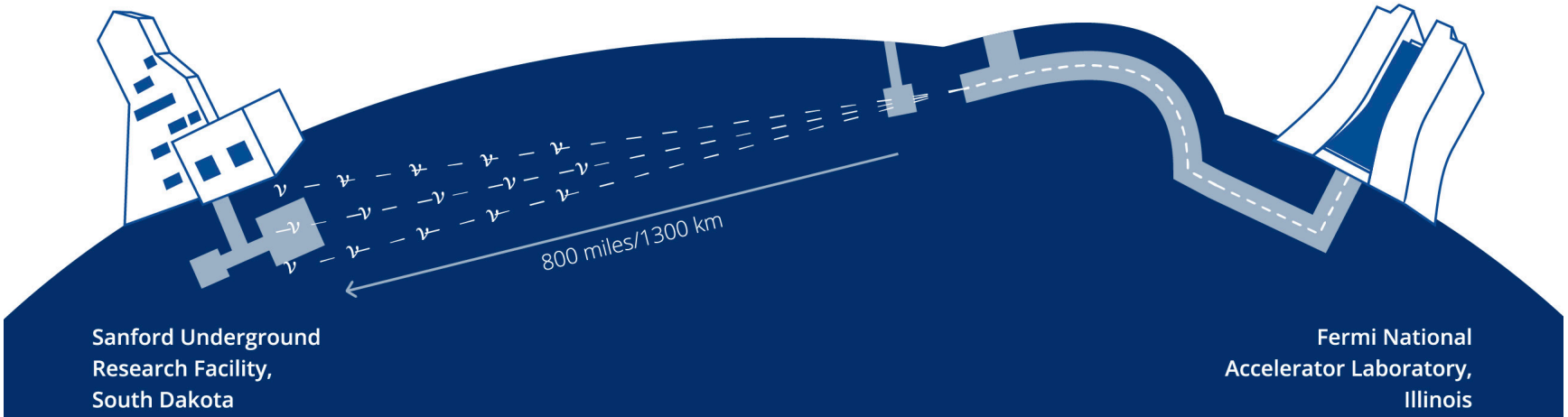



# Deep Underground Neutrino Experiment

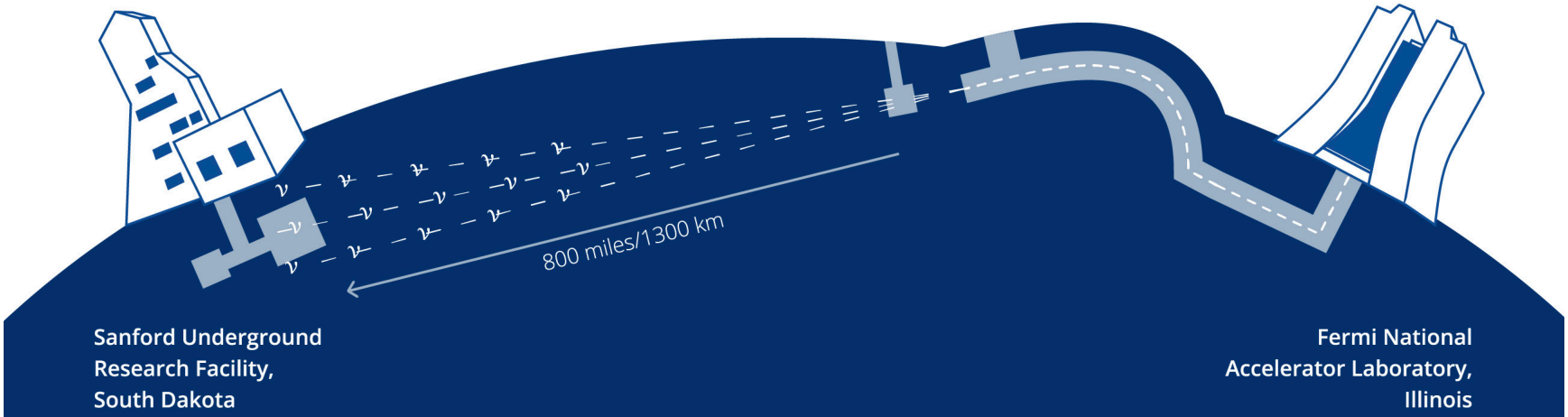
Mathew Muether for the DUNE International Collaboration

Neutrino 2022 – Virtual Seoul – June 2

NEUTRINO 2022

WICHITA STATE UNIVERSITY

# Outline




- The DUNE Experimental Design
  - DUNE TDR (Vol I,III,IV https://iopscience.iop.org/journal/1748-0221/page/extraproc95, Vol II arxiv:2002.03005)
  - ND CDR (arXiv:2103.13910)
- DUNE's unique physics potential
- Realizing DUNE: Progress and Prototyping

# Physics Goals

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

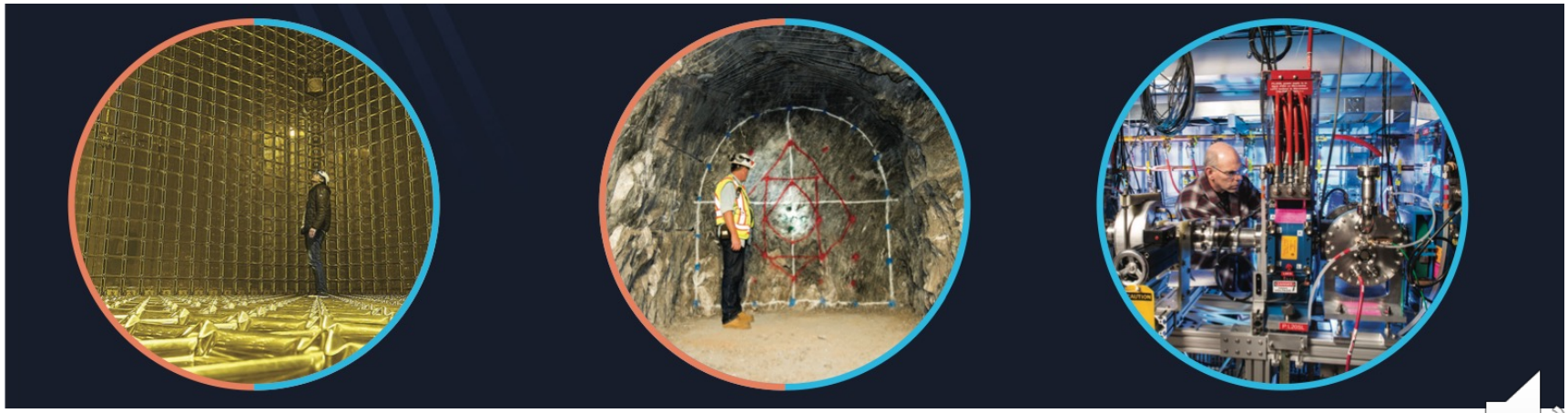
- Discovery sensitivity to CP violation, mass ordering, $\theta_{23}$ octant over a wide range of possible parameter values.

- Unambiguous, high-precision measurements of $\Delta m^2_{32}$, $\delta_{CP}$, $\sin^2\theta_{23}$, $\sin^2 2\theta_{13}$ 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

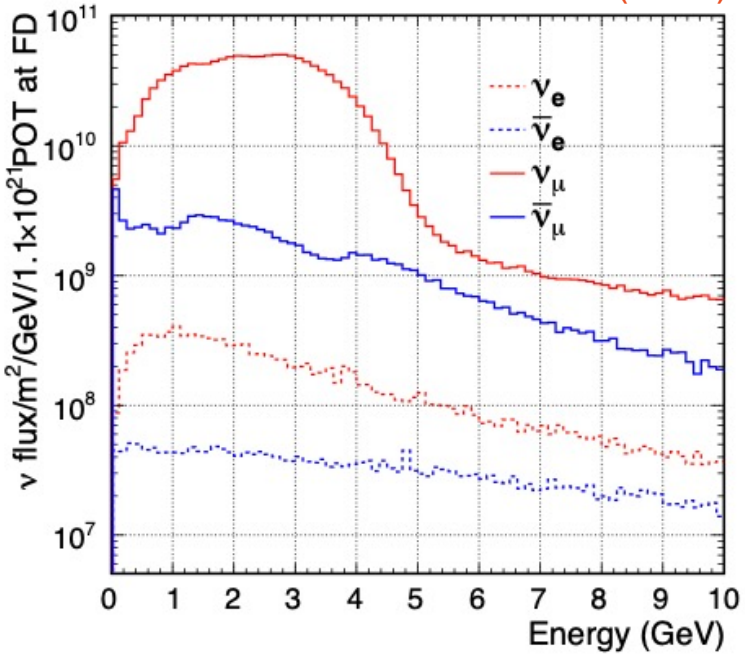
- Long baseline (1300 km) and wideband beam
- High stats: intense beam + large far detector
- Precise energy reconstruction over broad $E_\nu$ range with state-of-the art LAr TPCs
- Precise systematic control from near detector



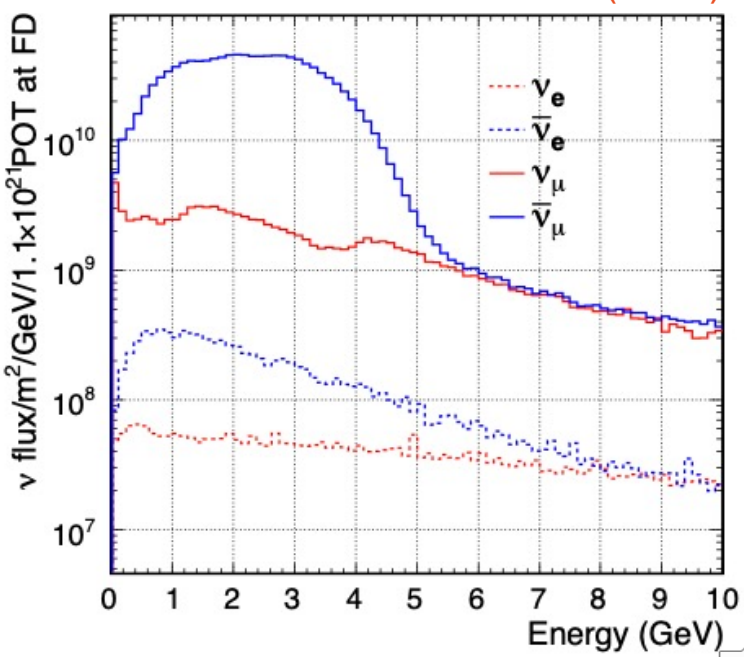
# DUNE Design: Wideband Beam

- The LBNF neutrino 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)

