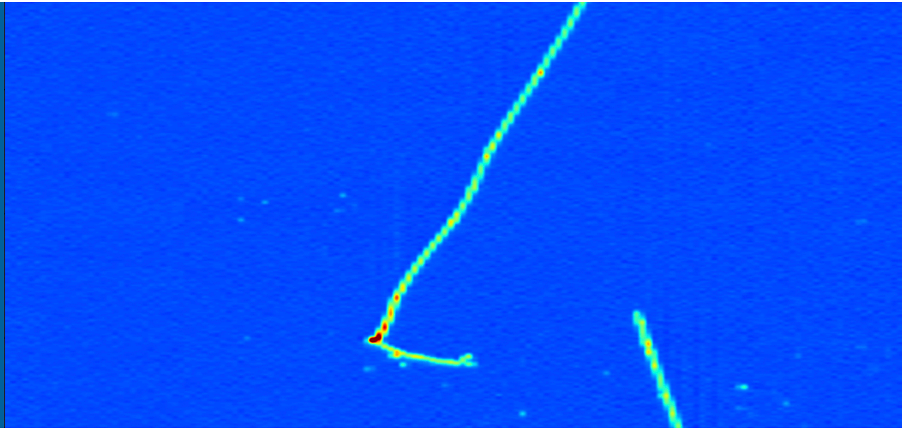
DEEP UNDERGROUND NEUTRINO EXPERIMENT

Argonne NATIONAL LABORATORY

DUNE: STATUS AND PHYSICS



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On behalf of the DUNE collaboration
NuSTEC 2021

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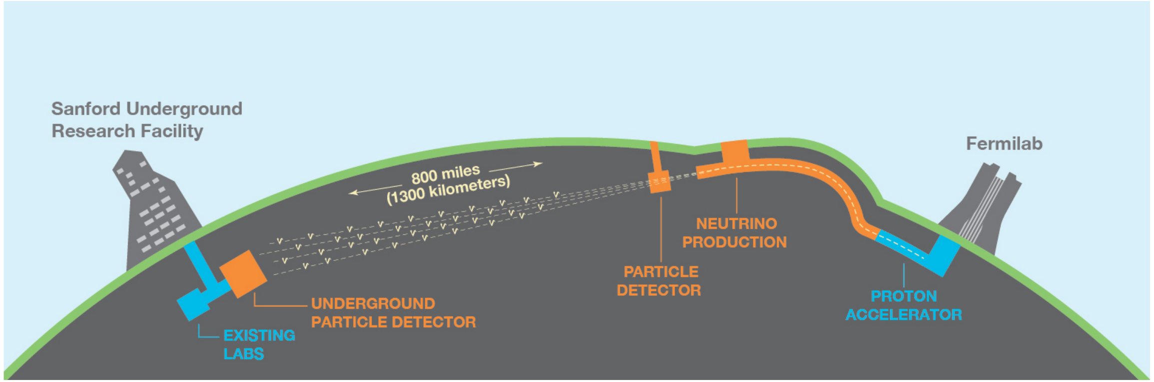
U.S. DEPARTMENT OF ENERGY | Office of Science

OUTLINE

- Introduction to the DUNE Experiment and physics goals
- DUNE Near & Far Detectors
- ProtoDUNE detector
- DUNE physics program
- Cross sections studies at ProtoDUNE-SP
- Summary

INTRODUCTION TO DUNE

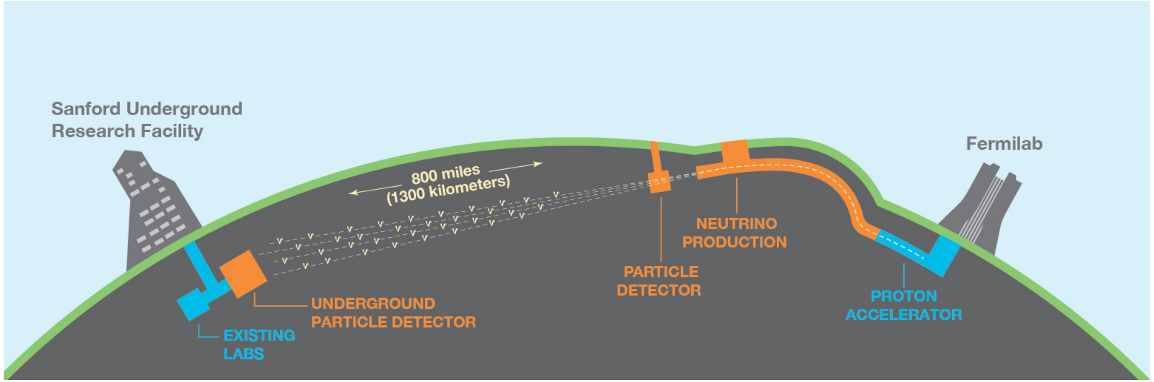
- The Deep Underground Neutrino Experiment (DUNE) is a future accelerator-based multi-detector long-baseline neutrino oscillation experiment.



