The DUNE Experiment: Status & Prospects

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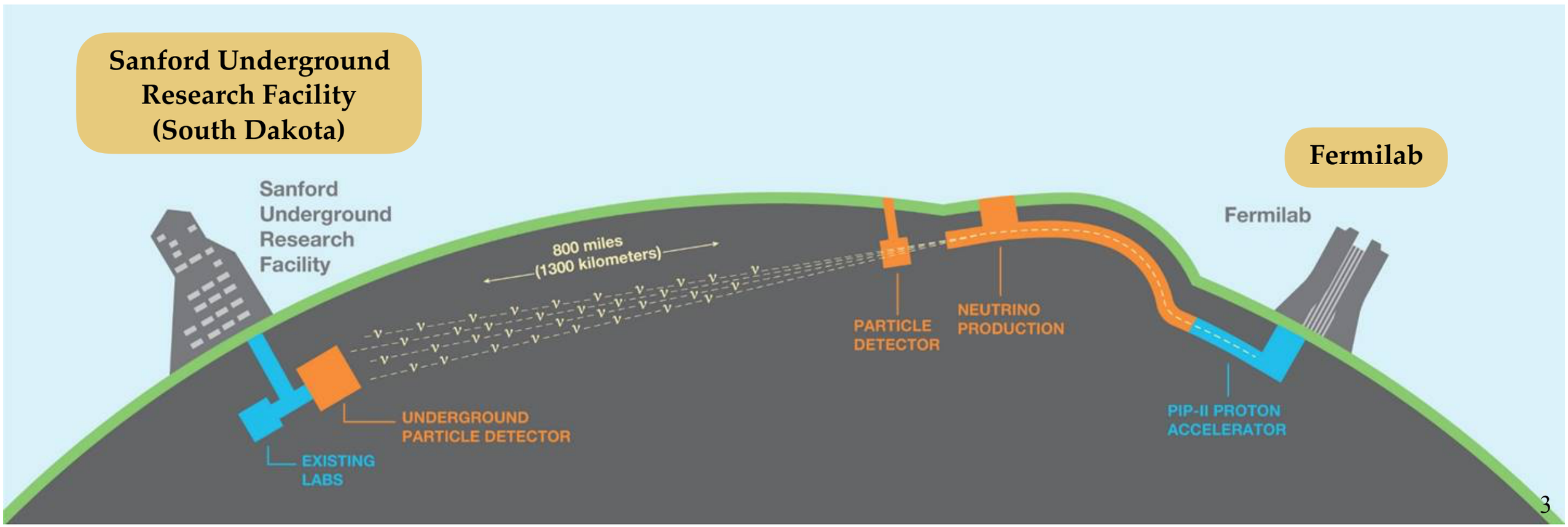
In This Talk

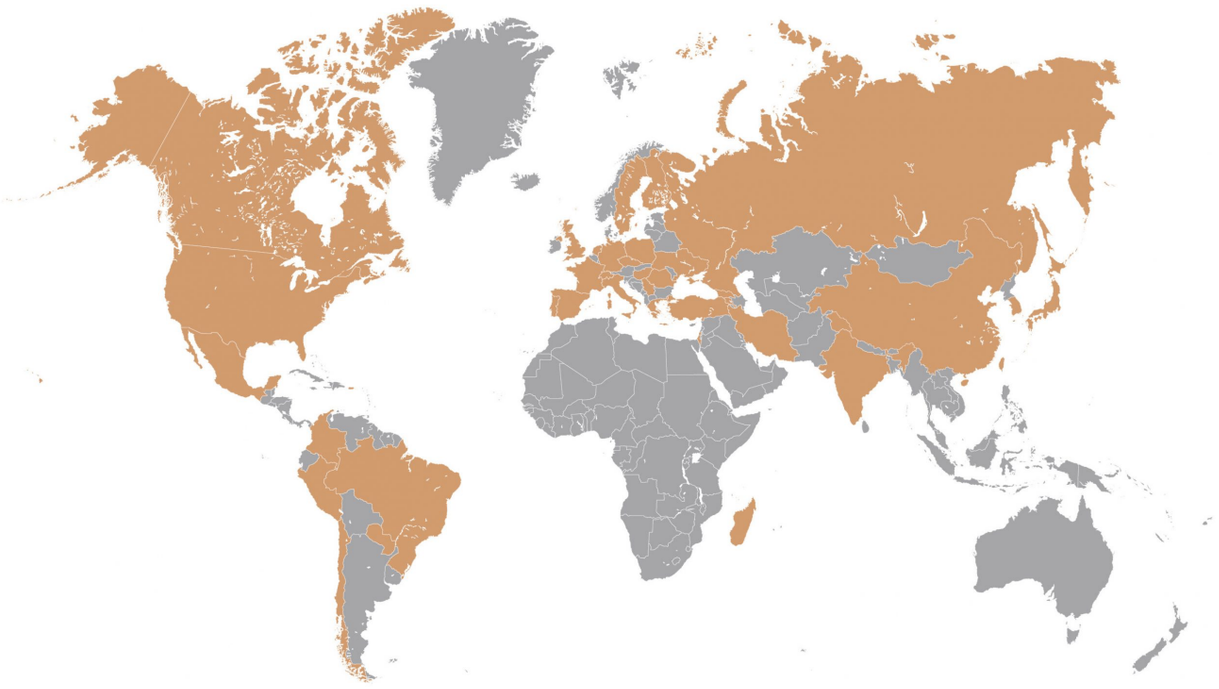
- DUNE Overview
- Neutrino Beamline
- Near Detector
- Far Detector & Technology
- DUNE Physics Potential
- Progress & Milestones
- Summary

The Deep Underground Neutrino Experiment (DUNE)

- MW-scale intense neutrino beam from Fermilab to South Dakota over 800 miles
- A multi-technology near detector complex (ND) at Fermilab
- Far site cavern at SURF will accommodate four 17 kt far detector (FD) modules
- The Long-Baseline Neutrino Facility (LBNF) provides the beamline and dual site facilities
- **Rich Physics program:** Precision neutrino oscillation physics, MeV-scale physics, Nucleon decay, and a suite of BSM Searches



The DUNE Collaboration

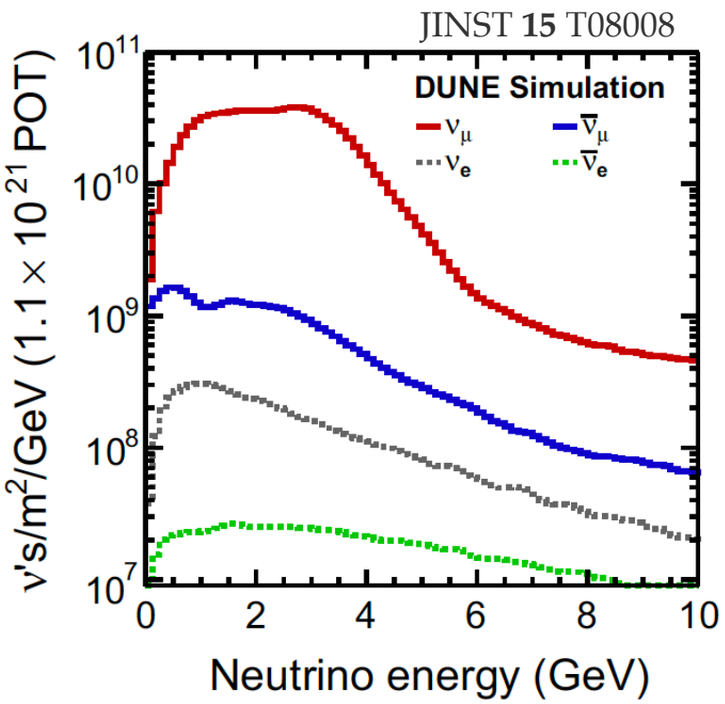


1400+ collaborators from 200+ institutions in 30+ countries plus CERN

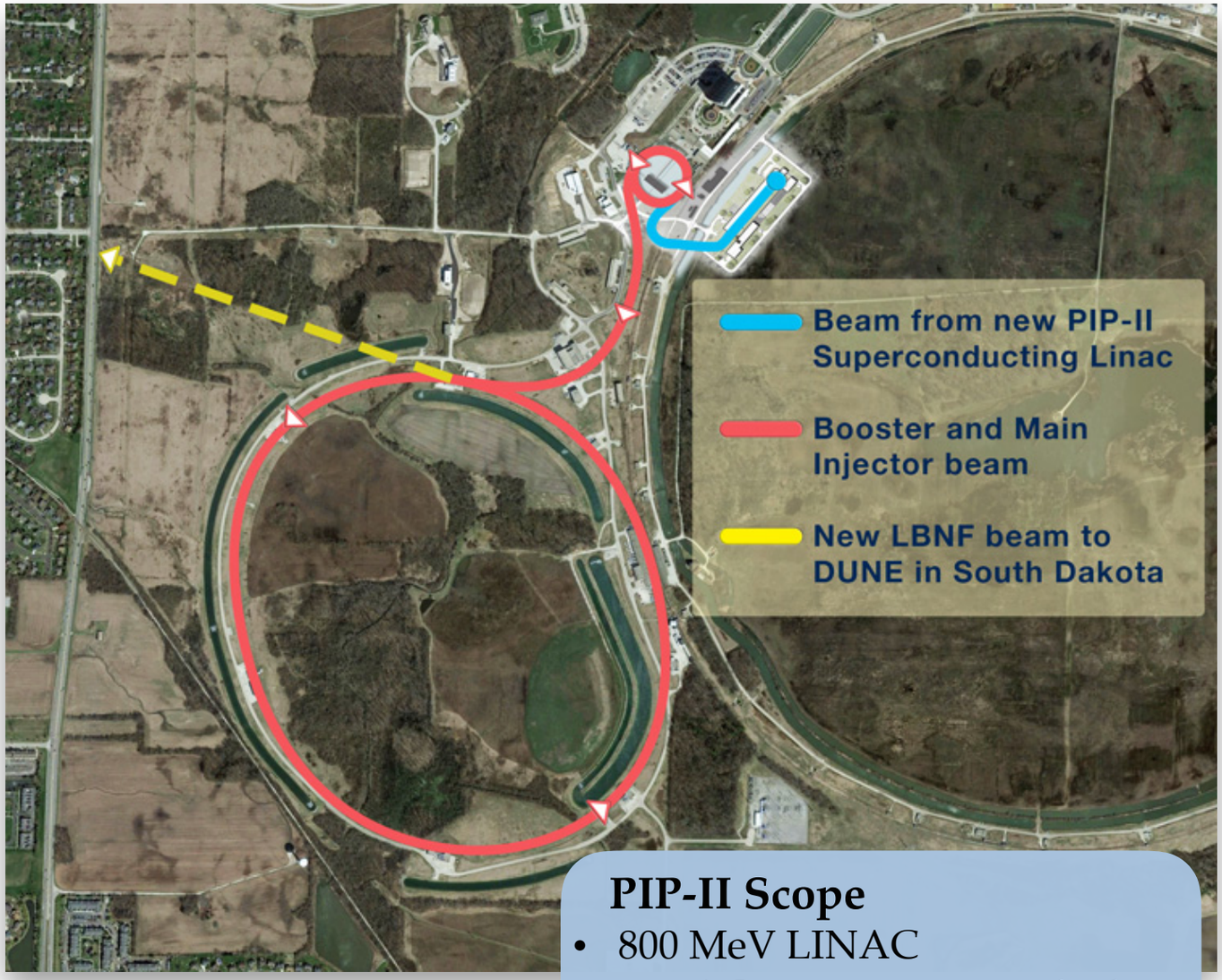
DUNE Collaboration Meeting, May 2022, Fermilab

The Neutrino Beamline

- The Proton Improvement Plan (PIP-II) will enable the **world's most intense beam of neutrinos** to DUNE
- 1.2 MW beam intensity, upgradable to 2.4 MW
- **Goal:** first MW-scale to DUNE by 2031

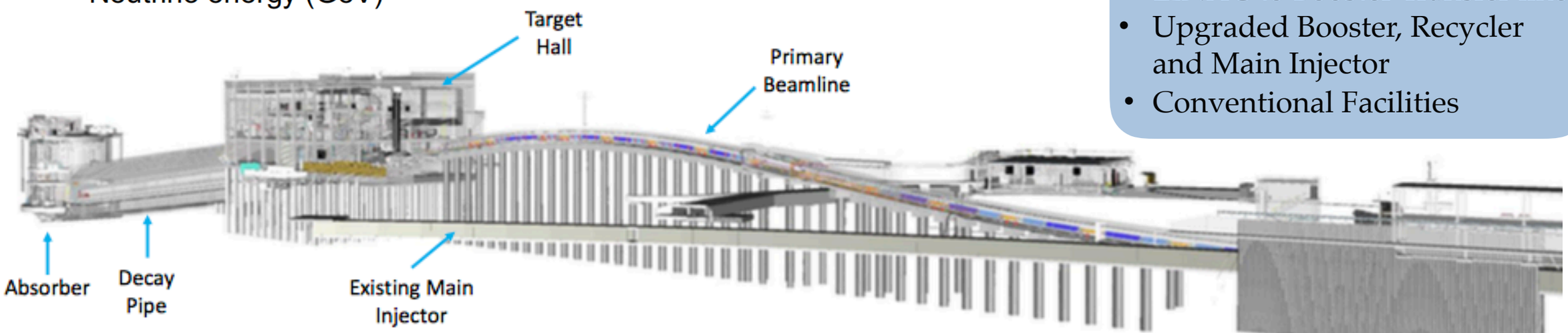


See talk by J. Eldred



PIP-II Scope

- 800 MeV LINAC
- LINAC to Booster Transfer line
- Upgraded Booster, Recycler and Main Injector
- Conventional Facilities



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

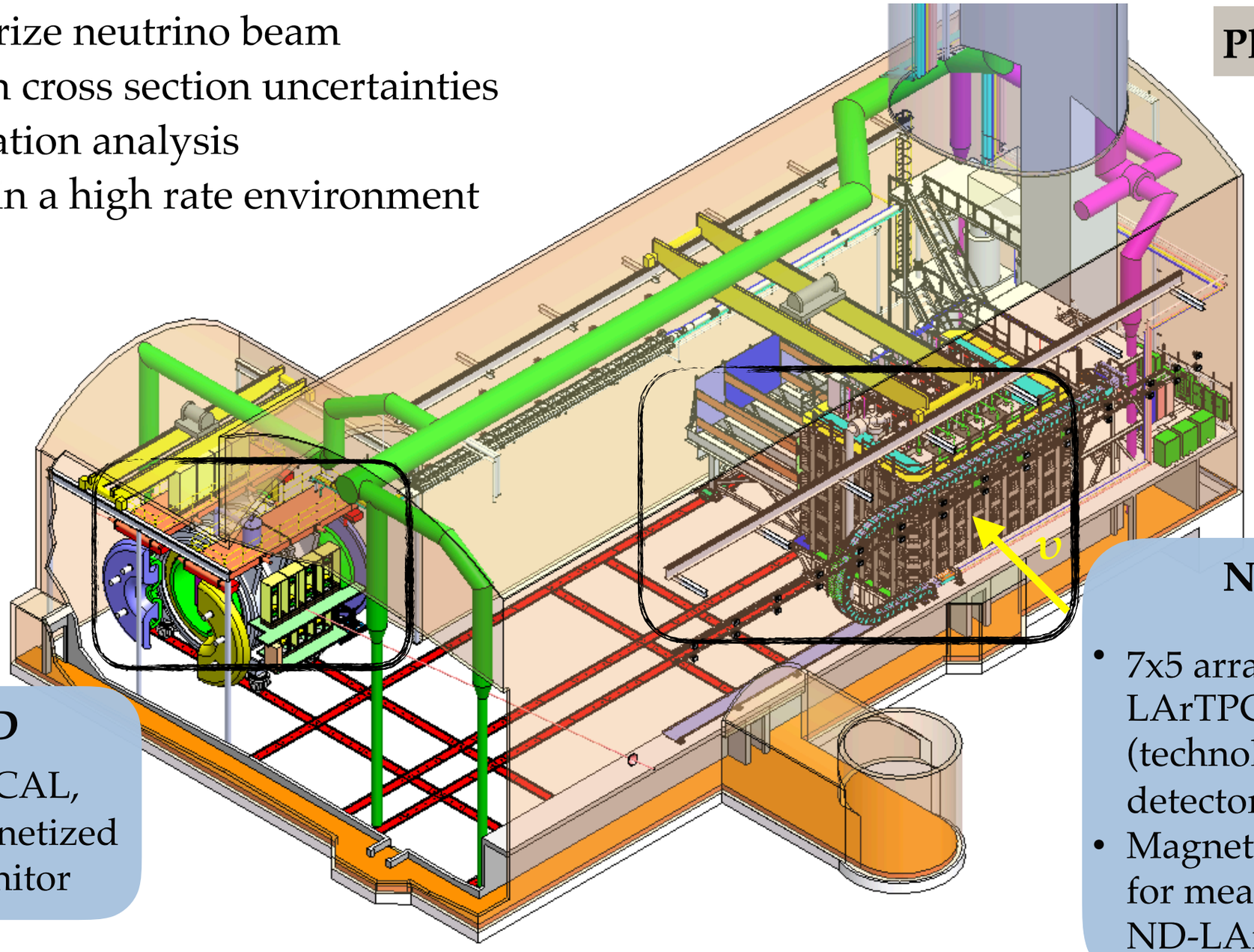
The DUNE Near Detector Complex

- Located **60 m** underground at Fermilab; **574 m** from neutrino beam target
- Comprises of multiple technologies; will be built in 2 phases

Primary Goals

- Characterize neutrino beam
- Constrain cross section uncertainties for oscillation analysis
- Perform in a high rate environment

Phase 1 design



See talks by Z. Vallari & J. Walcott

SAND

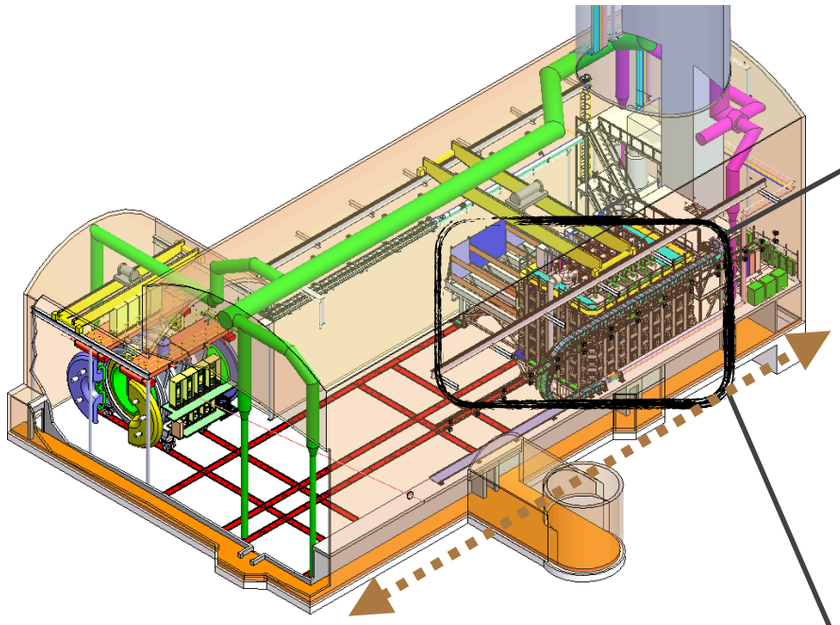
Tracker, ECAL,
On axis magnetized beam monitor

