Overview of the 2 x 2 Demonstrator: A Pixel-Based LArTPC Prototype for the DUNE Near Detector

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For more information on the DUNE program, please refer to the general talk

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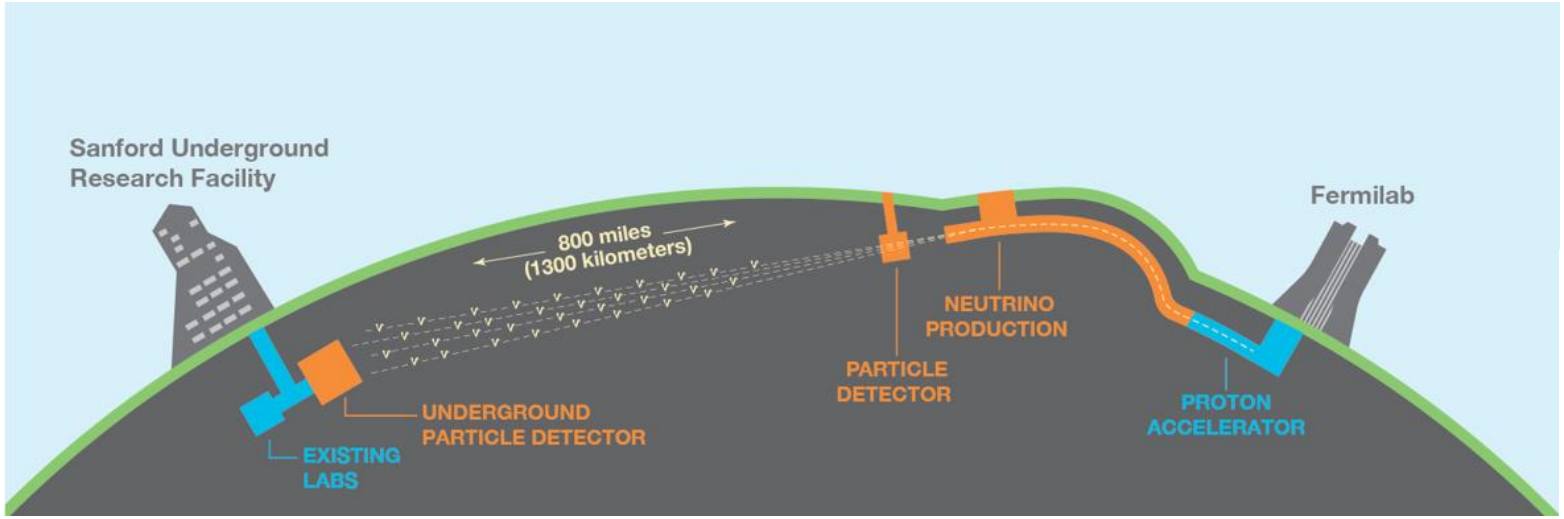
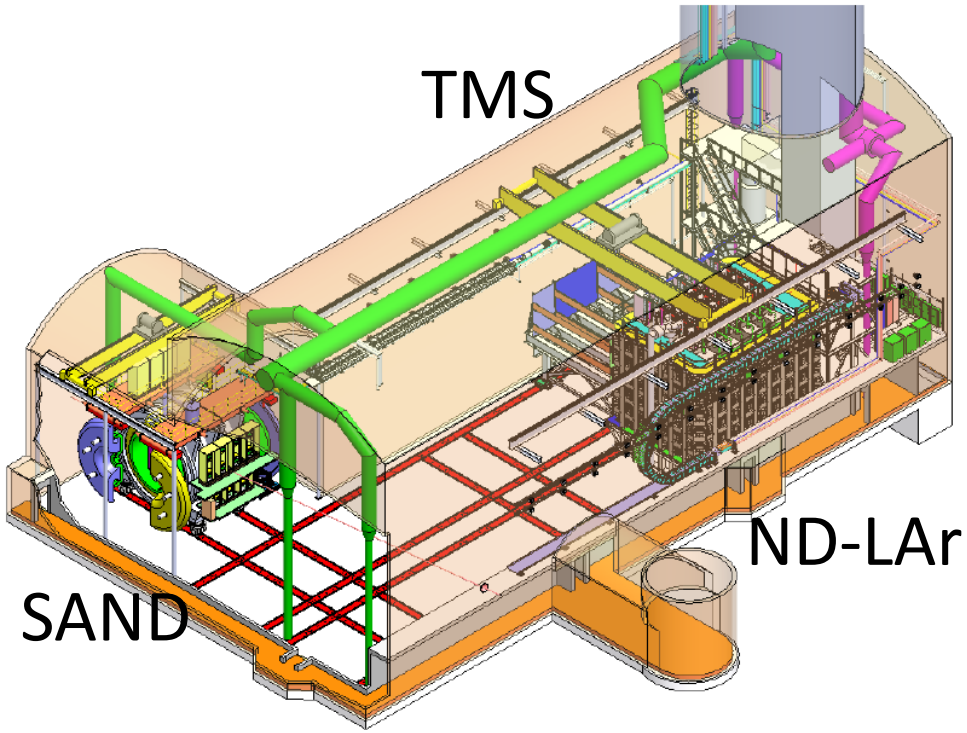
Deep Underground Neutrino Experiment

- Future long-baseline neutrino oscillation experiment based in the United States.
  - Primary Goals: Measure CP-violating phase and determine mass hierarchy.



Conceptual diagram of the DUNE oscillation program with the beam traveling right-to-left. Far site will contain around 70 kT liquid argon.

Near site and its three systems: the liquid argon detector (ND-LAr), the muon spectrometer (TMS), and the System for On-Axis Neutrino Detection (SAND). ND-LAr and TMS can move up to 30 m off-axis.



Neutrino Oscillation Measurements:

$N_{far\ detector}$=Det. Eff.*Cross Section*Flux*Osc. prob.

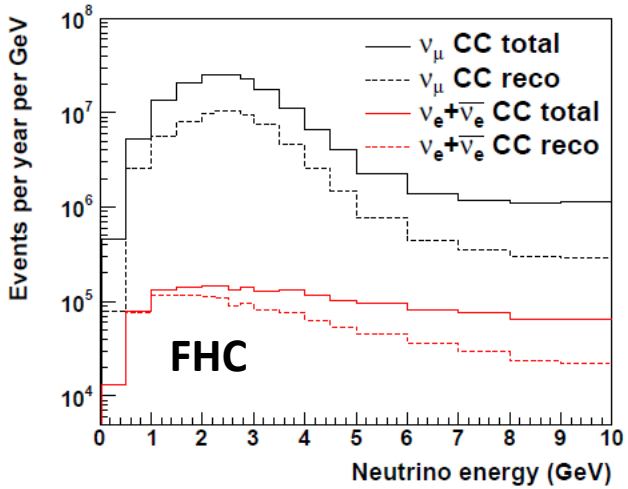
$N_{near\ detector}$=Det. Eff.*Cross Section*Flux

