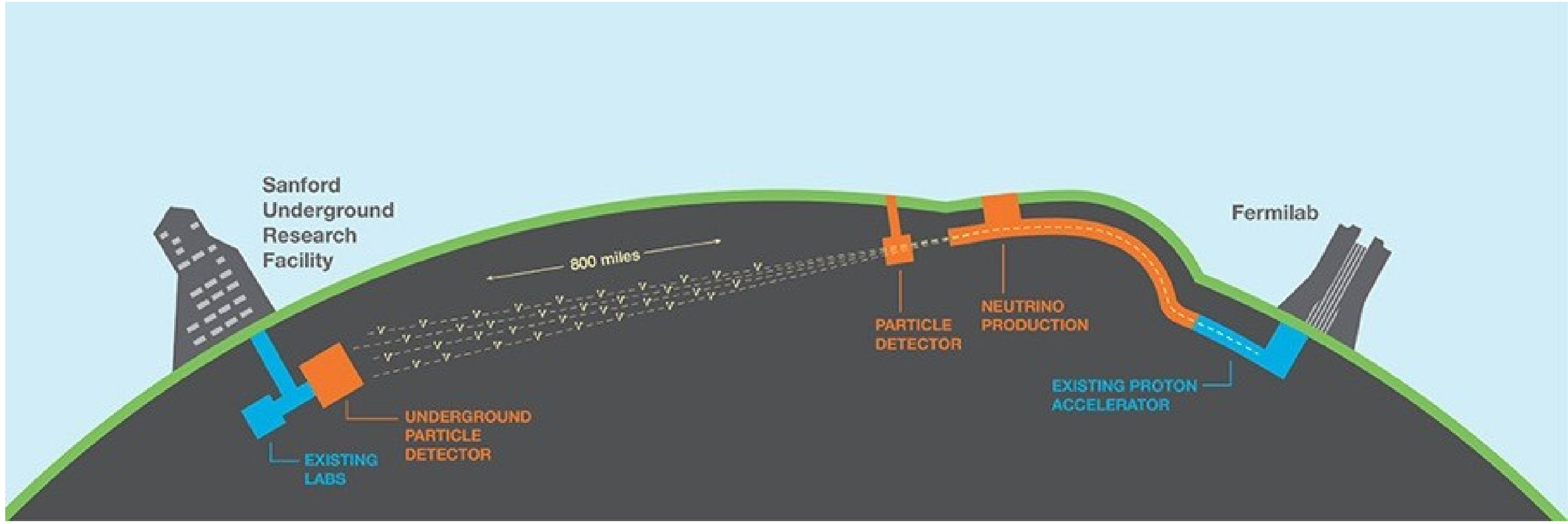
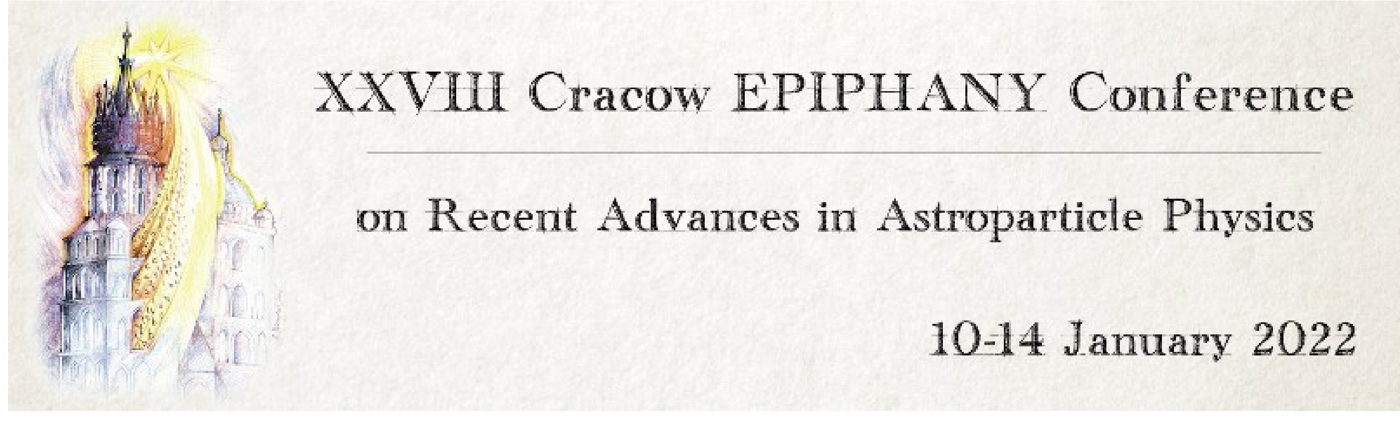


Status of the DUNE experiment

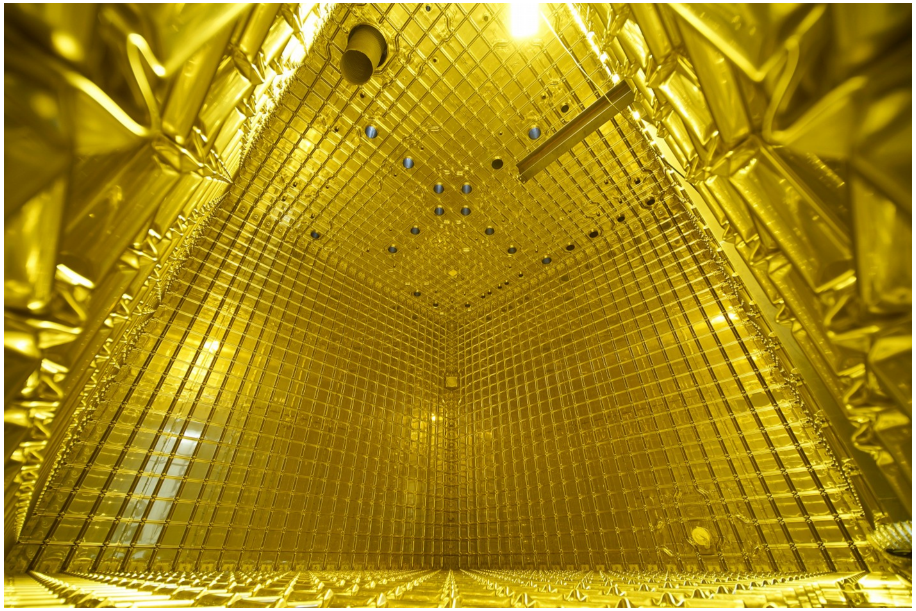
Andrzej M. Szelc
for the DUNE collaboration

University of Edinburgh



Introduction

- A crash course in neutrino physics
- The DUNE experiment and its main elements
- DUNE physics goals
- DUNE prototypes and plans



Crash Course in Neutrino Physics

- Three neutrino flavors: ν_e, ν_μ **and** ν_τ

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Neutrinos have mass and can oscillate changing flavour.

"amplitude"

$$P(\nu_x \rightarrow \nu_y) = sin^2(2\theta) sin^2(1.27\Delta m^2 \frac{L(km)}{E(GeV)})$$

"frequency"

Two flavour approximation is good enough in most cases.

- Energy (E) and baseline (L) define which parameters we can probe.

The Current State of Neutrino Knowledge

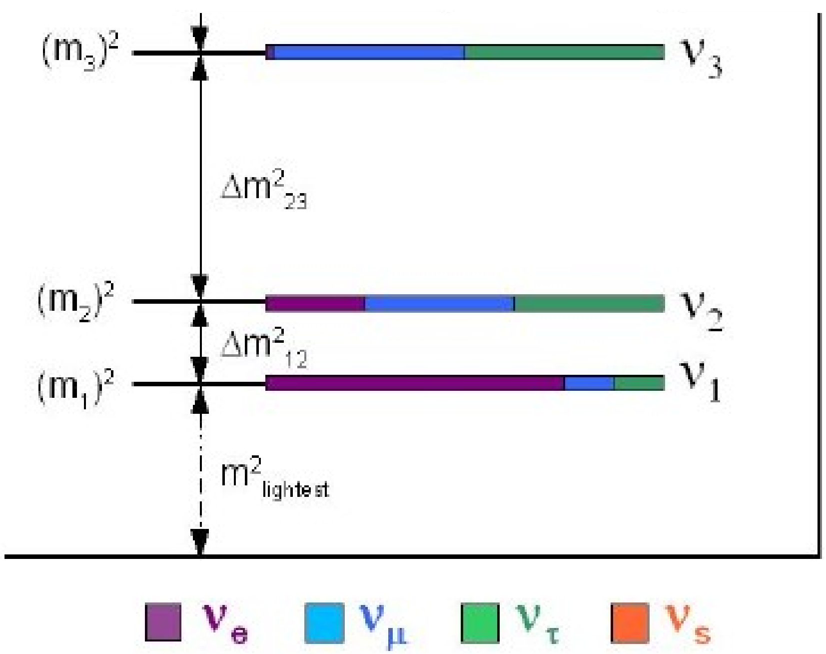
23 13 12

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric — Reactor/Interference — Solar

$\mu \Rightarrow \tau$ — $\mu \Leftrightarrow e$ — $e \Leftrightarrow \mu$

θ_{13} was first measured less than 10 years ago.



“Known” neutrino physics

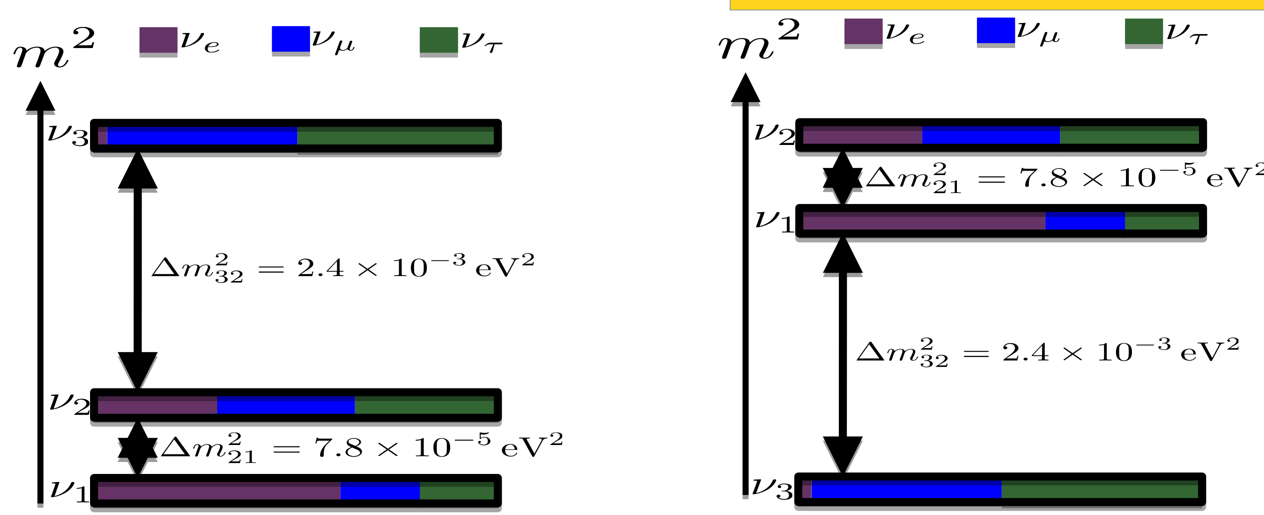
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.56 ± 0.19
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.55 ± 0.04
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	2.49 ± 0.04
$\theta_{12}/°$	$34.5^{+1.1}_{-1.0}$
$\theta_{13}/°$	$8.44^{+0.18}_{-0.15}$
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$
$\theta_{23}/°$	41.0 ± 1.1
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$
$\theta_{23}/°$	50.5 ± 1.0

Salas, Forero, Ternes, Tortola, Valle: 2017

Open Questions in (oscillation) Neutrino Physics

- Neutrino Mass Hierarchy
- CP Violation – is the δ phase non-zero?
- Is θ_{23} maximal?
- *Are there more than 3 neutrino families (sterile neutrinos?)*

Probed with oscillations from muon-neutrino beams.
Searching for electron-neutrinos (ν_e) appearing or muon-neutrinos (ν_μ) disappearing



Normal Inverted

Long-Baseline Oscillations

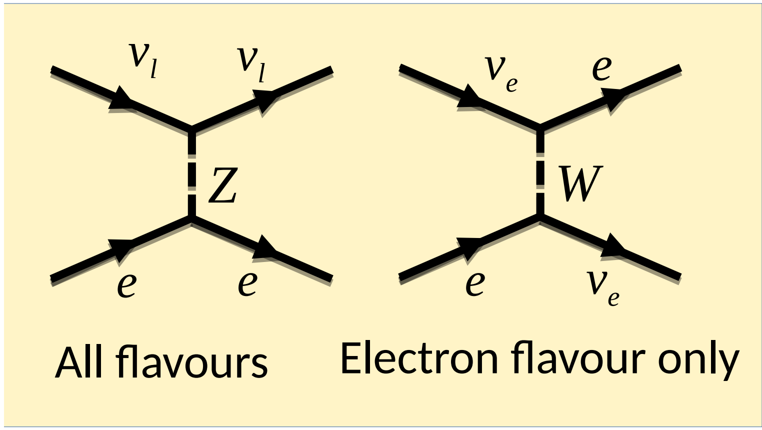
$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$
$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}$$
$$\times\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP})$$
$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a=\pm\frac{G_F N_e}{\sqrt{2}}\approx\pm\frac{1}{3500\ \mathrm{km}}\left(\frac{\rho}{3.0\ \mathrm{g/cm^3}}\right),$$

Matter effects (mass hierarchy)

