficiencies** (a priori not realistic values, shown as an example)

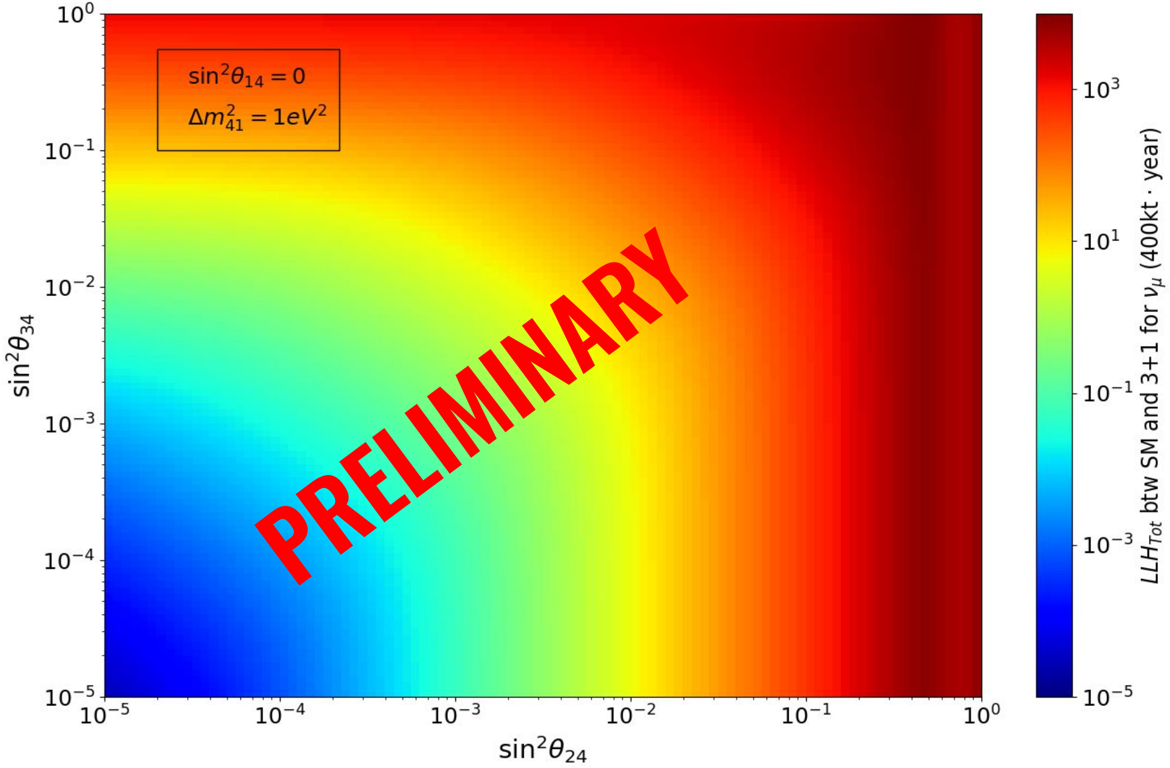
Next steps

- Finalize code adaptations of EarthProbe in order to obtain **sensitivity plots**
- Produce the same preliminary results as before as sanity check
- Understand **parameter fitting** with EarthProbe
- Produce sensitivity plots
- Add detector **reconstruction effects** and DUNE **systematics**
- After this, move on to the study with **atmospherics simulation and compatibility with Mach3**

  → will need to adapt the code

Thanks a lot for your attention !

Poisson LLH map



Poisson LLH map between SM and a 3+1 model with all mixing parameters fixed except for $\sin^2\theta_{24}$ and $\sin^2\theta_{34}$

→ SM is "data" and 3+1 is the "model"

→ interacting ν_μ events (no reconstruction stuff yet)

→ some work to do still but on good tracks to get contour plots

Standard mixing parameters

NuFIT 5.2 (2022)

