The Deep Underground Neutrino Experiment

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on behalf of the DUNE Collaboration

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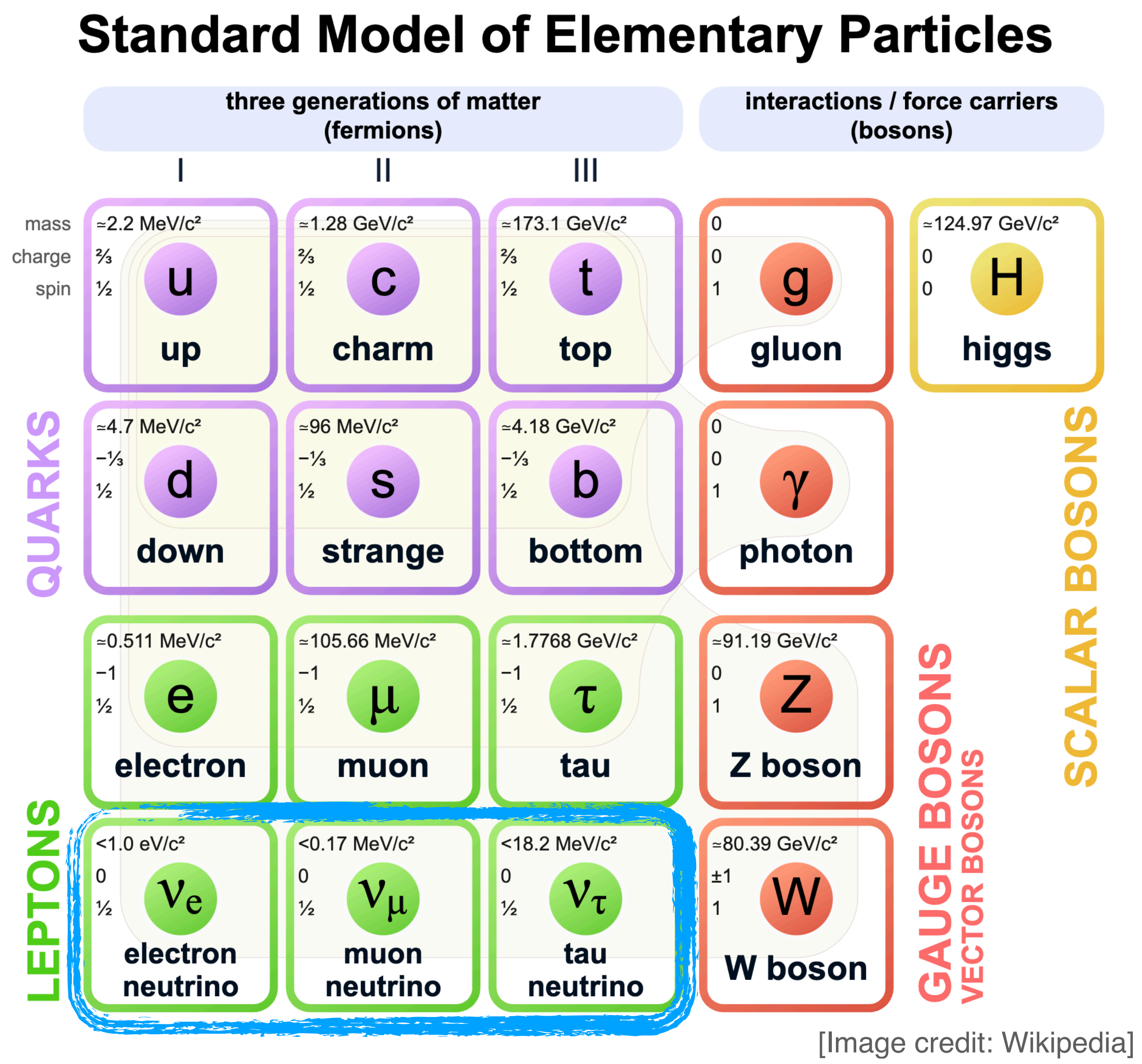
Outline

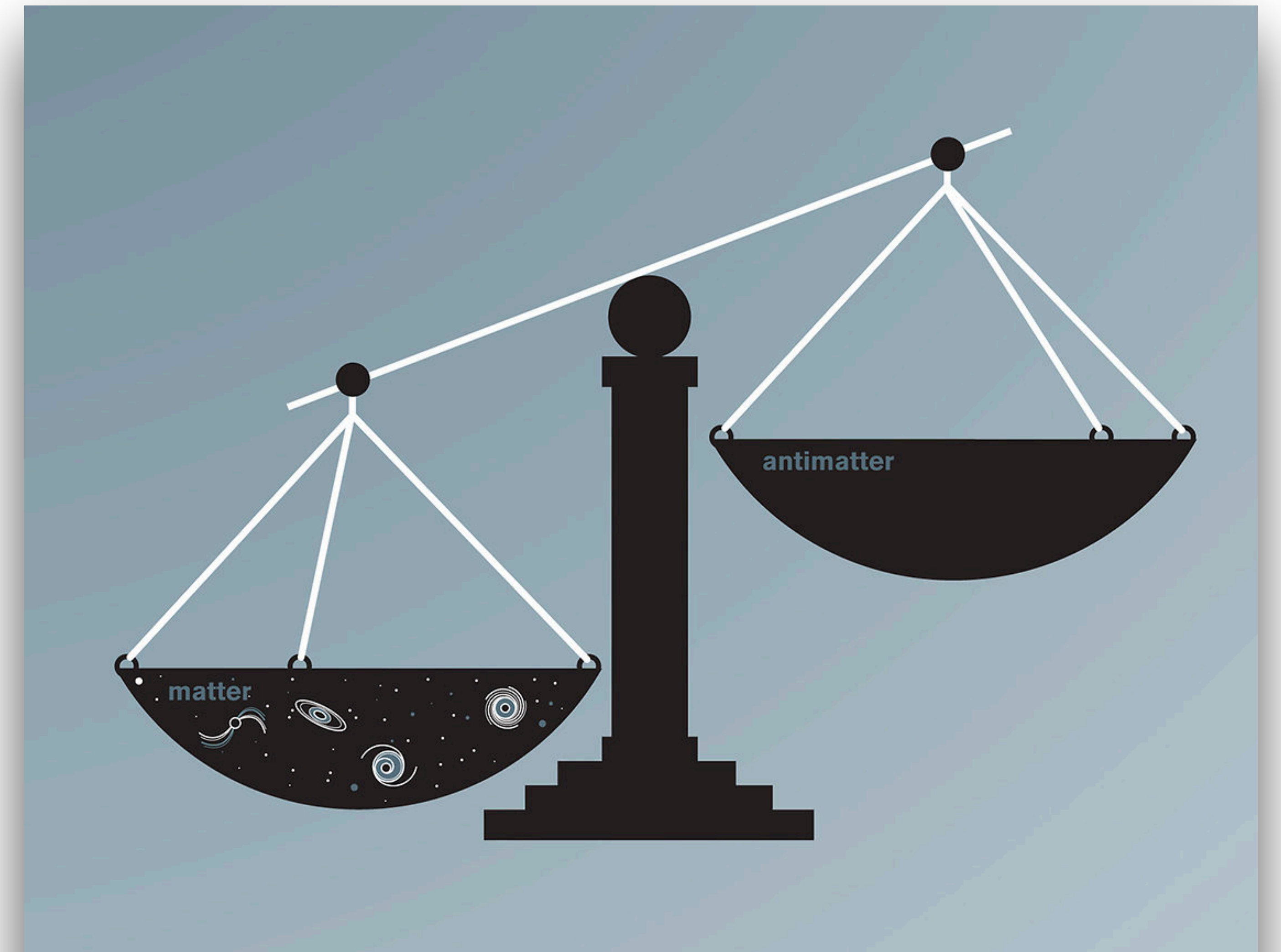
- Introduction to neutrinos
- Overview of the Deep Underground Neutrino Experiment (DUNE)
- DUNE beam and detectors
- DUNE physics
- DUNE prototypes

Introduction to neutrinos

- Neutrinos are the second most **abundant** particles in the universe, after photons
- Neutrinos are among the **fundamental particles** that compose the universe
  - Come in **3 flavors** (ν_e, ν_μ, ν_τ)
    ⇒ as well as there are 3 families of matter particles
  - Carry no charge + Only **weakly interacting**, very weakly…
    ⇒ need for huge-size detectors, long exposure times
  - Can change into different flavors over **long distances**
    ⇒ neutrino oscillations
- Neutrinos and their oscillations can be used to probe a wide variety of fundamental phenomena in the universe, from nucleus to Big Bang



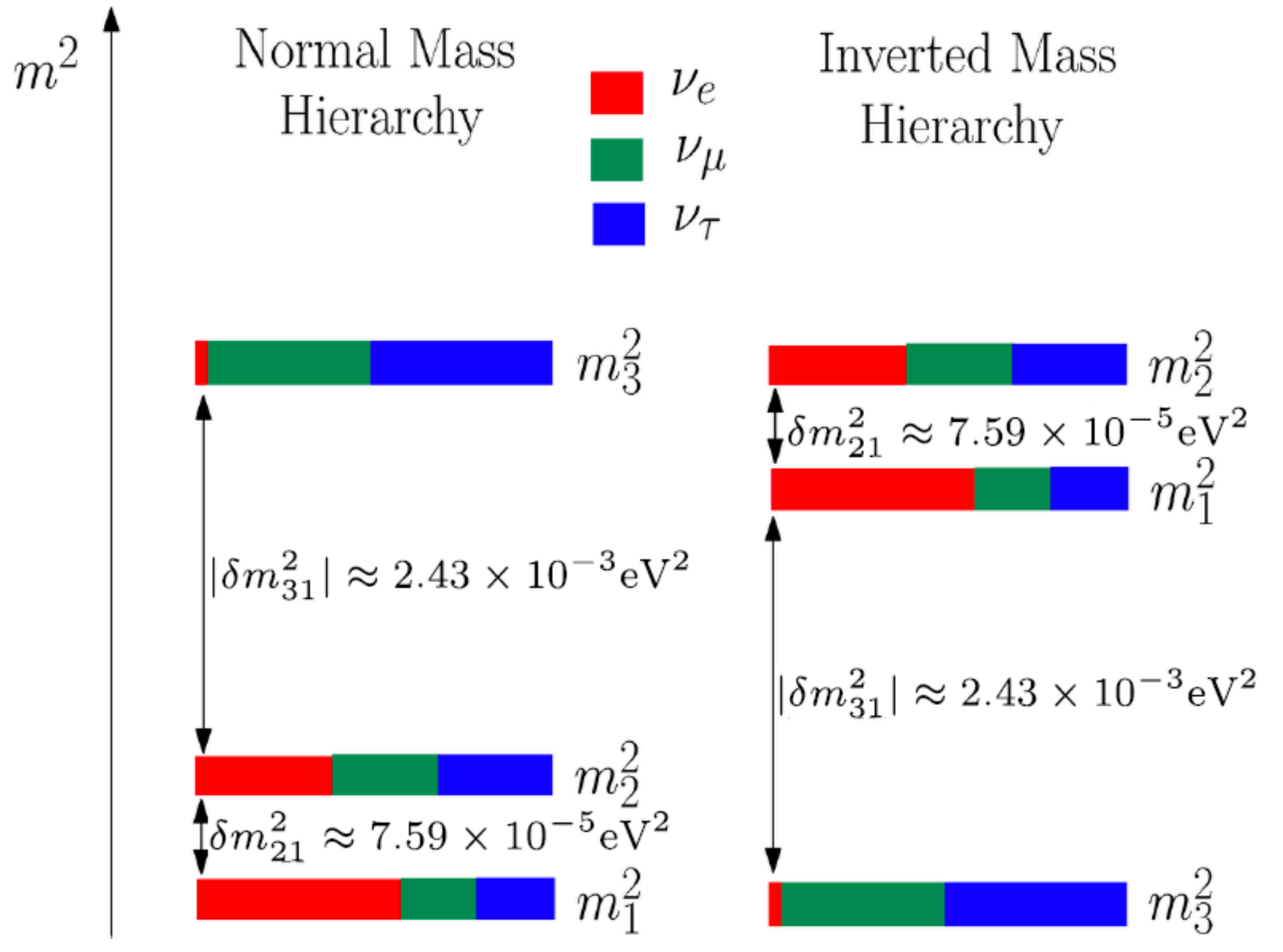
[Image credit: Wikipedia]



[Image credit: Fermilab]

Open questions about neutrinos

- Theorized in the 1930s, discovered in the 1950s, studied for about a century
- Much is still unknown:
  - What are the **absolute masses** of neutrinos?
  - Neutrino mass **hierarchy** - which neutrino is the lightest?
  - Why neutrino **mixing** is very different from quark mixing?
  - Are there more than 3 neutrino **flavors**?
  - **CP violation** in the neutrino sector - are neutrinos favored over antineutrinos in fundamental reactions?



