ND-LAr Overview

Brooke Russell on behalf of DUNE

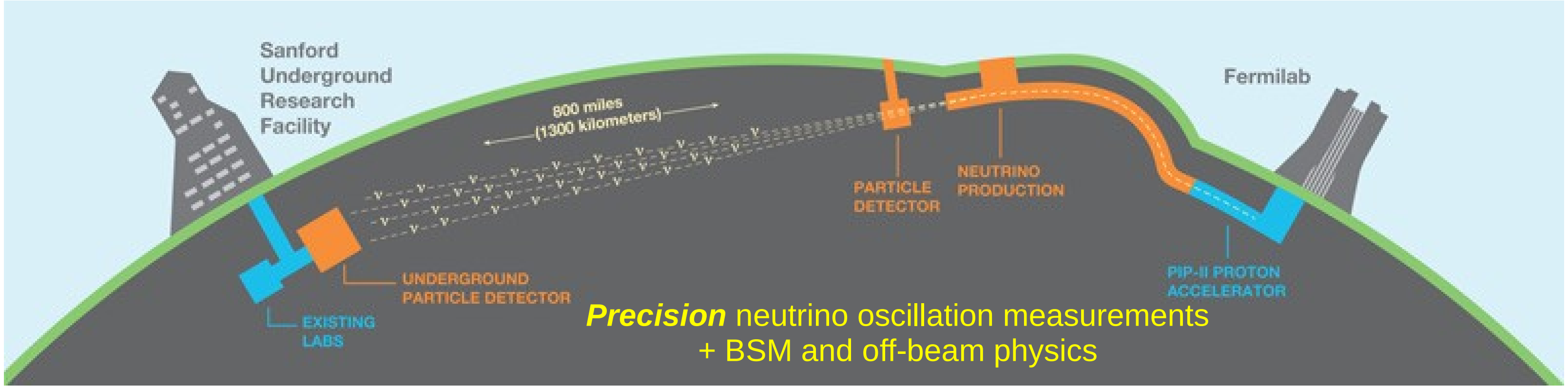
Wire-Cell Reconstruction Summit @ Brookhaven National Laboratory

April 11, 2024

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Massachusetts Institute of Technology

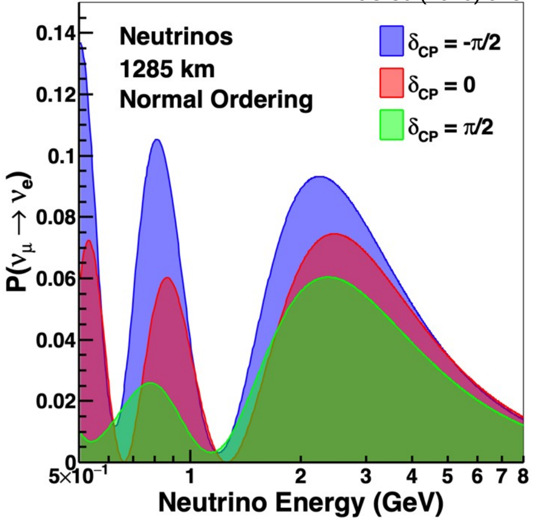
Deep Underground Neutrino Experiment



On-axis broadband beam with 1285 km baseline spanning near to far detector

- Measure neutrino spectra at Near Detector (ND) & Far Detector (FD) in ν-mode and $\bar{\nu}$-mode
- Infer neutrino mixing probability by comparing *measured* spectrum to *predicted* spectrum with no neutrino oscillation
- Fit neutrino mixing parameters

EPJC 80 (2020) 978



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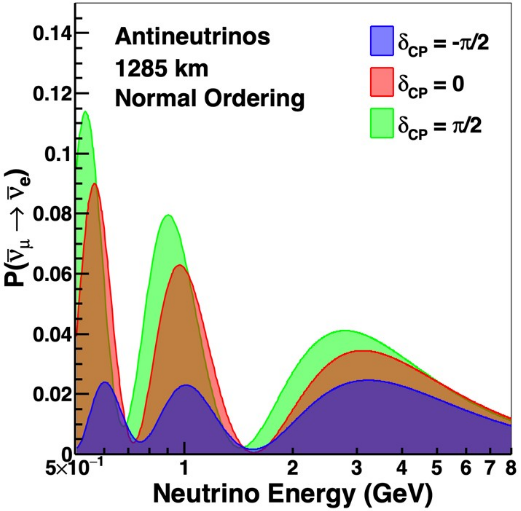

Neutrino Mass Ordering

Unambiguous mass ordering determination

$\nu_\mu \rightarrow \nu_\mu$

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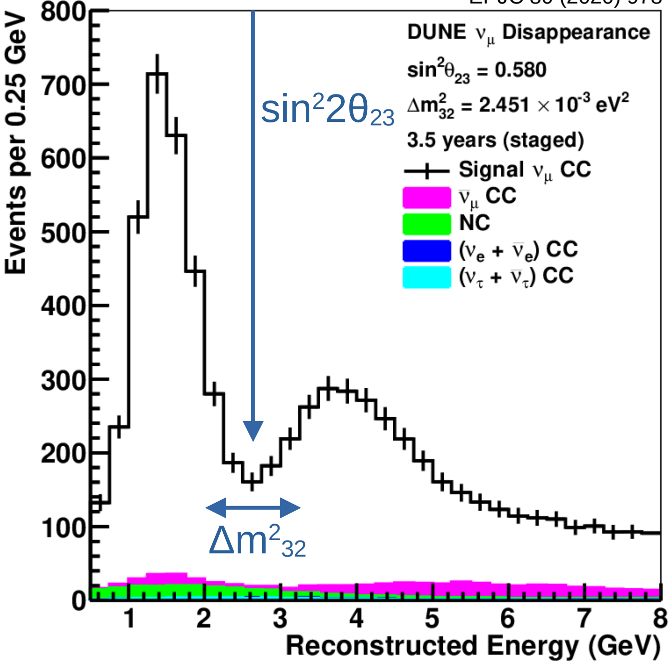

