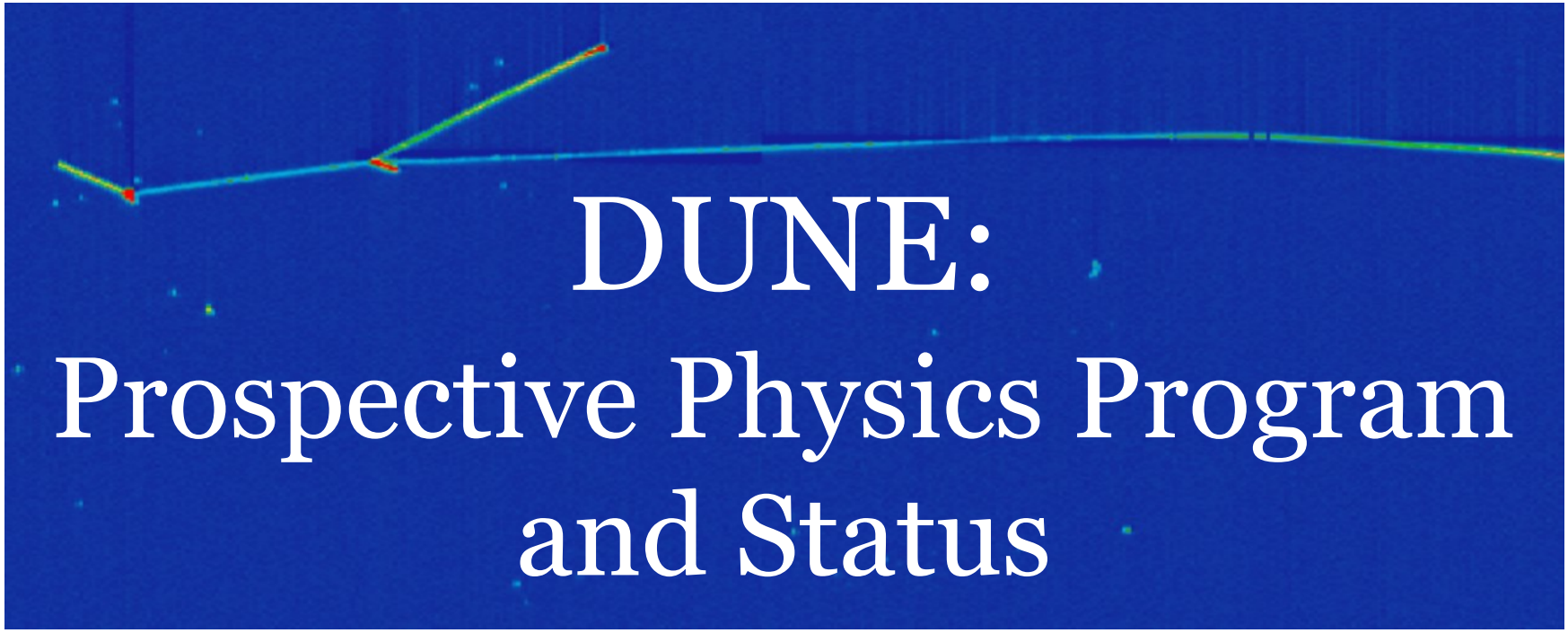


DUNE: Prospective Physics Program and Status

Michael Mooney – Colorado State University

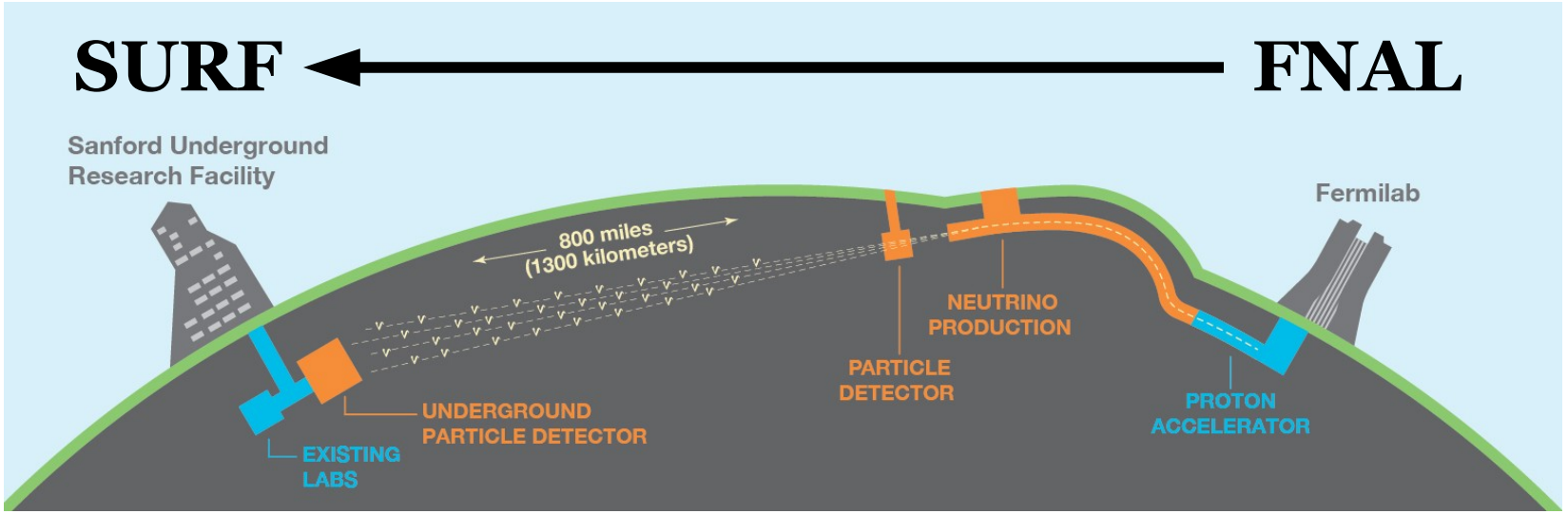
On behalf of the DUNE Collaboration

Conference on Science at the Sanford Underground Research Facility (CoSSURF 2022)

May 11th, 2022

Introducing DUNE

- "Deep Underground Neutrino Experiment"
  - 1300 km baseline
  - Large (70 kt) LArTPC **far detector** 1.5 km underground
  - **Near detector** w/ LAr component
  - 1.2 MW (2.4 MW) wide-band neutrino/antineutrino beam
- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - $\boldsymbol{\delta_{CP}}$, θ_{23}, θ_{13}, Δm^2_{32}
    - **Ordering of ν masses**
  - Supernova burst neutrinos
  - BSM processes (baryon number violation, NSI, etc.)



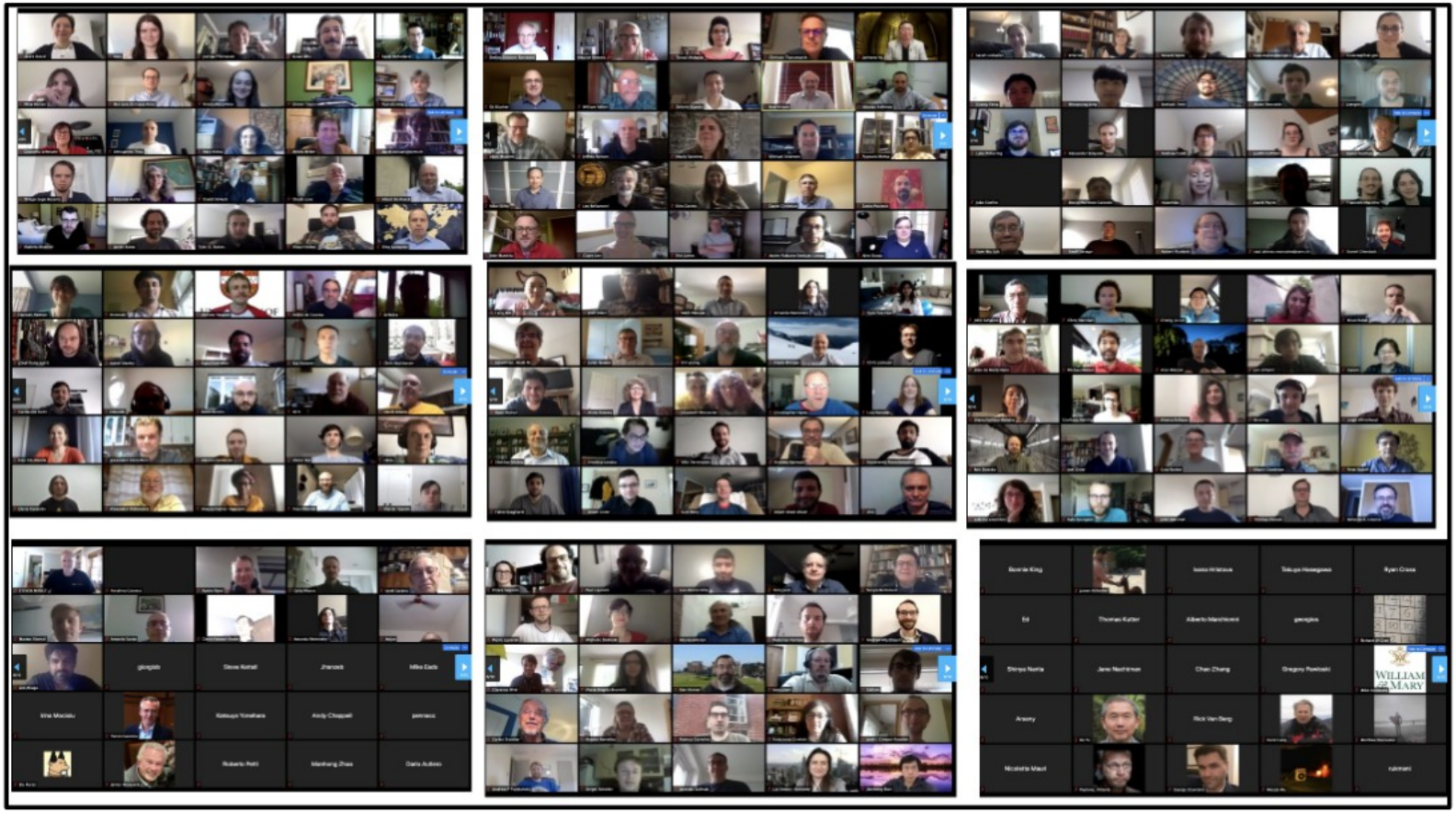
DUNE Collaboration

- **1400+ collaborators** from 200+ institutions in 36 countries (+ CERN)!

May 2019 Collaboration Meeting

DUNE Collaboration

- **1400+ collaborators** from 200+ institutions in 36 countries (+ CERN)!



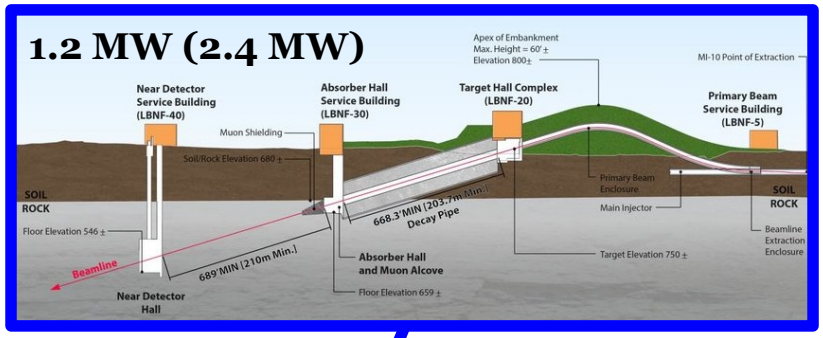
May 2020 Collaboration Photo

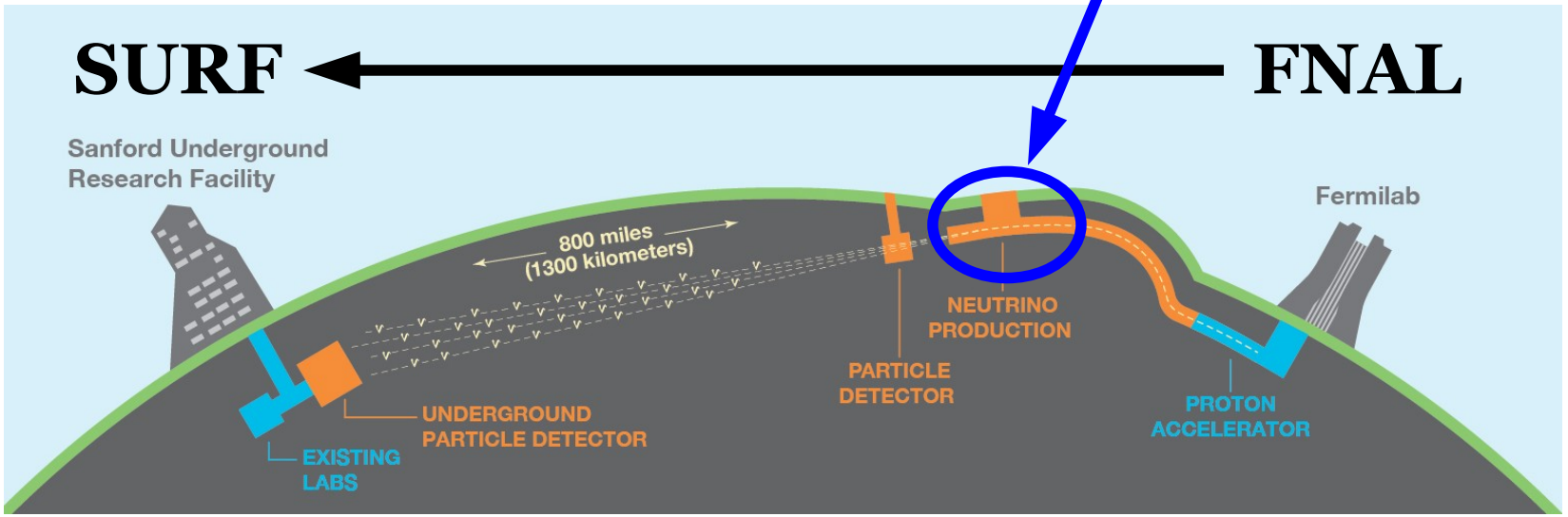
Beam and Detectors

DUNE's Neutrino Source

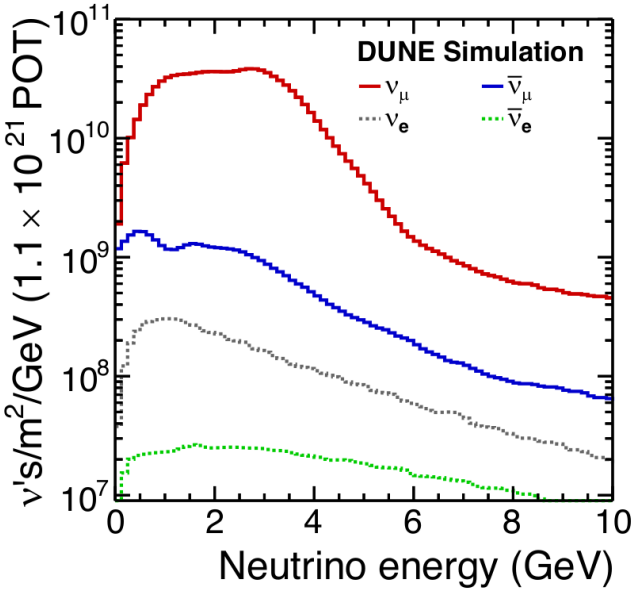
DUNE's Neutrino Source:

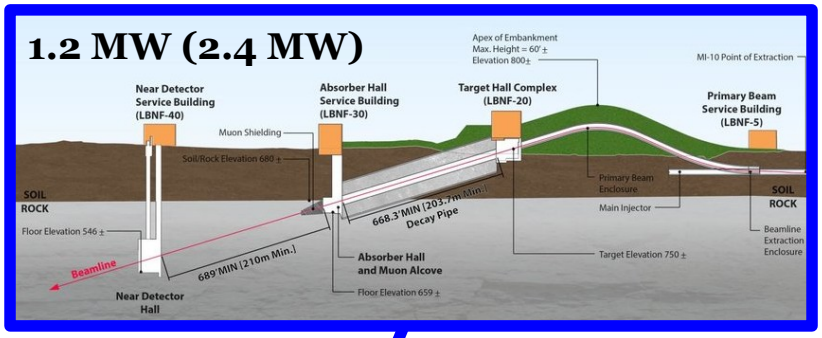
LBNF Beam

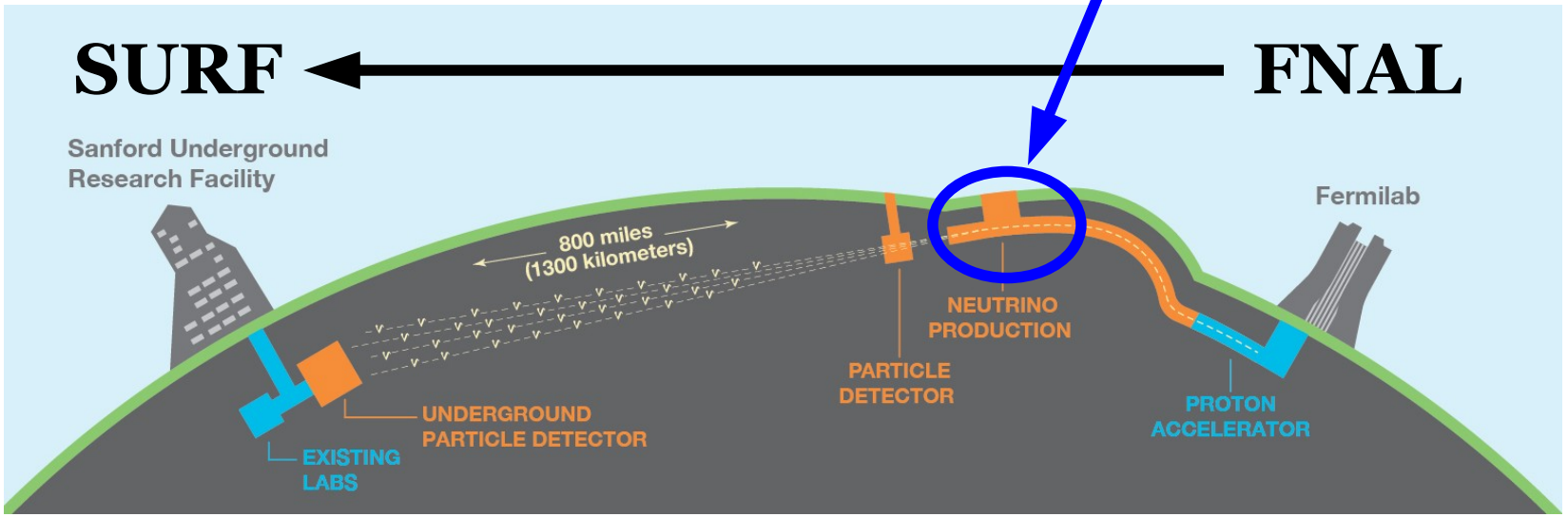




DUNE's Neutrino Source

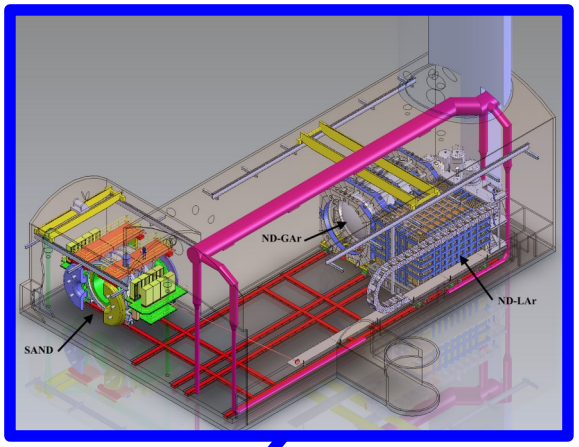


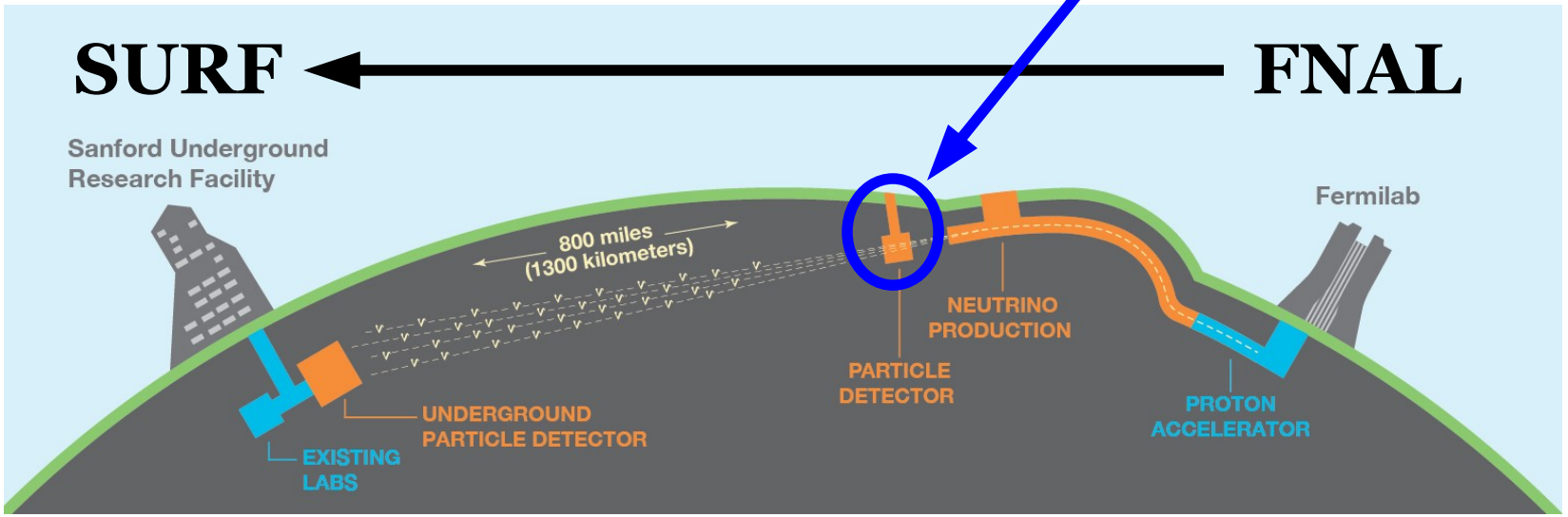




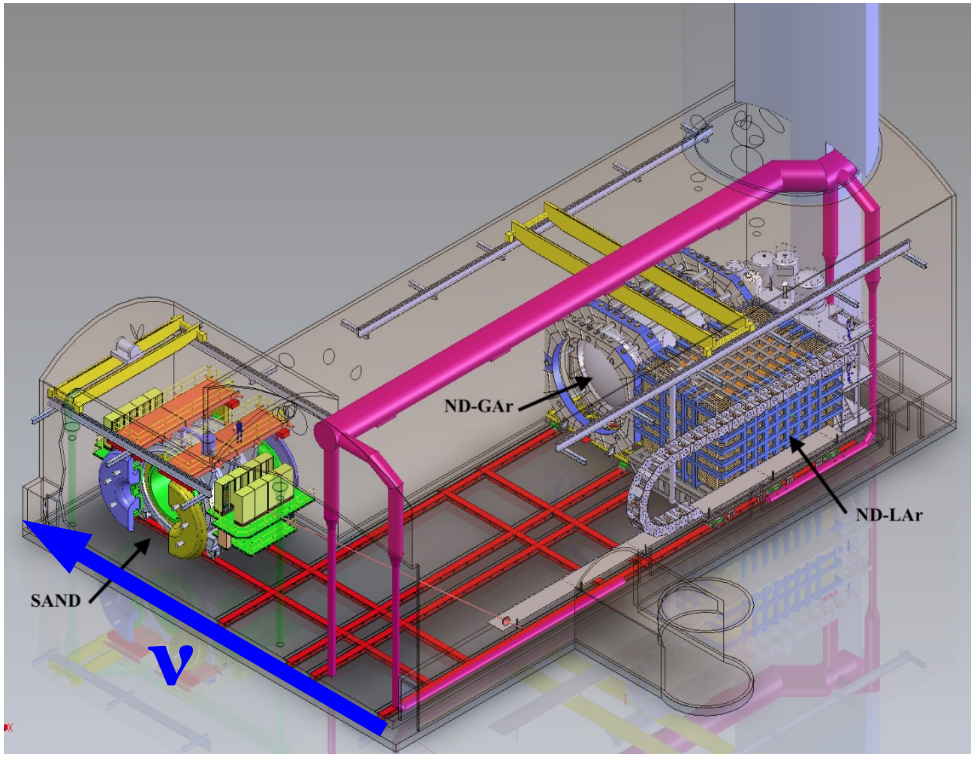
DUNE Near Detector (ND)

The DUNE Near Detector



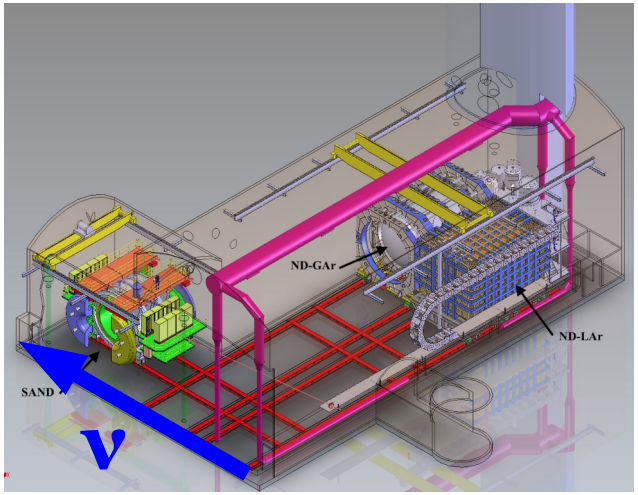


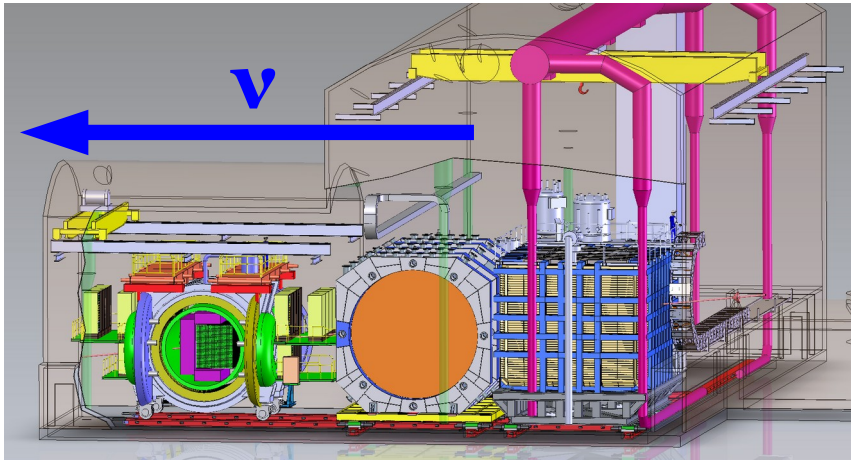
DUNE ND Overview



- DUNE ND located 574 m from neutrino beam target
- Primary purpose is to **characterize neutrino beam** and **constrain cross section uncertainties** in long-baseline neutrino oscillation analysis

DUNE ND Complex





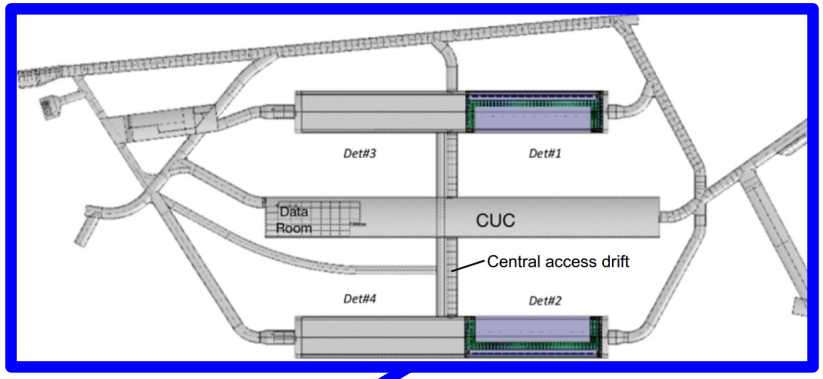
SAND ND-GAr ND-LAr

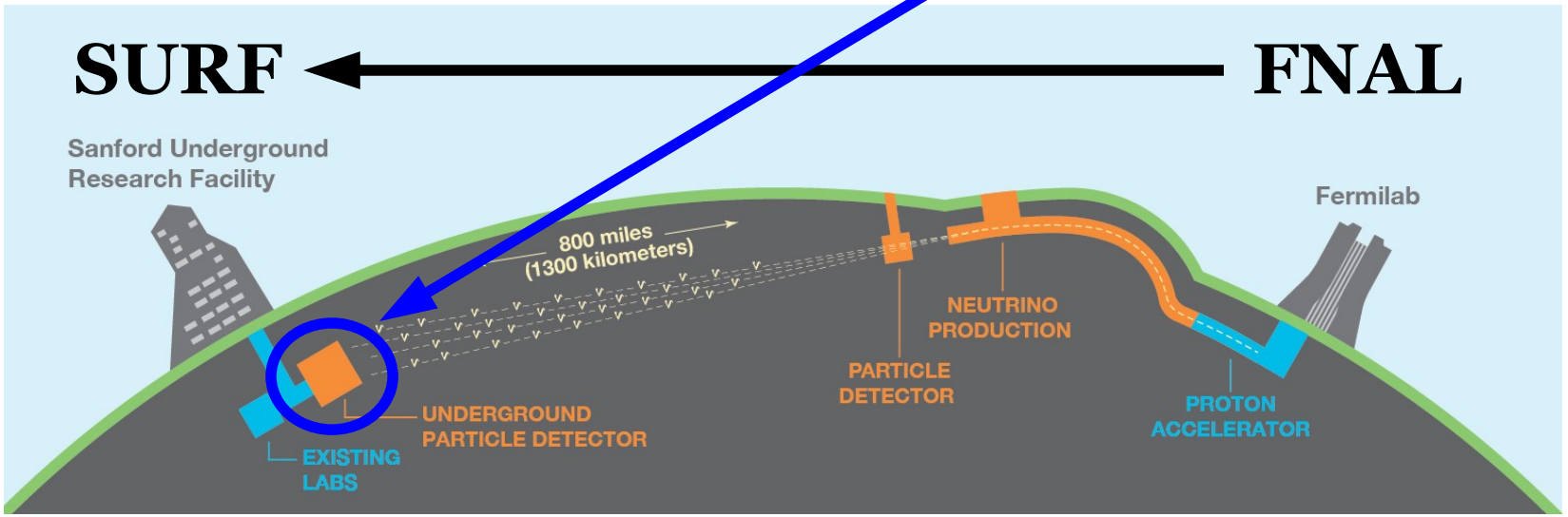
- DUNE ND complex: multiple complementary systems
  - ND-LAr: modular, pixelated LArTPC
    - Acts as primary target and is most similar to FD (both contain LAr)
  - ND-GAr: high-pressure GArTPC surrounded by ECAL and magnet
    - Constrains nuclear interaction model; muon spectrometer
  - SAND: tracker surrounded by ECAL and magnet
    - On-axis monitor of beam spectrum
- ND-LAr/ND-GAr can move off-axis (DUNE-PRISM)