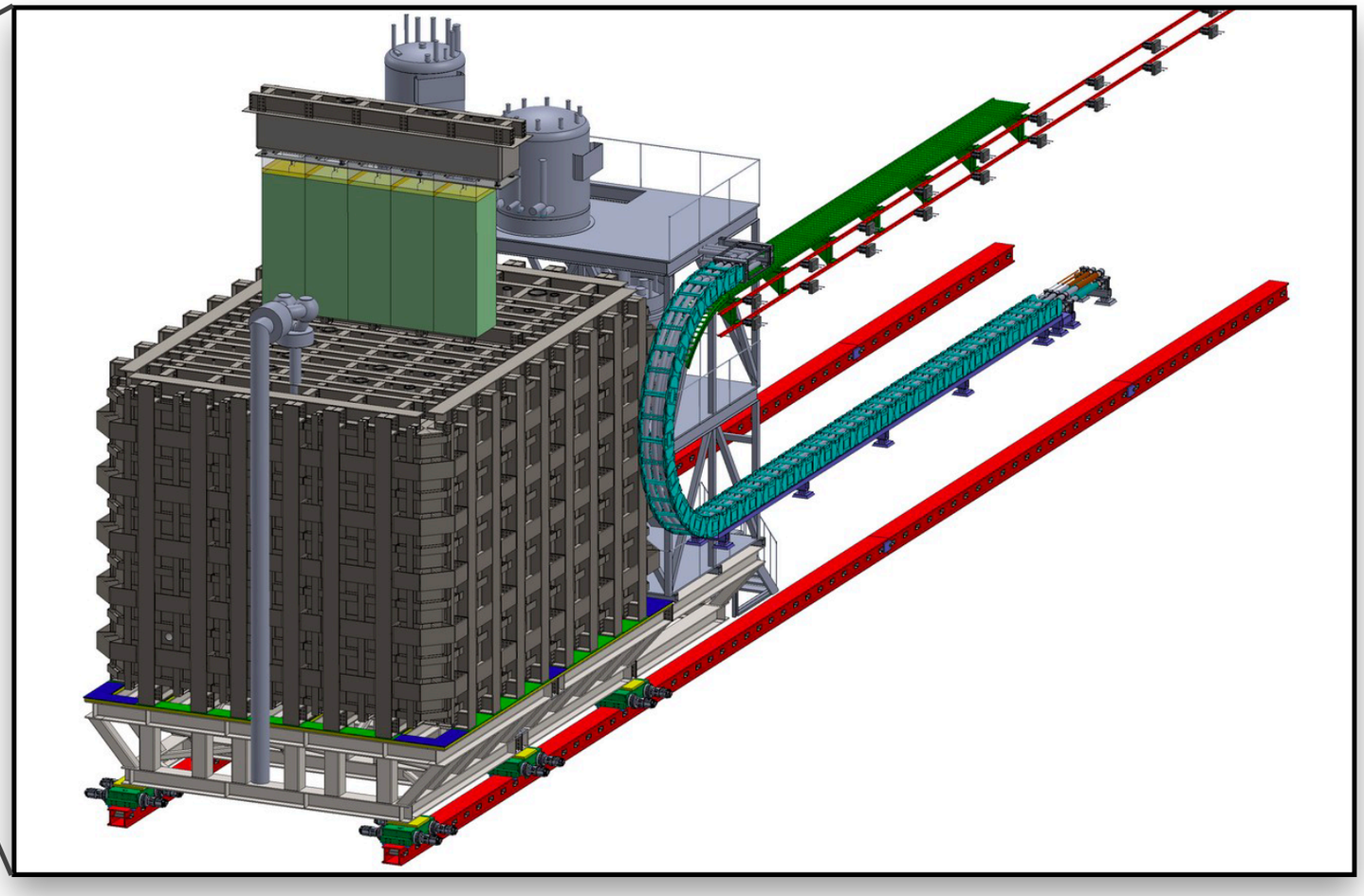
ND-LAr + TMS

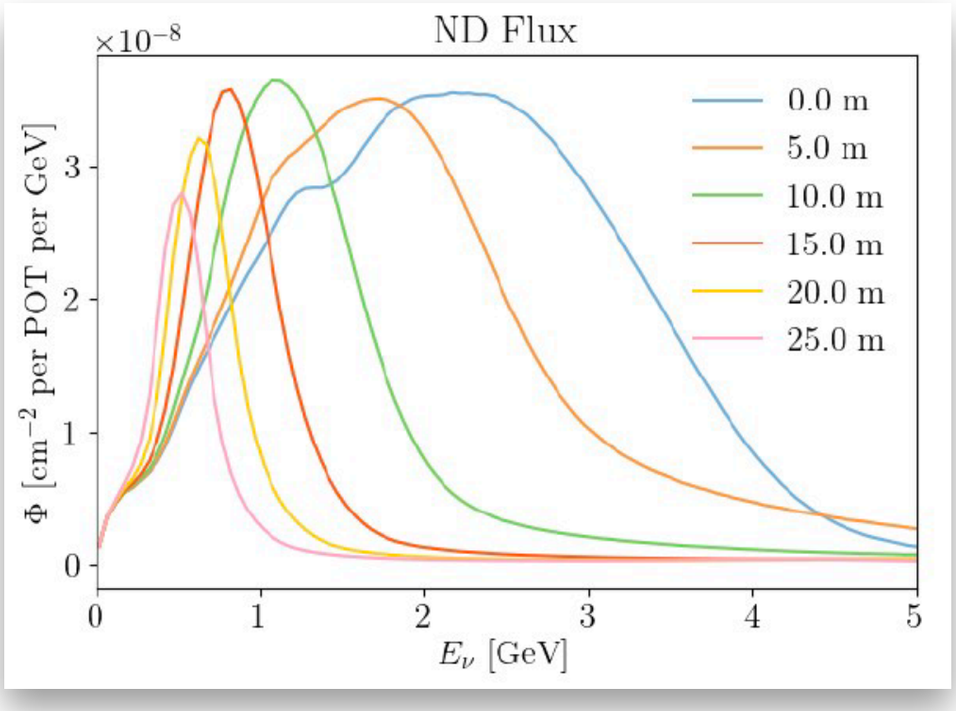
- 7x5 array of modular 1x1x3 m^3 LArTPCs with pixel readout (technology closest to far detector)
- Magnetized steel range stack for measuring muons that exit ND-LAr

CDR: arXiv:2103.13910

The DUNE-PRISM

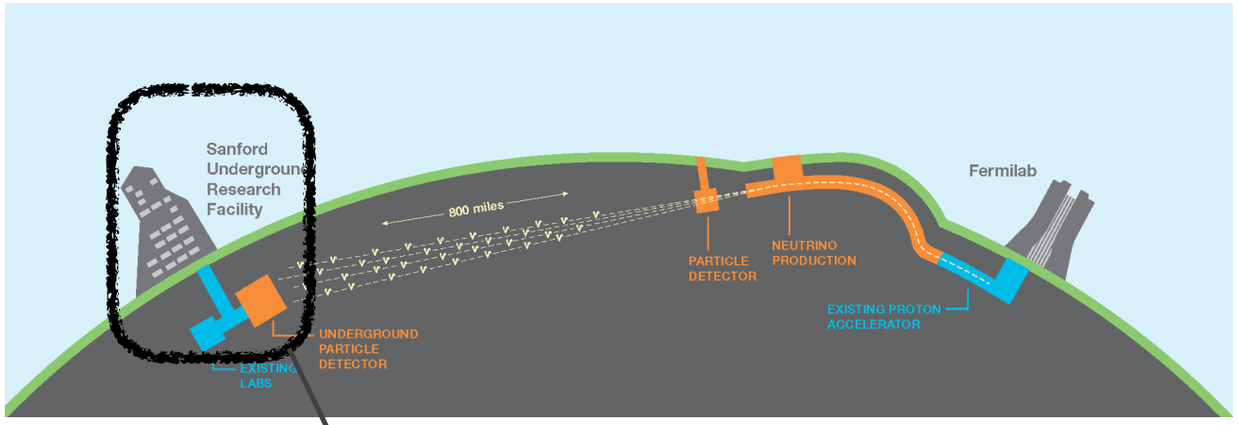


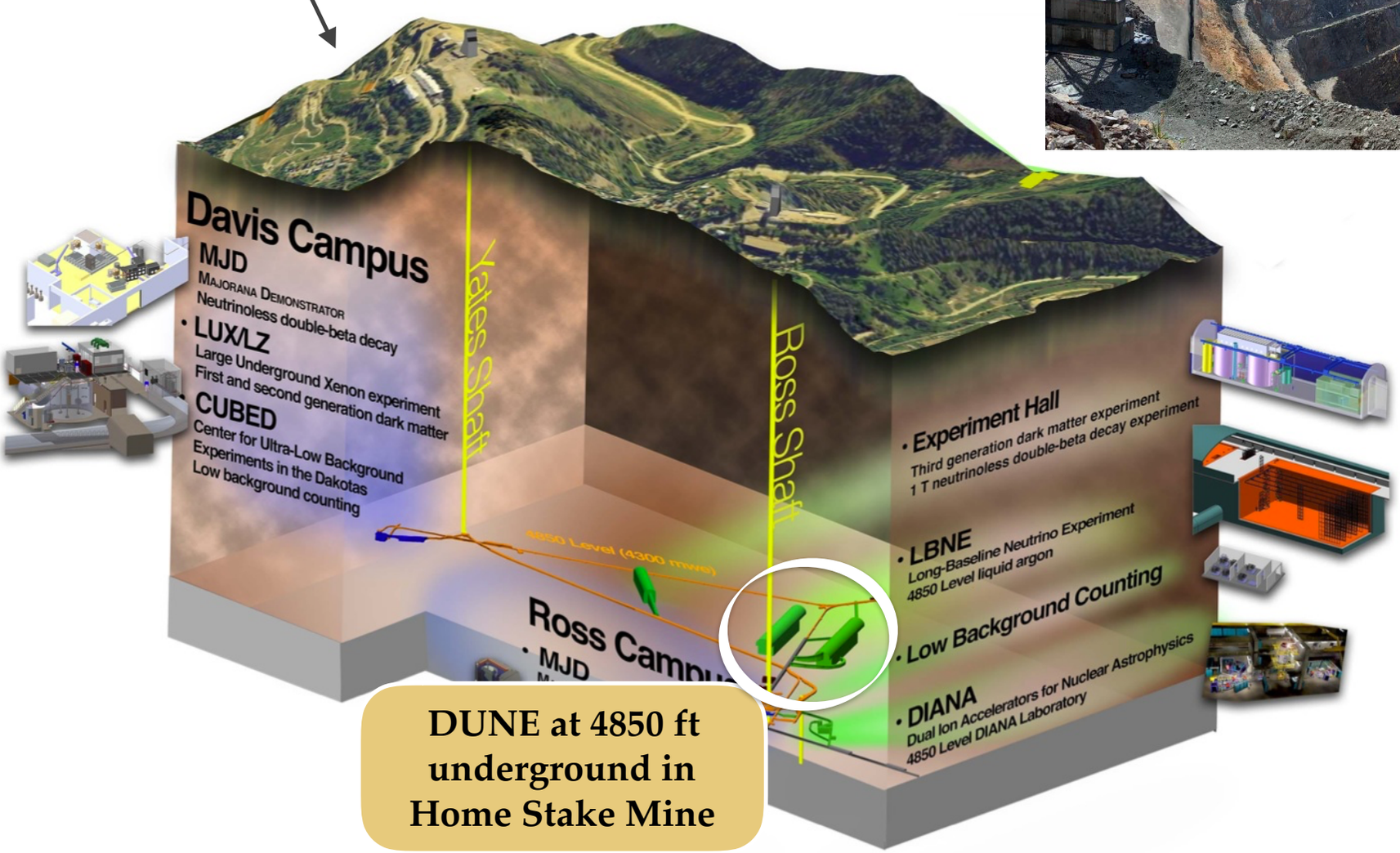




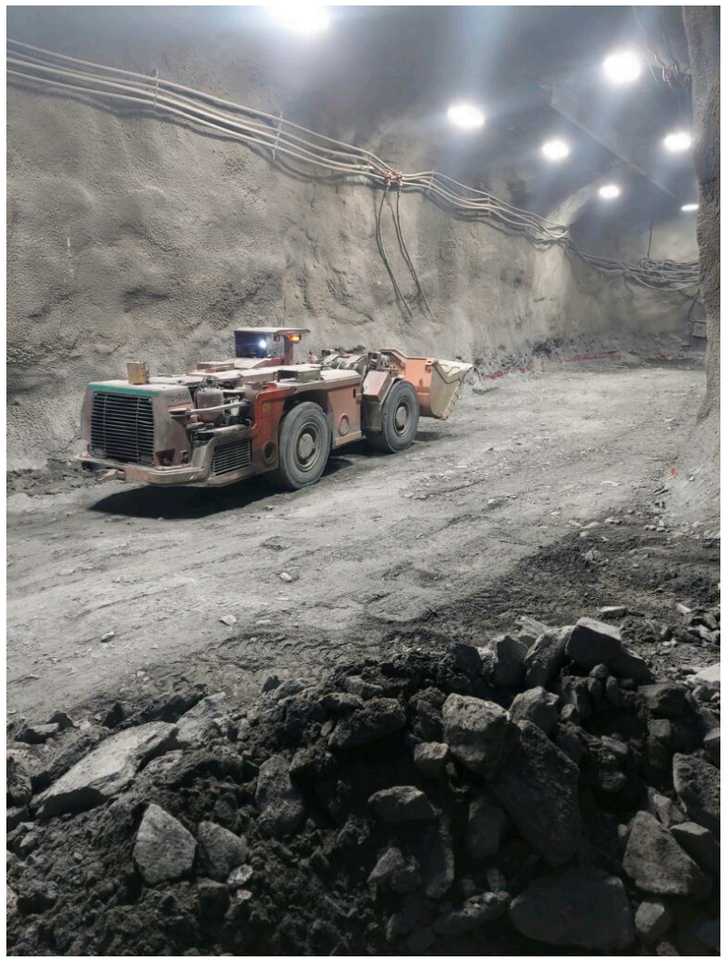
- ND flux changes with angle due to pion decay kinematics
- ND-LAr and TMS systems can move off-axis up to 28.5 m to observe varied beam spectra
- Will help address uncertainties in ND to FD extrapolation

The DUNE Far Site

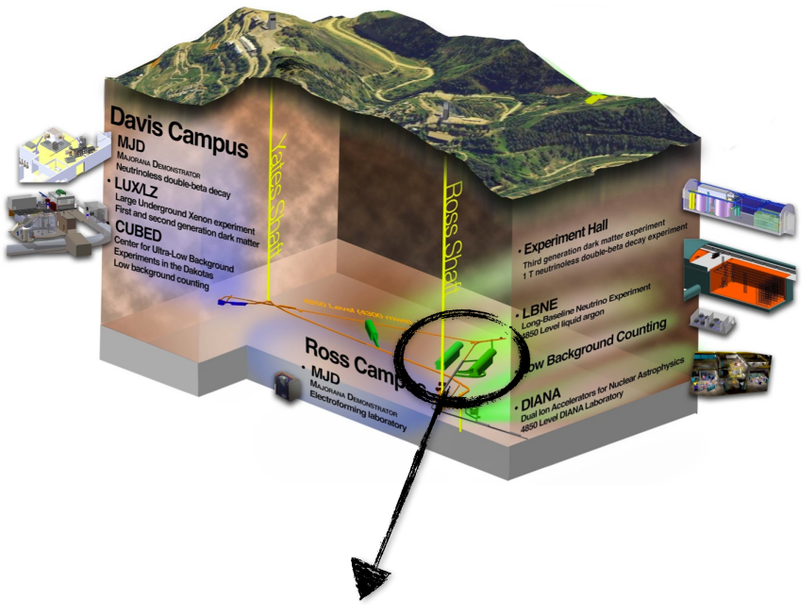


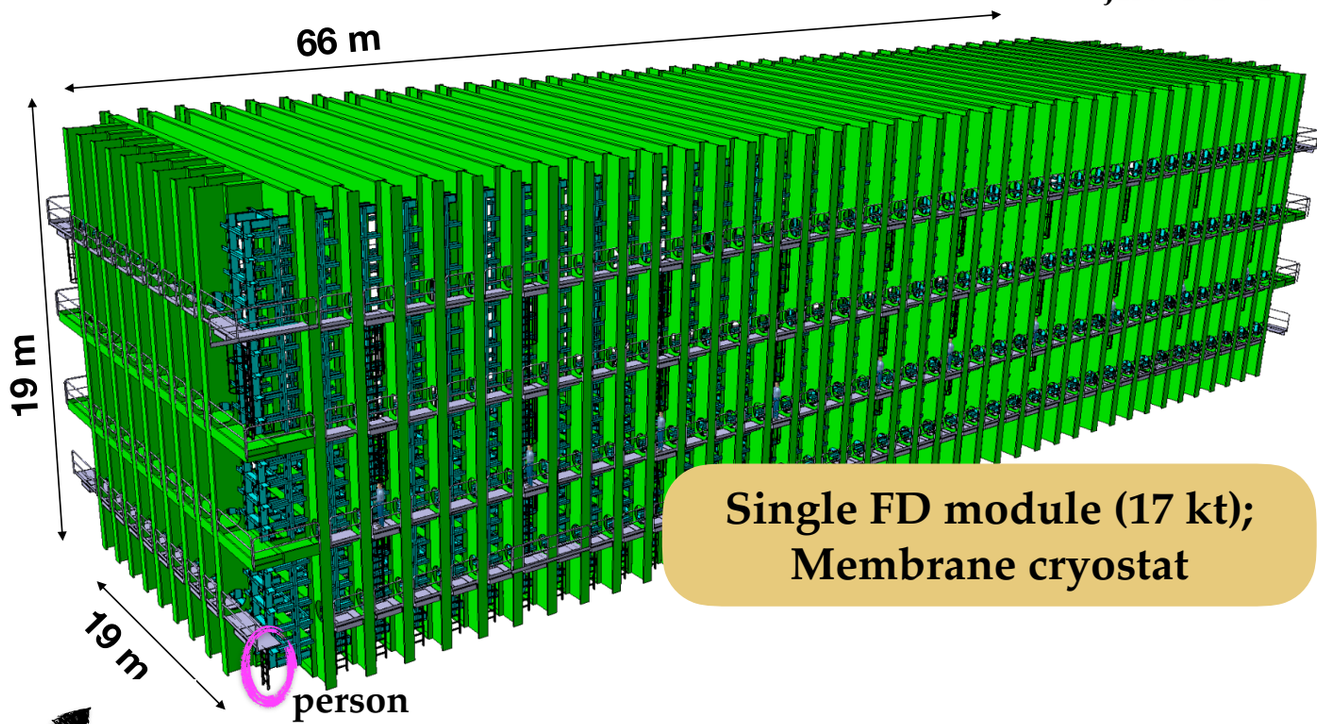


DUNE at 4850 ft underground in Home Stake Mine



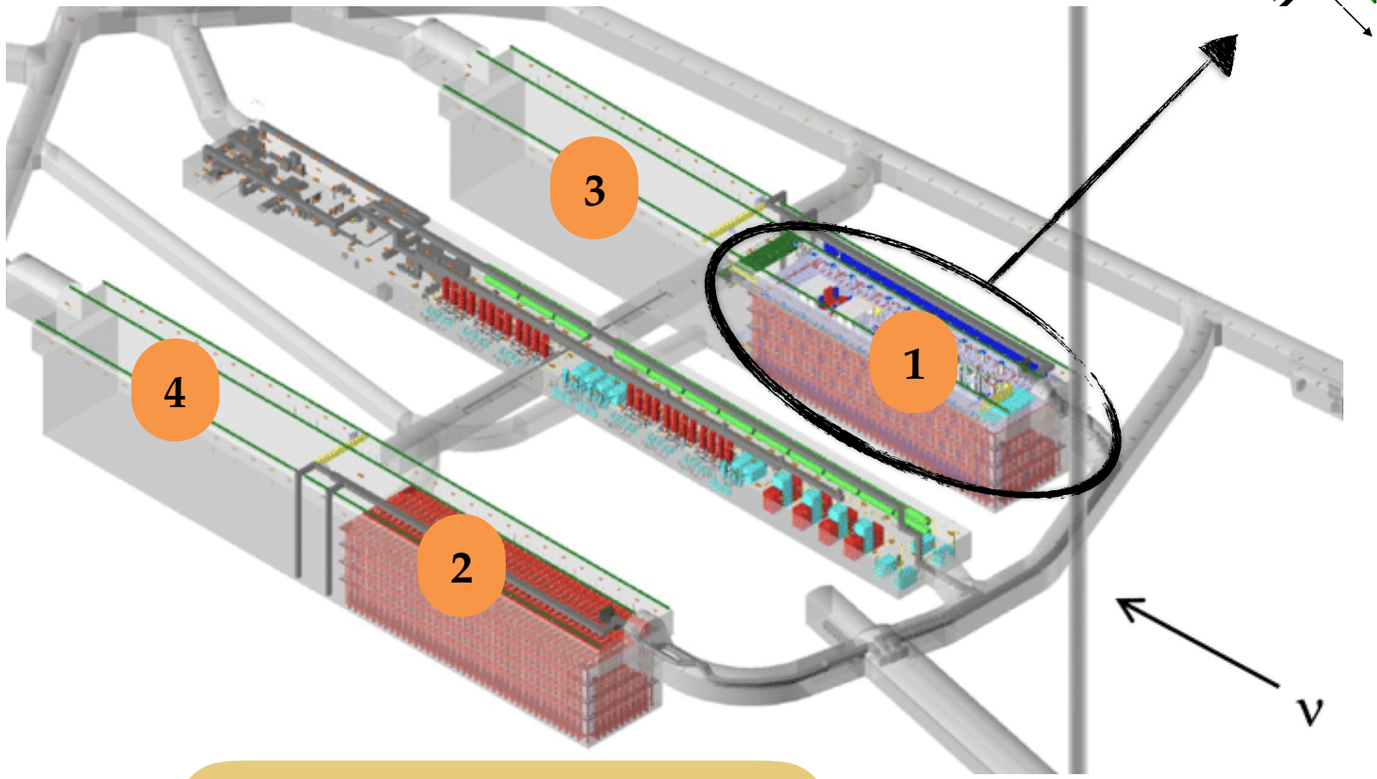
The DUNE Far Detector





JINST 15 T08010

Single FD module (17 kt); Membrane cryostat



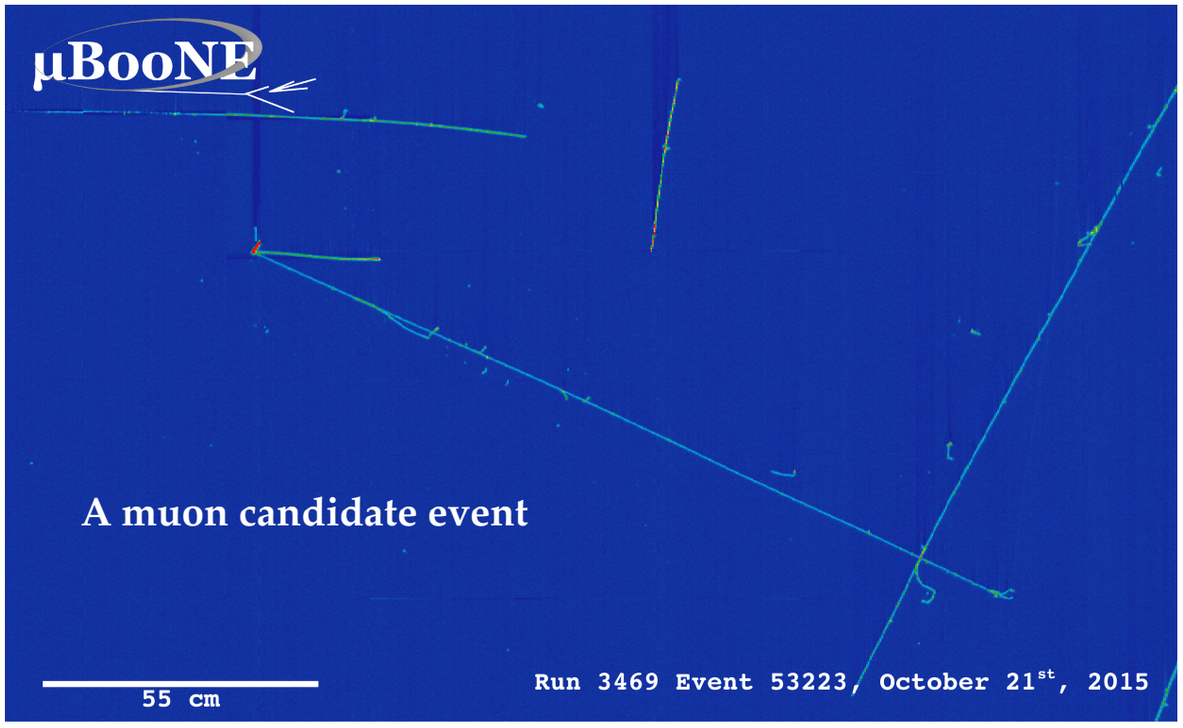
2 caverns, 4 detectors, **flexibility in design**

