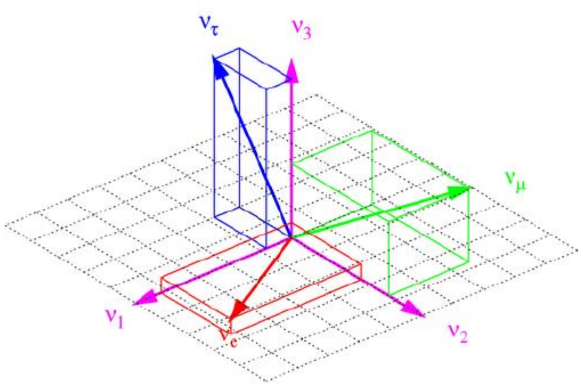
DUNE Perspectives for Atmospheric Neutrinos

Tarak Thakore for the DUNE Collaboration

Multi-messenger Tomography of the Earth (MMTE 2023)
July 6, 2023

Neutrino Oscillations



- Neutrino flavor eigenstates are superposition of mass eigenstates, related through a unitary mixing matrix U_{PMNS}), giving rise to the phenomenon of neutrino oscillations
- Neutrino oscillations are well established by many experiments in last 30 years. (Super-K, SNO, KamLAND, K2K, MINOS, Daya Bay, NOvA, T2K, IceCube and others)

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i} |\nu_i\rangle$$

Pontecorvo–Maki–Nakagawa–Sakata mixing matrix $\mathrm{U}_{\mathrm{PMNS}}$ is given as :

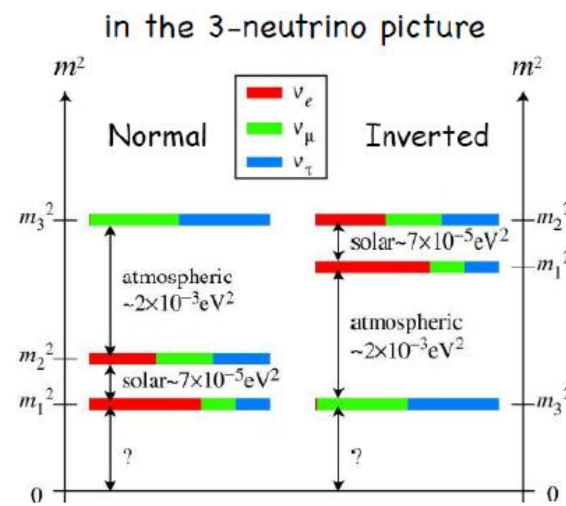
$$\mathrm{U}_{\mathrm{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric } (\theta_{23} \sim 45^\circ)} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor } (\theta_{13} \sim 9^\circ)} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar } (\theta_{12} \sim 33^\circ)} \begin{pmatrix} e^{\frac{i\alpha_1}{2}} & 0 & 0 \\ 0 & e^{\frac{i\alpha_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Current Status and Unanswered Questions

NuFIT 5.2 (2022)

without SK atmospheric data	Normal Ordering (best fit) bfp $\pm1\sigma$	Normal Ordering (best fit) 3σ range	Inverted Ordering ($\Delta\chi^2 = 2.3$) bfp $\pm1\sigma$	Inverted Ordering ($\Delta\chi^2 = 2.3$) 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}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

Neutrino Mass Ordering (NMO)



Global neutrino oscillation fit
NuFit v5.2 (www.nu-fit.org), JHEP 09 (2020) 178

Many of these parameters have been measured to a precision better than 10% at 3σ

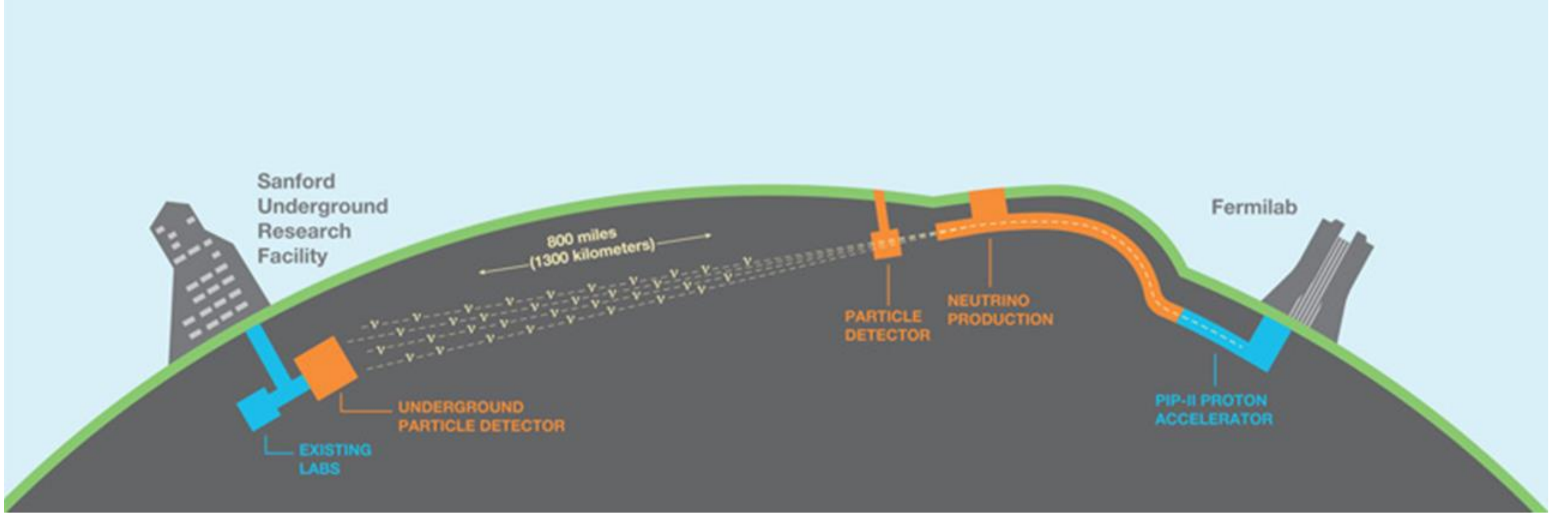
NMO : What is the sign of Δm^2_{31} ?

Is the CP symmetry violated in neutrino oscillations?
e.g. $\sin\delta_{CP} \neq 0$?

Is there new physics?

