The DUNE Experiment: Status and Outlook

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for the DUNE Collaboration

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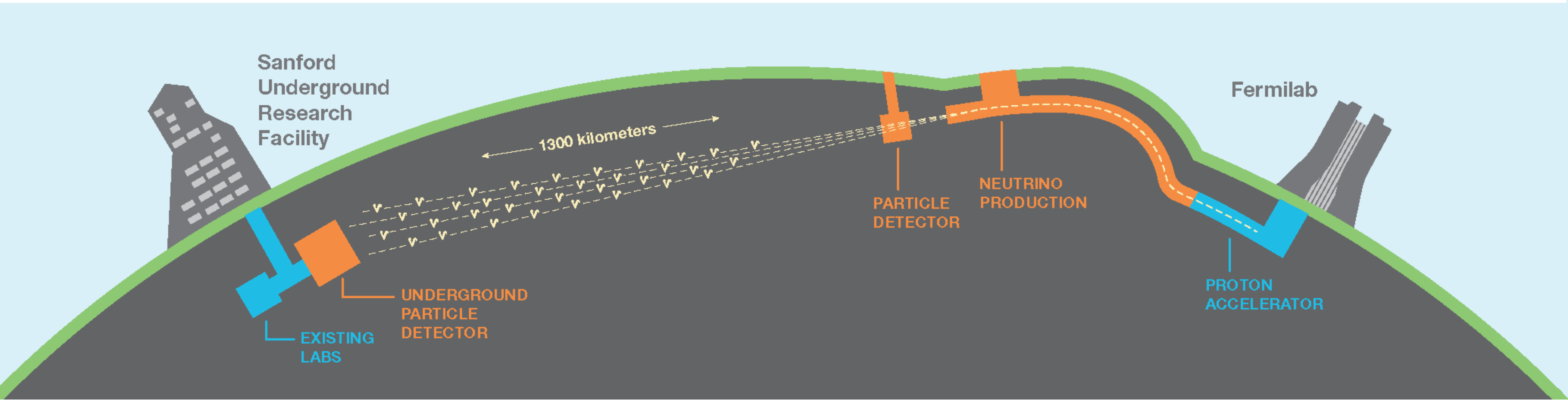
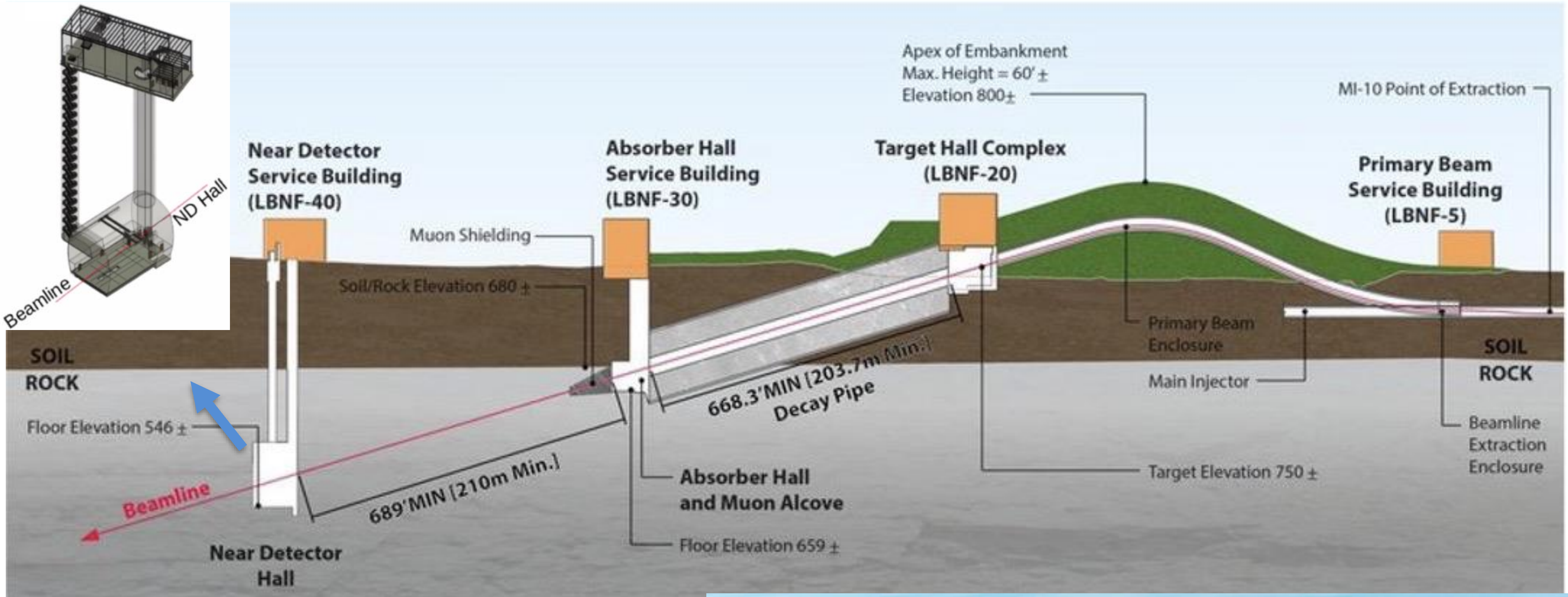
HQL 2025, Beijing

DEEP UNDERGROUND NEUTRINO EXPERIMENT



- New neutrino beam at Fermilab (upgradeable > 2 MW, most powerful beam ever built), 1300 km baseline
- Four 17 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector modules at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Multiple technologies for the Near Detector (ND)
- ν_e / anti-ν_e appearance and ν_μ /anti-ν_μ disappearance → Neutrino mass ordering and CP violation
- Large detector, deep underground, broad and high intensity beam→ Supernova burst neutrinos, atmospheric neutrinos, sterile neutrinos, nucleon decay, other BSM, etc

Long Baseline Neutrino Facility (LBNF)



- Proton beam
  - Proton Improvement Plan-II (PIP-II)
  - 1.2 MW, upgradeable to 2.4 MW
  - 60-120 Proton GeV from FNAL accelerator complex
  - Initial upward pitch, bent down at 5.8° to reach Sanford
- Horns/beam line designed to maximize CP violation sensitivity, long baseline optimizes MH measurement

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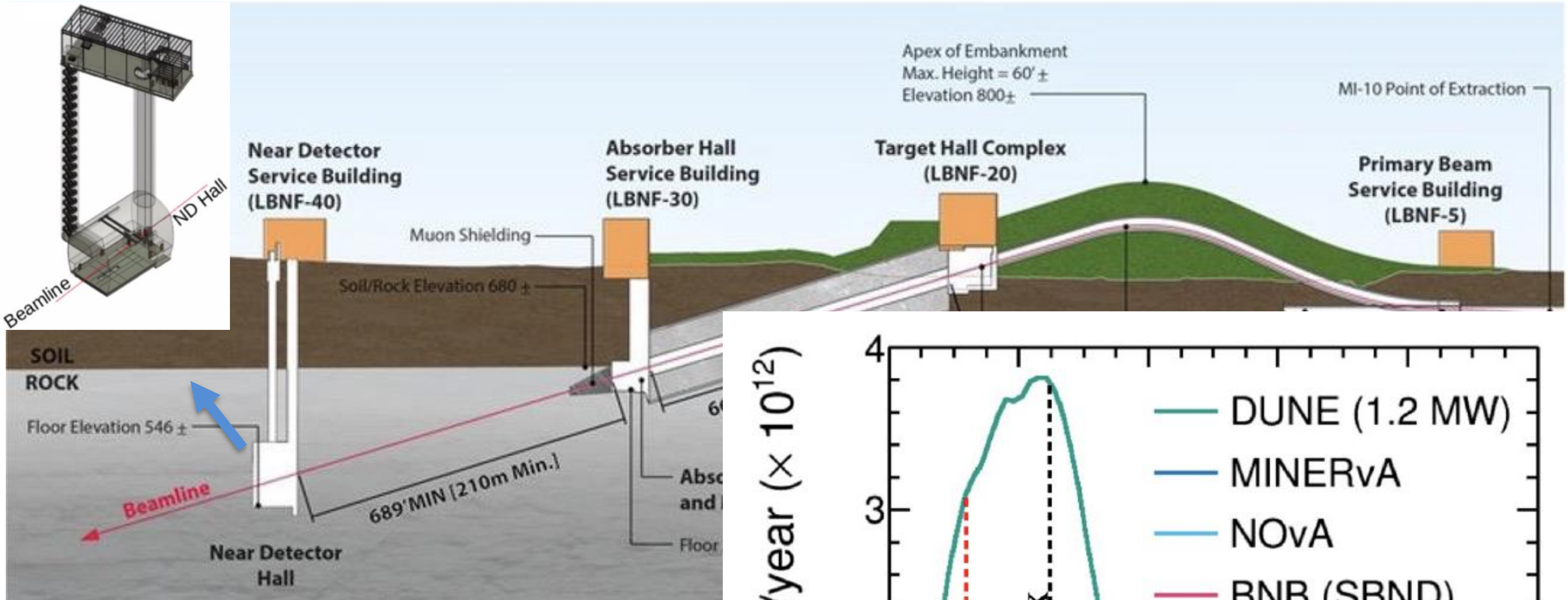

