

The 2x2 Demonstrator

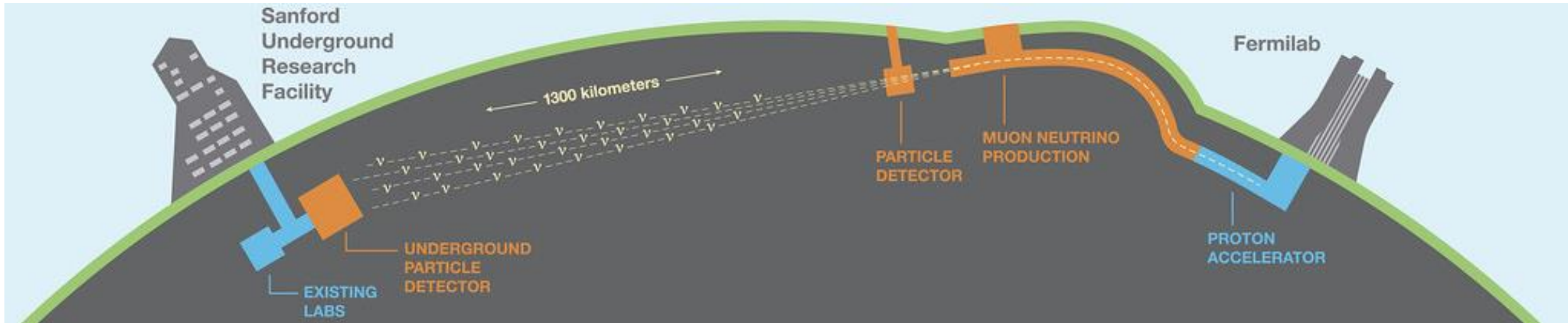
A demonstrator for the DUNE ND-LAr Near Detector based on the ArgonCube Design

Brooke Russell on behalf of the DUNE Collaboration

TAUP 2023 @ University of Vienna

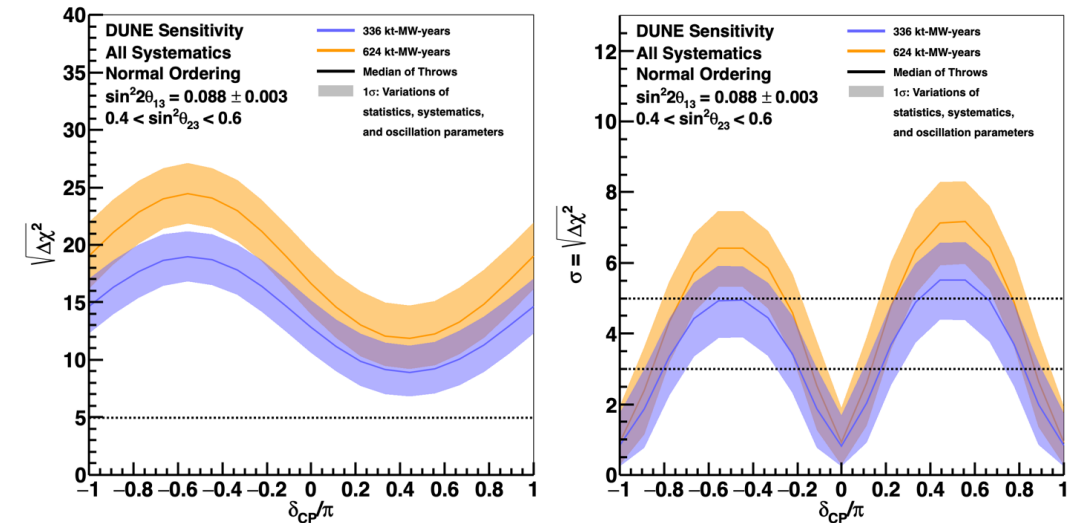
August 29, 2023

Deep Underground Neutrino Experiment (DUNE)



Compare measured far detector (FD) spectrum to predicted FD spectrum with no neutrino oscillation (given near detector (ND) constraints) to infer neutrino transition probability

