Sterile Neutrino search using atmospherics in DUNE

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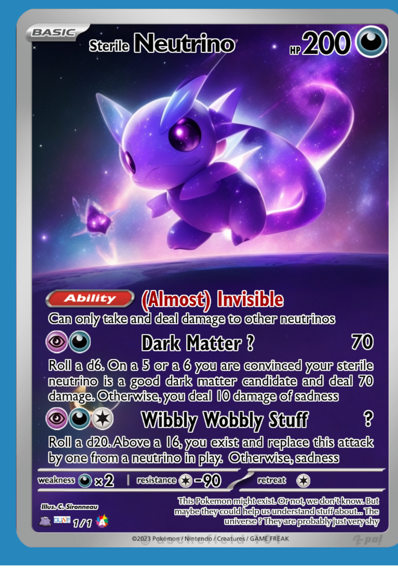
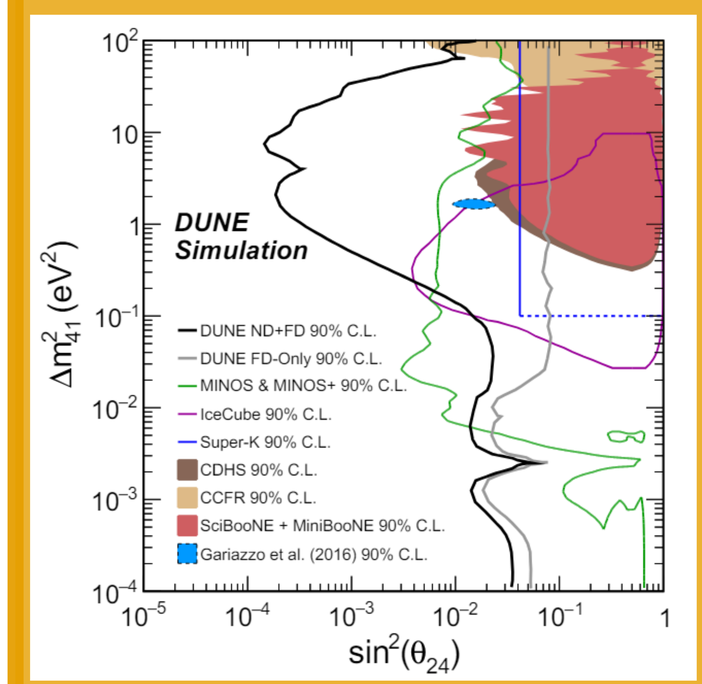


START

Atmospheric neutrinos and state of the art

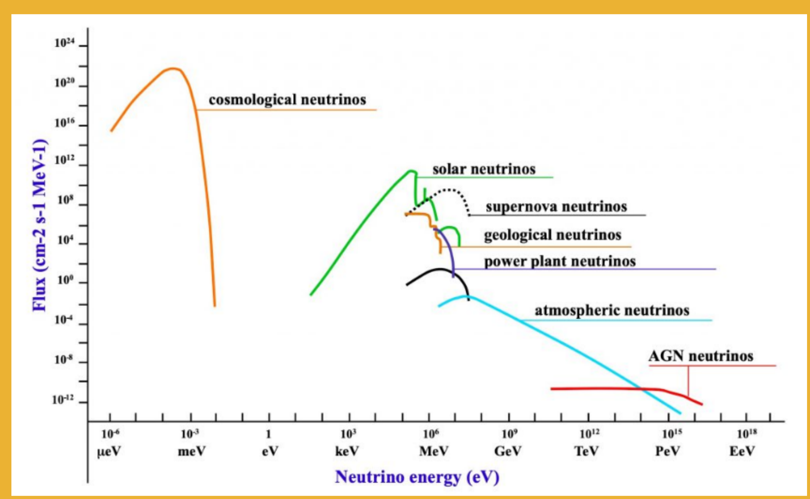
The Deep Underground Neutrino Experiment is a **next generation long-baseline neutrino experiment** set to have precise measurements of neutrino oscillation parameters using :