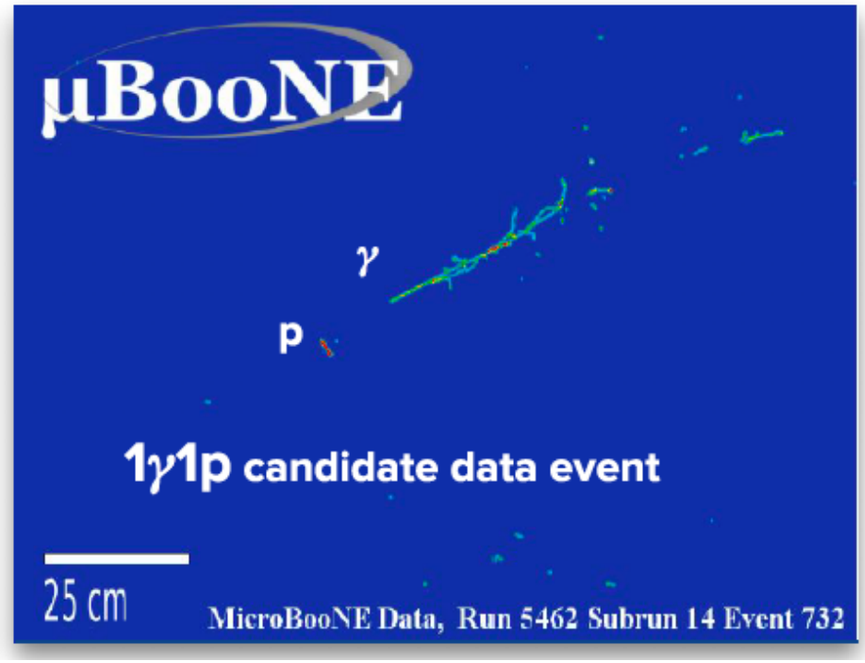
- The first two DUNE FD modules will be **Liquid Argon Time Projection Chamber (LArTPC)** detectors with 17 kt mass each
- **FD# 1:** Horizontal Drift (HD)
- **FD# 2:** Vertical Drift (VD)
- **FD# 3:** LAr technology TBD
- **FD# 4:** Module of opportunity (R&D ongoing)

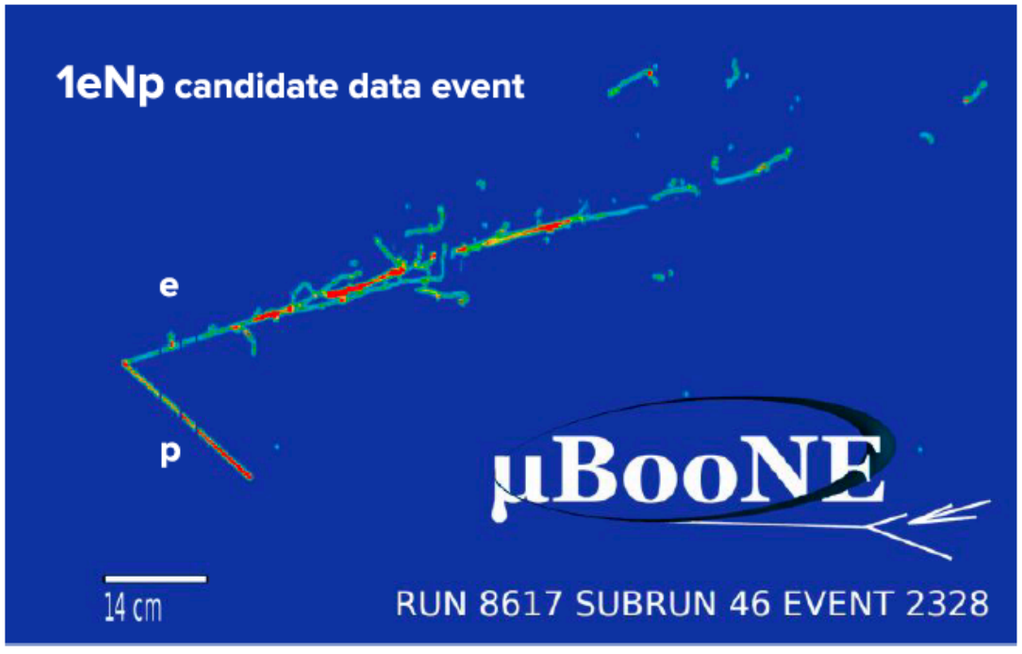
See talks by M. Guarise, A. Paudel, & A. Lowe on photon system R&D

Why LArTPC?

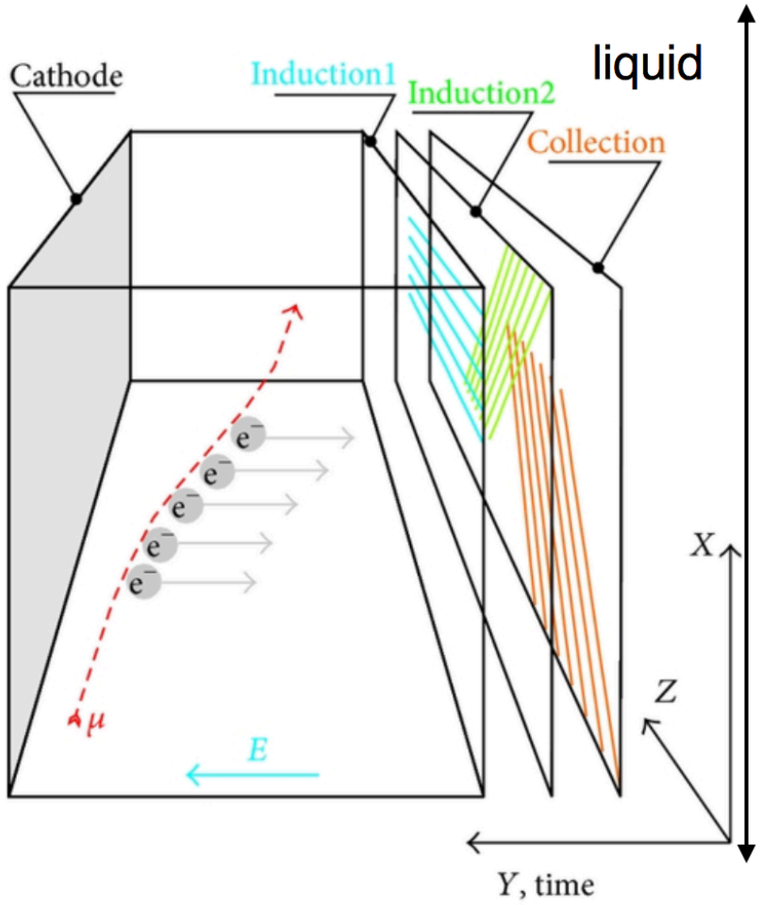
- ***Imaging Detectors that offer excellent energy reconstruction and high resolution***
- Interactions are presented with unprecedented amount of detail
- Argon makes an excellent target (dense, abundant, cheap etc.)
- Can separate Signal (υ_e CC) from background (NC π^0)
- Low energy thresholds enables MeV-scale physics
- Technology allows for scalability → massive detectors

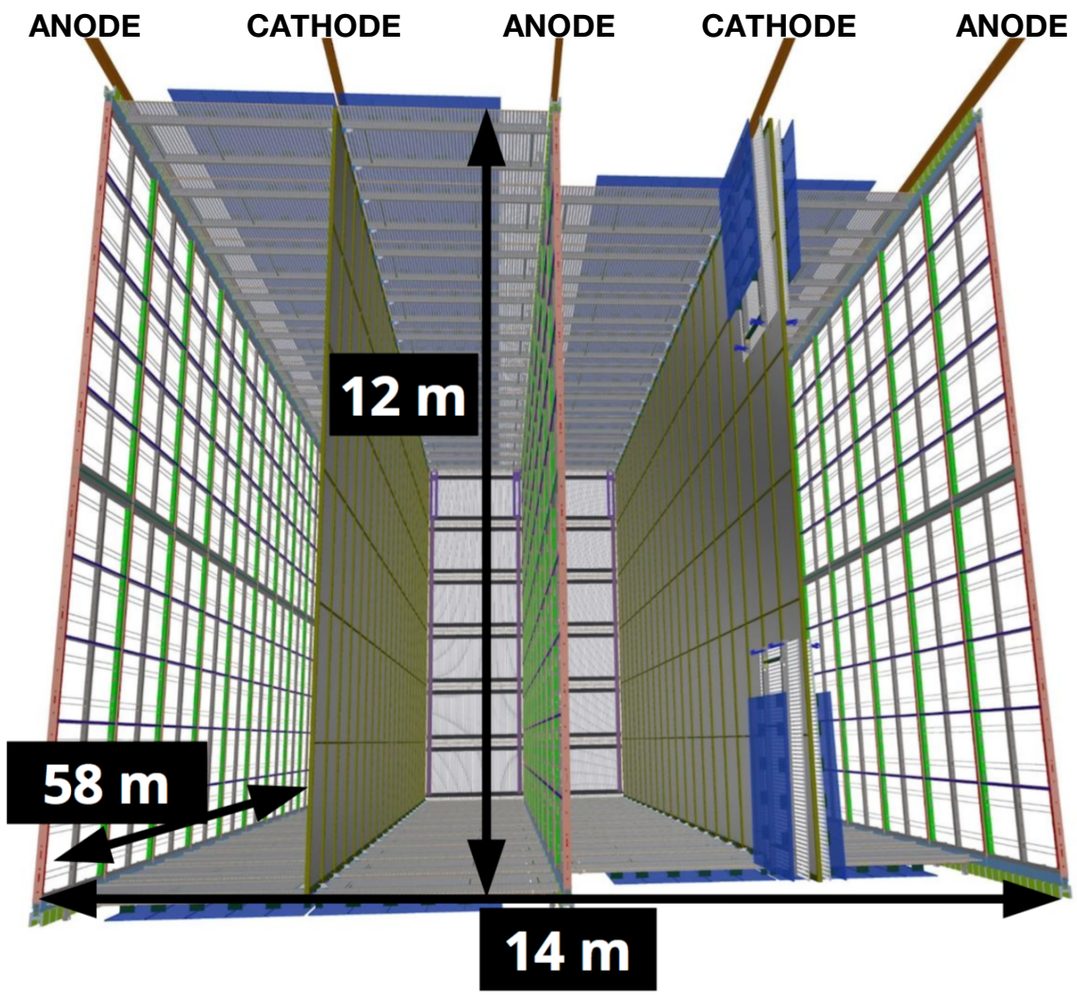






FD#1: Horizontal Drift LArTPC

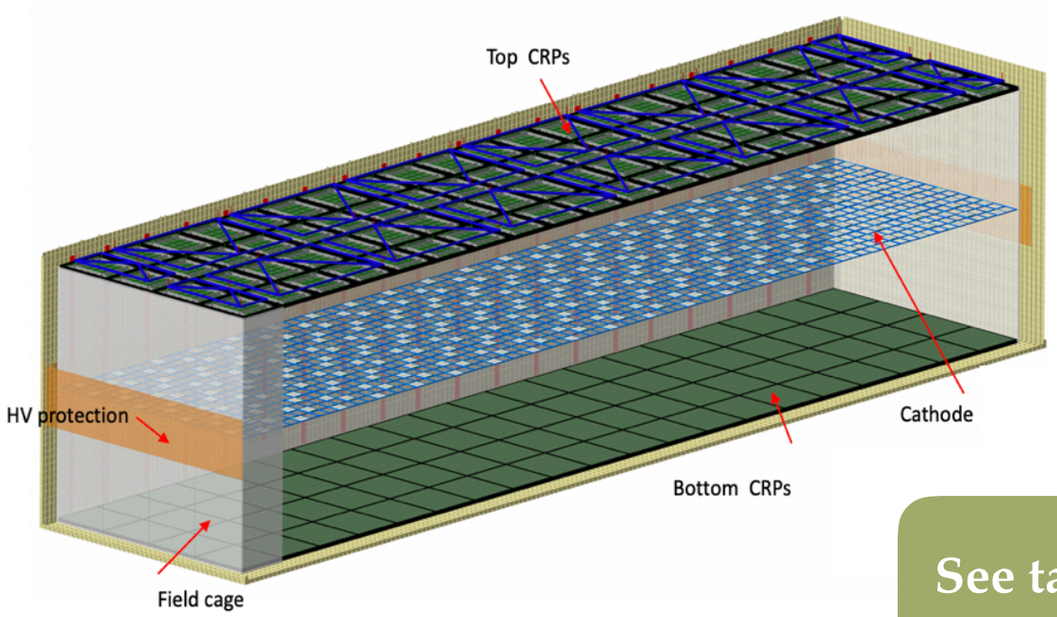




JINST 15 T08010 (2020)

- 12 m x 14 m x 58 m active volume
- Each Anode-Cathode chamber has 3.5 m drift
- Cathode at -180 kV
- 150 Anode Plane Assemblies (APAs) with 384,000 readout wires
- Anode planes have wrapped wires (readout on both sides)
- 6000 photon detection system (PDS) channels for light readout

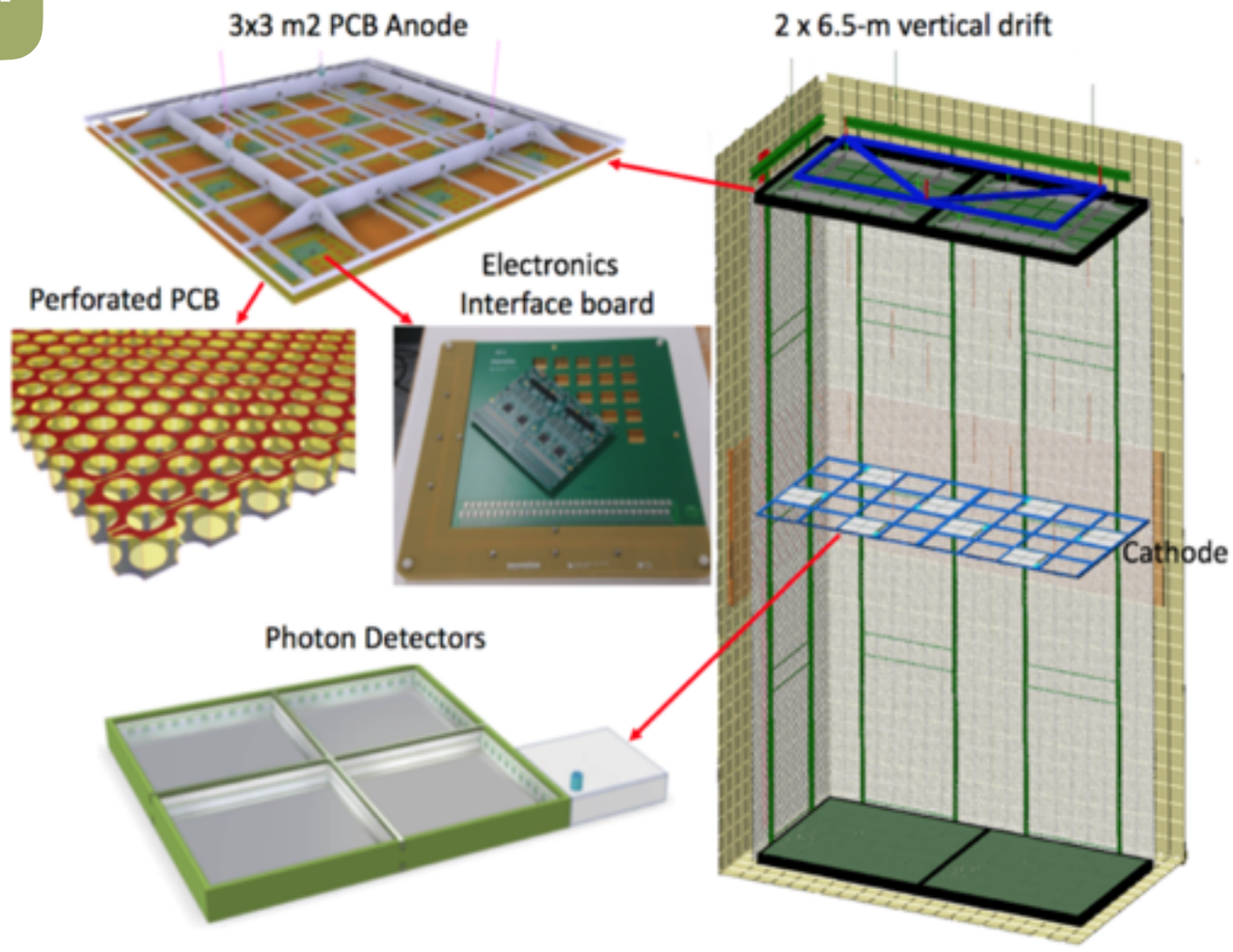
FD#2: Vertical Drift LArTPC



- VD technology evolved from extensive R&D from single and dual phase LArTPCs
- Designed to maximize active volume
- Perforated PCBs with segmented electrodes (strips) as readout units

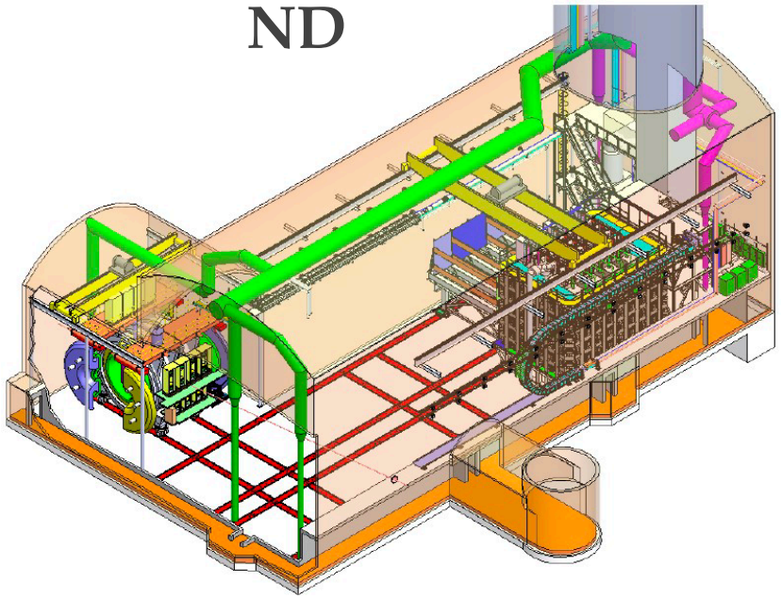
See talk by O. Lantwin

- Charge readout units at the top and bottom
- Cathode in the middle
- Photon detectors integrated on cathode and on cryostat walls
- Two 6.5 m drift chambers
- -300kV on cathode; 450 V/cm field



Phased DUNE Construction

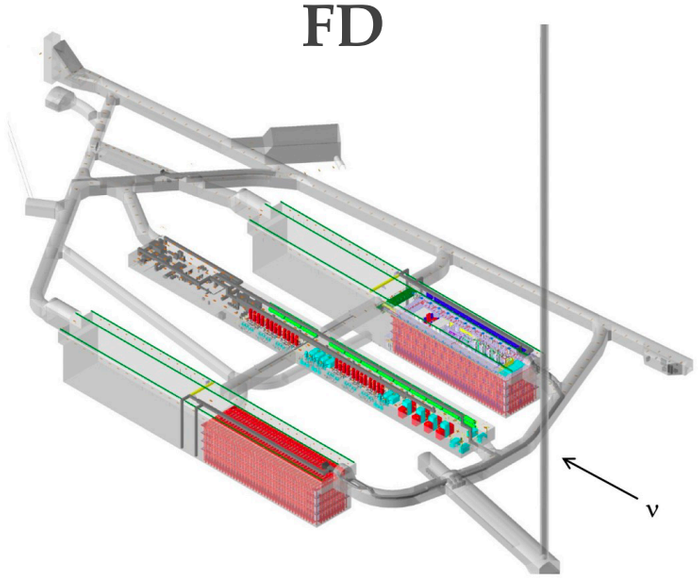
ND

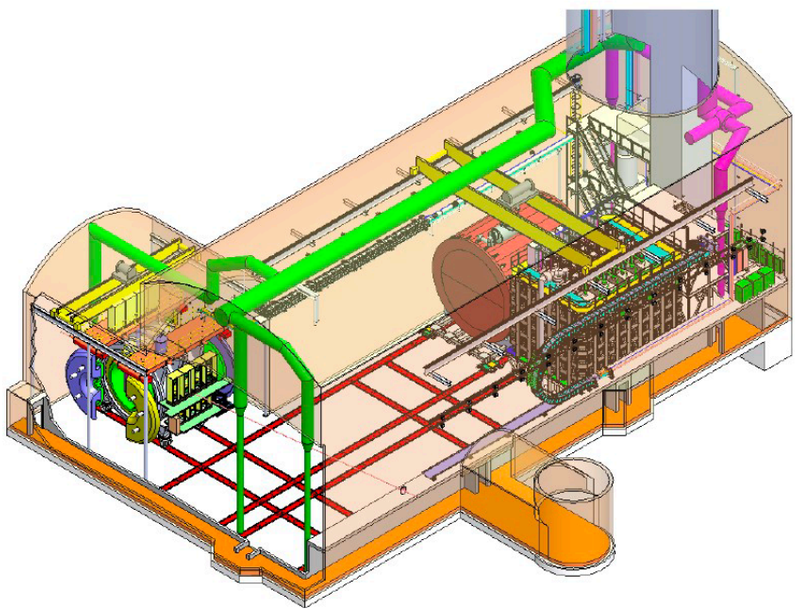


Phase I

- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- FD turns on late 2020s
- 1.2 MW capable beamline and ND by 2031

