

# DUNE's ND-LAr and its prototyping program (2x2 and FSD)

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Richard Diurba (Bern) for the DUNE Collaboration

September 2<sup>nd</sup>, 2025

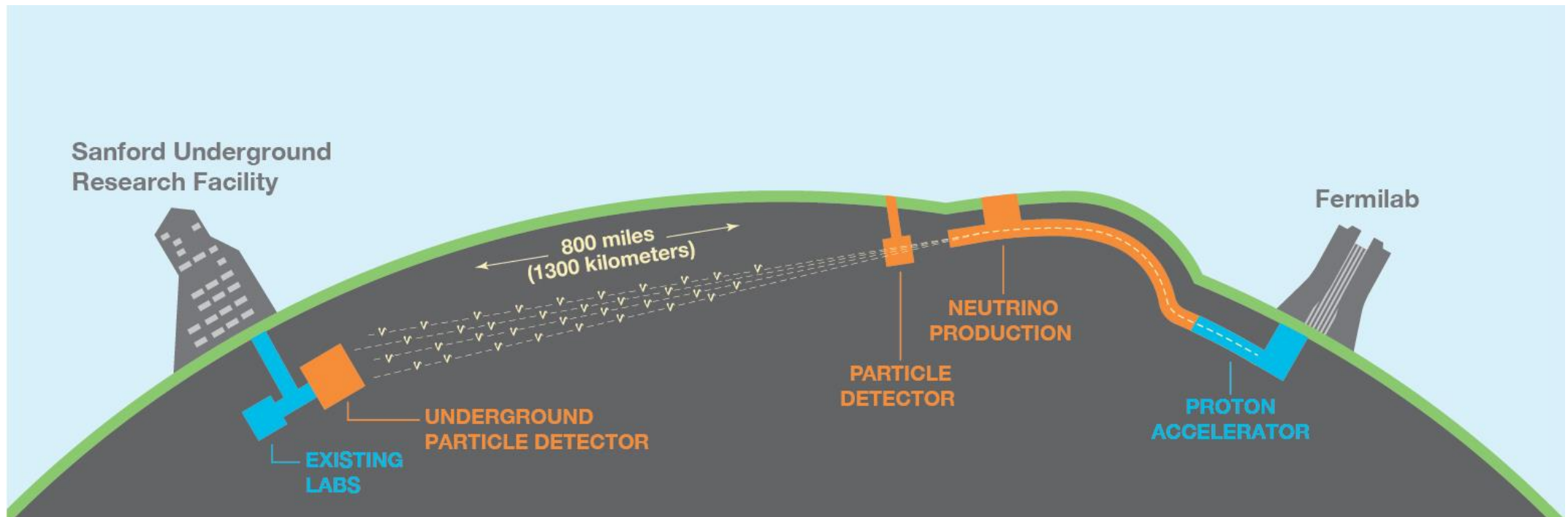
NuFACT 2025



**DEEP UNDERGROUND  
NEUTRINO EXPERIMENT**

# Deep Underground Neutrino Experiment

- DUNE is a next-generation long-baseline oscillation experiment under construction.
- LBNF beam will have world-leading intensity of 1.2-2.4 MW.
- DUNE design allows for independent determinations of mass ordering and CP-violation.
  - Relies heavily on the wide-band beam and long baseline.



# Necessity of the DUNE Near Detector

- Neutrino flux wide-band beyond 1 GeV.
- Beam extends heavily into RES and DIS.
- Requires precise knowledge of both the neutrino cross section and flux.
  - Difficult given GeV-scale modeling challenges and wide-band flux.

$$N_{\nu_a} = \int dE_{\nu_a} \sigma_{\nu_a}(E_{\nu_a}) \varepsilon_{\nu_a}(E_{\nu_a}) \varphi_{\nu_a}(E_{\nu_a}) P(\nu_a \rightarrow \nu_a)$$

$N$ : Number of neutrinos

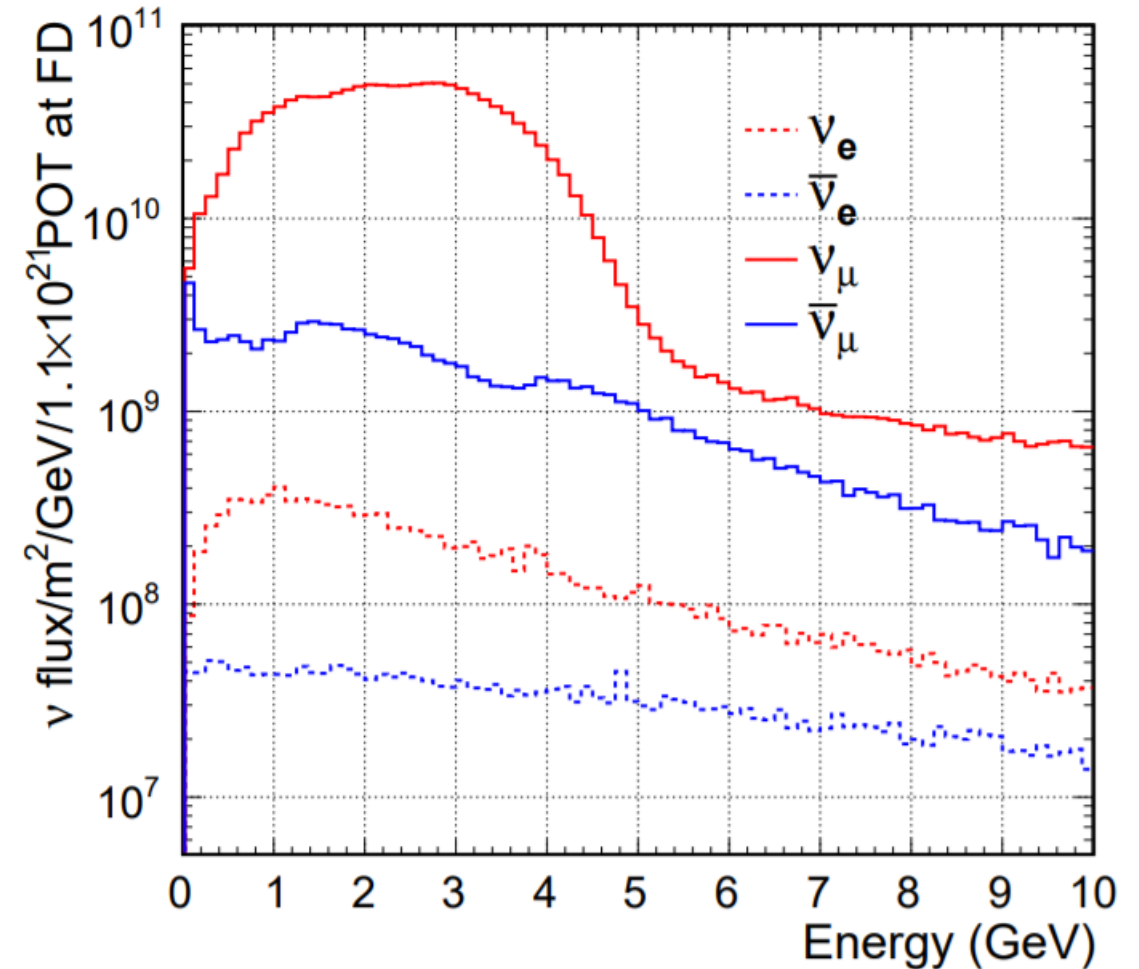
$E$ : Neutrino energy

$\sigma$ : Neutrino cross section

$\varepsilon$ : Detector efficiency

$\varphi$ : Neutrino Flux

$P$ : Probability of (non)transition (FD only)



Neutrino flux of the beam operating in neutrino mode.

[EPJ C 80 \(2020\) 978](#)

# Necessity of the DUNE Near Detector

- Challenges to quantifying neutrino cross section and flux make oscillation measurements difficult.
- Requires a Near Detector to measure neutrino cross section and neutrino flux.
  - CP-violation measurement unable to reach discovery-level precision without a ND.