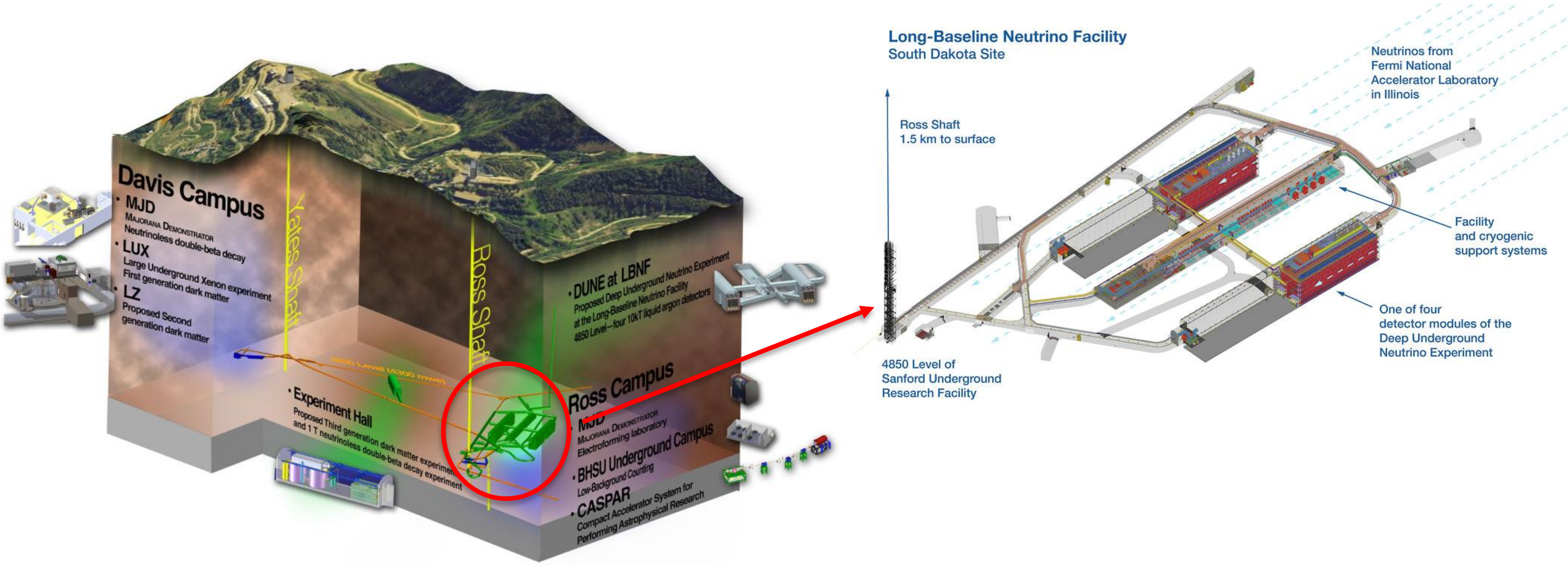
- Sterile Neutrinos
- Non-Standard Interactions
- Neutrino decays
- Nucleon decays
- Lorentz Invariance Violation

Deep Underground Neutrino Experiment (DUNE)



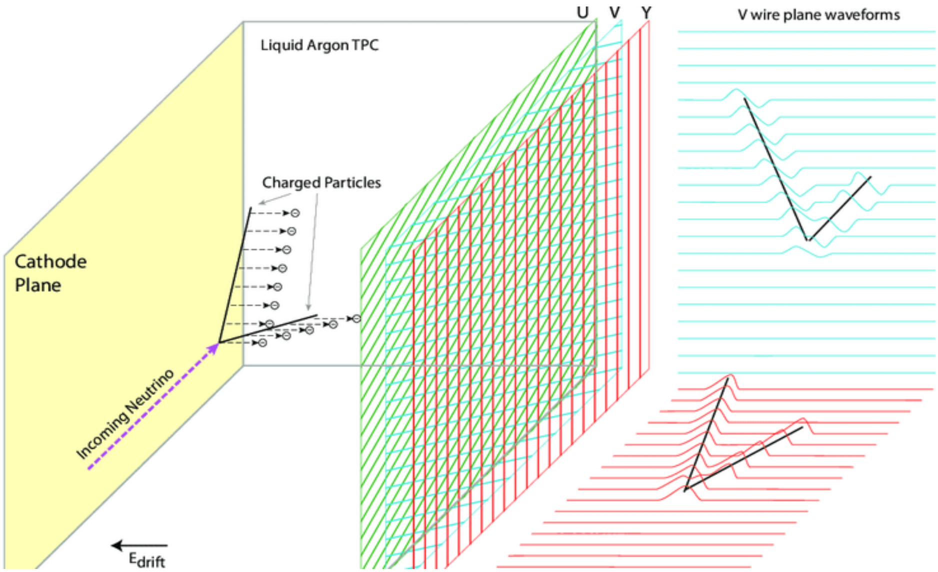
- The new PIP-II accelerator will direct a high intensity neutrino wideband beam from Fermilab to the Far Detector (FD) site in South Dakota
- Baseline of 1300 km for neutrino oscillation measurements
- The FD consists of four 17 kt Liquid Argon Time Projection Chambers (LArTPC)
- A suite of Near Detectors (ND) will be deployed to control neutrino interaction and flux systematics using data-driven techniques

Sanford Underground Research Facility



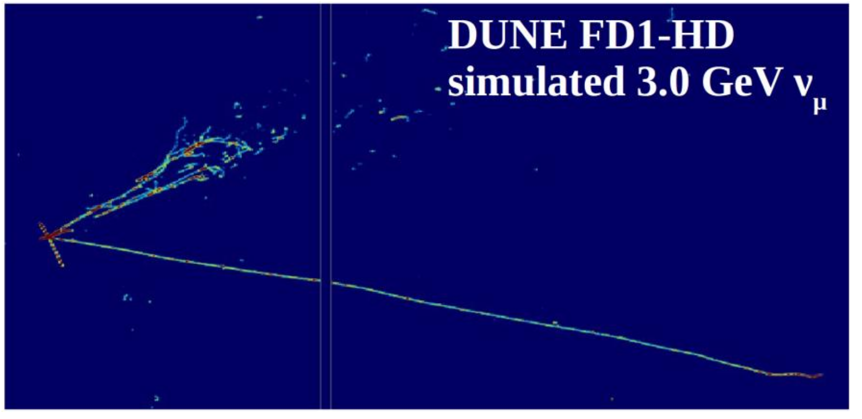
- The FD will be located in the SURF caverns with a rock overburden of 1500 m, lowering cosmic muon backgrounds for the experiment
- Cavern excavation at the FD site is 65% complete!