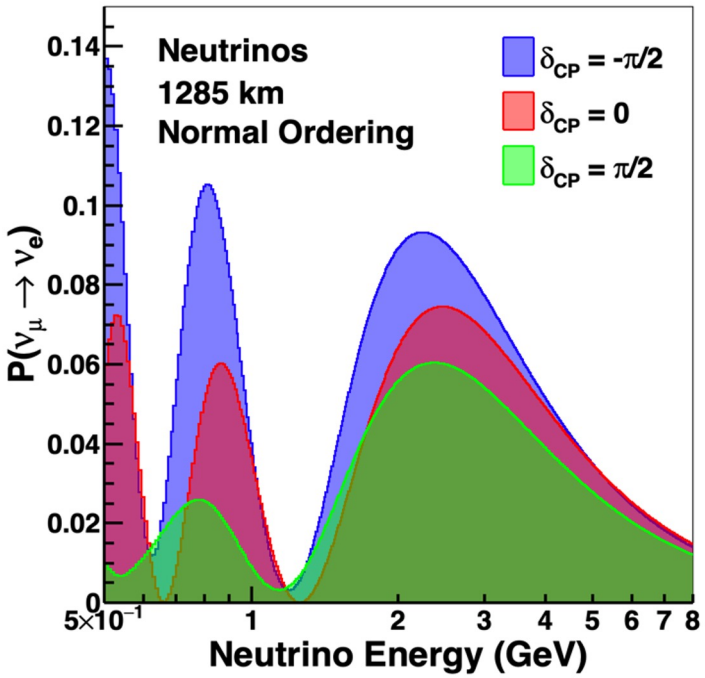


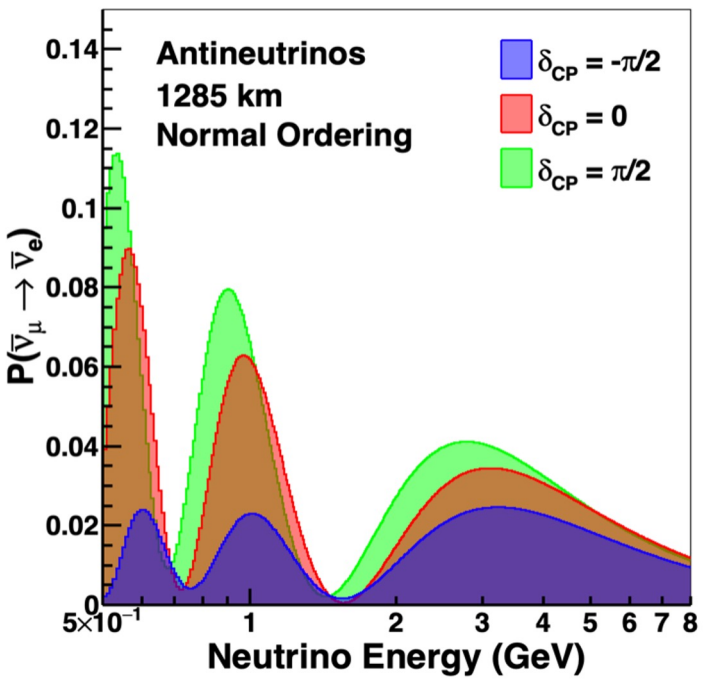

Reverse Horn Current (RHC)



# DUNE Design: 1300km Baseline

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

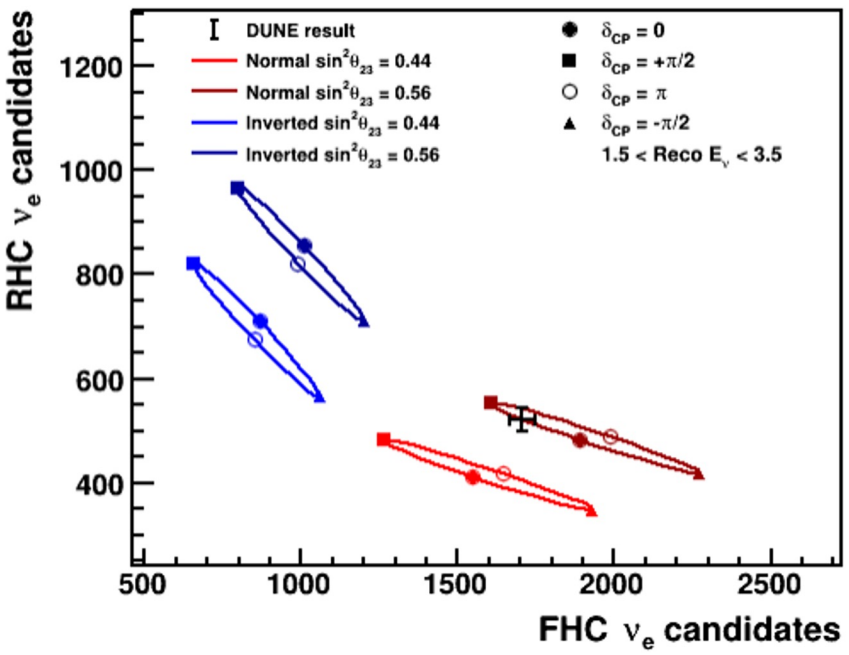


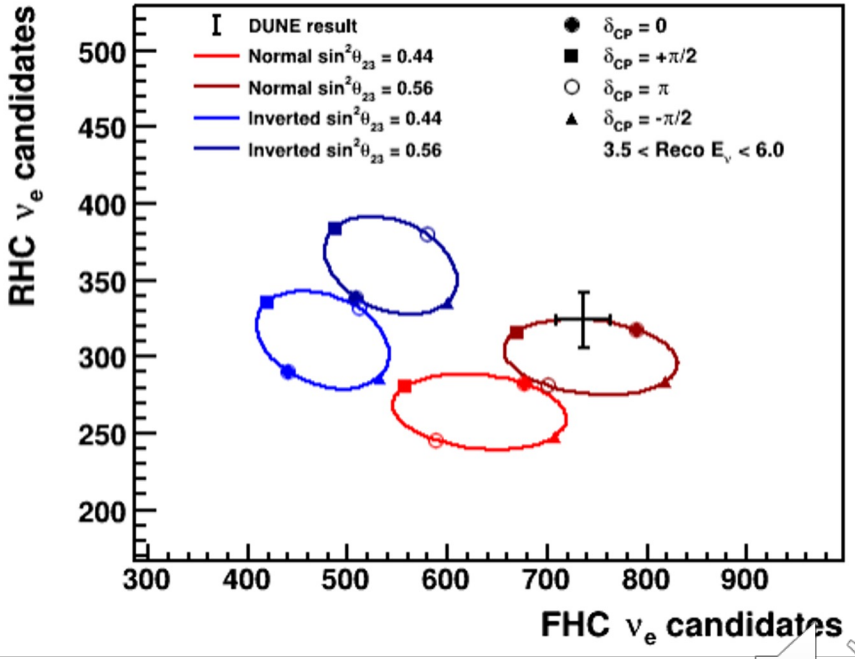
# DUNE Design: High Statistics

- 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

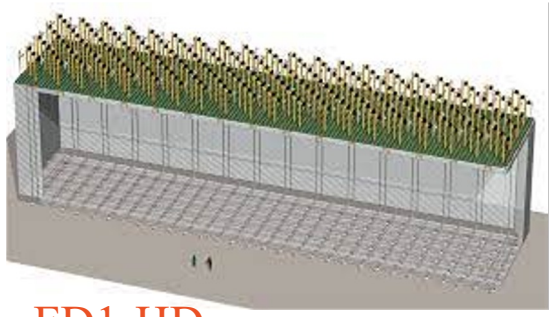



700 kt-MW-yrs, Higher energy

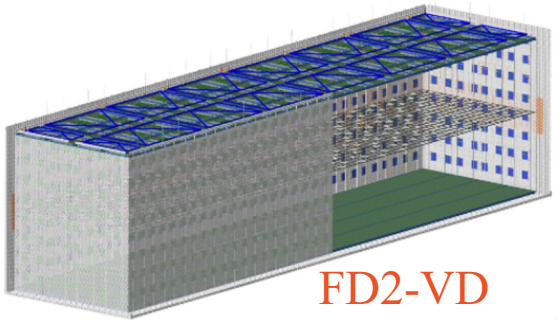


# DUNE Design: Precision Reco

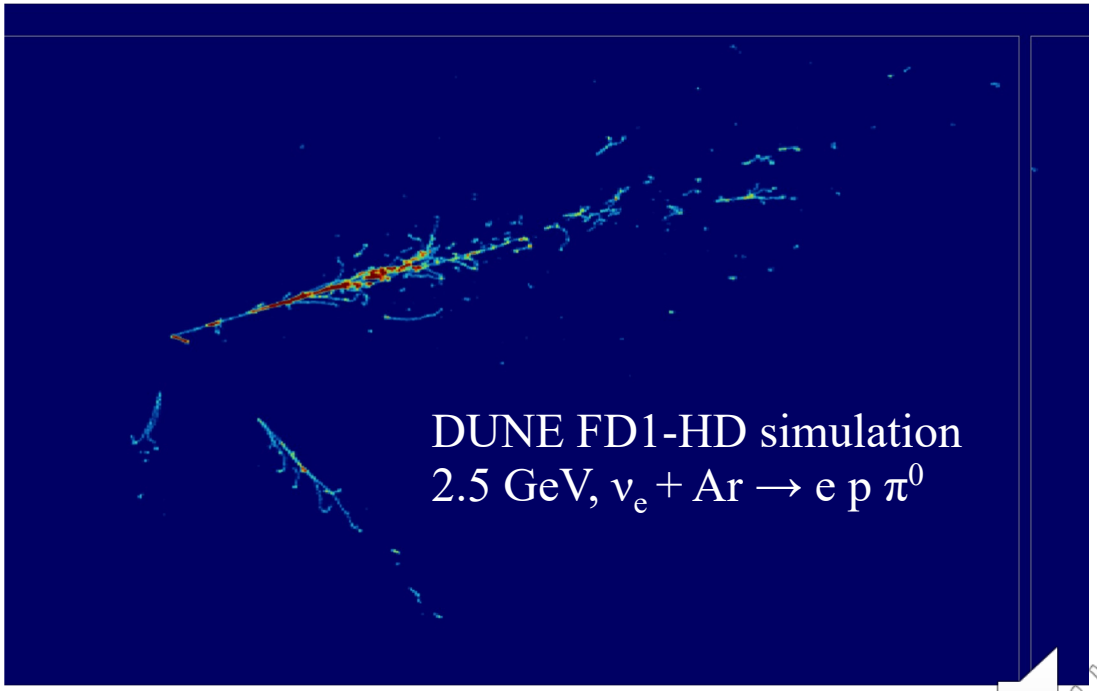
- The far detector must be able to identify flavor and reconstruct neutrino energy over the broad range over energies and interaction topologies provided by the beam.
- **LAr TPC** technologies fulfill both and scales to very large detector mass.
- DUNE will use a combination of horizontal drift and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



