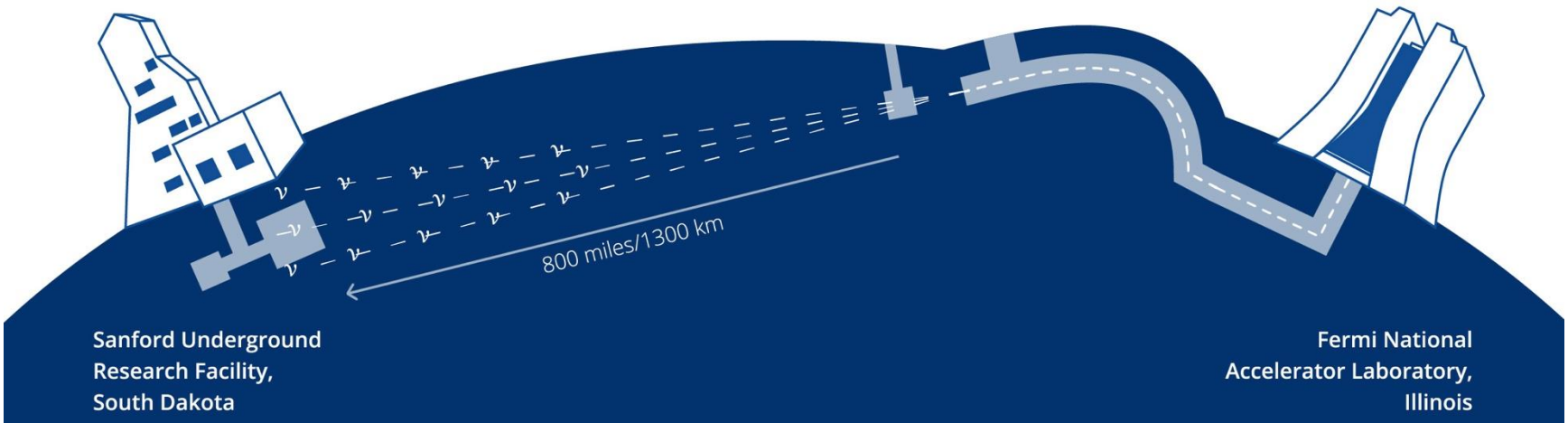


DUNE: Physics and Supporting Software

Mathew Muether for the DUNE International Collaboration

XIV International Conference
on New Frontiers in Physics
17-31 July 2025, OAC, Kolymbari, Crete, Greece

WICHITA STATE UNIVERSITY

Physics Goals

The DUNE design will enable precision measurements of neutrino oscillations and interactions providing

- Discovery sensitivity to CP violation, mass ordering, θ_{23} octant over a wide range of possible parameter values.

- Unambiguous, high-precision measurements of Δm^2_{32}, δ_{CP}, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ in a single experiment.
- Sensitivity to MeV-scale neutrinos, such as from a galactic supernova burst

- Low backgrounds for sensitivity to BSM physics including baryon number violation

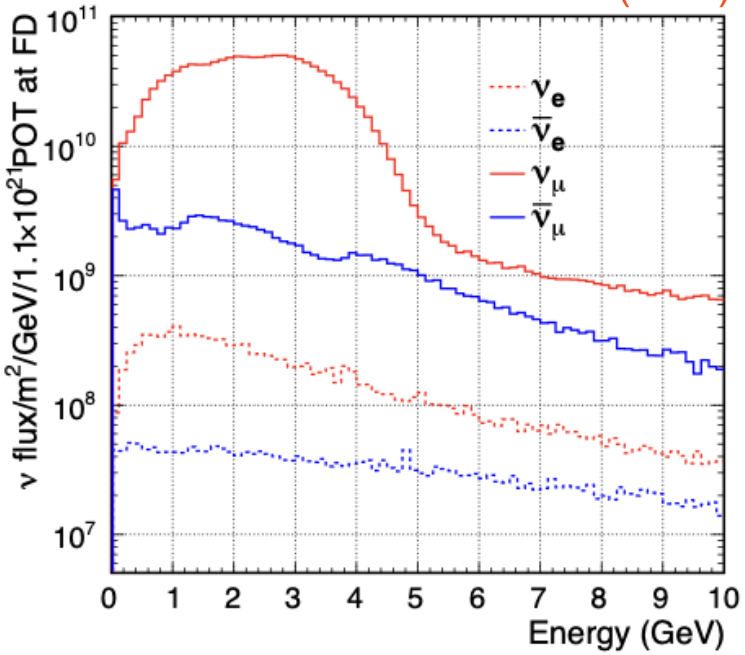
DUNE Design Requirements

- Long baseline (1300 km) and wideband beam
- High stats: intense beam + large far detector
- Precise energy reconstruction over broad E_ν range with state-of-the art LAr TPCs
- Precise systematic control from near detector

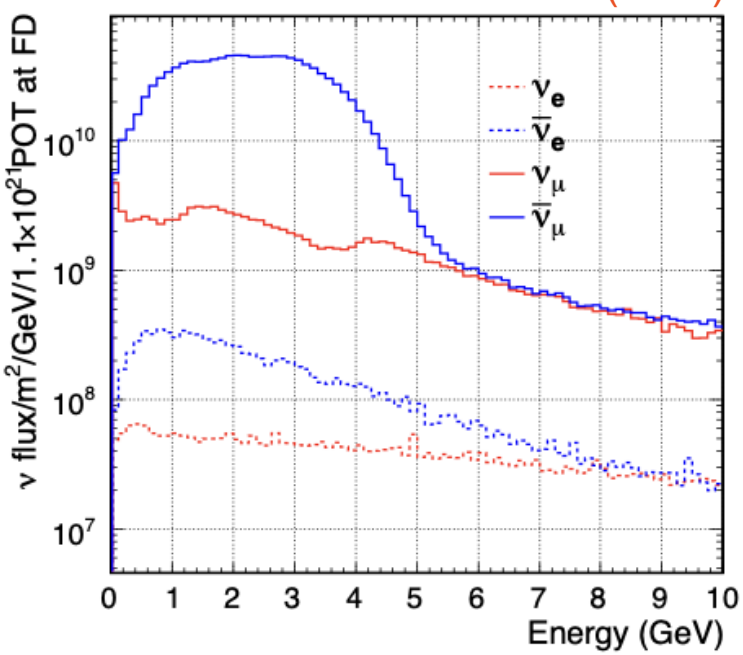
DUNE Design: Wideband Beam

- The (>2 MW) LBNF beam will provide neutrinos and antineutrinos with energies from 0-5+ GeV
- Simulated neutrino fluxes at the far detector are shown below.

Forward Horn Current (FHC)

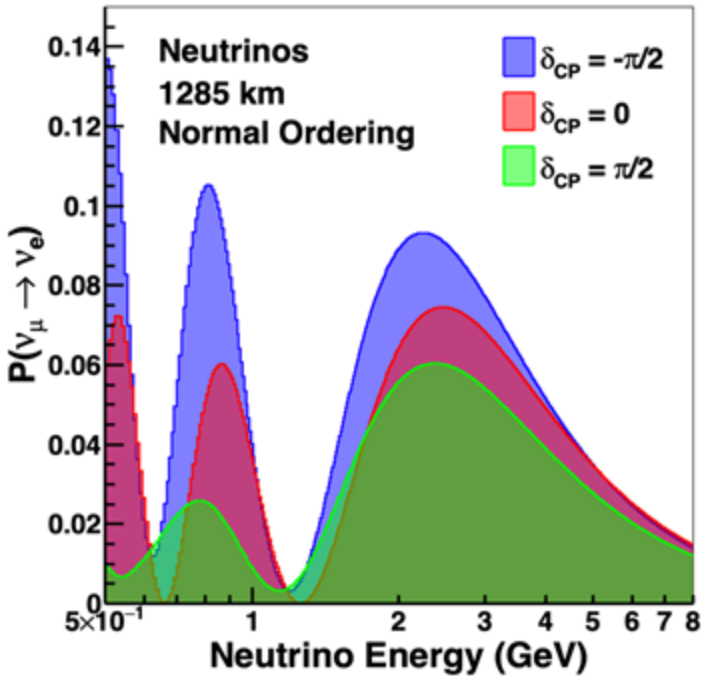


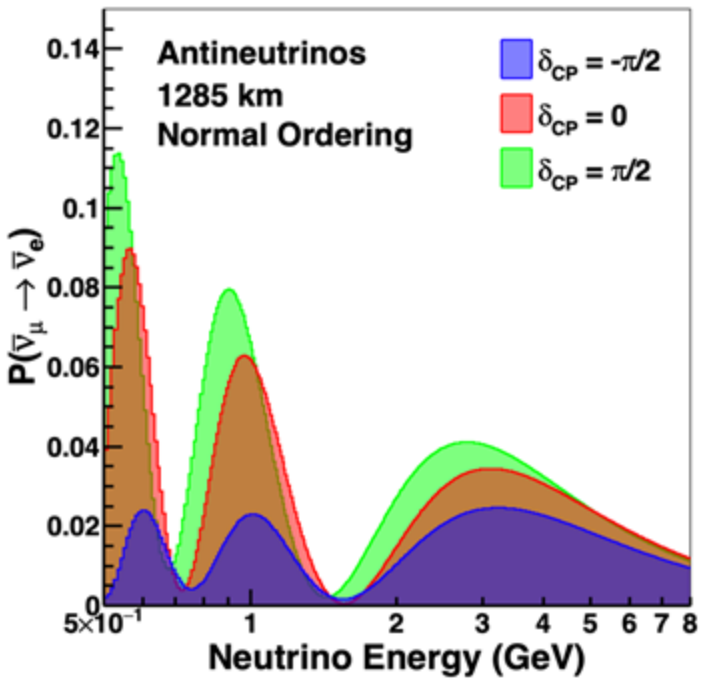
Reverse Horn Current (RHC)



DUNE Design: 1300km Baseline

- The long baseline + wideband beam provide opportunity to unambiguously determine Mass ordering, δ_{CP}, θ_{23} octant from oscillation probability.
- DUNE has a unique ability to measure ν_e appearance as a function of L/E, over more than a full oscillation period