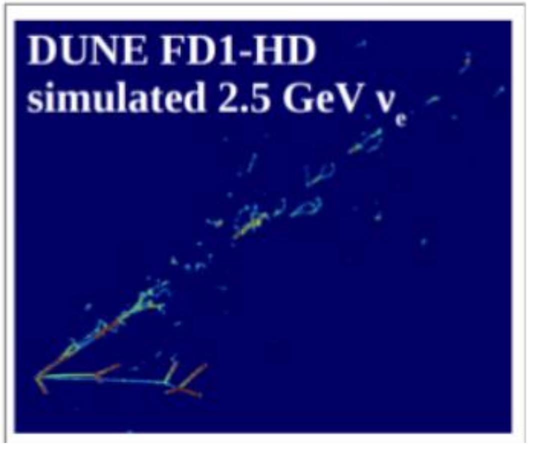
LArTPC Detector Operation



- Ionizing particles produced in neutrino interactions create free electrons
- A photon detection system determine t_0 and enable timing measurements for the vertex reconstruction
- Electrons drift in the LAr volume in a uniform electric field, and induce signals on two anode wire-planes oriented in different directions, providing two 2D tracks views
- Drift positions and timing information in these two views allow reconstruction of 3D trajectories of the particles with high spatial accuracy
- Particle energy is estimated through calorimetry and track length

Simulated Event Displays





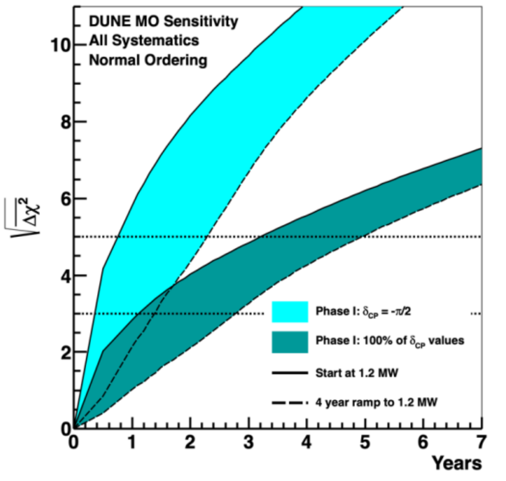
- The LArTPC technology is being validated by a 770 ton protoDUNE detector at the CERN neutrino platform in a charged particle beam.

- Bubble chamber-like high resolution particle tracks with mm-scale spatial resolution
- Various final state topologies produced in neutrino interactions can be well reconstructed, for example, using a variety of Machine Learning techniques

Phased Deployment

- **Phase -1 (2028 FD starts taking data, 2031 neutrino beam starts)**
  - Atmospheric neutrino data
  - Beam power 1.2 MW, 2 LArTPC module (1 HD, 1 VD)
  - NMO determination at 5σ in 5 years for any δ_{CP} value
  - CPV determination at 3σ for the most favorable δ_{CP} values
  - Limited BSM physics searches
  - Astrophysical, supernova neutrinos
  - Neutrino cross section measurements

Snowmass Neutrino Frontier: DUNE Physics Summary arXiv:2203.06100

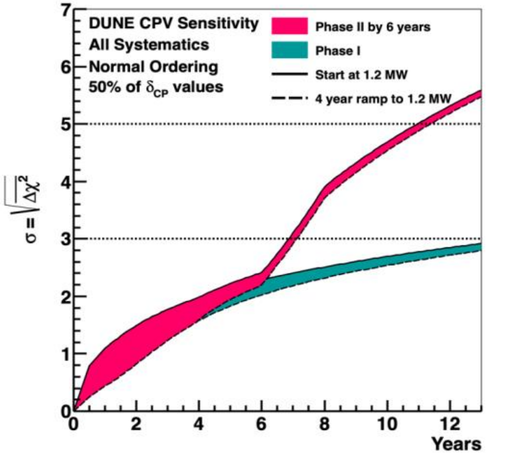


NMO discovery with Phase 1

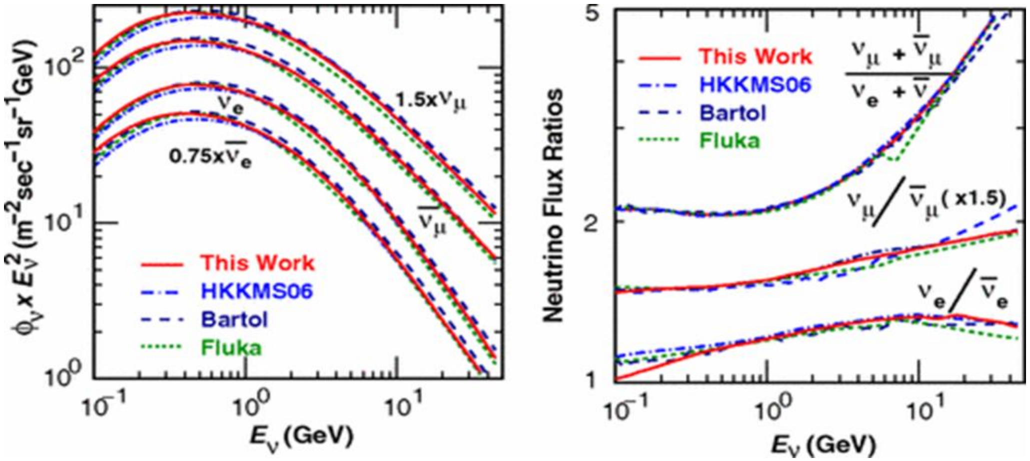
CPV discovery sensitivity with DUNE Phase-2 and the ND

- **Phase-2 (mid-2030 onwards)**
  - Beam power upgraded to 2.4 MW,
  - All 4 LArTPC modules taking data
  - NMO and CPV determination at 5σ
  - Extensive BSM physics program
  - Full non-accelerator physics program (atmospheric, supernova, nucleon decay)
  - Neutrino cross section measurements

- NMO discovery in 2-3 years
- CPV discovery for >50% δ_{CP} value at 5σ



DUNE FD as an Atmospheric Neutrino Detector



Honda et. al. Phys. Rev., D92(2) 023004, 2015

- Good neutrino energy and direction reconstruction over both multi-GeV and sub-GeV ranges is expected from preliminary studies in LArTPCs.
- Ability to tag protons and stopped muons to provide statistical discrimination of ν / $\bar{\nu}$
- Very good detector and neutrino interaction systematics control expected
- Good complementarity with the DUNE LBL physics program and other large neutrino telescopes