[Image credit: MPKI]

Quark mixing (CKM)

$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

~ Amplitude of transition

Neutrino mixing (PMNS)

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

~ Amplitude of transition

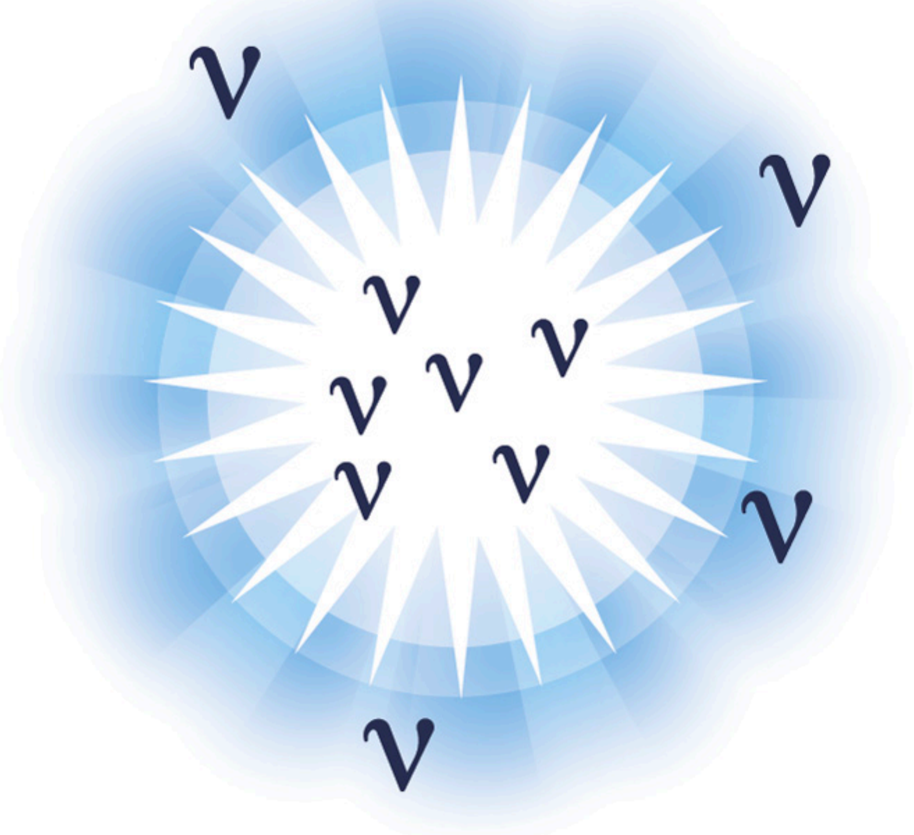
The Deep Underground Neutrino Experiment

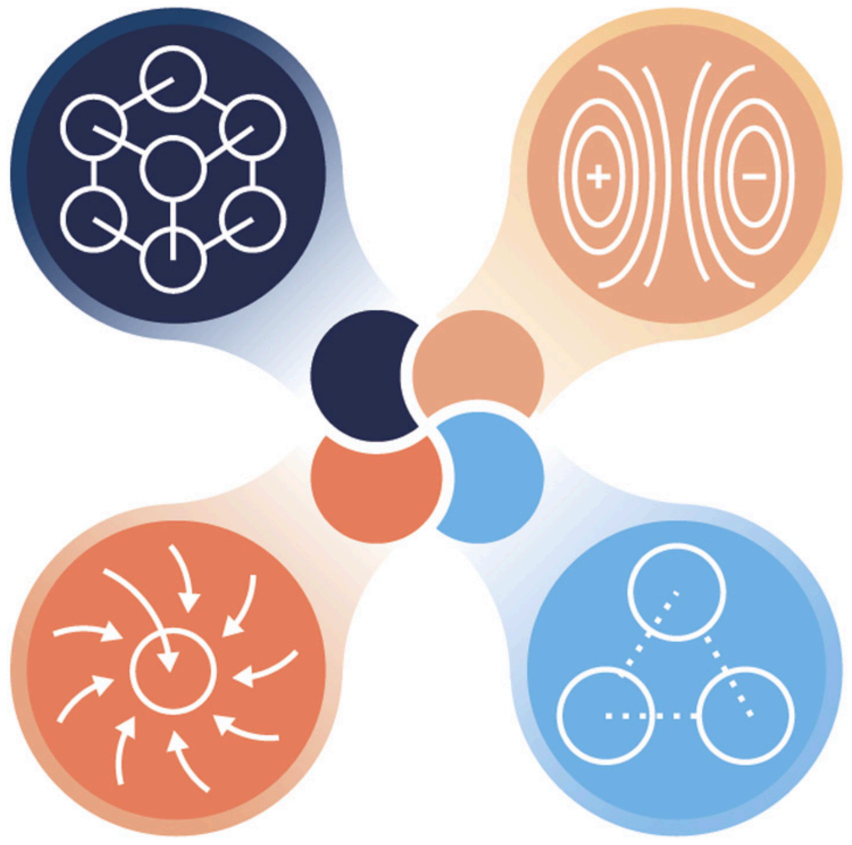
The next generation long baseline neutrino experiment

- Long baseline experiment: 800 miles from Fermilab to SURF, 14 k ft water equivalent depth
- The most intense neutrino beam ever: **1.2 MW**, upgradable to **2.4 MW**
- Two detectors, Near/Far, the largest liquid argon neutrino detector in the world (**70 kt**)
- A worldwide Collaboration: **1300+ people**, **200+ institutions**, **34 countries w/ CERN**

Science goals

- **Constrain flavor and mass models, search for the origin of matter, testing the three-flavors paradigm**:
  - Precise neutrino oscillation parameters for $\nu_e/\bar{\nu}_e$ appearance, $\nu_\mu/\bar{\nu}_\mu$ disappearance searches, CP violation, mass hierarchy in the ν sector
- **Learn about supernovae, neutron stars and black holes**
  - DUNE alone would detect > twice as many neutrinos as all the active detectors at the time of the last supernova core collapse
- **Shed light on Grand Unified Theories (GUT), physics beyond the Standard Model**:
  - Proton decay, baryon number violation, sterile neutrinos, non-standard interactions and more



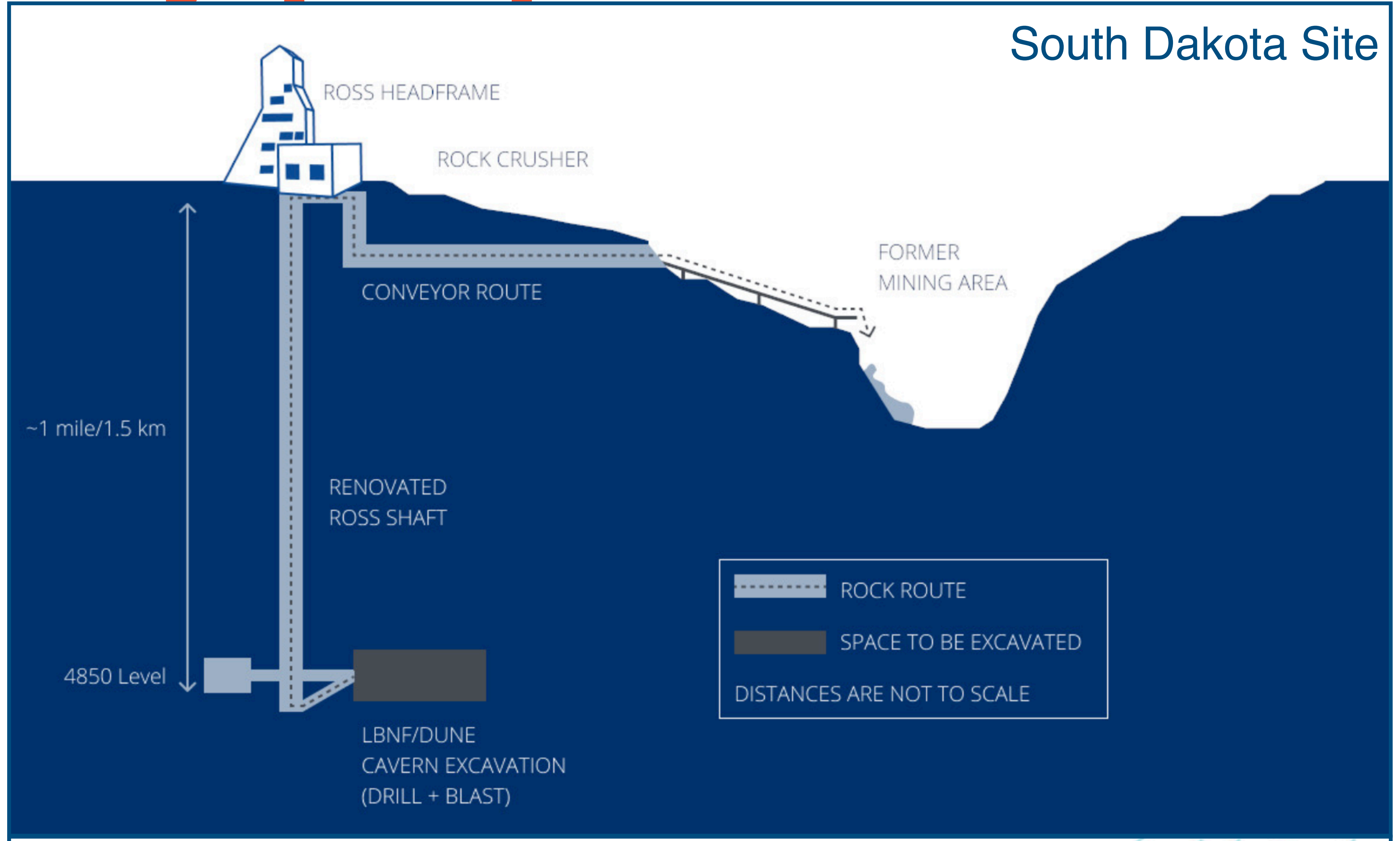


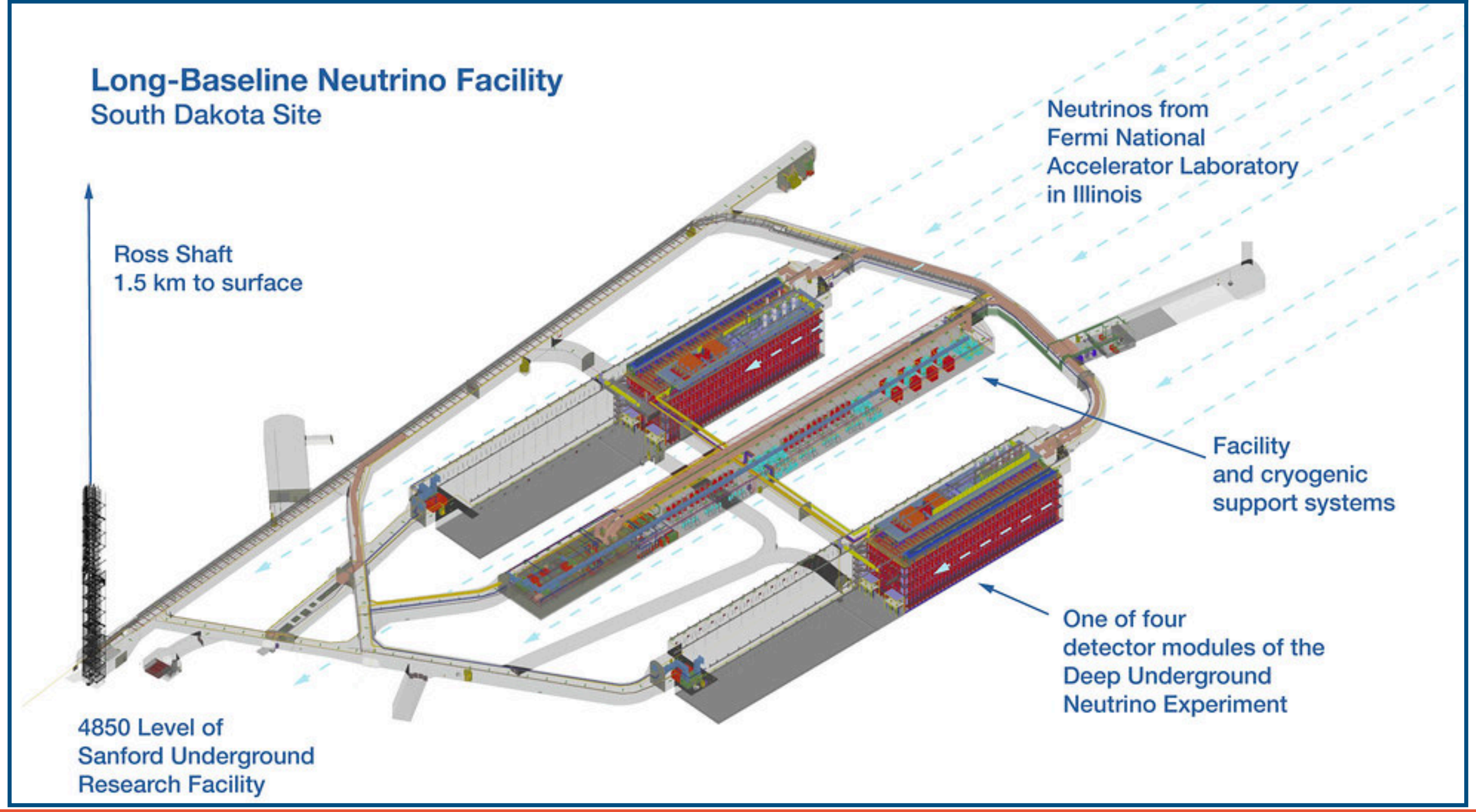
[Image credit: Fermilab]

