Sterile neutrino search with atmospheric neutrinos in DUNE

Camille Sironneau
On behalf of the DUNE Collaboration

JRJC
29/11/24

Presentation of DUNE

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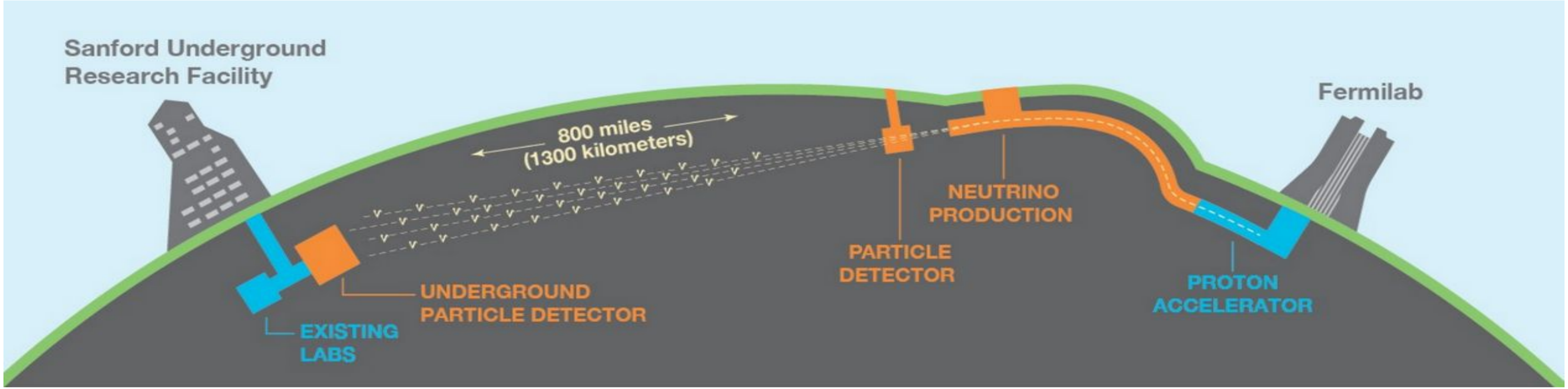


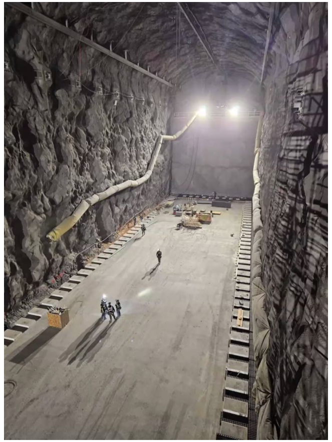
Goals

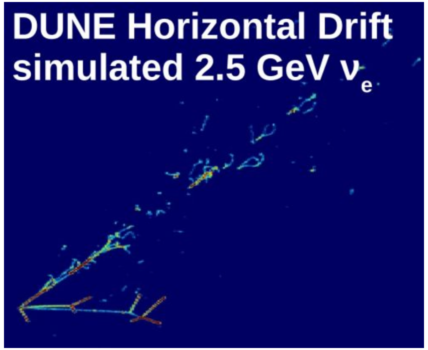
- Charge parity violation phase
- Neutrino mixing angles
- Neutrino mass hierarchy
- Search for proton decay
- Study of supernovae neutrinos

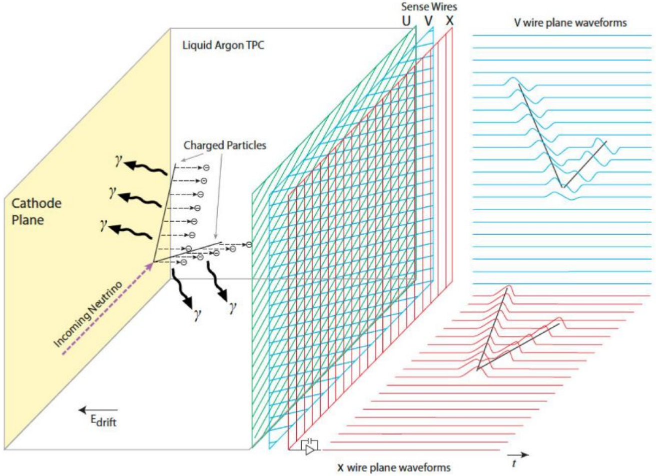
- **Neutrino beam** energy: 0.5 to 8 GeV
- **Near Detector** at 575m from the source
- **Far Detector (FD)** 1.5 km underground
- 4 LArTPCs modules of **17.5 kt each**

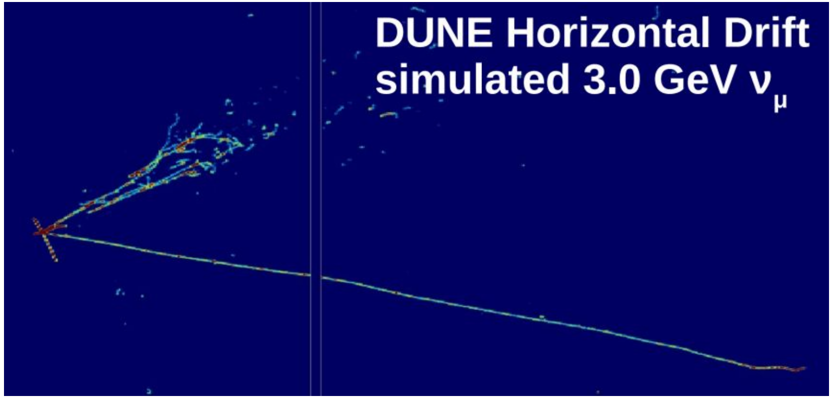
DUNE FD

- LArTPC **high resolution event imaging** → kinematic reconstruction of nu events
- Excellent **event type classification** (numu CC, nue CC, NC and potential for nutau)
- Excellent **particle id** (e, mu, proton)
- **Photon Detection System**: trigger, 3D reconstruction