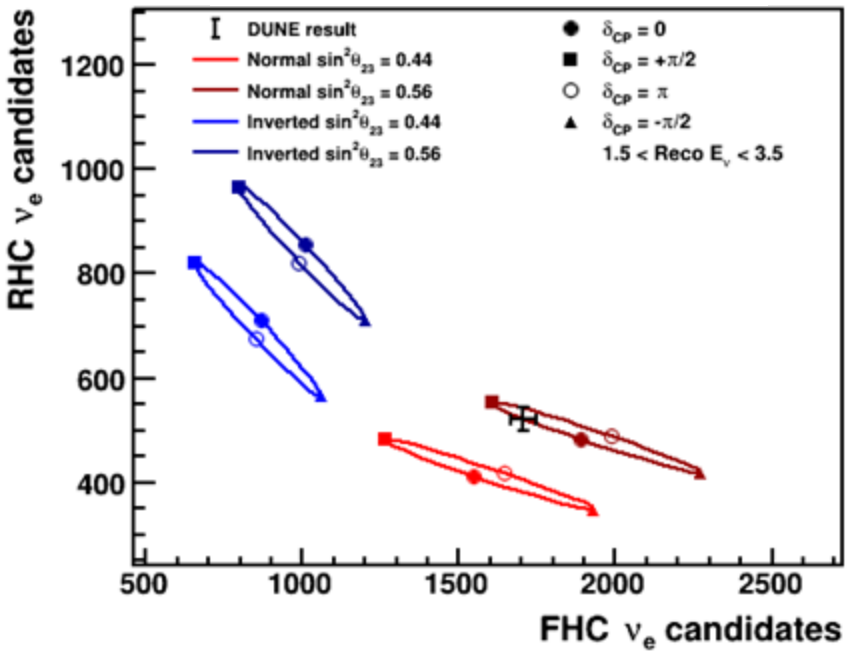




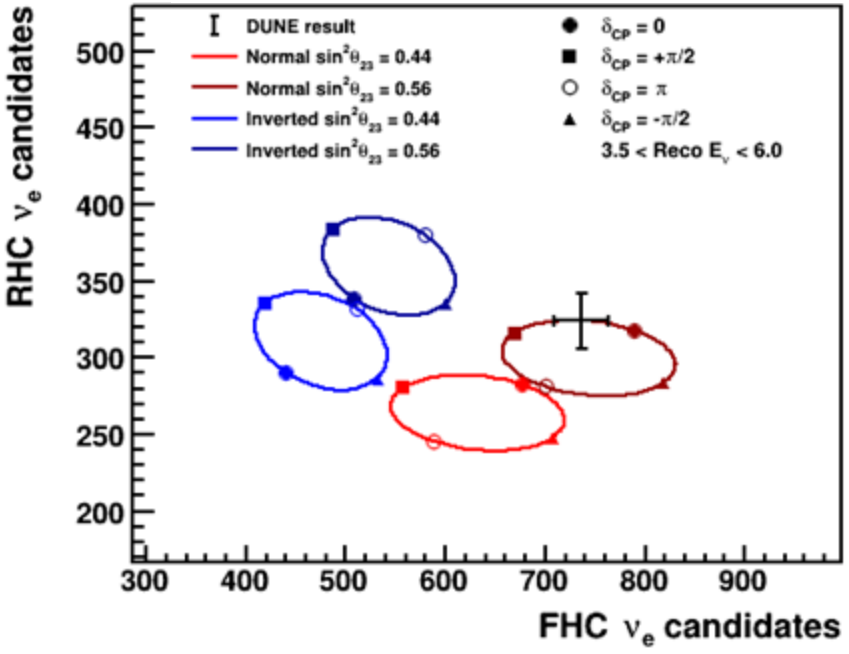
DUNE Design: High Statistics

- DUNE's long-term goal is four 17 kt Lar TPC FD modules in beam from 2.4 MW Fermilab proton beam providing few percent level statistical uncertainties.
- Power of high stats with wide band LBL shown in bi-event plots.

700 kt-MW-yrs, Flux peak

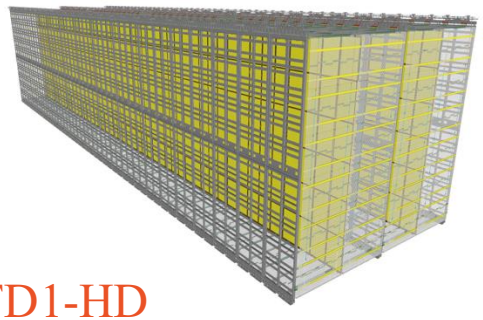


700 kt-MW-yrs, Higher energy

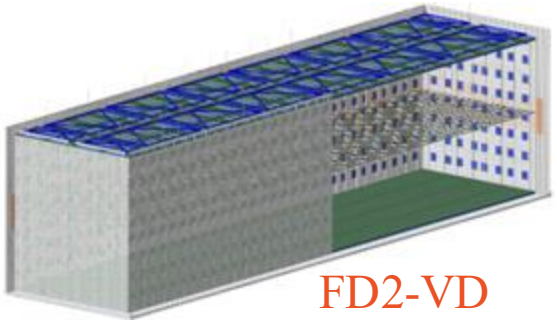


DUNE Design: Precision Reco

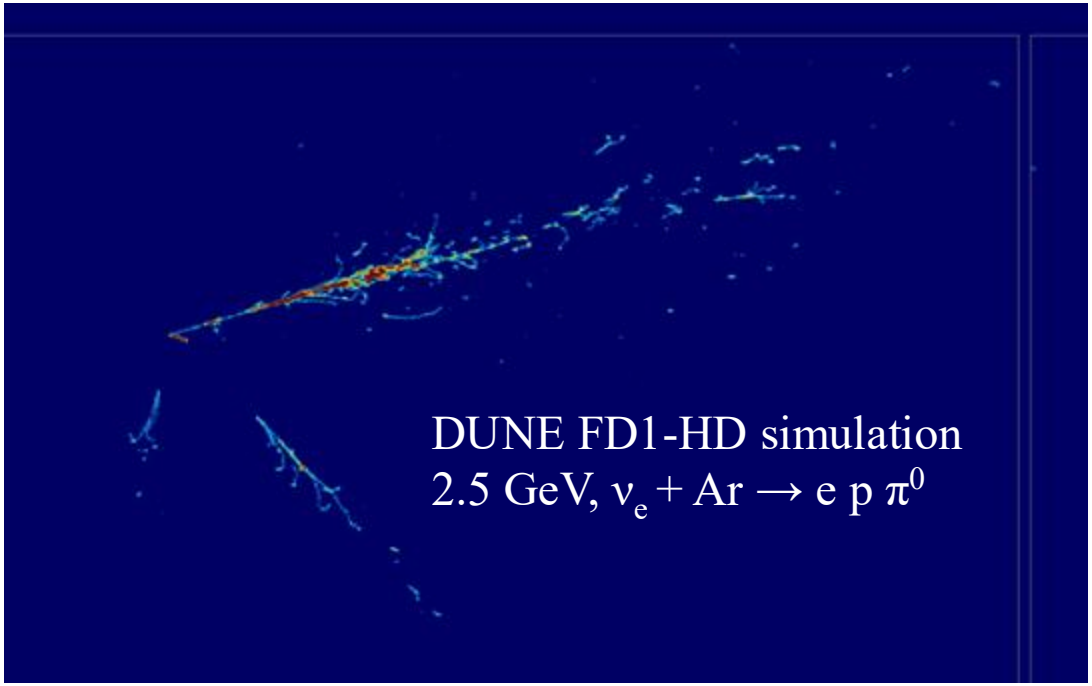
- The far detector must be able to identify flavor and reconstruct neutrino energy over the broad range over energies and interaction topologies provided by the beam.
- **LAr TPC** technologies fulfill both and scales to very large detector mass.
- DUNE will use a combination of horizontal drift and vertical drift modules.



