Physics Potentials of the 2×2 Demonstrator in the NuMI Beam

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On behalf of the DUNE Collaboration

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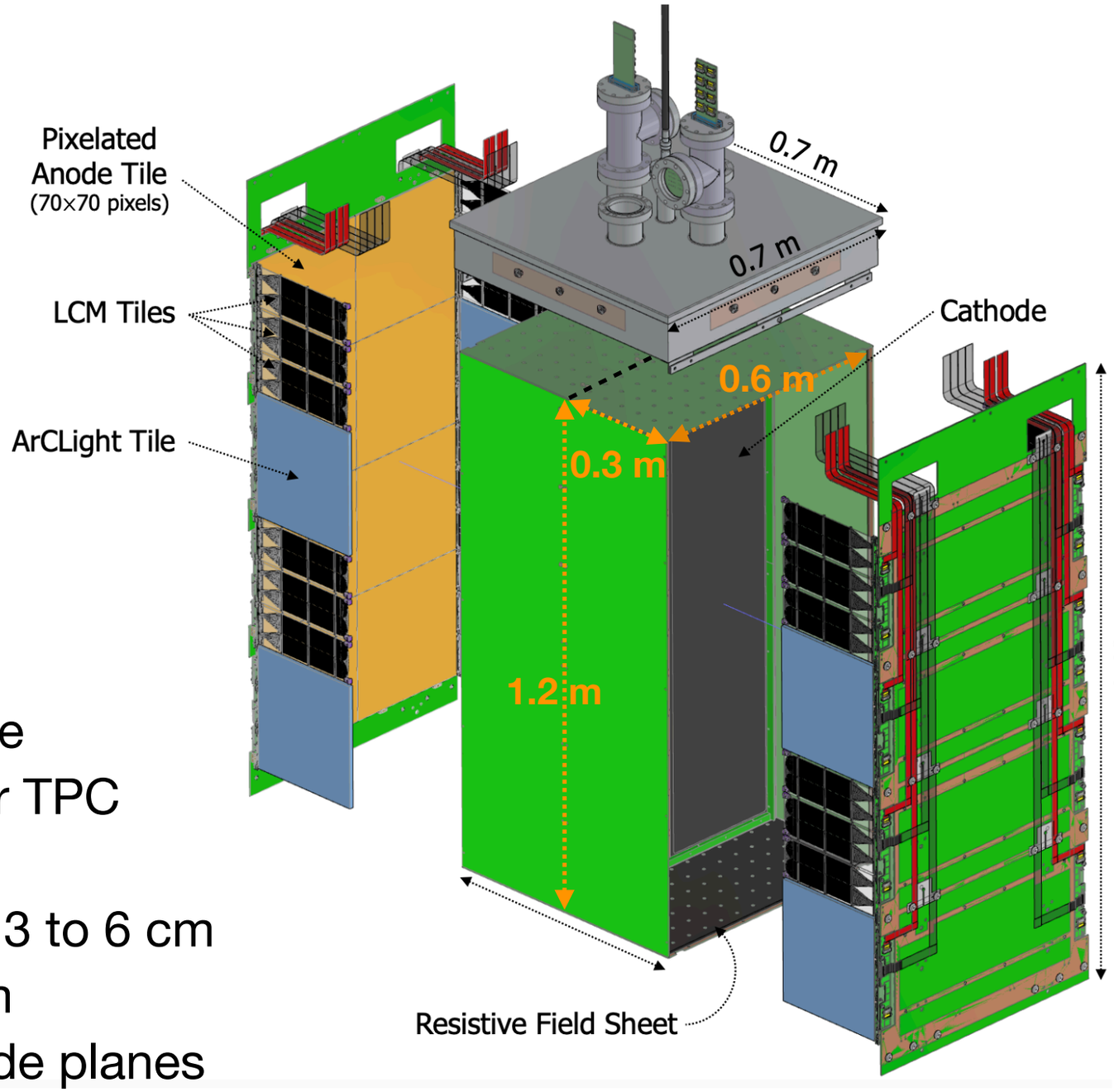
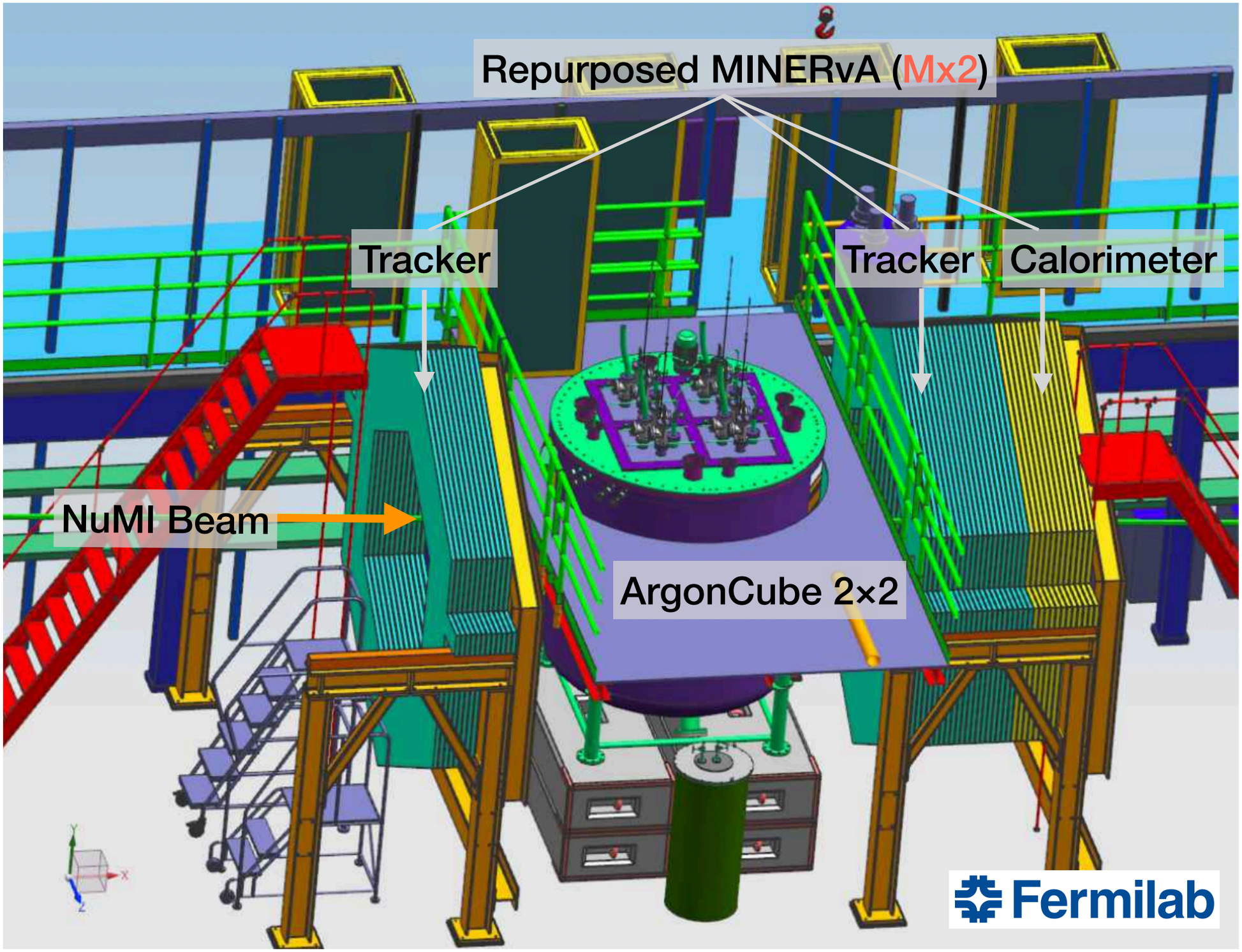
The 2×2 Demonstrator: A modularized LArTPC



- 4 modules in total, 2 TPCs per module
- 0.6 m (W) ×1.2 m (H) ×0.3 m (drift) per TPC
- 2×2 active mass ~2.4 t
- TPC gaps to the neighboring module 3 to 6 cm
- The nominal electric field is 0.5 kV/cm
- The NuMI beam is parallel to the anode planes

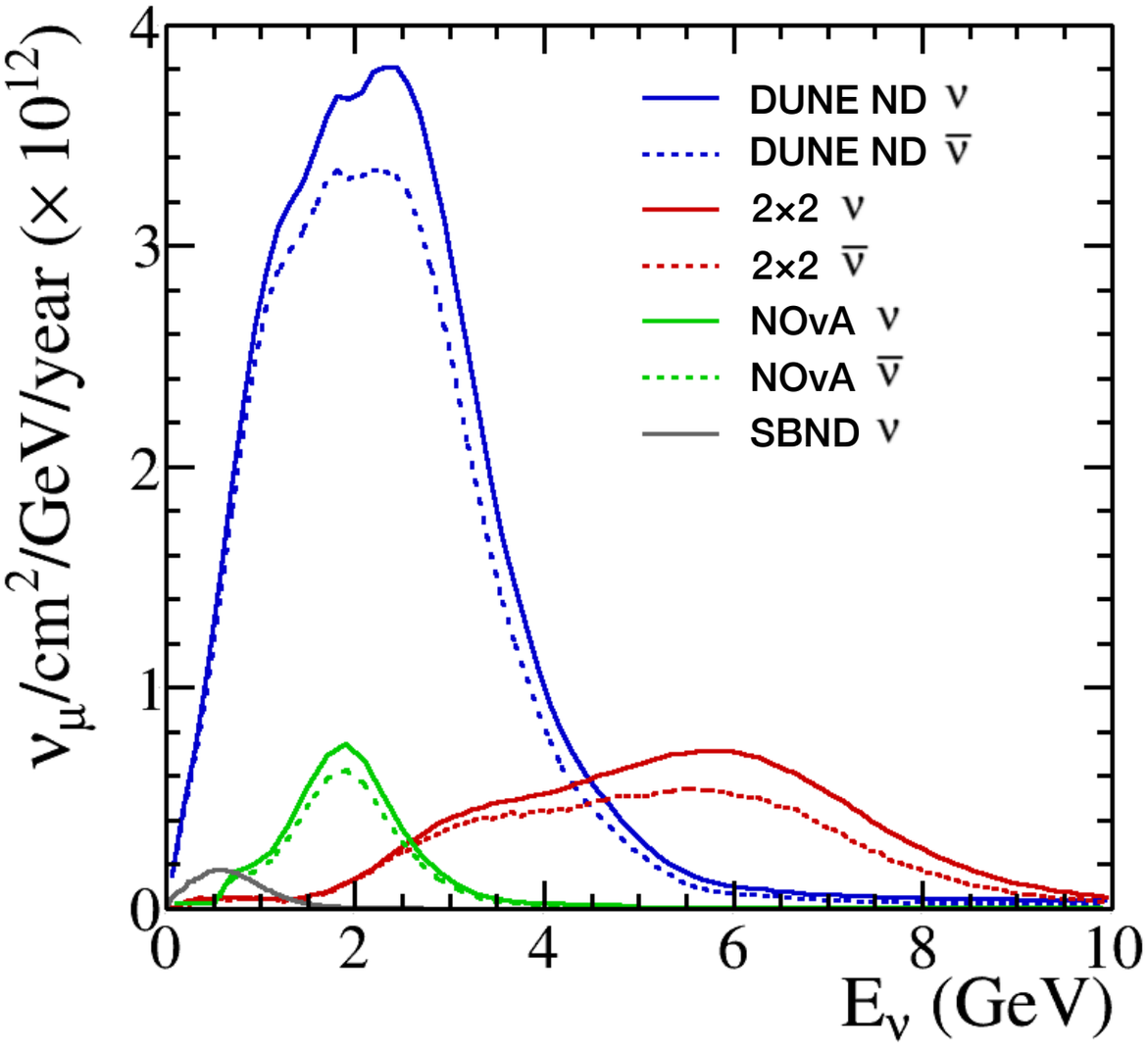
The 2×2 Demonstrator in the NuMI Beam



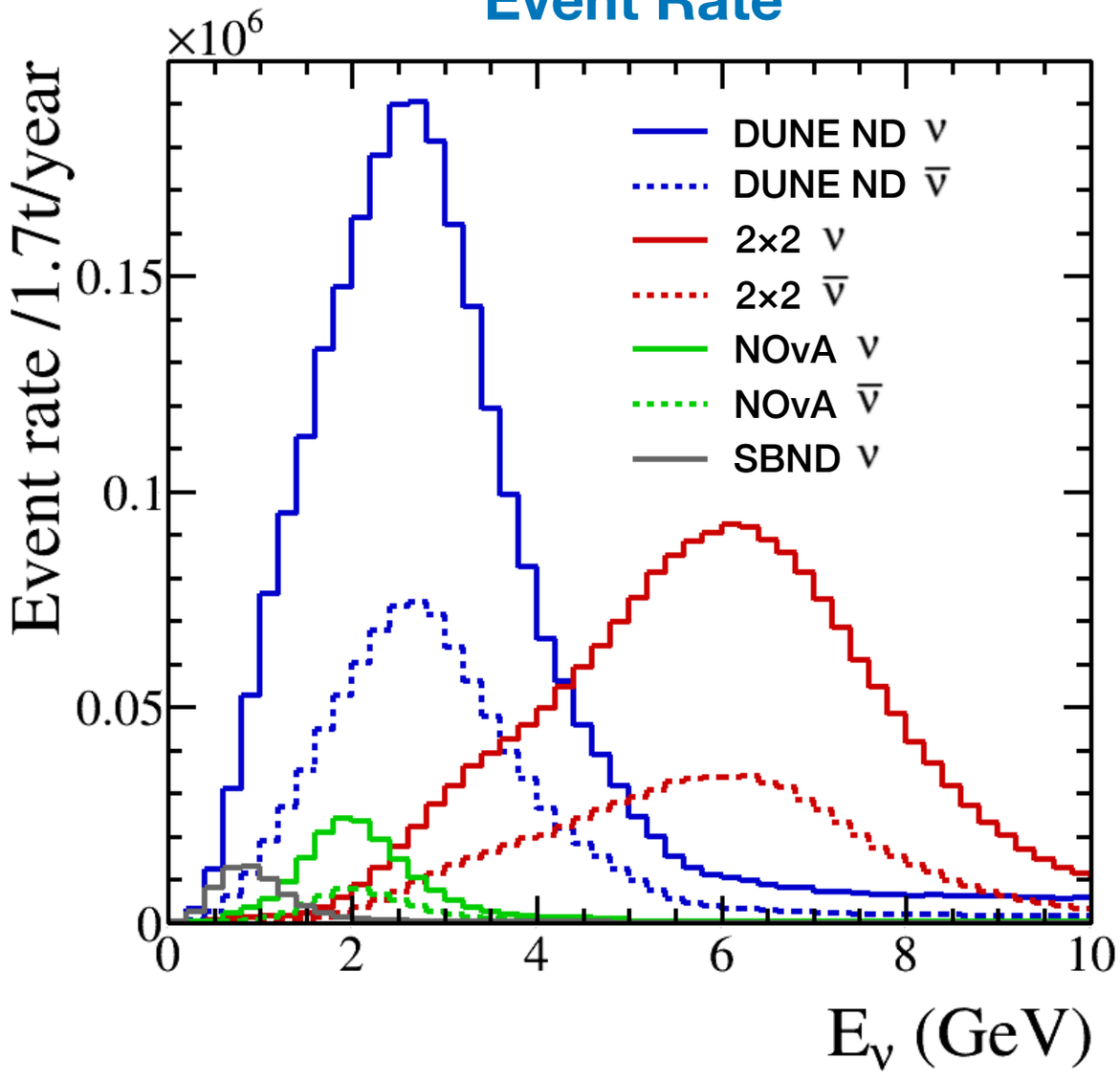
2×2 to Explore Neutrino-Argon Interactions

2x2 covers a wide range of phase space
towards the higher end of the energy spectrum on DUNE
Will measure ν-Ar interactions
Complementary to other experiments