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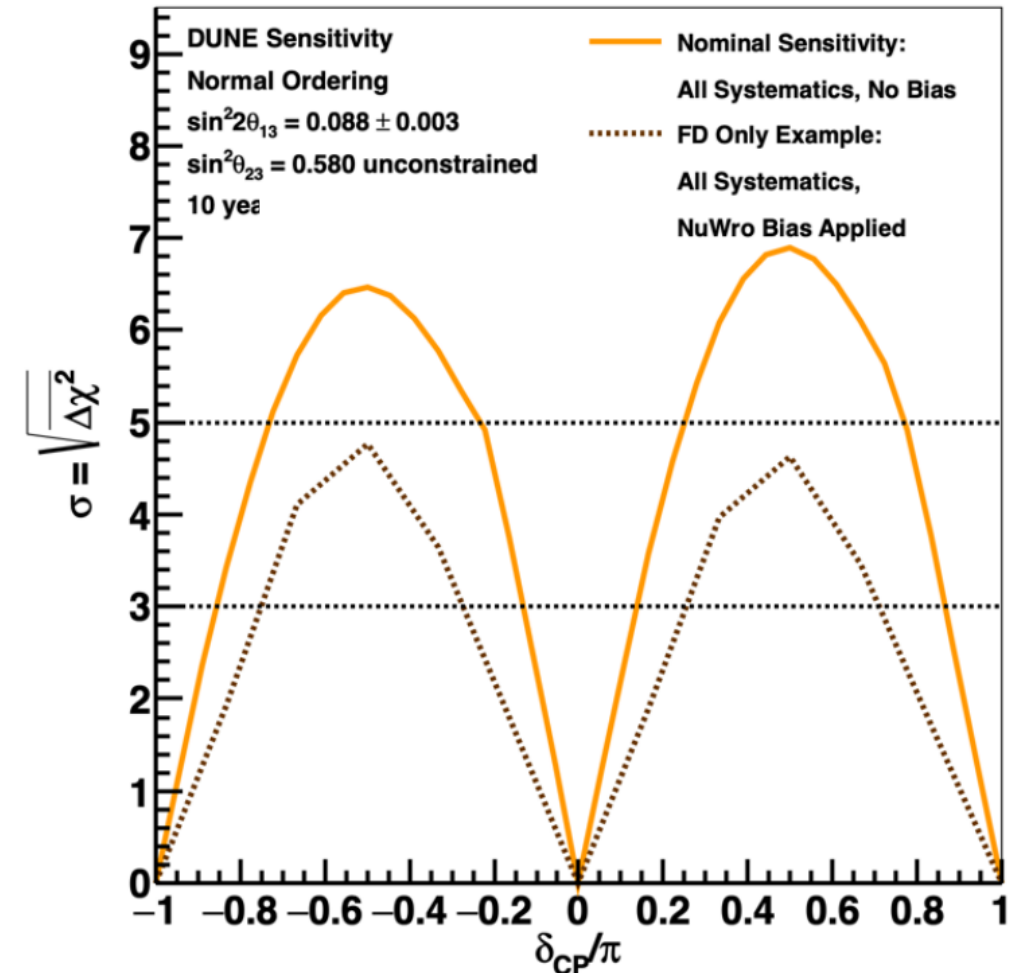
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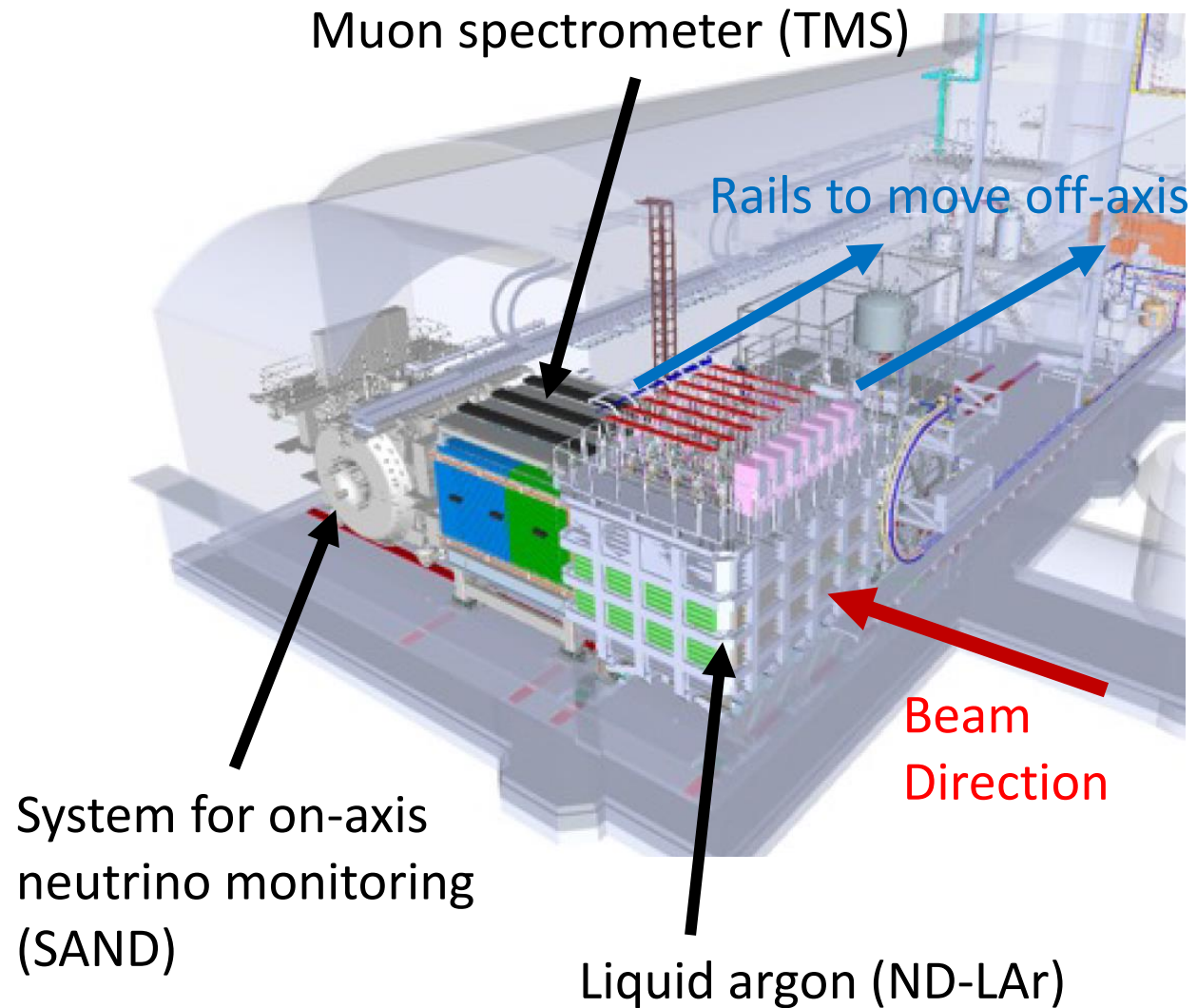


Sensitivity to CP-violation without an ND if an alternative neutrino model is used (NuWro fake data).

[arxiv:2002.03005](https://arxiv.org/abs/2002.03005)

# DUNE Near Detector Design

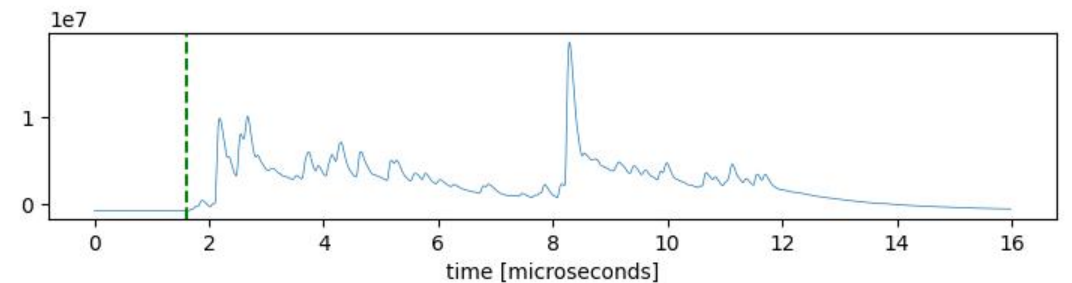
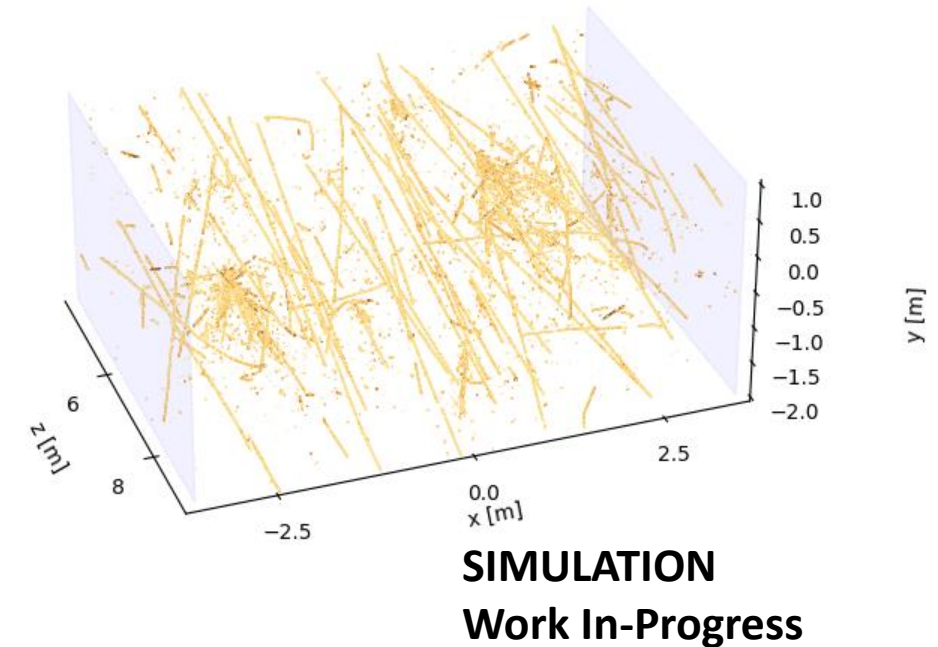
- Near Detector has three components:
  - Liquid argon detector (ND-LAr)
  - The muon spectrometer (TMS)
  - On-axis beam monitor (SAND)
- ND-LAr and TMS can move off-axis to sample different energy spectra of the neutrino beam.
  - Known as the Precision Reaction Independent Spectrum Measurement system (PRISM).
- Muons exit ND-LAr and pass into TMS.



[Instruments 2021,5\(4\), 31](#)