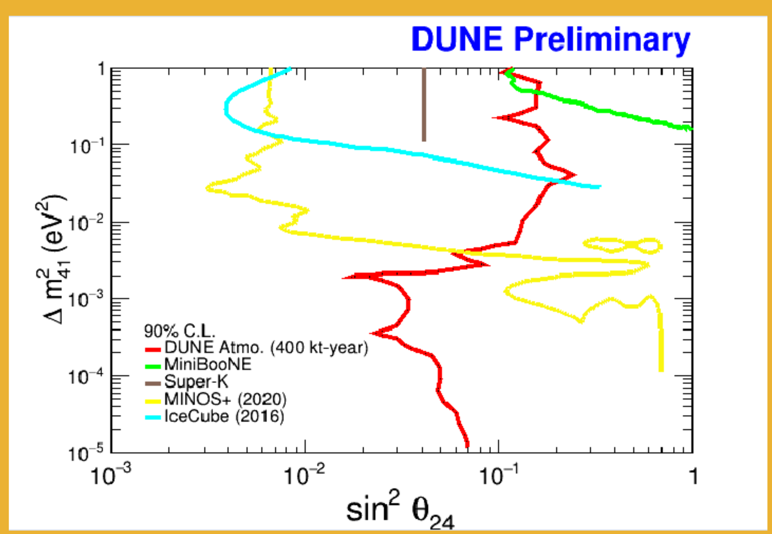
- ***4 Far Detector modules*** containing 17kt of liquid Argon each (underground)
- a ***1300km baseline***
- a ***ν_μ and anti-ν_μ beam with energies ranging from 0.1 to 10 GeV***



Many experiments use neutrinos as a probe to **BSM physics** (Ref 1). Existence of a 4th neutrino could be considered as long as it does not interact weakly; it is therefore a "**sterile neutrino**". **DUNE FDs are well suited to explore the existence of such a particle.**

DUNE FDs **can study both beam and atmospheric neutrinos** generated by incoming cosmic rays
-> **allow to explore a wide range of energy** (MeV up to TeV) **and baseline** (can come from all directions)





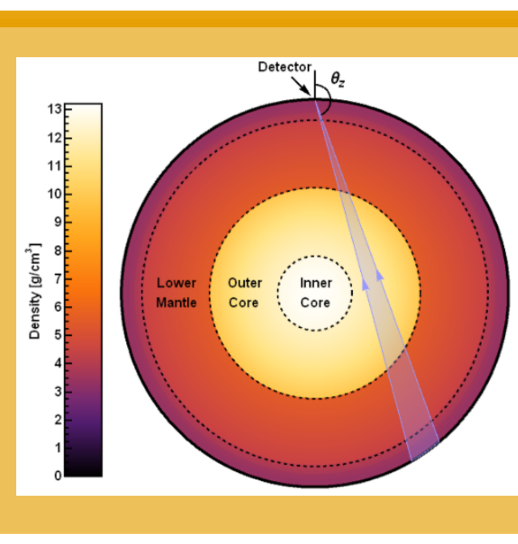
Preliminary phenomenological study of sterile neutrino sensitivity with atmospherics up to 11.5 GeV in DUNE was conducted (Ref 2) using simple assumptions regarding detector performances such as a constant 0.5% reconstruction efficiency for Neutral Current (NC) events

This work aims at understanding the potential impact of the different systematics and detector reconstruction parameters on the sensitivity trying to include NC. It will be further completed with full simulation studies