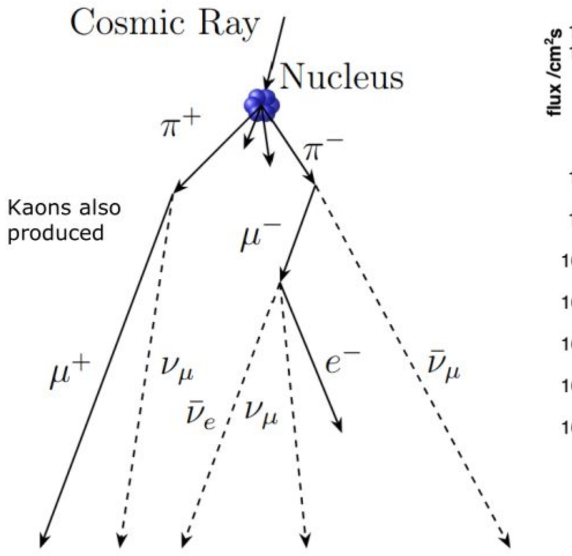




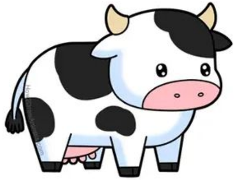


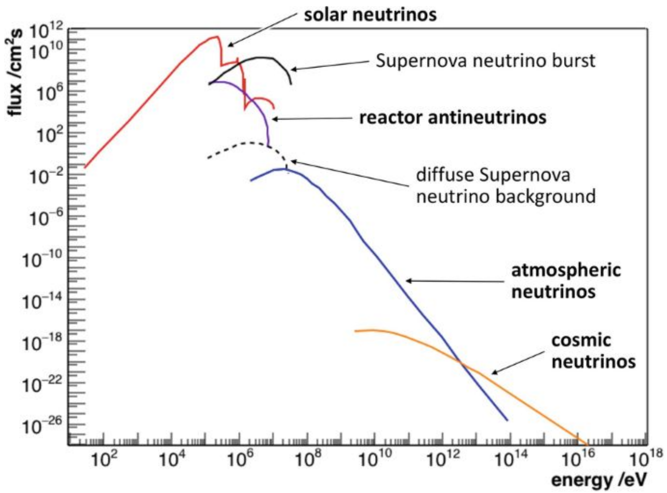


Atmospheric neutrinos

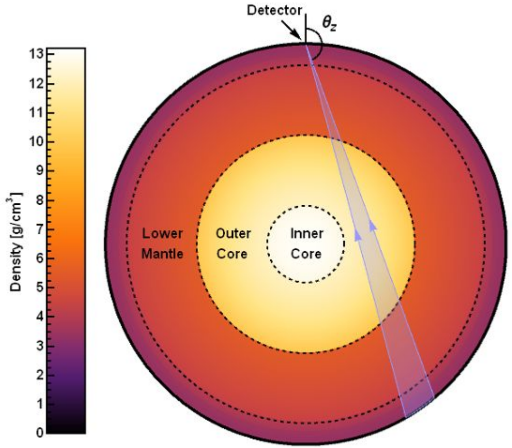


$$\frac{\nu_\mu + \bar{\nu}_\mu}{\nu_e + \bar{\nu}_e} \cong 2,$$



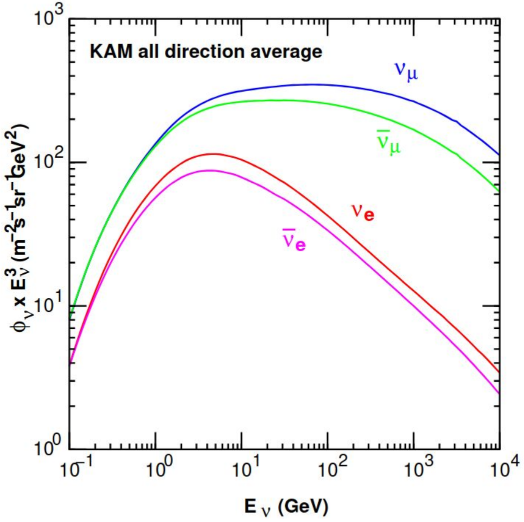


Wide energy range
→ from ~MeV to ~PeV

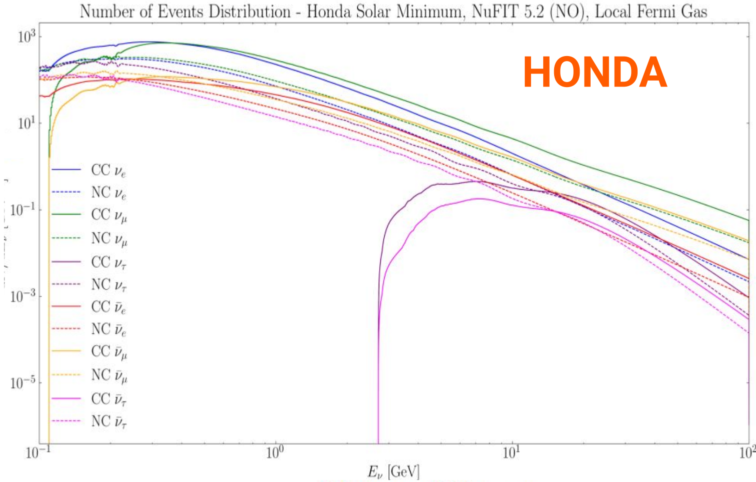


Come from every direction and go through different matter densities
→ different baselines/matter effects

Atmospheric neutrinos



Constant flux of multiple flavors of neutrinos



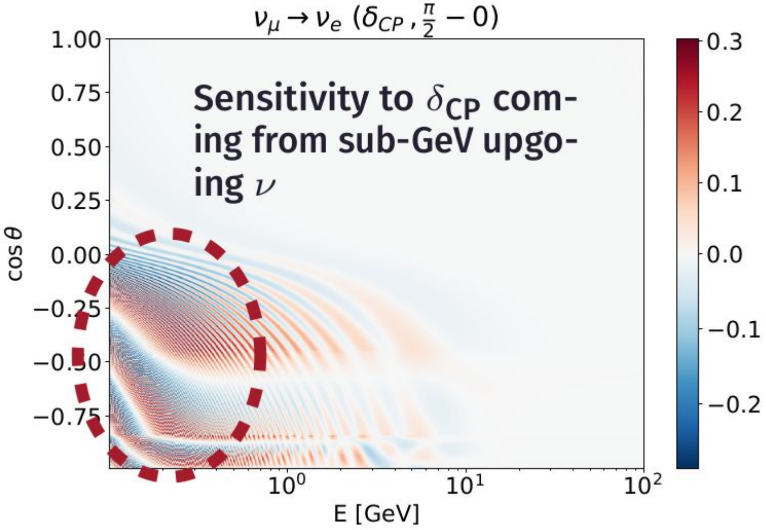
Totals per 10 kt · yr

	Solar Maximum, NuFIT 5.2 (NO), Local Fermi Gas			
	Sub-GeV [0.1 – 1.0] GeV	Multi-GeV [1.0 – 10.0] GeV	High-GeV [10.0 – 100.0] GeV	Total [0.1 – 100.0] GeV
CCν_e	391.8	216.6	13.5	622.0
CCν_μ	389.9	319.1	41.4	750.4
CCν_τ	0.0	2.5	4.3	6.7
CC$\bar{\nu}_e$	61.3	57.2	4.5	122.9
CC$\bar{\nu}_\mu$	74.2	102.4	14.9	191.5
CC$\bar{\nu}_\tau$	0.0	0.9	1.6	2.4
NC	565.9	293.8	29.4	889.2
Total	1483.1	992.5	109.5	2585.1