# DUNE Beam Pile-Up

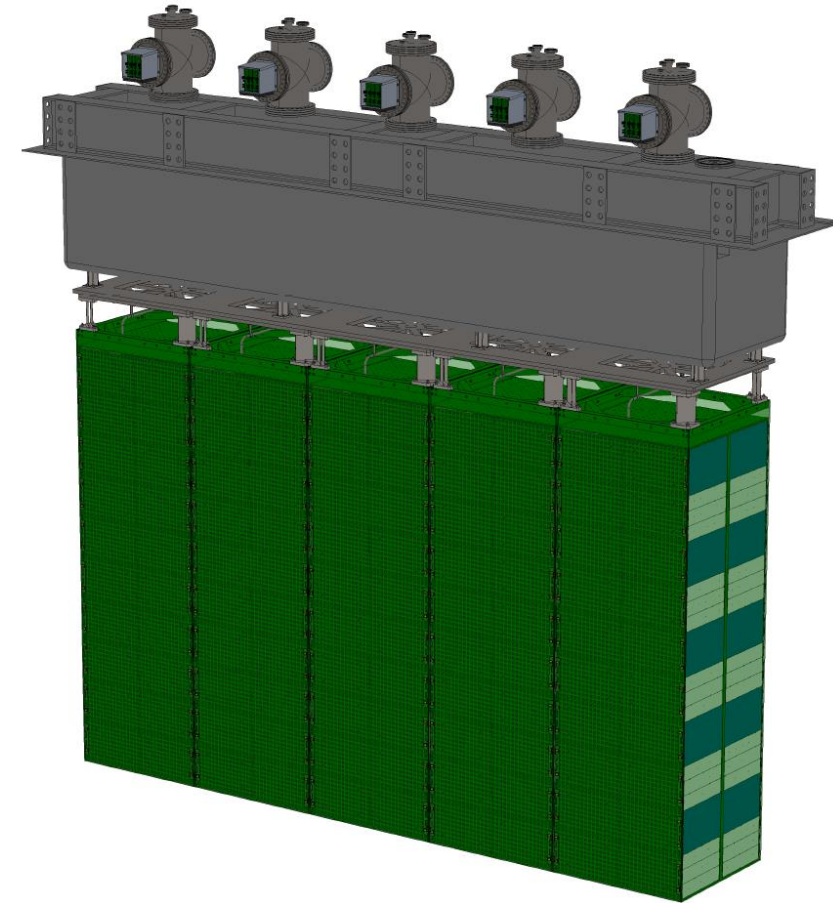
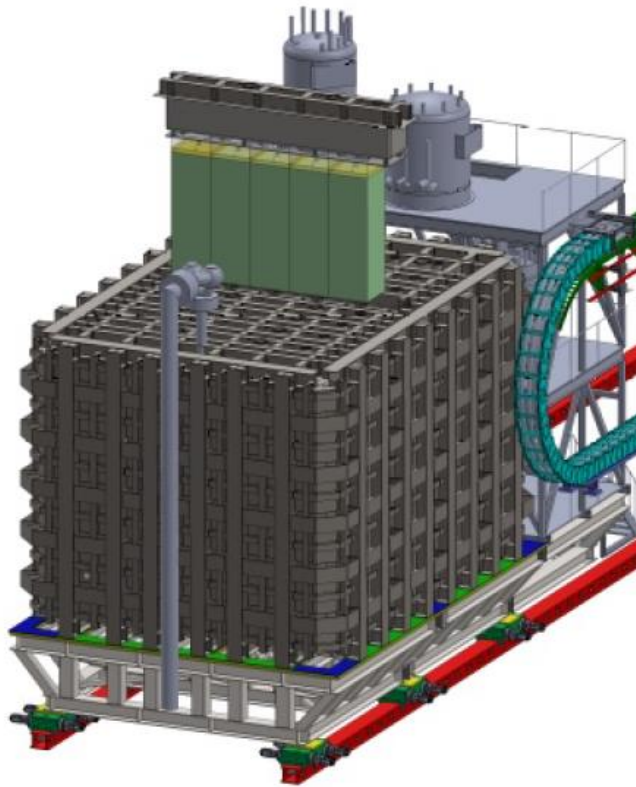
- The LBNF beam of DUNE produces over a hundred interactions per beam spill in ND-LAr!
- ND-LAr handles pile-up by:
  - Modularization of the argon volume into 35 modules.
    - Reduce signals per sensitive volume.
  - Pixelated charge readout
    - Prevents pile-up of charge signals.
  - Dielectric light traps in each module for fast readout.
    - Associate light to charge data to separate interactions.



Simulated beam spill of ND-LAr with charge (yellow) and light (green) signals.

# Liquid Argon Near Detector (ND-LAr)

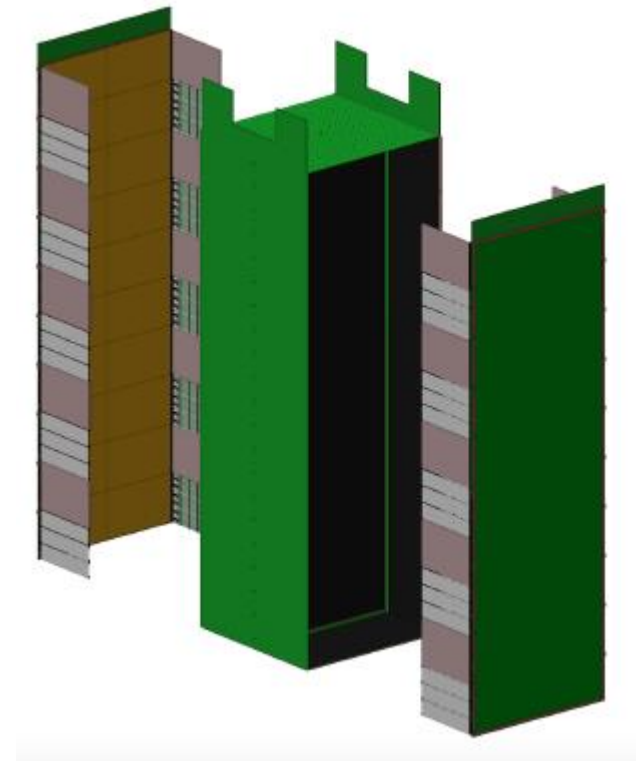
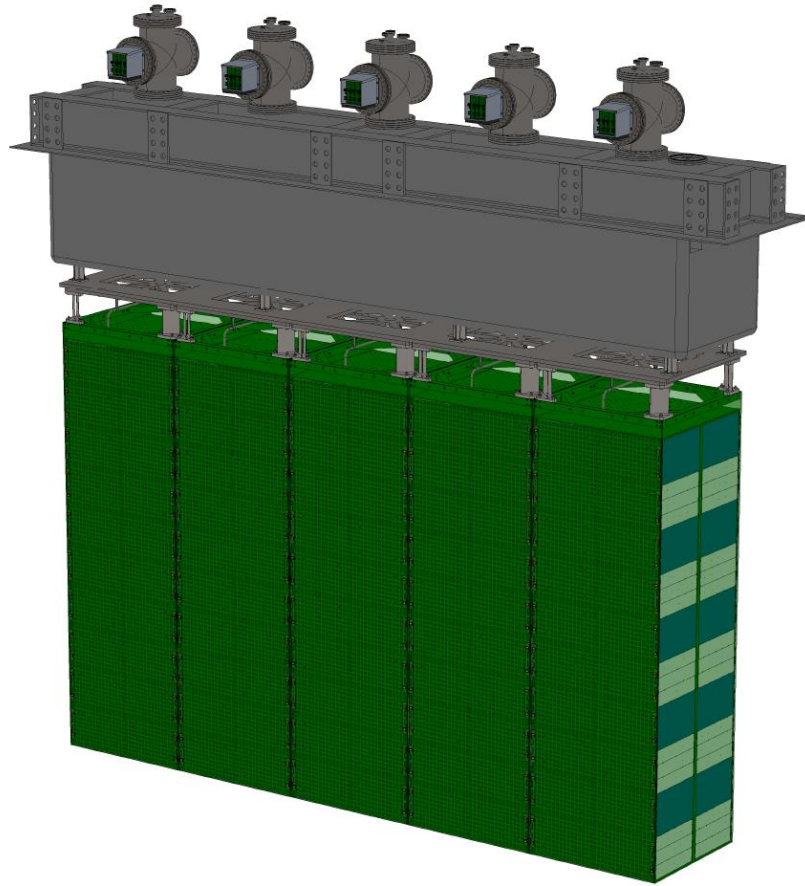
- ND-LAr consists of 35 modules, optimized for horizontal containment of hadrons.
  - Consists of seven rows of five modules.
  - Total fiducial mass of 67 tons.



[\*Instruments\* 2021,5\(4\), 31](#)

# Liquid Argon Near Detector (ND-LAr)

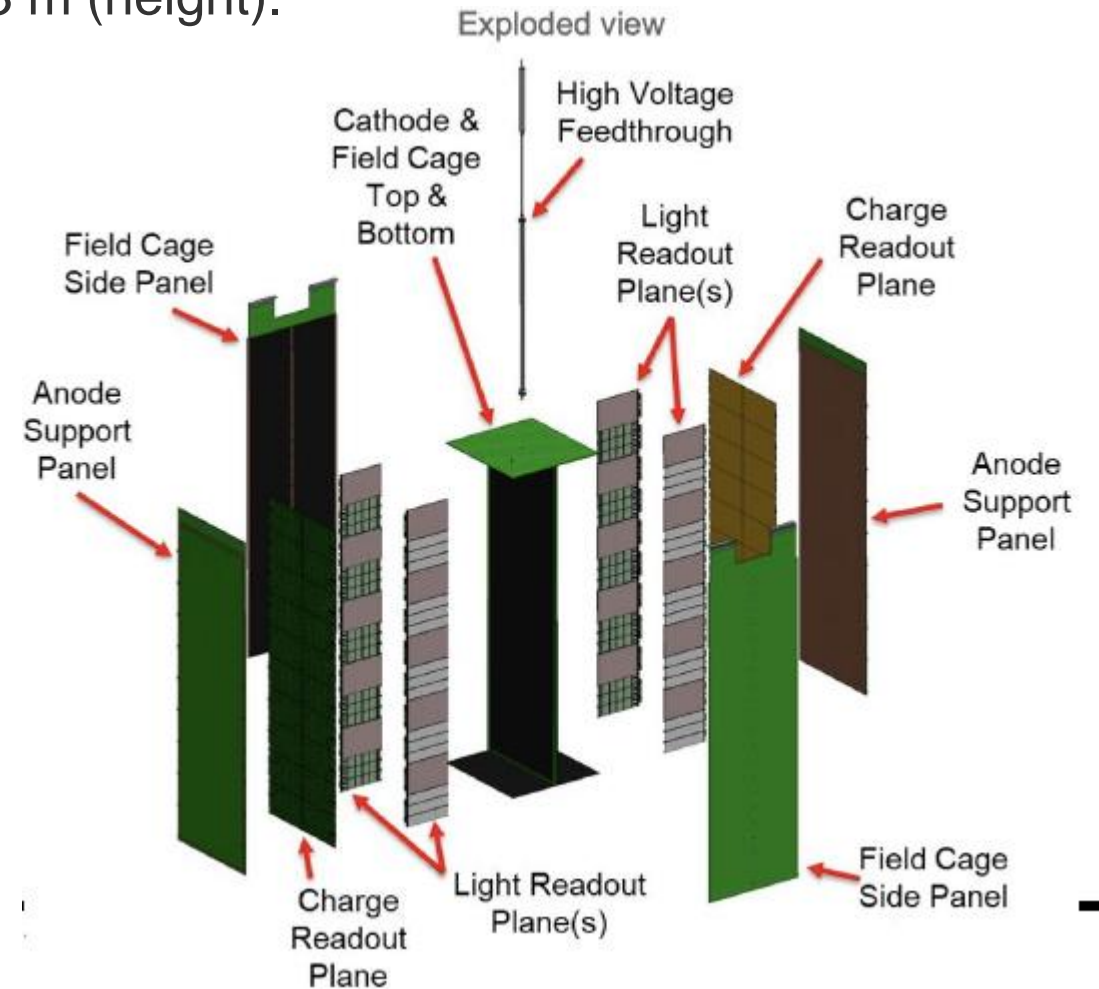
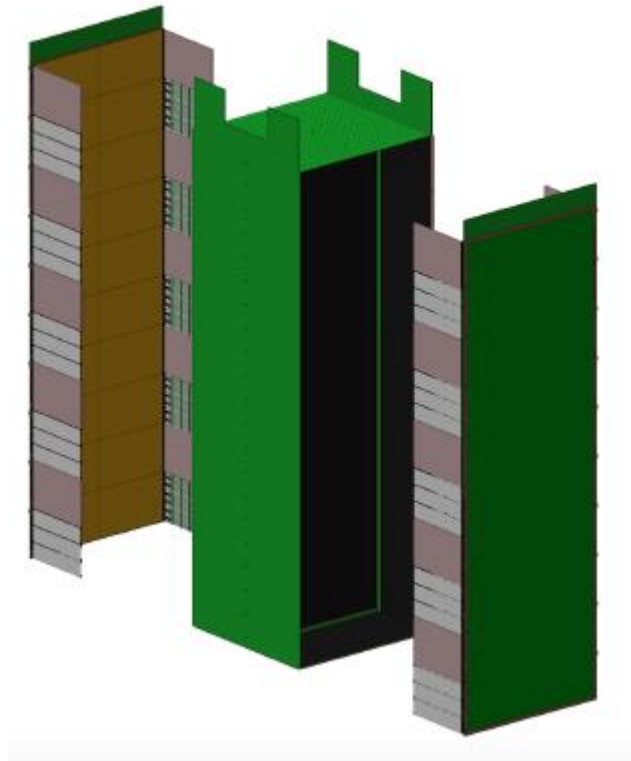
- Each row contains a module with two drift volumes that are optically segmented.
  - A module is 1 m (length) by 1 m (width) by 3 m (height).