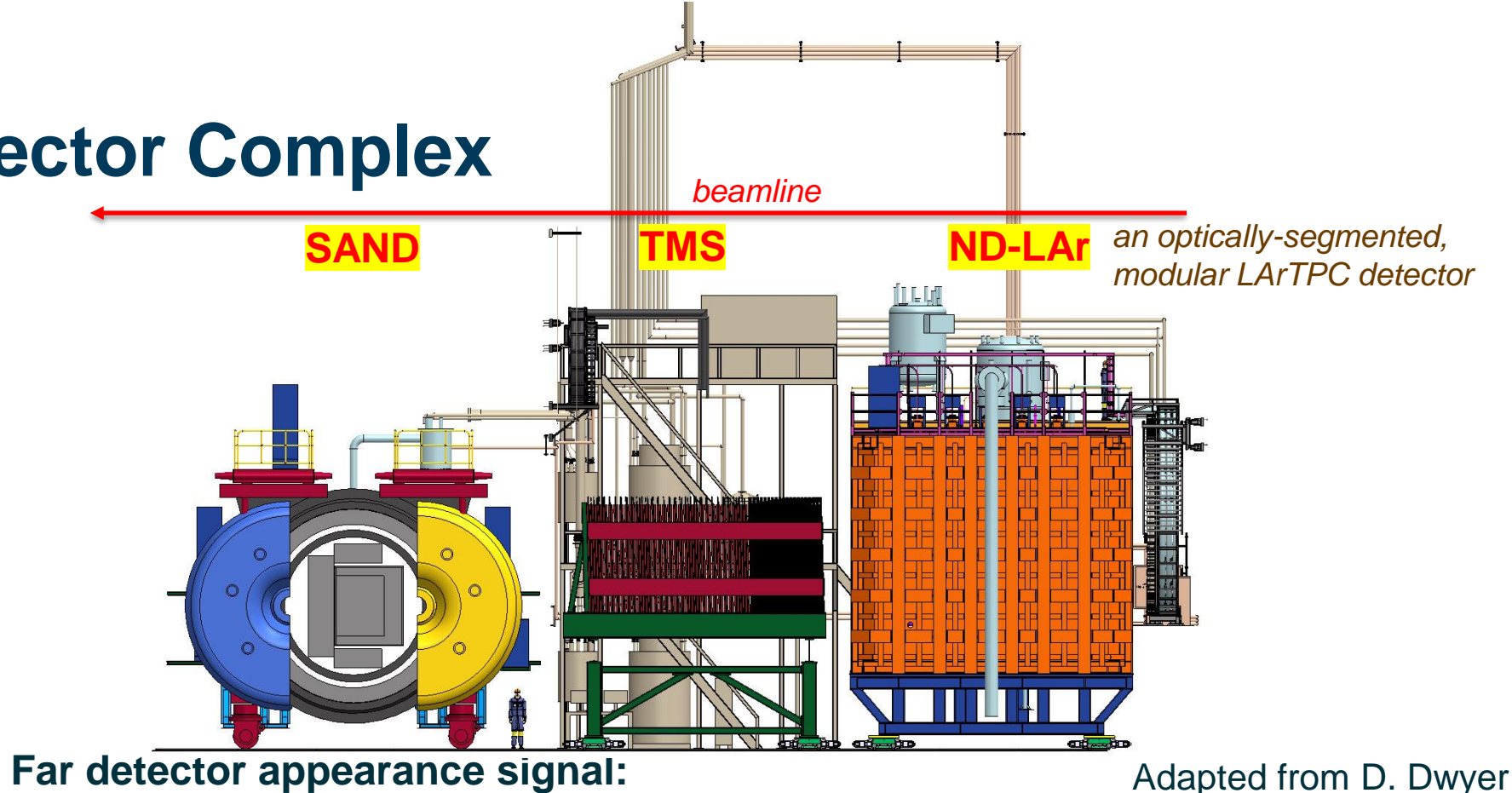
>> See *C. Wilkinson's talk for long-baseline oscillation analysis details*



DUNE Near Detector Complex

Three complementary detector systems working in concert to constrain

- neutrino flux
- interaction model
- detector response



Far detector appearance signal:

$$\frac{dN_{\nu_e}^{far}}{dE_{rec}} = \int_{E_\nu} D_{\nu_e-CC}^{far, inclus.}(E_{rec}; E_\nu) \sigma_{\nu_e-CC}^{inclus., Ar}(E_\nu) P_{\mu e}(E_\nu) \Phi_{\nu_\mu}^{far}(E_\nu) |_{l=0} dE_\nu$$

Near detector signal:

$$\frac{dN_{\nu_\mu-CC}^{near}}{dE_{rec}} = \int_{E_\nu} D_{\nu_\mu-CC, inclus.}^{near}(E_{rec}; E_\nu) \sigma_{\nu_\mu-CC}^{inclus., Ar}(E_\nu) \Phi_{\nu_\mu}^{near}(E_\nu) |_{l=near} dE_\nu$$

Far/near difference
constrained by
detector model

Far/near difference
constrained by
theory

Far/near difference
constrained by beam
model and near data
model

ND-LAr Prototyping

2016-2019 Component technology R&D

- Low-profile field cage
- LArPix pixel readout
- High-photocoverage light readout

