DUNE:
goals, status, progress, and plans

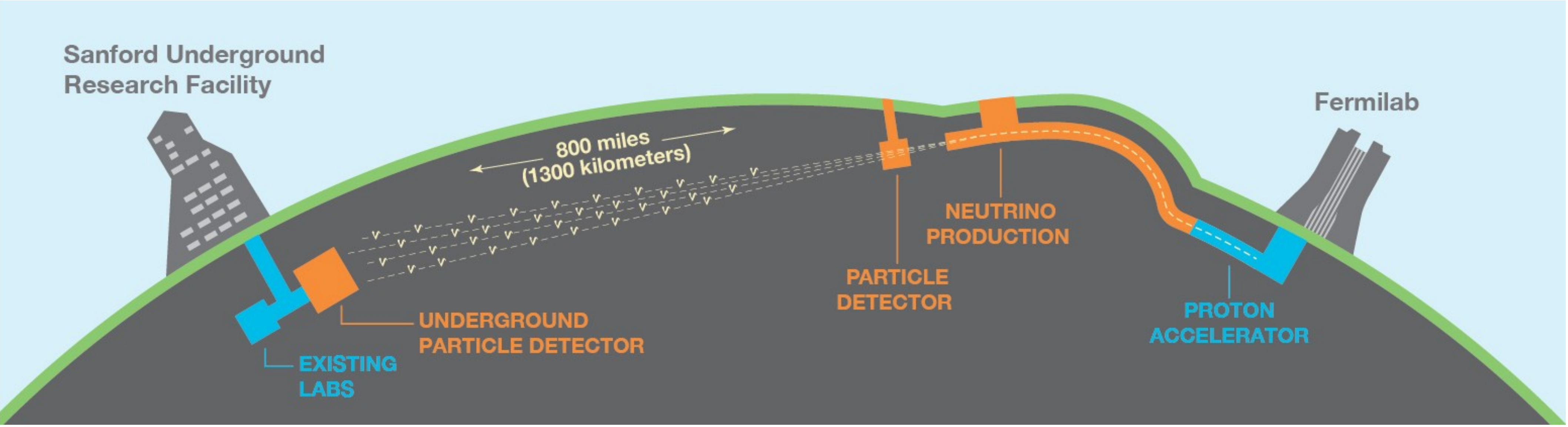
Chris Marshall, University of Rochester

55th Fermilab Users' Meeting

16 June, 2022

UNIVERSITY of ROCHESTER

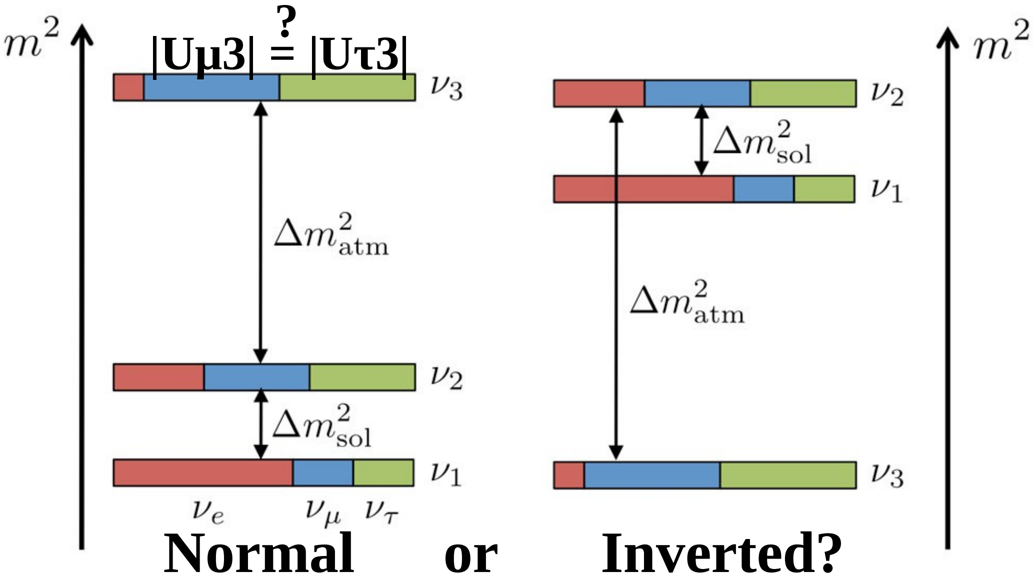
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- Long-baseline neutrino oscillations, including discovery sensitivity to CP violation and neutrino mass ordering
- MeV-scale neutrino physics, including supernova burst astrophysics and solar neutrinos
- Broad program of physics searches beyond the Standard Model, including baryon number violation, non-standard oscillations, dark matter

DUNE can address major open questions in neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



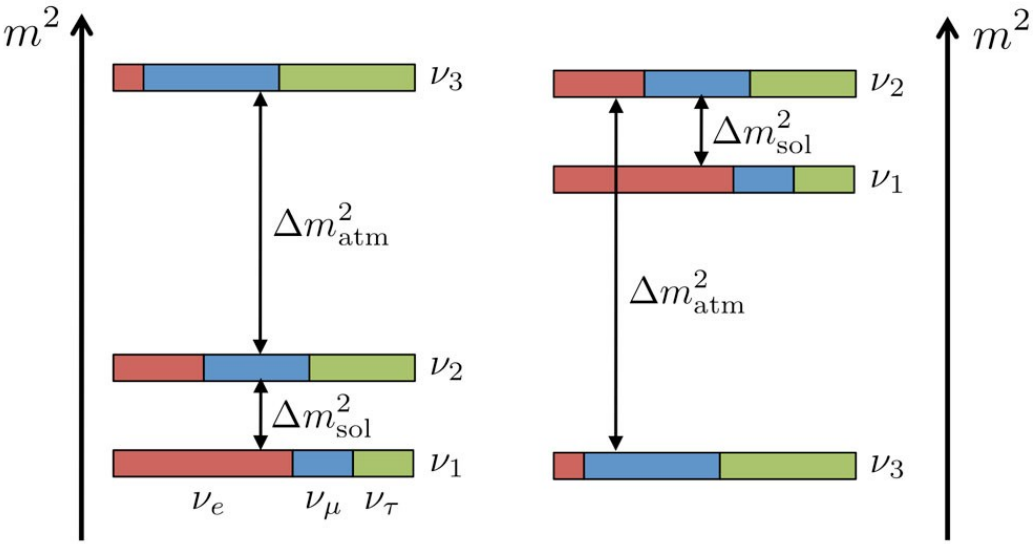
- Are the ν_e-rich mass states ν_1 and ν_2 heavier or lighter than ν_3? (Is the mass ordering normal or inverted?)
- Is CP symmetry violated by neutrinos? (Is $\sin\delta_{CP} \neq 0$?)
- Is $|U_{\mu 3}| = |U_{\tau 3}|$? (Is $\sin^2\theta_{23} = 0.5$?) If not, which is larger?

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$\sin\delta_{CP} \neq 0$?

DUNE will make precision measurements of ν oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\text{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

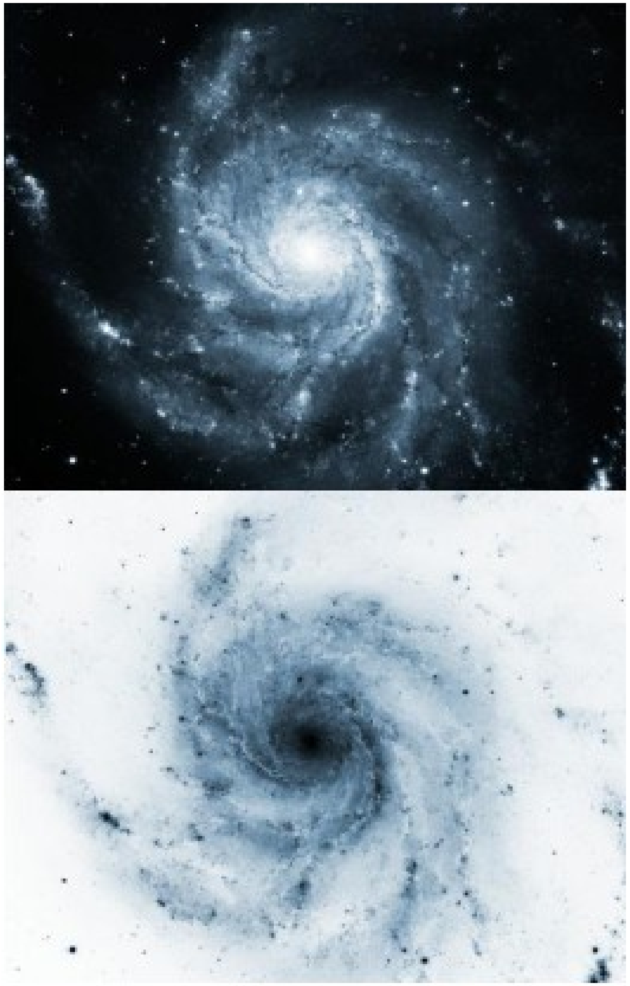


- What is the magnitude and sign of Δm^2_{32}?
- What is the value of δ_{CP}?
- What are the values of θ_{13} and θ_{23}?
- Is this three-flavor νSM picture correct?

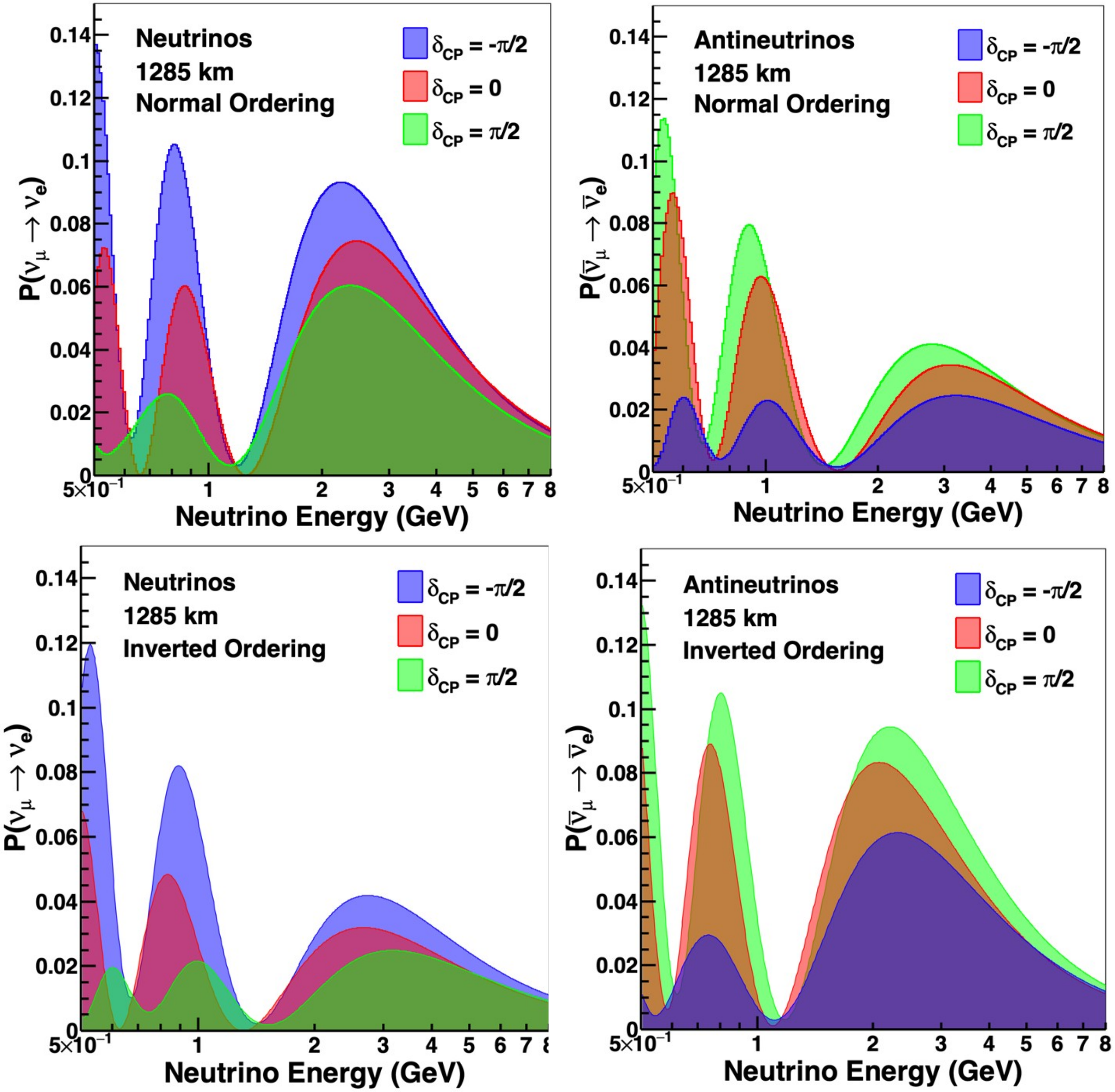
$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Open questions are connected to theoretical questions

- What is the origin of neutrino mixing? Is there an underlying flavor symmetry, and how is it broken?
- What is the origin of the neutrino masses? Why are the neutrinos so light?
- Is leptogenesis a viable explanation of the baryon asymmetry of the Universe?