FD1-HD

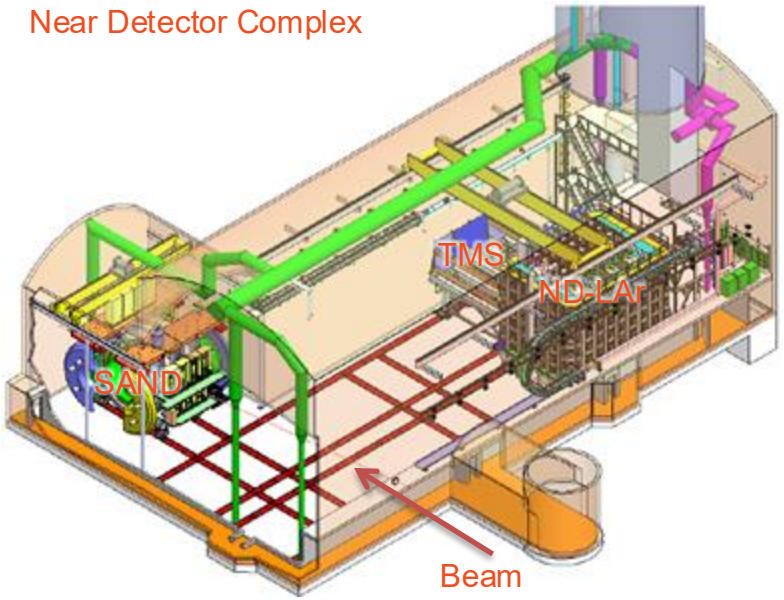


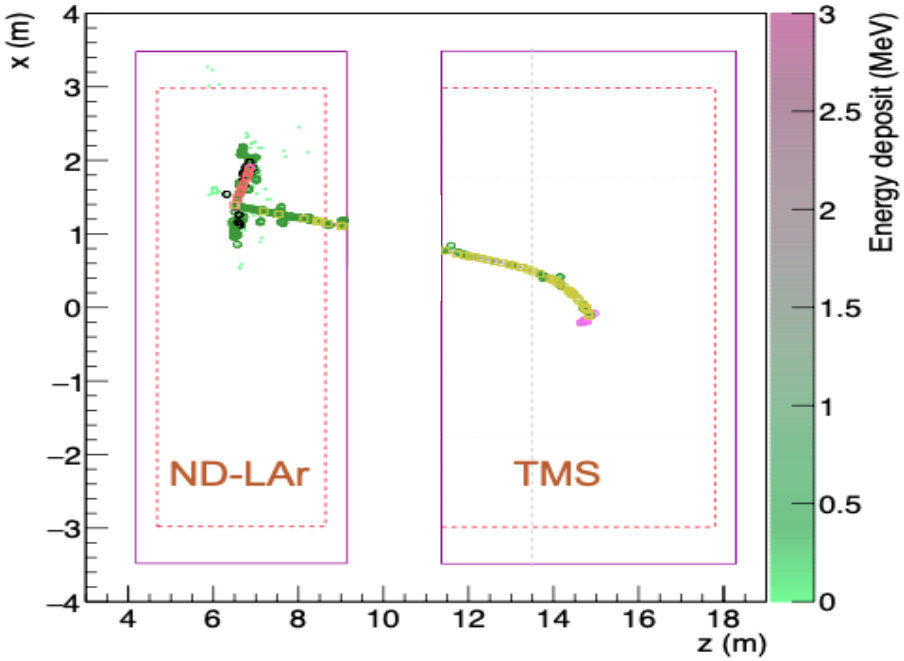
FD2-VD



DUNE Design: Syst. Control

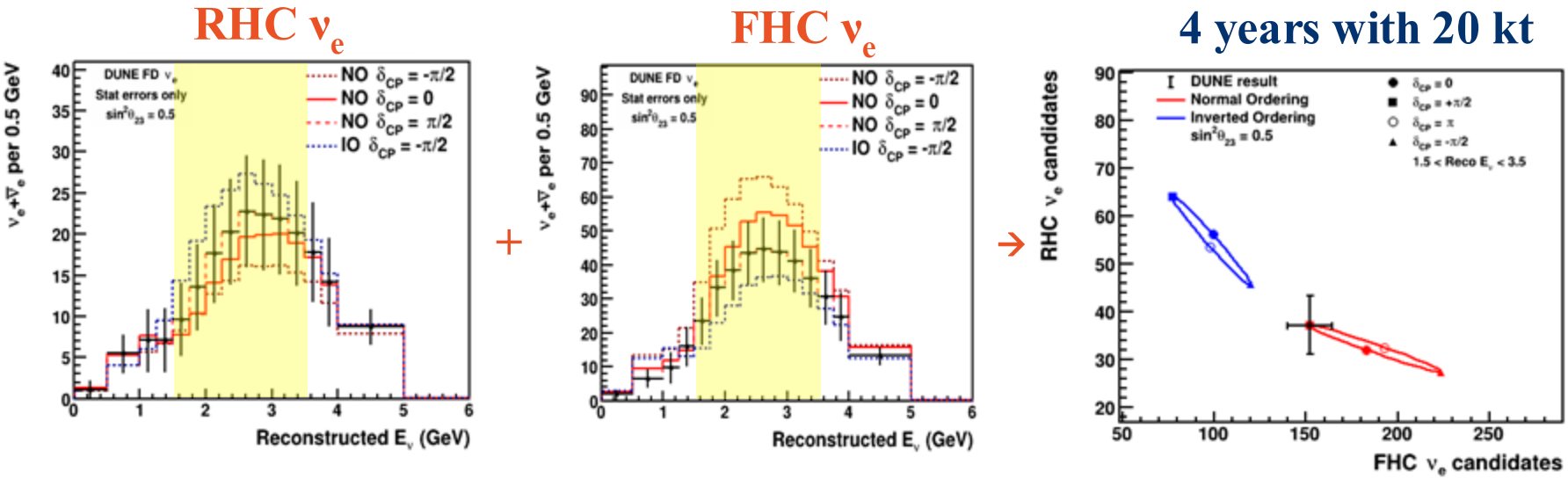
- DUNE Near Detector will measure the neutrino flux, neutrino interaction cross-section on Ar, and measure of LAr TPC response at few percent level.
- ND LAr is design similarly to FD with added modularity and pixelization to handle intense near source rate and sized to contain hadronic activity.
- Downstream systems measure muon momentum (TMS), flux (SAND) and provide additional interaction constraints .





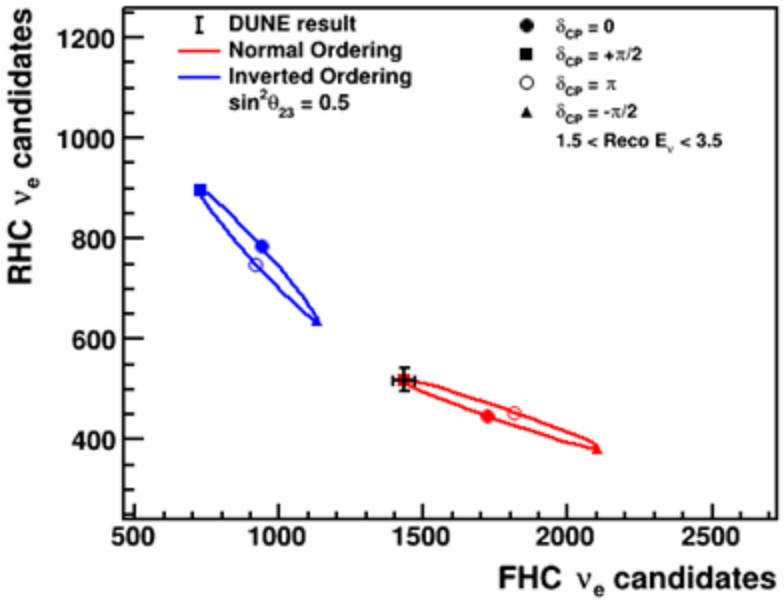
DUNE Physics: Mass ordering

- DUNE has unprecedented and unrivaled ability to definitively resolve the mass ordering independent of other experiments.
- 4 years of running with 2 FD modules in most conservative beam ramp to 1.2 MW provides clear discovery potential

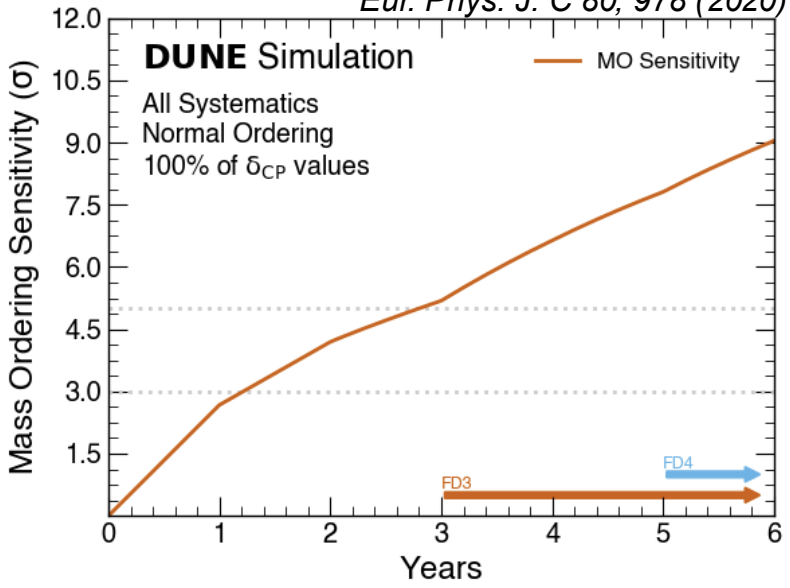


DUNE Physics: Mass ordering

- Statistics from 6 years of full DUNE with 2.4 MW (800 kt-MW-yrs total exposure) exploits enormous NO vs IO differences.
- DUNE maintains ability to definitively resolve the mass ordering regardless of the values of other parameters



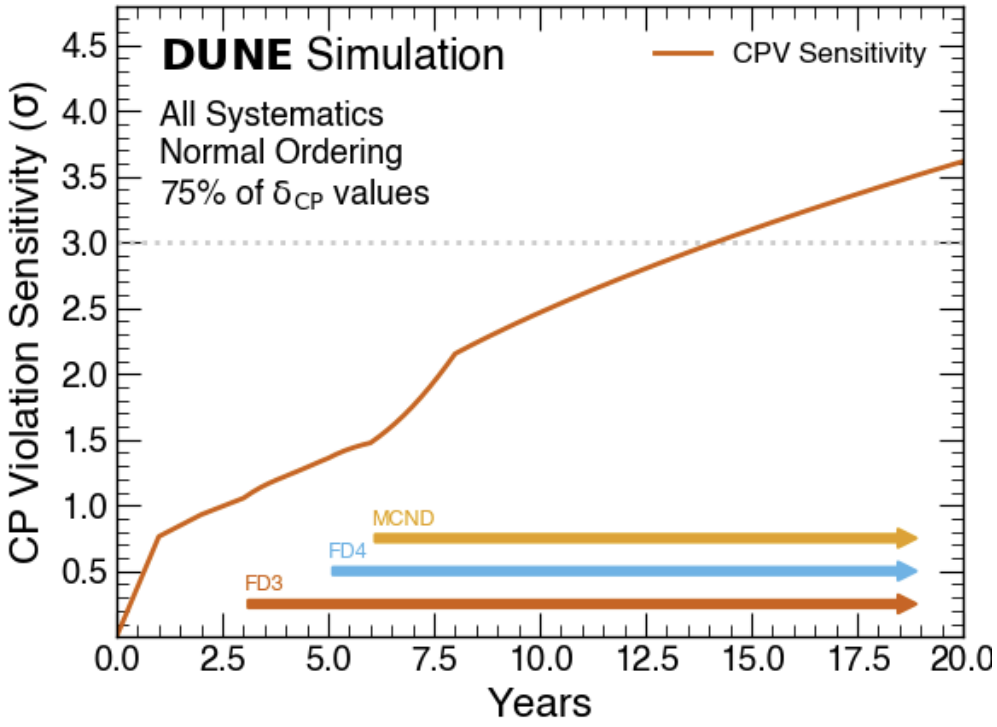
Eur. Phys. J. C 80, 978 (2020)

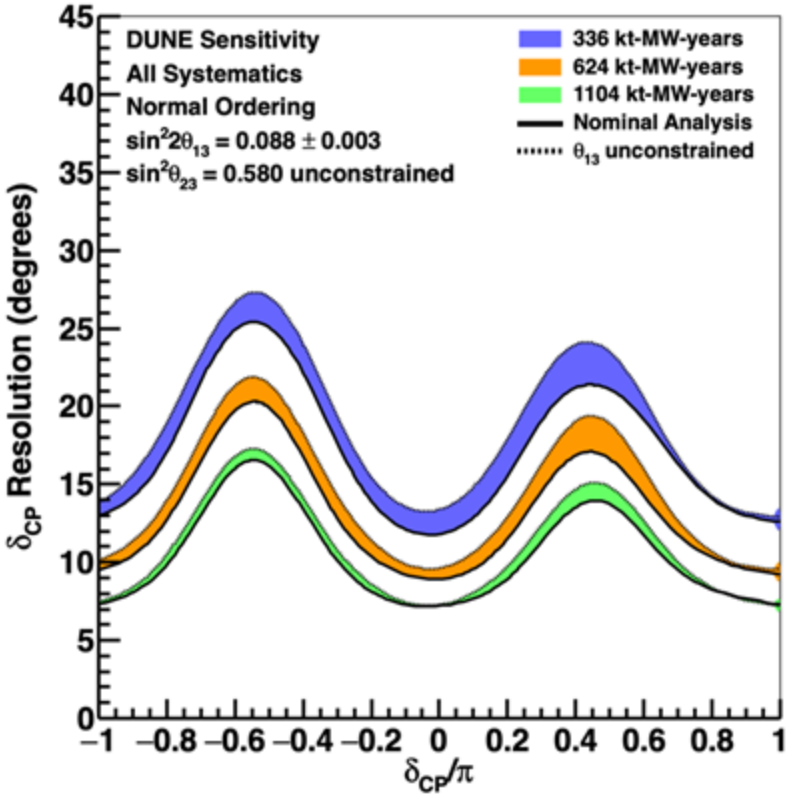


DUNE Physics: CP violation

- 3σ discovery potential for CP violation over >75% of δ_{CP} values
- 7-16° resolution to δ_{CP}, *with external input for only solar parameters.*