Near/Far Site facility preparation

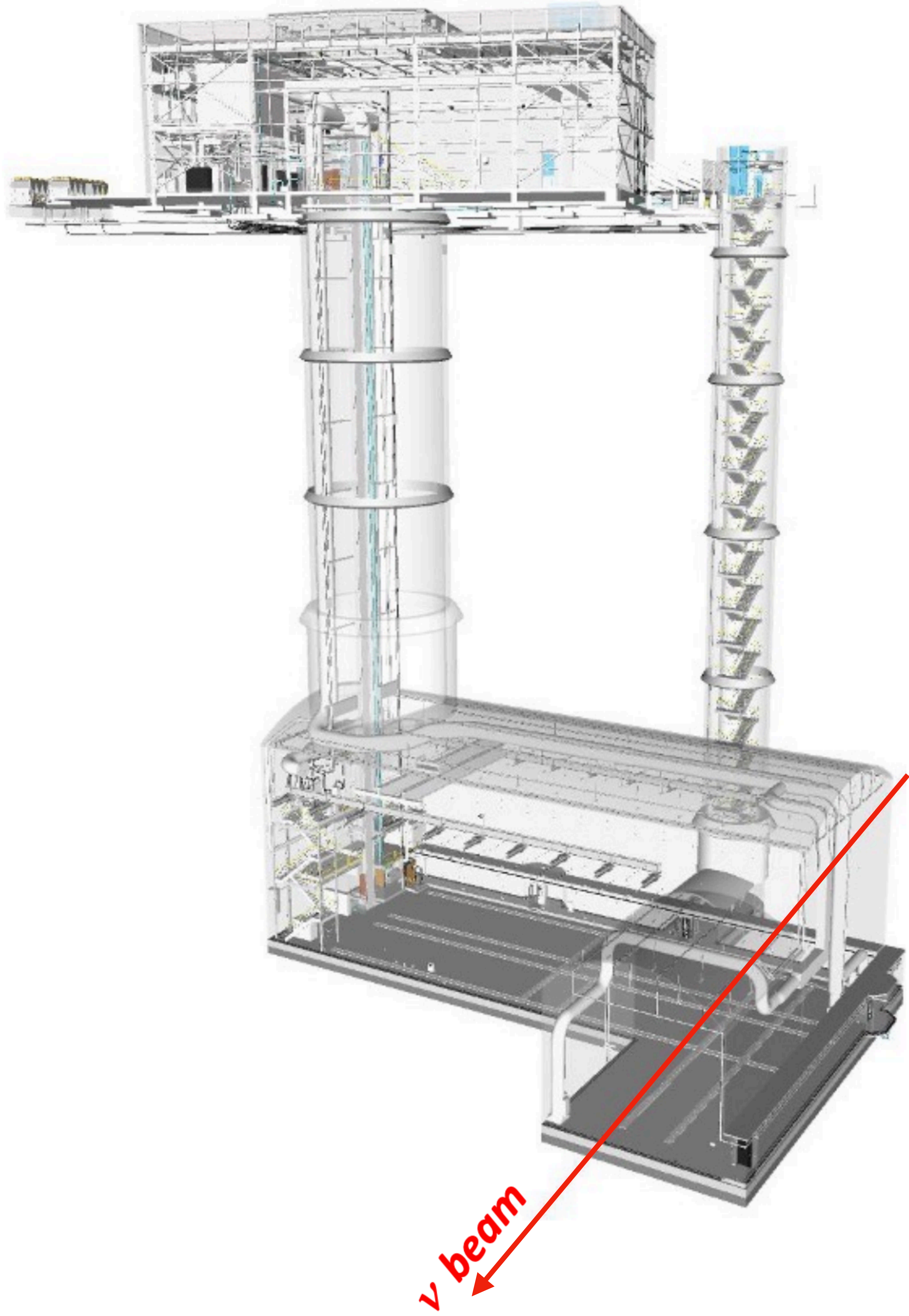
- **Far Detector (FD) site at SURF**
  - Deepest laboratory in the US: 1.5 km underground
  - Excavation work started in early 2019
  - Three main caverns:
    - 4 detectors halls in 2 caverns
    - 1 support cavern
  - Far Detector (FD) first module installation expected mid-2020's
- **Near Detector (ND) site at Fermilab**
  - 60 m underground, 574 m away from the neutrino source
  - Near Detector Conceptual Design Report (CDR) now finalized and accepted for publication [ArXiv:2103.13910]

South Dakota Site





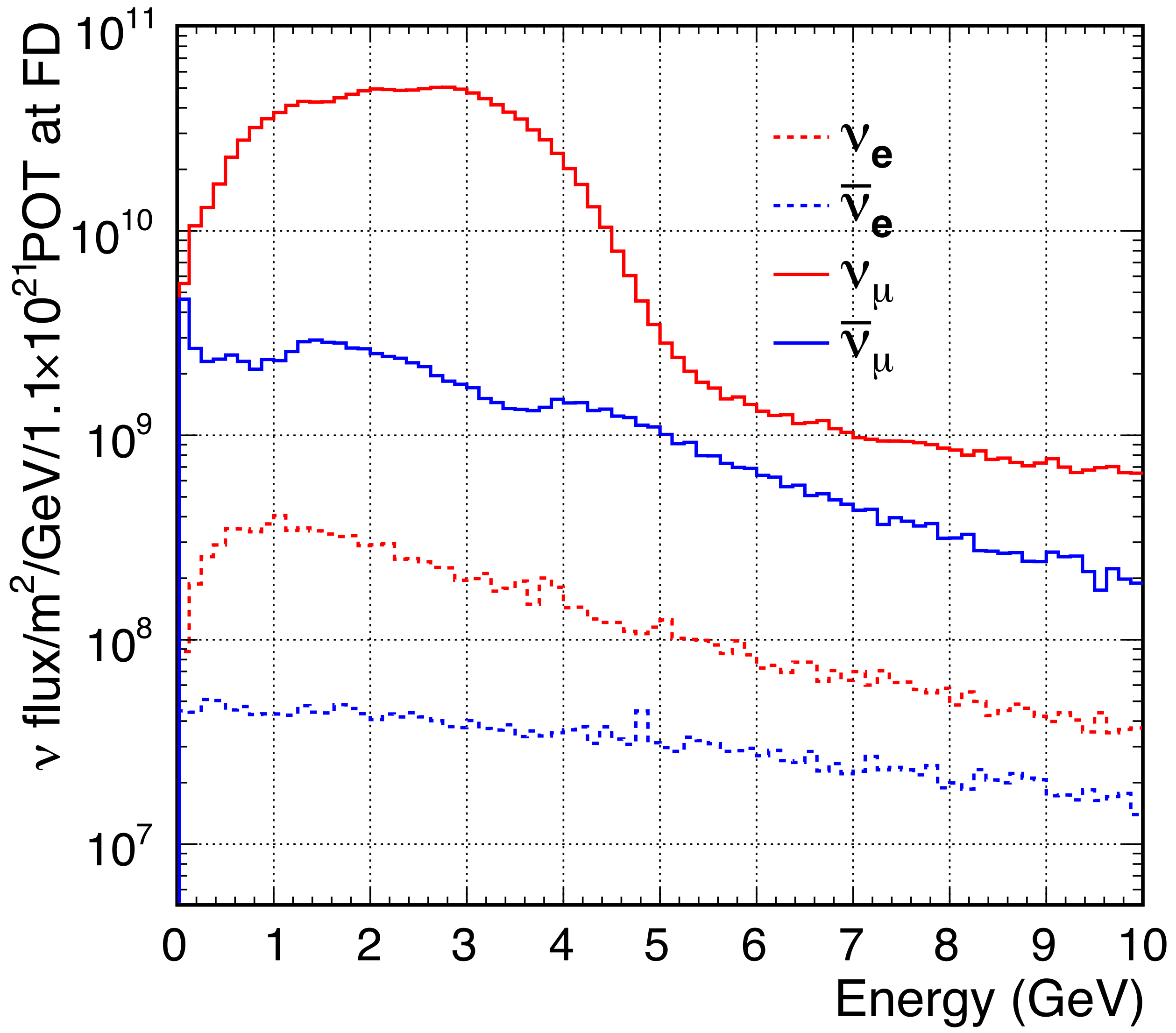
Fermilab Site

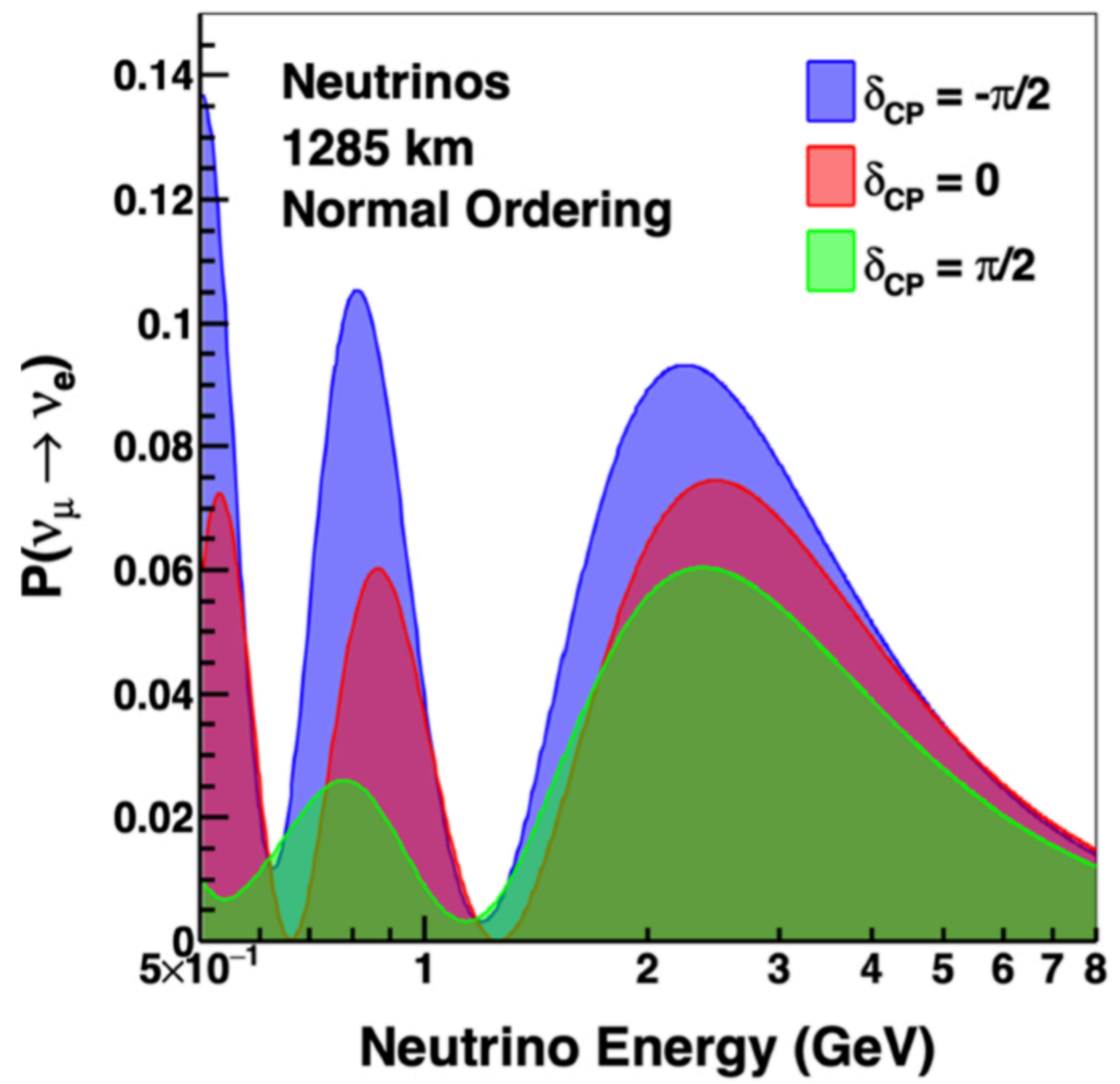


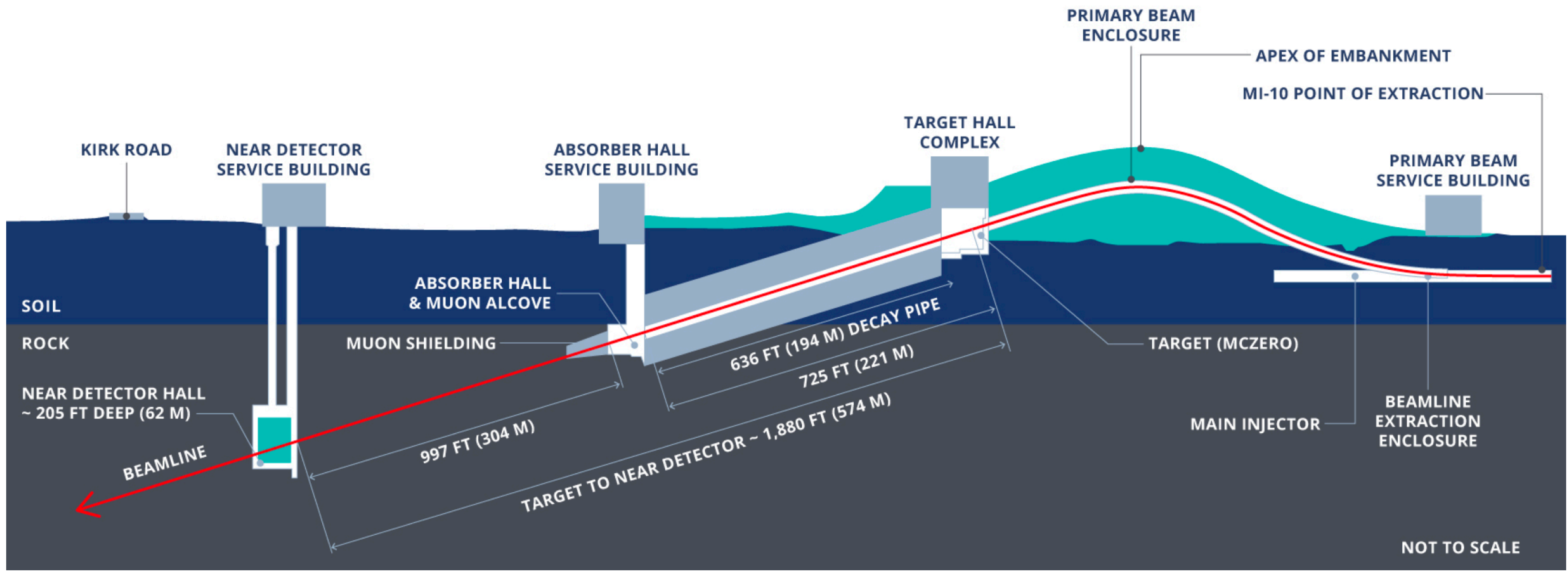
Beamline

- **Proton beam line**
  - Produce neutrino beam by focusing charged pions and allowing them to decay
  - Can operate in neutrino and antineutrino modes
- **Proton Improvement Plan-II (PIP-II)**
  - 1.2 MW (2.4 MW) proton beam, ready to operate late 2020s
  - Accelerated to 60-120 GeV by FNAL accelerator complex
  - Bent down at 5.8° to reach Sanford
  - Horns/beam line designed to maximize CP violation sensitivity
- **Expected neutrino fluxes available**:
  - Neutrino-enhanced, Forward Horn Current (FHC),
  - Antineutrino-enhanced, Reverse Horn Current (RHC)