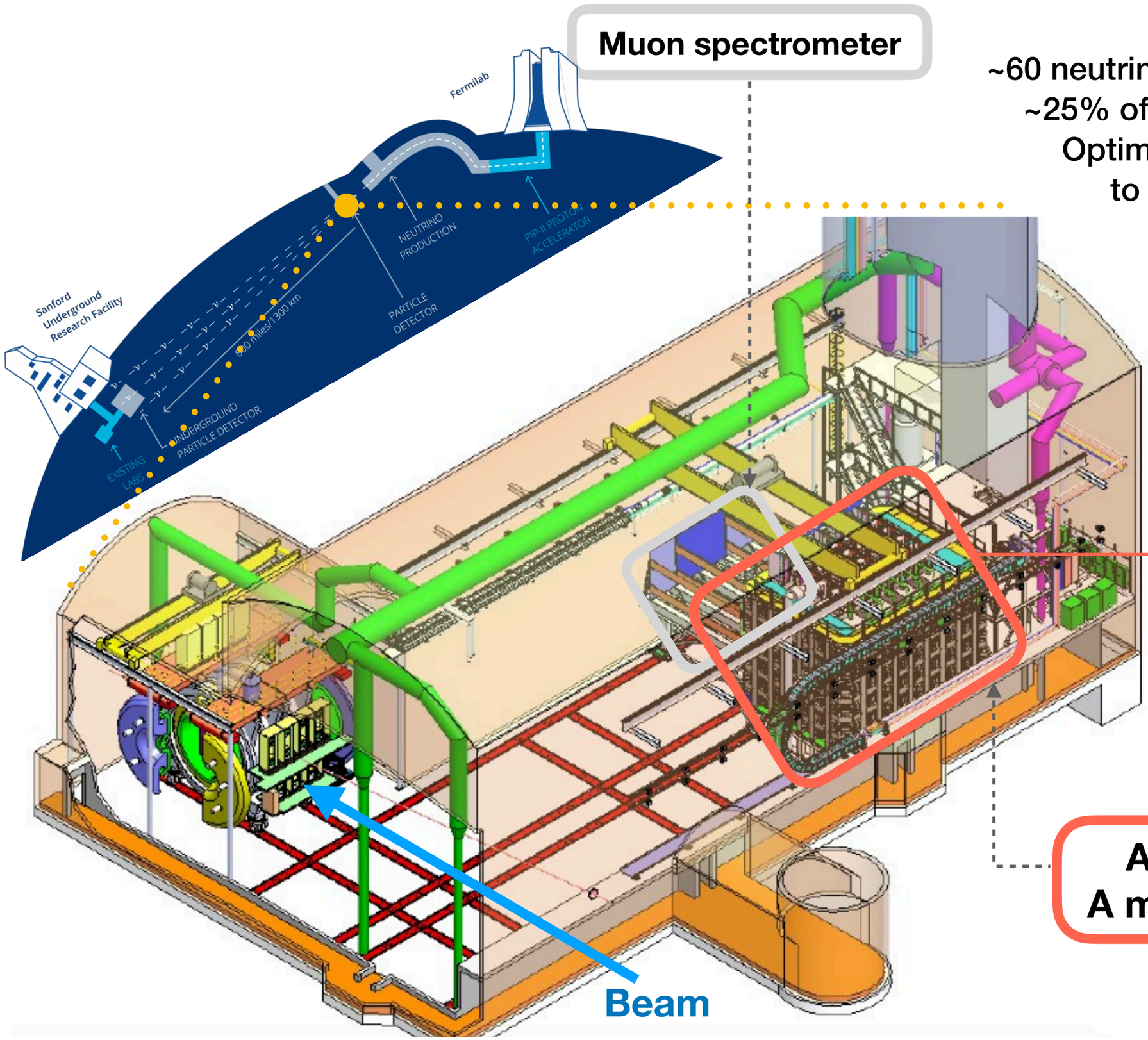
Flux



Event Rate



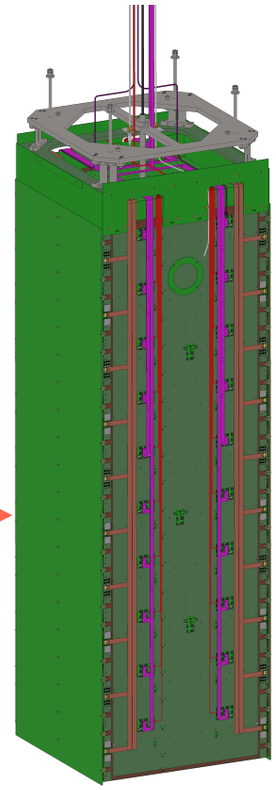
A Prototype for the DUNE Near Detector



~60 neutrino interactions per beam spill
~25% of them in the active volume
Optimized ArgonCube design
to deal with the pile-up

35 modules

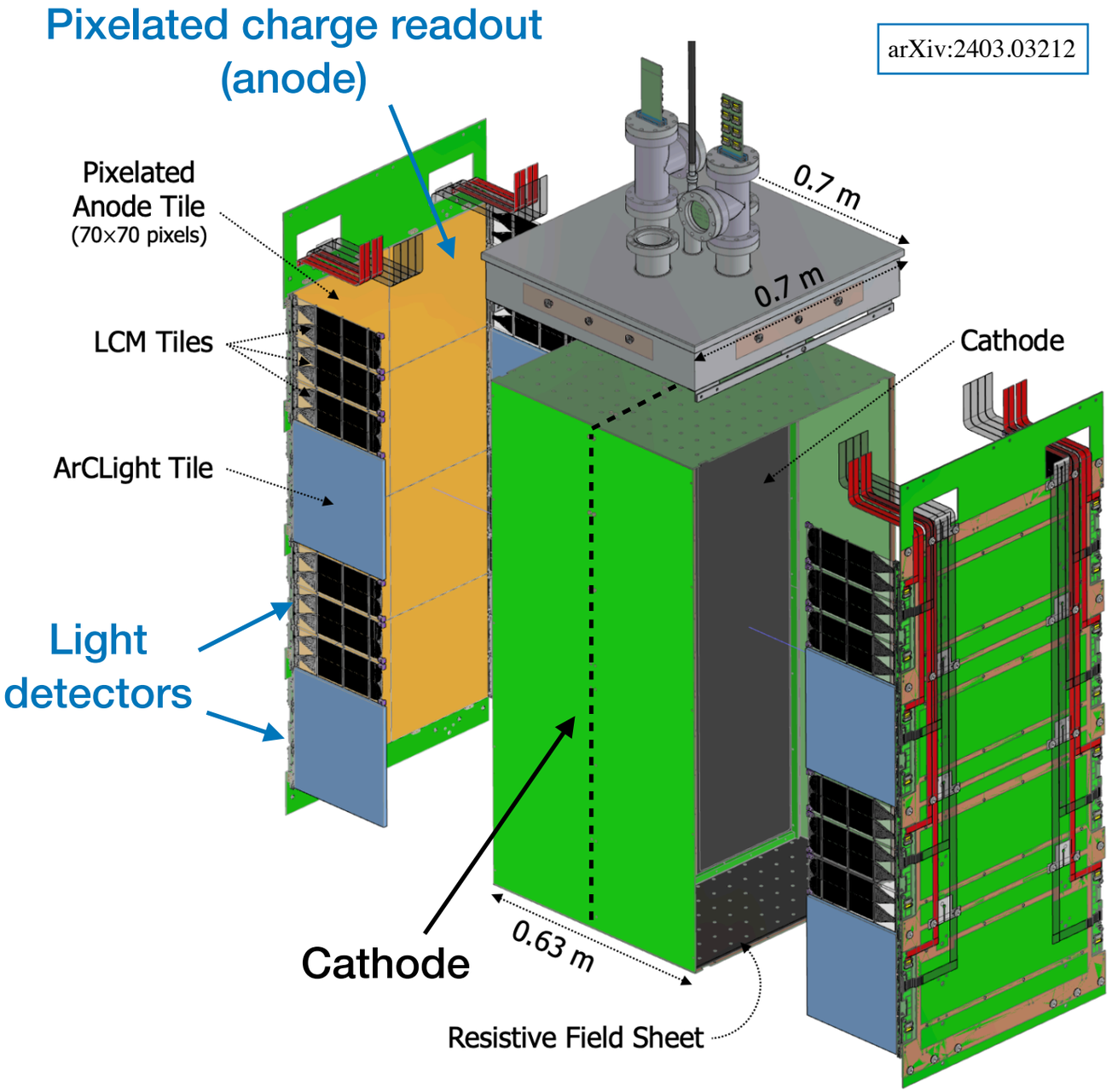
Scalability



ArgonCube design
A modularized LArTPC

ArgonCube Design on 2x2

Each module has two back-to-back TPCs with a shared cathode in the middle.



Short drift length (30 cm, 0.5 kV/cm)

- Significantly reduced cathode voltage and associated risks
- Relaxed requirement on electric field uniformity and electron lifetime
- Diffusion becomes trivial (sub-mm)

Modularized TPC

- Scalable self-contained detector module
- Isolate potential failures
- Scintillation light tight

Pixelated charge readout

- True 3D position + charge mitigates ambiguities for reconstruction
- Low channel capacitance reduces noise
- PCB-based construction; mechanically robust; scalable

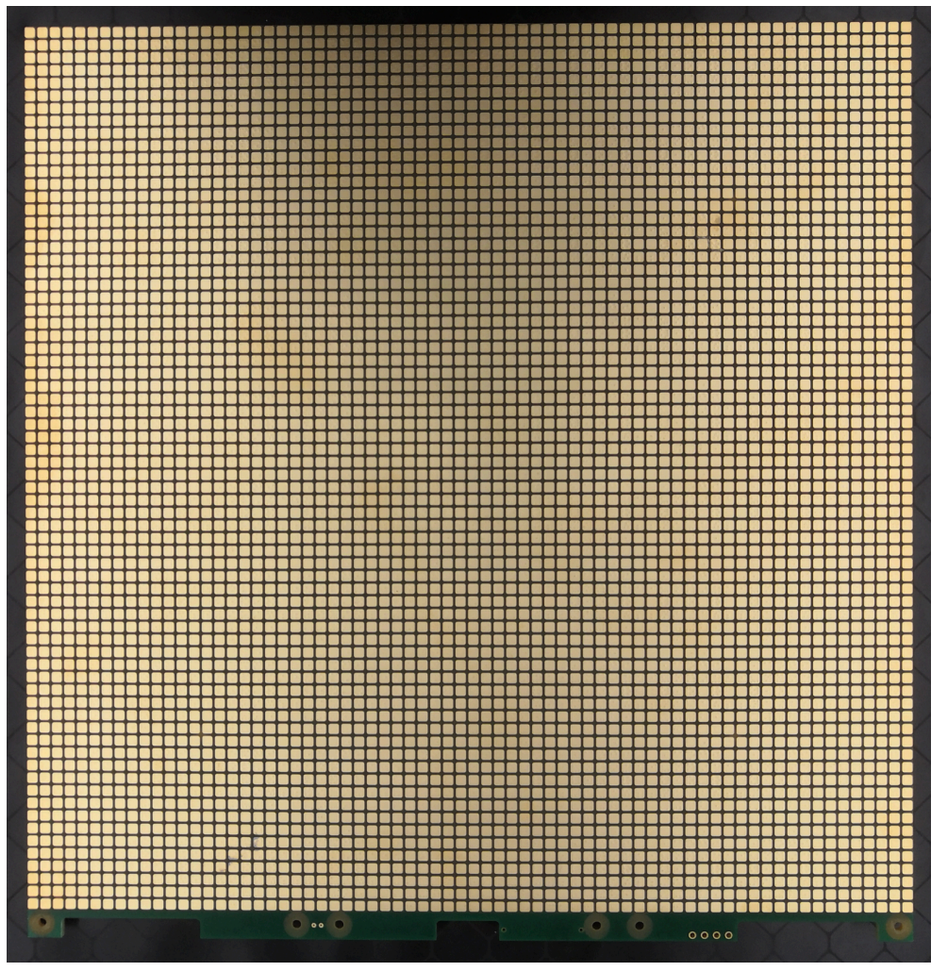
High-performance light readout

- 30% surface coverage, high efficiency
- O(5cm) spatial resolution

Pixelated Charge Readout: LArPix

LArPix v2 Tile

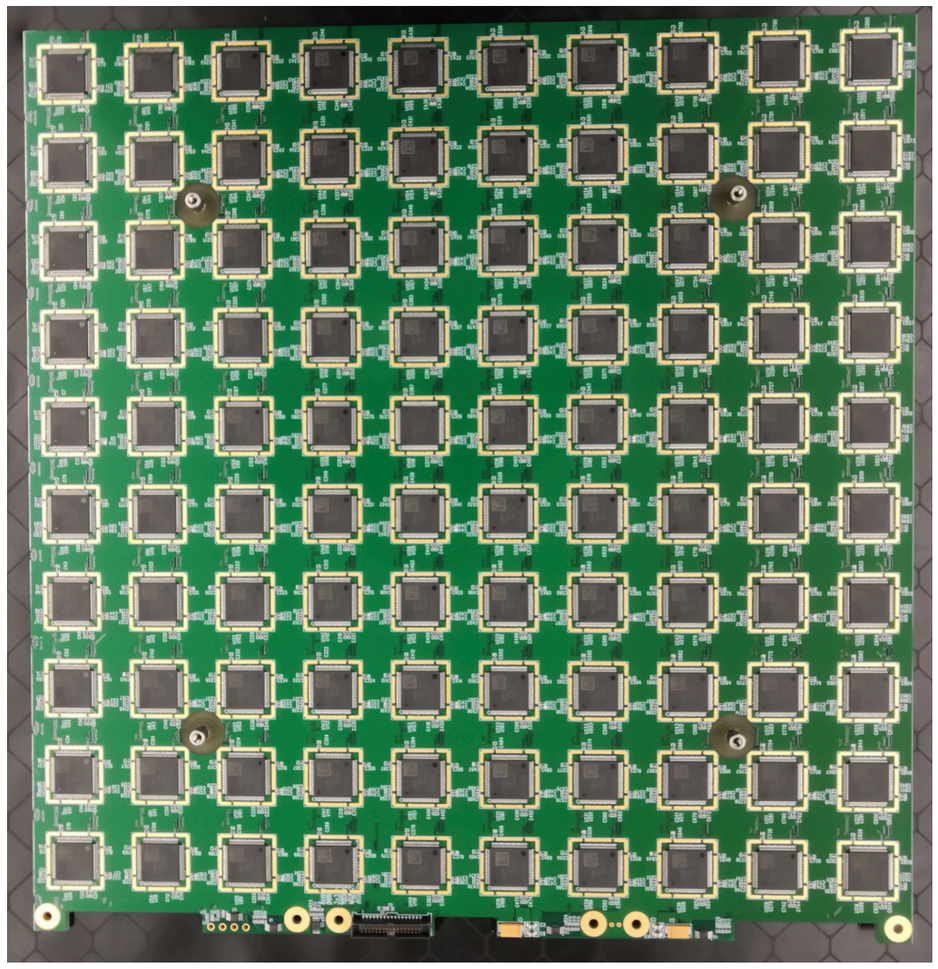
Front



- 32 × 32 cm² LArPix tile
- 8 LArPix tiles per TPC
- 4900 (6400) square pixels per tile
- 4.4 (3.8) mm pixel pitch
- ~300k channels in 2×2
- Each pixel can be independently self-triggered

arXiv:2403.03212

Back



- 10×10 grid of ASICs
- Continuous readout
- Hydra-I/O: dynamic routing, robust to chip failure
- Robust to repeated cryogenic cycling
- Flexible tile config for scaling
- Commercial mass production