2020 SingleCube

- 60%-scale single light & charge readout detector elements

2021 ArgonCube Module-0

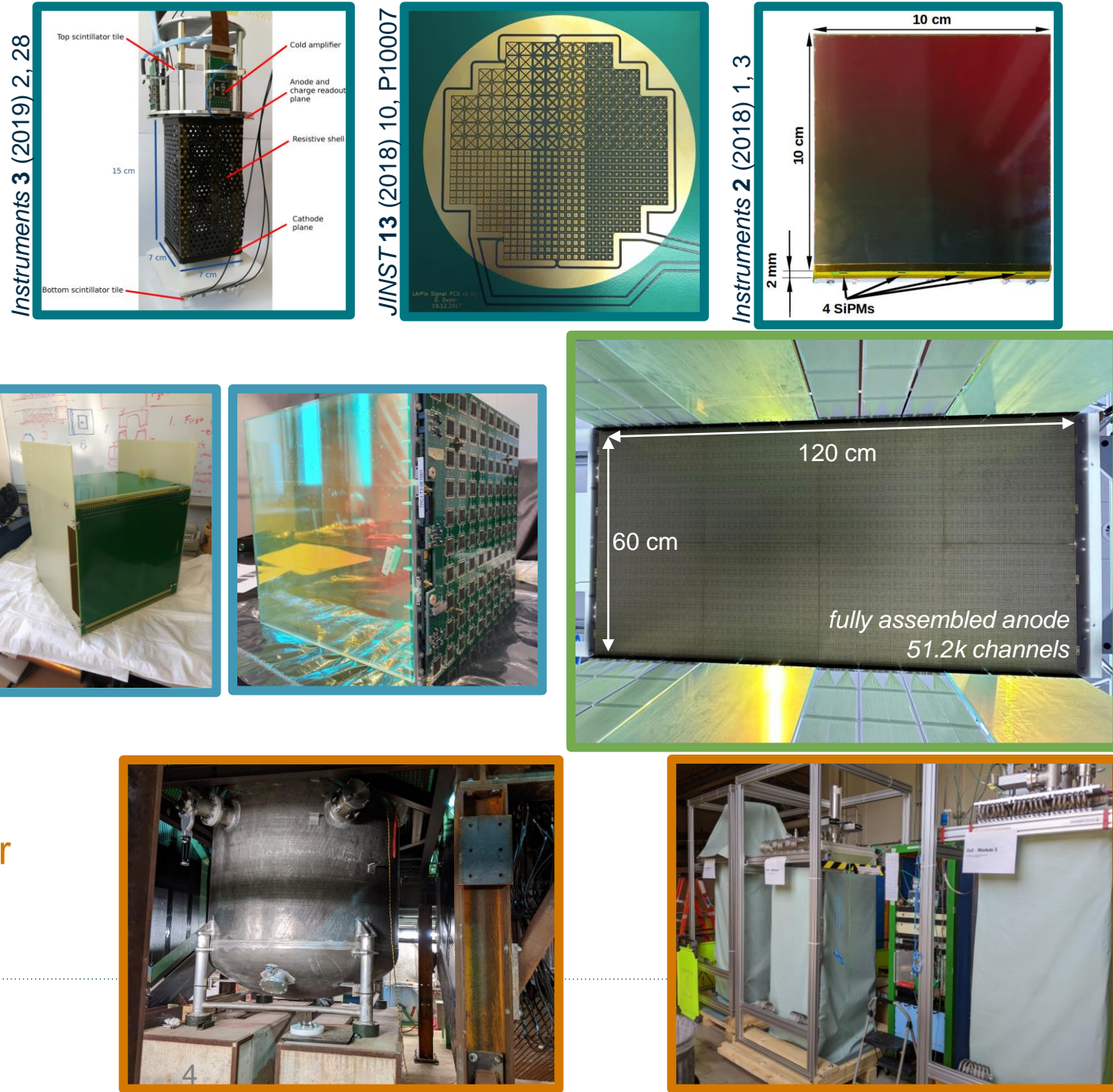
- 60%-scale fully-integrated detector module
- Four module cosmic-ray operation 2021-2023

