The DUNE 2x2 Demonstrator physics prospects and plans with neutrino data

Andrew Cudd on behalf of the DUNE Collaboration

NuFact 2024 – The 25th International Workshop on Neutrinos from Accelerators
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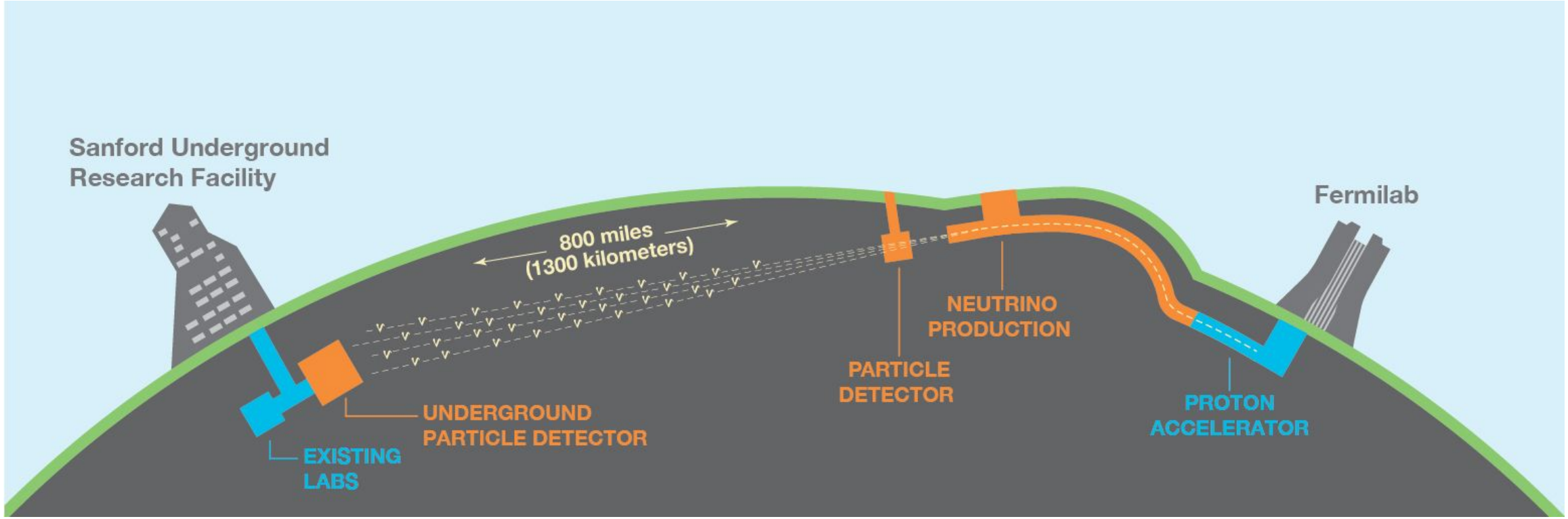
University of Colorado Boulder

DUNE: Deep Underground Neutrino Experiment



DUNE is a long-baseline neutrino oscillation experiment:

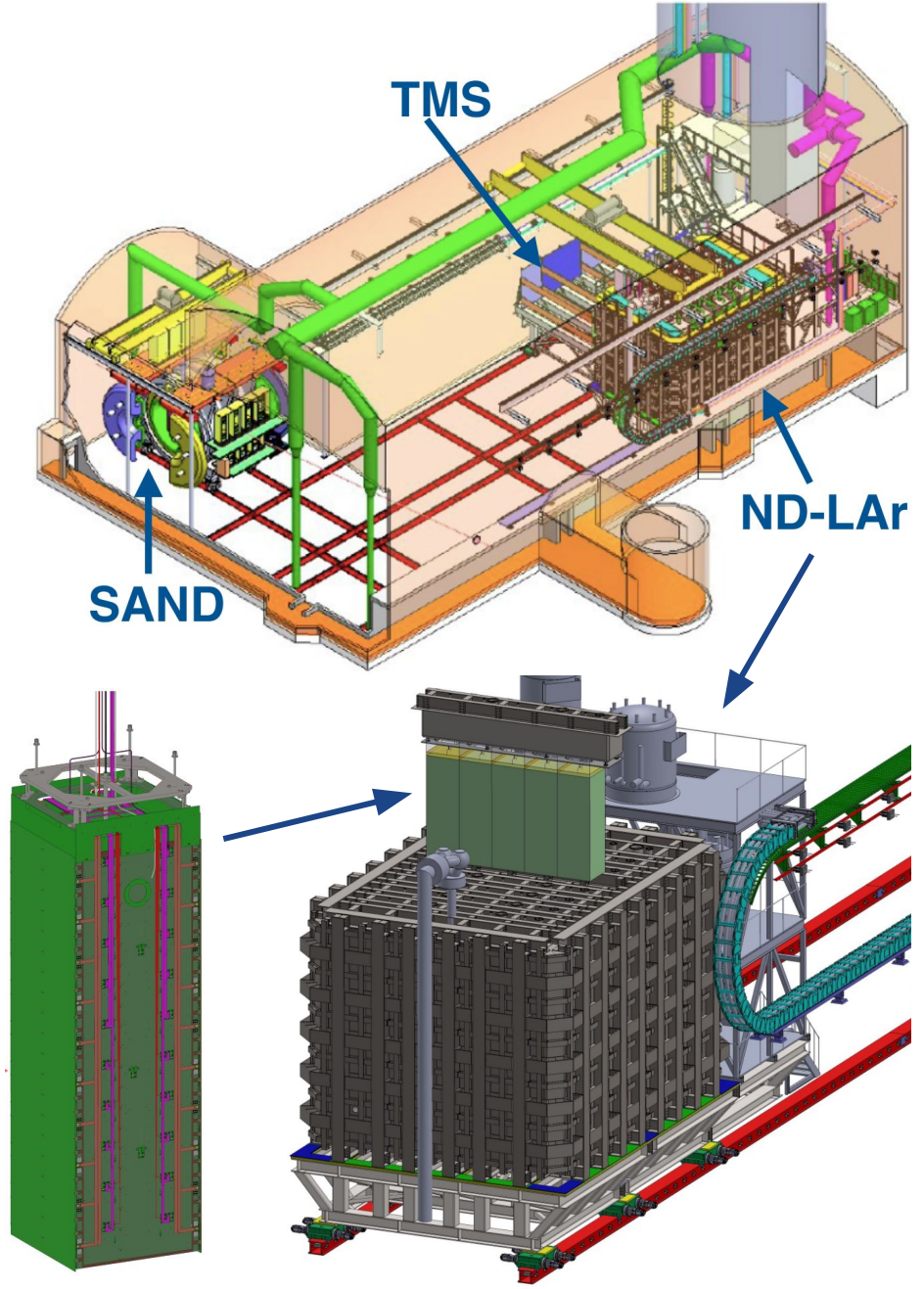
- 1.2 (2.4) MW neutrino beam is produced at Fermilab
- Travels nearly 1300 km to a far detector (FD) at the Sanford Underground Research Facility (SURF)
- Measured by a suite of near detectors (ND) about 0.5 km from the production target

DUNE Near Detector

Near detector consists of a movable liquid argon TPC (ND-LAr) plus muon spectrometer system (TMS) and a fixed on-axis detector (SAND)