- New neutrino beam at Fermilab,1300 km baseline
- Multiple technologies for the **Near Detector (ND)** at Fermilab
- 70 kton Liquid Argon Time Projection Chamber (LArTPC) **Far Detector (FD)** at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Excavation started in 2017, begin taking data in late 2020s

INTRODUCTION TO DUNE

- The Deep Underground Neutrino Experiment (DUNE) is a future accelerator-based multi-detector long-baseline neutrino oscillation experiment.



- **Primary physics goals:**
  – Neutrino oscillations: ν_μ / $\bar{\nu}_\mu$ disappearance, ν_e / $\bar{\nu}_e$ appearance
    - δ_{CP}, θ_{23}, θ_{13}
    - Neutrino mass hierarchy: normal/inverted
  – Supernova burst neutrinos
  – Beyond-Standard-Model physics: baryon number violation, sterile neutrinos, non-standard interactions, etc.

DUNE COLLABORATION

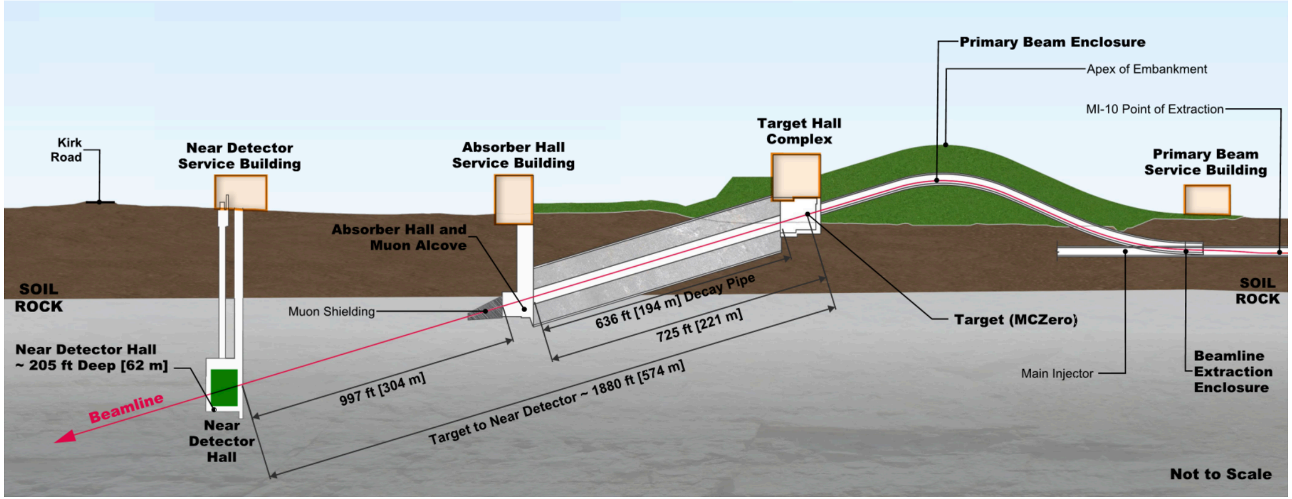
- 1317 members
- 208 institutions
- 33 countries

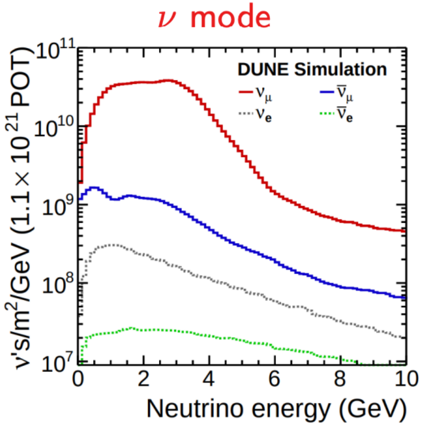
- Strong international partnership to execute the mega neutrino science project based at US

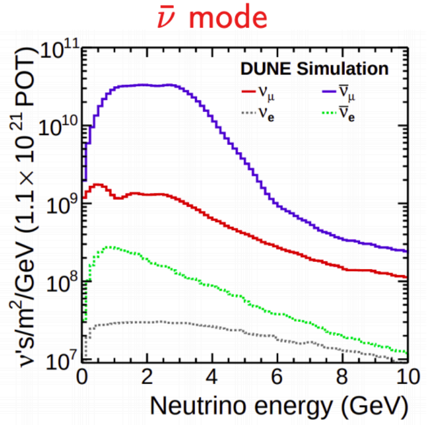
DUNE Virtual Collaboration Meeting, January 2021

DUNE NEUTRINO SOURCE: LBNF BEAM

- 1.2 MW source of 60-120 GeV protons
  - Upgradable to 2.4 MW
  - Incident on He-cooled graphite target
  - 194 m decay region
- Beam of mainly ν_μ or $\overline{\nu}_\mu$ produced at Fermilab
  - Measured in near detector