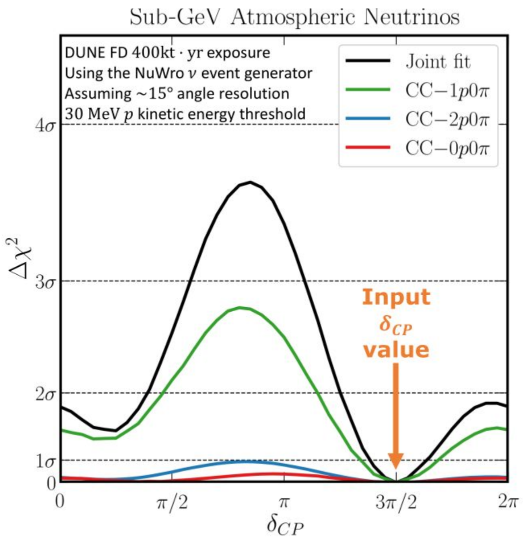
- Extra source of neutrinos **in addition to beam**
- Relevant → will operate DUNE FD(s) for **~2 years without beam**
- Expect **~2000 atmospheric neutrino events per 10kt per year** (including ~10 nutau events)
  → available data

Marcelo Oliveira-Ismerio

Physics with atmospherics : deltaCP

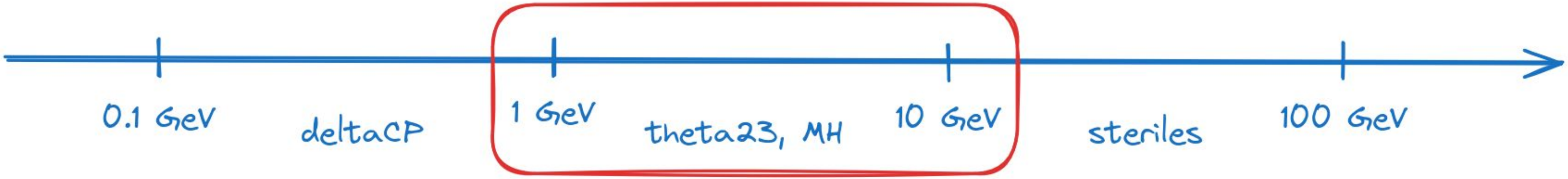


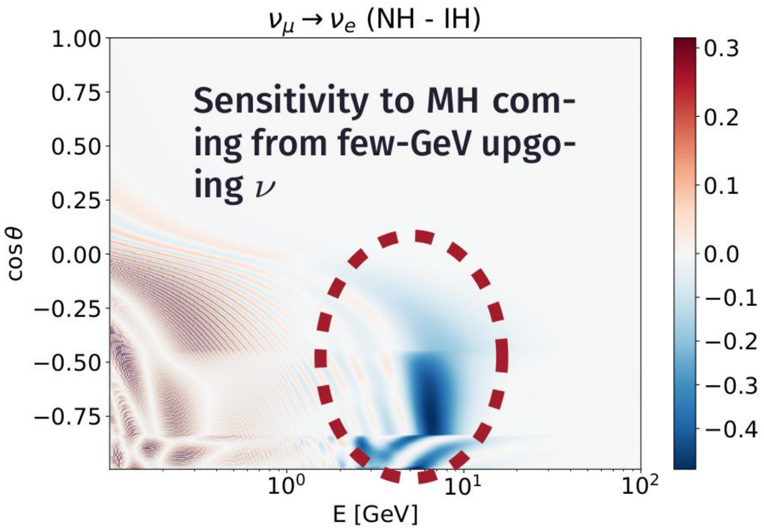
- Fast oscillations at low-E
- Expect DUNE to be able to reconstruct sub-GeV events
- Biggest challenge is handling Fermi motion as well as constraining the flux and cross-section systematics



https://arxiv.org/abs/1904.02751

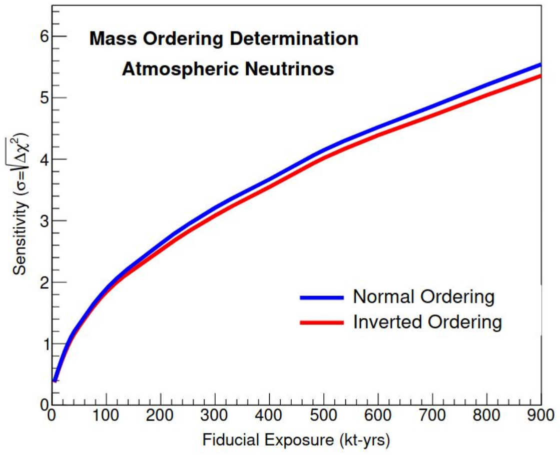
Physics with atmospherics : MH and θ_{23}



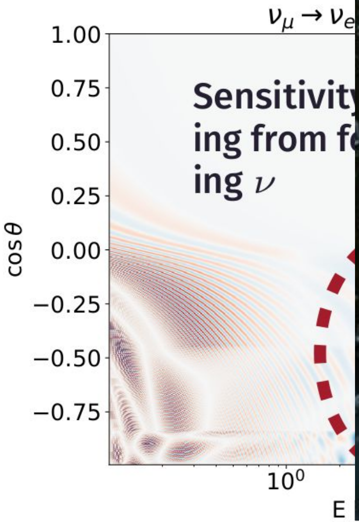


- Most visible effect ~5-10 GeV → well within the range of DUNE's capabilities (for both beam and atm)
- Ability to see 3 flavor oscillation modes with nutau events

DUNE TDR
https://arxiv.org/pdf/2002.03005



Physics with atmospherics : MH and θ_{23}



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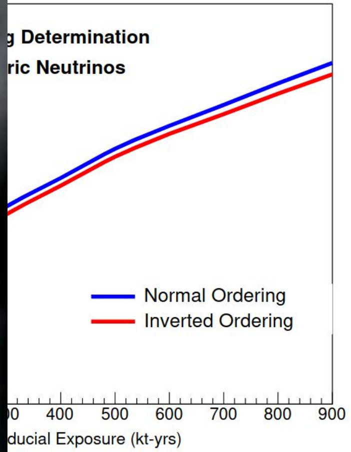
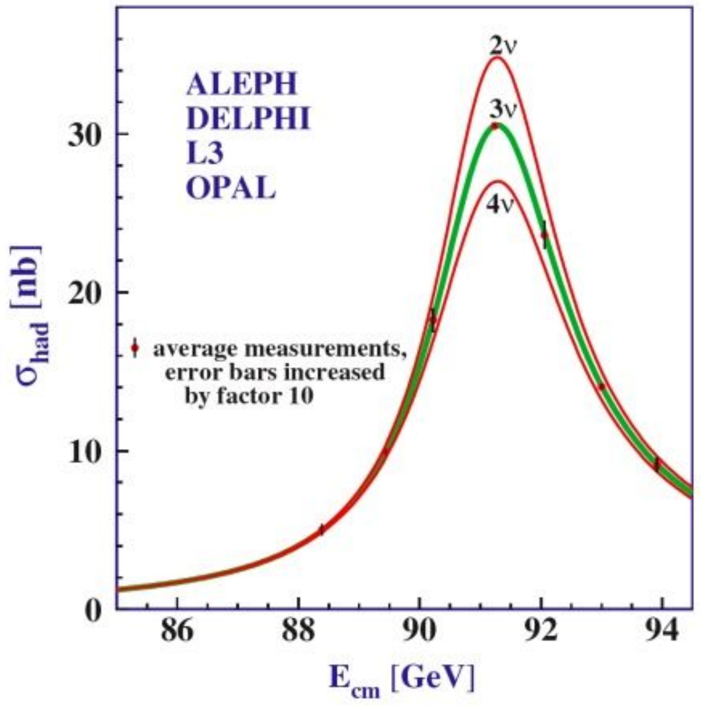
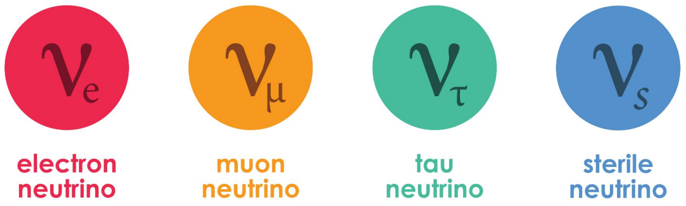