DUNE Far Detector (FD)

The DUNE Far Detector:

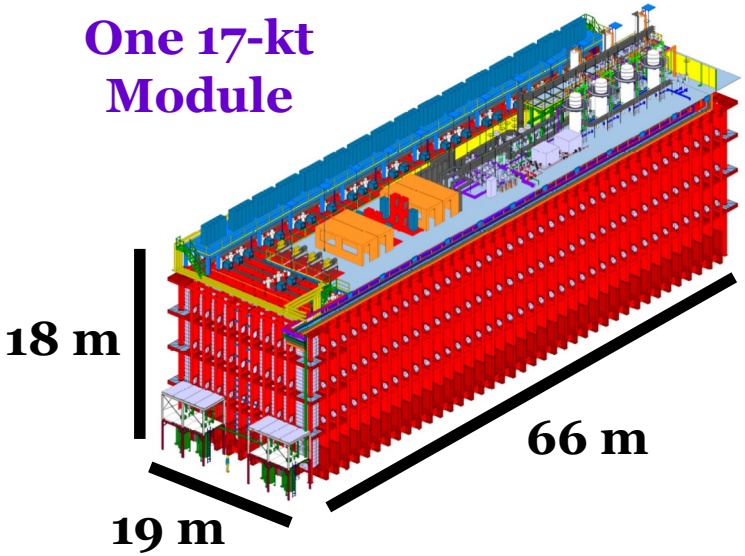
Four LArTPC Detector Modules

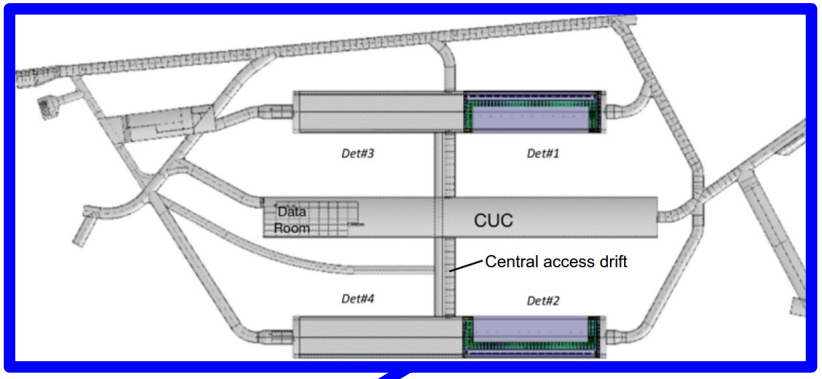


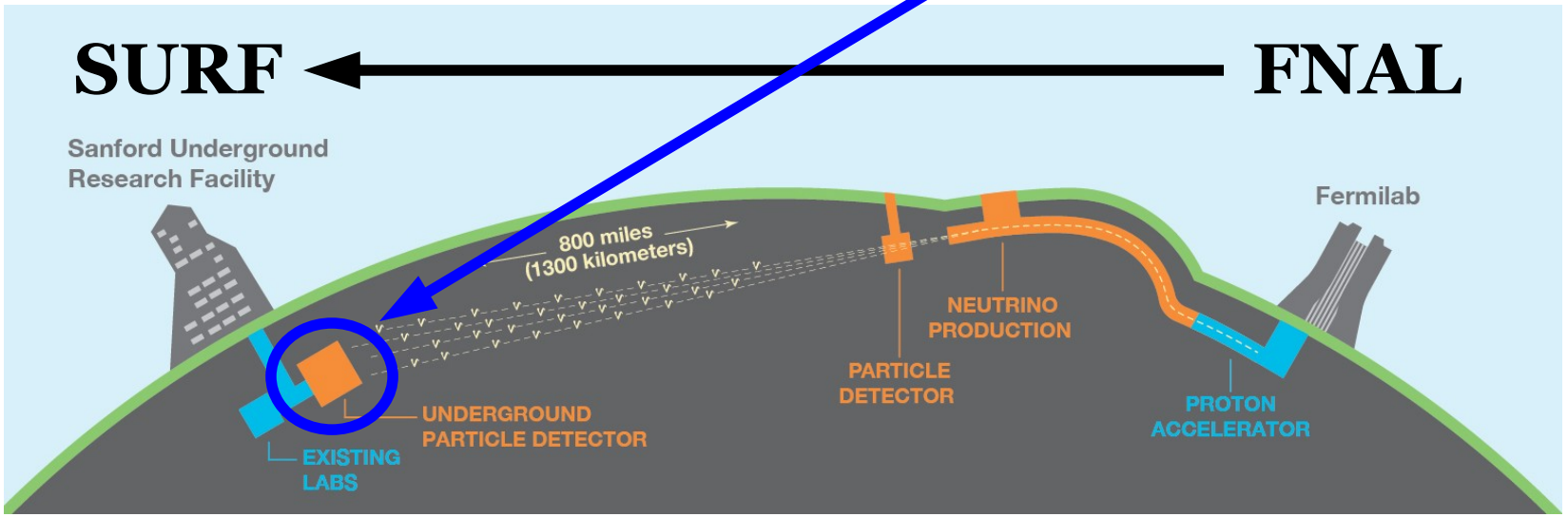


DUNE Far Detector (FD)

One 17-kt Module

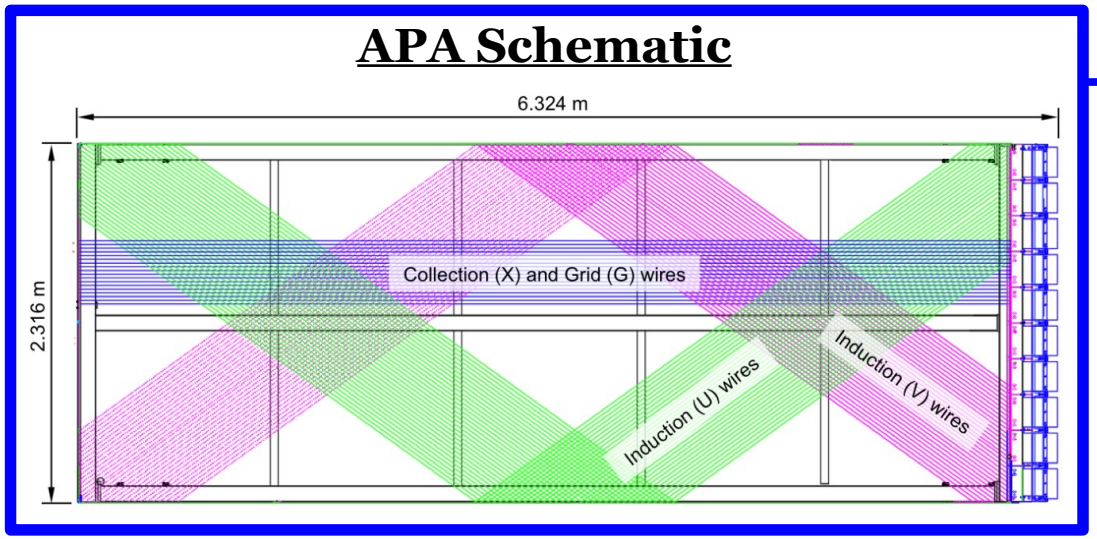


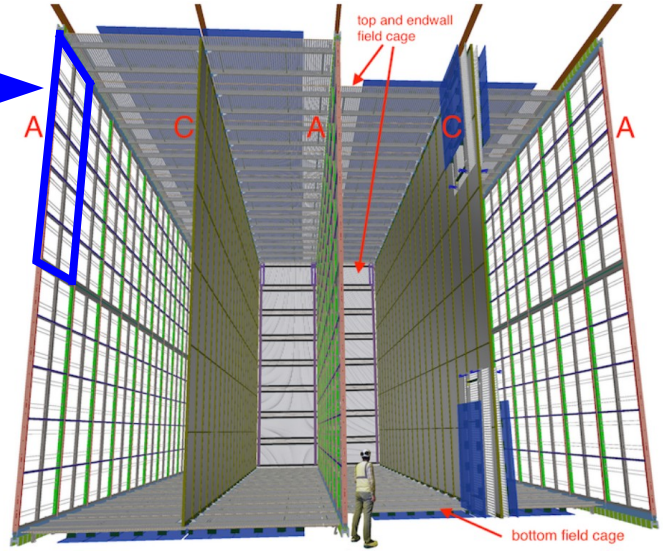




Far Detector LArTPC

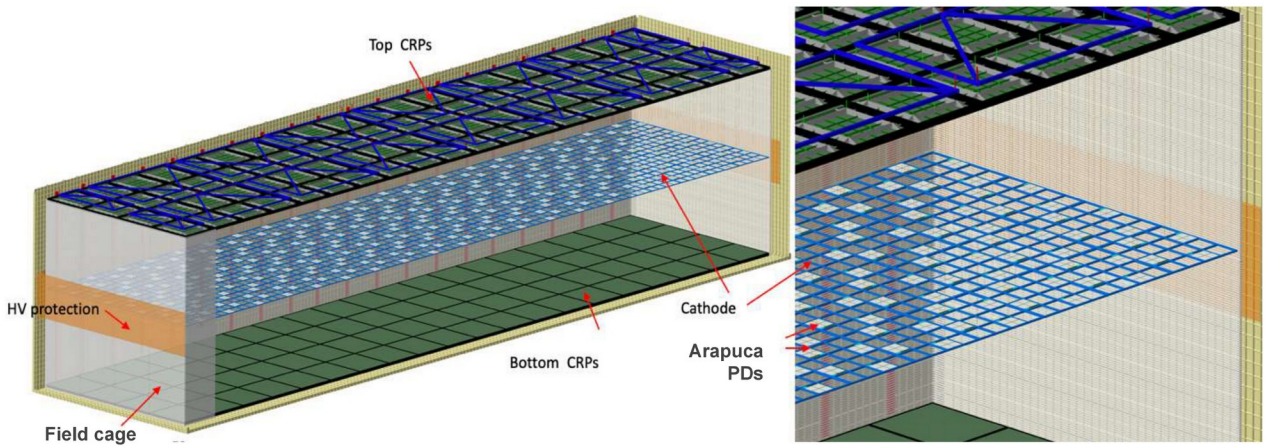
- Four 17-kt modules deployed in stages
- Two single-phase (LAr) far detector designs: horizontal drift (HD) and vertical drift (VD) – **first (second) module will be HD (VD)**
- HD FD – modular drift cells (scalable)
  - Suspended Anode and Cathode Plane Assemblies (APAs and CPAs)
  - **Wrapped wire** to reduce # of readout channels, cabling complexity
  - 3.6 m drift, 500 V/cm field; **photon detectors** for non-beam triggering

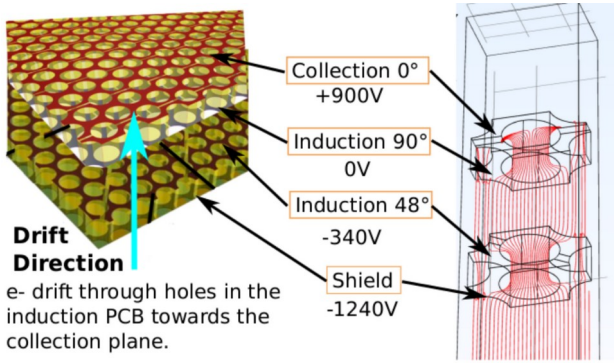




Far Detector LArTPC

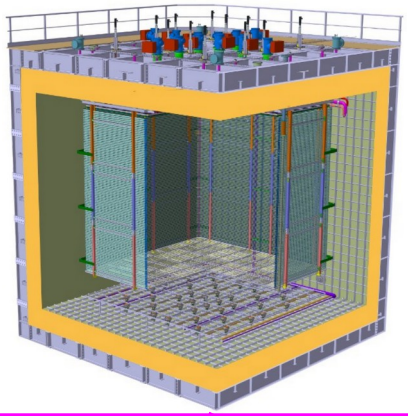
- Four 17-kt modules deployed in stages
- Two single-phase (LAr) far detector designs: horizontal drift (HD) and vertical drift (VD) – **first (second) module will be HD (VD)**
- VD FD – two drift volumes w/ charge readout at top and bottom
  - Charge Readout Planes (CRPs) at anodes: perforated PCBs w/ electrodes
  - Photon detectors embedded within cathode, placed outside of field cage
  - Doping w/ O(10 ppm) **xenon** for greater light collection uniformity



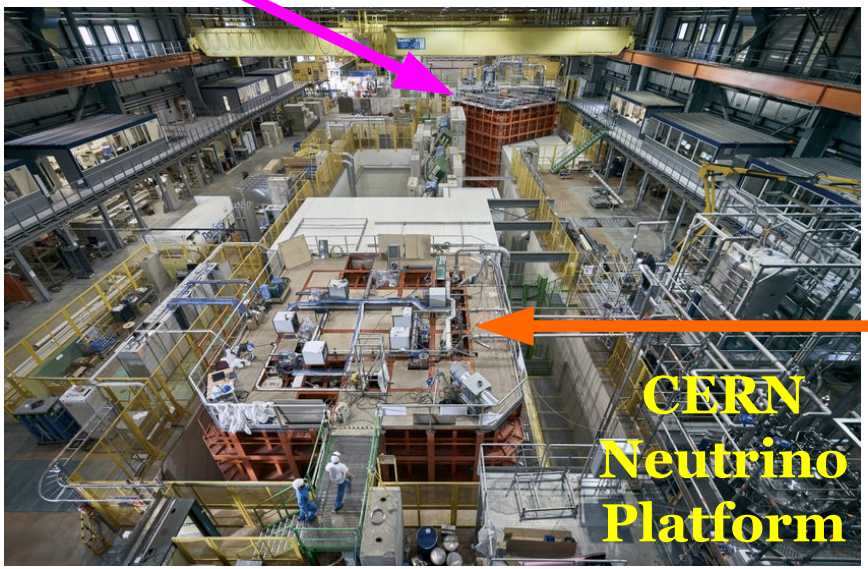


ProtoDUNEs

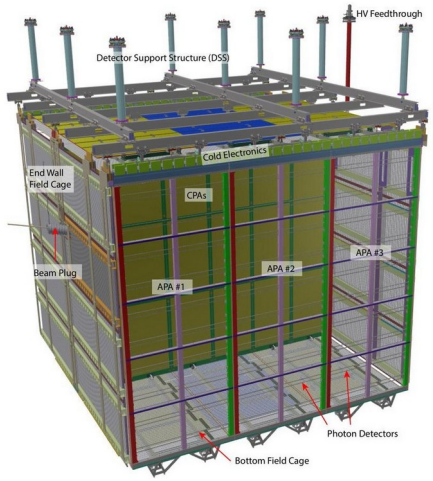
ProtoDUNE-DP



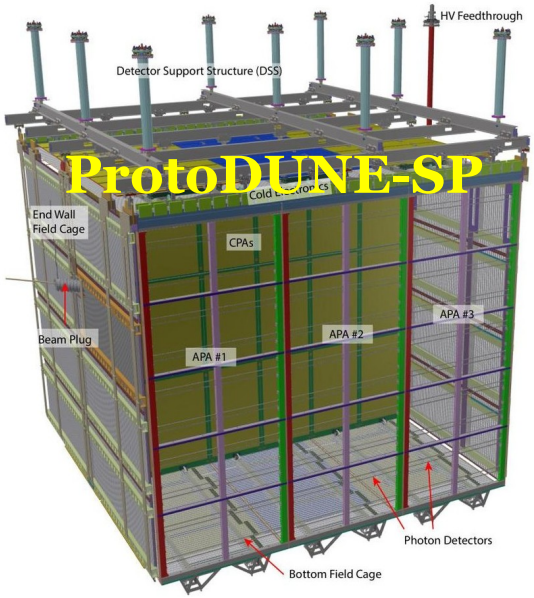
- Two 1-kt "ProtoDUNEs" in charged test beam at CERN: single-phase HD (LAr), dual-phase detector (LAr+GAr; no longer being pursued)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operations in 2018–2020; ProtoDUNE-DP operations in 2019–2020; **"ProtoDUNE II" (HD/VD) in 2022–2023**