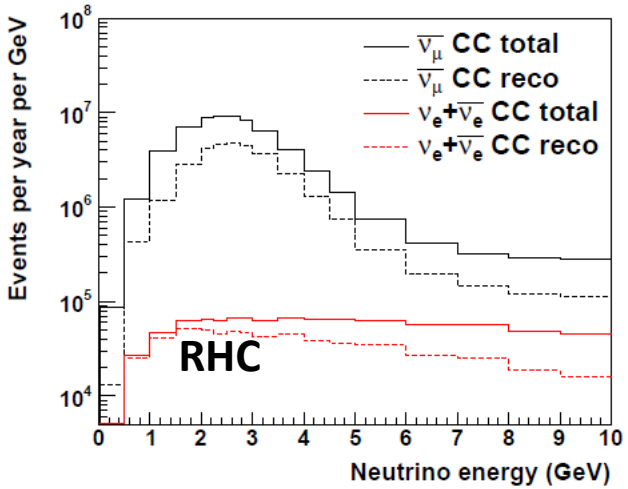
DUNE Neutrino Flux at the Near Site

- Will use a 1.2 MW beam, upgradeable to 2.4 MW.
- Estimated for ND-LAr to collect millions of neutrino interactions **per year** (1.1*1E23 POT).

Instruments **2021**, *5*(4), 31

Event rate as a function of energy (top) and event rate as a function of interaction type (bottom) for ND-LAr with 50-ton fiducial volume of liquid argon.





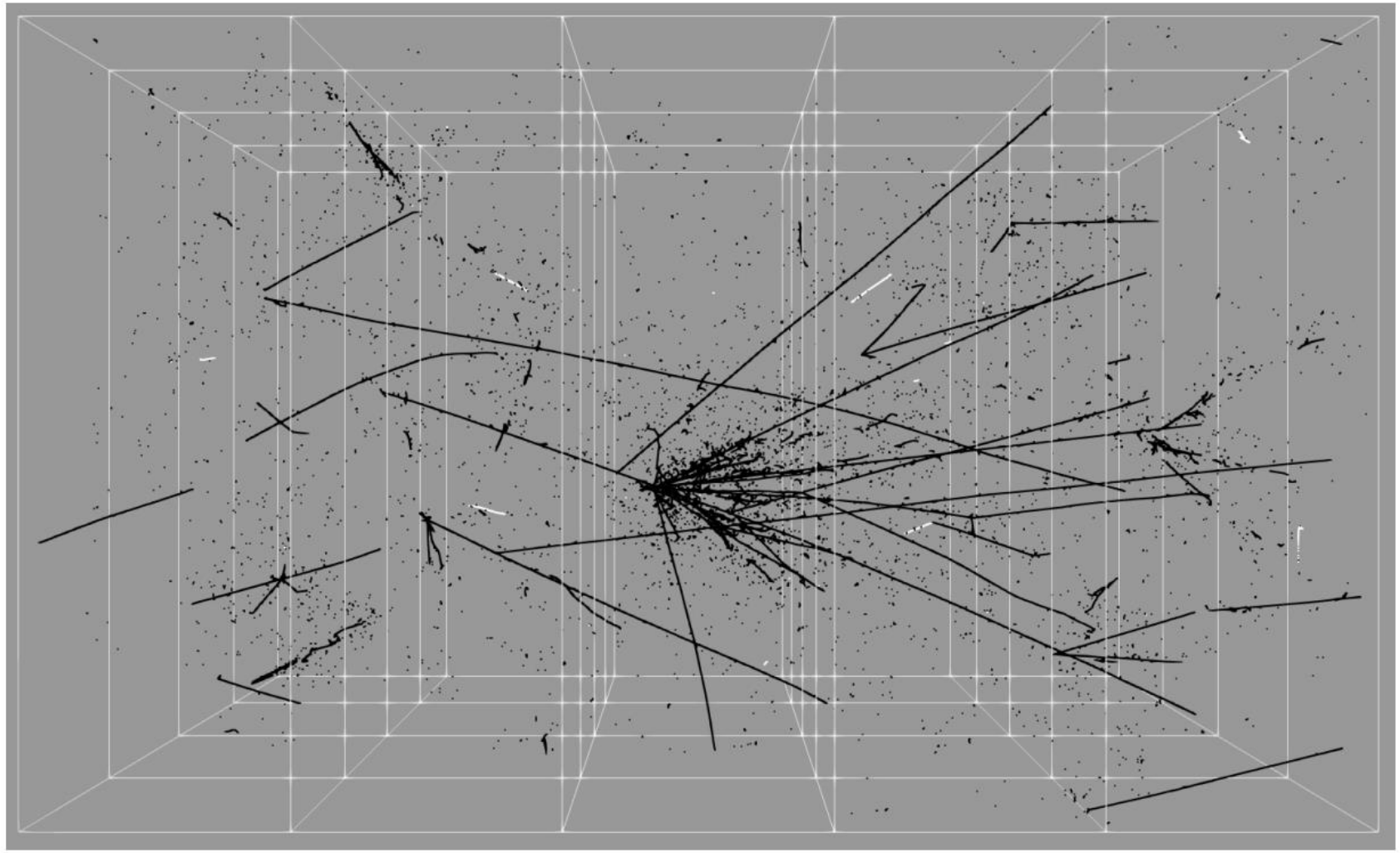
FHC

FHC mode	total	accepted	0.5 GeV to 4.0 GeV	accepted
ν_μ CC	8.2×10^7	3.0×10^7	5.9×10^7	2.4×10^7
$\bar{\nu}_\mu$ CC	3.6×10^6	1.4×10^6	1.1×10^6	4.6×10^5
NC total	2.8×10^7	1.6×10^7	1.9×10^7	1.3×10^7
ν_μ CC0π	2.9×10^7	1.6×10^7	2.6×10^7	1.3×10^7
ν_μ CC1$\pi^\pm$	2.0×10^7	7.5×10^6	1.7×10^7	6.0×10^6
ν_μ CC1π^0	8.0×10^6	2.9×10^6	6.5×10^6	2.2×10^6
ν_μ CC3π	4.6×10^6	7.2×10^5	1.7×10^6	3.8×10^5
ν_μ CC other	9.2×10^6	7.4×10^5	1.5×10^6	3.1×10^5
$\nu_e + \bar{\nu}_e$ CC	1.4×10^6	6.6×10^5	4.5×10^5	3.3×10^5
$\nu + e$ elastic	8.4×10^3	7.2×10^3	5.3×10^3	4.2×10^3

Neutrino Oscillation Measurements:
$N_{far\ detector}$=Det. Eff.*Cross Section*Flux*Osc. prob.
$N_{near\ detector}$=Det. Eff.*Cross Section*Flux

ND-LAr Simulated Event

- Tens of neutrino interactions per spill.
- Difficult to disentangle individual interactions and overlapping signals.