On-axis wide band beam covering main oscillation features





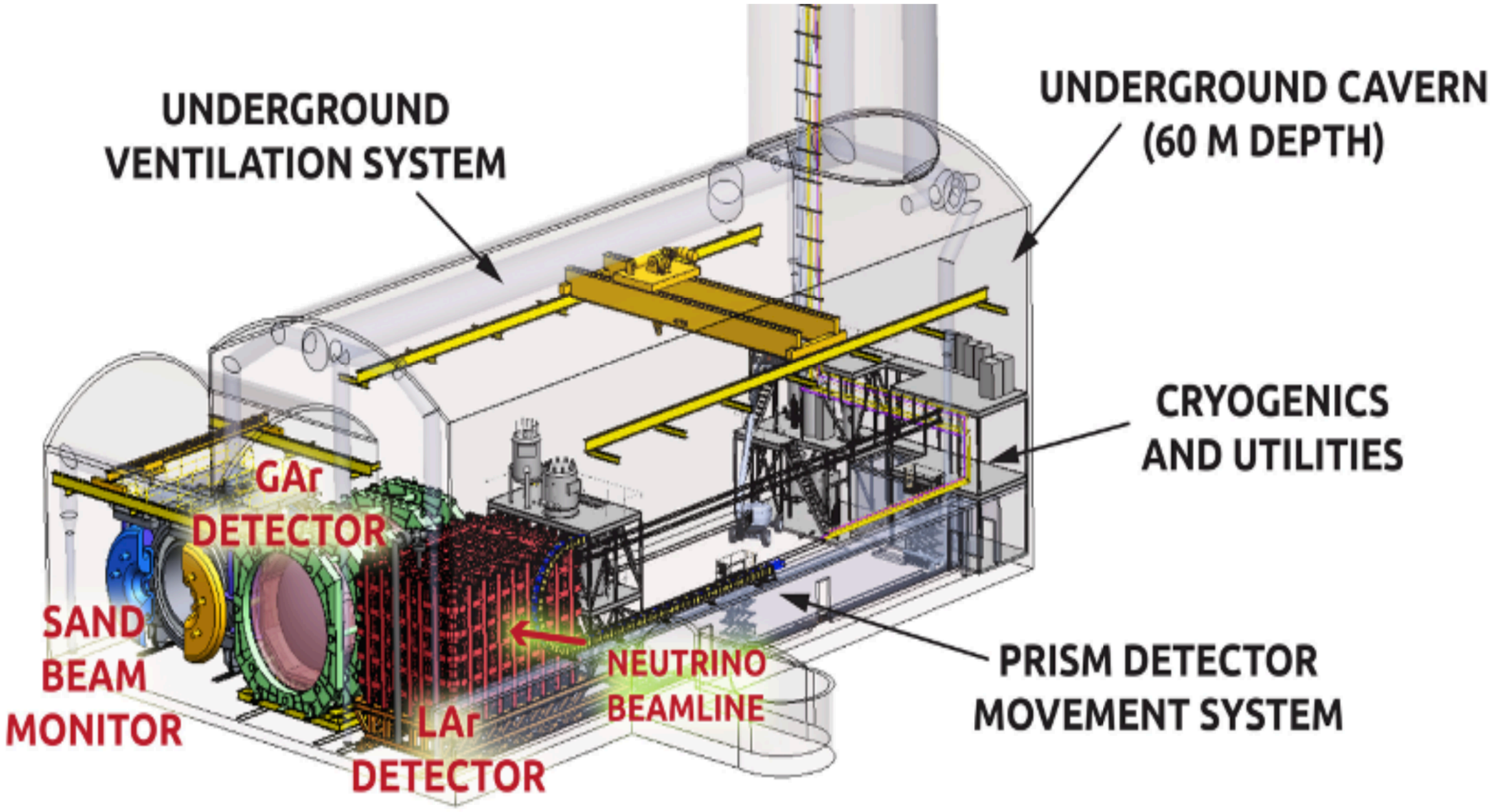


[Eur. Phys. J. C 80 (2020) 10, 978]

Near Detector

Independently constrain the cross section, flux, energy response, systematics

- Multiple complementary systems:
  - **ND-LAr** - Liquid Argon TPC
    - Primary target (300 t, 50 t fiducial volume)
    - Modular, pixel read-out
    - Module 0 successfully tested at Univ. Bern
  - **ND-GAr** - High Pressure Gas TPC
    - HP GAr TPC surrounded by ECal + magnet
    - Detects muons escaping LAr
    - Will come at a later stage. Either a Temporary Muon Spectrometer or a ND-GAr-Lite will start on Day 1
  - **SAND** - on-axis beam monitor
    - Inner tracker surrounded by 100 t ECal, SC magnet (0.6 T)
    - On-axis beam monitor for beam spectrum/stability

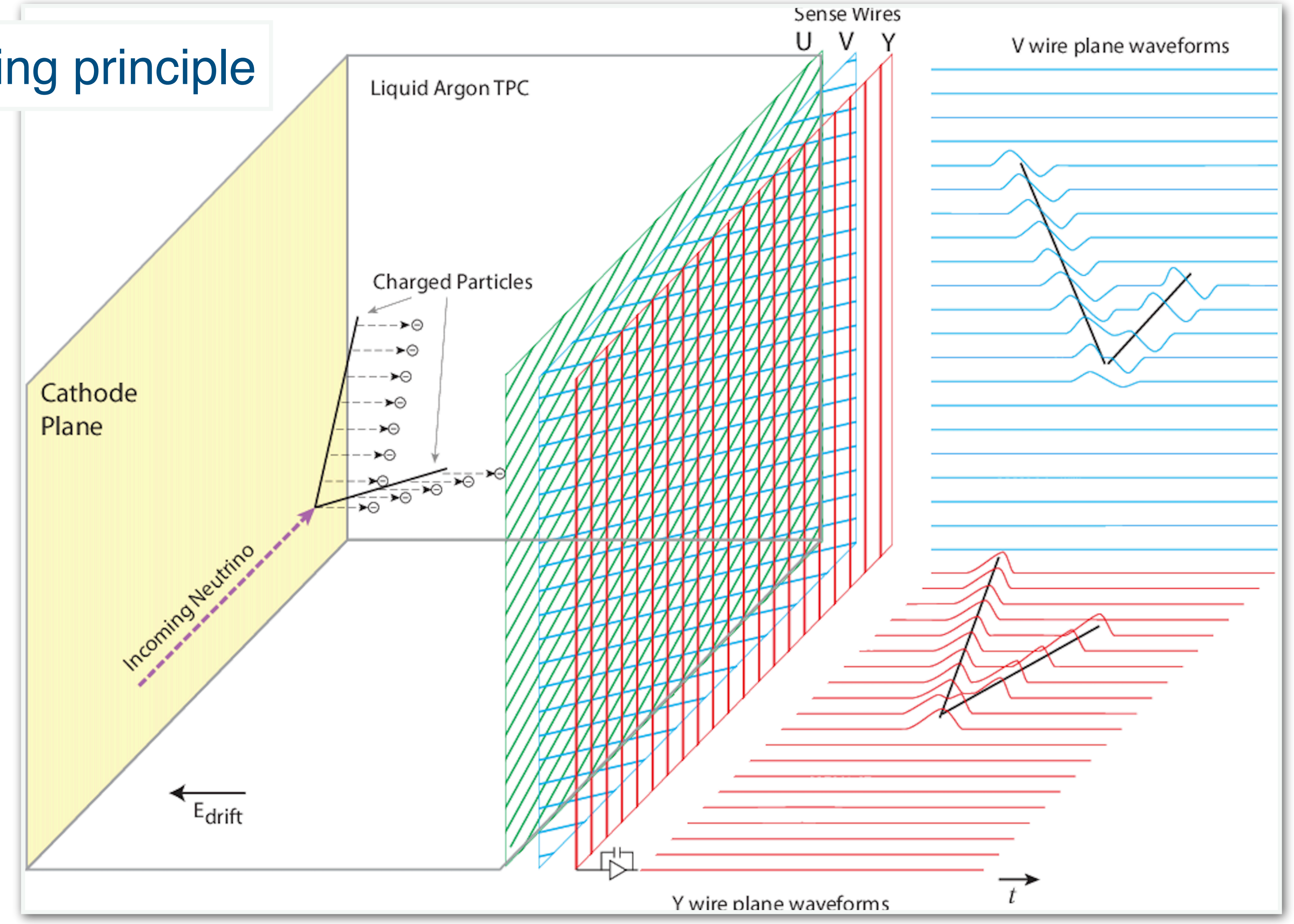


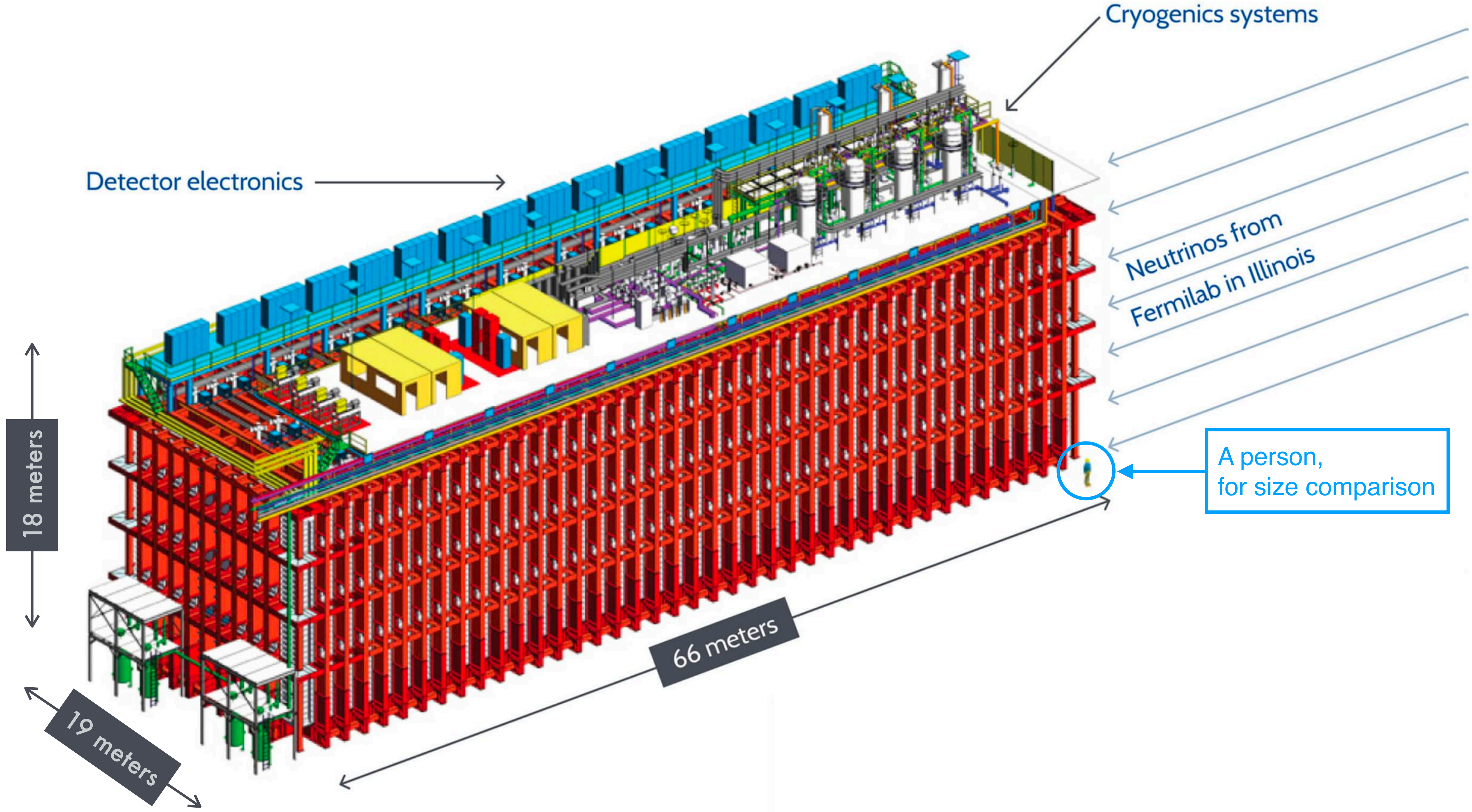
- **PRISM**
  - ND-LAr and ND-GAr move up to 30 m off-axis
  - Beam characterization dependent to the off-axis angle to minimize flux and cross section systematics

Far Detector

- 4 Detector modules, ~17 kt total volume each
- Single phase (SP) Liquid Argon Time Projection Chambers (LArTPC) - main detector technology
  - **FD #1**: SP LArTPC, Horizontal Drift (HD)
    - construction starts in mid 2020's
  - **FD #2**: SP LAr-TPC, Vertical Drift (VD)
    - construction starts in mid 2020's
  - **FD #3**: SP LAr-TPC HD/VD yet TBD
  - **FD #4**: Ongoing R&D for Module of Opportunity