$\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

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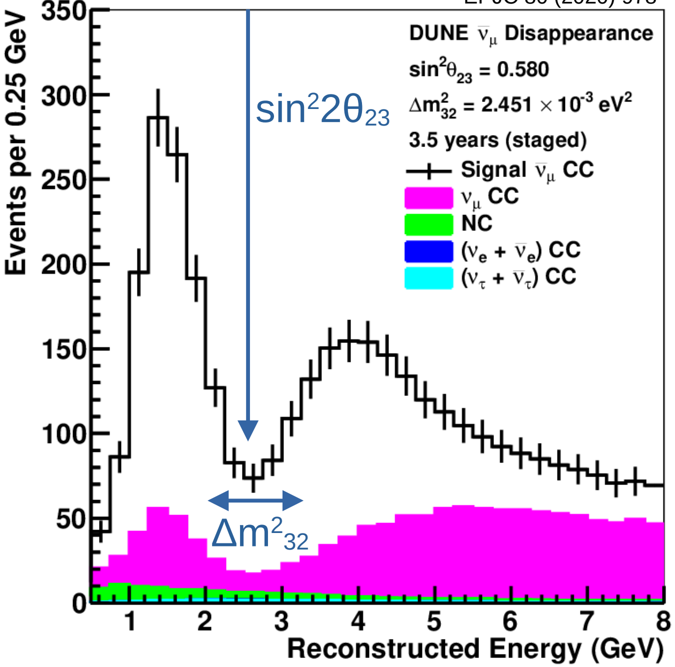
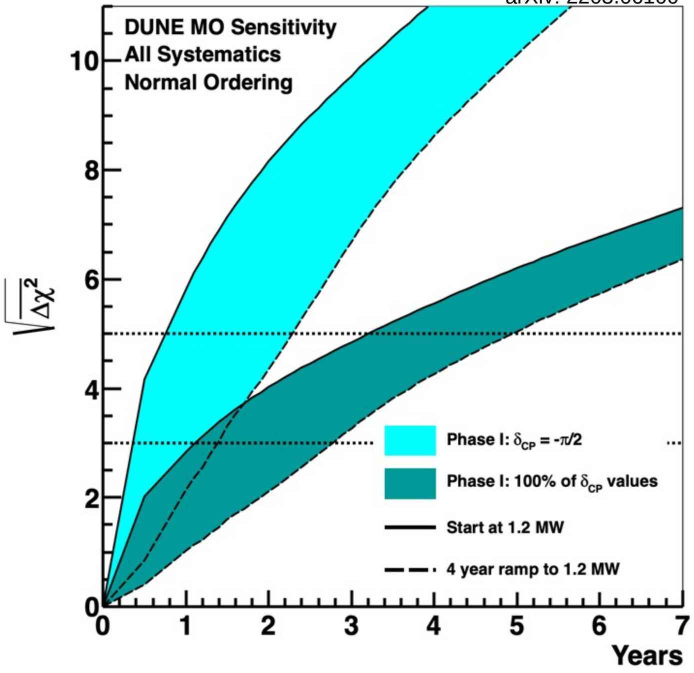


arXiv: 2203.06100



δ_{CP}

5σ sensitivity for 50% of δ_{CP} values
Precision measurements of δ_{CP} as well as Δm^2_{32}, θ_{23}, θ_{13}

$\nu_\mu \rightarrow \nu_e$

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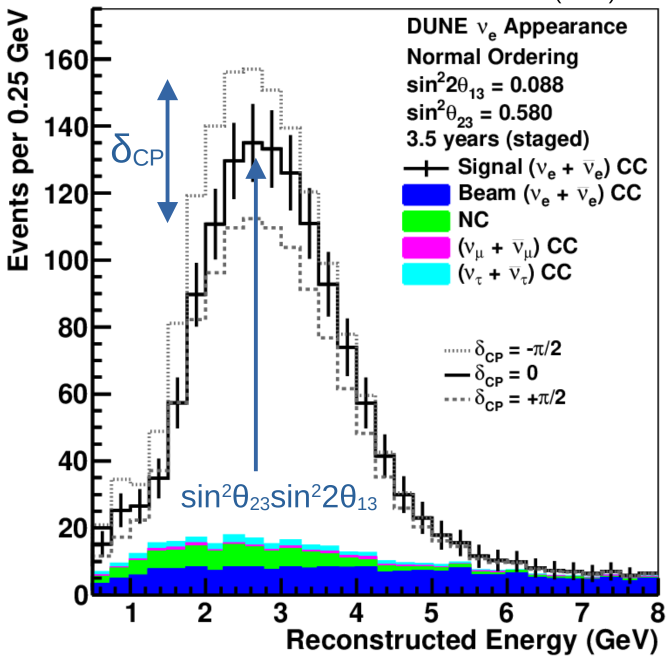

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

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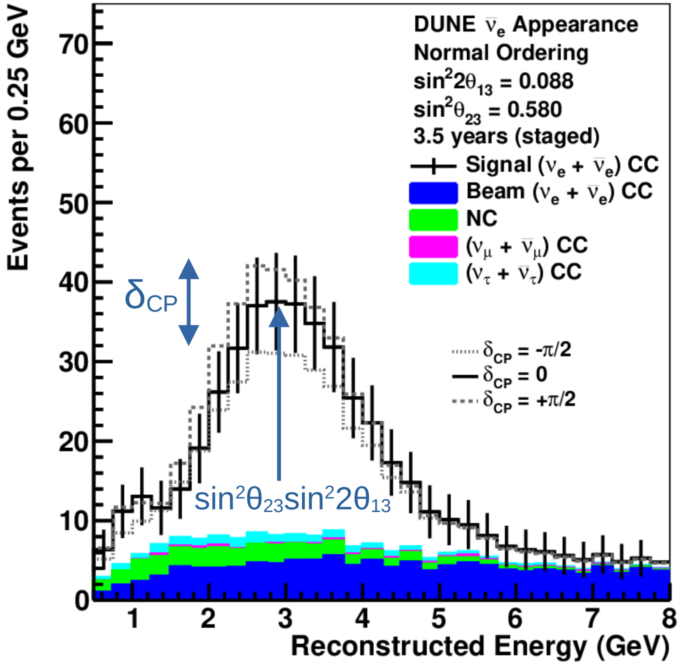