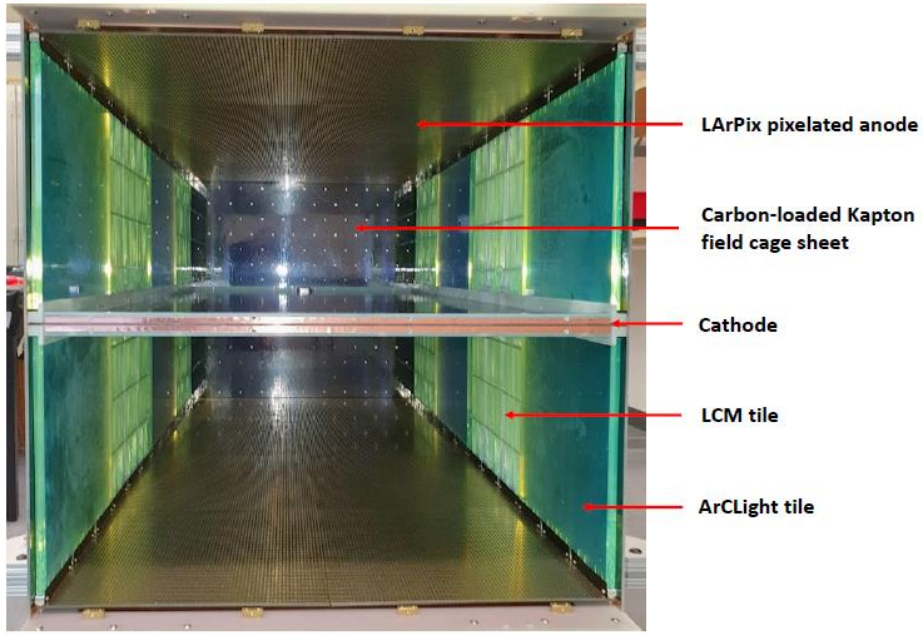
Neutrino Oscillation Measurements:
$N_{far\ detector}$=Det. Eff.*Cross Section*Flux*Osc. prob.
$N_{near\ detector}$=Det. Eff.*Cross Section*Flux

Simulated neutrino spill in a ND-LAr environment with charged particles from the neutrino interactio
(black) and secondary protons from primary neutrons scattering off the argon (white).

Instruments **2021**, *5*(4), 31

DUNE ND-LAr Design Concept

- Problem: Disentangling overlapping signals (pile-up)
  - Solution: Fully native 3D using pixel-based charge readout.
- Problem: Charge-light matching difficult for displaced signals.
  - Solution: 35 modular detectors in an array of 7 (wide) by 5 (long) with 70 optically segmented time projection chambers.



Cross section image of a ND-LAr prototype module looking from the bottom of the module. The sides are instrumented with the light readout system and the top and bottom with the pixel charge readout.

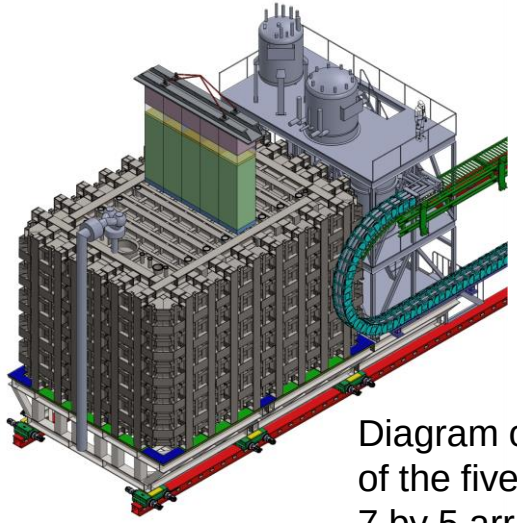
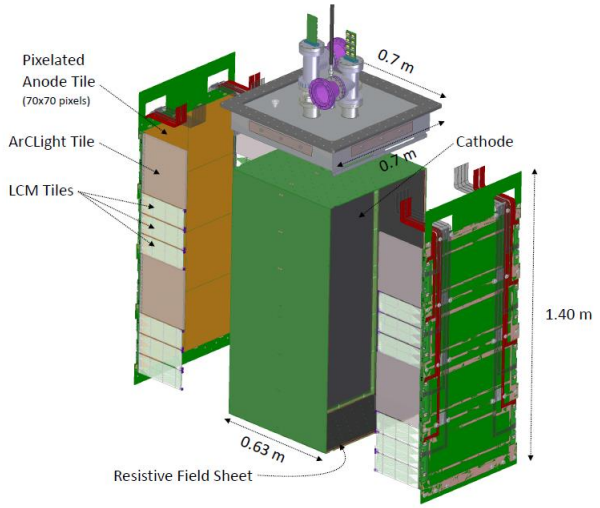


Diagram of the full ND-LAr system with one of the five rows of modules pulled out of the 7 by 5 array.

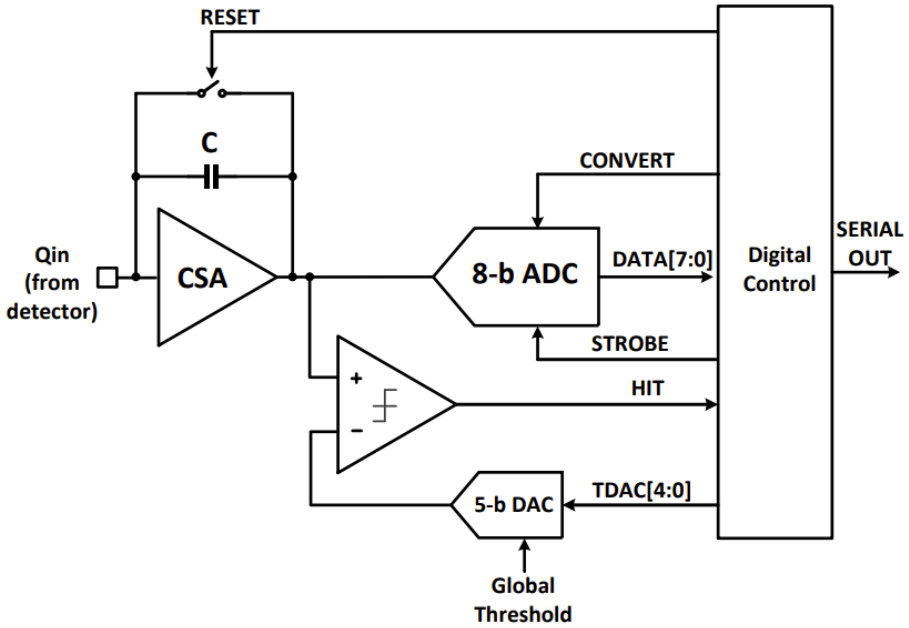


Conceptual drawing of a ND-LAr prototype module with full instrumentation. The full module will be 1 m wide x 1 m long x 3 m tall.

Charge Readout System

JINST **13** P10007

- Gold-plated readout plates connected to 64 channel readout ASICs, named LArPix.
- <4 mm spacing to match far site.
  - Over 60,000 channels per square meter!
  - ND-LAr will have 200 m^2 of channels.
    - 1.2 million channels!



Schematic drawing of the LArPix readout concept.