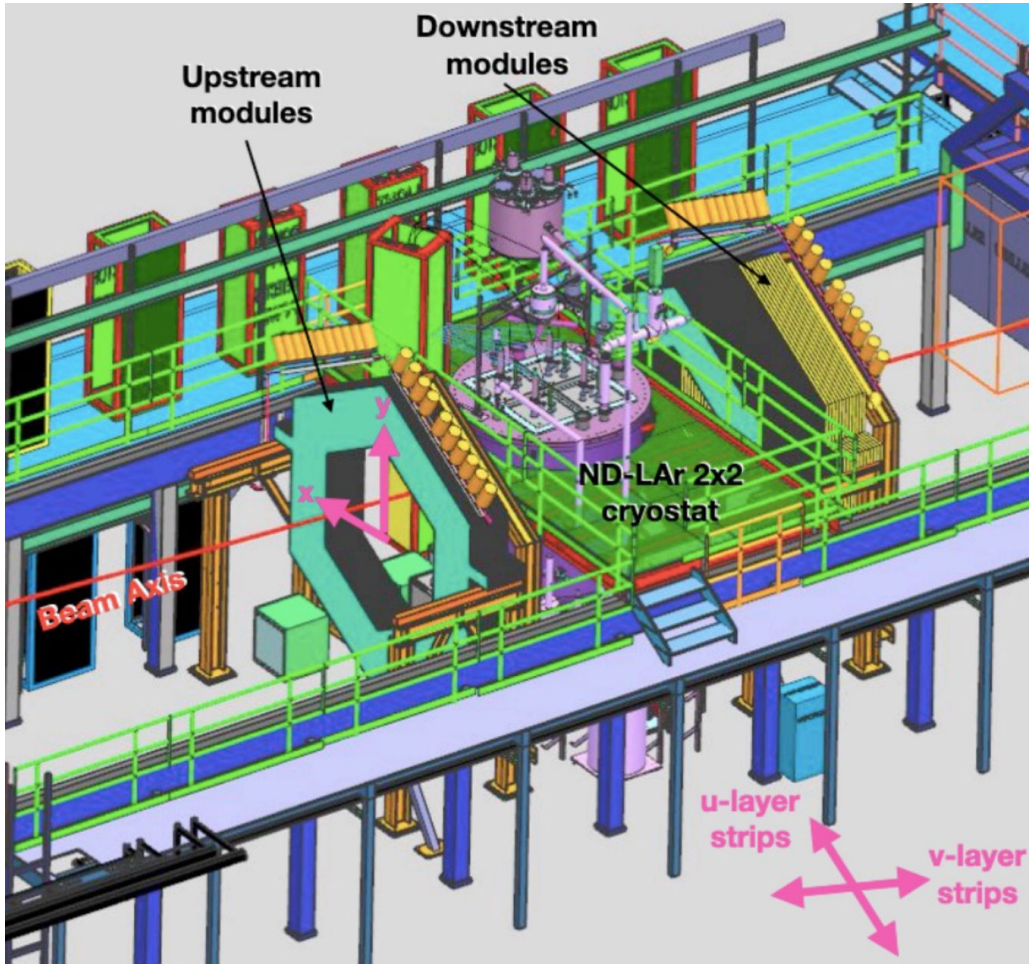
Features of ND-LAr:

- Pixel-based readout and optically separated modules to handle the high event rate and track multiplicity in the ND hall
- Light readout for measuring scintillation light from interactions in the liquid argon
- Composed of 35 modules measuring 1 m x 1 m x 3 m (LxWxH) all placed in a single cryostat in a 5 x 7 grid



ND-LAr 2x2 Demonstrator

Detailed talk on the 2x2 hardware and operational status from Sindhu Kumaran:
https://indico.fnal.gov/event/63406/contributions/297832/



MINOS Hall @ FNAL

Prototype experiment at Fermilab using the NuMI neutrino beam using four slightly smaller modules in a 2x2 array configuration

Uses repurposed MINERvA scintillator tracking planes upstream and downstream of the 2x2 modules

Physics & technical goals:

- Demonstrate the modular LArTPC technology in an high rate environment
- Development and testing of DUNE infrastructure, e.g. data acquisition
- Perform neutrino physics at DUNE energy and on argon

Diagram: arXiv.2403.03212

ND-LAr / 2x2 Module

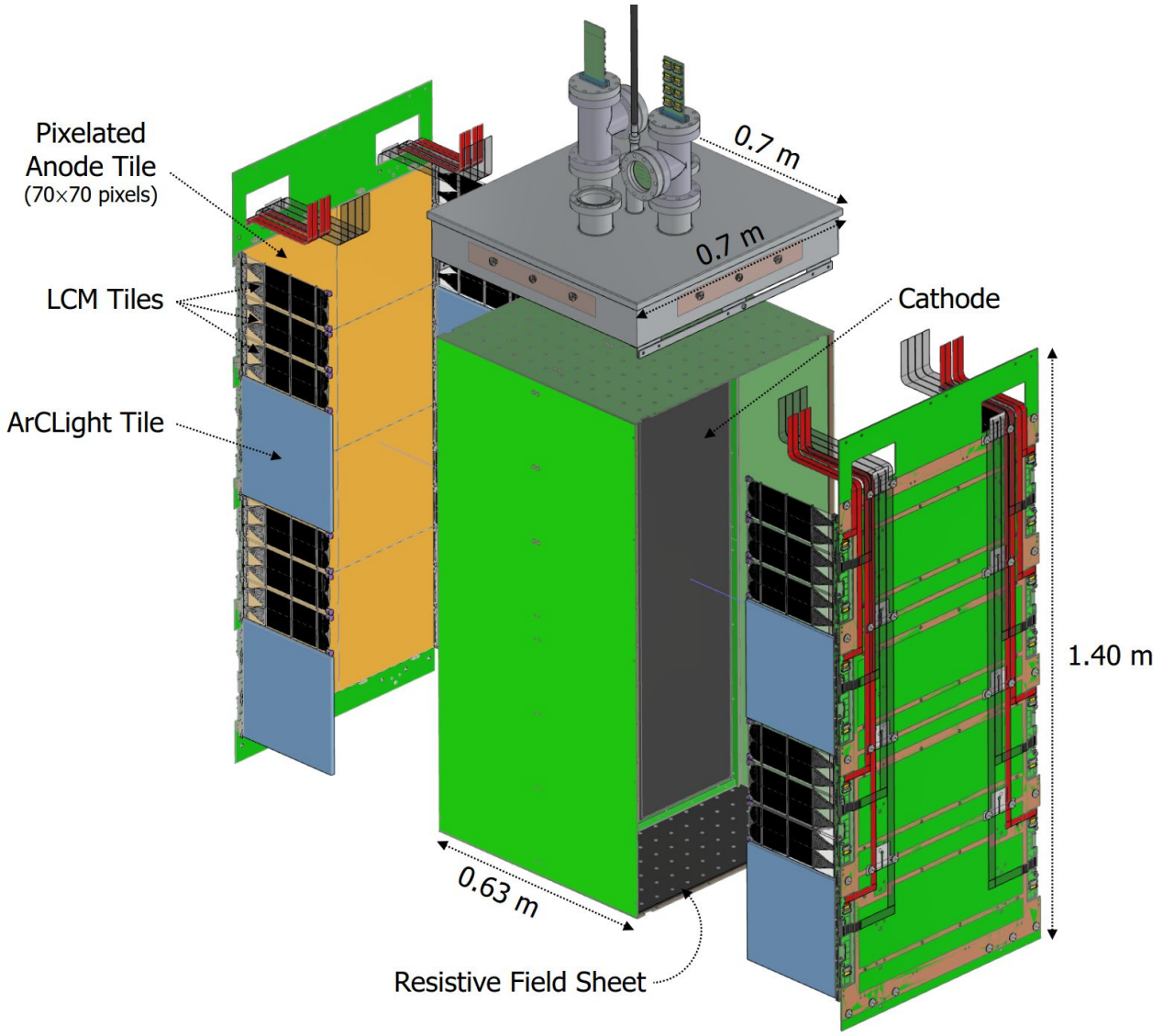
Each module has two optically separated liquid argon TPCs (drift regions)