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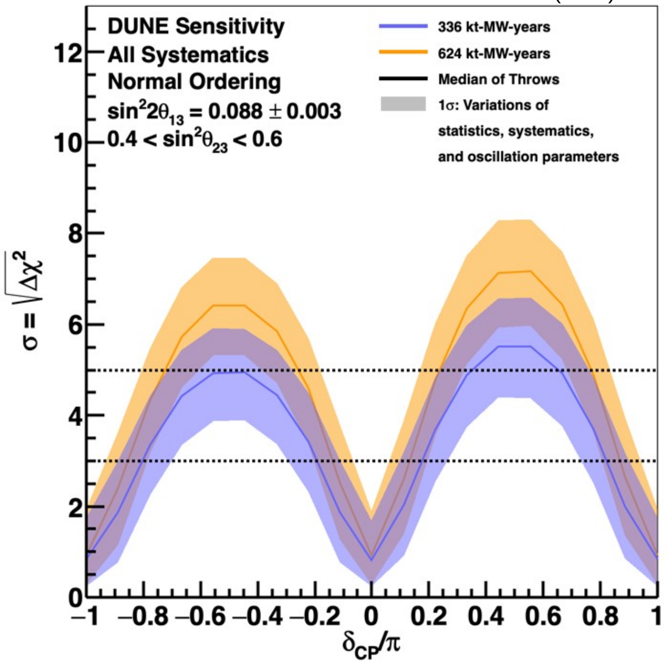
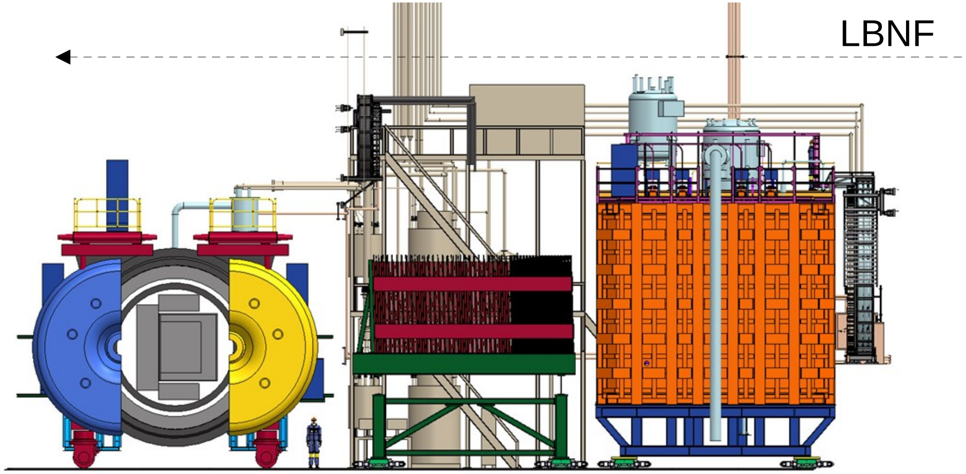
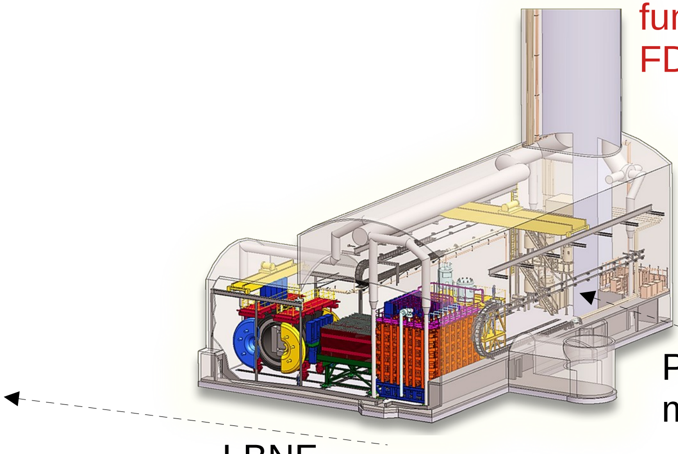


Constraining Systematics with the DUNE ND

- Enable precise prediction of DUNE FD neutrino signal
- Flux, cross section, and detector response uncertainties constrained to few percent level by Near Detector (ND) Complex detector suite
  - ND-LAr + TMS ν-Ar measurements
  - On-axis beam stability monitoring with SAND
- DUNE Precision Reaction-Independent Spectrum Measurement (PRISM)
  - Peak neutrino energy decreases with increasing observation angle relative to the beam direction
  - ND-LAr/TMS move up to 30 m off-axis
  - *Data-driven* oscillated FD flux prediction from ND data linear combinations





ND-LAr Detector

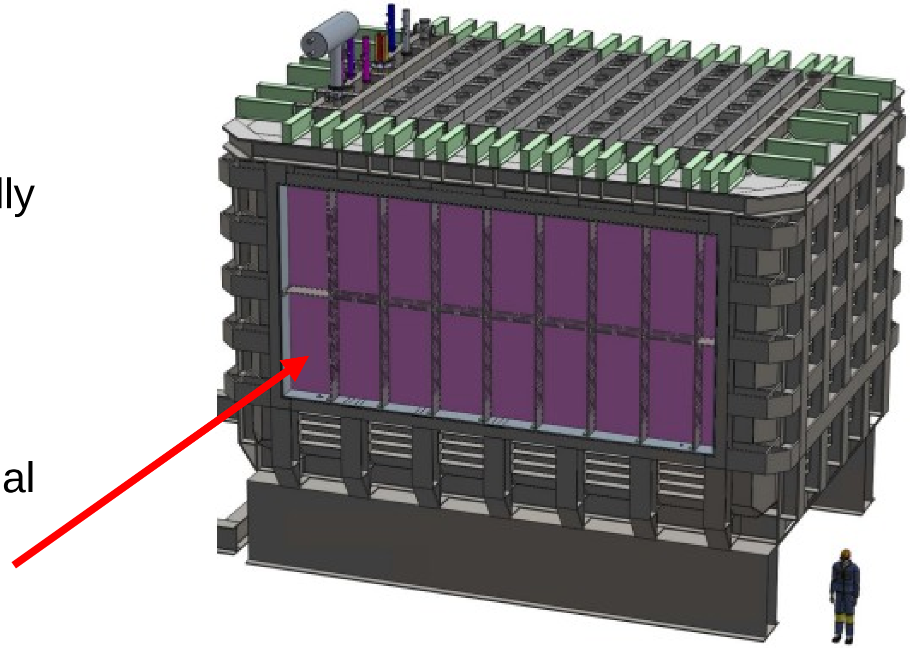
Principal objective:

Measure neutrino interactions on LAr with functionally similar detector response as FD

Design Drivers:

- ND LArTPC fiducial mass - sufficient ND LArTPC acceptance to accurately predict FD LArTPC signal
  - 5 m x 7 m x 3 m active volume
  - All-steel cryostat muon window (8.4 m x 4.1 m)

- Beam- pileup rejection efficiency - associate ionization signals to fiducial neutrino interactions with high fidelity
  - Optical segmentation with low-profile TPC components
  - Pixelated charge readout
  - High-photocoverage light readout

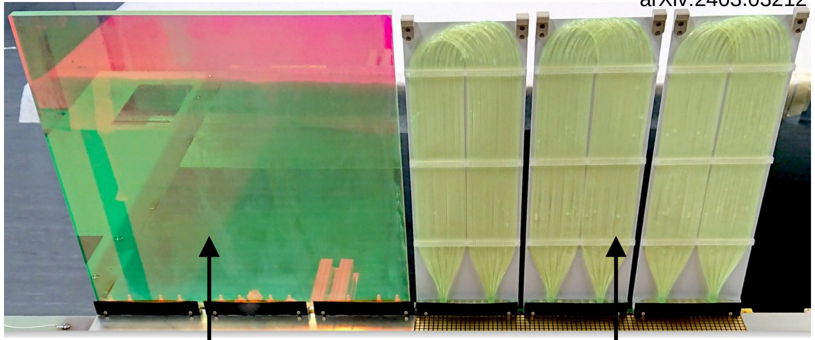


Specification	Value
Active LAr mass	138 metric tons
Module count	35
TPC count	70
Maximum ionization drift distance	50 cm
Drift electric field	500 V/cm (nominal)
Beam-transverse inter-module active LAr spacing	5.5 cm
Beam-downstream module-to-cryostat distance	20 cm (nominal)
Muon energy loss from downstream passive material	<3% at 600 MeV