CP violation

θ_{23} octant

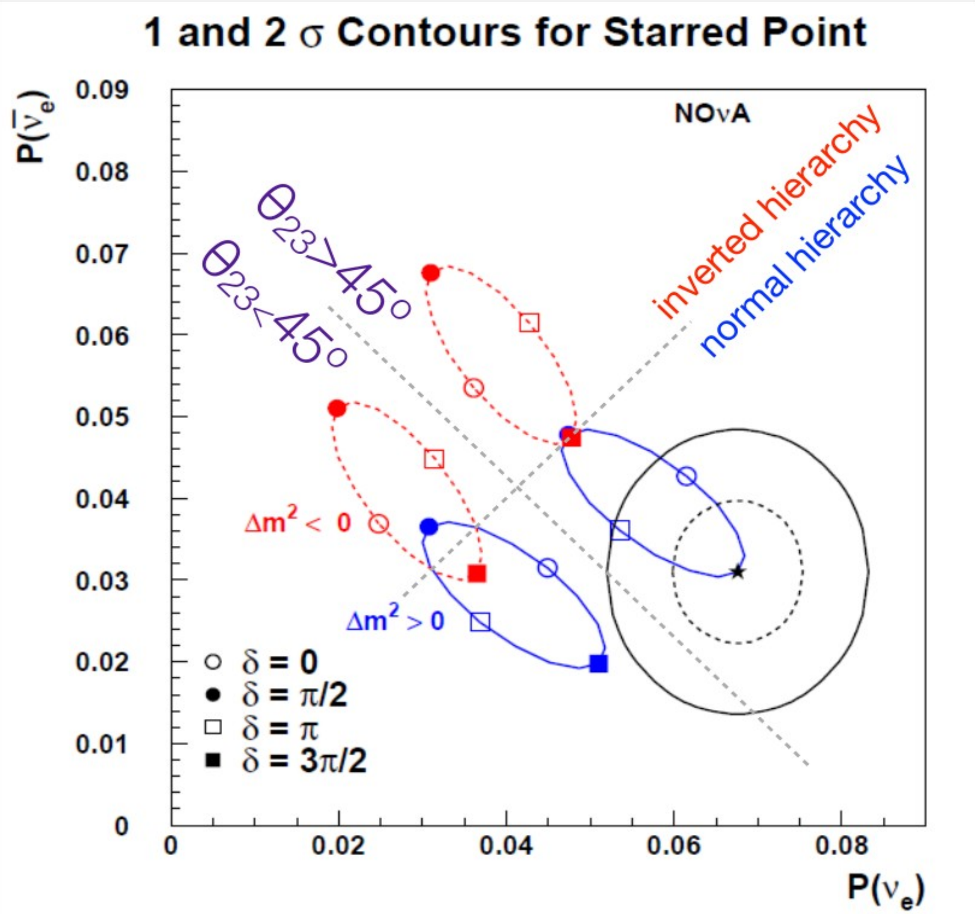


Matter Effects

Need to:

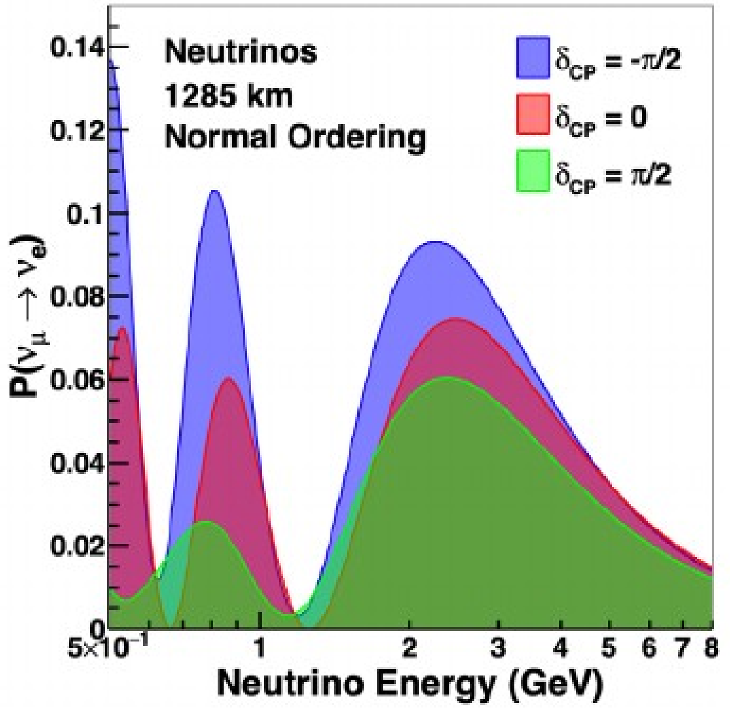
- measure ν_μ and ν_e after oscillation (and their energies)
- Repeat for $\bar{\nu}_\mu$ and $\bar{\nu}_e$
- Know the amount of ν_μ and ν_e before oscillation (near detector)
- Be able to differentiate effects of mass hierarchy, CPV and θ_{23}

Long-Baseline Oscillations



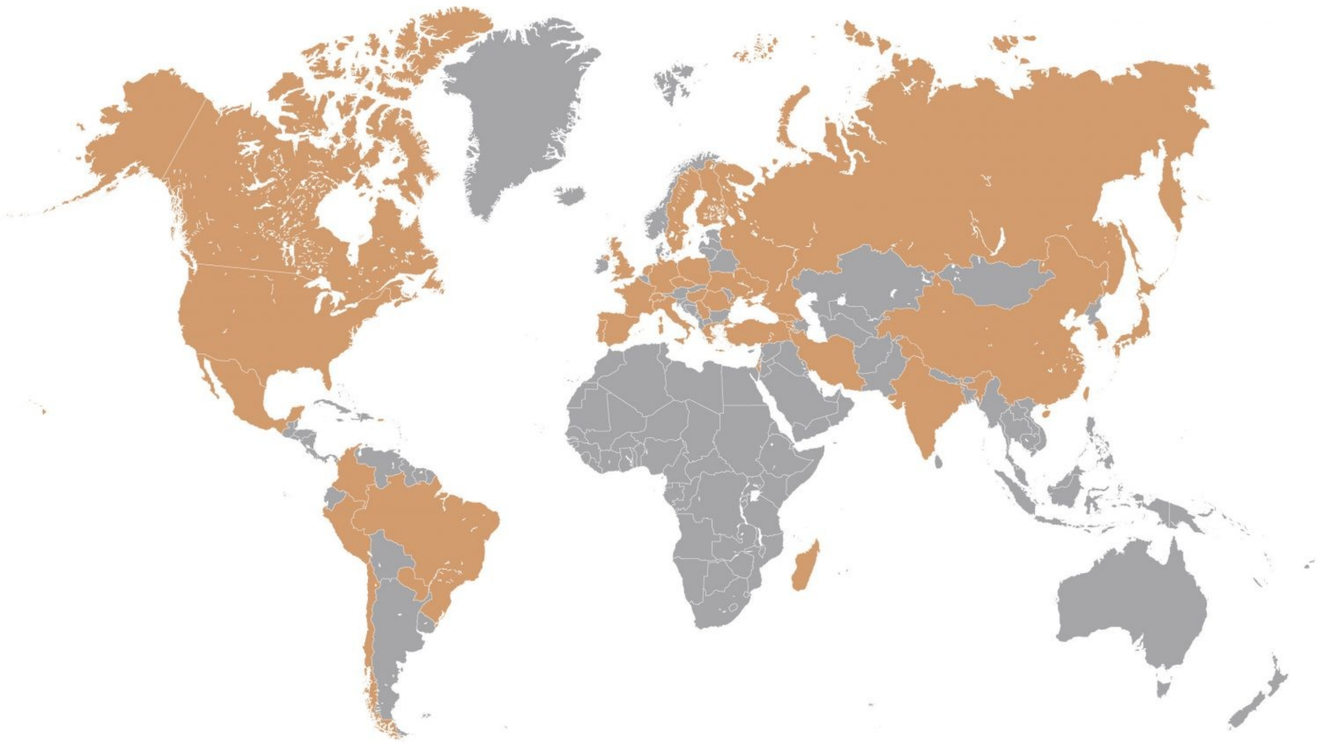
M. Messier

	$\nu_\mu \rightarrow \nu_e$	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
Normal hierarchy	Enhanced	Decreased
Inverted hierarchy	Decreased	Enhanced



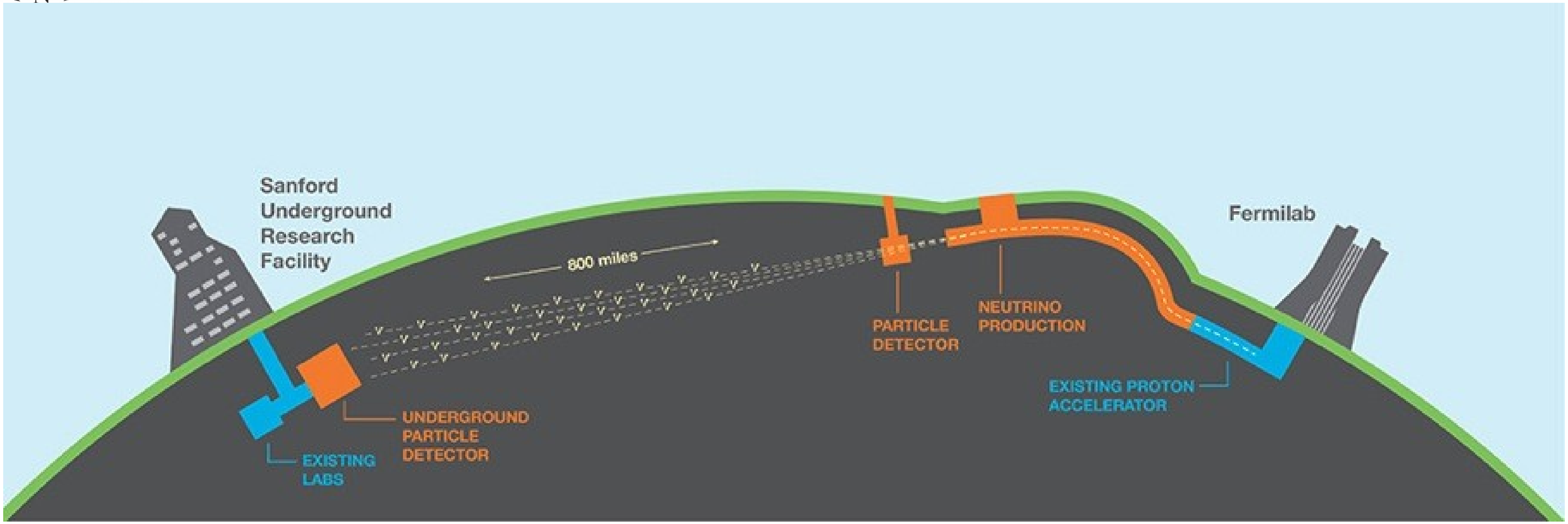
DUNE collaboration

Over 1300 collaborators from over 200 institutions in over 30 countries plus CERN



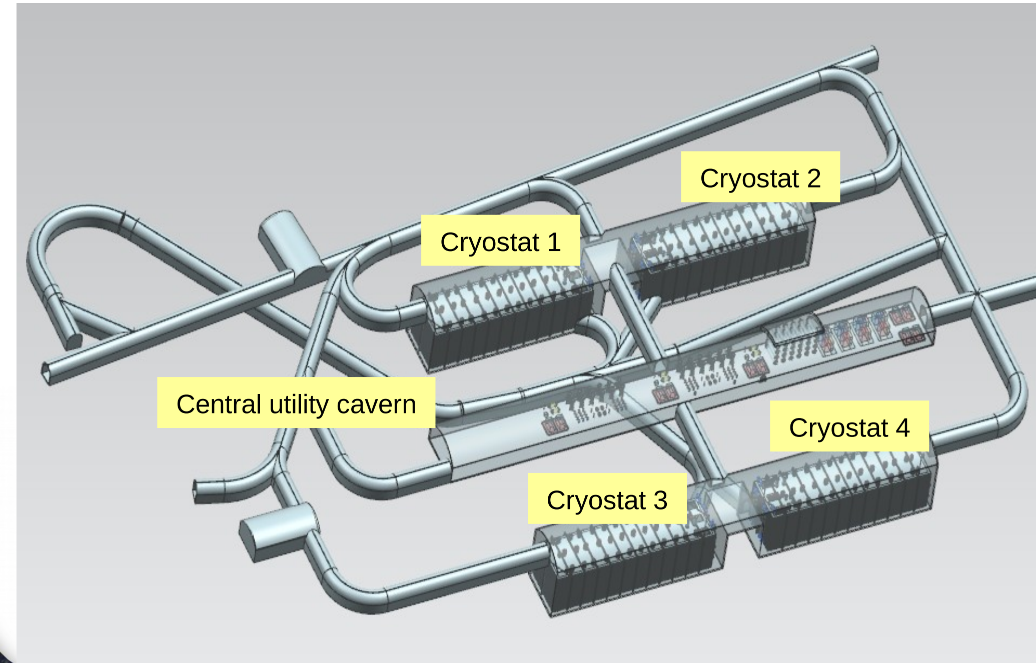
DUNE CM 2020
At CERN

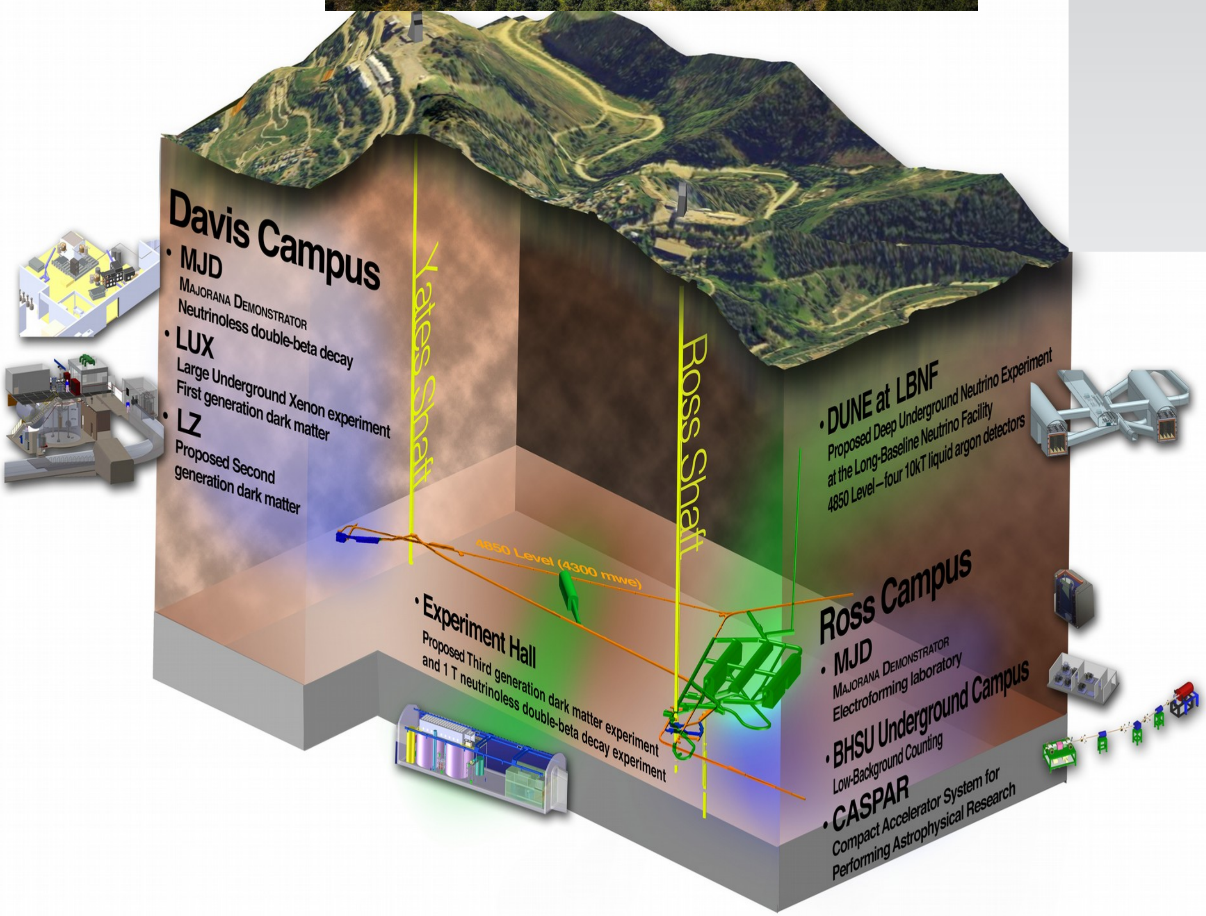
DUNE at a Glance



- High-intensity neutrino beam (1.2 MW – upgradeable to 2.4 MW)
- 70 kTons of liquid argon, 1.5 km underground.
- Detectors on-axis, observing a wide-band neutrino beam.
- 1300 km baseline, ample to provide matter effects.
- Multi-element near detector for excellent control of systematic effects.