2023-2025 ArgonCube 2x2 Demonstrator

- 4x 60%-scale fully-integrated detector module in NuMI @ FNAL

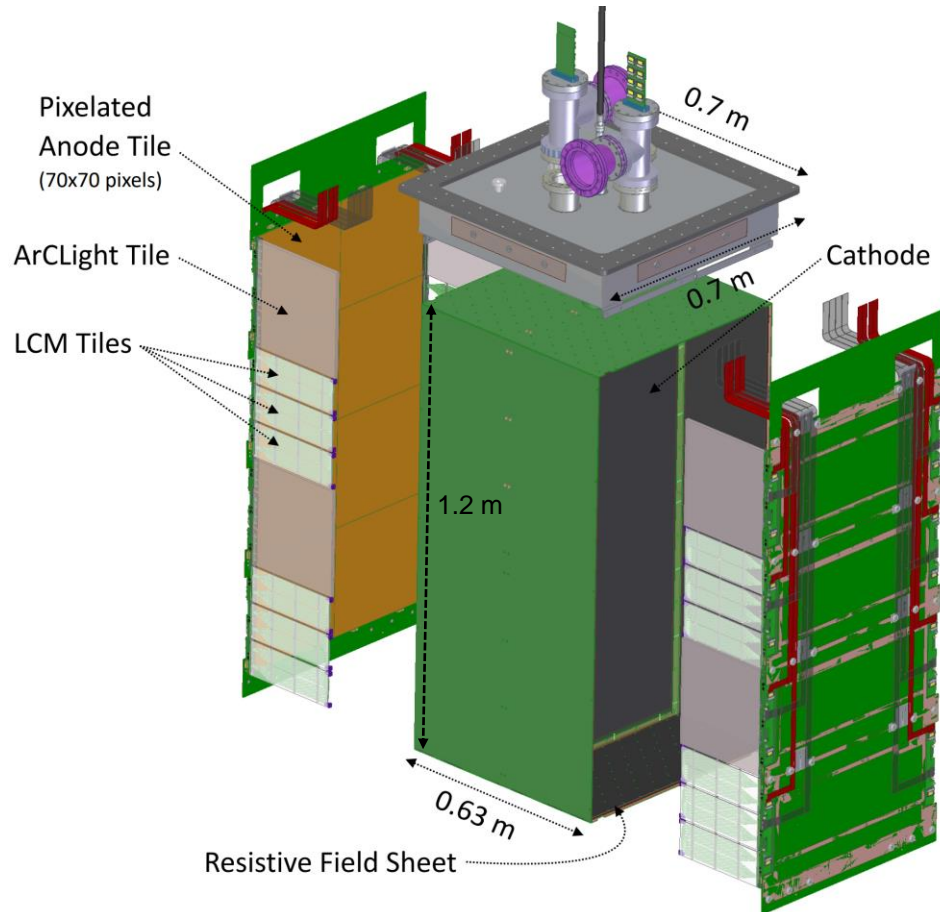
2024 Full-scale Demonstrator

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Module Design *a next-generation LArTPC*

Key design driver: maintain signal fidelity in high occupancy environment (beam ν pileup!)



60%-scale ND-LAr module prototype

Optical segmentation

- Contained scintillation light to mitigate ν pileup

Modular TPCs

- Potential failures contained to finite sub-region

Short charge drift distance

- Reduce requirements/risks associated with HV, purity, and field uniformity

Low-profile field cage

- Reduce inactive volumes

High-photocoverage light readout

- ν pileup mitigation with ~ 10 cm spatial resolution and < 10 ns timing resolution

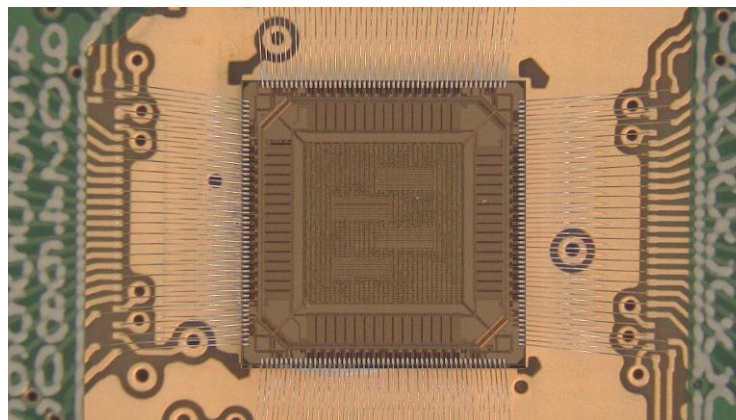
Pixelated charge readout

- ν pileup mitigation with true 3D readout
- Reduced sensitivity to system noise
- Scalable, mechanically robust, commercially produced PCB design



LArPix Concept

Low-power, integrating amplifier with self-triggered digitization and readout



Pixel dormant until signal exceeds tunable threshold

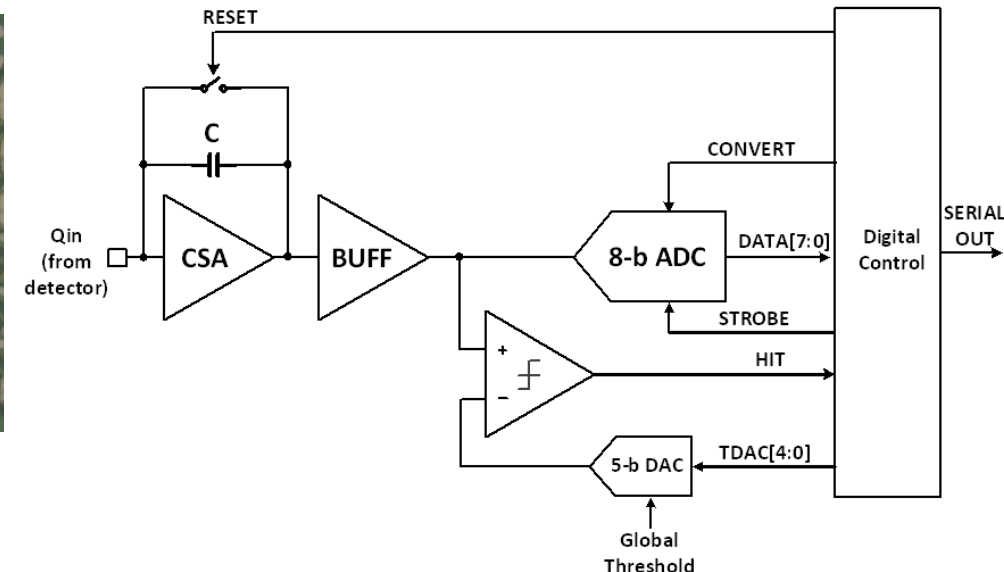
- Integrates charge for $\sim 3\mu\text{s}$ (4 mm drift), then digitizes
- Ready for next signal