[Instruments 2021,5\(4\), 31](#)

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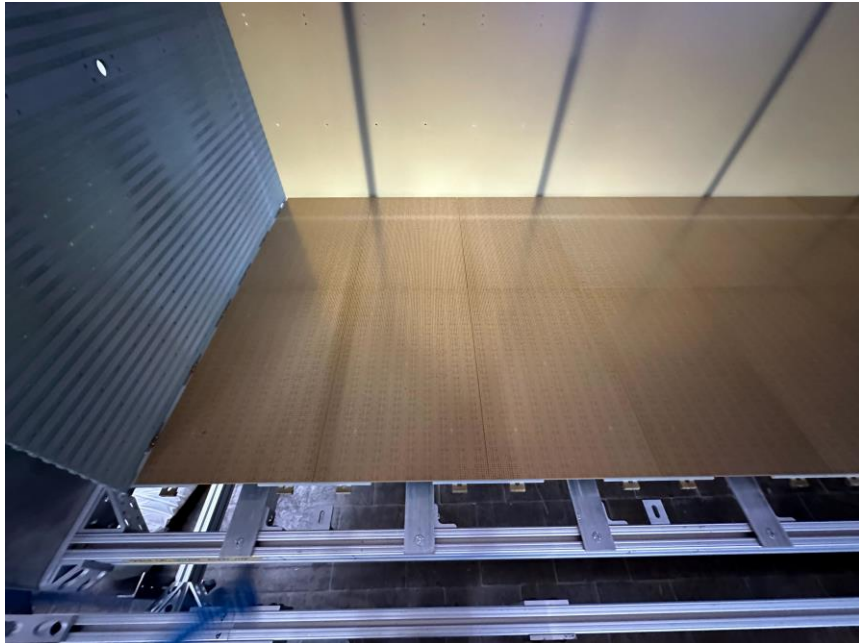
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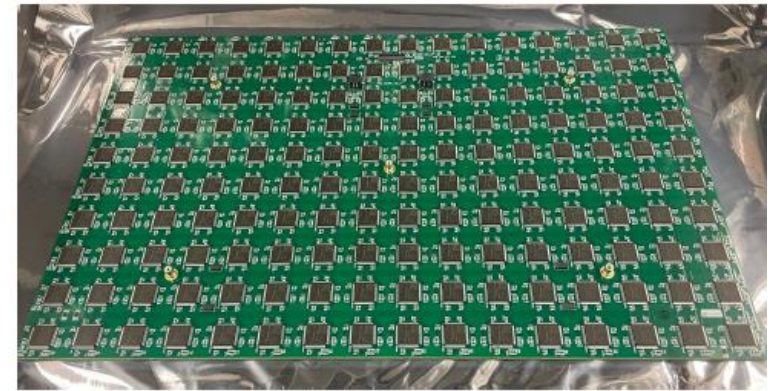
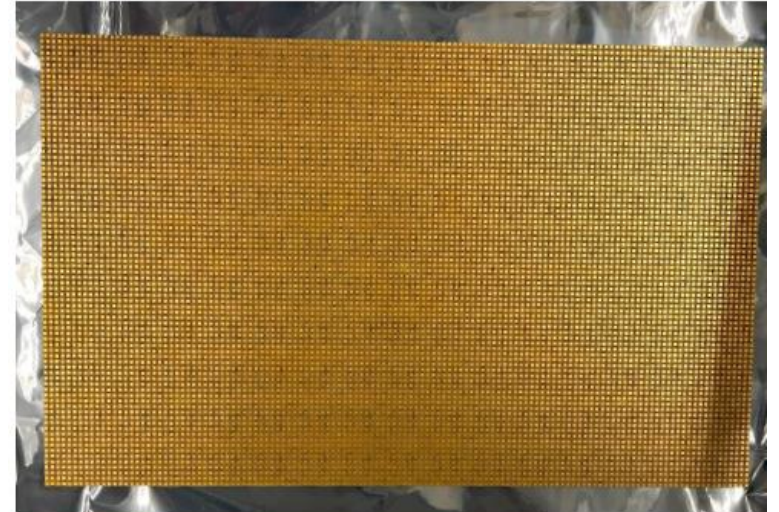
[Instruments 2021,5\(4\), 31](#)

# ND-LAr Charge Readout

- Unique pixelated charge readout using LArPix design.
  - Over 14M pixels in whole ND-LAr.
- Native three-dimensional reconstruction with self-triggering.
- Pixel pitch of 4 mm.
  - Low proton energy thresholds of approximately 10 MeV.



LArPix tiles installed in a full-size ND-LAr module prototype.

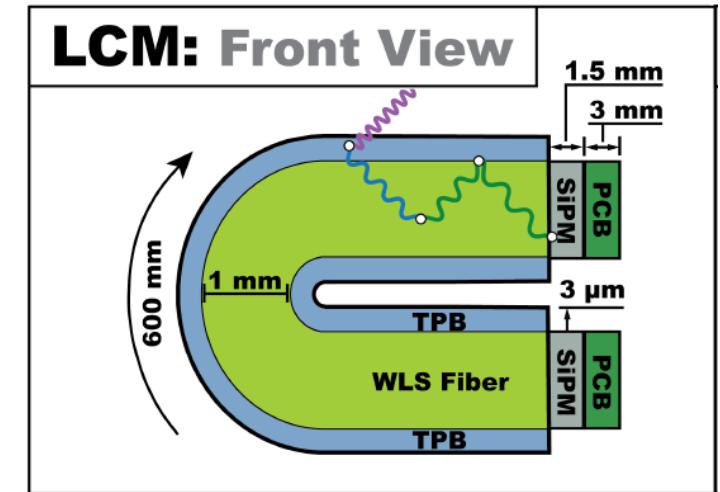
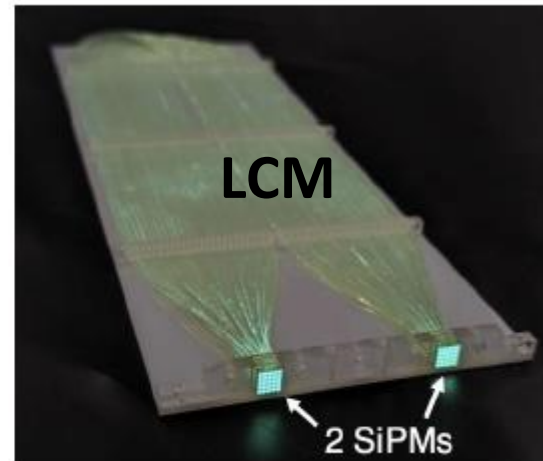
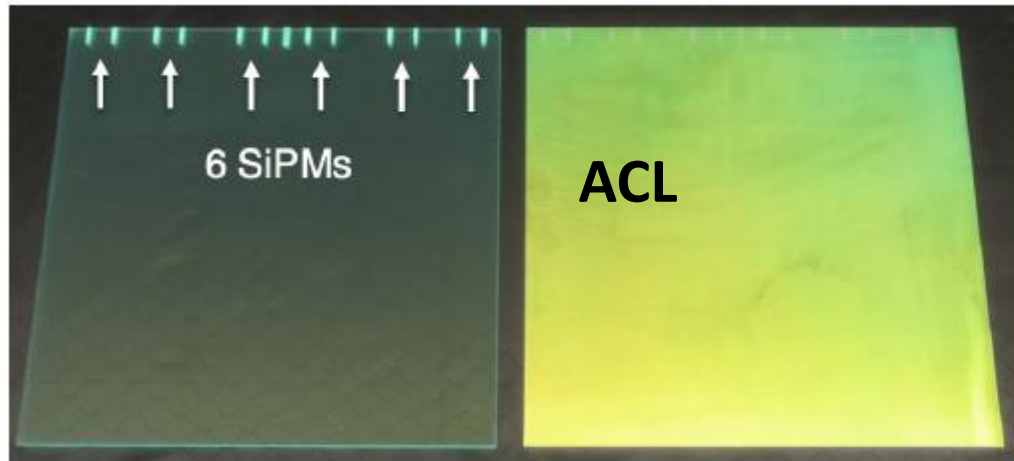
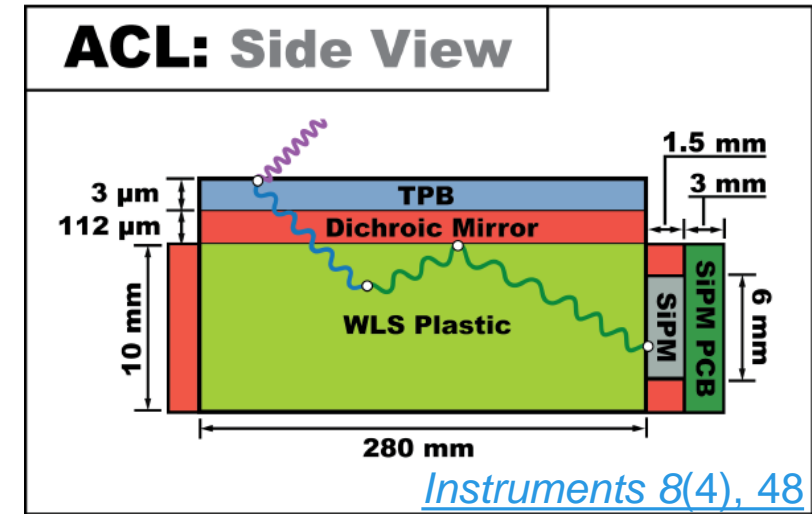


A single full-size LArPix tile.

