Characterization of liquid argon time projection chambers for the DUNE near detector

DEEP UNDERGROUND NEUTRINO EXPERIMENT

YORK UNIVERSITÉ UNIVERSITY

Rowan Zaki

CAP conference

June 19th 2023

Neutrinos oscillate, but why do we care?

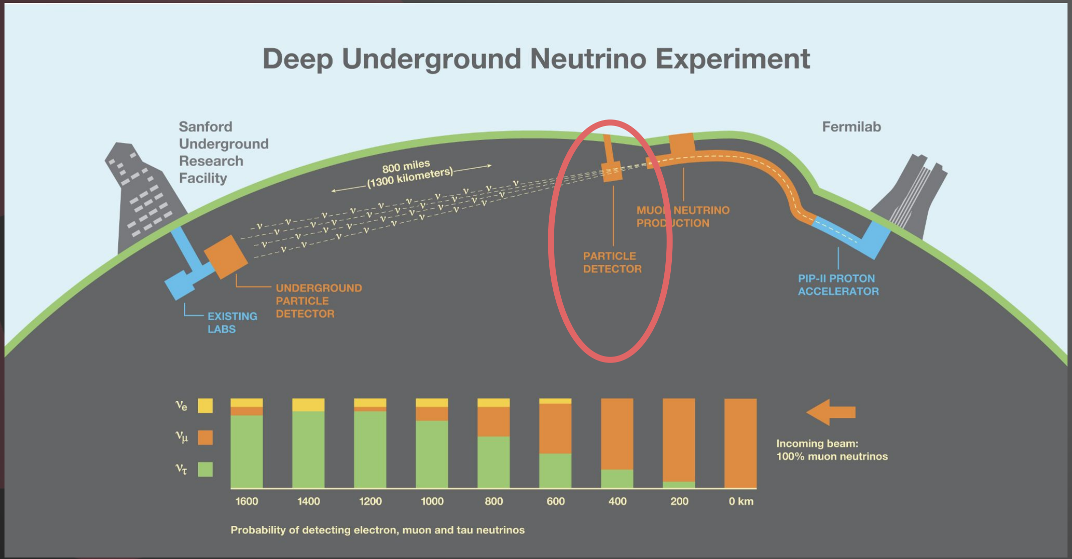
- Baryon asymmetry observed in present day universe
  - *Where did all the antimatter go?*
- Look for processes that violate charge-parity symmetry
  - Changing particle to antiparticle
- Charge-parity violation for quarks, but too small to justify observations
  - What about the neutrinos?
- CP-violating phase shows up in the mixing matrix

$$P = (\nu_\mu \rightarrow \nu_e)$$

$$P = (\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$$

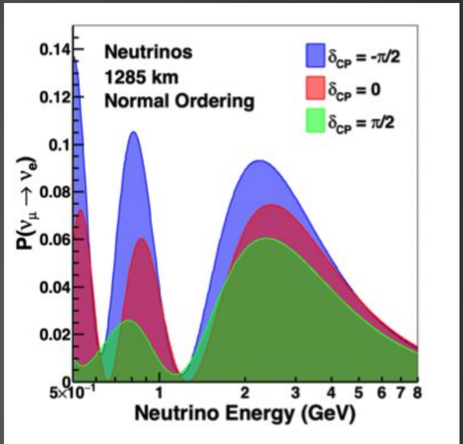
The Deep Underground Neutrino Experiment (DUNE)

- Can study this phase by looking at differences between muon to electron neutrino oscillations and the antiparticle counterpart
  - **Accelerator based neutrino experiments**



Fermilab, https://lbnf-dune.fnal.gov/

DUNE, Snowmass Whitepaper, arXiv:2203.06100



Near and **Far** detectors

- **Near detector** observes the unoscillated spectrum
- **Far detector** observes oscillated spectrum

The DUNE near detector complex

The complex consists of three complementary detectors

- The **liquid argon near detector** is key in reducing detector and cross-section uncertainties
  - Same technology & target material as the far detector
  - Argon allows for identification of hadronic part of the interaction