Pixels are continuously active

- Serial I/O data rate is slow ($\sim 5\text{ Mb/s}$ per I/O channel) to limit digital power
- Modest data volumes: $\sim 1\text{ MB/s}$ per square meter of anode in surface cosmic-ray flux

End-to-end system architecture – *large-format pixel anode tiles, cables, feedthroughs, controller, etc.*

- Hydra networking: dynamic chip-to-chip I/O routing
- Scalable to $O(M)$ channel systems
- Single active component in cryogenic environment
- Minimal and redundant connections to cryostat
- Mechanically and cryogenically robust
- $O(\$0.10)$ per channel system cost, incl. cables/controllers/assembly/etc.



| Specification | Value | Comment |
|---------------------------|------------------------------------|--------------------------|
| Analog inputs | 64 | Single-ended input |
| Gain | $4.5\ \mu\text{V}/e^-$ | |
| Power | $<200\ \mu\text{W}/\text{channel}$ | Static power dissipation |
| Dynamic range | 1.3 V | Chip configurable |
| ADC resolution | 8 bits | |
| ADC LSB | 4 mV | Chip configurable |
| Threshold range | 0 to 1.8 V | Channel configurable |
| Threshold resolution | 1.5 mV | |
| Channel linearity | $< 1.2\%$ | Pre-calibration |
| Multi-hit separation time | $1.2\ \mu\text{s}$ | Chip configurable |
| Operating temperature | 80 to 300 K | |

LArPix System Performance

MIP response

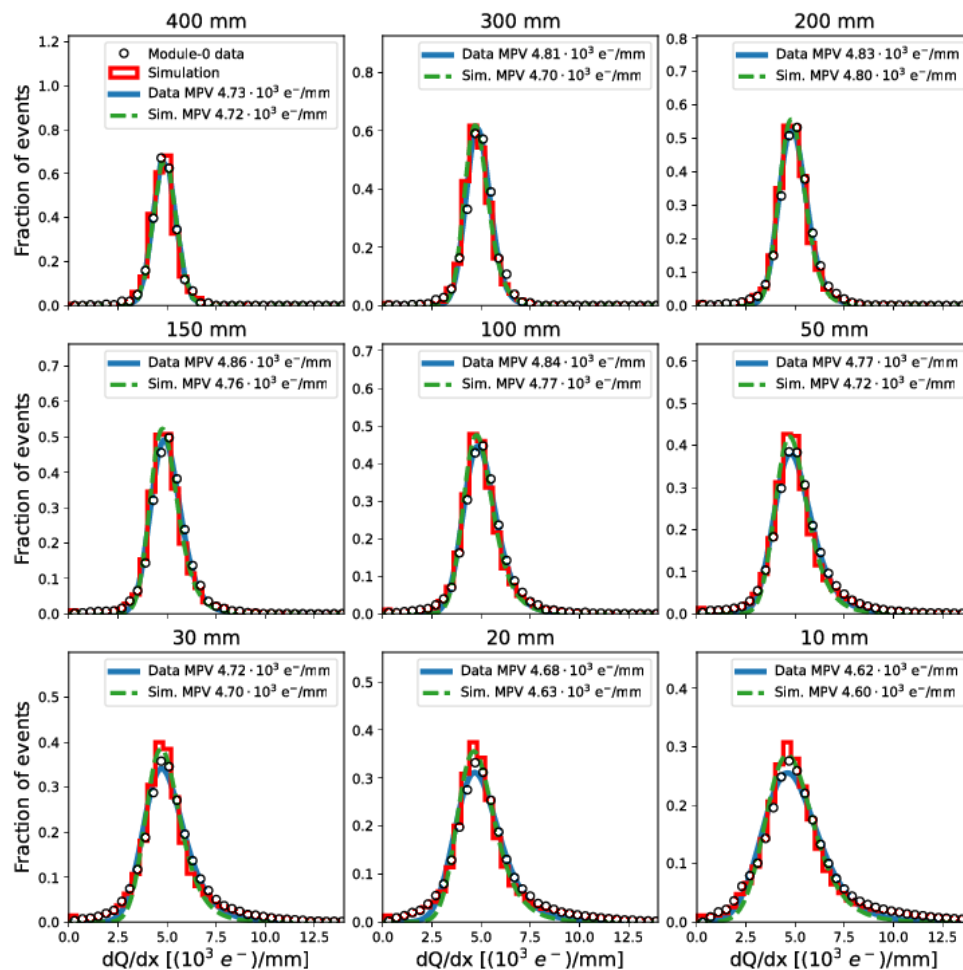
- Consistent with expectation
- Stable through data taking