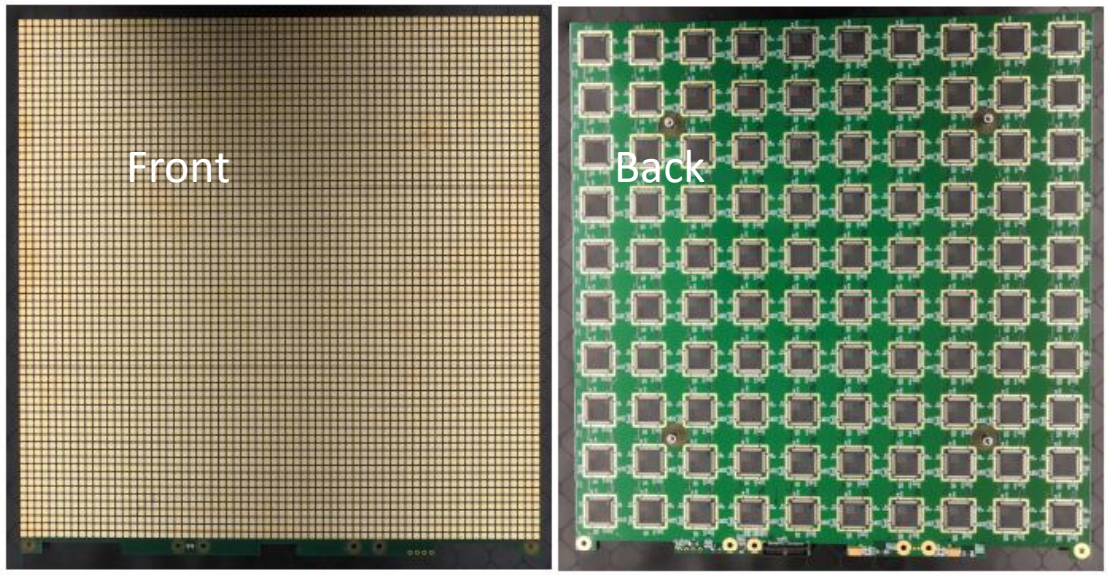


Image of a ND-LAr prototype charge readout board.

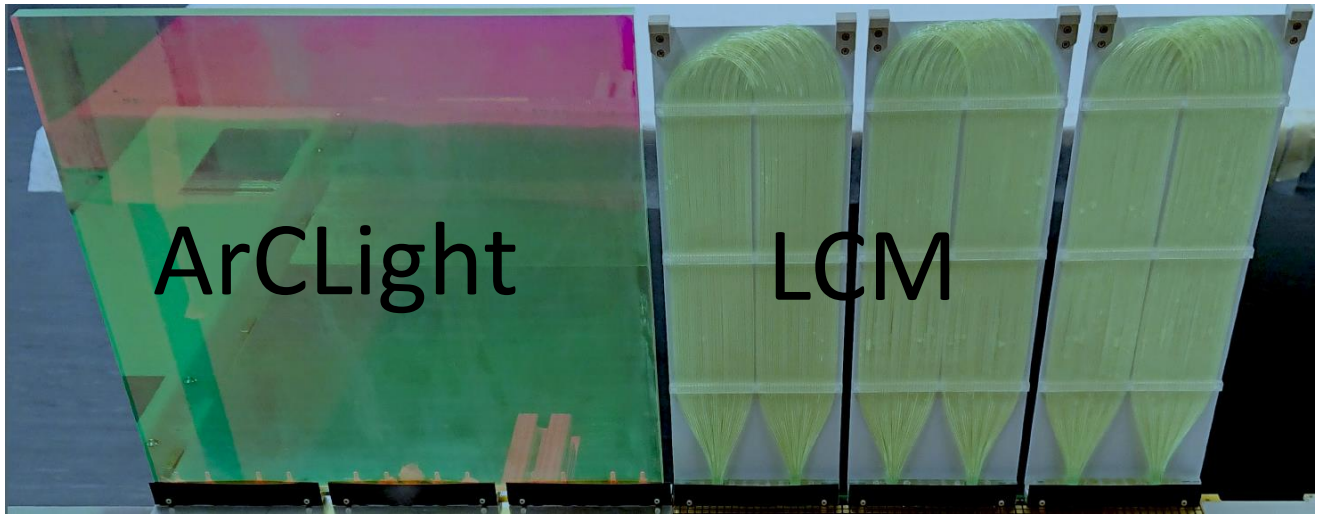
Specification	Value	Comment
Analog inputs	32	Single-ended input
Gain	4 μV/e$^-$	Optional high gain mode of 45 μV/e$^-$
Noise	500 e$^-$ ENC	
Power	<100 μW/channel	
Dynamic Range	1.2 V	Corresponds to ~3×10^5 electrons
ADC Resolution	8 bits	*(See discussion in section 3.7.)*
ADC LSB	(tunable)	Default: 2 mV
Threshold range	0 to 1.8 V	Tunable via global and channel trim DACs
Threshold resolution	<1 mV	Tunable via external bias resistor
Channel linearity	1%	
Timestamp precision	1 clock cycle	200 ns, with a 5 MHz system clock
Minimum resample time	11 clock cycles	From 0.55 μs to 4.4 μs (2.5 to 20 MHz)
Operating temperature	80 to 300 K	
FIFO event memory depth	2048	
Digital data rate	5 Mb/s	With a 5 MHz system clock