- 0.6 m (W) × 1.2 m (H) × 0.3 m (drift) active volume per TPC
- 2x2 active LAr mass ~ 2.4t

Pixel-based charge readout (LArPix) for full 3D reconstruction of interactions

Two complementary light collection systems (ArCLight and LCM)

Each module previously tested at the University of Bern in cryogenic conditions collecting cosmic rays



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MINERvA + 2x2 = Mx2

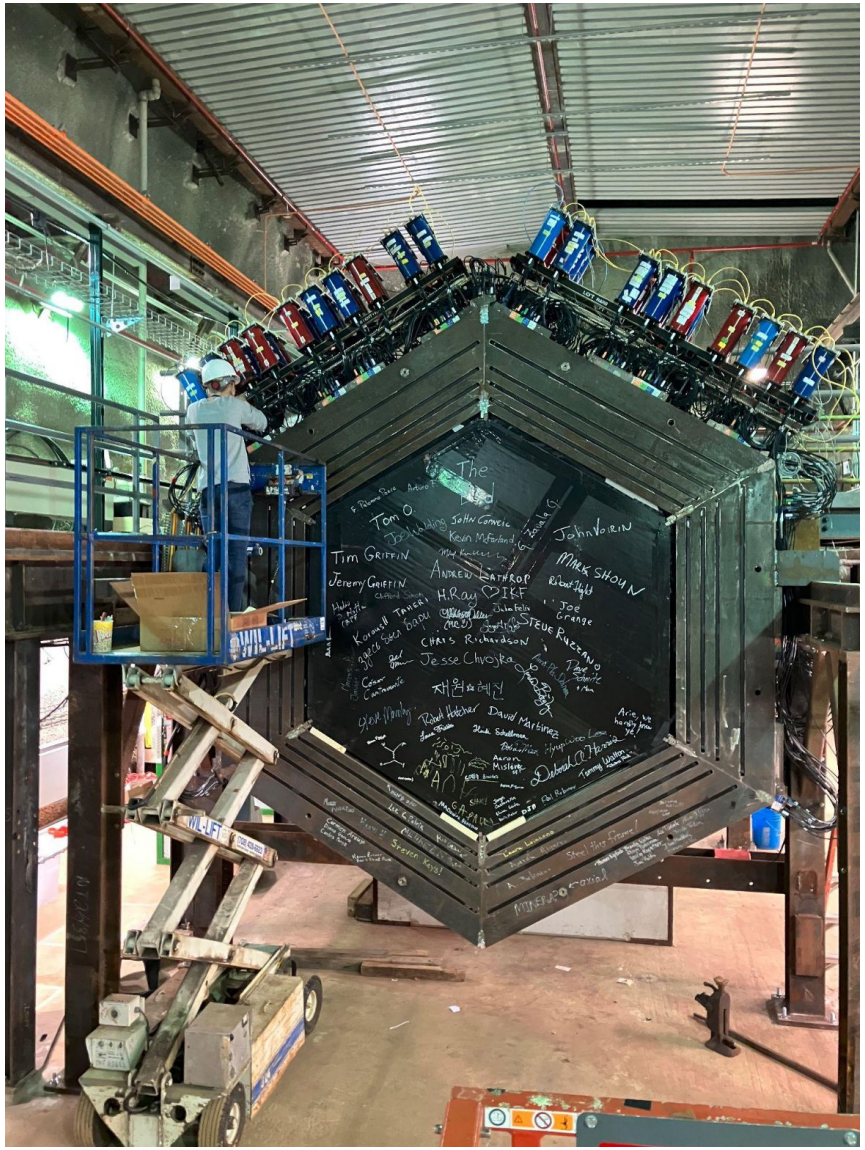
Repurposed MINERvA planes are placed upstream and downstream of the 2x2 modules for additional particle tracking

Primarily consists of triangular plastic scintillator bars arranged in X/U/V “views” for particle tracking

Contains some calorimetry modules/planes with thin lead or steel plates

Mx2 Configuration:

- 22 tracker, 10 ECAL, 12 HCAL modules (76 total planes)
- 11840 channels
- ~0.6 m upstream and ~1.5 m downstream



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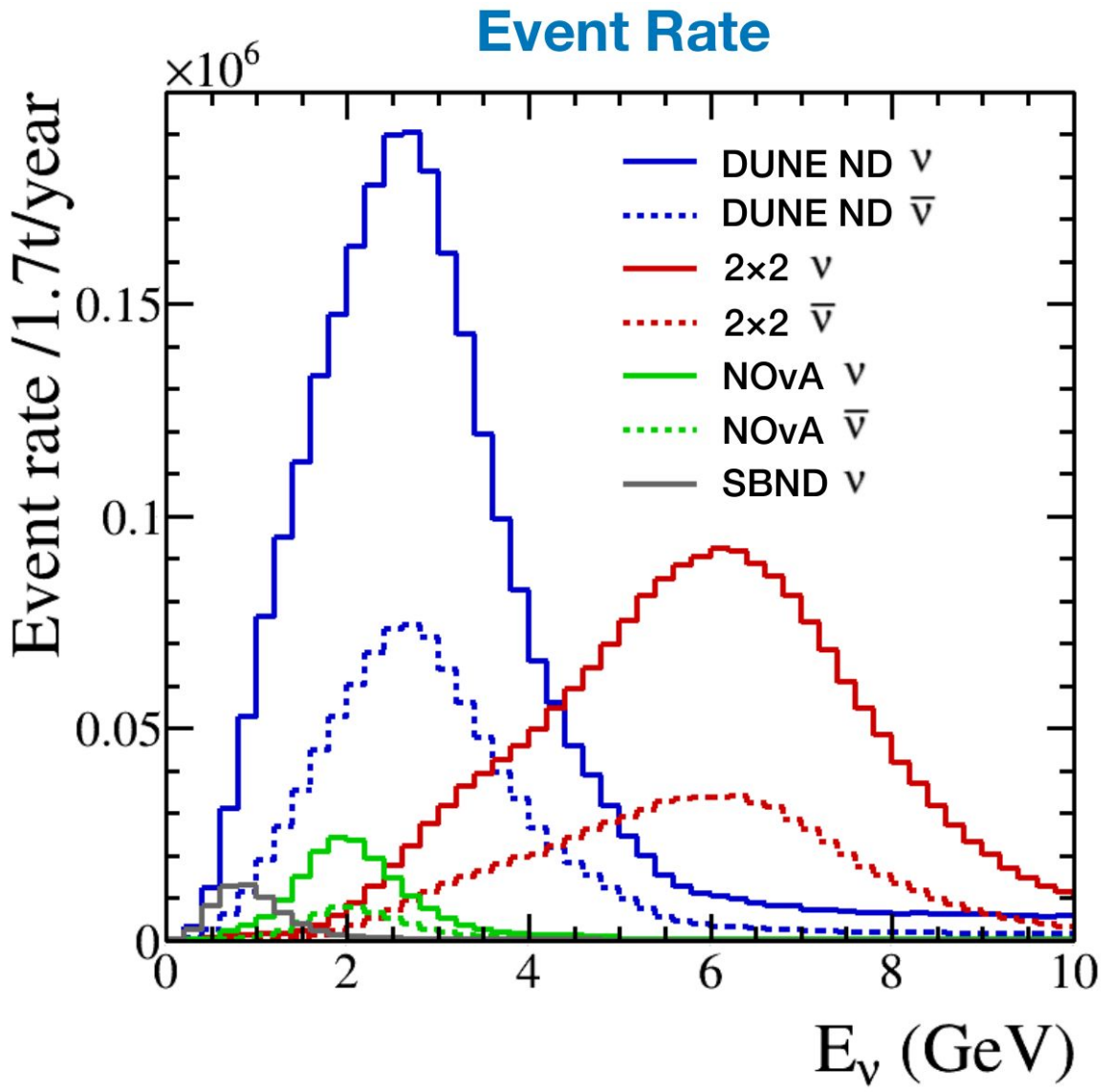
NuMI Beam and Event Rate

