Overview and Status of the 2x2 NDLAr Demonstrator: A Pixel-Based LArTPC Prototype for the DUNE Near Detector

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ICHEP 18th July 2024

ArgonCube

DUNE (Deep Underground Neutrino Experiment)

Far Detector

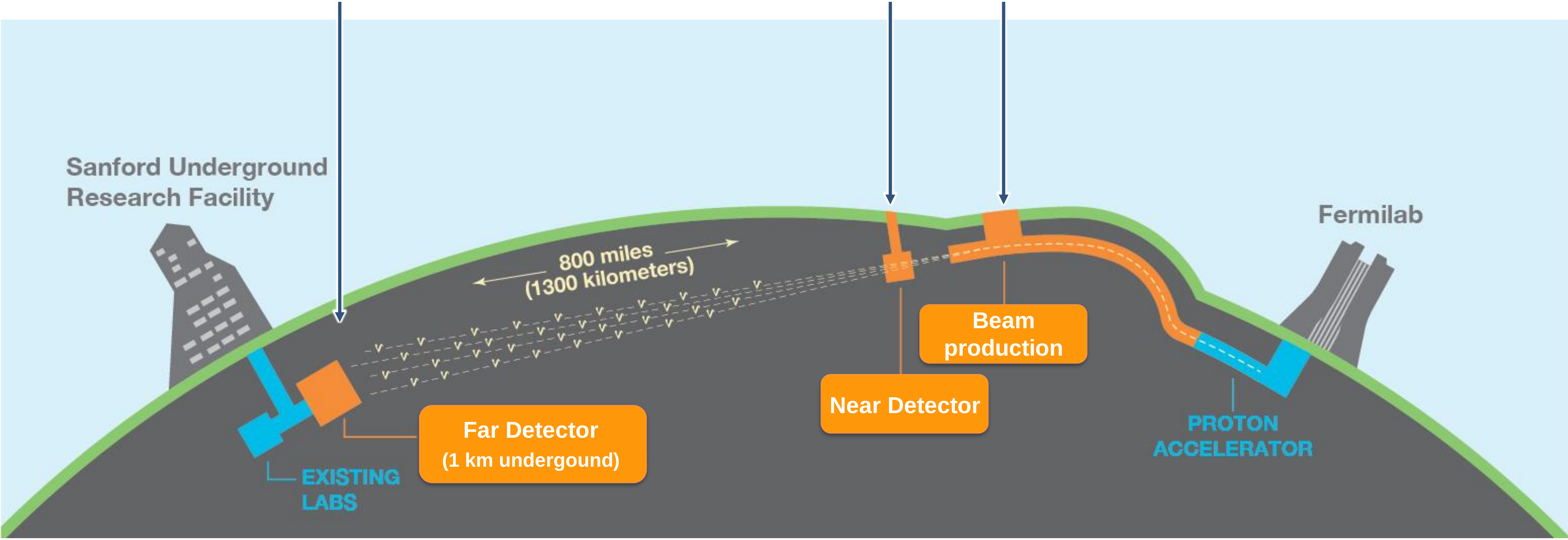
- 3 x 17 kton LAr modules + module of opportunity

Near Detector Complex

- Suite of detectors

World's most intense neutrino beam

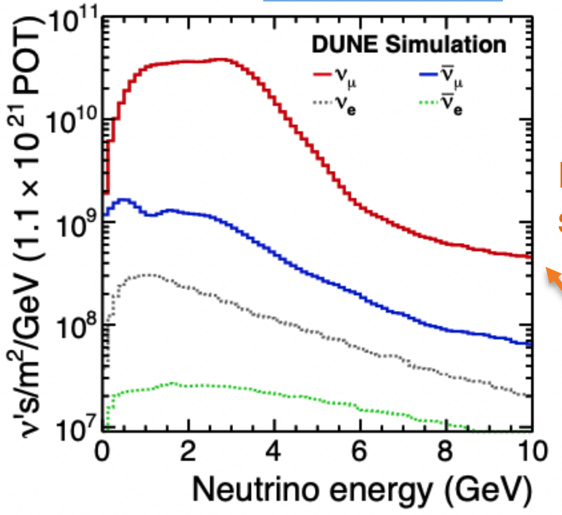
- 1.2 MW ⟶ 2.4 MW



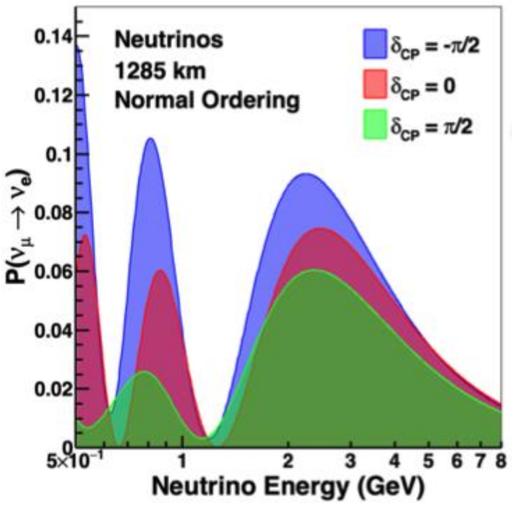
DUNE Physics

- **Rich physics program** including:
  - Precision measurements of neutrino oscillations
  - $5\sigma\ \delta_{CP}$ **discovery potential** over a wide range of allowed values and **determination of mass hierarchy** in a single measurement
  - And many, many more (supernova neutrinos, proton decay, solar neutrinos, BSM searches …)

arXiv:2006.16043



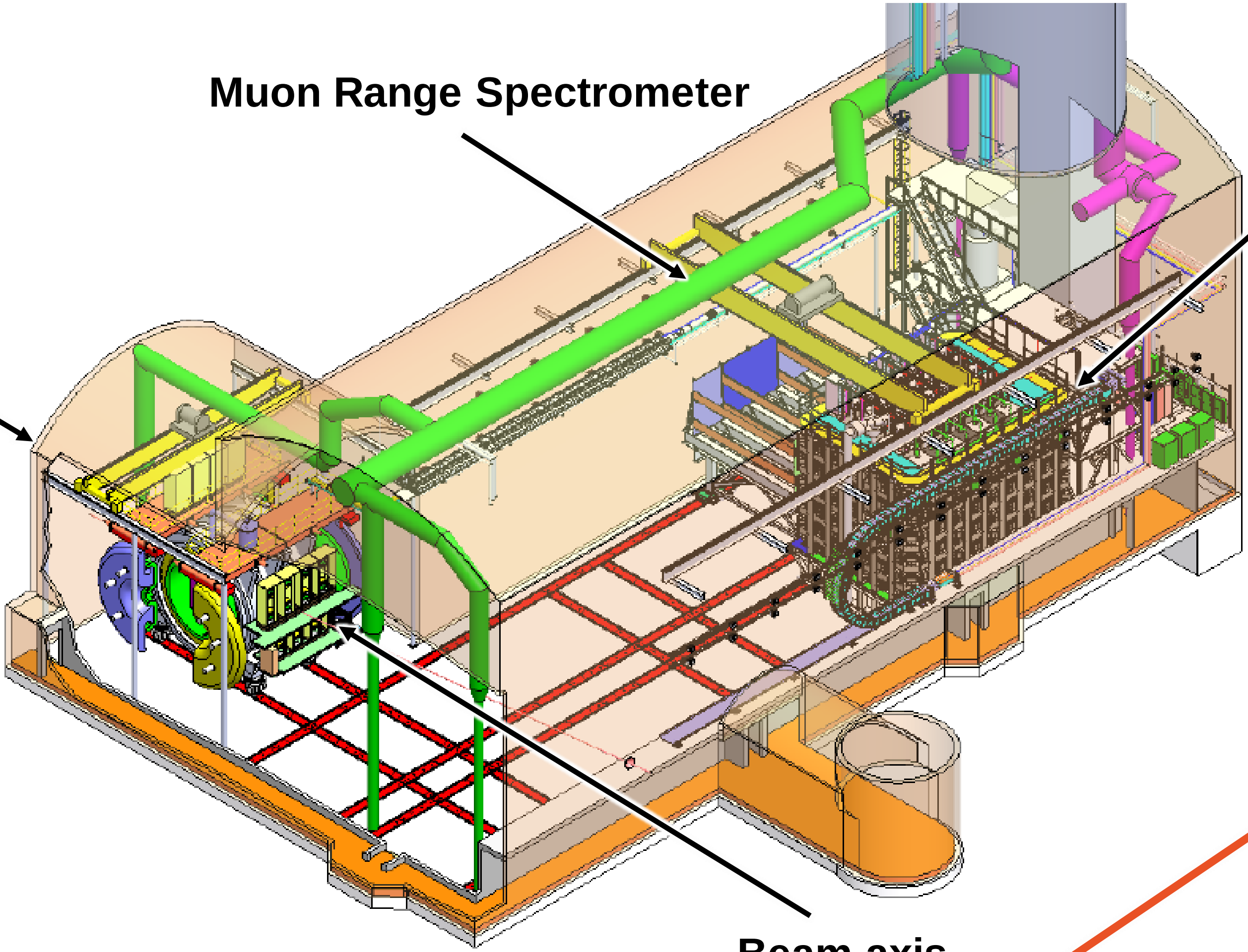
Broad energy spectrum …



… covers 2 oscillation maxima = sensitivity to neutrino oscillations

Day 1 Near Detector Complex

A suite of complimentary detectors to monitor and characterise the beam



NDLAr + muon spectrometer wil sample off-axis flux up to 30 m transverse to the beam

[DUNE Near Detector CDR]

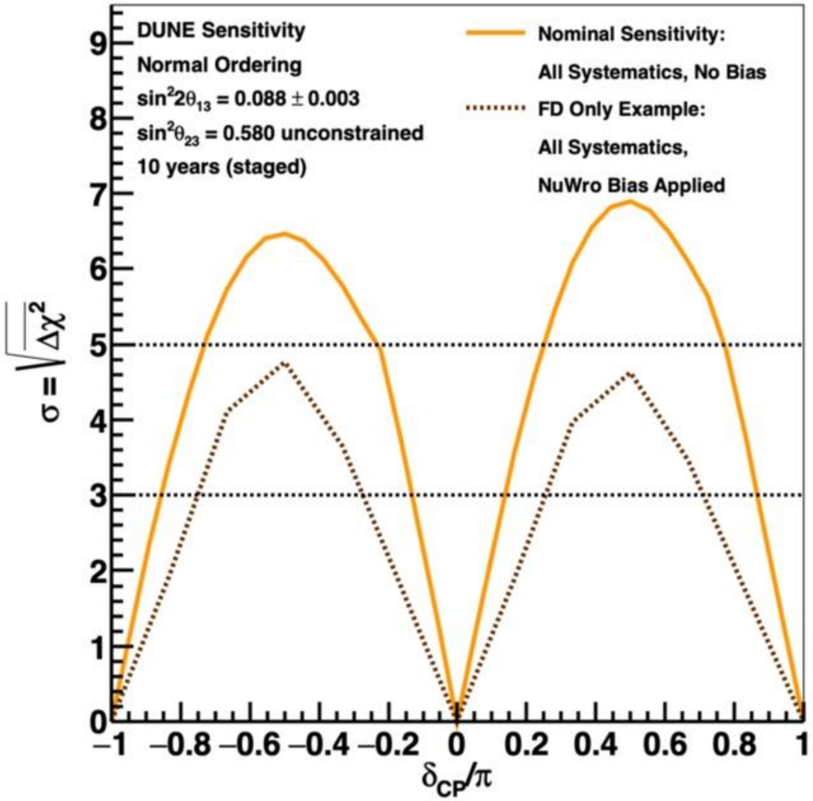
Mitigation of Systematic Uncertainties with NDLAr

Key features:

- Same nuclear target as the Far Detector (FD)
  ⟶ Constrain cross-section systematics
- Similar technology as the FD
  ⟶ Constrain detector systematics
- High performance LArTPC
  ⟶ Cope with the high-rate environment due to the intense beam

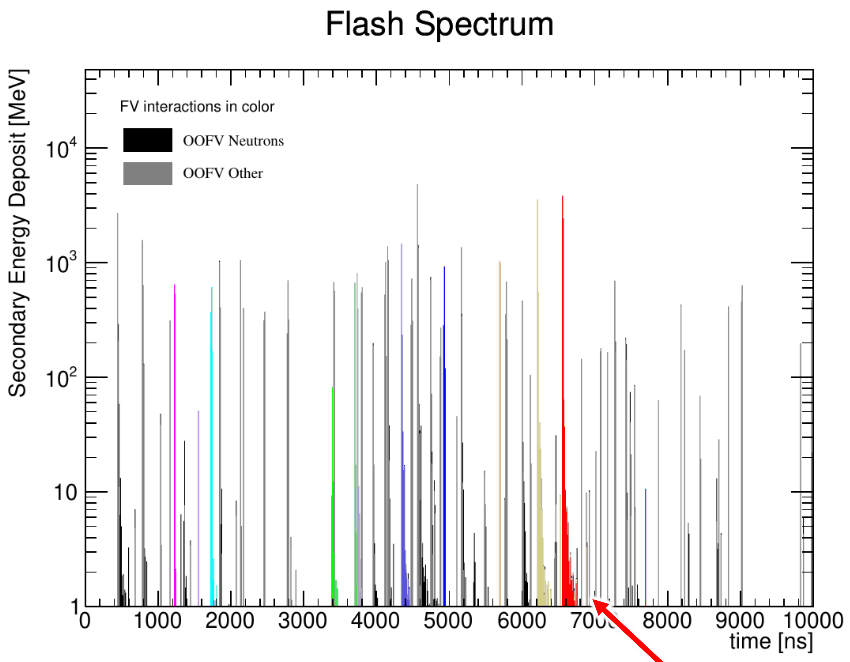
CP violation sensitivity with and without the ND

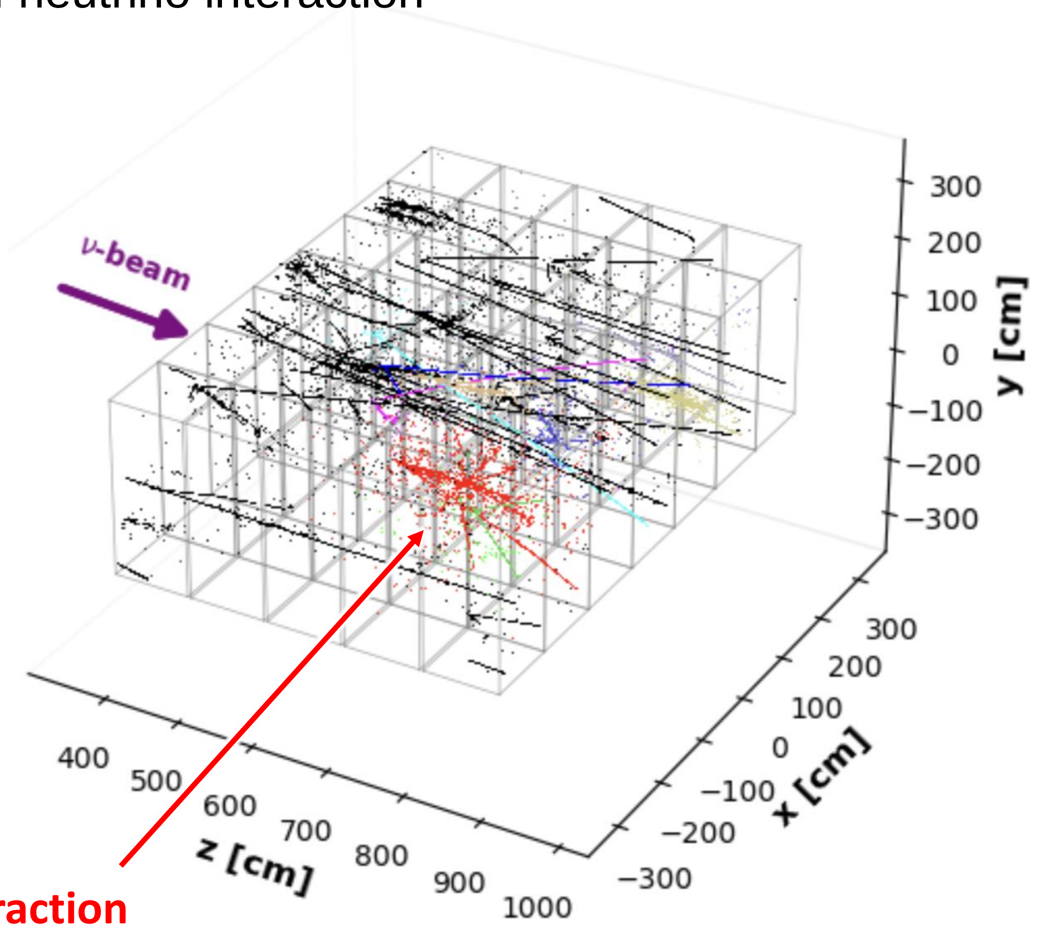
DUNE Far Detector TDR Vol II



Simulated 1.2 MW Beam Spill at NDLAr

- Order of **50 interactions per spill!**
- Must correctly match each charge deposit to individual neutrino interaction