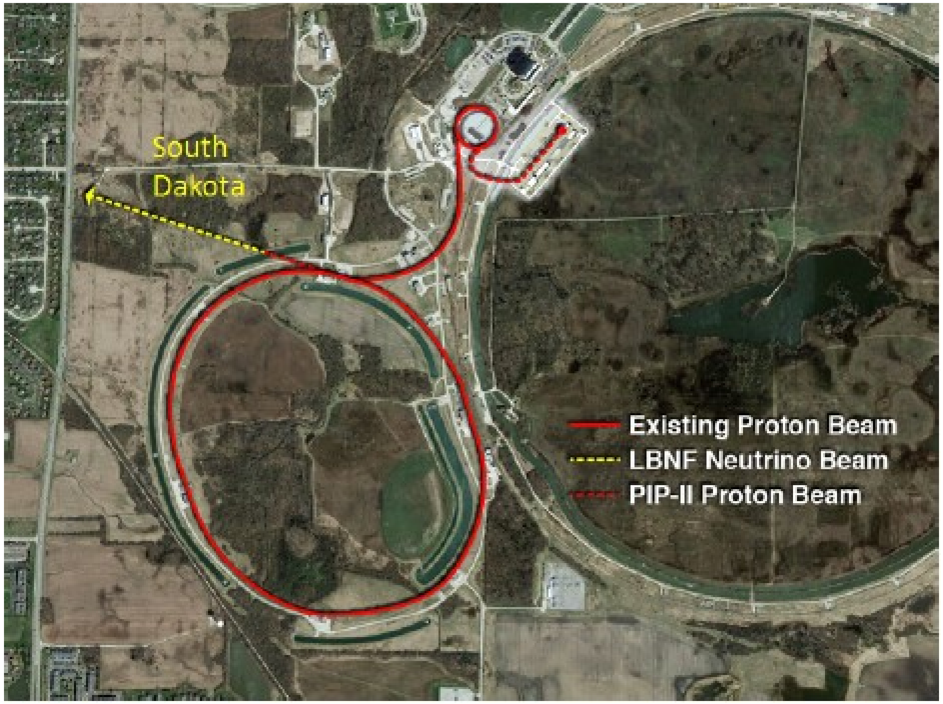
DUNE measures neutrino oscillations vs. energy directly

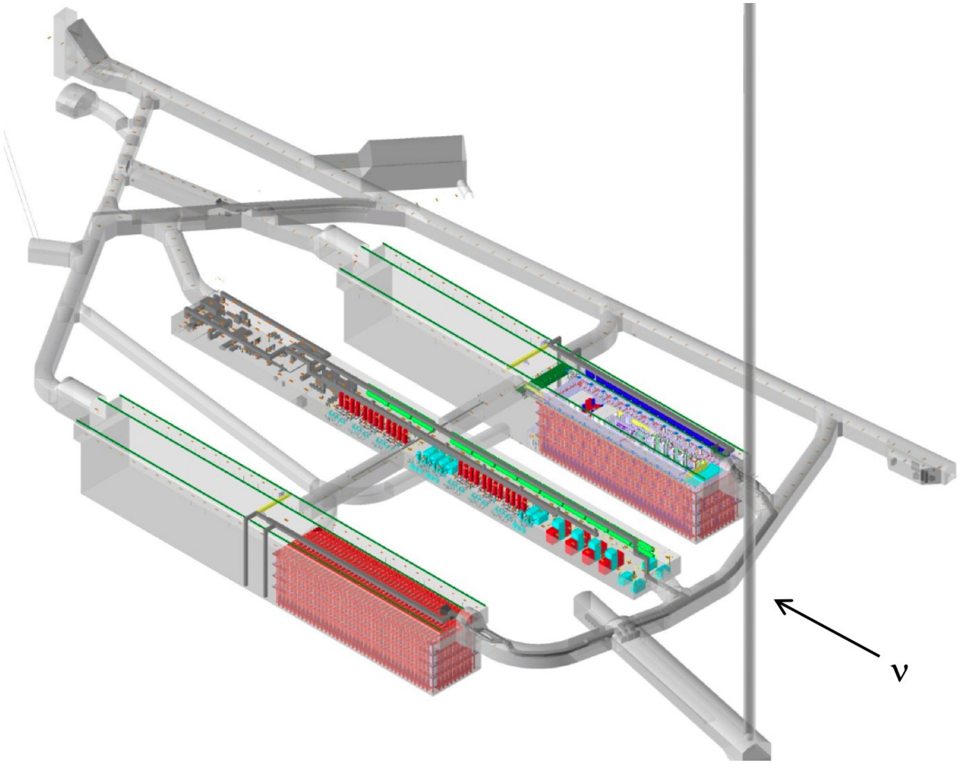


- DUNE will measure neutrino oscillations with unprecedented statistics as a function of neutrino energy
  - Long baseline → resolves degeneracy between CP phase and mass ordering effects
  - Wideband beam → cover a full oscillation period
- Enables measurement of θ_{23}, θ_{13}, Δm^2_{32}, δ_{CP} in a single experiment
- Physics requirements:
  - Very high statistics
  - Excellent flavor and energy resolution
  - Low backgrounds
  - Control of systematics at the level of the statistical uncertainty

LBNF: world-class neutrino beam and underground facilities

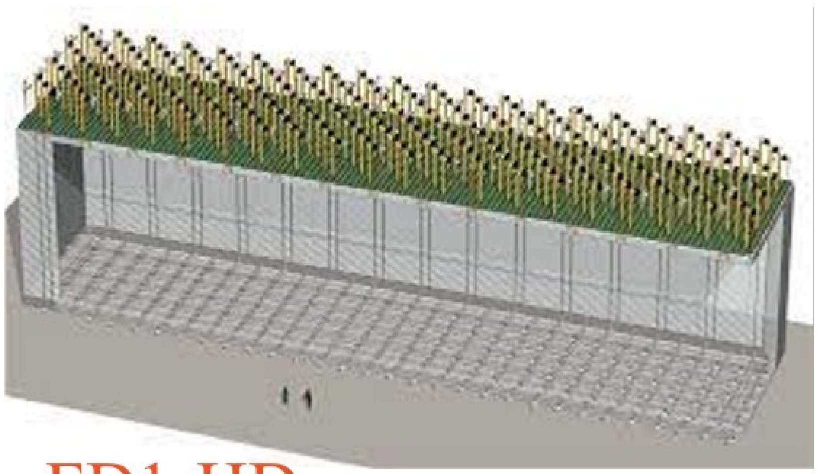
- Most intense neutrino beam in the world will provide up to 1.2 MW intensity, designed to allow for future upgrade to 2.4 MW
- Deep underground cavern at SURF to accommodate four 17-kiloton LArTPC Far Detector modules, and underground near site



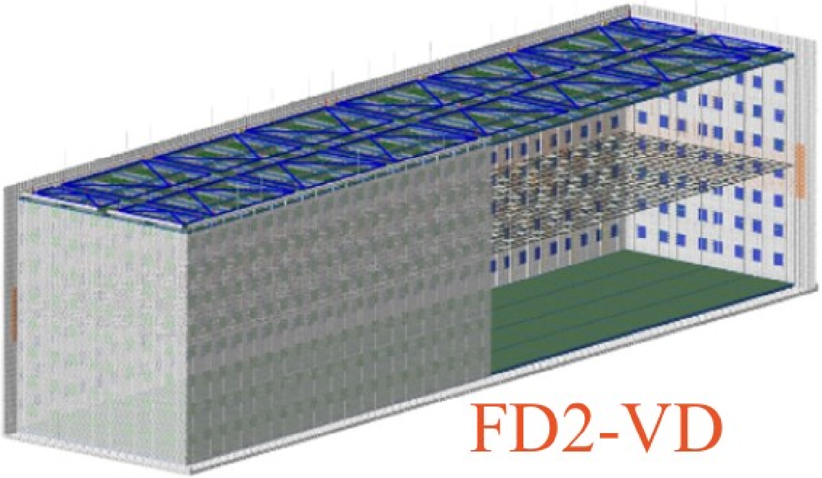


UNIVERSITY of ROCHESTER
DUNE

Two FD LArTPC designs: horizontal and vertical drift



FD1-HD

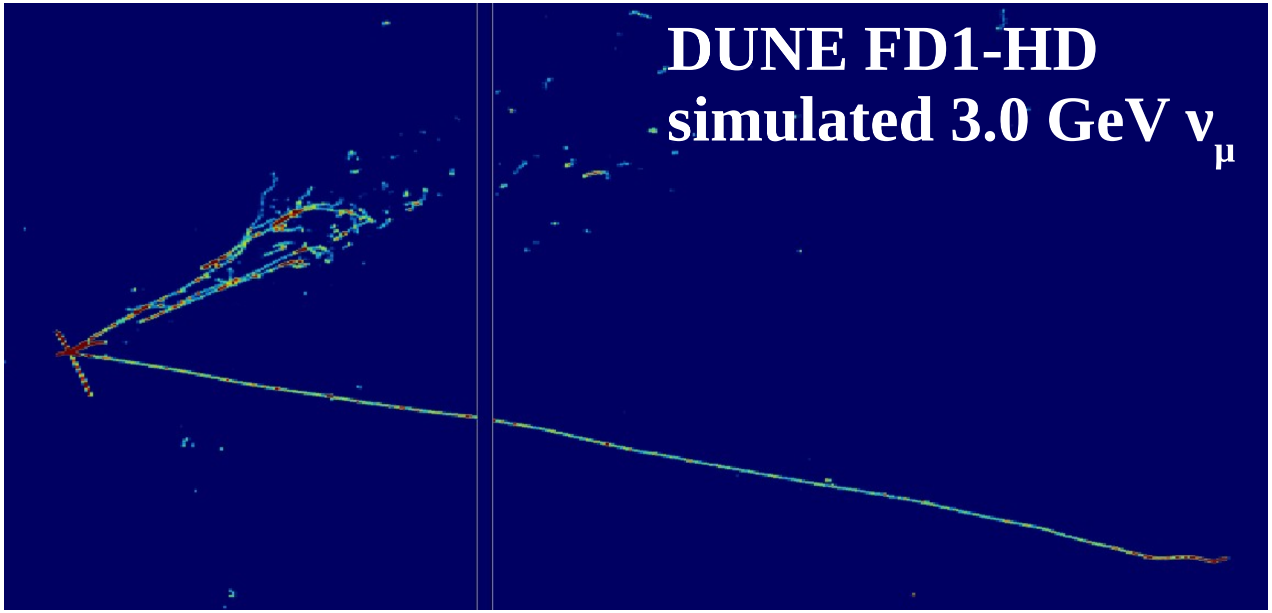


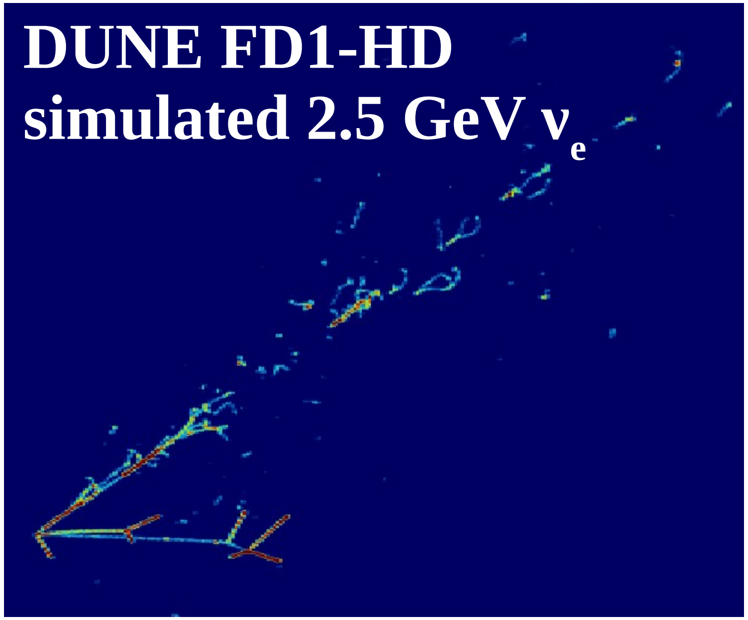
FD2-VD

- DUNE FD modules will have at least 10kt fiducial
- First module will use horizontal drift technology JINST 15 T08010 (2020)
- Second module will use vertical drift technology, incorporating many features from the dual phase prototype
  - TDR expected in early 2023