Motivations

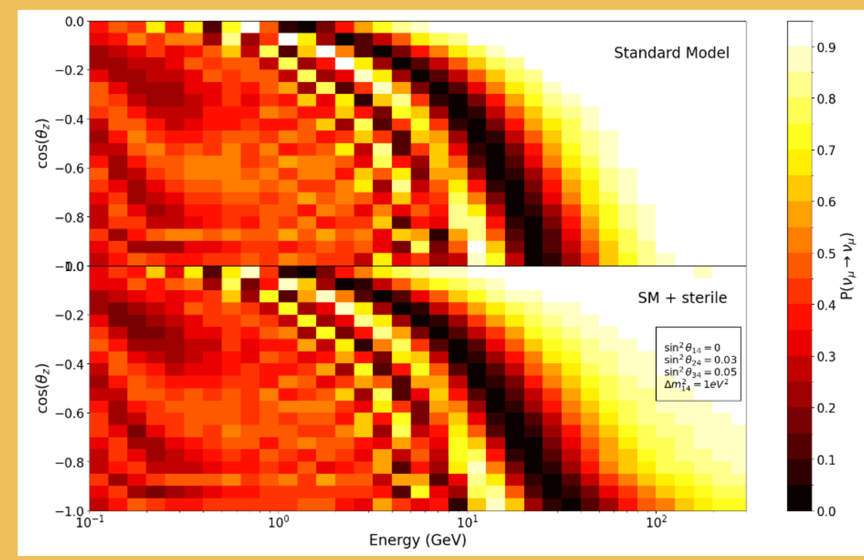
Ingredients for the analysis

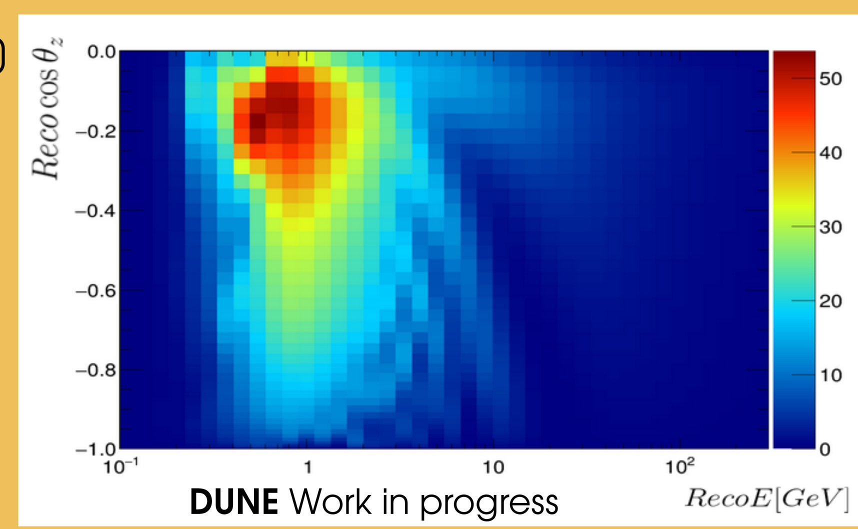
Addition of sterile neutrino -> modification of active neutrino oscillation probabilities -> main observable is **a change in baseline number of neutrino interactions we expect to see in our detectors as a function of energy and direction.**



In order to estimate our sensitivity to this effect, we need :

- expected ***neutrino flux***
- neutrino ***cross section*** with Ar
- ***Earth model*** to take matter effects into account (44 layers)
- ***oscillation probabilities*** computation for different models
- ***detector specificities*** (size, exposure, ...)
- ***reconstruction parameters*** (3)(4)
- ***systematic uncertainties***
- analysis tools to make a ***minimum Poisson log likelihood fit between "data" (prediction from SM) and model (3 active + 1 sterile)***





All these ingredients are handled using the code EarthProbe (Ref 3) which has been extended to make neutrino oscillation sensitivity studies

Ingredients

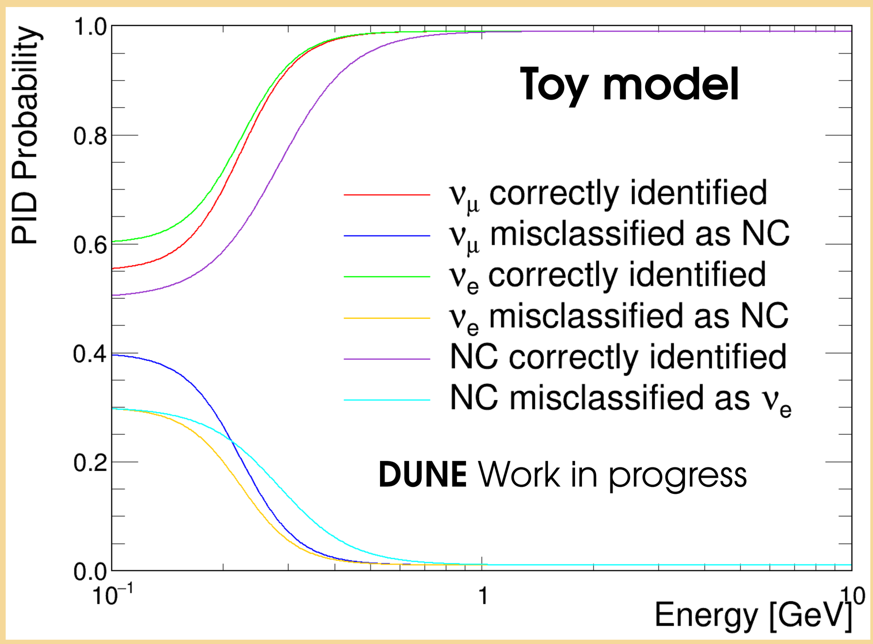
Classification

Event Classification

Ability to identify different types of events. Here classified in 3 categories :
ν_μ Charged Current (CC), ν_e CC and NC. Each topology has a probability to be correctly identified or misclassified depending on ν energy.