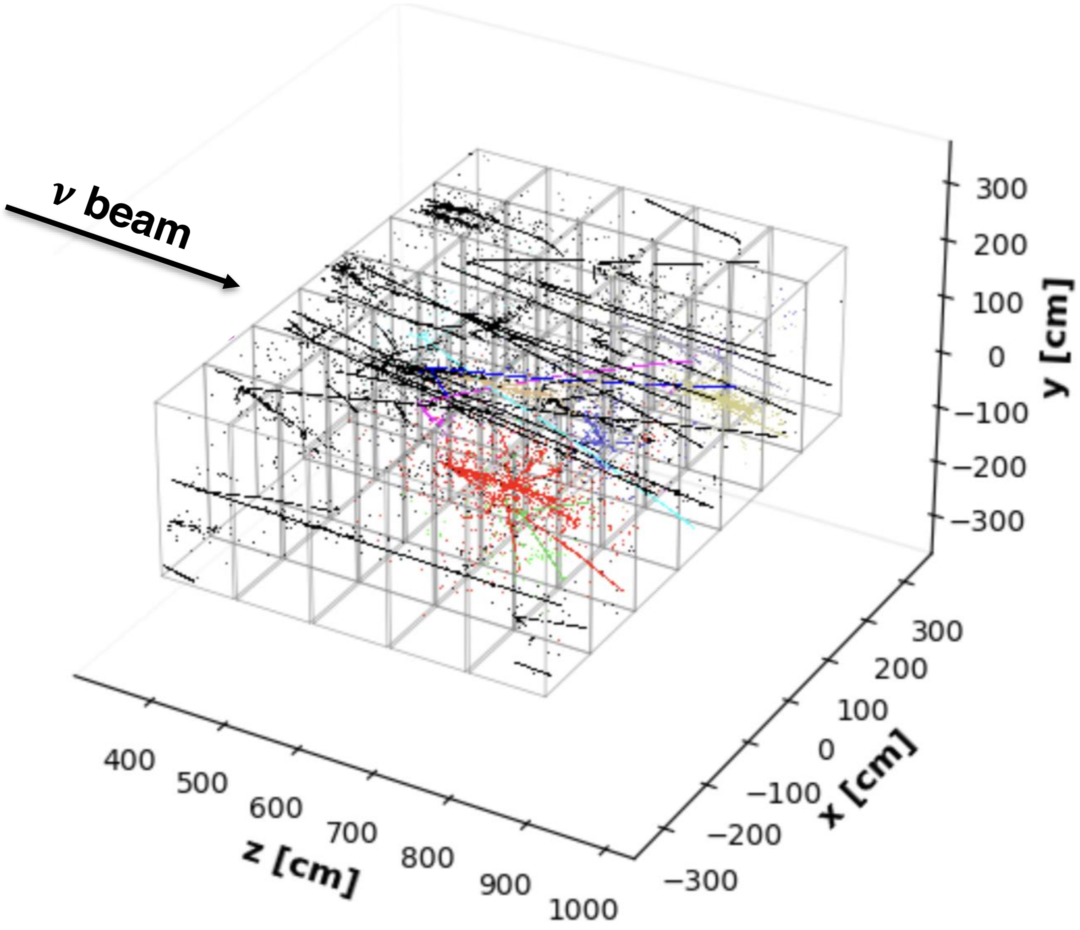


Single neutrino interaction

Reconstruction Challenges

- Overlapping charge deposits (pile-up)

- Charge read-out is slow (~100s of μs between interaction and detection vs 10 μs beam spill)



Reconstruction Challenges

- Overlapping charge deposits (pile-up)
  ⟶ Need a native 3D charge-read out to disentangle the pile-up

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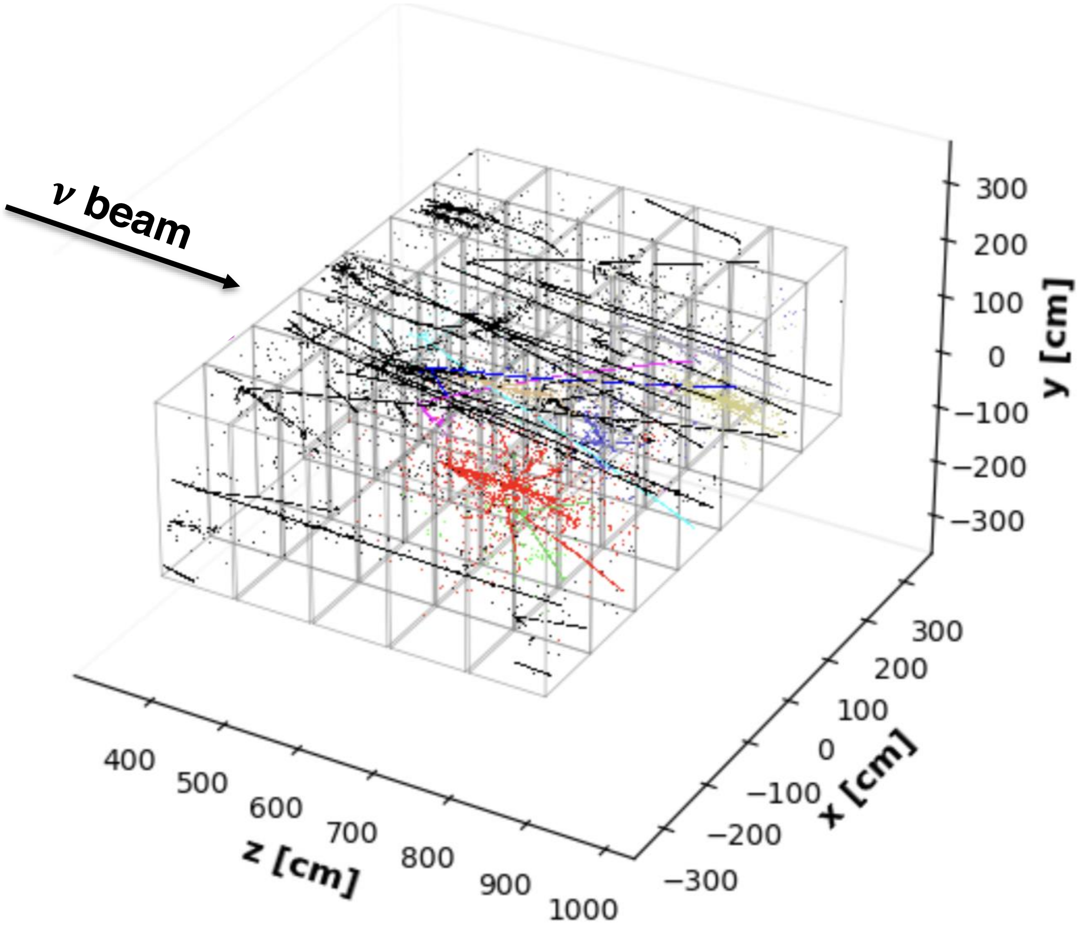
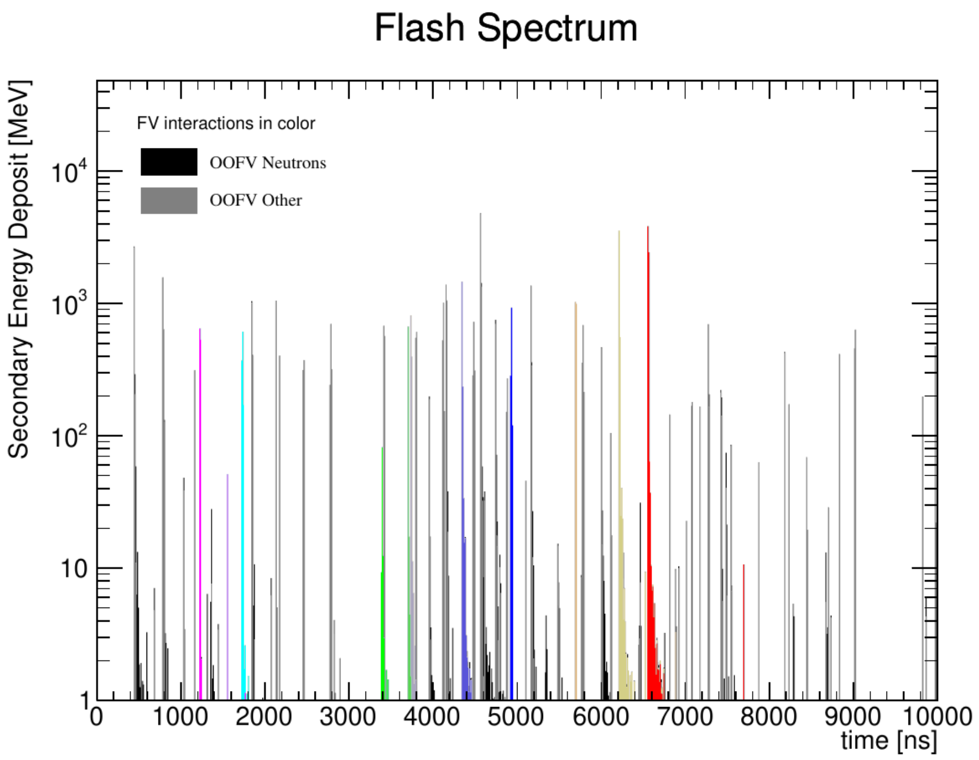


Reconstruction Challenges

- Overlapping charge deposits (pile-up)
  ⟶ Need a native 3D charge-read out to disentangle the pile-up

- Charge read-out is slow (~100s of μs between interaction and detection vs 10 μs beam spill)
  ⟶ Need a high-performance light read-out to match fast light signals to charge deposits

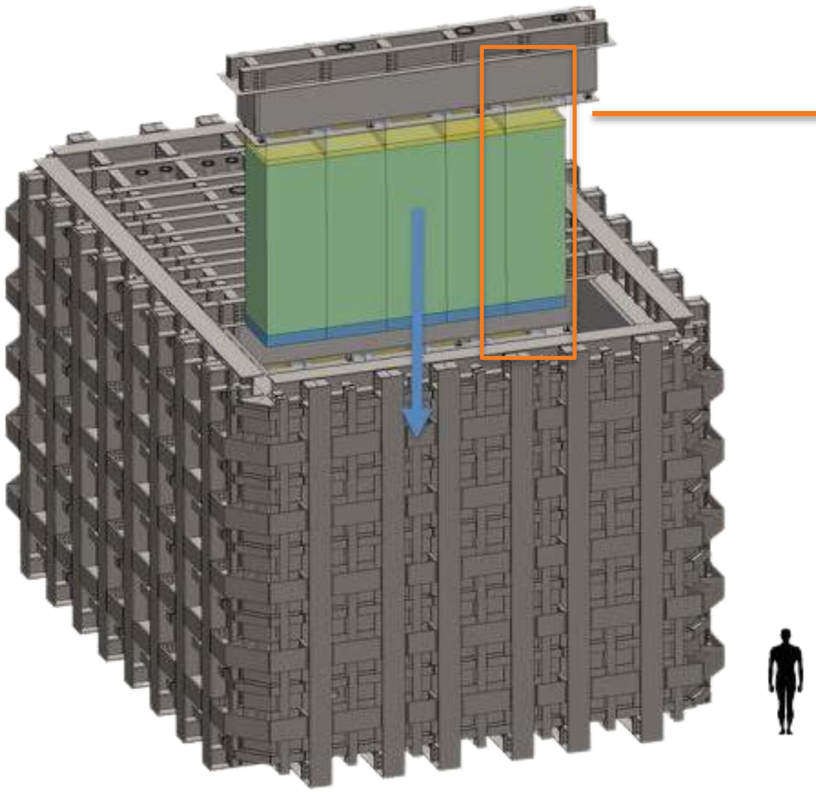


The First Modularised LArTPC

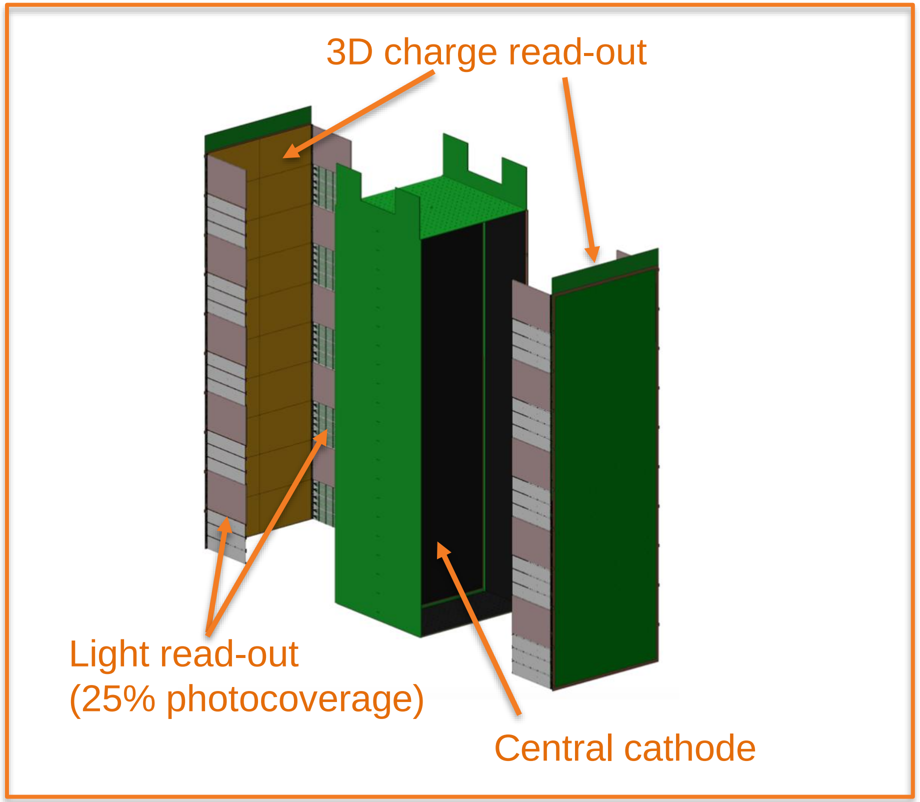
DUNE ND CDR: arXiv:2103.13910
ArgonCube concept: arXiv:1908.10956

- 35 individual 1x1x3 m^3 modules (= 70 optically isolated TPCs!)