The 3-Neutrino Model



While the 3 neutrino model is a good fit to most measurements, multiple anomalies have been detected by different experiments but it has been shown that there are only 3 “active” neutrino states

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



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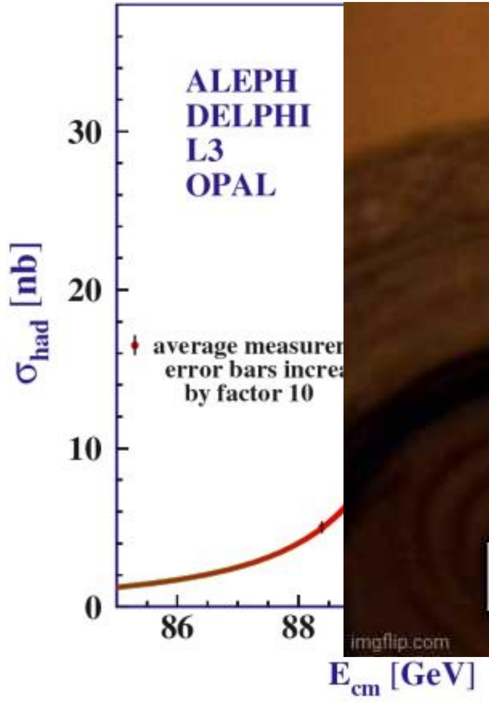
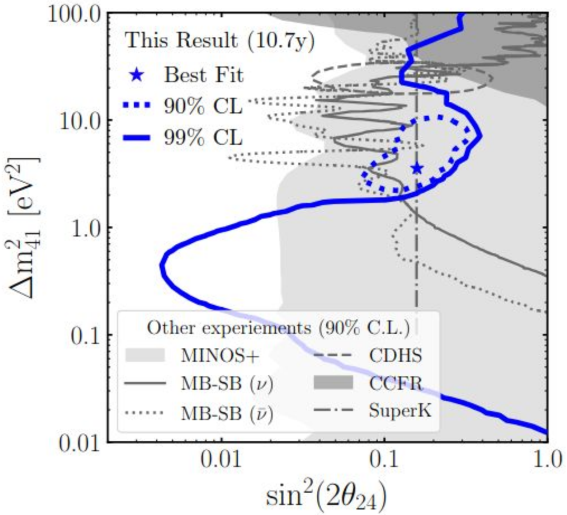


electron neutrino | muon neutrino | tau neutrino | sterile neutrino

Recent sterile studies

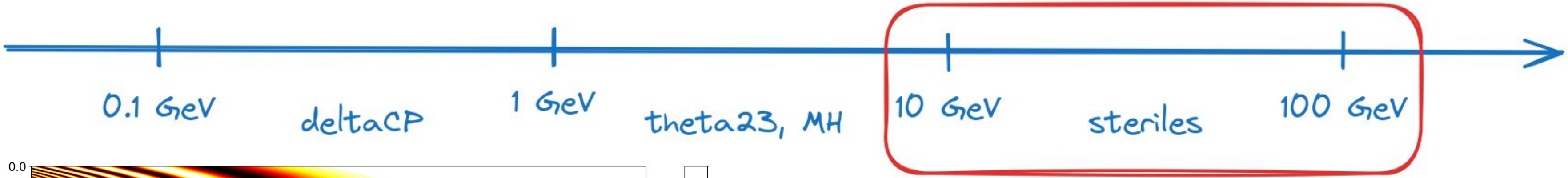
- **Reactor experiments :**
  → **Double Chooz**
  → **PROSPECT** and **STEREO** study the Reactor Antineutrino Anomaly
  → Future : **JUNO** with **RENO 50** sensitive to “super light sterile neutrino”
- **Accelerator experiments :**
  → **LSND**, low energy beam of anti numu, look for excess in nue 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**
  → **SuperK**, set limit on sterile mixing to tau and mu
- **Gallium based solar nu experiments :**
  → **GALLEX**, **SAGE**, **BEST** : anomalies could be explained with $\Delta m^2 \sim 1$ ev²

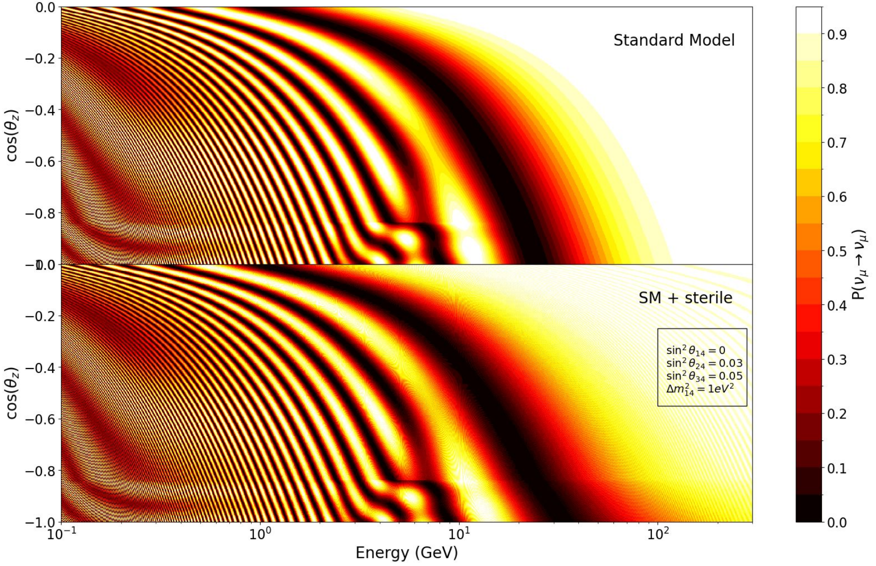
https://arxiv.org/pdf/2405.08070



Latest results from IceCube show best fit point in region excluded by other atmospheric experiments