DUNE FD as an Atmospheric Neutrino Detector

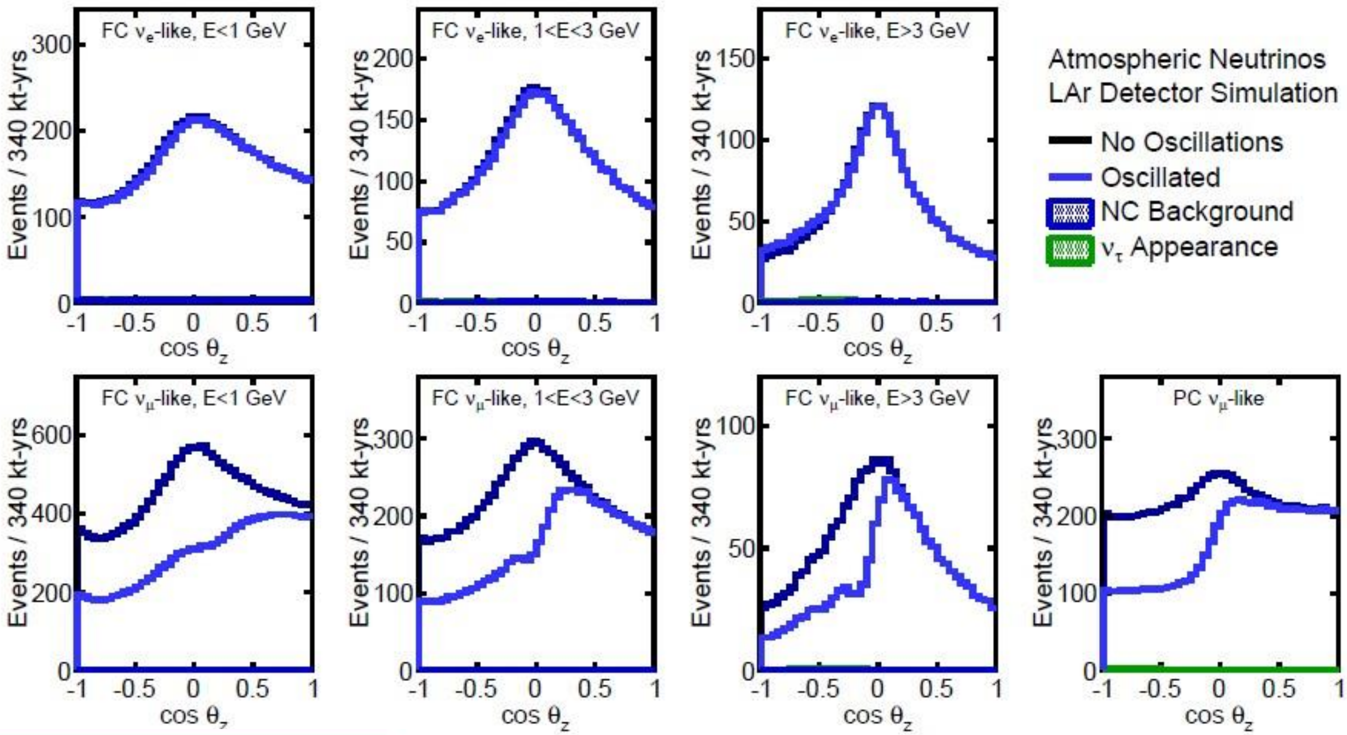
IceCube, KM3NeT	**Hyper-K**	**DUNE**
Very high energy astro-particle physics and atmospheric neutrinos	Accelerator LBL and atmospheric neutrino oscillation	Accelerator LBL and atmospheric neutrino oscillation
O(1) Mt O(10^5 events/year)	260 kt O(10^4 events/year)	40 kt O(10^3 events/year)
Coarse event reconstruction	Good event reconstruction, neutrino flavor identification	Excellent event reconstruction, neutrino flavor identification
E > O(1 GeV)	E > O(1 MeV)	E > O(1 MeV)

Fine reconstruction →

← High statistics

- Preliminary sensitivity studies performed with expected detector performance assumptions by the DUNE collaboration and phenomenologists
- Full atmospheric Monte Carlo simulations for the DUNE FD with the latest detector geometry is a work in progress, followed by a realistic physics sensitivity study

Atmospheric Neutrino Spectrum in the FD



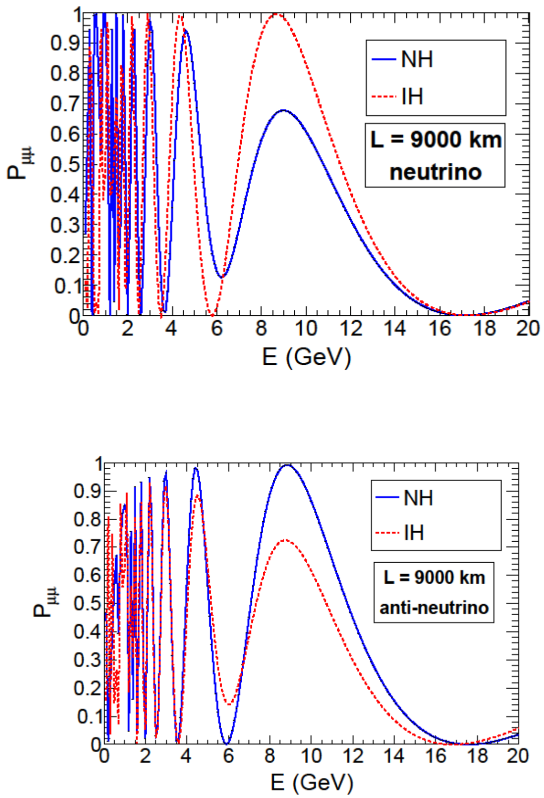
Particle	Resolution
Angular Resolutions	
Electron	1°
Muon	1°
Hadronic System	10°
Energy Resolutions	
Stopping Muon	3%
Exiting Muon	15%
Electron	$1\%/\sqrt{E(GeV)} \oplus 1\%$
Hadronic System	$30\%/\sqrt{E(GeV)}$