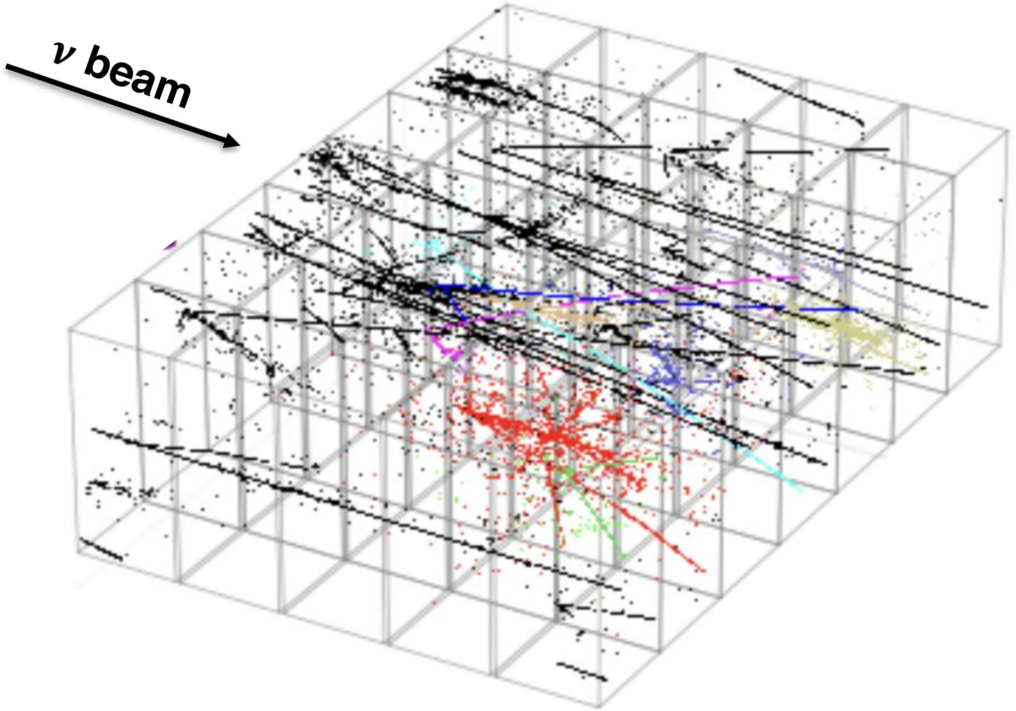
7x5 array of modules



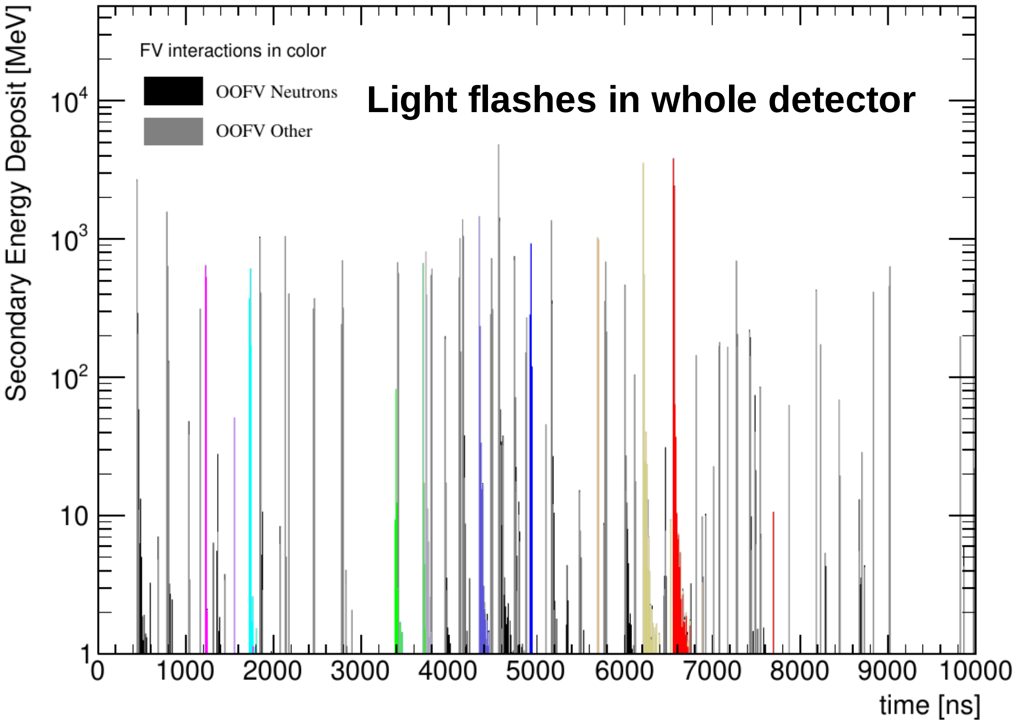
Single 1x1x3 m^3 NDLAr module



The First Modularised LArTPC

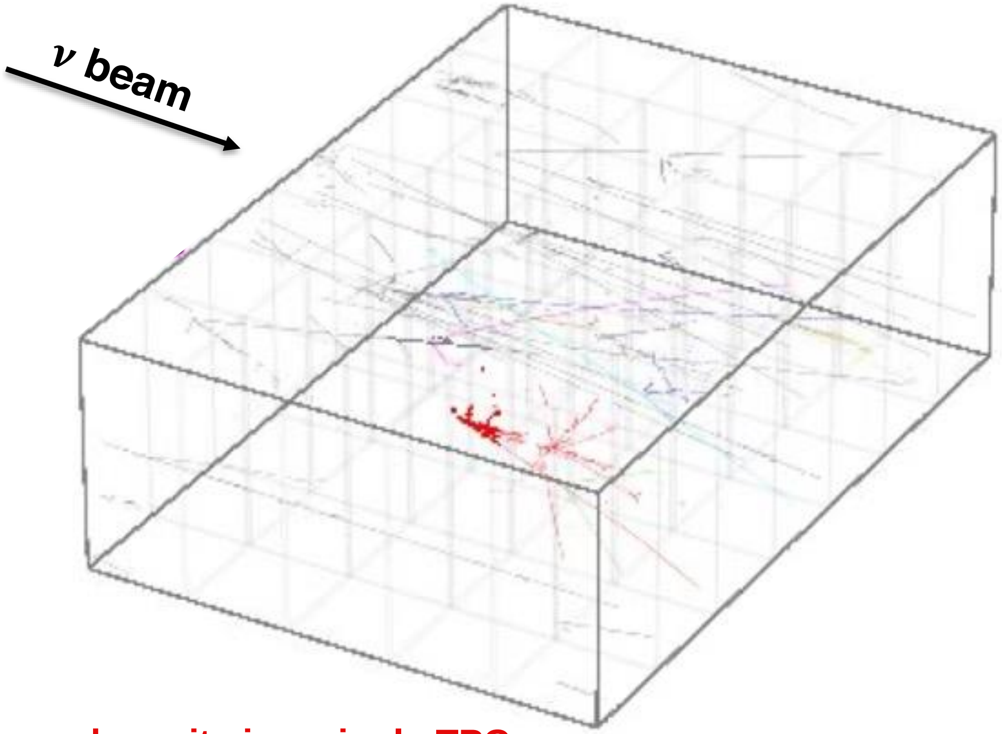


Charge deposits in whole detector

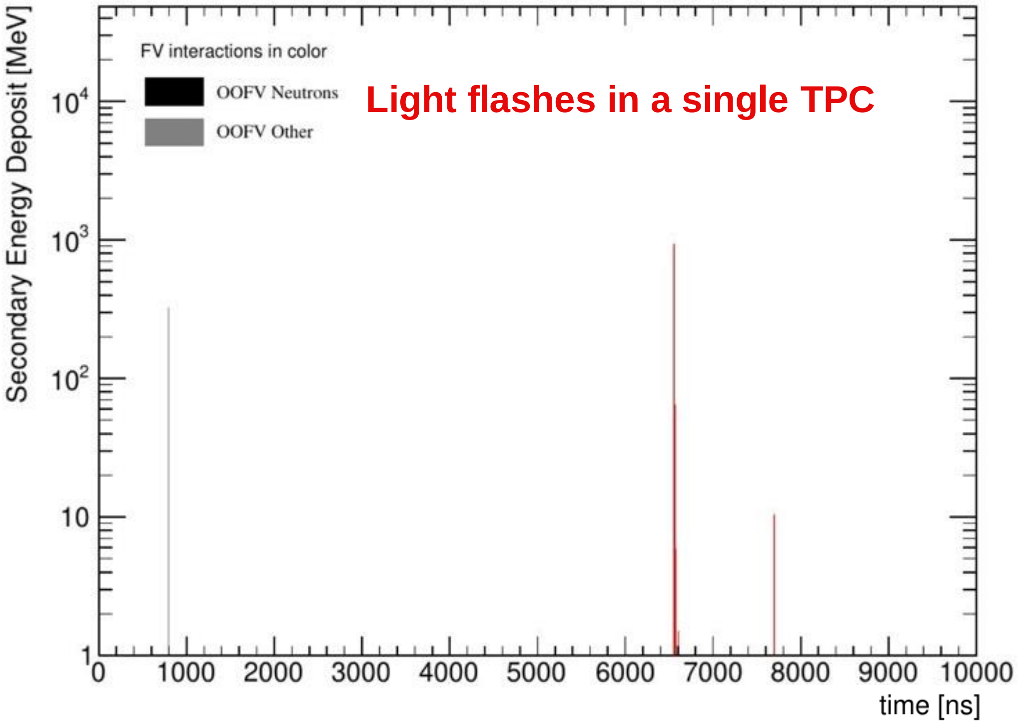


The First Modularised LArTPC

- Segmentation lowers the signal occupancy per TPC



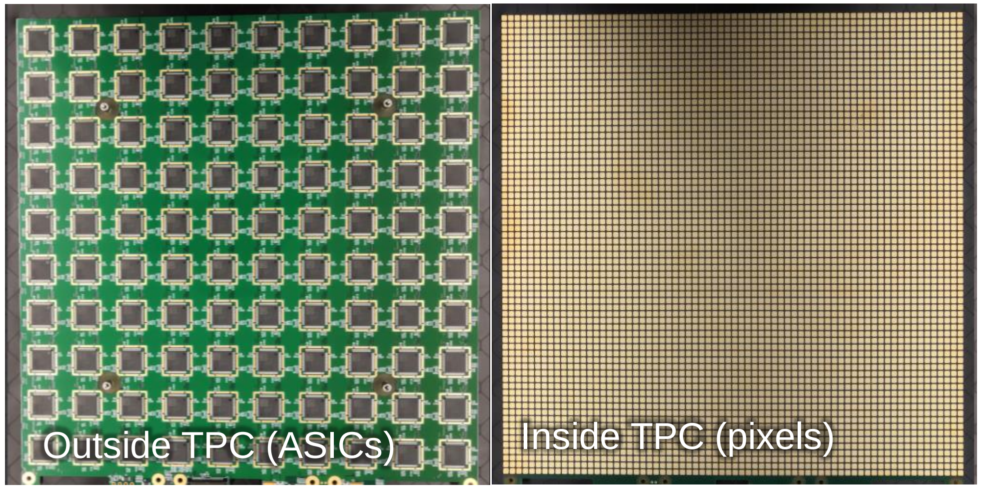
Charge deposits in a single TPC

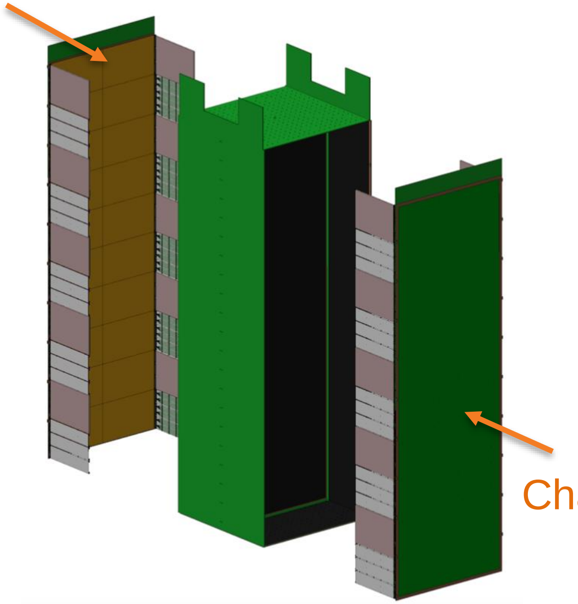


LArPix Charge Read-Out

- **64K channels/m^2** (NDLAr will have ~200 m^2 of LArPix)
- ~3-4 mm granularity
- **Low power dissipation** (<100 µW/channel) - cryogenics compatible
- **Continuous read-out and low data rates** enabled through self-triggering digitisation and read-out
- Dynamic chip network configuration - **robust to single-point failure**

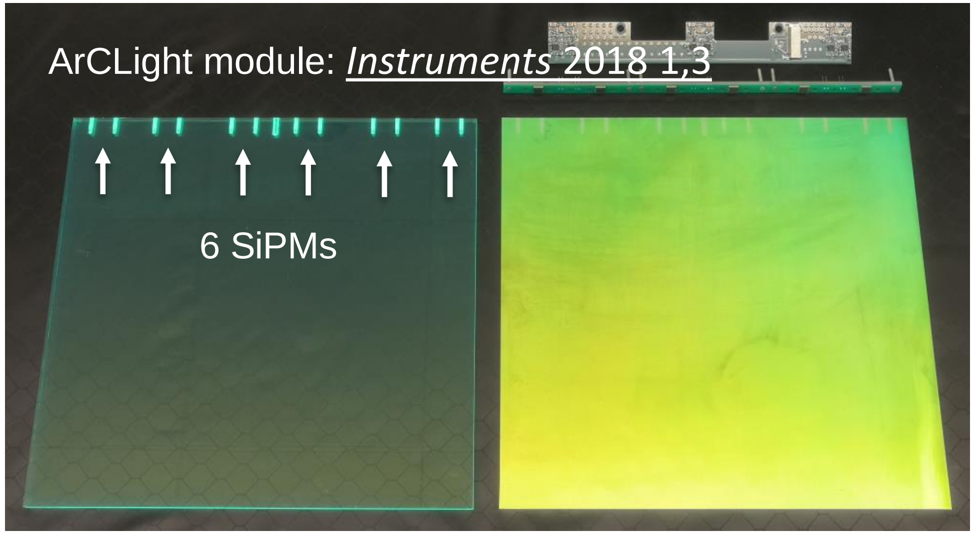
LArPix anode tile (prototype dimensions)

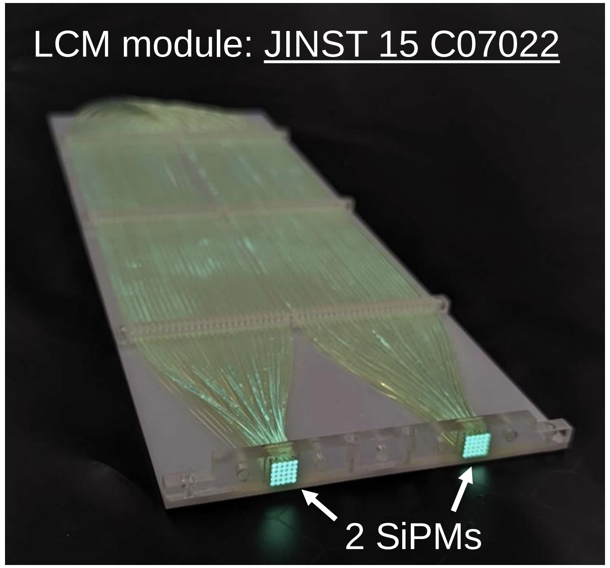




LArPix: *JINST* **13** P10007

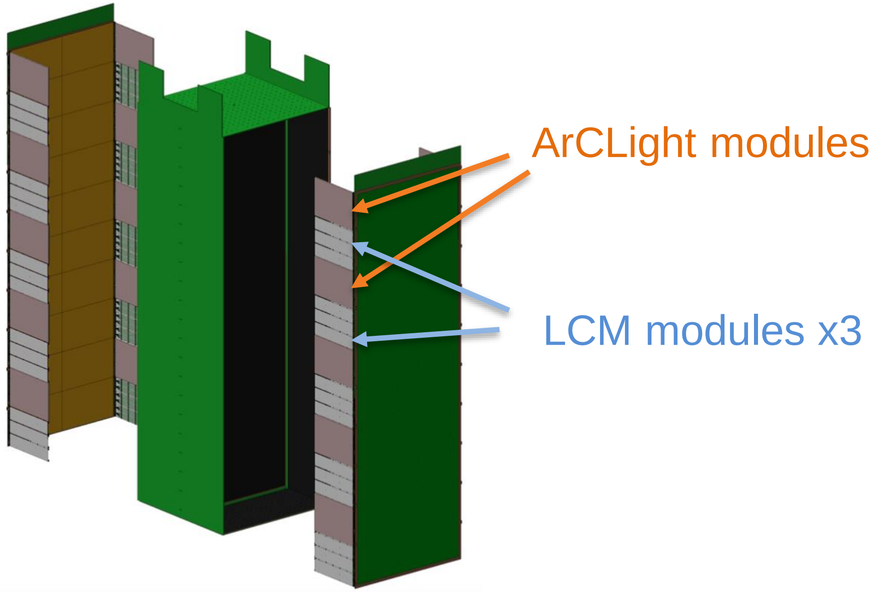
ArCLight and LCM Light Read-out





- **SiPM-based, dielectric** light collection modules
- Complimentary technologies:

	ArCLight	LCM
PDE	~0.2%	~0.6%
Spatial resolution	~5cm	~10cm
Additional notes	High dynamic range	O(ns) time resolution

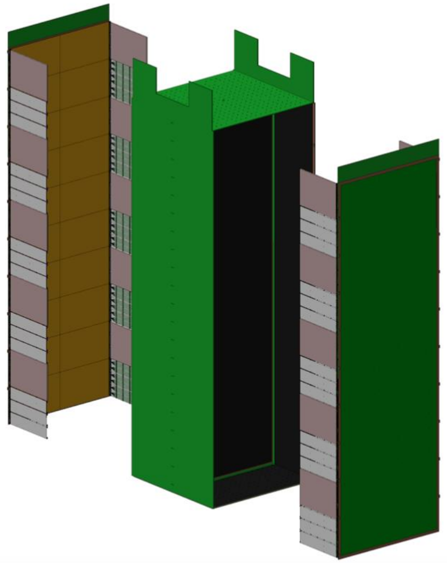


The 2x2 NDLAr Demonstrator

Single 1x3x3 m³ NDLAr module → Scale it down → **Single 2x2 module** → x4 → **2x2 NDLAr demonstrator**