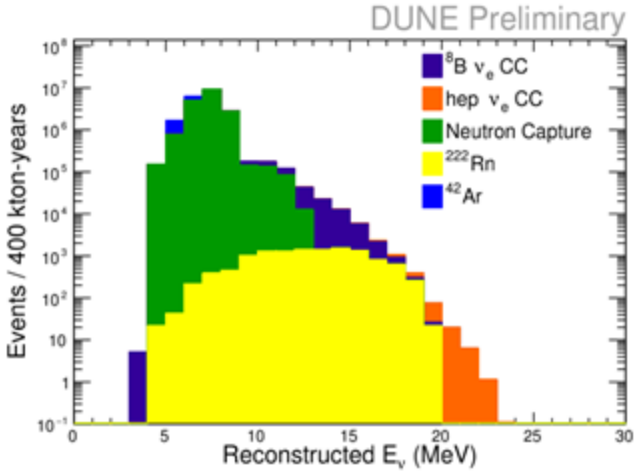
Eur. Phys. J. C 80, 978 (2020)

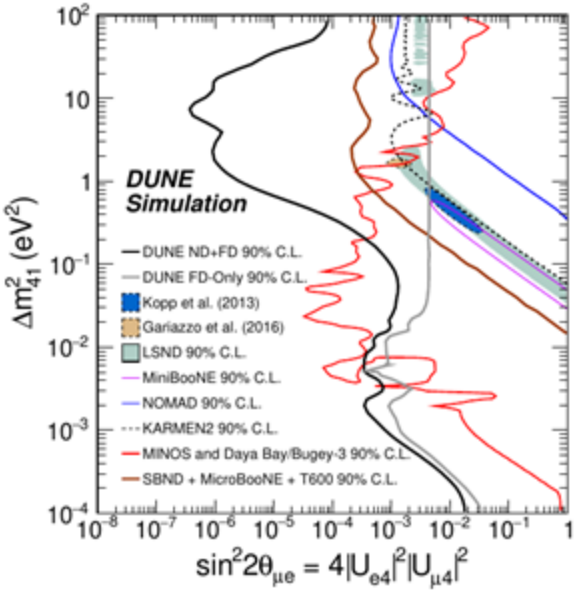




Additional Neutrino Physics

- DUNE will provide world-leading precision on Δm^2_{32} and θ_{23}, including octant allowing direct testing of PMNS unitarity.
- MeV-scale Physics
  - Galactic SNB will produce 1000s of events
  - Sensitivity to solar neutrinos in study.
- Searches for NSI and sterile neutrinos.



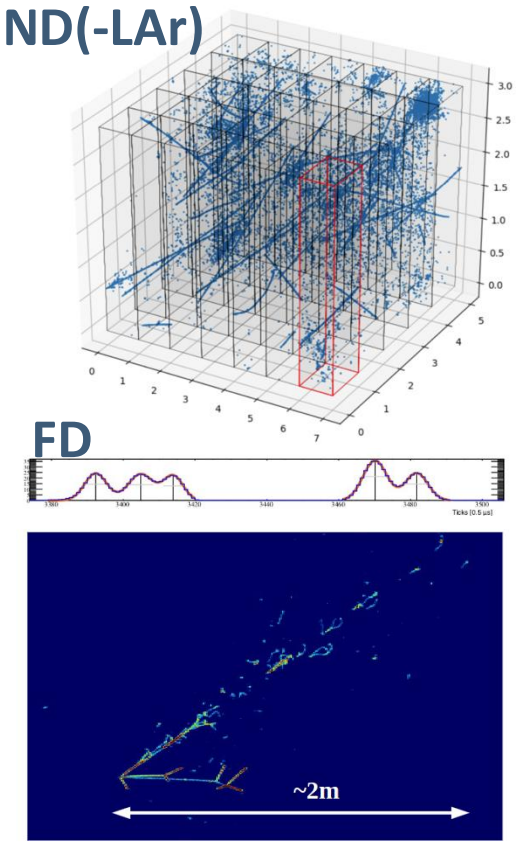


DUNE Reconstruction and Simulation

- DUNE's goals require handling disparate data streams:
  - **ND:** dense activity from 12M pixels, 5 MB /spill, ≈Hz
  - **FD beam:** 3M wires with digitized waveforms, ≈5 GB/trigger
  - **FD supernova:** ≈300 TB per module, ≈1 trigger/month

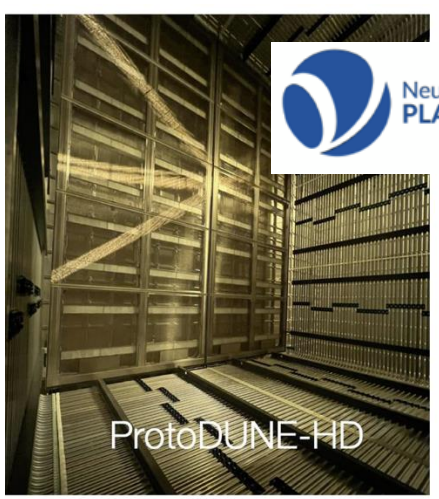
→ *Will need to process flexible and decomposable data groups*

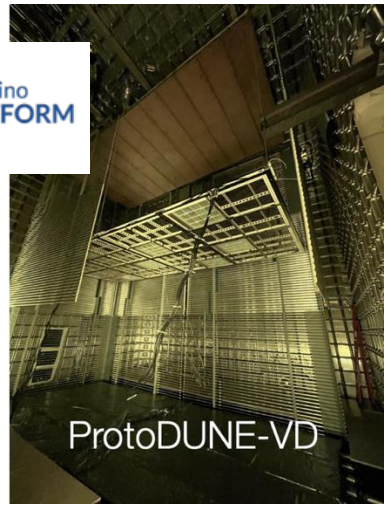
- Generating faithful simulation at scale is crucial
- To achieve this, DUNE's computing infrastructure must support:
  - A mix of GPU and CPU heavy algorithms
  - Multi-language support: python, C++
  - Utilization of modern computing facilities efficiently – grid/HPC
- Significant progress has been made on these front and testing on our active prototypes is crucial for DUNE.

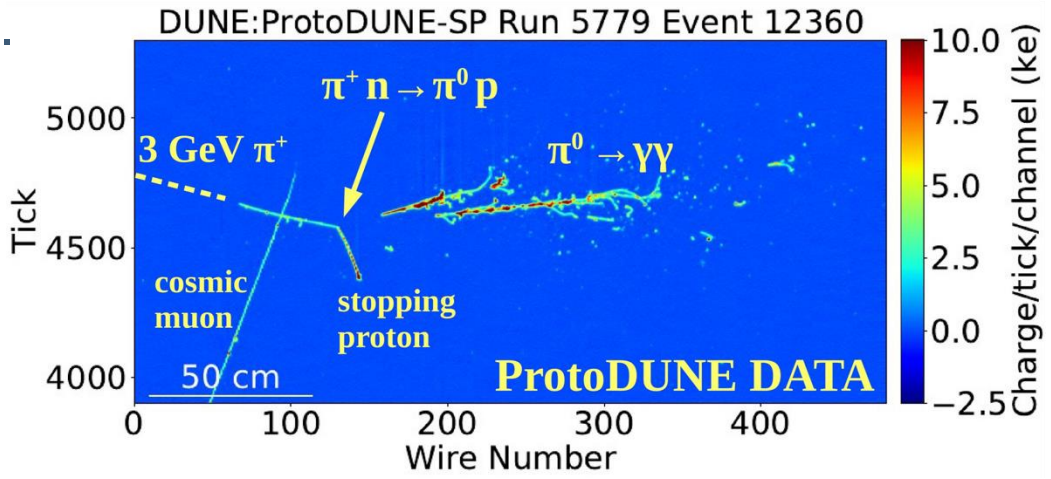


ProtoDUNE

- Phase I: 2018-2020
  - two (single and dual phase) 1-kt prototype LAr TPC detectors operated in a charged test beam at CERN.
- Phase II: Began in 2024
  - Will test final technical solutions for all FD-HD subdetectors. FD-VD tests are in progress.







First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform [2007.06722], JINST **15** P12004 2020

Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC [2108.01902], JINST **17** P01005 2022

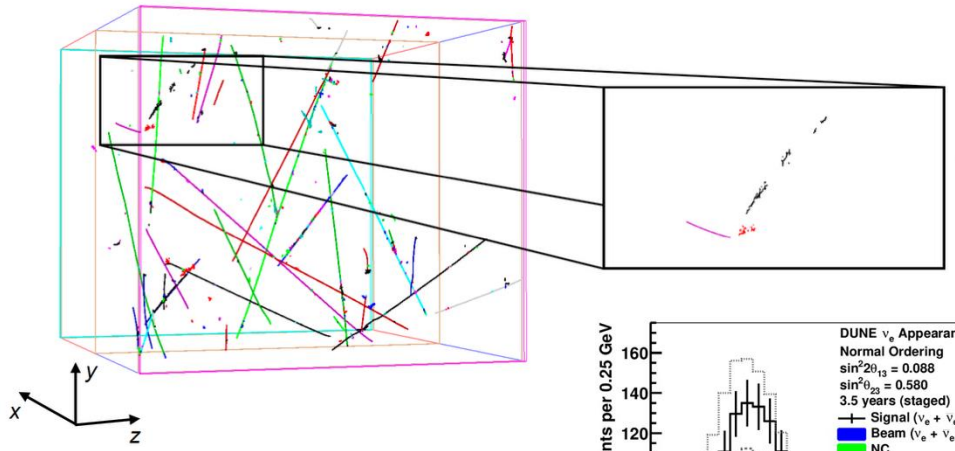
Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora [2206.14521], EPJC (2023) 83:618

First Measurement of the Total Inelastic Cross-Section of Positively-Charged Kaons on Argon at Energies Between 5.0 and 7.5 GeV [2408.00582], PRD **110** 092011 (2024)

and more!

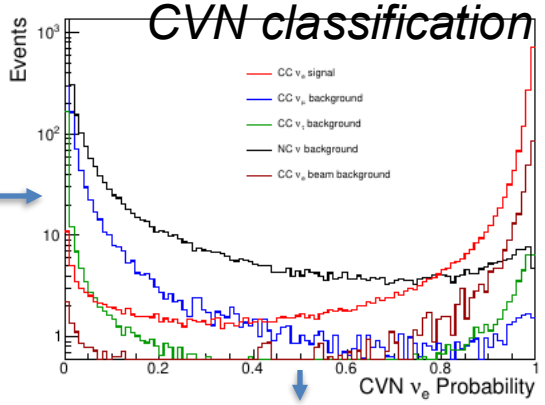
LAr Reconstruction Status

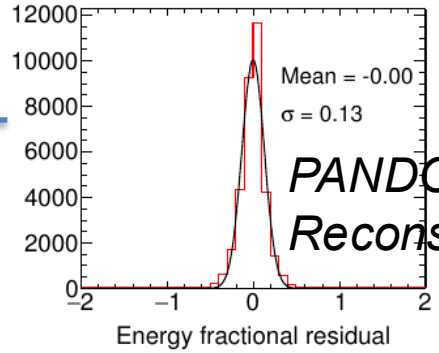
- Traditional reconstruction techniques via PANDORA tested on ProtoDUNE.
- Convolutional neural networks to reconstruct & classify events.
- Output to standard ROOT trees or CAF in DUNE format.