LArPix-v1

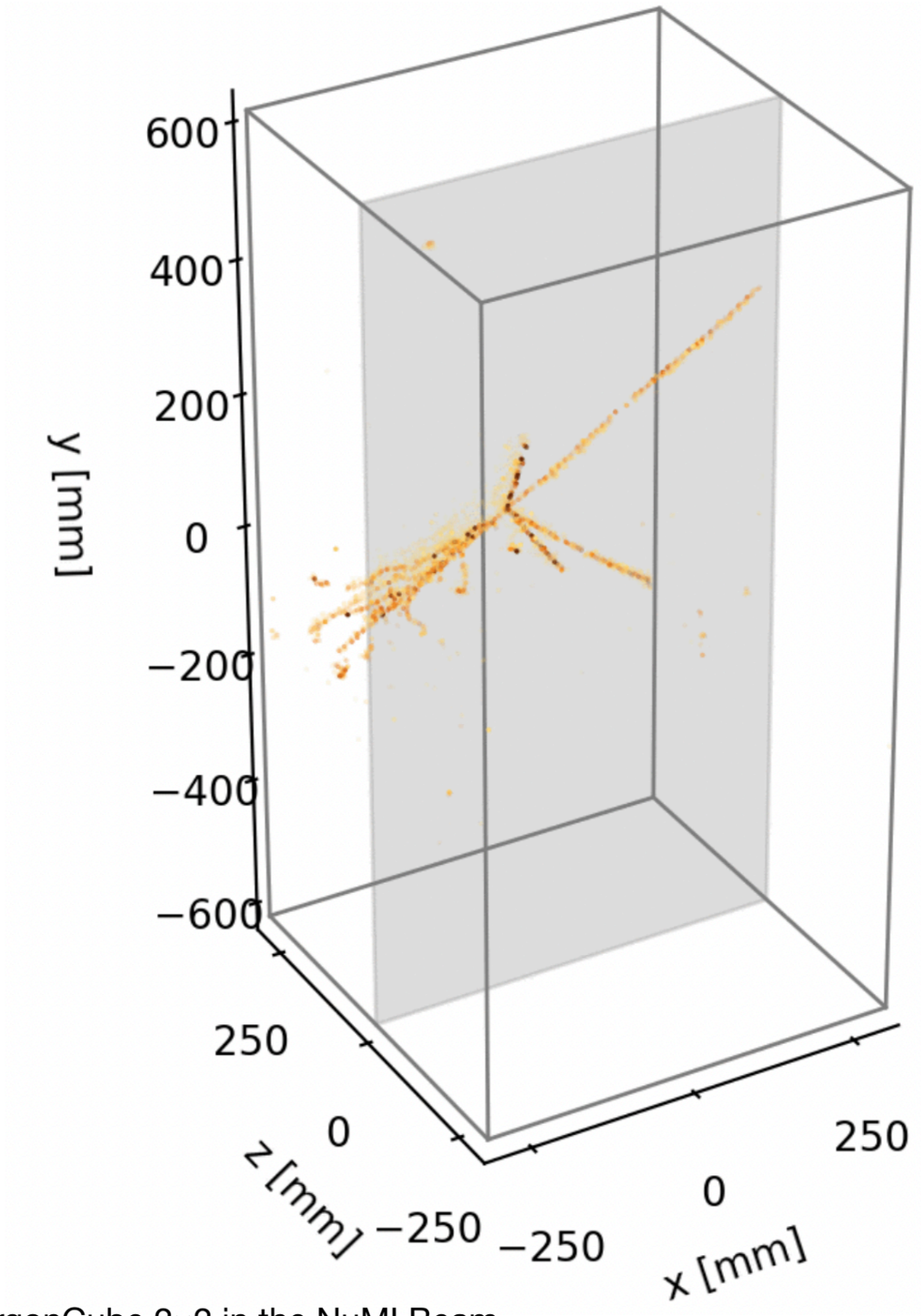
JINST **13** (2018) P10007

True projected 3D position in 2x2

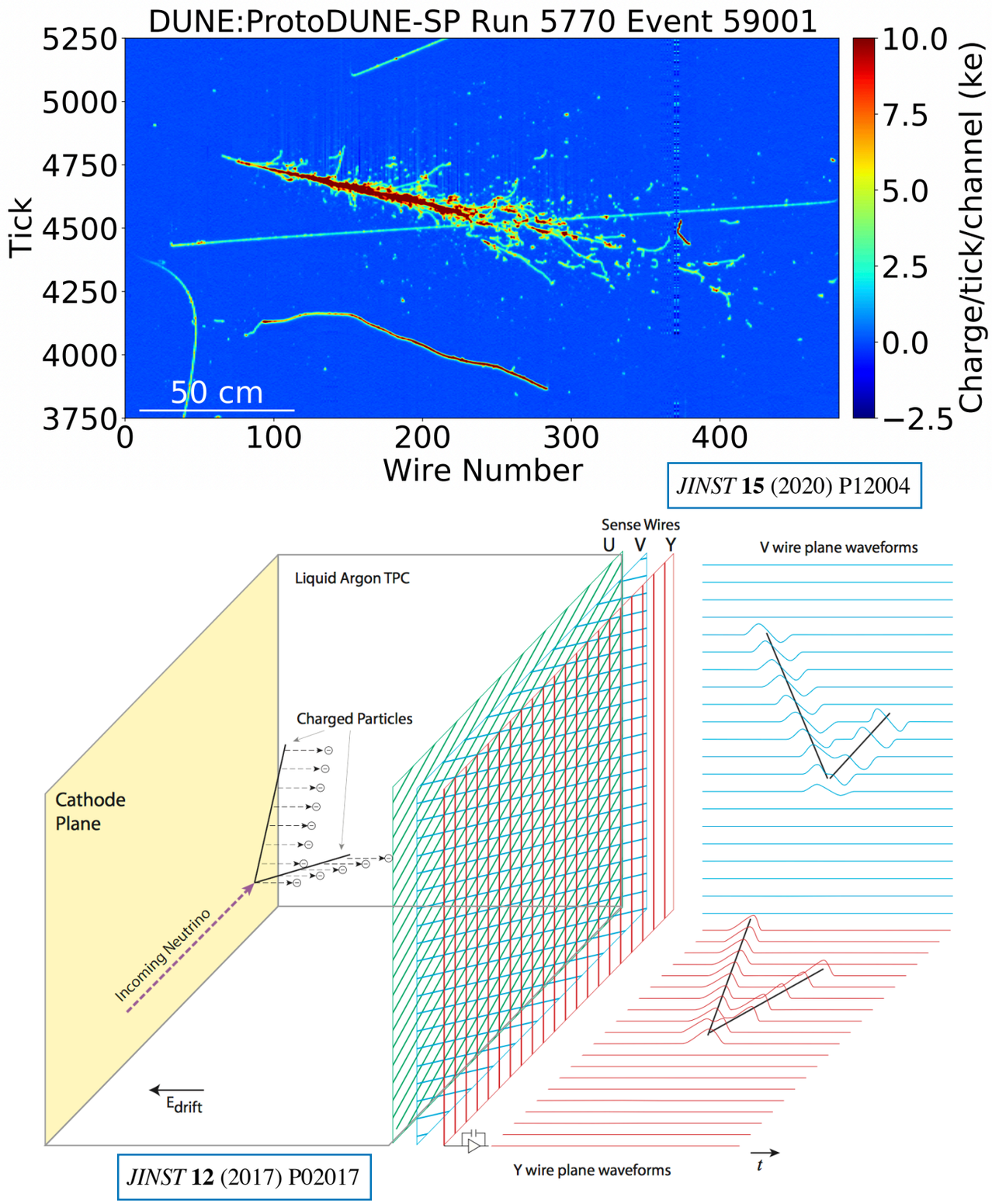
LArPix Charge Readout

Raw cosmic data

True projected 3D position



Conventional wire readout



JINST **15** (2020) P12004

JINST **12** (2017) P02017

Light Detector: ArCLight and LCM

ArCLight

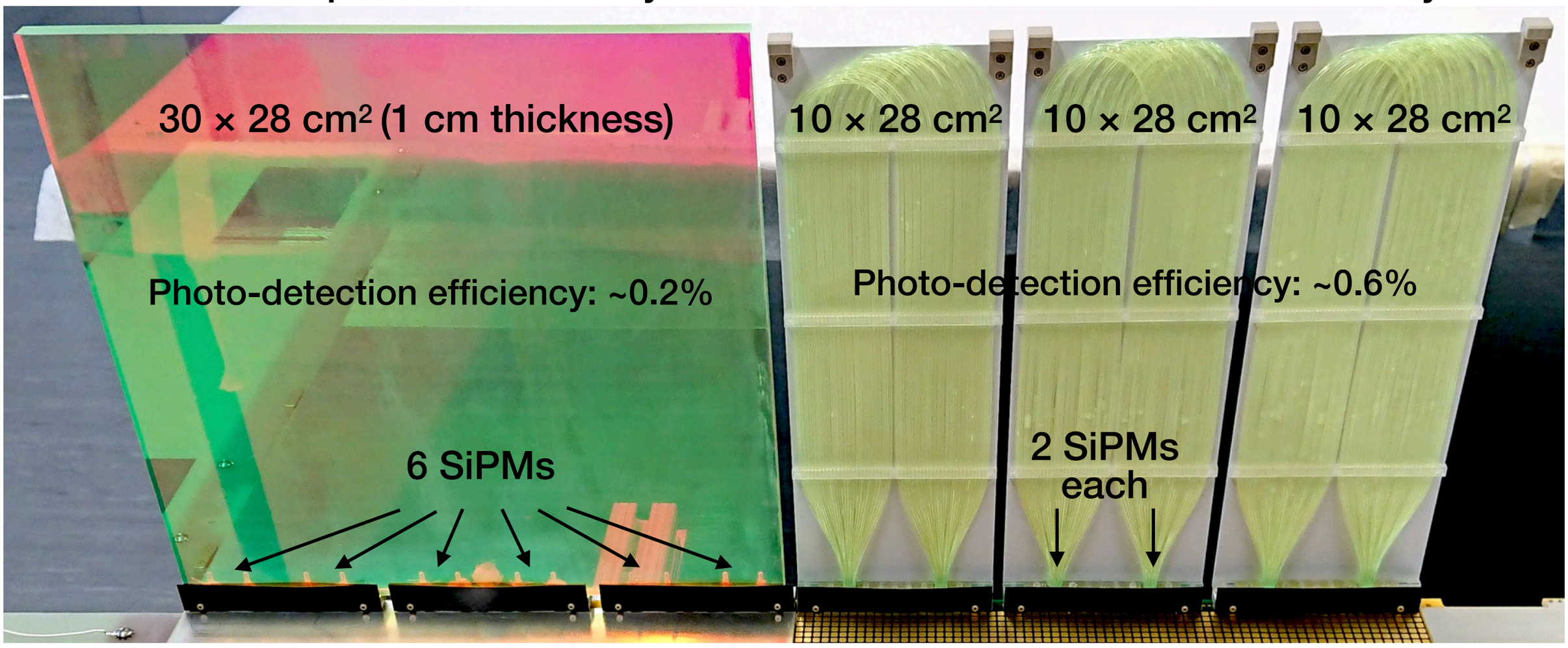
Instruments **2018**, 2(1), 3

Good at position sensitivity

LCM

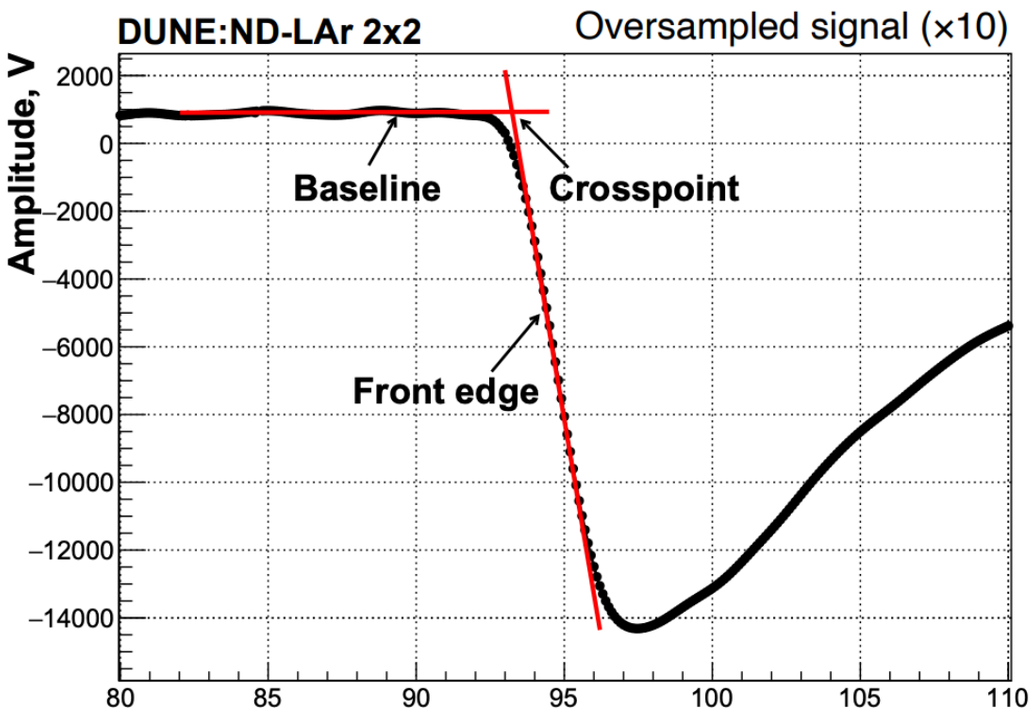
arXiv:2403.03212

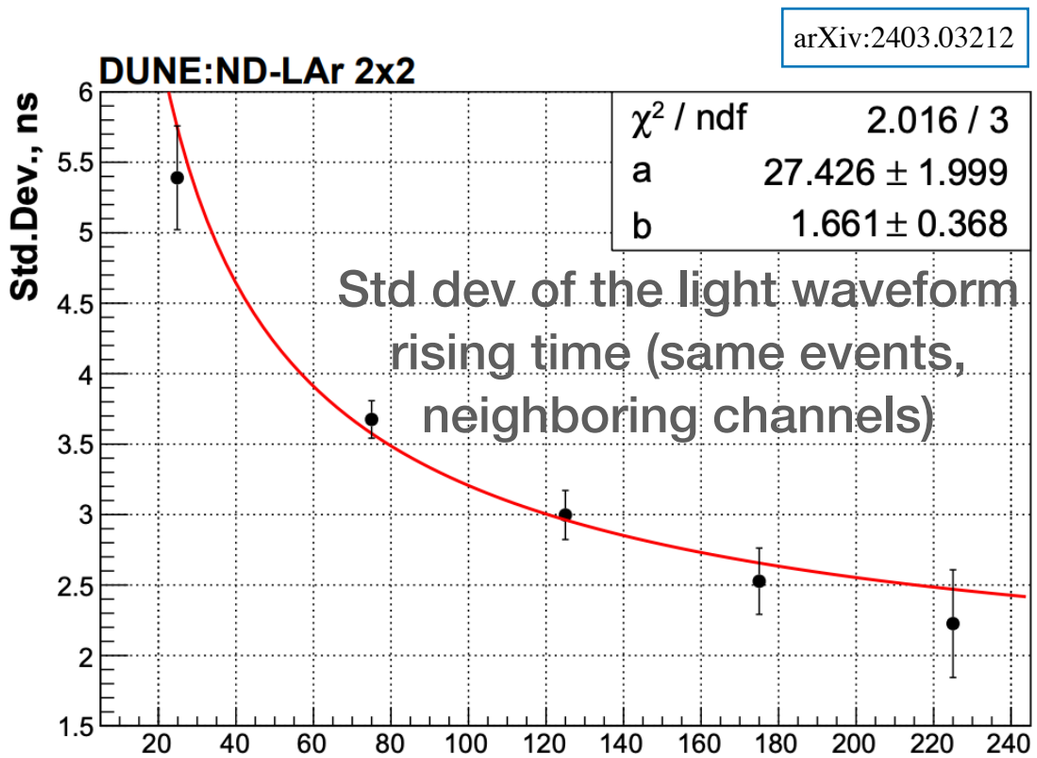
Good at detection efficiency

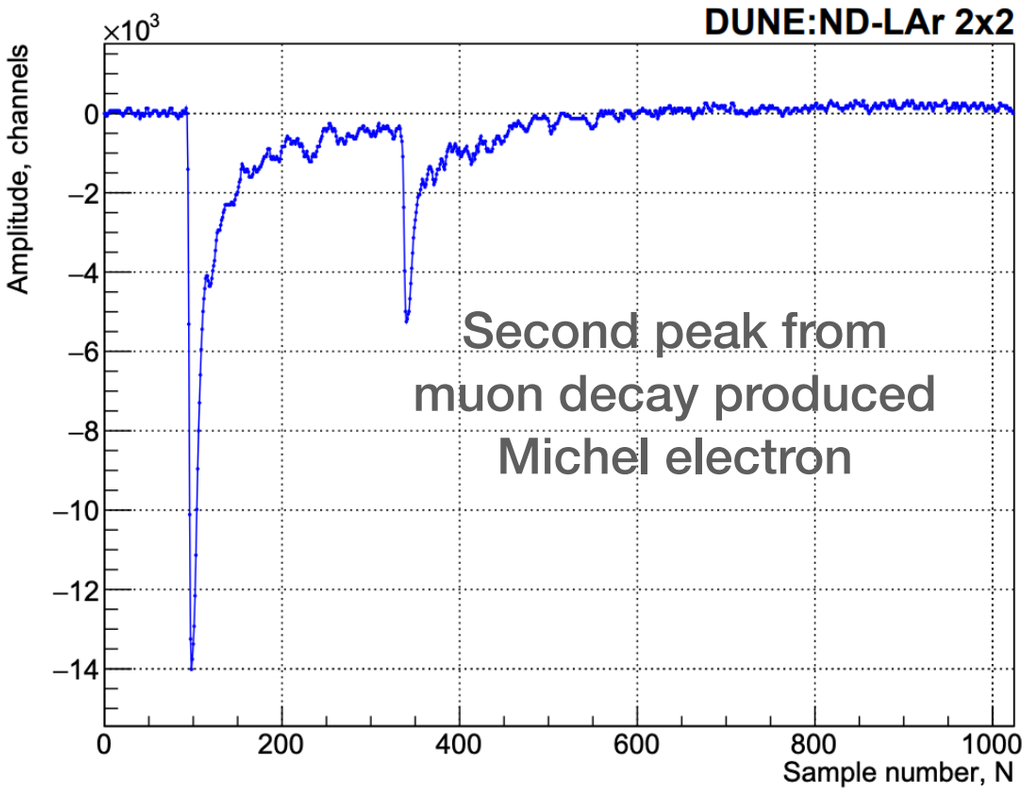


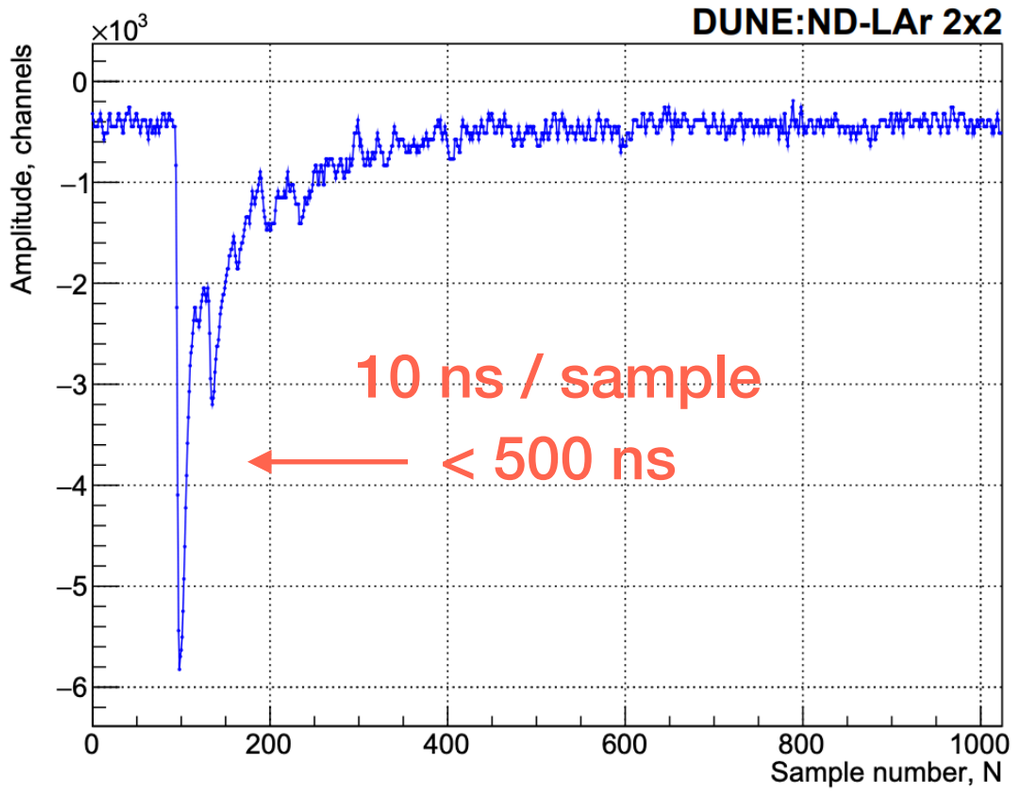
The light detector is perpendicular to the LArPix tiles
and right in front of the side wall of the field shell.
They laid out as 3 LCM, 1 ArCLight, 3 LCM and 1 ArCLight from top to bottom.
384 SiPM channels for 2×2.