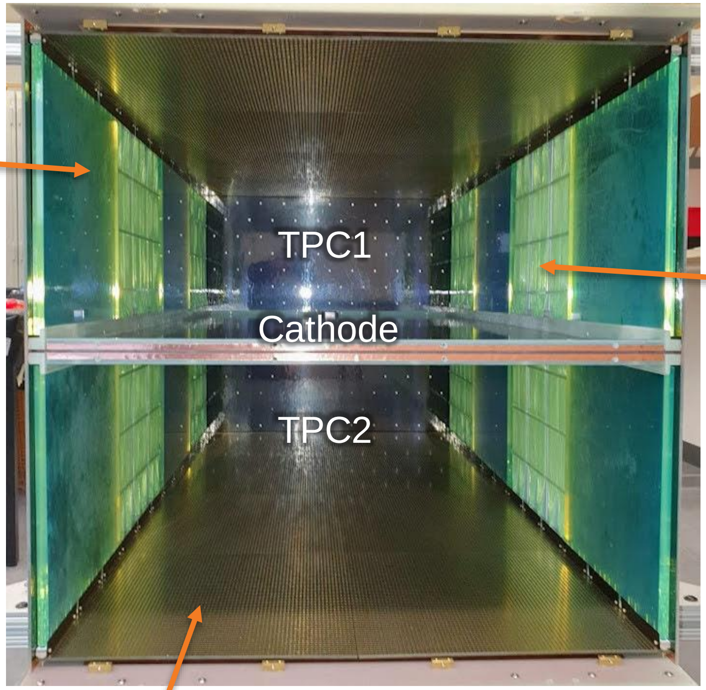
~60% of full NDLAr module

An ensemble of 4 individual ton-scale O(100K) pixel modules



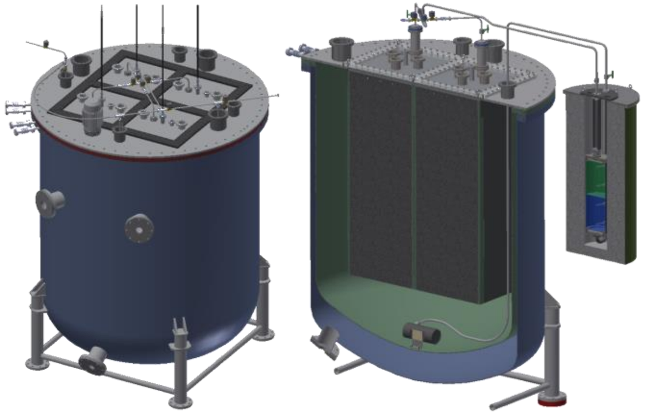
View Inside TPC

ArCLight



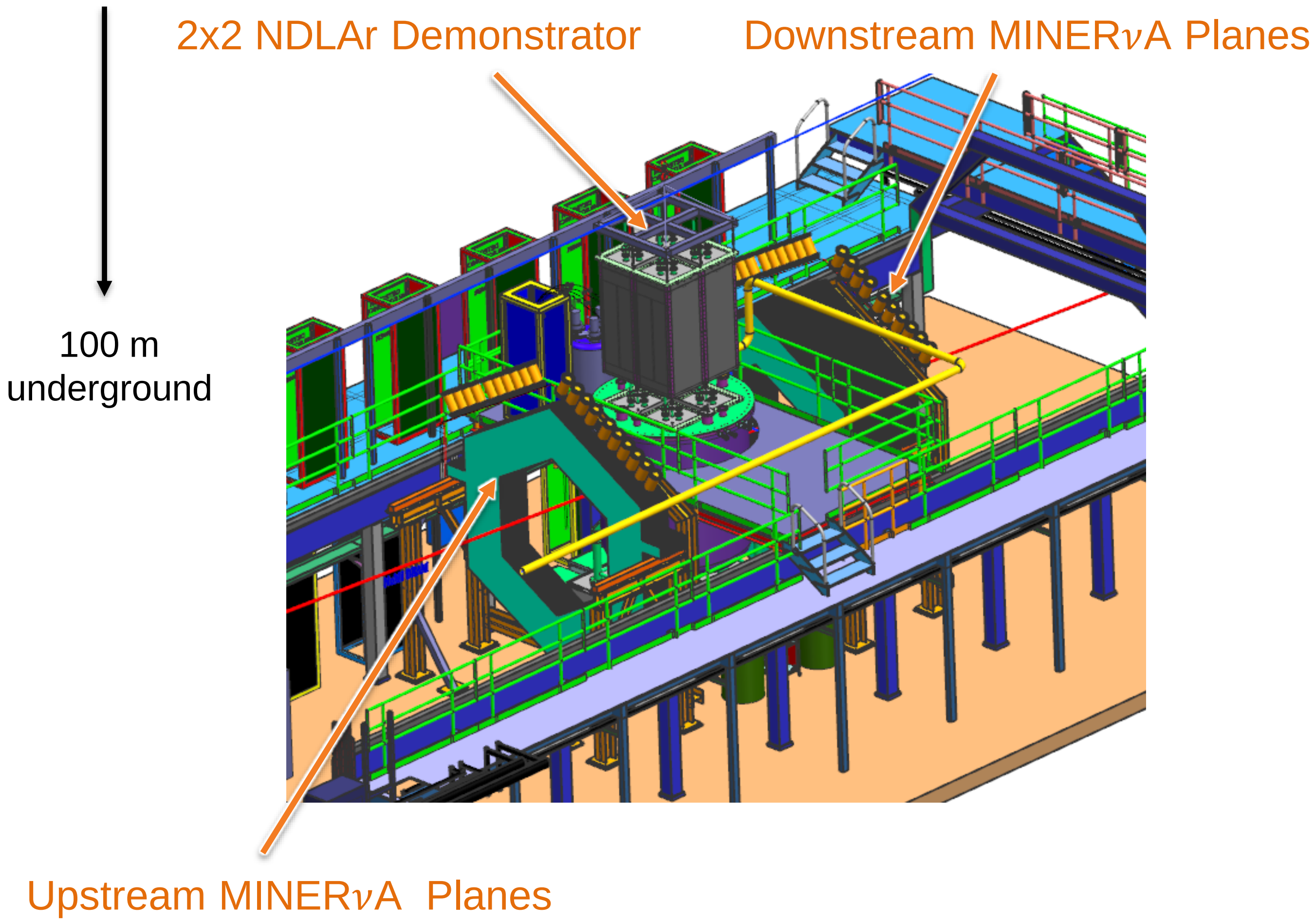
LCM

LArPix charge read-out



Module-0 perfomance paper: arXiv:2403.032012

The 2x2 Demonstrator + MINERνA



The 2x2 Demonstrator + MINERνA

- Receives GeV neutrinos from the NuMI beam

- Demonstration of
  - **robustness and long-term stability** of modularised approach and novel detector subsystems
  - **multi-module AND multi-detector reconstruction** capabilities

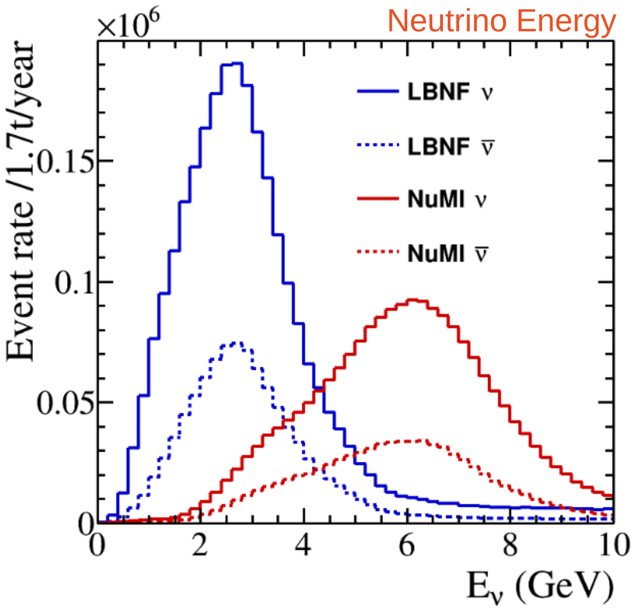
The 2x2

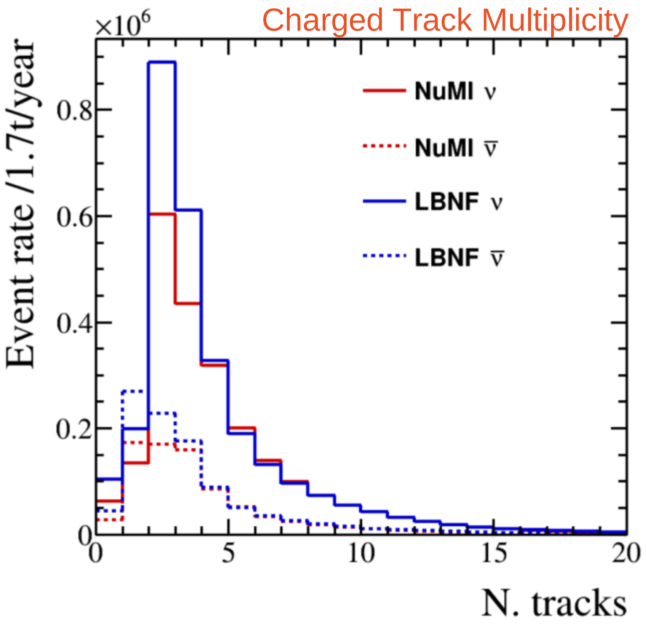
Downstream MINERνA Planes

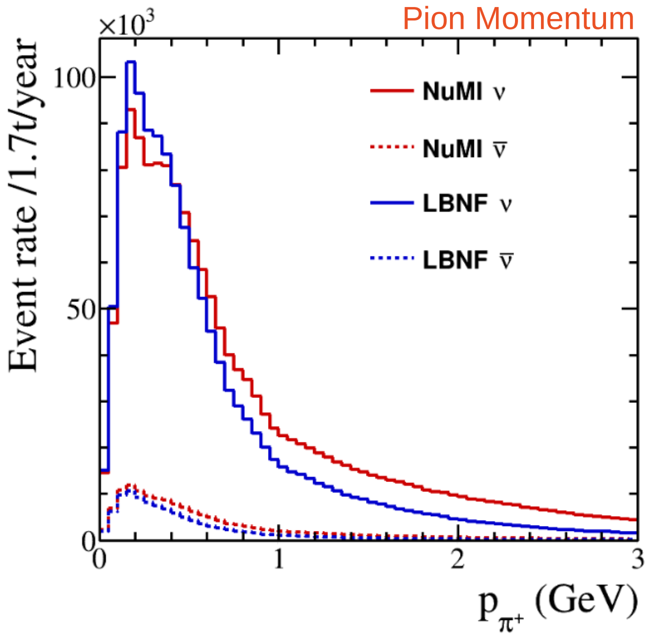
Upstream MINERνA Planes

Why NuMI Beam?

High-flux, ND-LAr-like environment!

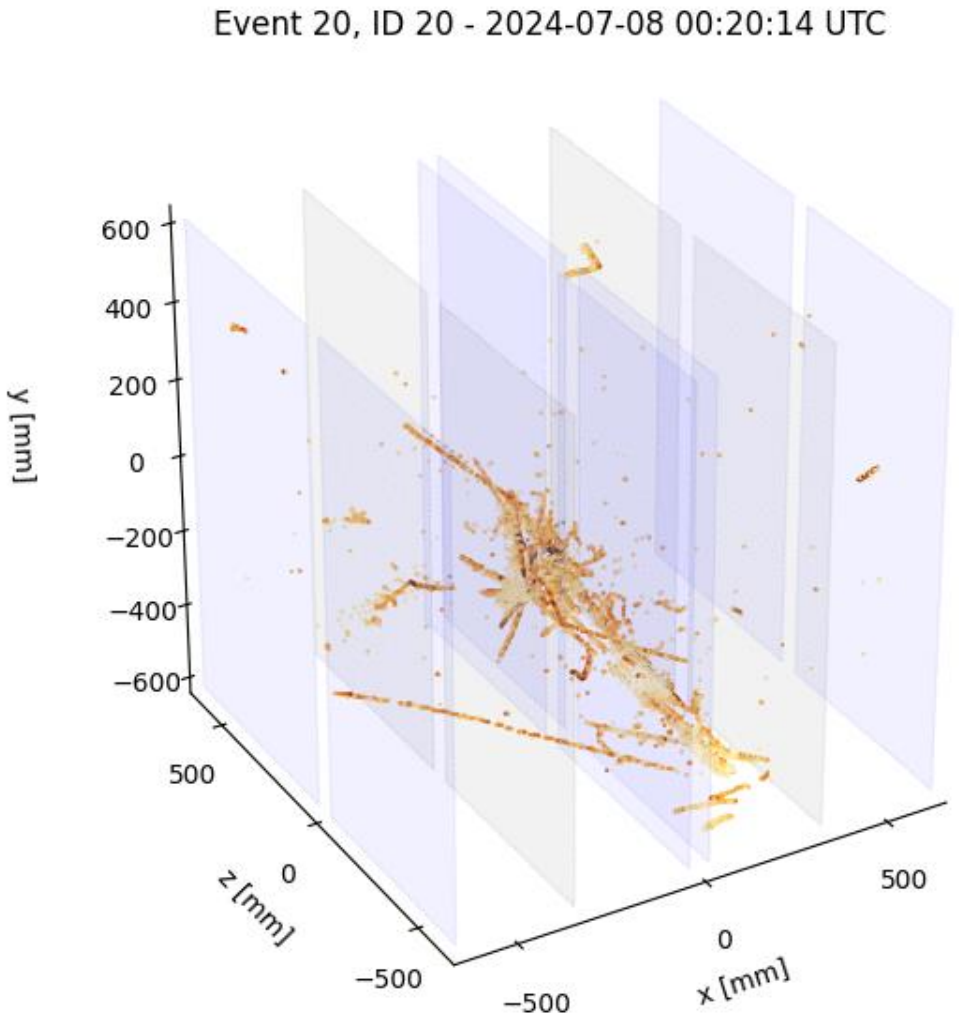






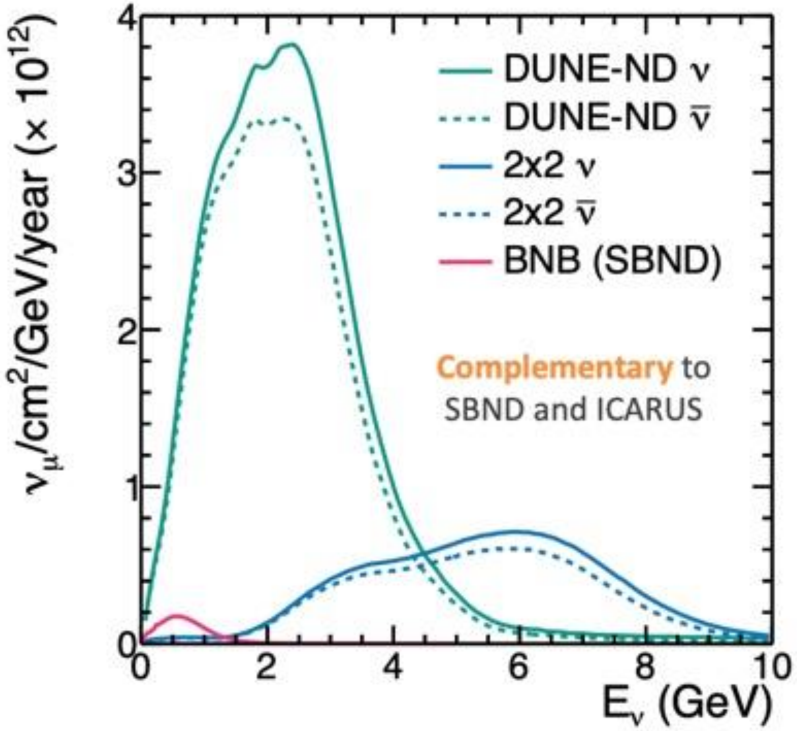
The First DUNE Neutrino Data

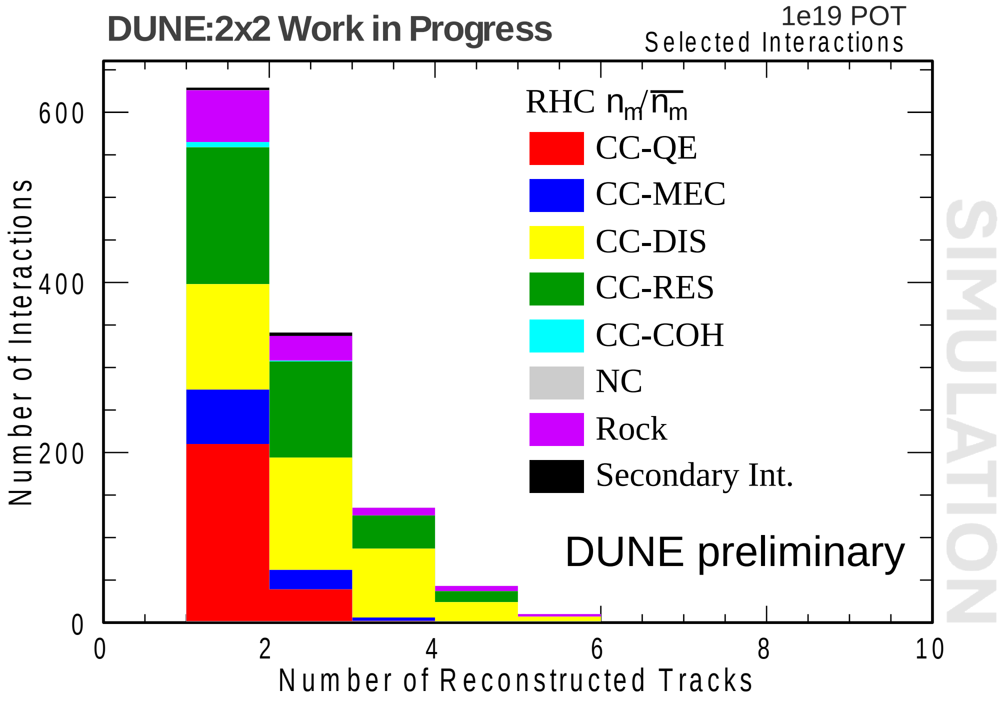
- Operations commenced on 8th of July
- Collecting data in $\bar{\nu}$ mode (300K events/year)
- ~ 5 days of physics quality data
- Preparing for another beam run in 2024/25



Physics Program Opportunity

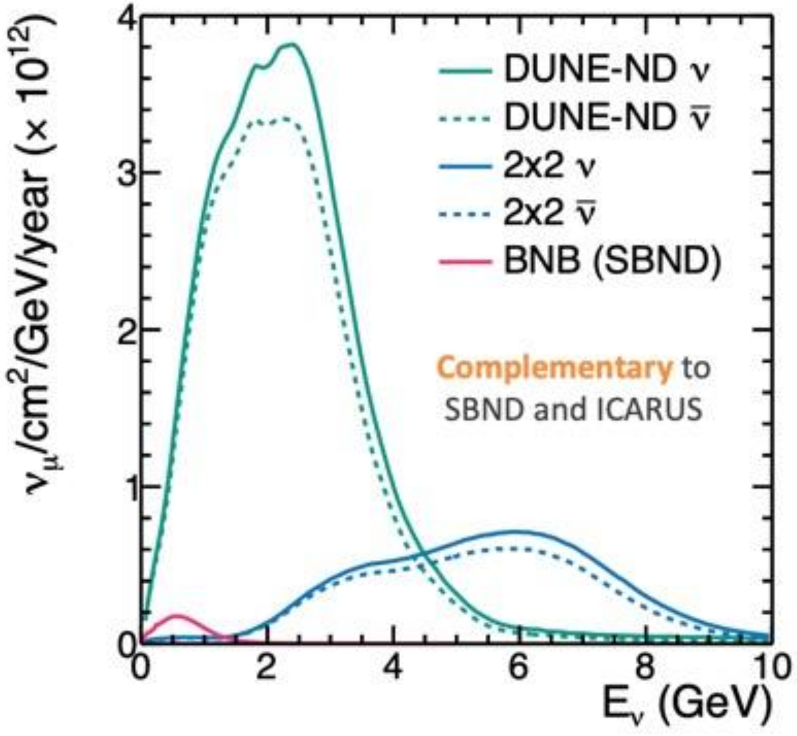
- The 2x2 will sample a phase space previously unexplored on argon
- Short term goals
  - **track multiplicity** measurement (sensitive to final state modelling)
  - **mesonless $\bar{\nu}_\mu$ cross-section** measurement (scarce data)