The FD Complex

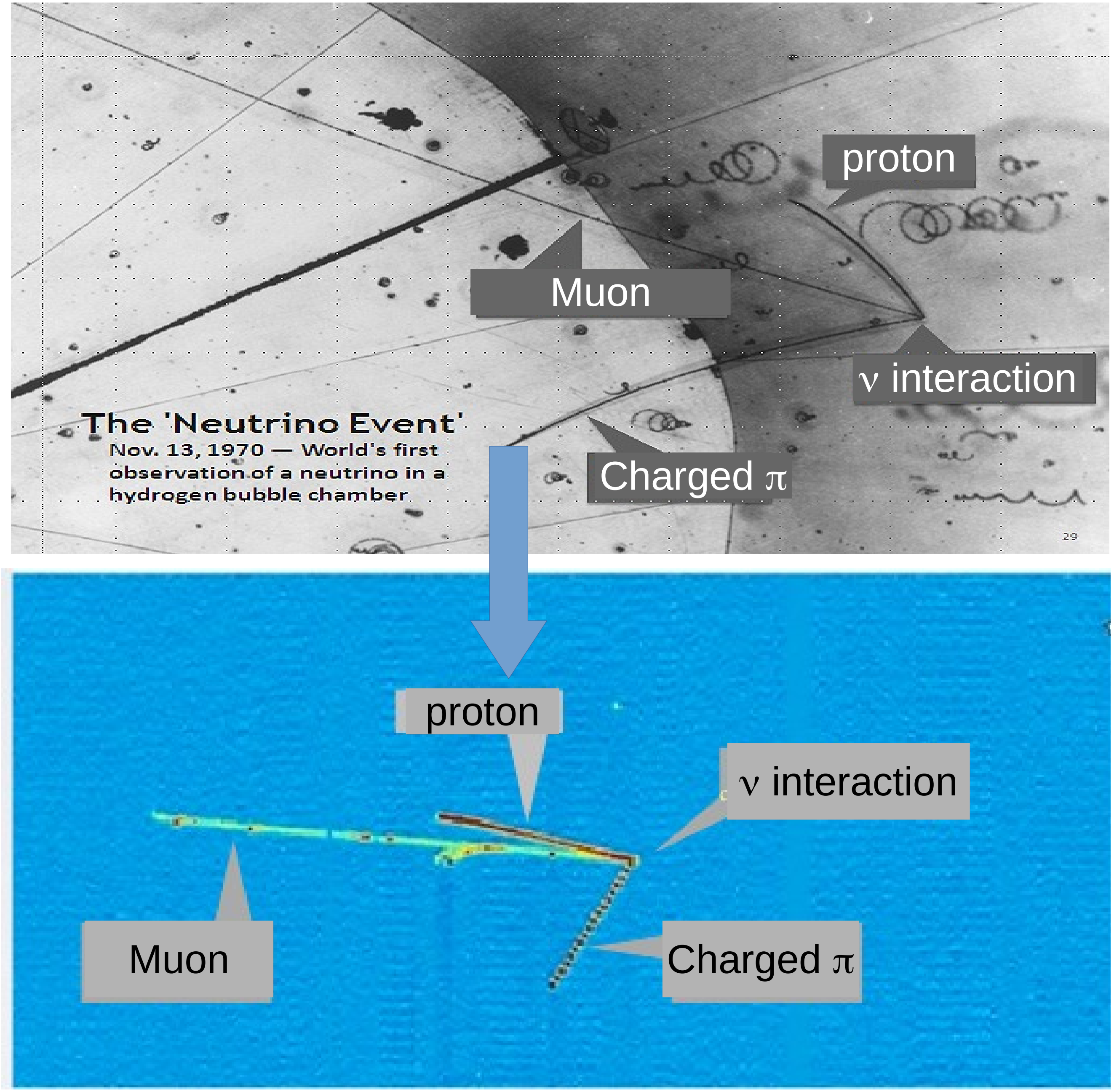




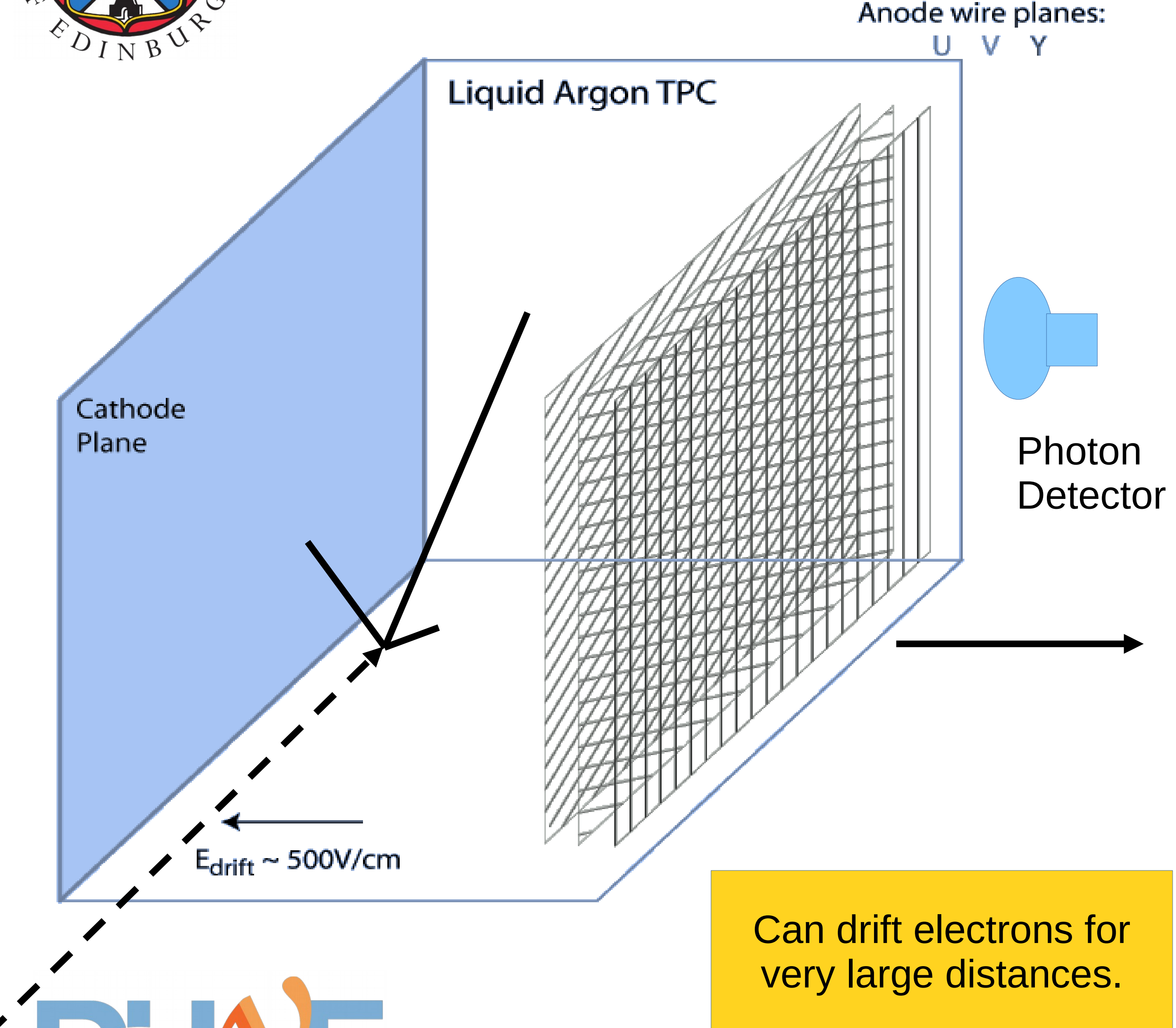
- Four modules (17kTons of argon each)
- Membrane Cryostats hold the detectors.
- Different module designs:
  - Horizontal Drift (HD)
  - Vertical Drift (VD)
  - Module of Opportunity - TBD

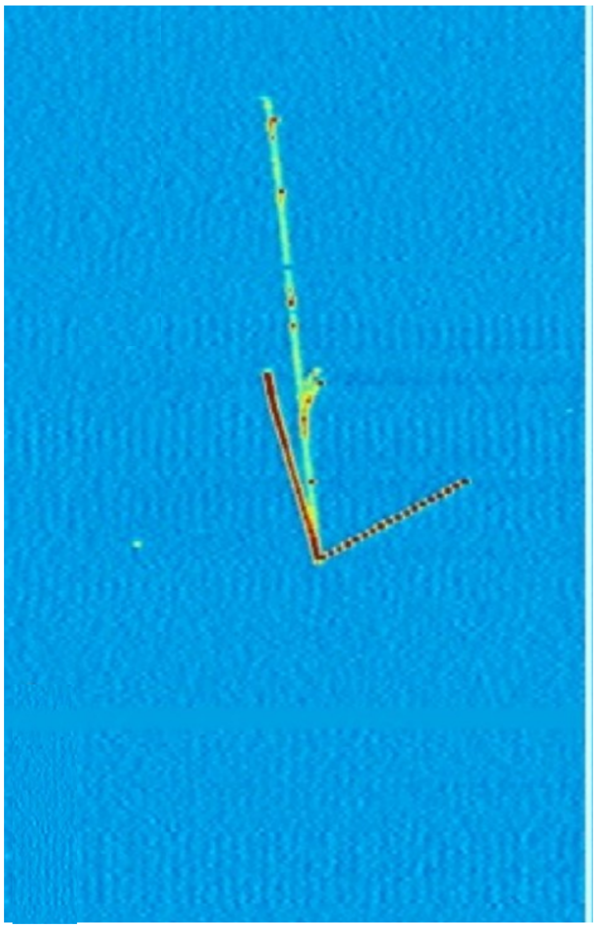
Why Liquid Argon?

Bubble chamber quality of data with added full calorimetry.



LArTPCs

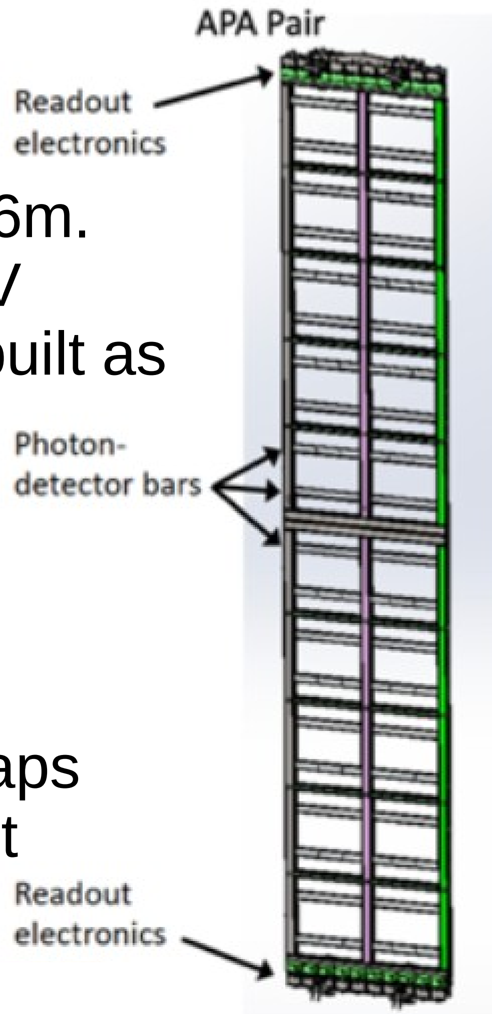


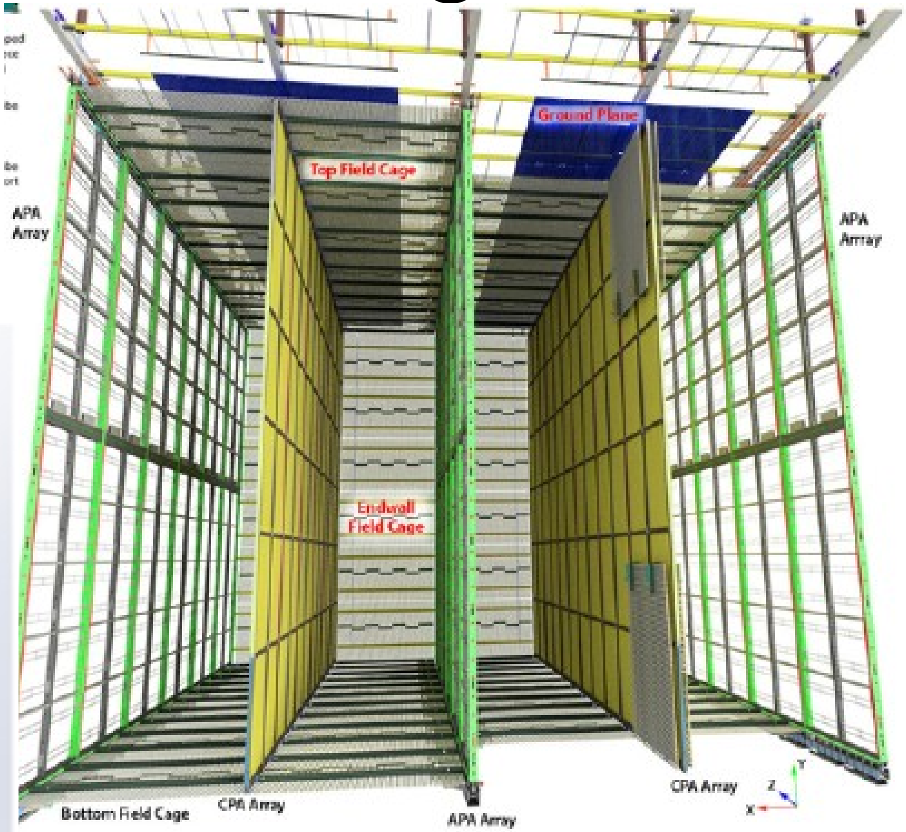


Can drift electrons for very large distances.