FD1-HD

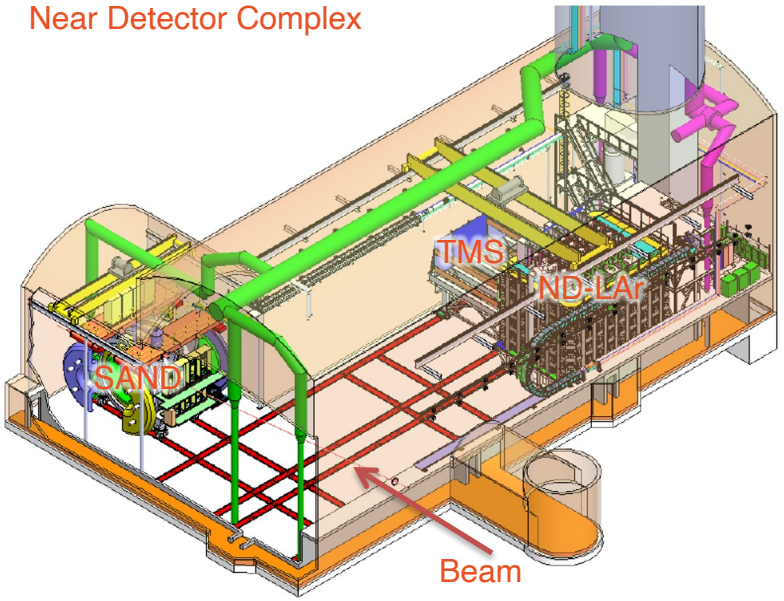


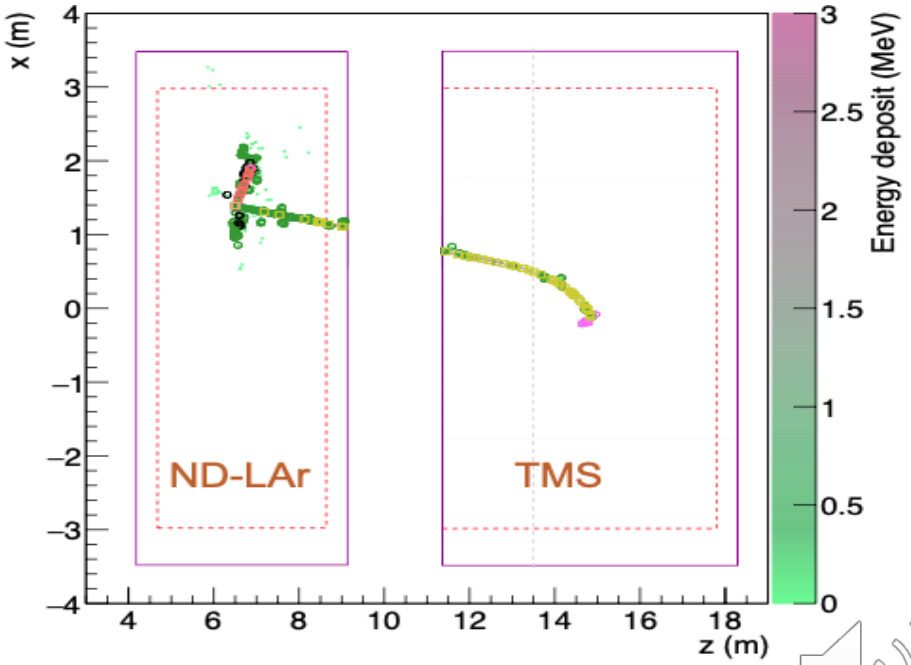
FD2-VD



# DUNE Design: Syst. Control

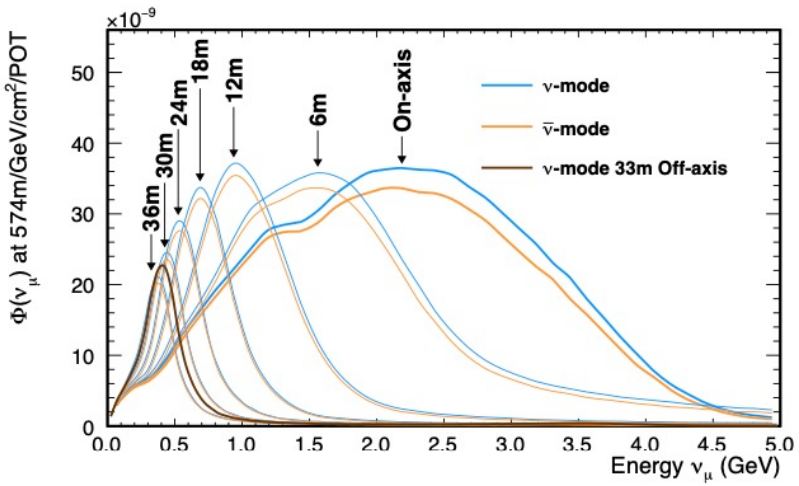
- DUNE Near Detector will measure the neutrino flux, neutrino interaction cross-section on Ar, and measure of LAr TPC response at few percent level.
- ND LAr is design similarly to FD with added modularity and pixelization to handle intense near source rate and sized to contain hadronic activity.
- Downstream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

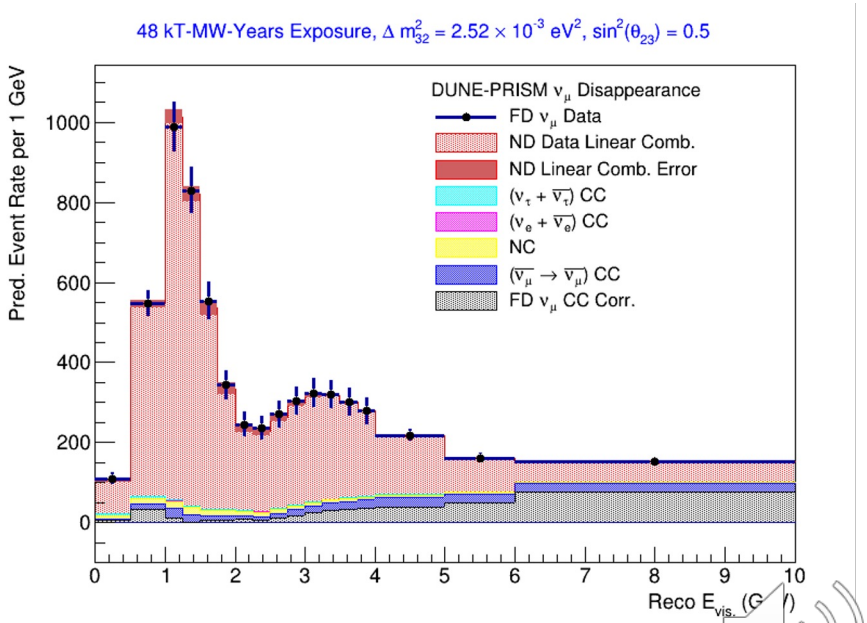


# DUNE Design: PRISM

- 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.



# DUNE Plans and Installation

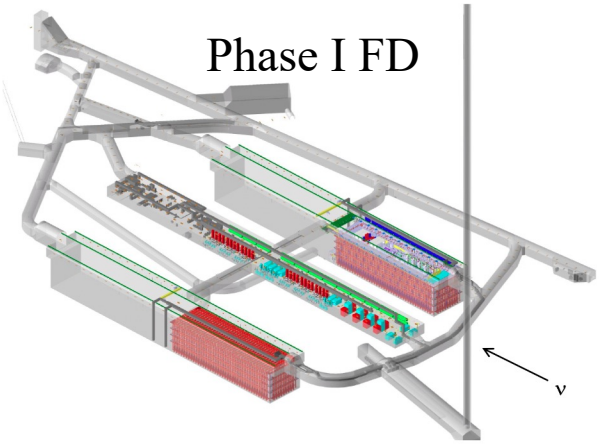
- DUNE construction is phased to provide continuous progress toward physics goals beginning this decade.