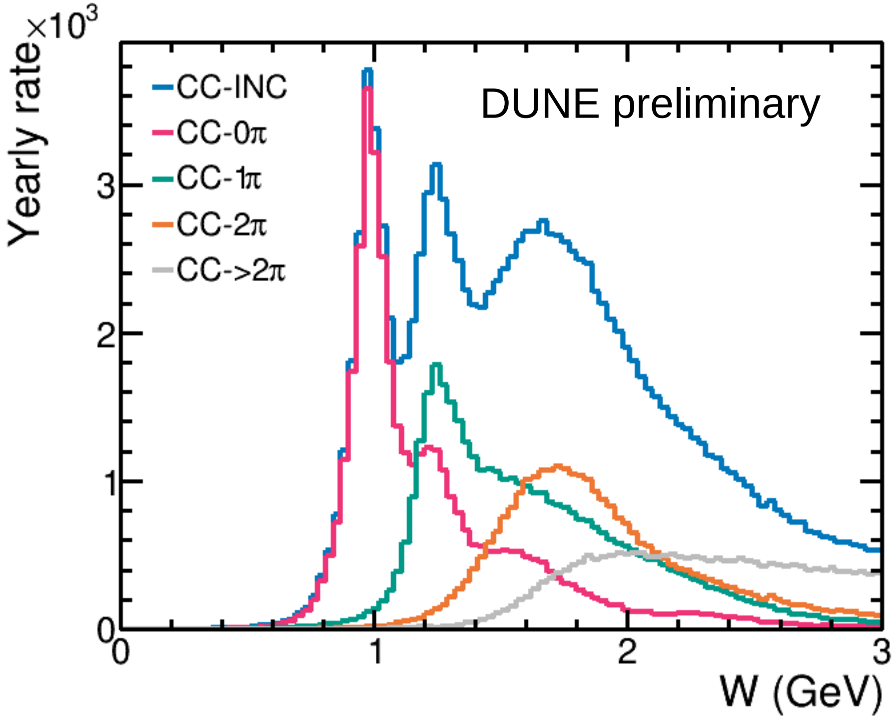




Physics Program Opportunity

- Future work includes **pion production** measurements (dominant topology at DUNE), **neutron tagging** (important for energy reconstruction) and possibility of **off-beam studies** (enabled through self-triggering charge read-out)





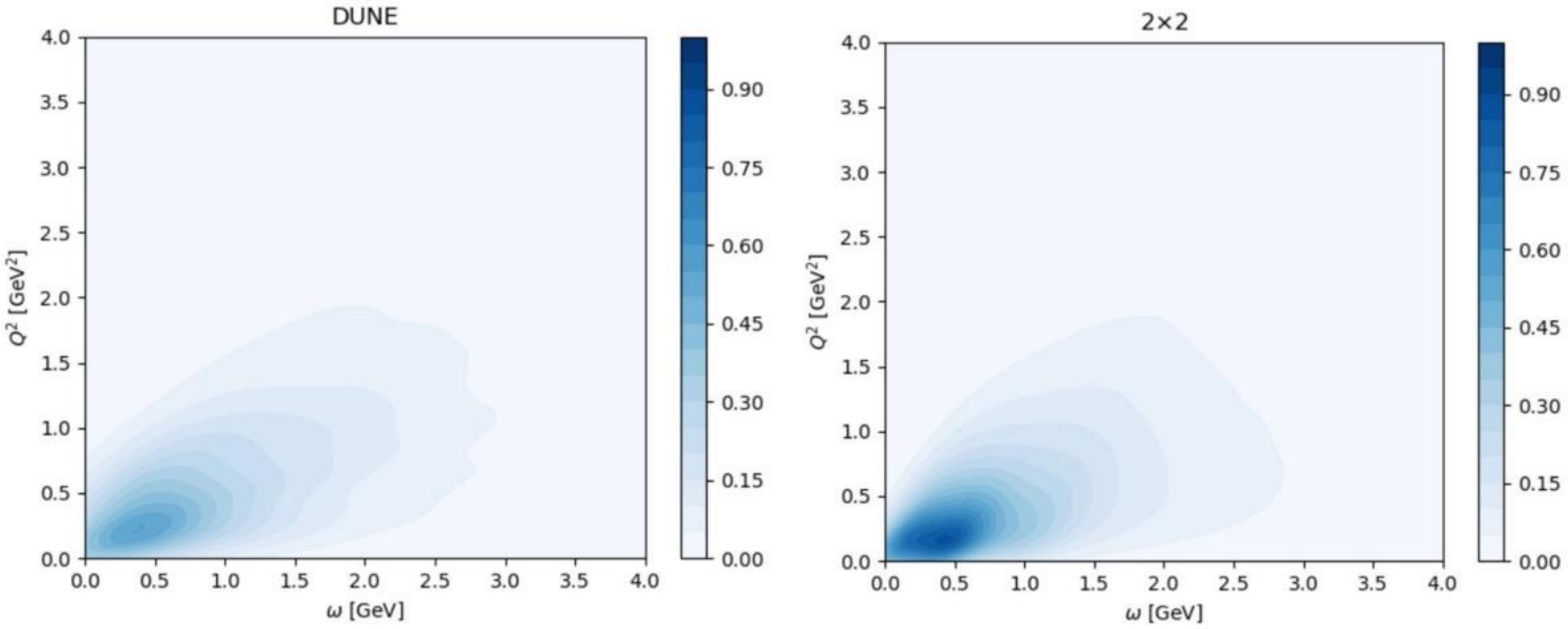
Summary

- NDLAr will play a key role in mitigating systematic uncertainties for DUNE long-baseline oscillation measurements.

- Mitigation of event pile-up due to the intense beam enabled by
  - Modularised detector design
  - Novel charge read-out (first native 3D event readout in LArTPC)
  - High performance light read-out

- The 2x2 + MINERνA is currently taking NuMI $\bar{\nu}$ data enabling
  - Performance demonstrations
  - Development of neutrino analysis pipelines
  - Physics measurements on argon in an unexplored region of phase space

Back-up

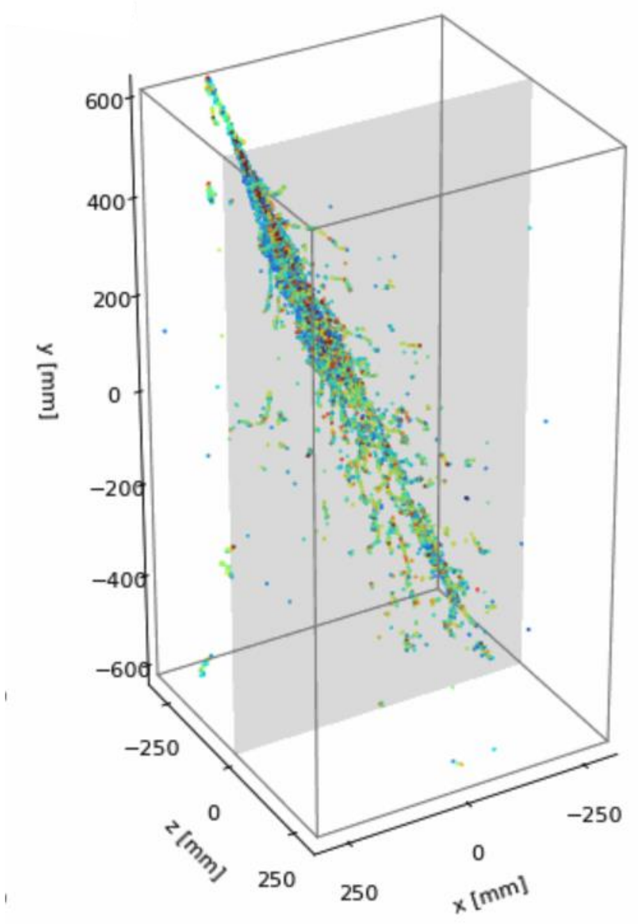

DUNE
2×2
Q^2 [GeV^2]
ω [GeV]
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0.00
0.15
0.30
0.45
0.60
0.75
0.90

Single Module Commissioning

2-year effort (2021-2023)

- Modules assembled and commissioned individually
- Collected O(100)s millions of cosmic ray data
- First performance demonstration of the cutting-edge 3D charge read-out and light detection technologies
    - Full details in: Module-0 perfomance paper: [arXiv:2403.032012]

Module-0 cosmic ray event



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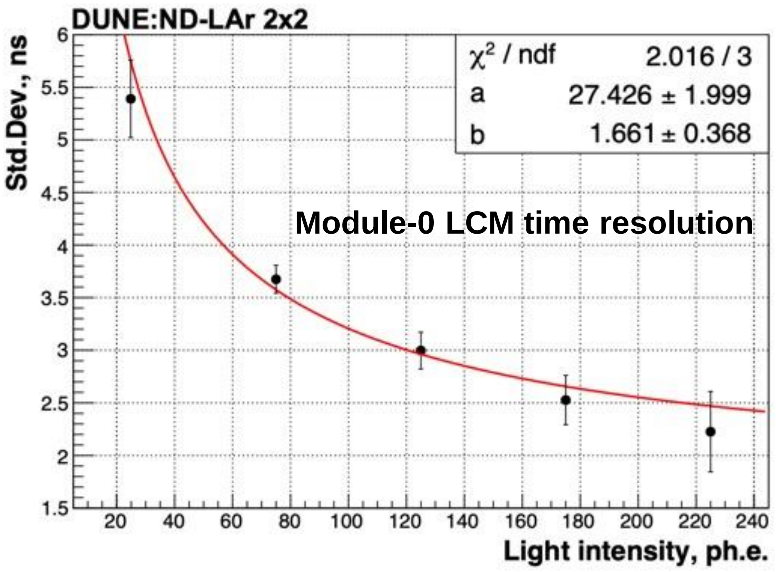
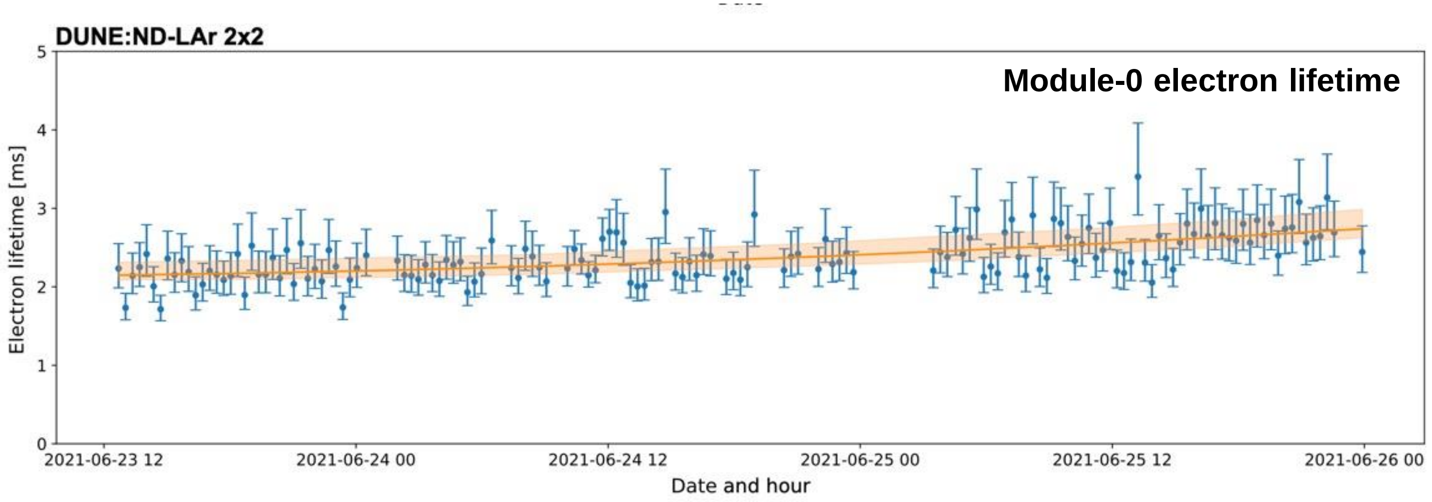
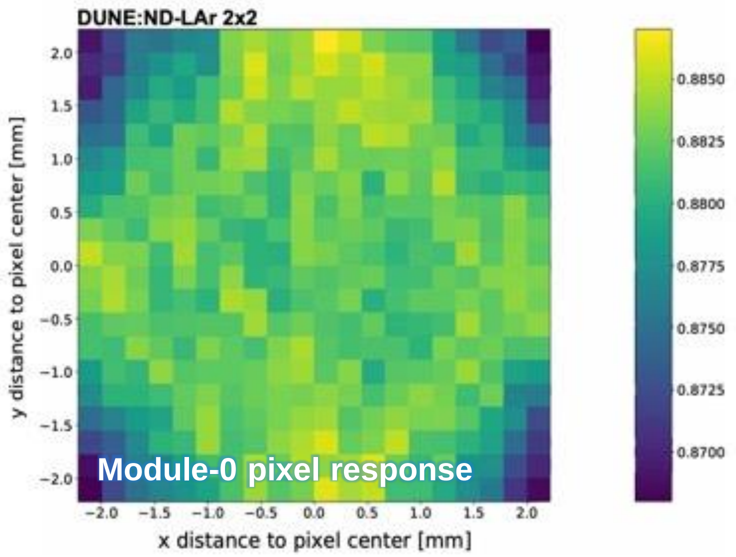
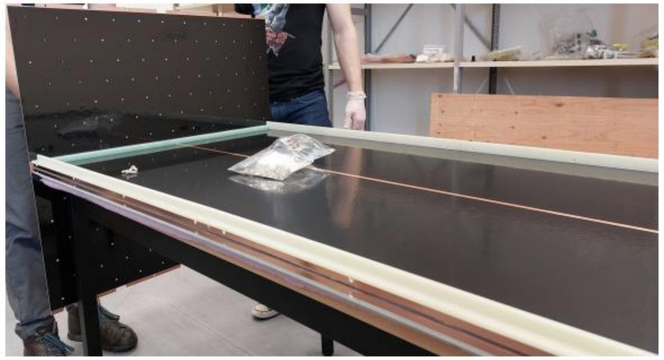


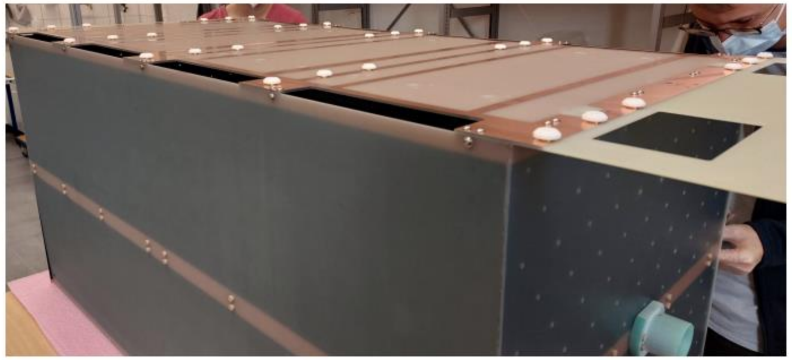




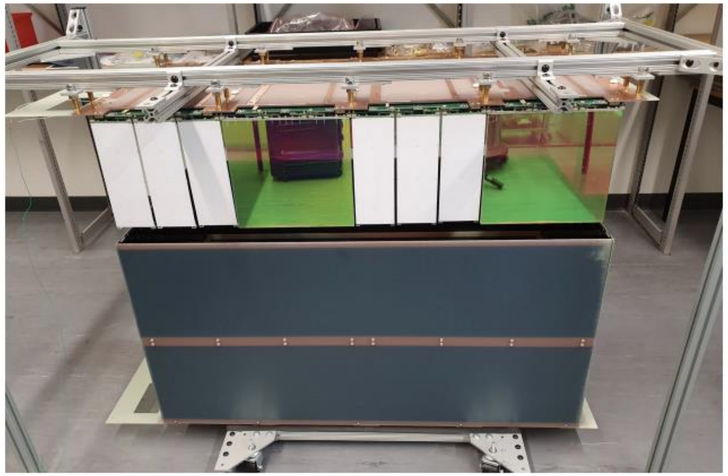
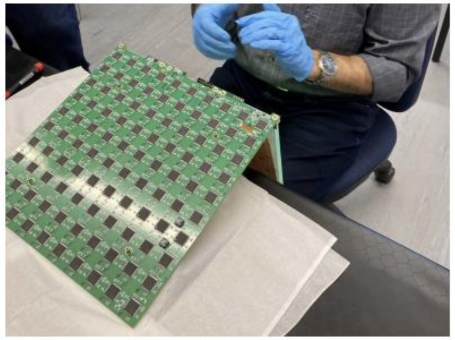
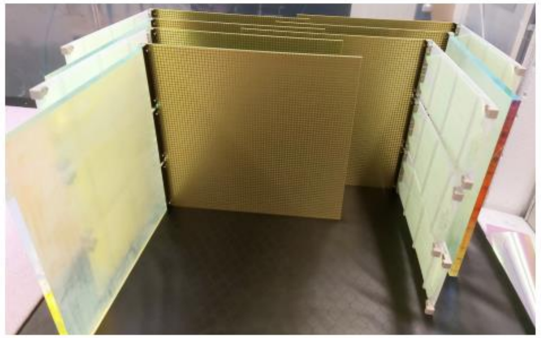
Single Module Assembly