Mature charge readout system design

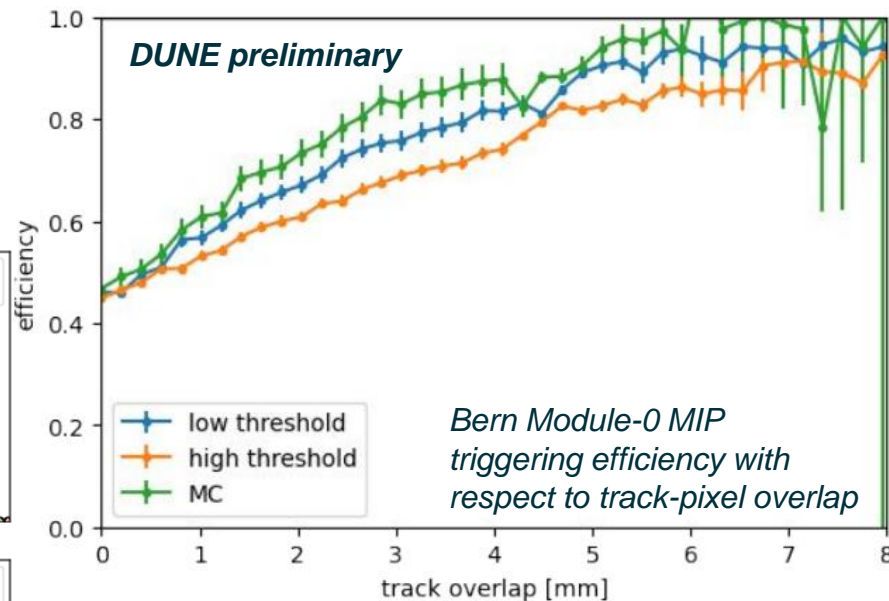
- Efficacy evaluated with prototype data
- >10k ASICs and O(100) pixel tiles tested to date

On-going development

- Improved ASIC physics performance
- Optimized pixel geometry
- Calibration
- Native 3D reconstruction



JINST 18 (2023) 04, P04034



| Specification | Value | Comment |
|-----------------------|-----------------------------|--------------------|
| Heat density | ~13 mW/ASIC | |
| Pixel multiplexing | 6.4k channels/cable | |
| Noise | ~850 e ⁻ ENC | |
| Tile leakage current | < 5 e ⁻ / 500 μs | |
| Charge resolution | < 1200 e ⁻ | < 5% MIP charge |
| Spatial resolution | 1.1 to 1.3 mm | Geometry dependent |
| Timing resolution | 0.7 μs | Chip configurable |
| Saturation level | > 200 ke ⁻ | |
| Triggering efficiency | ~80% for MIP | |
| MIP S:N | >20:1 | |

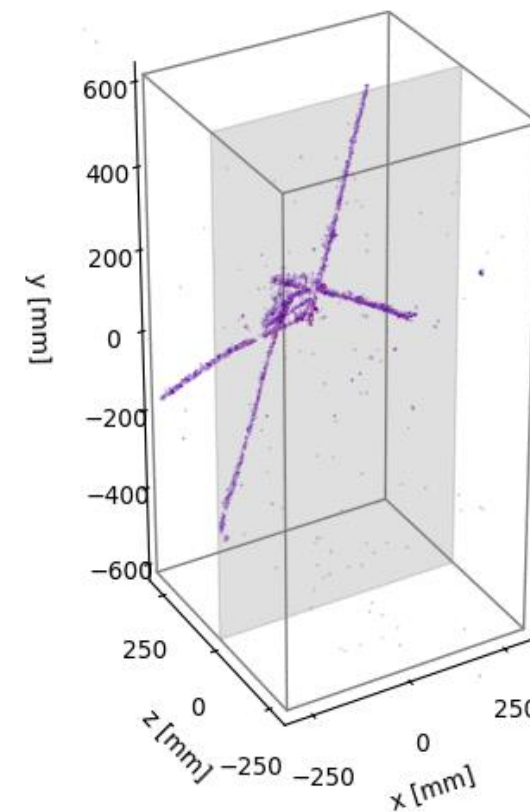
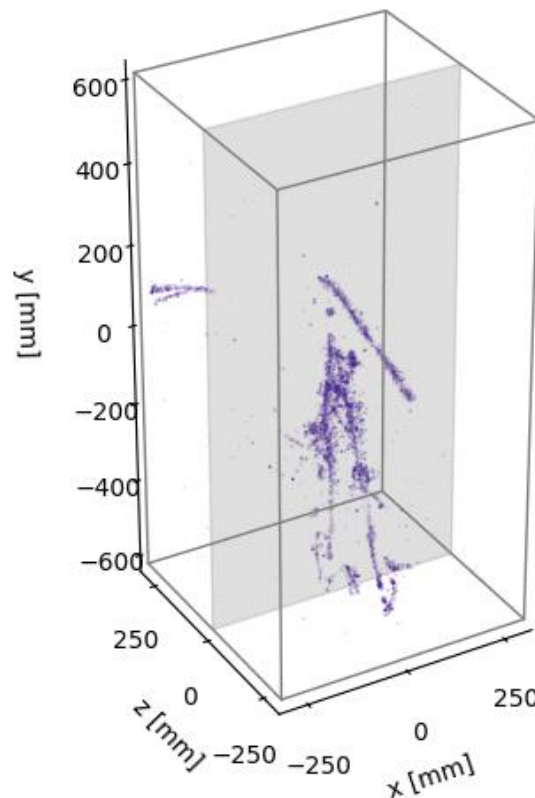
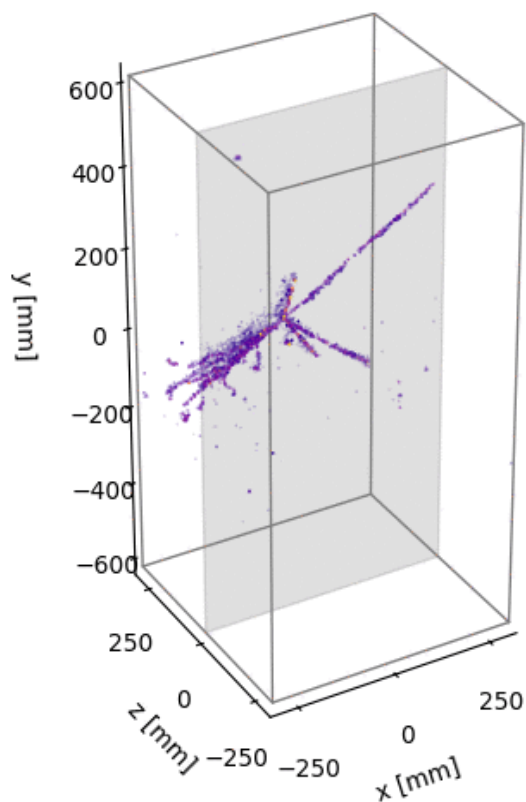
Module QC @ University of Bern