TPC working principle

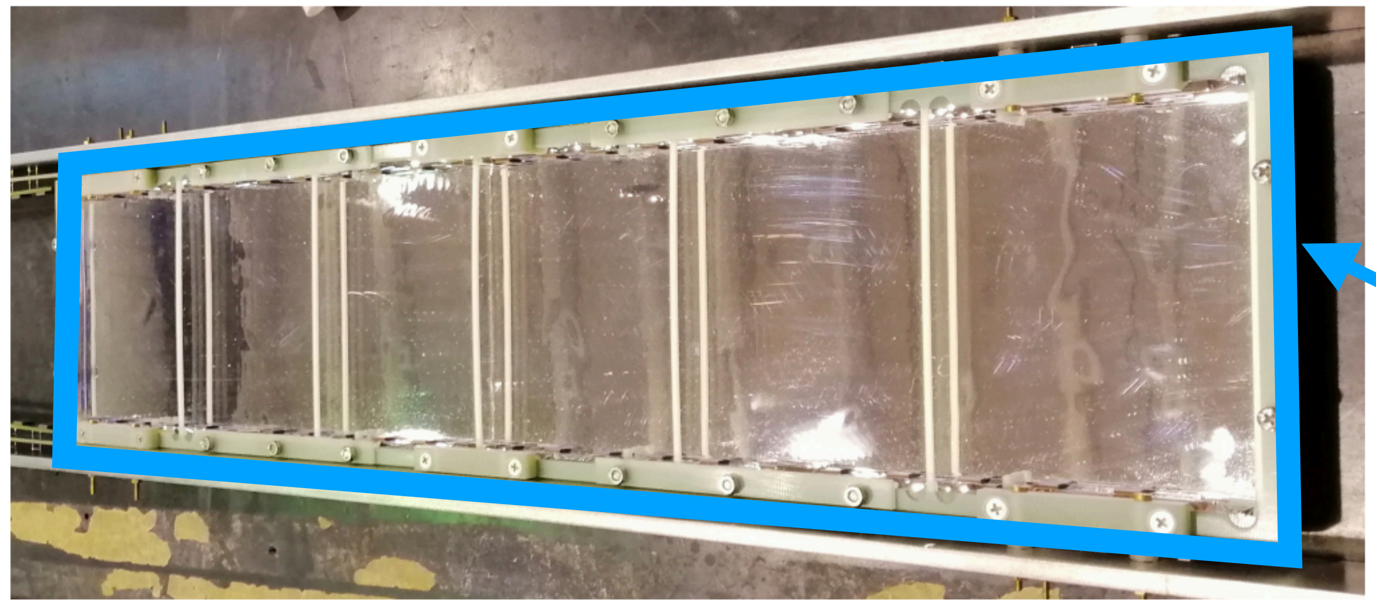




FD#1 - LAr-TPC Horizontal Drift Technology

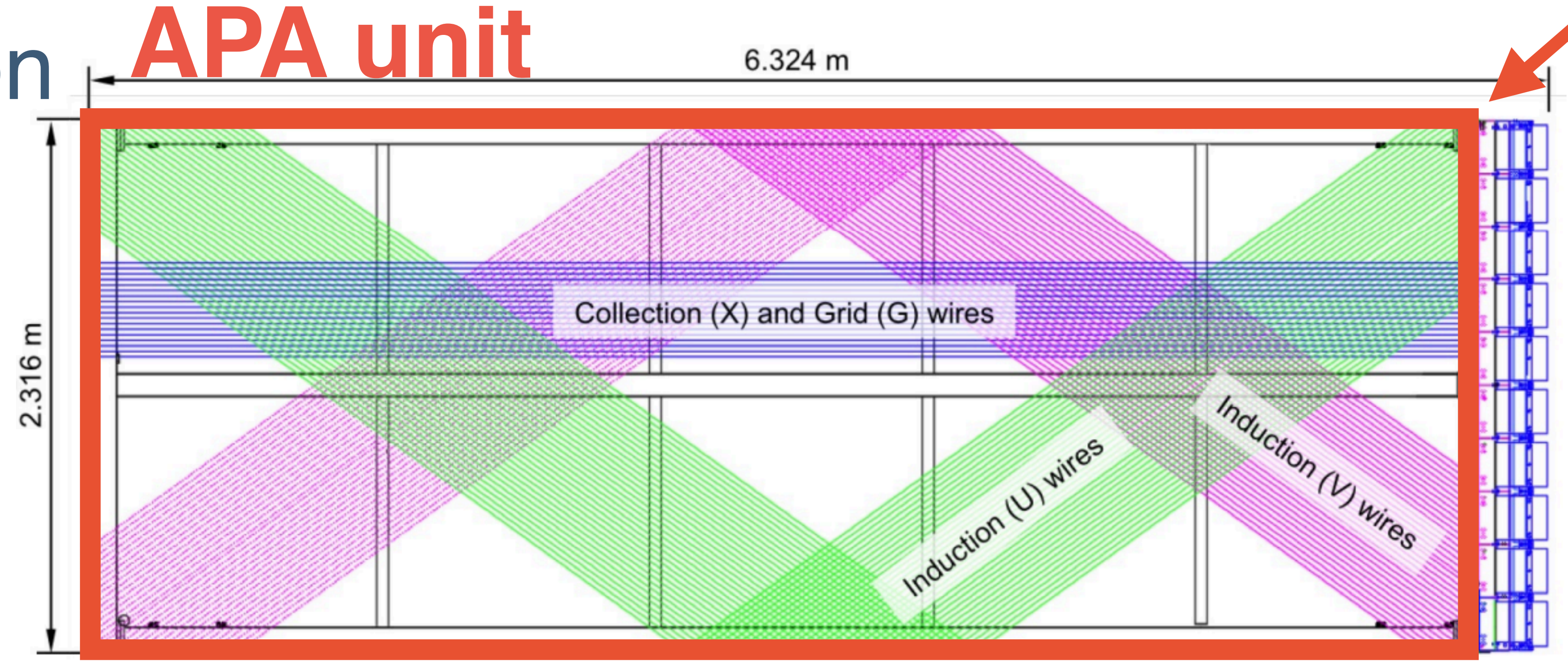
- Alternated APA/CPA **Anode and Cathode Plane Assemblies**
  - Segmented: 4 drift volumes, Drift distance: 3.6 m
  - Electric field = 500 V/cm (HV = -180 kV)
  - Anode: 150 APAs 4 wire planes each Grid, 2x Induction, Collection
  - High-resistivity CPAs to prevent fast discharge
- **Photon Detectors**: X-ARAPUCA light traps

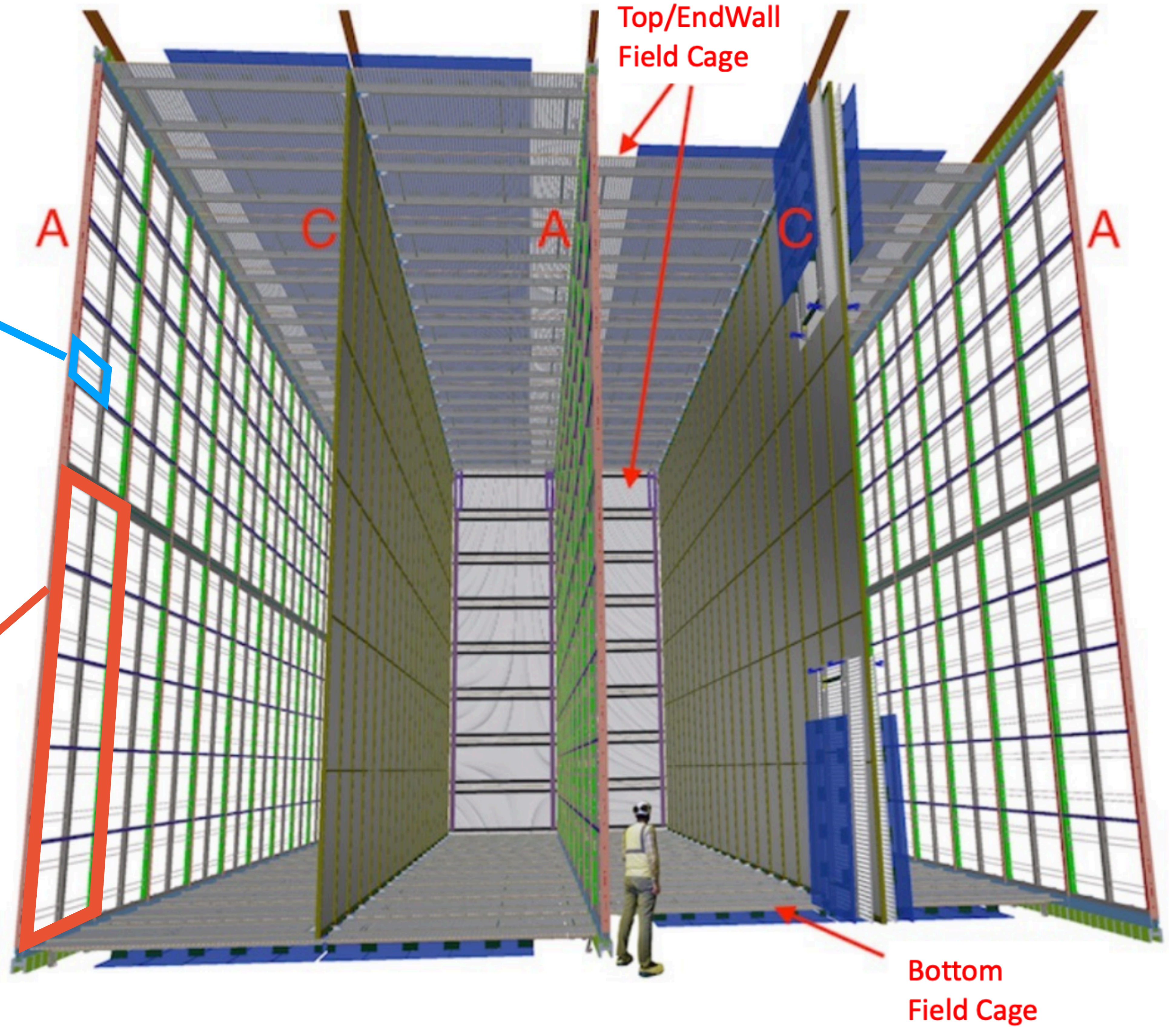
X-ARAPUCA module



1 SuperCell = ¼ PDS module -- SiPM readout
High-reflectivity inner surfaces
Wavelength-shifting + dichroic filter for light trapping

APA unit

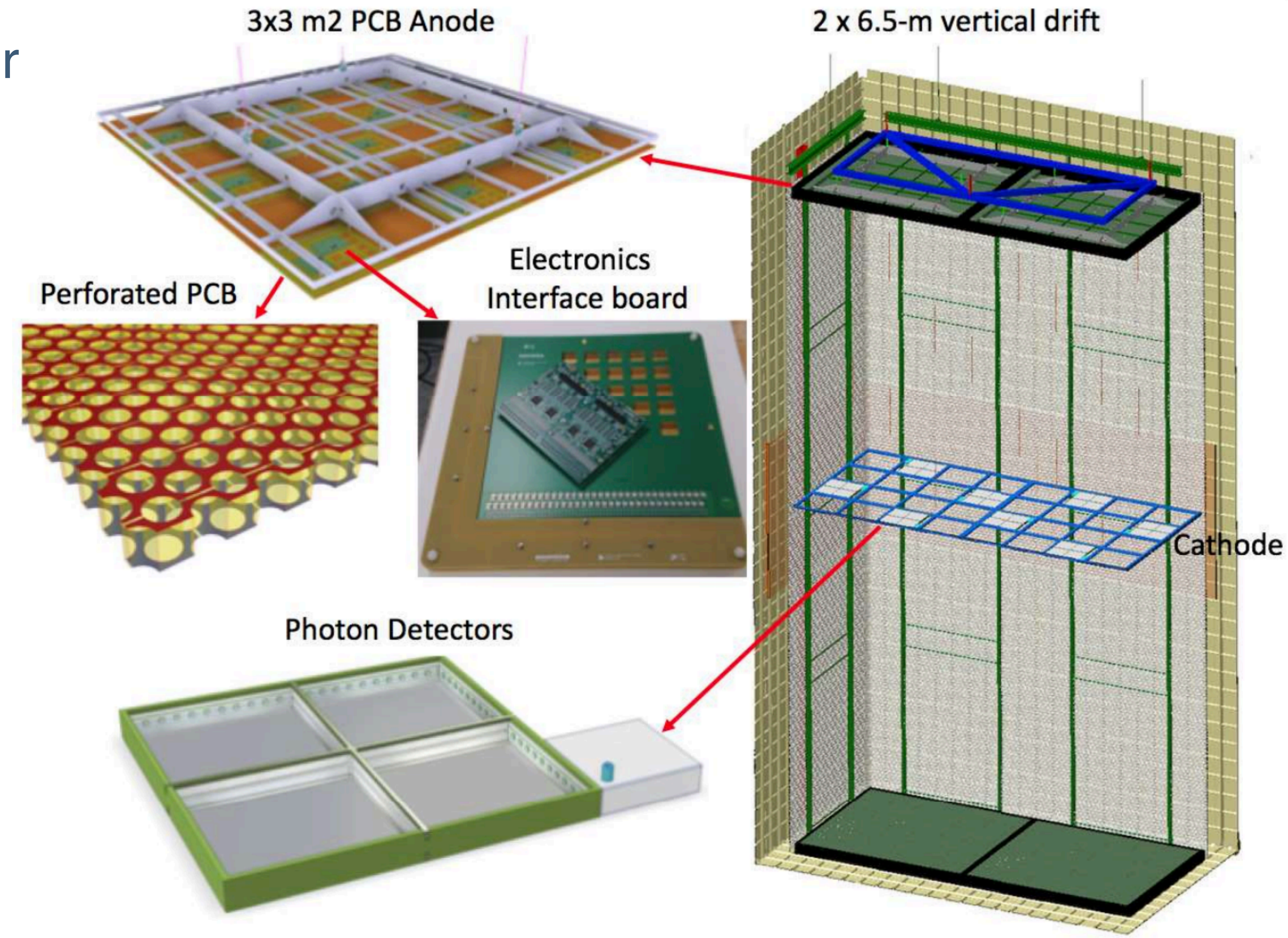




[DUNE TDR, B. Abi *et al* 2020 *JINST* **15** T08010]