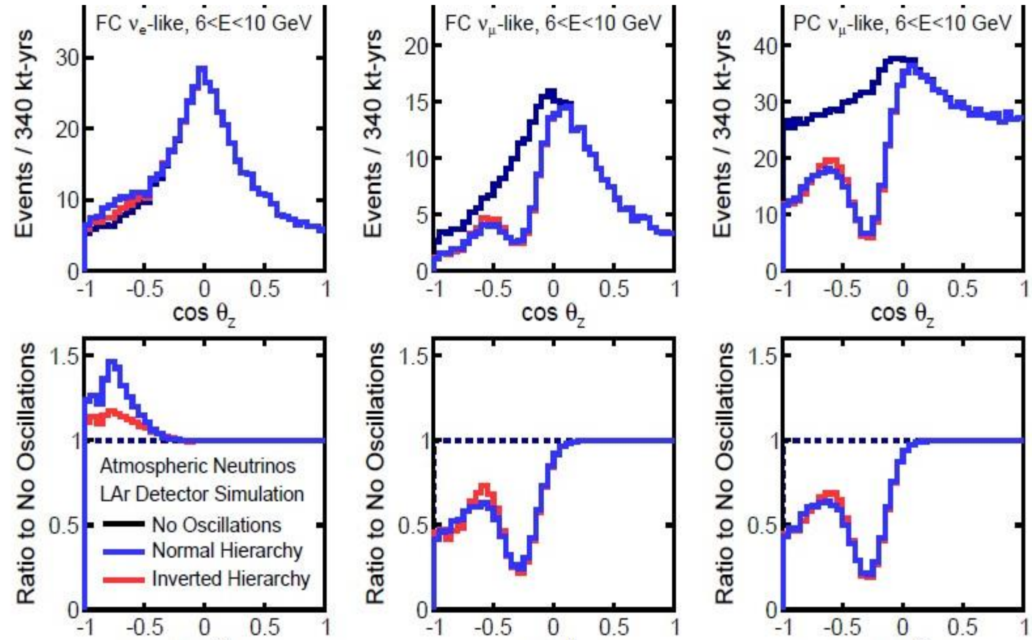
arXiv:1307.7335

Event rates scaled to 40 kt-year

Sample	Event rate per year
fully contained electron-like	1600
fully contained muon-like	2400
partly contained muon-like	790

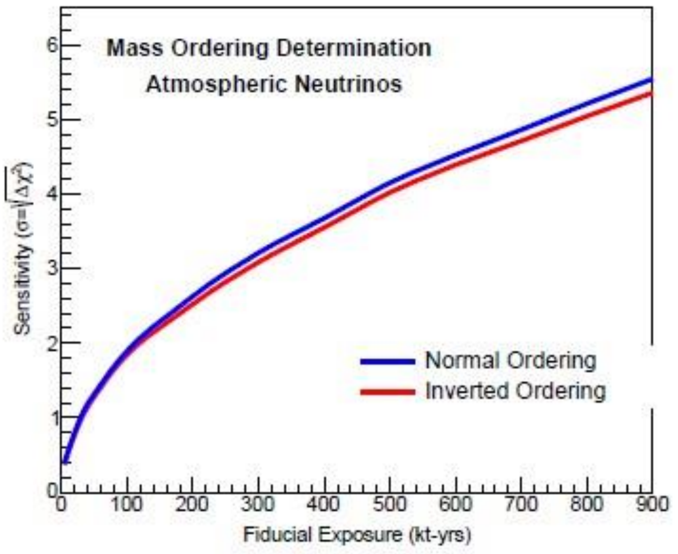
NMO Determination through Matter Effects

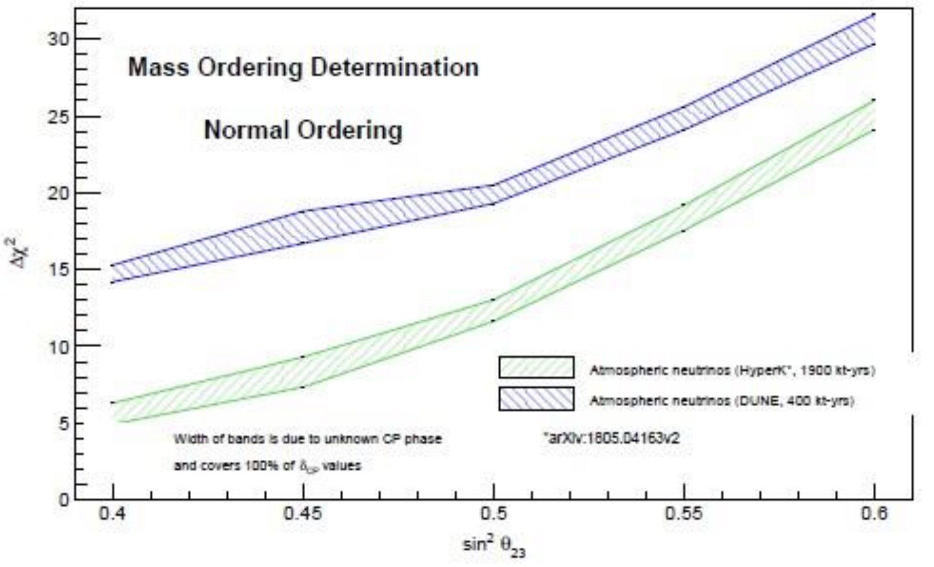




- Neutrino propagation is affected by coherent forward scattering with electrons as they pass through the Earth matter.
- The MSW resonance effect allows for a determination of the NMO using multi-GeV atmospheric neutrinos.