TPC-sensitive Detectors

Scintillation Light Readout

arXiv:2403.03212

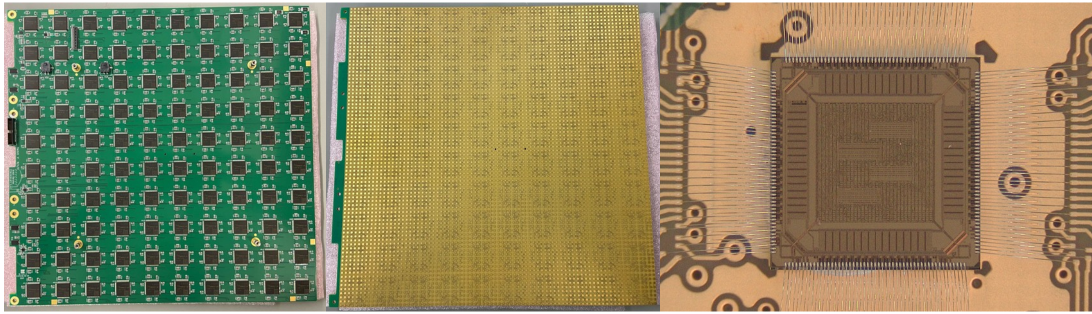


ArCLight
Better spatial resolution

LCM
More sensitive to lower energy activity

Specification	Value
Photocoverage	30%
Light trap count	700 (ArCLight), 2100 (LCM)
SiPM count	8,400
Sampling rate	62.5 MHz
ADC synchronization	<1 ns
Photon detection efficiency	0.2% (ArCLight), 0.6% (LCM)
Timing resolution	~2 ns @ 200 PE (LCM)

Charge Readout



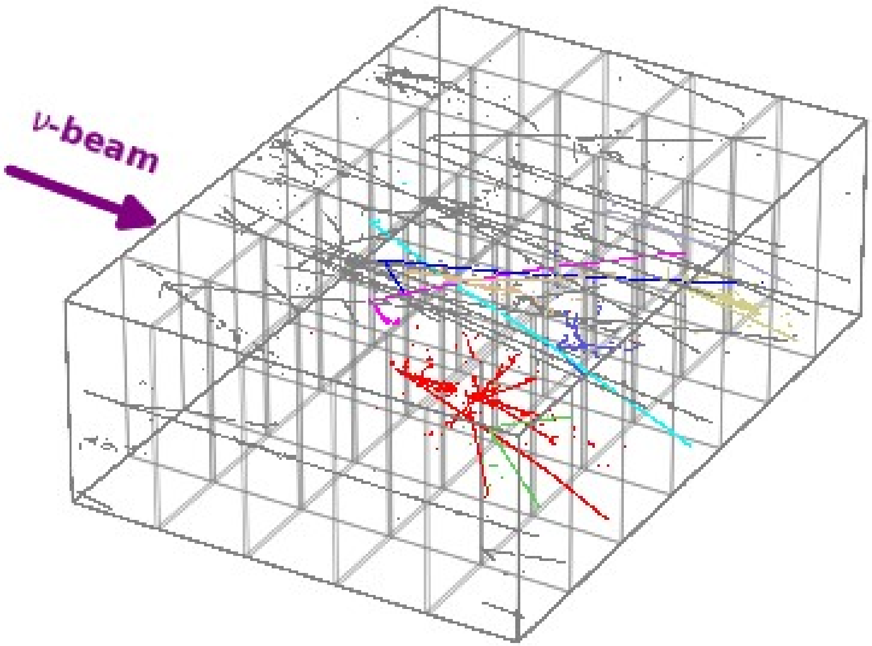
LArPix

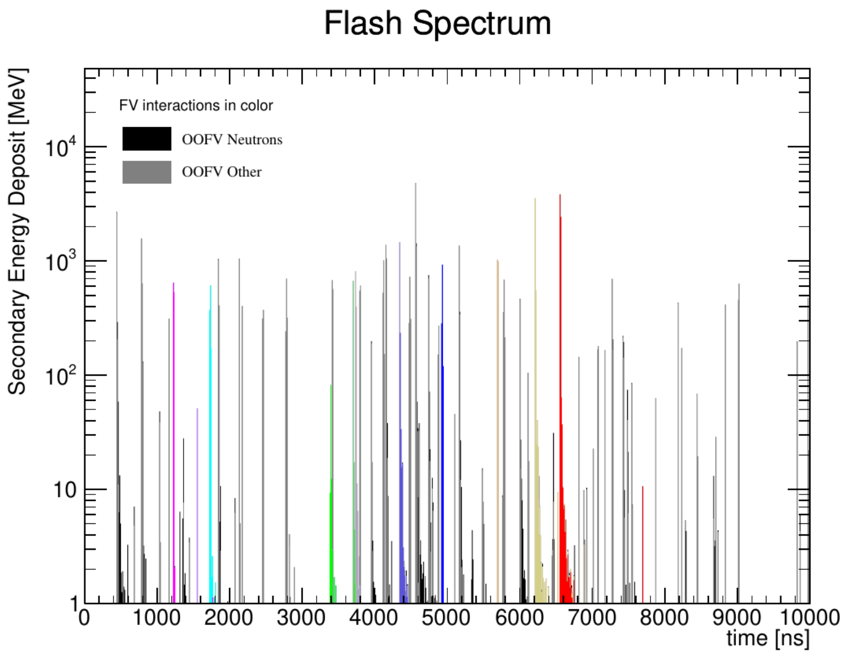
- Low-power, integrating amplifier with self-triggered digitization and readout
- Pixels are continuously "live", dormant until signal exceeds tunable threshold
- End-to-end system architecture – large-format pixel anode tiles, cables, feedthroughs, controller, etc.

Specification	Value	Comment
Channel count	14,336,000	64 single-ended analog inputs / ASIC
Pixel pitch	3.7 mm	
Timestamp precision	100 ns	
Multi-hit separation time	1.2 μs	Chip configurable
Noise	800 e- ENC	
Gain	4 μV/e- (nominal)	Optional 2 μV/e- mode
Dynamic range	1.2 V	300 ke- at nominal gain
Channel linearity	< 1.2%	Pre-calibration
Tile leakage current	< 100 fA	
Power	2×10^{-4} W/channel	

Beam- Pileup at ND-LAr

LBNF is anticipated to be the world’s most powerful neutrino beam, upgradeable to 2.4 MW





On average, **55** neutrino interactions per 10 μs-wide LBNF beam spill at 1.2 MW beam power within 105 m^3 active volume