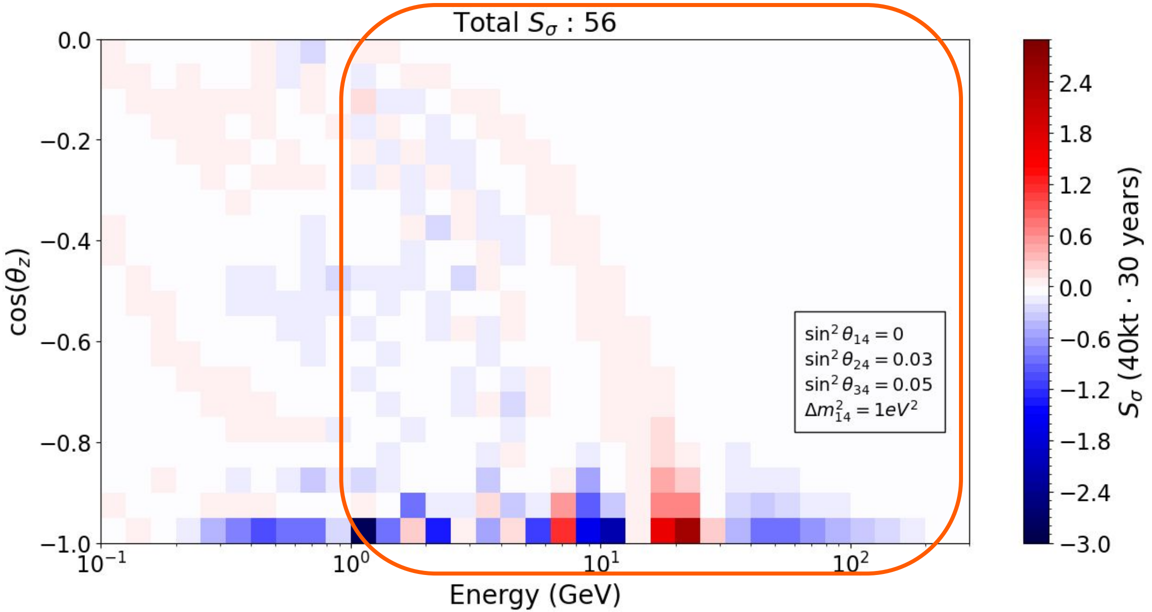
without SK atmospheric data

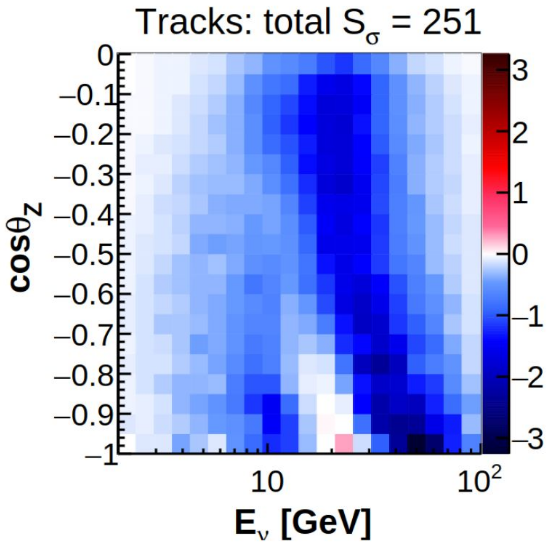
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