High rate of neutrino interactions from the NuMI on-axis beam → important overlap with DUNE beam energy

Wide variety of expected interactions, including many different pion production channels

Important measurements for the DUNE oscillation analysis along with (anti)neutrino cross sections never before measured on argon

Complementary to other experiments measuring neutrino interactions



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2x2 Collected Data

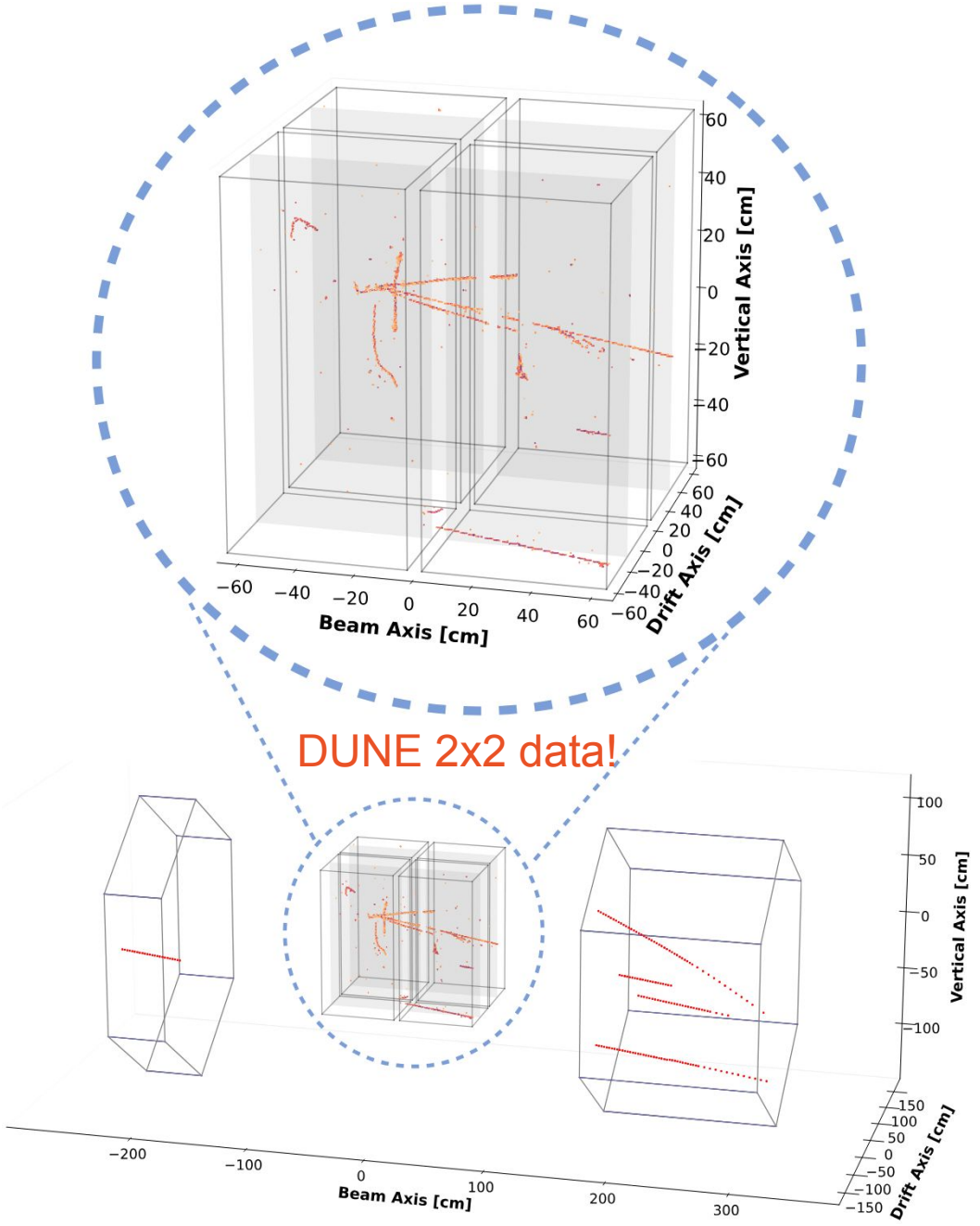
Event display showing the charge readout in the 2x2 liquid argon and the up and downstream MINERvA modules for a NuMI beam event

Collected ~1E19 POT over ~5 days in antineutrino beam mode this past summer

About 10k neutrino interactions per day!

Also includes cosmic events and low energy radiation activity in the total data sample

Planning to take more data when the NuMI beam returns this fall and in 2025



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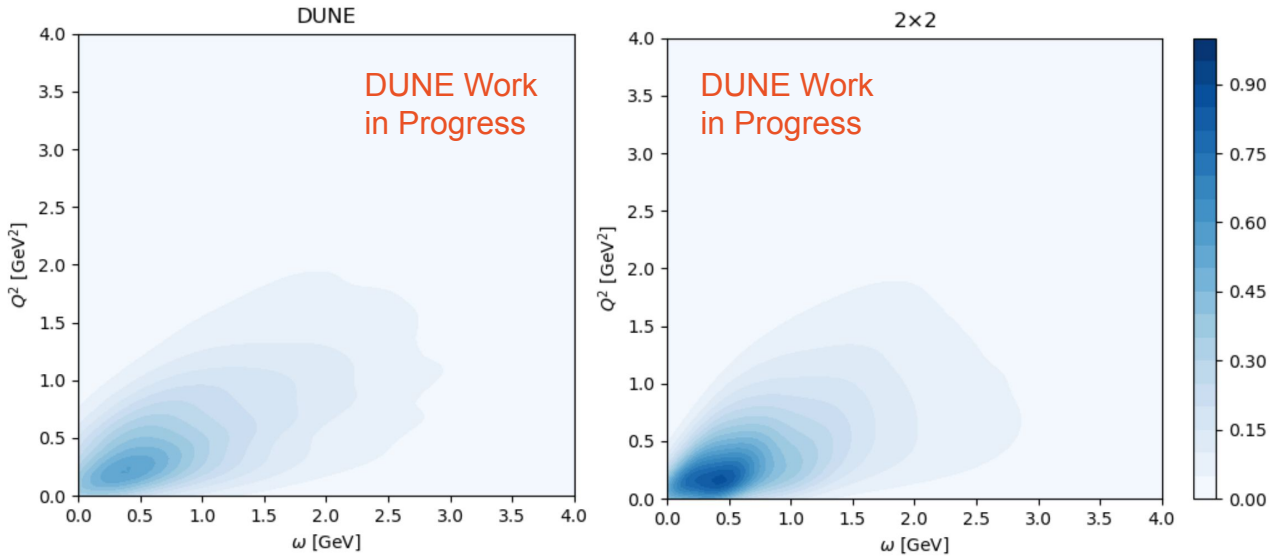
Physics with the 2x2