LArTPC provides excellent flavor and energy reconstruction

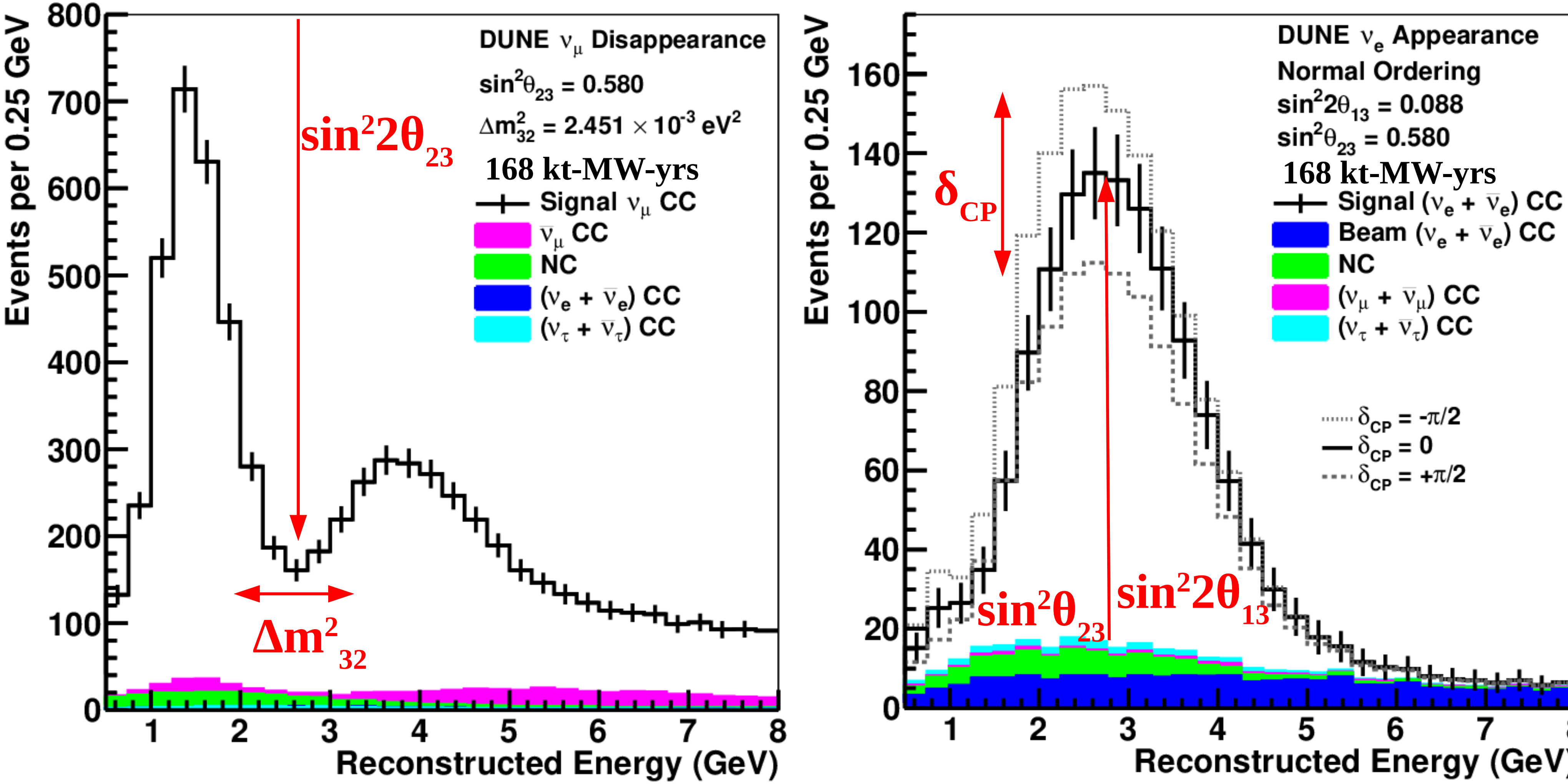
- Exquisite imaging of LArTPC enables very clean separation of muons and electrons
- Ability to directly measure hadron energies with very low thresholds → excellent neutrino energy resolution





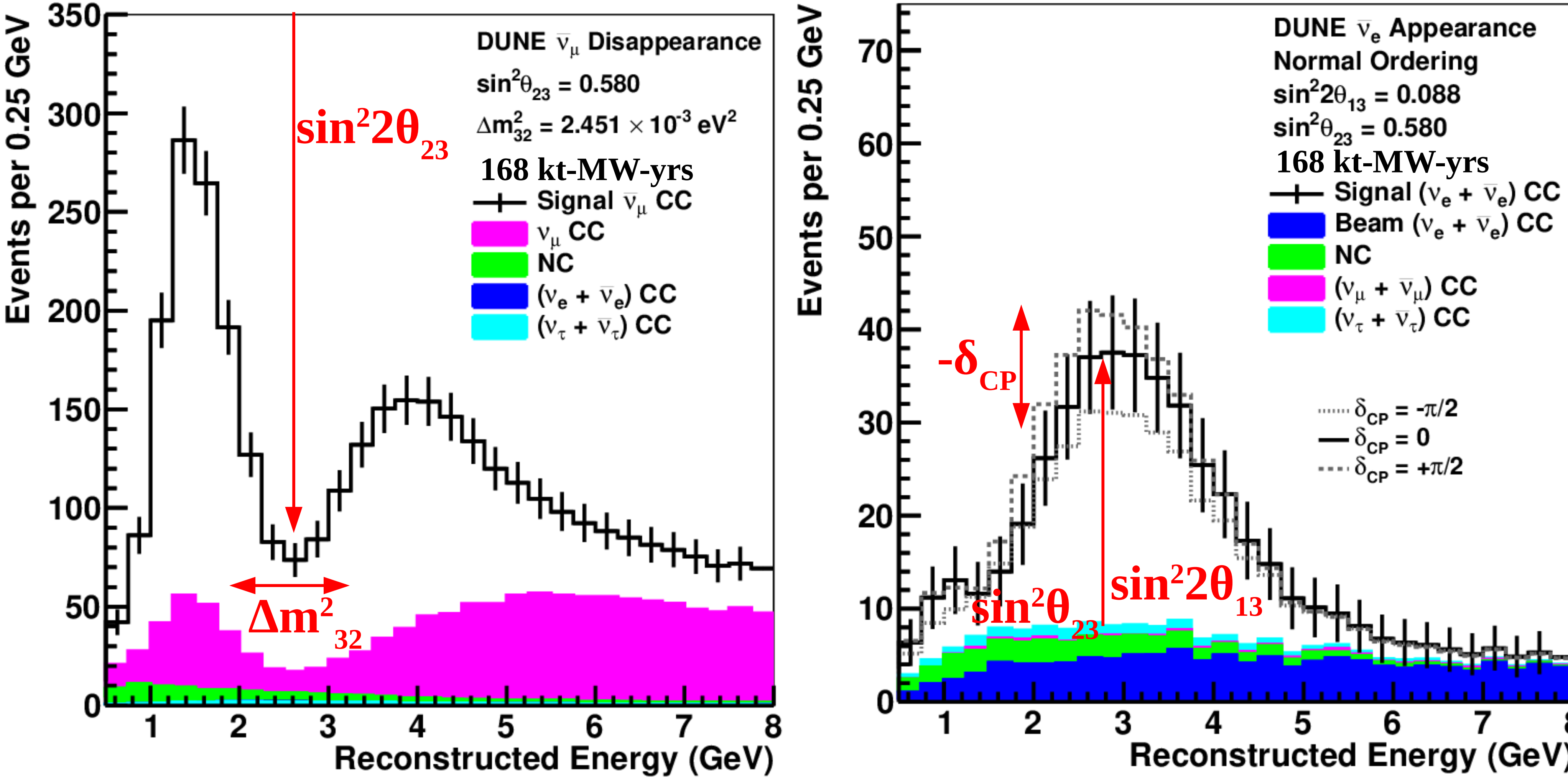
Oscillations affect FD E_{rec} spectra

FHC = neutrinos



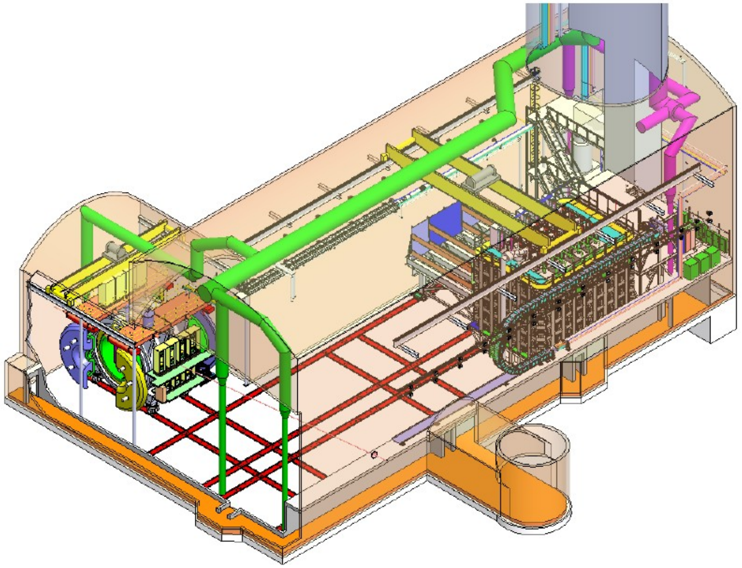
Oscillations affect FD E_{rec} spectra

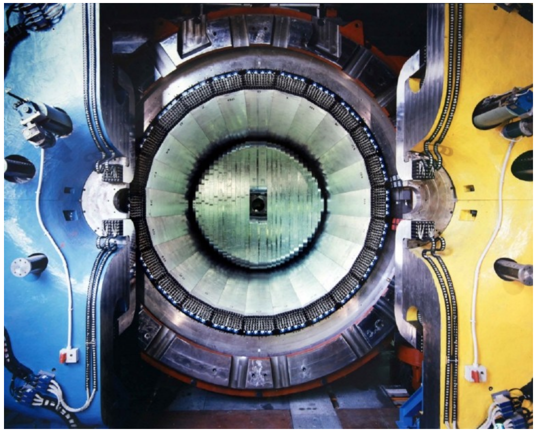
RHC = antineutrinos

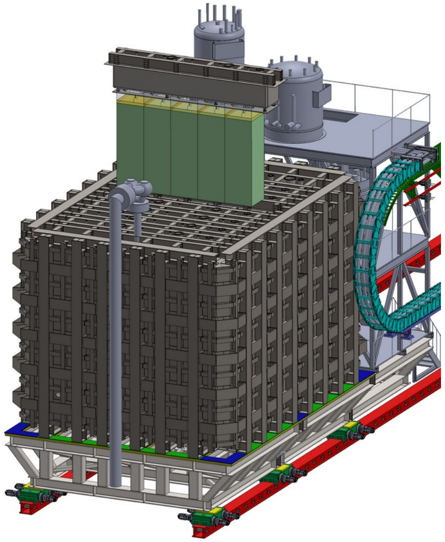


Near Detector at Fermilab constrains critical systematics

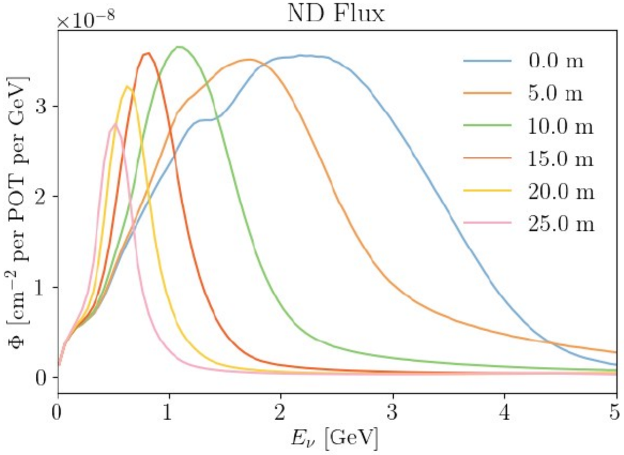
- ND-LAr uses the same technology as the FD → measure ν-Ar interactions in the same way
- TMS measures muons that exit ND-LAr
- SAND measures neutrino interactions on various targets and monitors the neutrino beam stability