Physics with atmospherics : sterile neutrinos

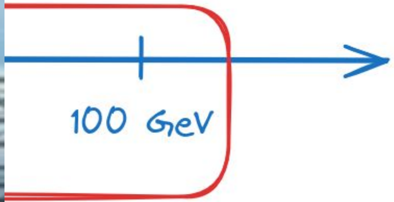


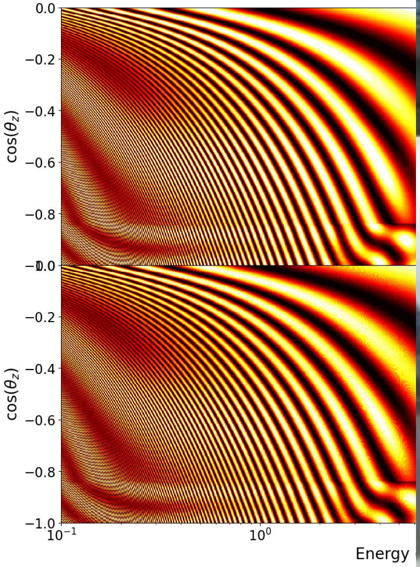


$sin^2\theta_{14} = 0$, $sin^2\theta_{24} = 0.03$, $sin^2\theta_{34} = 0.05$, $\Delta m^2{}_{14} = 1\ eV^2$

- Big part of sterile neutrino effects are at high energy → atmospherics are good sources to see that
- Important to properly reconstruct events (both energy and angle) and tag neutrino flavors to estimate this
- DUNE could be competitive with other experiments for sterile mass < 1 eV^2
- Containment effects will be challenging, plan is to improve reco with ML (see I Cheong's talk)
- Complementarity with beam

Physics wit trinos





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Principle of this phenomenological study

- Addition of a neutrino in model **modifies oscillation probabilities** and produces **appearance/disappearance of neutrino flavours** depending on energy/angle
- **6 new oscillation parameters :** θ_{14}, θ_{24}, θ_{34}, Δm^2_{41}, δ_{14} and δ_{24}
- Can compute **difference in expected number of events** assuming Standard Model and model with one sterile neutrino (“3+1” model)
  → see if difference can be seen with enough significance in our detector
- Simulation not fully ready so preliminary study with no data, just computations
- Example of calculation for ν_μ events

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

Atmospheric neutrino flux for different flavors

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Oscillation probabilities to numu or numu_bar

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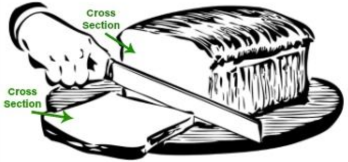
Interaction cross section with Ar40



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

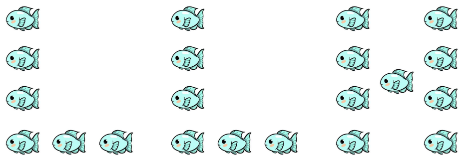
Number of target atoms

Δt : time of data taking in seconds

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

Sensitivity

The big question : if we see some data in our detector, how can we say whether it's compatible or not with the potential existence of a sterile neutrino ?



Use something called the Poisson log-likelihood (or LLH)

$$-2\ln L_{\text{Poisson}} = \sum_{\text{bins}} 2 \times \left(N_{\text{model}} - N_{\text{data}} + N_{\text{data}} \cdot \ln \frac{N_{\text{data}}}{N_{\text{model}}} \right)$$

Energy and angle bins

Number of expected event in our model → here "3+1" model

Number of events we see → for this study, we assume "data" to be Standard Model expectation

The higher this value, the more incompatible the "data" is to the "3+1" model → high LLH means that we have good confidence in distinguishing between "3+1" and SM

What can impact the sensitivity ?

Likelihood depends on

- **Parameter values assumed in the model**
  - Choice for mass hierarchy → **Here choose normal ordering**
  - Standard oscillation parameters have some uncertainty
  - Don't know value for sterile oscillation parameters
- **Some systematic uncertainties on different effects**
  - Atmospheric neutrino flux
  - Neutrino cross section
  - Neutrino production height
  - Many more
- **How well we reconstruct neutrino events (to put them in the correct energy and angle bins)**
  - Energy reconstruction
  - Angular reconstruction
  - Neutrino flavor identification
- **Detector specificities**
  - Detector size
  - Exposure time
  - Range of neutrino energy that we can detect

Have some previous information so can put limits on these (standard oscillation parameters, sterile oscillation parameters, atmospheric neutrino flux)

Variations of these were not taken into account here (neutrino cross section, neutrino production height, many more)

Related to performance of detector and reconstruction algo → currently estimated with simulation studies

For this study, assume exposure of 400 kt.year and neutrino energies between 100 MeV and 300 GeV

Minimum likelihood fit

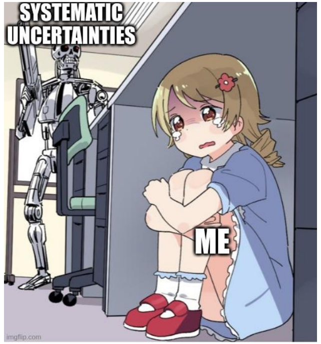
Standard oscillation parameters can vary in a certain range defined by previous experiments

		Normal Ordering (best fit)	
		bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \rightarrow 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \rightarrow 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \rightarrow 0.603$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \rightarrow 51.0$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \rightarrow 0.02398$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \rightarrow 8.91$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \rightarrow 350$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \rightarrow 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \rightarrow +2.590$

Atmospheric flux model involves different parameters that are not perfectly known

$$\begin{pmatrix} \phi^{\nu_e}(E,\cos\theta_z) \\ \phi^{\nu_\mu}(E,\cos\theta_z) \\ \phi^{\overline{\nu_e}}(E,\cos\theta_z) \\ \phi^{\overline{\nu_\mu}}(E,\cos\theta_z) \end{pmatrix} = \Phi_0 \left(\frac{E}{\text{GeV}}\right)^\gamma \begin{pmatrix} w_{\nu_e}(r_{\mu,e}, r_{\nu,\overline{\nu}}) \cdot f^{\nu_e}(E,\cos\theta_z) \\ w_{\nu_\mu}(r_{\mu,e}, r_{\nu,\overline{\nu}}) \cdot f^{\nu_\mu}(E,\cos\theta_z) \\ w_{\overline{\nu_e}}(r_{\mu,e}, r_{\nu,\overline{\nu}}) \cdot f^{\overline{\nu_e}}(E,\cos\theta_z) \\ w_{\overline{\nu_\mu}}(r_{\mu,e}, r_{\nu,\overline{\nu}}) \cdot f^{\overline{\nu_\mu}}(E,\cos\theta_z) \end{pmatrix}$$