1. Field shell + cathode






2. Assemble charge and light readout components

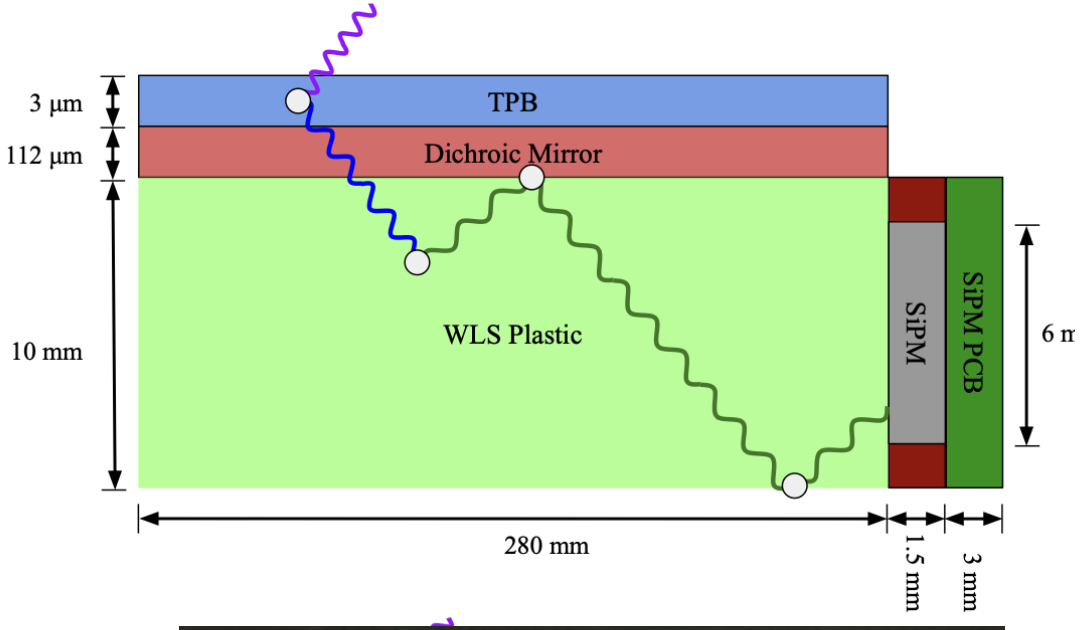




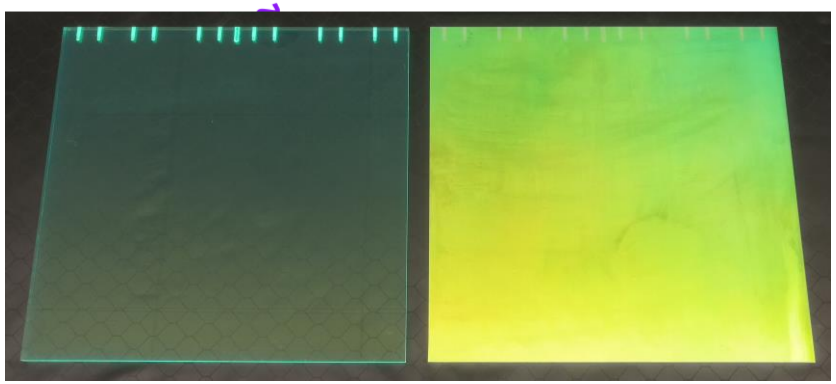

Single Module Commissioning Summary

Bern Single module test	Module-0	Module-1	Module-2	Module-3
LArPix ver.	v2A	v2A	**v2B**	v2A
Pixel pitch,mm	4.434	4.434	3.8	4.434
CRS Threshold	5.8 ke, ~ ¼ MIP	4.5 ke, ~ 1/5 MIP	7.5 ke, ~ 2/5 MIP	6.1 ke ~ ¼ MIP
Inactive channels	7.8%	2.4%	9%	3.9 %
LRS PDE: LCM	0.6 %	0.6 %	0.6 %	tbd
LRS PDE: ACL	0.06%	0.2 %	0.2 %	tbd
LRS threshold	~ 5 MeV	~ 1.6 MeV	< 1.6 MeV	~ 1.6 MeV
LRS timing	< 2 ns	1.2 ns	1.2 ns	1.2 ns
LRS inactive channels	8.3%	1%	0	2%
Field shell	DR8	DR8	DR8	DR8
R shell	**71.193 MΩ**	**82.582 MΩ**	**71.285 MΩ**	**61.791 MΩ**
Max E-Field tested	1 kV/cm	0.5 kV/cm	0.8 kV/cm	0.7 kV/cm
Electron lifetime	> 2 ms	> 2 ms	> 2 ms	> 2 ms

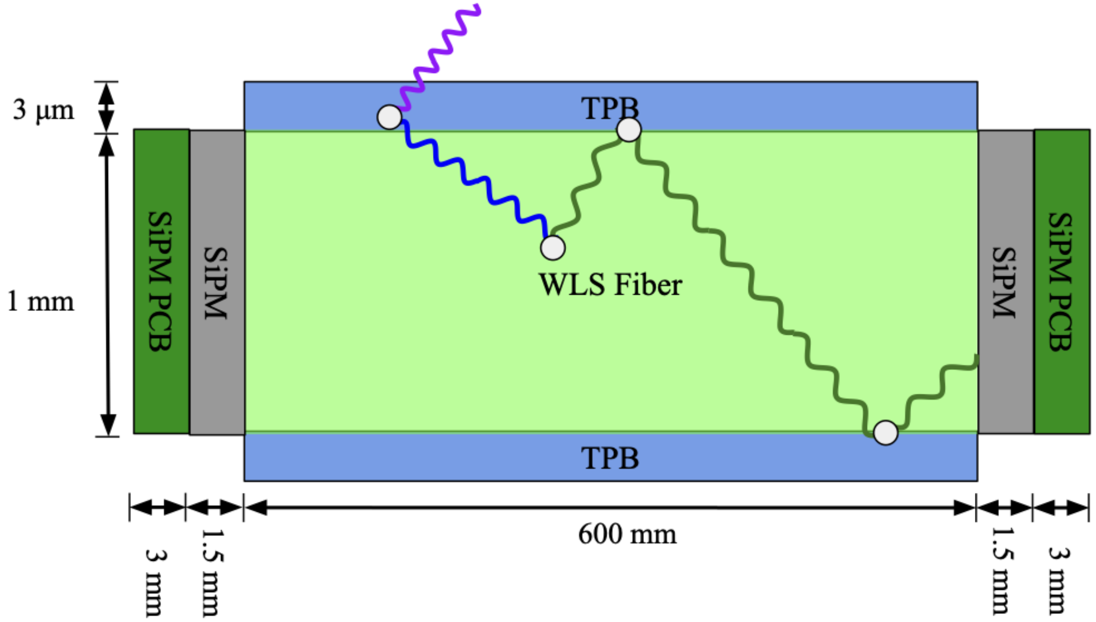
Light Collection Principle

ArCLight



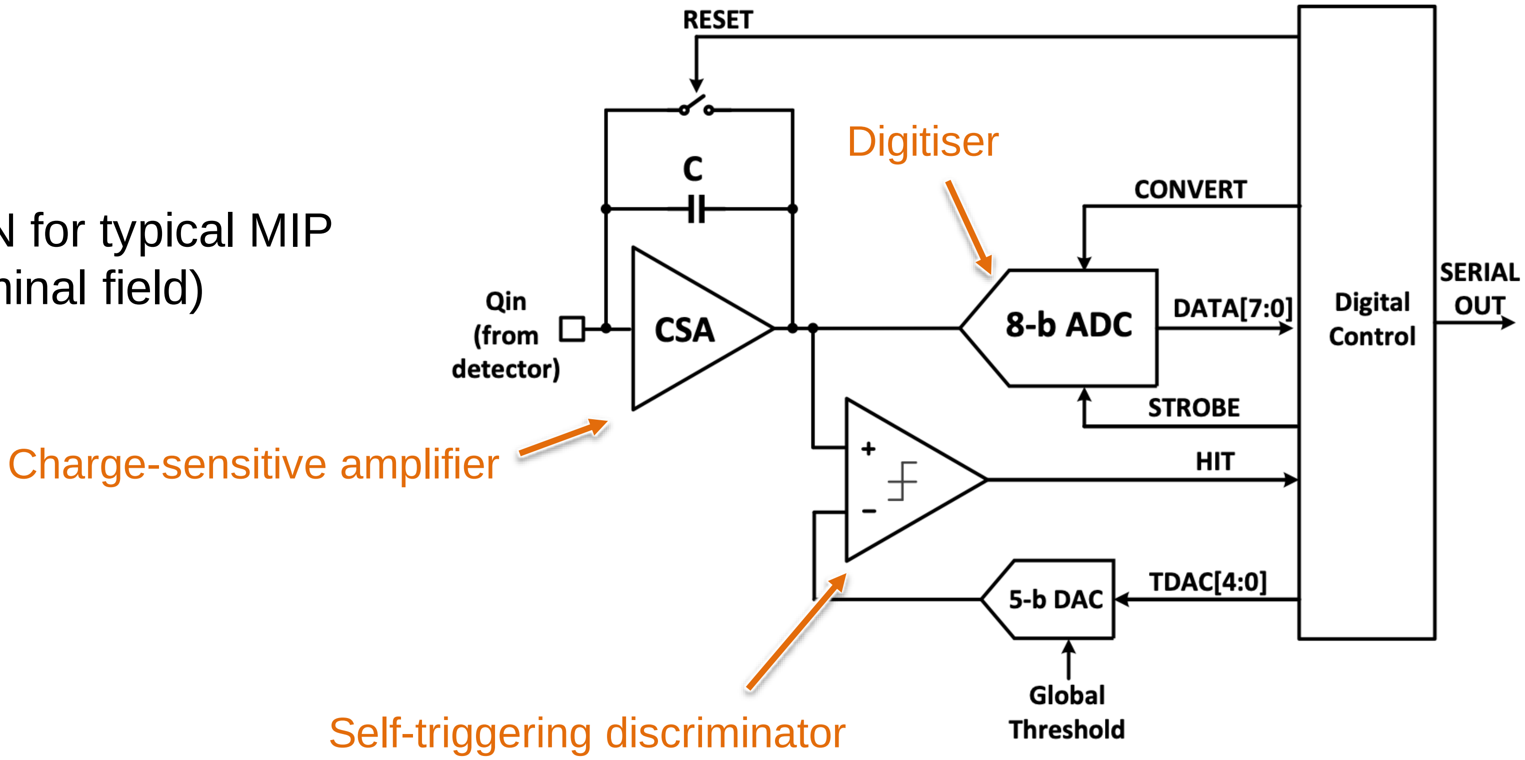


LCM



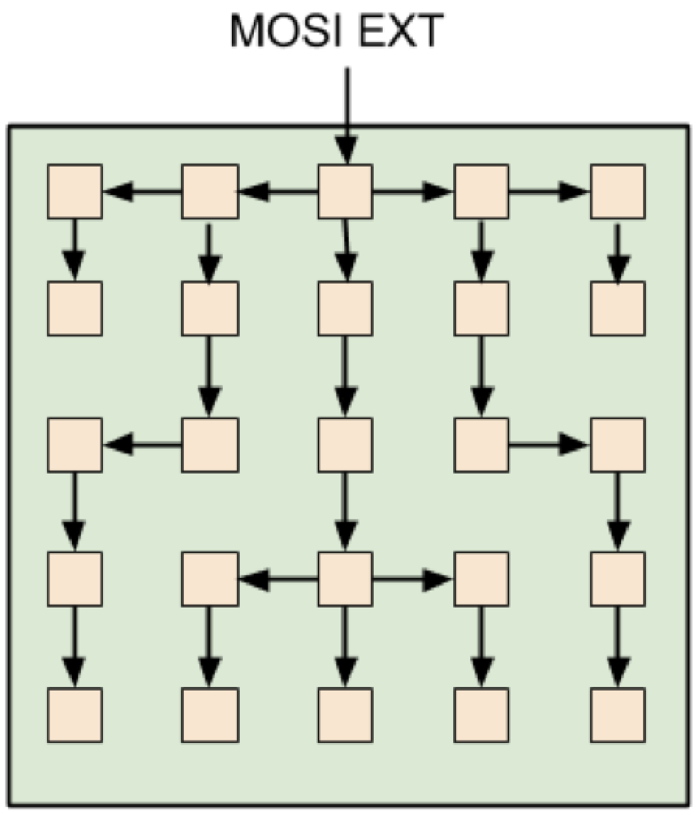
LArPix Performance

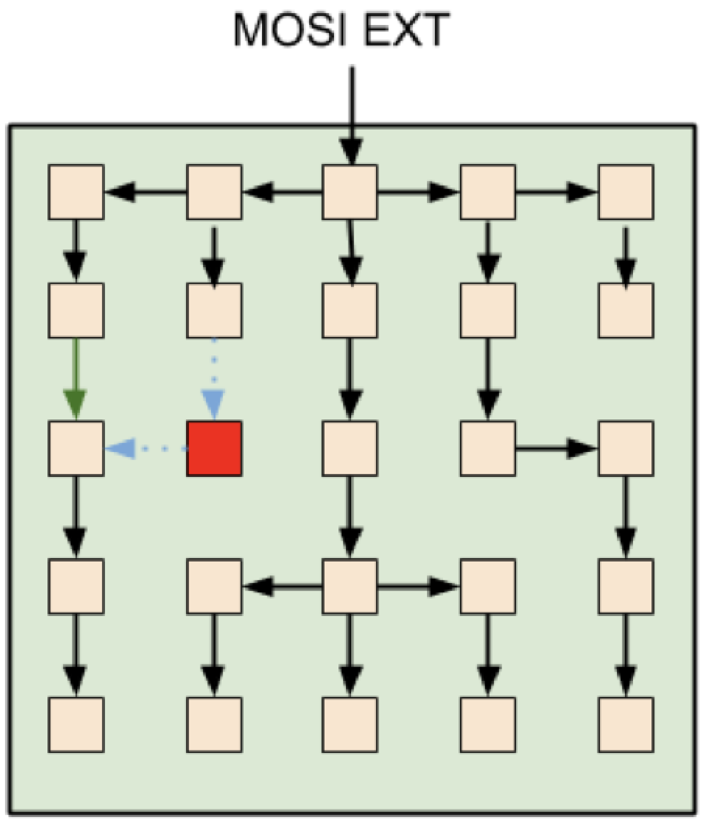
- Target design:
  - $< 100 \mu W / channel$
  - $< 500\ e^{-}\ ENC$ for 30:1 S:N for typical MIP (~5K electrons/mm at nominal field)
- Achieved:
  - $< 62 \mu W / channel$
  - $< 375\ e^{-}\ ENC$ (55:1 S:N)



[LArPix: arXiv:1808.02969](https://arxiv.org/abs/1808.02969)

Dynamic HYDRA Network Configuration

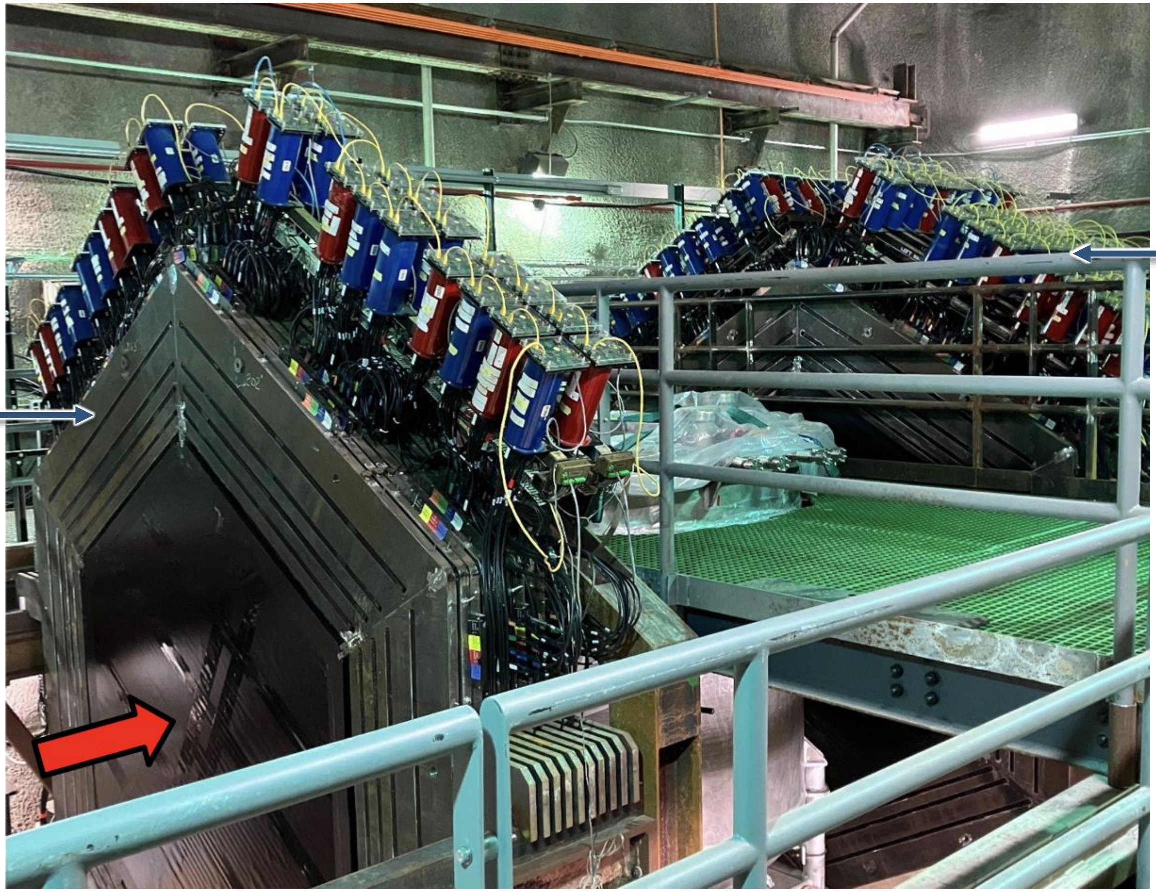




MINERvA Installation

Scintillator Planes

(rock muon tagging)