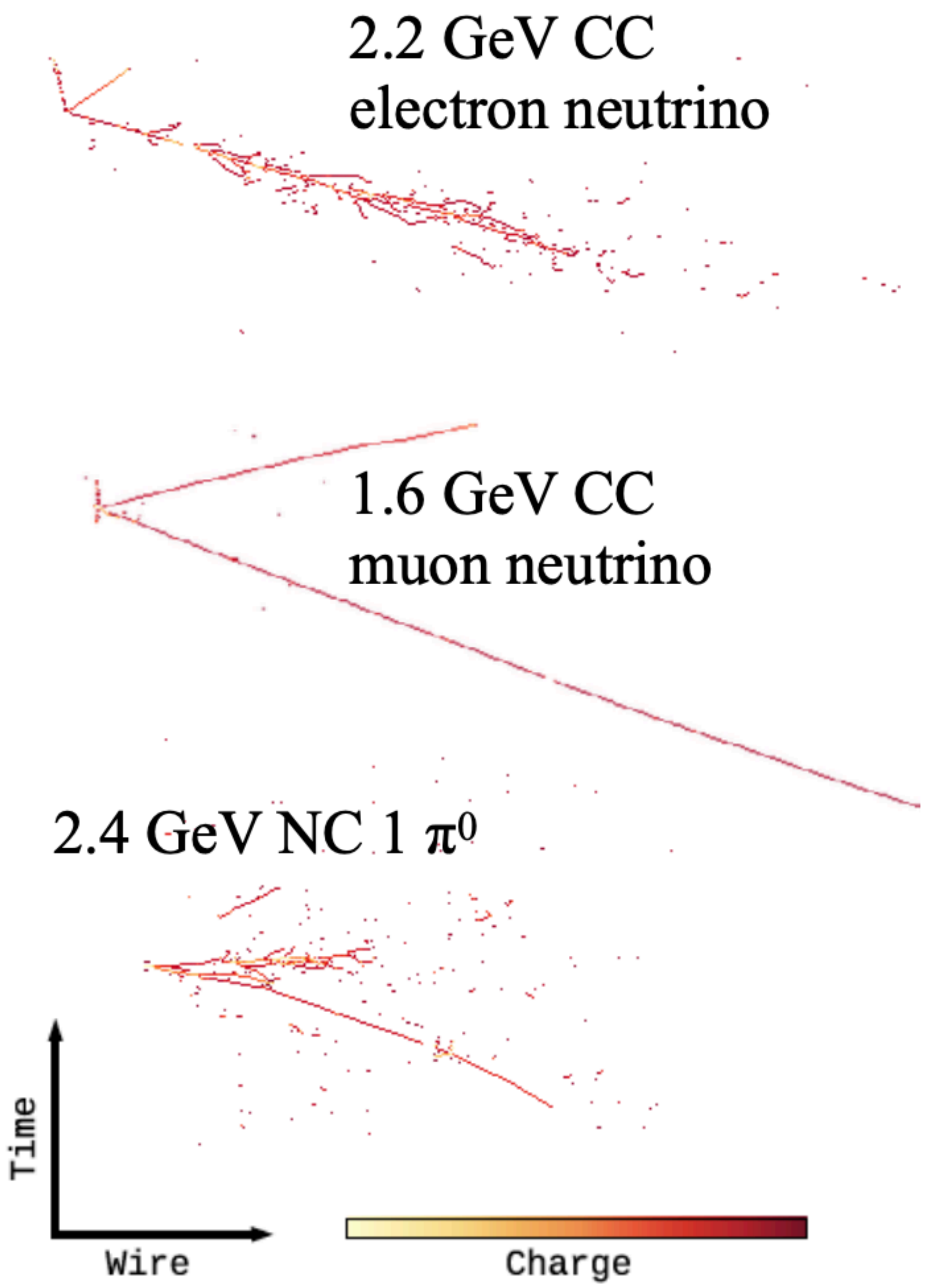
FD#2 - LAr-TPC Vertical Drift Technology

- 2 x 6.5 m vertical drift with horizontal Printed Circuit Board anode and cathode planes and photon detector
- **Charge readout**:
  - Drift along vertical direction and cathode plane in the middle
  - Readout on strips etched on PCBs
  - Two induction and one collection readout
  - Cathode at -300 kV, drift field of 450 V/cm
- **Photon Detection**
  - Based on X-ARAPUCA – “4π” reference design
  - SiPM and electronics partially on Cathode: @ 300 kV
  - Enhanced scintillation yield by doping with Xenon (tested in ProtoDUNE-SP)

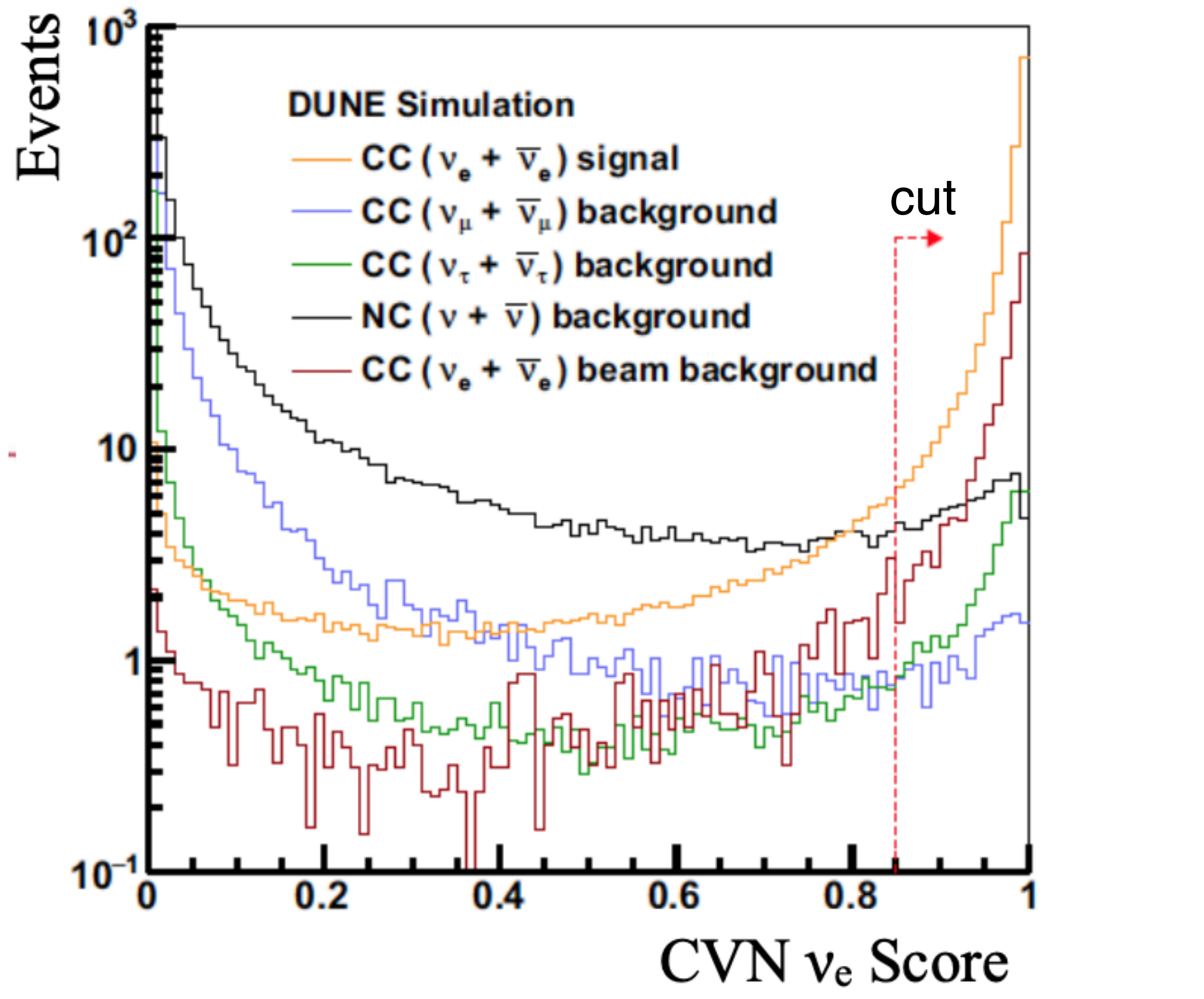


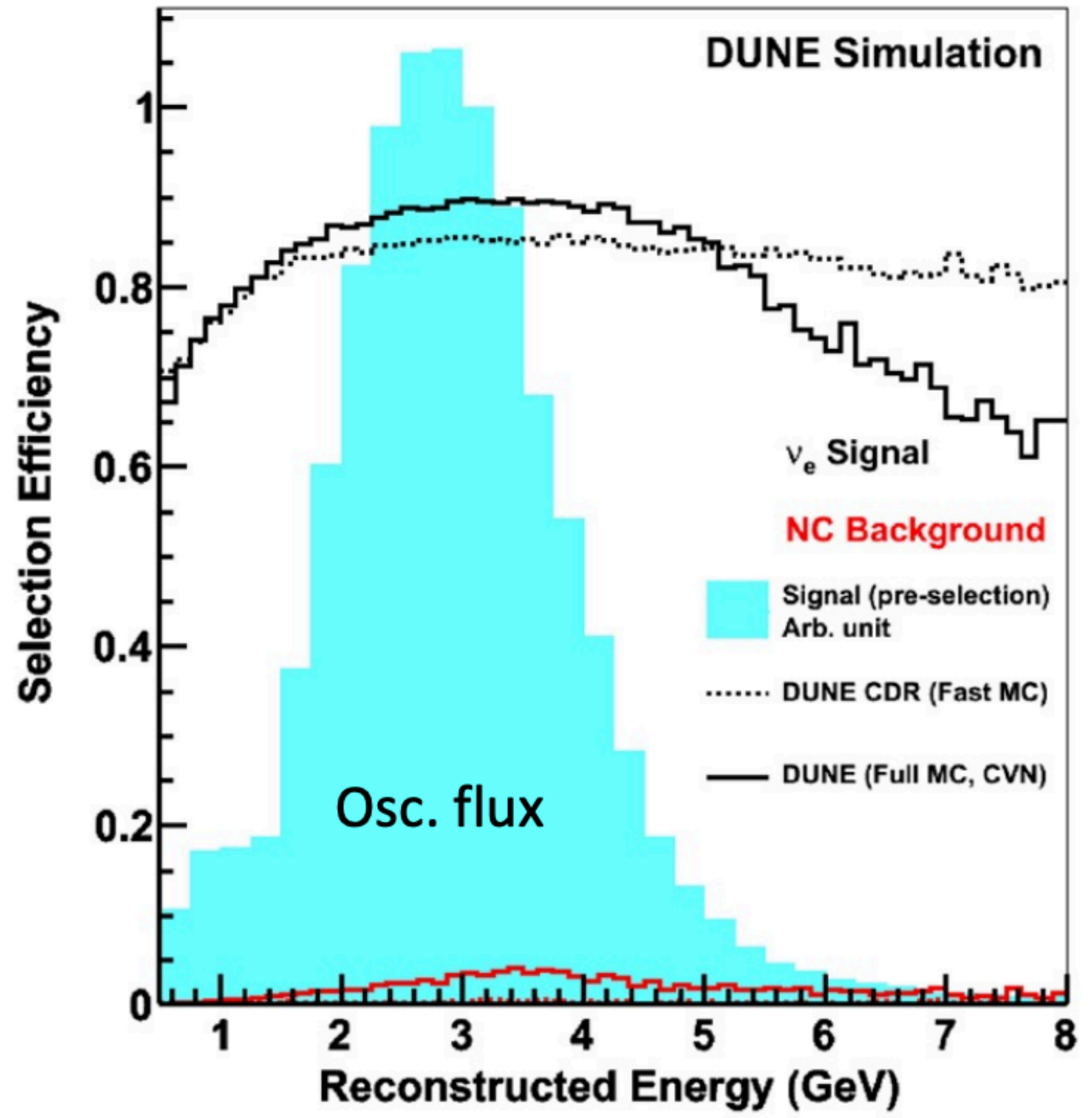
DUNE-SP-HD Reconstruction

DUNE Simulated Events
Collection plane



- **Energy Reconstruction**
  - Dedicated techniques, all at 15-20% resolution
- **Event classification algorithms trained on Convolutional Neural Networks (CNN)**
  - 3D events produced from matching of 2D hits
  - CNNs trained on TPC views
  - ➡ Convoluted Visual Network (CVN) on TPC event images
    - > 80% efficiency on ν_e and, ν_μ,
    - low mis-identification rates