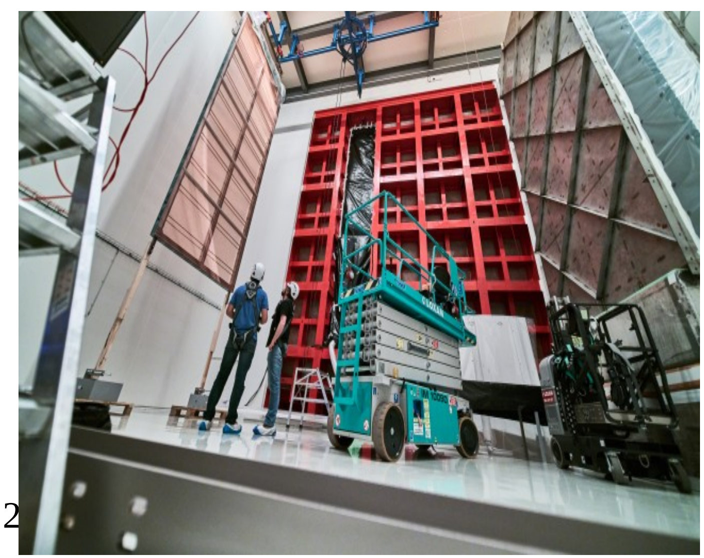
Horizontal Drift design

- First module built will be Horizontal Drift
- Alternating Anode and Cathode Plane assemblies – drift 3.6m.
- Requires HV=-180kV
- Anode = 150 APAs built as wire planes.
- Cathode highly resistive to prevent fast discharges.



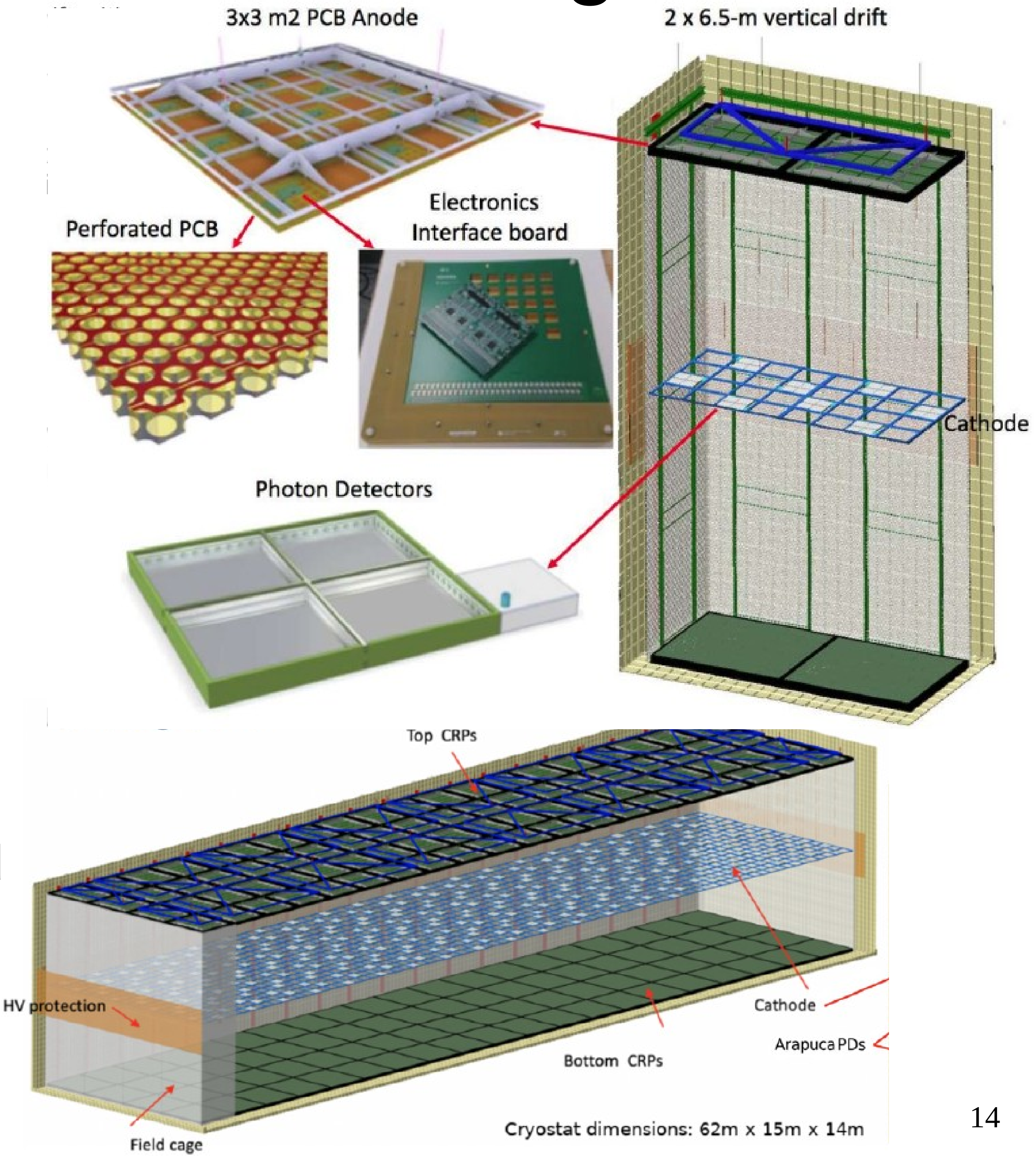


- X-ARAPUCA light traps inside APAs to detect scintillation light



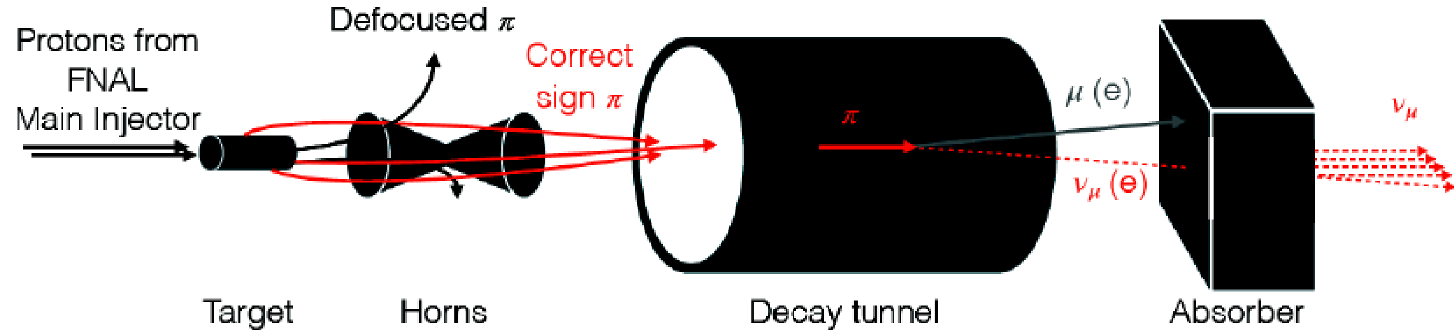
Vertical Drift design

- Second module built will be Vertical Drift.
- Evolution of the double phase concept.
- Charge drifted vertically (6.5m), cathode in the middle.
- Requires HV= -300kV
- Anode built out of strips etched on PCBs.
- Large X-ARAPUCA detectors on cathode and walls.



Excavation is ongoing!

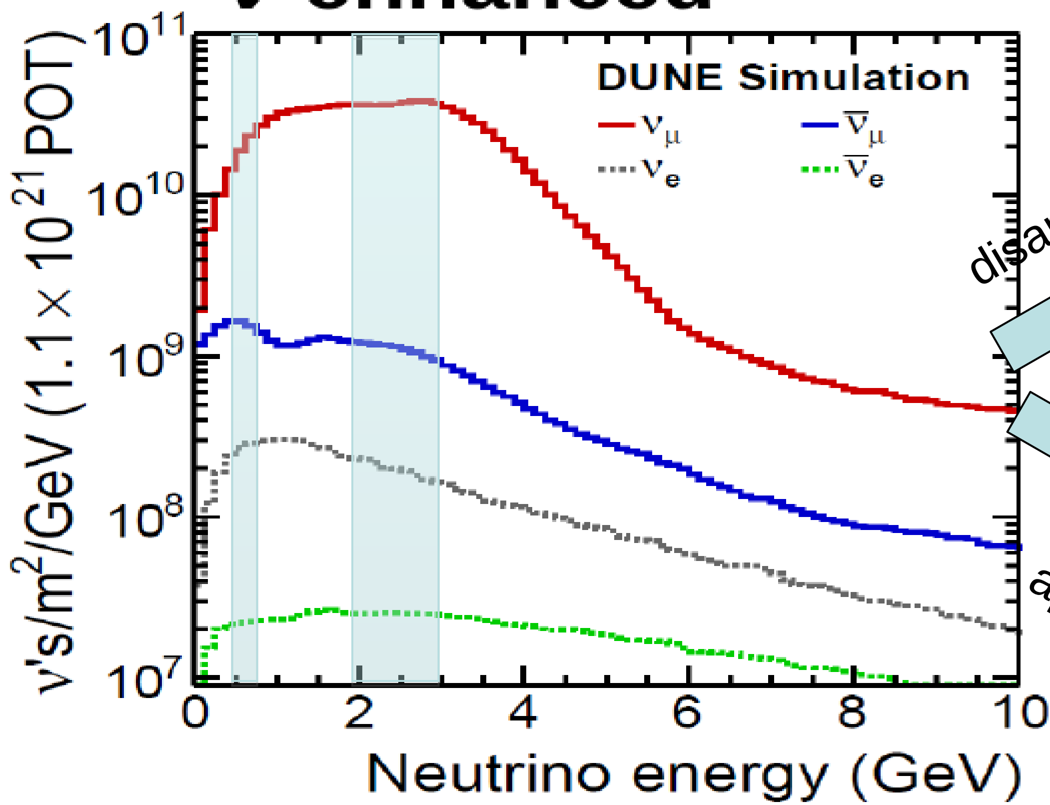
ν_μ beam



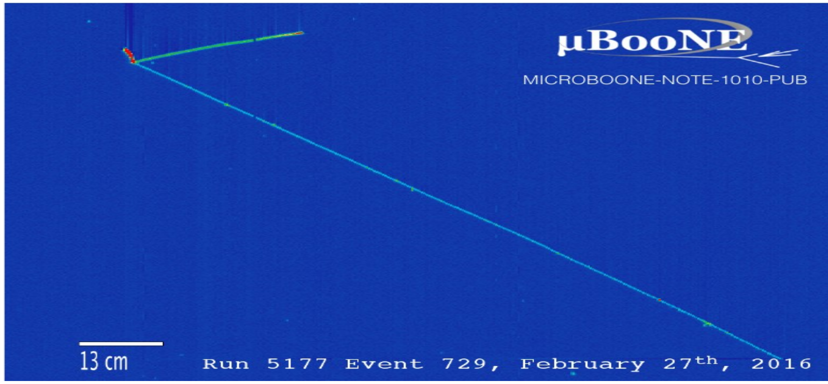
$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