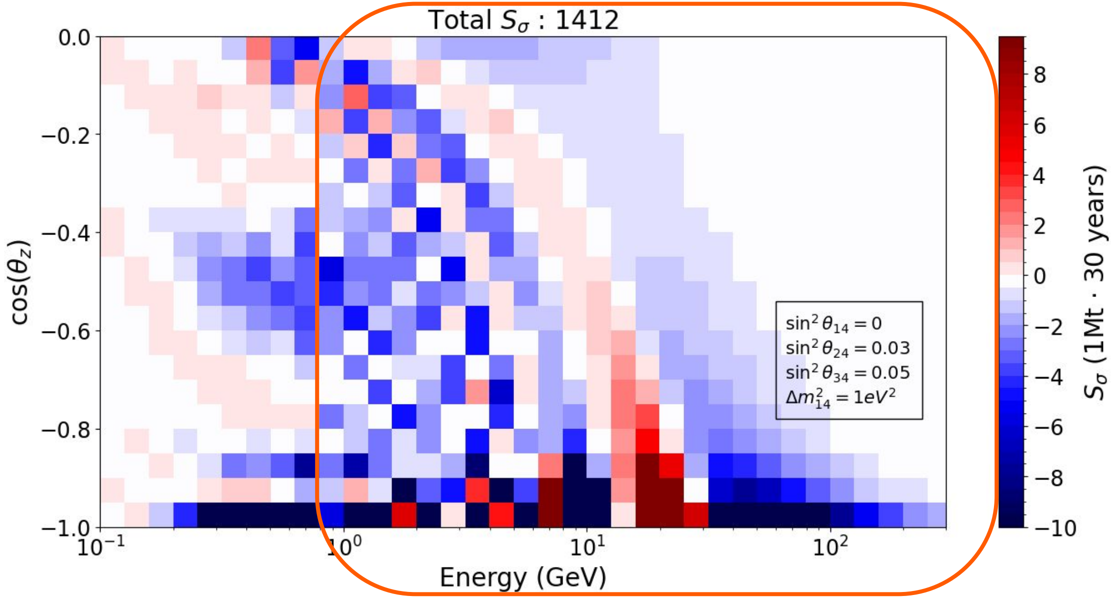
Sensitivity estimator

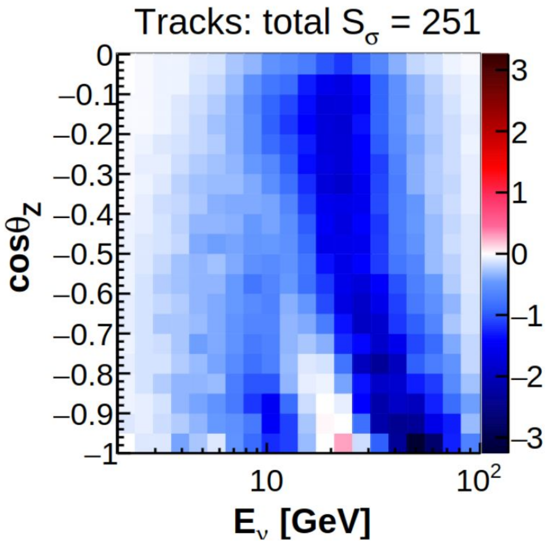




- We obtain a similar behaviour → excess around 20 GeV and deficit above and below but unclear due to low statistics
- Possibility to explore lower energy ranges
- The S parameter is intended for higher statistics → **will be updated to log-likelihood**

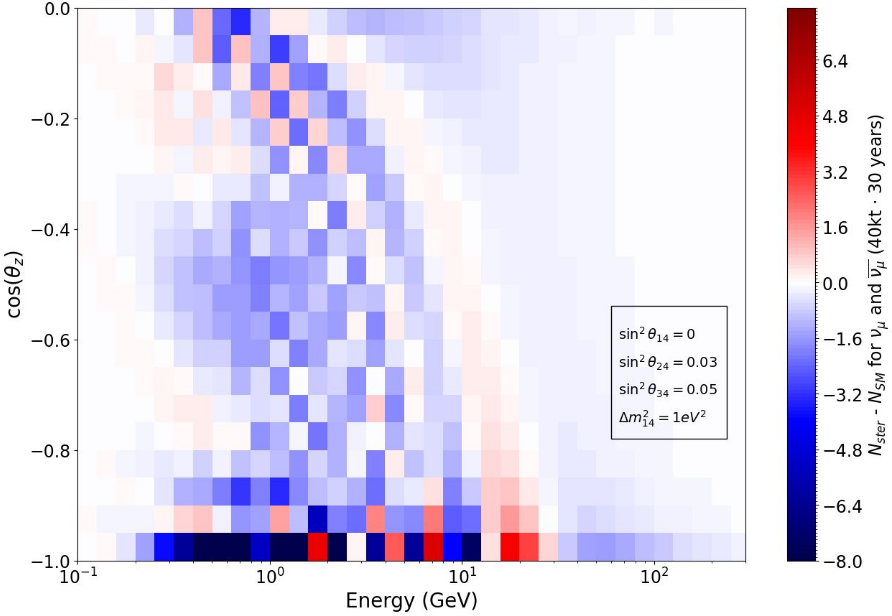
Sensitivity estimator

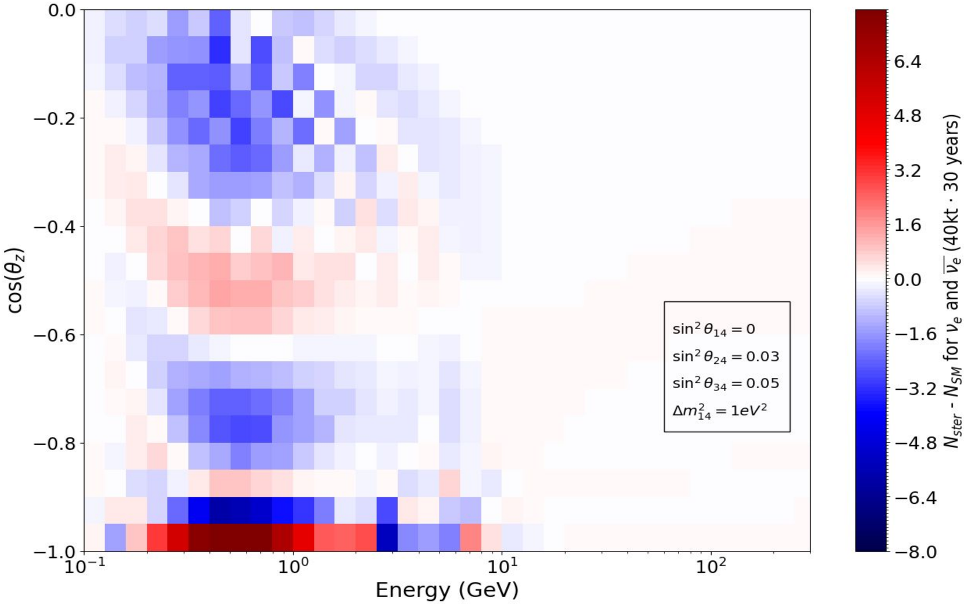




- Increasing the size of the detector to 1Mt to allow a better cross-check of result
  → shows **similar behaviour** as KM3NeT/ORCA plot
- Higher frequency effect has been investigated and will likely be diffused when detector effects are included

Expected number of events





Can calculate **number of expected events** and do the difference between 4-neutrino and 3-neutrino models for numu and nue (also anti-nu) depending on **true angle and true energy** of incoming neutrinos