Scintillation pileup obfuscates ionization association using scintillation light

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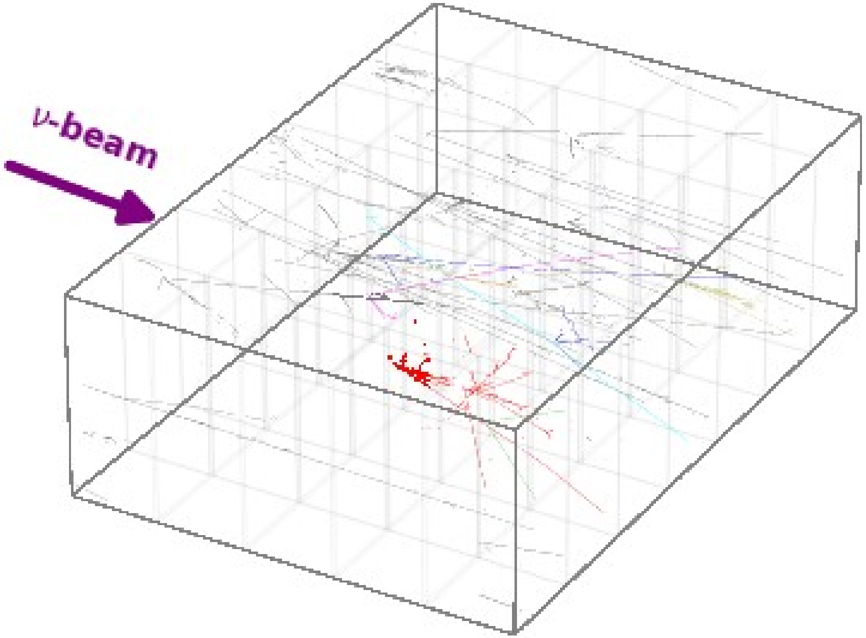
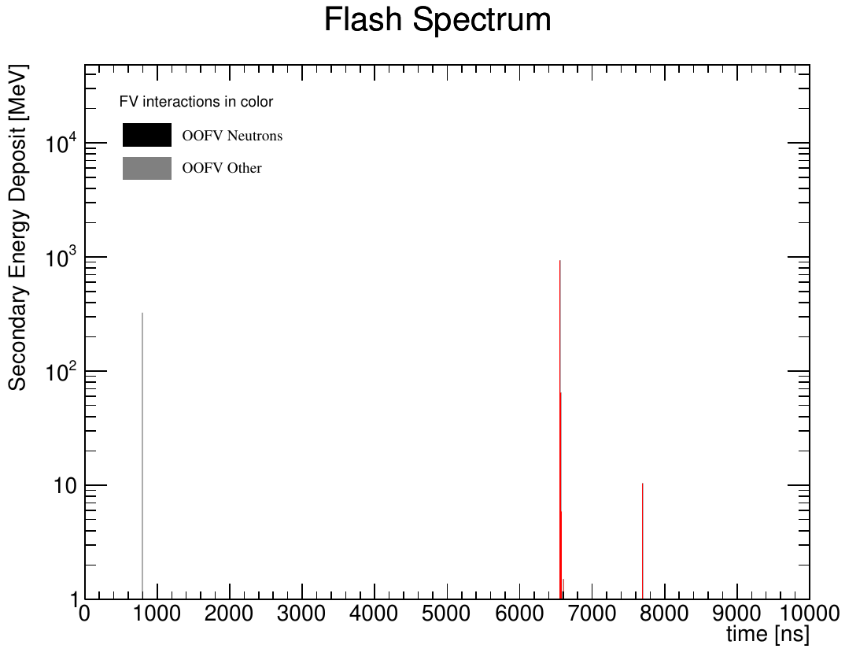


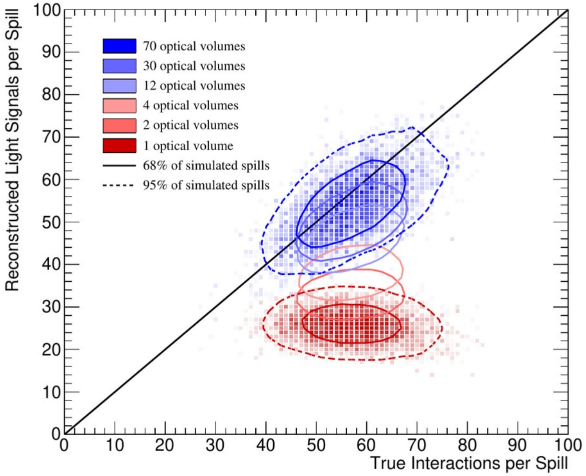


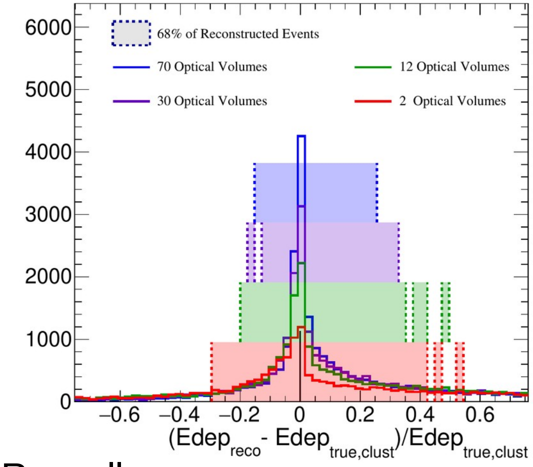
A light-tight meter-scale module design affords **few-to-few** charge-light signal association combinatorics, **a tractable challenge** for software solutions

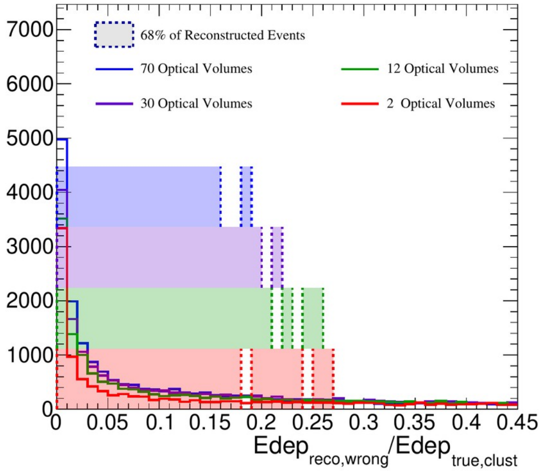
Pileup Mitigation with Optical Segmentation

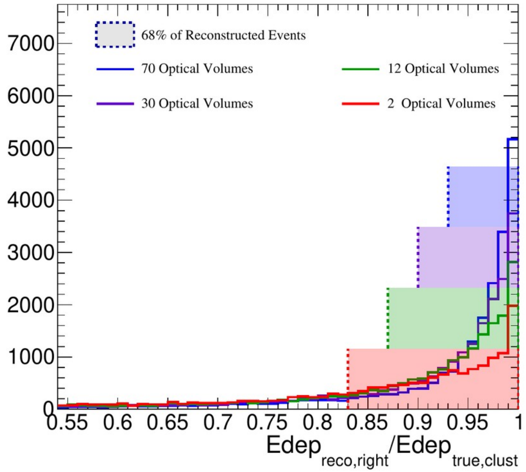
- Modularized detector provides additional timing information to enhance charge-light signal association through *a tractable few-to-few linear system*

- Geant4-level simulation studies motivate the degree of segmentation
  - Demonstrated lower bound on pileup mitigation performance with rudimentary reconstruction methods