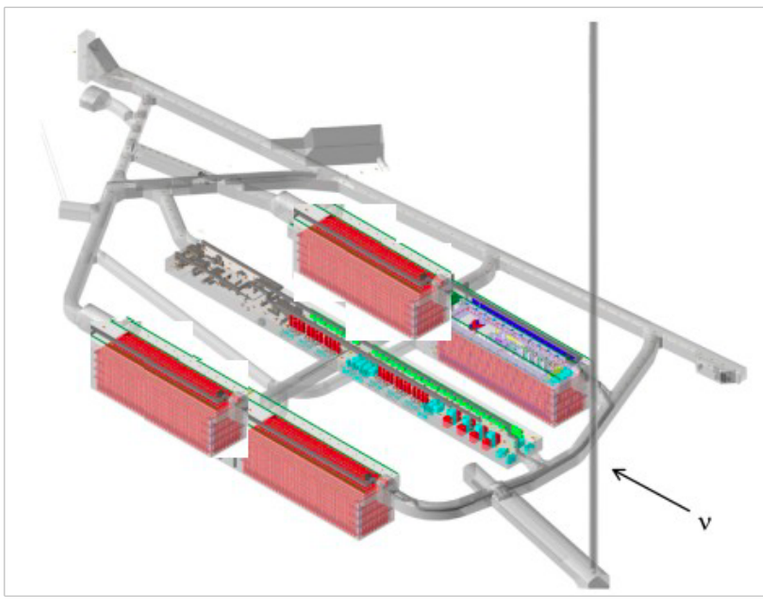
FD





Phase II

- **FD:** 4 x 17 kt modules
- **ND:** ND-LAr+ND-GAr (with PRISM) + SAND
- Proton beam 1.2 MW to 2.4 MW



υ_e Appearance & Matter Effects

- DUNE aims to probe CP violation by comparing neutrino and anti-neutrino oscillations
- A $\upsilon_\mu \rightarrow \upsilon_e$ appearance experiment in matter will be sensitive to rich physics: θ_{23}, θ_{13}, **δ** and matter effects

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

(For antineutrinos, a → -a and δ → -δ)

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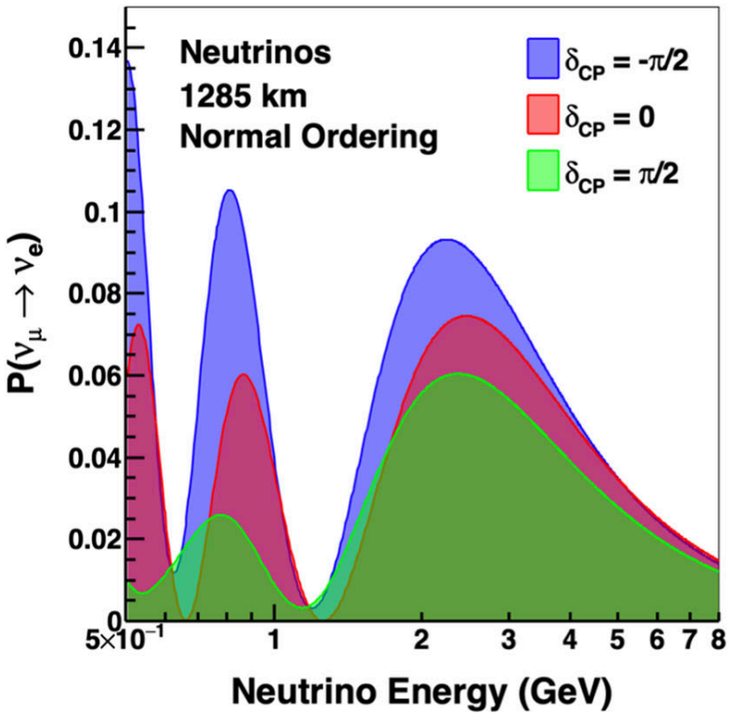

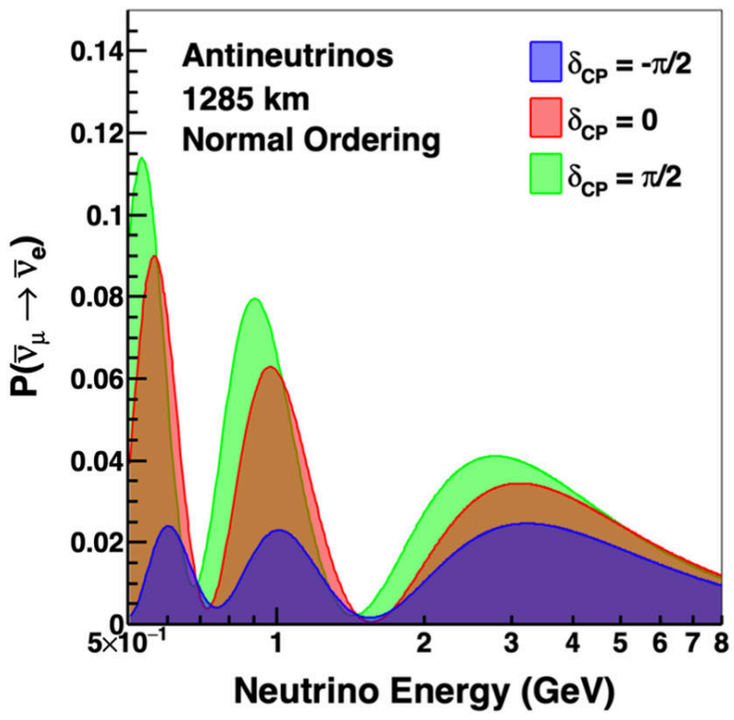

Expected Event Rates

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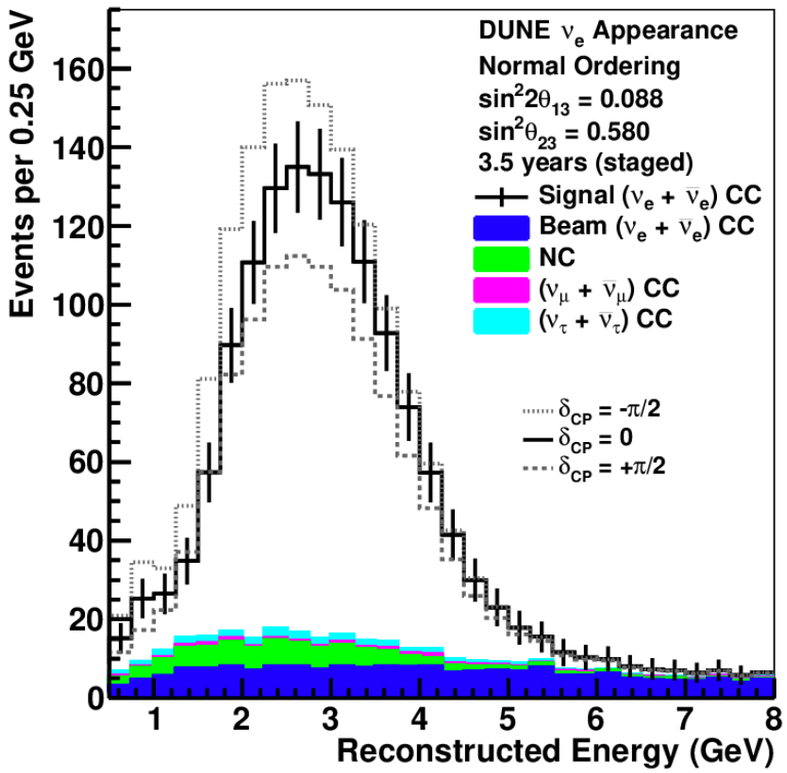
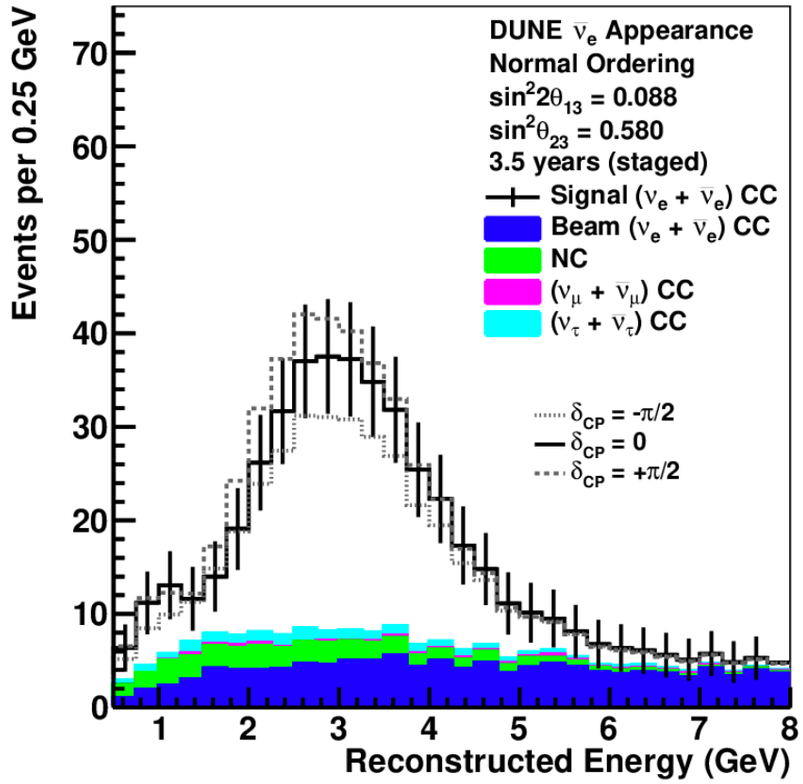
Neutrino Mode