Diverse program of neutrino interaction measurements and other physics planned for 2x2 data

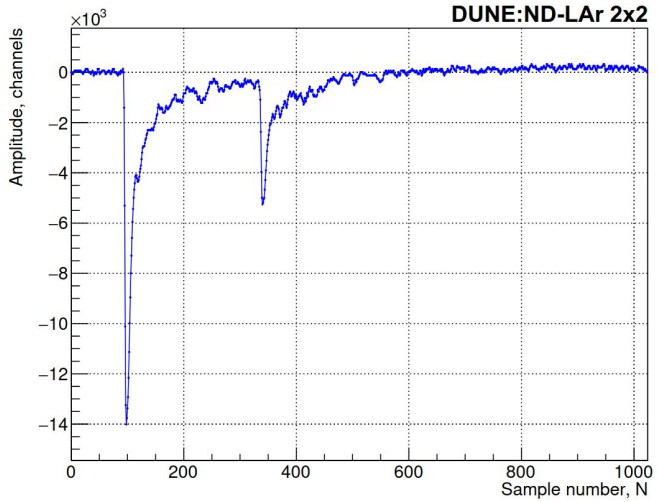
Several signal channels are already being investigated along with systematic uncertainty development

Native 3D reconstruction for a LAr TPC using pixel-based charge readout

Light readout for identifying interactions (e.g pile up) and separating/tagging delayed activity



Similar phase space between DUNE and the 2x2



Example of light signals from stopping muon and delayed michel electron in Module 0 test at Bern

arXiv.2403.03212

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Track Multiplicity

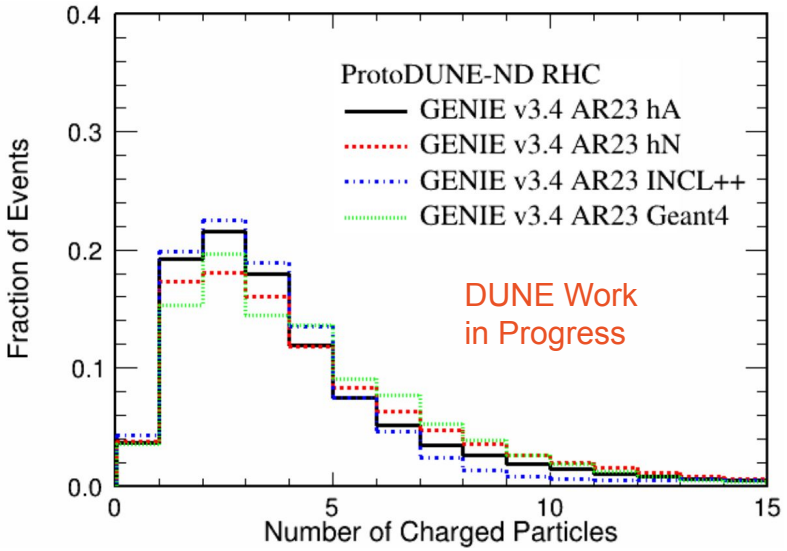
Studying charged particle production can provide insights on final state interactions (FSI)

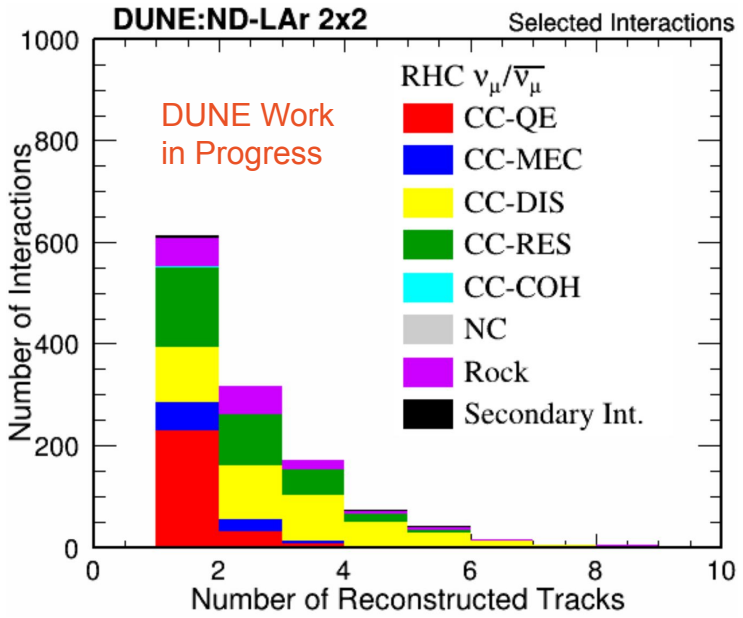
Selecting neutrino interactions inside the liquid argon fiducial volume and counting the number of charged particle tracks

Very preliminary selection requires a muon to exit out the back of the downstream MINERvA modules and achieves ~90% purity

Numbers shown here are normalized to ~3.5 days of POT in anti-neutrino mode

Track Multiplicity (no min. track length)





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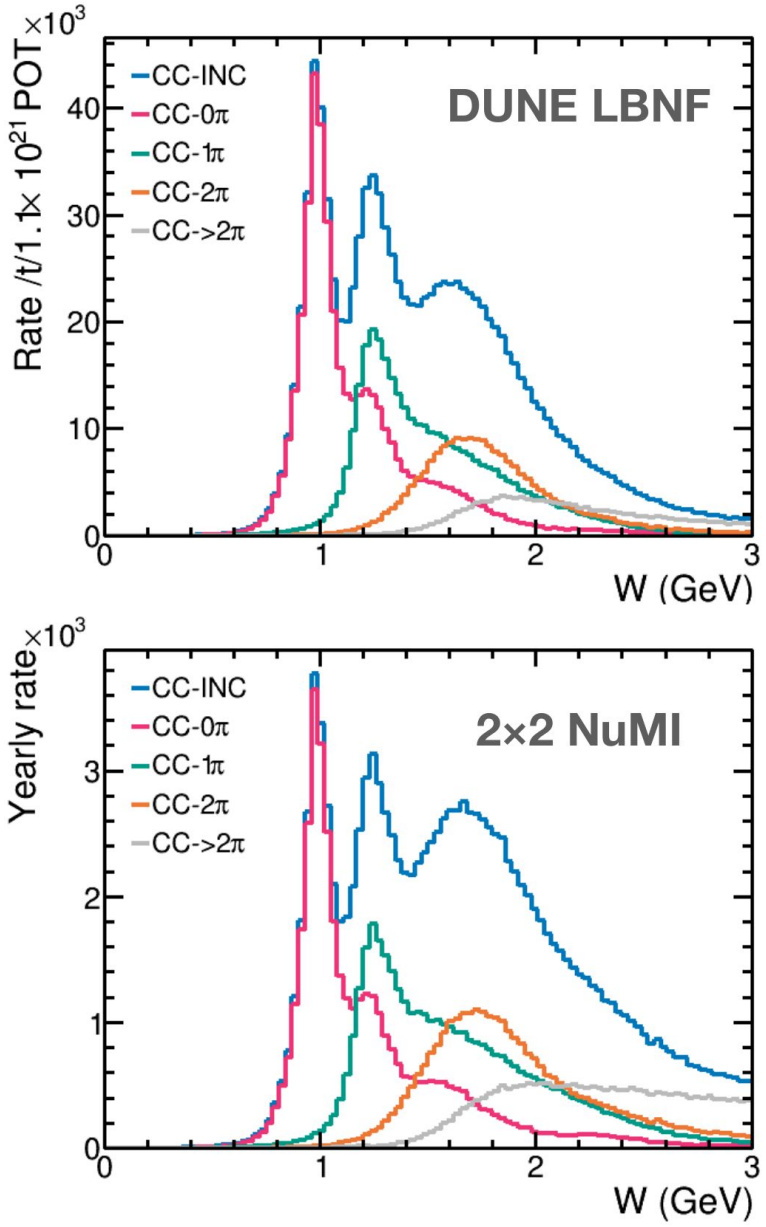
Pion multiplicity