ϕ_0 : global normalization term
γ : spectral distortion factor
$r_{\mu,e}$: ν_μ/ν_e ratio
$r_{\nu,\overline{\nu}}$: $\nu/\overline{\nu}$ ratio



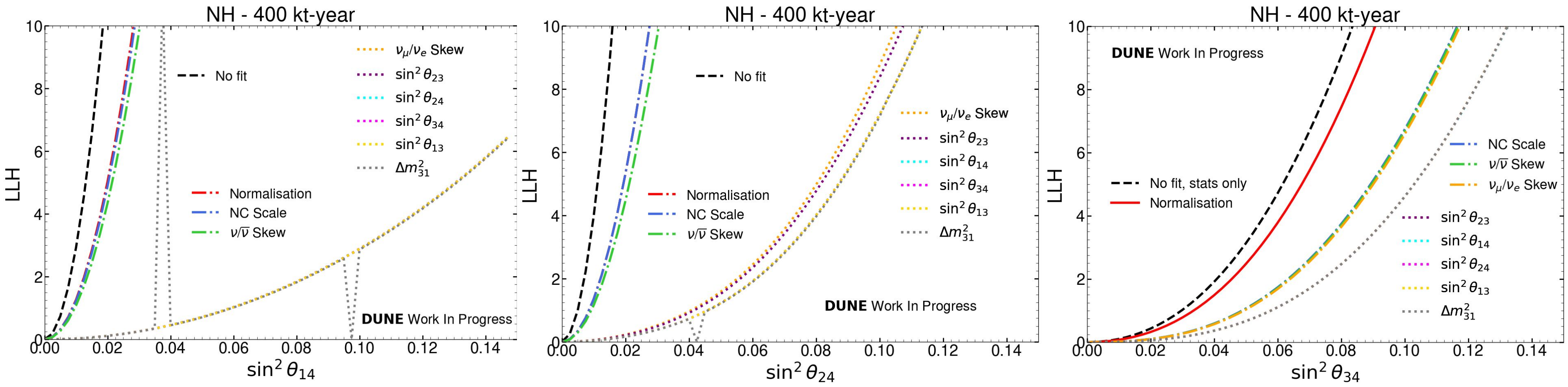
Values for sterile parameters are not known so can also vary

→ Perform minimization of the Poisson LLH on all these parameters to get sensitivity → low LLH is "worst-case scenario" where we can distinguish the least between SM and "3+1"

Impact of fit parameters

- **Fitting all parameters at the same time can be very time consuming** → good to see if can fix some
- Can **fix θ_{12} and Δm^2_{21}** to their best fit value because don't expect DUNE to be sensitive to them (mostly constrained by solar neutrino experiments)
- Perform **one-dimensional LLH fit studies** to evaluate the impact of each individual systematic and fit parameter in the likelihood
- **Release each parameter one by one** to see impact it has on the fit → Start with no fit

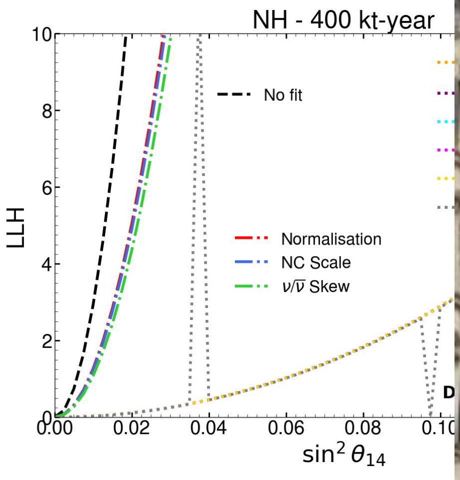
Qualitative impact of fit parameters

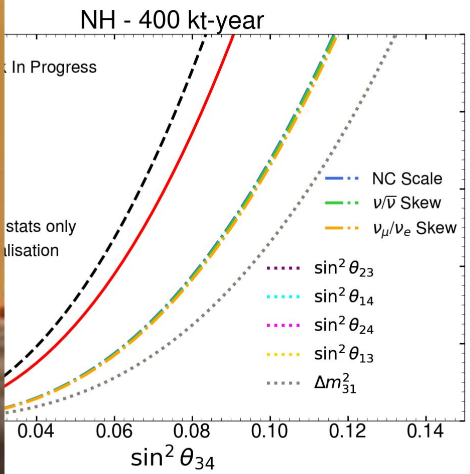


- **All systematic uncertainties have some impact** in fit result for at least one of the sterile oscillation parameters
  - **With exception of θ_{23}, standard oscillation parameters have little to no impact in the results of the fit**
- Cause of discontinuities investigated by changing order of parameter release: **found to be related to Δm^2_{31}**

→ Decision to fix Δm^2_{31} and θ_{13} to obtain global fit plots

Qualitative





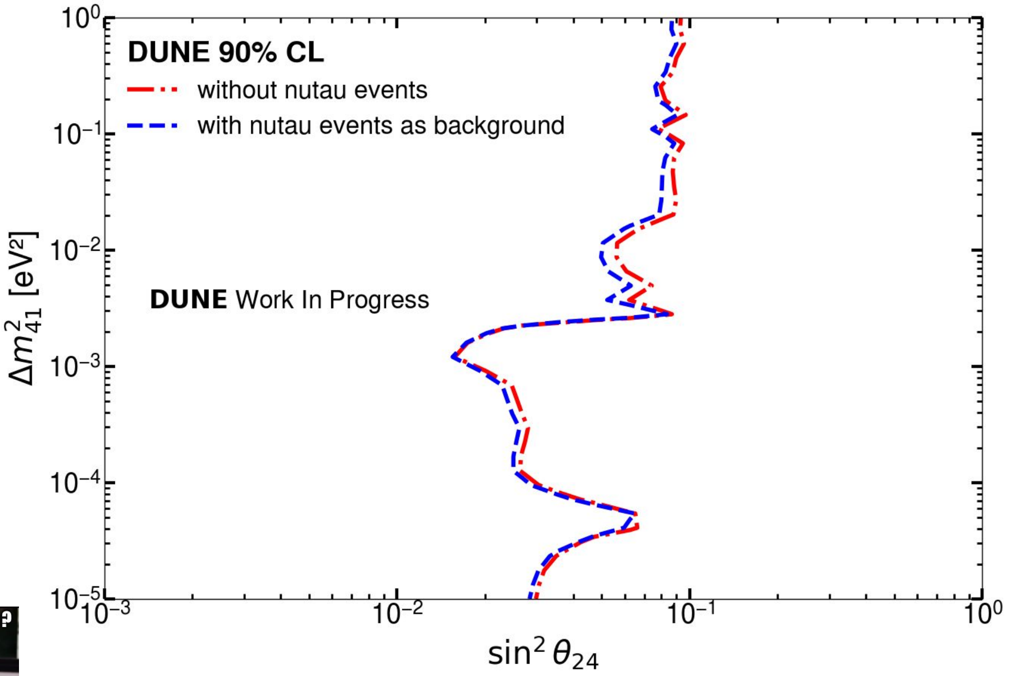
- **All systematic uncerta** … erile oscillation parameters
    - **With exception of** … **in the results of the fit**
- Cause of discontinui … **nd to be related to Δm^2_{31}**