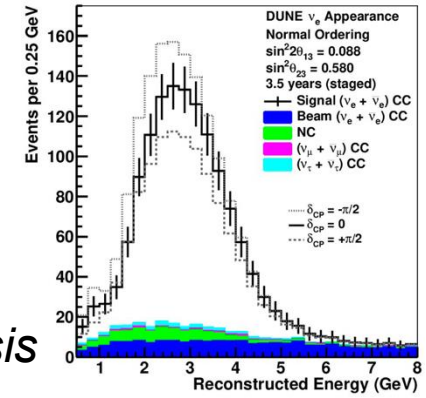
PANDORA 3D reconstruction output

CVN classification





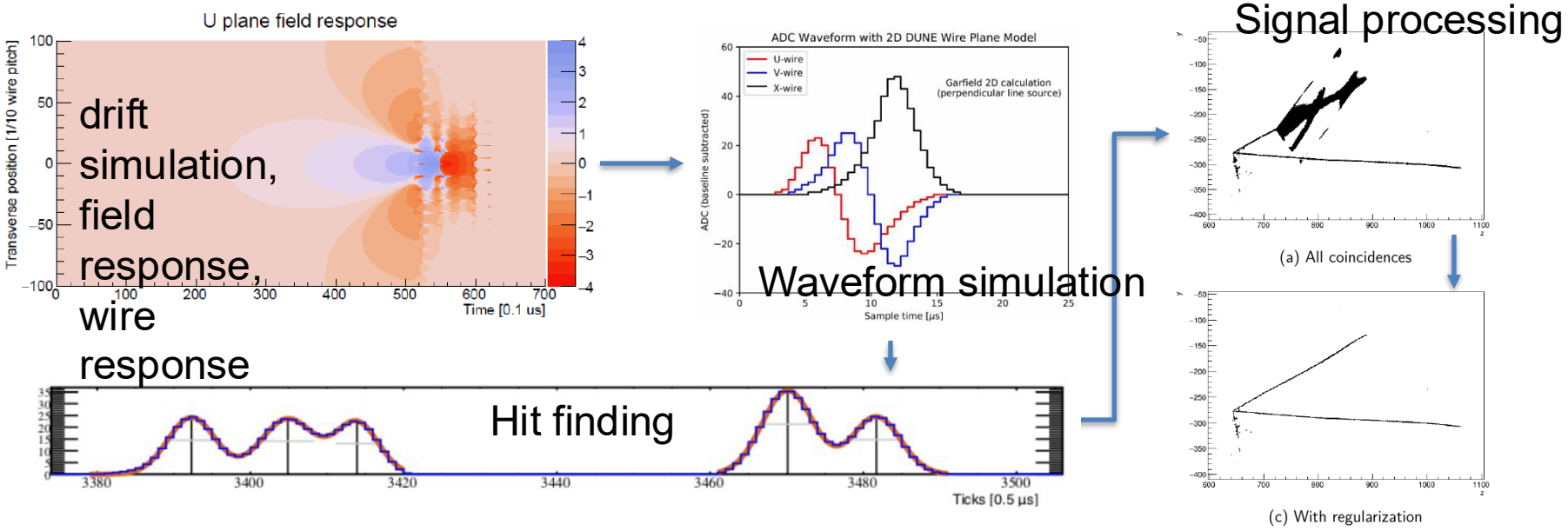
PANDORA Energy Reconstruction



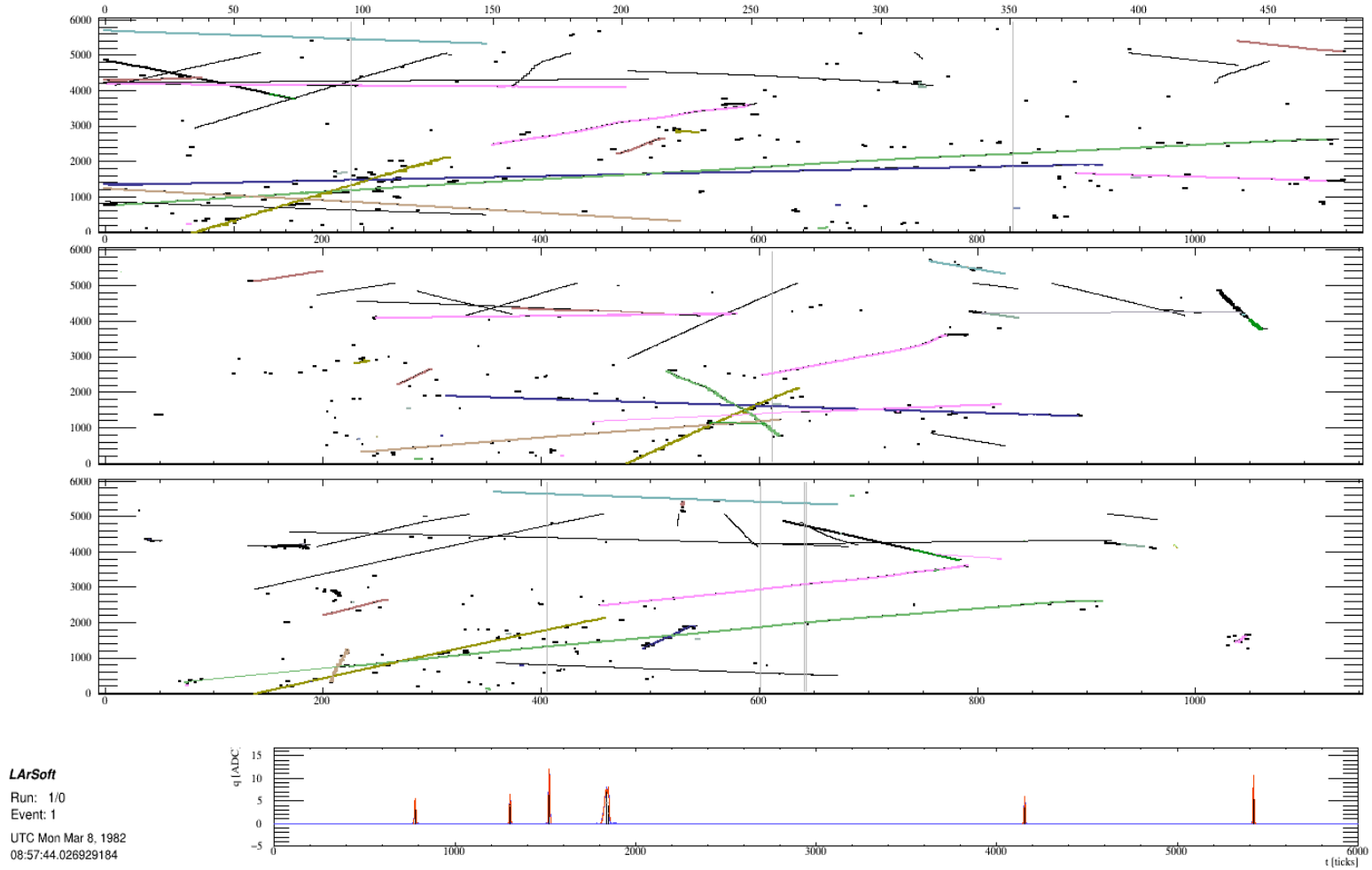
DATA Fit/Analysis

Far Detector Sim/Reco Status

- Vertical and horizontal drift detector supported by LArSoft.
  - ART-Based framework for LArTPC Sim and Reco.
  - Supporting SBN, and ProtoDUNE programs.
- LArTPC specific Simulation and Reconstruction Toolkit.
  - Scintillation photon propagation and detection.
  - Low-energy drift electrons, signal induction and wire response via Wire-Cell Toolkit (WCT).



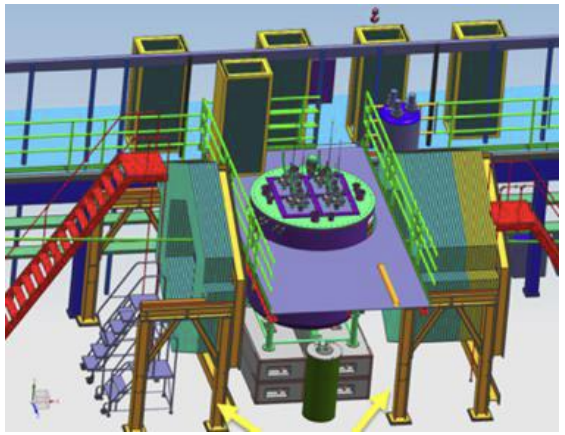
LArSoft Simulation and Reco in PD



Example reconstructed data display produced with LArSoft. One APA's worth of simulated data are shown. Reconstructed hits and tracks are displayed in the top three panels.