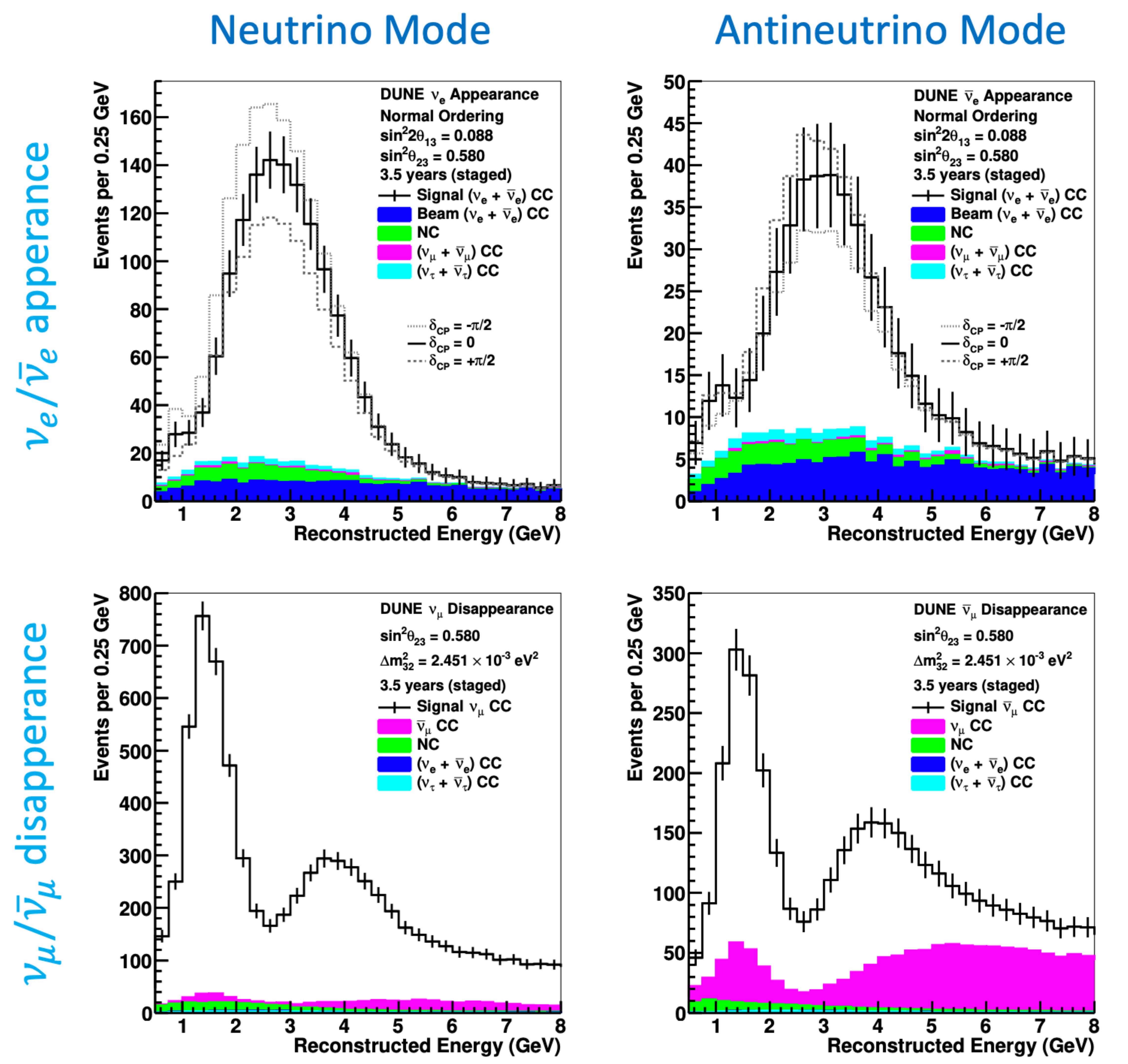




[Phys. Rev. D 102, 092003 (2020)]

DUNE Neutrino Oscillations

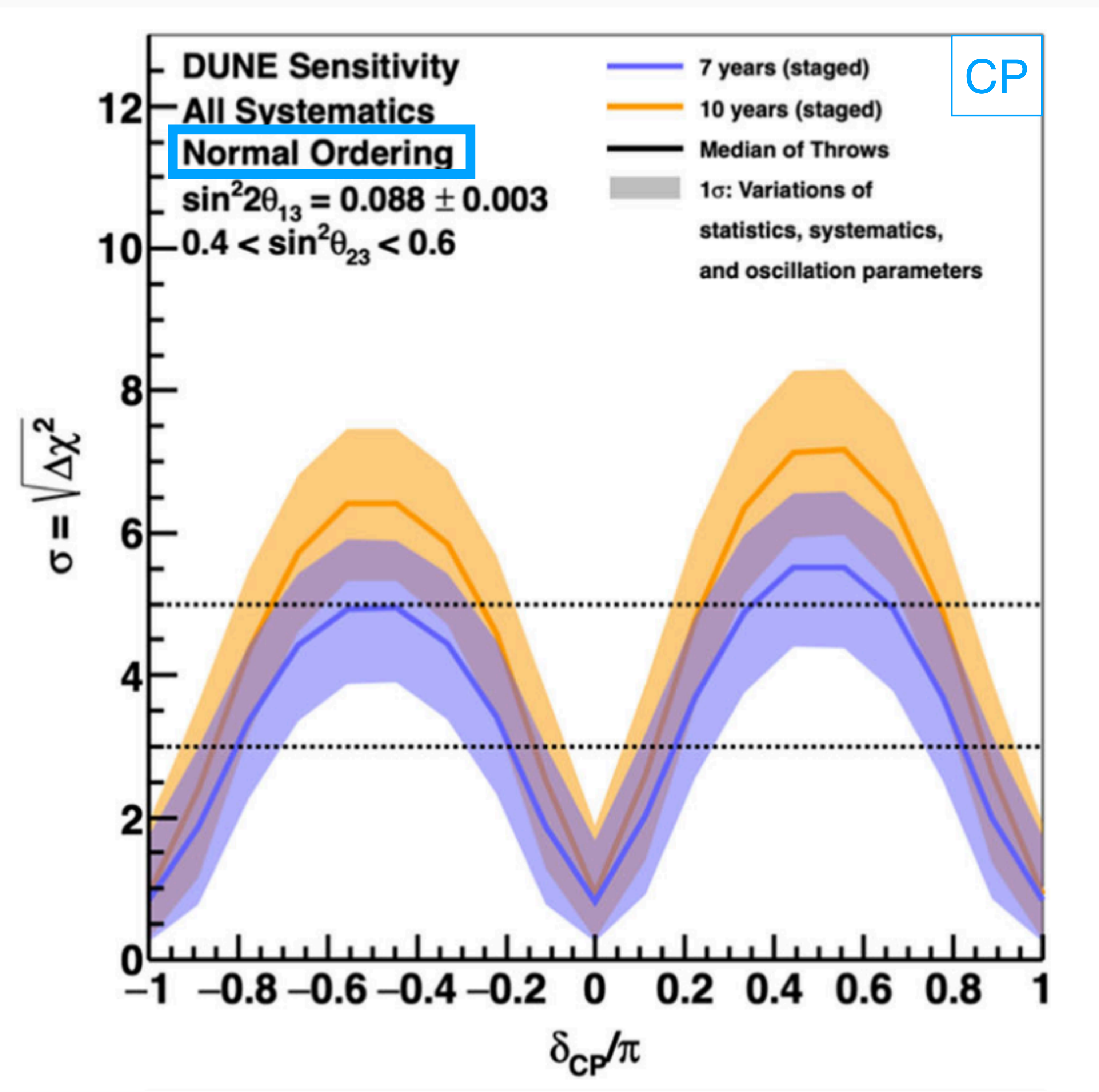
- Projected results for $\nu_e/\bar{\nu}_e$ **appearance**, $\nu_\mu/\bar{\nu}_\mu$ **disappearance**, assuming:
  - Normal ordering
  - 7-staged years (3.5 yrs ν-beam mode, 3.5 yrs $\bar{\nu}$-beam mode)
- **Reconstructed spectra** of selected Charged Current events
- **Sensitivity assessment** includes full FD systematics treatment (flux, cross-section, and detector) and ND constraints
  - ~1000 ν_e appearance events in 7 years
  - ~10,000 ν_μ disappearance events in 7 years

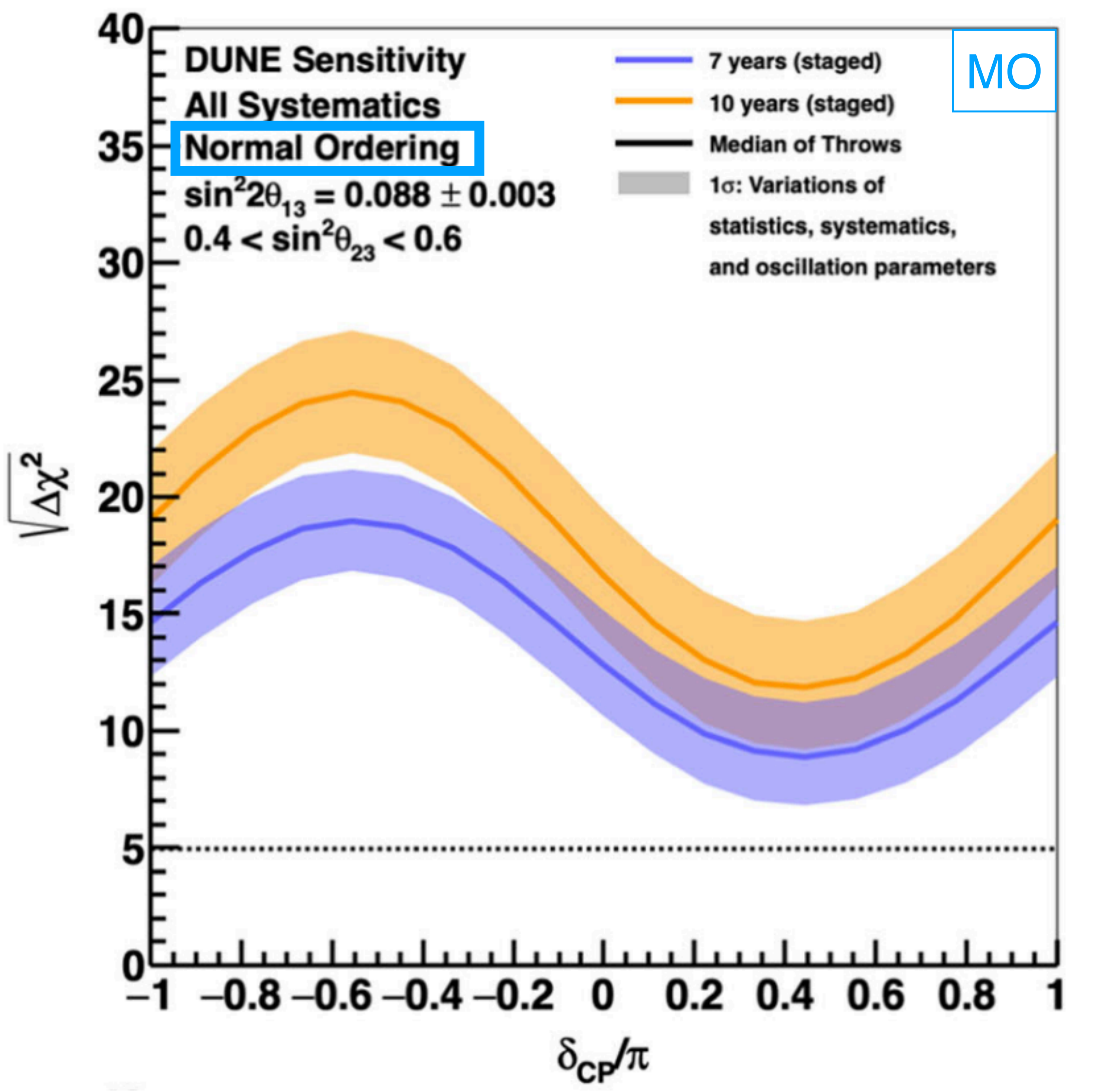


[EPJC (2020) 80, 978]

DUNE CP violation and mass ordering

- Assumed **staged running** (ν-beam / $\bar{\nu}$-beam mode)
- Potential of **CP-violation** (δ_{CP}) discovery in 7-10 years
- 2-3 years to determine **mass hierarchy** (Normal Ordering vs Inverted Ordering) for all parameters