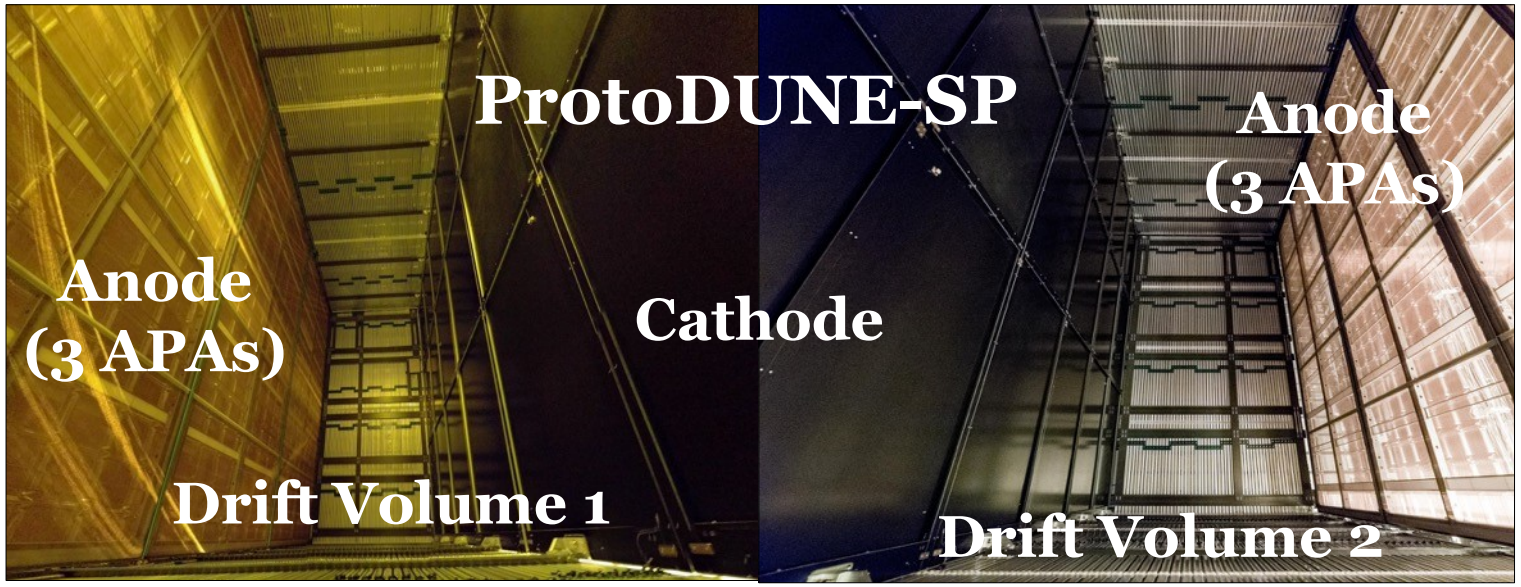
ProtoDUNE-SP



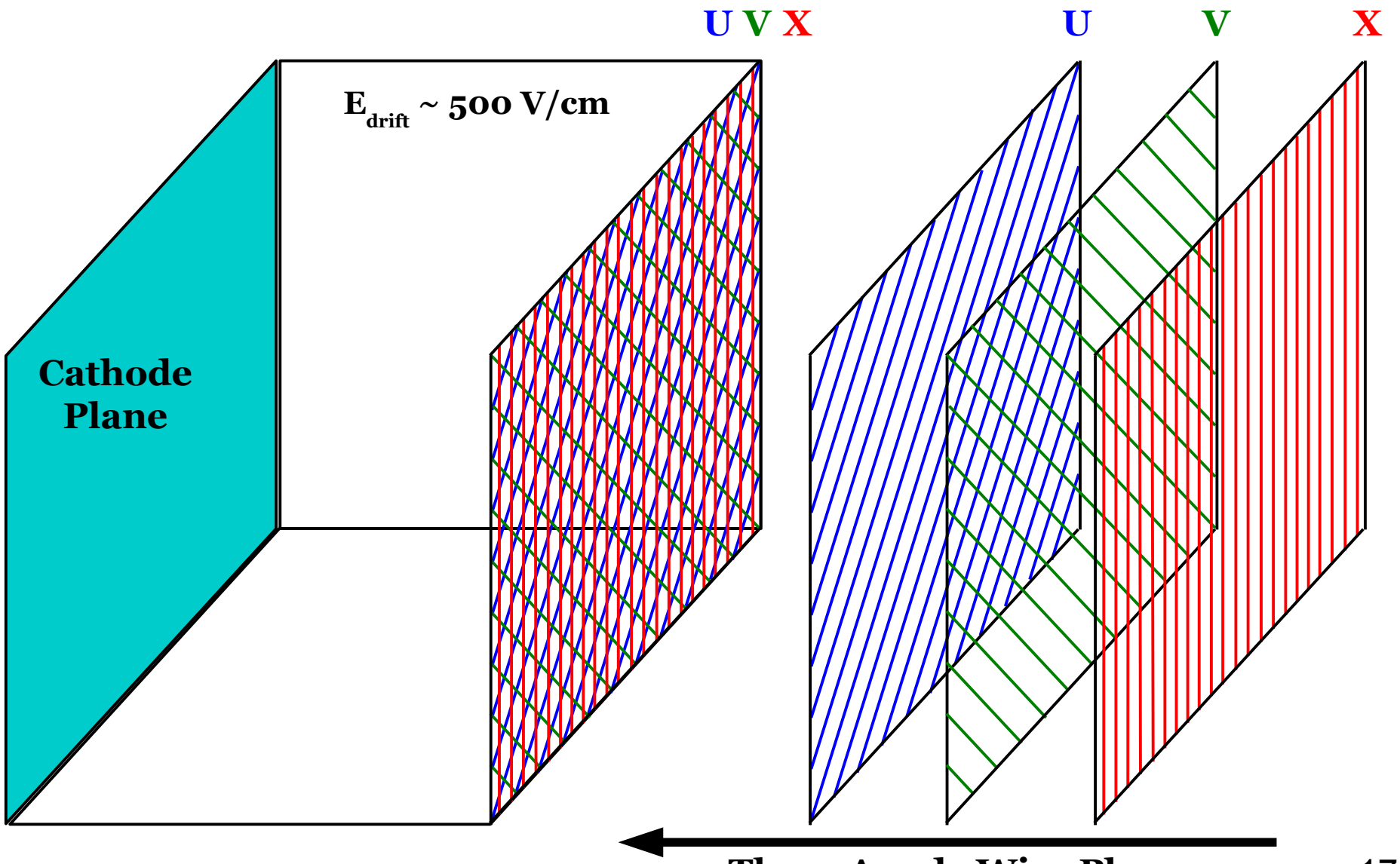
ProtoDUNEs



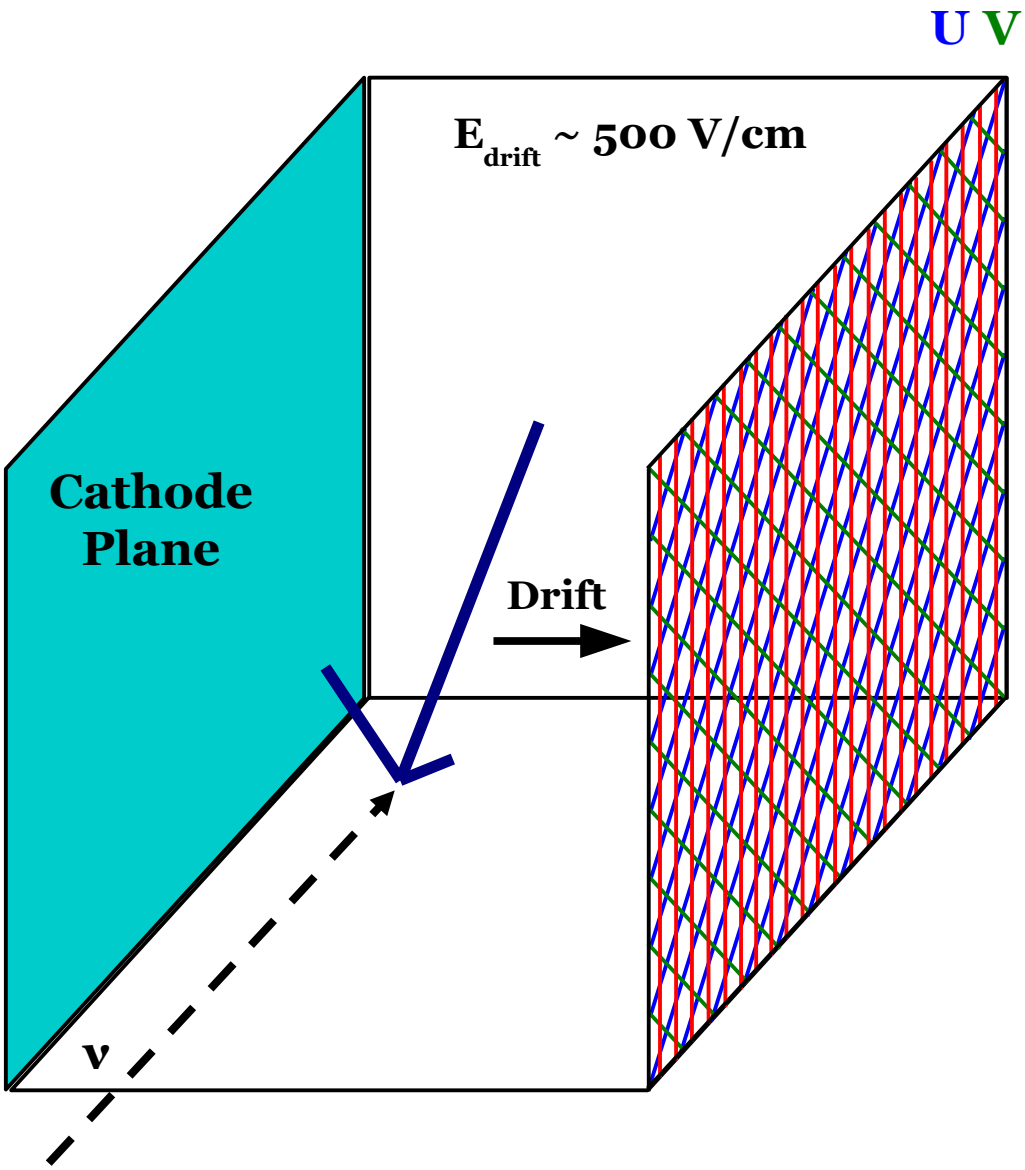
- Two 1-kt "ProtoDUNEs" in charged test beam at CERN: single-phase HD (LAr), dual-phase detector (LAr+GAr; no longer being pursued)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operations in 2018–2020; ProtoDUNE-DP operations in 2019–2020; **"ProtoDUNE II" (HD/VD) in 2022–2023**