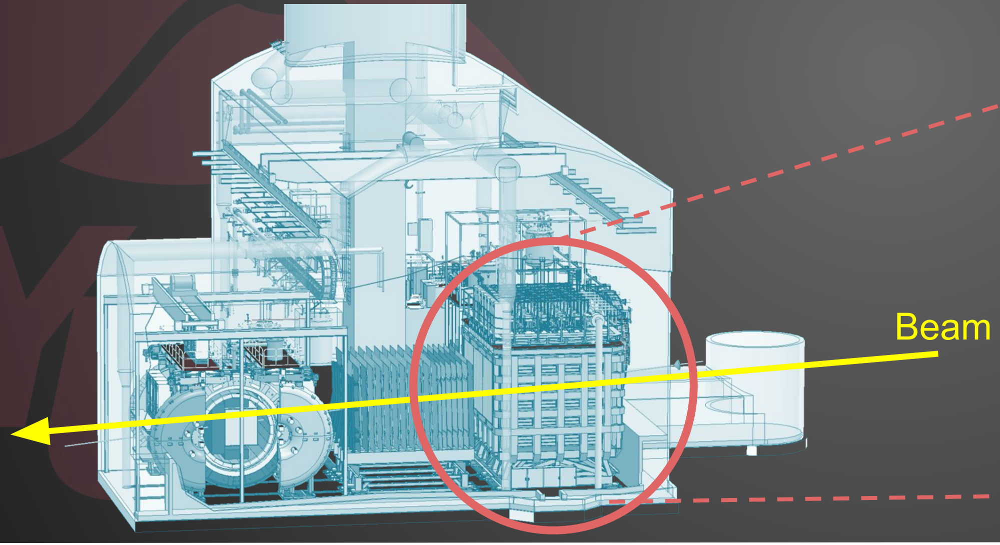
Intense neutrino beam of 1.2 MW

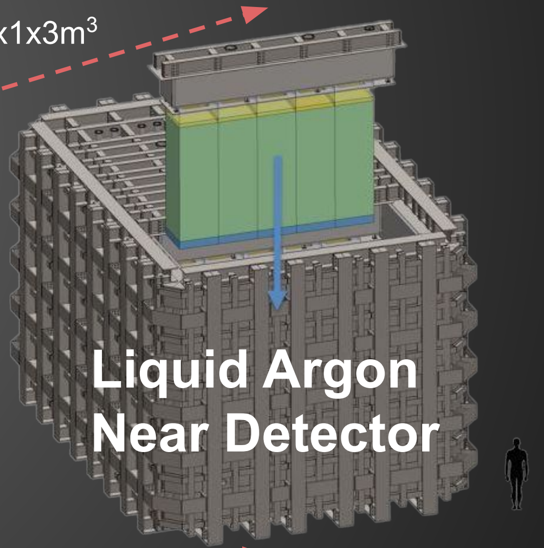
★ ~ 50 interactions per spill

Modular approach to deal with light signal pile-up

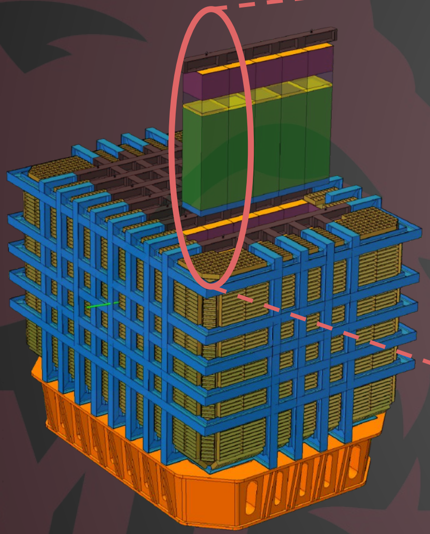
★ 35 modules in a 7 by 5 array

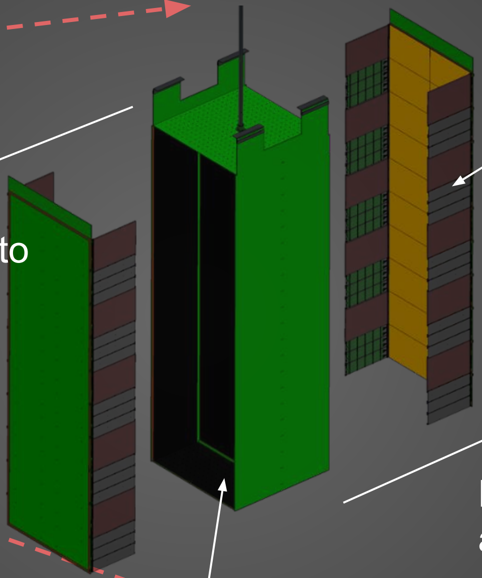
★ Modules are $1x1x3m^3$



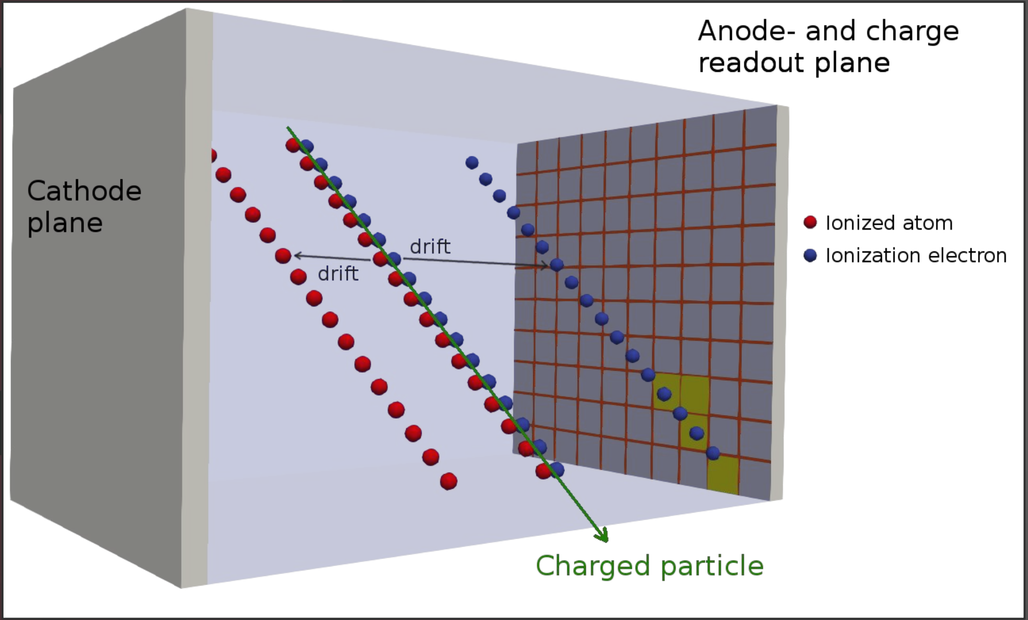


The Liquid Argon Time projection chambers