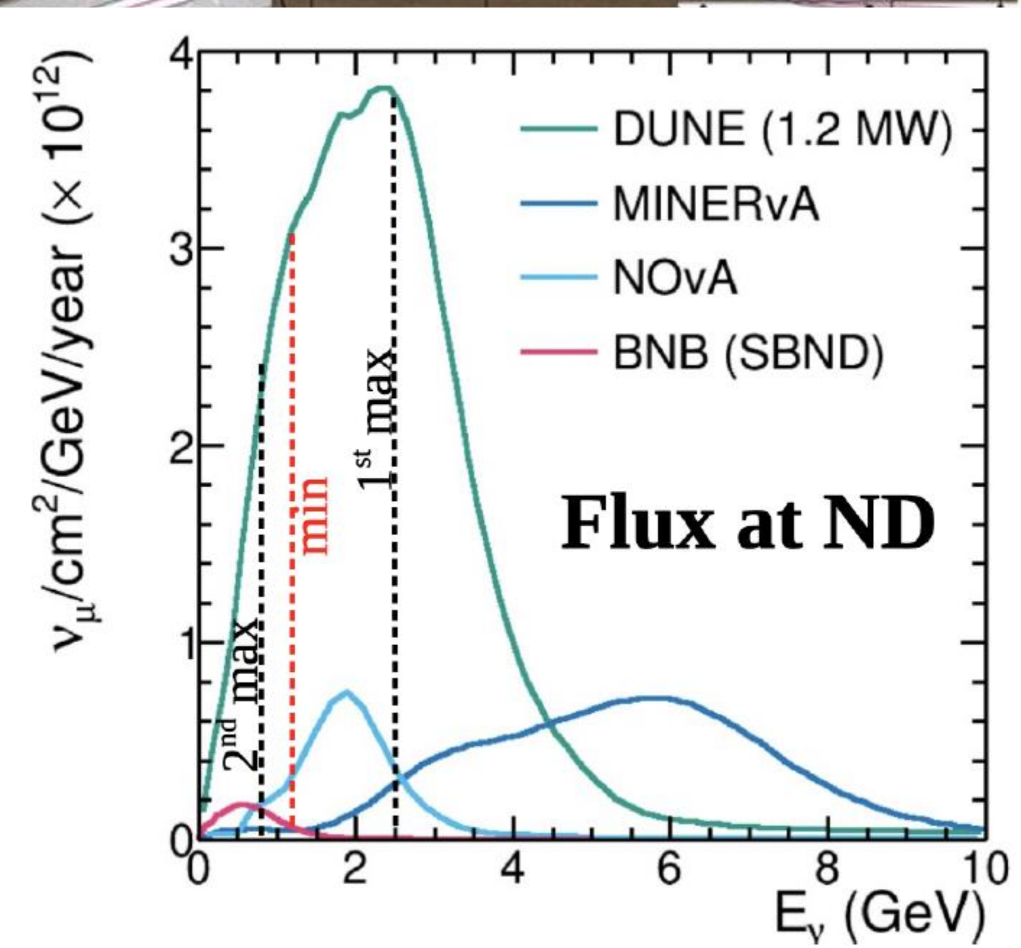

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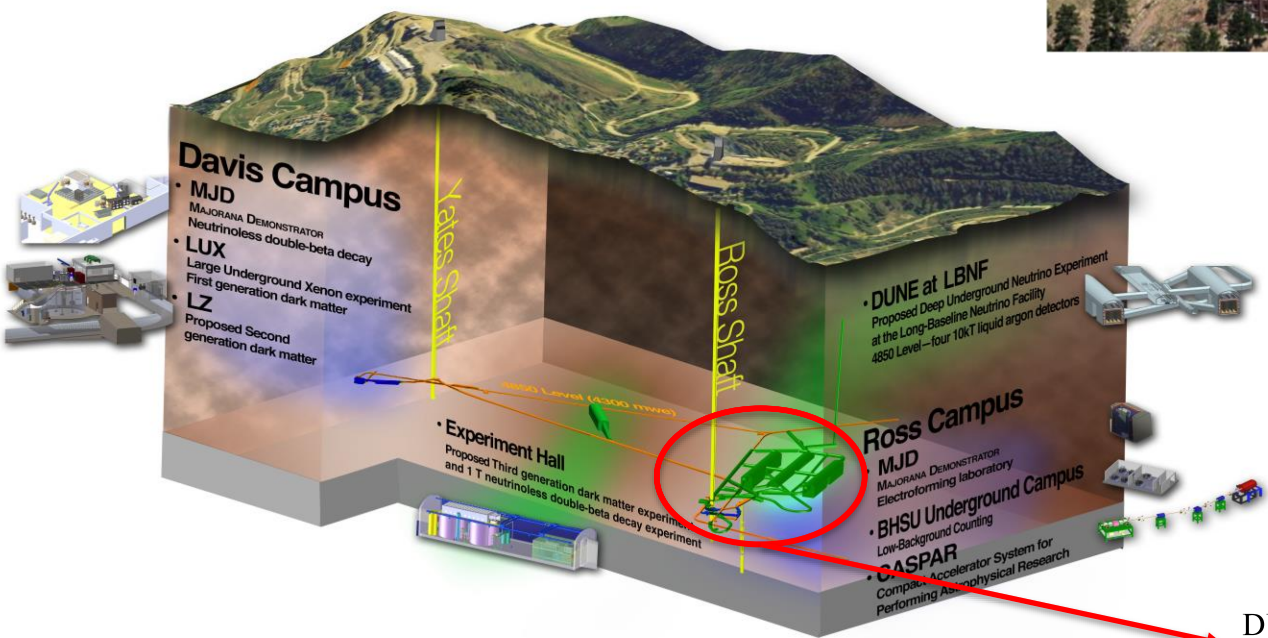
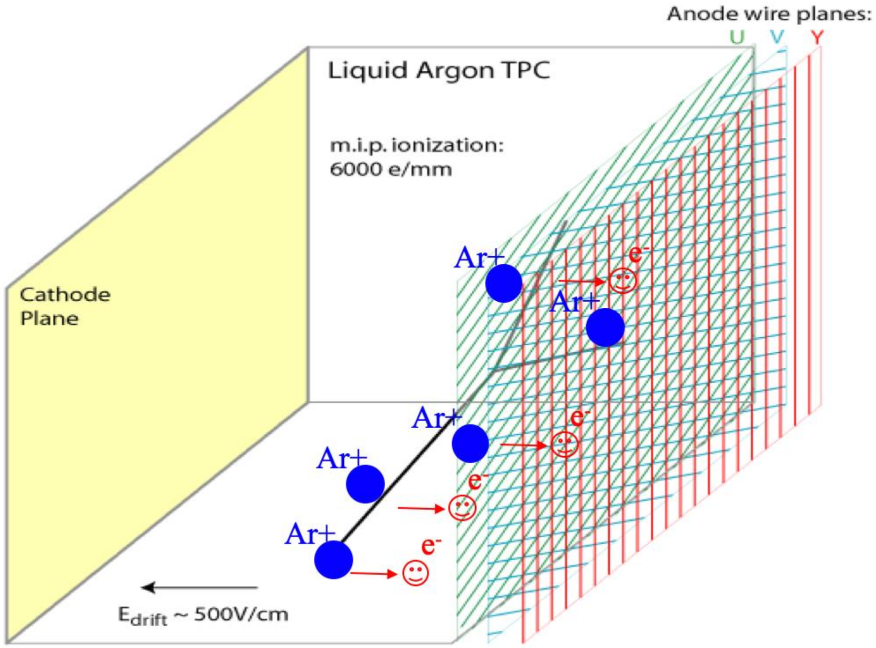
Sanford Underground Research Facility (SURF)

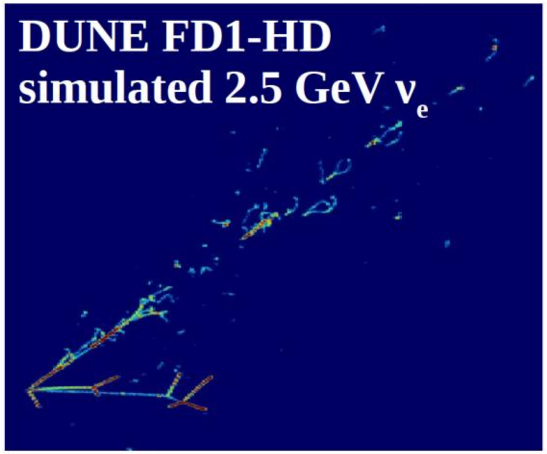


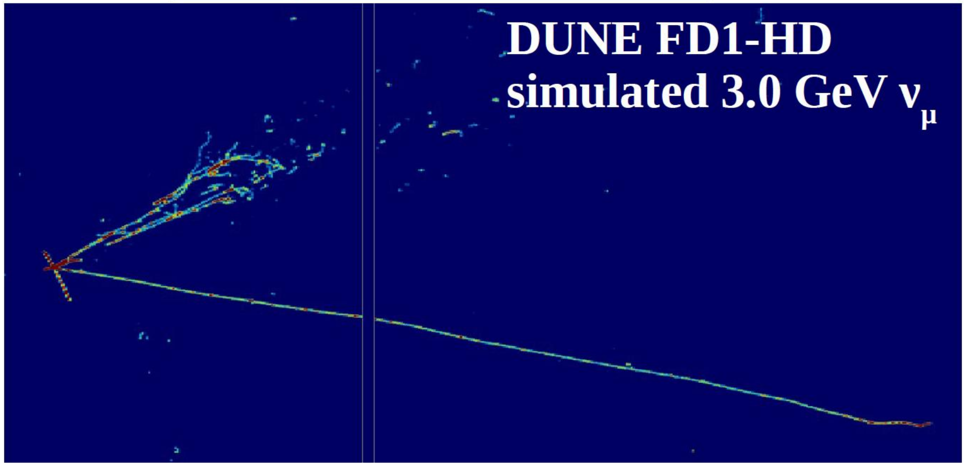
DUNE facility,
4850 ft (1.5km, 4300 mwe)

- In the Homestake gold mine, Lead, S. Dakota
- Home of Ray Davis's solar neutrino experiment
- 4 caverns for detector and 1 utility hall for DUNE
- Far site excavation complete

Far Detectors: Liquid Argon Time Projection Chamber (LArTPC)

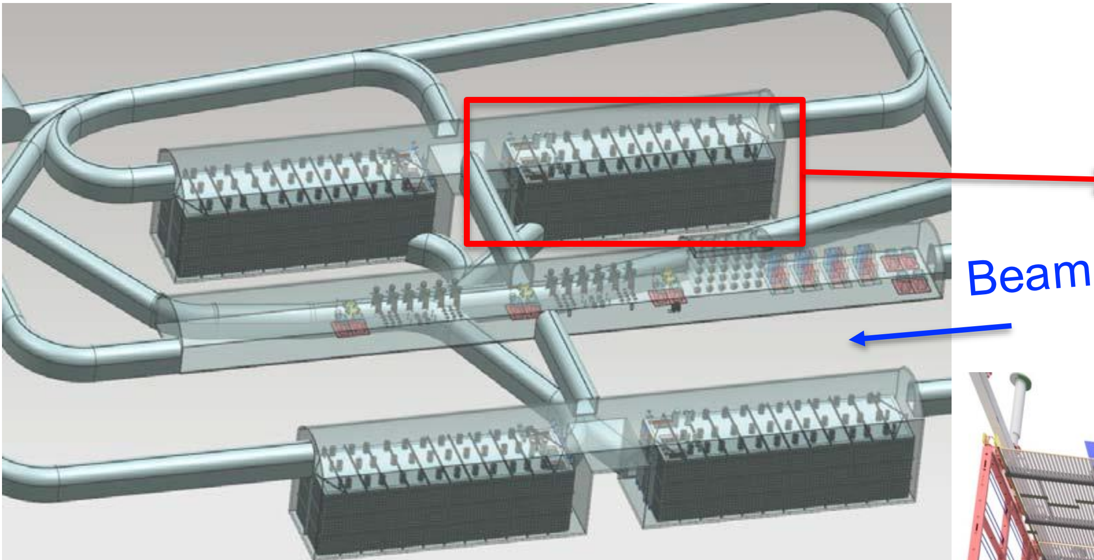




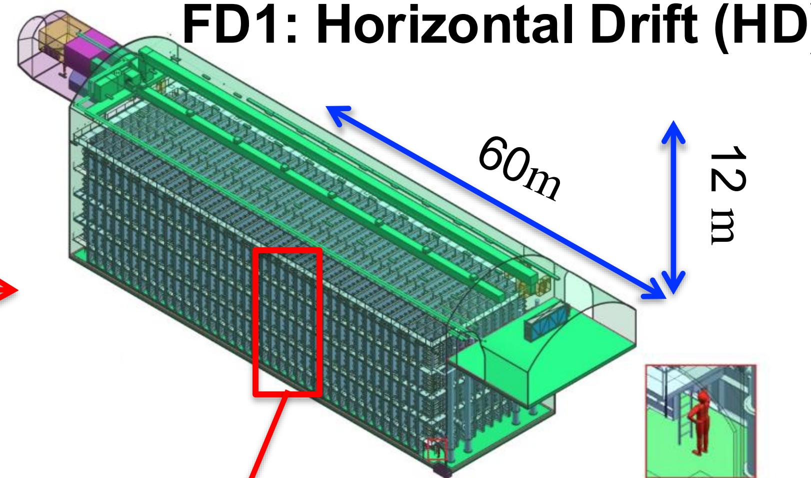


- High resolution 3D track reconstruction
  - Charged particle tracks ionize argon atoms
  - Ionized electrons drift to anode wires (~ms) for XY-coordinate
  - Electron drift time projected for Z-coordinate
- Argon scintillation light (~ns) detected by photon detectors, providing t_0