Sensitivity contours : ν_τ events

Consider 3 "classes" of events in the study :
ν_μ CC, ν_e CC and NC

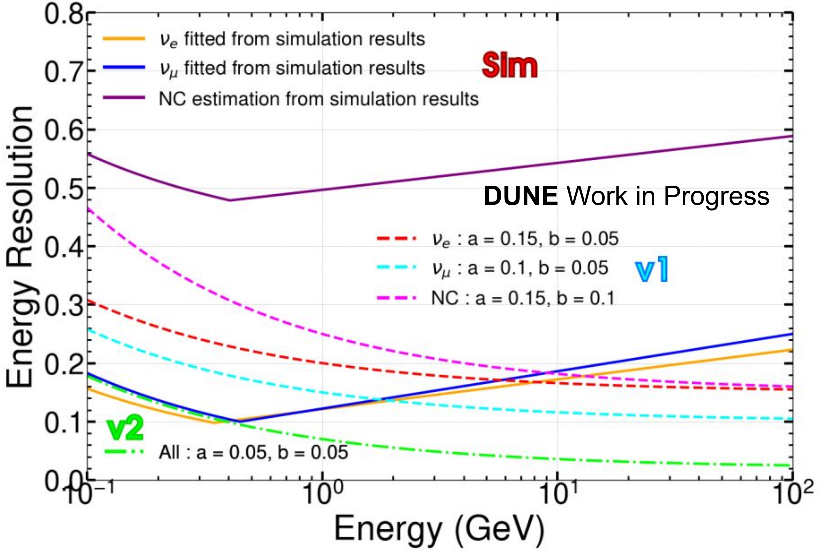
No studies available yet for reconstruction of atmospheric ν_τ events so can't put realistic parameters for resolution. Implement 2 "extreme" cases to evaluate potential effect :

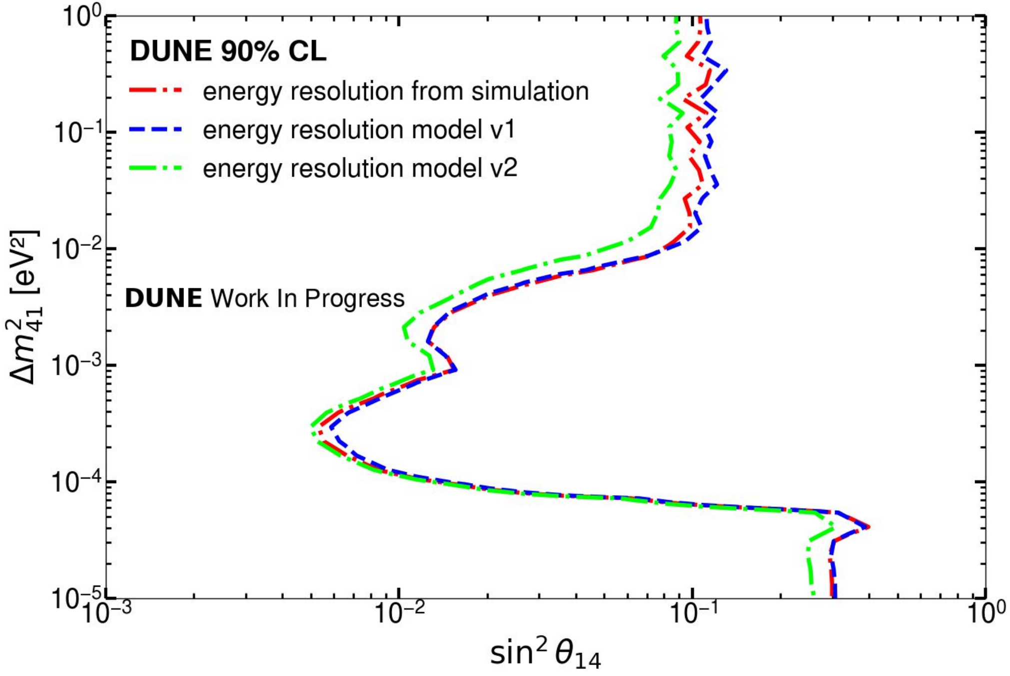
- **Assume they don't exist** (not included in computations at all)
- **Assume that they are fully mis-classified as other types of neutrinos** (kind of a "background") in a way that's proportional to its interaction modes



→ Study doesn't seem to be too sensitive to inclusion of ν_τ events

Sensitivity contours : energy resolution



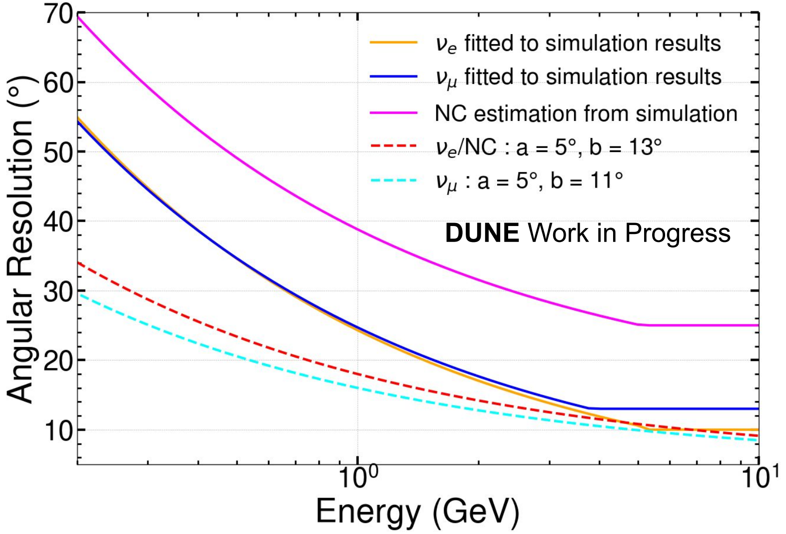


Test how the energy resolution impacts the overall sensitivity. Compare the one currently derived from simulation to 2 other models of the form