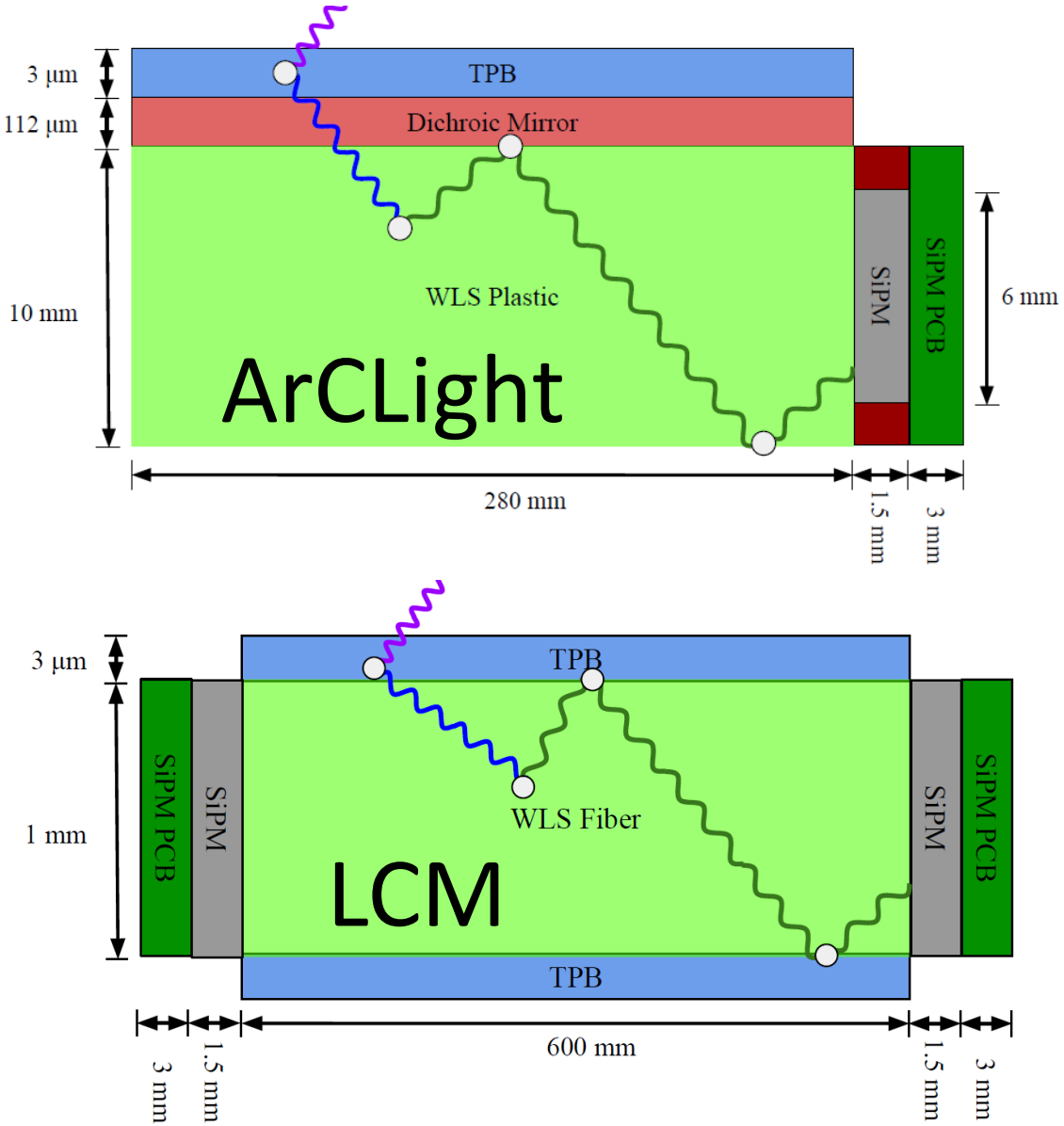
Specifications of LArPix charge readout chip.

Light Readout System

JINST **18** C04004

- Two small-footprint systems based on concept of a light trap (*JINST* **11** C02004).
  - Light collection module (fiber)
  - ArgonCube Light System (plastic)
- Both use Hamamatsu S13360-6050PE SiPMs read by a 62.5 MHz ADC

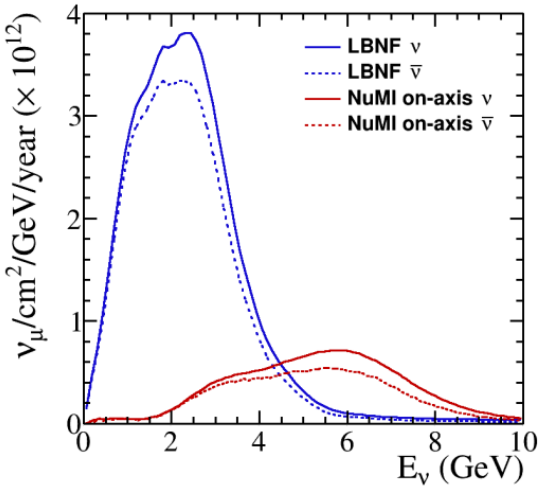




Picture of the two light readout systems (left) and cartoon of their operating principles (right).

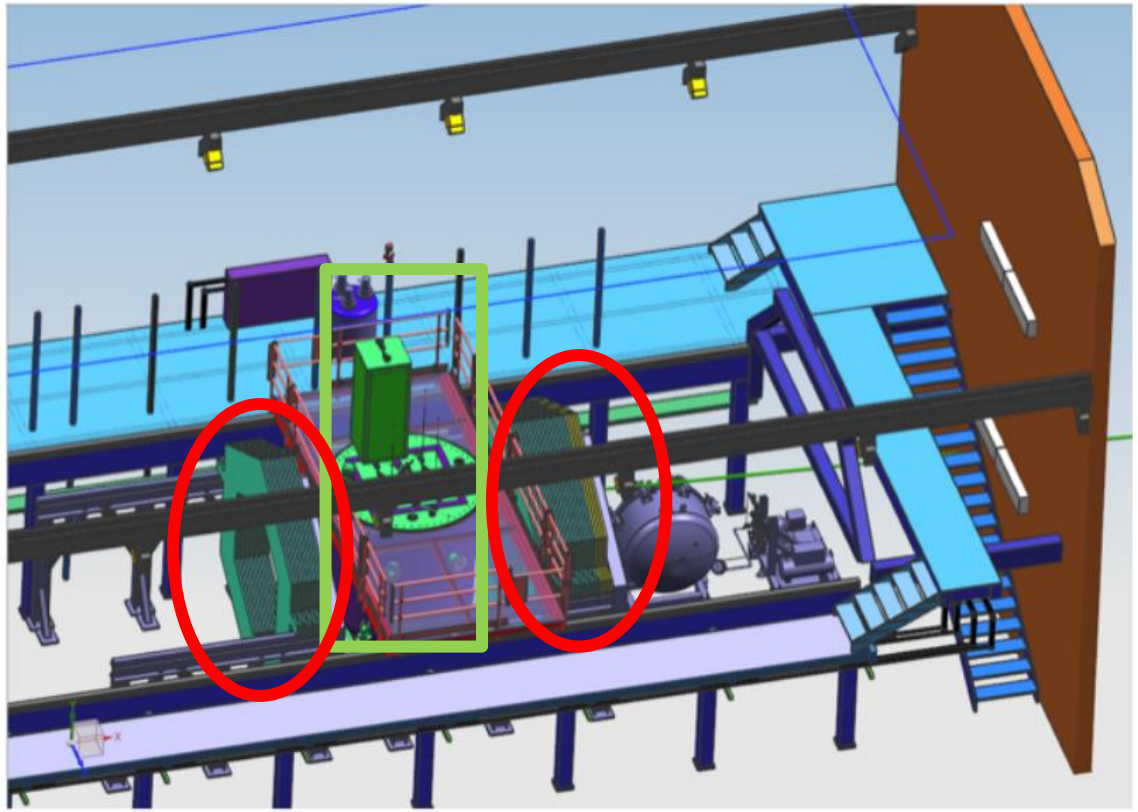
2 x 2 Demonstrator at Fermilab

- Prototyping campaign using NuMI beam in the MINOS Near Detector cavern at Fermilab.
- Contains four, slightly smaller, modules.
  - Module: ~0.6 m by ~0.6 m by ~1.2 m.
- Demonstrate novel technologies in an intense-beam environment.



Expected event rate between DUNE and NuMI.

Image of the cryostat.