Oscillation maxima

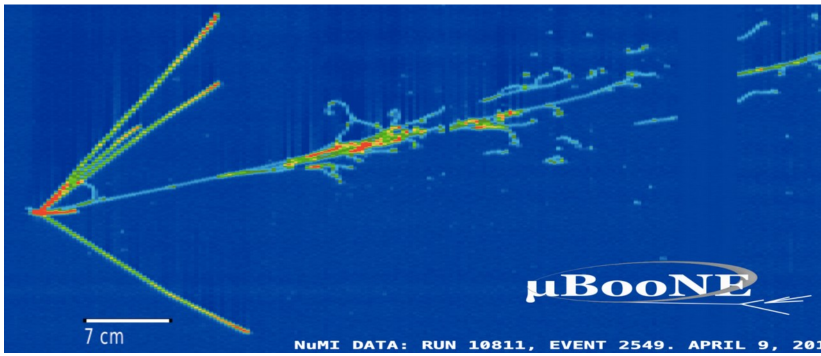
ν-enhanced



ν_μ disappearance

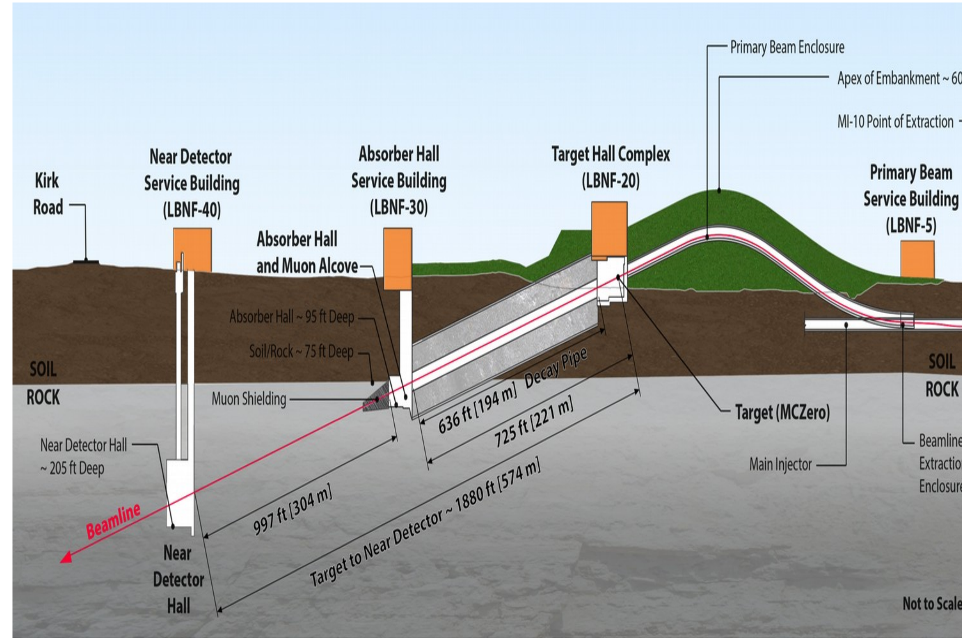


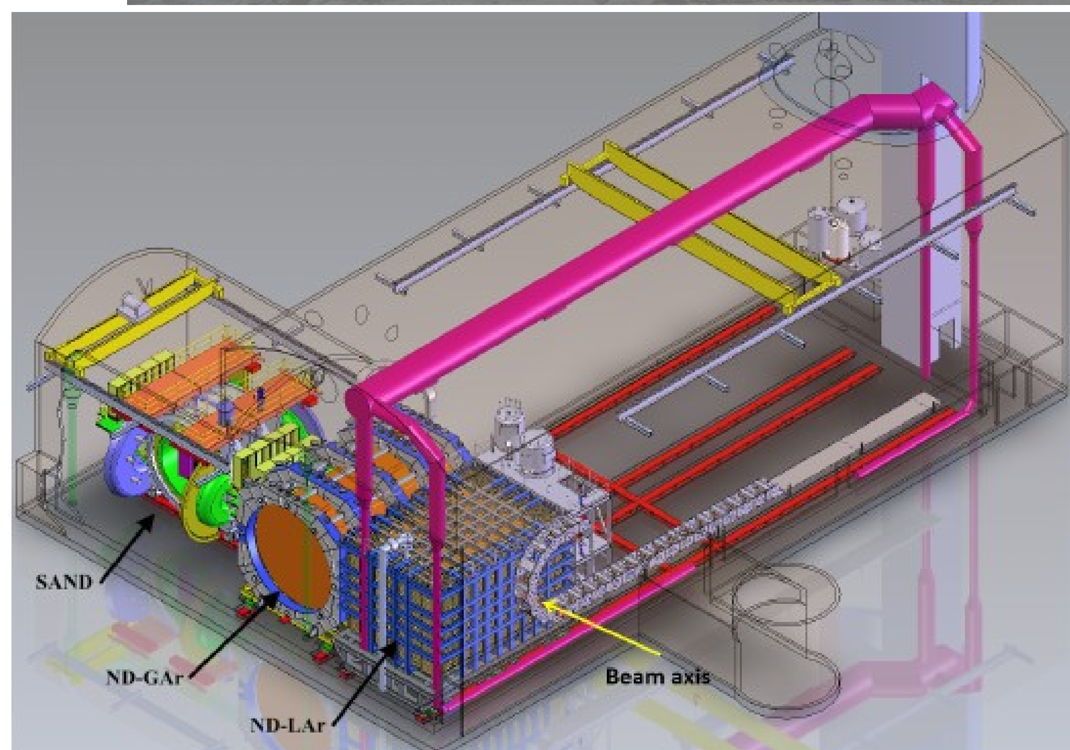
ν_e appearance



Near Detector

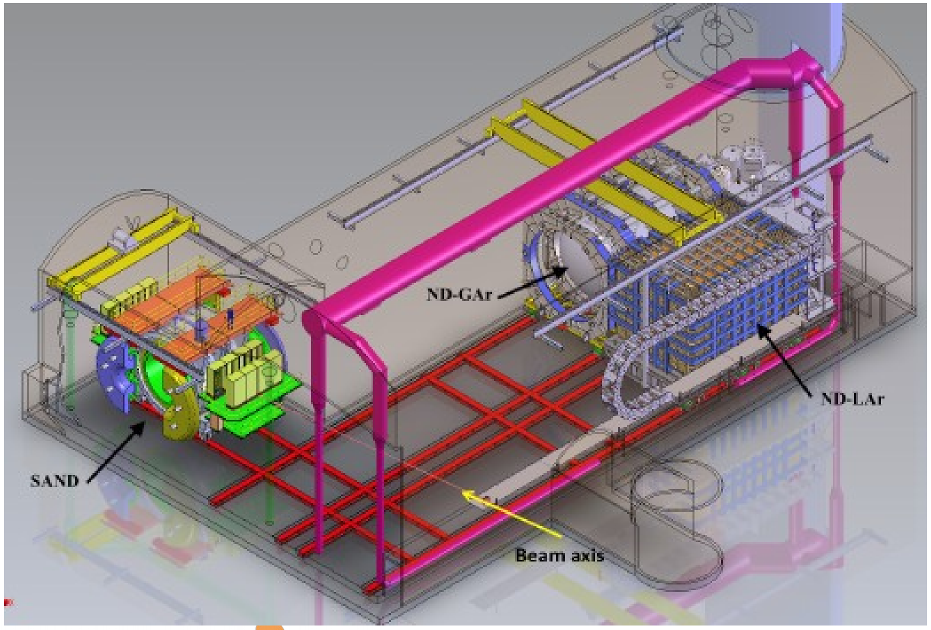
- Multi-component near detector will ensure excellent control of systematics.
- **ND-LAr:** Modular LAr TPC - pixel readout.
- **ND-GAr:** HP GAr TPC + magnet.
- **SAND:** tracker detector, surrounded by an ECAL and magnet: on-axis beam monitor.

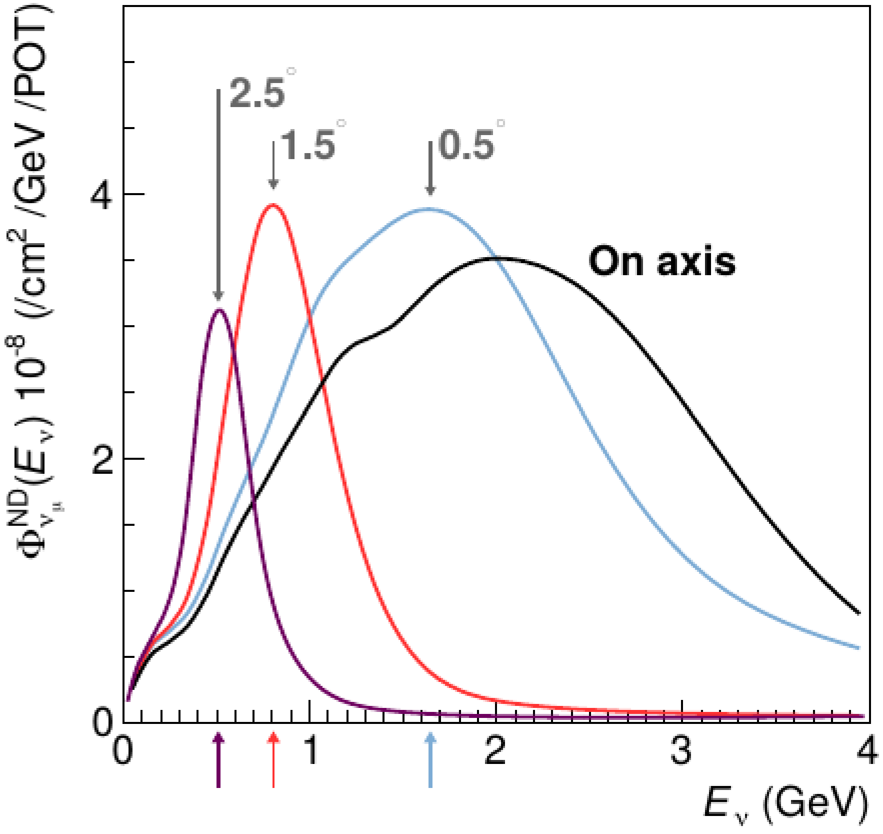




DUNE - Prism

DUNE-PRISM: **ND-LAr** and **ND-GAr** can move sideways to constrain flux and interaction uncertainties.

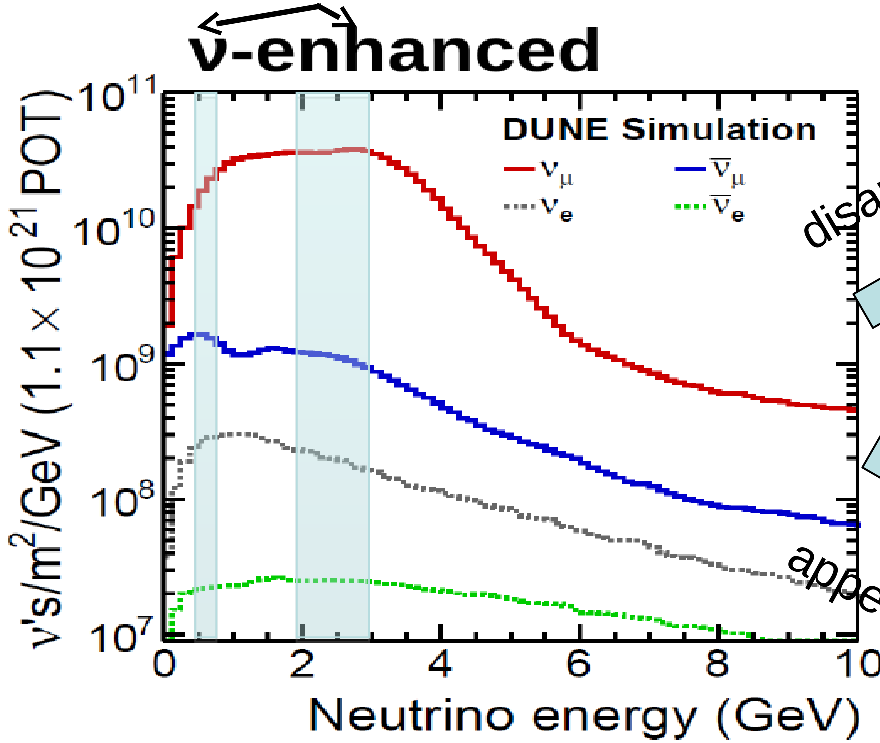




Physics Sensitivities

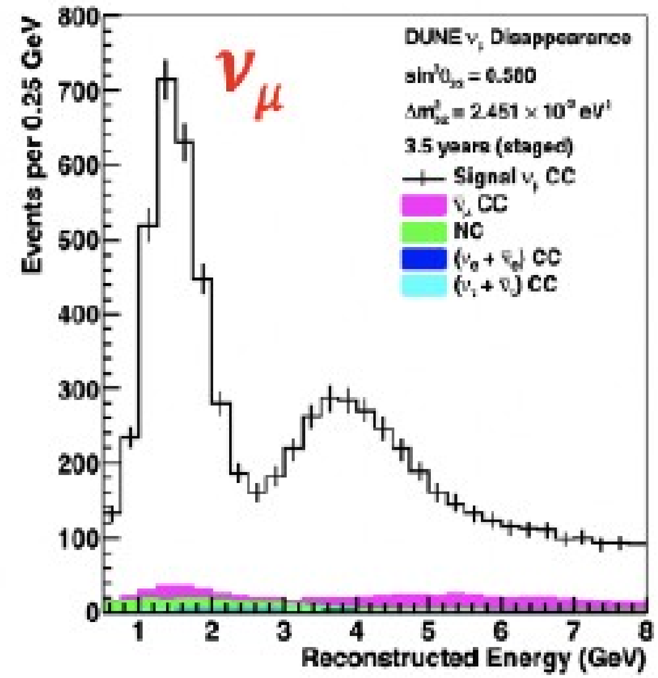
~10k events in 7 years
(surviving)

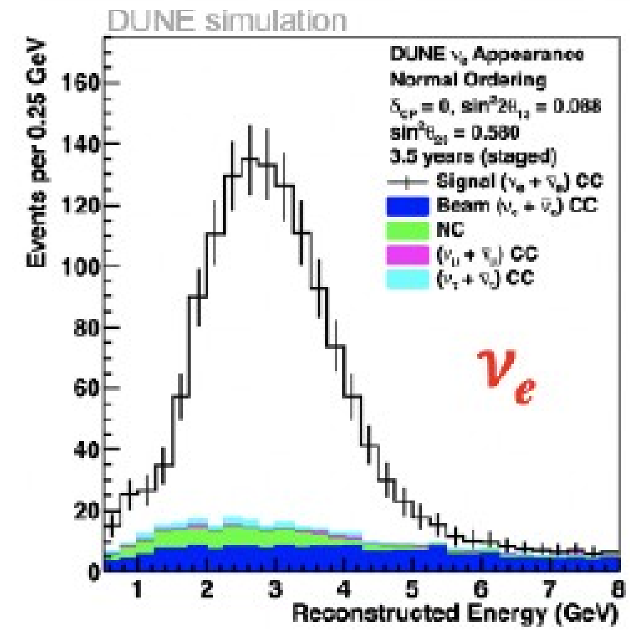
Oscillation maxima



ν_μ disappearance

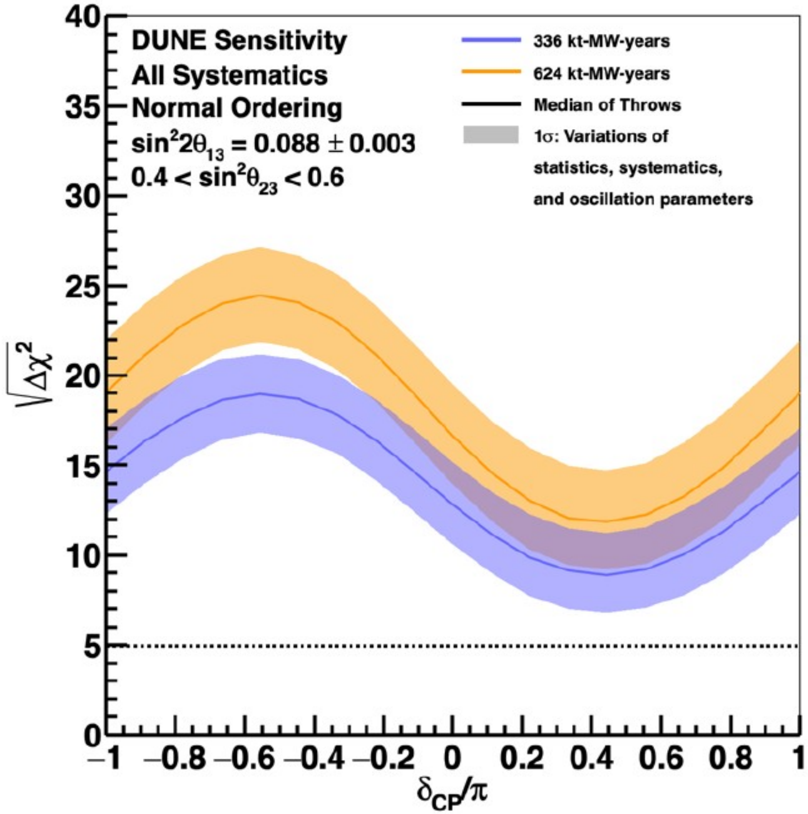
ν_e appearance



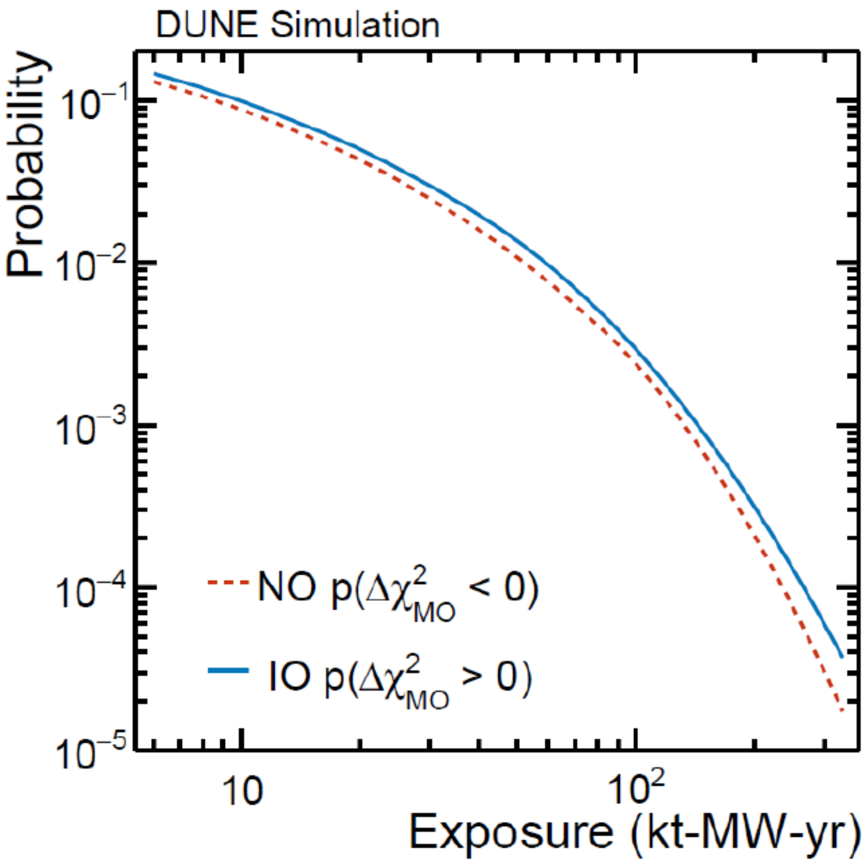


~1k events in 7 years
(appearing)