Light Detector Timing Resolution in 2x2









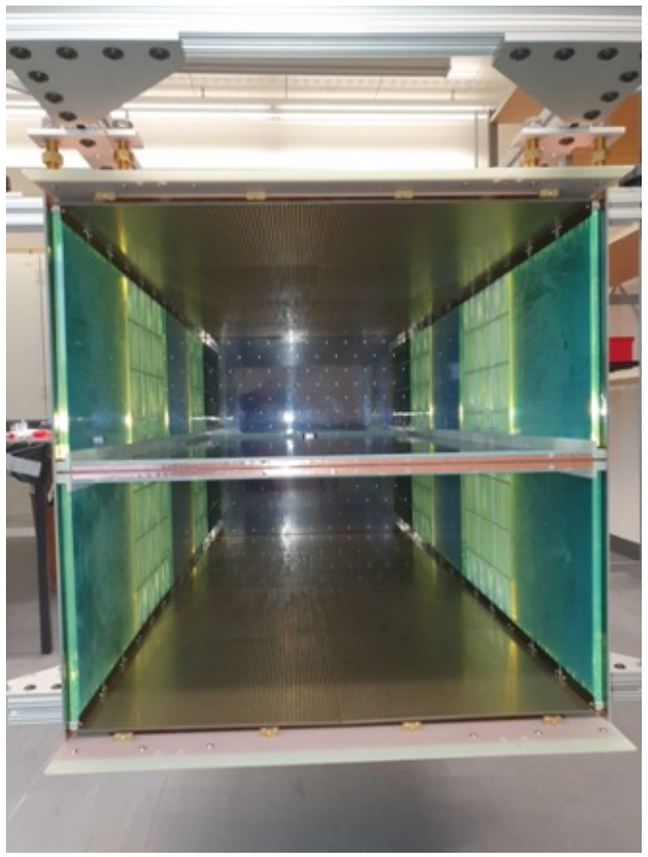
Single 2×2 Modules

Module tests in Bern (proof of module integrity)

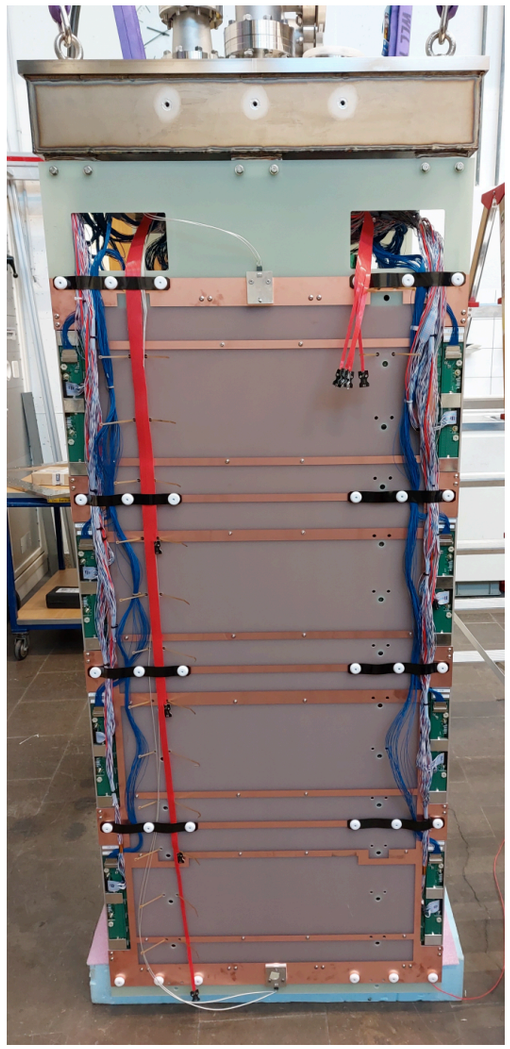
Module 0 **Module 1** **Module 2** **Module 3**

Detector components assembled as modules at the University of Bern
Tested and operated for cosmic data taking

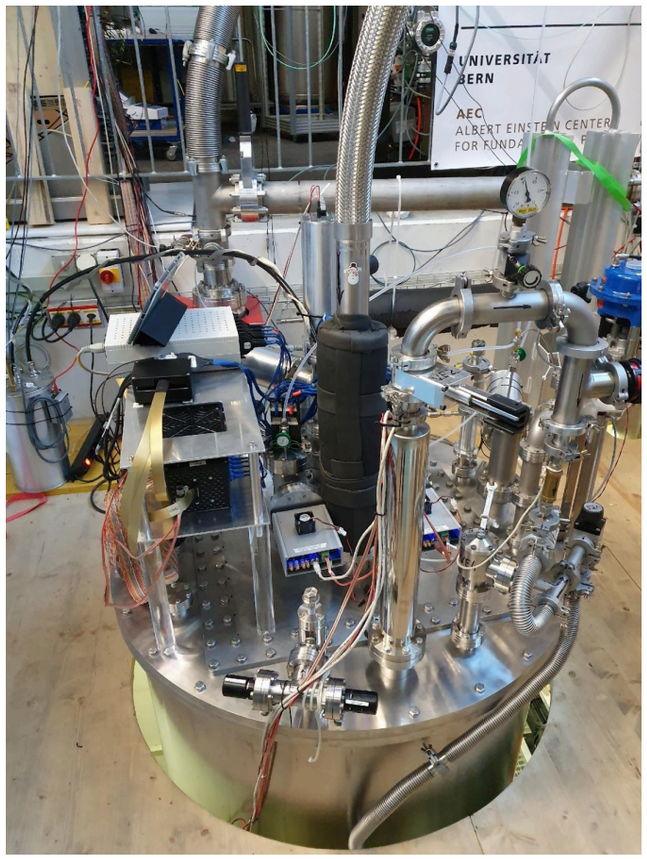
Single 2×2 module cryostat



View of the TPCs
from the bottom

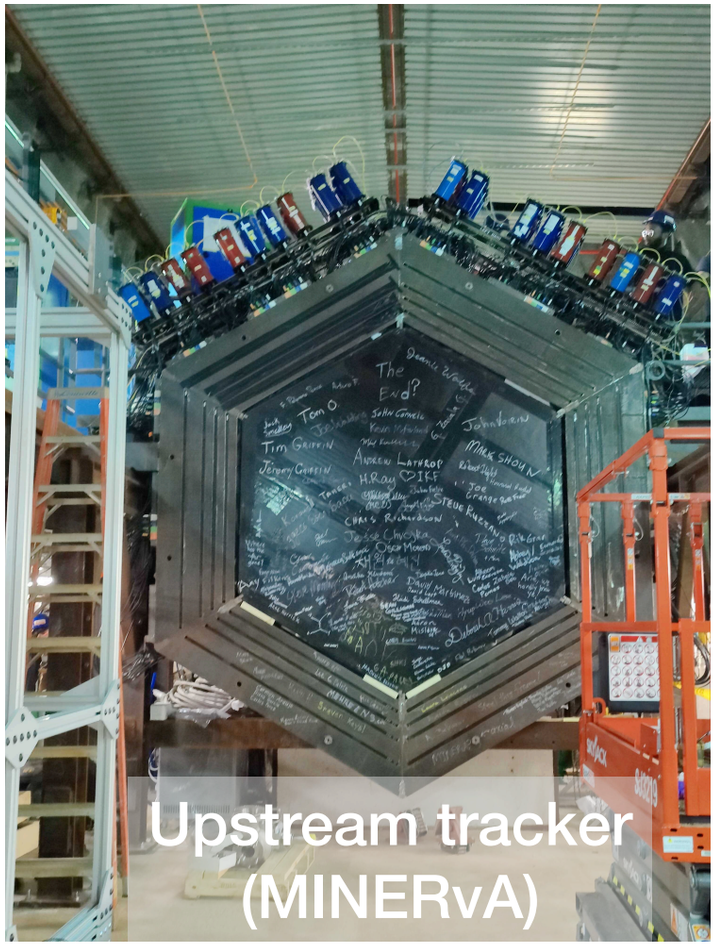


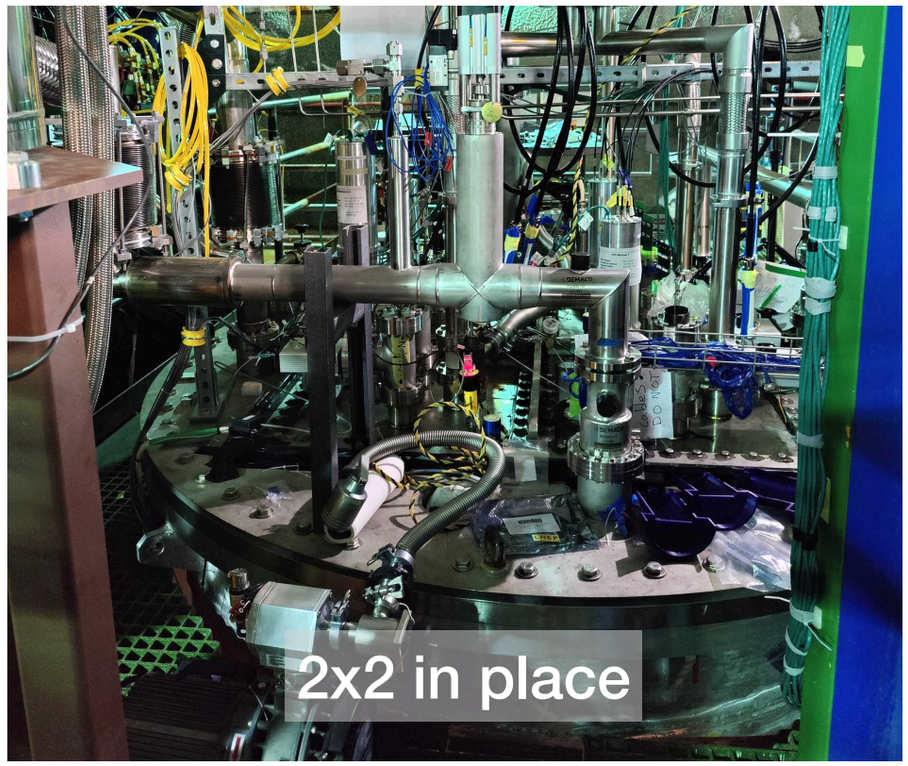
Assembled module



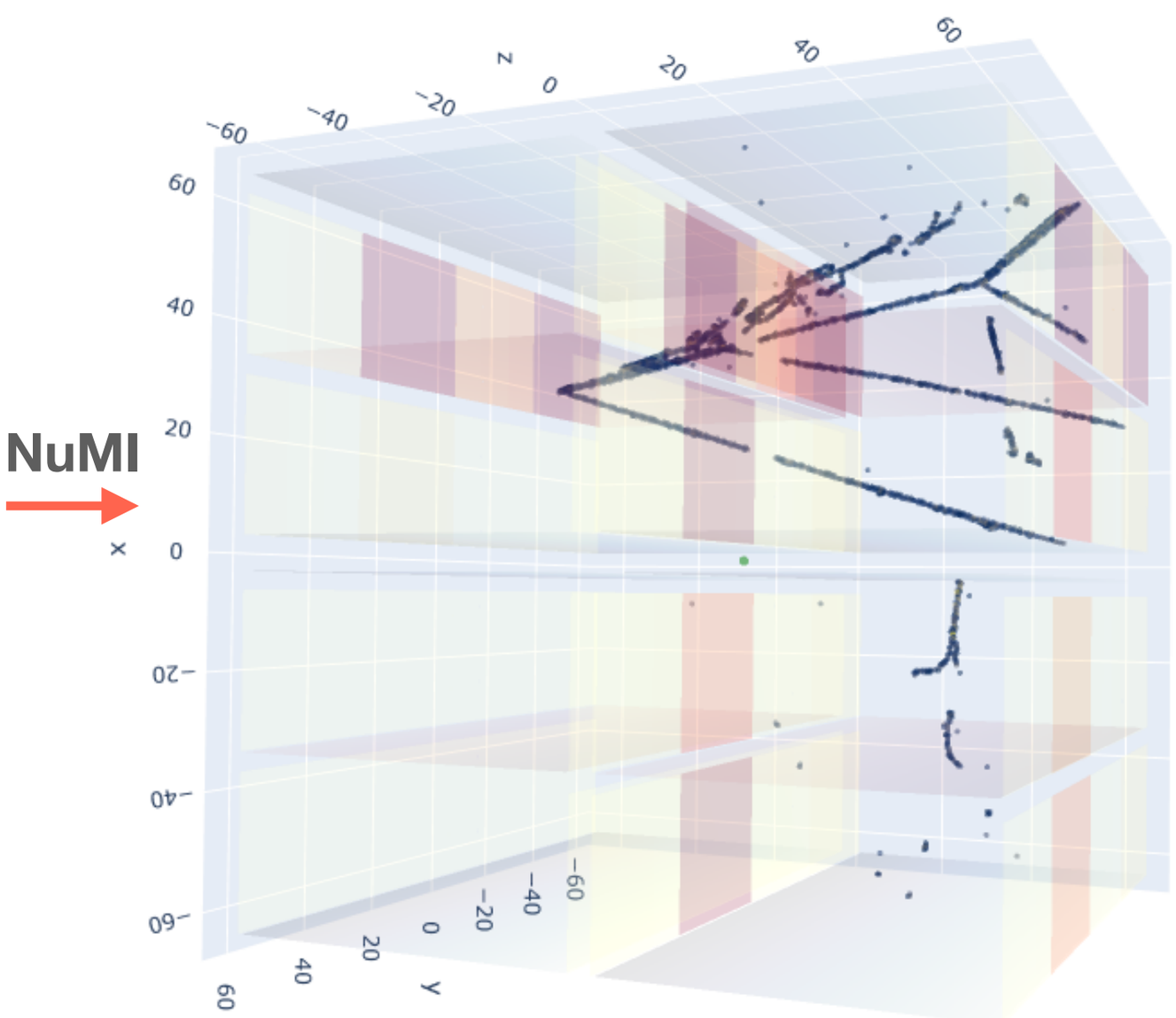
Module in operation

2x2 in the MINOS Hall at Fermilab



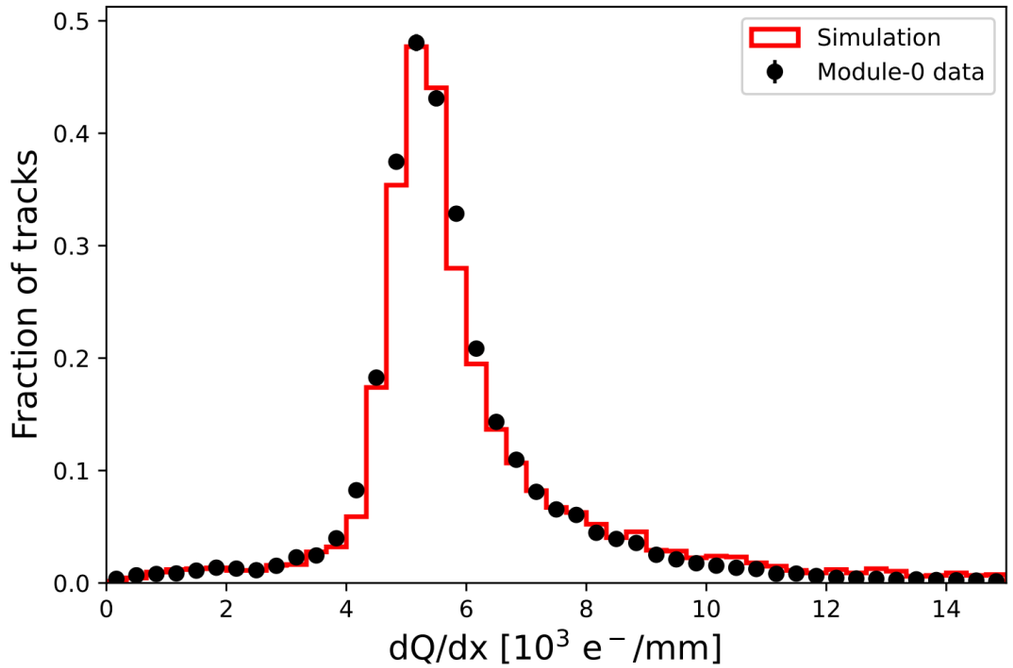


2×2 Simulation and Calibration



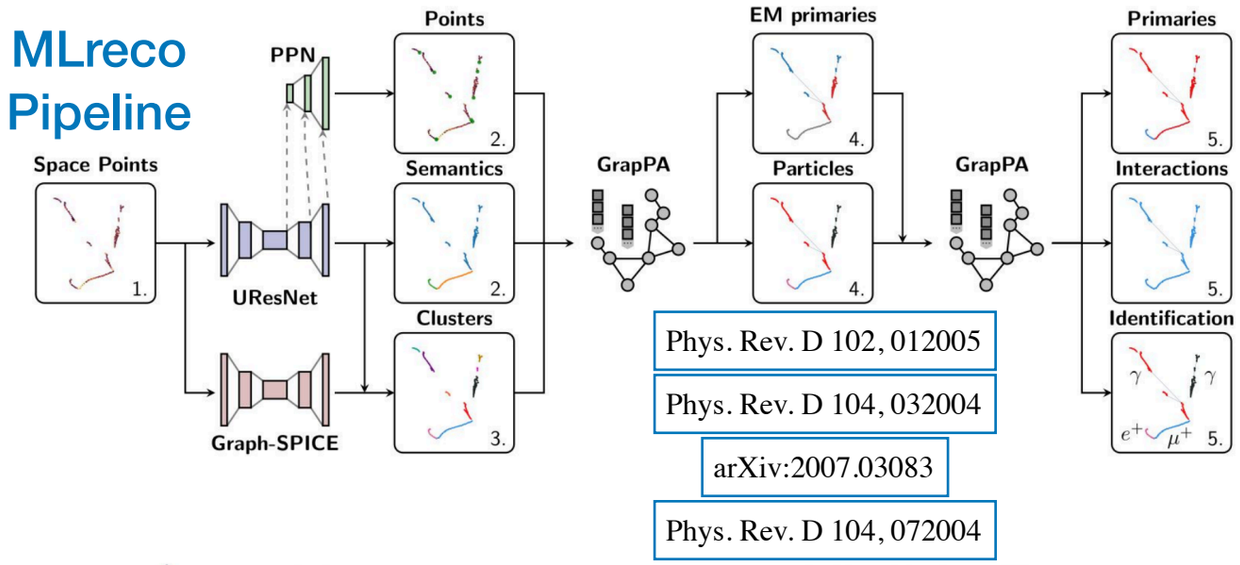
- Detailed underground cavern and 2x2 + MINERvA detector geometry
- *edep-sim* as the Geant4 wrapper
- NuMI spill building
- *larnd-sim* for charge and light readout signals with high fidelity
- *ndlar_flow* for event building, signal processing and calibration