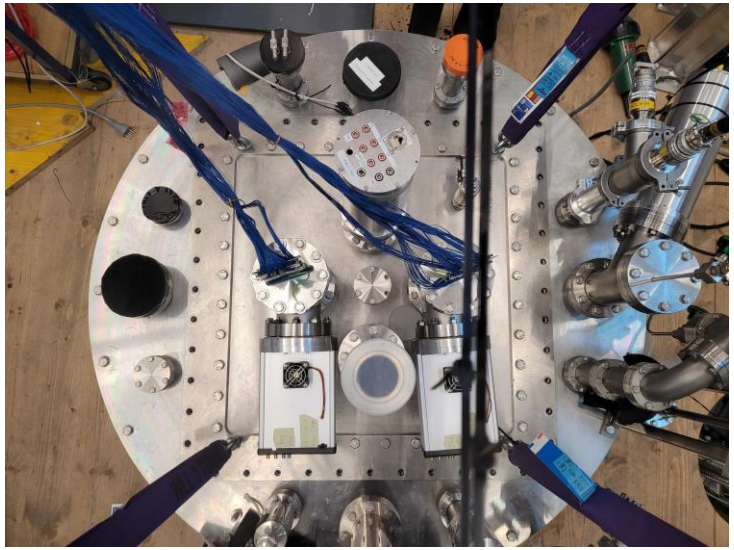


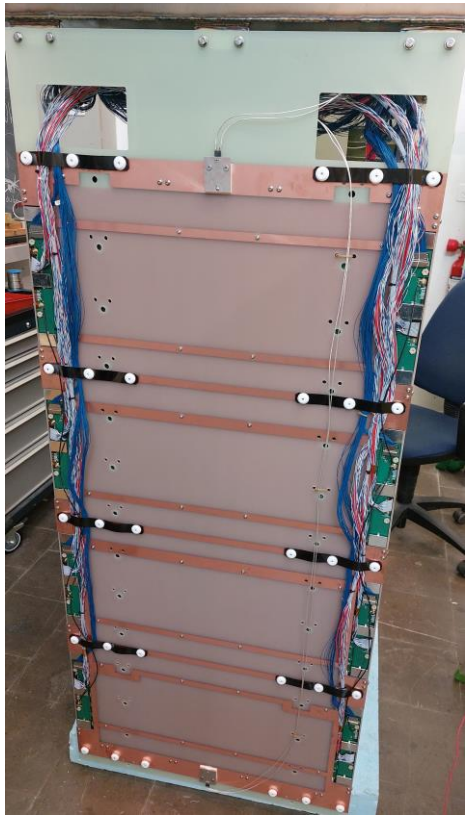
Conceptual diagram of the 2 x 2 Demonstrator (rectangle in green) with MINERvA scintillation detectors as muon taggers (circled in red).

Instruments **2021**, *5*(4), 31

Path to the 2 x 2 Demonstrator

- Four prototype modules were constructed between 2021-2022.
- Commissioned at the University of Bern.

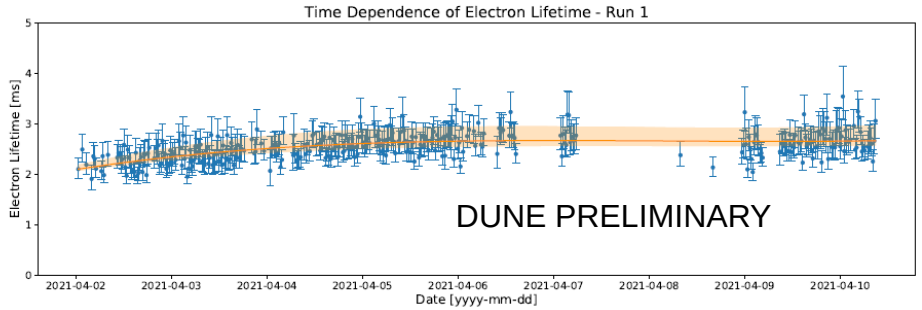


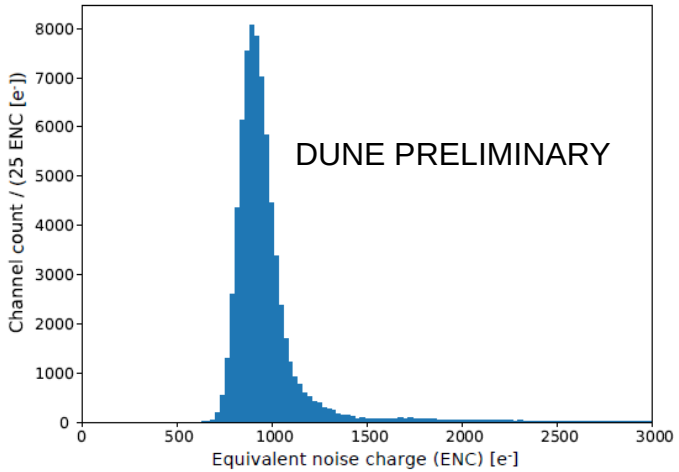


Commissioning Results at Bern

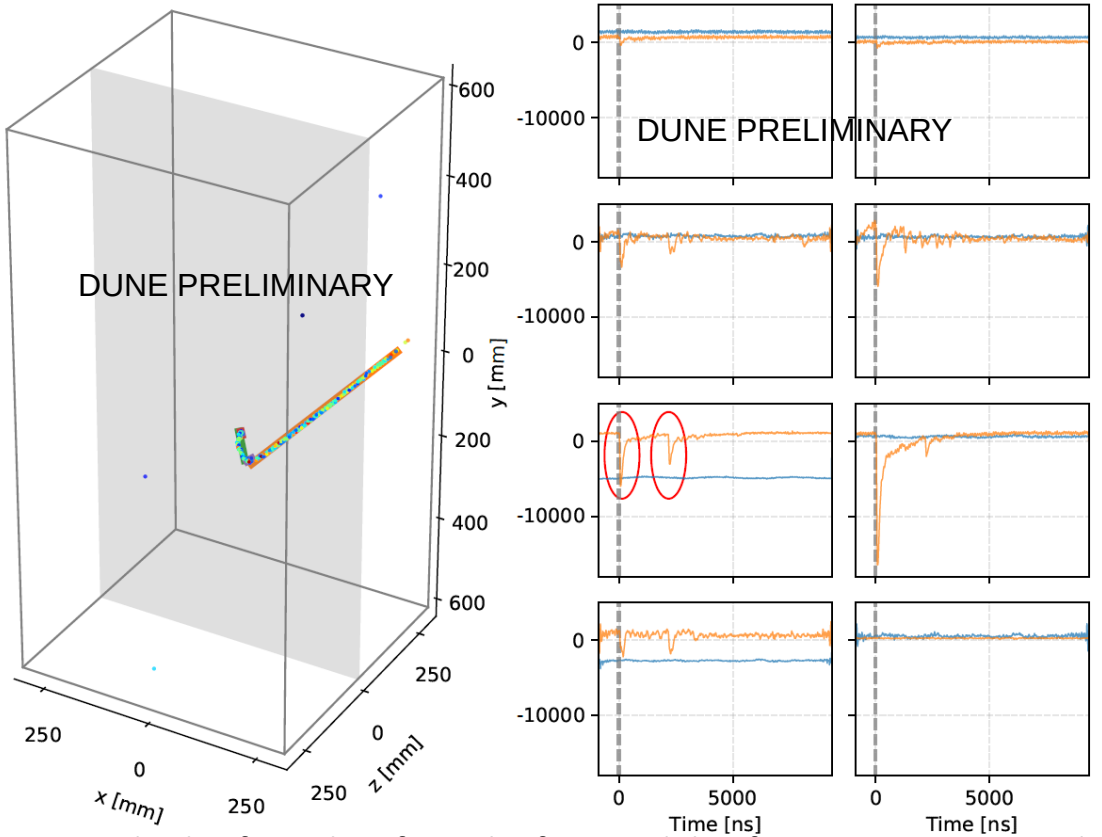
- All four modules took cosmic-ray data at the University of Bern.
  - Hundreds of millions events taken across all four detectors.