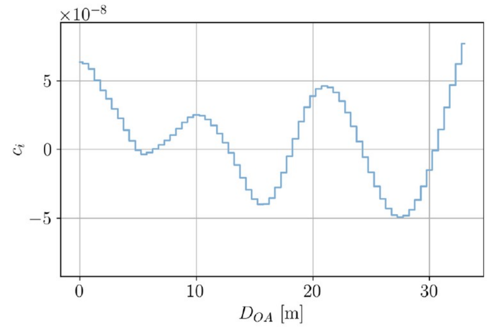




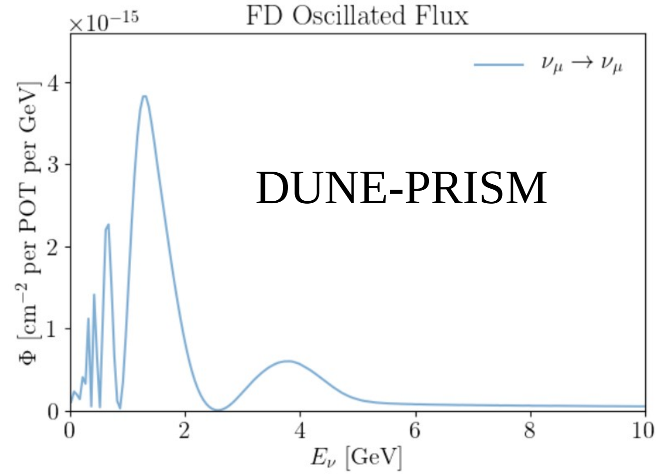
PRISM plays a critical role in enabling DUNE's precision

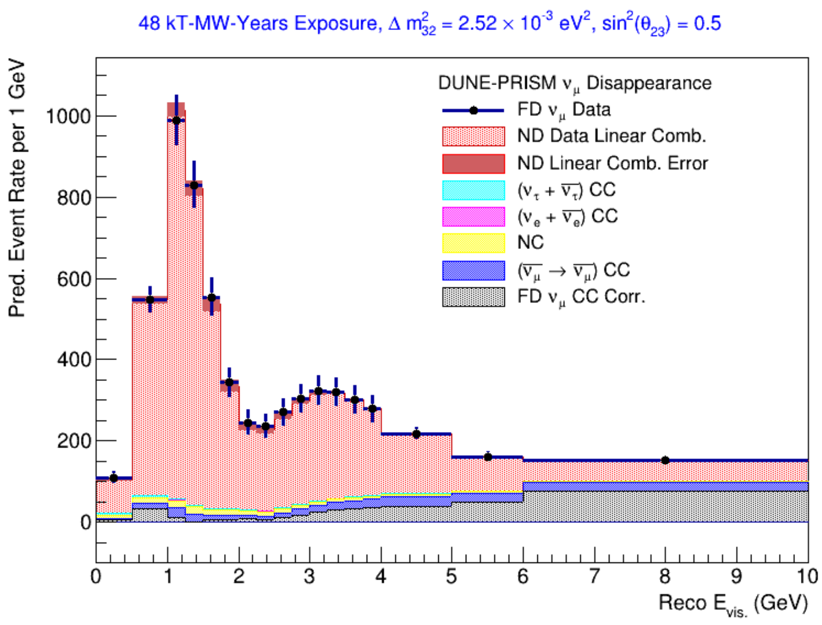


x



→



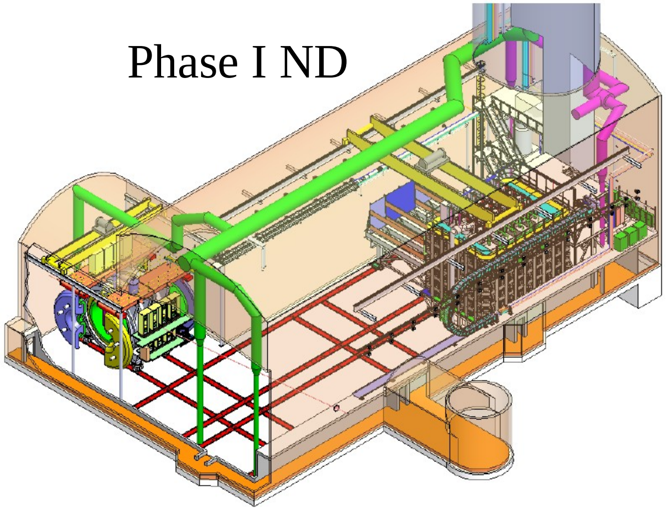


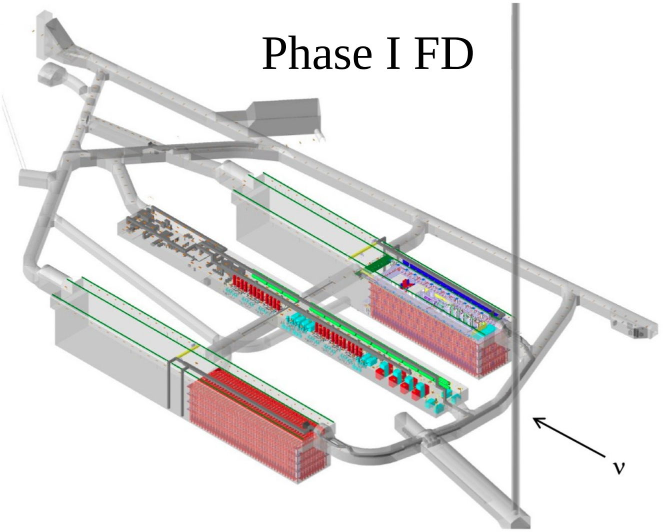
- FD flux ≠ ND flux → uncertainties in energy extrapolation
- ND flux changes with angle due to pion decay kinematics
- Take ND data in different fluxes → build linear combination to match FD *oscillated* spectra
- Robust analysis approach with very minimal dependence on interaction modeling

UNIVERSITY of ROCHESTER

DUNE will be built in two phases: Phase I

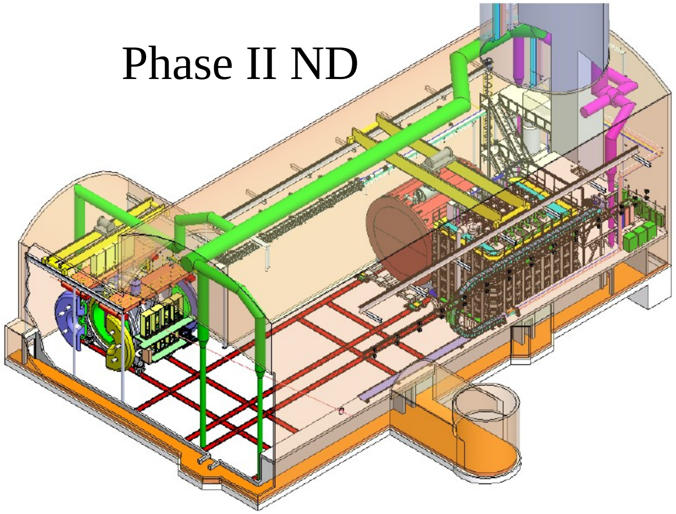
- DUNE construction is phased
- DUNE Phase I:
  - Ramp up to 1.2 MW beam intensity
  - Two 17kt LAr TPC FD modules
  - Near detector: ND-LAr + TMS (movable) + SAND
- First physics results in this decade, with FD turning on in ~2028
- Beamline and ND by 2031 to complete DUNE Phase I

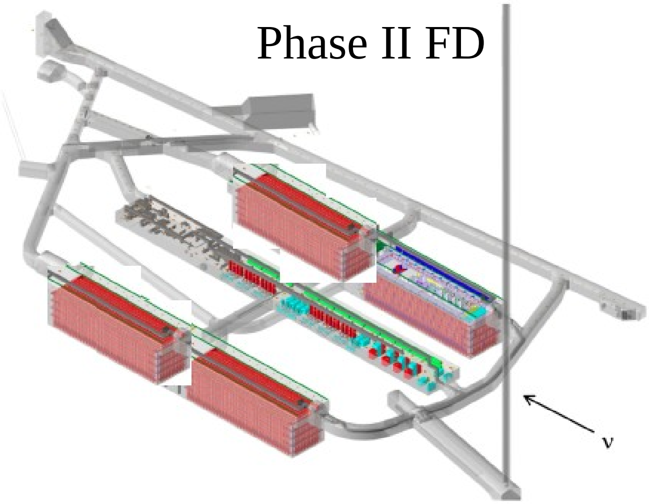




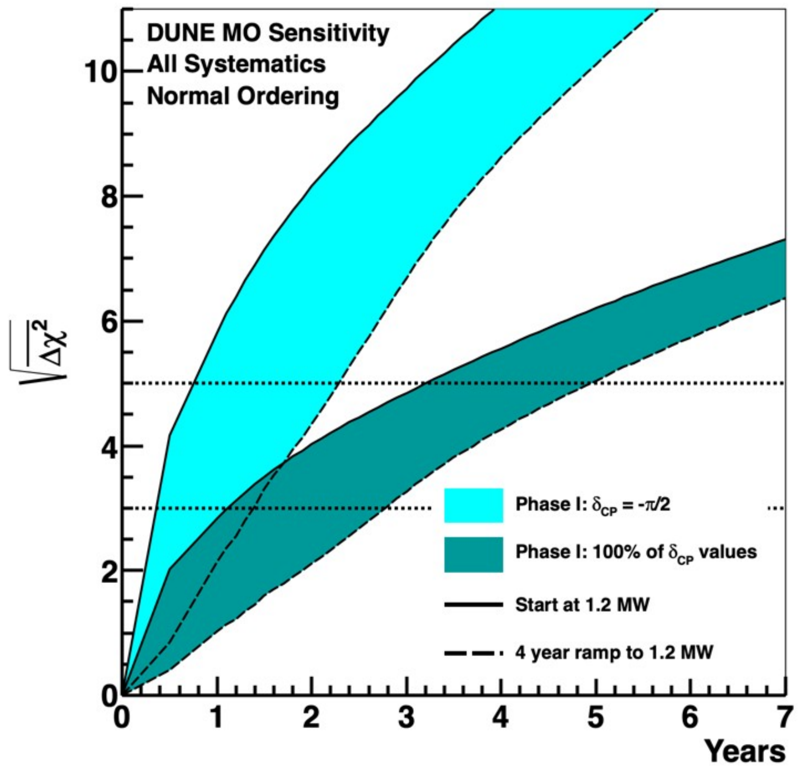
DUNE will be built in two phases: Phase II

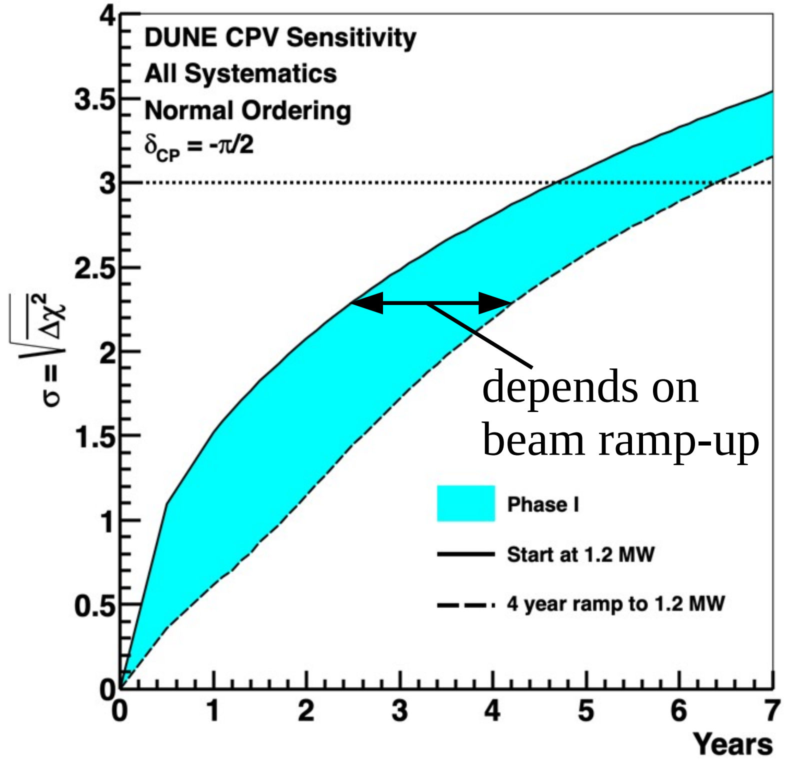
- DUNE construction is phased
- DUNE Phase II:
  - Fermilab proton beam upgrade to 2.4 MW
  - Four 17kt FD modules
  - Near detector: ND-LAr + MCND (movable) + SAND
- Beam upgrade and 40kt FD mass are needed to reach required statistics
- TMS → ND-GAr replacement is driven by enhanced physics capability of ND-GAr, reducing systematics to required level