JINST 18 (2023) 04, P04034

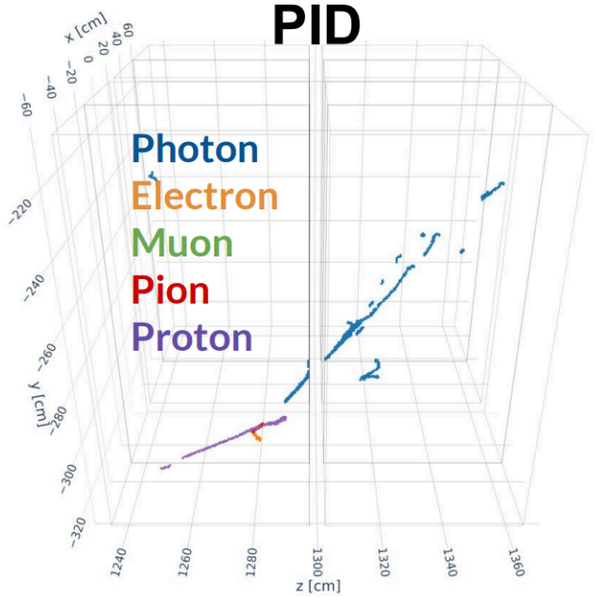


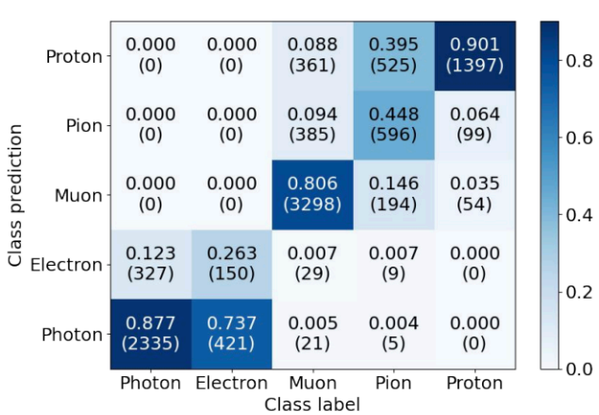
2×2 Reconstruction

- Led by mature effort: MLreco and Pandora
- Very preliminary performance by MLreco
  Expect noticeable improvement after fixing known issues
- The reconstructed output are propagated to analysis files (CAF)

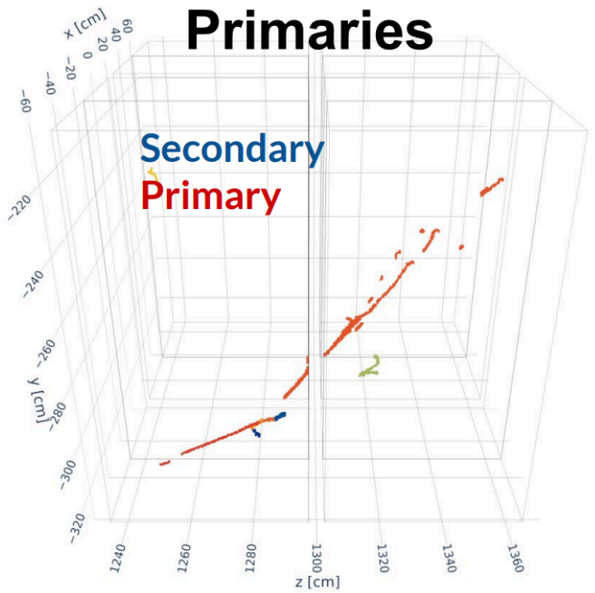


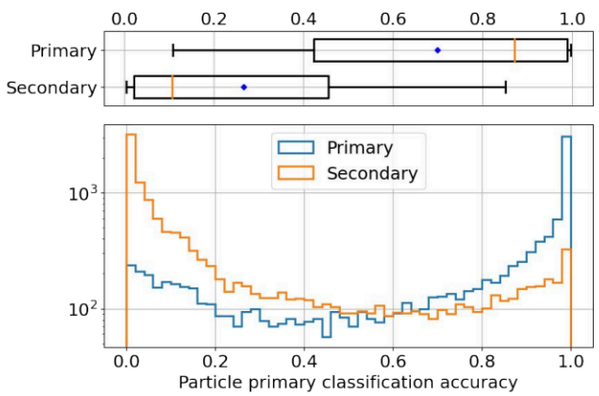
PID



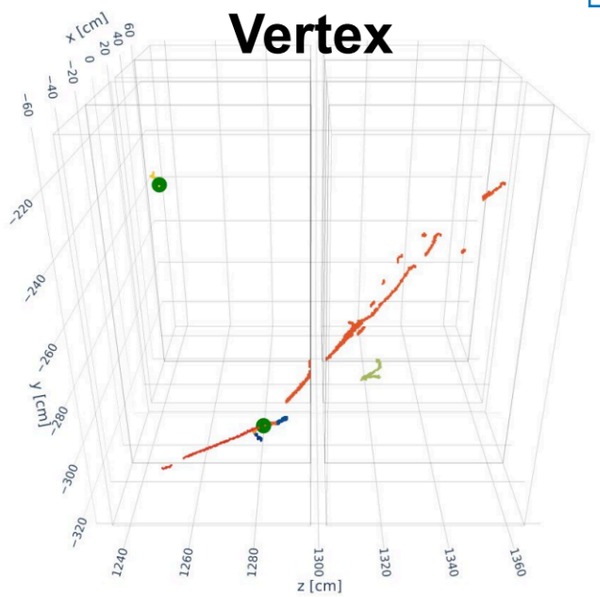


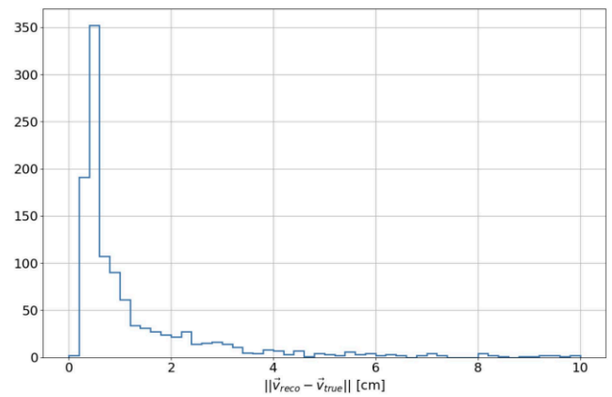
Primaries



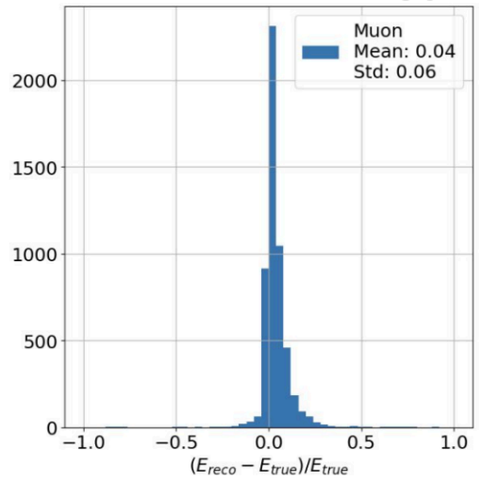


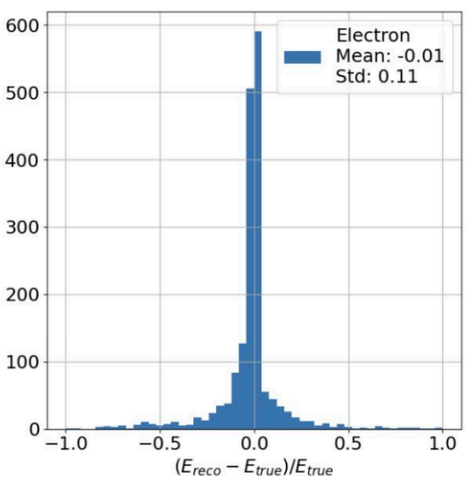
Vertex





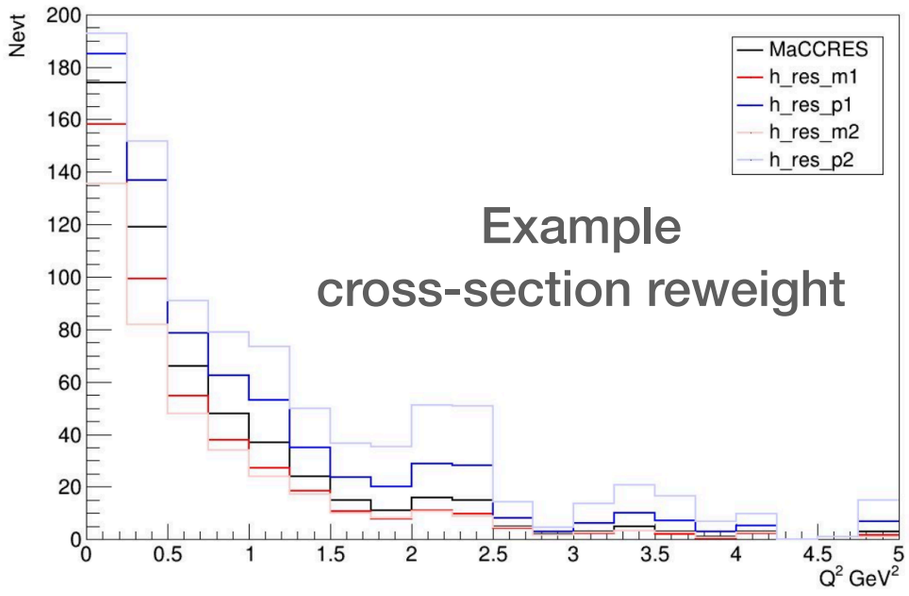
Visible Energy

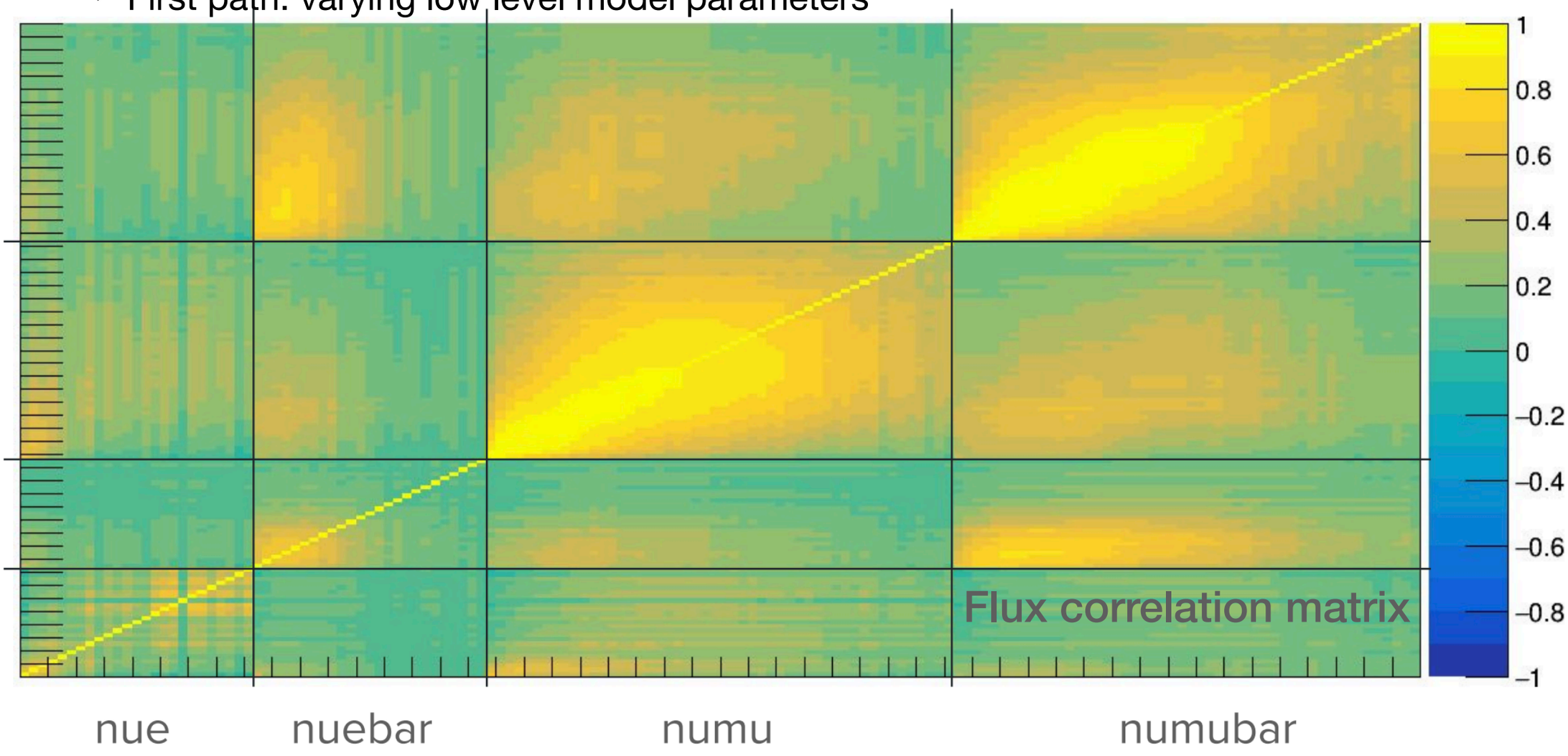




Considerations of 2×2 Systematics

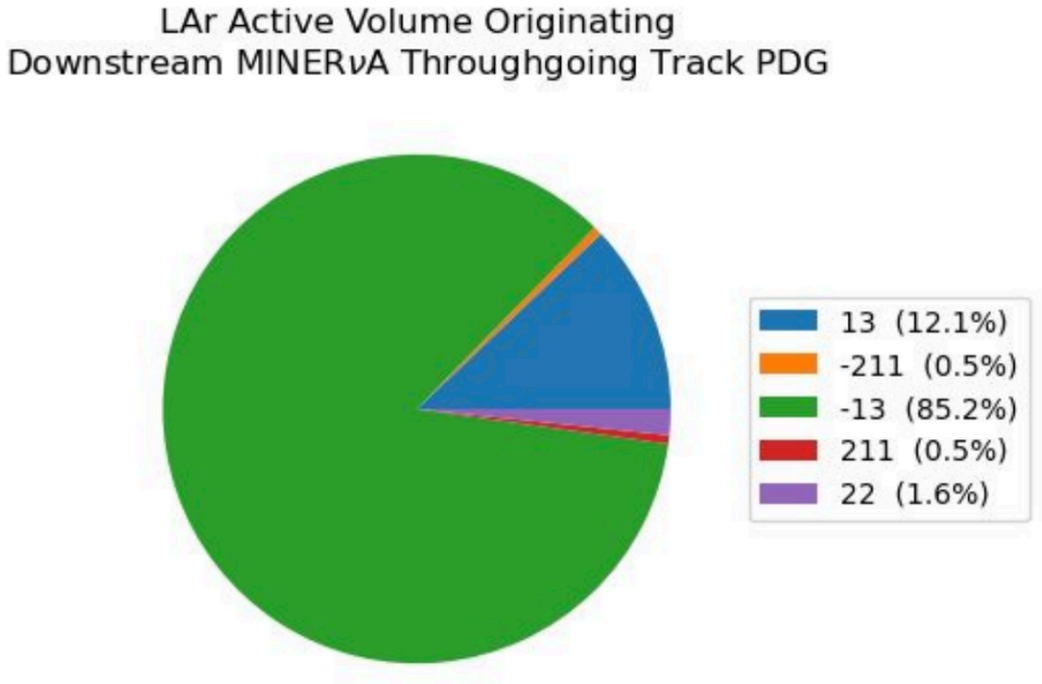
- **Flux**
  - Similar to MINERvA flux
  - Benefit from MINERvA, ICARUS, NOvA's work
- **Cross section**
  - GENIE reweighting
  - Alternative generators
- **Secondary interaction**
  - Geant4Reweight *JINST 16 (2021) 08*
- **Detector**
  - First path: varying low level model parameters