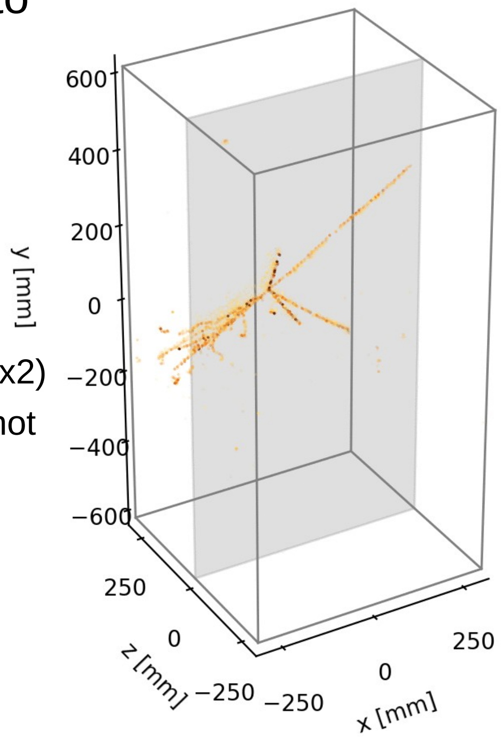




See R. Diurba's talk earlier today on ND-LAr/2x2 Software Interfaces

Wire-Cell at ND-LAr

- Wire-Cell native 3D charge pattern recognition should be very natural to apply to ND-LAr pixel readout data
  - Existing software infrastructure is well equipped to study the nuanced differences between the native Wire-Cell tomographic imaging and true 3D charge data from LArPix
    - `larnd-sim` detector simulation is benchmarked against O(10 M) cosmic-ray events
  - LArPix effects likely to complicate Wire-Cell adaptation:
    - Single channel successive triggers - configurable electronics response (can modify at 2x2)
    - Far-field advanced hits and lobing effects - geometry-dependent hardware effects (cannot modify at 2x2 without detector extraction)
- Wire-Cell toolkit has demonstrated the capability to adapt scintillation light signal processing to aid charge reconstruction
  - Small modifications to existing Wire-Cell techniques have the potential to quickly make a significant impact on interaction-level charge-light signal association
    - Scintillation light waveform unfolding with compressed sensing
    - Many-to-many charge-light signal matching with fast external-tracker boundary conditions

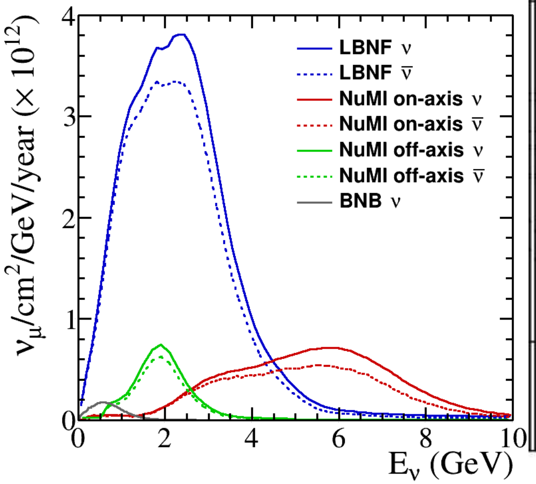


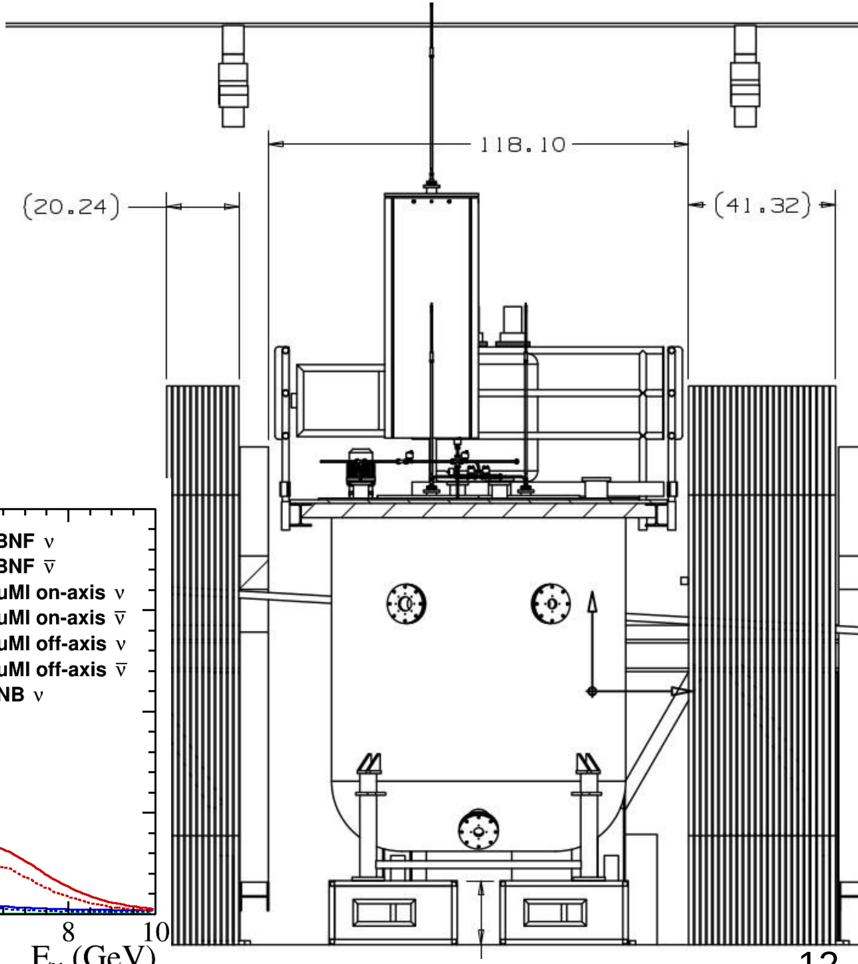
Cosmic-ray raw data

2 x 2 Demonstrator

- ND-LAr design technical demonstration
- ν-Ar interactions in the at few-GeV regime

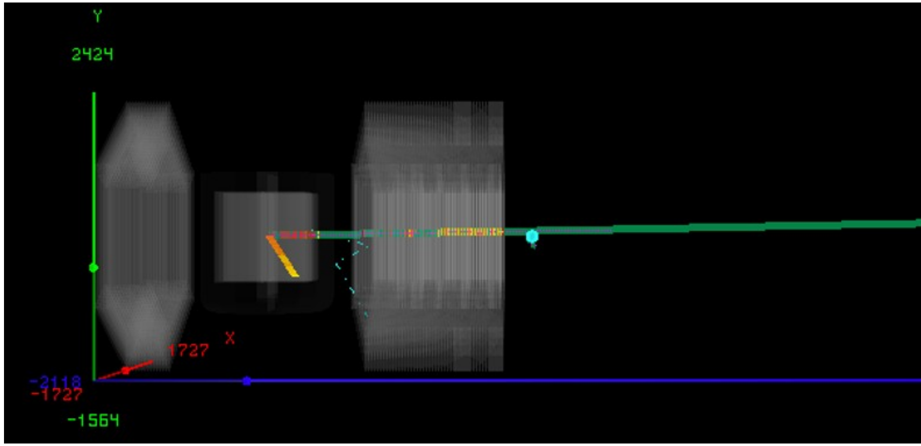
- 4x 60%-scale fully-integrated detector modules
  - 2.6 metric ton active LAr mass
  - 337,600 charge-sensitive pixels at ~4 mm pitch and ~200 keV threshold
  - 25% light trap optical coverage with 384 6-mm SiPMs
  - Continuously live charge readout, independent of photon system trigger
- Repurposed MINERvA planes
  - 12 upstream tracking planes
  - 8 downstream tracking planes
  - 4 downstream tracker-ECAL planes
  - 8 downstream ECAL planes
  - 12 downstream HCAL planes
- FNAL medium energy NuMI ν beamline
  - Detectors stationed on-axis 1.04 km from the NuMI target in the MINOS underground hall at Fermilab
  - 100 m underground cavern depth (225 m.w.e. overburden)