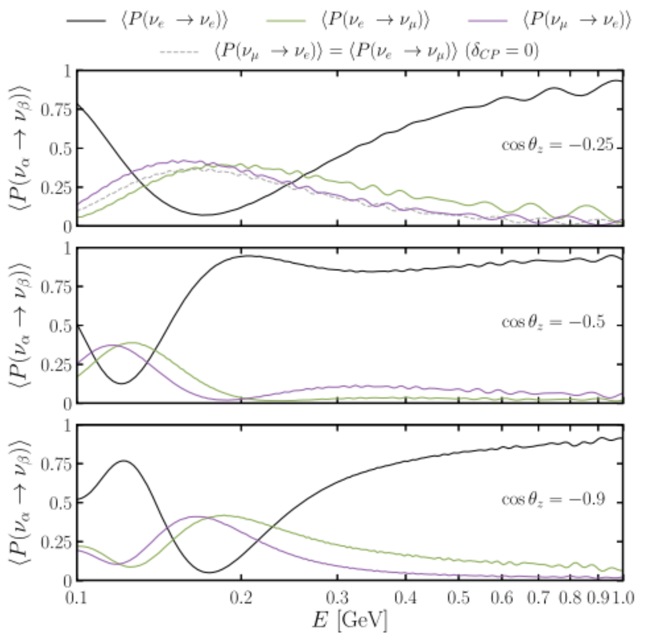
NMO Sensitivity

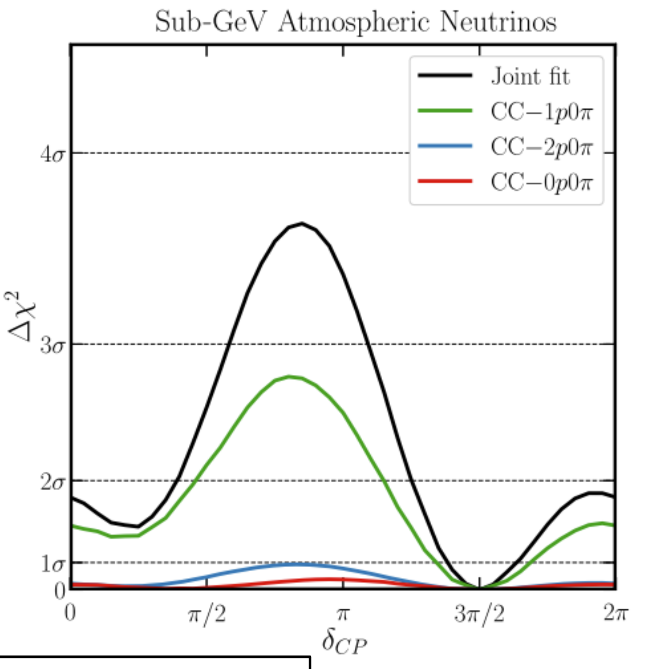




- 3σ sensitivity to the NMO in about 12 years with a 400 kt-year exposure, independent of δ_{CP} value.
- Though the NMO sensitivity is lower compared to the beam neutrinos, good to have an independent measurement within the same experiment
- Combination of DUNE LBL and atmospherics will result in higher significance --> Could be important in the Phase-1 operations of oscillation parameter measurements

Probing CPV with Sub-GeV Atmospheric Neutrinos



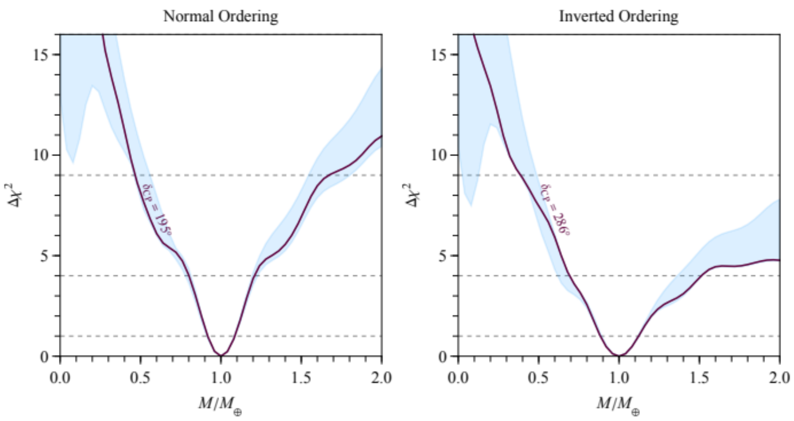


Kelly et. al. Phys. Rev. Lett. 123, 081801

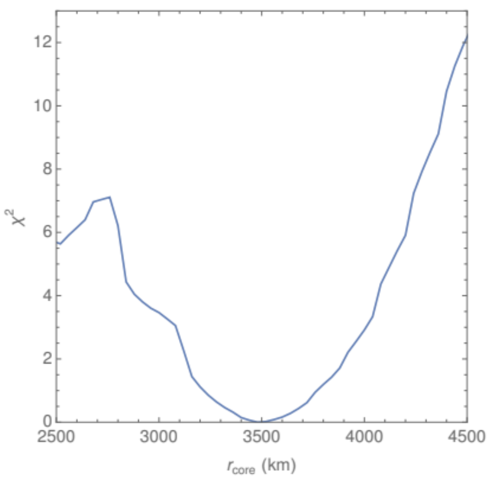
- LArTPC reconstruction will allow measurements of sub-GeV neutrino interactions with a possibility to detect low energy protons, a feature unique to DUNE
- CPV sensitivity present over a broad energy range, need very good direction reconstruction.
- Significant challenges in the neutrino interaction modelling at sub-GeV energies -> Could be overcome by using a movable ND (DUNE-PRISM)

Earth Tomography with sub-GeV Atmospheric Neutrinos

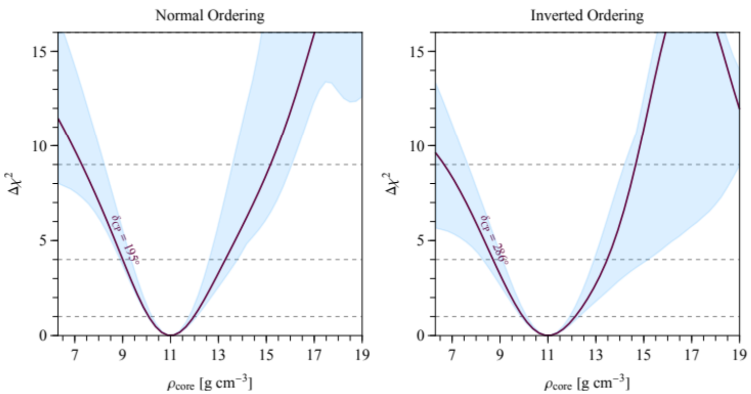
- Accelerator LBL and reactor neutrino experiments will make very precise measurements of the oscillation parameters over the next decade.
- In turn, they can be used to constrain the matter density profile in the atmospheric neutrino propagation through the Earth.