LArPix Design Paper: [JINST 13 P10007](#)

# ND-LAr Light Readout

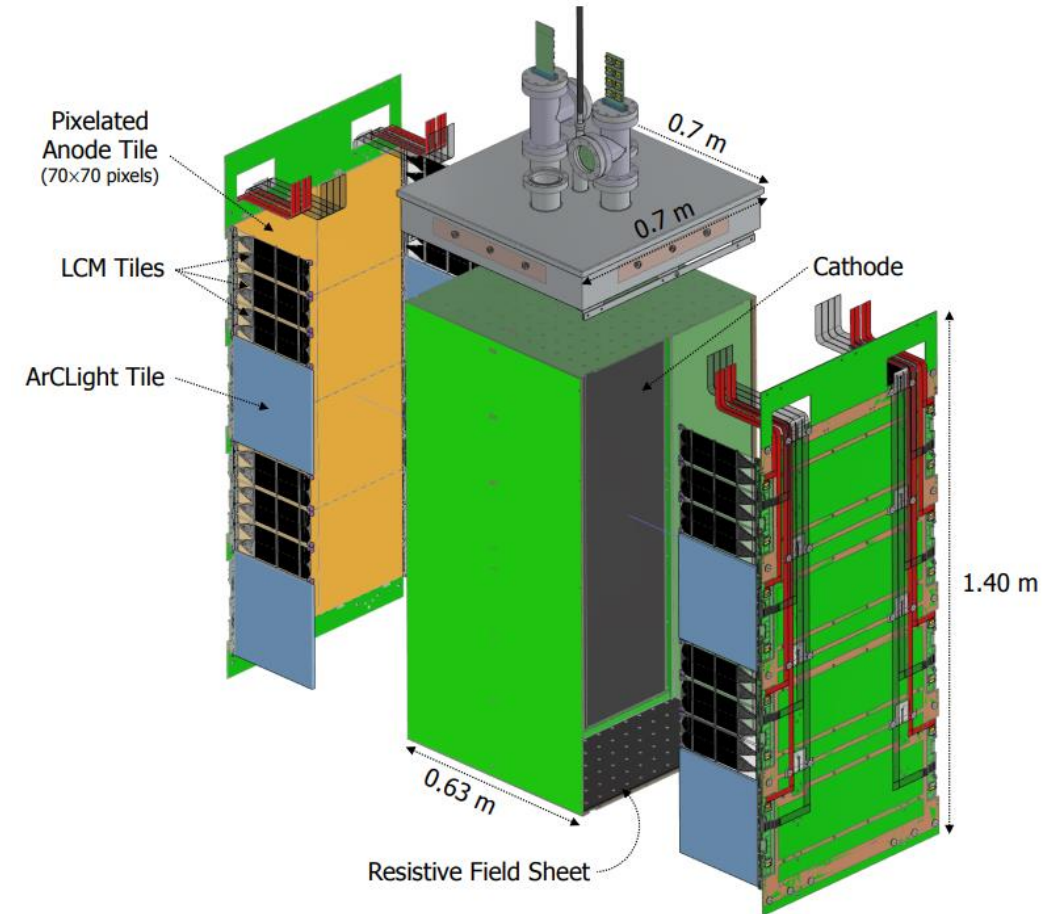
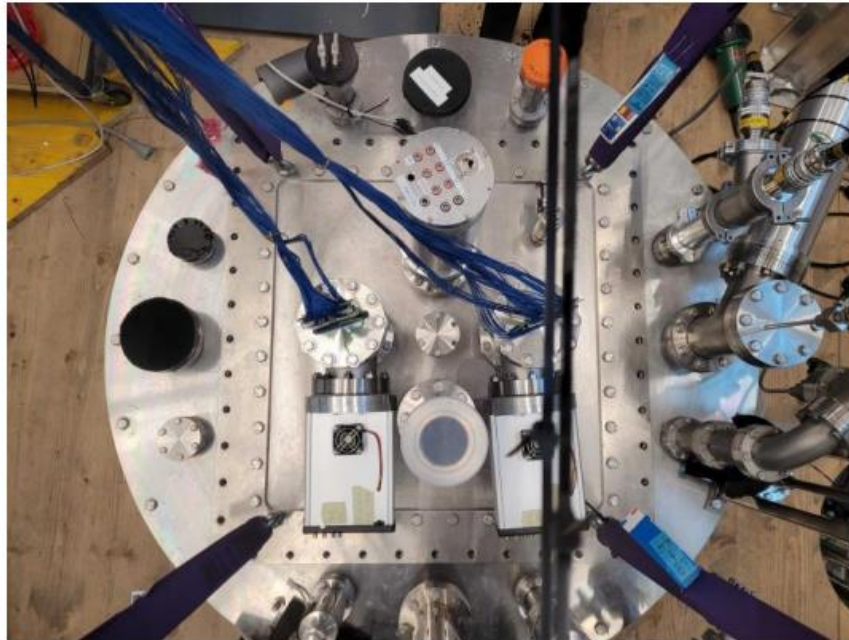
- Dielectric traps based on ARAPUCA concept with ns-scale timing.
- Two complementary technologies for position and timing:
  - ArgonCube Light Readout System (ACL)
    - Plastic with high spatial resolution (~10 cm).
  - Light Collection Module (LCM)
    - Wrapped fiber with higher PDE (~1%).



[JINST 15 C07022](#)

# ND-LAr Prototyping Campaign: Ton-Scale Module

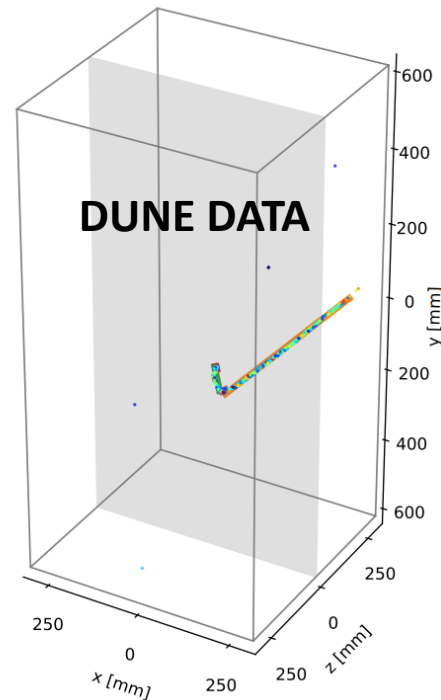
- Constructed four ton-scale modules from 2021-2023.
  - Dimensions of 60 cm by 60 cm by 1.2 m.
  - Approximately 60% of ND-LAr module size.
- Collected over 100M cosmic-ray events over several months of data-taking at the University of Bern.



Performance from Cosmic Ray Data:  
[Instruments 2024, 8\(3\), 41.](#)

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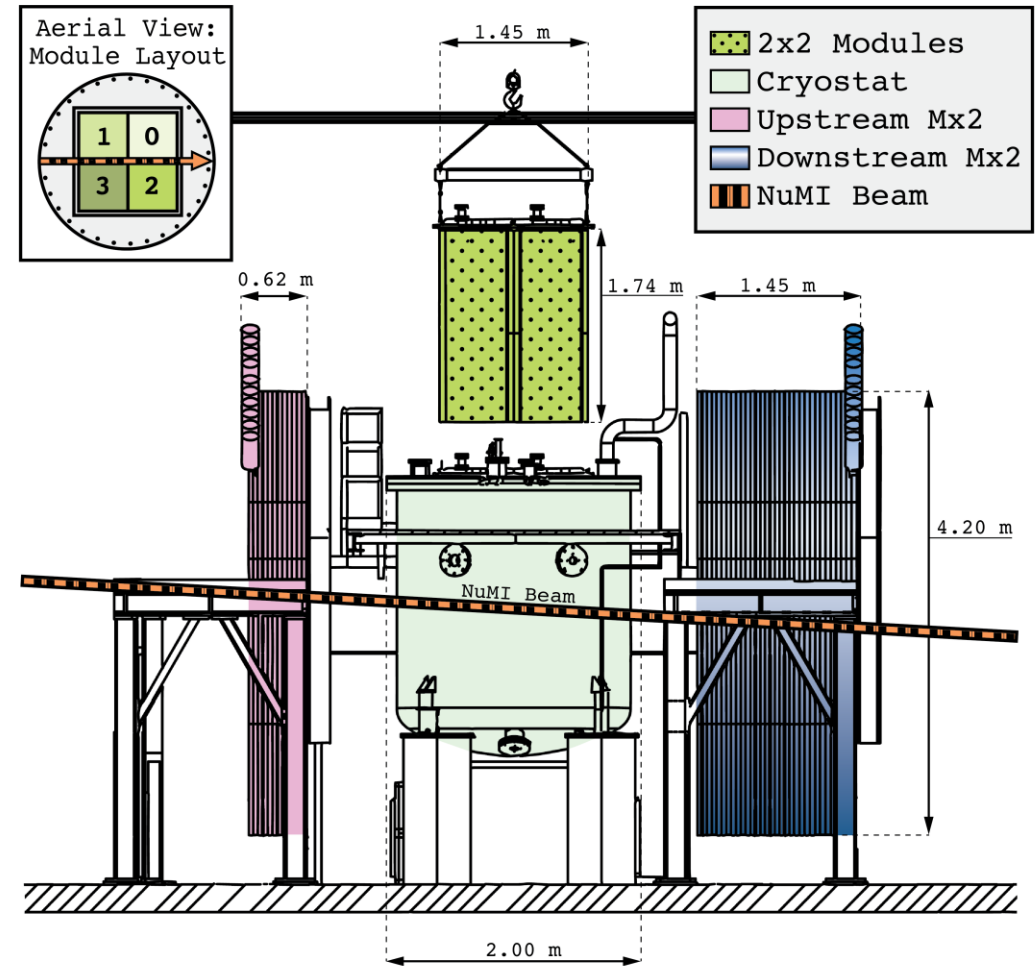
Michel candidate event



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[Instruments 2024, 8\(3\), 41.](#)