See talks by S. Dennis (next) and J. Micallef (tomorrow) on Pandora and MLReco, respectively, reconstruction at ND-LAr/2x2

Technical Demonstrations at the 2x2 Demonstrator



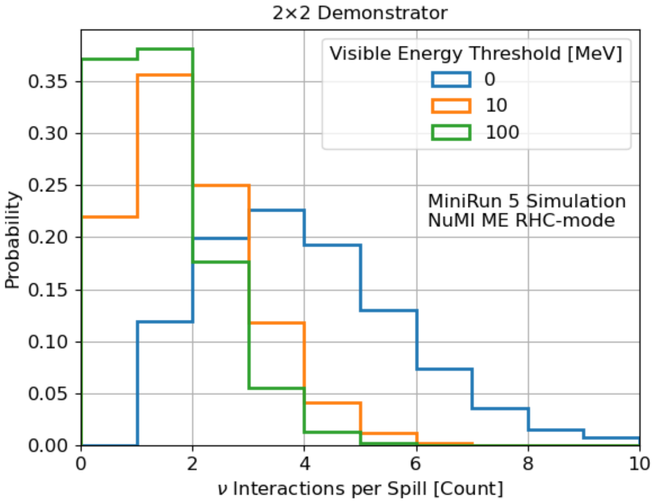
3D reconstruction of neutrino signals

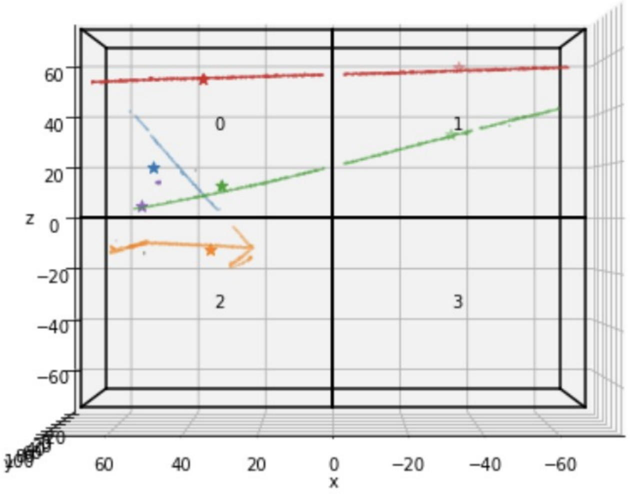
Evaluation of impact of un-instrumented volumes

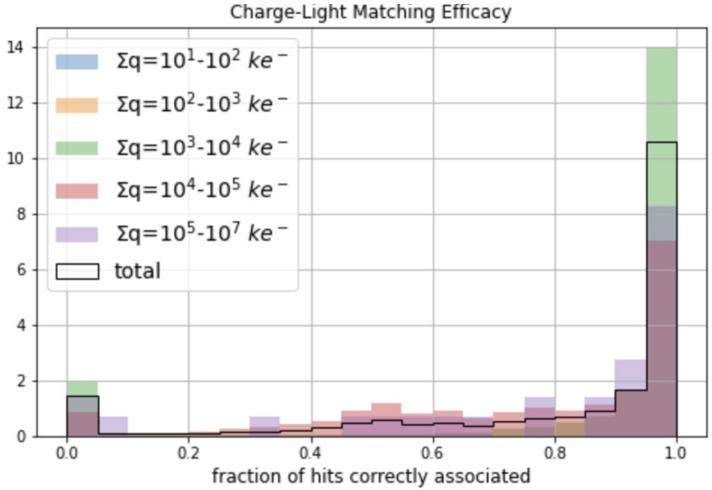
Track-matching with fast external trackers

Charge-light signal correlations in a high intensity neutrino beam

Excellent opportunity to test reconstruction at LBNF-like neutrino energies before DUNE