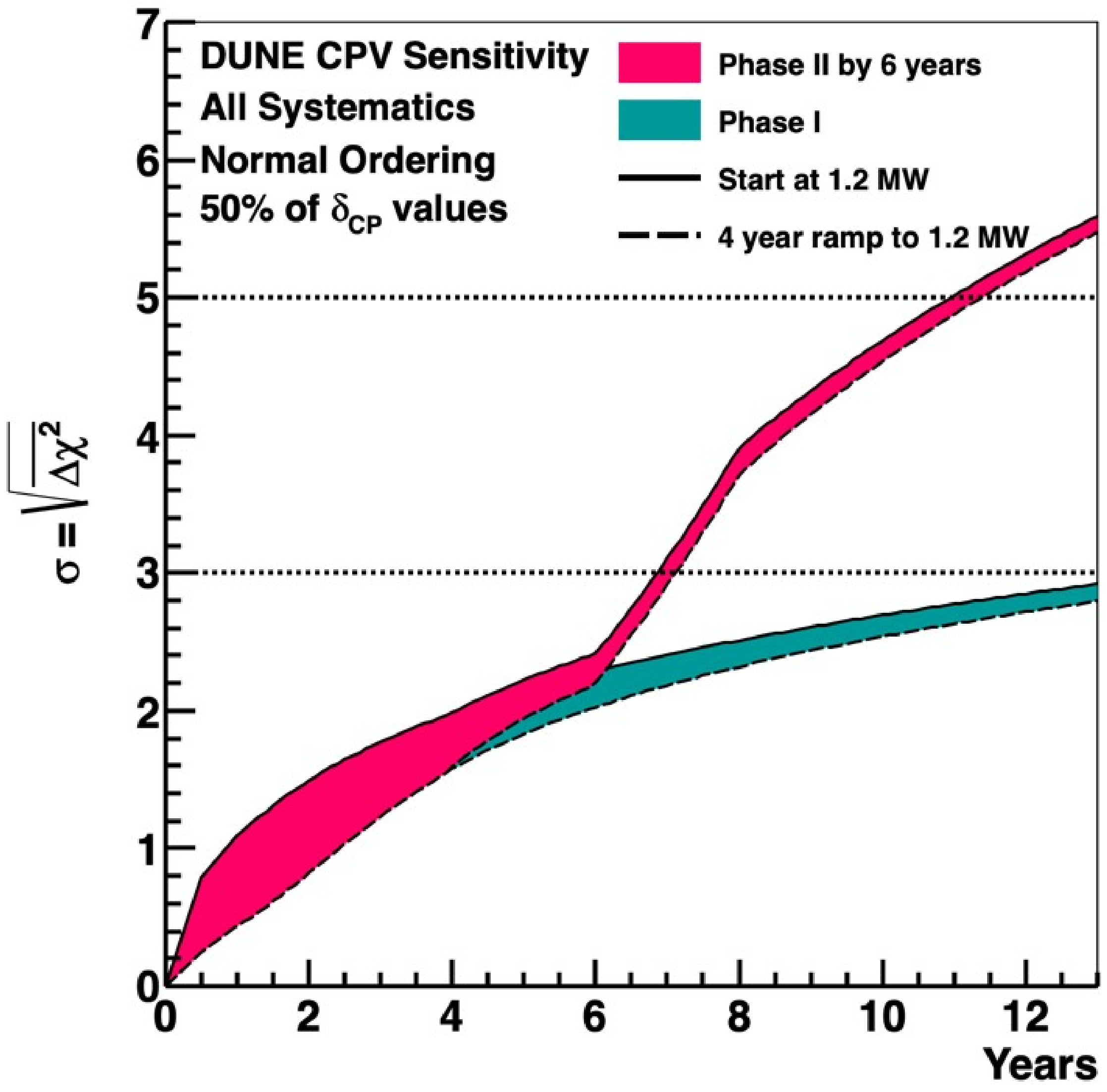
DUNE Phase I: world-leading MO, sensitivity to maximal CPV





- Phase I will do world-class long-baseline neutrino oscillation physics:
  - Only experiment with 5σ mass ordering capability regardless of true parameters
  - Discovery of CPV at 3σ if CP violation is large
  - World-leading precision on Δm^2_{32}, and other oscillation measurements

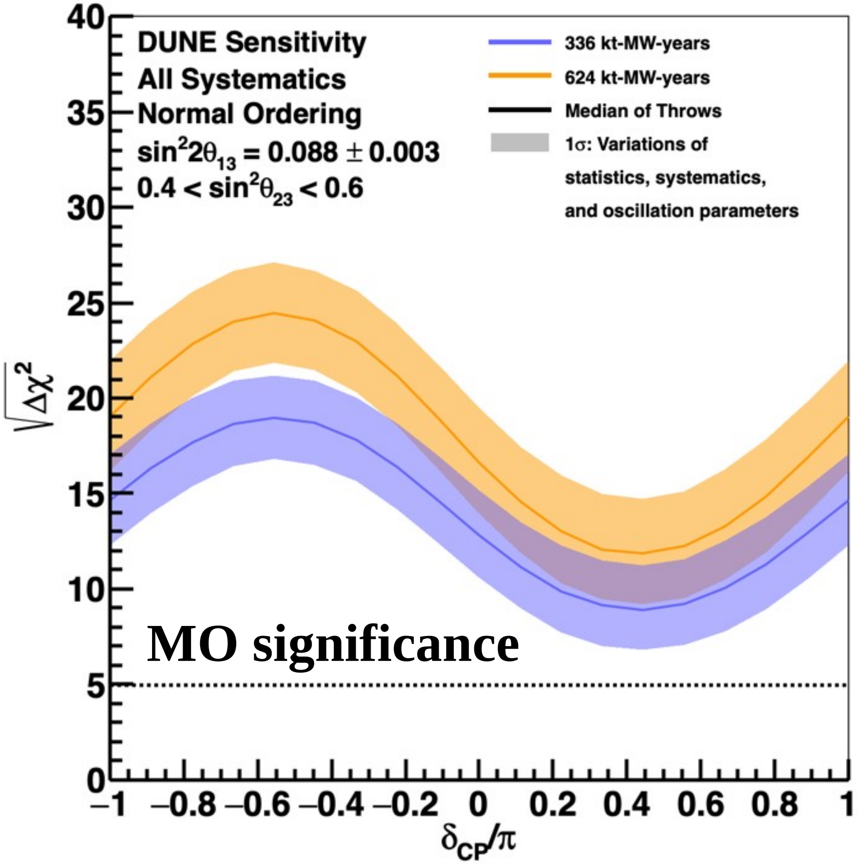
DUNE's long-term goals require full scope (Phase II)

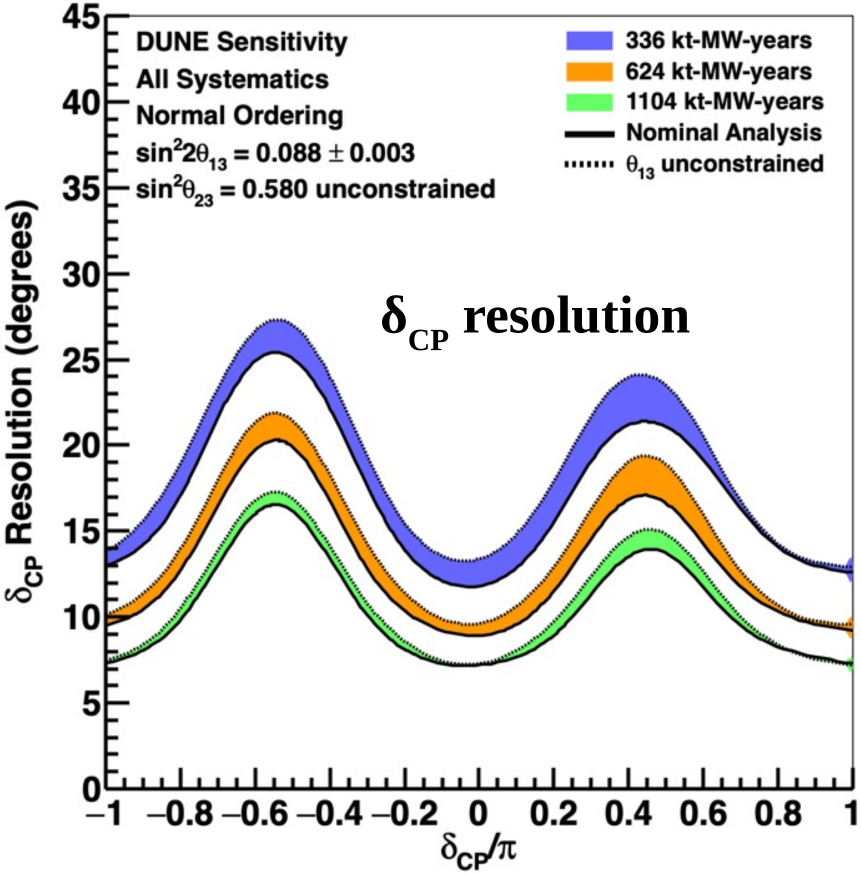


- DUNE needs full Phase II scope to achieve precision physics goals defined in P5 report
- CPV sensitivity for 50% of δ_{CP} values shown, precision measurements are similarly affected
- Timescale for precision physics is driven by achieving full scope on aggressive timescale

UNIVERSITY of ROCHESTER

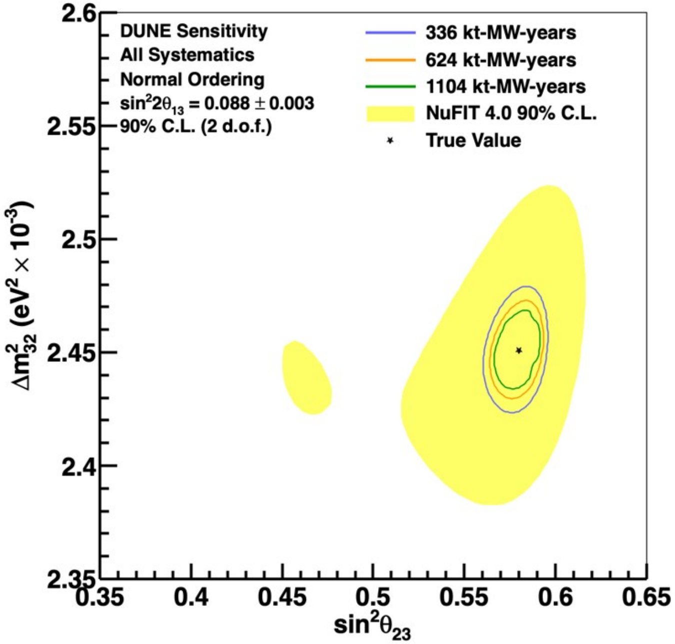
DUNE has world-leading oscillation physics sensitivity