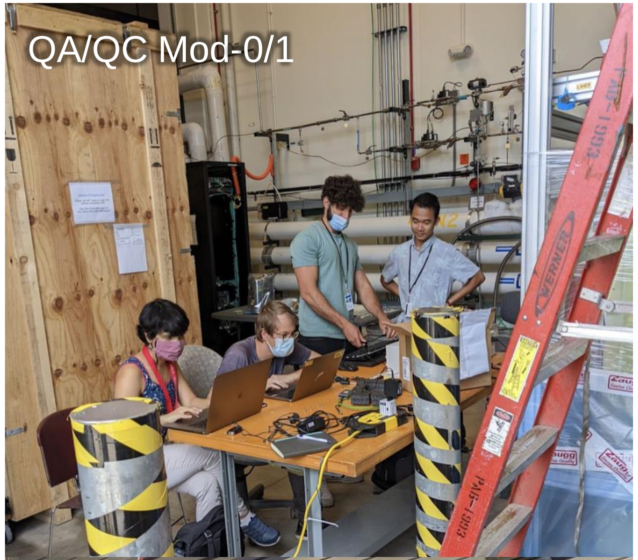


Scintillator Planes

+ ECAL + HCAL

(muon identification and reconstruction)

The 2x2 @Fermilab


QA/QC Mod-0/1

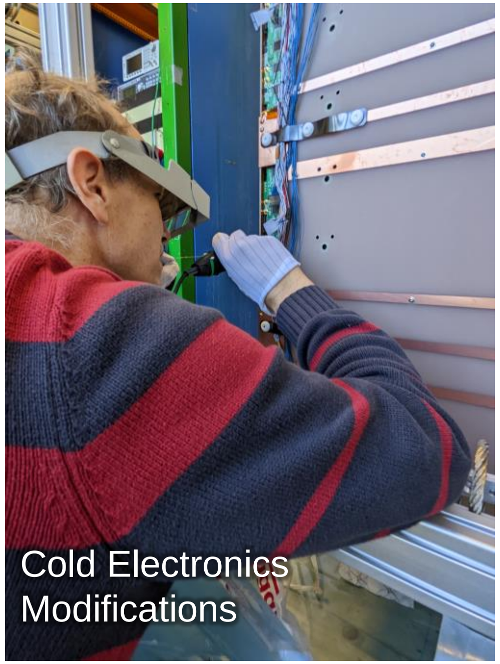

Read-out Electronics Installation

Single module testing @Fermilab

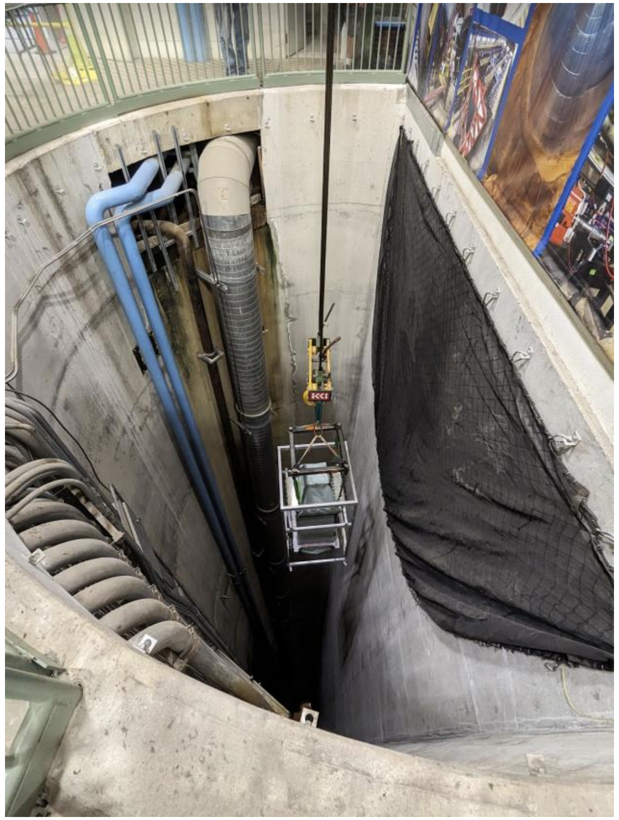
Summer 2022 (Mod-0/1) → Winter 2022/23 (Mod-2) → Spring 2023 (Mod-3)

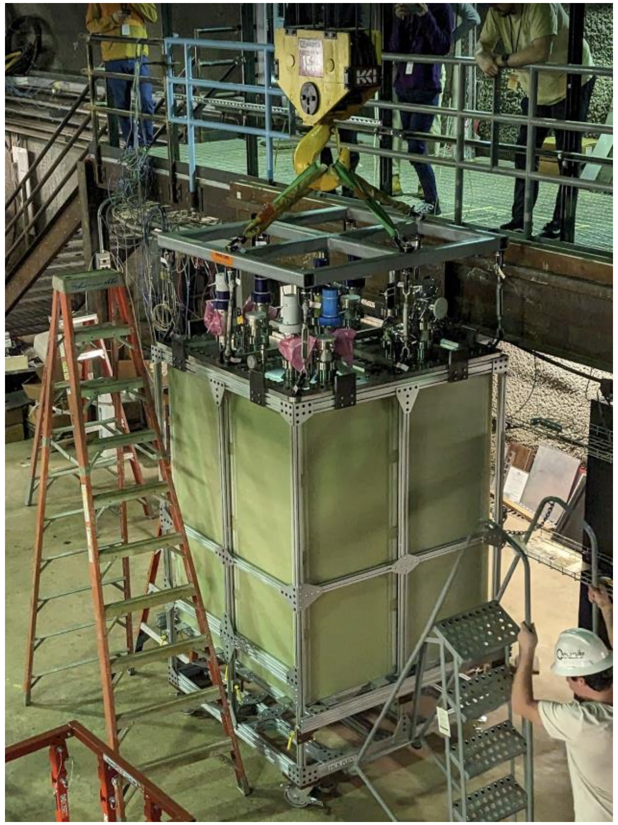

Warm Electronics Assembly


Top Flange Modifications


Cold Electronics Modifications

The 2x2 @Fermilab





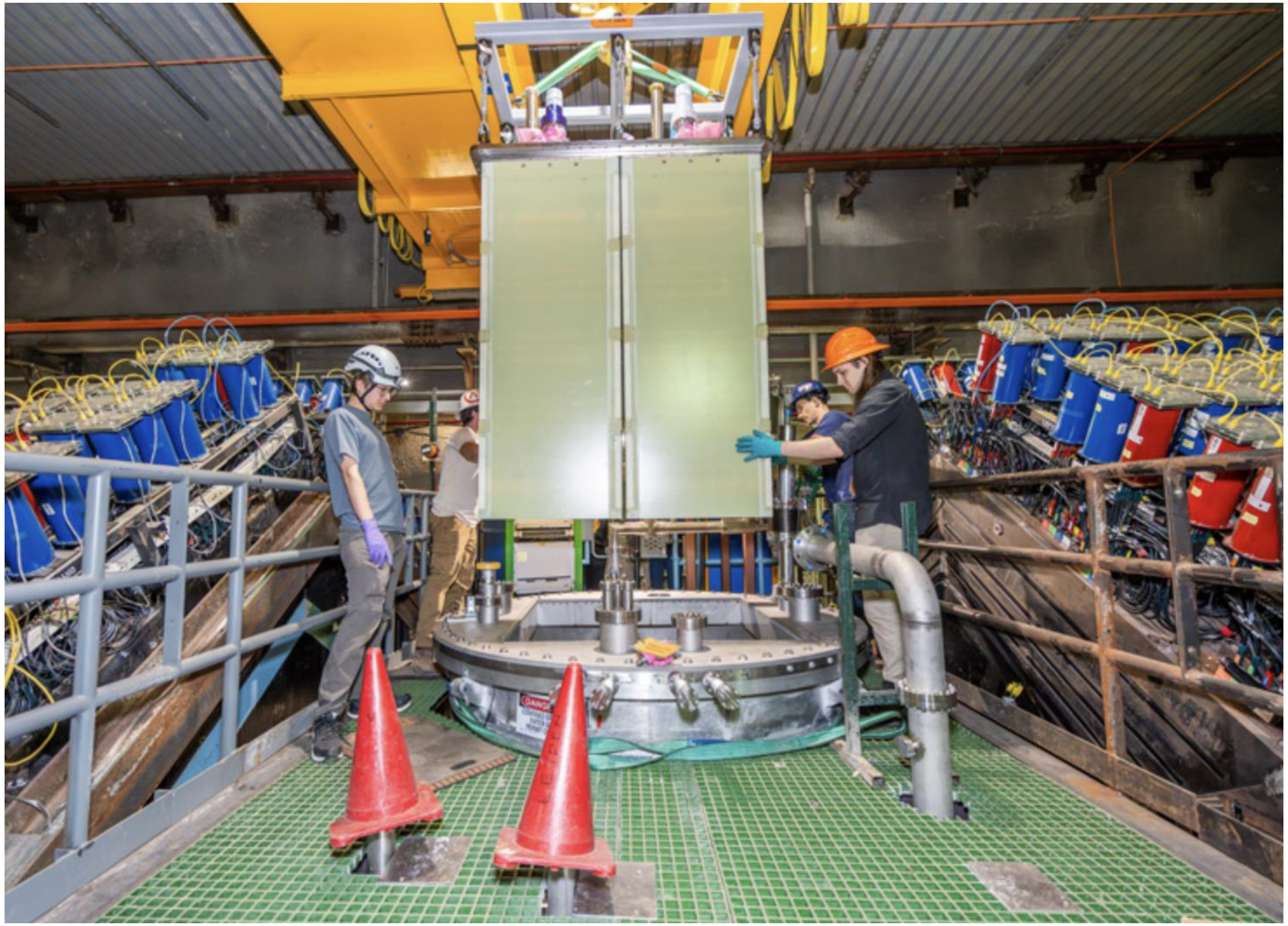
2x2 Commissioning

Charge read-out:
- 330,000 pixels
- ~200 keV pixel energy thresholds
- 97% active pixels

Light read-out:
- 383 SiPMs
- All active

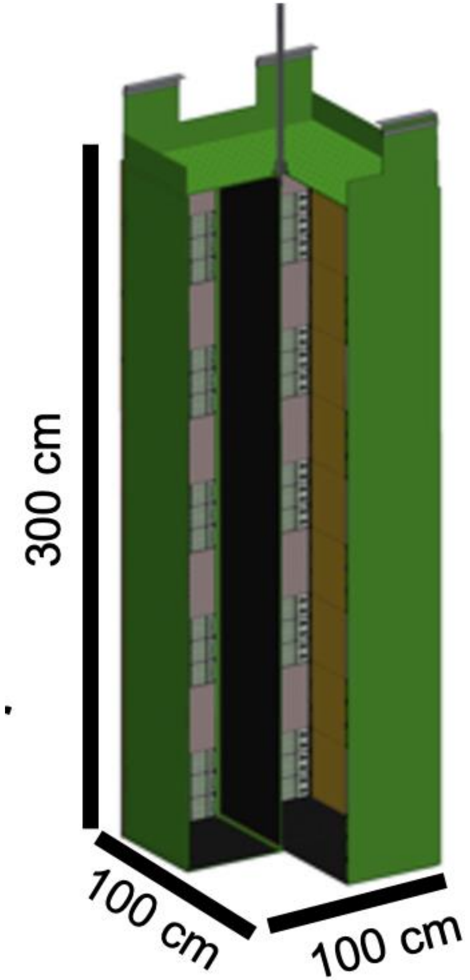
- Nominal voltage of 500 V/cm

- 30 days of data = 1.5e20 POT = 10k events

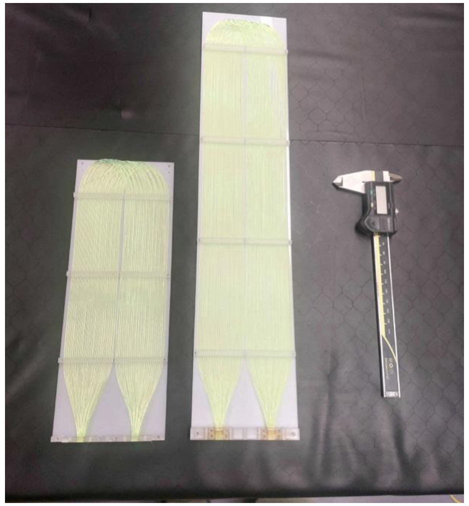


Full-Scale Demonstrator (FSD)

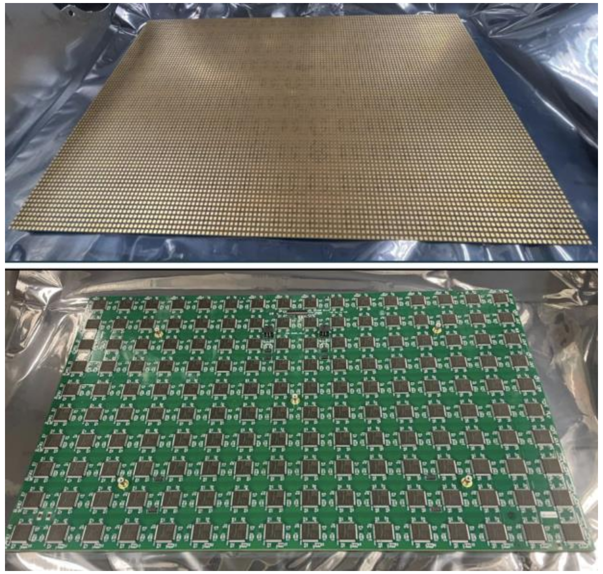
- Assembly and commissioning later this year
- Goals:
  - Exercise component and full-scale module production
  - Establish testing program
  - Confirm technical goals achieved with mod0-3 continue to be met



LCM size comparison (2x2 vs NDLAr)

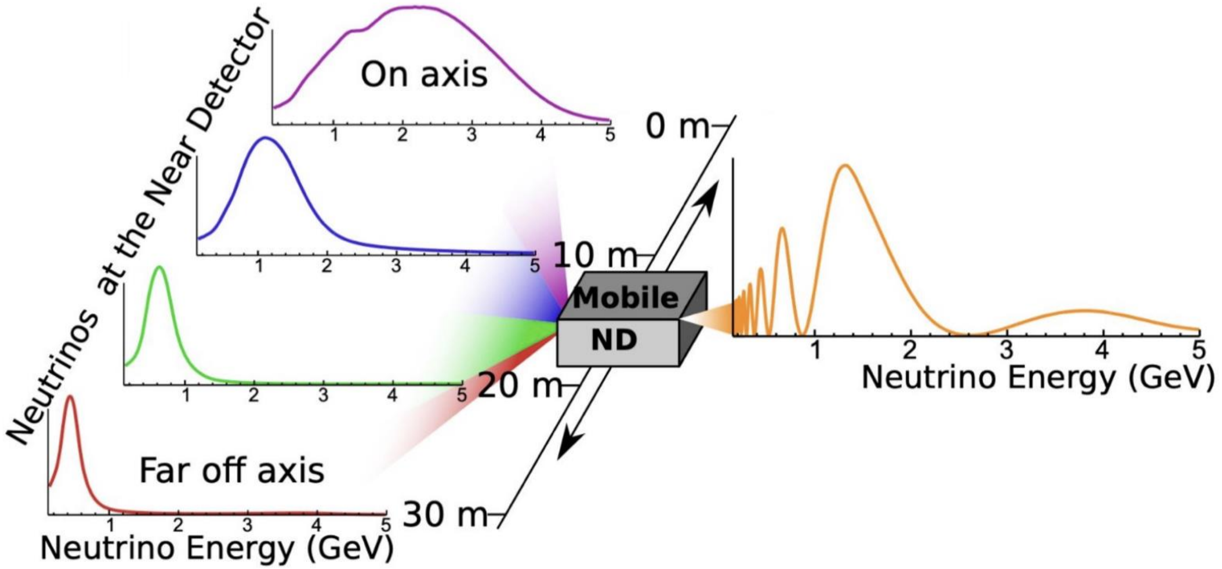


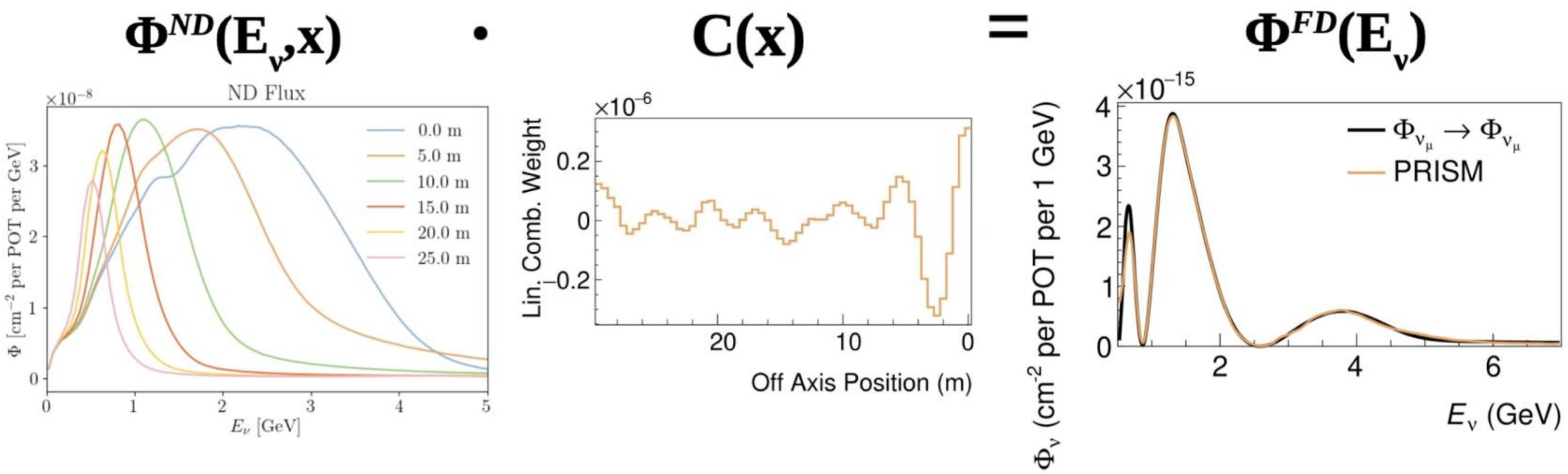
NDLAr LArPiX anode tile



DUNE PRISM

- Oscillated FD flux through a linear combination of ND flux at various off-axis positions
- Cross-section and flux modelling becomes largely decoupled