The pixelated charge readout system



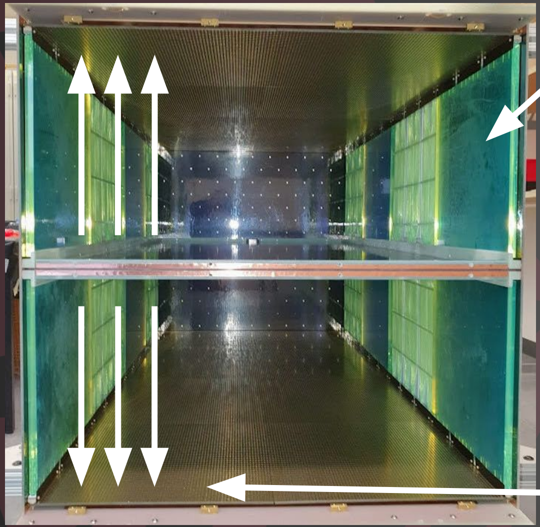
Ion vs electron drift is not to scale!

- Neutrino interacts in the Argon volume which produces charged particles
- Charged particles ionize Argon atoms along their trajectory
- Released electrons drift towards the anode plane and sense wires
- **The near detector uses pixelated charge readout**
  - **No position ambiguities compared to wire readout**