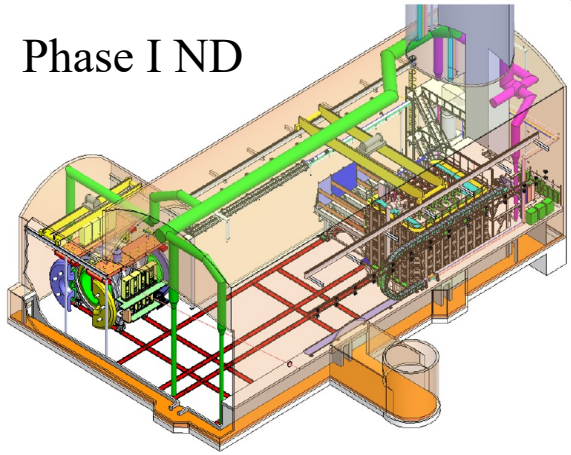
**Phase I**

- 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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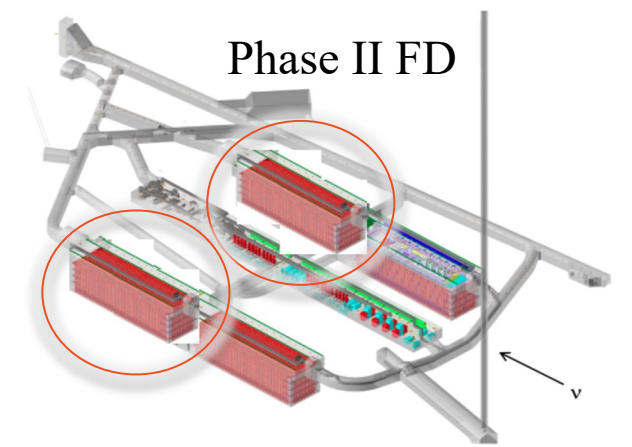
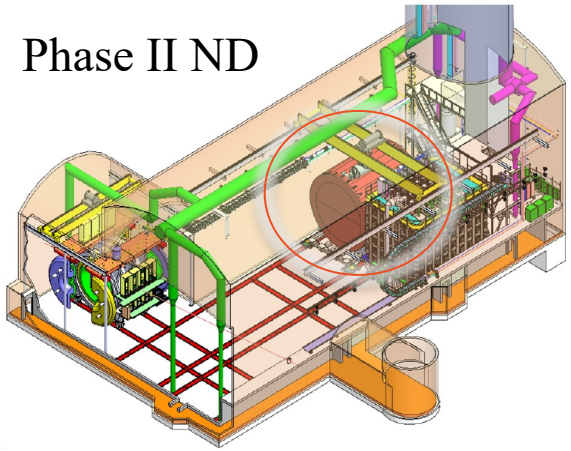
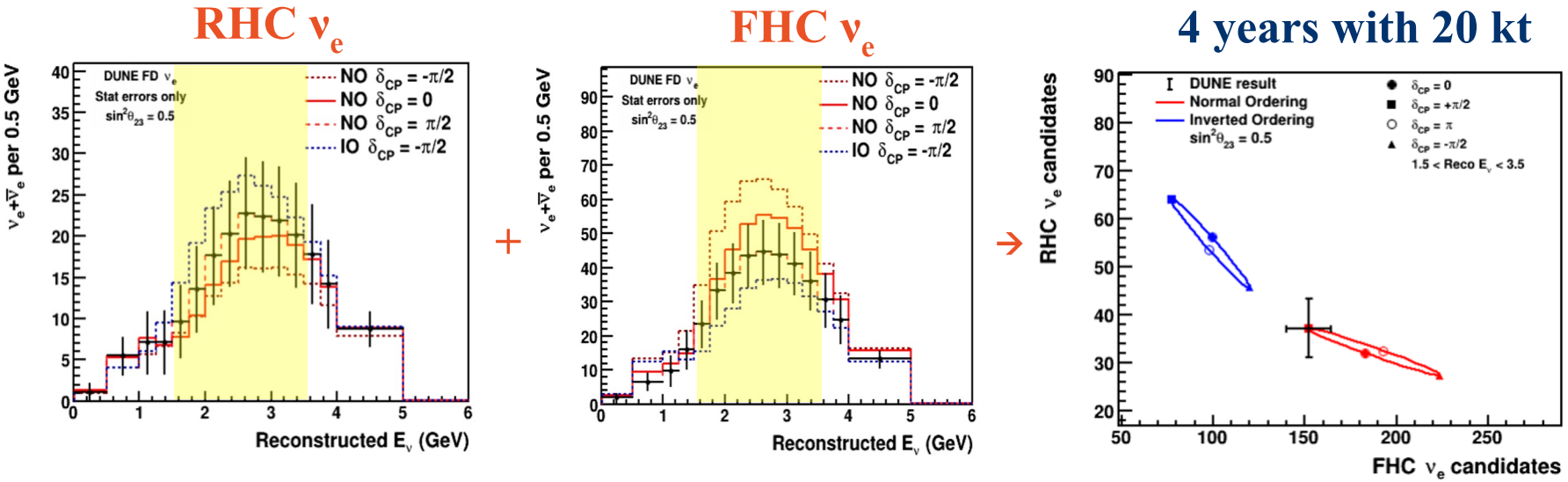


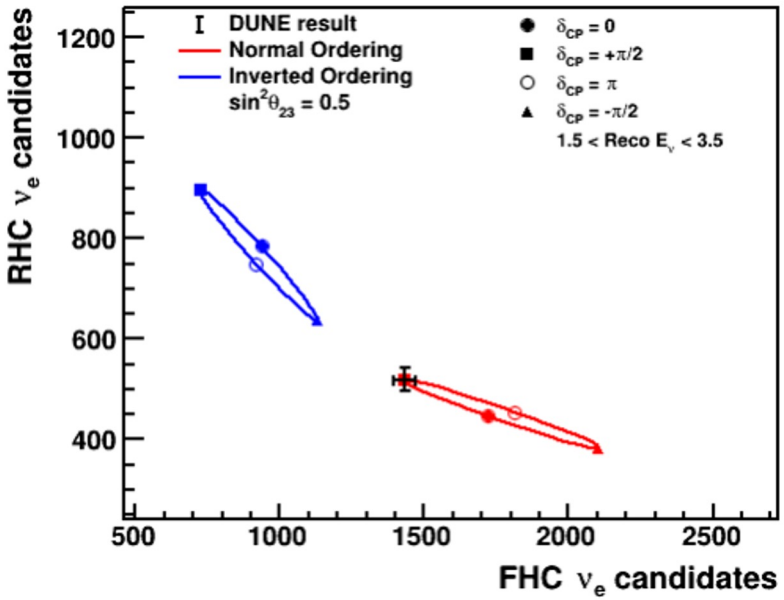
# DUNE Physics: Mass ordering

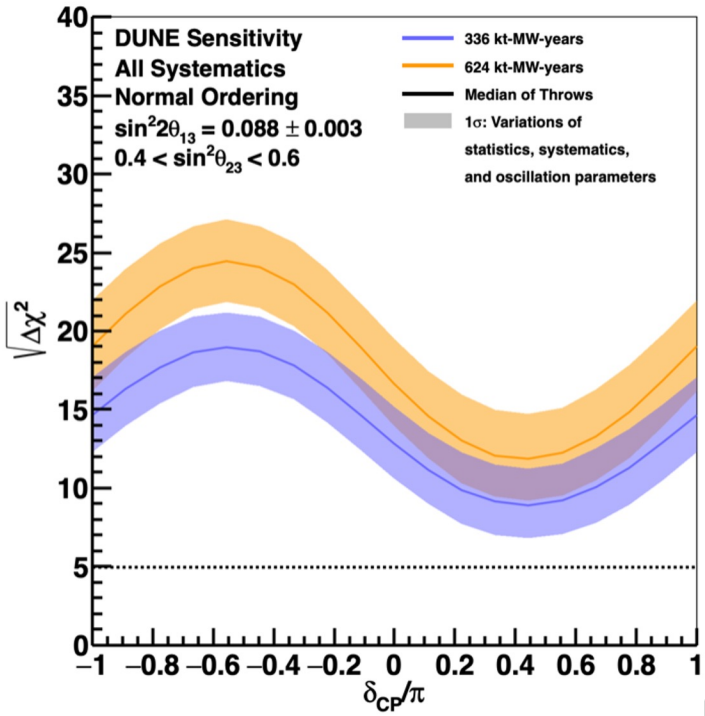
- DUNE has unprecedented and unrivaled ability to definitively resolve the mass ordering independent of other experiments.
- 4 years of running with 2 FD modules in most conservative beam ramp to 1.2 MW provides clear discovery potential



# DUNE Physics: Mass ordering

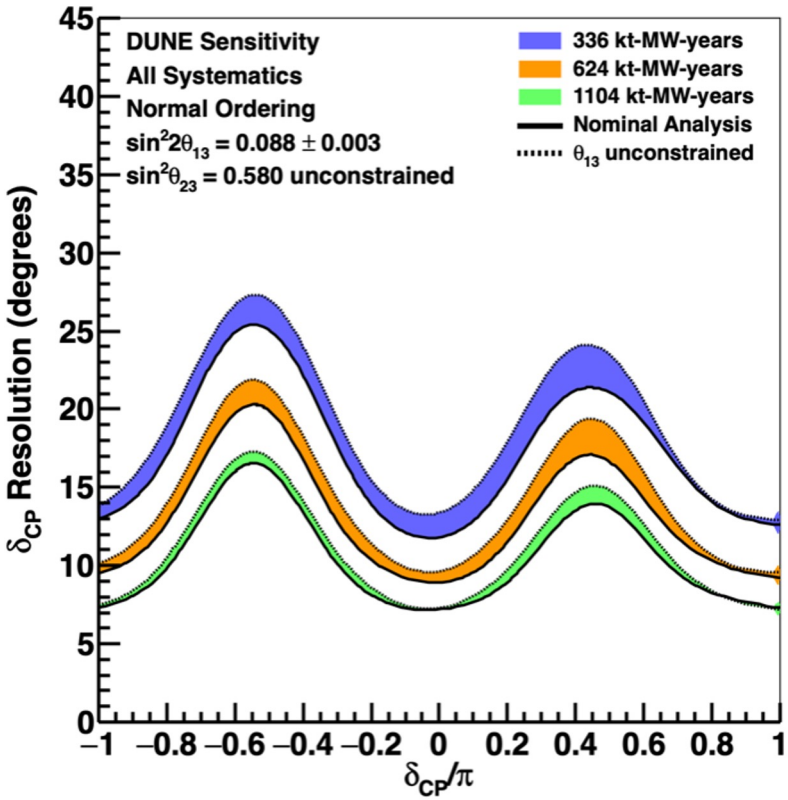
- Statistics from 6 years of full DUNE with 2.4 MW (800 kt-MW-yrs total exposure) exploits enormous NO vs IO differences.
- DUNE maintains ability to definitively resolve the mass ordering regardless of the values of other parameters