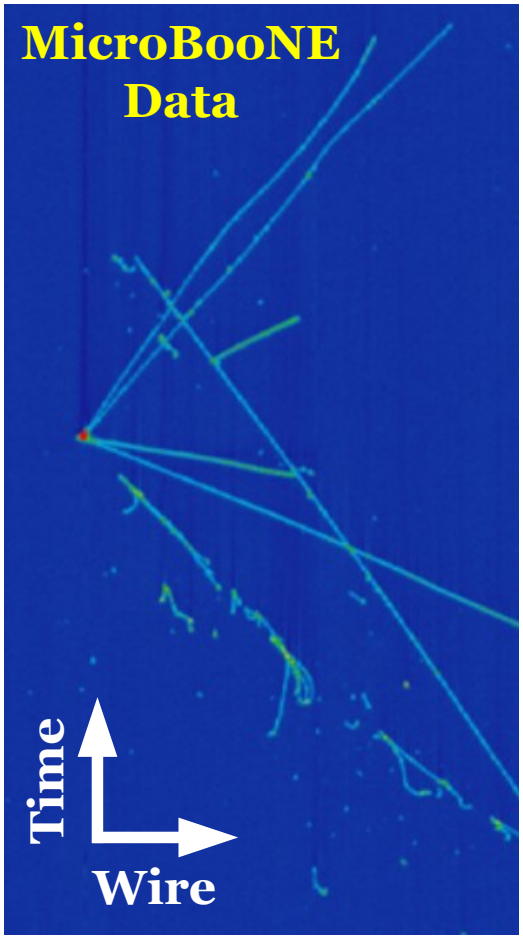


LArTPC Signal Formation



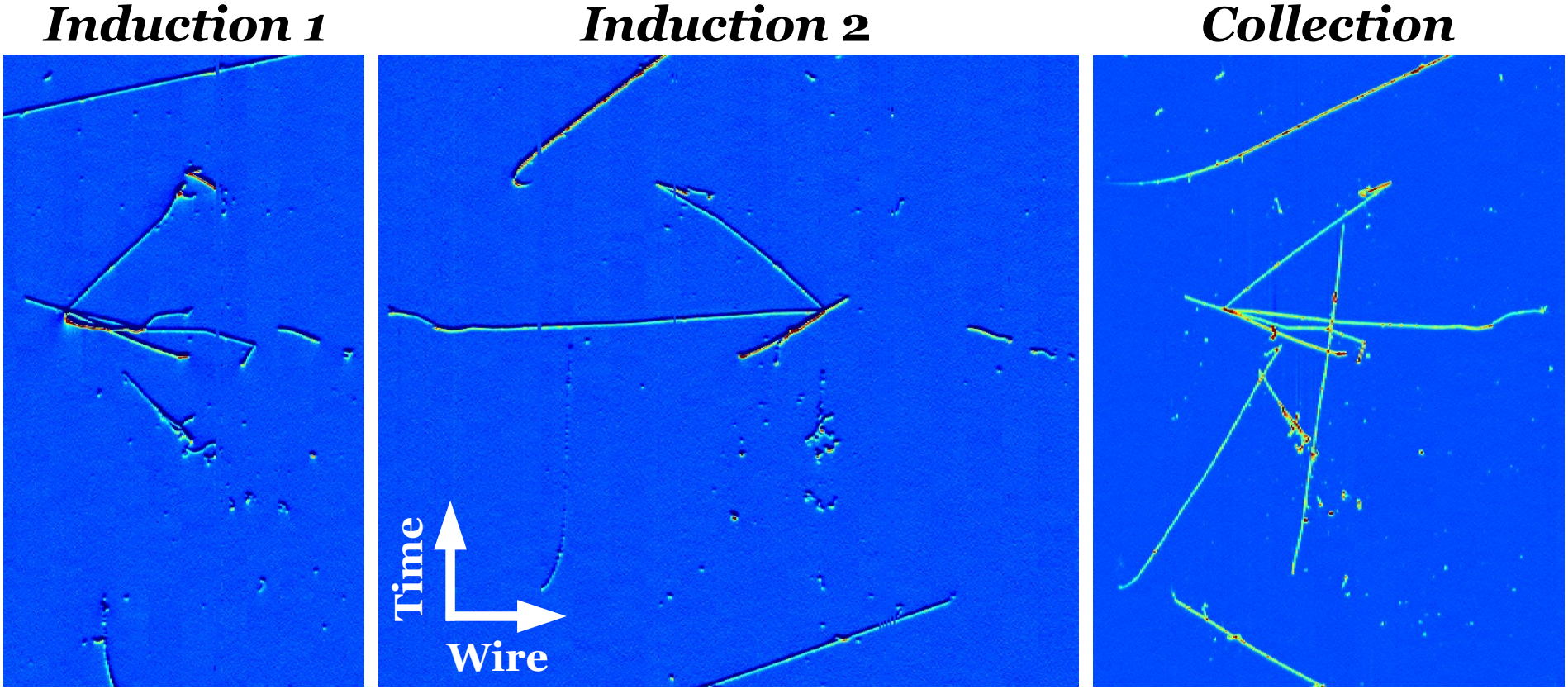
LArTPC Signal Formation





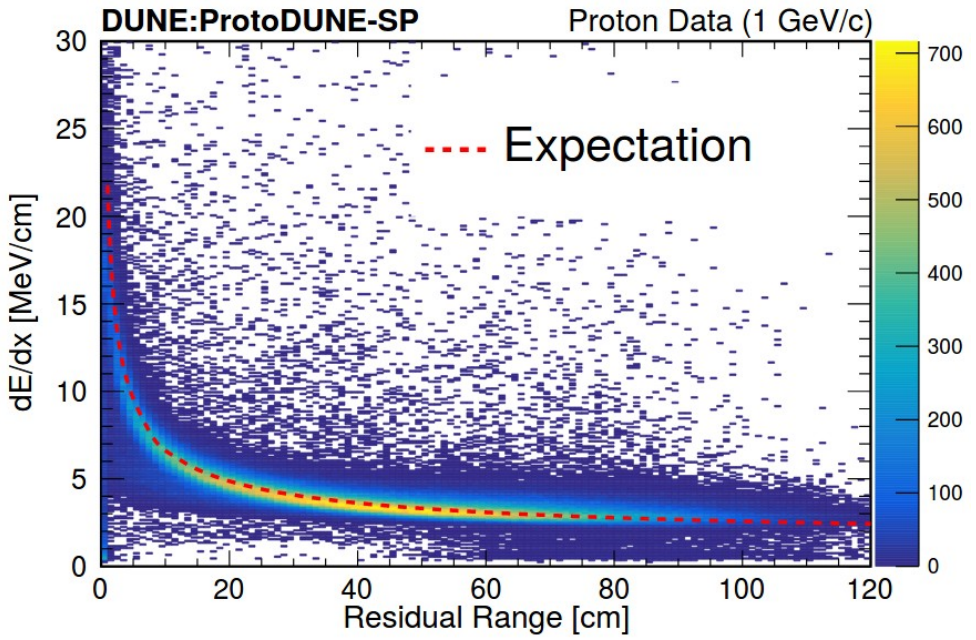
Three Images (One Per Wire Plane)

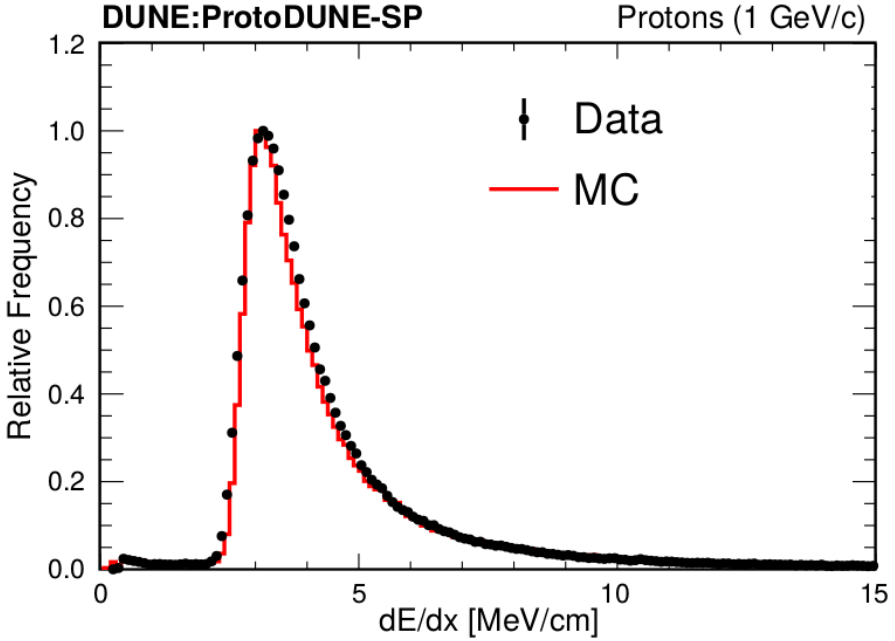
First ProtoDUNE-SP Events



- First beam data events: **noise levels low** on all three planes
- S/N ratio > 10 in all cases (> 40 for collection plane)
- **Stable running** throughout period of operations

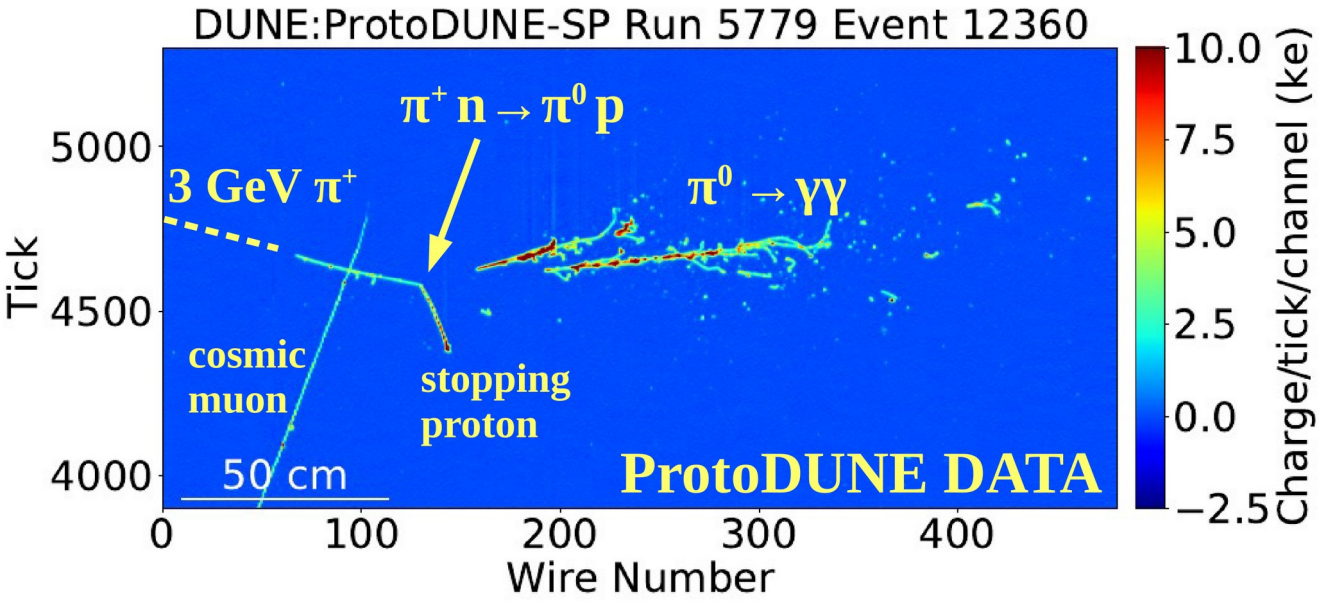
First ProtoDUNE-SP Results





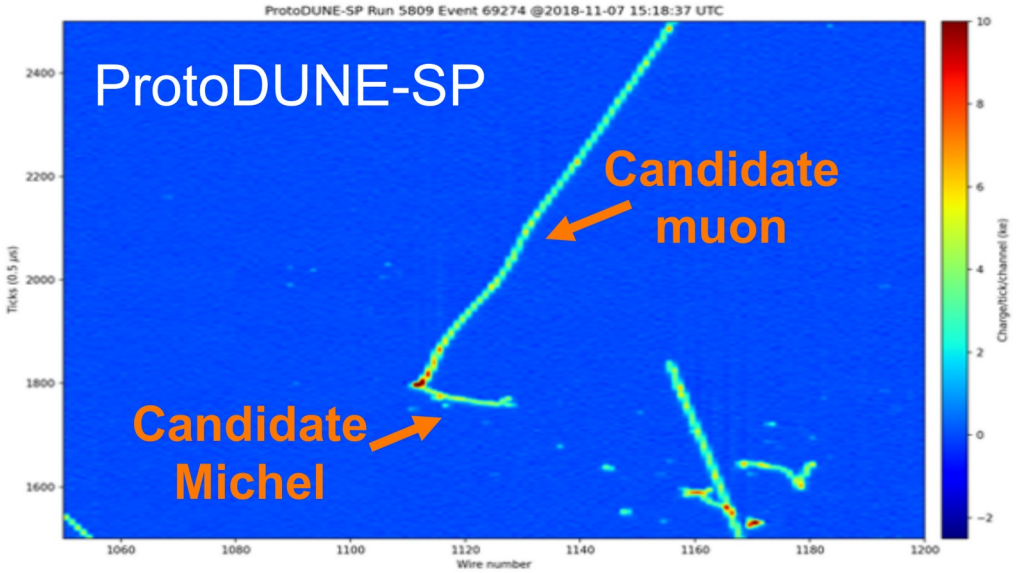
- First results from ProtoDUNE-SP informing **calibrations** and **reconstruction** for single phase DUNE FD
  - Above left: dE/dx vs. residual range for 1 GeV protons (data)
  - Above right: dE/dx distribution of 1 GeV protons (data vs. MC)
  - See **JINST publication** for full set of results: "First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform"

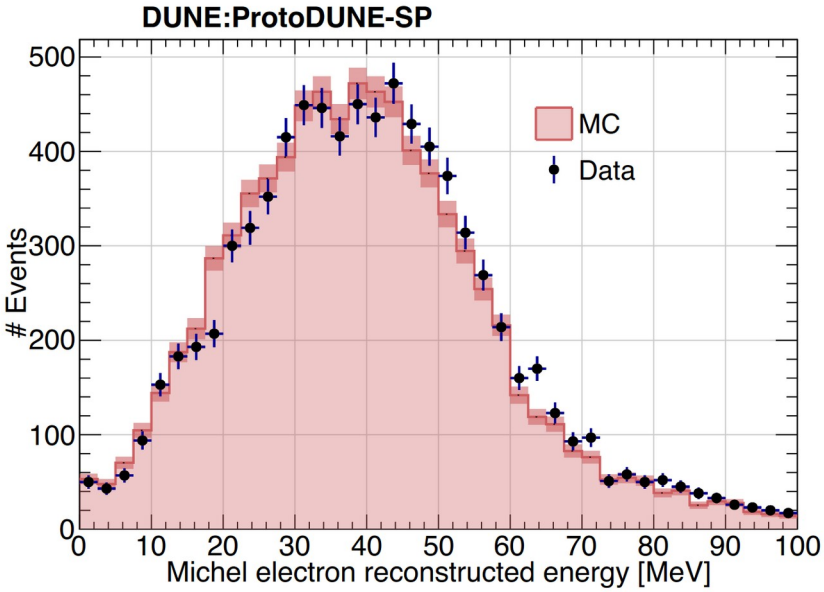
New ProtoDUNE-SP Studies



- More recent studies using ProtoDUNE-SP data leading to new publications in near future
  - **Pionic charge-exchange events** – yields neutral pions, standard candle for electromagnetic shower (photon/electron) energy scale
  - **Michel electrons** – important standard candle for low-energy electron energy scale, relevant for supernova/solar neutrinos
  - Many more studies that I don't have time to mention!

New ProtoDUNE-SP Studies



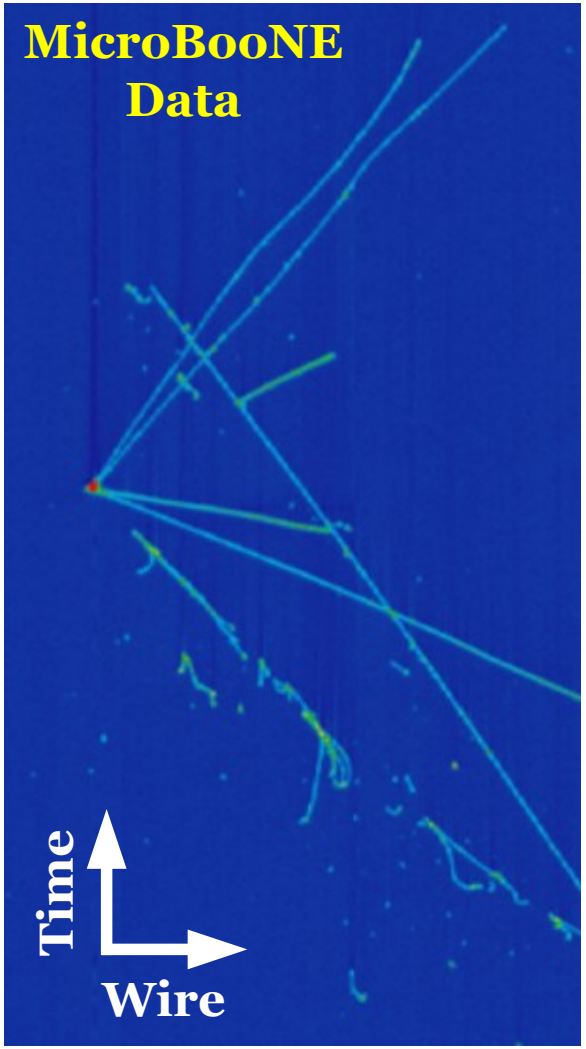


- More recent studies using ProtoDUNE-SP data leading to new publications in near future
  - **Pionic charge-exchange events** – yields neutral pions, standard candle for electromagnetic shower (photon/electron) energy scale
  - **Michel electrons** – important standard candle for low-energy electron energy scale, relevant for supernova/solar neutrinos
  - Many more studies that I don't have time to mention!