2021-2023 successful deployment and operation
of four fully-integrated ton-scale $O(100k)$ pixel
channel systems

Raw data with ~ 200 keV channel thresholds

Collected >100 M cosmic-ray events

DUNE preliminary



Proto-DUNE ND

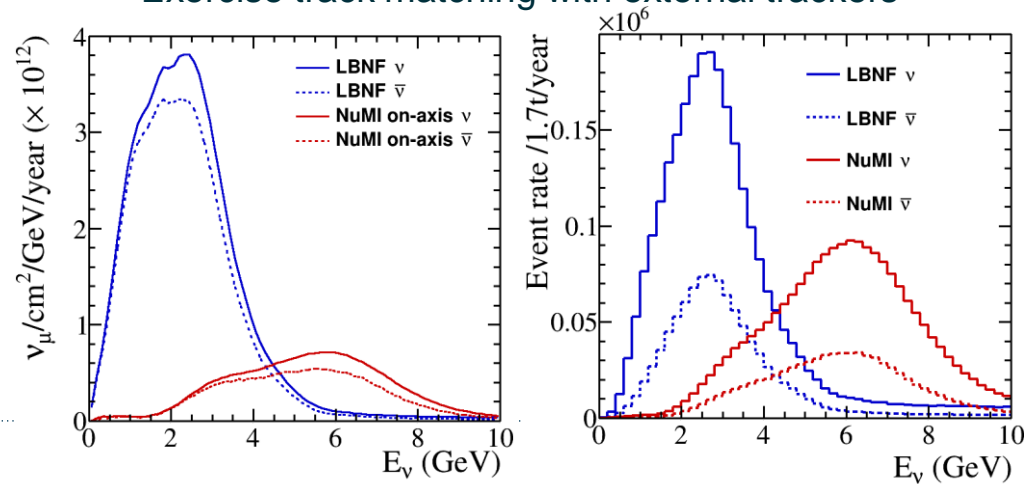
Operating conditions

- On-axis operation in medium energy FNAL NuMI ν beam
- 107 m rock overburden (300 m.w.e.)
- 2.4 metric ton LAr target mass
- 25% optical coverage
- 337k charge-sensitive pixels at 4 mm pitch
- Continuous charge readout, independent of photon system trigger
- ~200 keV charge threshold