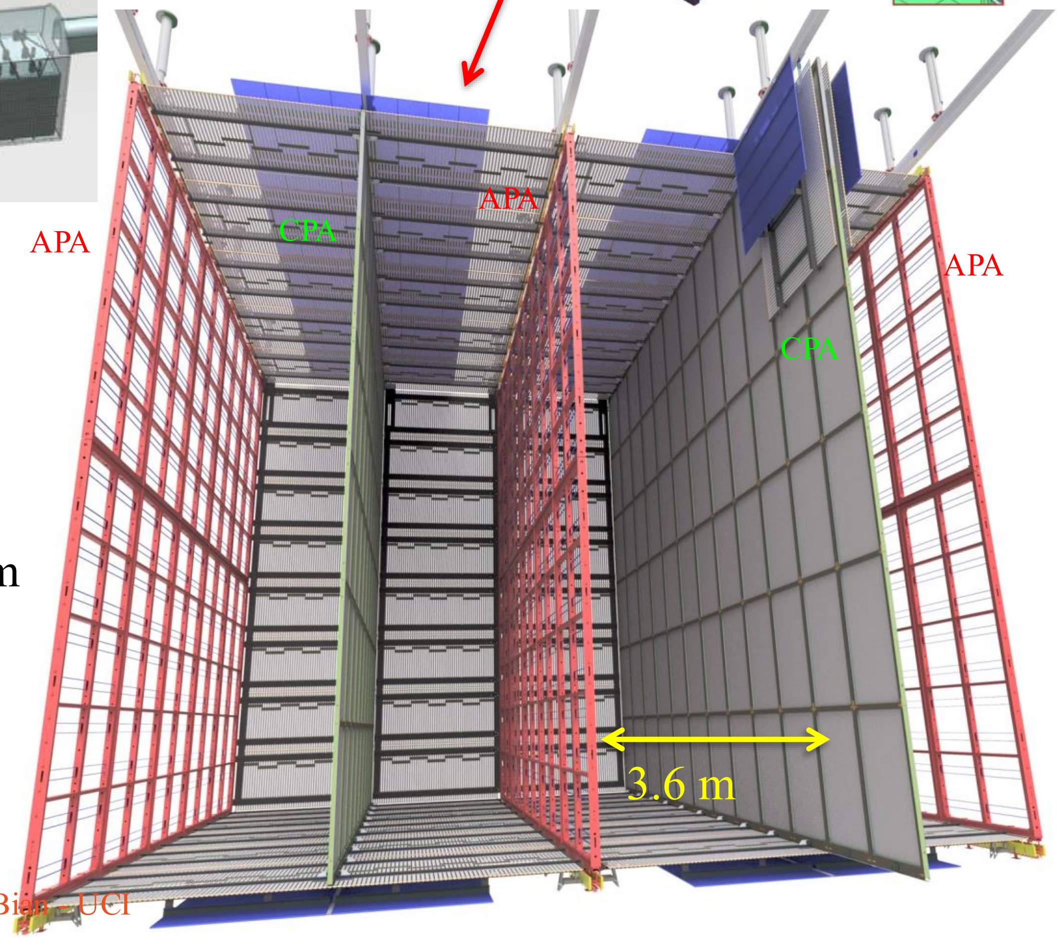
Far Detectors (FD): LArTPC



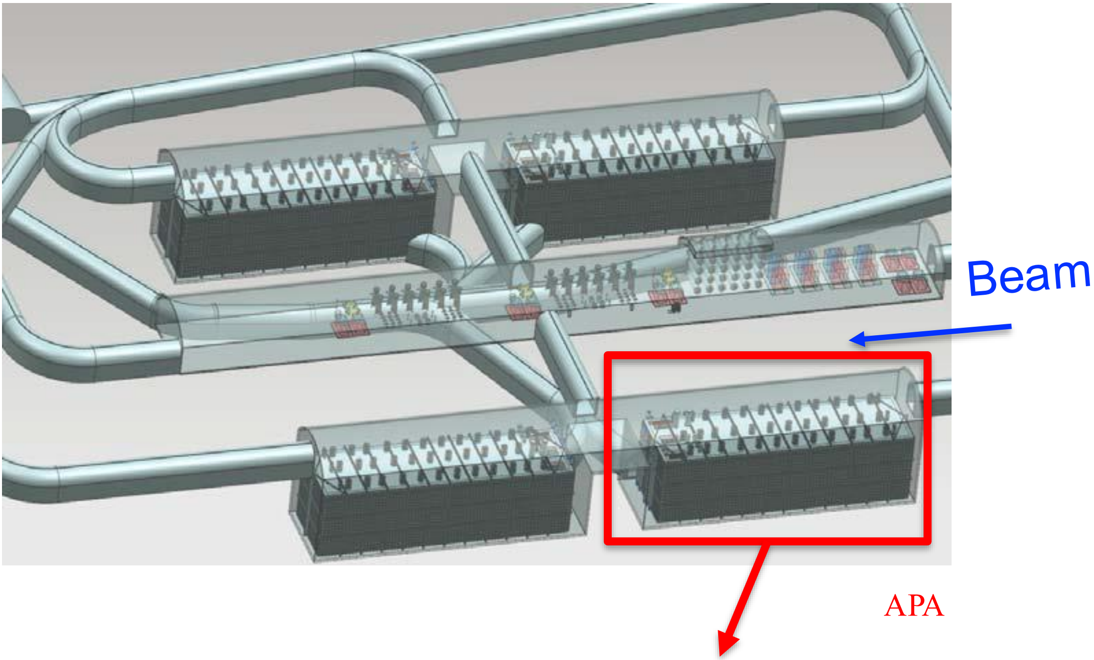
FD1: Horizontal Drift (HD)



- Fiducial volume: 10 kt per module
- Anode wire planes (2 induction, 1 collection) immersed in LAr
- Anode and Cathode Plane Assemblies (APA, CPA) suspended from ceiling
- Drift distance: 3.6 m, wire pitch: 5 mm
- Induction wires +-37.7° to collection wires, wrapped around APA
- Drift field: 500V/cm; HV: 180kV
- Photon detectors: SiPMs based, embedded in APAs