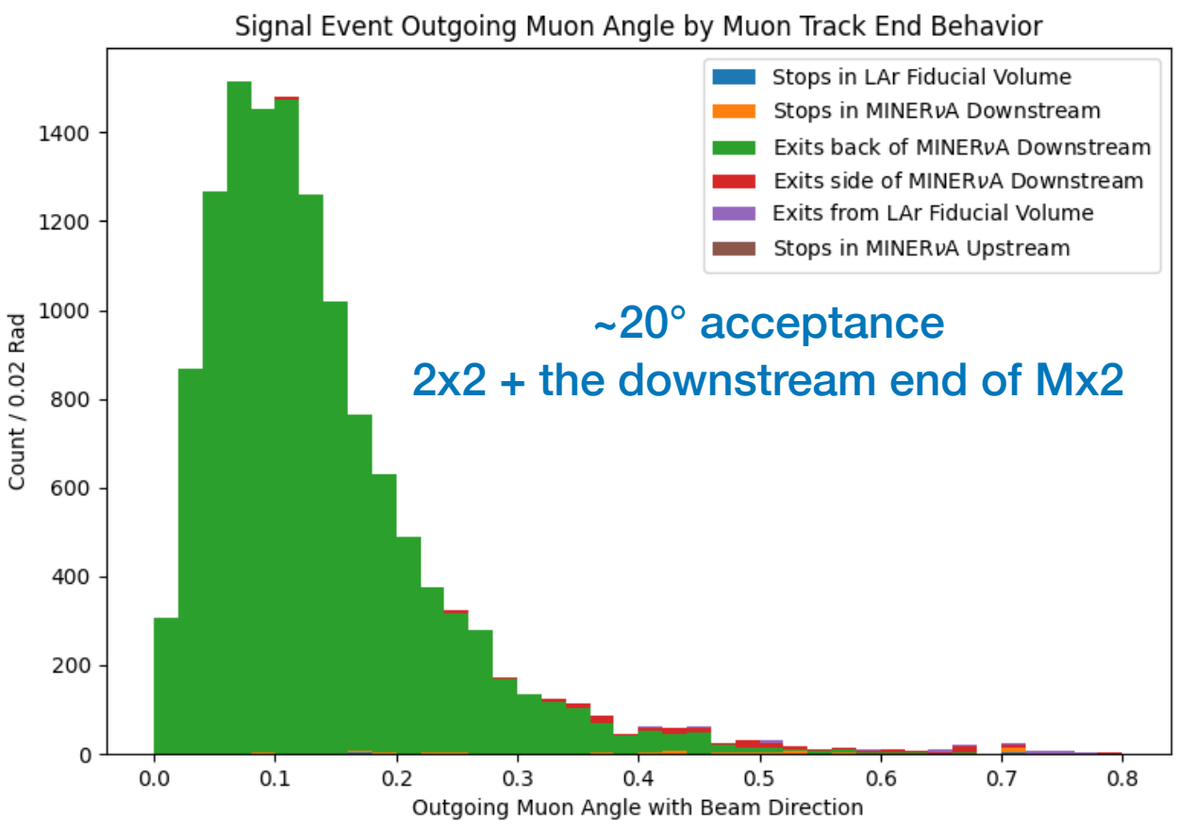




$\overline{\nu}_\mu$ Charged Current Mesonless

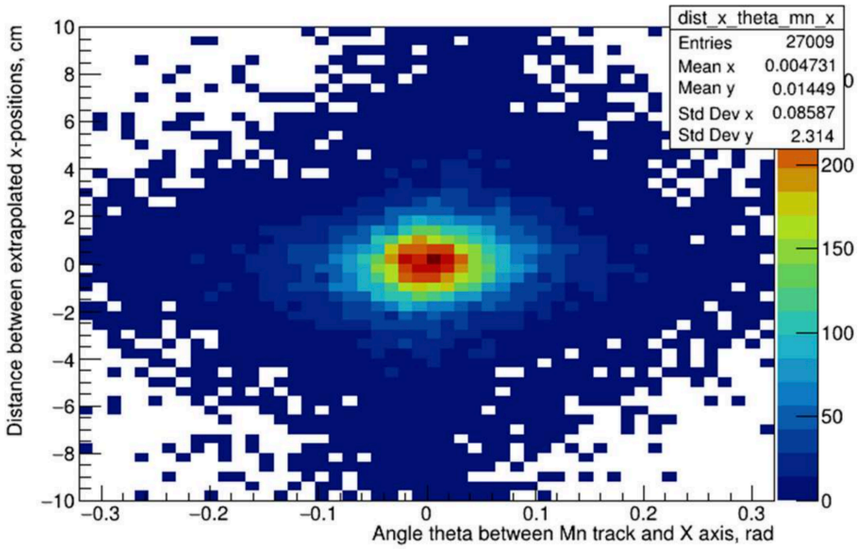
- Rare opportunity to measure $\overline{\nu}_\mu$-Ar cross sections (check out ArgoNeuT's results)
- Able to measure the outgoing muon angle well
- Able to measure the proton systems in details
- Downstream MINERvA is helpful for muon tagging (angle constrained)

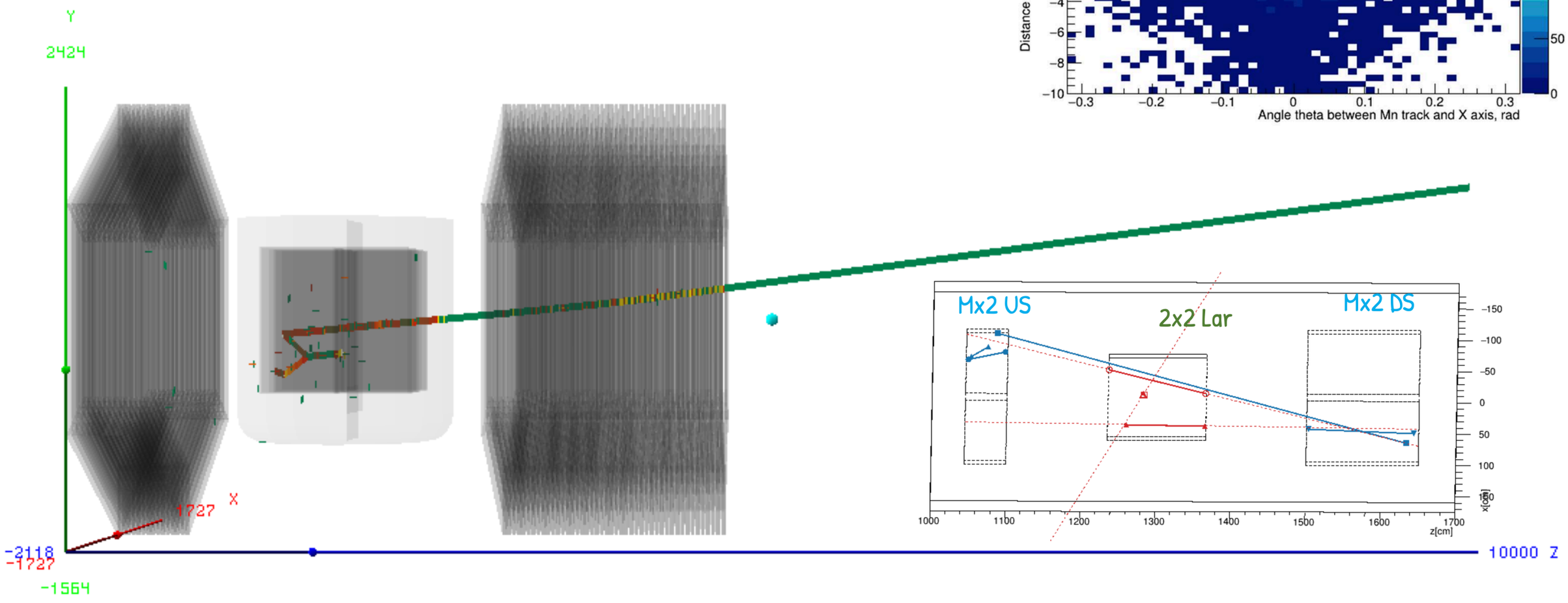




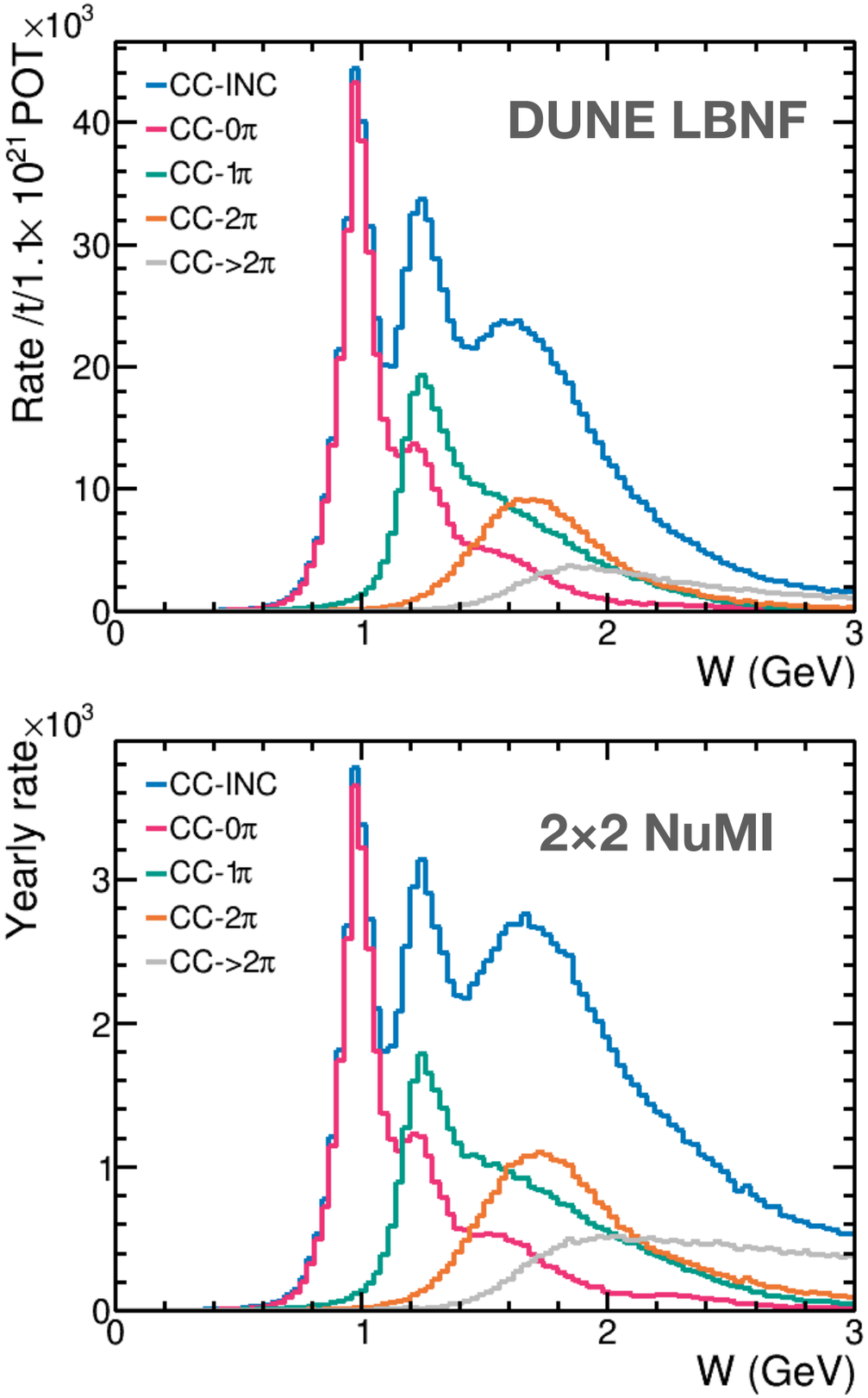
Mx2 for Muon Tagging

- Tracks that punch through downstream Mx2 are mostly muons
- Track matching between Mx2 and 2x2
  - Leverage mature MINERvA reconstruction; Compare track angles and distances
  - Developing combined reconstruction in MLreco

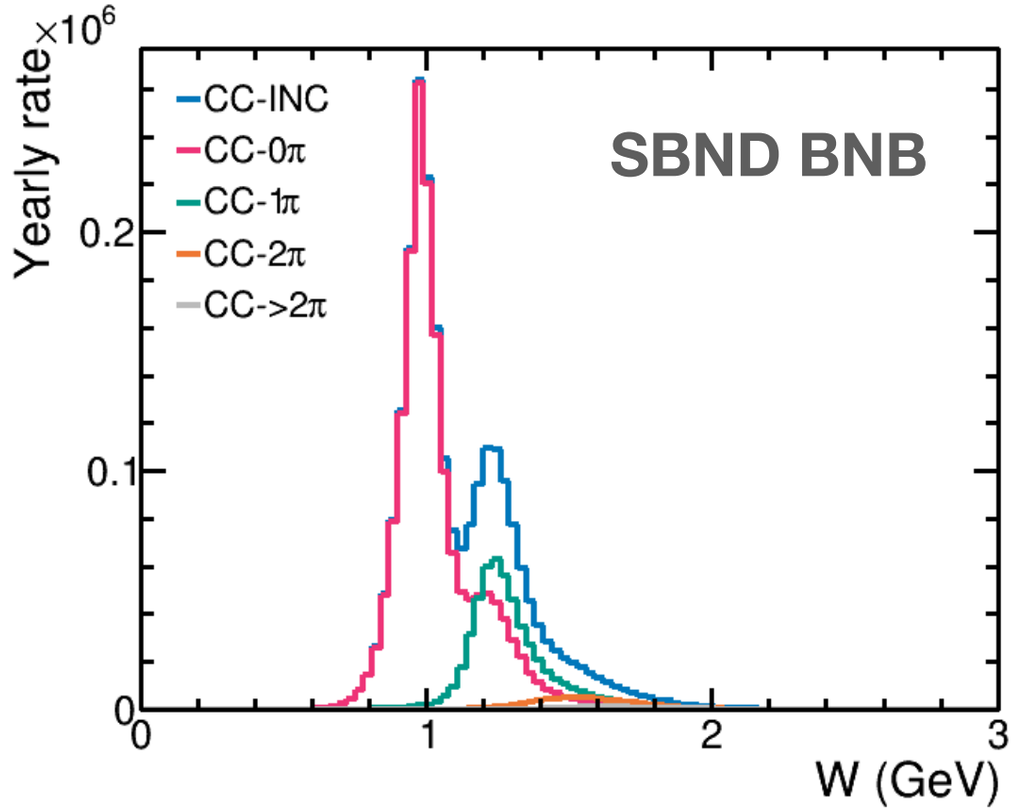




Pion Production

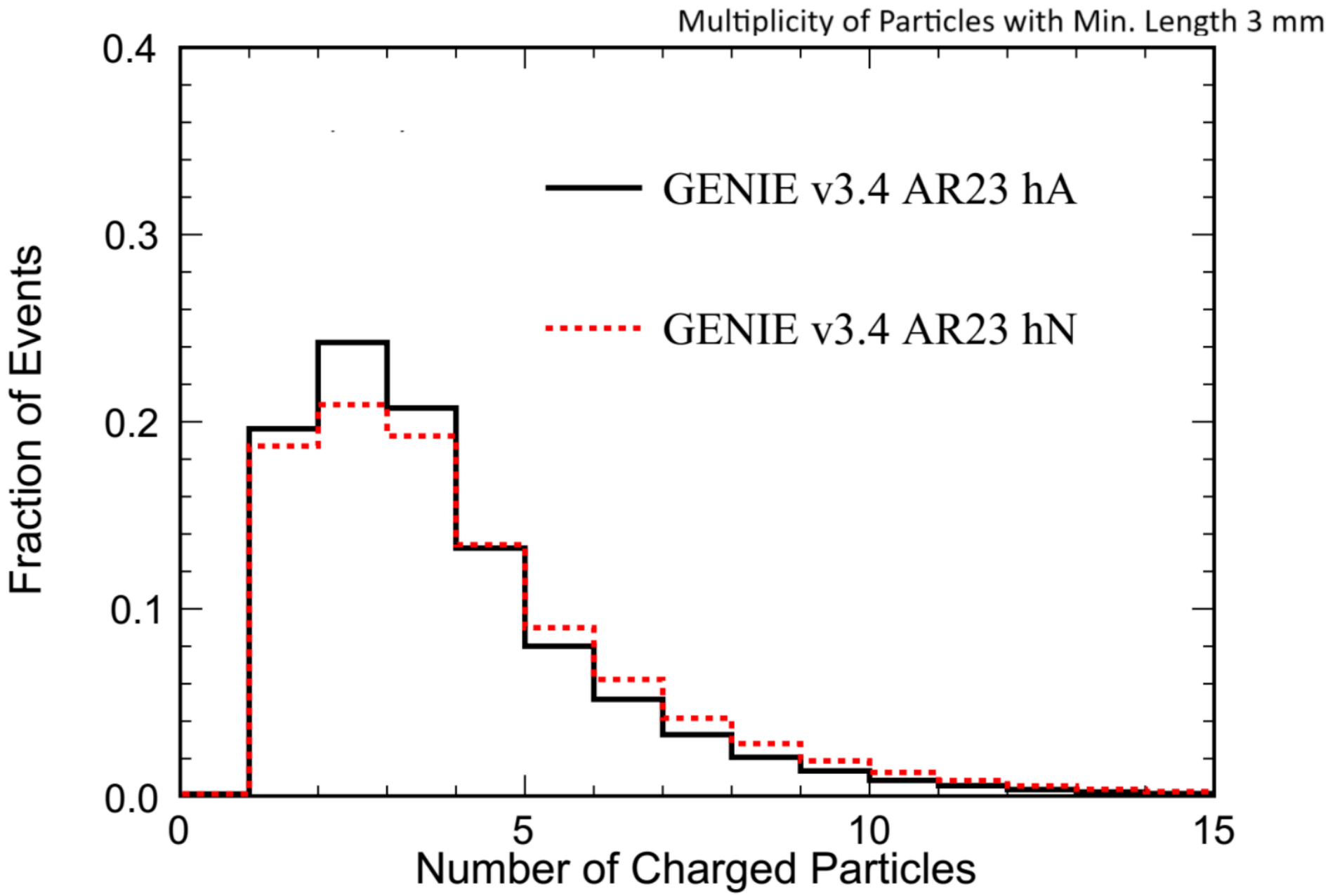


- A significant fraction of DUNE neutrino events will be produced with pions in the final states
- 2×2 will cover this phase space and will be able to study pion production in depth
- SBND data will be dominated by quasi-elastic-like events
- SBND will have more events in total