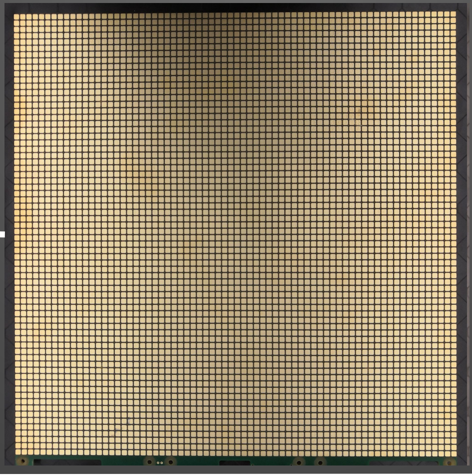
The pixelated charge readout system

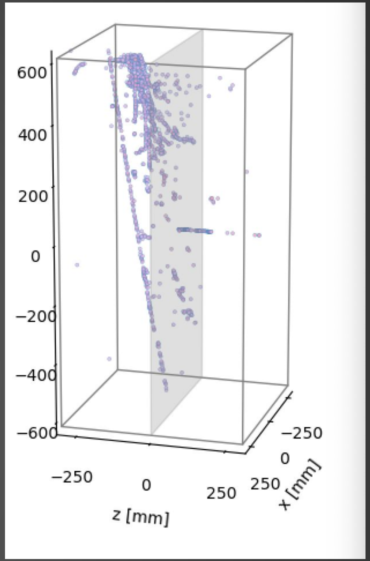
Drift direction to anode plane

Perpendicular light readout



Parallel pixelated charge readout
LArPix

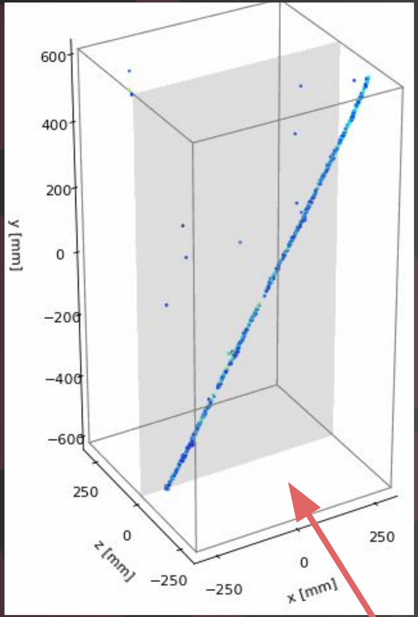




Drift direction to anode plane

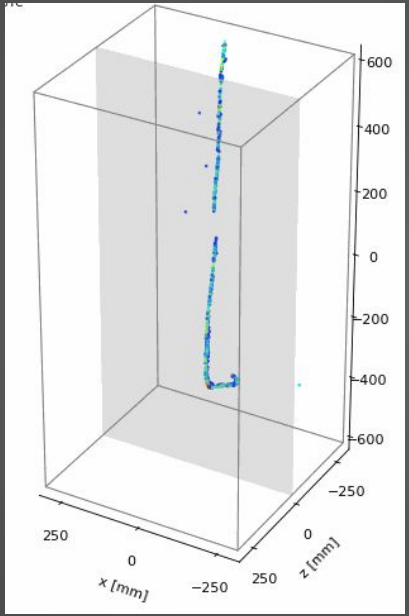
- ★ Pixel pitch of 4.434 mm
- ★ ~ 80000 channels

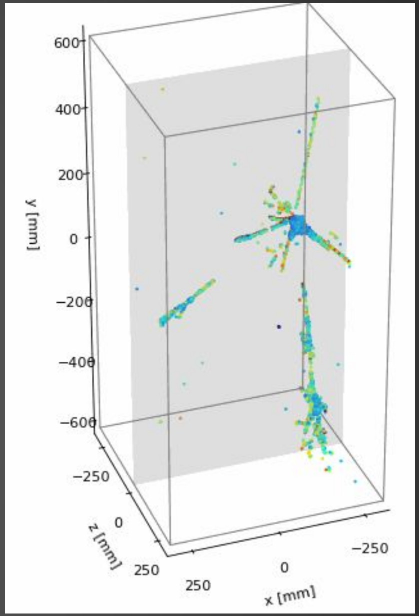
Individual module runs



Throughgoing muon

Decaying muon with michel electron



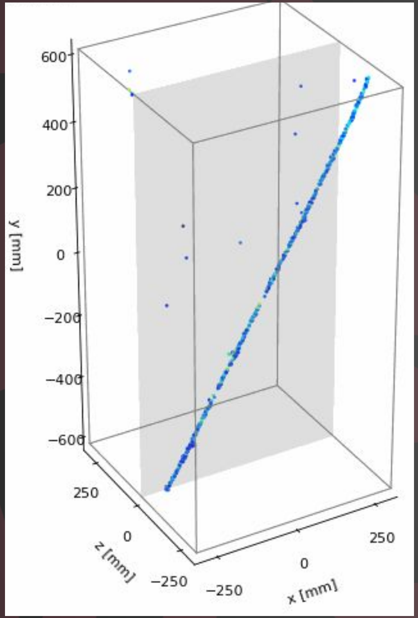


Multiparticle interaction with photons & protons

Ideal for calibration purposes, as energy deposition is very well understood

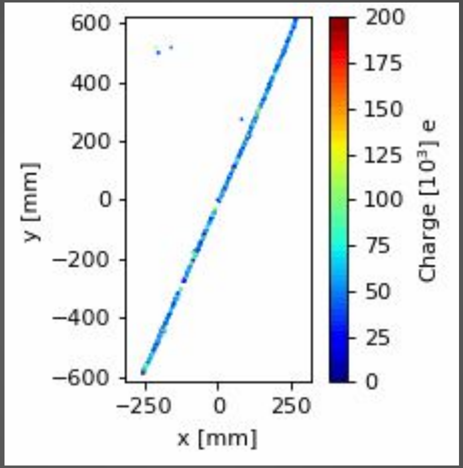
Methods to characterize the pixel performance