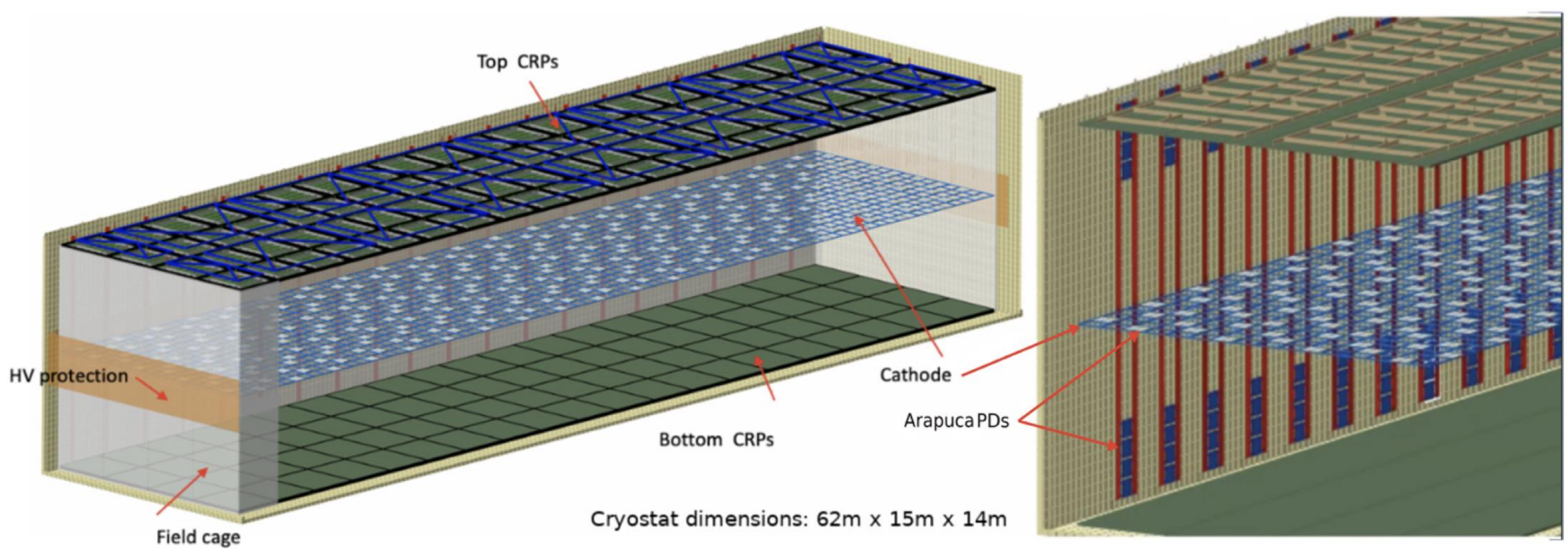


Far Detectors (FD): LArTPC

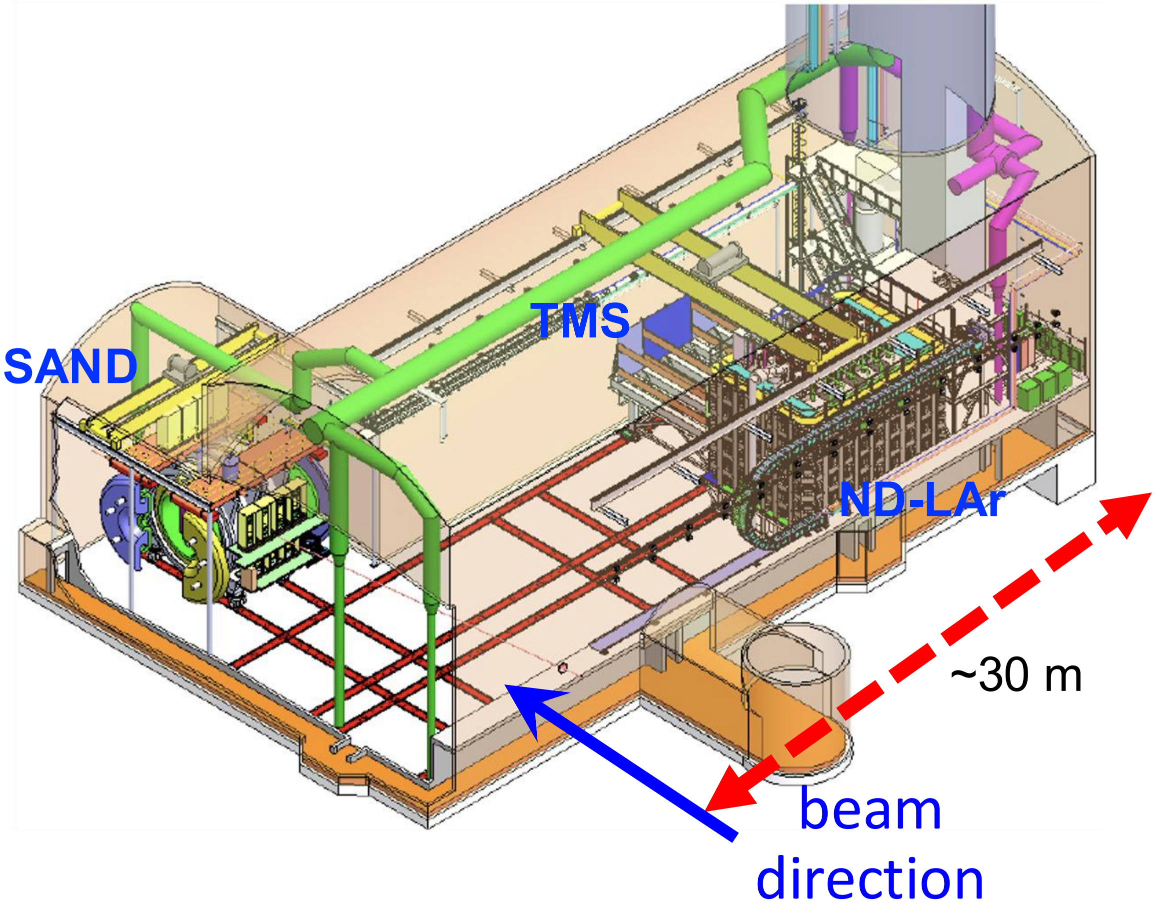


FD2: Vertical Drift (VD)

- Fiducial volume: 10 kt per module
- Anode of stacked segmented and perforated printed PCBs with etched electrodes
- 2 × 80 (top and bottom) Anode Charge Readout Planes (CRPs), with 3.4 m × 3 m each
- Cathode suspended at mid-height
- Photon detectors embedded in the cathode and cryostat walls for timing and triggering



DUNE Near Detector Complex



ND-LAr and TMS move off-axis to receive different beam fluxes for disentangling flux and cross sections and constraining systematics (PRISM)

Hall location
- 574 m from target
- ~60 m underground

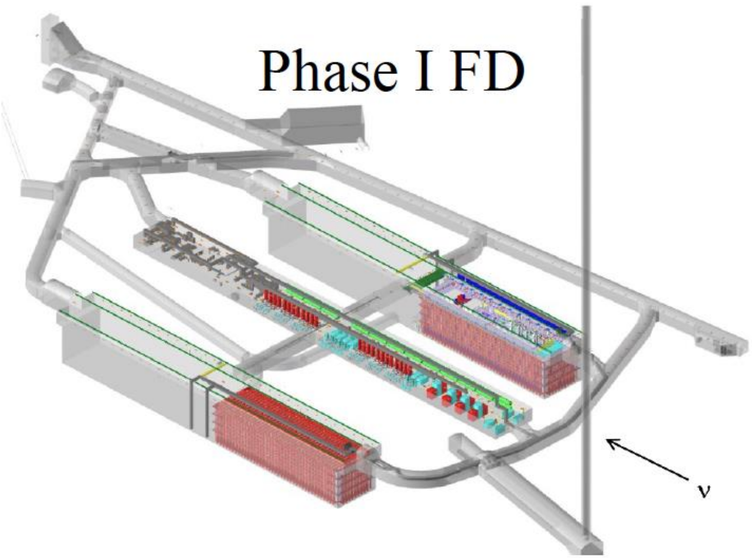
- ND-LAr: LArTPC with 3-D pixelated readout; segmented into 35 modules
- TMS: Muon Spectrometer (Phase I) built from steel and scintillator with magnetic field, will upgrade to ND-Gar (Phase II)
- SAND: Magnetized on-axis neutrino detector for beam monitoring

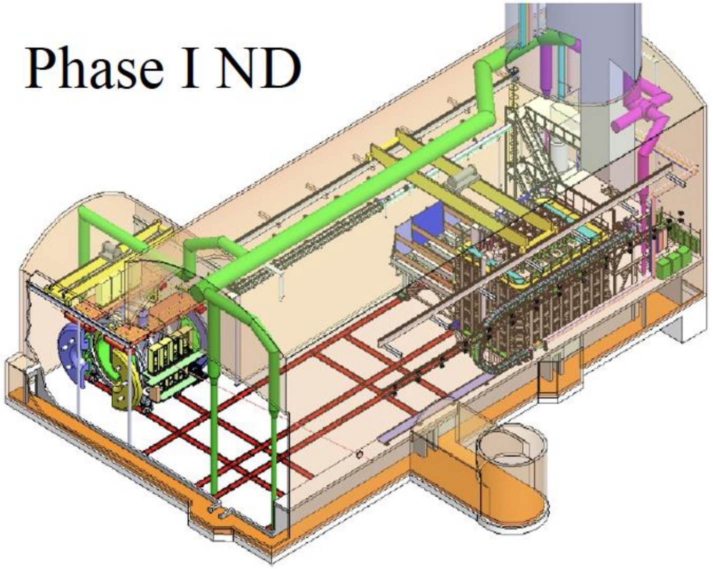
DUNE Plans and Installation

- 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.
- 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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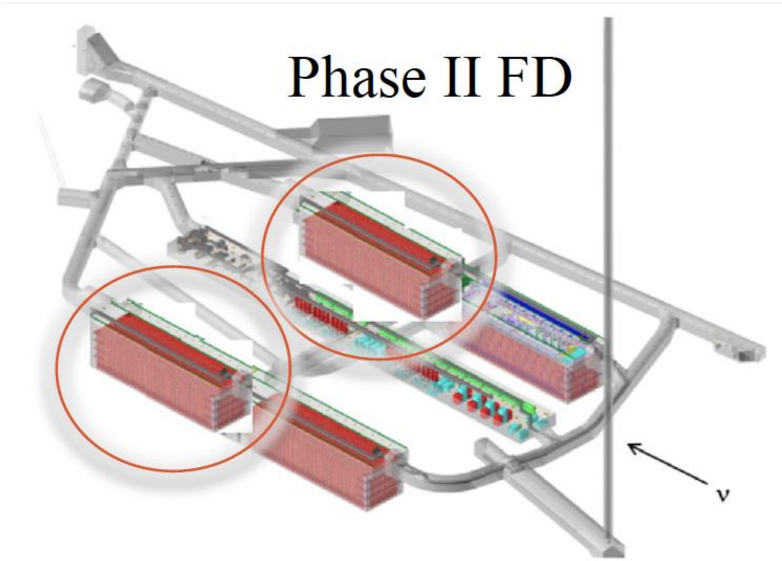
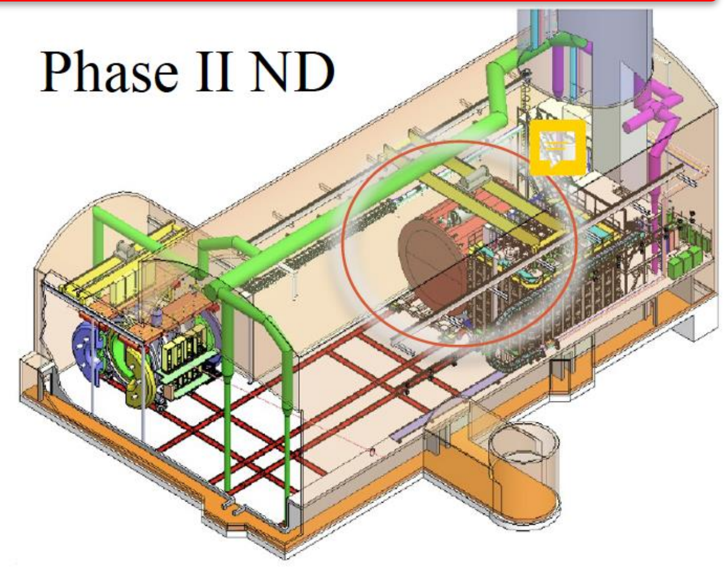
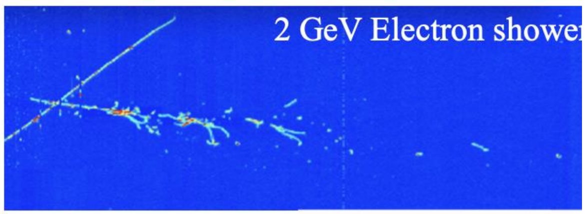
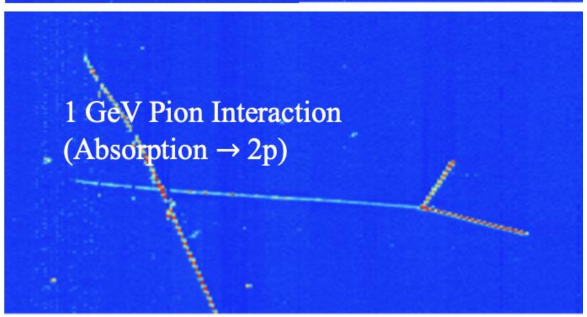