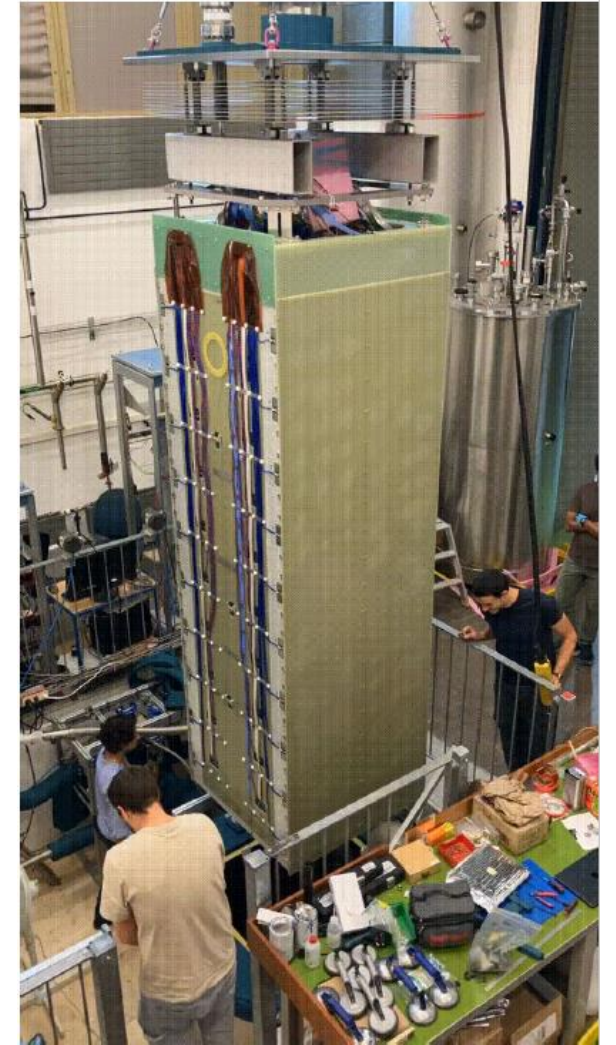
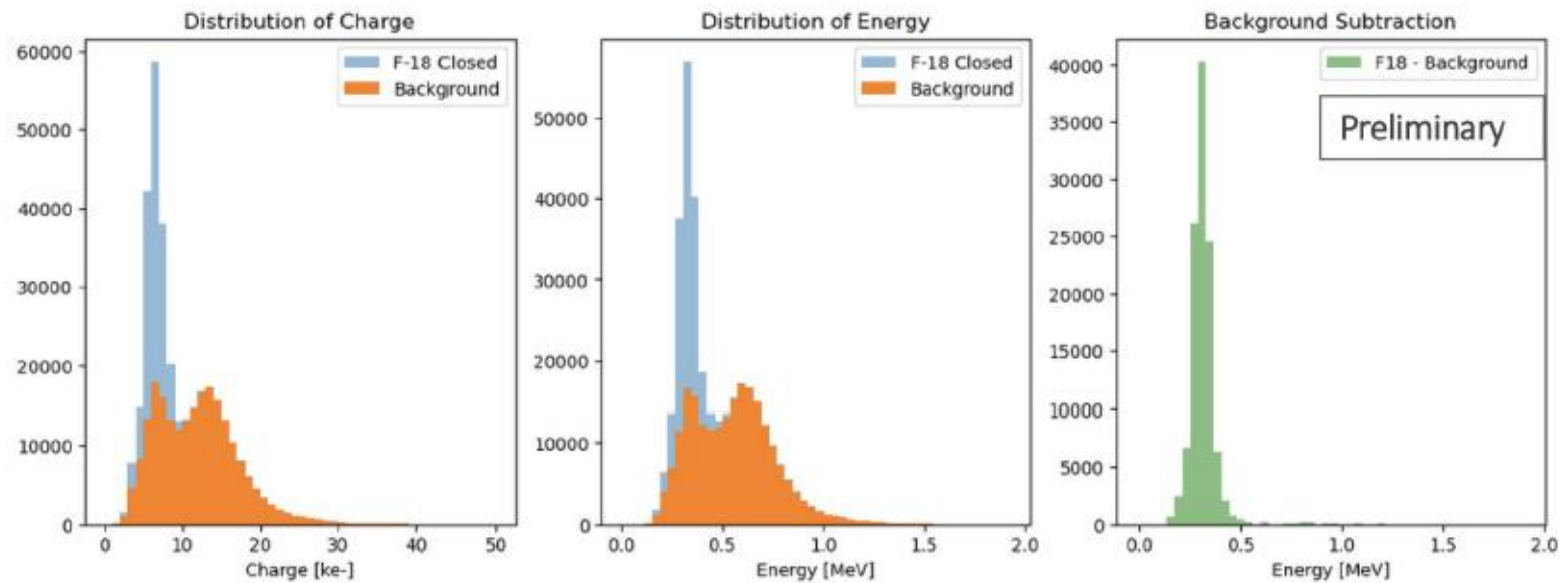
# Prototyping Campaign: 2x2 Demonstrator

- These four modules were sent to Fermilab to be placed in the MINOS hall in a 2 by 2 configuration.
- On-axis with the NuMI neutrino beam.
- Operated in July 2024 and currently going through a second run to collect non-beam data.



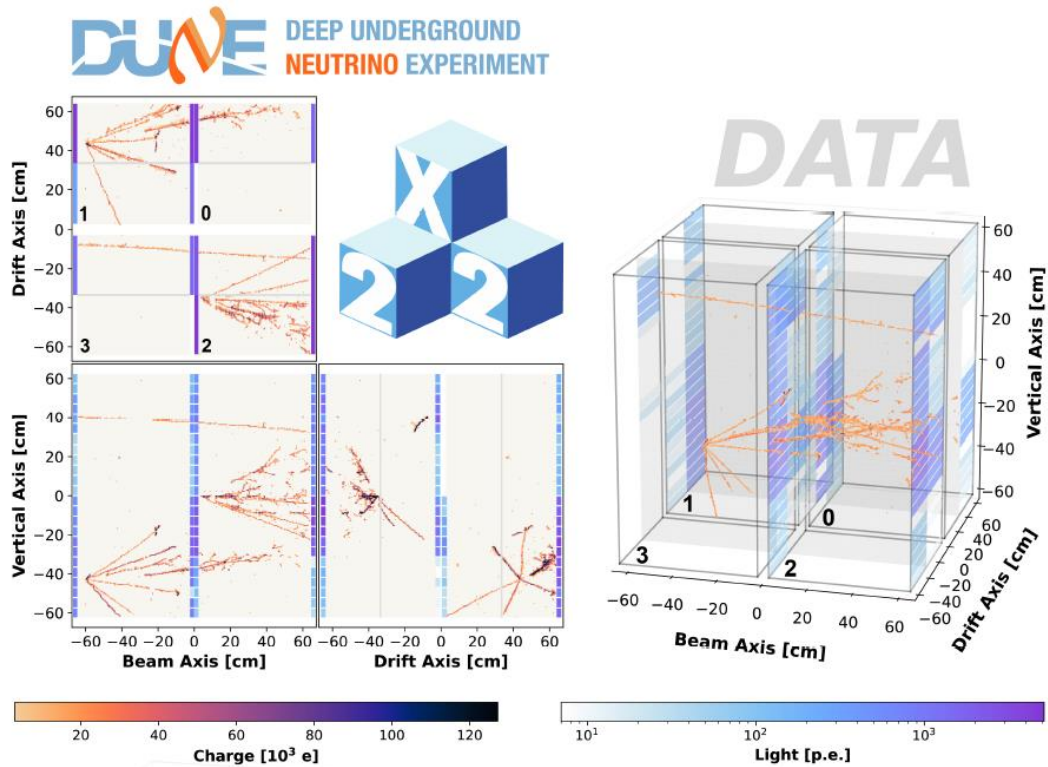
# Prototyping Campaign: Full-Scale Demonstrator

- In summer 2024, DUNE assembled and operated the first full-scale ND-LAr module at the University of Bern.
- Collected 70M cosmic-ray events over several weeks of data-taking.
  - Additionally took radioactive data with fluoride to measure low-energy EM-scattering.

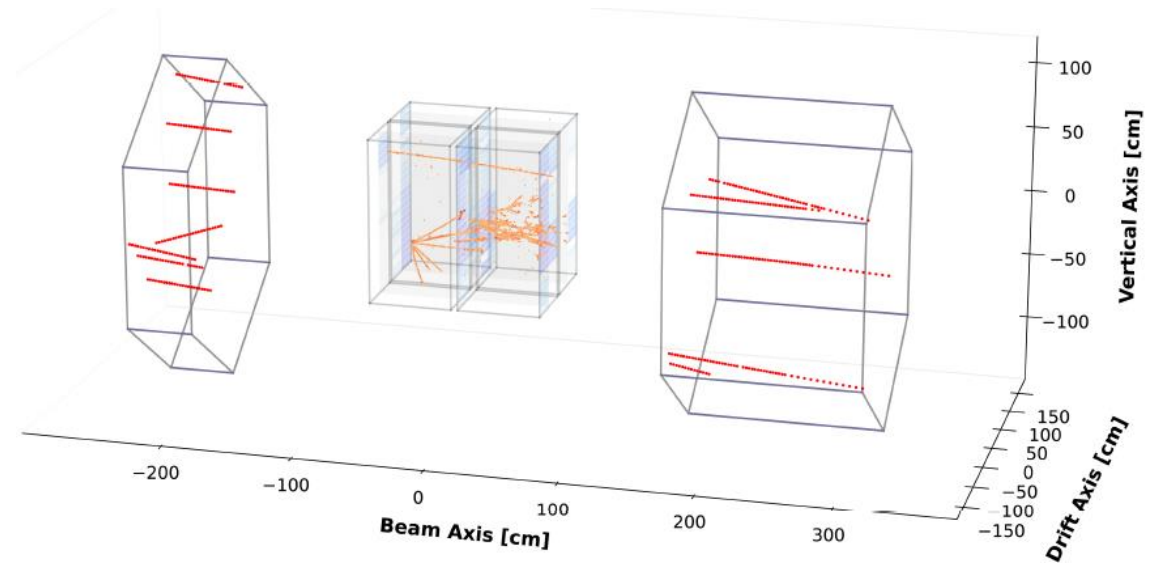


# 2x2 Neutrino Beam Data-Taking

- Collected 4.5 days of NuMI data.
- Total exposure of  $1.3E19$  POT.
  - Approximately 45k neutrino events.



Event display of charge and light data.