Throughgoing muon



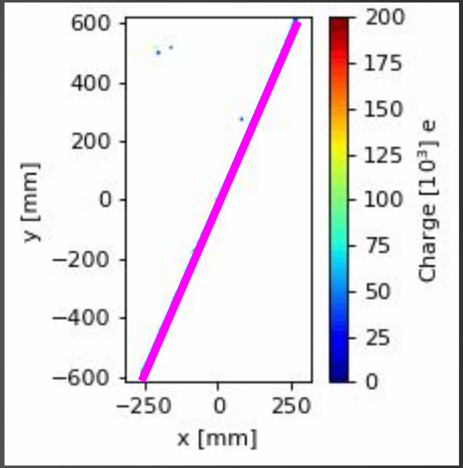
2D projection

Actual charge deposits



Find all charge within an 8 mm cylinder around the reconstructed track

Reconstructed track

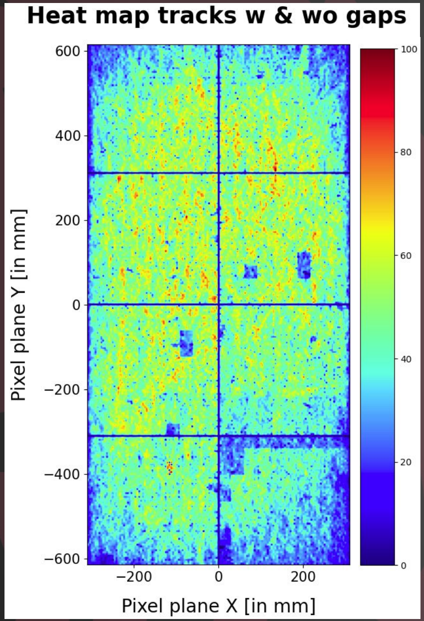


Find all pixels within an 8 mm cylinder around the reconstructed track

Repeat for large set of tracks

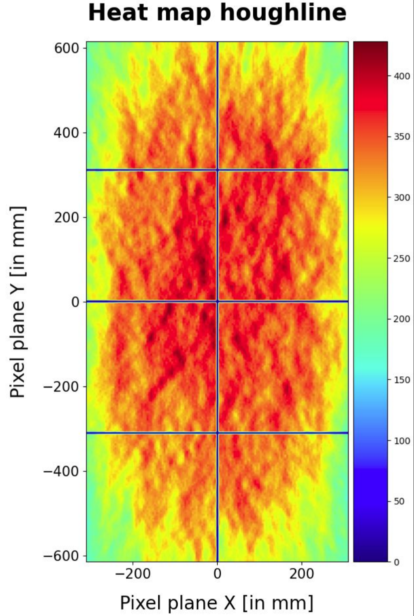
Pixel response maps (global)

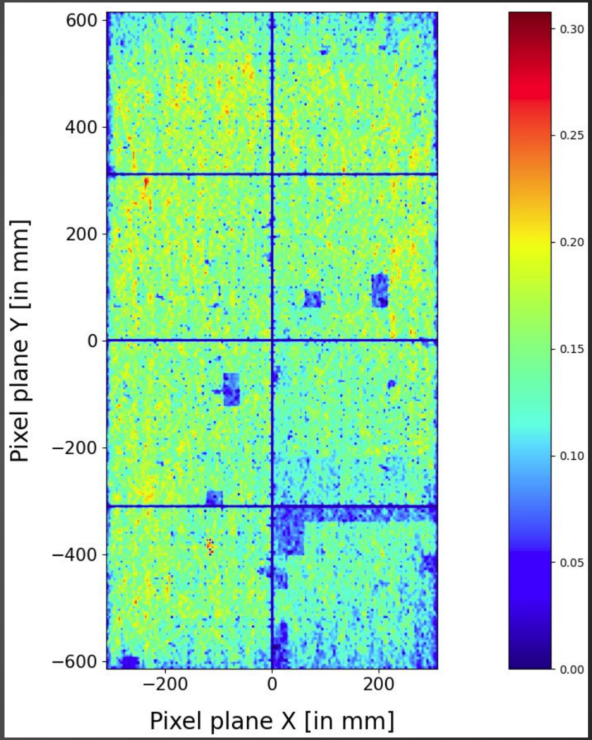
All charge within an 8 mm cylinder around the reconstructed track



Division

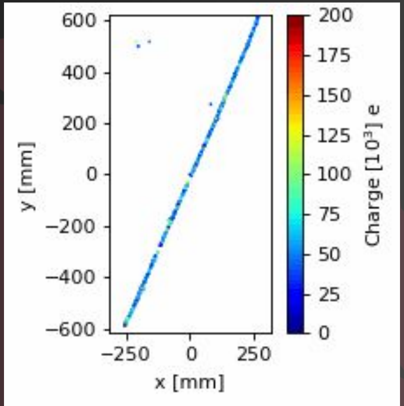
All pixels within an 8 mm cylinder around the reconstructed track



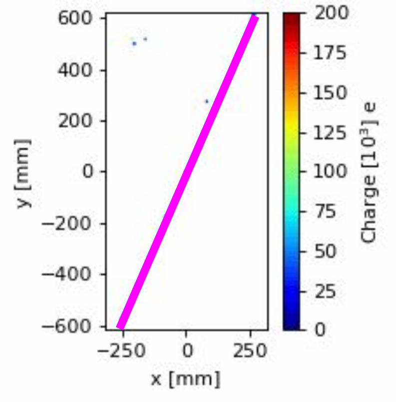


Quickly scan uniformity of the response map!