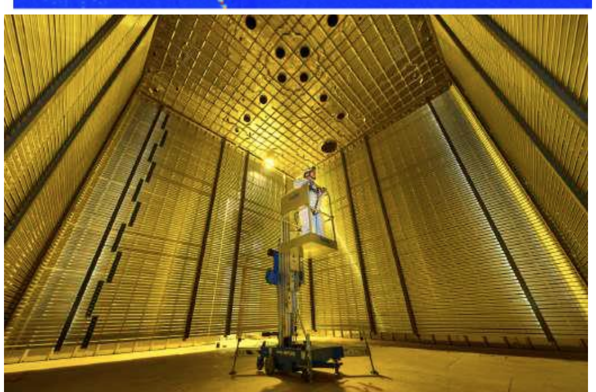


ProtoDUNEs at CERN

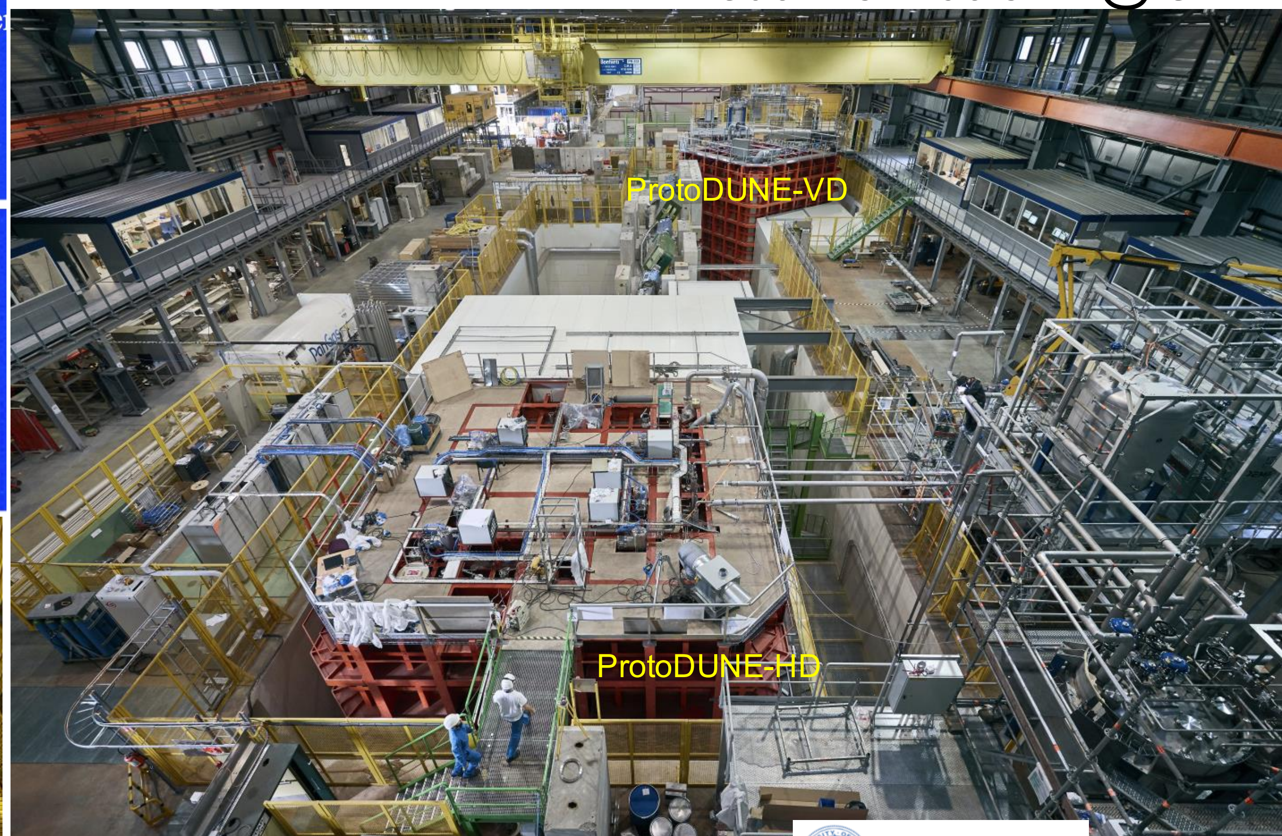
- Two major DUNE prototype LArTPCs at CERN
  - 770 t LAr mass each
  - Exposed to test beams at CERN, momentum-dependent beam composition contains e, $K^{\pm}$, μ, p, $\pi^{\pm}$
  - Both Horizontal (ProtoDUNE-HD) and Vertical (ProtoDUNE-VD) design successfully operated
- Demonstrating DUNE Far Detector technologies
- Input to DUNE FD physics (e.g. had xsec)
- First physics publications, with many analyses ongoing







Neutrino Platform @ CERN



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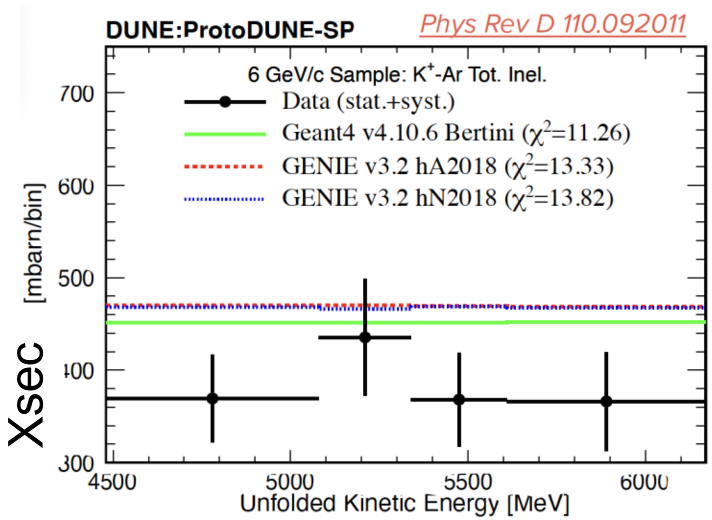
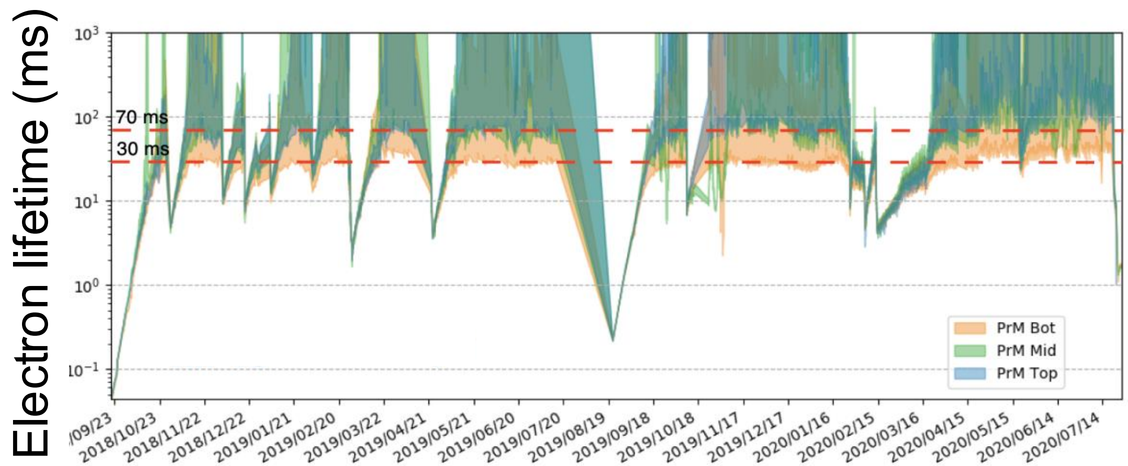
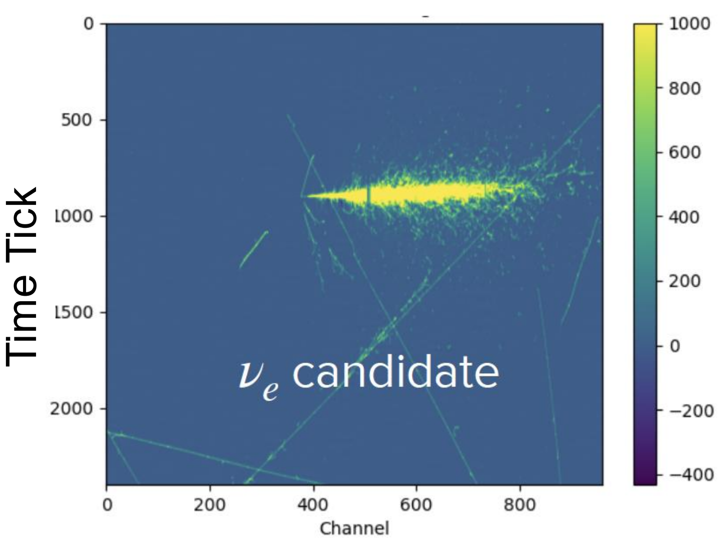
ProtoDUNE-HD Performance and Results



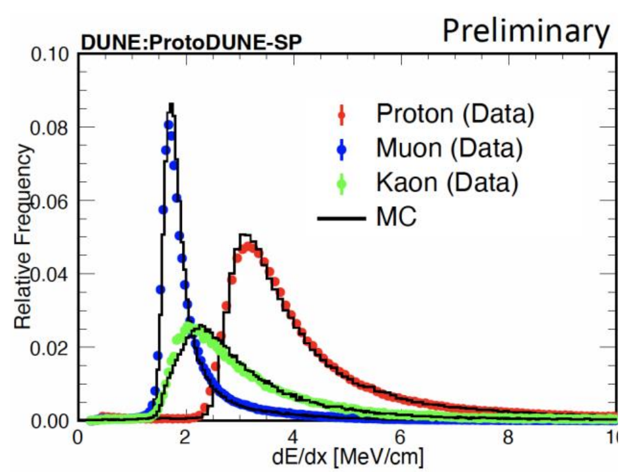
First measurement of kaon cross section on Ar at 5 GeV



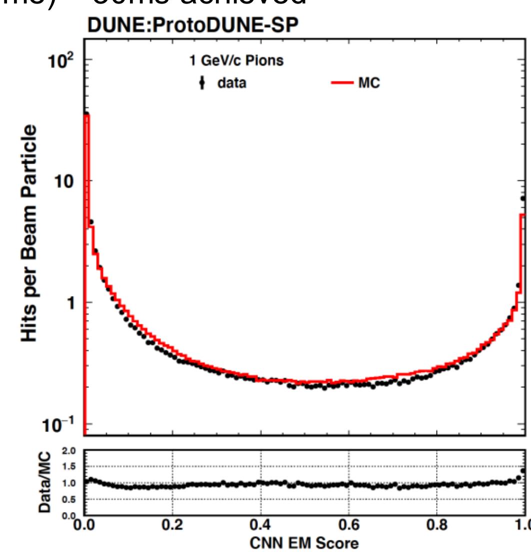
LAr purity (electron drift lifetime) > 30ms achieved