DUNE Physics Program

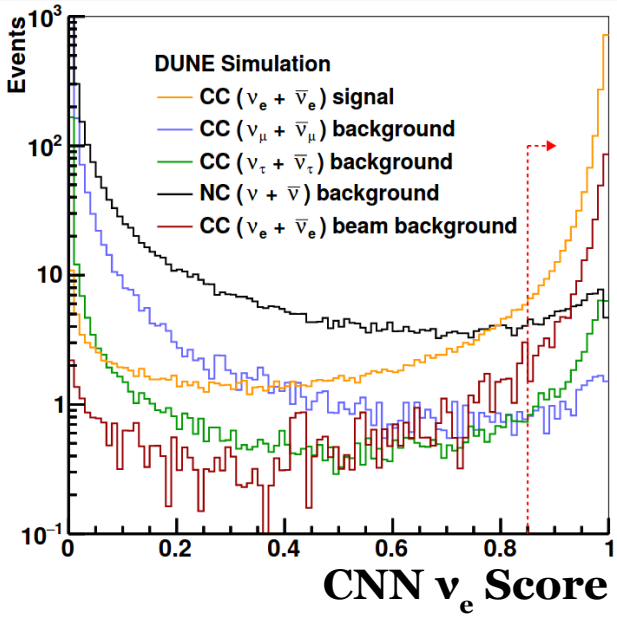
FD Event Reconstruction/Classification

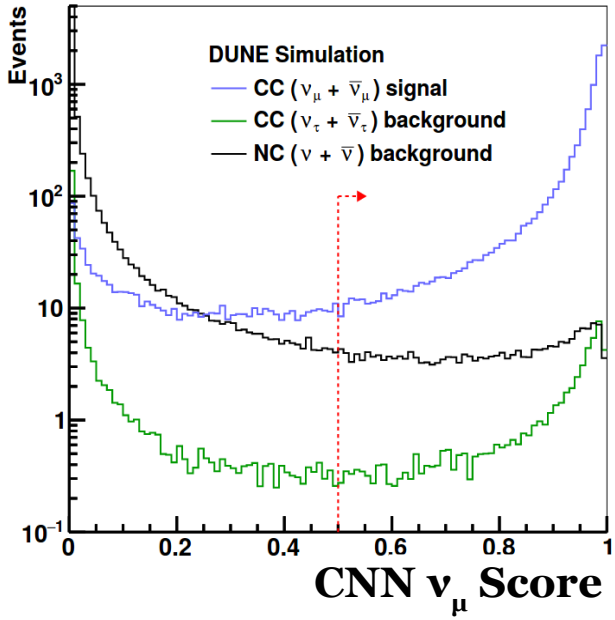
- Perform pattern recognition to reconstruct neutrino event in 3D
- Use convolution neural network (CNN) to classify events (images)
- Results: 80-90% efficiency for both ν_μ and ν_e selections
- See **PRD publication**: "Neutrino interaction classification with a convolutional neural network in the DUNE far detector"



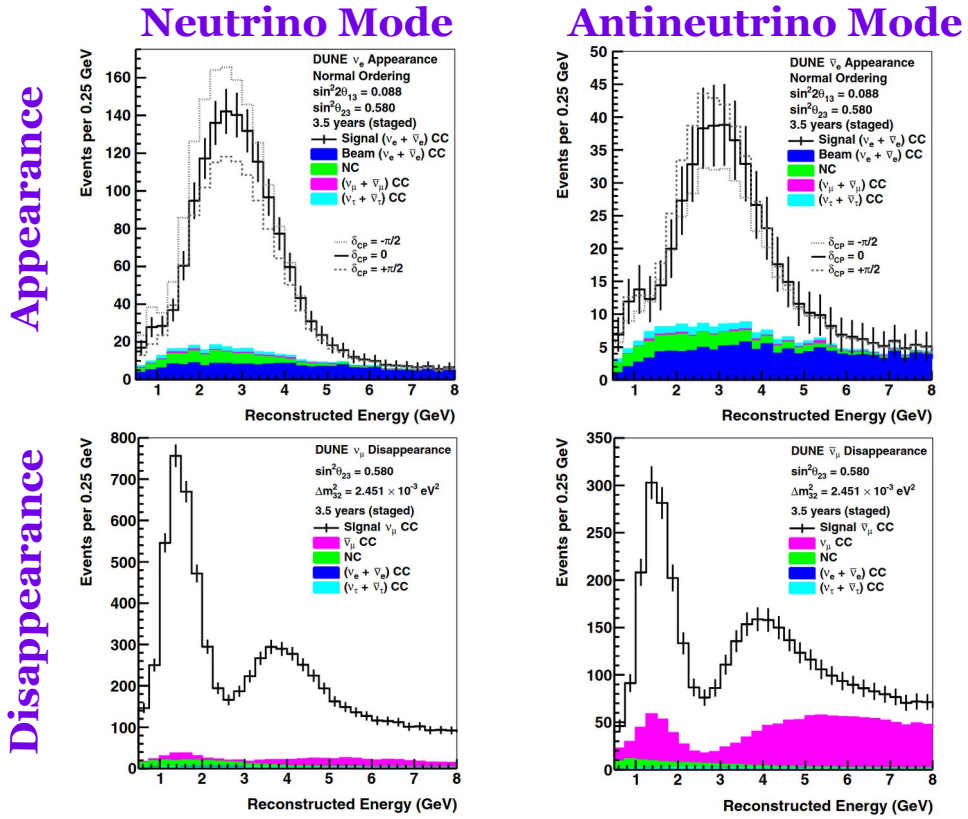
FD Event Reconstruction/Classification

- Perform pattern recognition to reconstruct neutrino event in 3D
- Use convolution neural network (CNN) to classify events (images)
- Results: 80-90% efficiency for both ν_μ and ν_e selections
- See **PRD publication**: "Neutrino interaction classification with a convolutional neural network in the DUNE far detector"





FD Oscillation Spectra

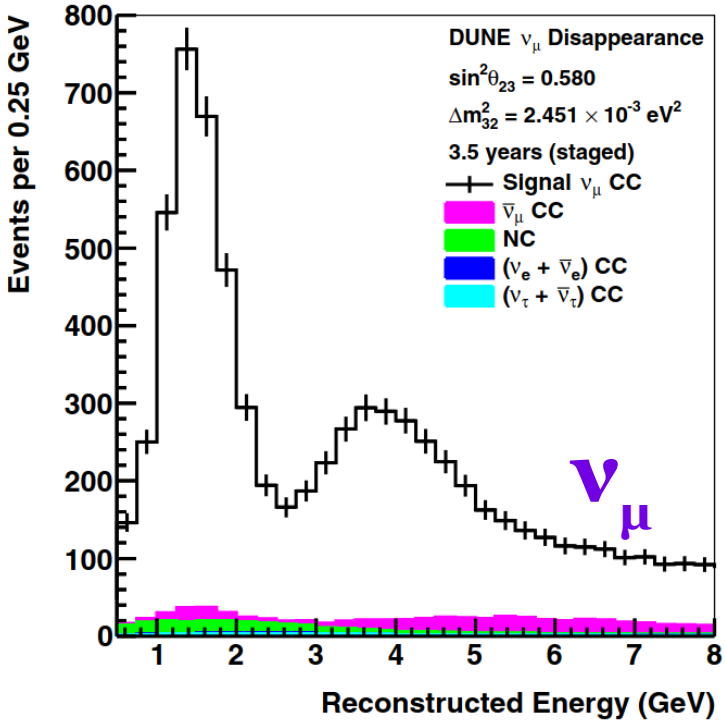


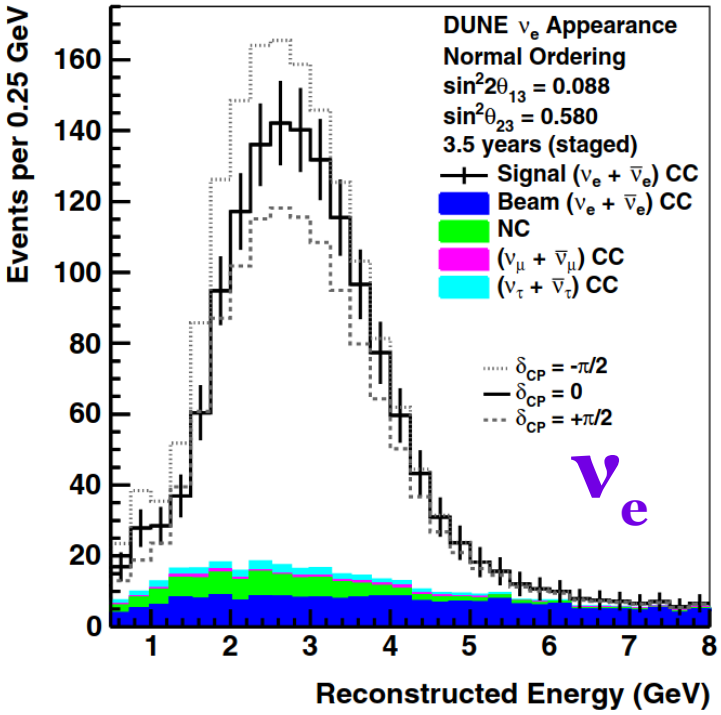
~1,000 ν_e events

~10,000 ν_μ events

- Four-component fit of FD data w/ constraint from ND data
- **Full systematics** (flux, cross section, detector) included
- See **EPJC publication**: "Long-baseline neutrino oscillation physics potential of the DUNE experiment"

FD Oscillation Spectra

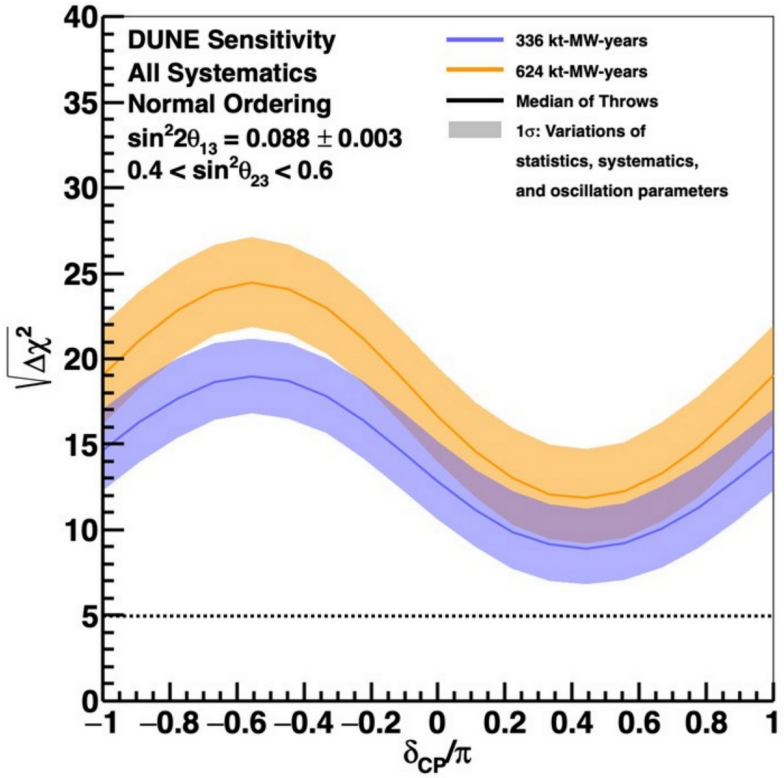




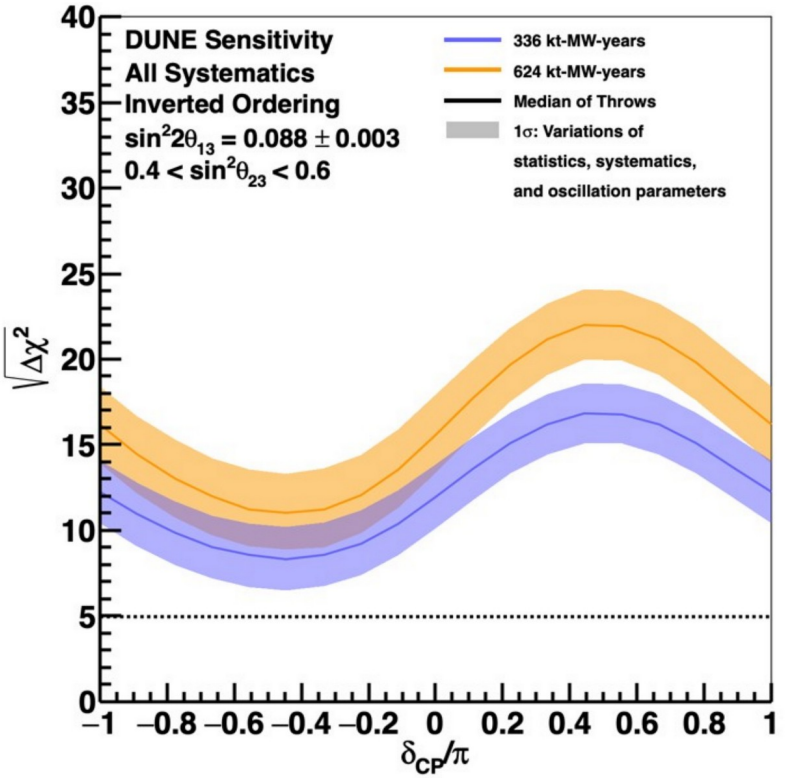
- Four-component fit of FD data w/ constraint from ND data
- **Full systematics** (flux, cross section, detector) included
- See **EPJC publication**: "Long-baseline neutrino oscillation physics potential of the DUNE experiment"

Mass Ordering Sensitivity

True Normal Ordering



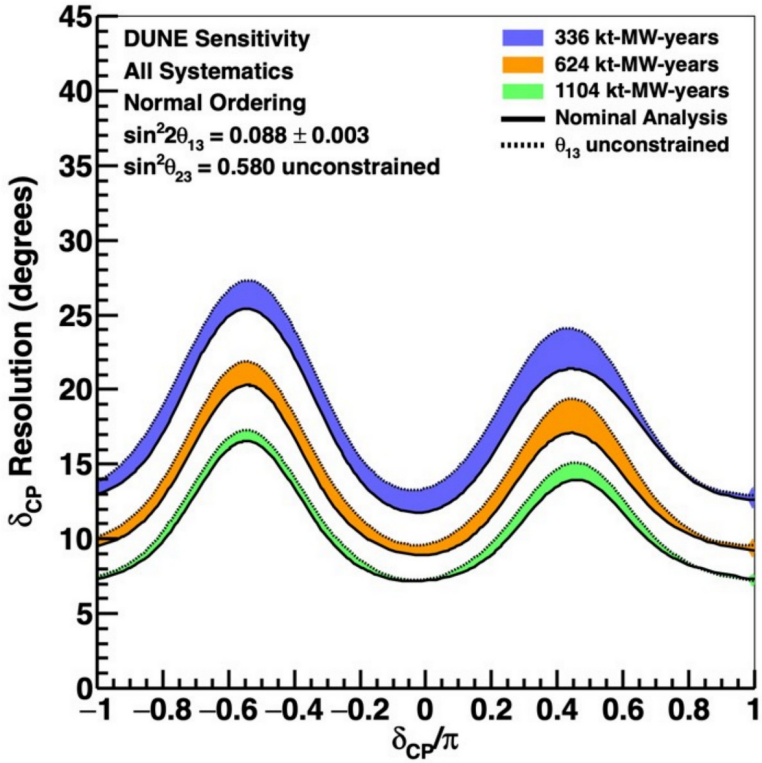
True Inverted Ordering



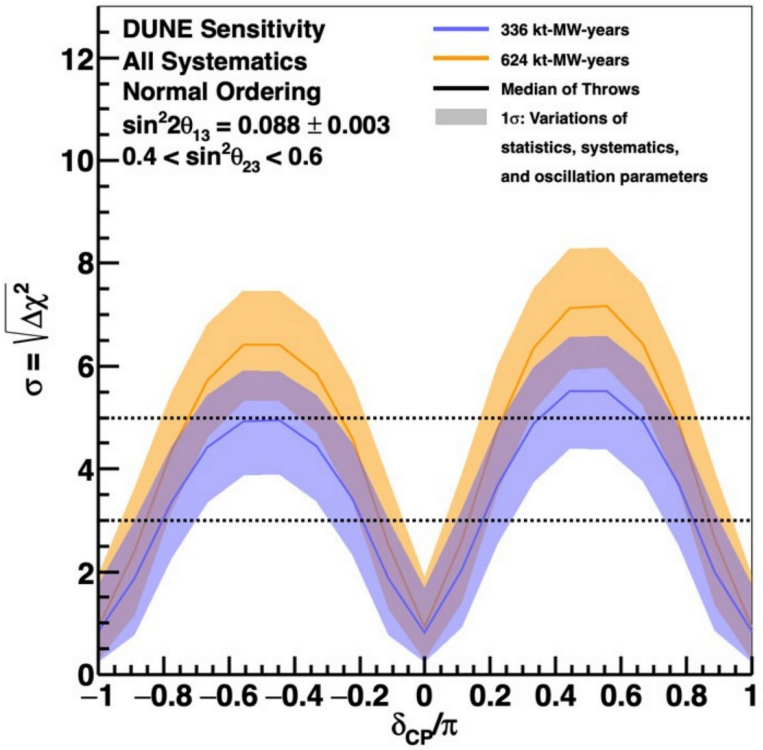
- Definitive determination of neutrino mass ordering for all possible parameters without external constraints
- Determination of neutrino mass ordering within first few years