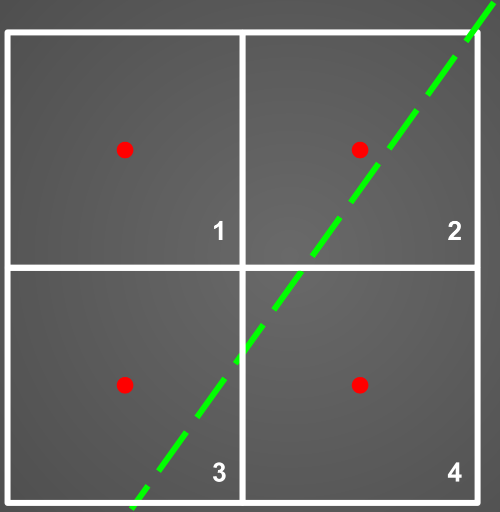
Pixel efficiency maps (individual)



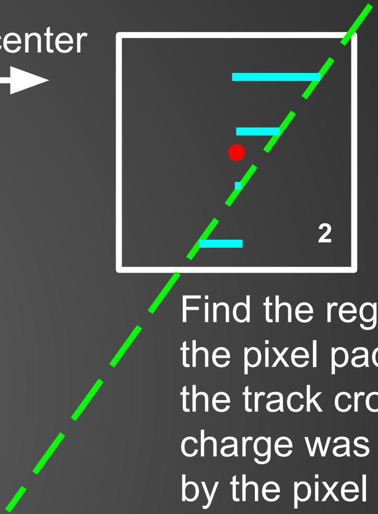
Find the track



Divide the track into **segments**



Study **distance** track to pixel center

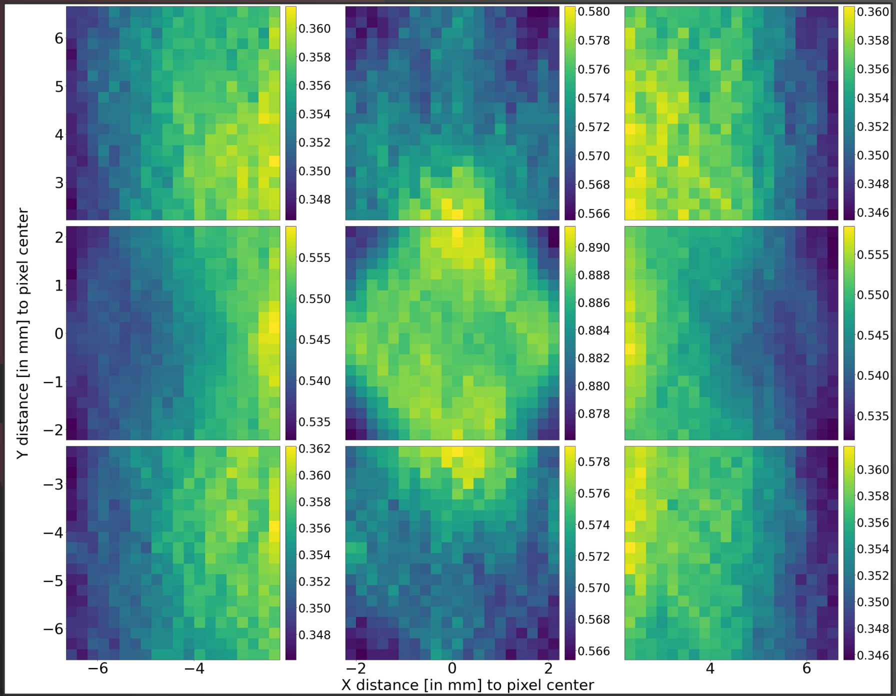


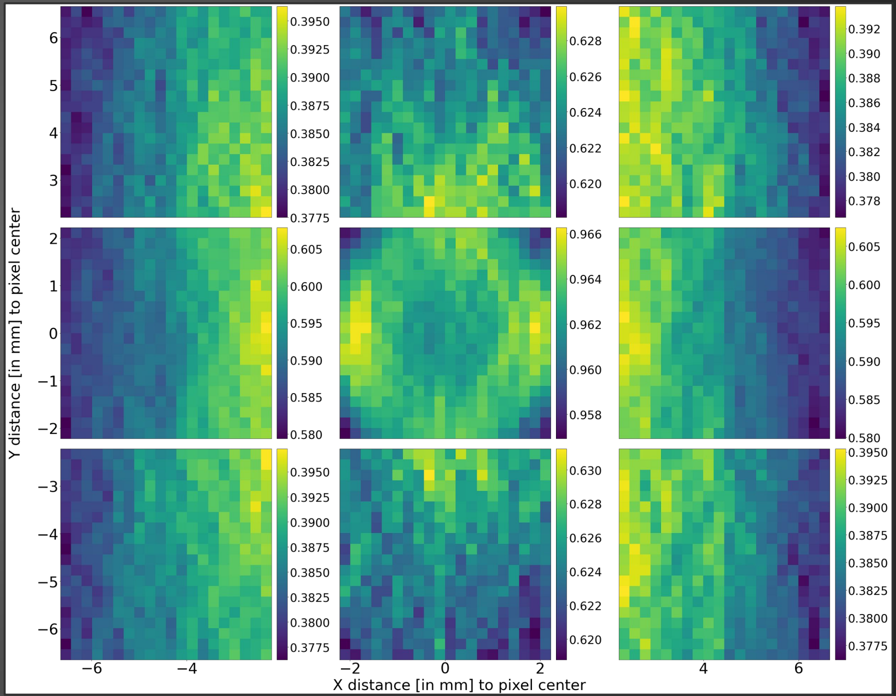
Find the regions on the pixel pad where the track crossed and charge was collected by the pixel