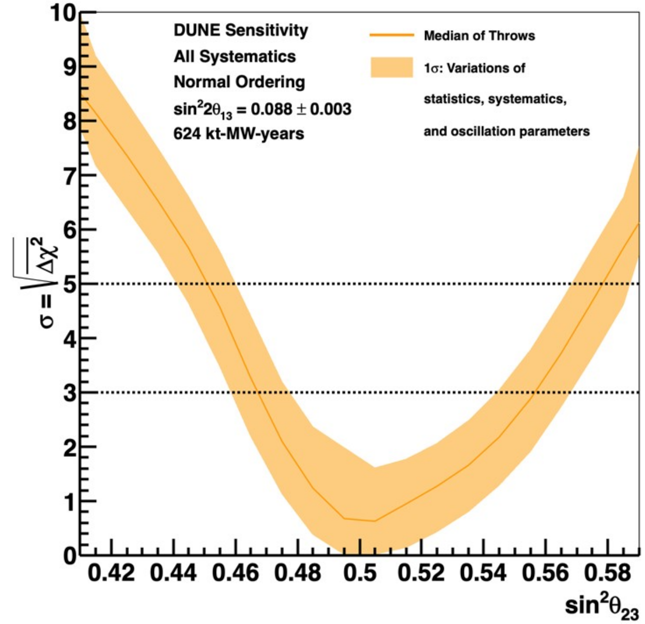


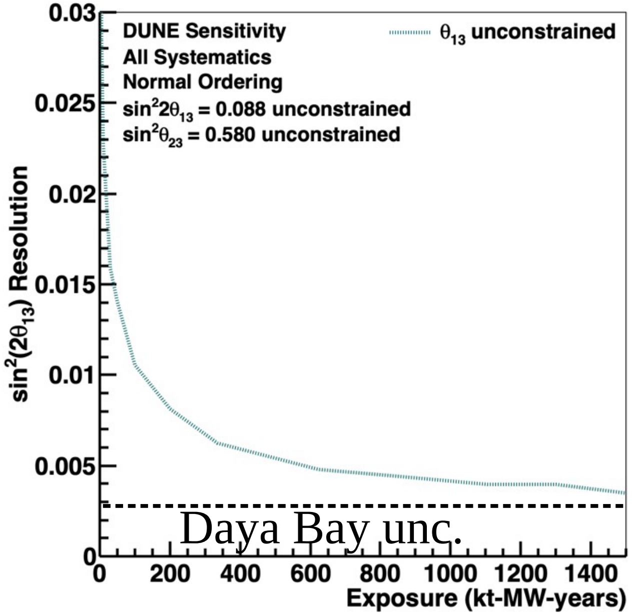


- Mass ordering significance is unmatched, >5σ in first few years
- δ_{CP} resolution of ~7° at CP-conserving values → discovery sensitivity to CPV over a broad range of possible values of δ_{CP}

Physics potential: precision measurements, non-unitarity tests



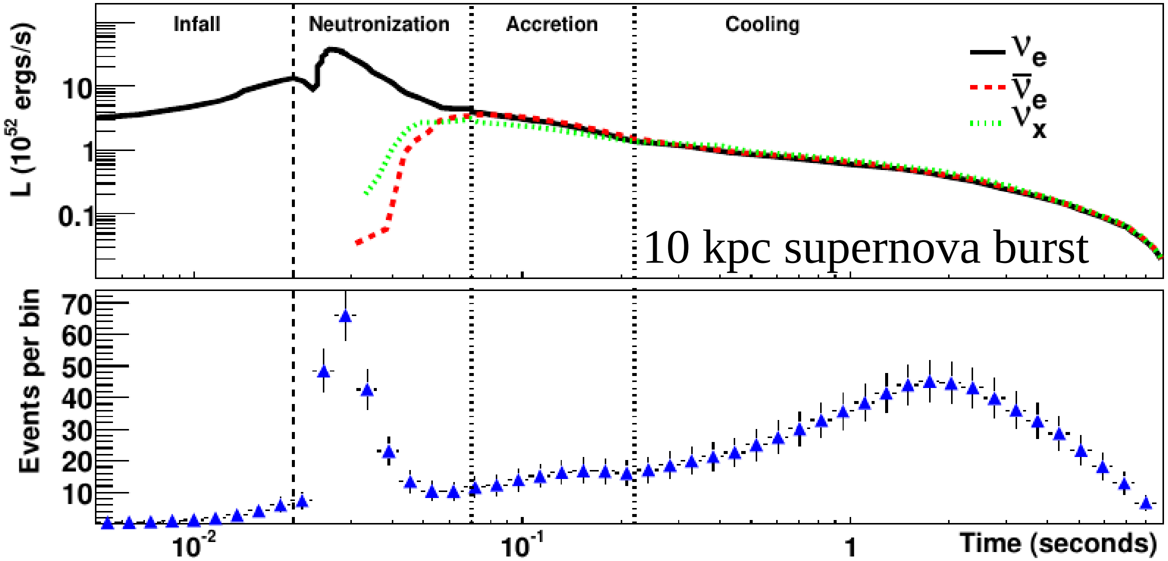


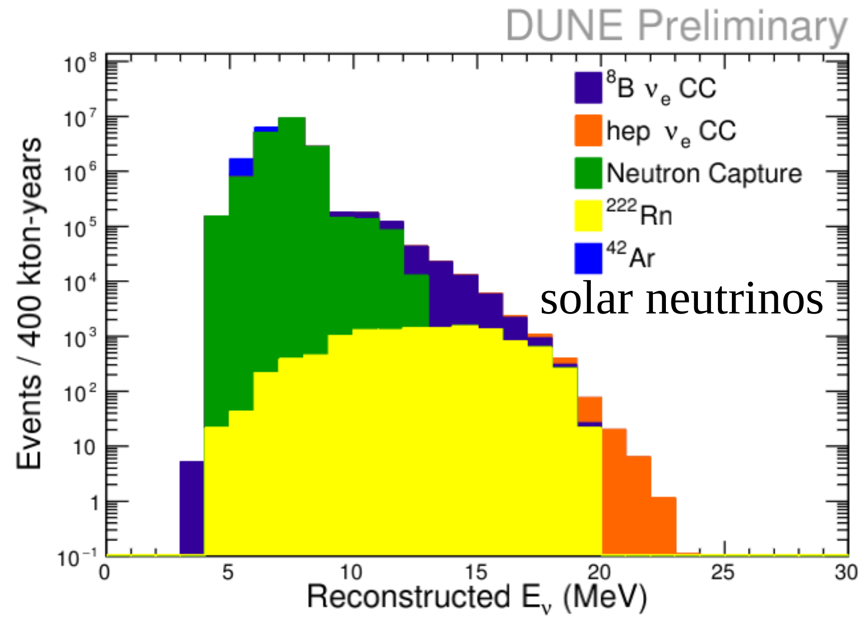


- World-leading precision on Δm^2_{32} and θ_{23}, including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data tests PMNS unitarity

UNIVERSITY of ROCHESTER

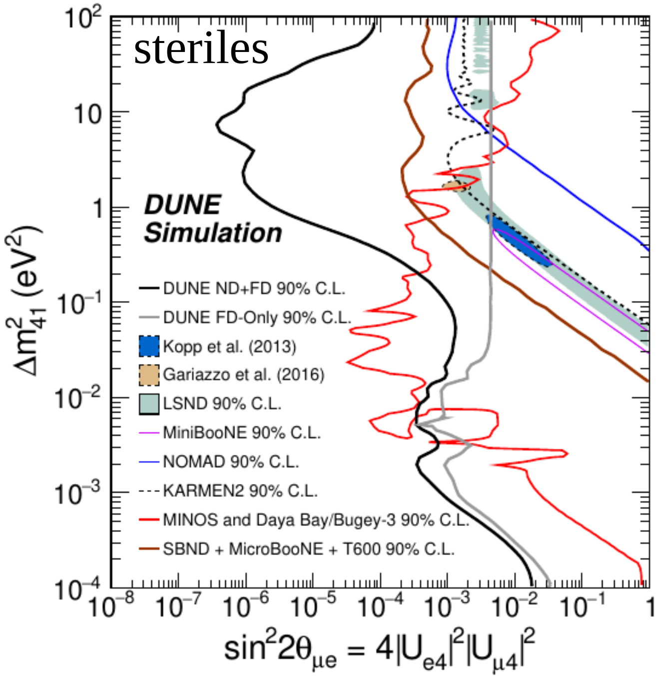
MeV-scale physics: unique opportunities with ν_es

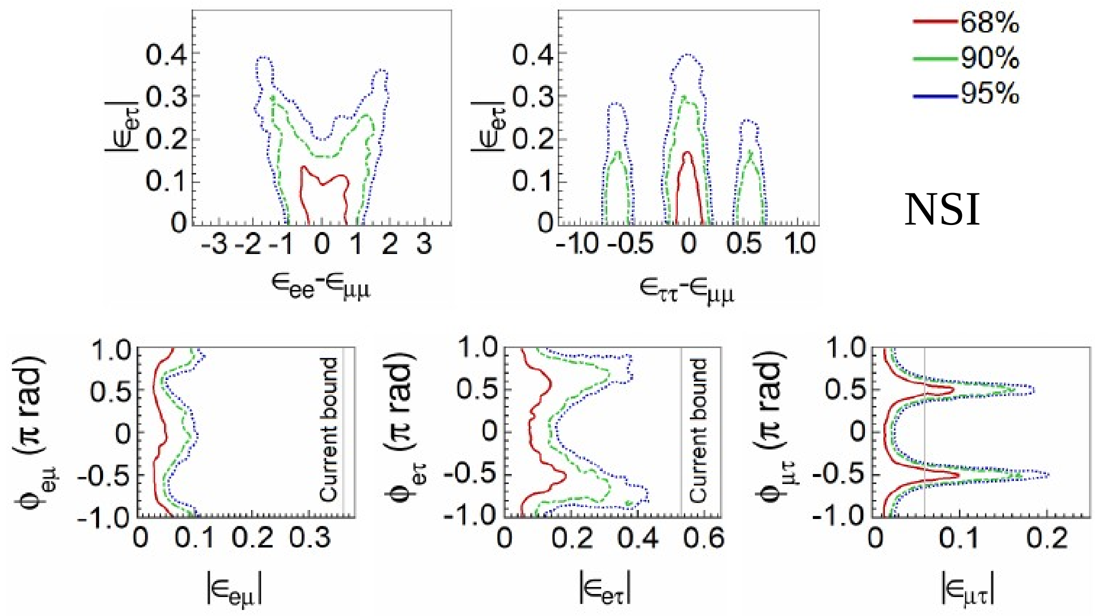




- Supernova neutronization produces ν_e burst → DUNE is uniquely sensitive to this flux compared to water-based experiments, and measure O(1000s) of events for a galactic SNB
- Much recent work on solar neutrinos, sensitivity to ^{8}B and hep fluxes, and capability to measure solar mixing parameters θ_{12} and Δm^2_{12}
- Several proposals for FD-4 would enhance the low-energy program, possibly to include $0\nu\beta\beta$ capability

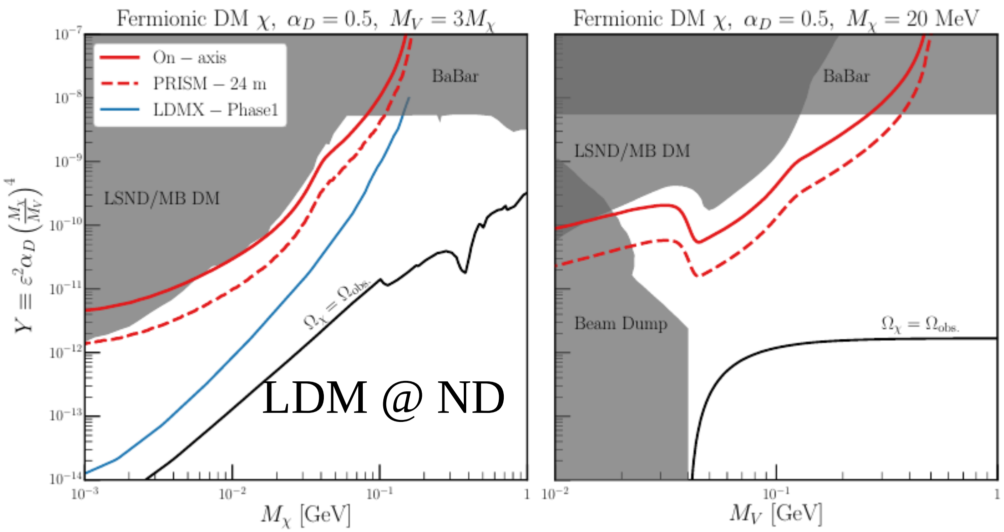
Beyond the 3-flavor SM picture: steriles and NSI