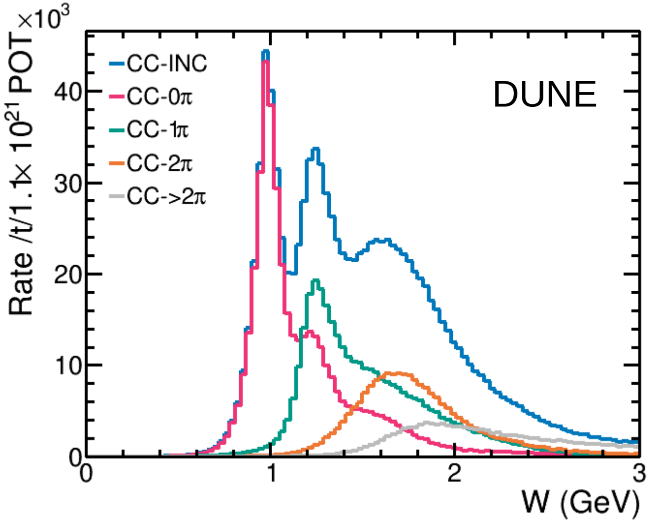


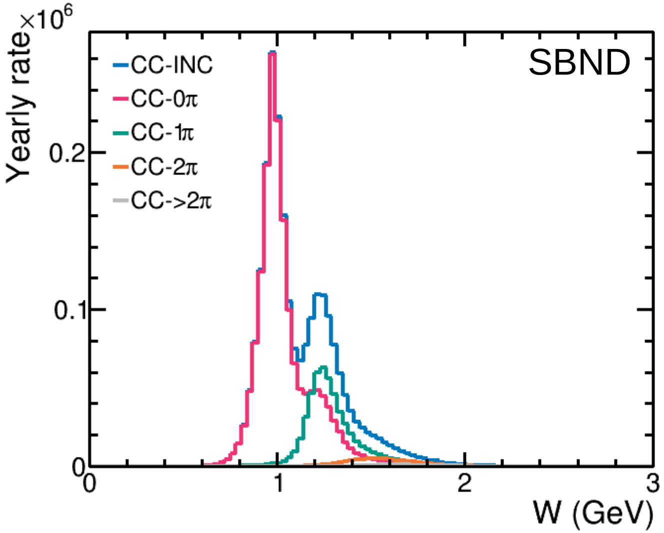


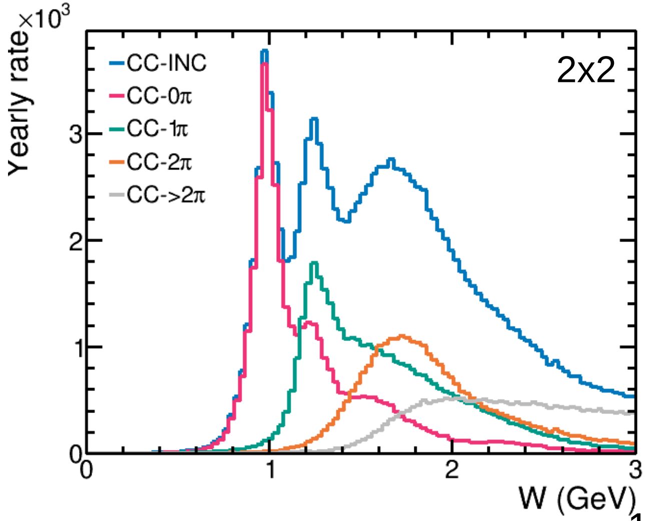
Physics at the 2x2 Demonstrator

Pion production

- ν-Ar interactions at DUNE are expected to have a high hadronic invariant mass component
  - Multi-pion channels are less theoretically mature relative to other, simpler topologies (e.g. CC 0π)
  - Absence of measurements on Ar-40
- Both on-axis 2x2 Demonstrator (and off-axis ICARUS) will measure this phase space with NuMI

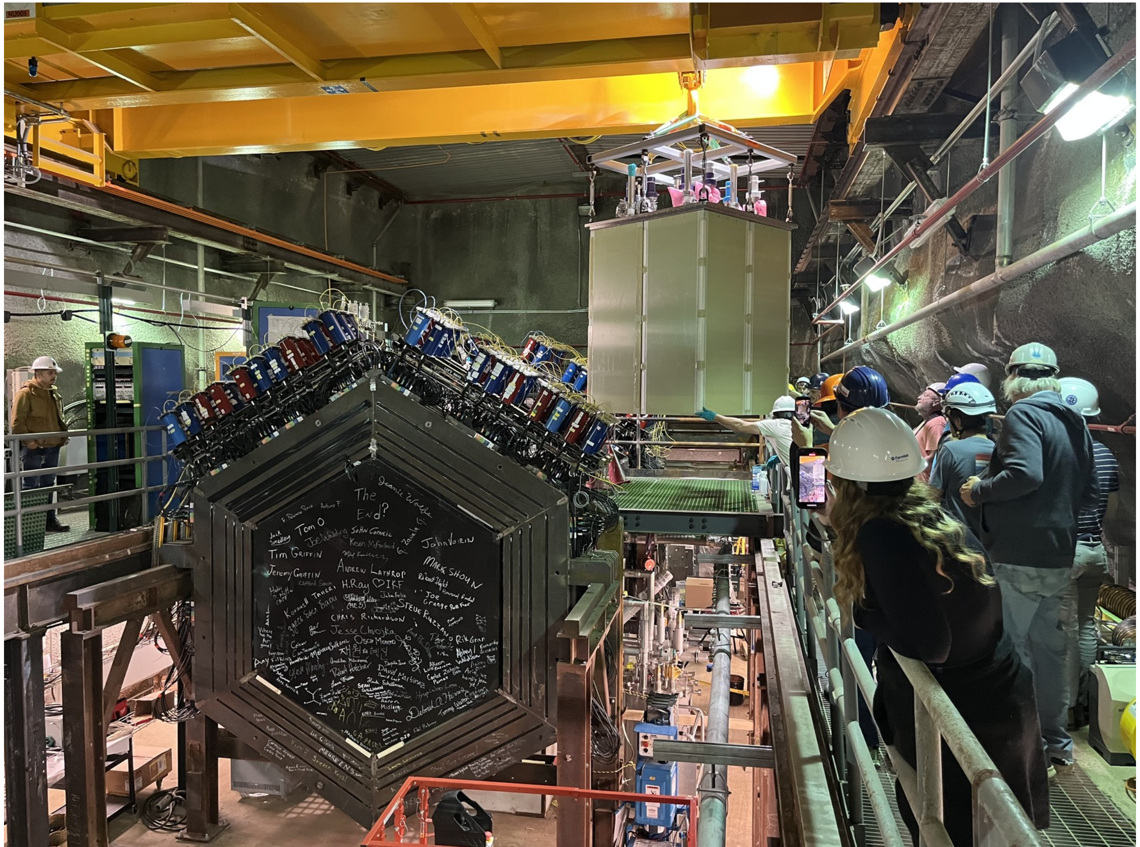


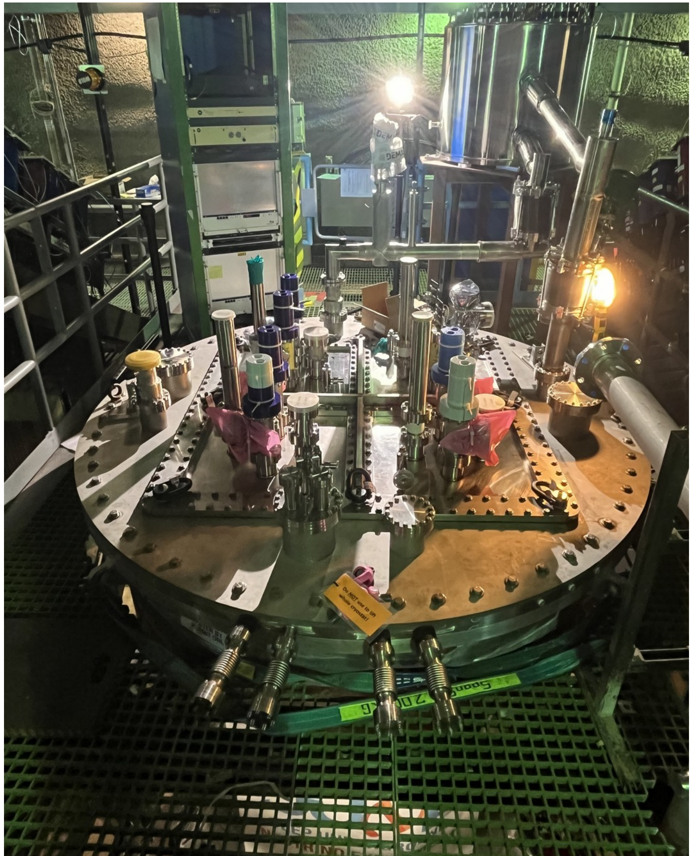




2x2 Status

- ✔ Module acceptance testing
- ✔ Module-cryostat integration in NuMI underground hall
- ✔ Detector infrastructure construction
- ✔ Warm electronics checkout
- ✗ LAr fill & cold electronics checkout (imminent)
- ✗ NuMI beam operation (shortly after)





Summary

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

- ND-LAr is a critical component in the DUNE oscillation program providing constraints on flux, interaction, and detector responses
- An optically segmented LArTPC with pixelated charge readout is required to maintain signal fidelity with beam-neutrino pileup

The 2x2 Demonstrator will provide critical input to eventual ND design

- Demonstrating charge-light signal association at high fidelity is a near-term priority

Wire-Cell is a natural reconstruction approach to apply to ND-LAr data