Four pixels out of ~80k

Pixel efficiency maps (individual)

- Data and MC agree on shape of the distributions
  - Radially decreasing efficiency moving away from the center
- Describe the differences between the modules in terms of efficiencies, so we can correct for it

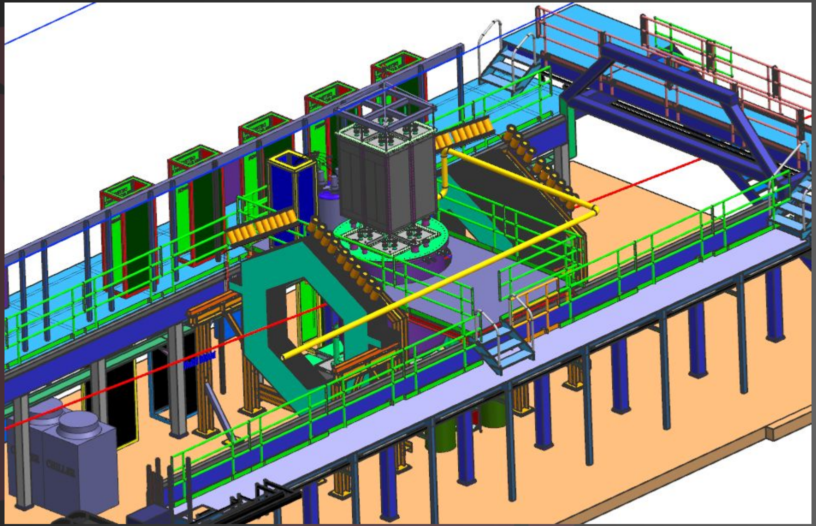




Cosmic ray data

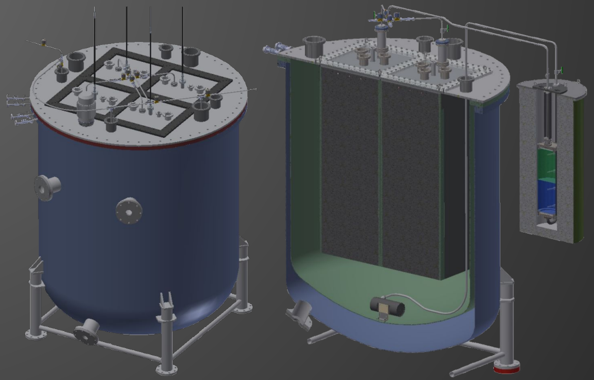
Simulation

The ArgonCube 2x2 prototyping



Prototype run in the NuMI neutrino beamline at Fermilab starting in Fall 23'

- 2x2 modules of decreased size to show viability of modular approach
- Test the novel pixelated charge readout system in a neutrino beam



Modules have been tested individually using cosmic rays

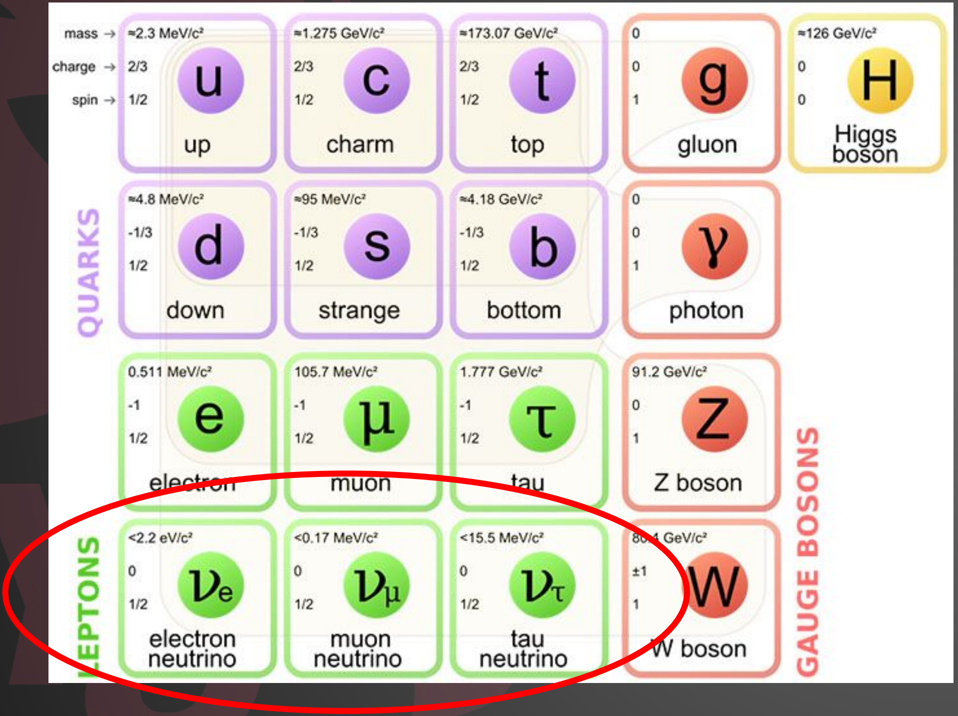
- Charge calibration and pixel performance studies ongoing