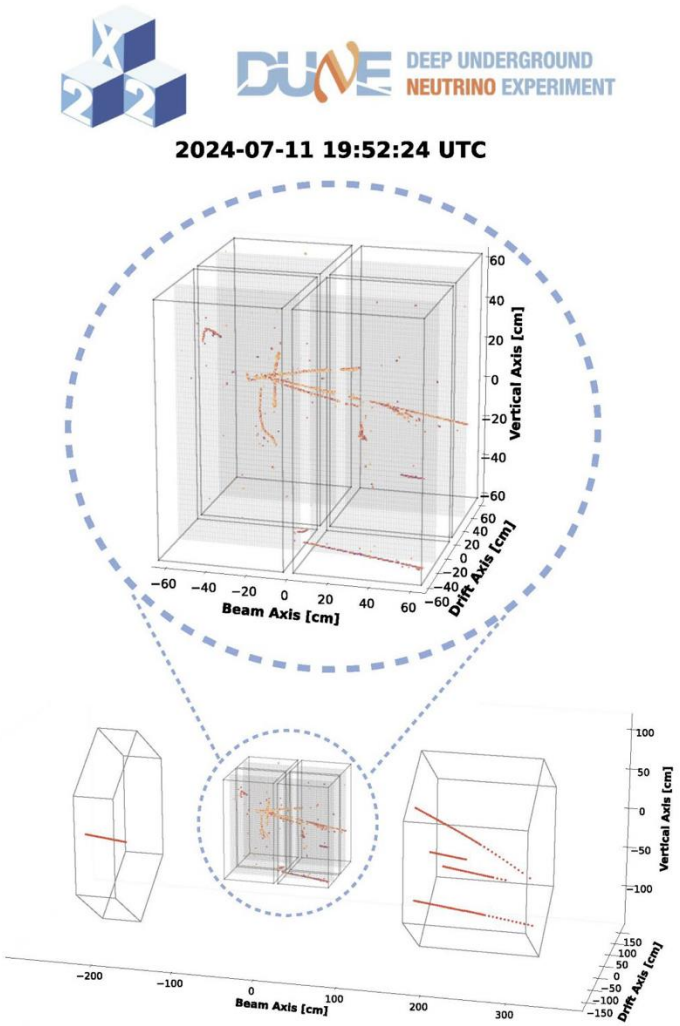
ND 2x2 Demonstrator at FNAL

- Four LArTPC modules were built and operated in LAr in Bern with a total of ~330k pixel channels
- Operation of 2x2 ND-LAr in NuMI Neutrino Beam began in 2024
  - Four TPC modules installed in former location of MINOS-ND
  - Includes upstream/downstream trackers, repurposed from MINERvA
  - 1E19 protons of targets (POT) → 10k neutrinos/day
- Goals: Demonstrate reconstruction with natively 3D readout in a neutrino beam with similar event rate to



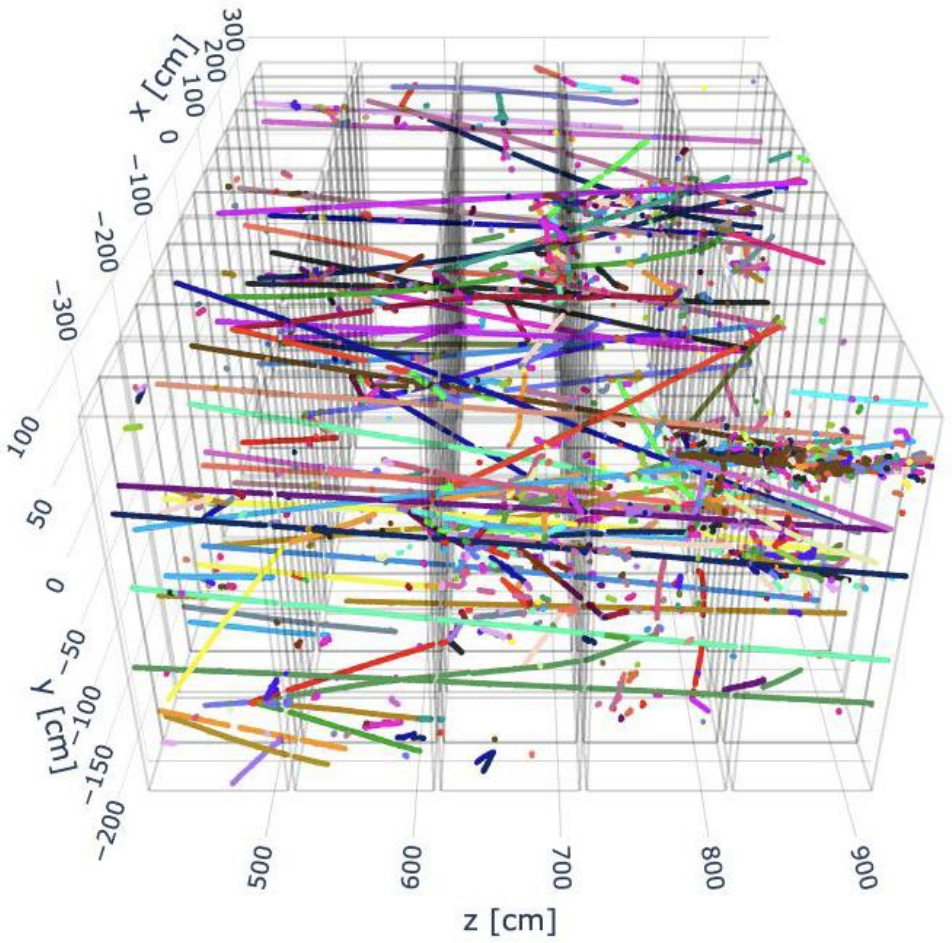
2x2 Simulation and Reco

- 2x2 simulations and reconstruction are advancing.
  - Pixelated LAr detector simulation is inherently parallelizable
    - Well matched to GPUs
  - Testing Deep-learning based Reconstruction toolkit SPINE. (arXiv:2102.01033)
  - Tracking matching with muon tracker will give experience like ND-Lar +TMS



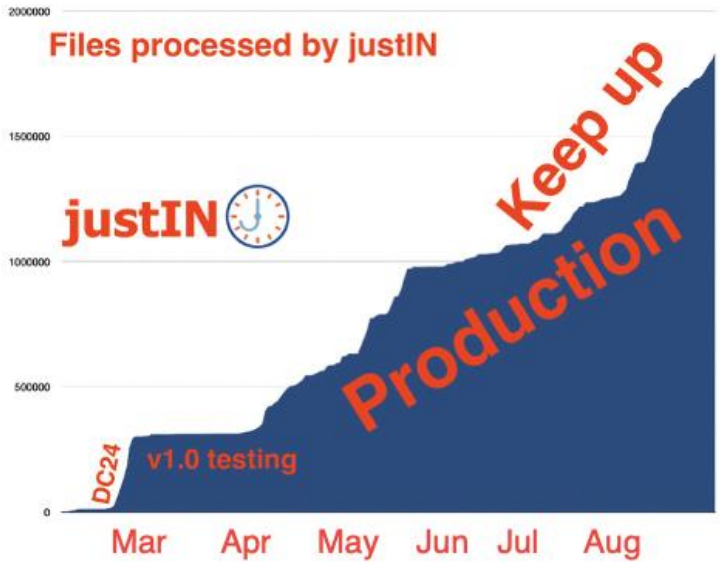
ND Sim and Reco

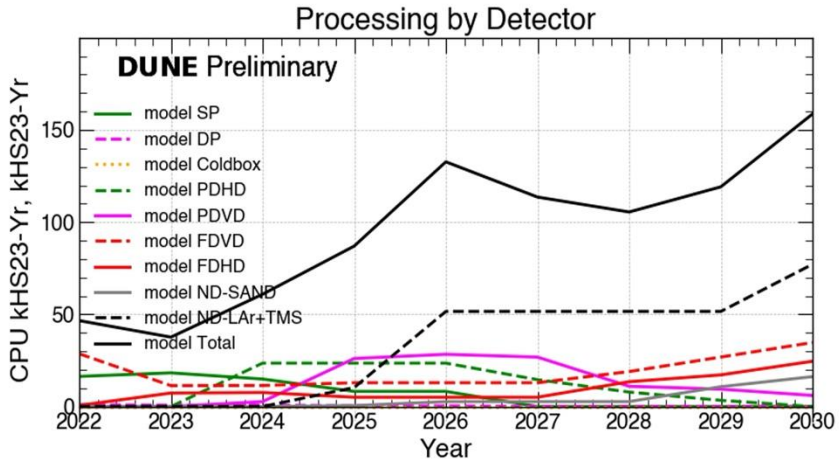
- Recent production of 1.2 K full spill NDLAr + TMS events are allowing us to test these systems at full scale and begin to understand performance.
  - This spill has ~30 in-fiducial interaction and ~100 through going muons.
- Effort are also in progress to utilize PANDORA for the ND.

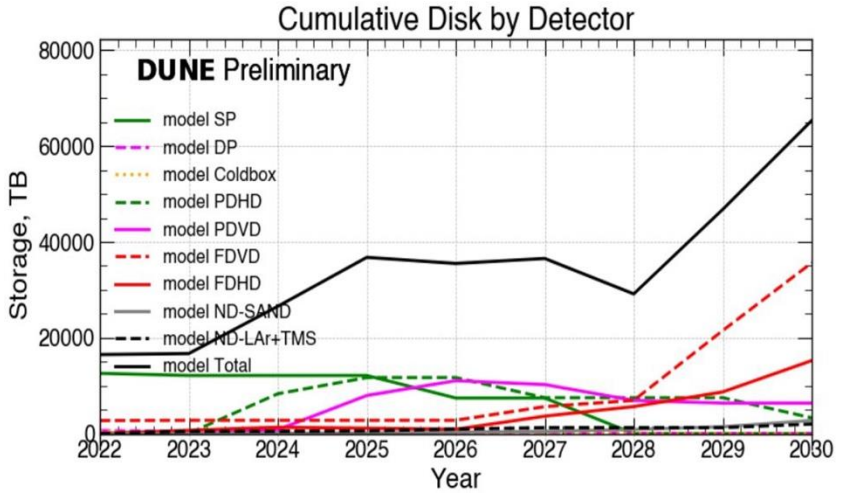


Computing I

- Based on current simulation, prototype experience, and performance from regular Data Challenges DUNE Computing is modeling computing resource demand and building systems to handle data transfer, cataloging, and processing.