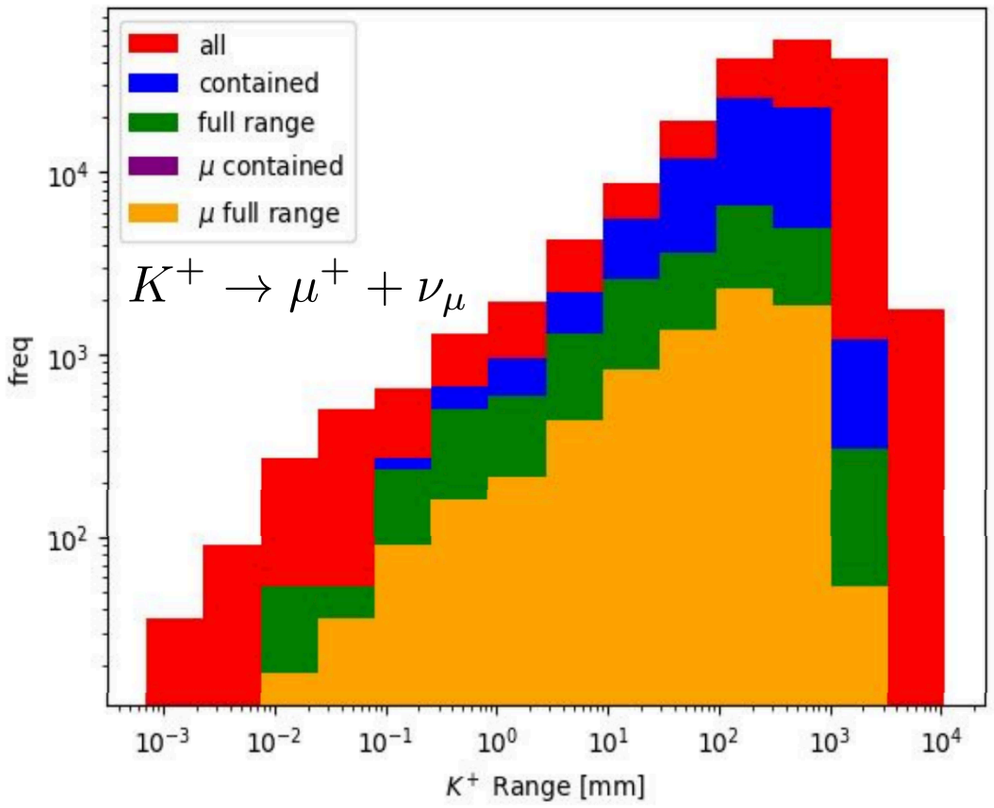


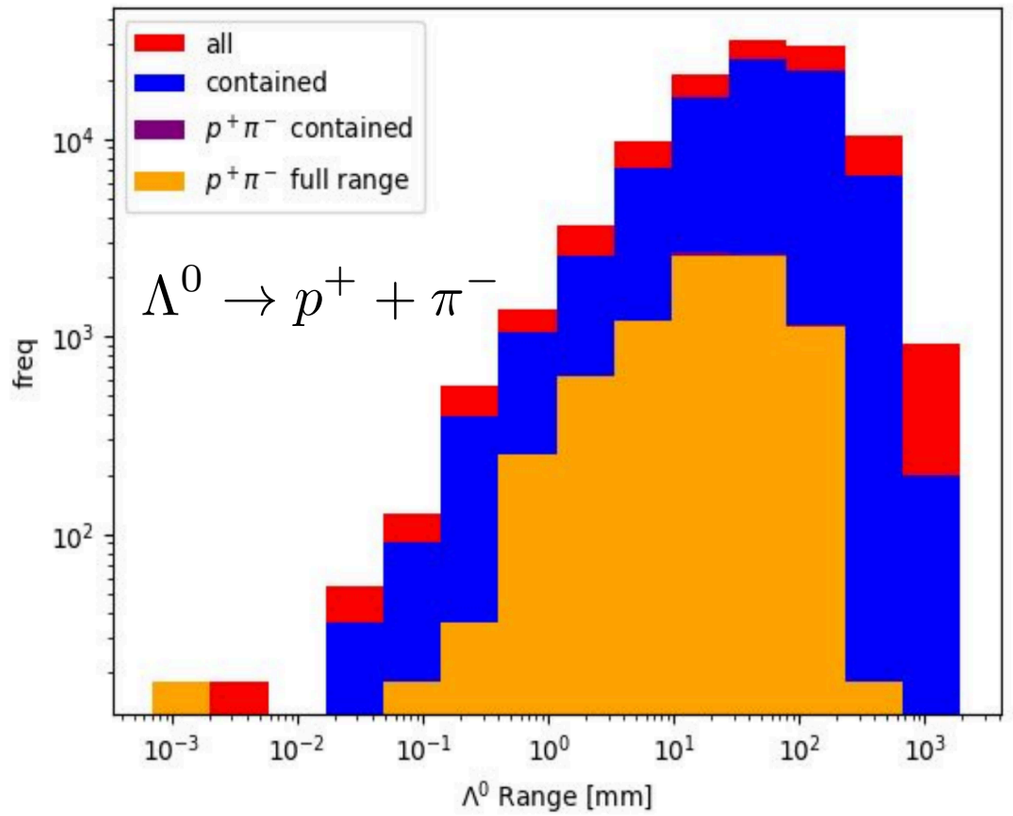
Probe Final-state Interaction Modeling

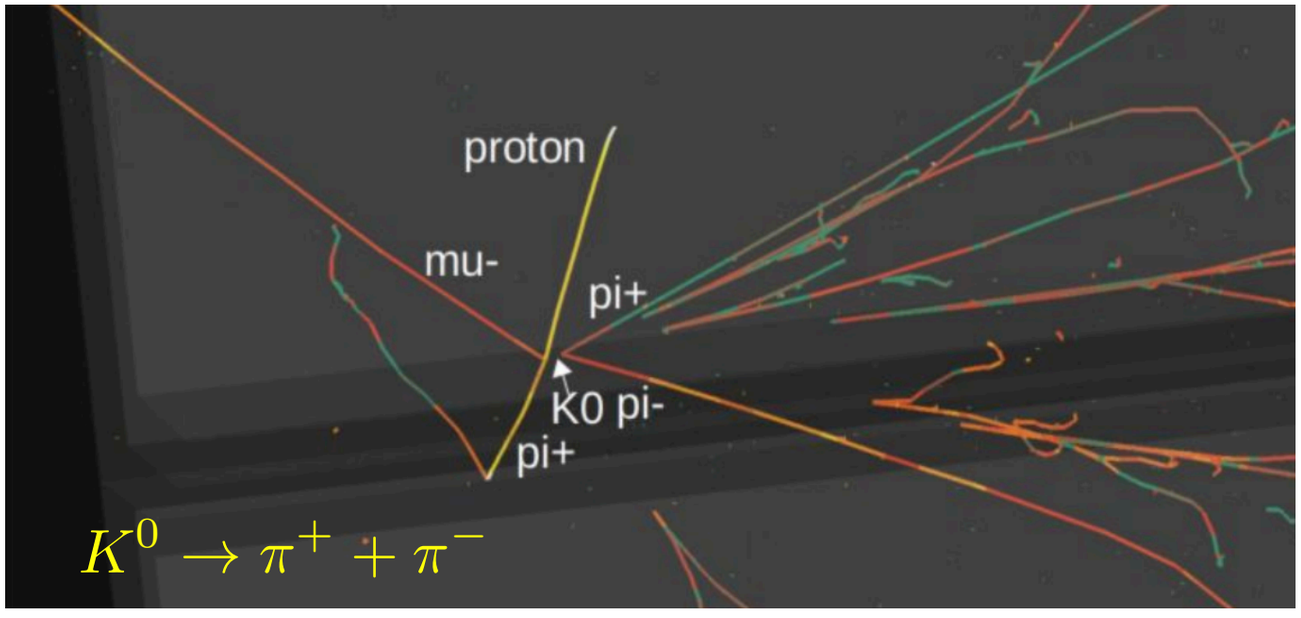
- Studies such as track multiplicity are sensitive to test final state interaction modeling