Summary

- The modular design with novel pixelated charge readout has been designed to withstand a powerful neutrino beam and is capable of dealing with pile-up
- Prototypes for individual modules have been built and tested and are being prepared for modular operation at Fermilab
- Pixel efficiency maps can be used to scan the overall responsiveness of the charge readout plane and identify aberrant regions
- Pixel pad studies can help understand the efficiency of the individual pixel pad and help with calibration

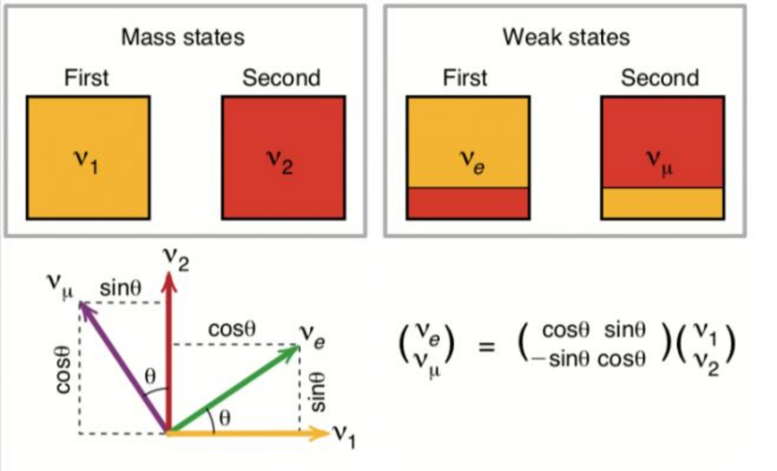
BACK-UP: Neutrinos

Standard model of particle physics

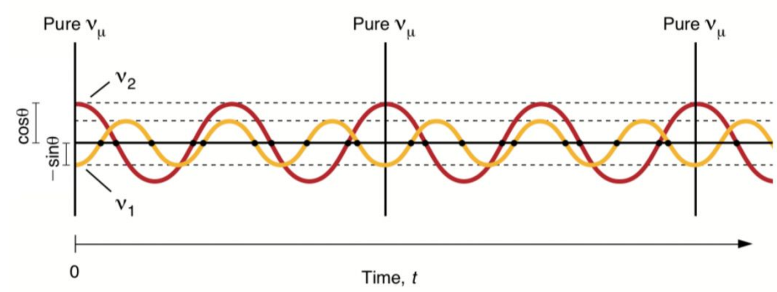


- Three flavors of neutrinos ν_e, ν_μ, ν_τ related to the charged leptons
- Very light and only interact through the weak force
- Second most abundant particle in the universe
- Wide variety of sources: Accelerators, Reactors, Stars, Supernovae and other galactic objects

BACK-UP: Neutrino oscillations



$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$



- Neutrino flavor eigenstates do not coincide with the mass eigenstates
- Flavor states are thus linear combinations of mass eigenstates and vice versa defined by the mixing matrix
- Detect the flavor eigenstate, mass states oscillate while the neutrino travels through space
- What starts off as a muon neutrino could end up as an electron neutrino
  - Neutrino oscillations!

BACK-UP: Neutrinos oscillate

- Big Bang should have created matter and antimatter in equal parts
- Yet there is Baryon asymmetry observed in present day universe
  - *So where did all the antimatter go?*
- Charge-parity violation for quarks, but too small to justify observations
  - What about the neutrinos?
- CP-violating phase shows up in the mixing matrix

$$U_{PMNS} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}}_{\theta_{23}} \underbrace{\begin{bmatrix} c_{13} & 0 & e^{-i\delta_{cp}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{cp}} s_{13} & 0 & c_{13} \end{bmatrix}}_{\theta_{13}} \underbrace{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\theta_{12}}$$