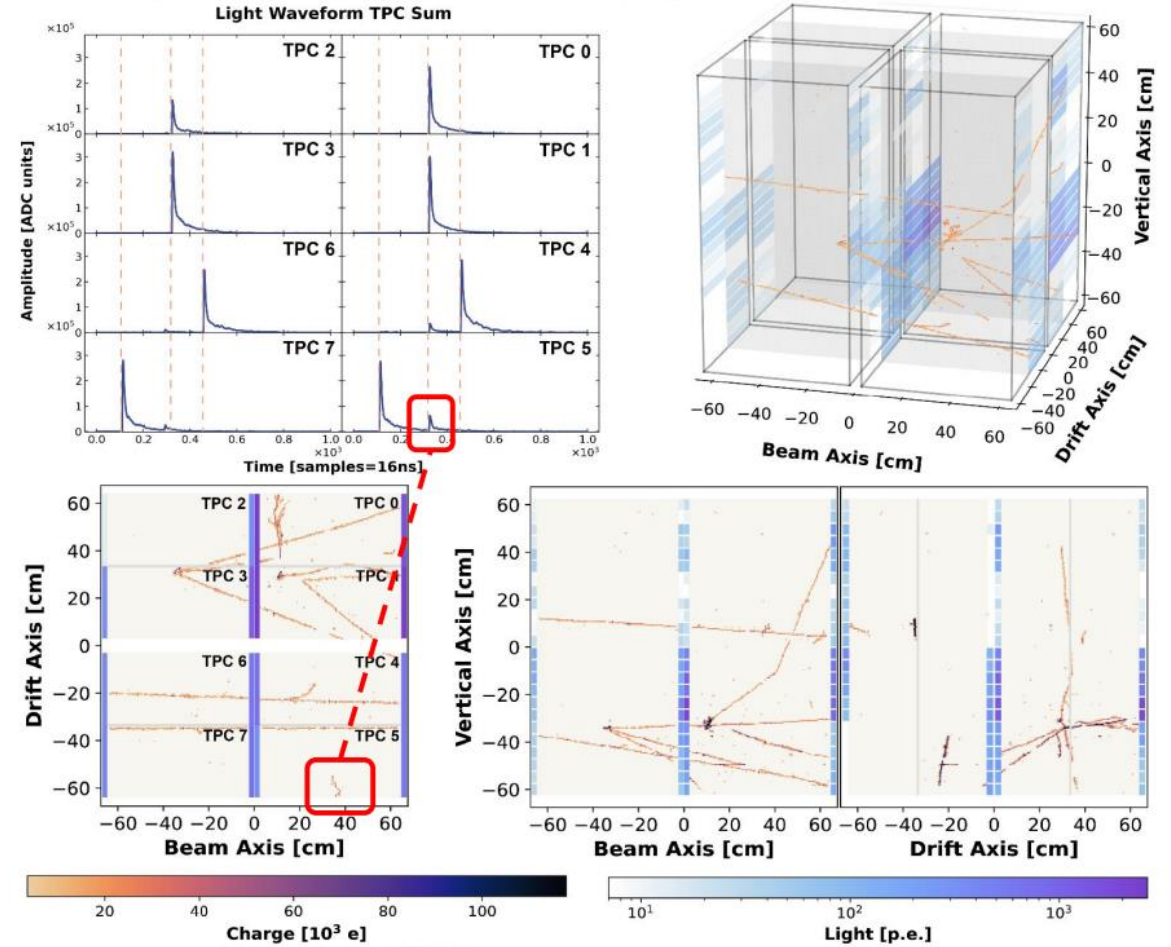
Event display of 2x2 charge data and tracks in MINERvA (red)

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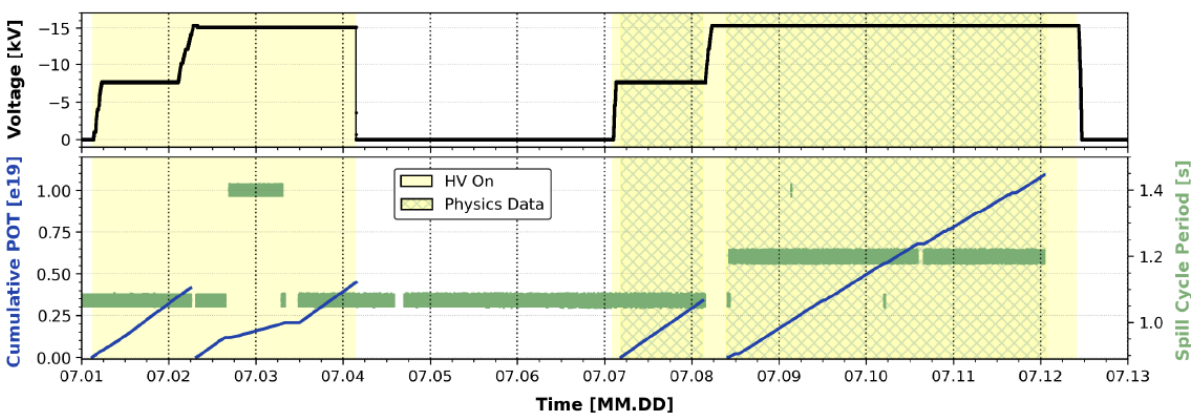
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DATA



NuMI Beam Status During 2x2 Voltage-On Periods

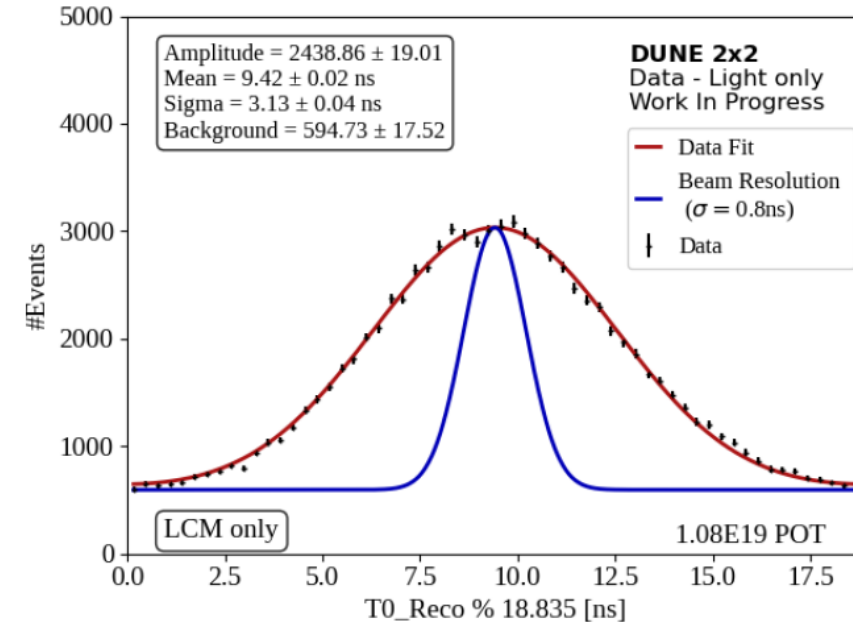


Collection of  $1.3E19$  P.O.T. over July 2024.

Event display of charge and light data, showing background rejection when compared to the through-going muon.

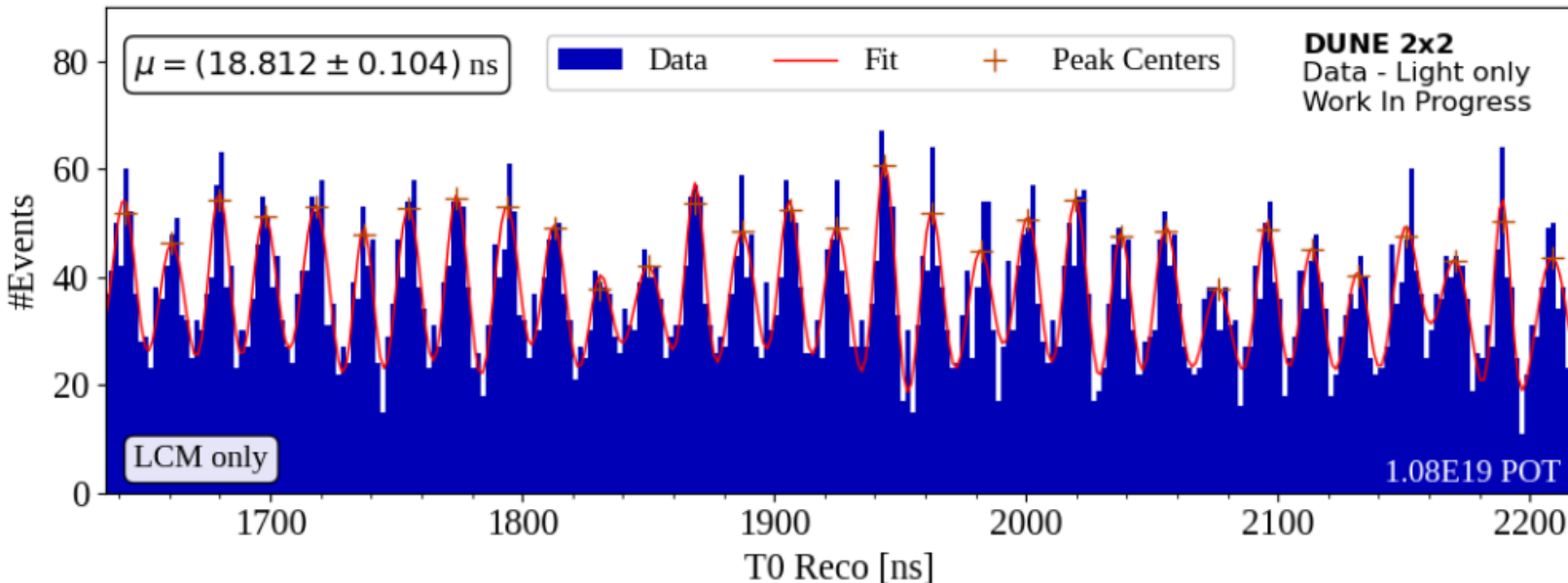
# 2x2 Preliminary Results

- Able to extract the beam structure using only the light readout.
- Timing resolution of 3.1 ns, showing definitive evidence of nanoscale timing with respect to the beam with ND-LAr concept.
  - Important for studying neutrino beam and BSM searches.



Fit of a single bunch of the NuMI beam using the scintillation light observed in 2x2 using a triple Gaussian function.