On the right, show **sigmoid dependence on energy** considered :

- ***parameters extrapolated from preliminary studies***
- ***upgoing*** sigmoids -> probability to be ***correctly classified***
- ***downgoing*** -> probability for the ***most-likely mis-classification***
- other mis-classification probability obtained so that the ***sum of all 3 is 1***



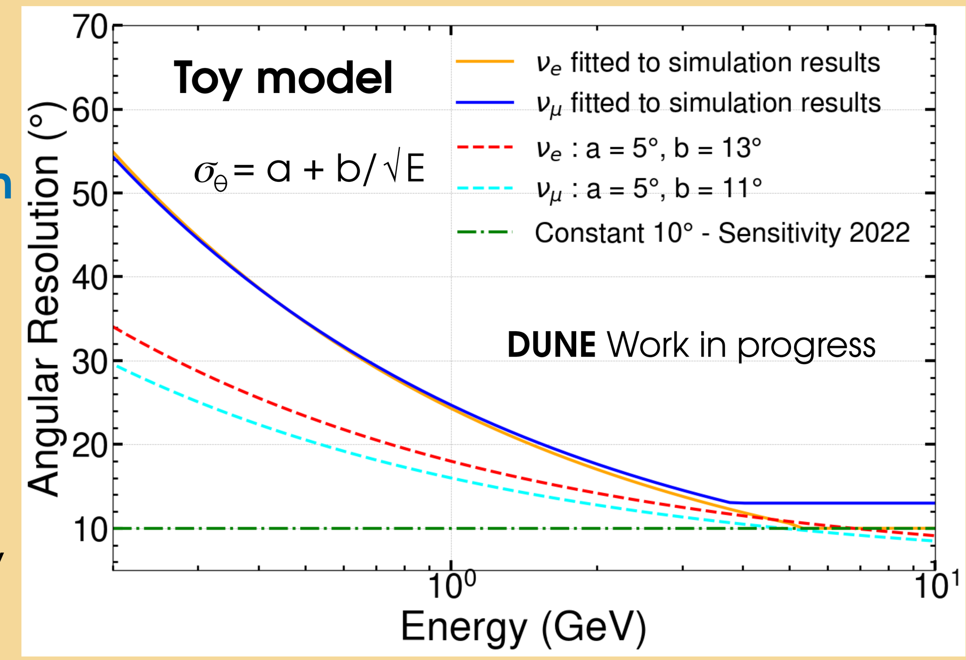
Angle

Angular resolution

Smearing applied to computed number of events depending on direction (and energy) of ν

A linestyle in the plot corresponds to a specific set of parameters used for one study

- ***Dash-dot line*** -> constant model used in previous study for all types of events (Ref 2)



- ***Dashed curves*** -> plotted considering $\sigma_\theta = \mathbf{a + b/\sqrt{E}}$ energy dependence as ***estimation***
- ***Solid lines*** : ν_μ and ν_e angular resolutions ***fitted to results obtained from recent preliminary atmospherics simulation analysis*** (Ref 4)

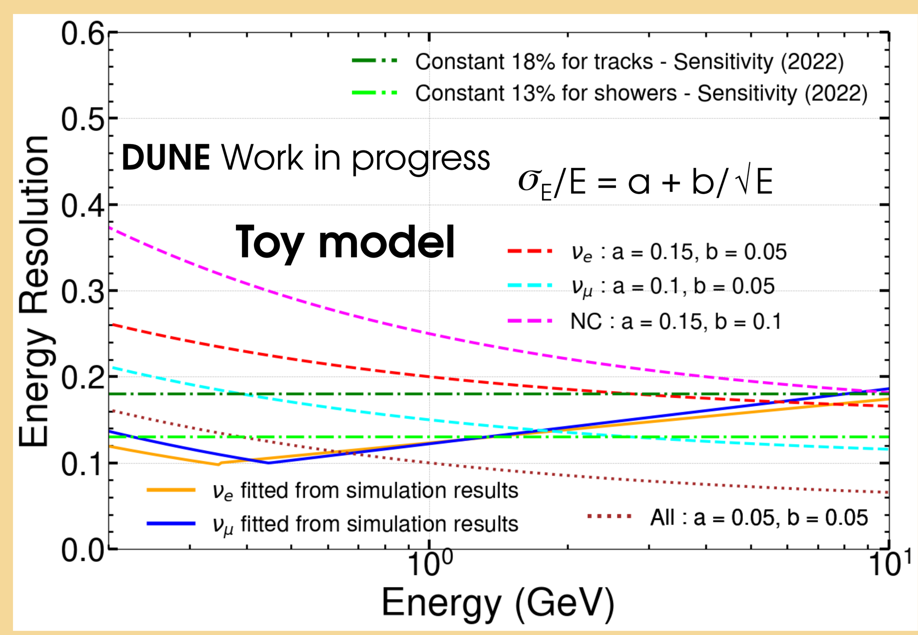
-> Assume that angular resolution is the same for NC and ν_e CC