Anti-neutrino Mode

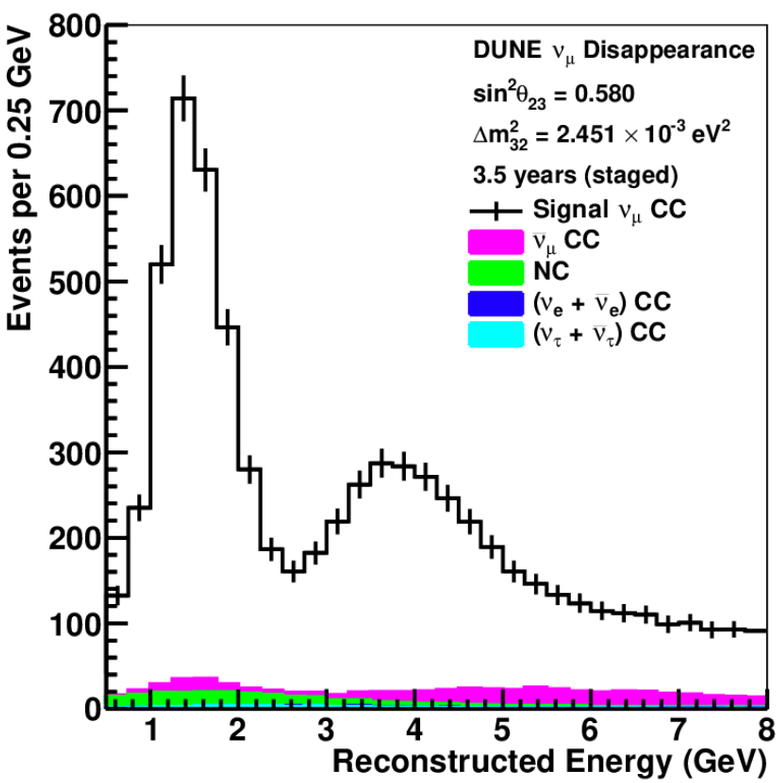
υ_e Appearance

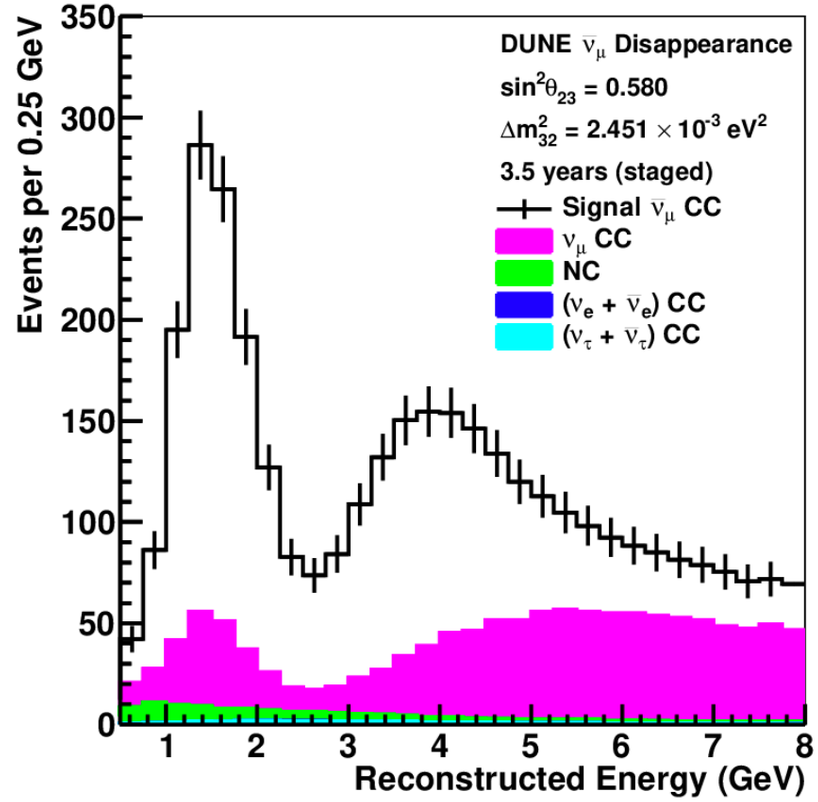




O(1000) appearance events in 7 years

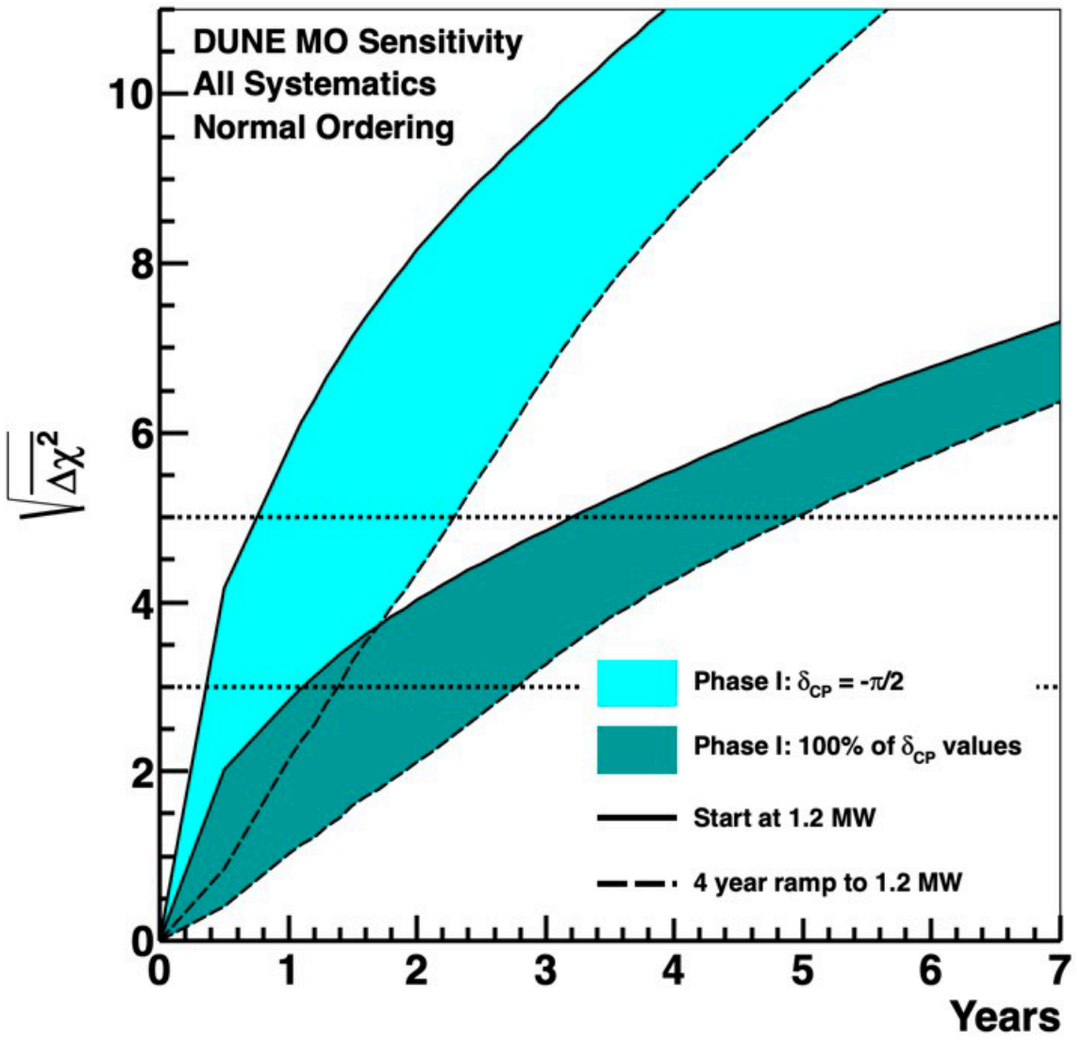
υ_μ Disappearance

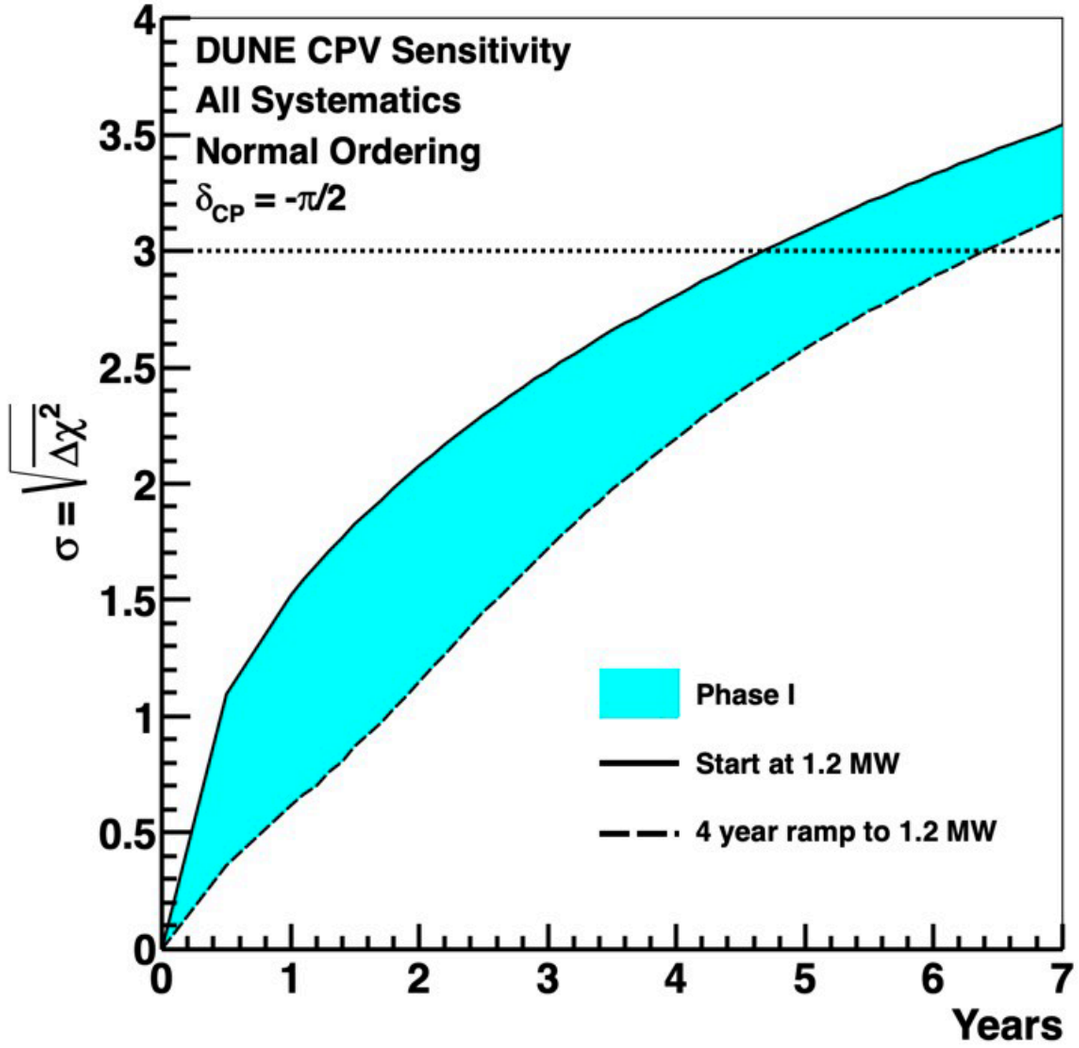




O(10,000) disappearance events in 7 years

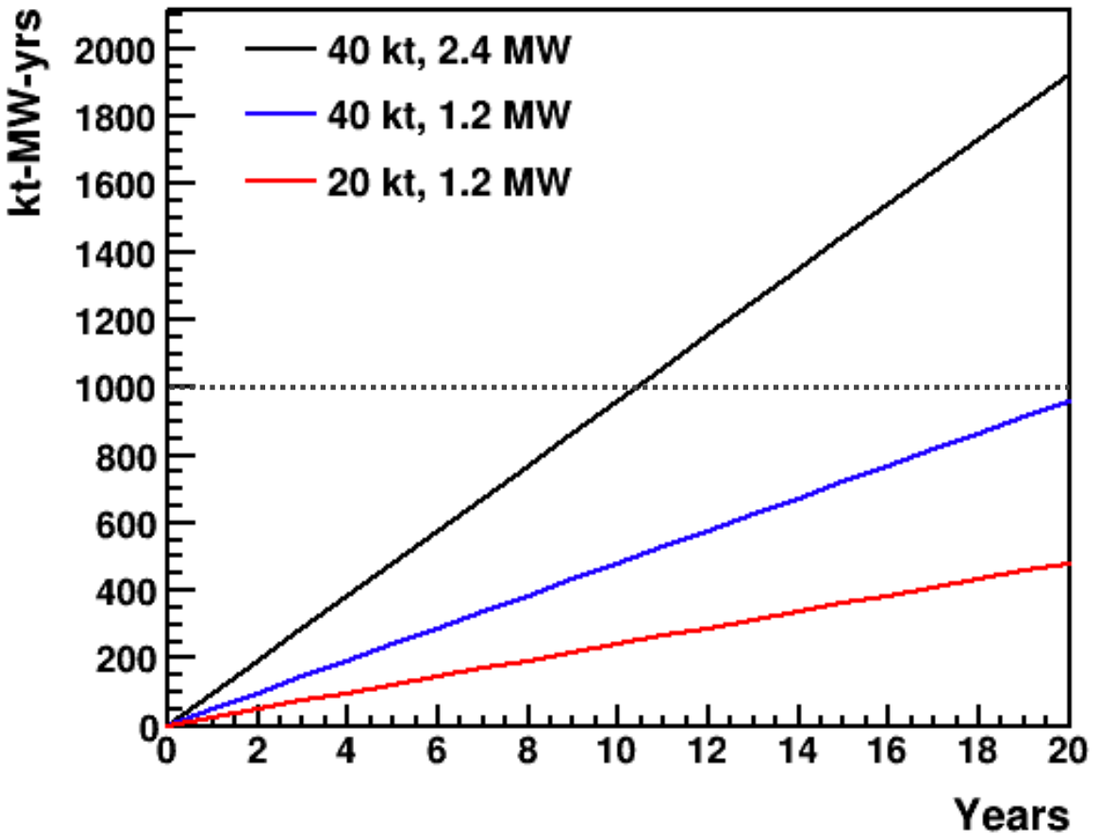
DUNE Phase I: Physics Potential

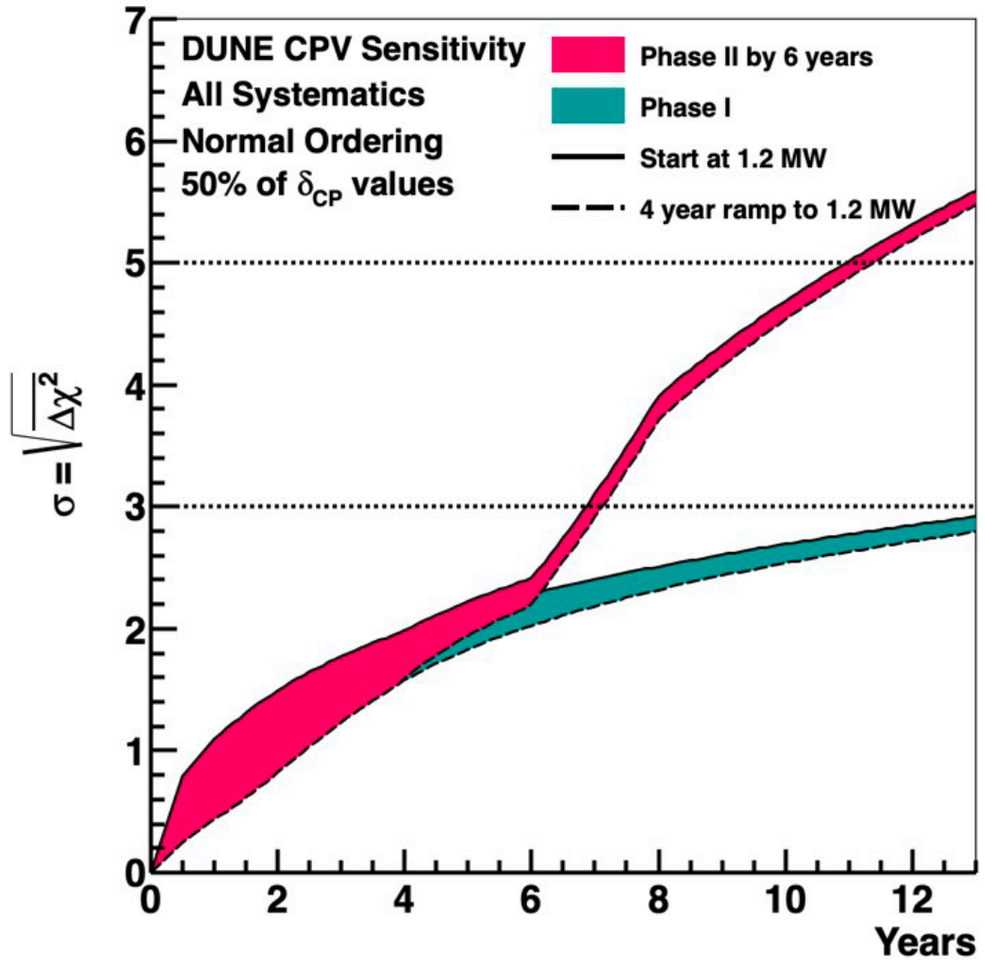




- Beam ramp up schedule can impact sensitivity reach over time
- Regardless, within first few years
  - $> 5\sigma$ MH sensitivity
  - 3σ CPV sensitivity at maximal δ_{CP}

DUNE Phase II: Physics Potential





- O(1000) kt-MW-yrs beam exposure needed to achieve full physics scope
- With phase-II, full precision physics results can be achieved in a decade (in 11-12 years)

Oscillation Physics Sensitivities with Phase-II

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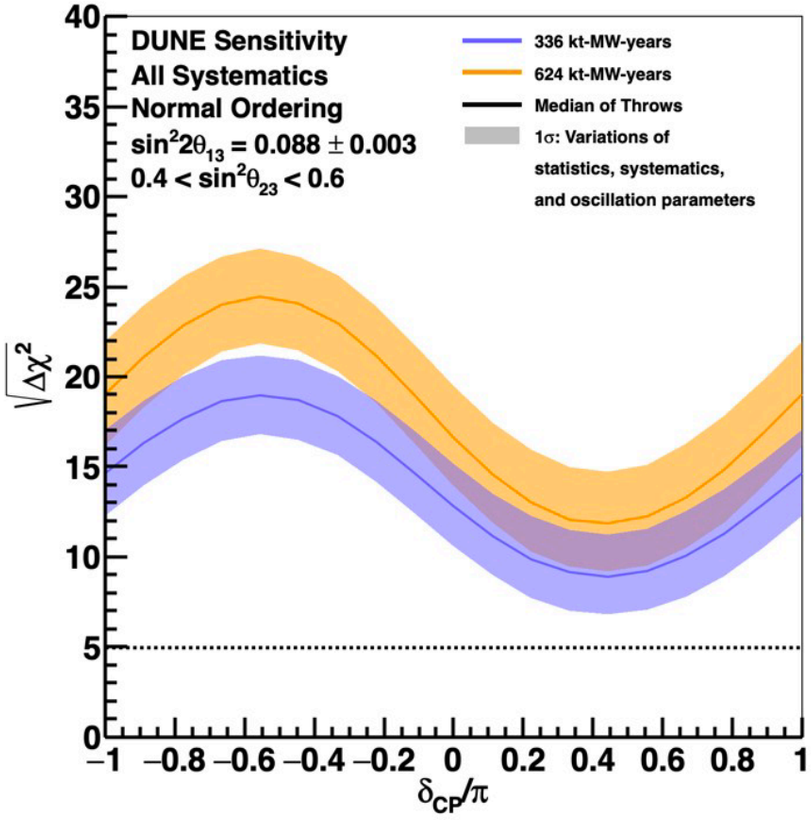
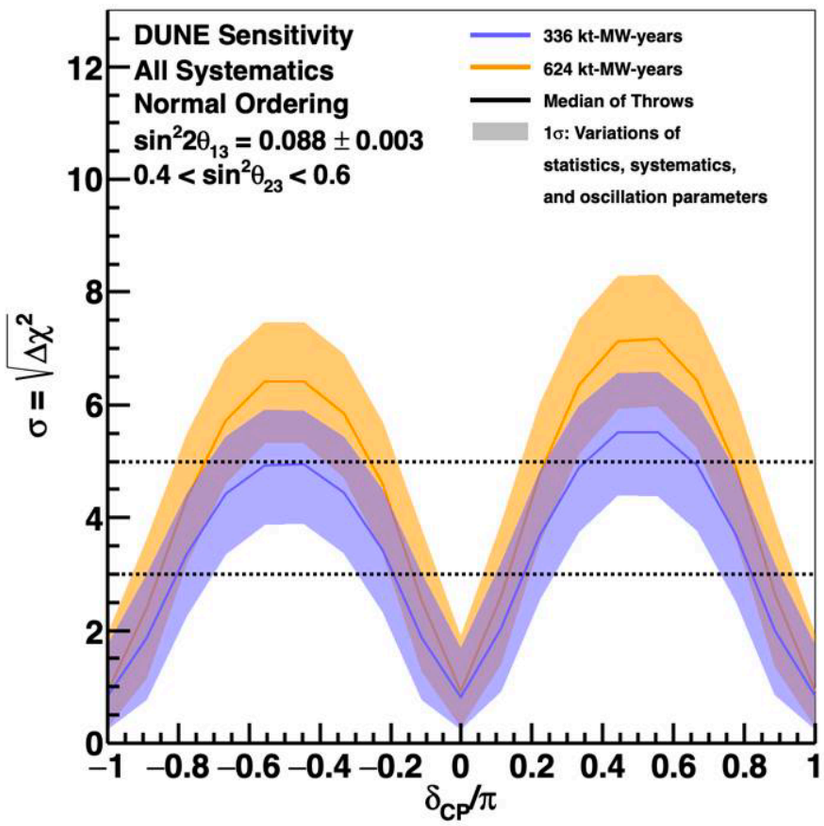
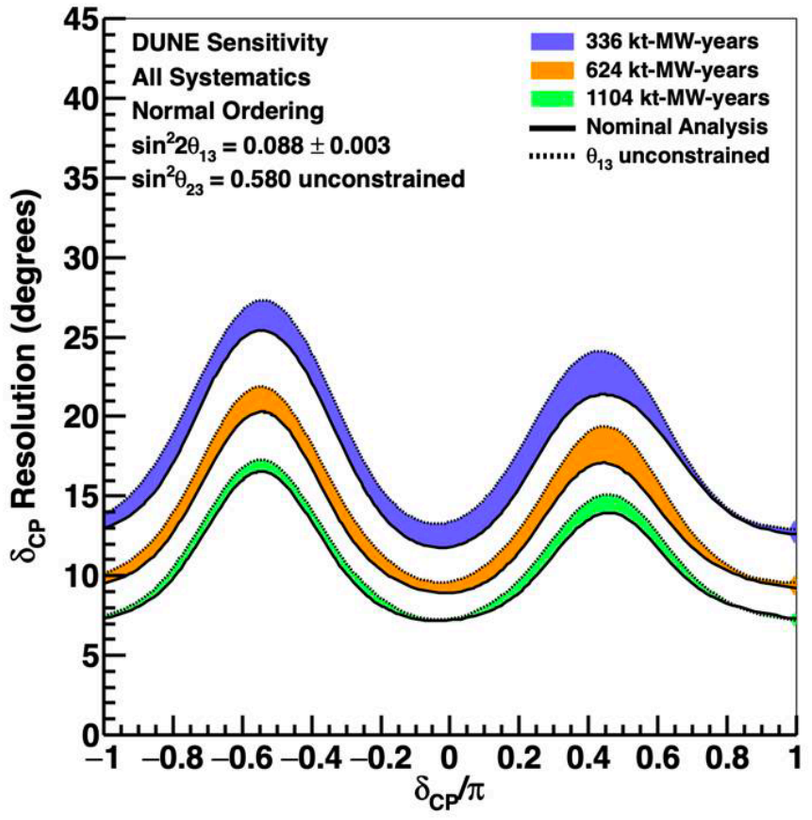
Mass Ordering Sensitivity



CP Violation Sensitivity



δ_{CP} Resolution

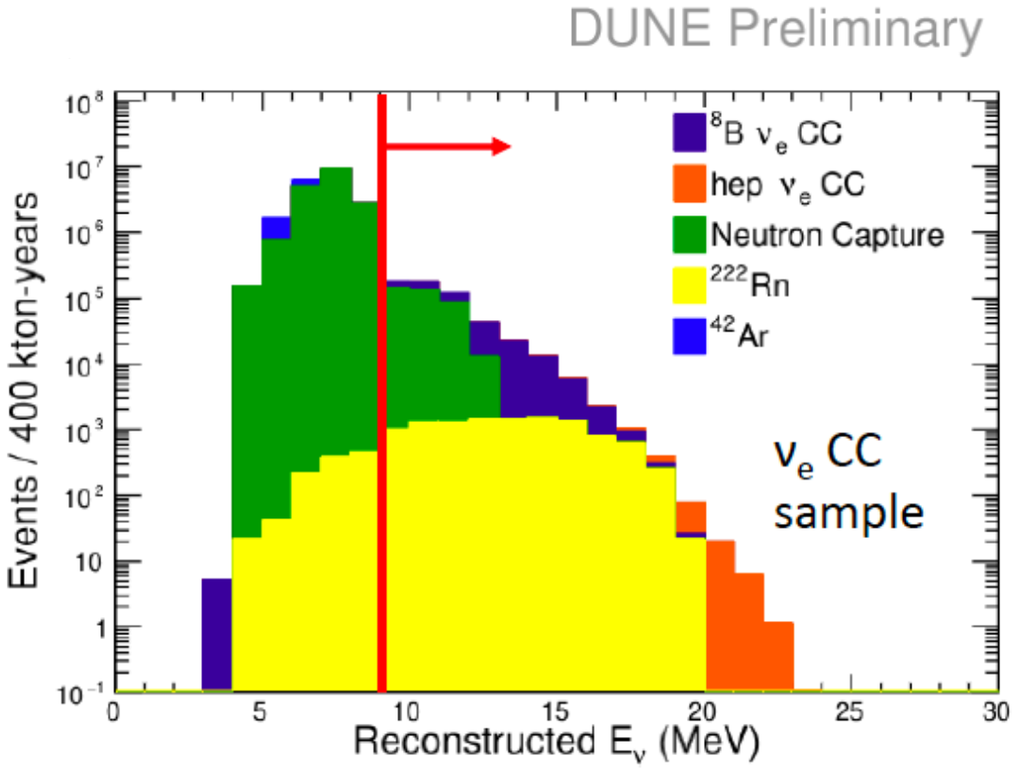


- Unambiguous MH sensitivity ($> 5\sigma$) regardless of other parameter choices
- 5σ CPV sensitivity for 50% of δ_{CP}
- 7–16° δ_{CP} resolution regardless of true values

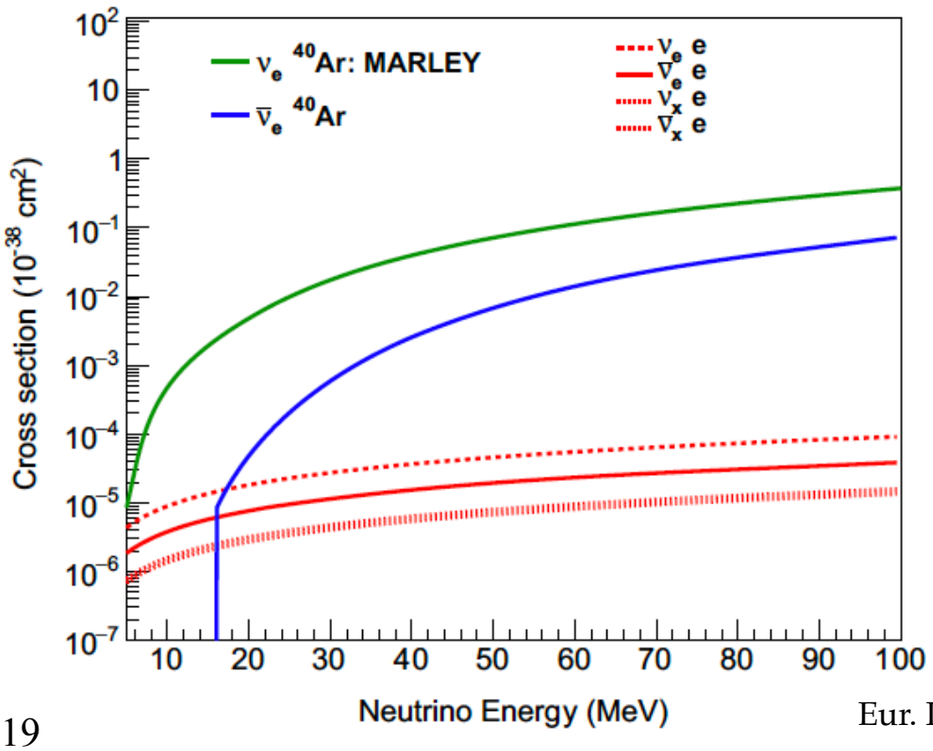
See talks by C. Wilkinson & M. Singh

DUNE has the potential to deliver neutrino oscillation results with world-leading precision!