DUNE will see a significant fraction of events that produce one or more pions

Accurately counting pions produced will be important for reconstructing neutrino energy for the DUNE oscillation analysis (e.g. FSI effects)

2x2 in the NuMI beam can cover the higher hadronic mass interactions that produce multiple pions with high statistics

Contained charged pion event rate ($CC N\pi^{+/-}$) with a muon exiting downstream MINERvA to select events

POT	4.7E20	7.1E20	11.8E20
$1\pi^{+/-}$	26320	39760	66080
$2\pi^{+/-}$	6683	10096	16780
$3\pi^{+/-}$	1457	2201	3658

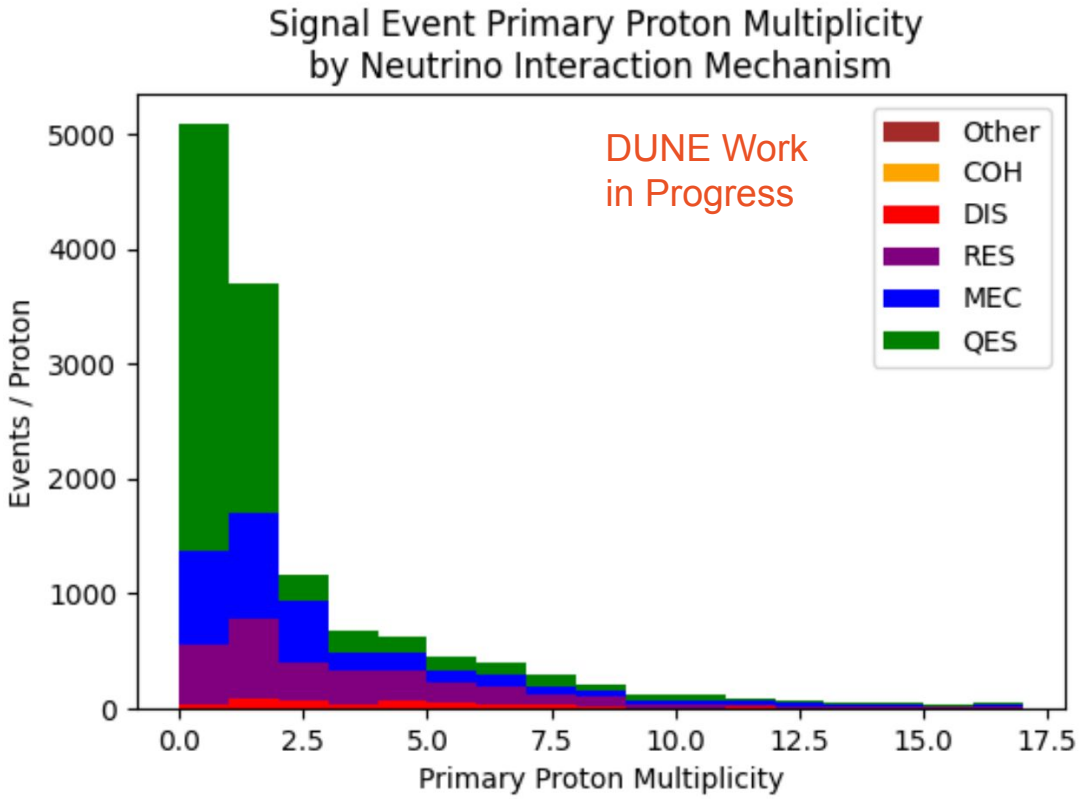
(Anti)neutrino CC0π in argon

Measurement of CC0π interactions → no pions in the final state

Signal includes both muon antineutrino and neutrino interactions since the 2x2 has no sign selection capabilities

Very preliminary selection requires a muon to exit out the back of the downstream MINERvA modules → currently at ~78% purity

Measurement focussed on proton kinematics and multiplicity from the interaction (and muon–proton angle)



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Neutron Production & Tagging

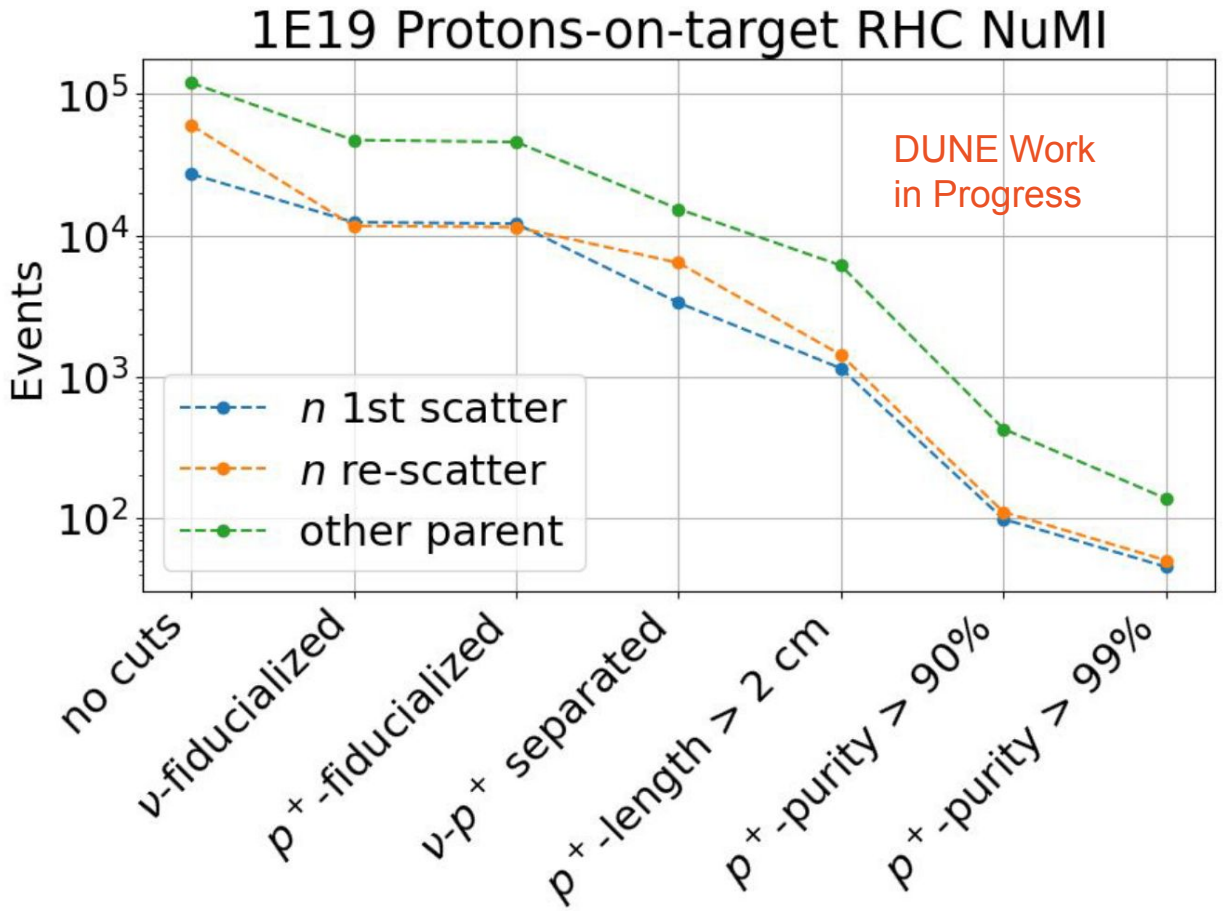
Neutrons are a large source of missing energy in neutrino interactions → very important when doing calorimetry