Energy

Energy resolution

Same principle as for angular resolution considering linestyle :

- ***Dash-dot*** -> constant models used in previous study (Ref 2)
- ***Dash*** -> ***estimation*** of more detailed behavior considering $\sigma_E/E = \mathbf{a + b/\sqrt{E}}$ dependance for the 3 topologies
- ***Dot*** -> ***optimistic*** resolution using same model dash set and same parameters for all topologies



- ***Solid*** : ν_μ and ν_e energy resolutions ***fitted to results obtained from recent preliminary atmospherics simulation analysis*** (Ref4)

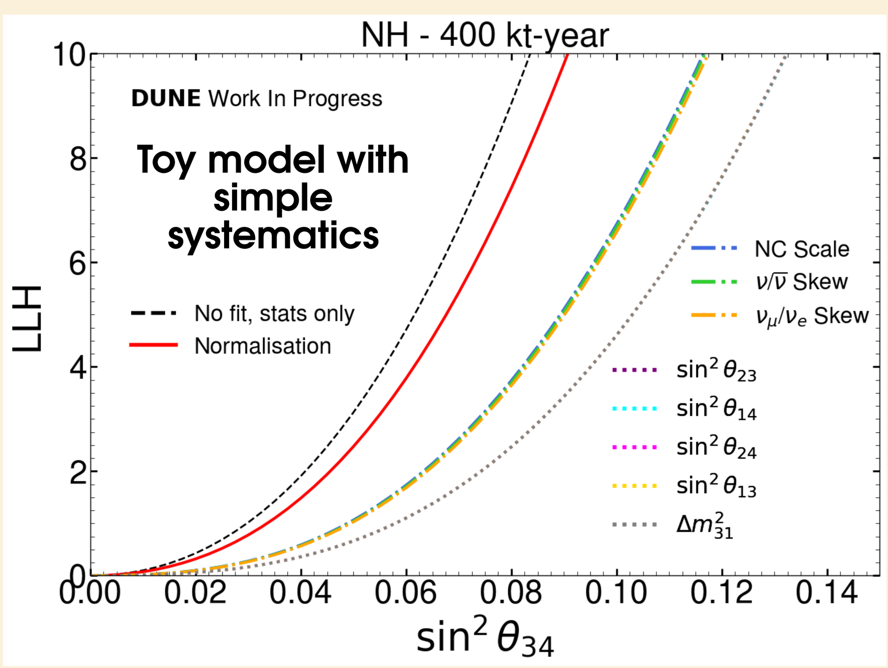
One-dimensional log-likelihood fits

Study **impact of different parameters on the minimum Poisson log-likelihood fits"pseudo data" - model** as a function of each sterile neutrino mixing angle : θ_{14}, θ_{24}, and θ_{34}

Parameters included in the fit are :

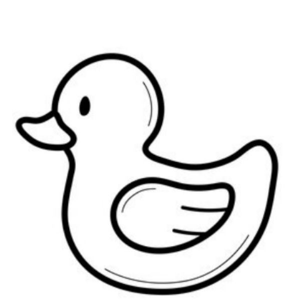
-> **Systematics** : ***flux normalisation*** with a 10% prior, ***scale of NC contribution*** with a 5% prior, ***v/anti-v skew*** with a 5% prior and ***ν_μ/ν_e skew*** with a 3% prior (fairly optimistic values, more studies on the way)
-> **δ_{CP} phase, Δm^2_{12} and θ_{12} fixed to Nufit 5.2 values**
-> **all other parameters set free**

First fix all parameters then release them sequentially. Observe likelihood change from one curve to the next going left to right
-> impact of each released parameter can be understood
Dotted curves show set of parameters having ~ same impact on fit
-> possibility to fix or put priors on some of them



1D Fit

Soon : fully upated contours with different models for detector performances



(1) Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics, DUNE Collaboration, 2002.03005 (hep-ex)
(2) Tarak Thakore for the DUNE Collaboration, "Sensitivity study to Neutrino Mass Ordering and sterile neutrino model parameters with atmospheric neutrinos measurements at DUNE", Neutrino 2022 poster
(3) L. Maderer, E. Kaminski, J. A. B. Coelho, S. Bourret and V. Van Elewyck, "Unveiling the outer core composition with neutrino oscillation tomography", Front. Earth Sci. 11 (2023), 1008396
(4) Henrique Souza for the DUNE Collaboration, "Angle and energy reconstruction of atmospheric neutrinos in DUNE experiment", Neutrino 2024 poster