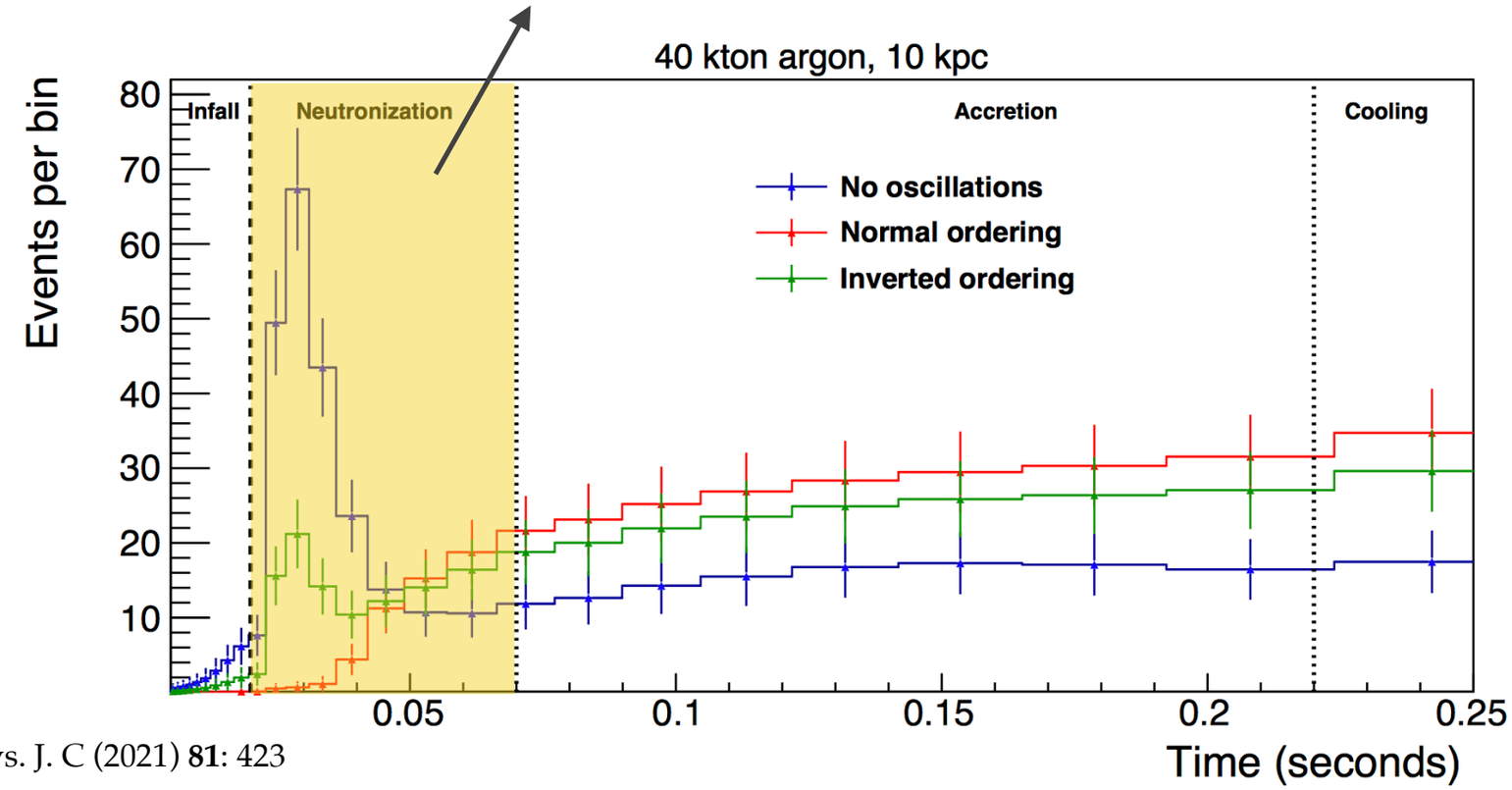
Low-Energy Physics at DUNE



- DUNE will be sensitive to ^{8}B and solar mixing parameters
- Unique capability to detect SN *electron neutrinos:* CC ν_e capture of SN neutrinos on Ar: $\nu_e + Ar^{40}(18) \rightarrow K^{40}(19) + e^-$
- Detection requires sensitivity to low energy gammas (<50 MeV) and electrons



Early development of the signal is sensitive to neutrino mass ordering



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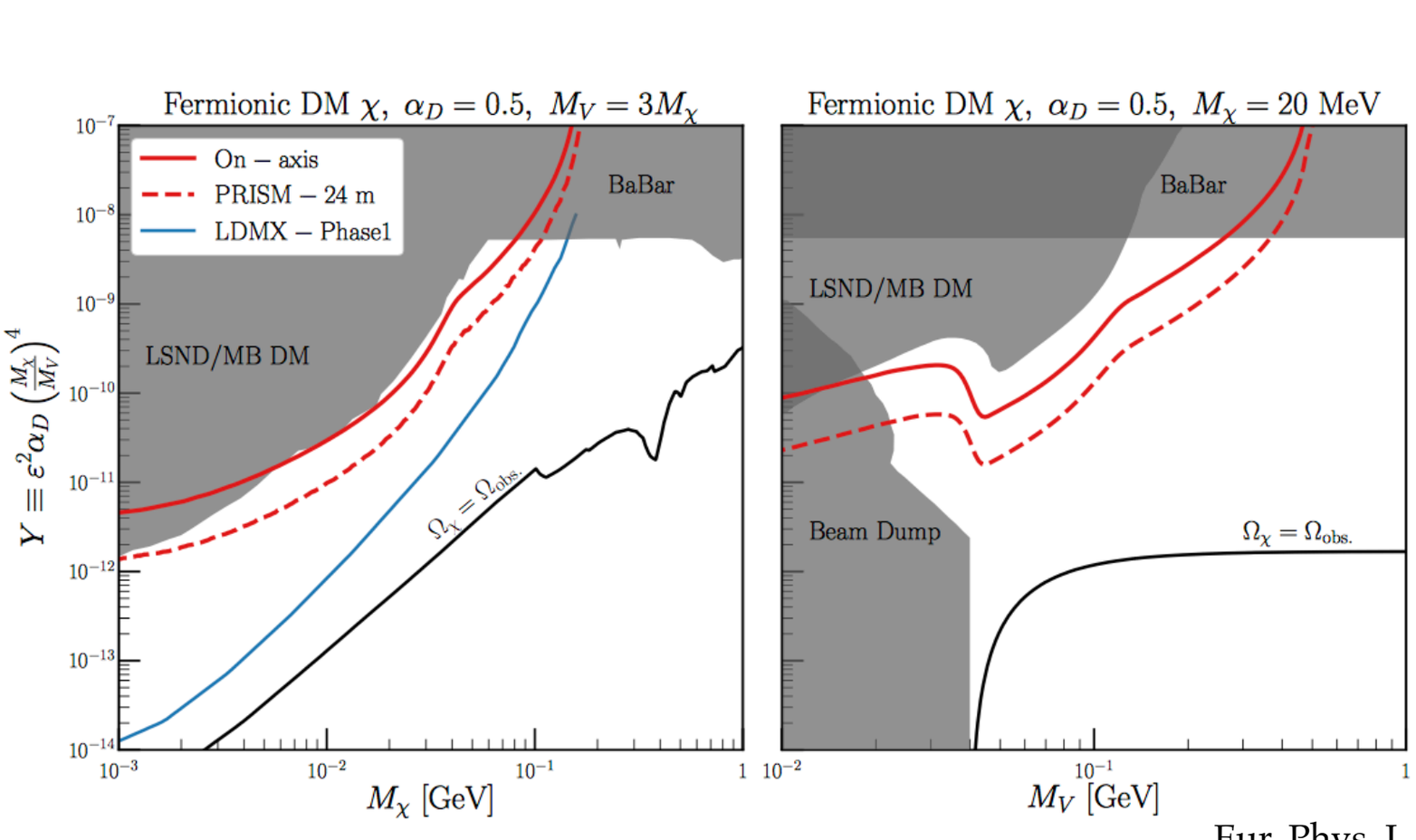
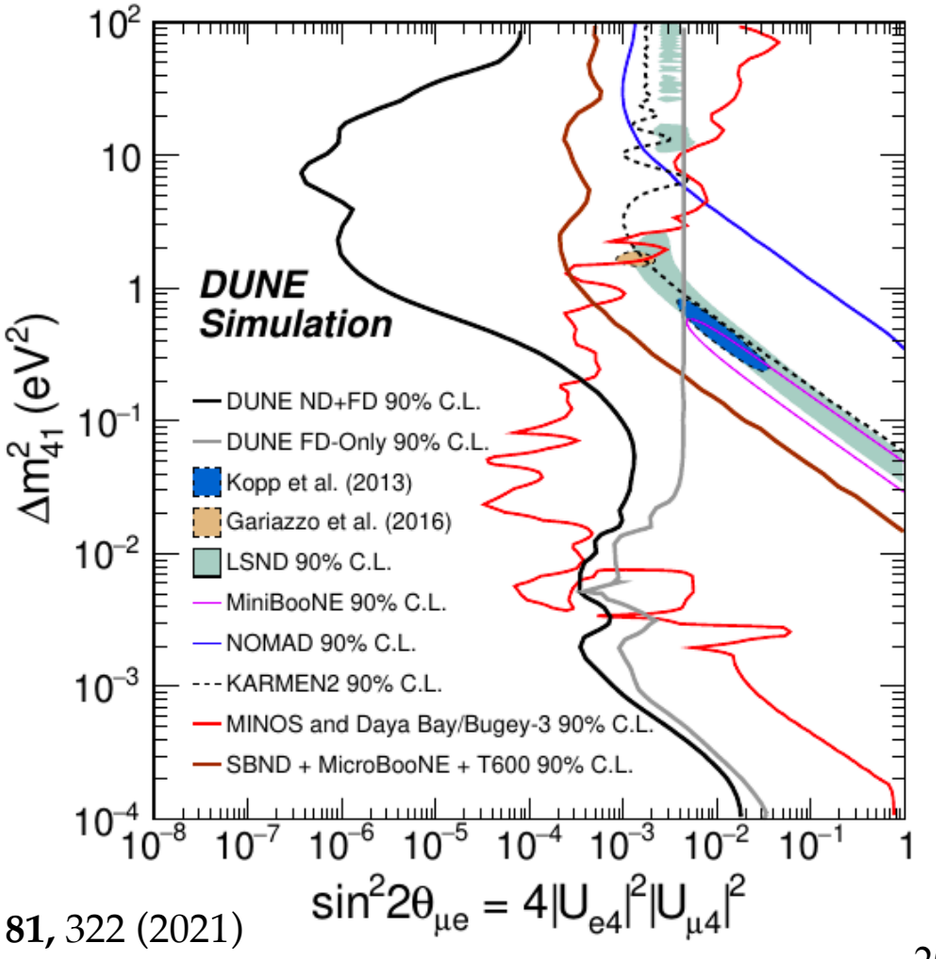
Other Physics Searches

- DUNE will be able to probe many potential BSM searches such as
  - Sterile neutrino mixing
  - Dark Matter (beam induced and cosmogenic origin)
  - Heavy neutral leptons (HNL), neutrino trident production
  - Non-standard interactions (NSIs)
  - CPT symmetry violation





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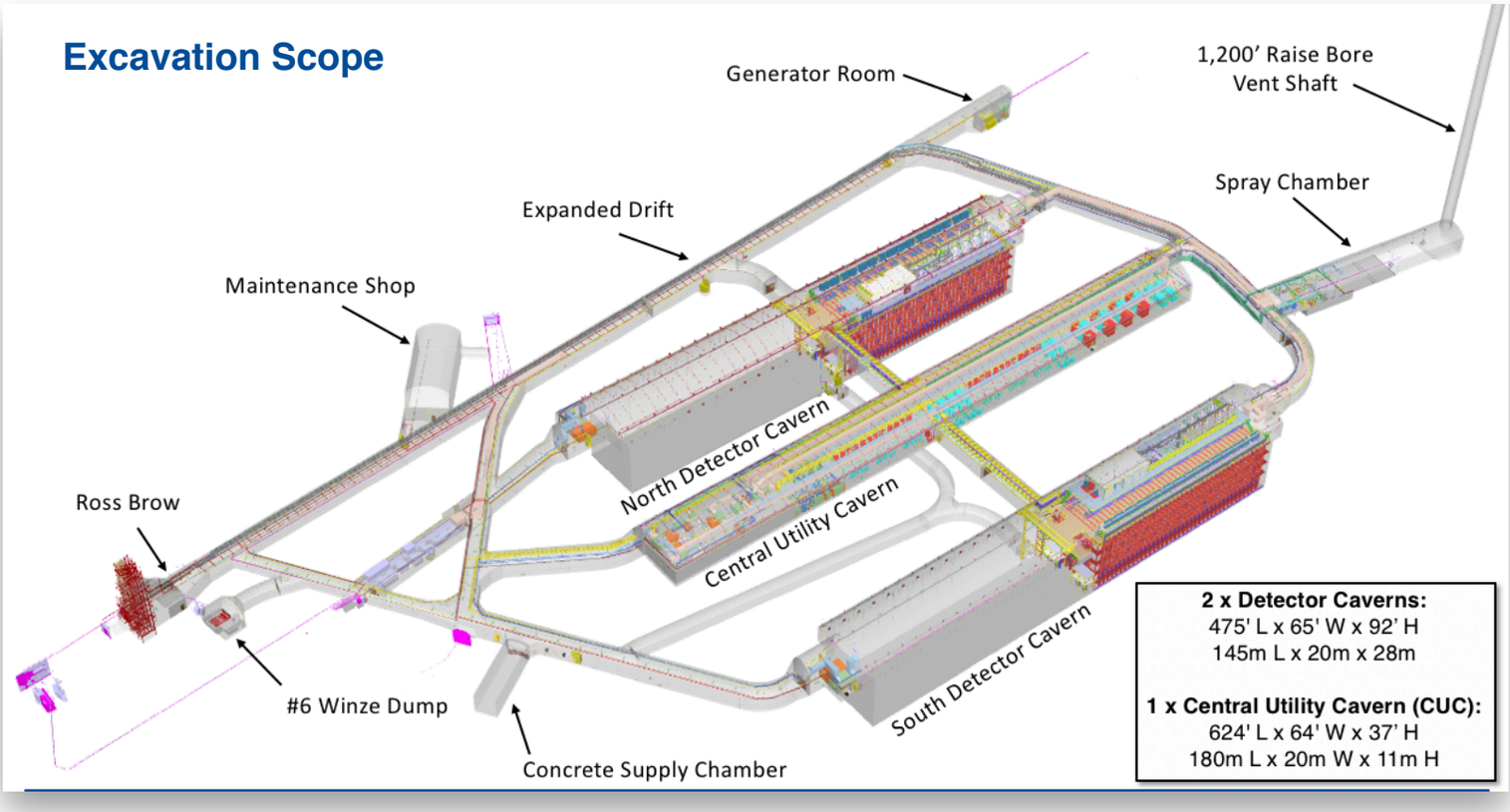
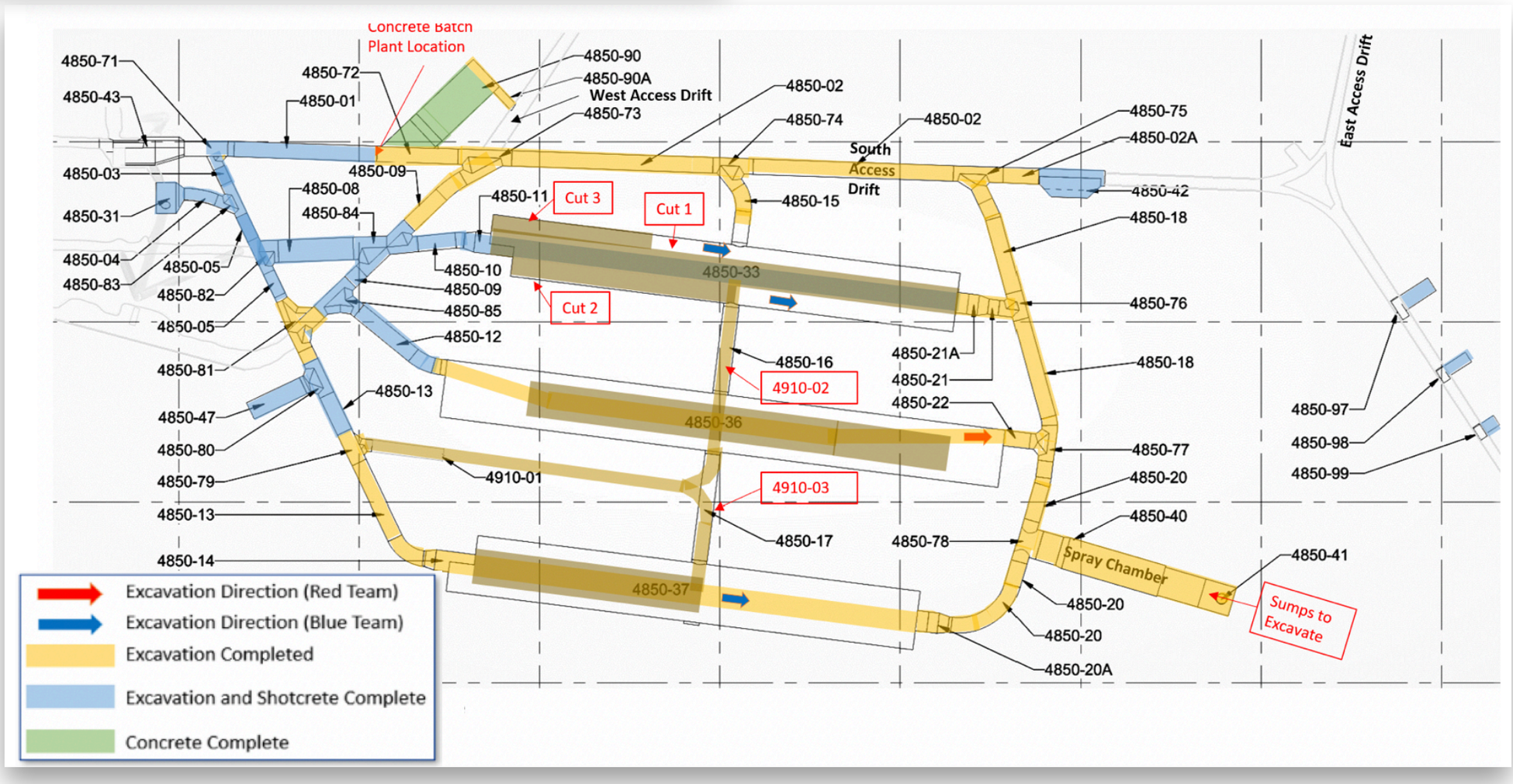
Far Site Status



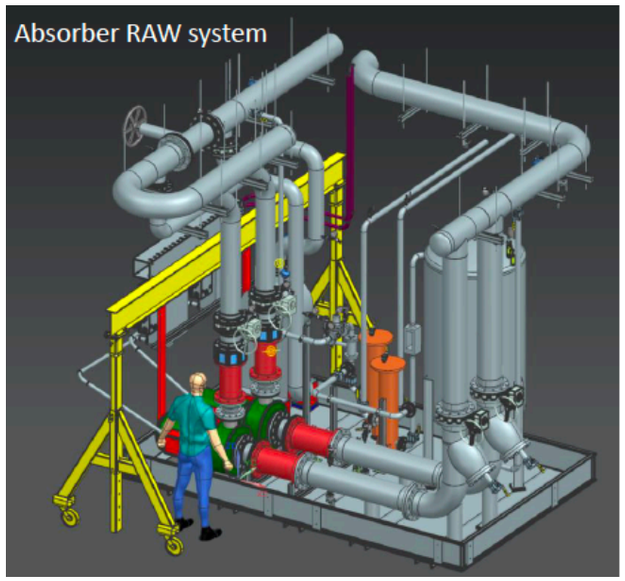
- SURF far site excavation well underway
- North Cavern excavation began in May 2022
- Total excavated rock volume: **35%** as of July 19, 2022

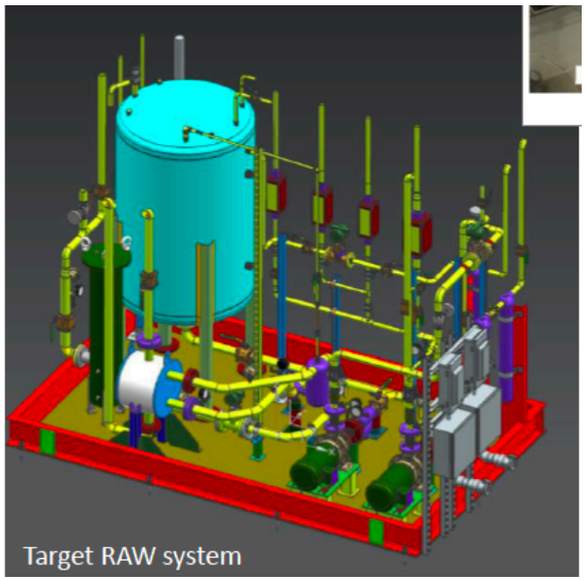
North Cavern

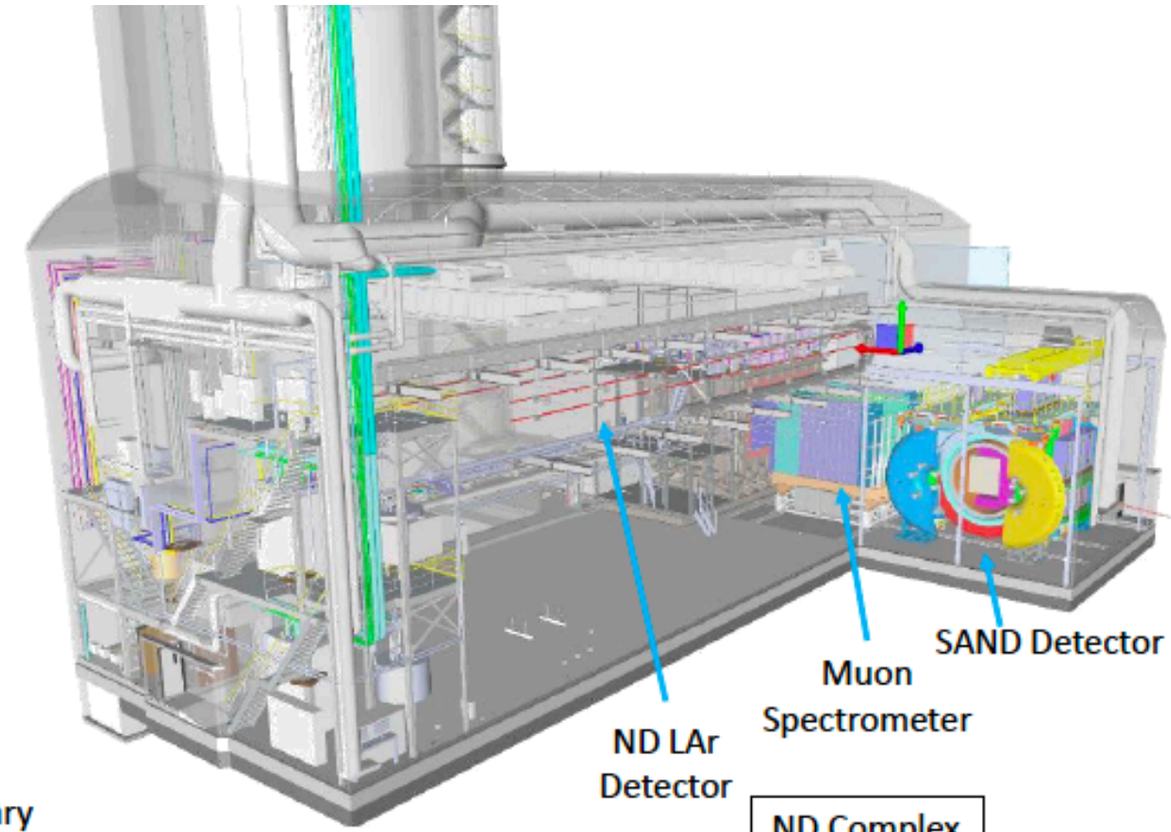


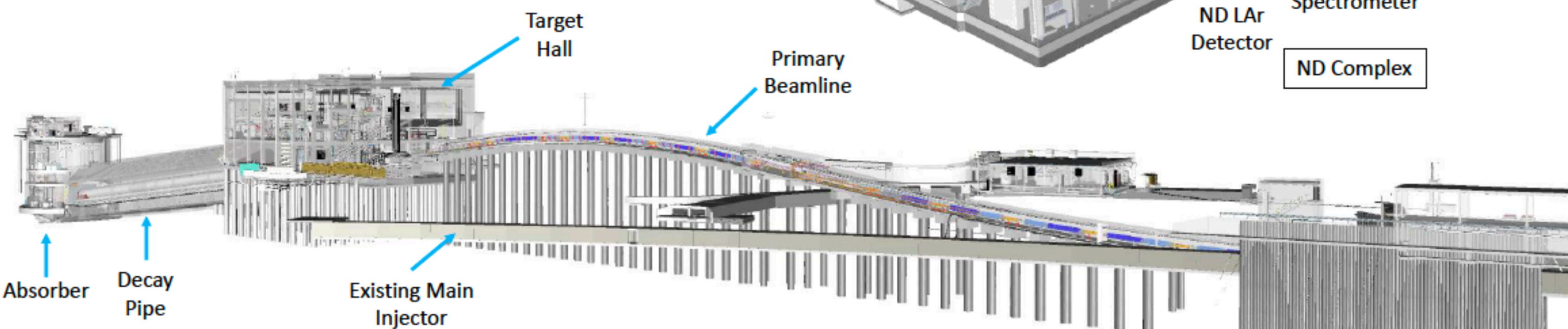
Beamline & Near Site Status

100% final design completed on 28 Sep 2021 for the Beamline Complex and Near Detector Complex