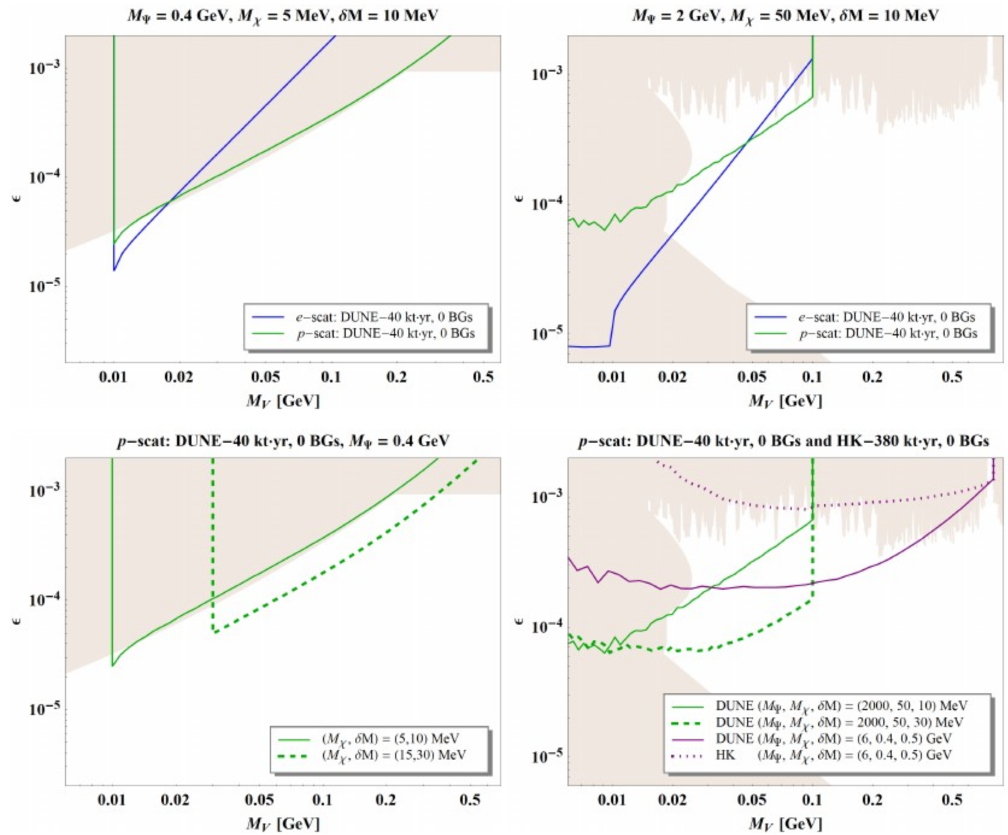




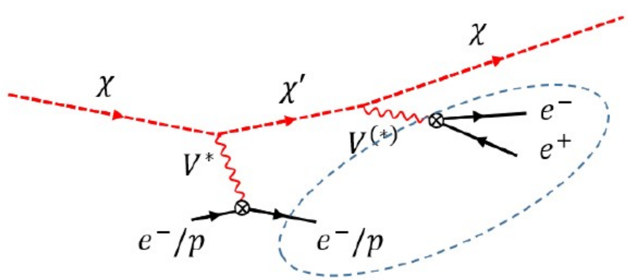
- FD spectra not consistent with 3-flavor model could be due to non-standard interactions (NSI)
- Additional oscillation effects due to sterile neutrinos can be seen at either the ND or FD, depending on mass scale
- If inconsistency is observed, having multiple experiments at different baselines but the same L/E will be important for understanding the origin

Not just neutrinos: Dark matter at DUNE ND & FD





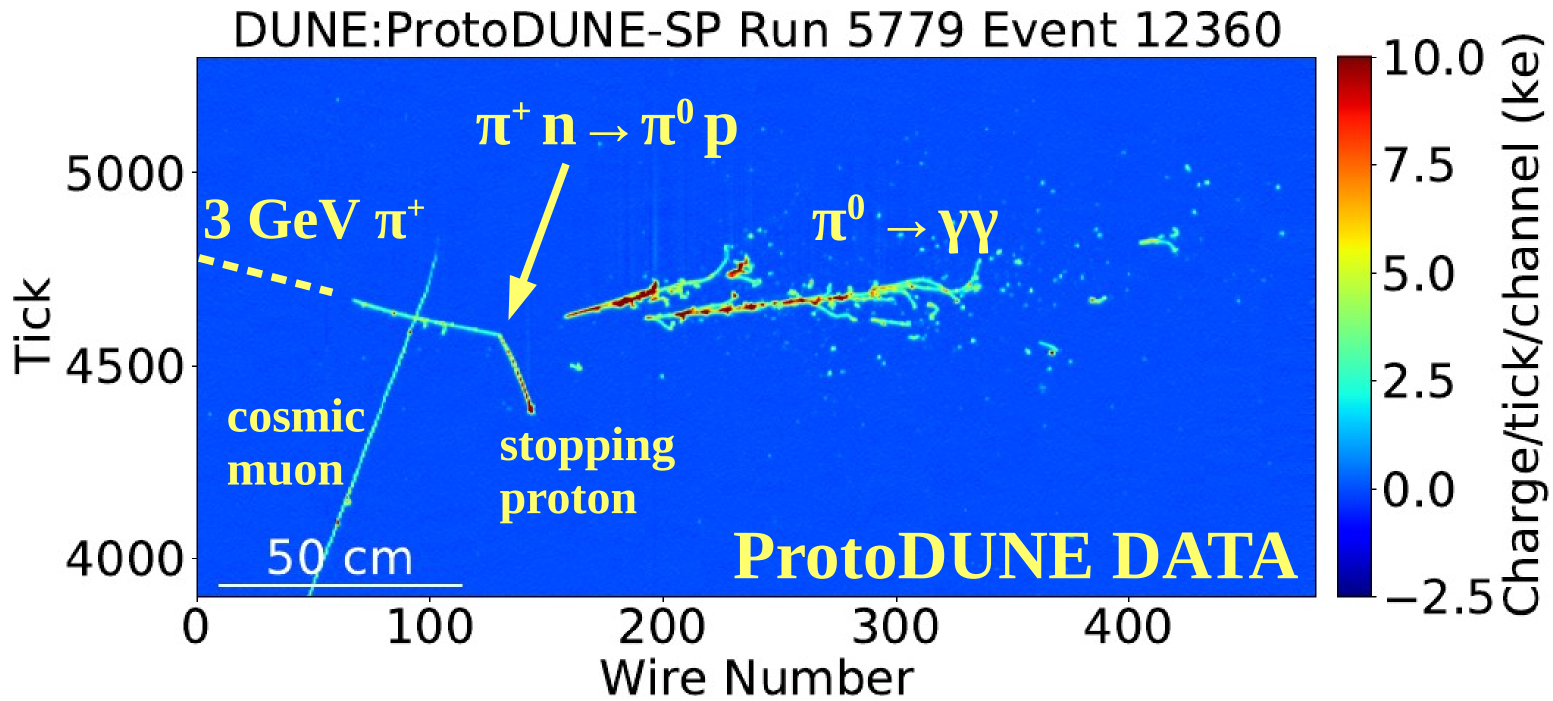
- ND-LAr is sensitive to DM produced in beamline, off-axis data helps to control SM backgrounds
- FD is sensitive to inelastic dark matter of cosmic origin
- (Not pictured) ND-GAr is sensitive to HNL decays with very low backgrounds due to low density



UNIVERSITY of ROCHESTER

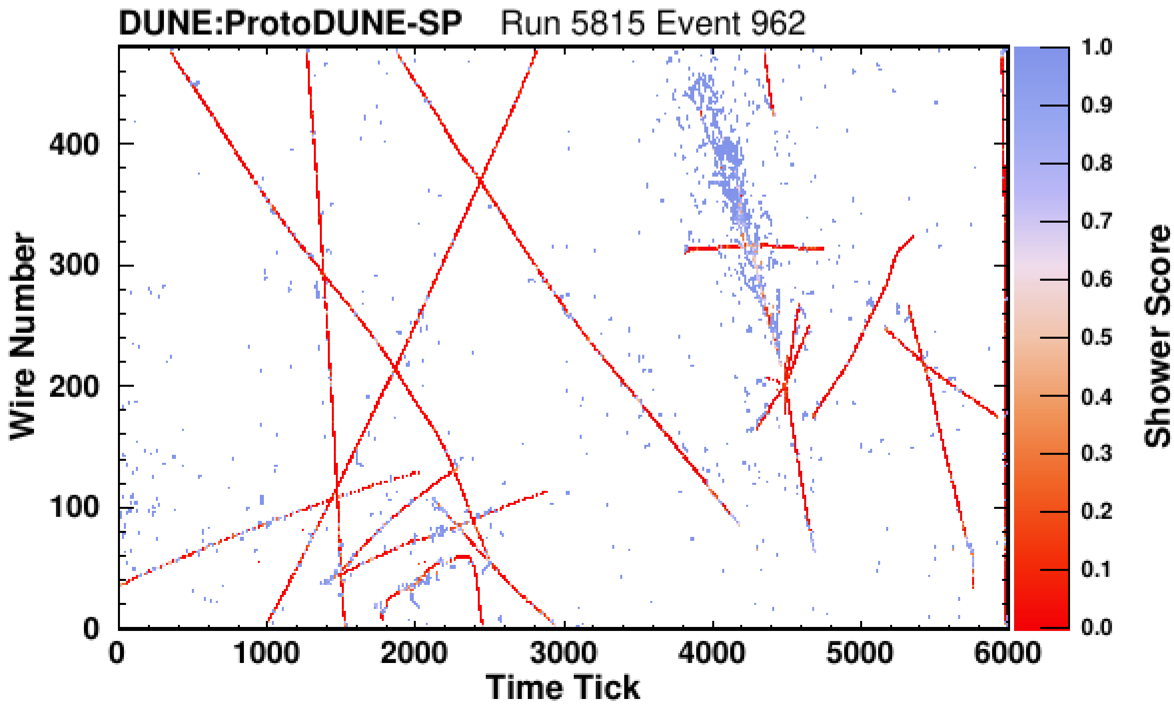
Successful ProtoDUNE run demonstrates DUNE technology

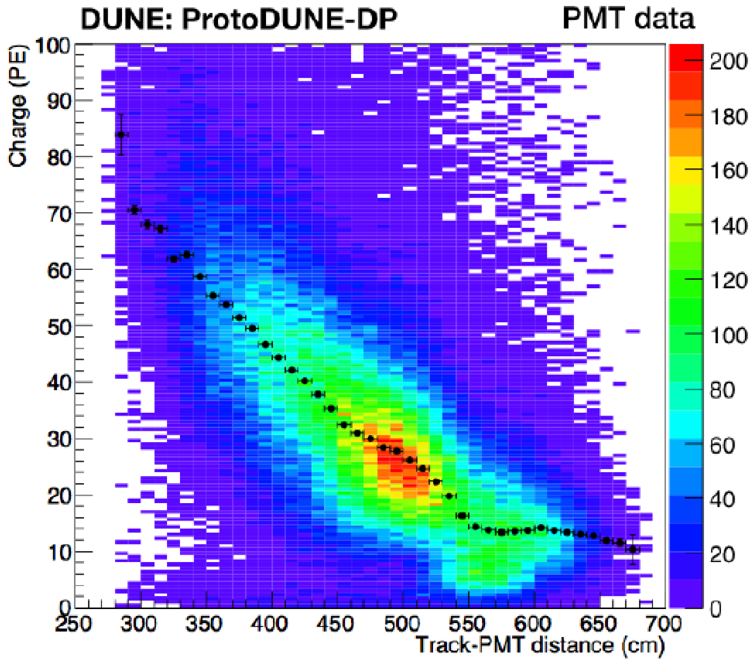
- Large-scale DUNE prototypes operated at CERN Neutrino Platform with low noise, stable HV, high purity
- Stable operation of ProtoDUNE shows that the technology will work, and is scalable to full DUNE



Science results from ProtoDUNE: Two new papers, more to come!