Mass Ordering



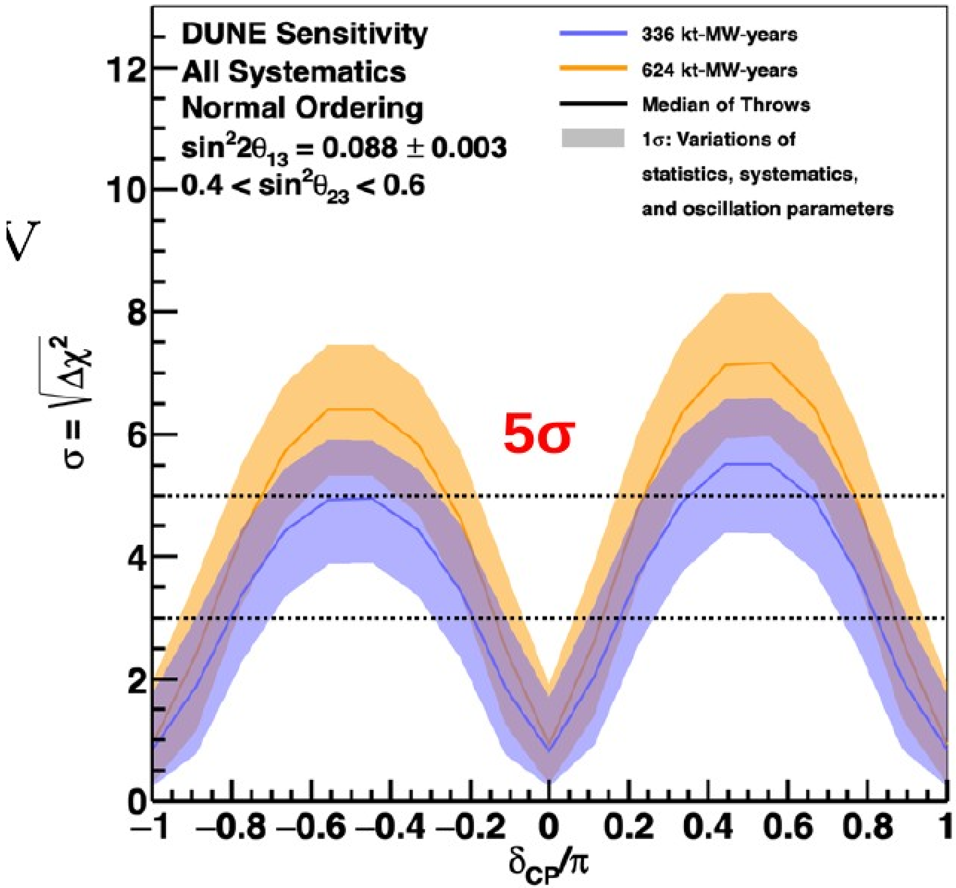
EPJC 80 (2020) 978



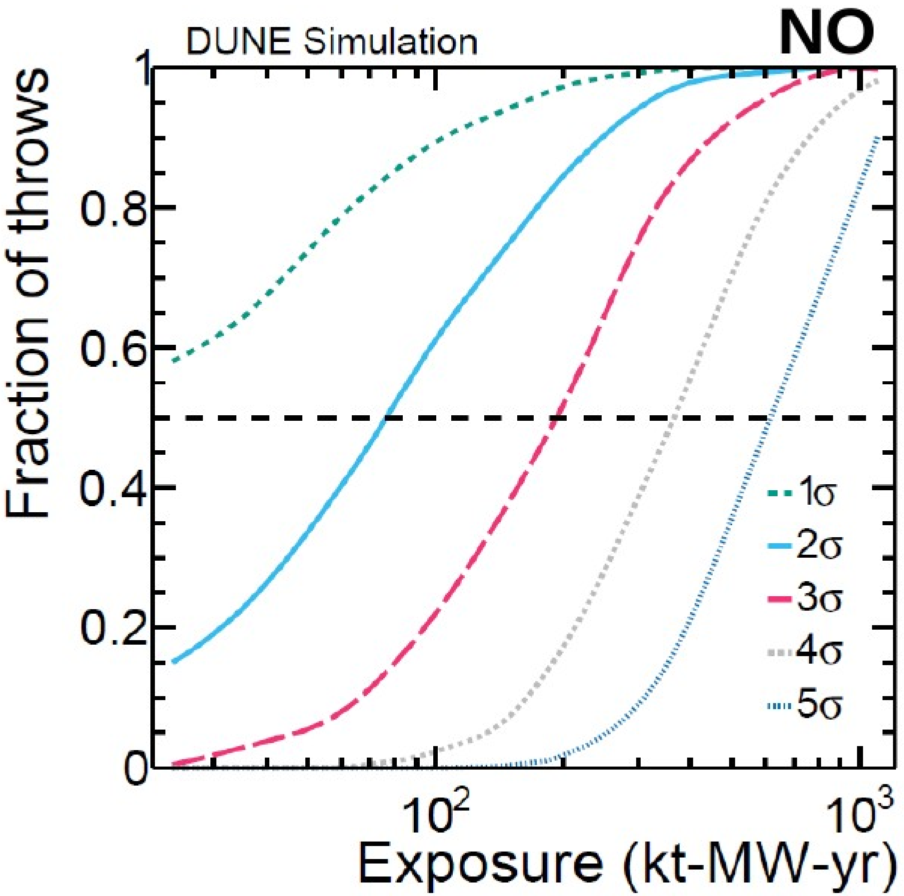
arXiv:2109.01304

- DUNE will determine the MO soon in its run.
- By exposure of 66 kt-MW-yr, probability to extract wrong ordering < 0.01.

CP Violation



EPJC 80 (2020) 978



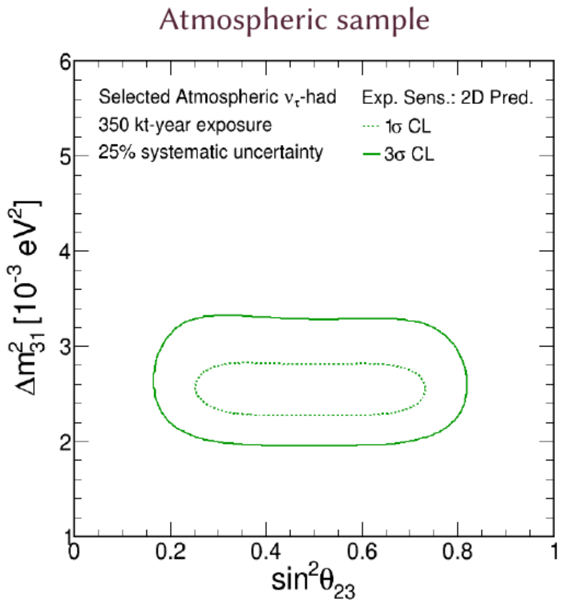
arXiv:2109.01304

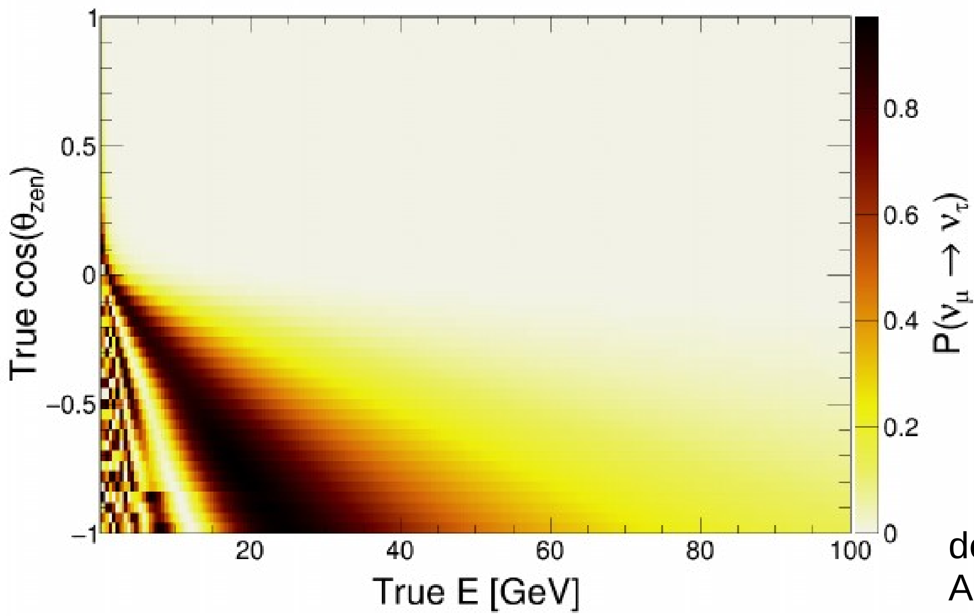
- Sensitivity to over 50% of δ_{CP} values at 5σ, with full exposure.
- Median sensitivity for 50% δ_{CP} above 3σ after 197 kt-MW-yr

Atmospheric Neutrinos

- DUNE will detect atmospheric neutrinos:

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



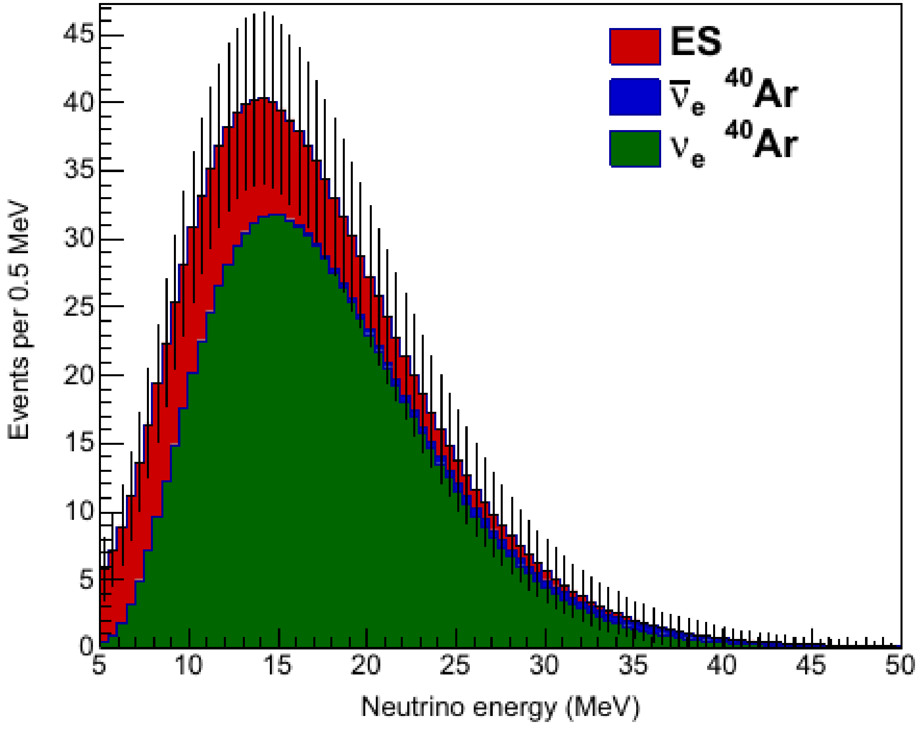


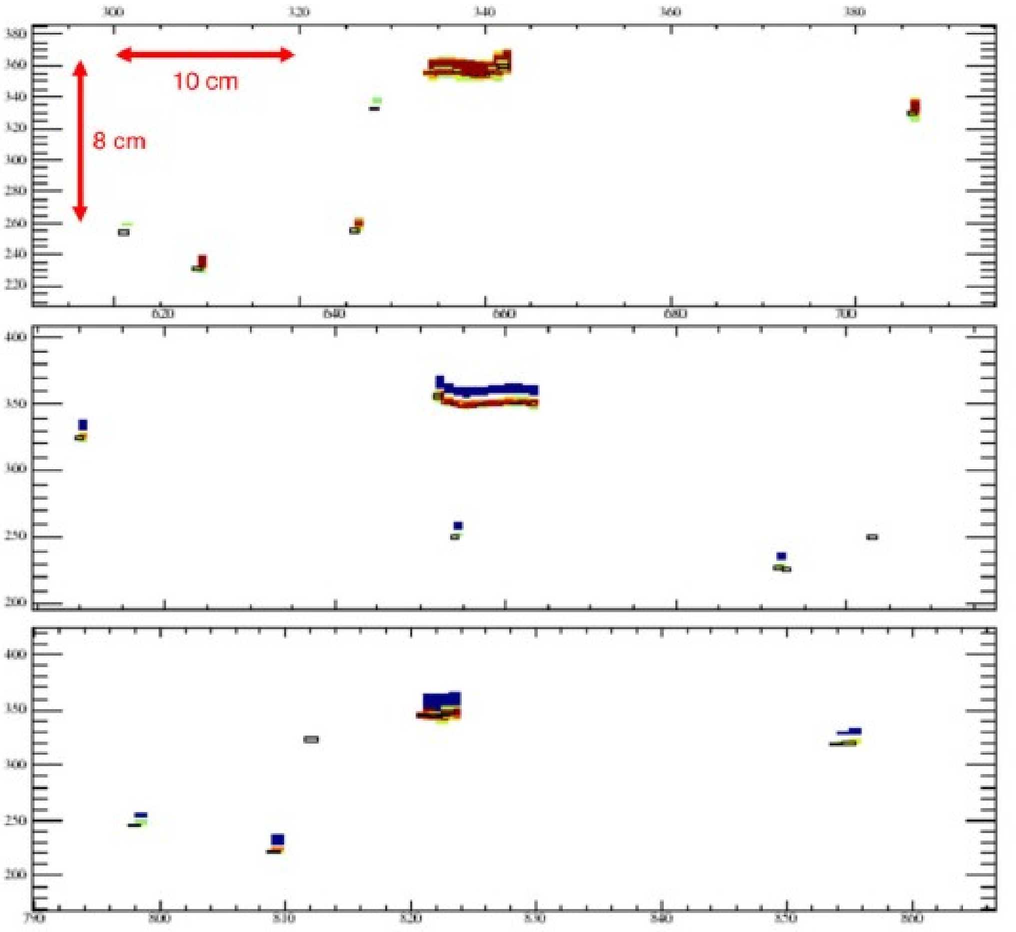
ν_τ appearance is possible.
Expect 1 ν_τ /kton-year
Possible tests of non-unitarity.