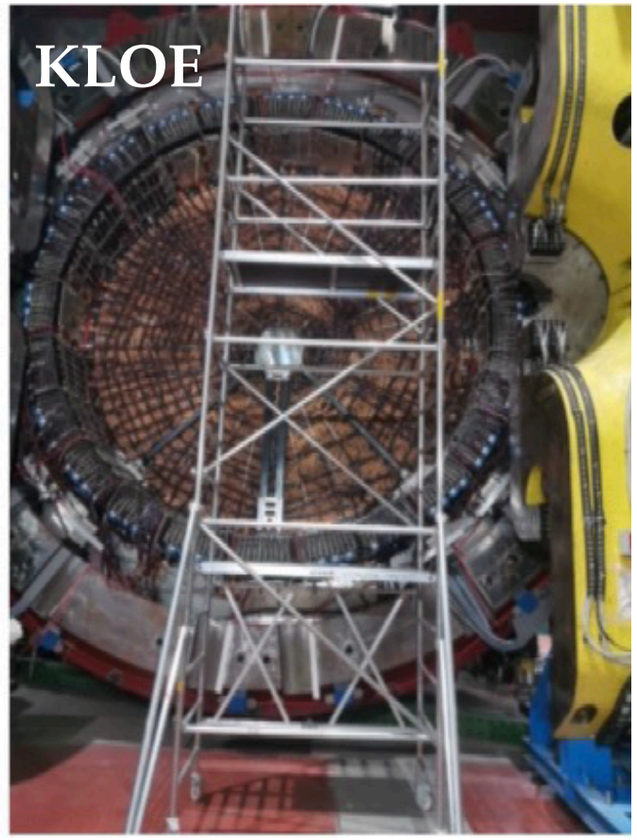




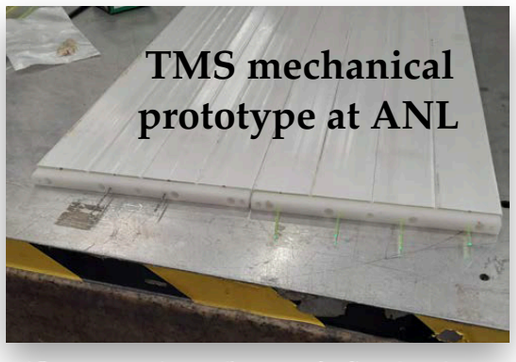
Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

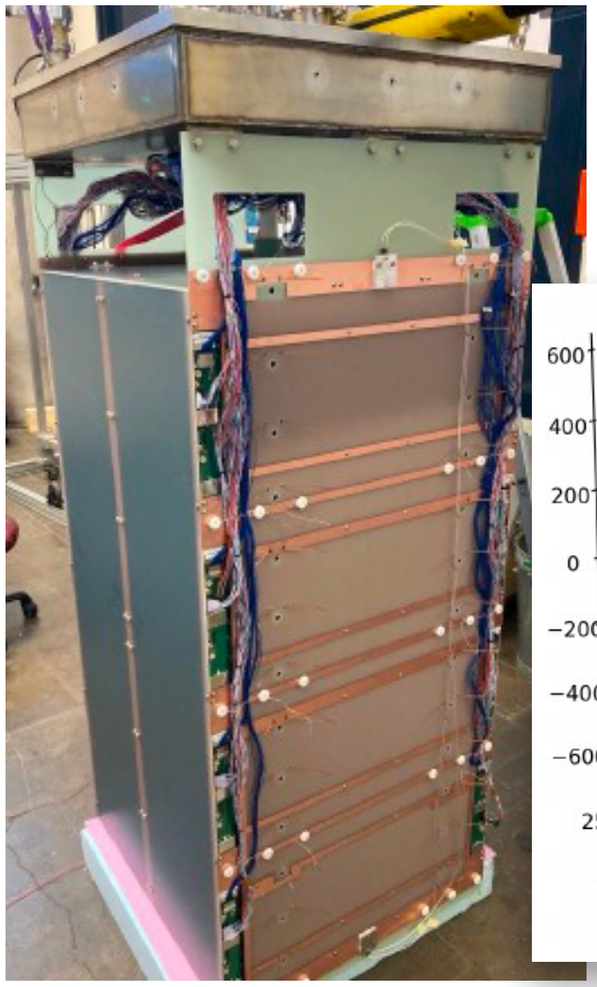
Near Detector Prototyping

- **ND-LAr:** 2x2 prototype at Fermilab for neutrino beam tests
- **TMS:** simulations in progress; mechanical prototyping in progress
- **SAND:** dismantling of ECAL and magnet from KLOE expt. in Italy
- **ND-GAr:** R&D gas TPCs at Fermilab and RHUL undergoing gas and high voltage tests

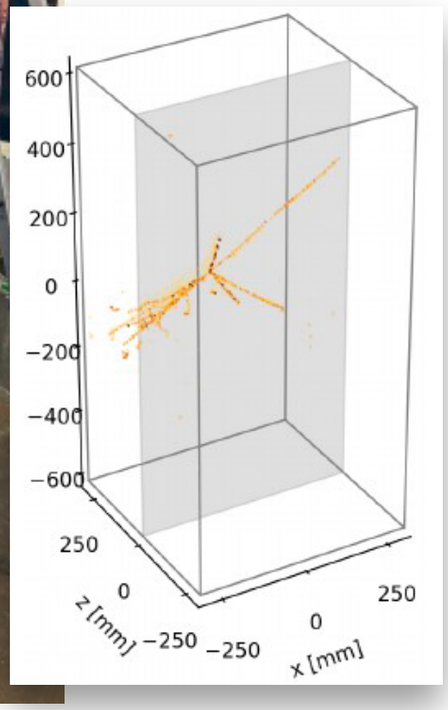


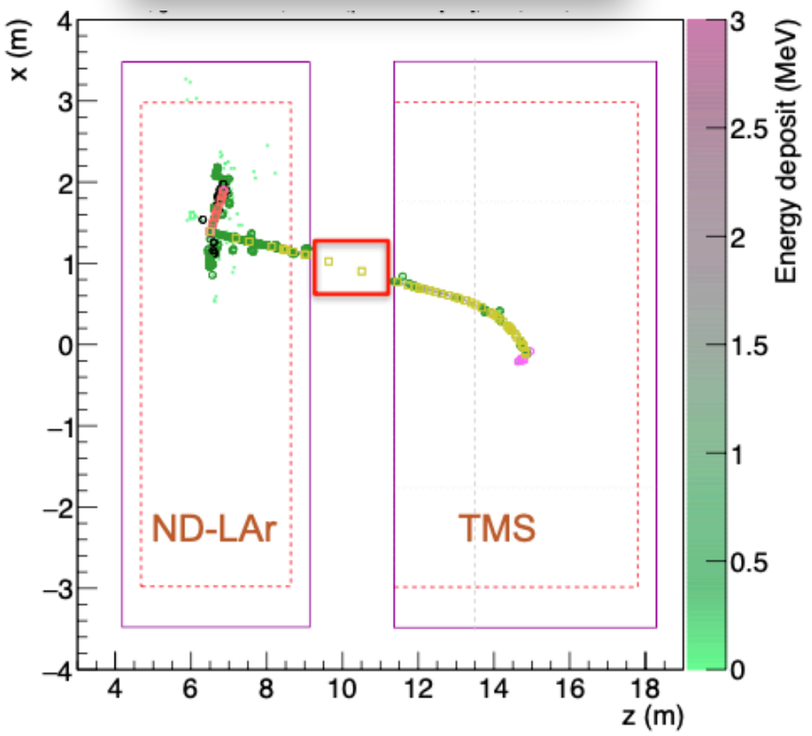
See talks by Z. Vallari & J. Walcott

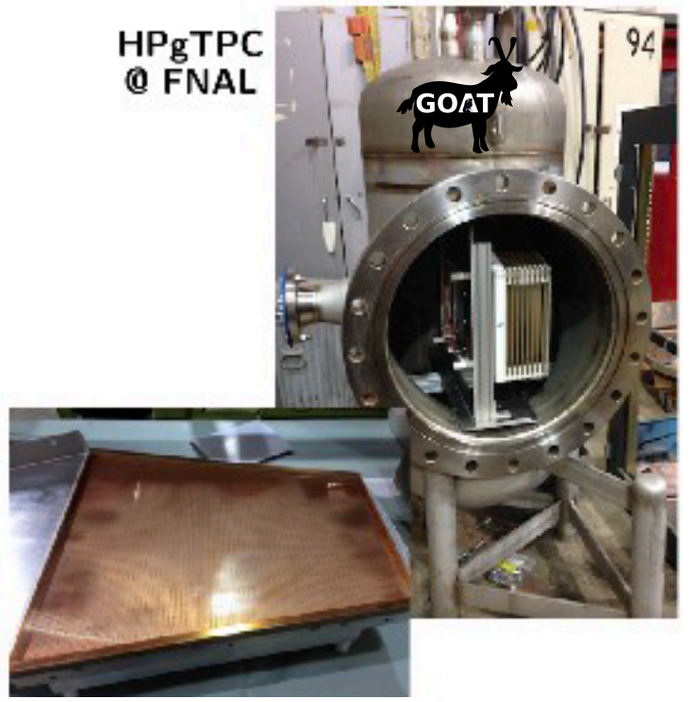




ND-LAr

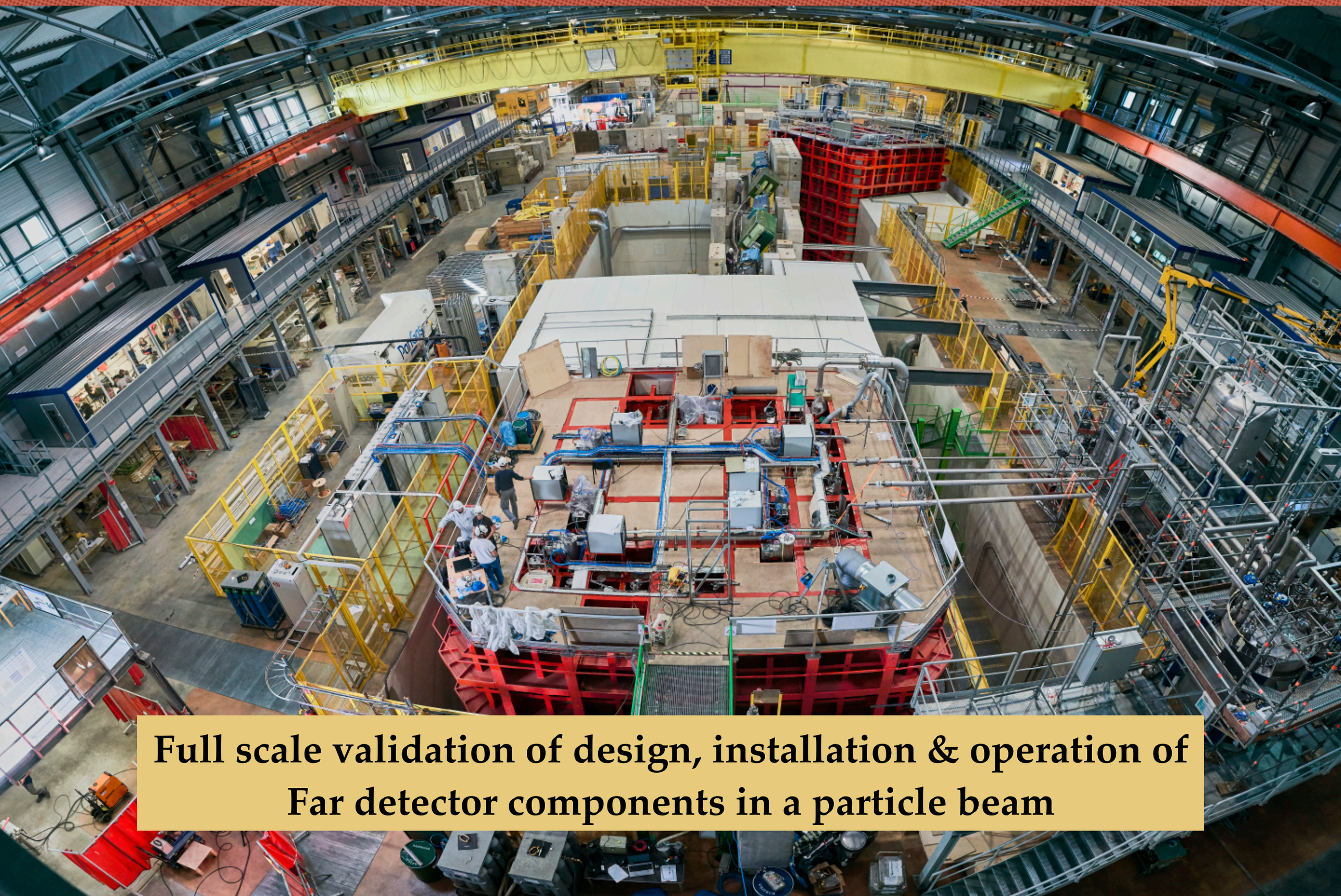






ALICE Readout Chamber

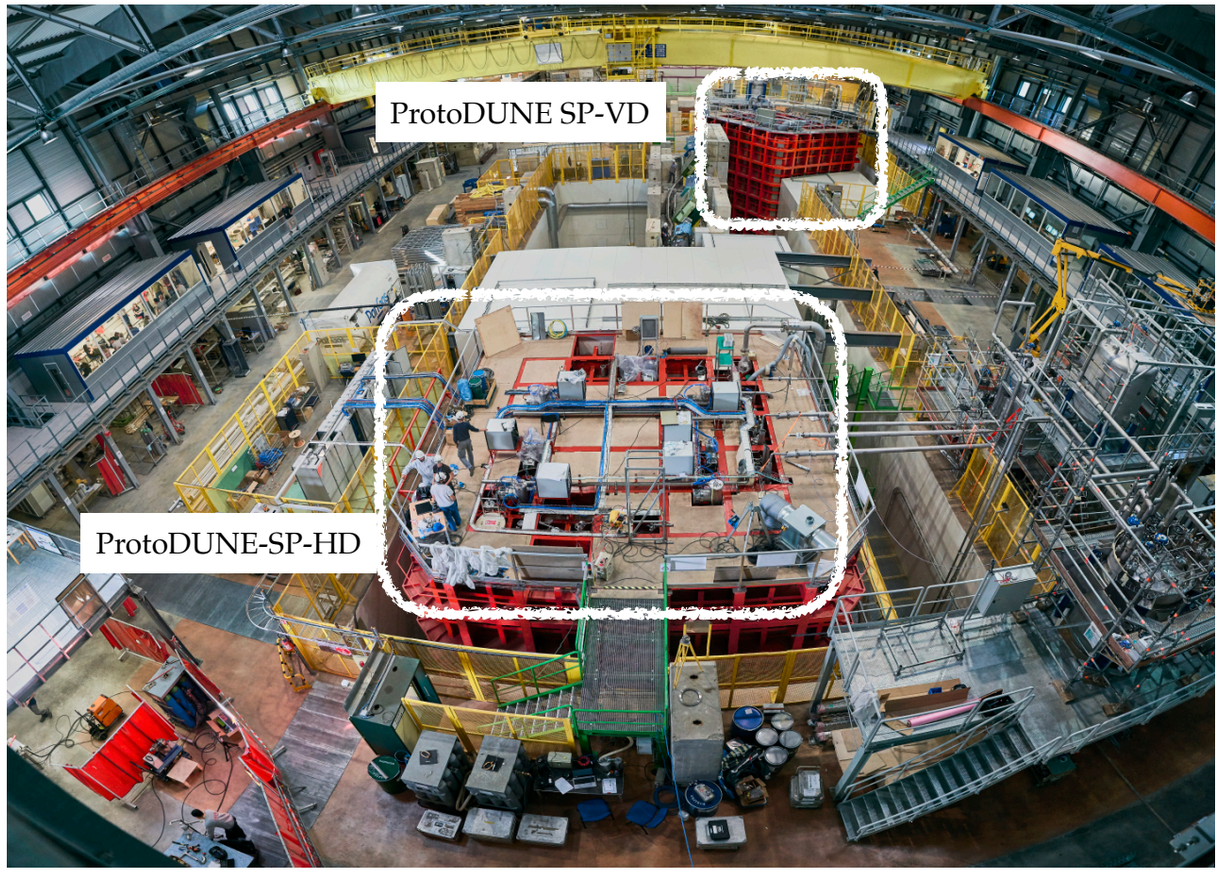
CERN Neutrino Platform



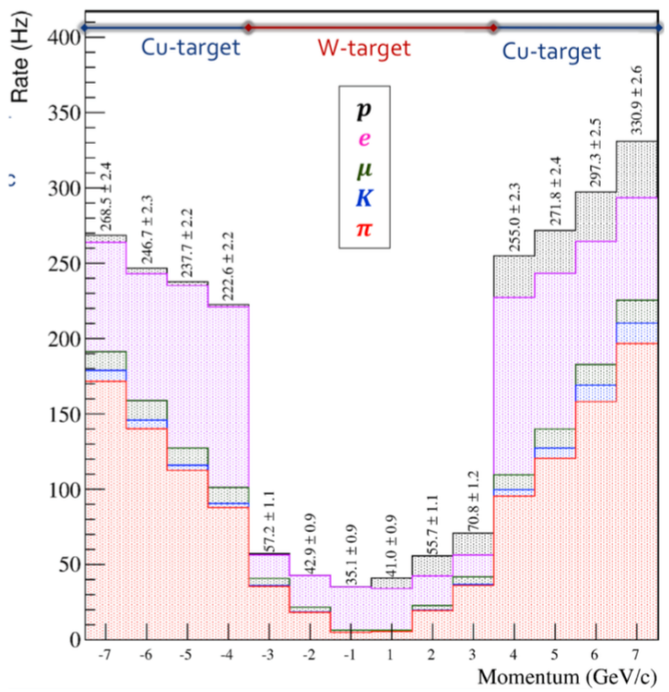
Full scale validation of design, installation & operation of Far detector components in a particle beam

ProtoDUNEs at CERN

Two 770 ton prototypes (~8x8x8 m³)