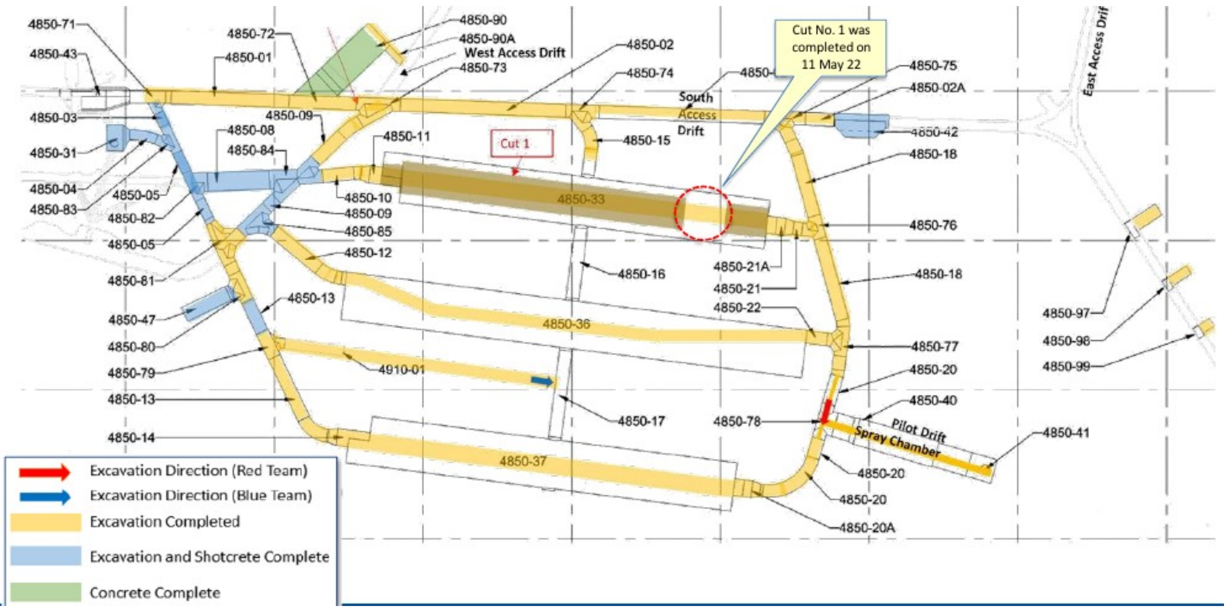
- Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a Convolutional Neural Network arXiv:2203.17053
- Scintillation light detection in the 6m drift-length ProtoDUNE Dual Phase liquid argon TPC arXiv:2203.16134
- Many more in the pipeline, covering event reconstruction, Michel electrons, pion, proton, kaon, neutron inclusive and exclusive cross sections





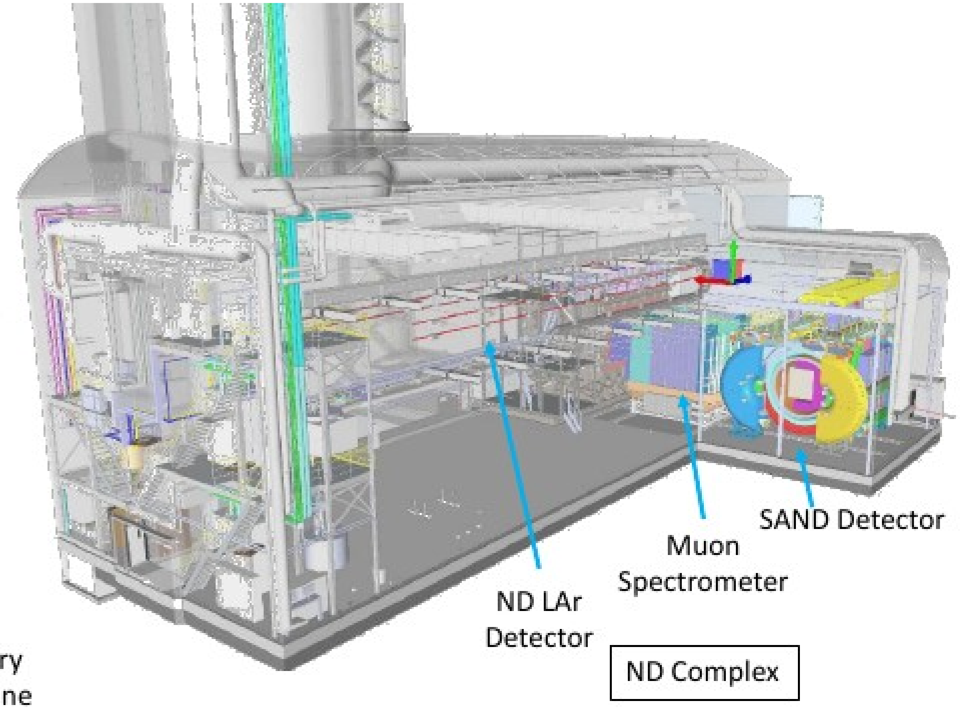
Far site excavation is well underway at SURF

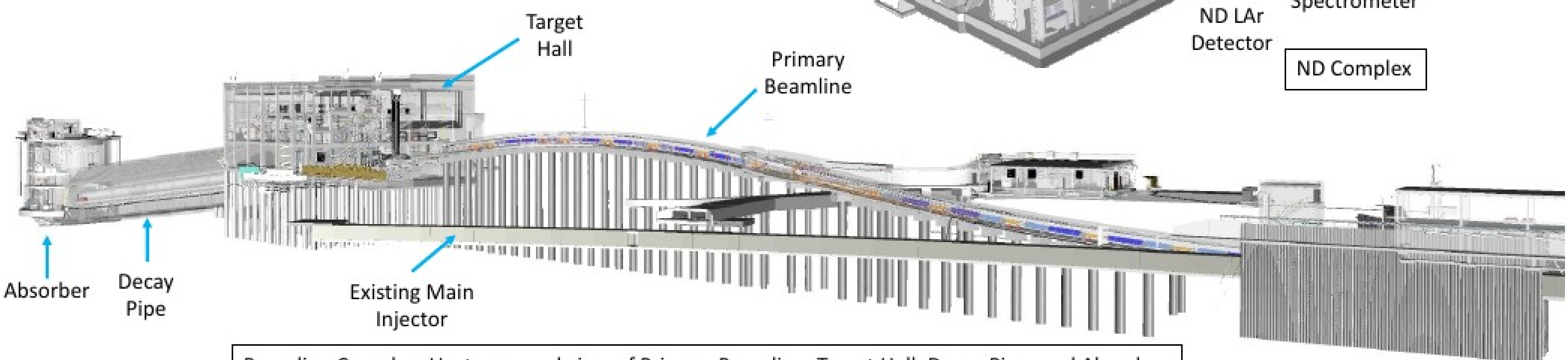
- Excavation is 27% complete by total rock volume
- Yellow shows complete excavation, including first cut of north detector cavern



Beamline and Near Detector site at Fermilab: design is 100% complete

- Conventional facilities for the neutrino beamline and the Near Detector underground site have completed their designs

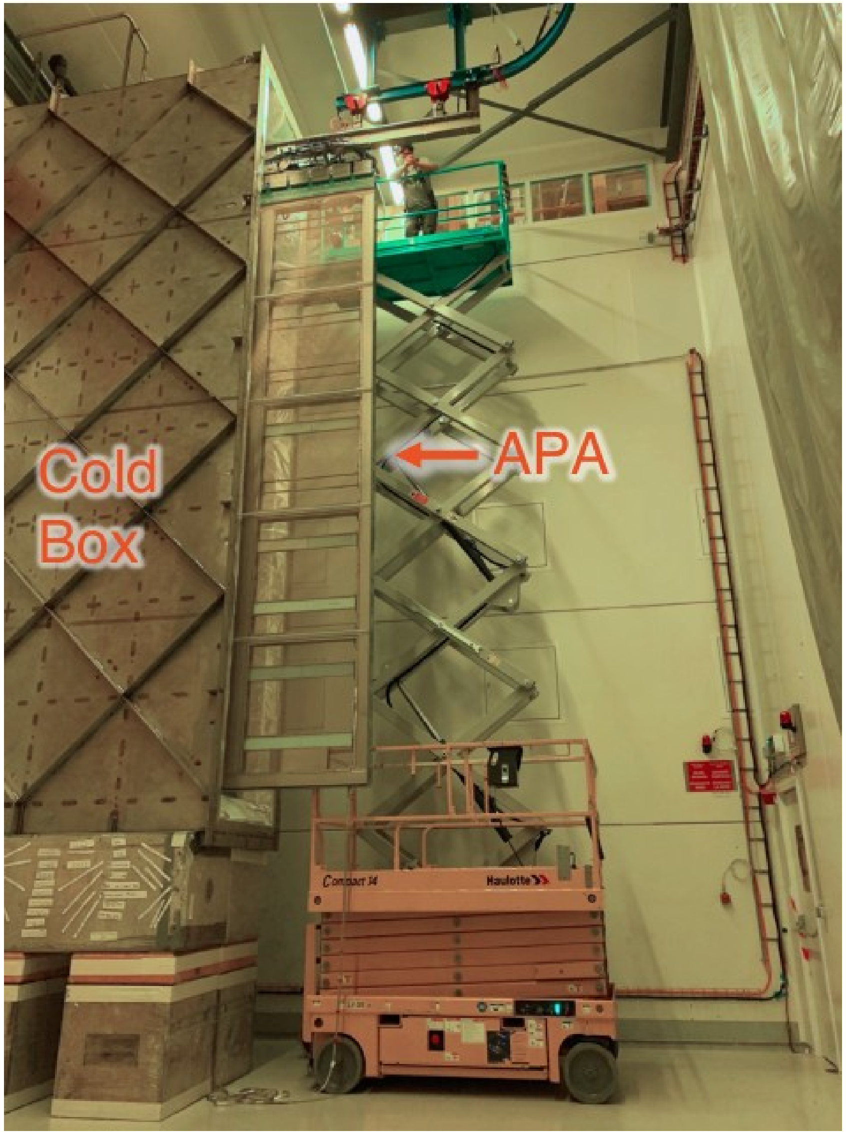




Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

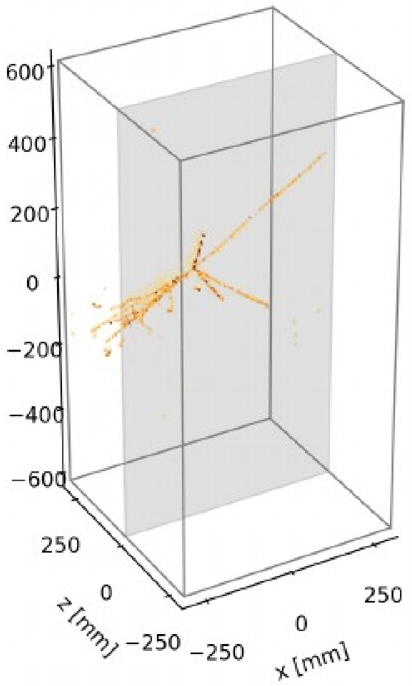
Preparations for APA production are well underway

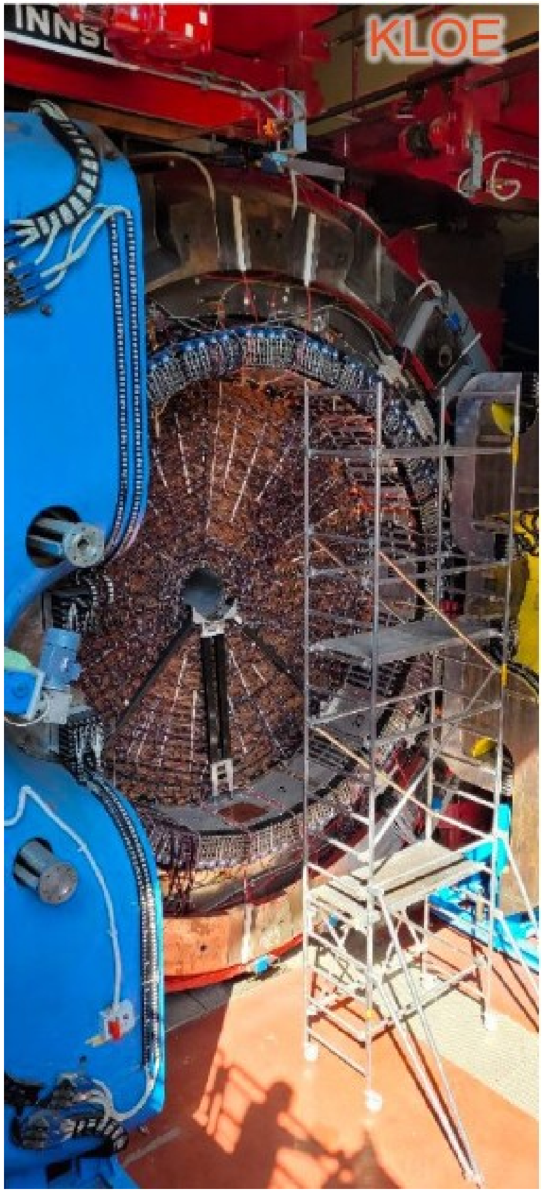
- “Module-0” APA was tested in CERN cold box
- Plan to install in ProtoDUNE cryostat for a second run in 2022
- APA production at Daresbury (UK) to begin this summer



Near detector prototyping efforts

- ND-LAr 2x2 prototype Module-1 operated successfully at Bern, preparation for neutrino beam test at Fermilab underway
- Dismounting of KLOE for SAND is underway





Summary

- DUNE is a best-in-class long-baseline neutrino oscillation experiment, neutrino observatory, and new physics search machine
- We are on track to deliver Phase I:
  - ProtoDUNE has demonstrated the technology
  - Far site civil construction is progressing well, and near site and beamline is fully designed
  - Additional FD and ND prototyping is going well, with initial FD construction set to begin soon
- This is an exciting time for DUNE!

Thank You

DUNE Collaboration, May 2022, Fermilab