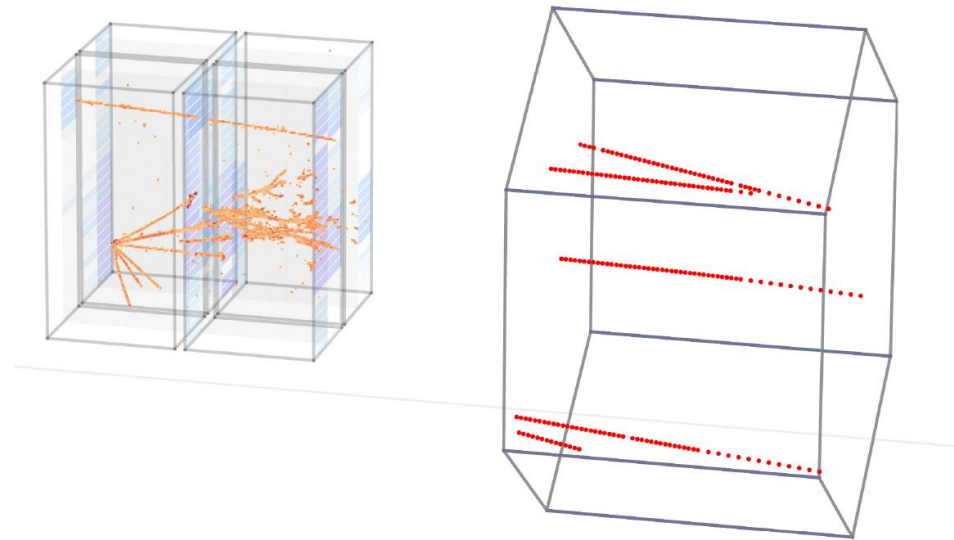
[Calivers, Livio. \*Demonstration of a Novel Modular Neutrino Detector\* \(PhD Thesis\).](#)



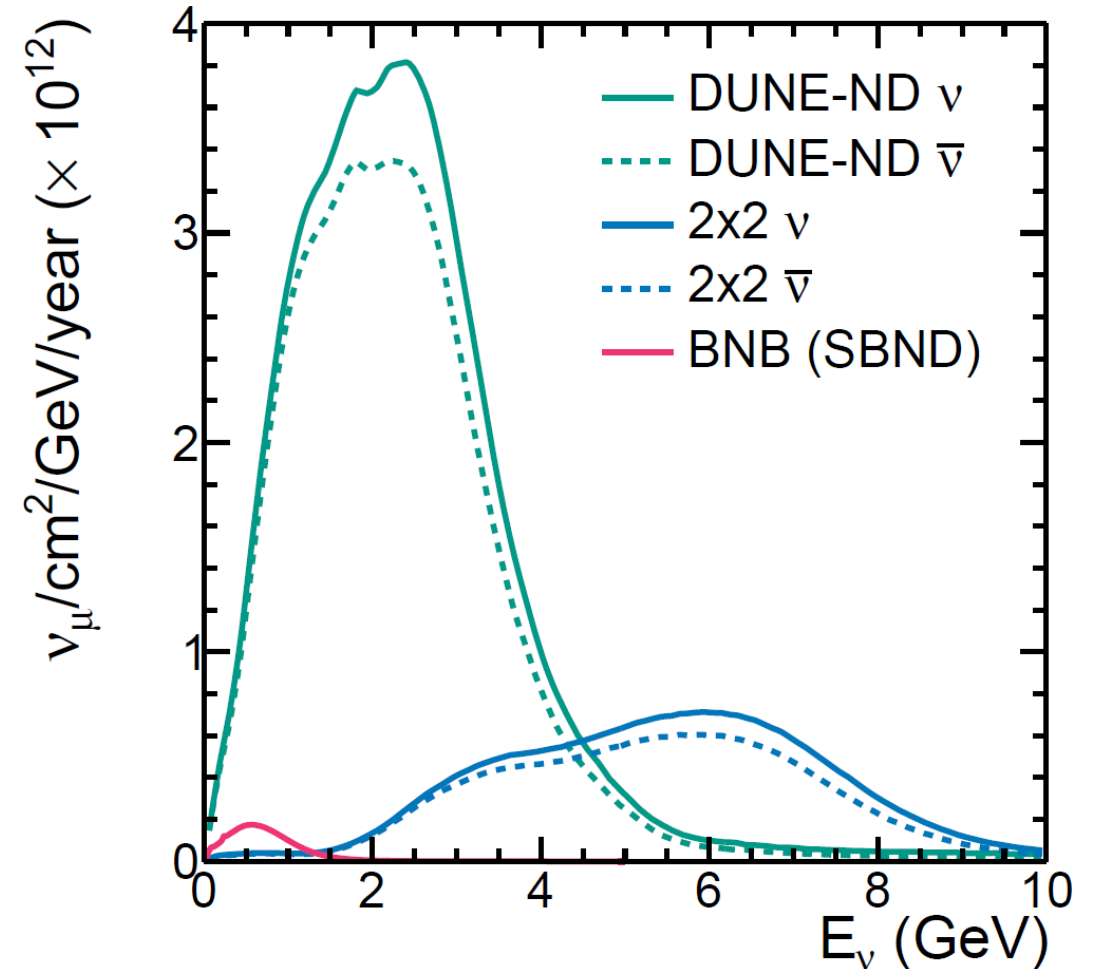
Timing distribution of the beam structure as measured by the light sensors and fit to multiple Gaussians (18 ns bunch spacing).

# 2x2 Ongoing Physics Studies

- Neutrino analyses are investigating:
  - Inclusive measurements
    - Includes 66% of DIS and RES interactions.
  - Neutron production (See [L. Mora-Lepin's talk!](#))
  - Mesonless with muon antineutrinos
  - Neutral pion production
  - NC elastic



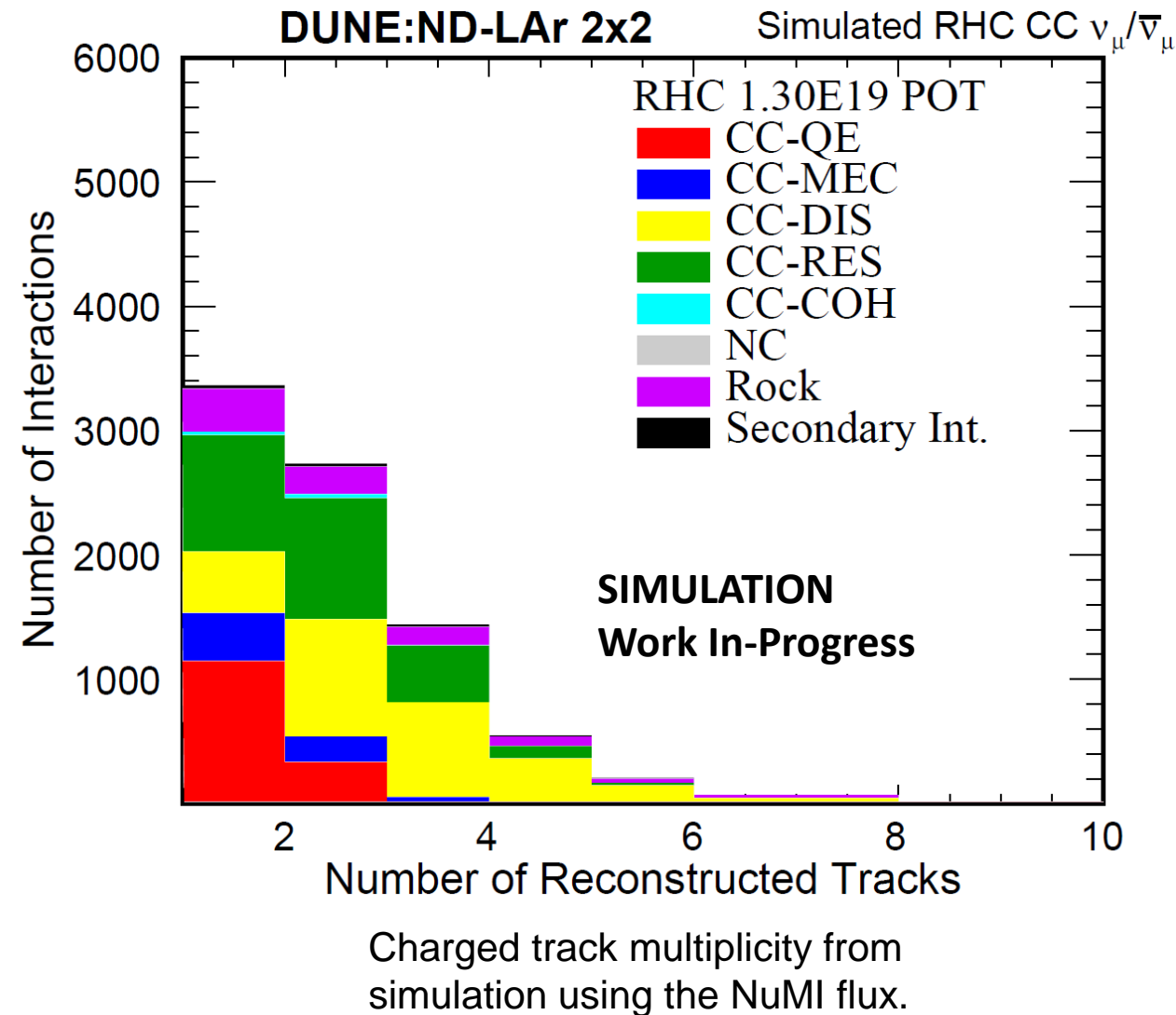
Like ND-LAr, muons are not contained and MINERvA acts as a muon catcher.



Comparisons of NuMI on-axis flux to BNB and DUNE (LBNF) fluxes.

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# Conclusion

- DUNE is a neutrino experiment under construction that needs a capable liquid argon near detector.
- ND-LAr addresses beam pile-up using modular, pixelated detectors with dielectric light traps.
- An extensive prototyping campaign has been developed over the past decade. These include:
  - Multiple ton-scale modules at the University of Bern.
  - A new neutrino detector based at Fermilab.
  - The first full-scale ND-LAr module at the University of Bern.
- Currently, we are operating the 2x2 Demonstrator for cosmic-ray and radioactive data-taking.
- In the future we plan to:
  - Operate the 2x2 Demonstrator in 2026 (aiming for data with ~1M neutrinos).
  - Continue operating full-scale demonstrator runs.
  - Begin production of the 35 ND-LAr modules.