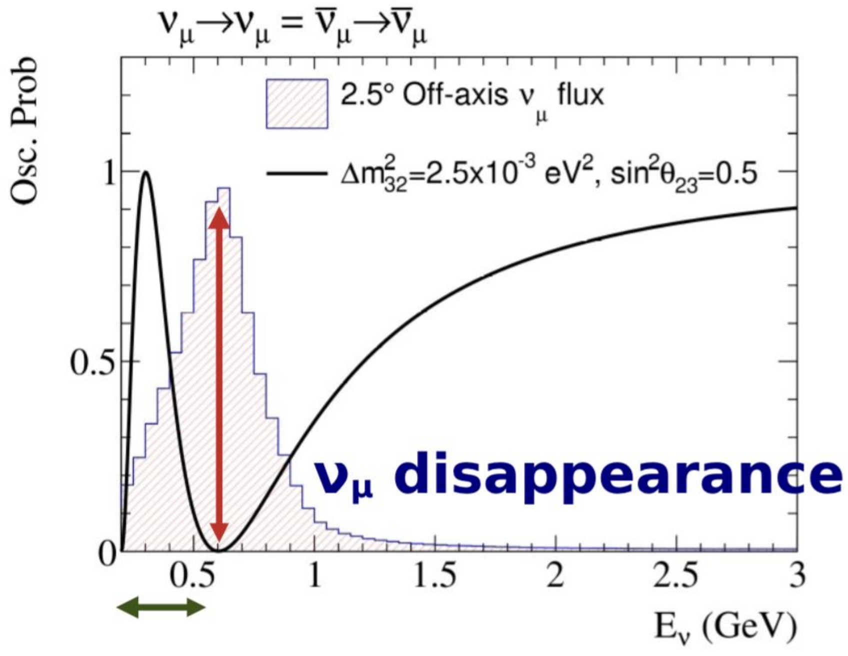




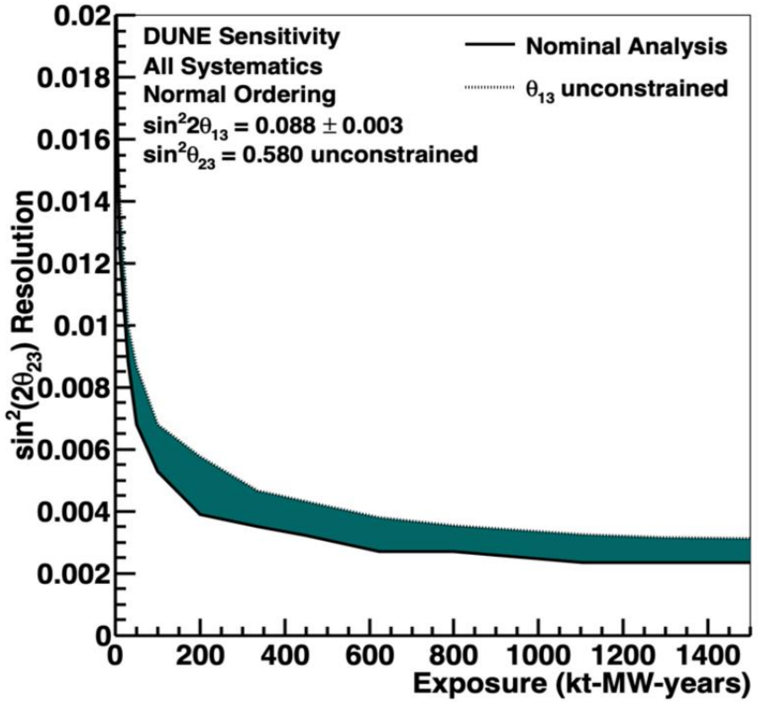
Probing θ_{23} Octant

Neutrino disappearance measurement:

$$P\left(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu\right) \approx 1 - \sin^2 2\theta_{23} \sin^2\left(\Delta m^2_{32}\frac{L}{4E}\right)$$



T2K FD Reconstructed energy spectra

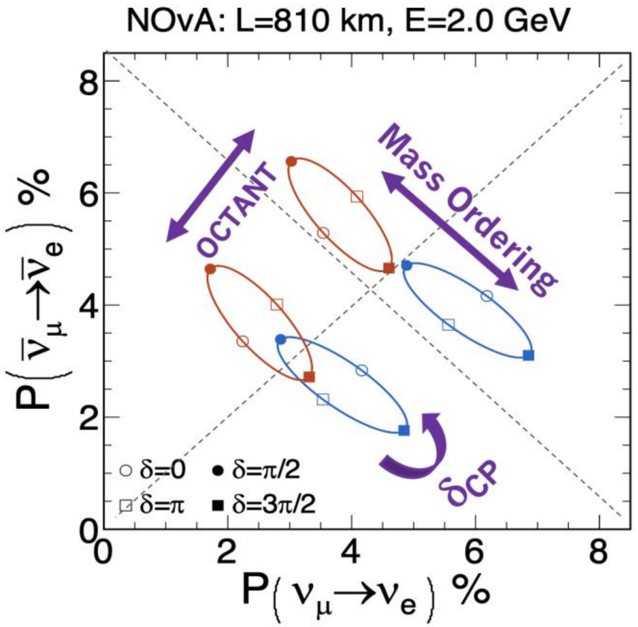


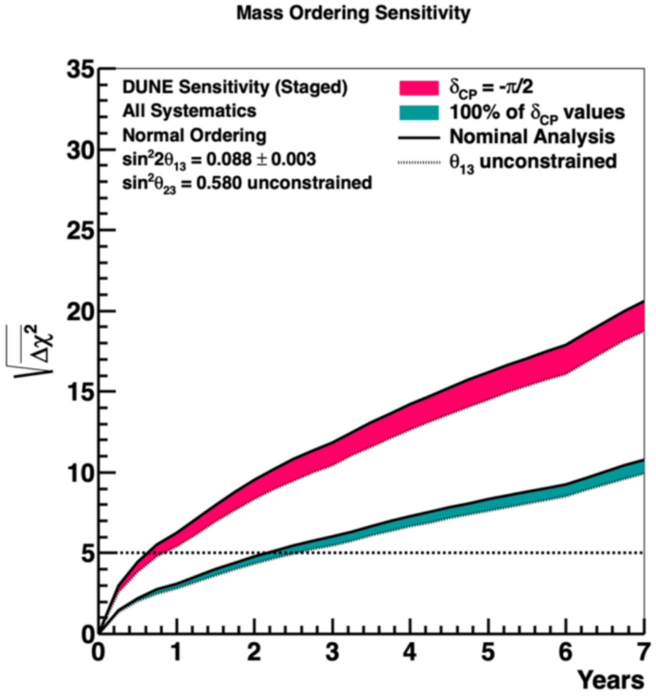
arXiv:2006.16043

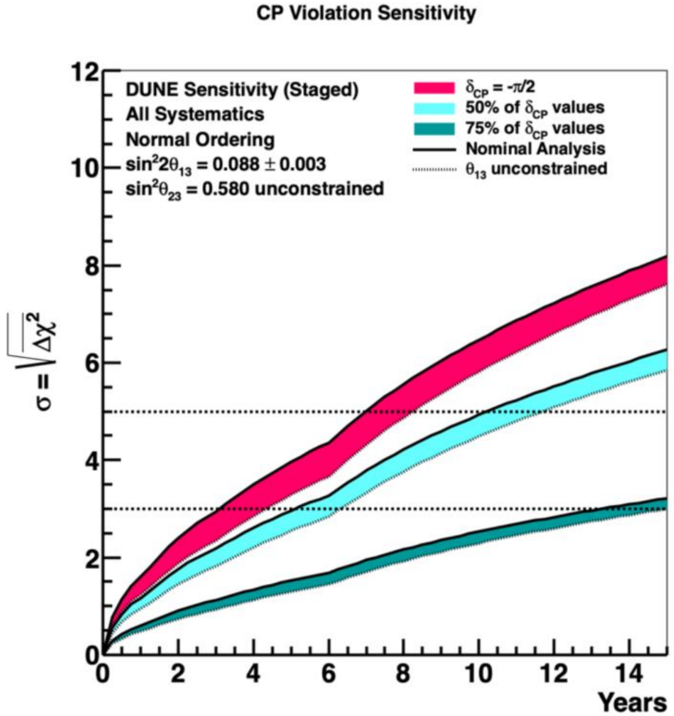
Probing δ_{CP} and Mass Hierarchy

Neutrino appearance measurement

- Interplay of θ_{13}, θ_{23}, δ_{CP} and MH through matter effect on $P(\nu_\mu \to \nu_e)$







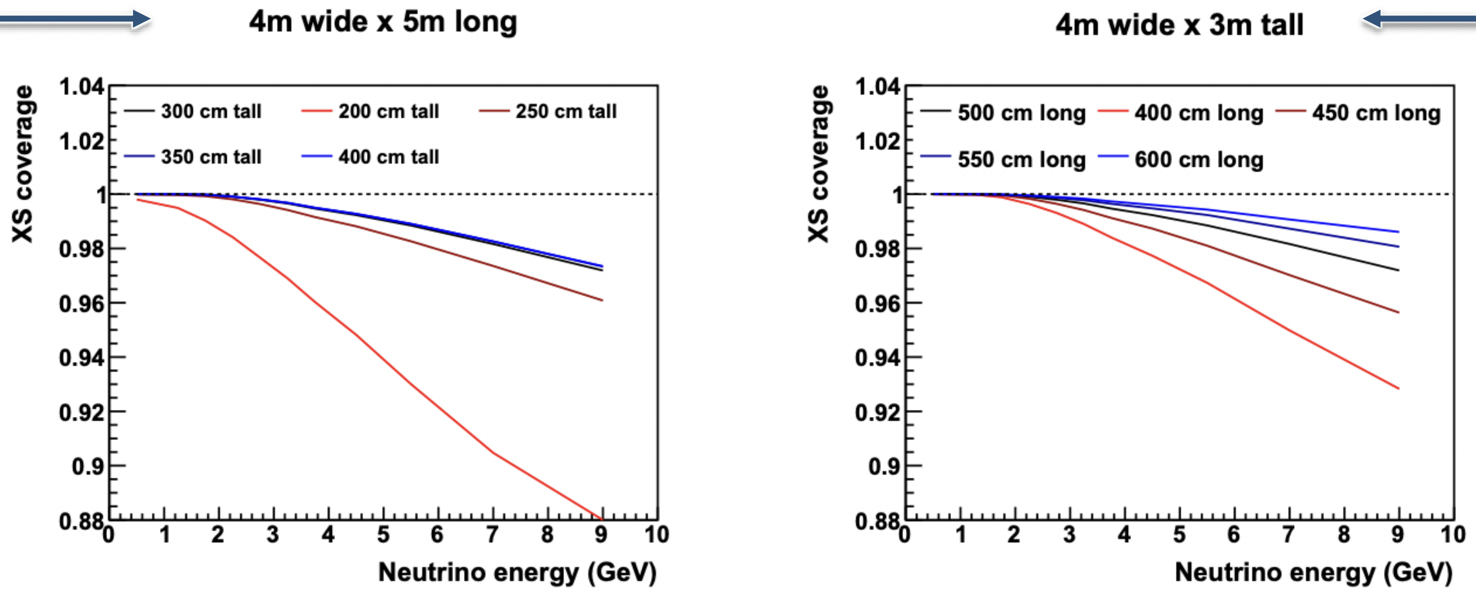
arXiv:2006.16043

NDLAr Dimensions

- High event-rate: detector size driven by energy resolution and coverage requirements

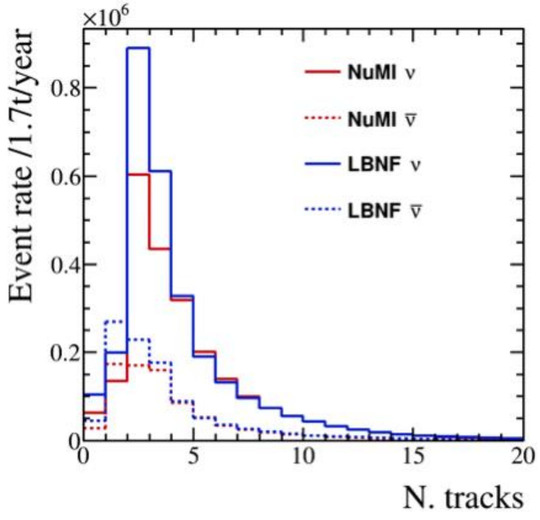
Hadronic shower containment

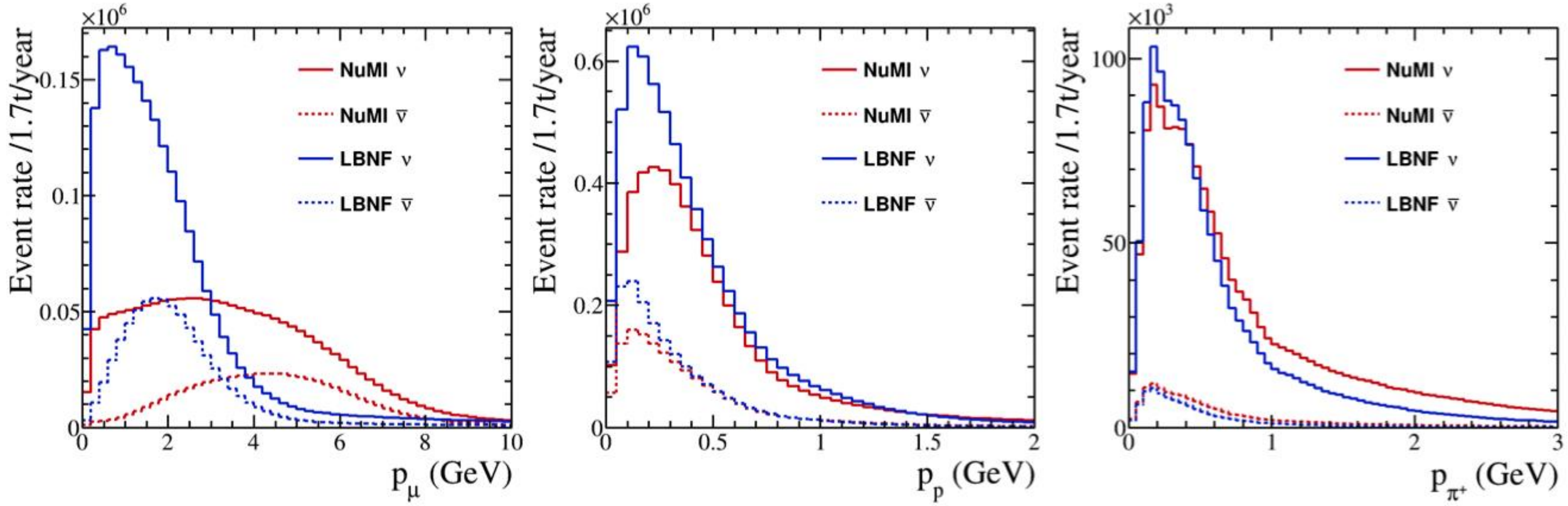
Containment of low E, high angle muons



DUNE ND CDR: arXiv:2103.13910

NuMI vs DUNE Beam





(a) $\mu^\pm$ (b) Protons (c) π^+

DUNE ND CDR: arXiv:2103.13910

NuMI vs DUNE Beam