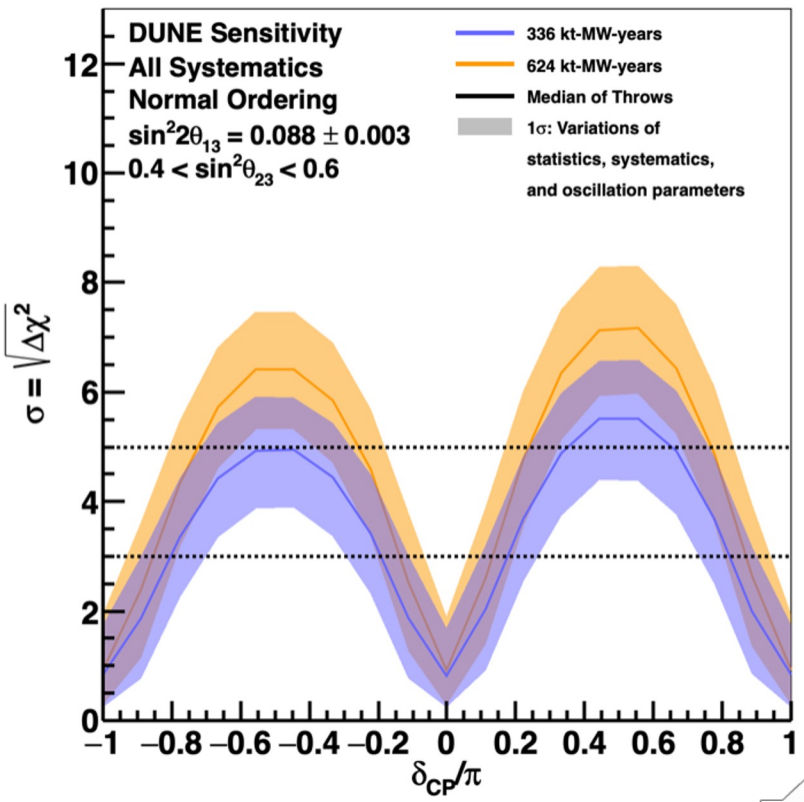


# DUNE Physics: CP violation

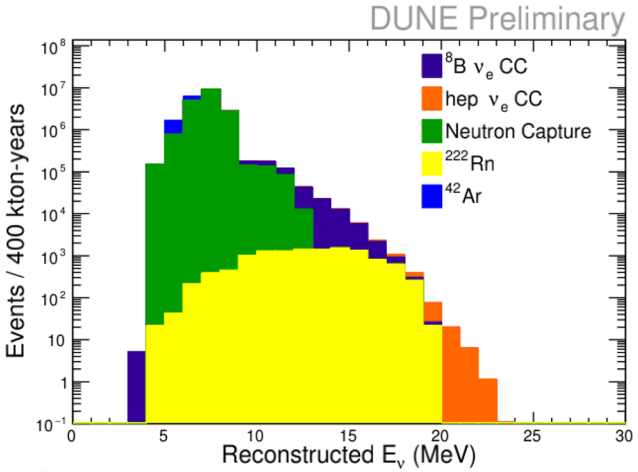
- 5σ discovery potential for CP violation over >50% of $\delta_{CP}$ values
- 7-16° resolution to $\delta_{CP}$, *with external input for only solar parameters.*

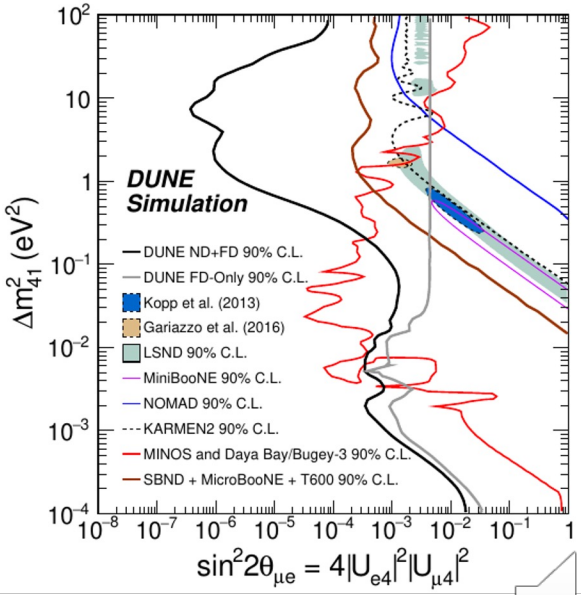


# Additional Neutrino Physics

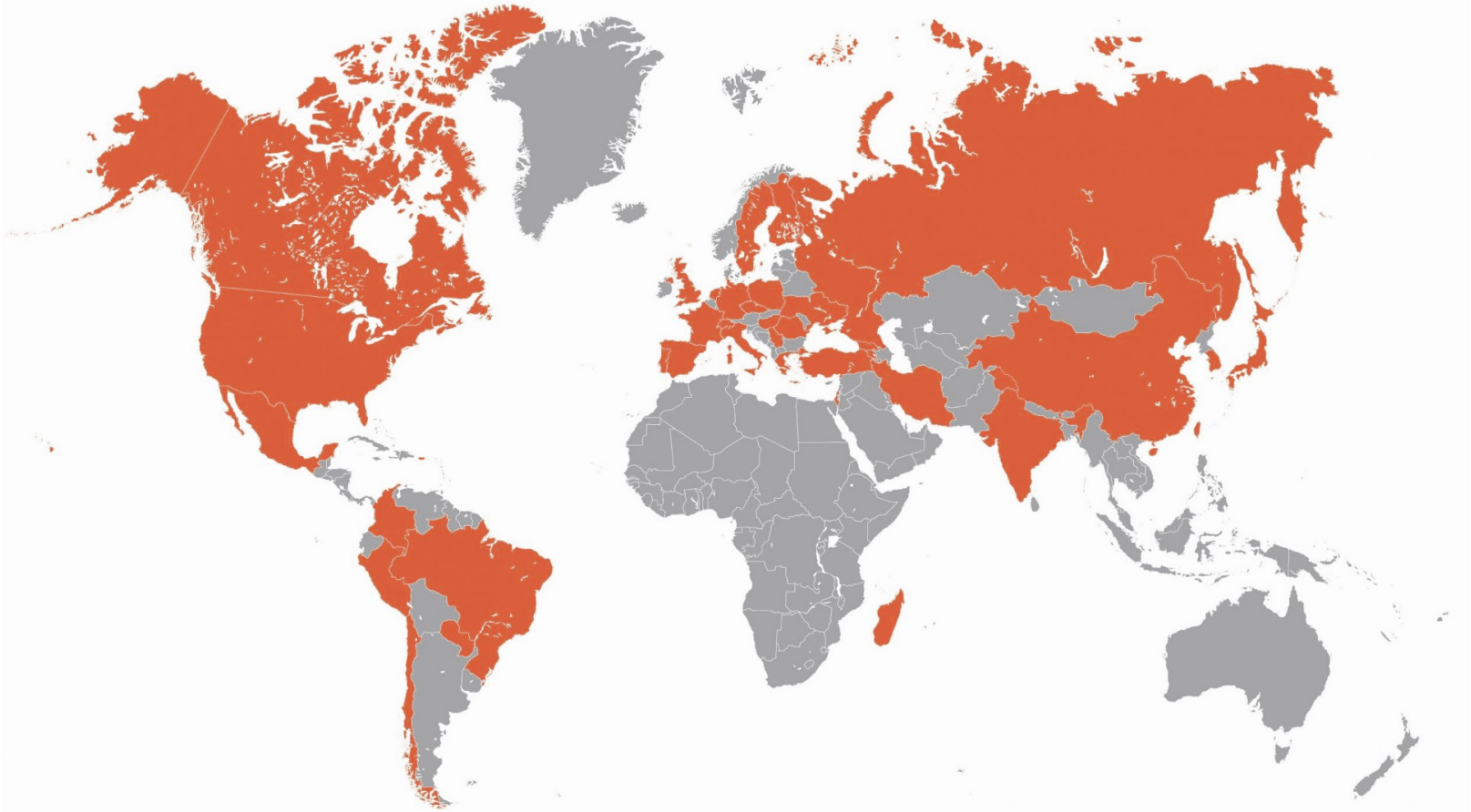
- DUNE will provide world-leading precision on $\Delta m^2_{32}$ and $\theta_{23}$, including octant allowing direct testing of PMNS unitarity.
- MeV-scale Physics
  - Galactic SNB will produce 1000s of events
  - Sensitivity to solar neutrinos in study.
- Searches for NSI and sterile neutrinos.



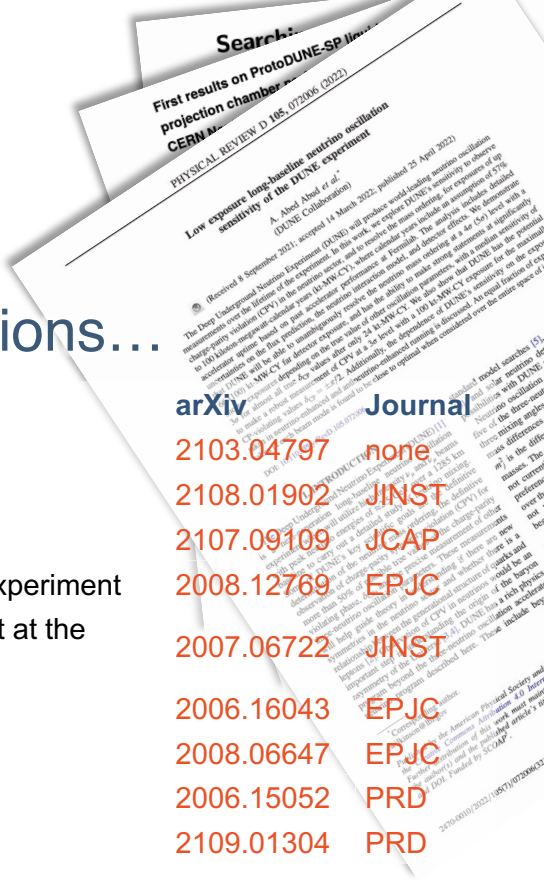



# DUNE Collaboration

- DUNE is an international collaboration of >1300 scientists and engineers from 37 countries + CERN (and counting)



# DUNE Publications



- DUNE collaborators have produced 29 publications…

| Title (Most Recent Full Collaborations Publications) | arXiv | Journal |
|---|---|---|
| Experiment Simulation Configurations Approximating DUNE TDR | 2103.04797 | none |
| Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC | 2108.01902 | JINST |
| Probing KDAR in the Sun with DUNE | 2107.09109 | JCAP |
| Prospects for Beyond the Standard Model Physics Searches at the Deep Underground Neutrino Experiment | 2008.12769 | EPJC |
| First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform | 2007.06722 | JINST |
| Long-baseline neutrino oscillation physics potential of the DUNE experiment | 2006.16043 | EPJC |
| Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment | 2008.06647 | EPJC |
| Neutrino interaction classification with a convolutional neural network in the DUNE far detector | 2006.15052 | PRD |
| Low exposure long-baseline neutrino oscillation sensitivity of the DUNE experiment | 2109.01304 | PRD |

- …with many others in progress

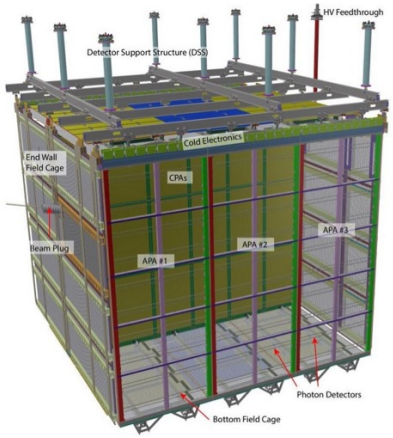
| Title (Nearing Publication) | arXiv |
|---|---|
| Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora | |
| Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a Convolutional Neural Network | 2203.17053 |
| Scintillation light detection in the 6-m drift-length ProtoDUNE Dual Phase liquid argon TPC | 2203.16134 |
| Identification and reconstruction of low-energy electrons in the ProtoDUNE-SP detector | |
| Deep-Learning-Based Kinematic Reconstruction for DUNE | |