Constraining the total mass of the Earth
8.4% precision at 1σ



Constraining the radius of the Earth's core:
9% precision at 1σ

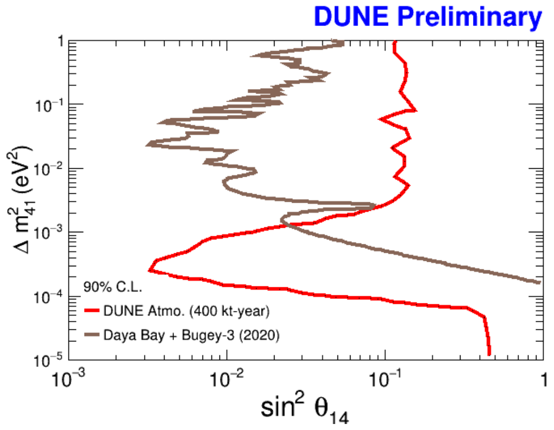


Constraining the density of the Earth's core
8.8% precision at 1σ

Denton et. al. Phys.Rev.D 104 (2021) 11, 113007

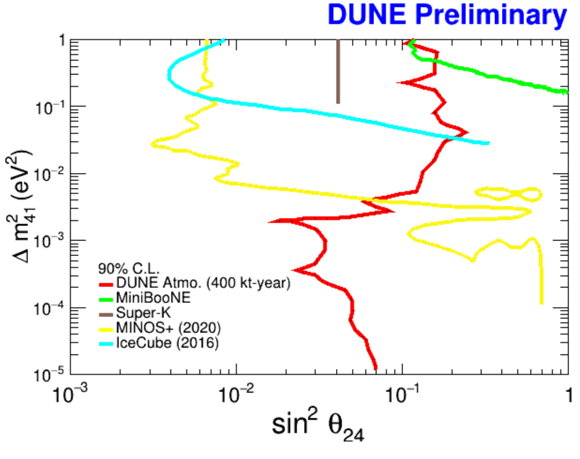
Kelly et. al. JHEP 05 (2022) 187

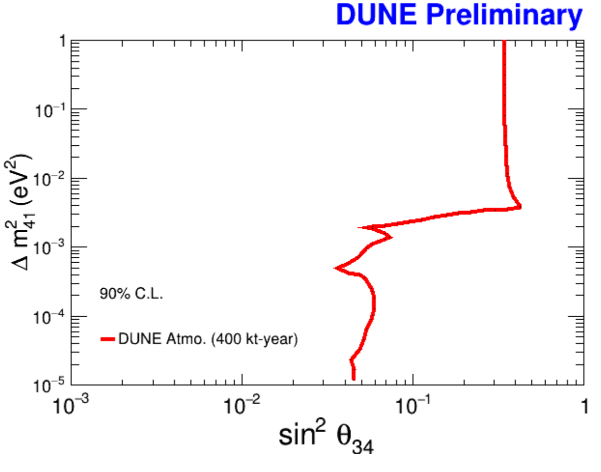
Sterile Neutrino Search with Atmospheric Neutrinos



- Is there a 4th neutrino species (sterile neutrino)?
- DUNE atmospheric data will provide competitive limits to the (3+1) mixing model.

	Track-like events	**Shower-like events**
Reconstruction efficiency (CC)	80%	80%
Reconstruction efficiency (NC)		0.5%
Neutrino energy resolution	18%	13%
Neutrino direction resolution	10 degrees	10 degrees





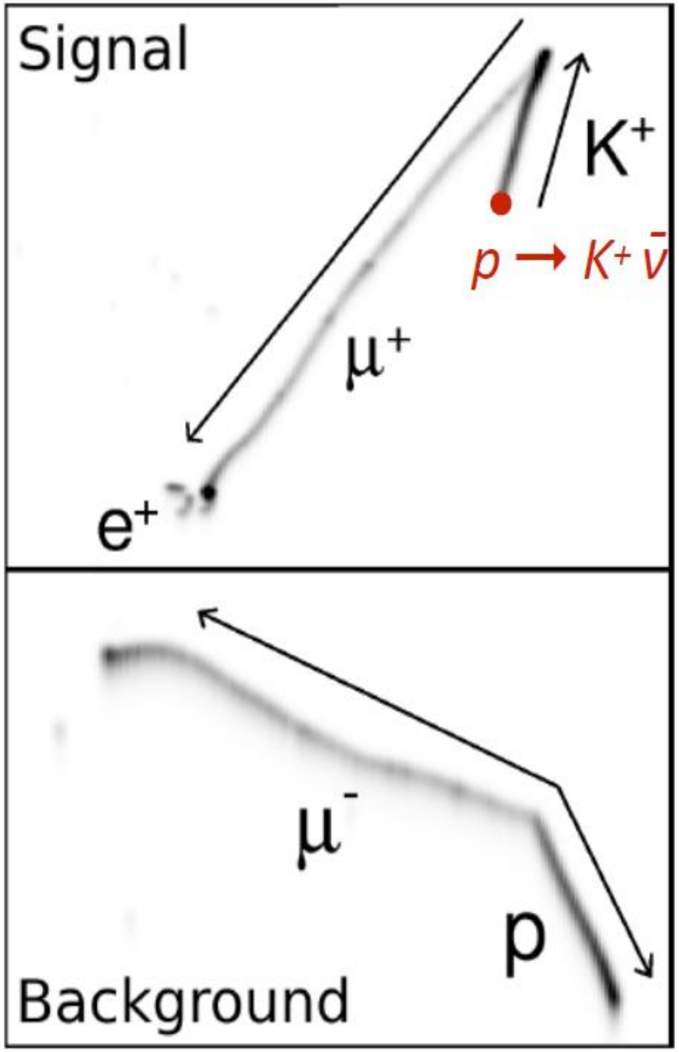
•DOI: 10.2172/1874285

Proton Decay Search

- Some Grand Unified Theories predict proton decays with a lifetime of 10^{34} – 10^{36} years
- DUNE is most sensitive to the channel:

  $p \to K^+ + \bar{\nu}$

- LArTPC tracking enables good separation of signal and atmospheric neutrino background.
- Lower limit on proton lifetime (90% C.L.):
  - DUNE (400 kt-year) : 1.3 x 10^{34} years
  - Current limit (Super-K, 260 kt-year) : 5.9 x 10^{33} year

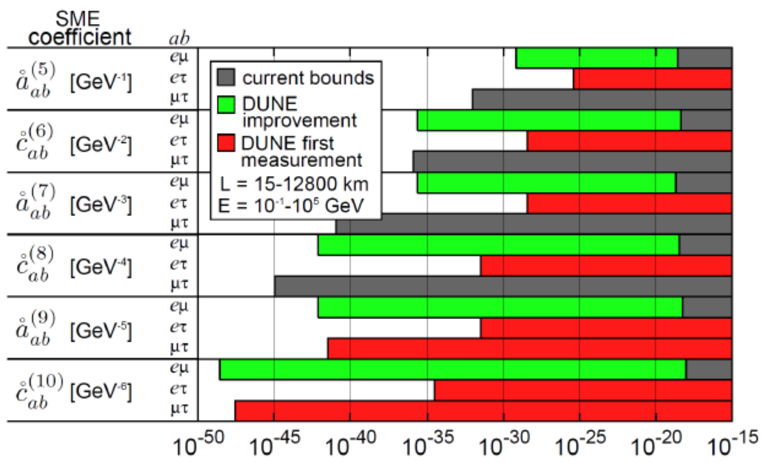


Proton decay search with both DUNE and Hyper-K highly anticipated by the HEP community