Parasitic neutrinos in SPS beam



dE/dx of test beam particles



ML based PID

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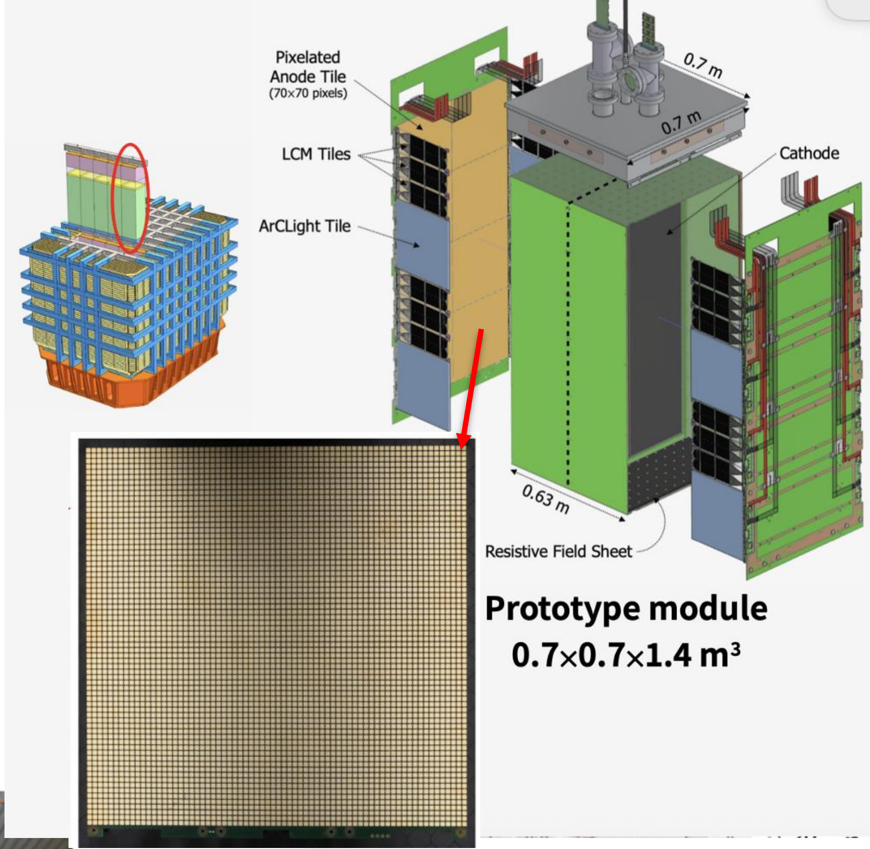
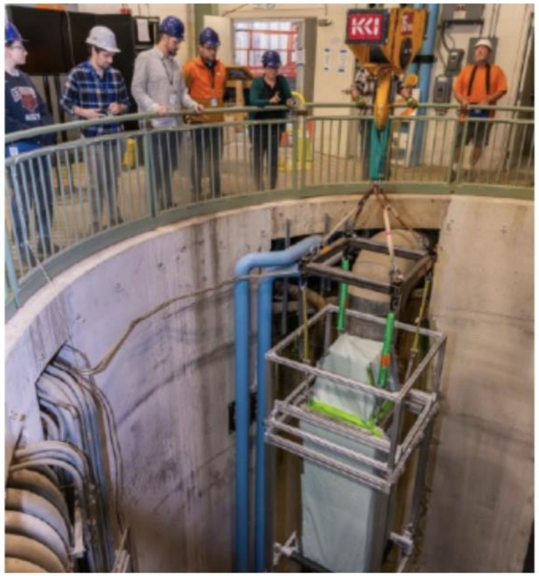
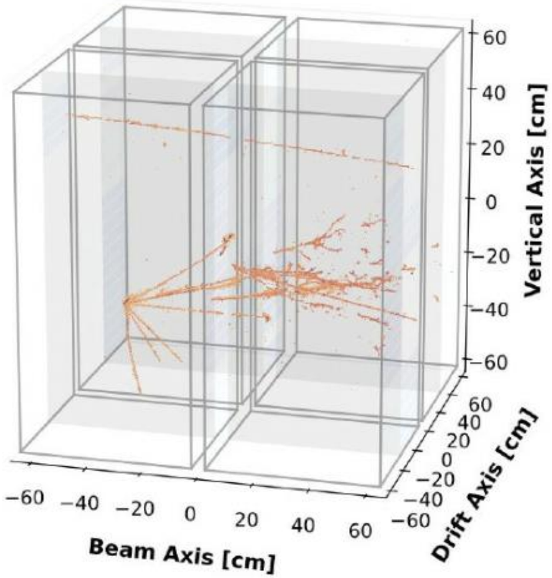
ND-LAr Prototype at Fermilab

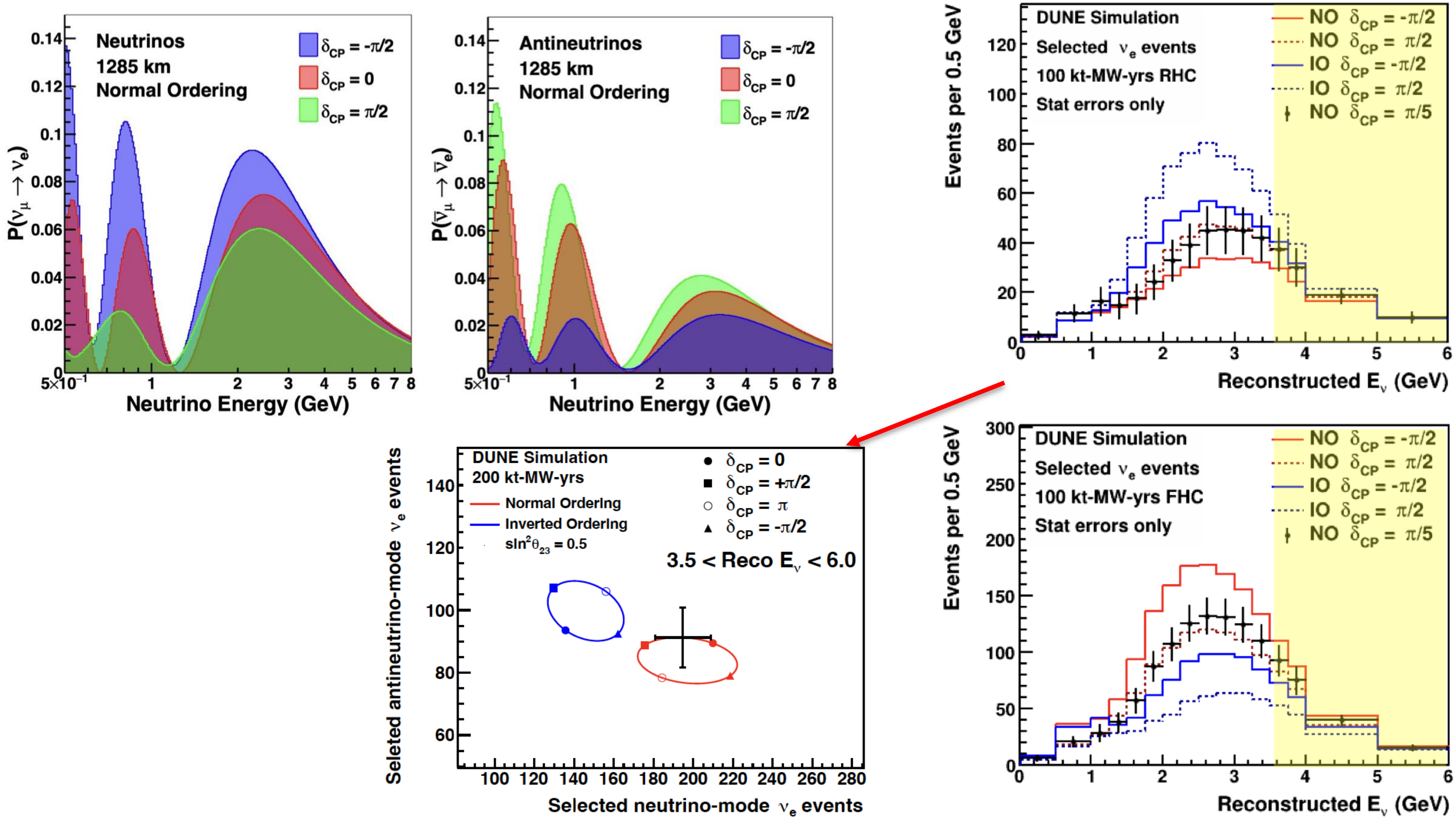
- 2x2 prototype of ND-LAr operated in NuMI neutrino beam in summer 2024
- Pixel readout LArTPC → direct 3D image
- Neutrino data taken
- Analysis ongoing, additional beam run planned for 2026





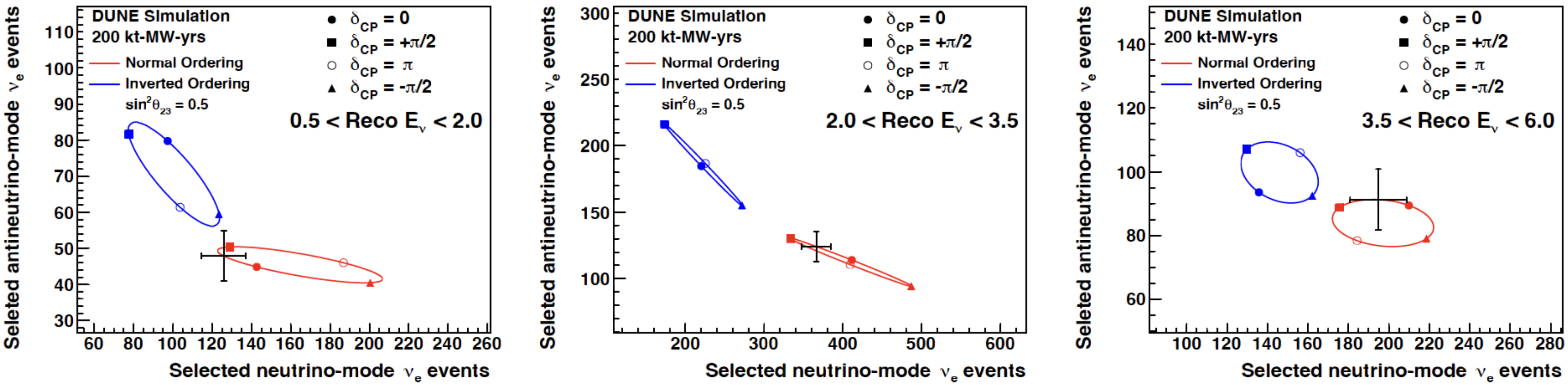


ν_e appearance - ν_e vs anti-ν_e events



- Few percent statistical uncertainties utilizing wide band LBL
- Allow measure oscillation parameters at each L/E bin

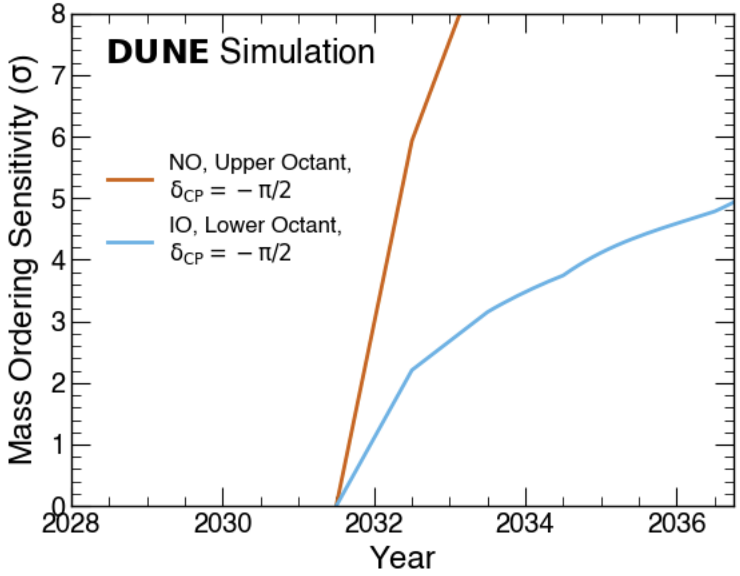
ν_e appearance - ν_e vs anti-ν_e events



- Will make unambiguous, high-precision measurements of mass ordering, δ_{CP} and θ_{23} octant, without relying on other oscillation parameters and experiments
- New physics would likely distort observations as a function of L/E → unique sensitivity from DUNE