Measurement of the free electron lifetime in Bern cryogenic system. Corresponds to maximum charge loss of 5.9%.





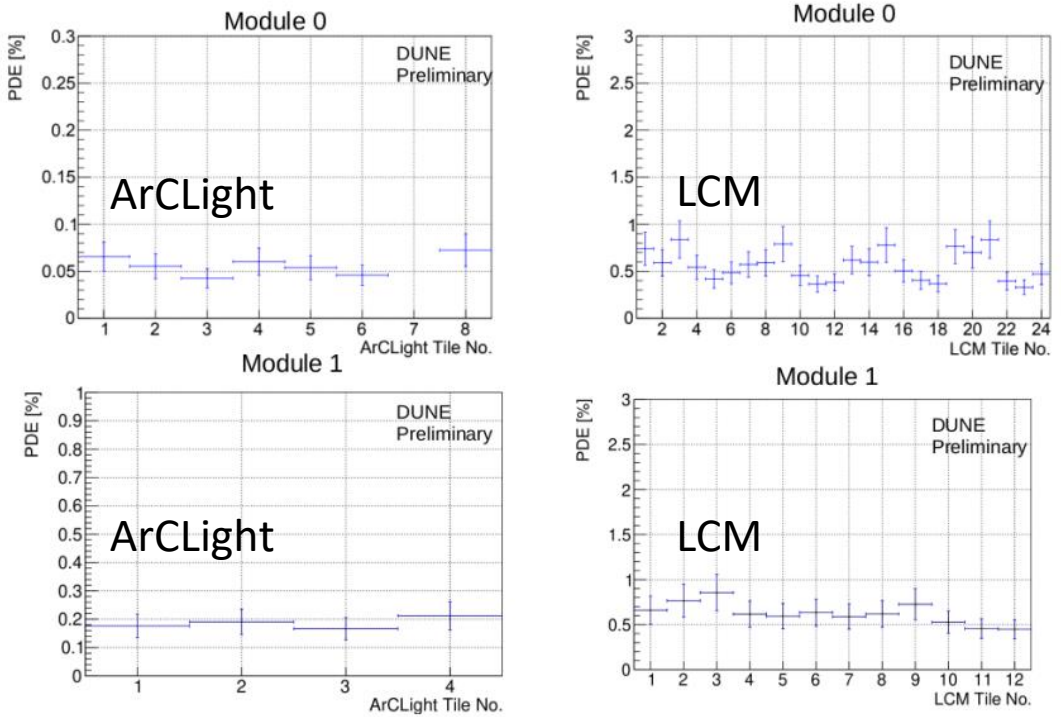
Measurement from first module of charge readout noise.



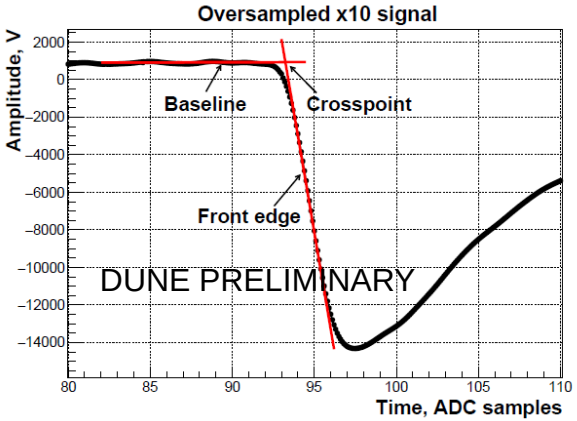
Event display from data from the first module of a muon stopping and decaying to a Michel electron. Charge readout (left) and light readout (right) are shown.

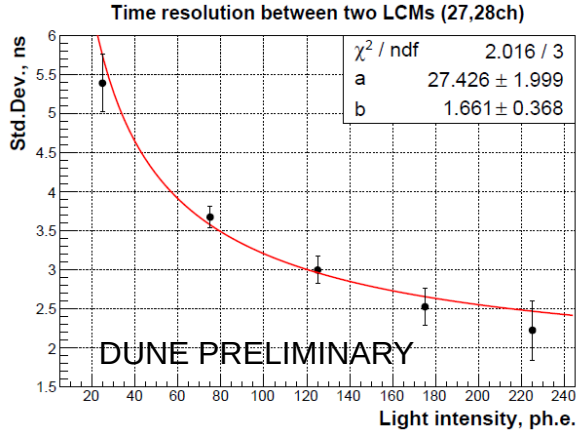
Commissioning Results at Bern

- Light detector specifications:
  - Timing resolution: <10 ns (Both)
  - Spatial resolution <10 cm (ArCLights)
  - Photon detection efficiency >1% (LCMs)
- All achieved using cosmic-ray muon data.



Photon detection efficiency for the ArCLights and LCMs for the first (top) and second (bottom) prototype modules produced (Module 0 and Module 1) for ArCLights (left) and LCMs (right) (*JINST* **18** C04004).