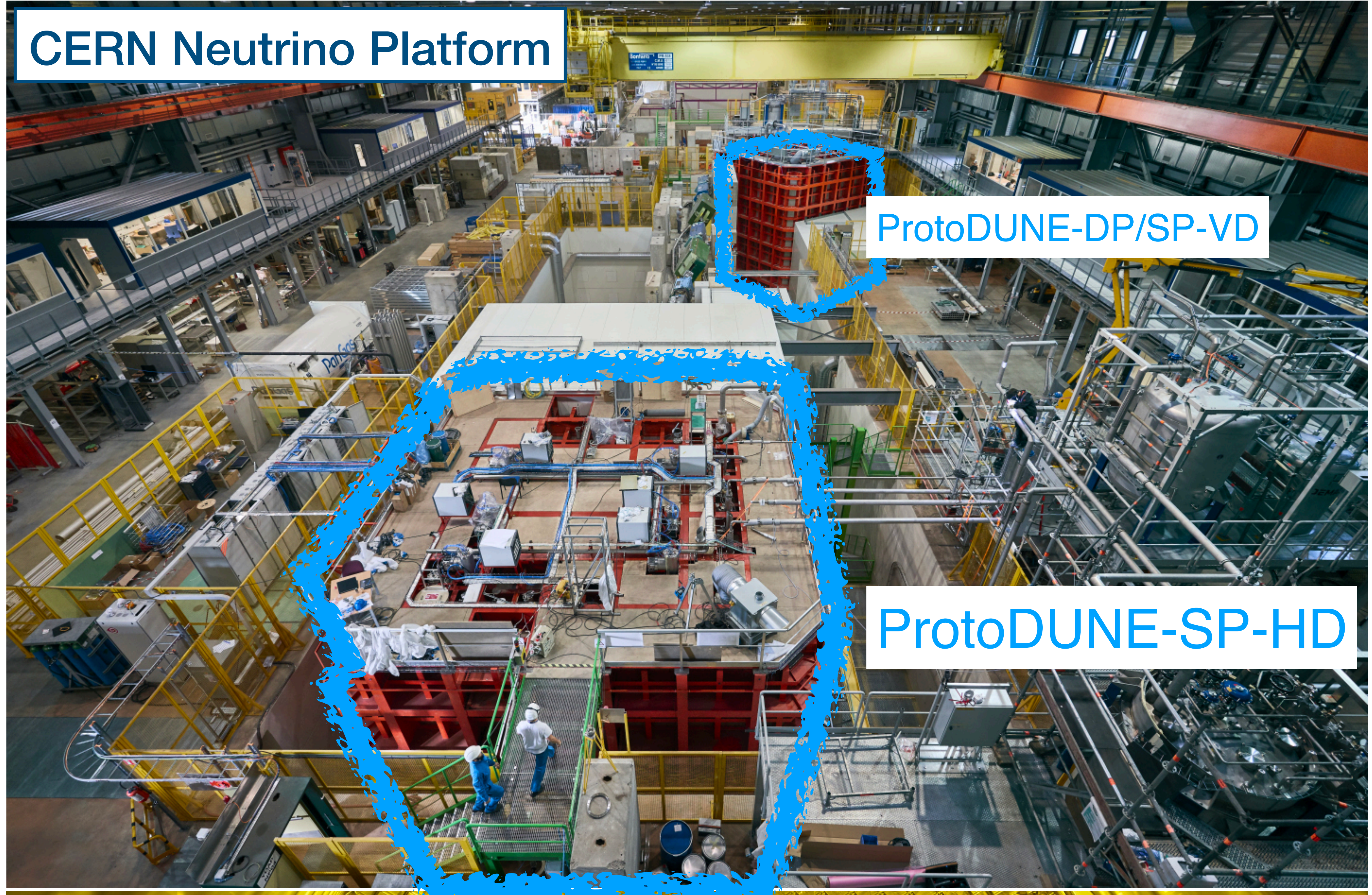


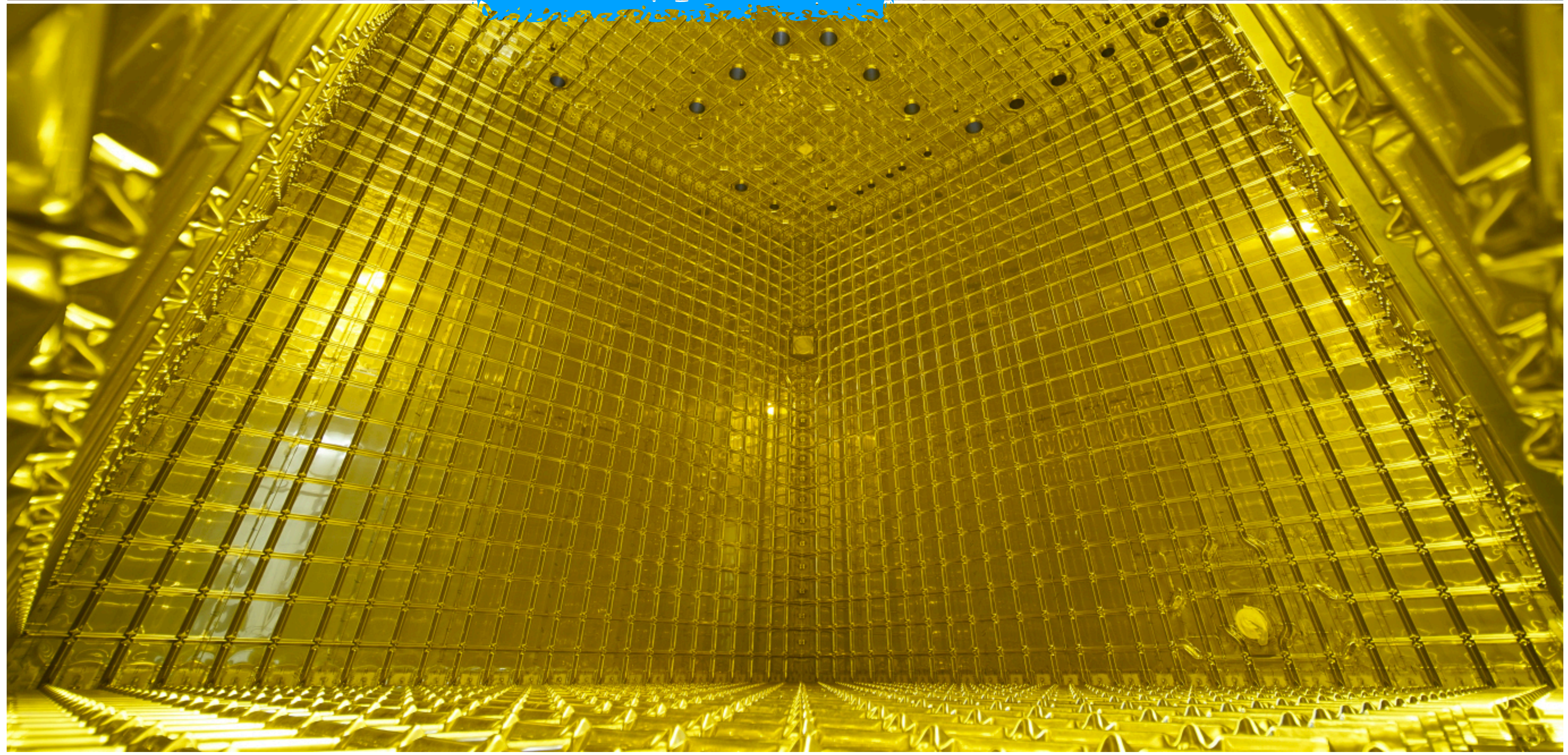


[EPJC (2020) 80, 978]

ProtoDUNE at CERN

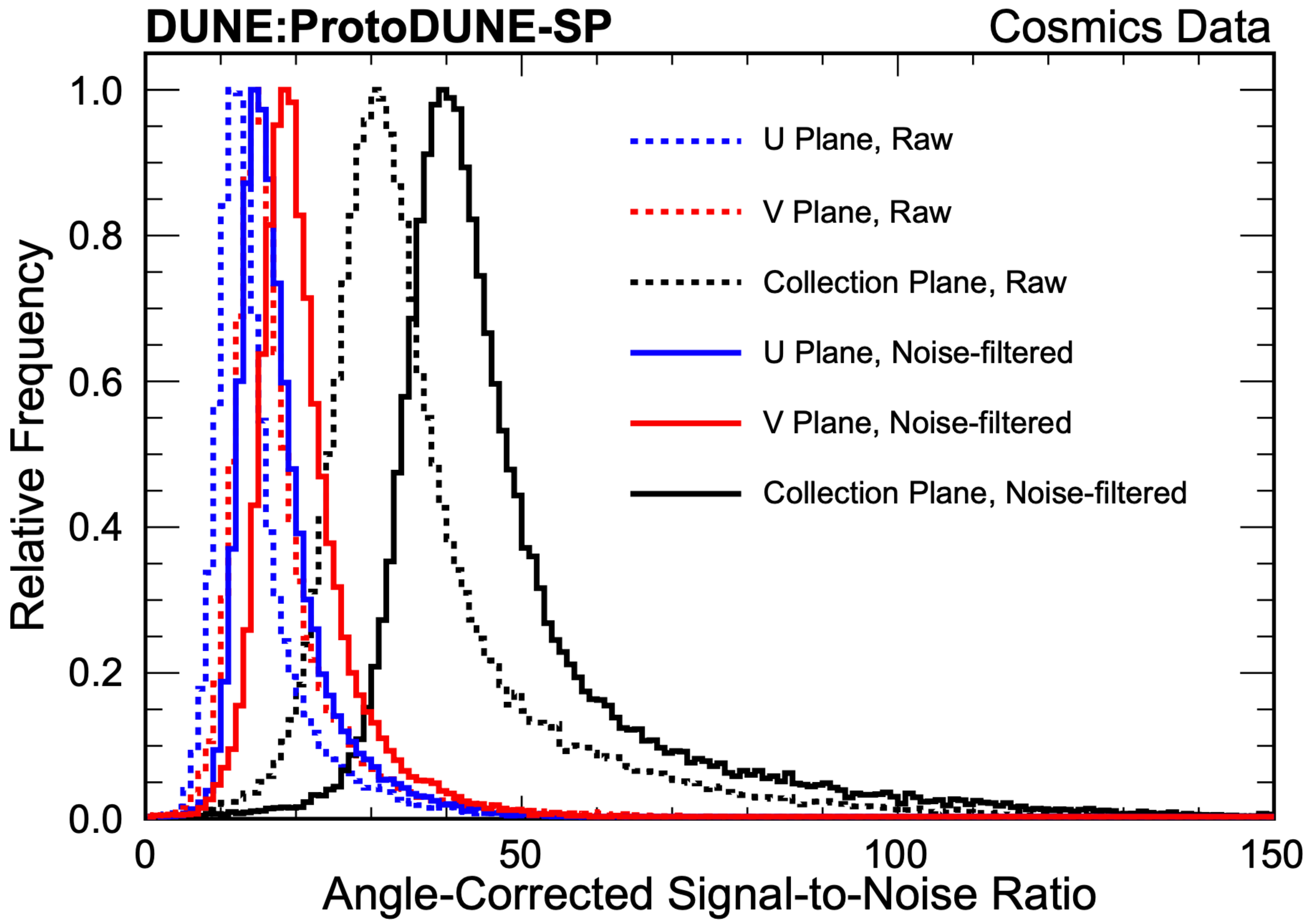
- **Two ~1 kt prototypes 7.2 x 6.1 x 7.0 m**
  - Design validation of all components at full scale
  - **Single-phase (SP), HD: 2018-20**
    - Charged particle beam + cosmic rays
    - Event reconstruction, full analysis
    - Neutron calibration, Xe doping, HV tests
    - Phase-II starting in 2022
  - **Dual-phase (DP): 2019-20**
    - Signals produced in Liquid,Gas phases
    - **Evolved into SP-Vertical Drift**

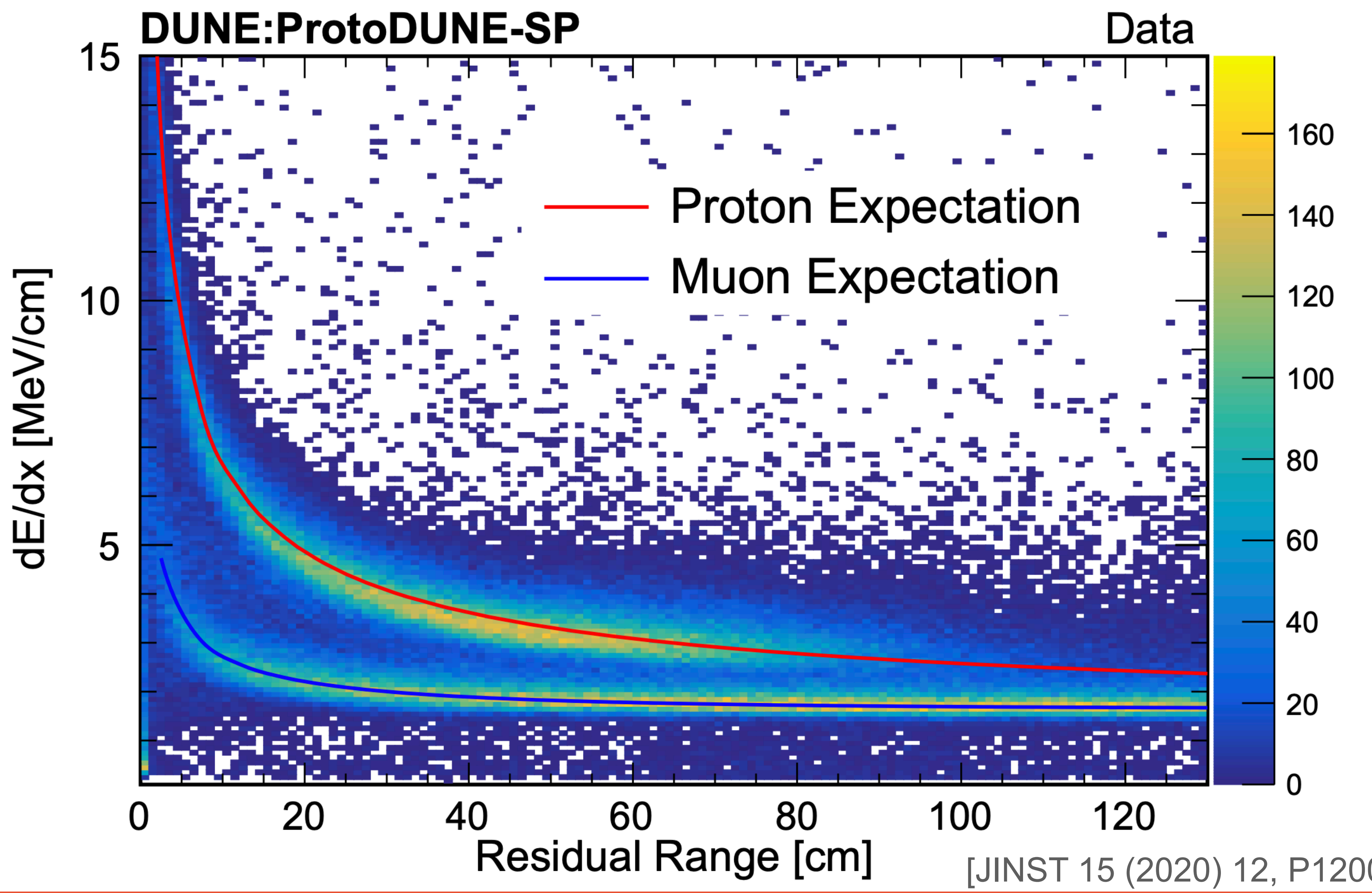




ProtoDUNE-SP Performance

- **Detector performance validation**
  with cosmic rays, beam charged particles;
  photon detector demonstration
- **Stable operation**
  - > 99.5% of HV uptime for cosmic rays and beam data taking
  - High purity, well above requirements
    (> 30 ms e-lifetime most runs, > 20 ms all runs)
  - > 99% of TPC channels (wires) active
- **Low noise in all readout channels**
  - S/N > 10 - induction wires
  - S/N > 40 - collection wires
- **Test of full analysis chain**
  - Hit clustering, track reconstruction, particle ID
  - Simulation tuning - detailed paper





[JINST 15 (2020) 12, P12004]

Summary

- DUNE will measure neutrino oscillations providing insights on matter/antimatter imbalance in the Universe and other open questions in physics
- DUNE far detector site under construction; excavation ongoing
- Detector technologies defined for far detector modules 1 and 2. Prototyping efforts underway at CERN with test beam runs planned in 2022-2023
- Excellent performance in ProtoDUNE-SP-I with many exciting physics results coming out
- First DUNE far detector installation in mid-2020s with first neutrino beam data in late 2020s


Collaboration Meeting
September 2021
DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT