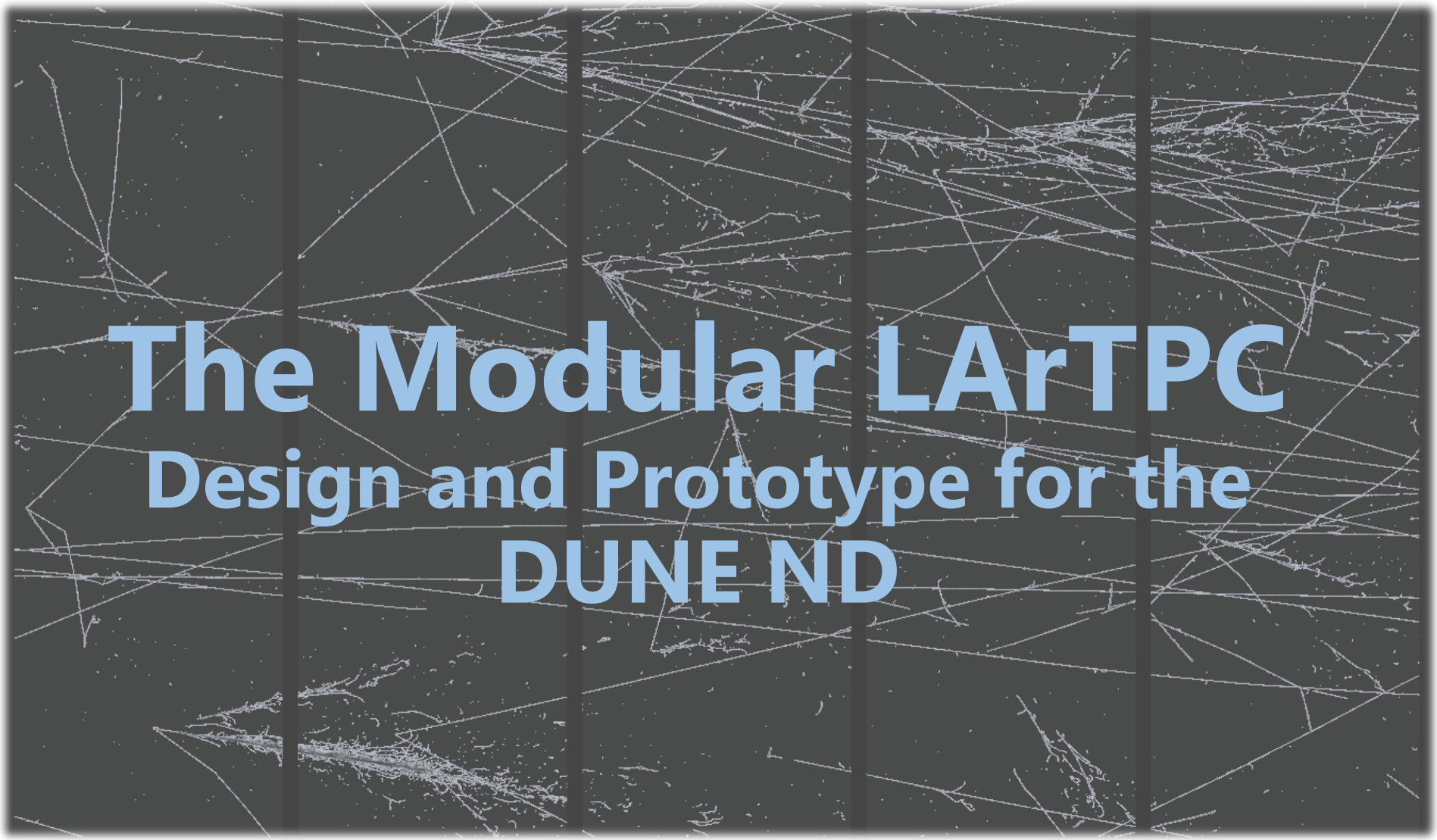


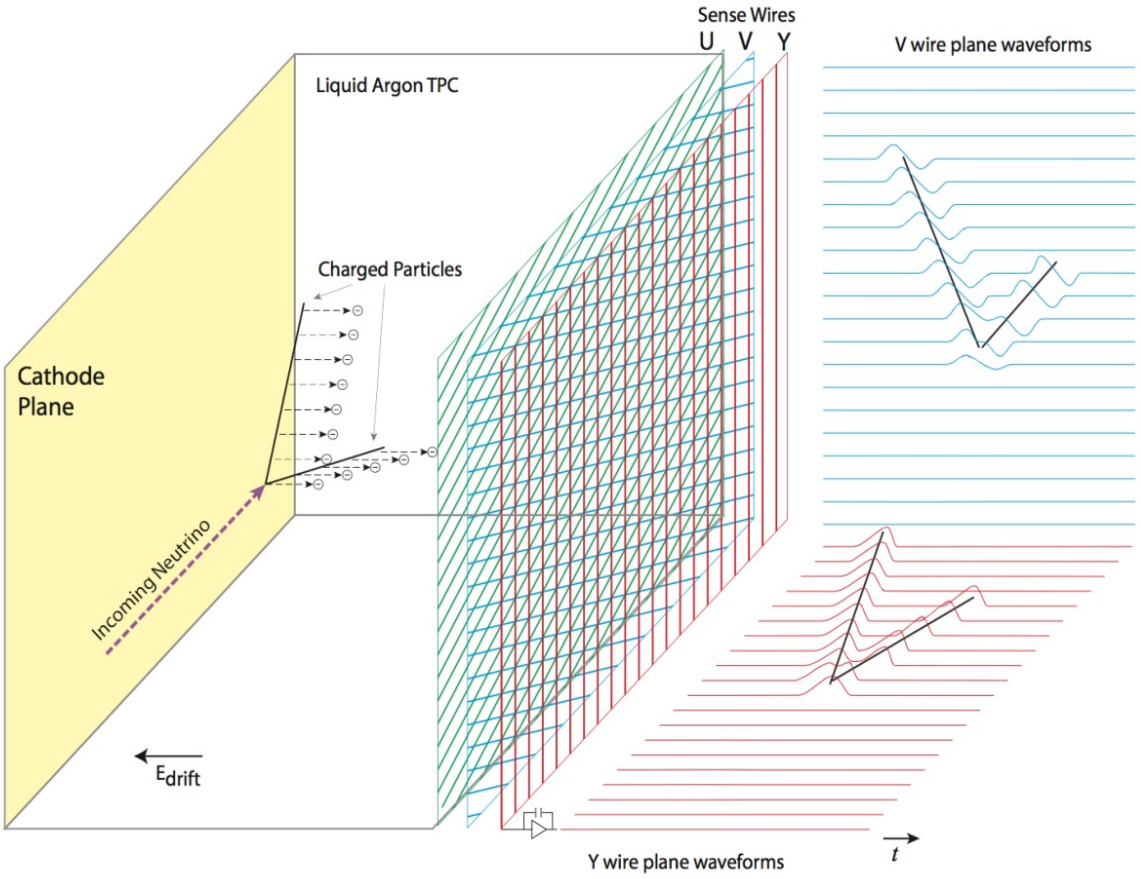
The Modular LArTPC
Design and Prototype for the DUNE ND

Zoya Vallari

On behalf of the DUNE Collaboration

Caltech

The classical LArTPC

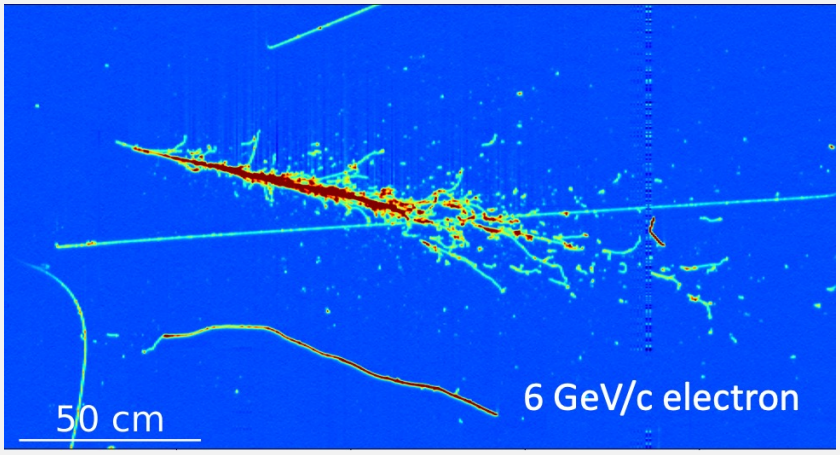


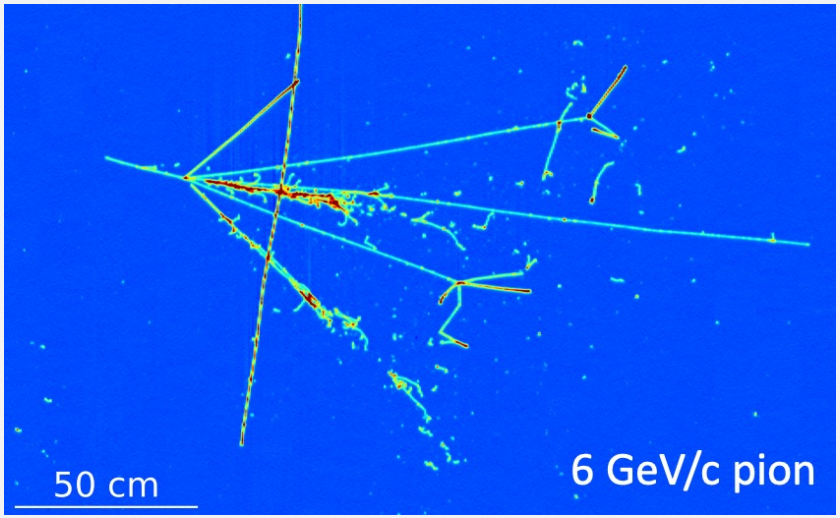
- The Liquid Argon TPCs are fully-active tracking calorimeters.
- Neutrino interaction in LAr produces ionization and scintillation light
- The ionization charge drifts in a uniform electric field to finely segmented wire planes.
- The scintillation light is collected using PMTs.

Why LArTPC ?

- Excellent spatial and calorimetric resolution provides exceptional capabilities for precision study of neutrinos.
- Multiple wire orientations give independent views of the same event.
- Scintillation light provides valuable timing information.

⟹ LArTPCs provide 3D reconstruction!

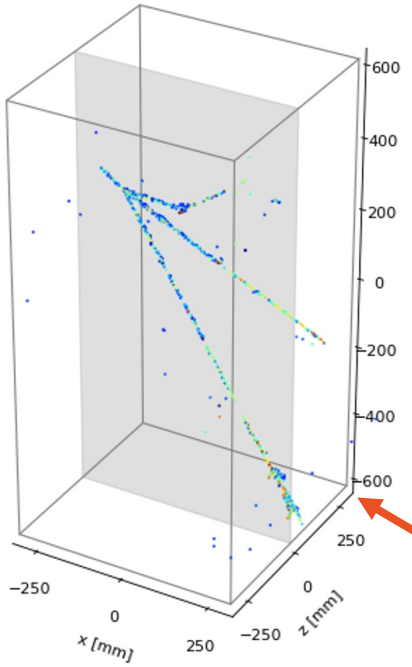




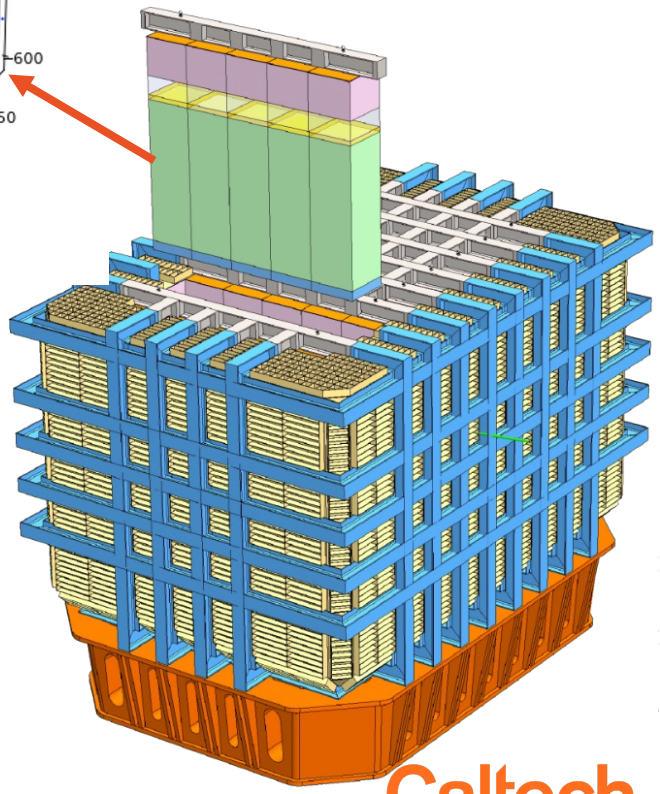
ProtoDUNE SP LArTPC Events

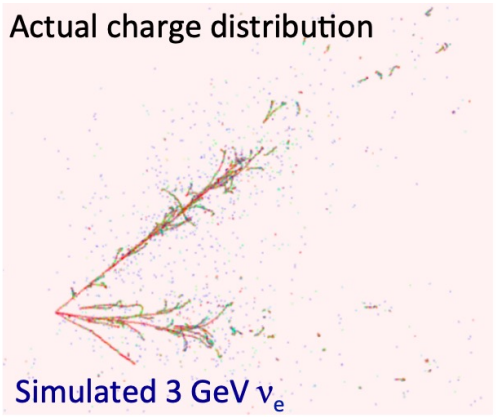
Modular Pixelated LArTPC

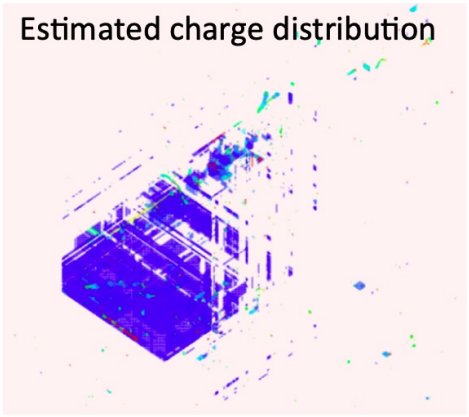
- However, classical TPCs infer 3D reconstruction by combining 2D views.
- Ambiguities in projective wire readout aggravate in high multiplicity environment.



Modular Pixelated LArTPC provides *True 3D imaging*







Caltech

Why Modular LArTPC for DUNE?

Simulation of 1.2 MW LBNF beam spill at DUNE ND

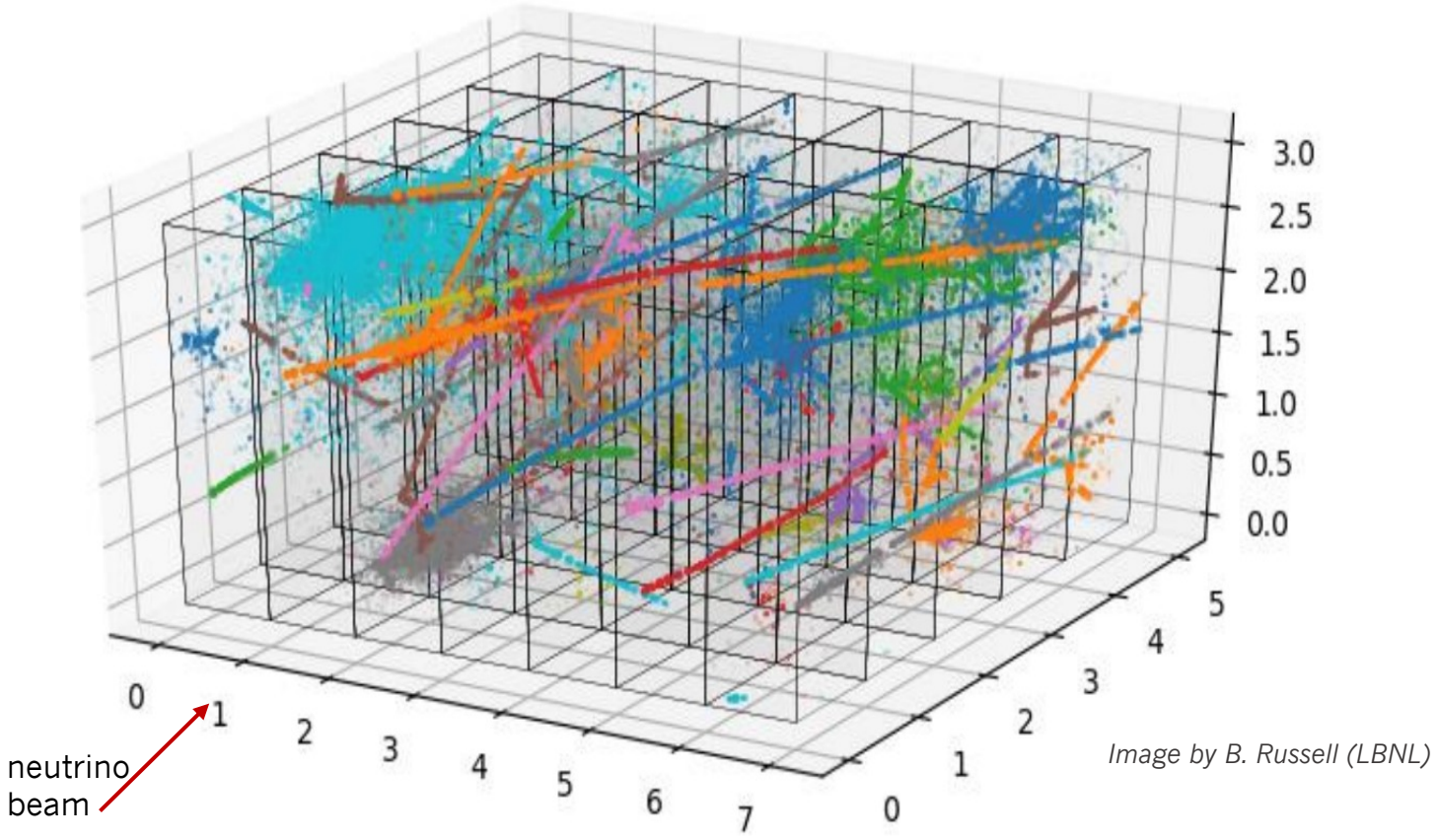


Image by B. Russell (LBNL)

Geant4 visible energy deposits - color indicates independent visible interactions.

The DUNE Experiment

DUNE Overview @ Snowmass: C. Marshall July18th

- DUNE will use the most intense accelerator neutrinos from the LBNF beam and detect them at SURF 1300 kms away. Near Detector (ND) at Fermilab will provide crucial in-situ constraints for measurements at the FD.

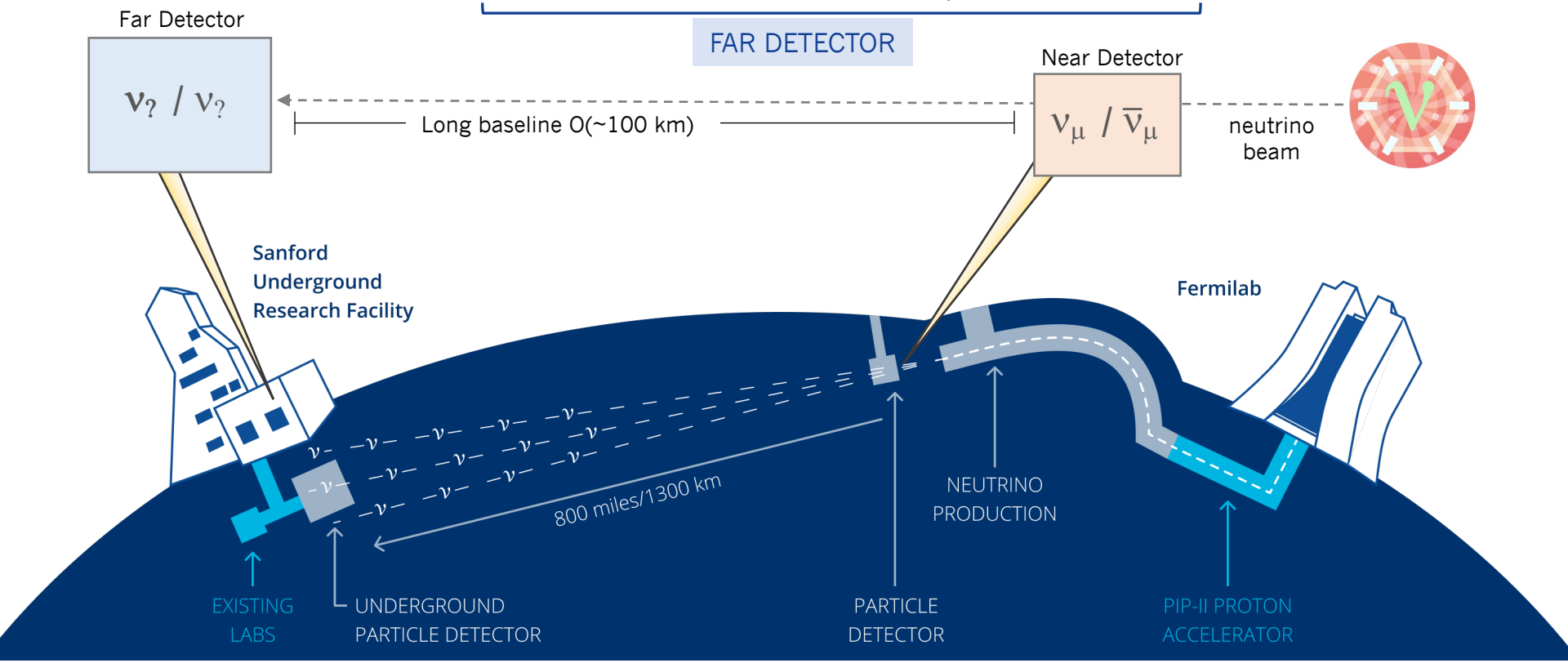
NEAR DETECTOR

Event rate — cross-section — oscillation probability

$$R(\vec{x}) = \phi(E_\nu) \times \sigma(E_\nu, \vec{x}) \times \epsilon(\vec{x}) \times P(\nu_A \to \nu_B)$$

neutrino flux — detector response

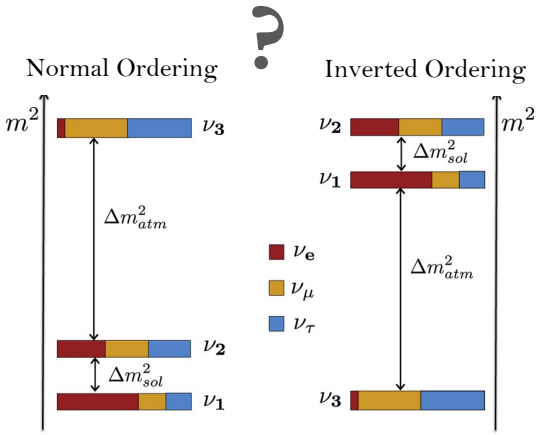
FAR DETECTOR



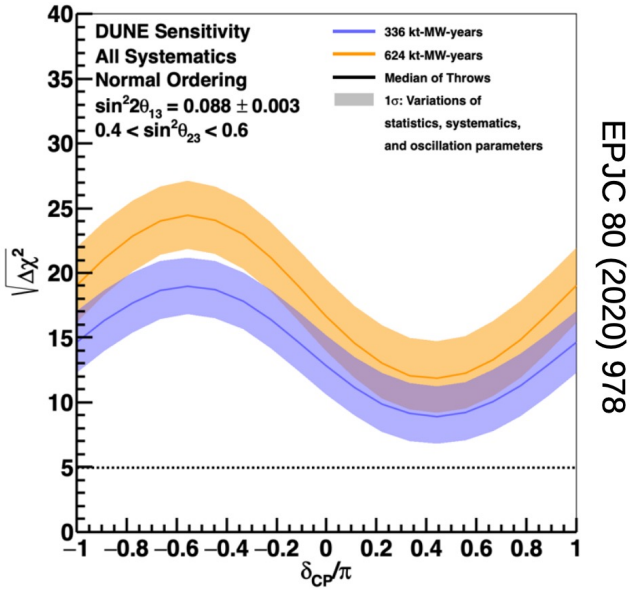
DUNE Physics goals* : Discovery

oscillation

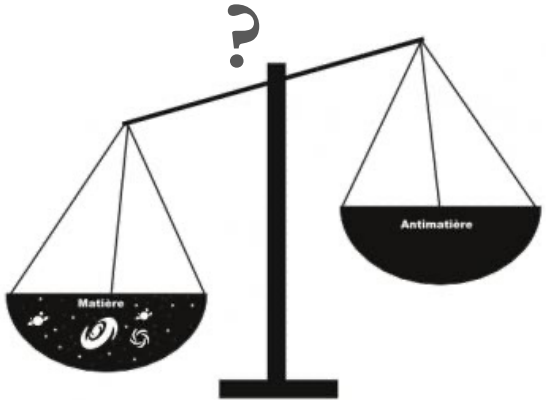
DUNE Oscillation Overview @ Snowmass: C. Wilkinson July19th



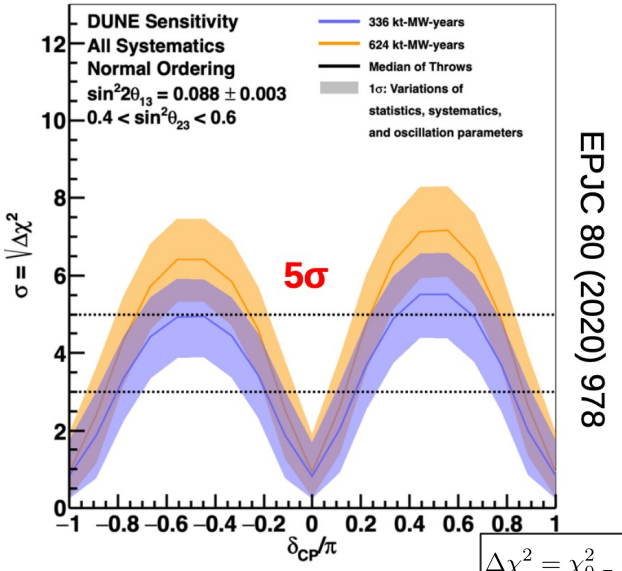
Mass Ordering: Normal or Inverted?



EPJC 80 (2020) 978



δ_{CP}: Do neutrinos violate CP?



EPJC 80 (2020) 978

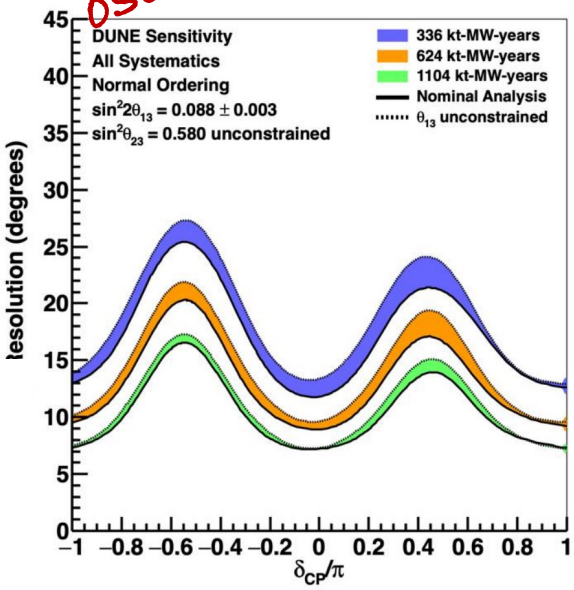
*other cool searches for supernova, DSNB, BSM physics and sterile searches not included here!

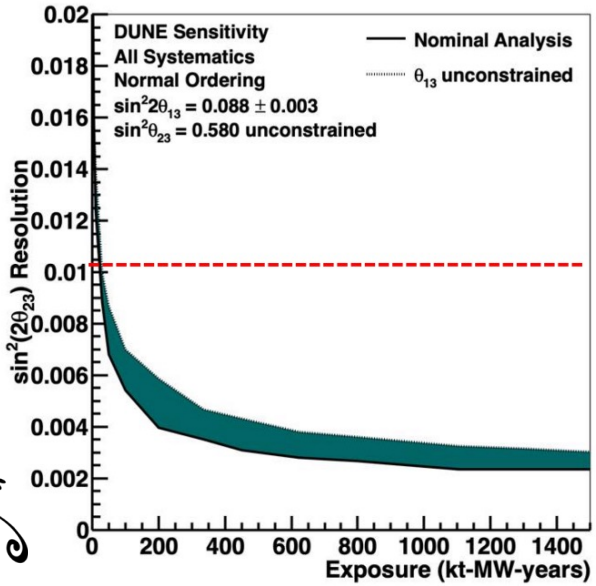
$\Delta\chi^2 = \chi^2_{0,\pi} - \chi^2_{\mathrm{CPV}}$

Caltech

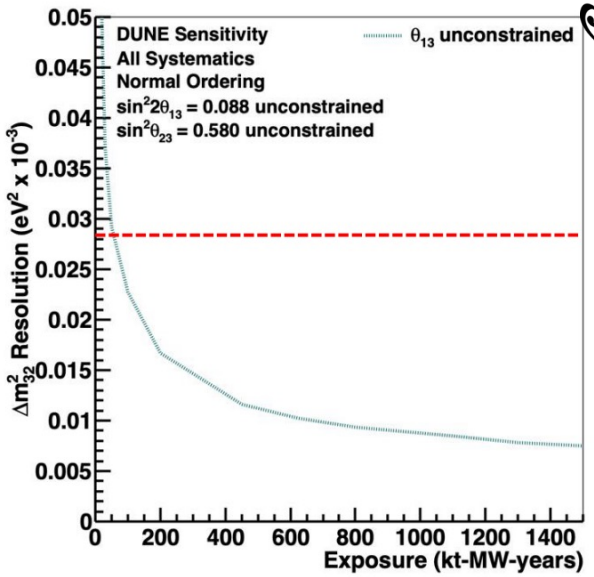
DUNE oscillation Physics goals* : Precision

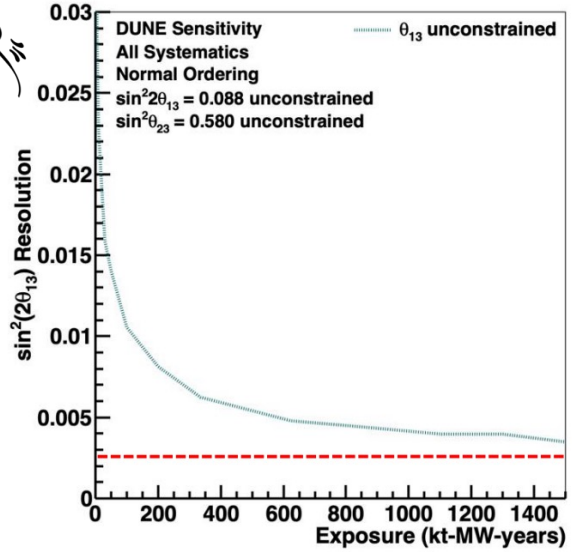
DUNE Oscillation Overview @ Snowmass: C. Wilkinson July19th





Unambiguous high precision measurements of Δm^2_{32}, δ_{CP}, θ_{23} and θ_{13} with a single experiment.





EPJC 80 (2020) 978

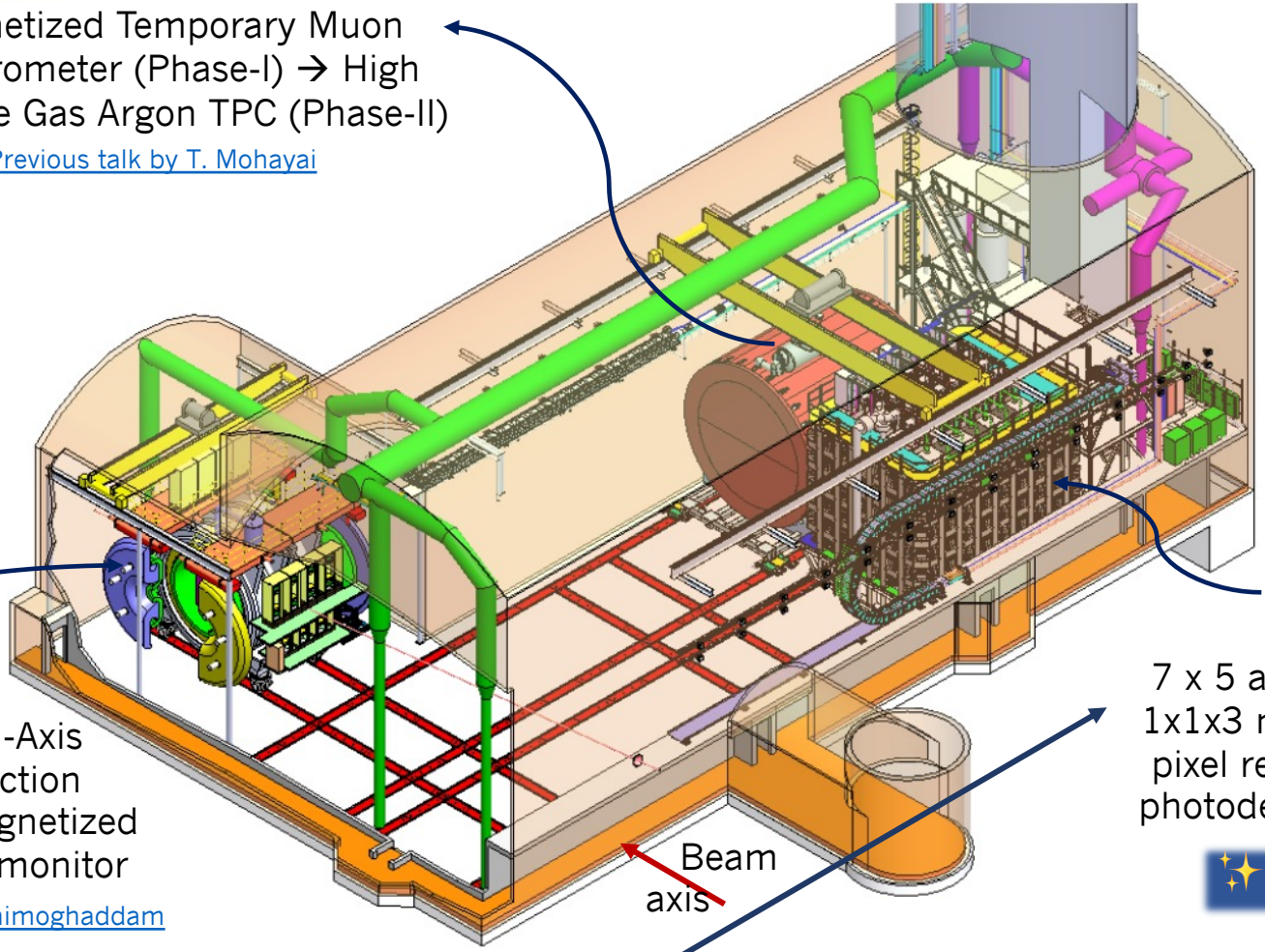
*other cool searches for supernova, DSNB, BSM physics and sterile searches not included here!

The DUNE ND Overview

DUNE Oscillation Overview @ Snowmass: D. Cherdack July19th

Magnetized Temporary Muon Spectrometer (Phase-I) → High Pressure Gas Argon TPC (Phase-II)

Previous talk by T. Mohayai



SAND

System for On-Axis Neutrino Detection
Fixed On-axis magnetized beam spectrum monitor

Next talk by Z. Ghorbanimoghaddam

ND-LAr

7 x 5 array of modular 1x1x3 m^3 LArTPCs with pixel readout and high photodetector coverage.

✨ This talk ✨

Beam axis

PRISM

System for moving the LArTPC + muon tracker up to 30m transverse to the beam direction to enable scans of beam at multiple off-axis positions

The Near Detector

Objective: Predict the observed neutrino spectrum at the FD

Requirements

- Measurements transferable to the FD
- Constrain the cross-section model
- Measure the neutrino flux
- Obtain measurement with different fluxes
- Monitor time variations of the neutrino beam
- Operate in high-rate environment

Never go on a long baseline adventure without a near detector – Anonymous.

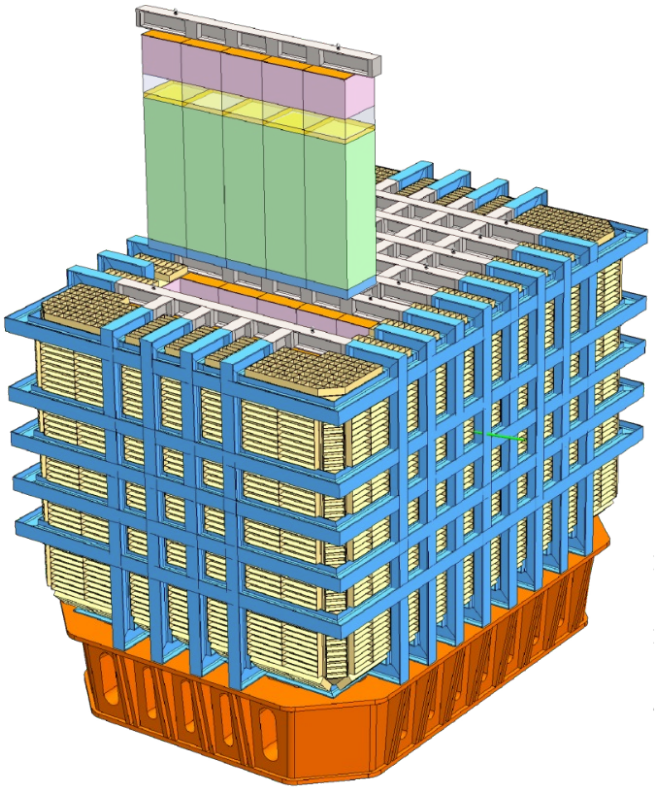
arXiv 2103:13910 DUNE ND CDR

ND-LAr Report Card

Objective: Predict the observed neutrino spectrum at the FD

Requirements

- ✓ Measurements transferable to the FD
- ND-GAr ✓ Constrain the cross-section model
- ✓ Measure the neutrino flux
- PRISM ✓ Obtain measurement with different fluxes
- SAND ! Monitor time variations of the neutrino beam
- ✓ Operate in high-rate environment

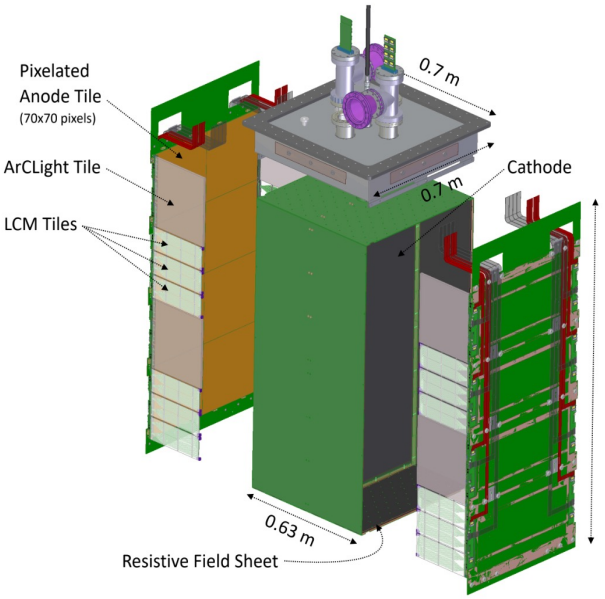


arXiv 2103:13910 DUNE ND CDR

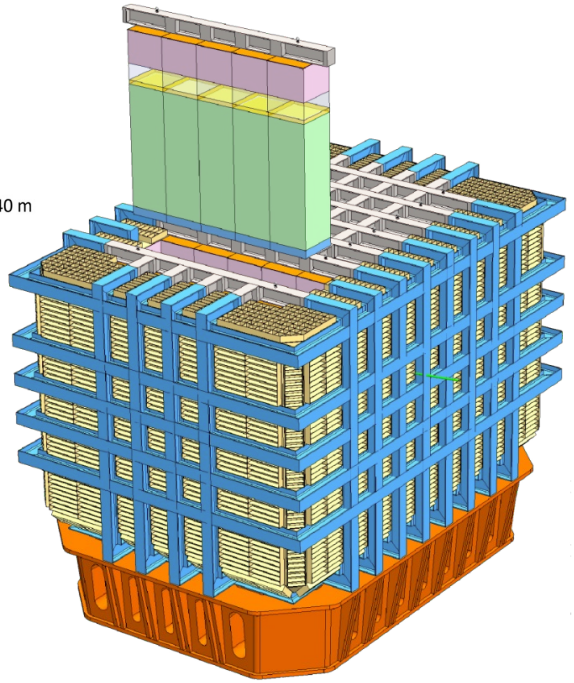
ND-LAr Design

Key Features:

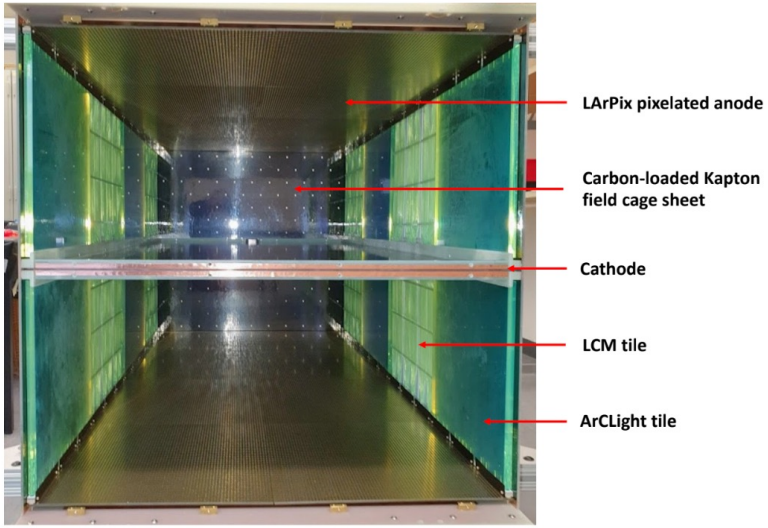
- Pixelated charge readout
- High photodetector coverage with a large are dielectric photon detection system
- Highly resistive foil for electric field shaping
- Modular design provides optical segmentation



60%-scale module prototype



Top-down view of the module prototype

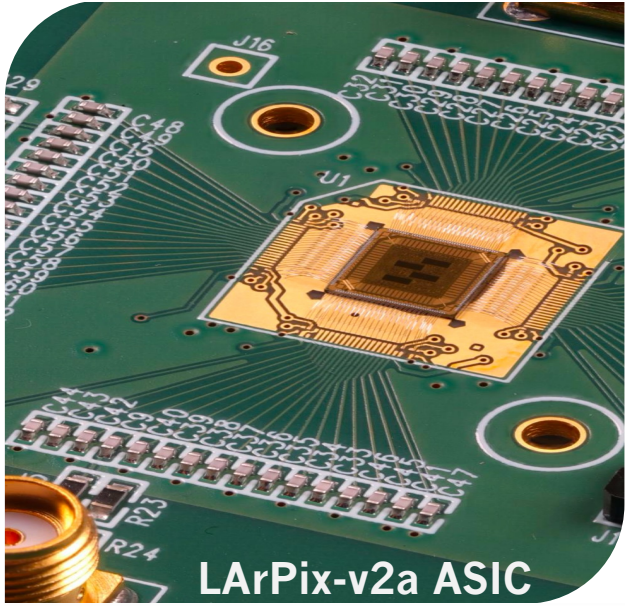


ND-LAr Design :

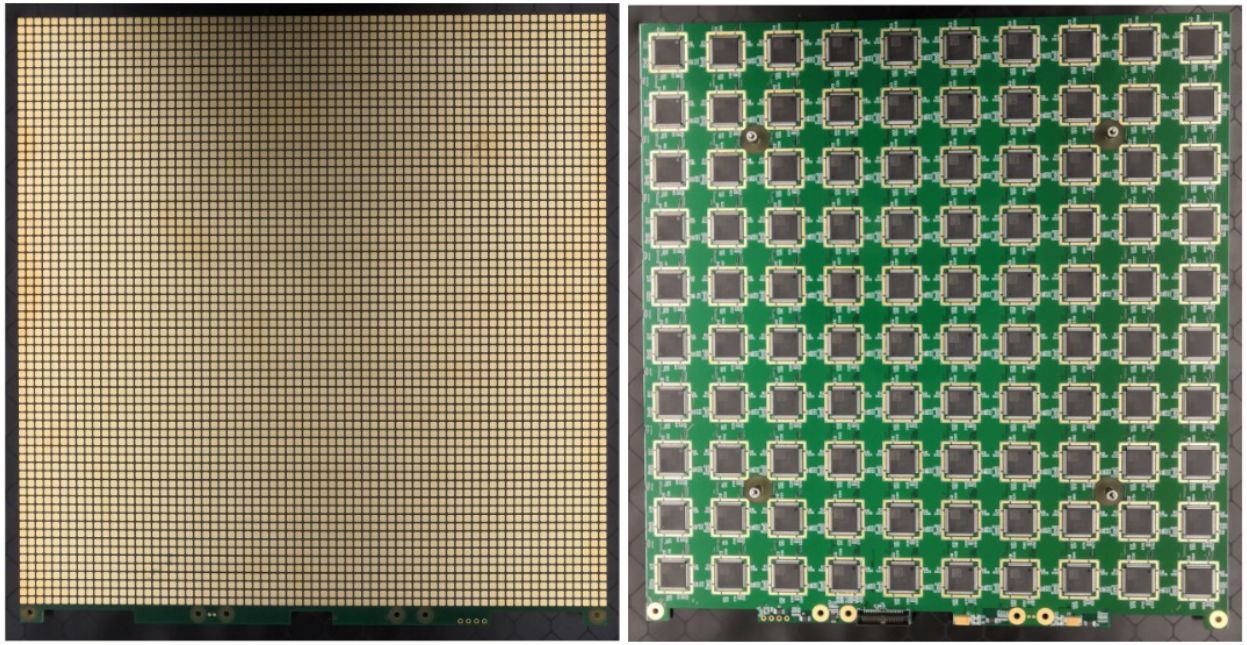
- Active size: 5m deep, 7m wide and 3m tall
- 5 x 7 hermetic TPC modules – 1m x 1m x 3m
- Short drift (50 cm)
- Minimal inactive material with density similar to LAr

Pixelated Charge Readout

- Provides unambiguous 3D tracking of charged particles crossing a LArTPC.
- Low-power, low-noise integrating amplifier with self-triggered digitization and readout
- Charge stays on pixel until digitization and/or reset
- Always active – continuous self-triggering



LArTPC Pixelated Readout @ Snowmass: B. Russell July 20th



LArPix Pixel tile with pixel pads(front) and ASICS(back)

LArPix

Dan Dwyer *et al. JINST 13 (2018) P10007*

BERKELEY LAB

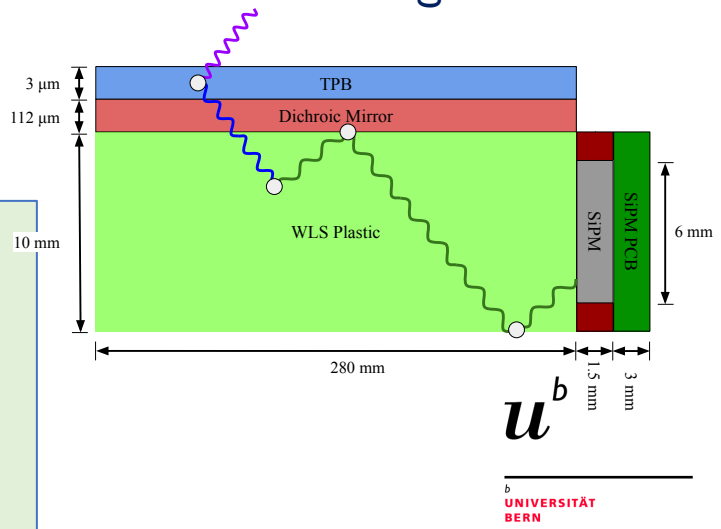
LArPix Pixel tile

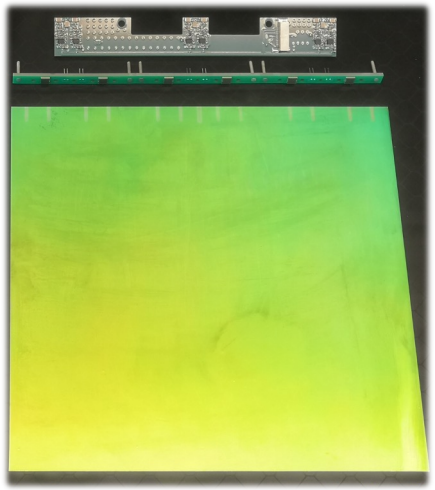
- 32 cm x 32 cm large-format mixed signal PCB
- 100 LArPix-v2a ASICs/tile
- 4900 pixel pads with 4.4 mm pixel pitch

Light Readout System

- LAr produces scintillation light of wavelength ~128 nm.
- The TPC needs a high-performance light detection system with:
  - High coverage with a dynamic range
  - Fast readout to provide precise spatial resolution
  - Capability to operate in high-rate environment

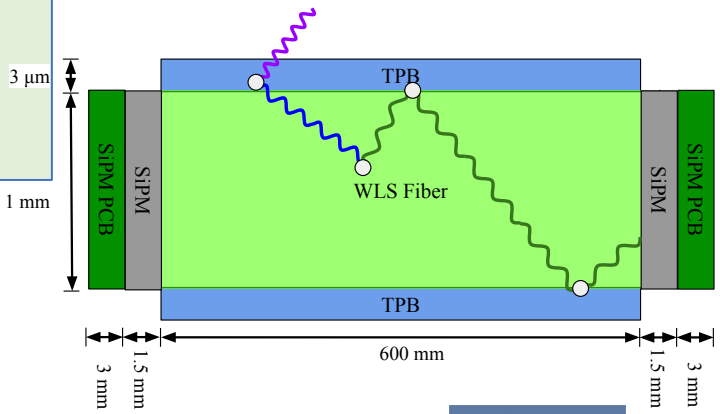
ArCLight Tiles

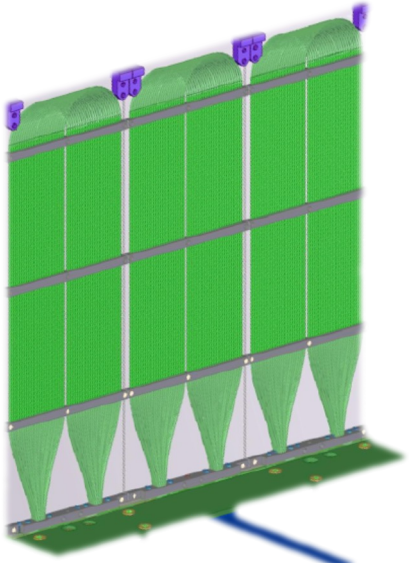




UNIVERSITÄT BERN

LCM Tiles





JINR DUBNA

Caltech

Timeline of Technical Demonstrations

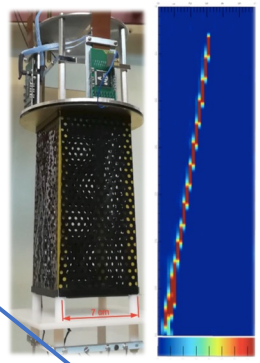
2018-2020
- Demonstration of individual novel technologies

2020
- Single cube prototypes: first combined test of charge readout and light readout systems

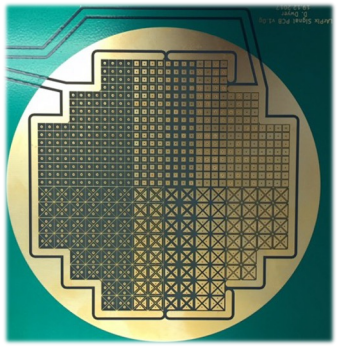
2021-2022
- Single modules : Ton-scale, fully-integrated prototype of ND-LAr module (Next Slides)

2022-2023
- 2x2 demonstrator from four single modules in the neutrino beam at Fermilab: ProtoDUNE ND (discussed ahead!)

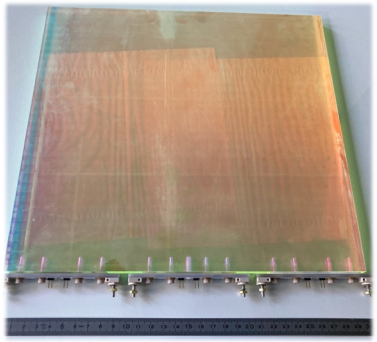
Resistive Shell

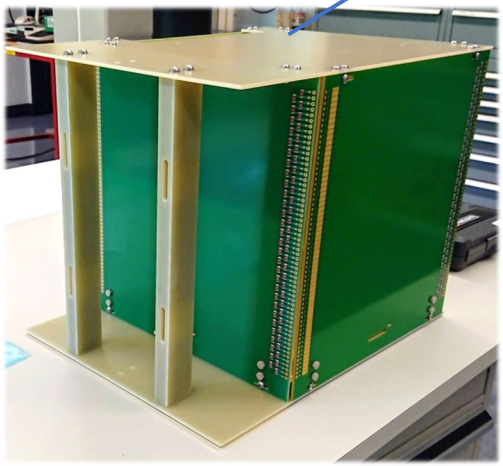


Charge readout



Light readout

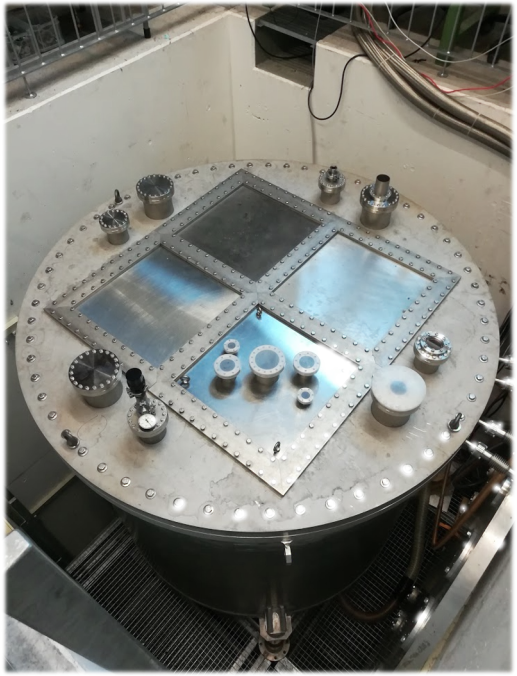




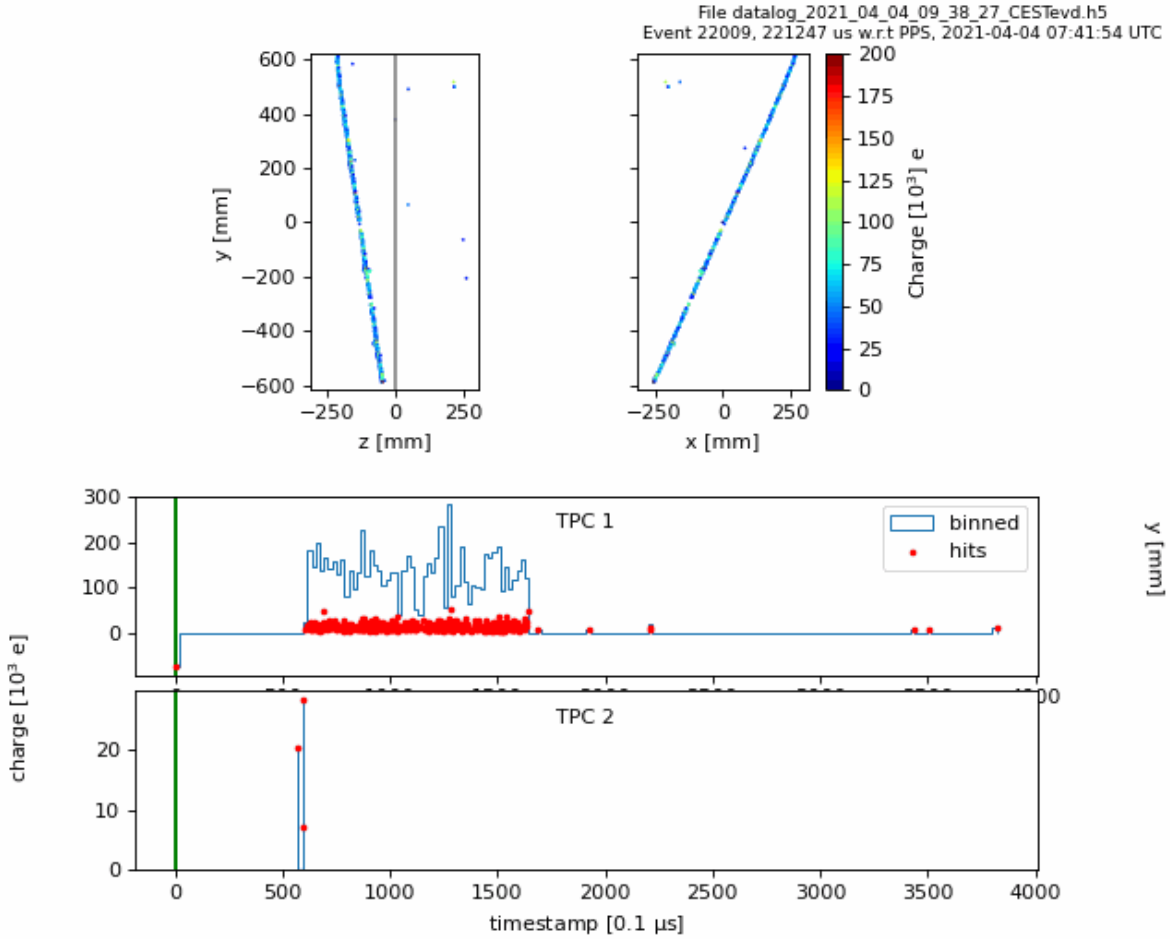
Single Cube

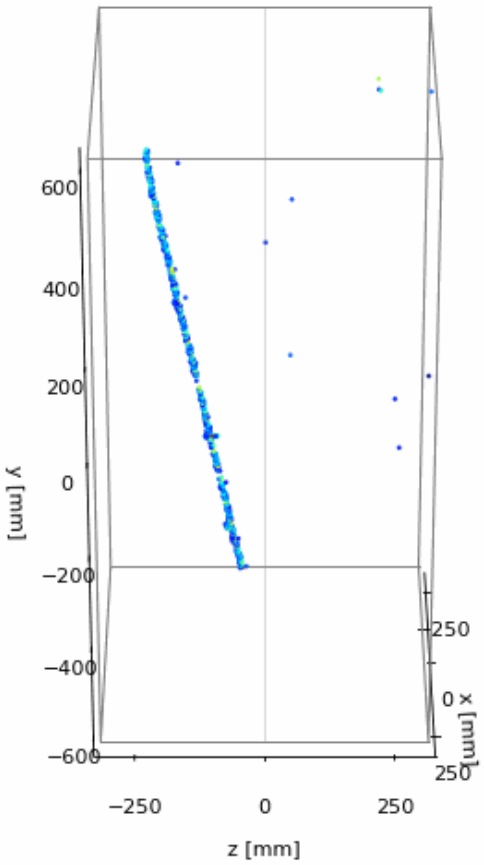
Single Module Demos @ BERN

- 4 individual fully integrated, ton-scale LAr Modules are being tested at Bern at cryogenic temperatures.
- Collected data from O(~100M) cosmic ray induced events during Module-0 and Module-1 runs.




Single Module Demos @ BERN

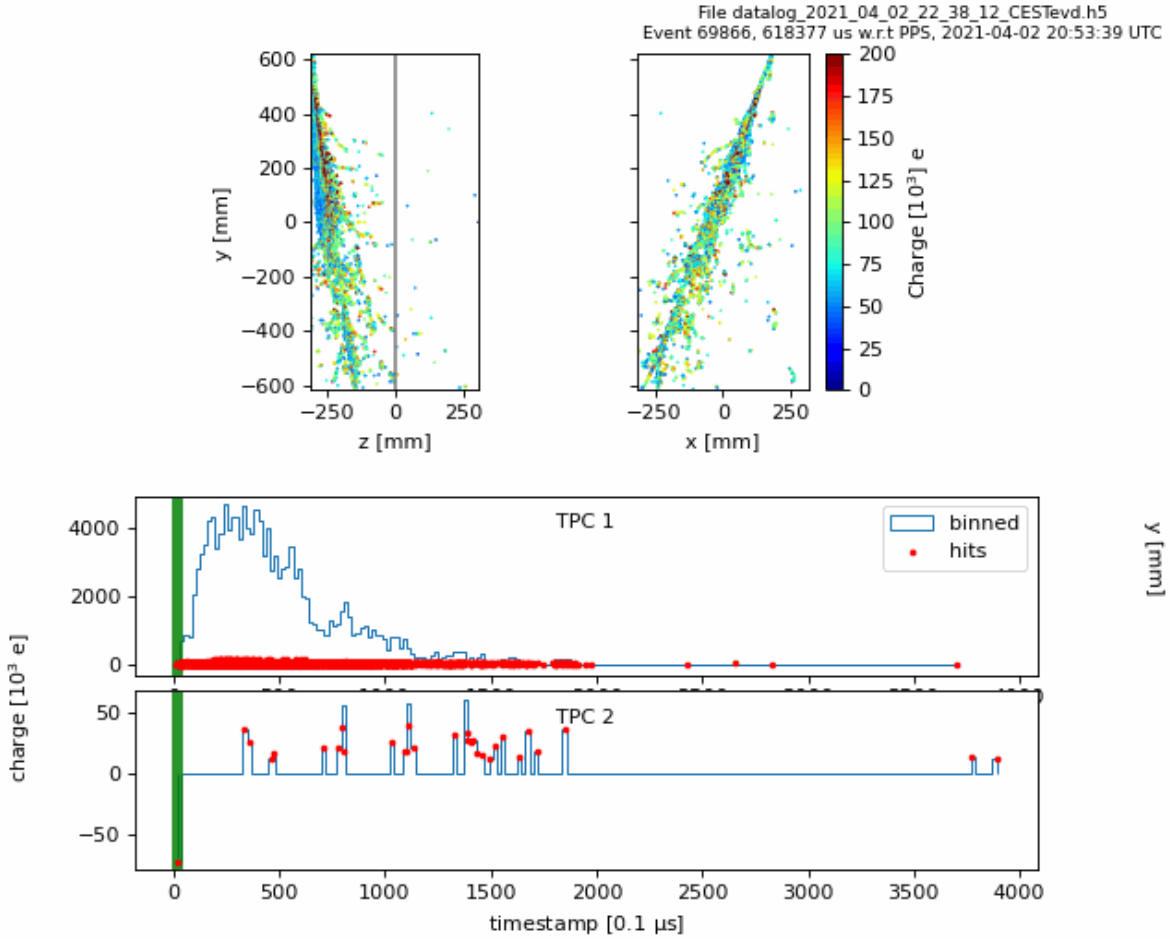


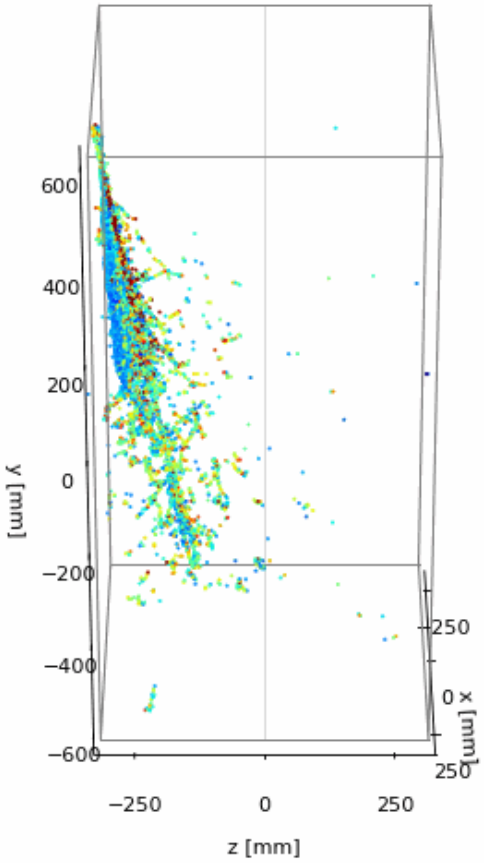


Through-going muon track

Caltech

Single Module Demos @ BERN





Shower event caused by very high-energy mons

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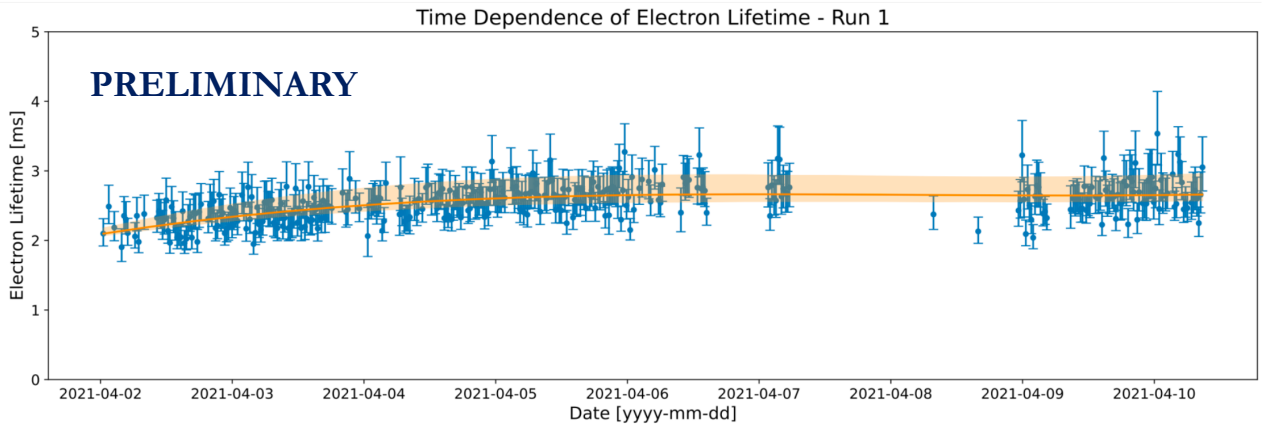
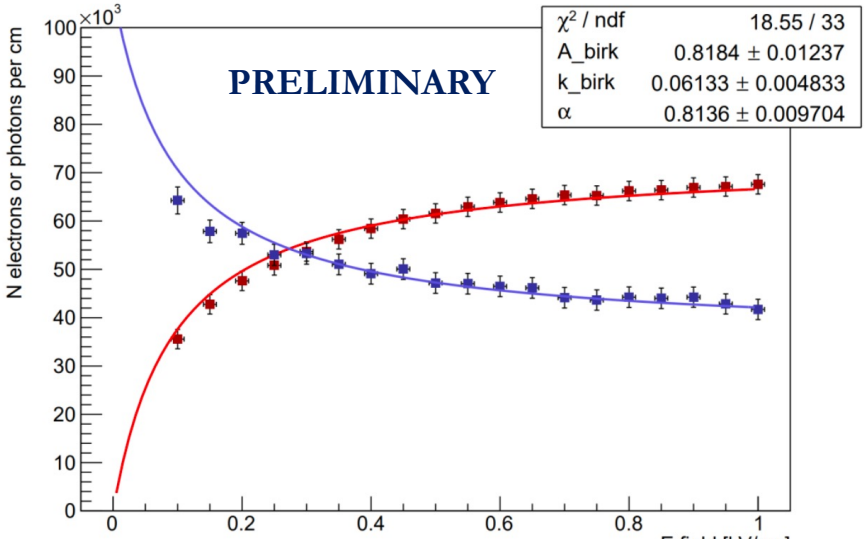
Single Module Demos @ BERN

- With high statistics data, Module-0 is already producing competitive measurements.
  - Simultaneous fit of charge and light yield gives measurements that are consistent with ICARUS and ArgoNeut.



- Publication on Module-0 data analysis is in preparation: *"Performance of a modular ton-scale pixel-readout liquid argon Time Projection Chamber"*.

Coming Soon

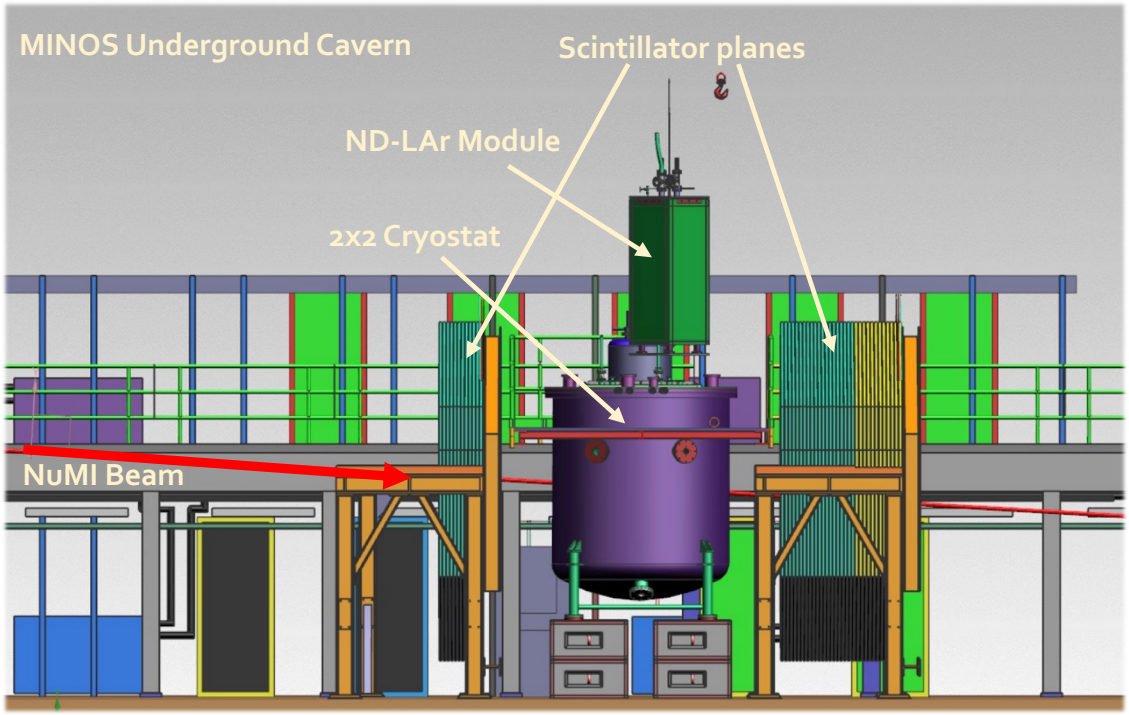


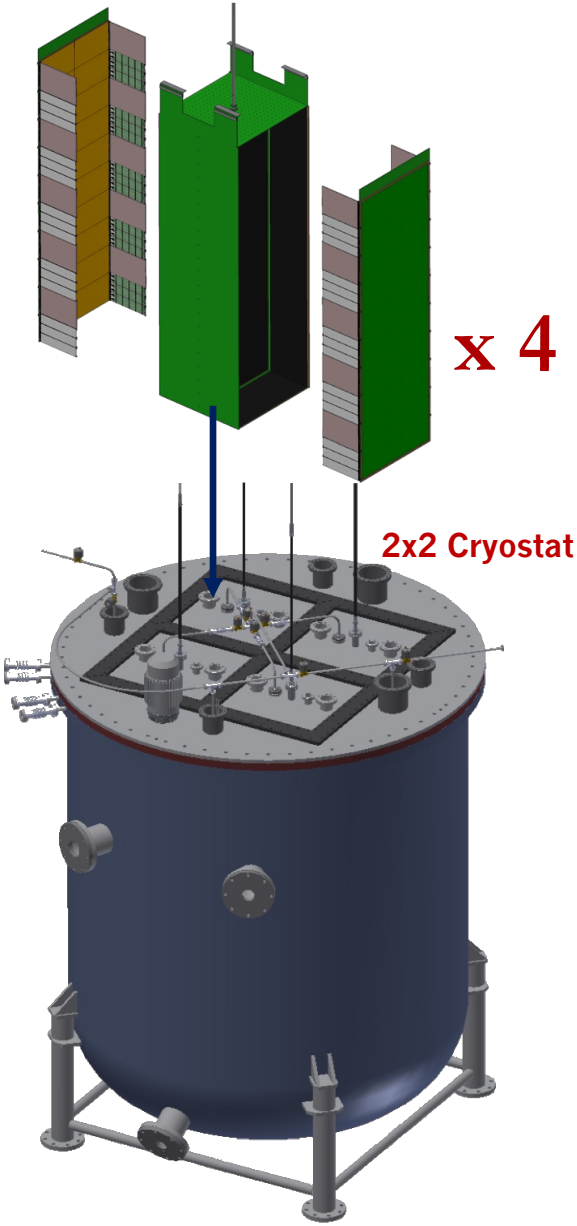
Experiment	A [kV g cm^{-3} MeV^{-1}]	k_E [kV g cm^{-3} MeV^{-1}]	Reference
ICARUS	0.800 ± 0.003	0.0486 ± 0.0006	[31]
ArgoNeut	0.806 ± 0.010	0.052 ± 0.001	[32]
This work	0.794 ± 0.004	0.047 ± 0.002	

Caltech

2x2 Demonstrator : Fermilab

- All 4 LArTPC modules will be assembled as a prototype modular detector with repurposed scintillator planes from Minerva providing additional tracking.
- A run in the NuMI beam would provide the first neutrino beam run with comparable intensity to the LBNF beam.





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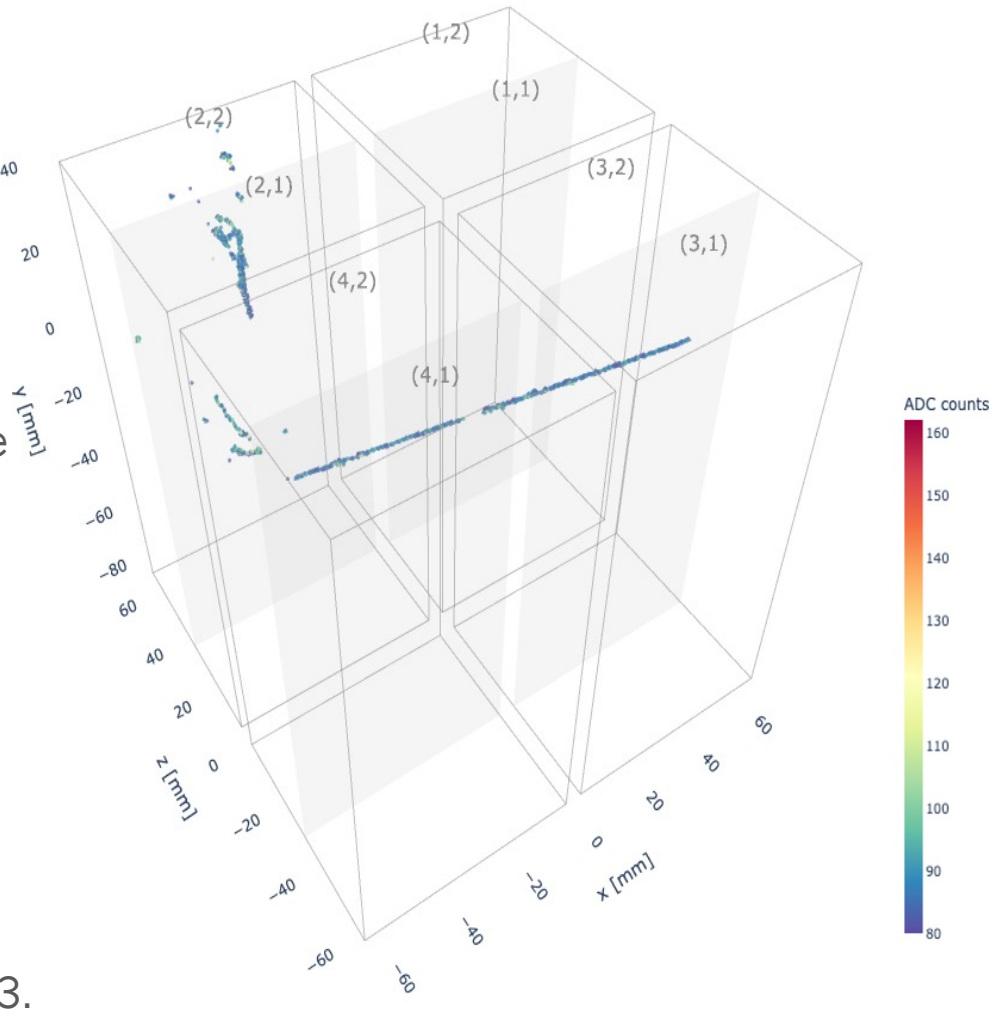
2x2 Demonstrator : Fermilab

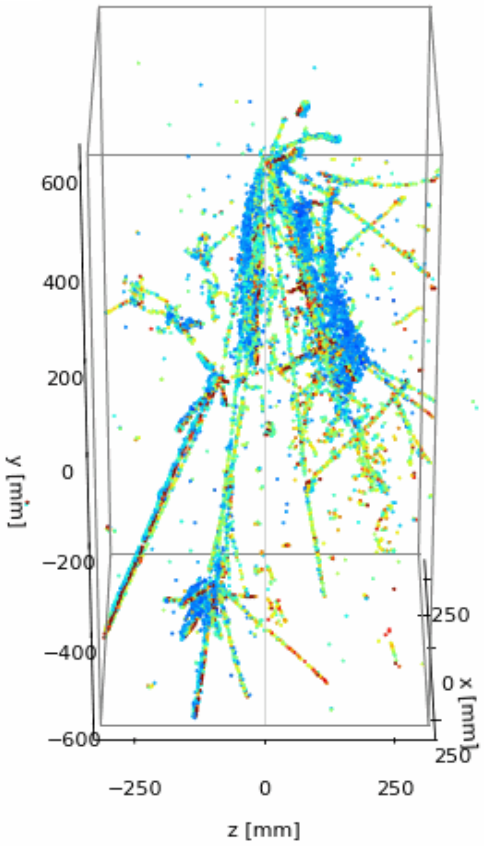
- Goals:
  - Integration and installation of modules in a cohesive detector.
  - Operations protocol for underground operations.
  - Neutrino signal identifications and reconstruction.
  - Understanding detector performance with pile-up in a neutrino beam.
- Status:
  - Module-0 and Module-1 are undergoing rigorous acceptance and checkout tests at Fermilab.
  - Module-2 and Module-3 will be assembled and shipped from Bern over the next couple of months.
  - On-schedule for a run in 2022 - 2023.



Simulation of a neutrino event producing muon and EM shower in 2x2 demonstrator

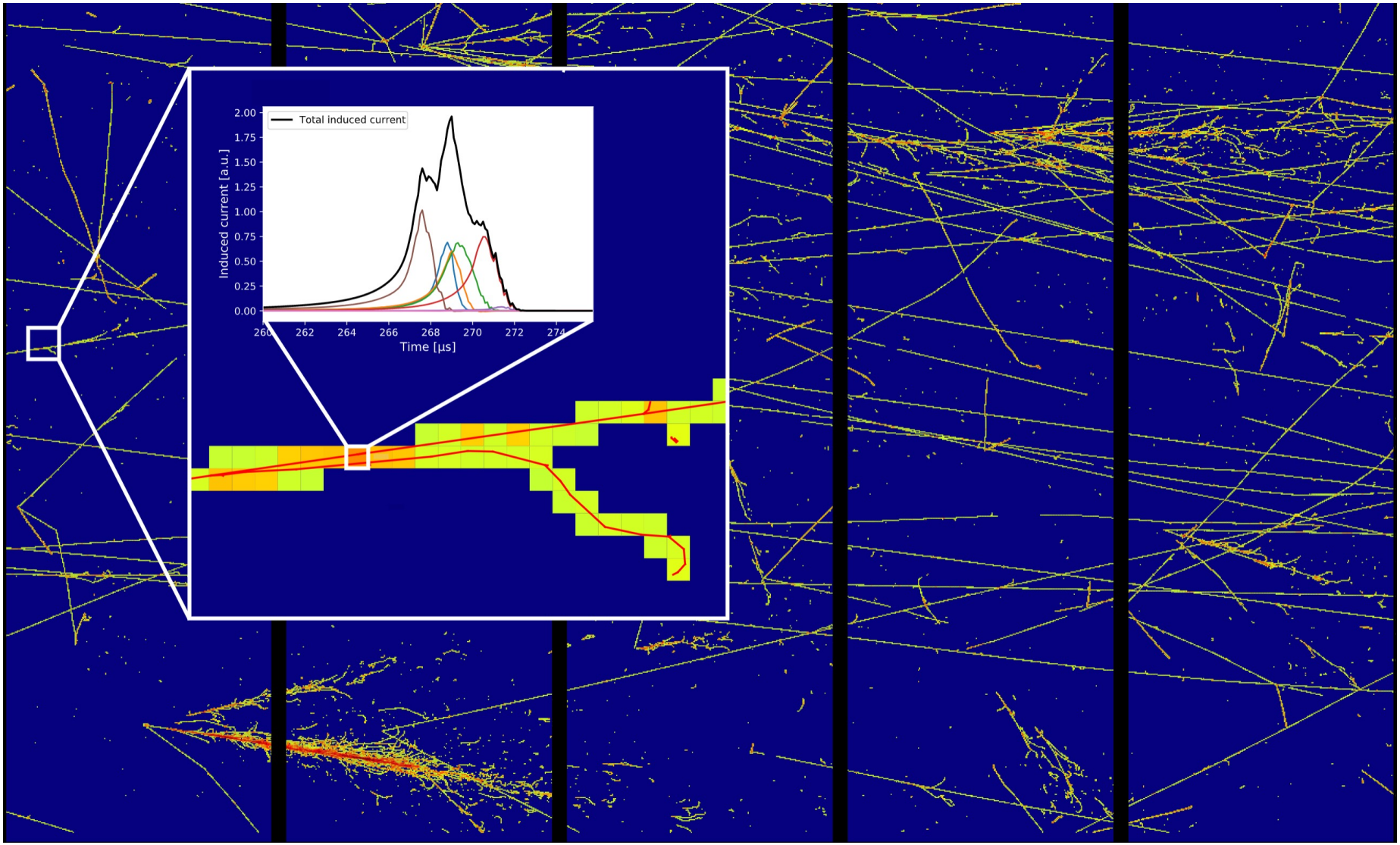
Summary

- DUNE is the next generation precision neutrino experiment with discovery potential for CP violation in leptons and neutrino mass ordering.
- ND will provide critical constraints to neutrino flux and cross-sections at the FD.
- A Modular-LArTPC is needed to tolerate the extremely high event rate at the DUNE ND.
- Novel technologies designed for DUNE ND-LAr have been demonstrated to work successfully in a single module.
- ProtoDUNE-ND (2x2 demonstrator) is currently being assembled and a run in NuMI neutrino beam is coming up soon!
- Provides exciting new physics opportunities to the community both short and long-term!



Thank You!

Image by R. Soleti (LBNL)



Measuring neutrino interactions pixel-by-pixel!

Caltech