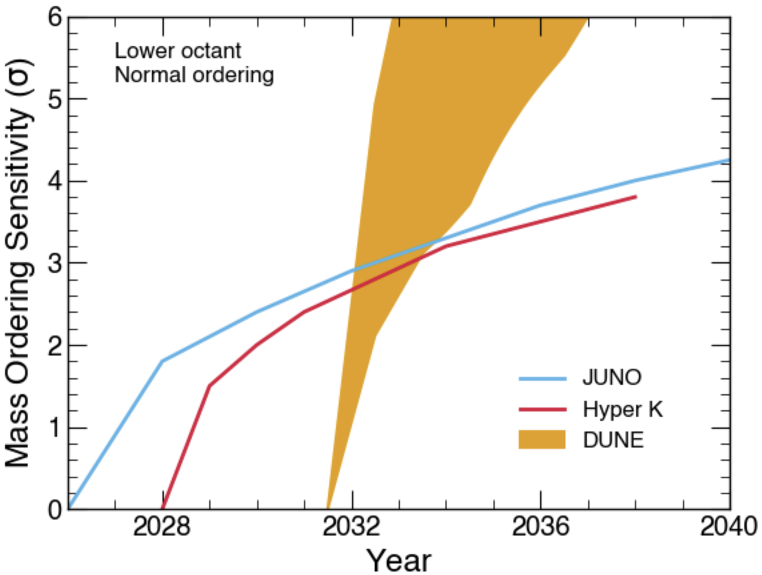
DUNE sensitivity to mass ordering

- In the most favorable scenario (CP value), DUNE surpasses 5σ in under 1 year.

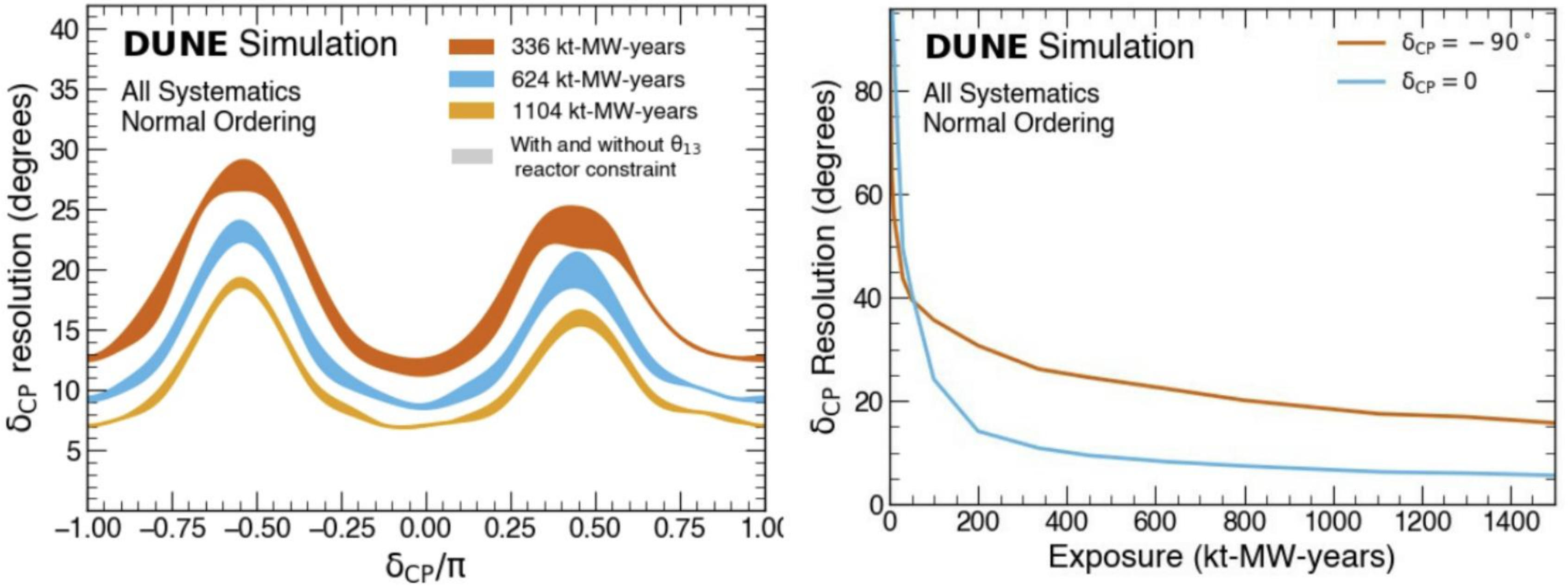


- In the least favorable scenario, DUNE reaches 5σ in about 5 years.

- DUNE will determine the neutrino mass ordering for any value of δ_{CP}

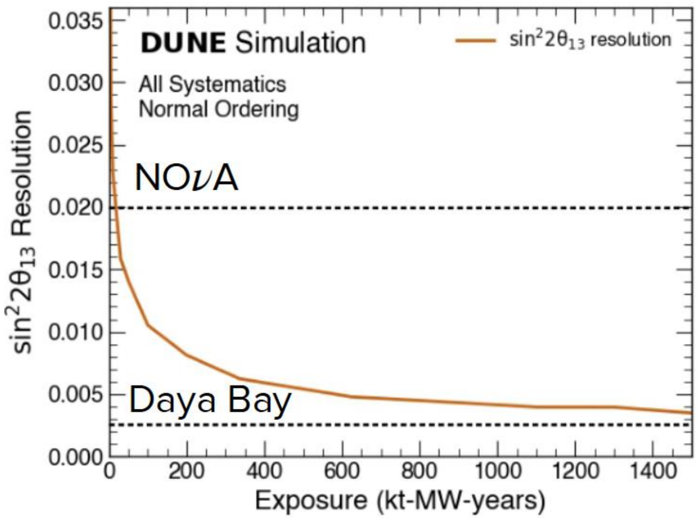


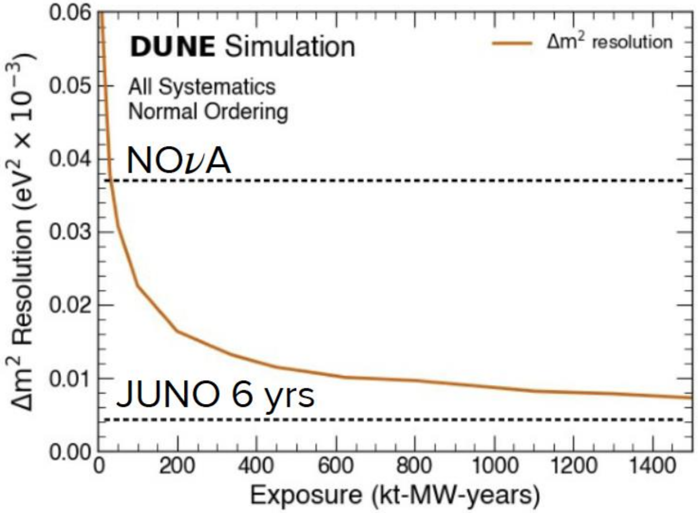
DUNE Resolution of measurement δ_{CP}



- Ambiguity such as $\boldsymbol{\delta_{CP}}$=p/4 vs. 3p/4 can be resolved due to DUNE's broad energy spectrum
- DUNE has the best ultimate $\boldsymbol{\delta_{CP}}$ resolution especially if CP is violated

Testing the 3-flavor paradigm with precision measurements at DUNE





- Measurements of θ_{13} obtained from ν_e appearance long-baseline and reactor experiments $\overline{\nu_e}$ disappearance are only equivalent if unitarity is assumed
- DUNE approaches JUNO precision of Δm^2
- Opportunity to test the 3-flavor paradigm

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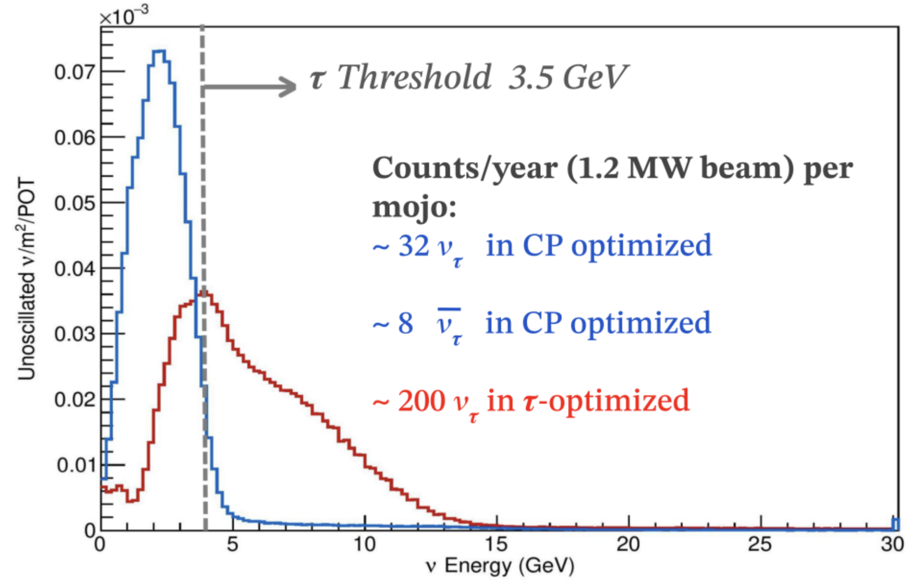
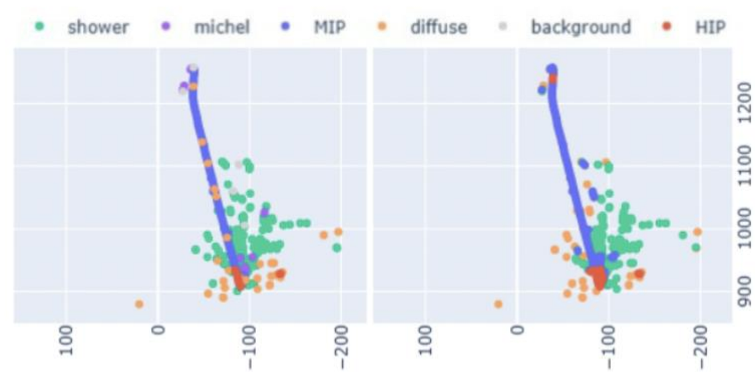
ν_τ appearance in DUNE beam