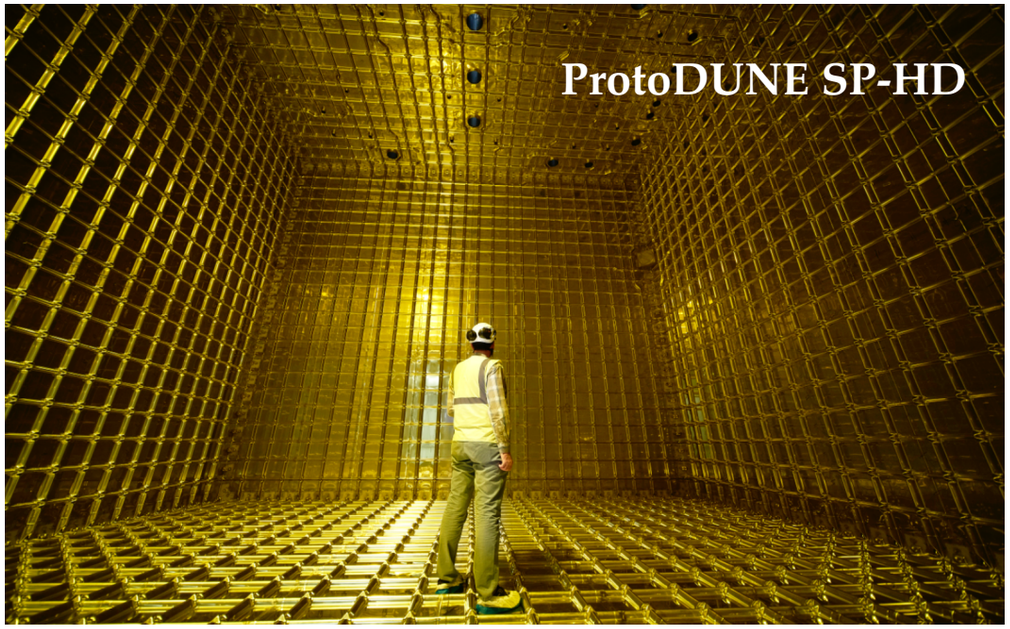


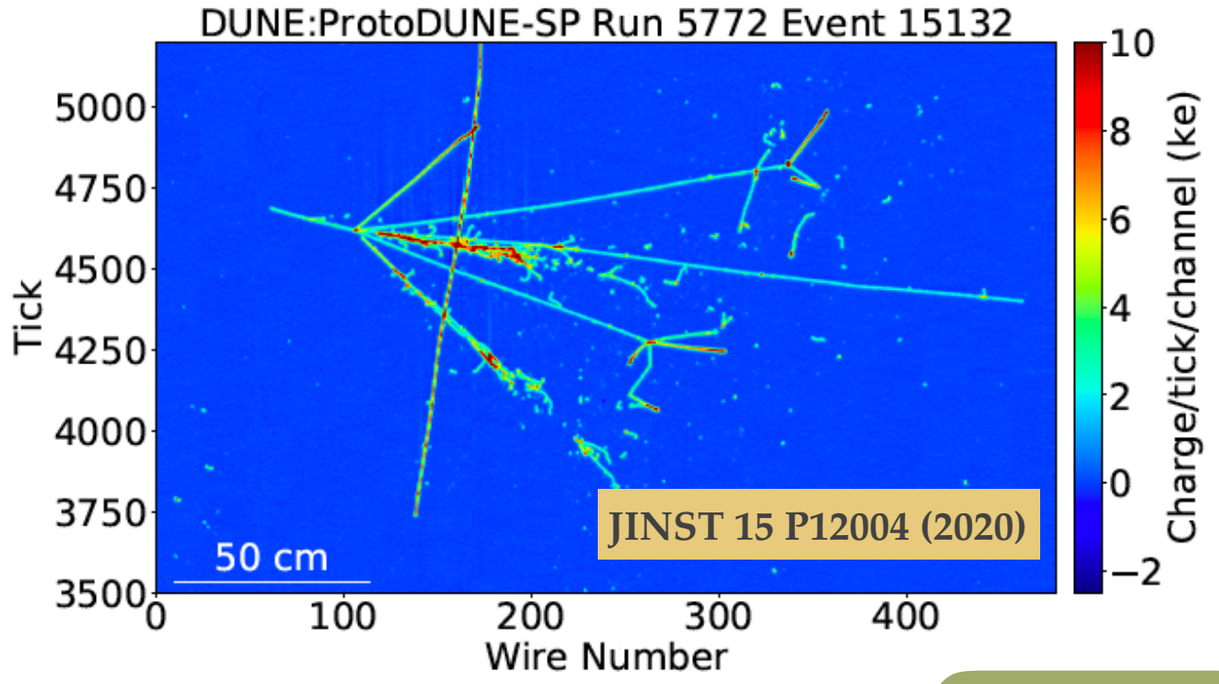
- **ProtoDUNE SP-HD**
  - *Largest LArTPC constructed to date!*
  - Ran successfully from 2018-20 collecting over 4 million events!
  - Charged particle beam and cosmic runs
  - Low noise, stable HV, high purity, neutron calibration, Xe doping
  - Calibration & detector physics; hadron-argon cross section measurement program
  - Phase-II with updated detector configuration — starting in Fall 2022



- **ProtoDUNE SP-VD**
  - Ran as Dual Phase (DP) from 2019-20
  - DP: signals produced in liquid and amplified in gas phase
  - Demonstration of longer drifts and outstanding purity; low S/N ratio
  - Evolved in to vertical drift from late 2020

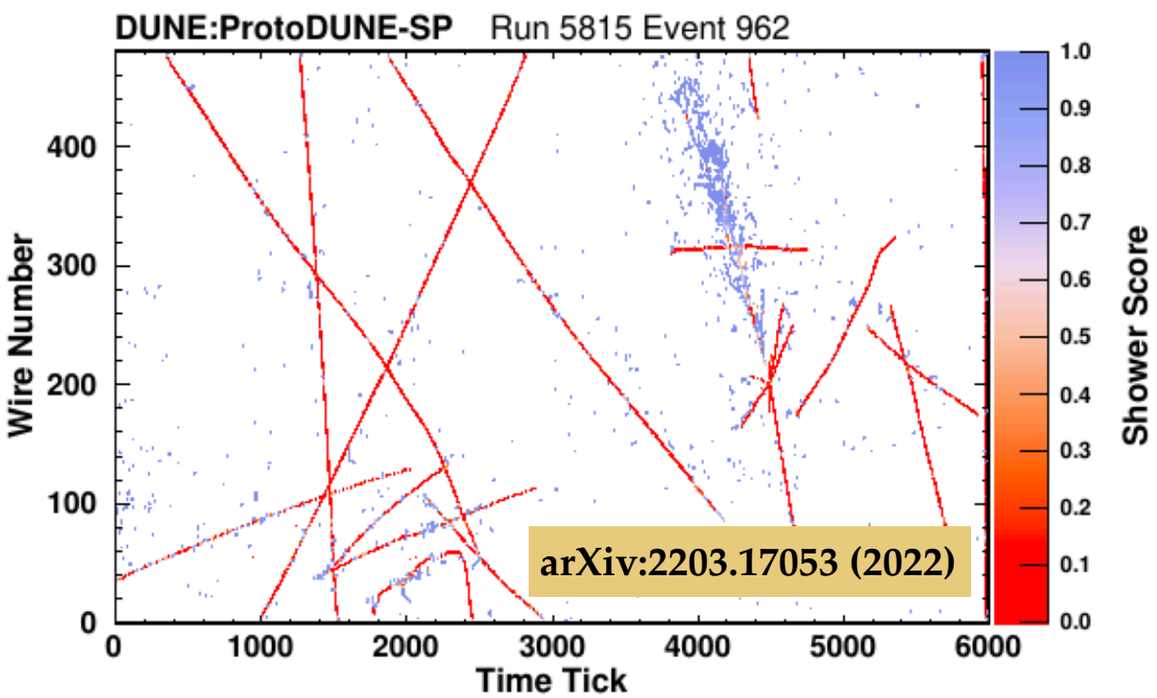
ProtoDUNE Run-I Results

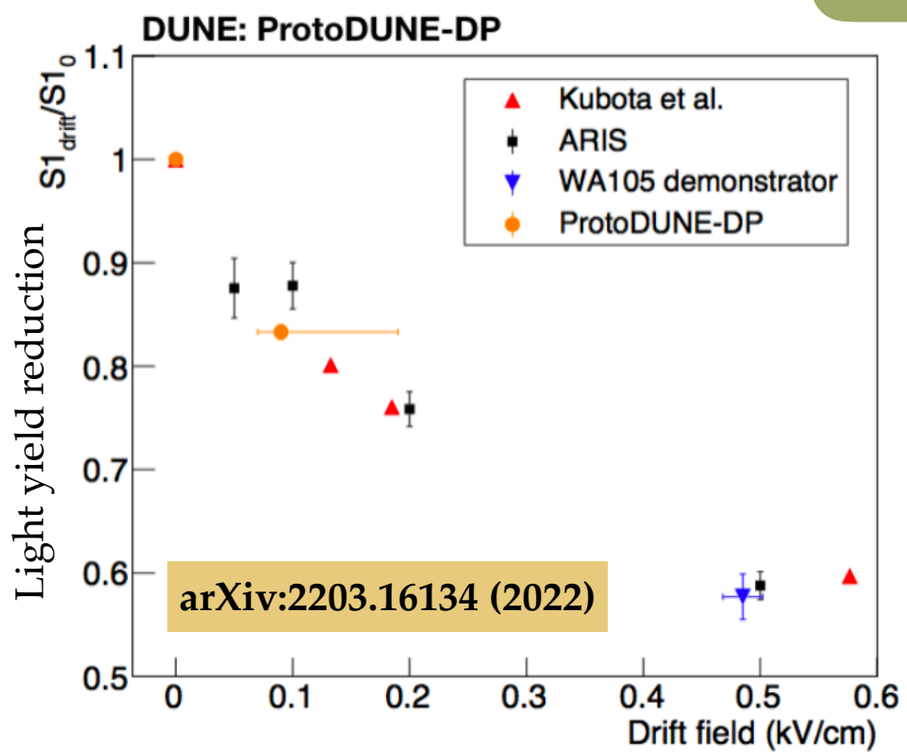




More results to come soon: hadron cross sections (neutron/pion/kaon/proton), event reconstruction, Michel electrons etc. — *Stay tuned!*

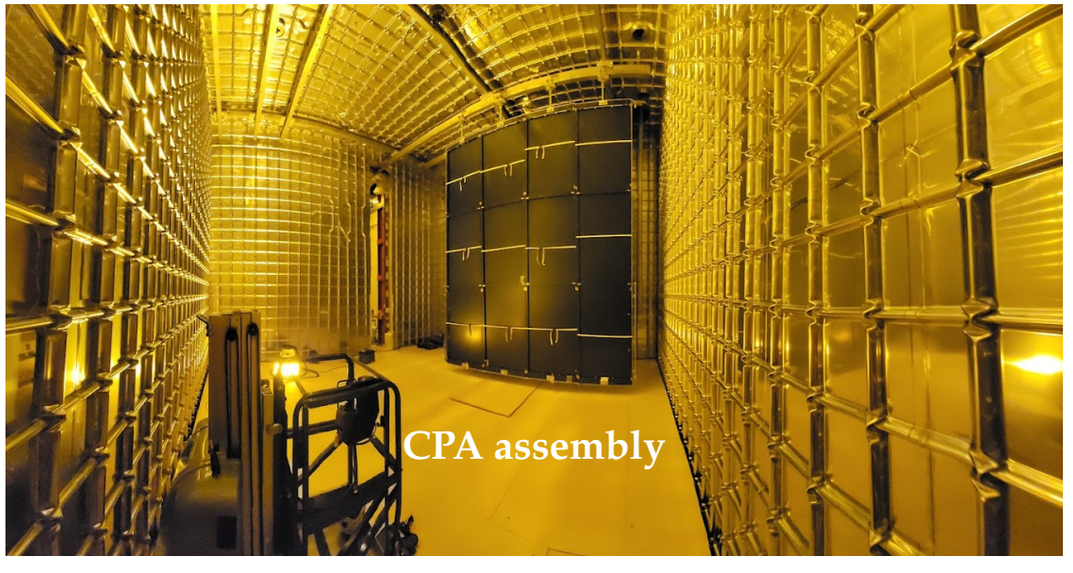
See talks by C. Sarasty & Y. Liu

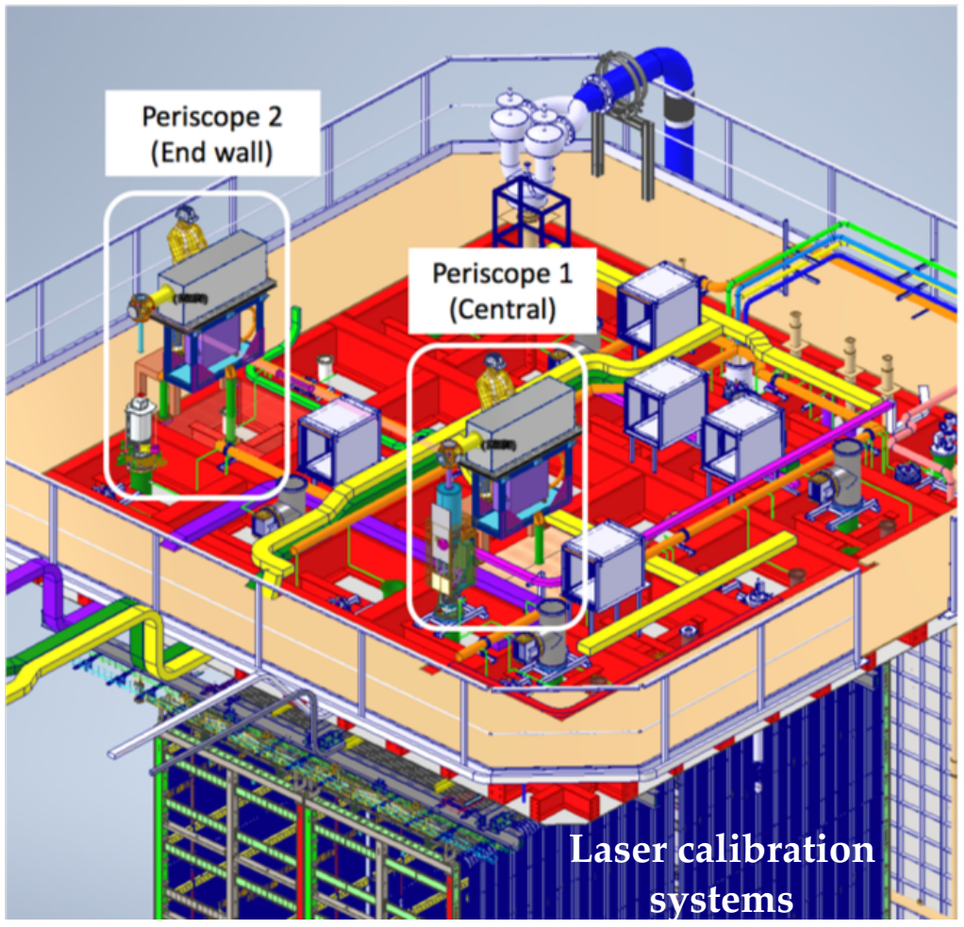


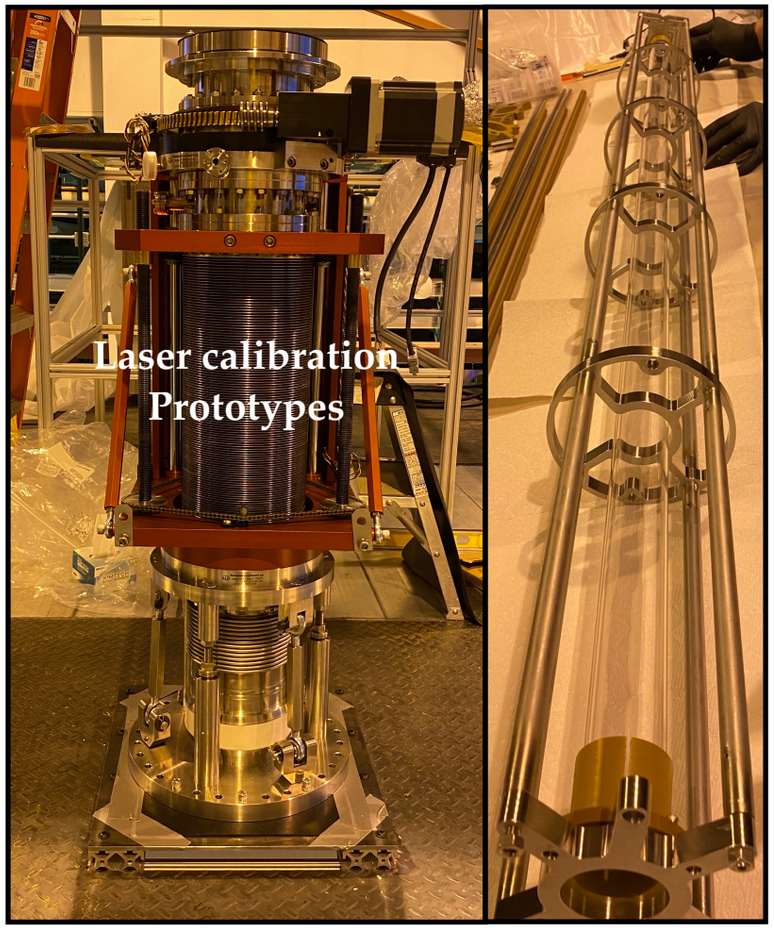


ProtoDUNE SP-HD Phase-II

- Plan to install and operate the first FD1 production components (APAs, Cold electronics, laser and neutron calibration systems etc.) in ProtoDUNE SP-HD in Phase-II
- Installation activities are well underway at CERN
- Plan to commission in Fall 2022





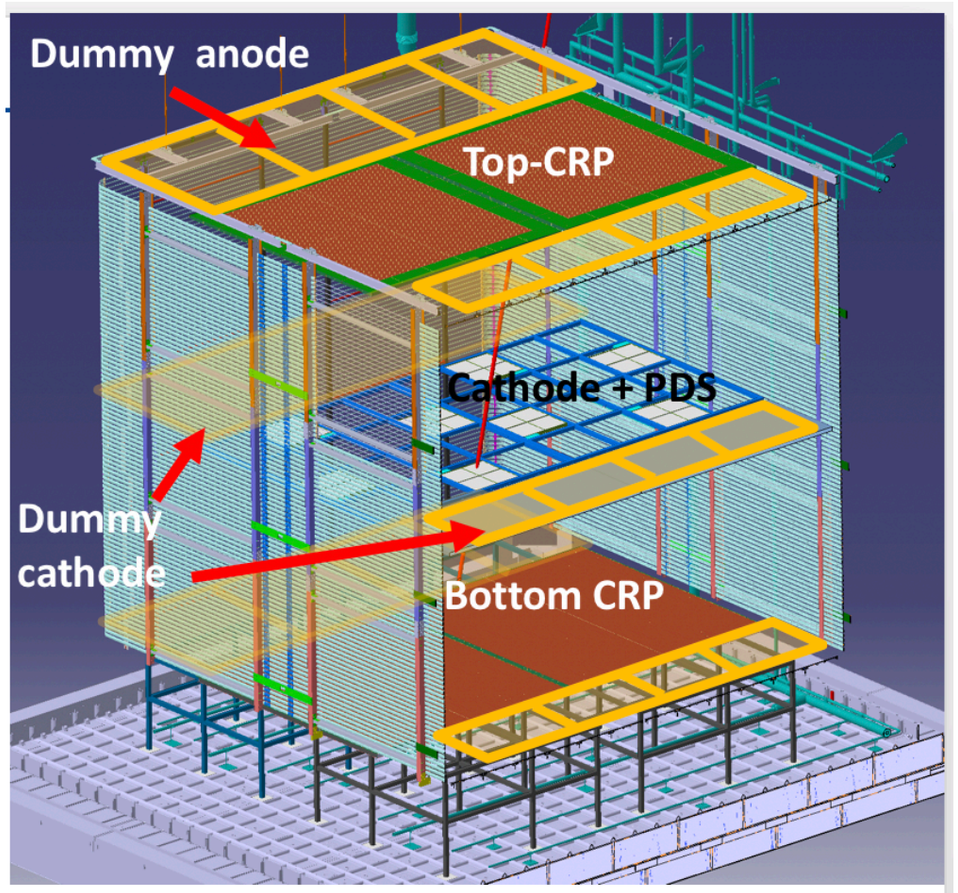


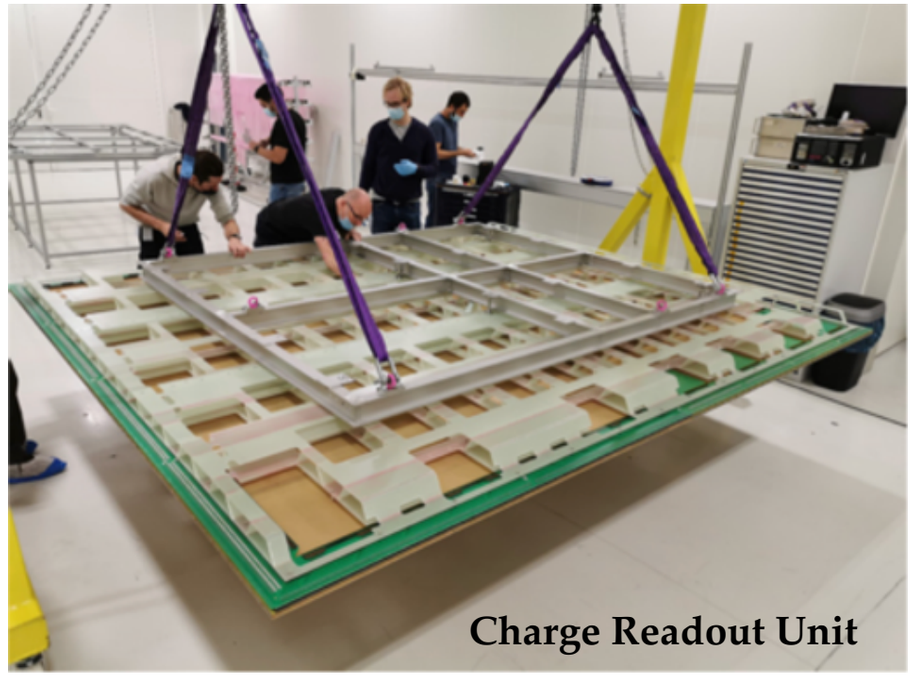
ProtoDUNE SP-VD Status

- The vertical drift technology development is advancing rapidly
- Intense R&D ongoing on main detector components (charge readout, high voltage and photon systems)
- Completion of Technical Design Report (TDR) by end of 2022

ProtoDUNE SP-VD Module 0 planning well underway for operation in 2023

ProtoDUNE SP-VD (module 0)





Summary & Outlook

- **DUNE is poised to make most precise measurements of neutrino oscillation parameters along with other rich physics**
- **DUNE is advancing rapidly on all fronts**
  - Far site excavation is well underway
  - Beamline and near site finished 100% design
  - Both Near and Far detector prototyping is progressing successfully
- **DUNE completed US-DOE CD-1RR approval in July 2022 and is on track for Phase 1 construction**
- **Stay tuned for more exciting developments on DUNE!**

Summary & Outlook

- DUNE is poised to make most precise measurements of neutrino oscillation parameters along with other rich physics
- DUNE is advancing
- The
- There are more exciting developments on DUNE!

DUNE @NuFACT

There are a total of 12 parallel talks on DUNE + *many* posters.

Only some of them I could highlight.

Make sure to check them out for more information!

Thank you!