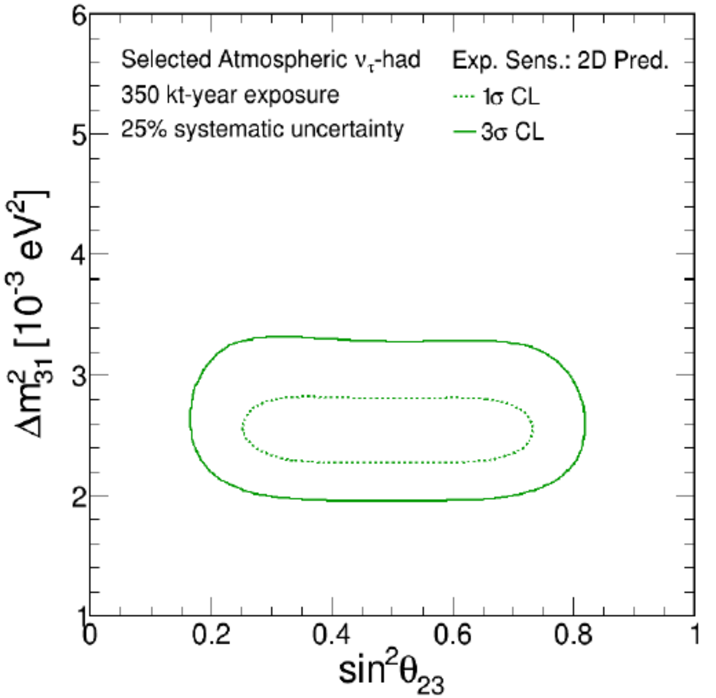
More Atmospheric Neutrino Studies

- Tau neutrino appearance
- Non-Standard Interactions
- Mass-varying neutrinos
- Lorentz and CPT violation
- Combined atmospheric and neutrino beam oscillation physics

DUNE atmospheric sensitivities to Lorentz and CPT Violation

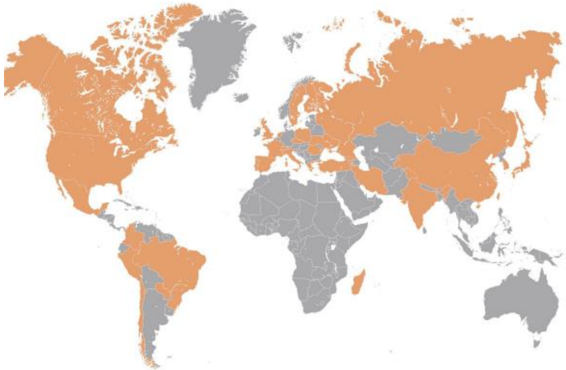


Atmospheric sample



Assume a 25% normalization uncertainty

Summary



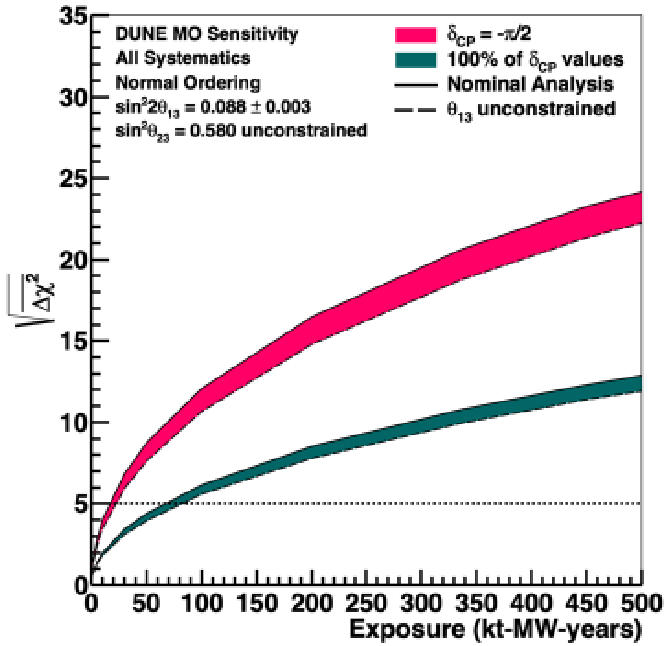
Collaboration
- 1300 Members
- 211 Institutes
- 34 Countries

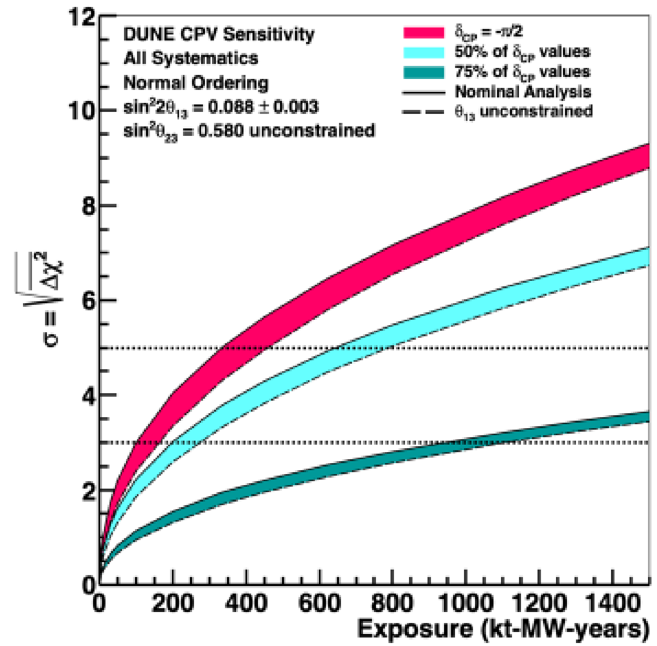
Collaboration Meeting May 2023

- DUNE is an ambitious neutrino oscillation experiment with a great potential with both long-baseline and atmospheric neutrinos powered by the novel LArTPC technology.
- The atmospheric neutrino physics program will be highly complementary to its accelerator physics program as well as with other large atmospheric neutrino telescopes for SM and BSM physics
- The DUNE collaboration is in the process of exploring its atmospheric physics potential with full detector simulations.
- Stay tuned for rapid progress!

Backup Slides

NMO and CPV Determination Sensitivity with DUNE LBL





Snowmass Neutrino Frontier:
DUNE Physics Summary
arXiv:2203.06100

Systematics for the Atmospheric NMO Study

	Atmospheric	Beam (Assumes ND)
Normalization	Overall (15%)	μ-like (5%) e-like (1%)
NC Background	e-like (10%)	μ-like (10%) e-like (5%)
Spectrum Ratios	up/down (2%) ν_e/ν_μ (2%) $\overline{\nu}_\mu/\nu_\mu$ (5%) $\overline{\nu}_e/\nu_e$ (5%)	
Spectrum Shape	$f(E < E_0) = 1 + \alpha(E - E_0)/E_0$ $f(E > E_0) = 1 + \alpha \log(E/E_0)$ where σ_α=5%	
Energy Scales (Correlated)	Muons (stopping 1%, exiting 5%) Electrons (1%) Hadronic System (5%)	