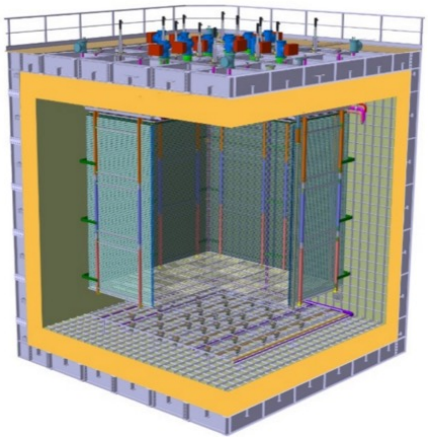
# DUNE @ Neutrino 2022

- Saturday June 4: *DUNE Neutrino Beam,* Rob Ainsworth, FNAL
- 22 Posters on DUNE Physics and Prototyping:
  - *DUNE ND-LAr Design & Status* - Roberto Mandujano, UCI
  - *Seasonal Variation of Cosmic Muon Rate with the ProtoDUNE-SP Detector* - Pantelis Melas, NKUA Greece
  - *The cold electronics of the DUNE Photon Detection System* - Esteban Cristaldo, Univ. MIB
  - *Demonstration of novel, ton-scale, single-phase LArTPCs with pixelated readout* - Stefano Roberto Soleti, LBNL
  - *Ionization Laser Calibration for the DUNE Time Projection Chamber - Eric Emerson Deck, LANL*
  - *Analysis of data taken with DUNE Vertical Drift demonstrator using LARDON - Laura Zambelli, LAPP/CNRS*
  - *Sensitivity study to Neutrino Mass Ordering and sterile neutrino model parameters with atmospheric neutrinos measurements at DUNE* - Tarak Thakore, Cincinnati
  - *Performance studies of ProtoDUNE Dual Phase with cosmic tracks* - Pablo Kunzé, LAPP
  - *Probing Sterile Neutrino Mixing with DUNE* - Mike Wallbank, Cincinnati
  - *Tau Neutrino Physics at DUNE* - Adam Aurisano, Cincinnati
  - *Studies of tau neutrino appearance at the DUNE Near Detector complex* - Soamasina Herilala Razafinime, Cincinnati
  - *Purity monitoring for ProtoDUNE-SP* - Wenjie Wu, UCI
  - *Tau Neutrinos and DIS Cross-Sections at DUNE's Far Detector* - Barbara Yaeggy, Cincinnati
  - *Calibration of Pixelated Liquid Argon Time Projection Chambers* - Lane Kahur, CSU
  - *Devel. of the Pandora LArTPC event reco. to optimise the sensitivity to CP violation at DUNE* - Isobel Mawby, Warwick
  - *Opt. of the Pandora pattern recognition for EM showers in neutrino interactions at DUNE* - Maria Brigida Brunetti, Warwick
  - *LBNF Neutrino Beam Focusing Uncertainties on DUNE and DUNE-PRISM Neutrino Fluxes* - Pierce Weatherly, Drexel
  - *The DUNE Neutrino PRISM* - Ciaran Hasnip , Oxford
  - *Neutrino interaction vertex-finding in a DUNE far-detector using Pandora deep-learning* - Andy Chappell, Warwick
  - *Low energy physics reach of DUNE* - Pablo Barham Alzás and Clara Cuesta, Ciemat
  - *Prototyping the DUNE Vertical Drift TPC* - Oliver Lantwin, CAPP
  - *Use of cosmic ray muons to measure drift charge attenuation in DUNE far detector* - Viktor Pec, FZU

# ProtoDUNE

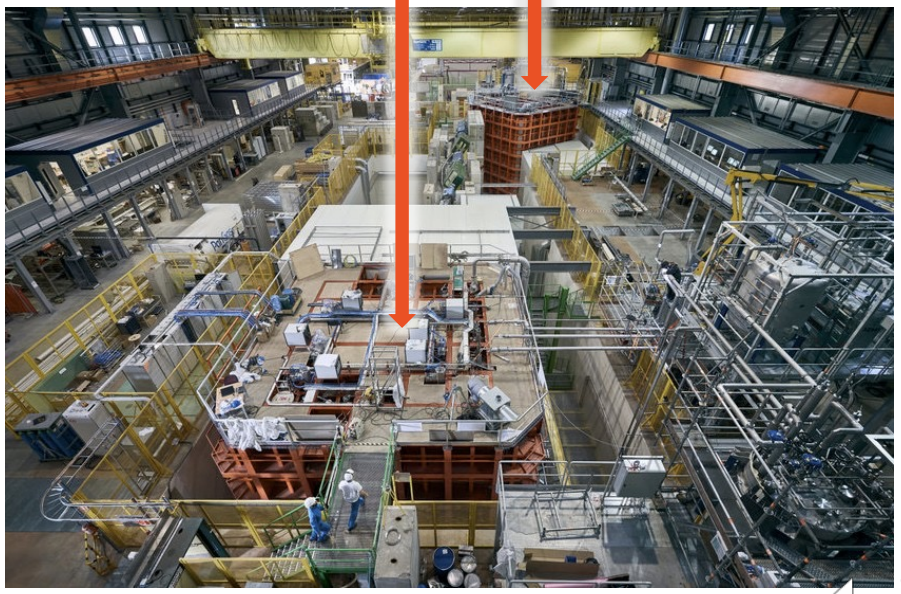
- Between 2018 and 2020 two (single and dual phase) 1-kt prototype LAr TPC detectors were operated in a charged test beam at CERN
- This platform provides a test of component installation, commissioning, analysis and performance.