de Gouvea, Kelly, Stenico, Pasquini, PRD 100, 016004 (2019)
And. A. Aurisano talk at NuTau 2021

Supernova neutrinos

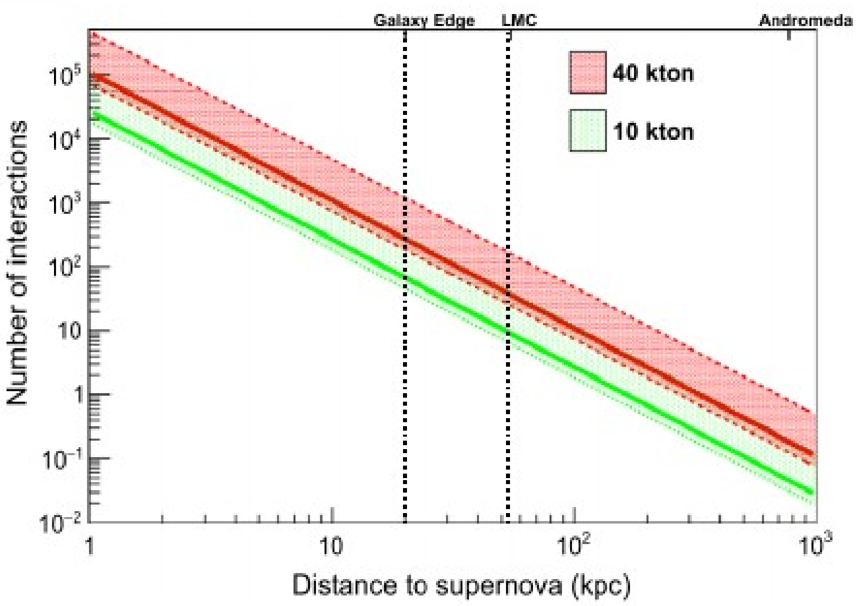
- LAr detectors are mainly sensitive to ν_e via: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$



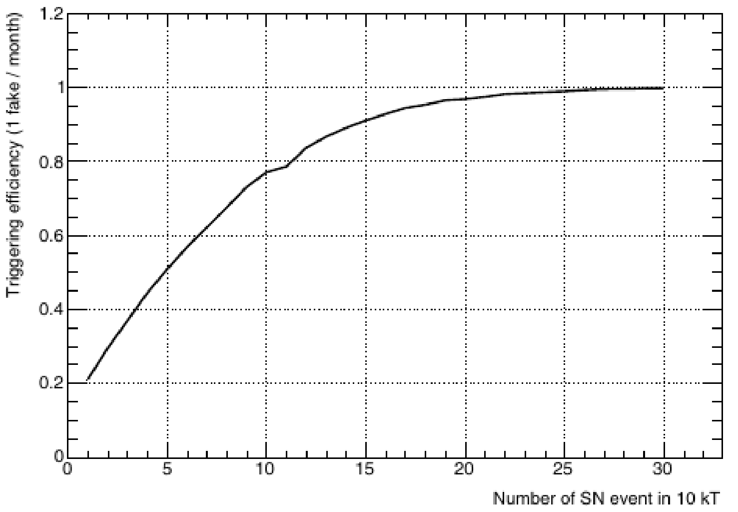


Eur. Phys. J. C 81 (2021) 5, 423]

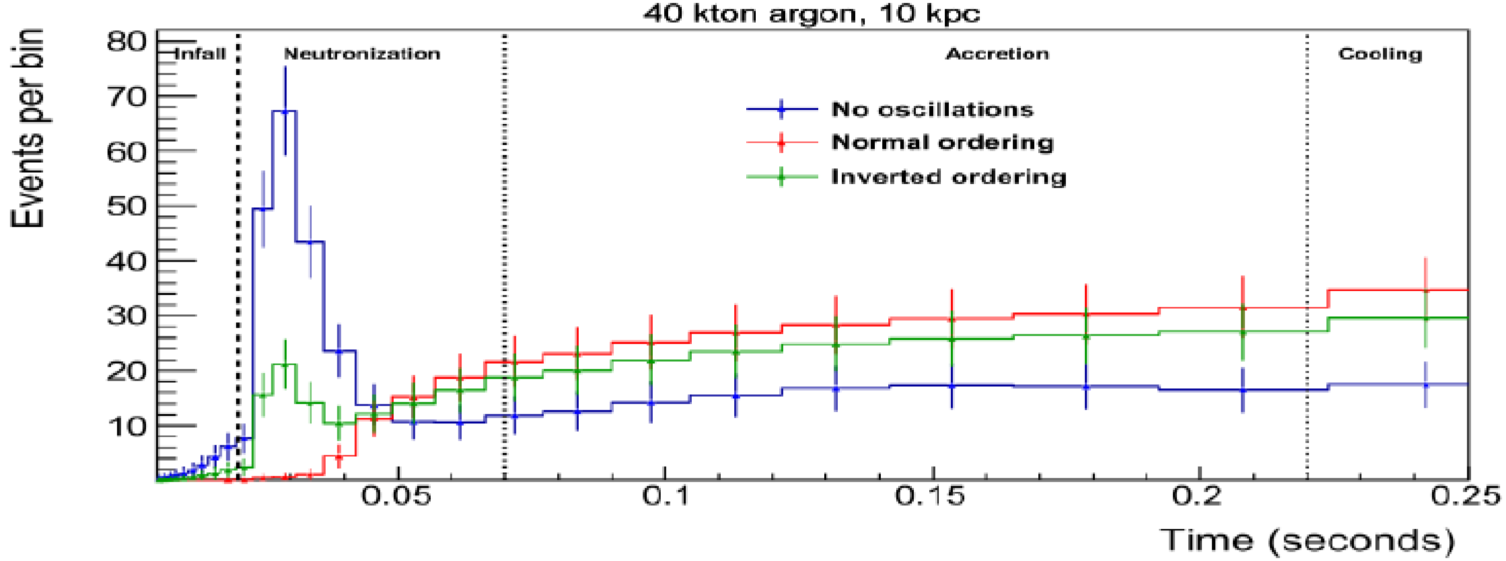
Supernova neutrinos



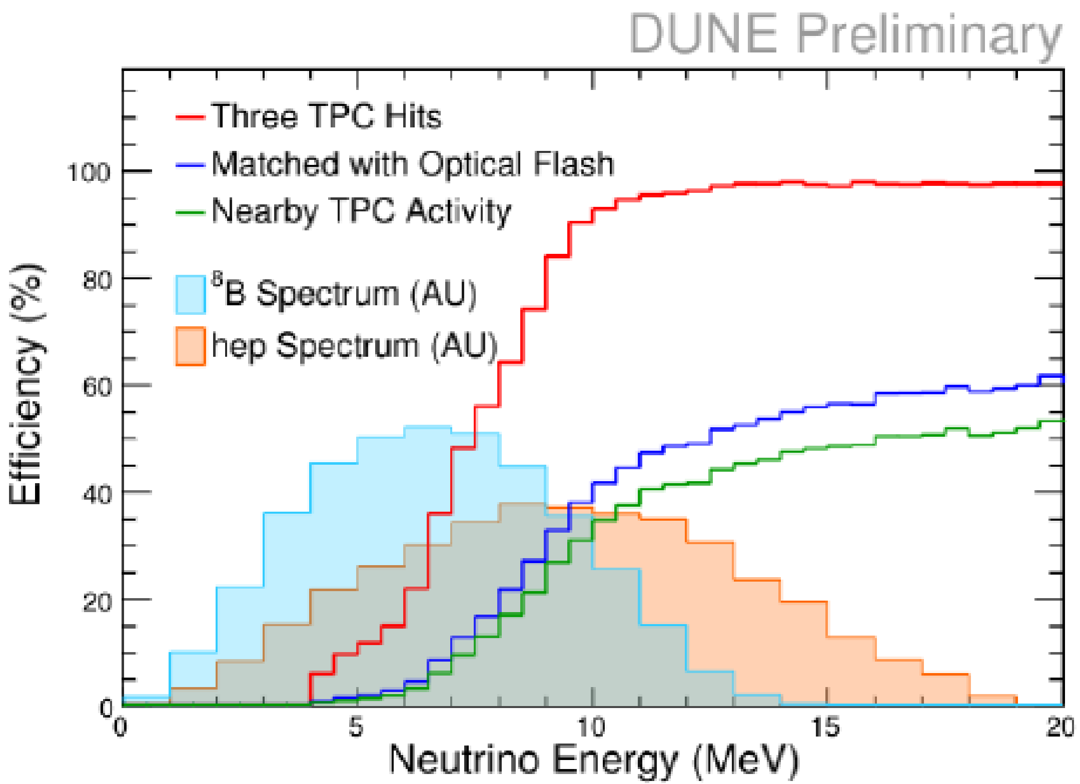
SN burst trigger efficiency

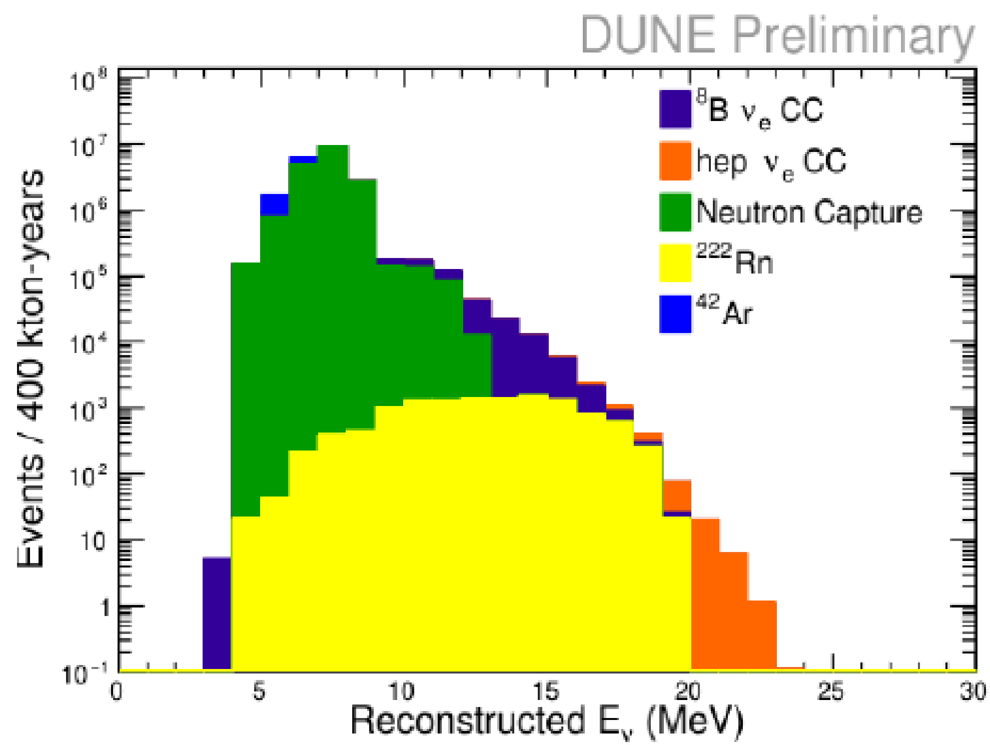


- Sensitivity to neutronization burst
- Sensitivity to mass hierarchy



Solar Neutrinos



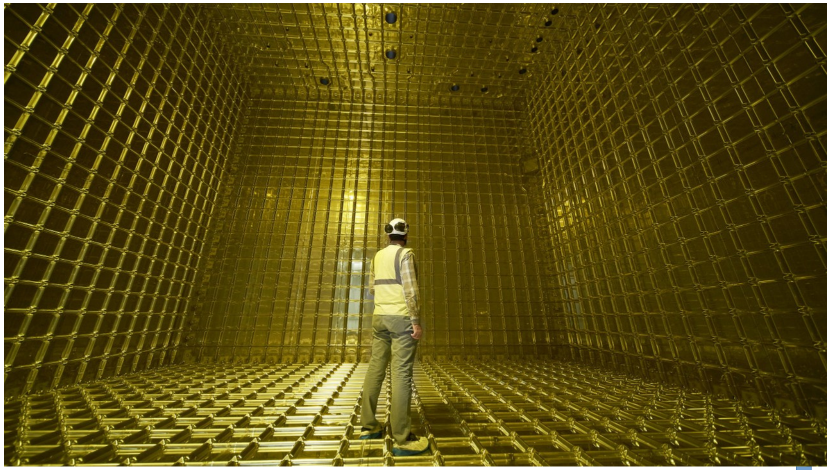


- DUNE should be sensitive to solar neutrinos, with a potential to observe hep neutrinos.
- Main backgrounds: neutrons and Rn-induced alpha-gamma interactions.

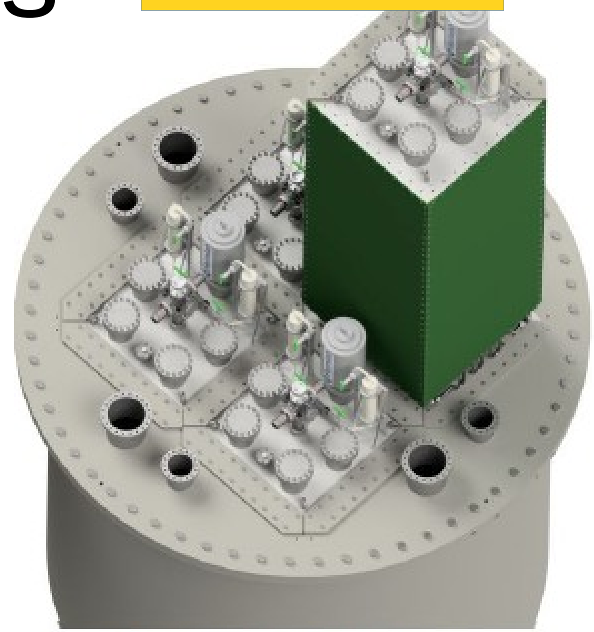
DUNE Prototypes

- ProtoDUNEs at CERN
- 2x1kTon cryostats used to validate FD components at full scale.
- Succesful run from 2018-2020.
- Next phase starting in summer 2022.