CP Violation Sensitivity

δ_{CP} Resolution



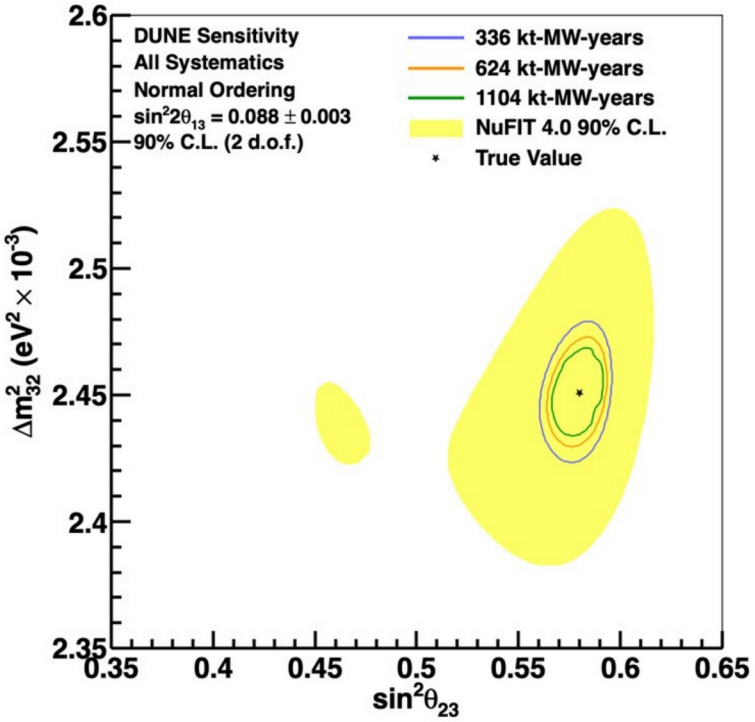
CPV Sensitivity



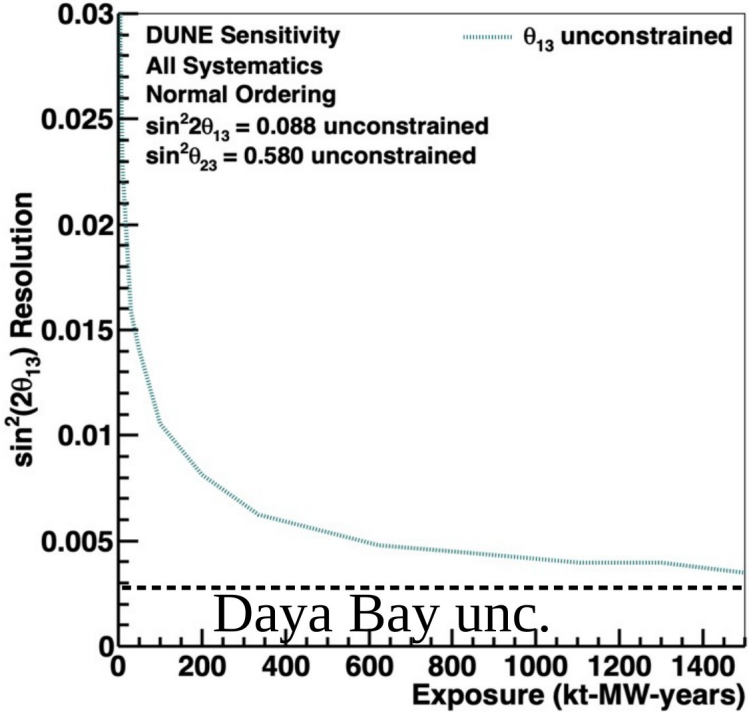
- 5σ discovery potential for CP violation for > 50% of δ_{CP} values
- 7-17° δ_{CP} resolution without external constraints

Precision Measurements, Unitarity

Δm^2_{32} vs. θ_{23}

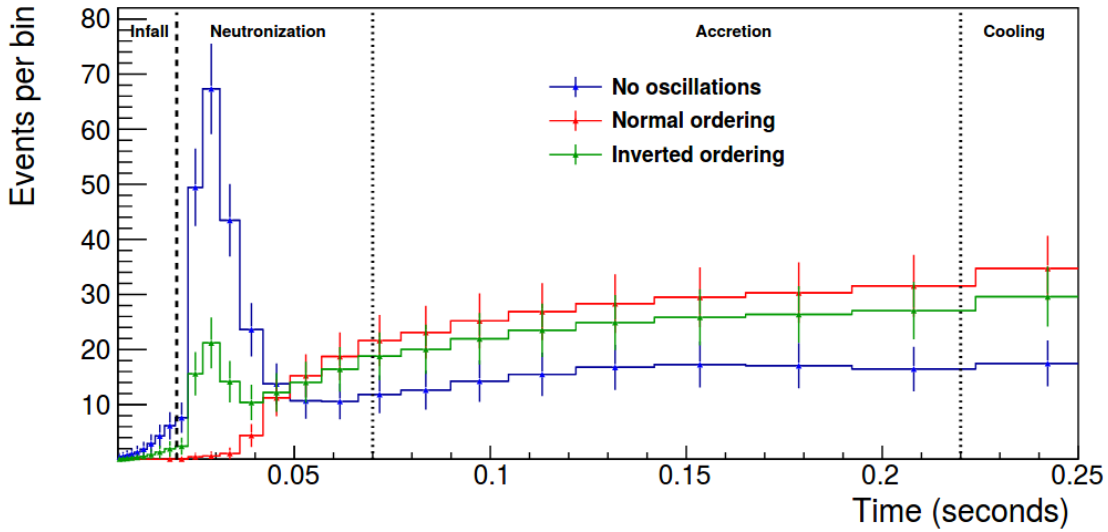


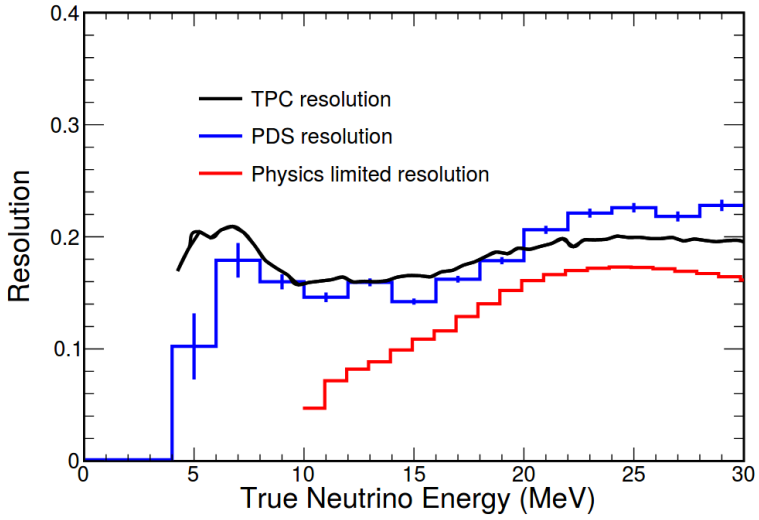
θ_{13} Resolution



- World-leading precision on Δm^2_{32} and θ_{23}
- Ultimate θ_{13} precision comparable with reactor experiments, allowing tests of PMNS unitarity

Supernova Neutrino Bursts

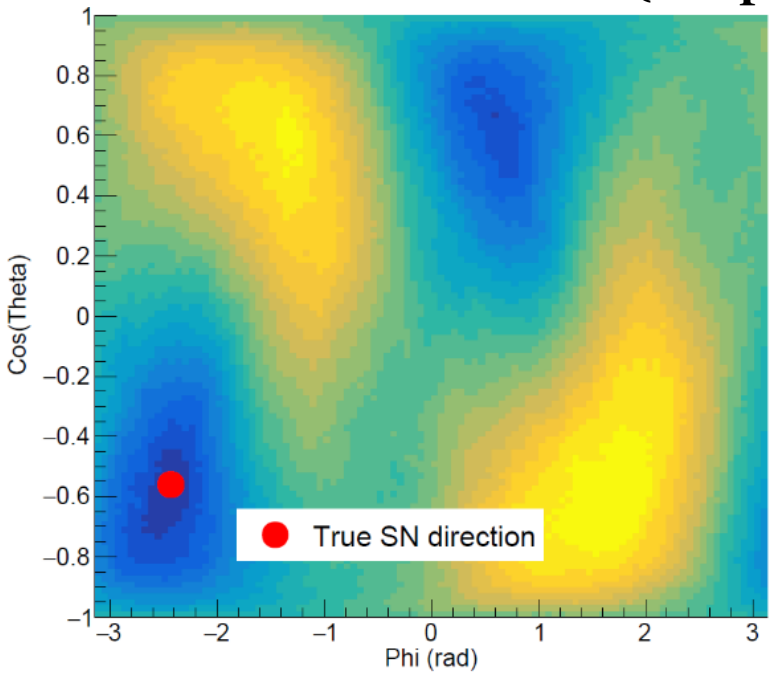




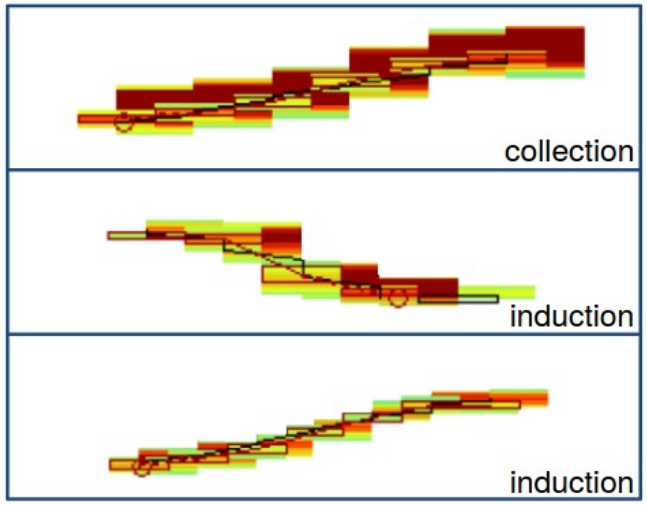
- Exciting physics aside from long-baseline physics program: **neutrino bursts** from **stellar core-collapse supernova**
- Primary interaction in argon: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$
- Probe of interesting supernova physics (e.g. core-collapse mechanism) and particle physics (e.g. ν flavor transformations)
- Excellent energy resolution with both TPC and photodetectors

SNB Directionality

Direction Likelihood Surface (10 kpc SN)

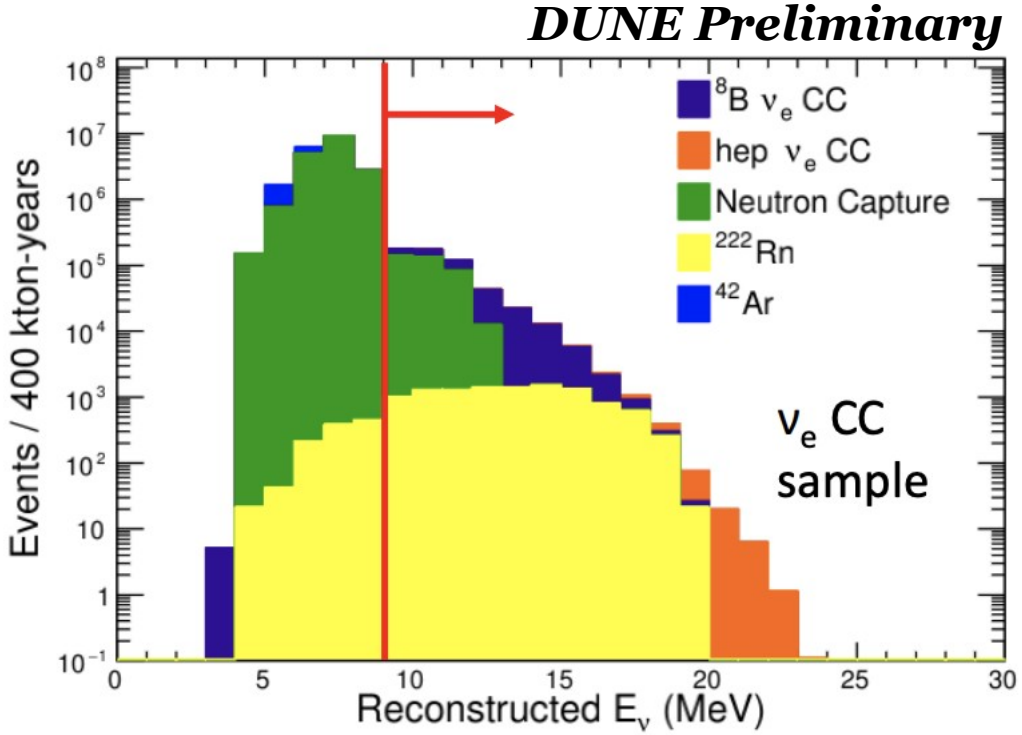


10 MeV Electron (Simulated+Reconstructed)



- Also sensitive to neutrino-electron elastic scattering, which can provide directionality of supernova neutrino burst
  - Can achieve **4.5° pointing resolution**
- See **EPJC publication**: "Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment"

Solar Neutrinos



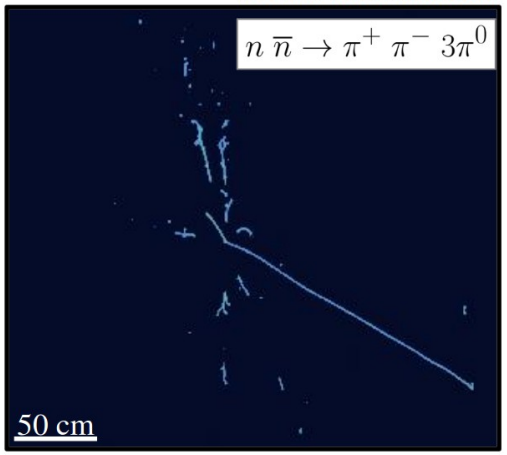
- Also sensitive to other low-energy neutrinos: **solar neutrinos**
  - **^{8}B solar neutrinos**
  - **hep solar neutrinos**
- Currently under investigation – difficult, but very promising!