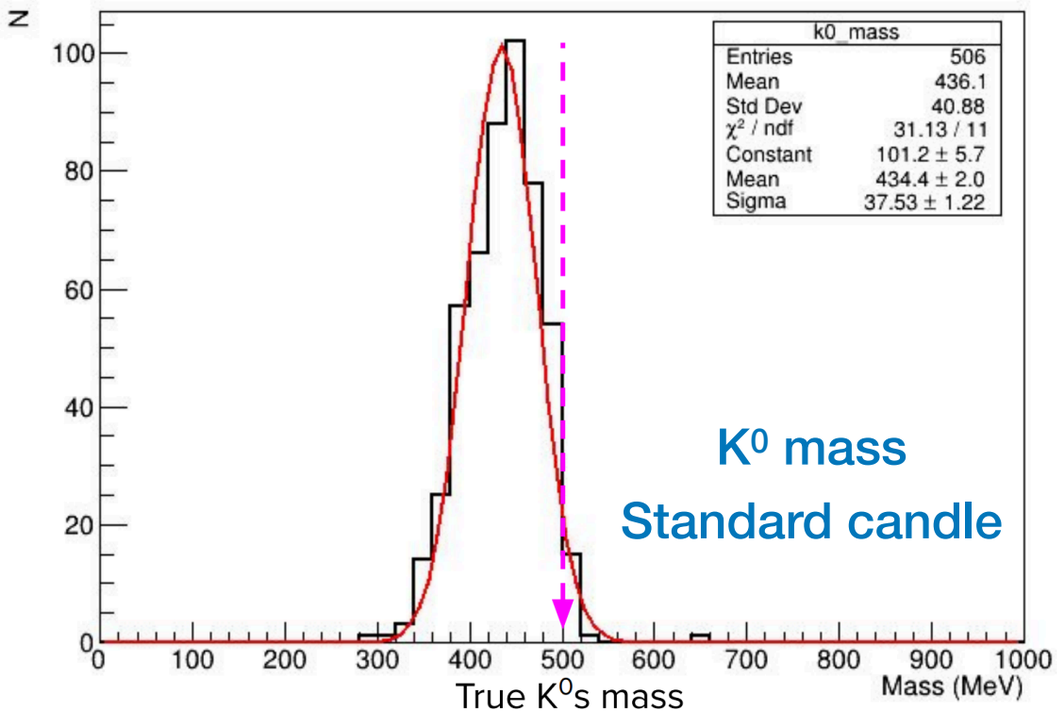


Kaons and Lambdas



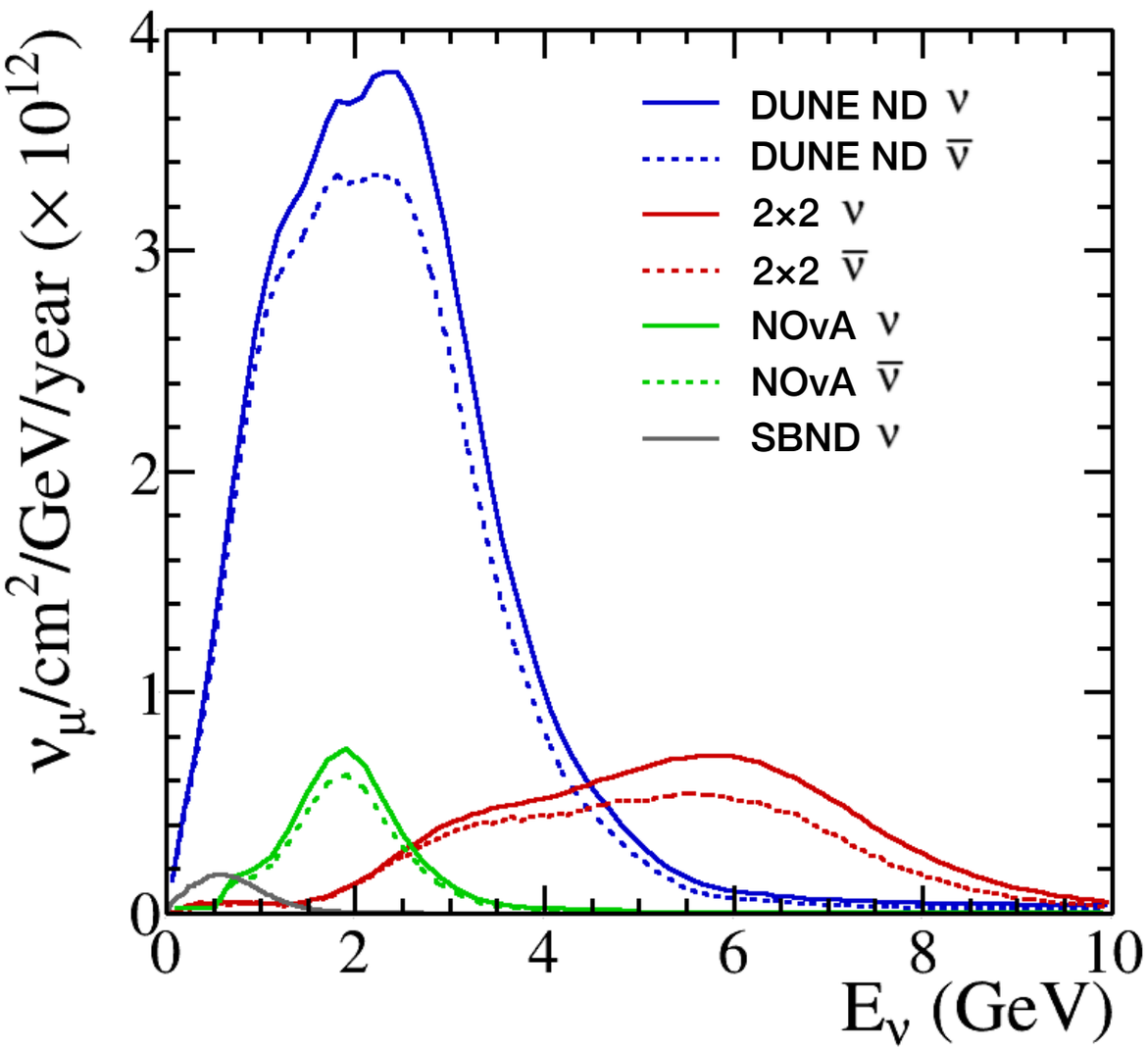






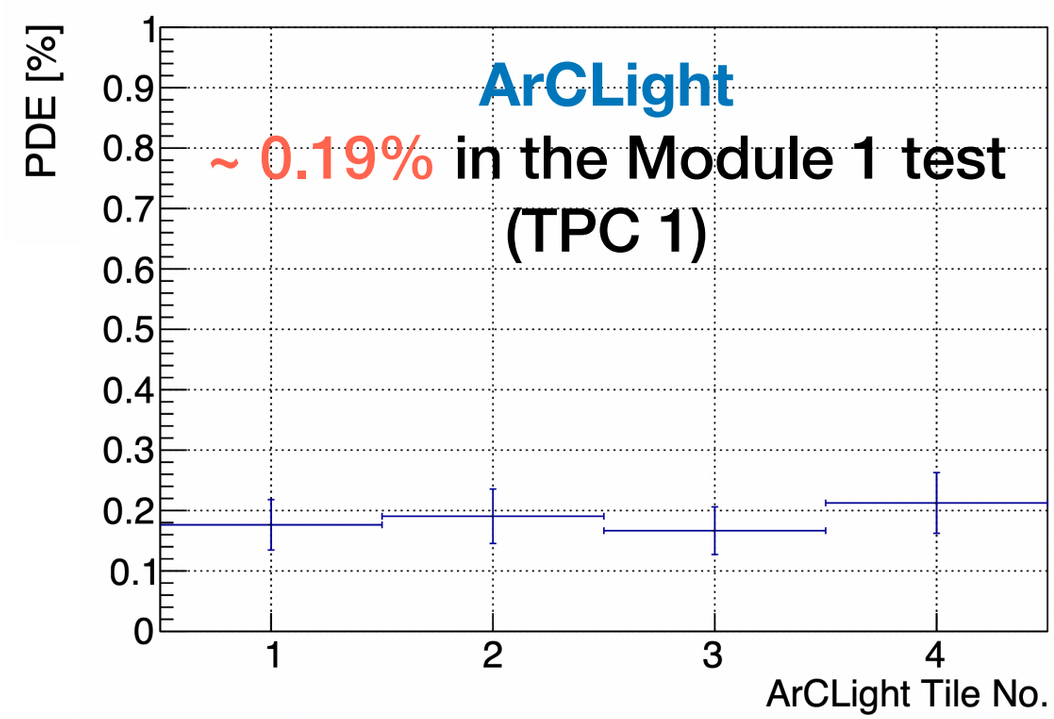
Physics Potentials of 2×2 in NuMI

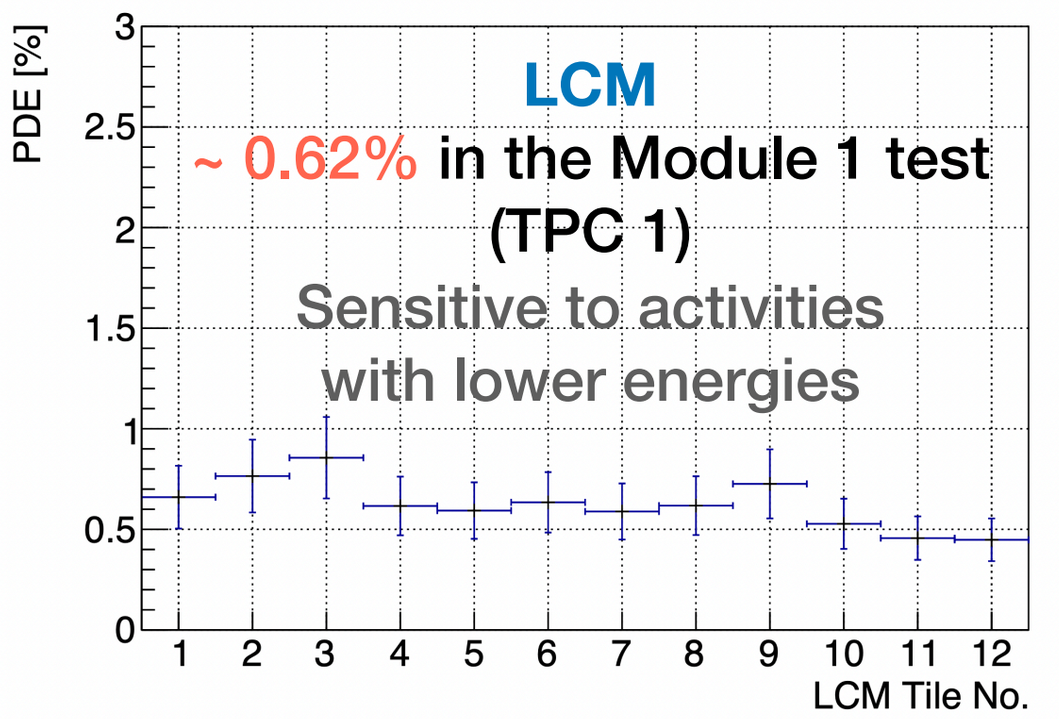
- Opportunity to explore ν-Ar interactions over a large phase space
- Innovated modularized LArTPC detector design, greater measurement potential
- 2×2 NuMI data will be available imminently
- Many interesting neutrino interaction related topics to be studied:

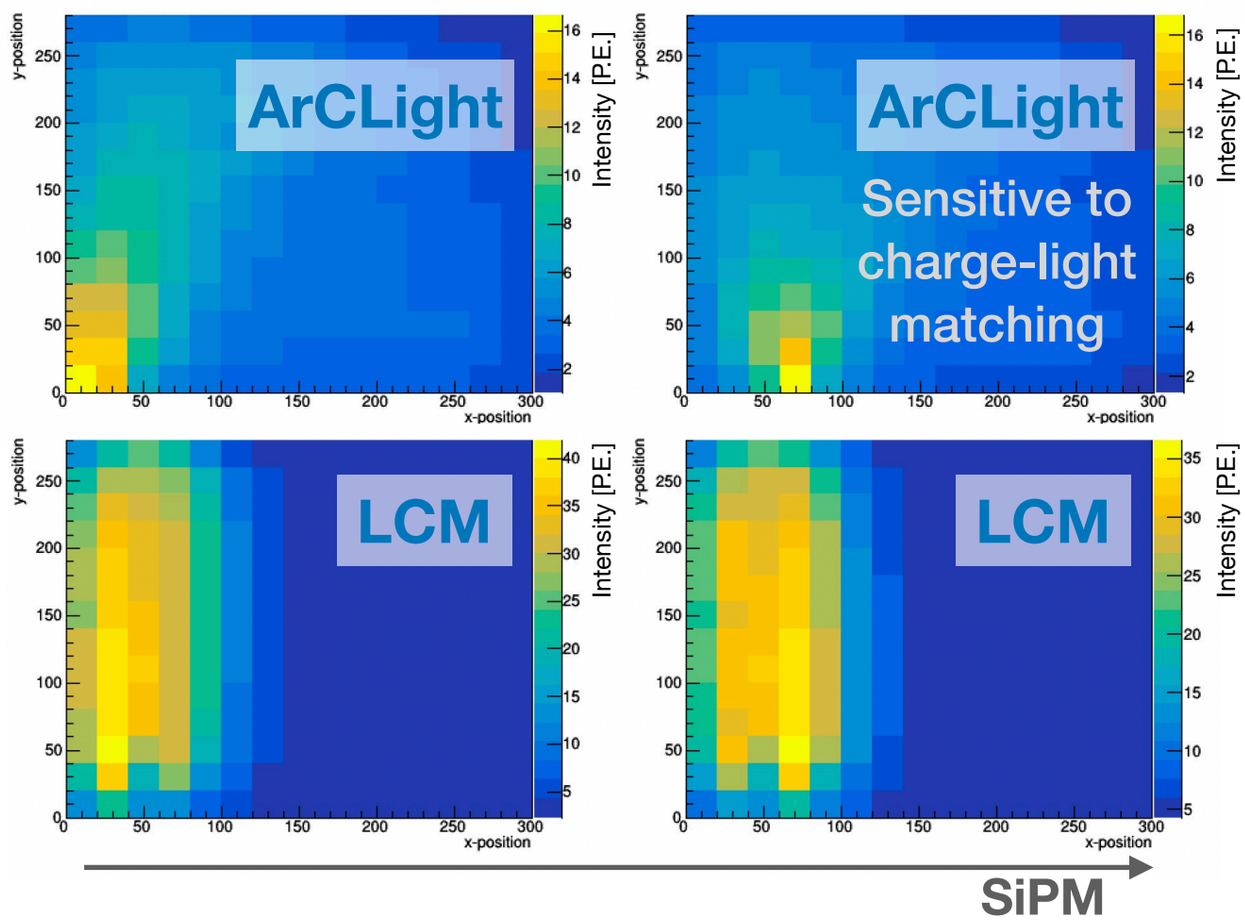


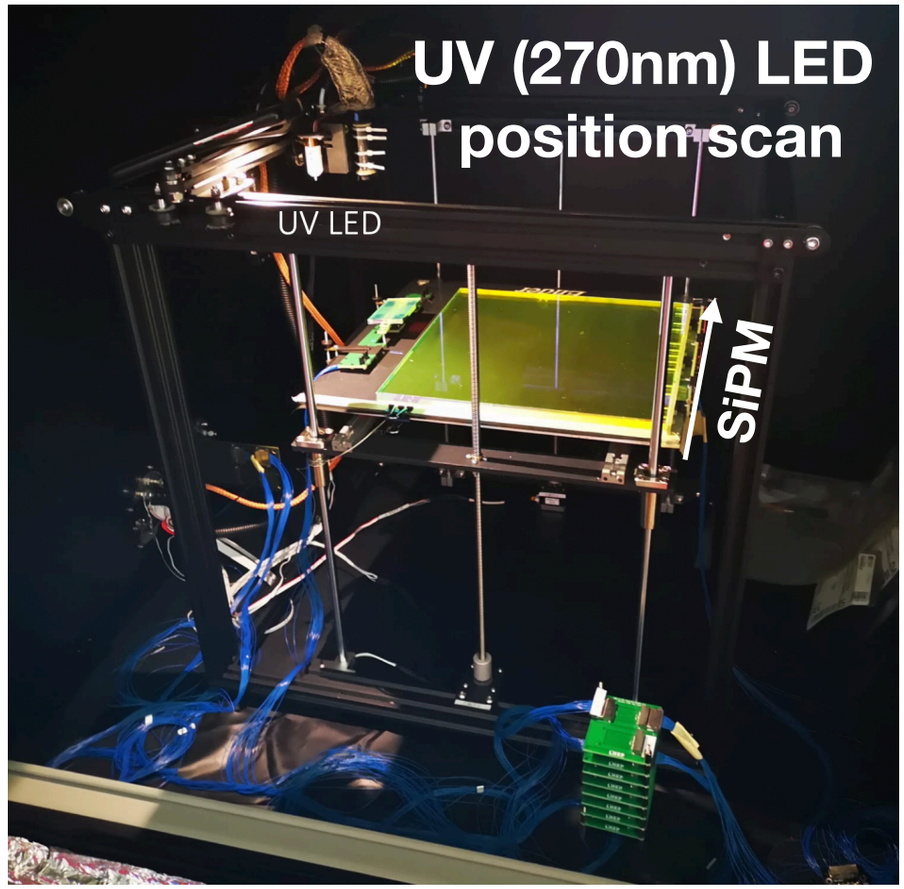
- $\bar{\nu}_\mu/\nu_\mu$ CC inclusive measurement
- CC0π measurement
- Pion production measurement
  - Pion multiplicity
  - Neutral pion production
- Track multiplicity
- Kaon production
- Lambda production
- Neutron tagging
- ν_e CC measurements
- NC1p measurement
- ν-e scattering
- $\bar{\nu}_\mu$ & ν_μ, ν_μ & ν_e
- A-scaling study on 2x2
- 2x2 and MINERvA

Photon Detection Efficiency and Position Sensitivity



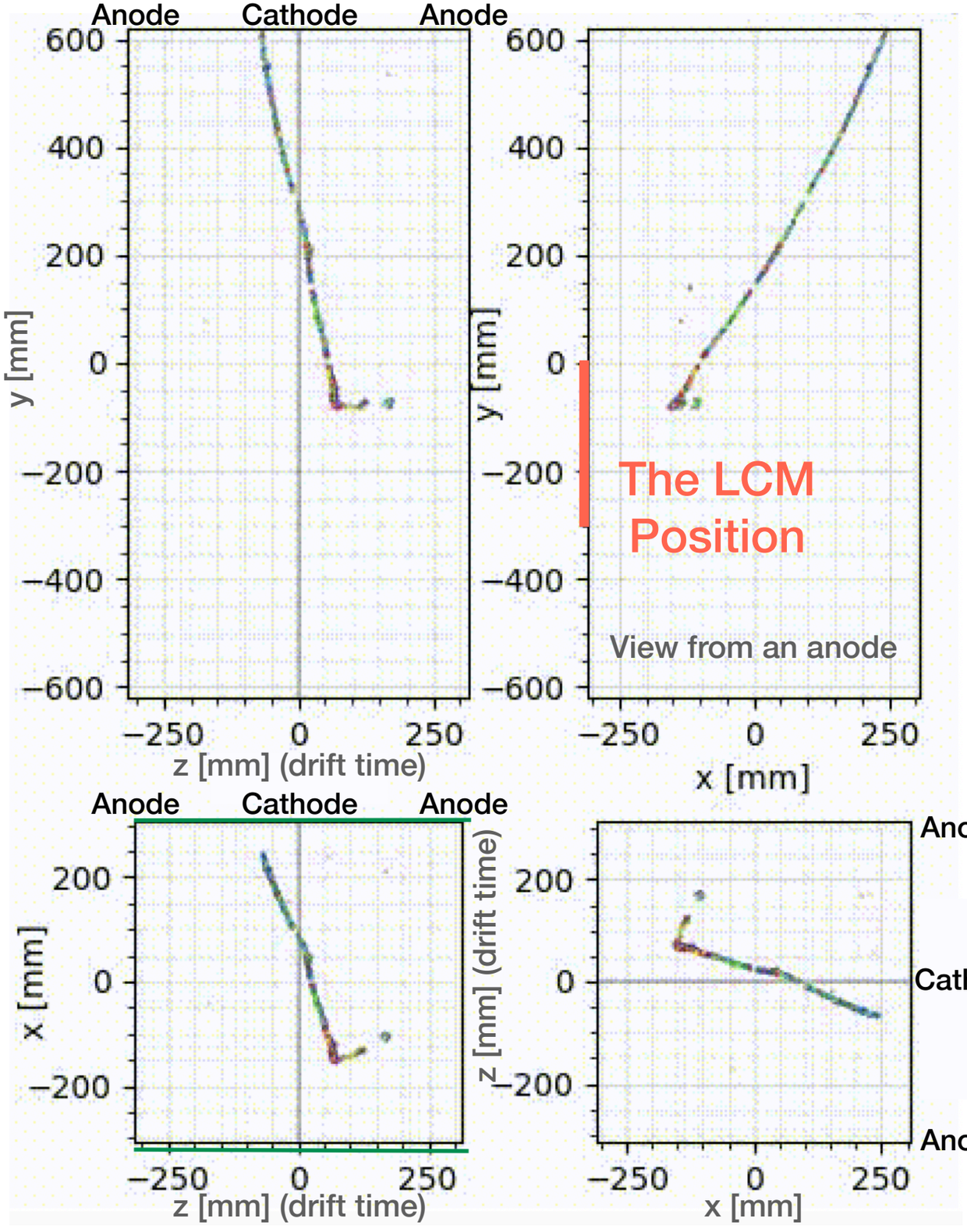


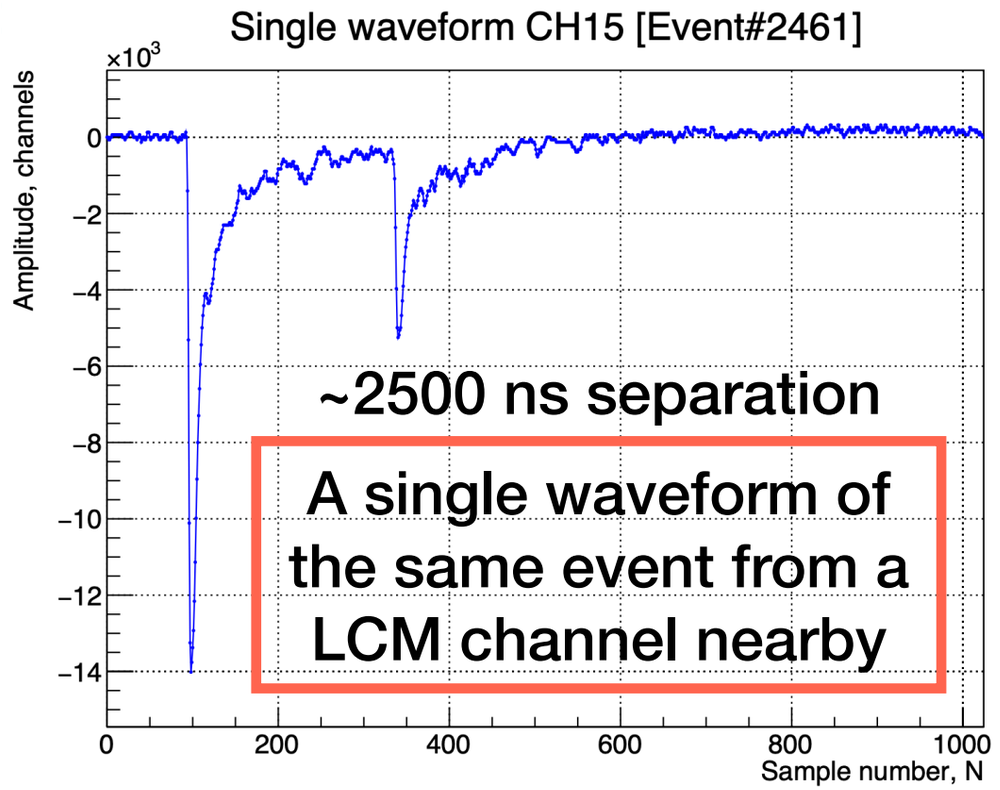




Michel Electrons in 2×2 Modules

An example of Michel electron in Module 0 test





- Michel electron energy O(10 MeV)
- Able to distinguish two light signals ~250 ns apart in Module 0 data and double-pulse LED signals with 100 ns separation
- Modules are scintillation light tight; prevent optical pile-up
- Potential to identify disconnected charge deposit (e.g. neutron recoil)