Far Detector



Near Detector



ArgonCube 2x2 ND-LAr Demonstrator.

4 independent modules, test In NuMI beam scheduled in 2022

Conclusions

- DUNE is a next-generation long-baseline oscillation experiment set to discover CP violation in the lepton sector and determine the neutrino mass ordering.
- A rich physics programme includes astrophysical and atmospheric neutrinos and BSM physics (proton decay).
- Excavation of the far site is underway, and technologies for first two modules have been selected.
- Extensive prototyping efforts at CERN and Fermilab ongoing, with test runs planned in 2022-2023.
- First DUNE far-detector installation in mid-2020s, with neutrino beam data in late 2020s.

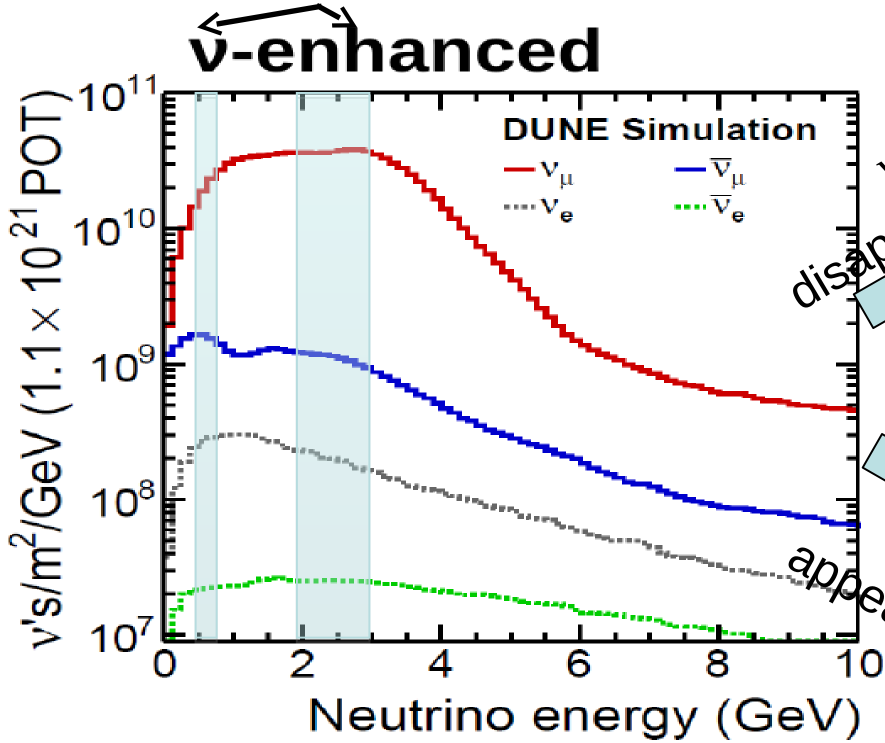
Thank you

Backup Slides

Physics Sensitivities

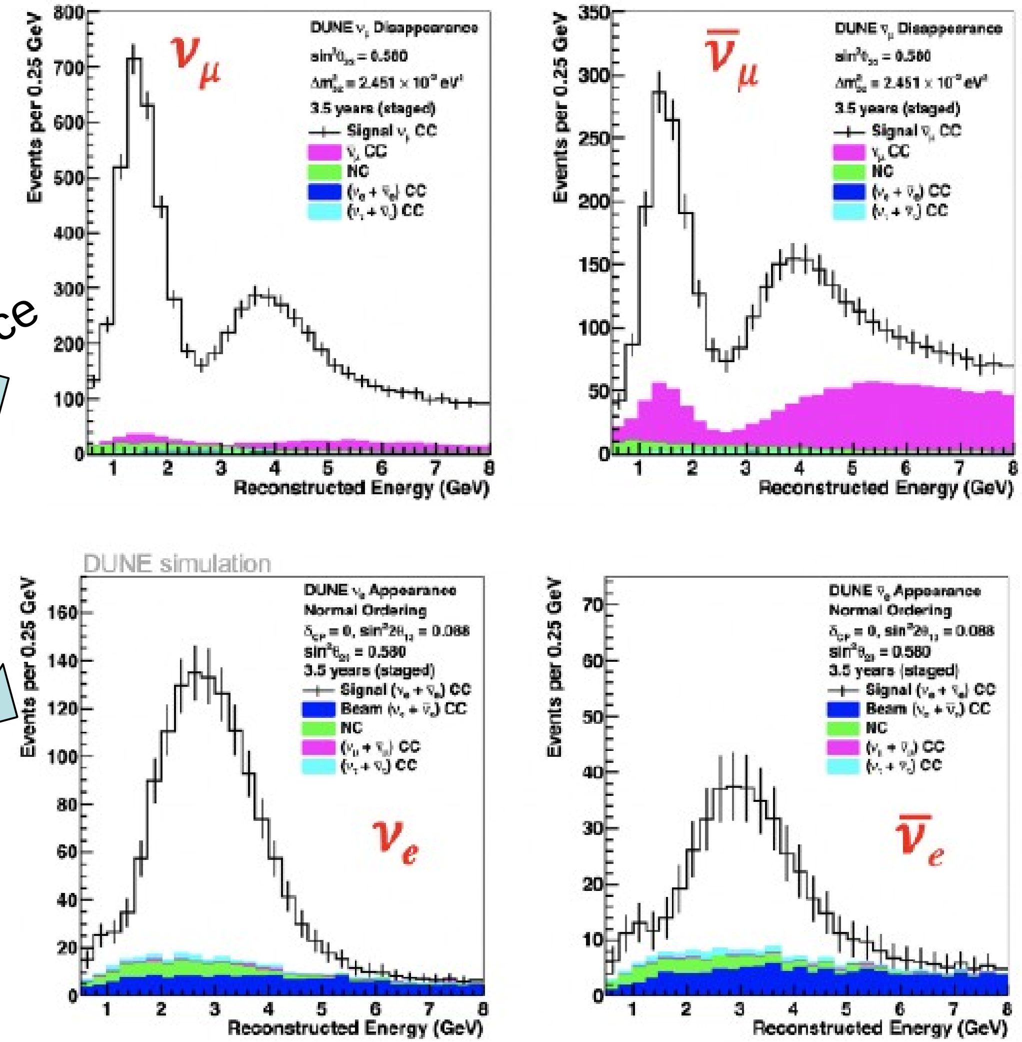
~10k events in 7 years

Oscillation maxima



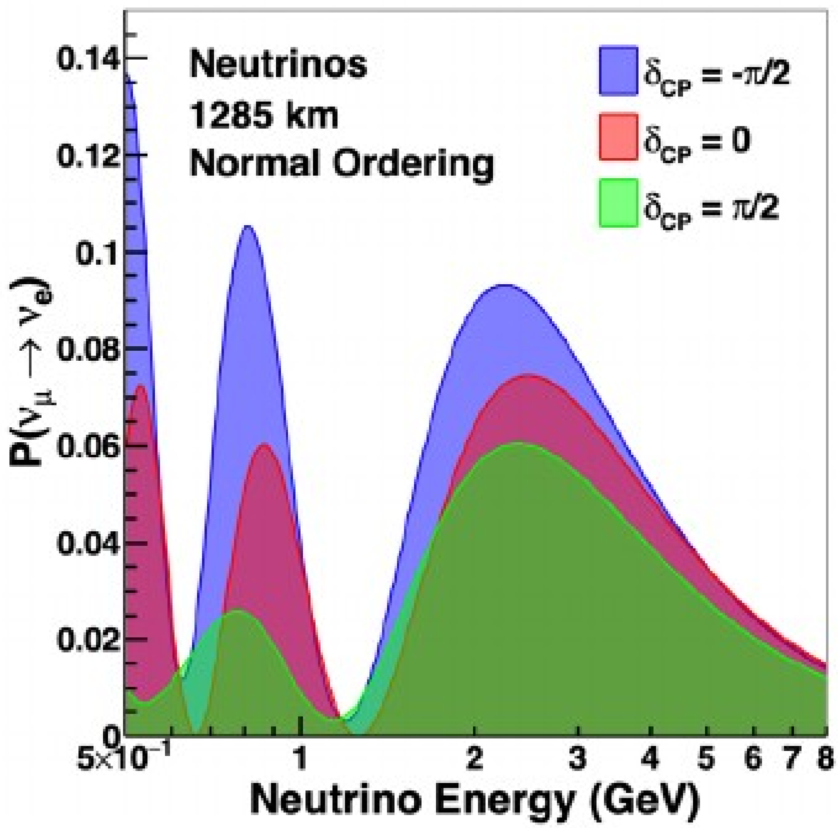
ν_μ disappearance

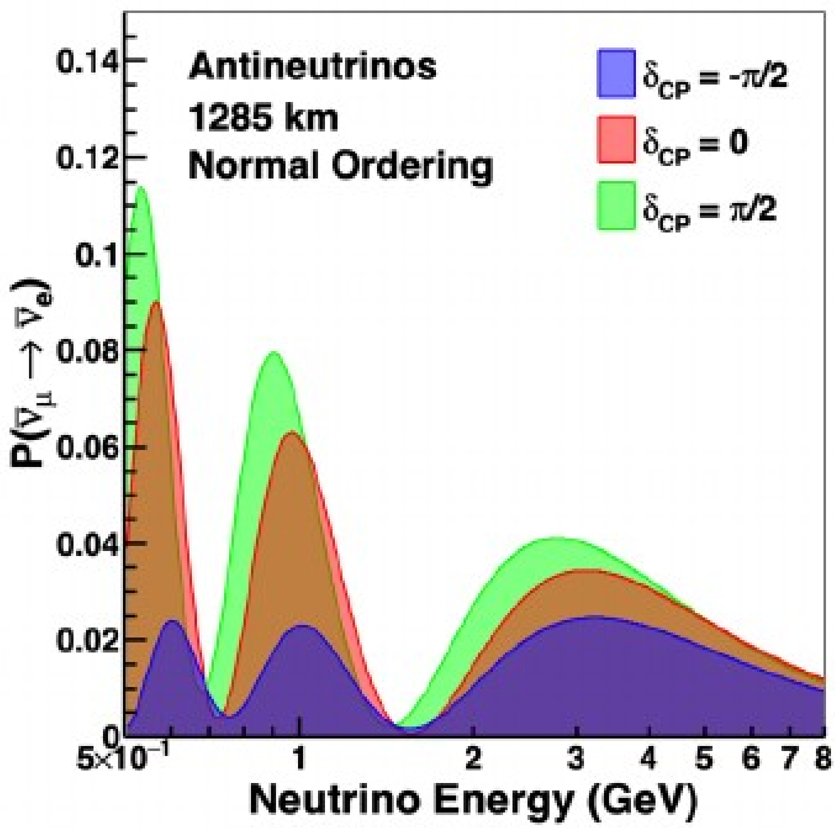
ν_e appearance



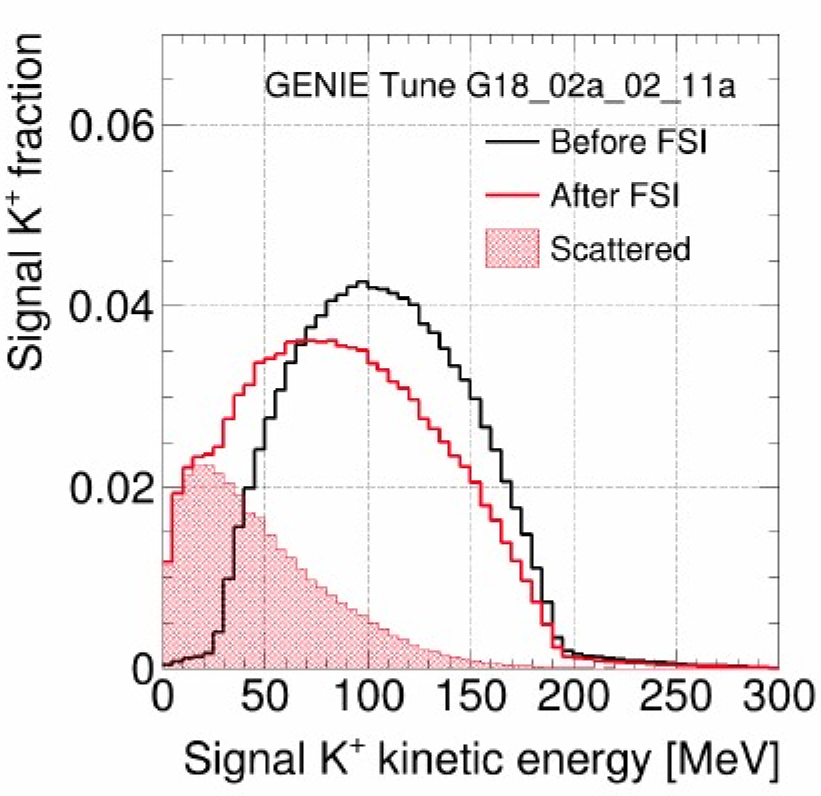
~1k events in 7 years

CP phase in ν_e appearance

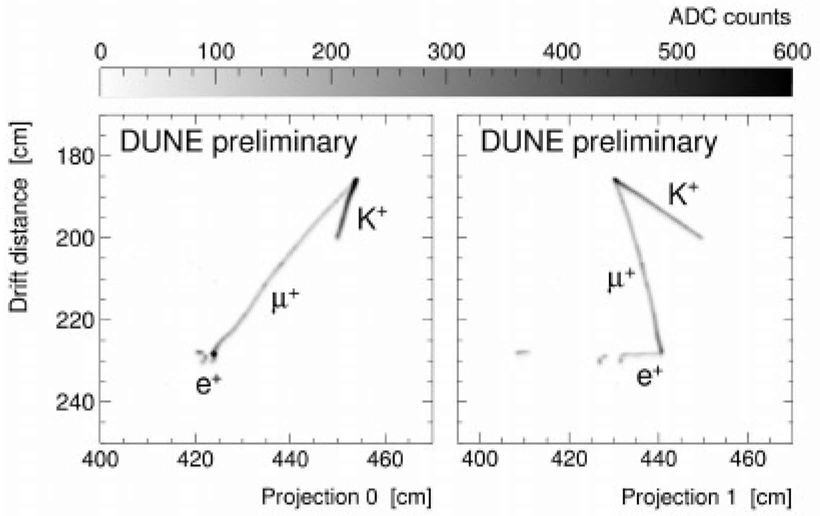




Nucleon Decay



Backgrounds:
Atmospheric neutrinos



https://doi.org/10.22323/1.390.0226

DUNE will be competitive for favoured SUSY decay channel:
$\tau(p \rightarrow \bar{\nu}K) > 1.3 \times 10^{34}$ yrs @ 90 % CL after 400 kt · yrs