BSM Physics Program

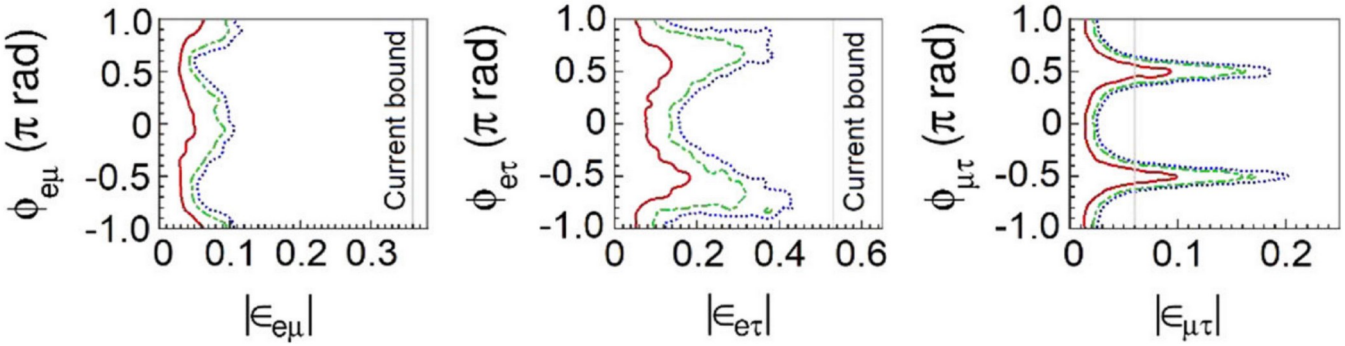
- **Large catalog of BSM searches at DUNE** – proton decay, NSI, large extra dimensions, sterile neutrinos, dark matter… **very small subset of analyses shown here**
- n-$\bar{n}$ oscillations: spherical spray of hadrons with E ~ $2m_n$, net momentum < p_F ~ 300 MeV

  Free neutron-equivalent sensitivity:

  $\tau_{free,osc} > 5.5\times10^8$ s (90% C.L.)



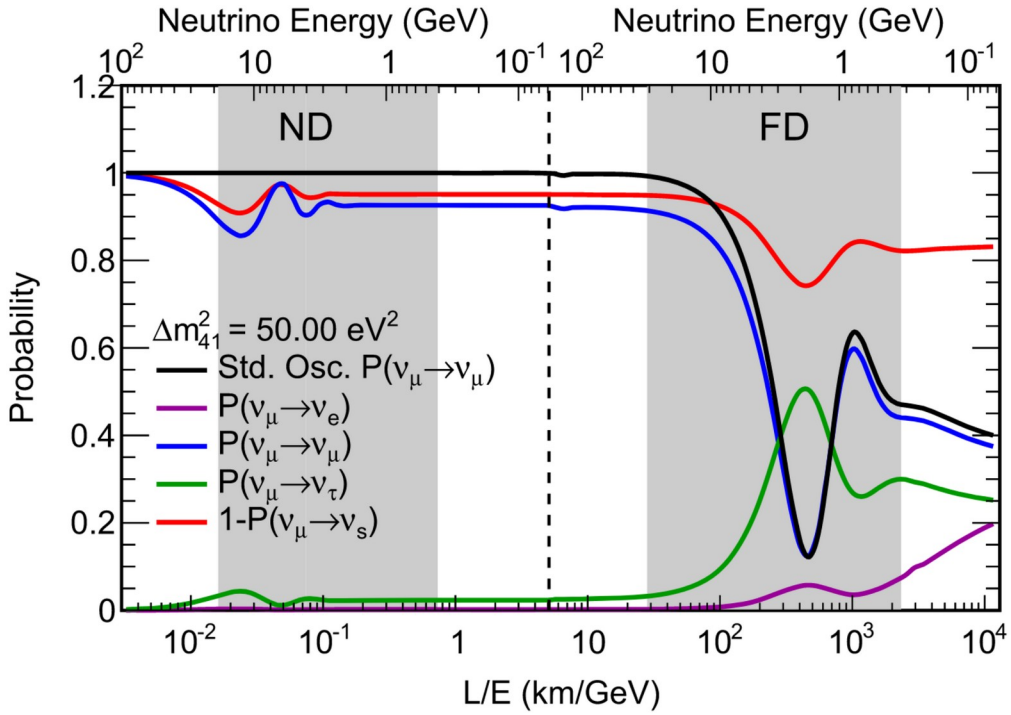
- Non-standard interactions (NSI): modifications to standard matter effects over DUNE's long baseline

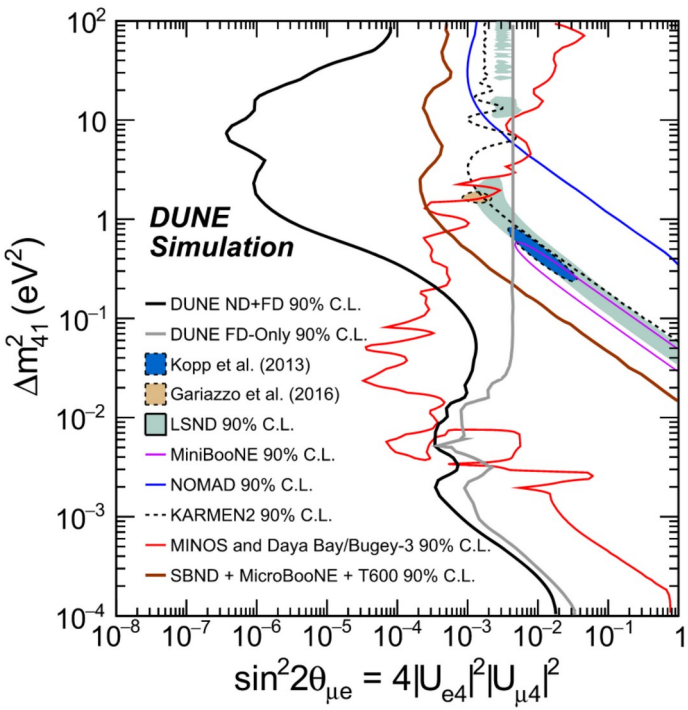


EPJC publication: "Prospects for beyond the Standard Model physics searches at the Deep Underground Neutrino Experiment"

BSM Physics Program

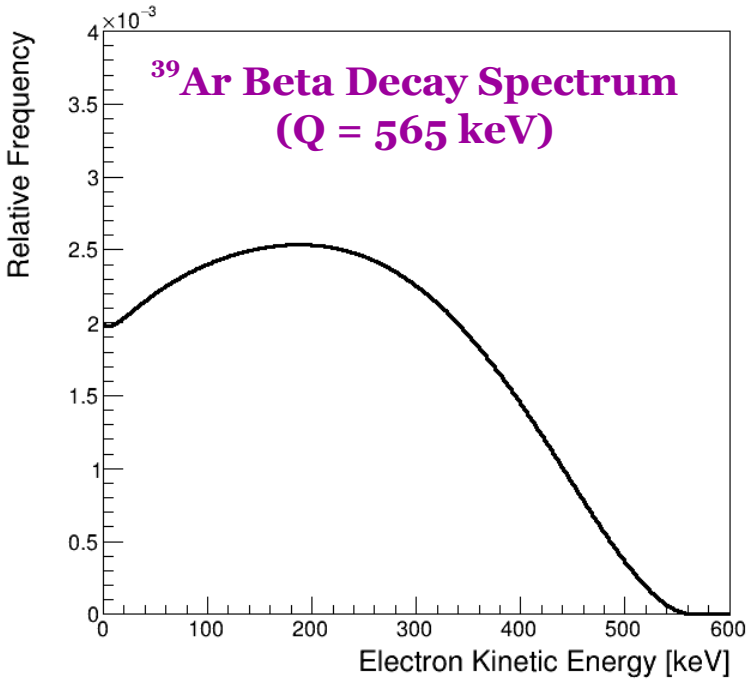
- **Large catalog of BSM searches at DUNE** – proton decay, NSI, large extra dimensions, sterile neutrinos, dark matter… **very small subset of analyses shown here**
- Sterile neutrinos: extra states mixing with three SM neutrinos; probe w/ **ν oscillations**, ^{39}Ar β decay spectrum "kink" search

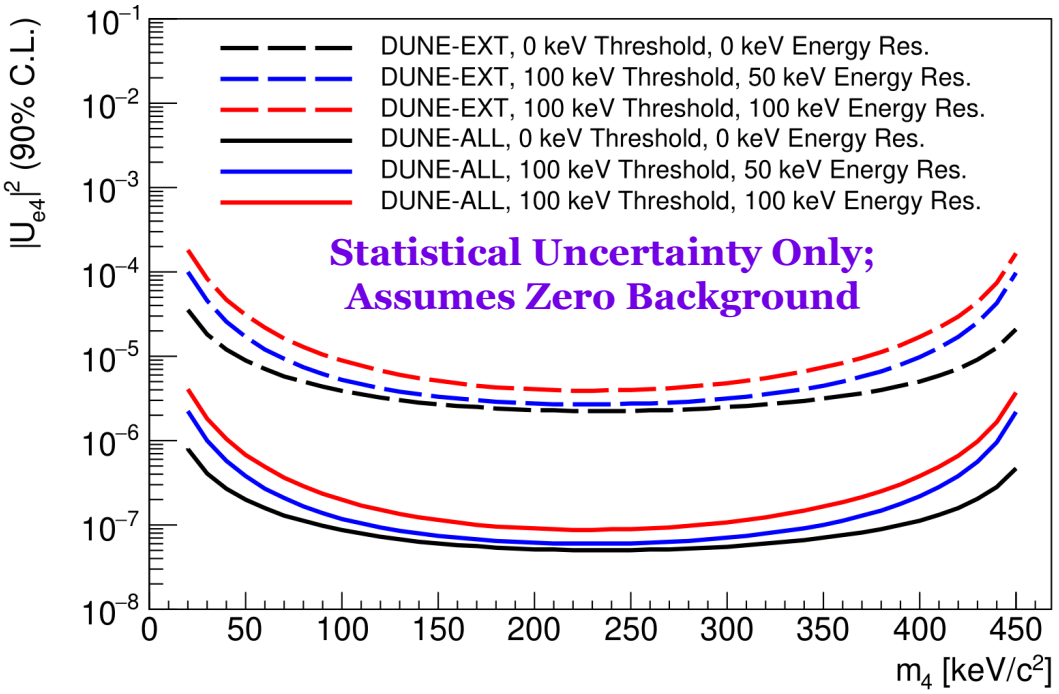




BSM Physics Program

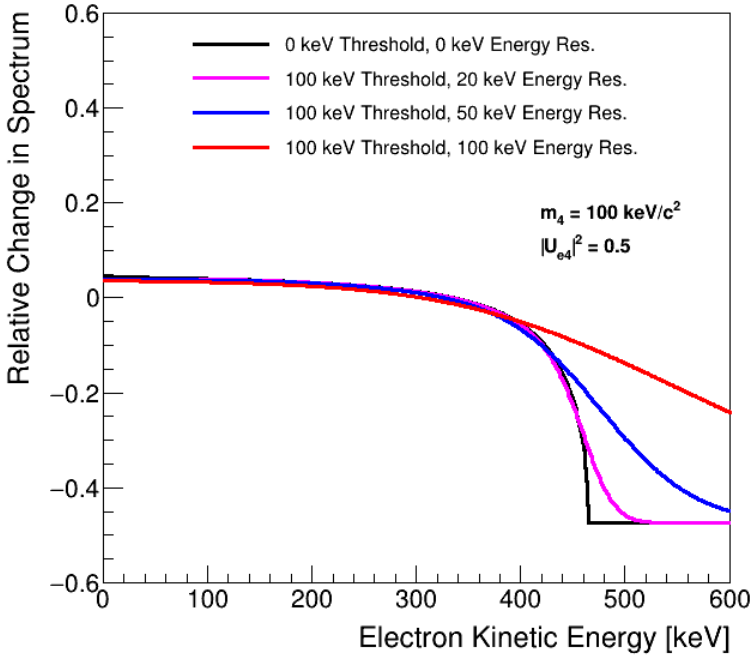
- **Large catalog of BSM searches at DUNE** – proton decay, NSI, large extra dimensions, sterile neutrinos, dark matter… **very small subset of analyses shown here**
- Sterile neutrinos: extra states mixing with three SM neutrinos; probe w/ ν oscillations, **^{39}Ar β decay spectrum "kink" search**

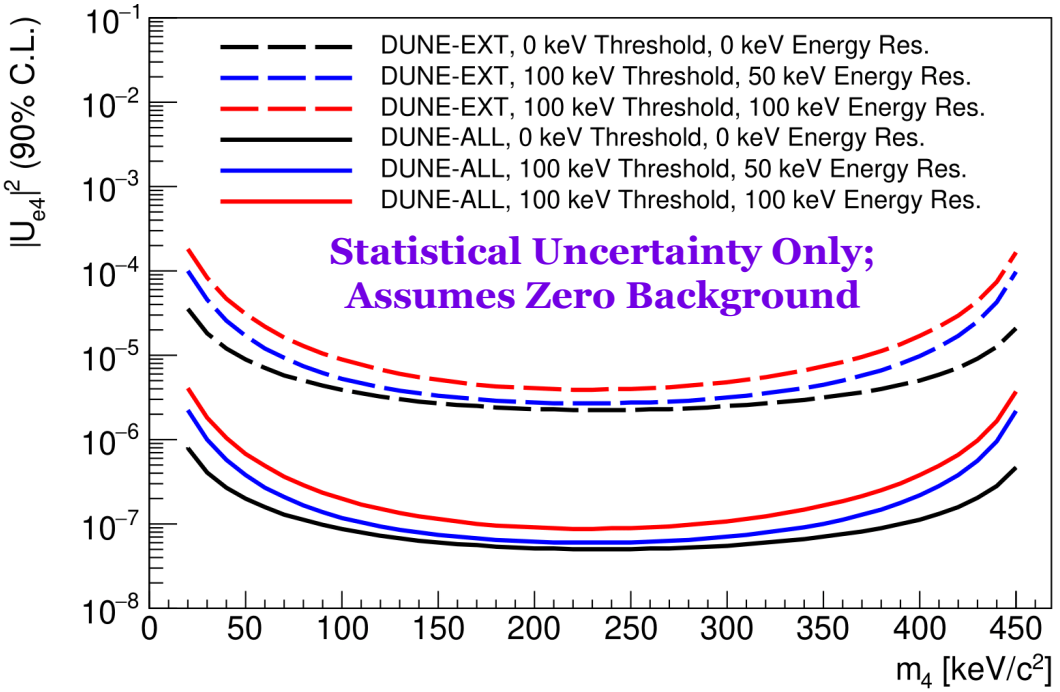




BSM Physics Program

- **Large catalog of BSM searches at DUNE** – proton decay, NSI, large extra dimensions, sterile neutrinos, dark matter… **very small subset of analyses shown here**
- Sterile neutrinos: extra states mixing with three SM neutrinos; probe w/ ν oscillations, **^{39}Ar β decay spectrum "kink" search**





Summary

- DUNE making good progress toward enabling high-precision neutrino measurements in next decade
  - **Exciting physics program** including CP violation measurement, neutrino mass ordering determination, supernova neutrino burst physics, solar neutrino detection, and many BSM searches
- Technical milestones:
  - Technical Design Report for DUNE FD complete: **I**, **II**, **III**, **IV**
  - ProtoDUNE successfully operated at CERN with first results published (more coming soon); ProtoDUNE II starting late 2022
  - Conceptual Design Report for DUNE ND now on **arXiv**
- Plenty of opportunities for additional **international participation**

See DUNE parallel talks and posters for more detailed information!

Thanks!