Also a source of background from neutrons produced outside the detector fiducial volume

Select neutrino vertices with a muon and look for a short proton track nearby

Measure neutron time-of-flight to get neutron kinetic energy

Light signal in the 2x2 can be used to help identify neutrino interaction and the neutron scattering



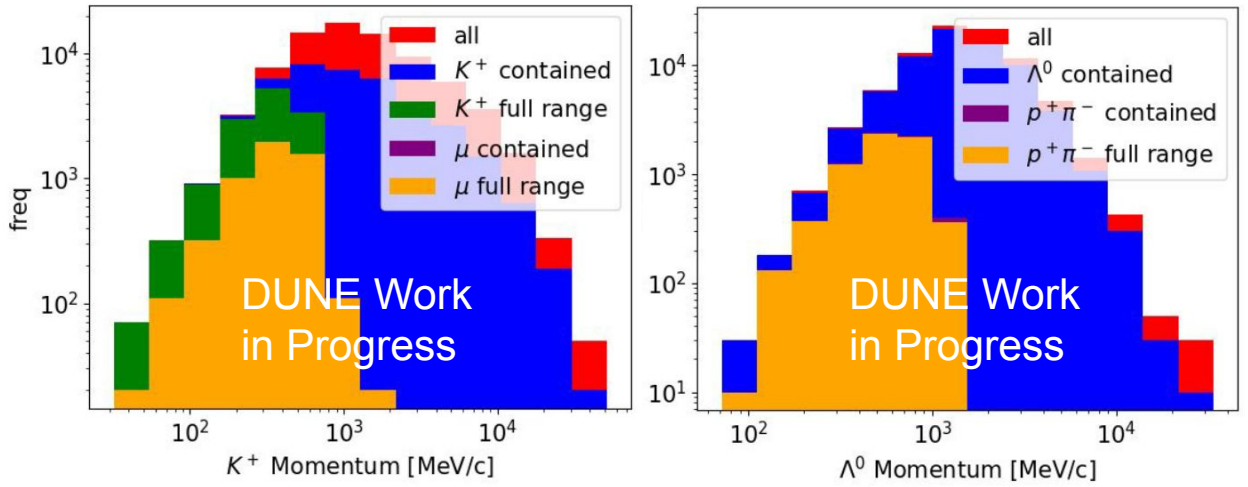
Strange Particle Production

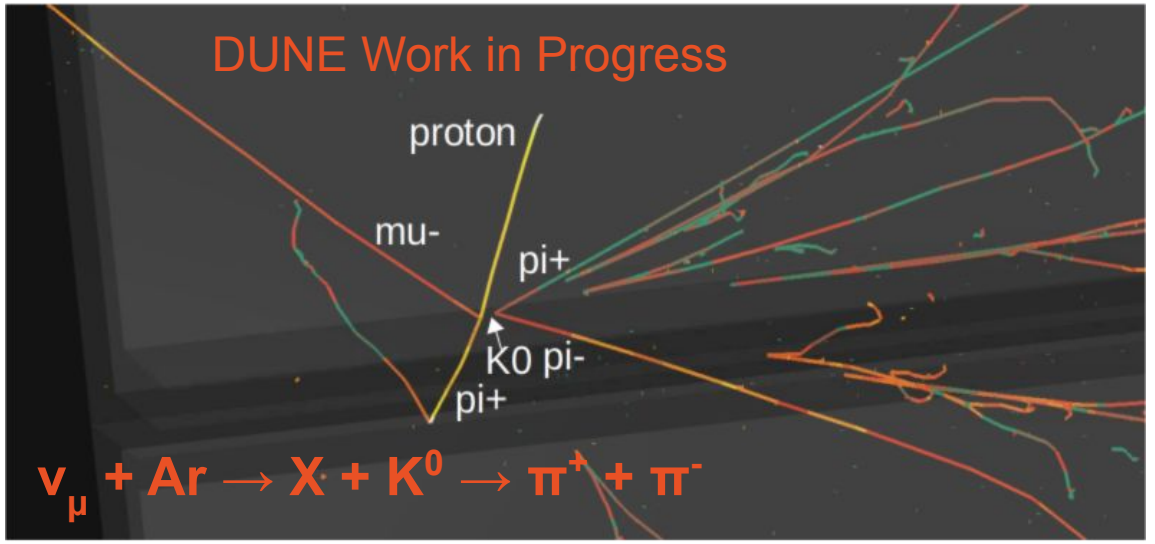
2x2 will see a high rate of interactions that produce strange particles, particularly kaons and lambdas

Very few measurements of strange particle production from neutrino interactions

Measurement of charged kaon production useful for proton decay searches in DUNE

Measurements of K^0 shorts can be used as a standard candle for energy calibration





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Summary

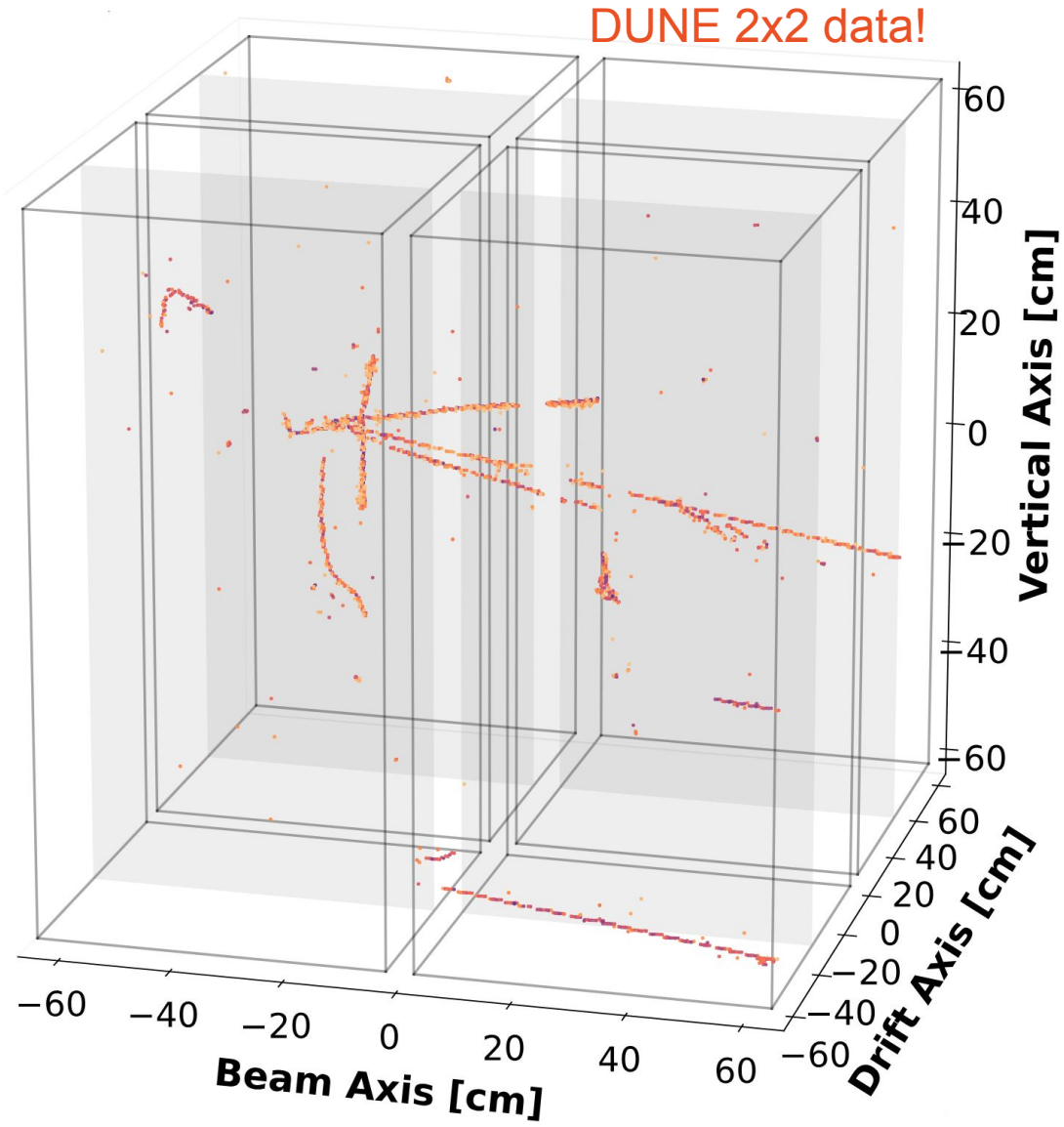
The 2x2 demonstrator presents an exciting opportunity to measure neutrino interactions over a wide range of energies