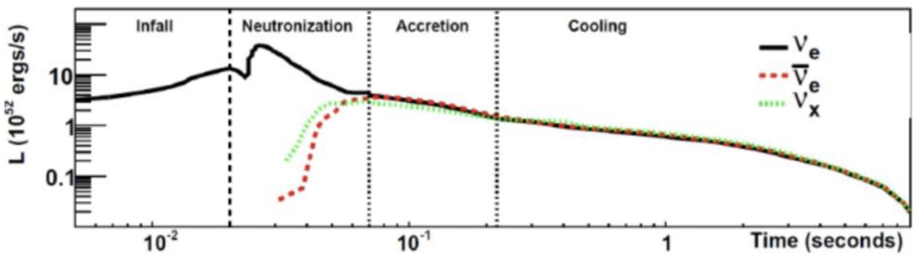
- DUNE has a substantial flux above 3.5 GeV CC threshold → possibility to measure ν_τ appearance
- Imaging capabilities of DUNE's LArTPCs makes it possible to reconstruct complex τ final states kinematically
- ML-driven reconstruction based on hierarchical graph neutral network (GNN) being pursued
- Opportunity to directly measure 3-flavor oscillations and test unitarity

arXiv:2203.05591

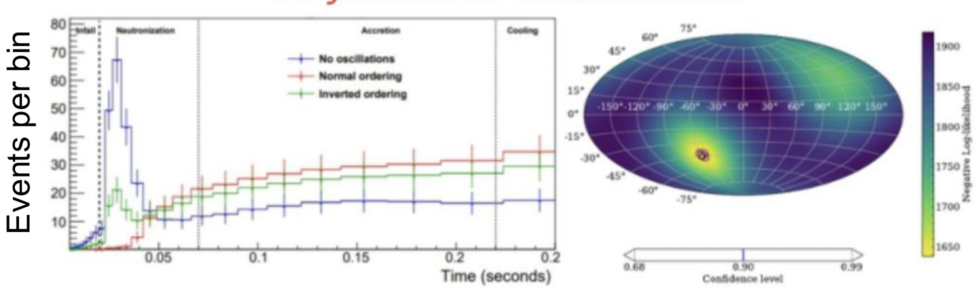




Supernova Burst (SNB)



Phys Rev D 111.092006



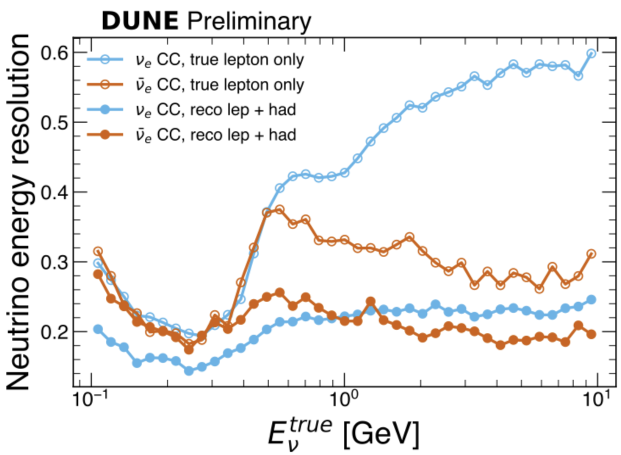
	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

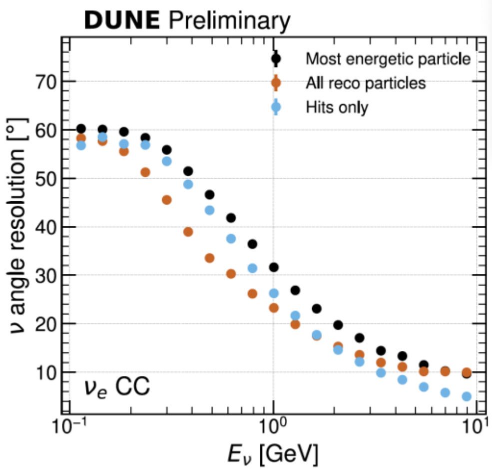
[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

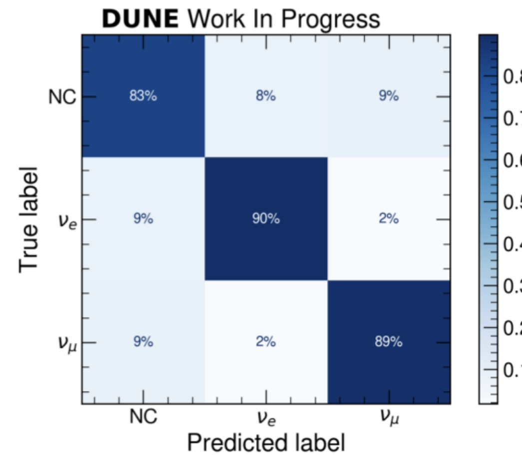
- Time and energy profile of SNB neutrino flux is rich is supernova astrophysics
- ~ 5° pointing resolution depending on SNB location
- Flux includes ν_e/ $\overline{\nu_e}$ and other flavours - **only DUNE measures $\boldsymbol{\nu_e}$ due to Argon target**
- DUNE is uniquely sensitive to mass ordering via SNB detection
- SNB program starts once the first FD module is turned on, earlier than beam physics

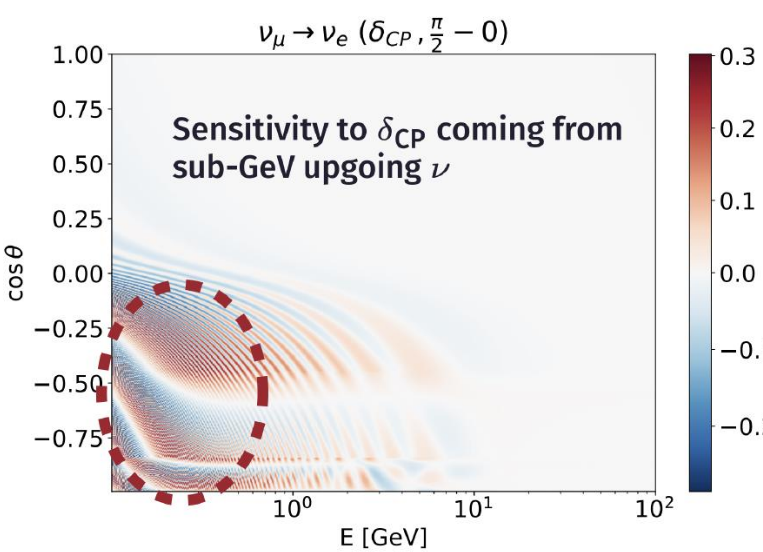
Atmospheric Neutrinos

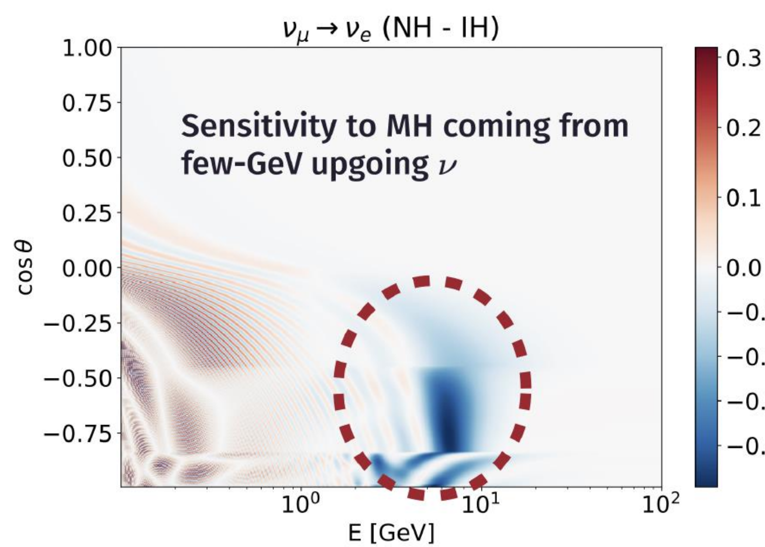
- Atmospheric neutrinos will be DUNE's first data
- Including reconstructed hadrons substantially improves angle resolution





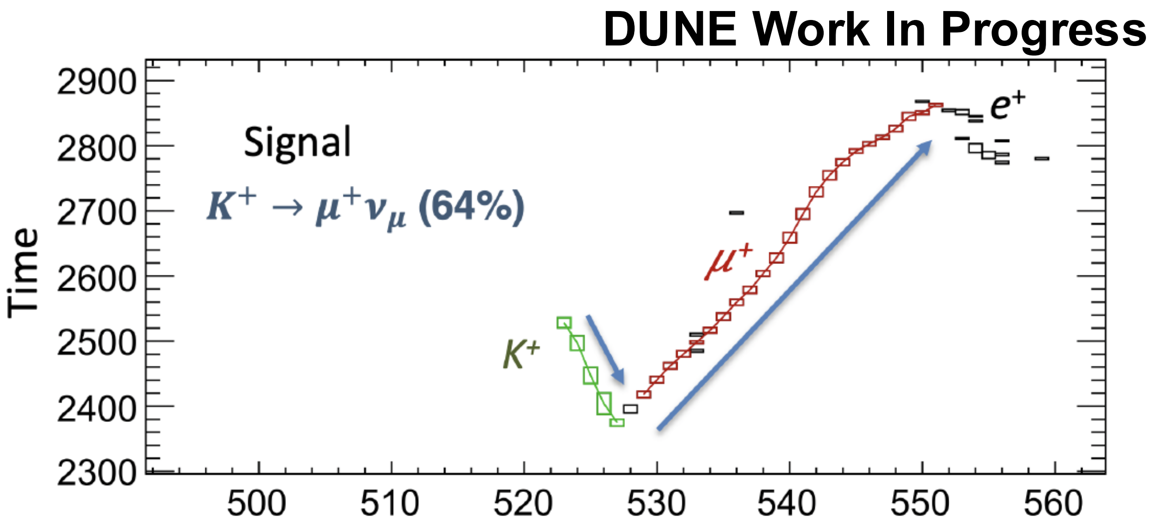






Proton decay

- DUNE will be an excellent detector to perform nucleon decay searches: Underground location, Very large fiducial mass; Millimetre size imaging capabilities
- Golden channel in DUNE: $p \to K^{+}\bar{\nu}$



- DUNE can image the 3 particles
- DUNE sensitivity comparable to larger Cherenkov detectors:

$$\tau/\mathrm{Br}(p \to \bar{\nu}K^{+}) > 1.3 \times 10^{34}\ \text{years}$$

UCIrvine

DUNE Status and timeline

- Far site excavation complete
- Building, Site and Beam Infrastructure ongoing
- Cryostat installation by Jan. 2026
- FD1 Installation by Mid 2027
- Physics by the end of 2029: Solar, atmospheric and astrophysical neutrinos
- Beam physics with near detector by 2031

DUNE Collaboration

- More than 1,400 collaborators
- Over 200 institutions
- Over 35 countries + CERN

Summary

- DUNE will make decisive measurements for neutrino oscillations, including mass ordering and CP violation
- DUNE will test the 3-flavor paradigm and search for new physics in neutrino oscillations
- DUNE Near Detector has rich physic programs (cross-sections, BSM, etc)
- DUNE has unique capabilities to explore a broad range of non-beam physics
- DUNE prototype programs are successful
- DUNE is under construction and on track to deliver science

Thank you!