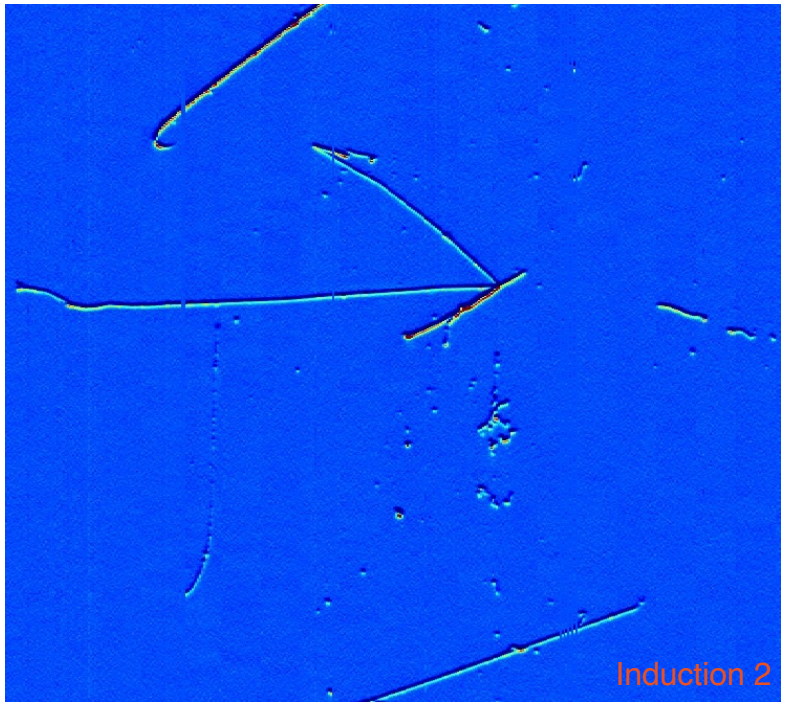
Single phase

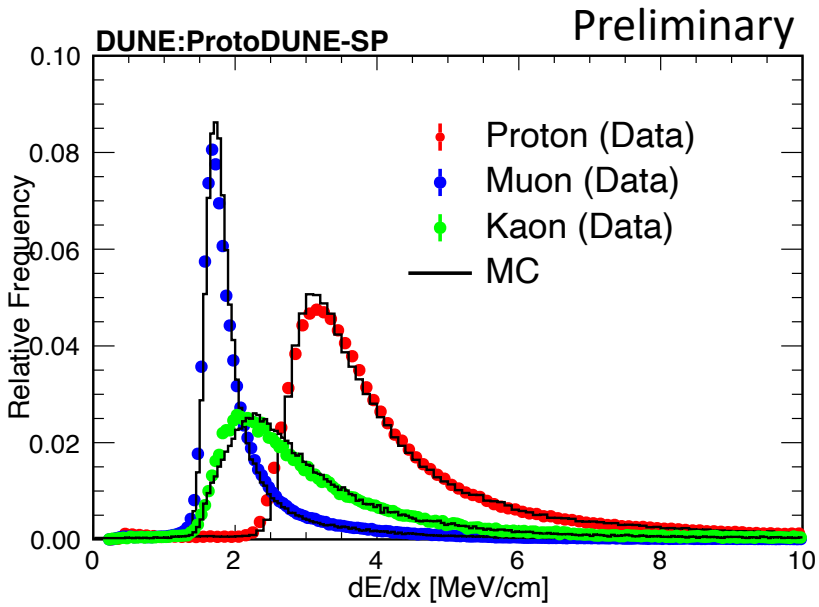
Dual Phase



# Initial ProtoDUNE Results

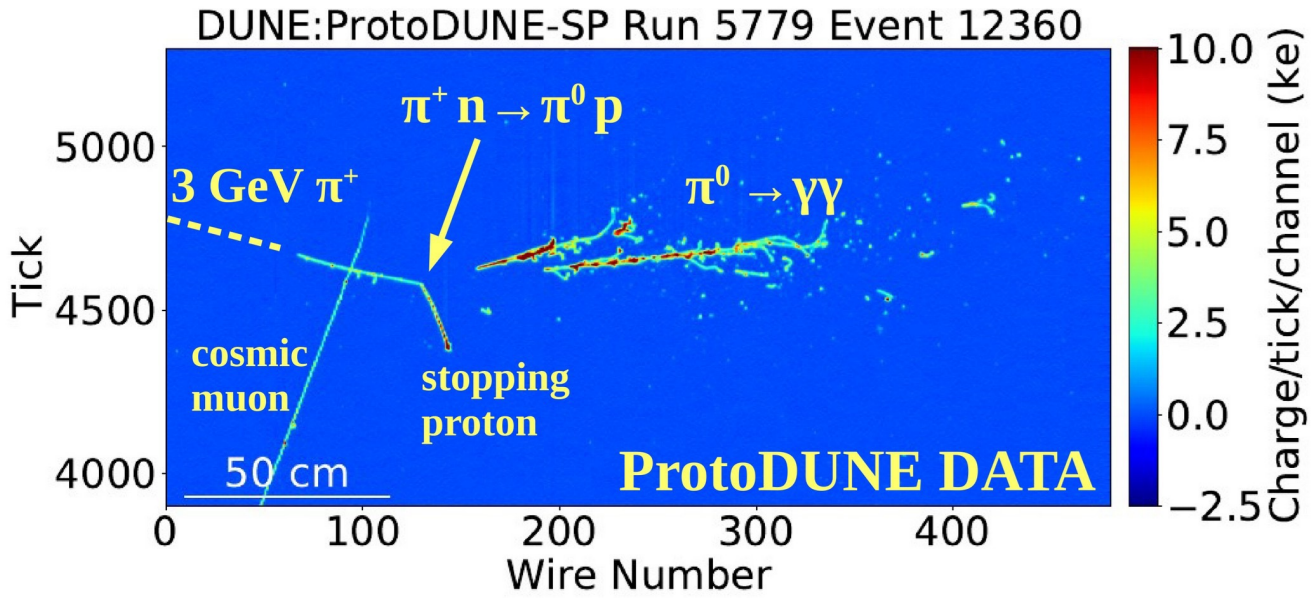
- First beam events: **low noise** on all three planes with S/N ratio > 10 in all cases.
- **Stable running** throughout operations, dE/dx distributions for protons, muons, and kaons shows good performance.
- ProtoDUNE shows the fundamental **DUNE technology works and will scale**!



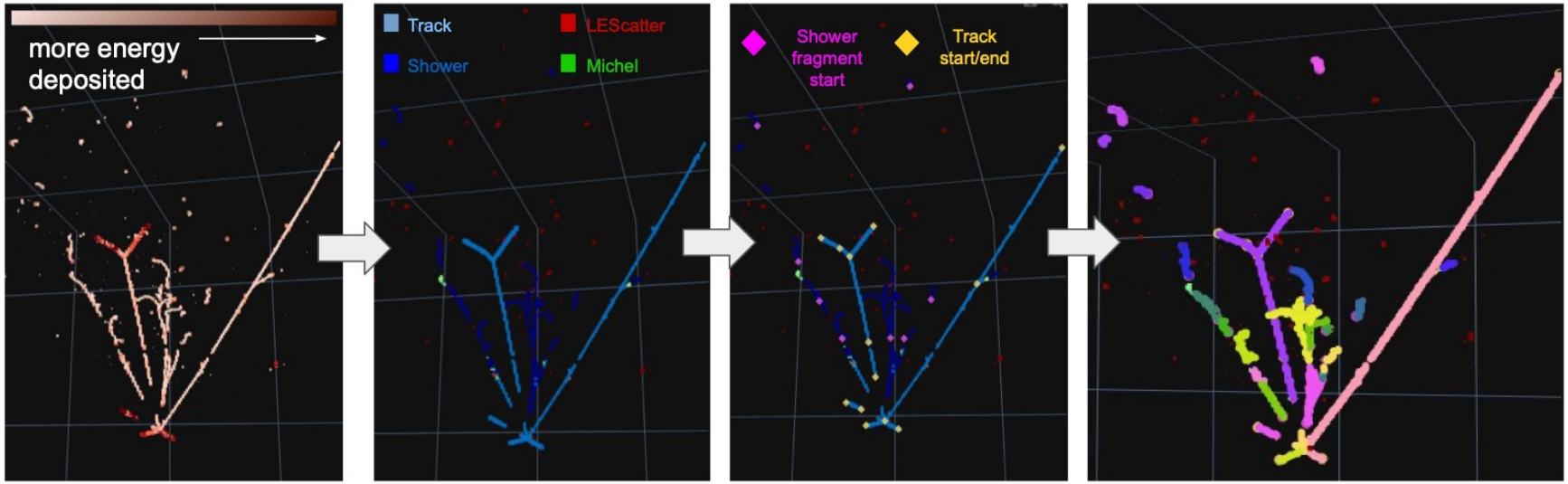
# Ongoing SP Studies

- Many more studies studies are in progress with publication of 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

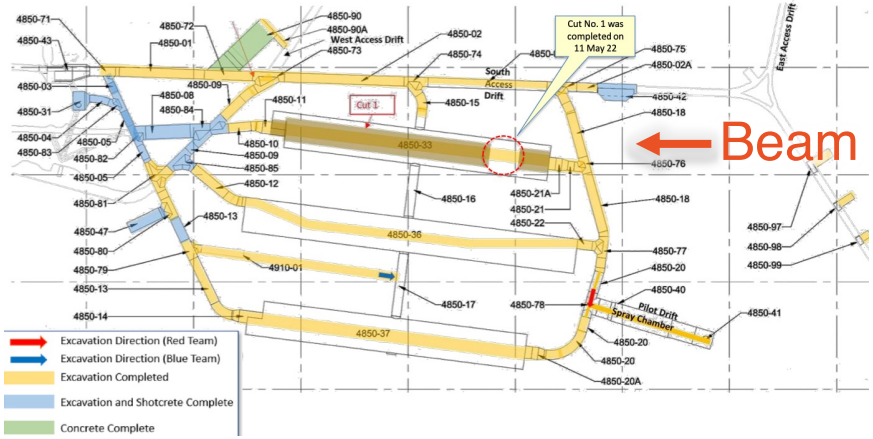


# Simulation/Reconstruction

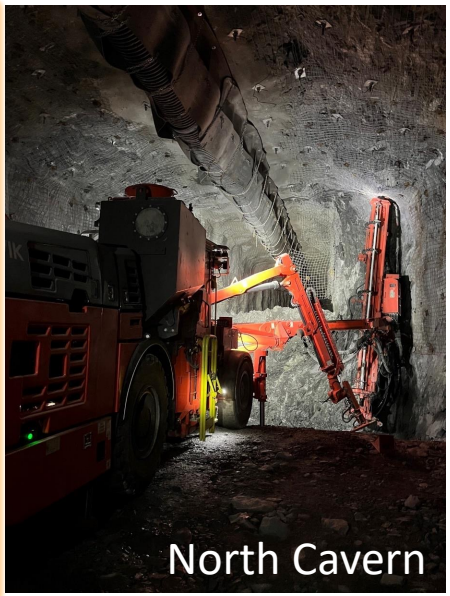
- Full simulations and reconstruction are advancing.
- Prototype detectors have provided invaluable opportunities for early testing of our tools.
- This is an example of simulation and ML based reco in the ND-LAr



# Far Site Progress

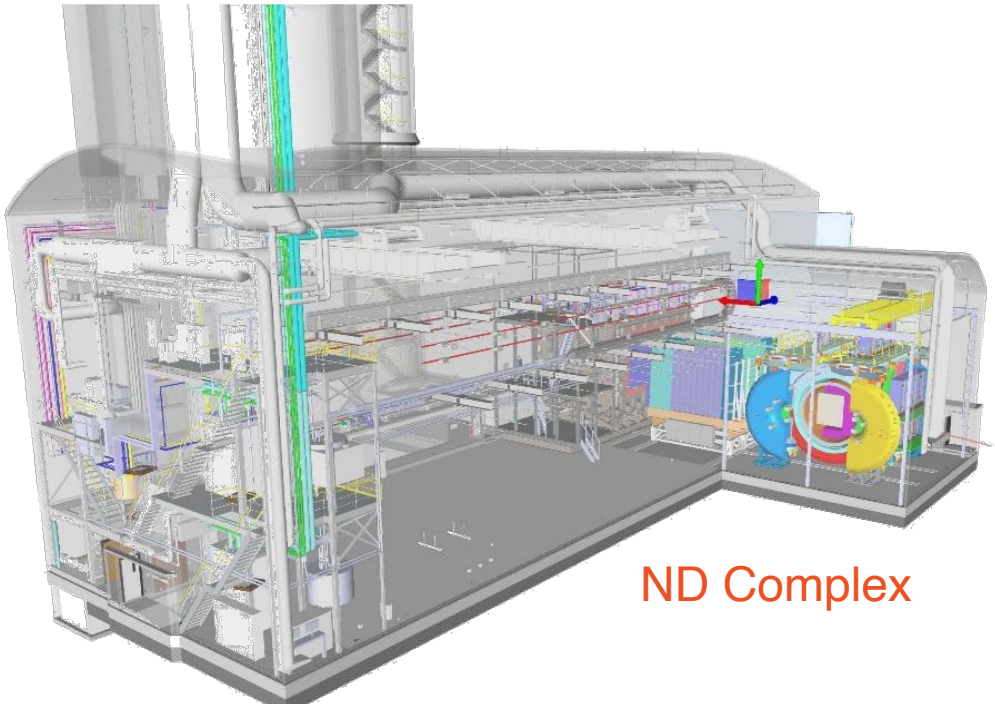



- Excavation work is in progress and advancing on schedule and on budget.

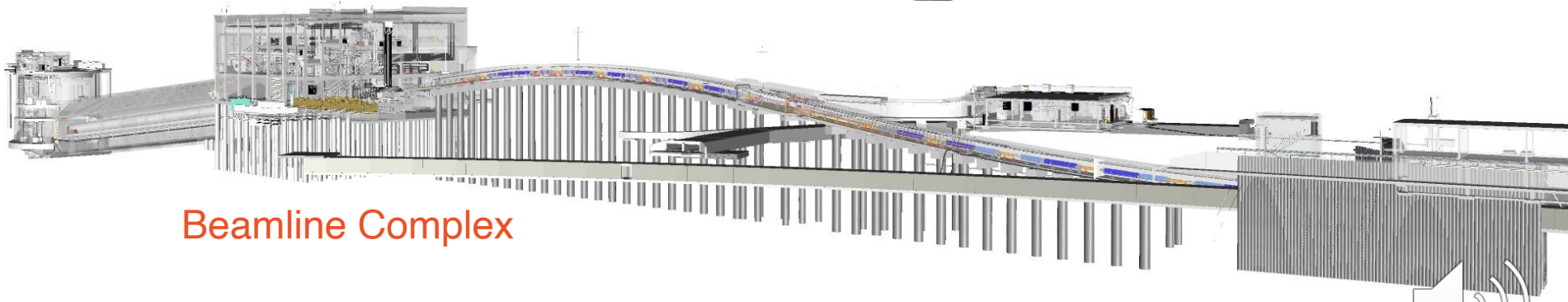




# Near Site Progress

- Beamline Complex and Near Detector Complex Design 100% complete.