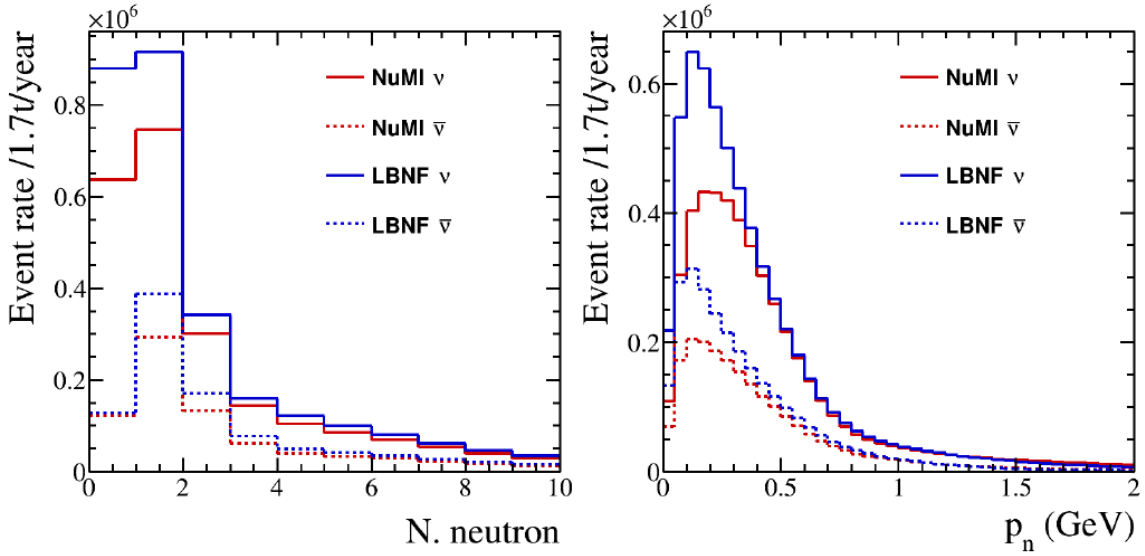




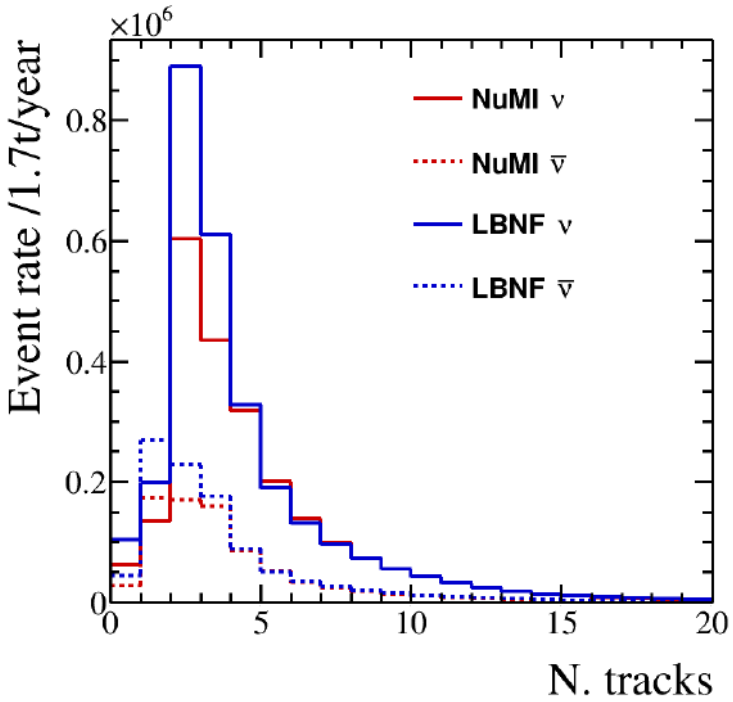
Timing resolution measured using oversampling for cosmic-ray muon waveforms from the LCMs, sampling frequency is 16 ns (*JINST* **18** C04004).

~~Detector~~ Physics Program

- First DUNE neutrino data (NuMI on-axis RHC)
- Unique det. with comparable beam dist. to DUNE beam:
  - Test reconstruction of ν-induced charged particles.
  - Tag and reconstruct neutrons using secondary protons.
  - Show precision light-charge matching across modules.



Number of neutrons and the neutron momentum distributions for the simulations of the NuMI and DUNE beams.



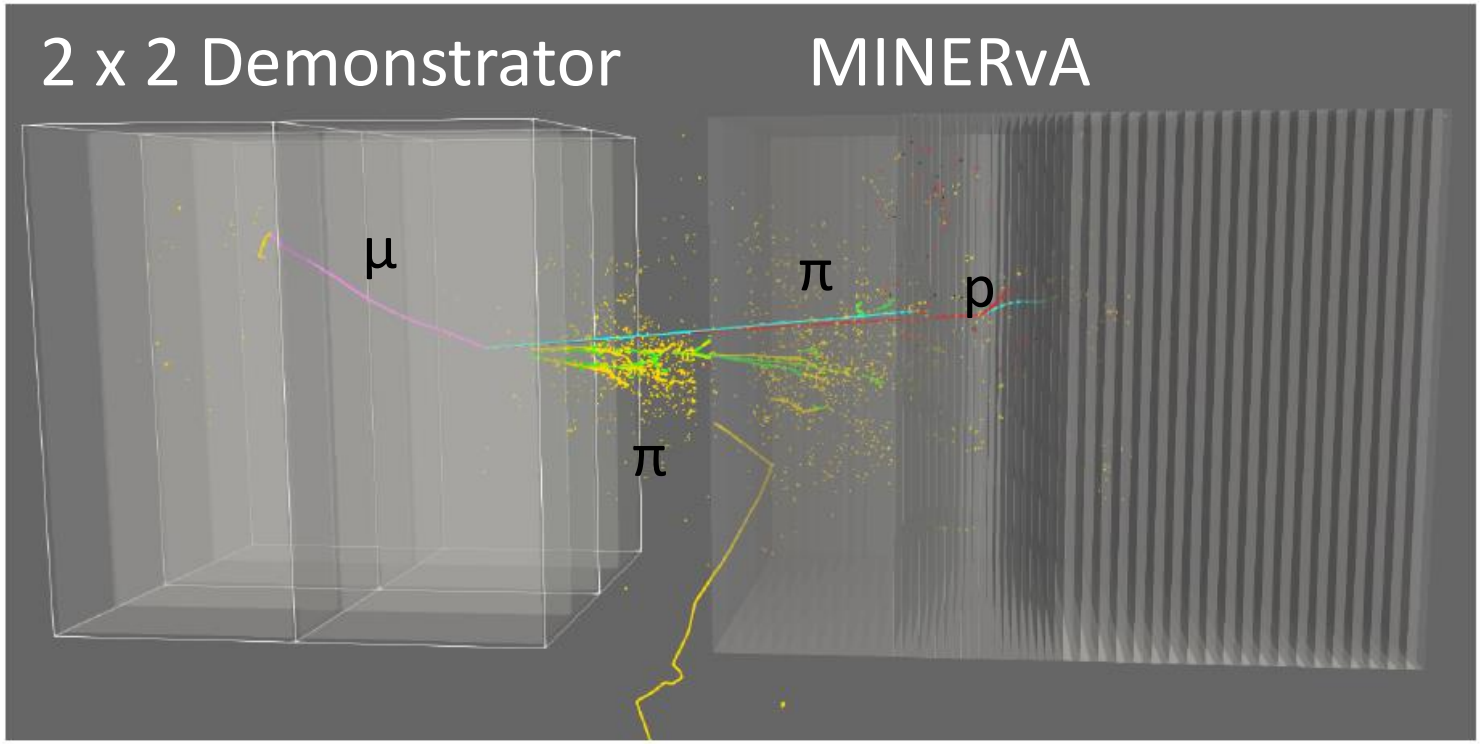
Number of charged particle tracks from simulation comparing the NuMI beam and the DUNE beam with the forward horn current beam. Similar to first study by MicroBooNE.

Instruments **2021**, *5*(4), 31

Conclusion

- DUNE ND-LAr is a modular liquid argon detector planned to handle the high intensity of the DUNE beam.
- The 2 x 2 Demonstrator prototypes DUNE ND-LAr technology and reconstruction capabilities in the NuMI beam at Fermilab.
  - Begins neutrino beam data-taking in early 2024.

Instruments **2021**, *5*(4), 31



Example neutrino event with a 7 GeV/c muon neutrino in the 2 x 2 Demonstrator with containment aided by MINERvA.