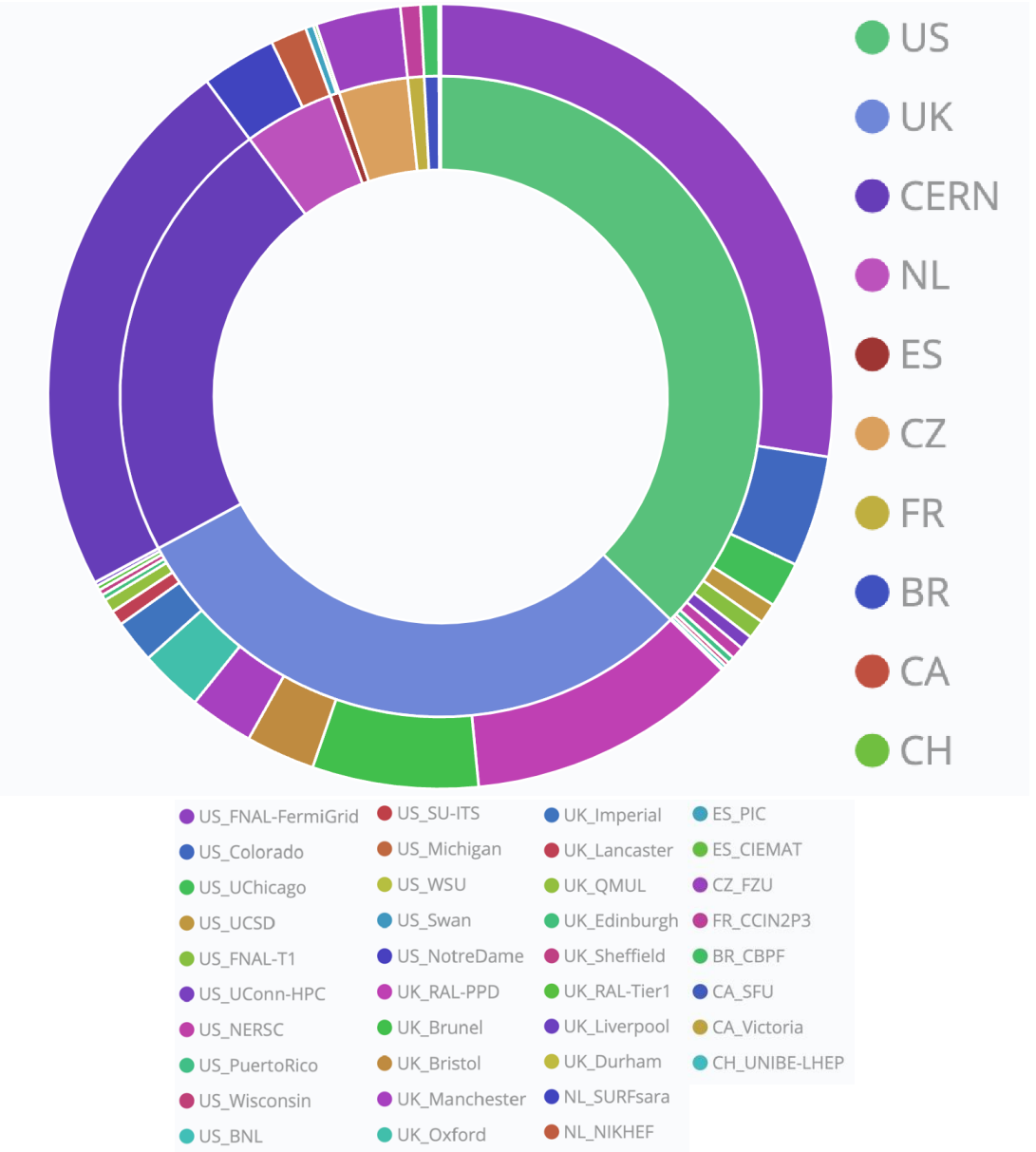




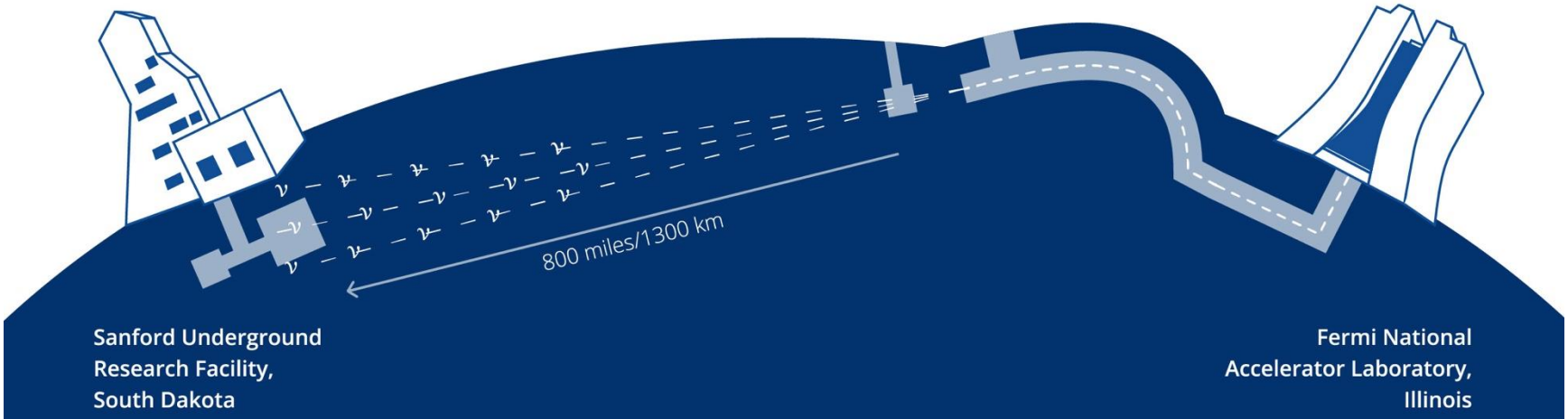


Computing II

- DUNE is also gaining valuable experience deploying jobs on a wide variety of compute sites around the world.
- Development has begun on an updated production offline framework to better fit the need of the collaboration.



Conclusions



- DUNE will provide a world leading, high precision measurements of neutrino oscillations and interactions.
- DUNE will also lead a broad physics program to explore non-beam neutrino sources, BSM, NSI and more.
- The DUNE collaboration has developed a wealth of experience recently operating and analyzing data form its Prototype detectors.
- Software and Computing tool continue to advance and show excellent early performance.

Thank you for your attention.

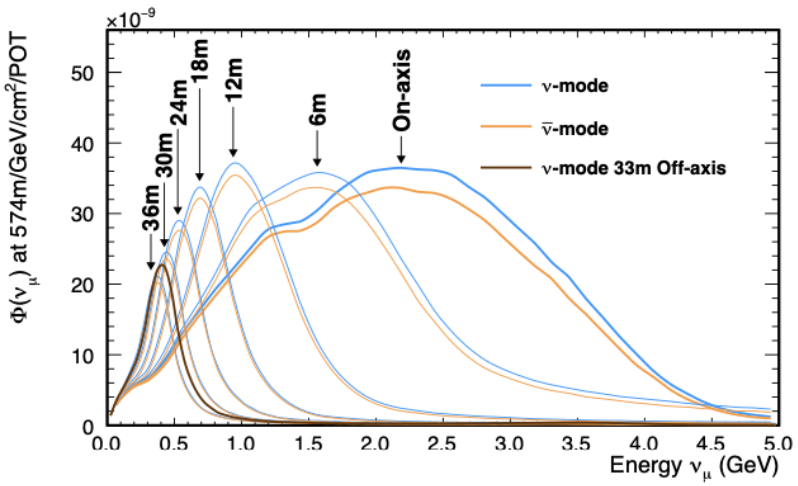
DUNE Collaboration Meeting, Fermilab, May 2025

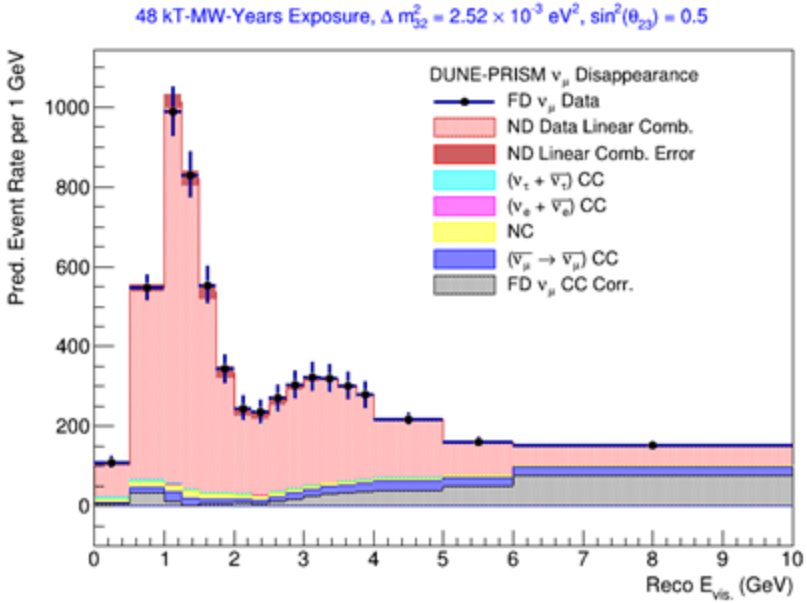
DUNE: >1300 scientists and engineers from 37 countries and growing

BACKUP

DUNE Design: PRISM

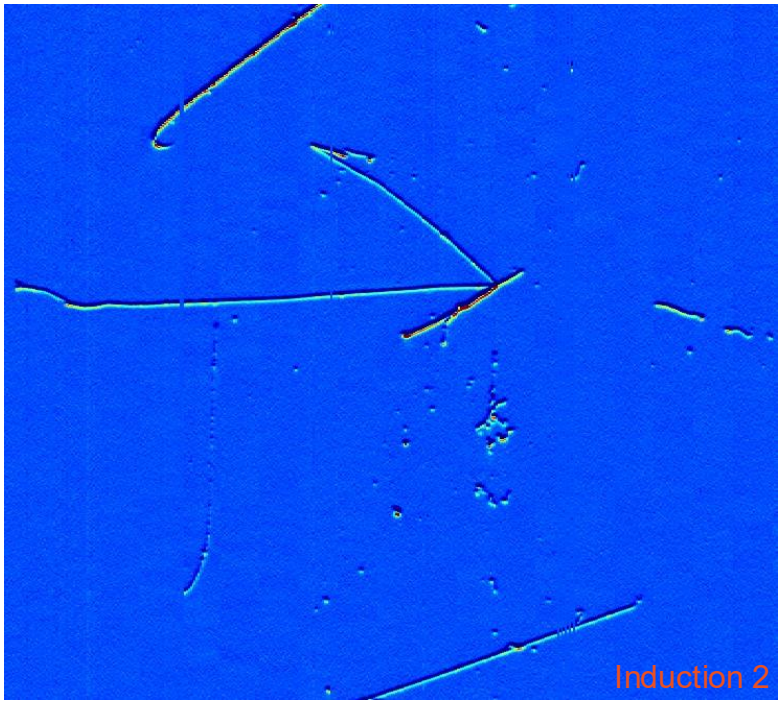
- ND-LAr + Spectrometer can be moved off-axis to enhance flux at lower energies.
- These samples allow one to build a linear combination to match FD *oscillated* specta and build analysis with minimal interaction modeling.

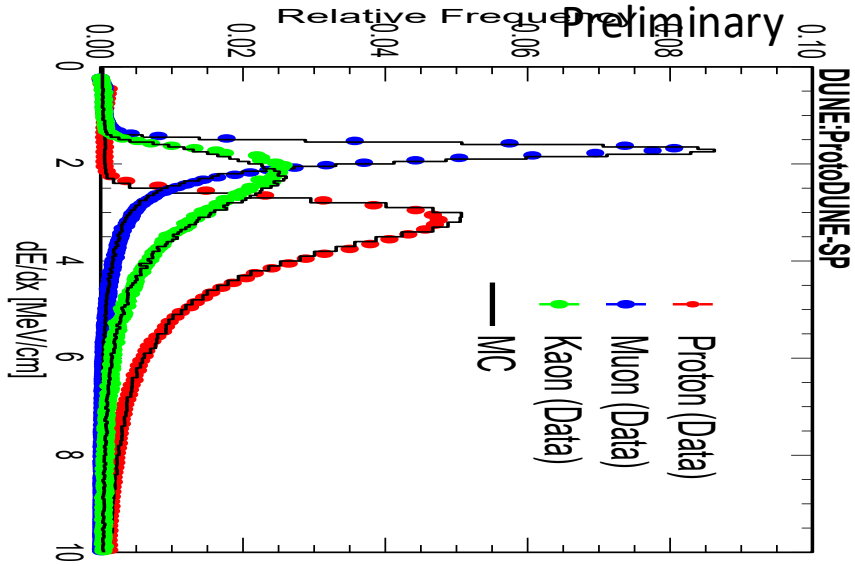




Initial ProtoDUNE Results

- First beam events: **low noise** on all three planes with S/N ratio > 10 in all cases.
- **Stable running** throughout operations, dE/dx distributions for protons, muons, and kaons shows good performance.
- ProtoDUNE shows the fundamental **DUNE technology works and will scale**!