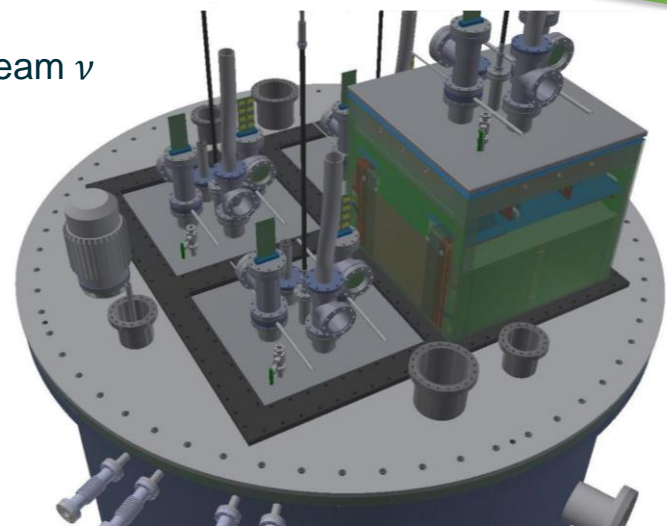
$(\bar{\nu})$ -Ar physics

Technical demonstrations

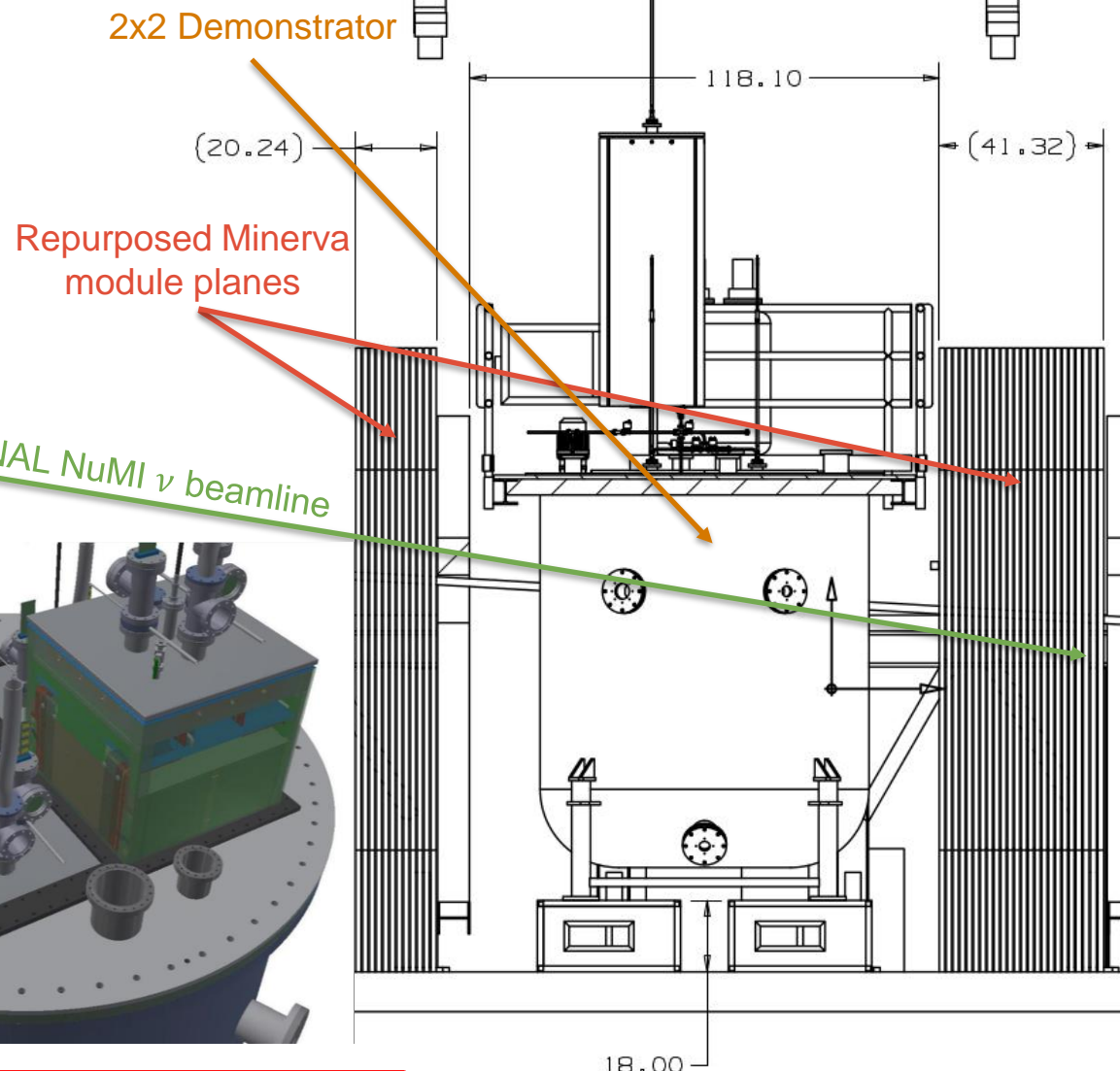
- Signal reconstruction fidelity in high-intensity environment
- Evaluation of impact of uninstrumented volumes
- Assess LArTPC module performance in response to beam ν
- Exercise track matching with external trackers



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$\bar{\nu}$ -Ar physics



Summary

DUNE is a next-generation long-baseline neutrino oscillation program designed to measure neutrino mixing parameters to high precision

- ND-LAr is a critical component in the DUNE oscillation program
- Single module prototype performance have demonstrated cutting-edge, highly performant LArTPC design

Successfully produced, qualified, and deployed multiple O(100k) channel charge readout systems

- Low-noise, low-power cryogenic-compatible detector readout SOC ASIC
- Self-triggering, ~100% live true 3D pixelated charge readout for LArTPCs
- Full commercial production/assembly of system at O(\$0.10)/channel
- On-going R&D to realize the full promise of this technology

The 2x2 Demonstrator is a testbed to evaluate novel ND-LAr technologies in a ν beam

- Installation/commissioning Fall 2023
- ME NuMI RHC operation expected Winter 2023