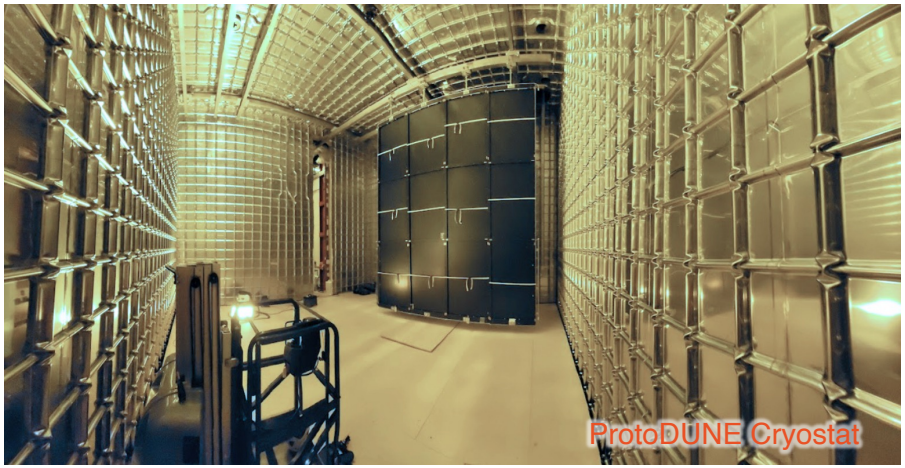
ND Complex

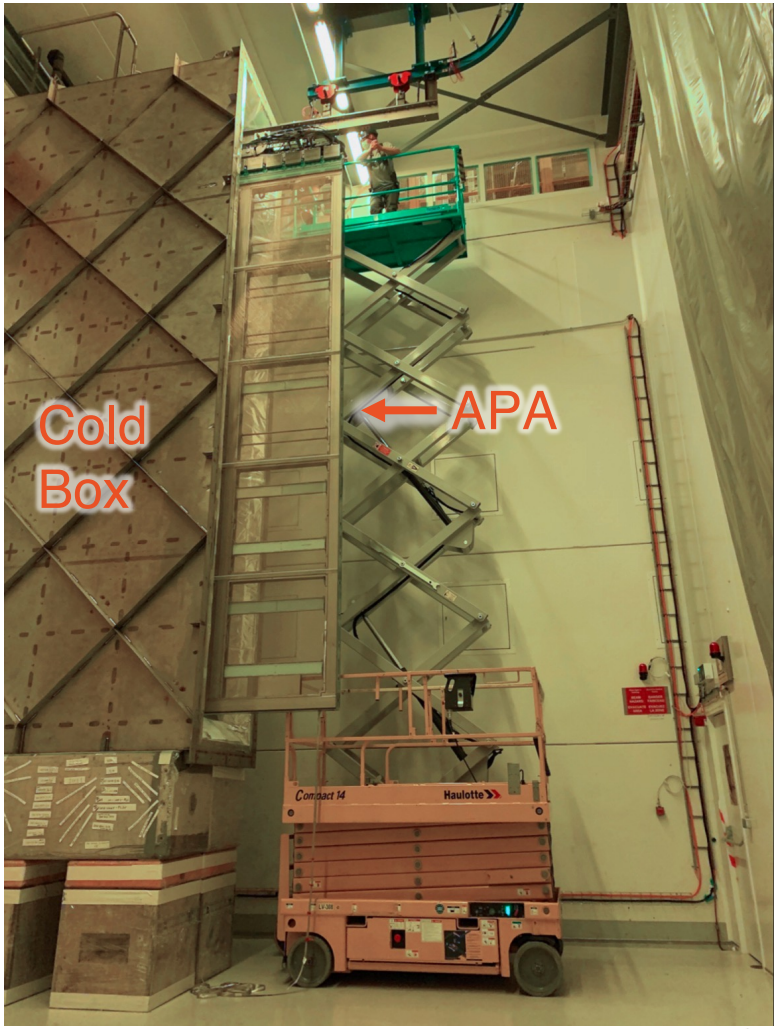


Beamline Complex

# Anode Plane Assembly Status

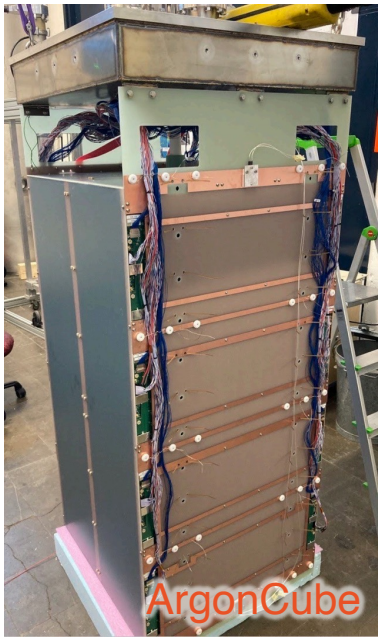
- Successful test of Module 0 HD APA in CERN cold box conducted in December 2021.
- Preparations are underway to install and operate the first FD1 production components in ProtoDUNE-II during 2022.
- VD concept is advancing rapidly.

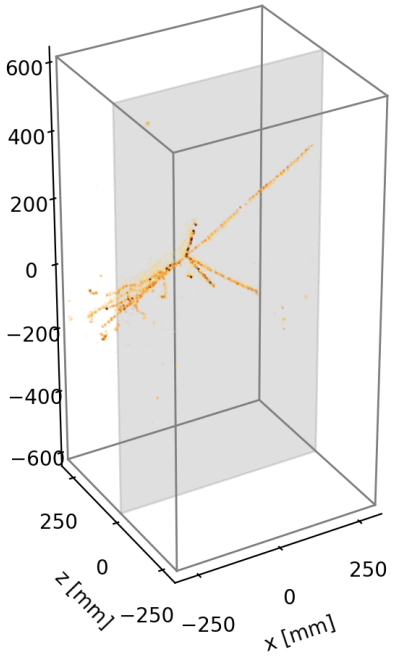


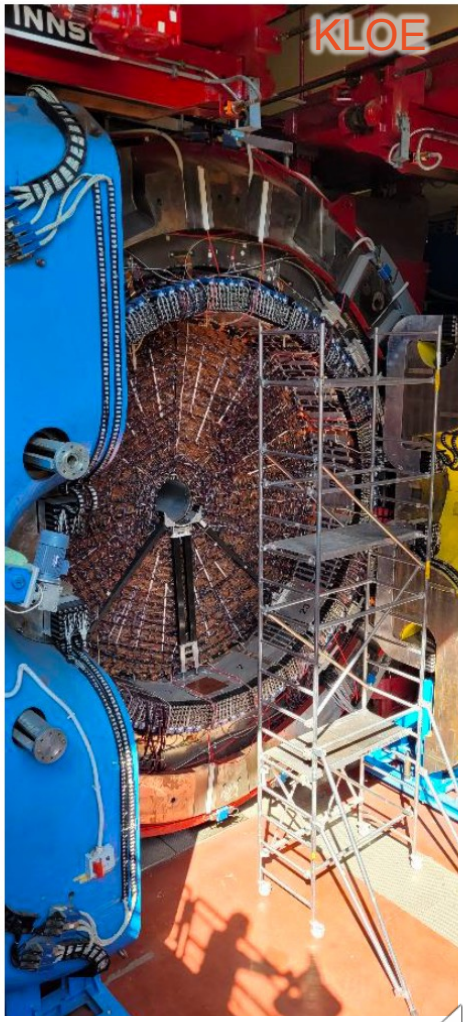
# Near Detector Progress

- ArgonCube 2x2 Module 1 operated at Bern in Feb. Preparation for NuMI test underway.
- Dismounting of KLOE for SAND has begun.
- ND-Gar FTBF teststand shipping in July

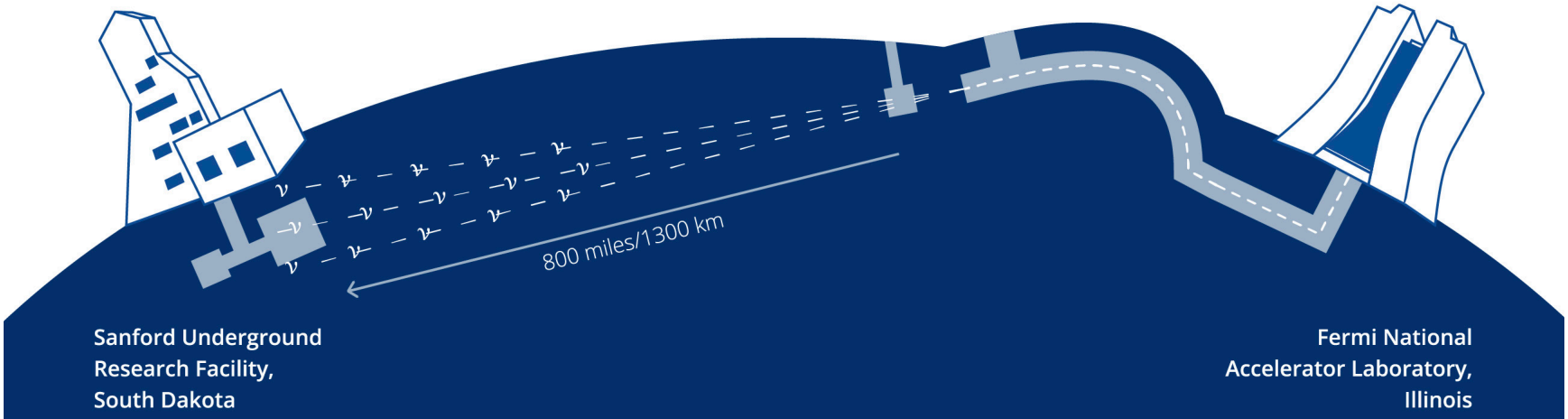






# Conclusions




- 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.
- DUNE detector development, civil infrastructure, simulation/reco, and physics are rapidly advancing, and physics should begin this decade.
- The collaboration is active in planning upgrades to achieve full scope in the 2030's.

# Thank you for your attention.

*DUNE Collaboration Meeting, Fermilab, May 2022*