Measurements performed using the 2x2 will provide valuable input and knowledge for the DUNE physics program

Techniques developed for the 2x2 will also be transferable to the full ND-LAr detector

High statistics from the on-axis NuMI beam

Complementary to other neutrino experiments



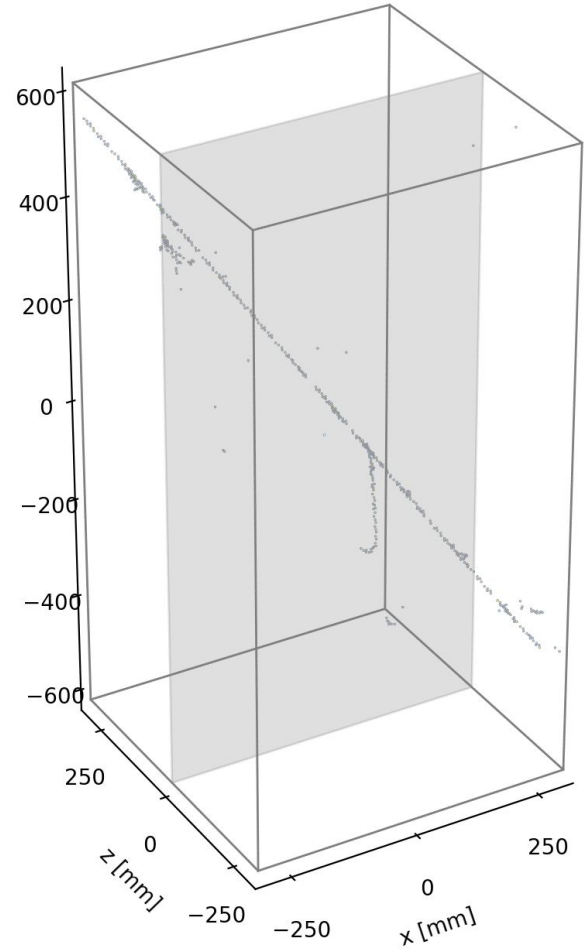
Related NuFact 2024 talks:

- S. Kumaran - 2x2 hardware and status: https://indico.fnal.gov/event/63406/contributions/297832/
- J. Micallef - Machine learning reconstruction for 2x2: https://indico.fnal.gov/event/63406/contributions/297837/

2x2 April 2024 Workshop Photo

This material is based upon work supported by the U.S. Department of Energy, Office of Science.

Cosmic data from single module testing



Thank you!

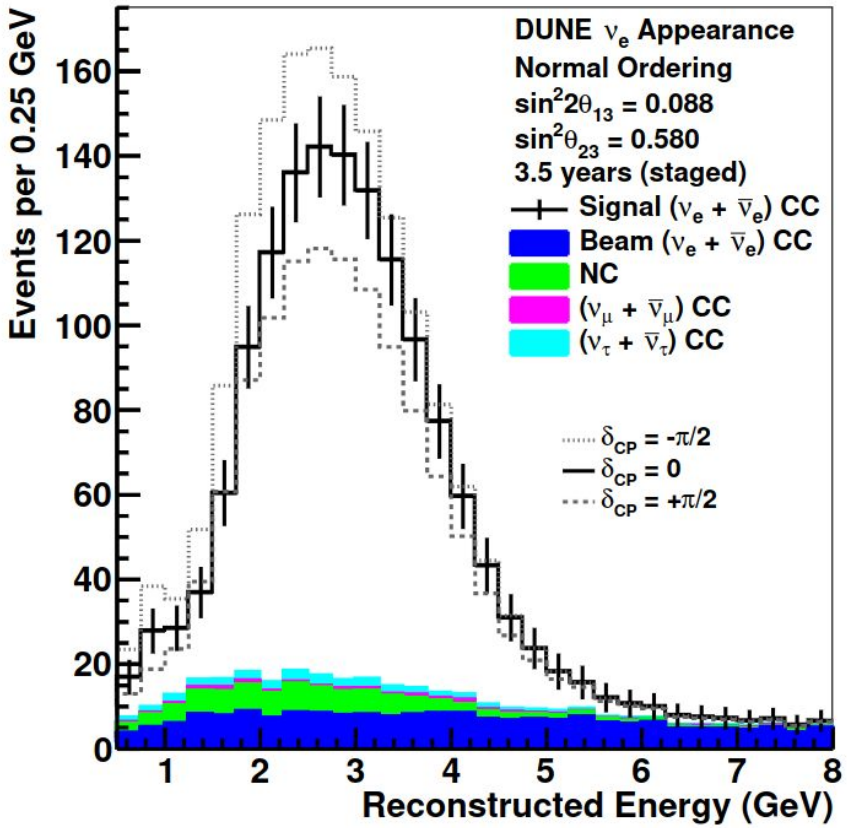
Backup Slides

Abi, B., Acciarri, R., Acero, M.A. *et al.* Long-baseline neutrino oscillation physics potential of the DUNE experiment. *Eur. Phys. J. C* **80**, 978 (2020). https://doi.org/10.1140/epjc/s10052-020-08456-z

Physics of DUNE

DUNE has a wide variety of physics goals, both with neutrinos and other physics

- Measurement of neutrino oscillations from both accelerator and atmospheric neutrinos
  - Increase precision of the known oscillation parameters
  - Determine the neutrino mass hierarchy
  - Measure the value of δ_{cp}
  - Precision tests of the three-flavor model
- Diverse program of neutrino interaction measurements for different channels, targets, etc.
- Detection of solar neutrinos and neutrinos from a core-collapse supernova
- Searches for beyond the standard model physics, such as proton decay or dark matter



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