$$\frac{\sigma_E}{E} = a + \frac{b}{\sqrt{E}}$$

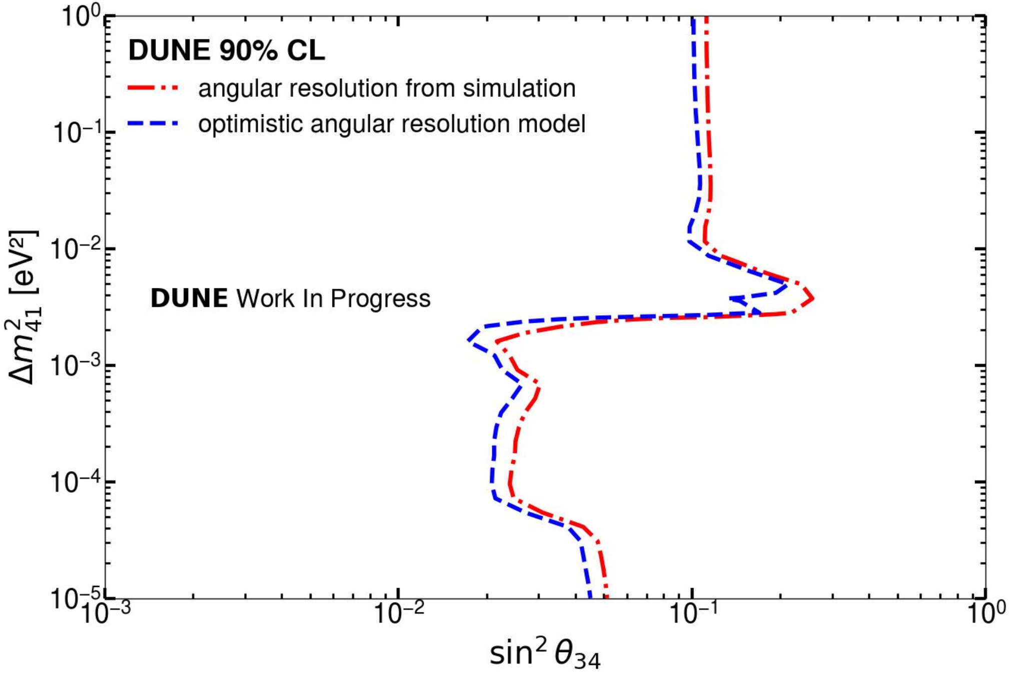
→ Model v2 is very optimistic and shows potential limit to sensitivity improvement we could get wrt energy resolution

Sensitivity contours : angular resolution



Test how the angular resolution impacts the overall sensitivity. Compare the one currently derived from simulation to a more optimistic one of the form

$$\sigma_\theta = a + \frac{b}{\sqrt{E}}$$



→ **Improving angular reconstruction could lead to overall improvement of sensitivity**

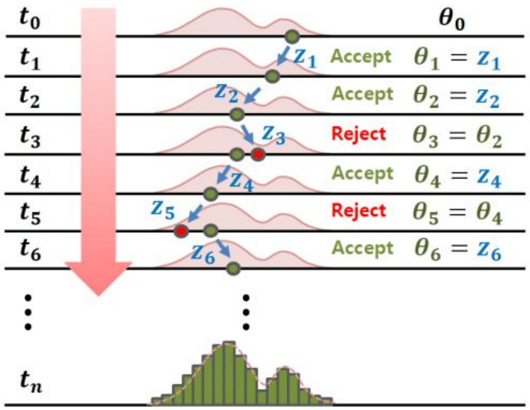
What's next ?

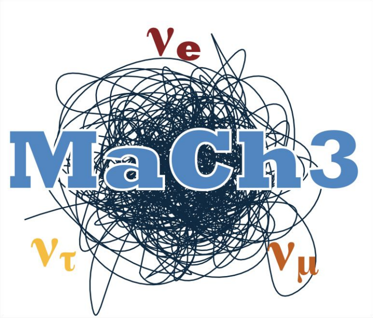
MaCh3 used as oscillation fitter → relies on the sampling of posterior likelihood using Markov Chains

Implementation of DUNE atmospherics in MaCh3 ready to go

Next steps:

- First statistics-only fits with the reconstructed atmospheric sample
- Implementation of realistic flux, cross-section and detector systematics
- Currently working on implementing exotic neutrino models in MaCh3 to produce sterile neutrino sensitivity studies using the full DUNE simulation of atmospheric events





Trugarez evit hoc'h evezh

(Thanks for your attention !)

Current info on oscillation parameters

Global fit information

Global 6-parameter fit (including δ_{CP}):

- **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + Borexino;
- **Atmospheric**: SK-1 + SK-2 + SK-3 + SK-4; + IceCube
- **Reactor**: KamLAND + Double-Chooz + Daya-Bay + Reno;
- **Accelerator**: Minos (DIS+APP) + T2K (DIS+APP);
  + NOvA (DIS+APP)

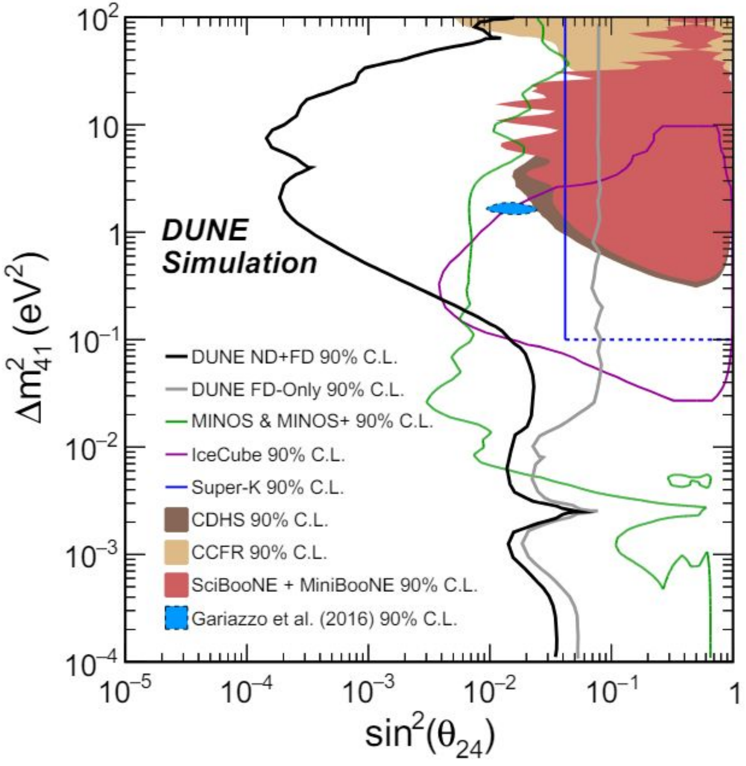
- **θ_{23} octant** is **not resolved** yet (slight preference for the second octant)
- The sign of **Δm^2_{32}** is **unknown** (Normal Ordering preferred at ~2.5σ)
- **δ_{CP} unknown**: Some tension between current LBL and atm experiments in NO. CP-violation for IO at ~3σ

θ_{12}, Δm^2_{12} = solar

θ_{23} = atmos

θ_{13} = reactor

Sterile sensitivity with beam



Sensitivity contours : energy range

Current energy range :
[0.1, 300] GeV

Limited energy range :
[0.5, 11.5] GeV