DUNE Plans and Installation

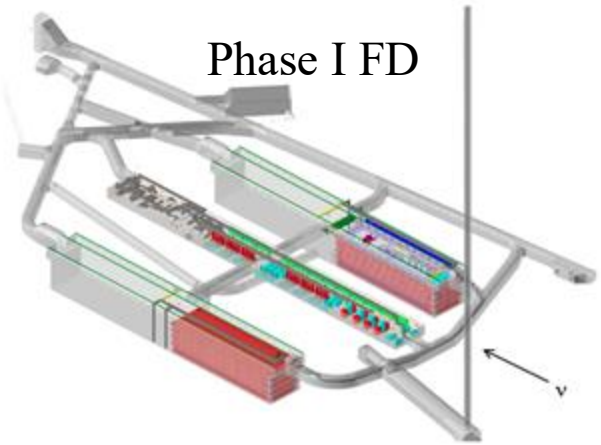
- DUNE construction is phased to provide continuous progress toward physics goals beginning this decade.

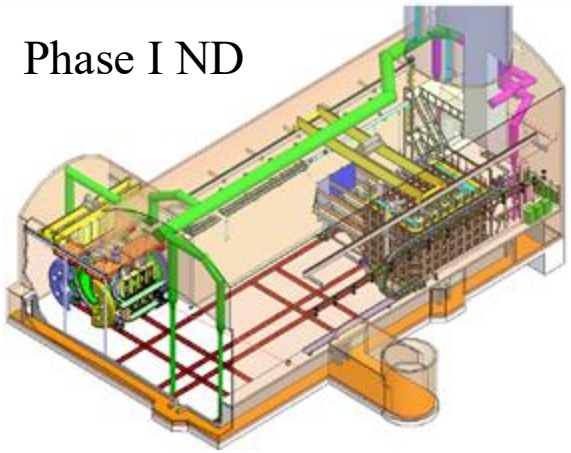
Phase I

- Ramp to 1.2 MW beam intensity
- Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.
- Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND
- Moveable to enable PRISM

Phase II Upgrades

- Proton beam increase to 2.4 MW
- Four 17kt LAr TPC FD modules
- TMS Upgraded to ND-Gar to provide enhanced ND interaction physics capabilities.





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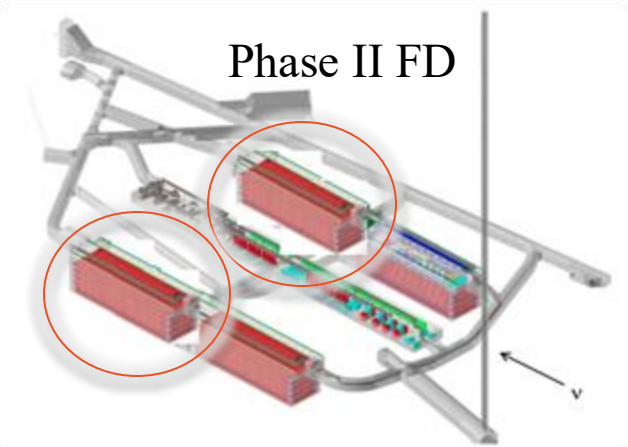
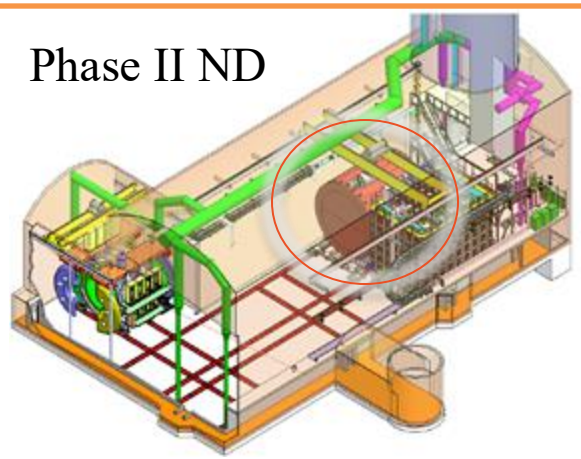
- Ramp to 1.2 MW beam intensity
- Two 17kt (10kt fid.) LAr TPC FD modules. One HD on VD.
- Near detector: ND-LAr + TMS (steel/scint. range stack) + SAND
- Moveable to enable PRISM

Phase II Upgrades

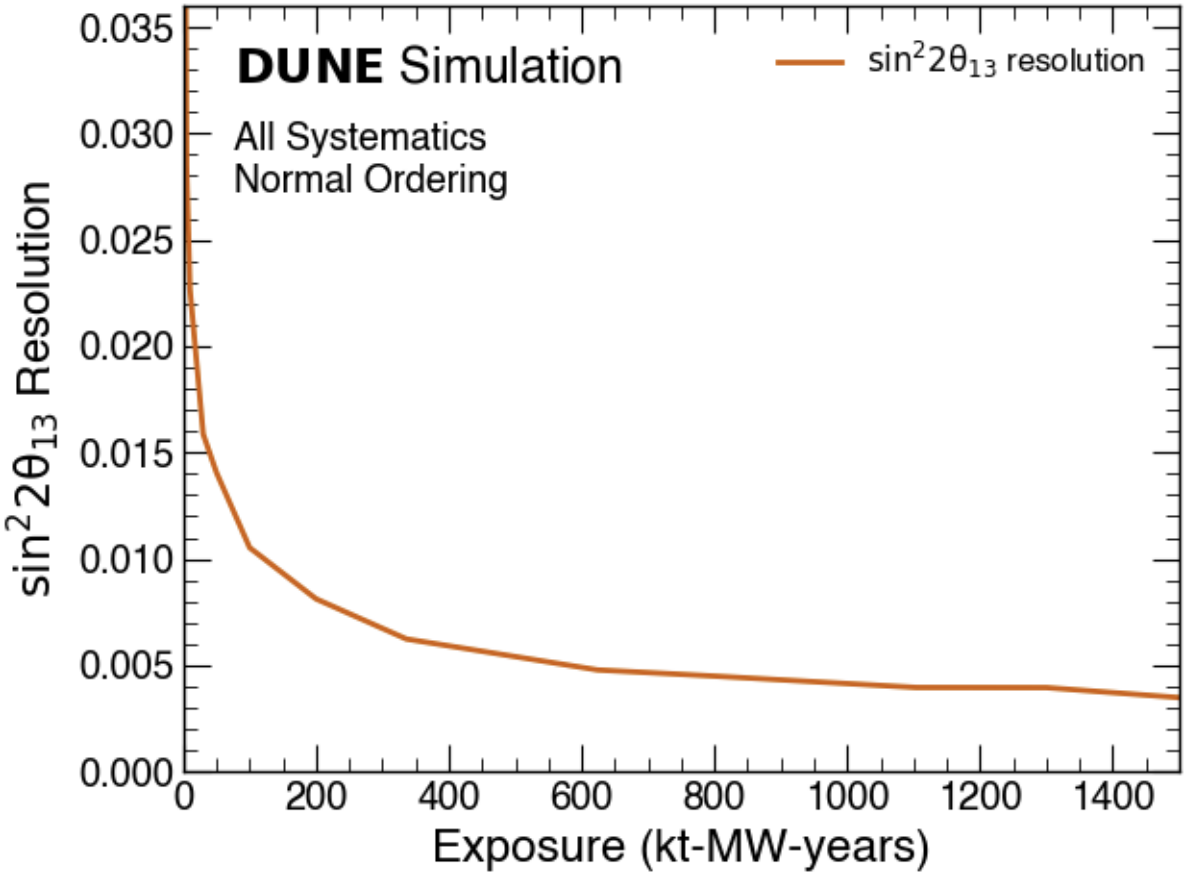
- Proton beam increase to 2.4 MW
- Four 17kt LAr TPC FD modules
- TMS Upgraded to ND-Gar to provide enhanced ND interaction physics capabilities.



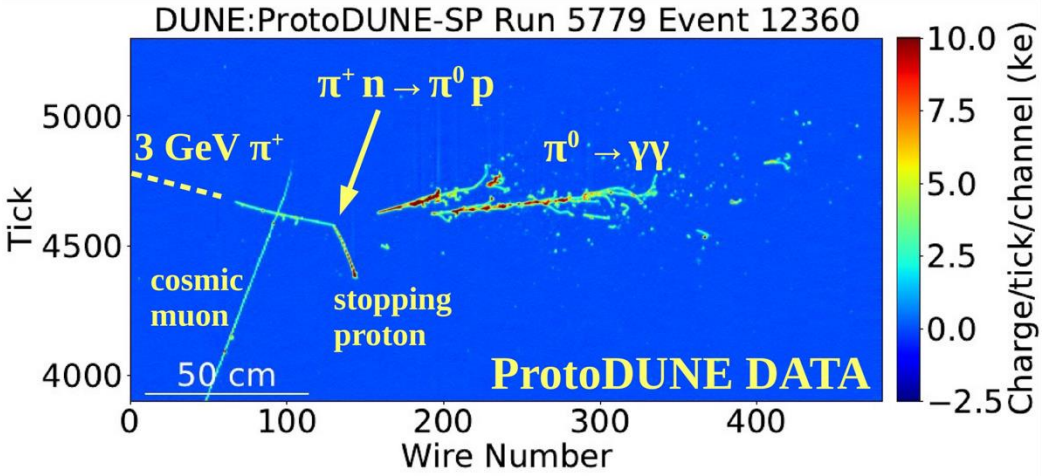


θ_{13} Resolution

World-leading precision (for long-baseline experiment) in **θ13** → comparisons with reactor measurements are sensitive to new physics



ProtoDUNE Studies



First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform [2007.06722], JINST **15** P12004 2020

Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC [2108.01902], JINST **17** P01005 2022

Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora [2206.14521], EPJC (2023) 83:618

First Measurement of the Total Inelastic Cross-Section of Positively-Charged Kaons on Argon at Energies Between 5.0 and 7.5 GeV [2408.00582], PRD **110** 092011 (2024)

and more!

- Many studies studies are in progress with publication of physics results expected soon including:
  - **Pionic charge-exchange events (below)** – yields neutral pions, standard candle for electromagnetic energy scale
  - **Michel electrons** –standard candle for low-energy electron energy scale