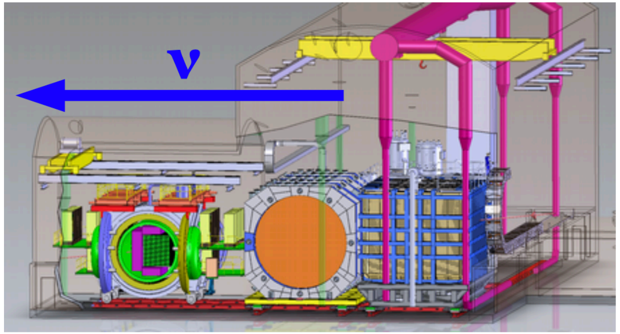


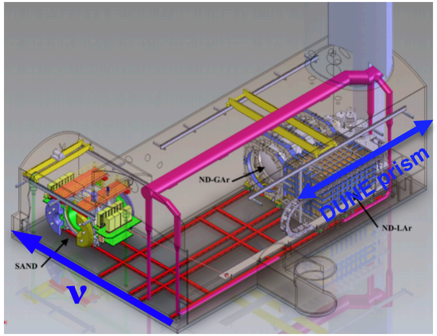




DUNE NEAR DETECTOR (ND)

- Primary purpose:
  - characterize neutrino beam
  - constrain cross section uncertainties in long-baseline neutrino oscillation analysis
- Anticipate high-rate environment with proximity to beam source and lower overburden



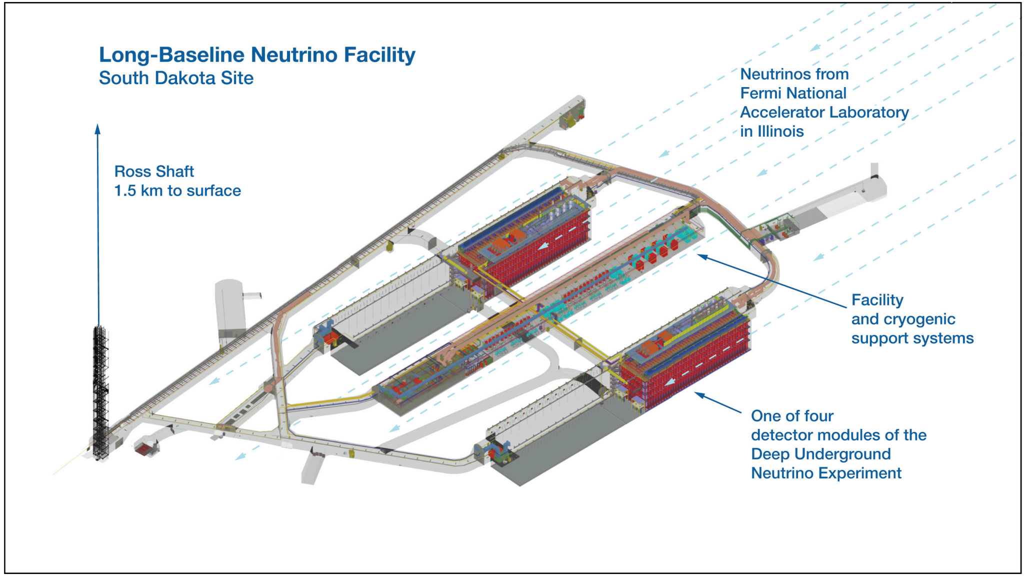


SAND ND-GAr ND-LAr

- **ND-LAr:** modular, pixelated LArTPC
  - Same detection principle as far detector with design optimized to large pileup at near detector site
- **ND-GAr:** high-pressure GArTPC surrounded by ECAL and magnet
  - Calorimetry for low particle thresholds; muon spectrometer
- **SAND:** High density plastic scintillator detector with tracking chambers surrounded by ECAL and magnet
  - On-axis monitor of beam spectrum
- **DUNE-PRISM:** ND-LAr + ND-GAr can move up 30 meters transverse to the beam
  - Sampling different E_{ν}

DUNE FAR DETECTOR (FD)

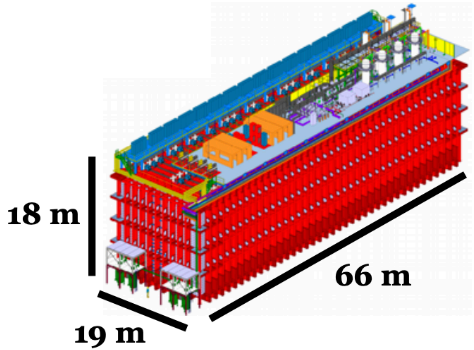
- Far detector is located 1.5 km underground at SURF
- Consists of 4 modules, each with a total mass of 17 kt
- The first of these modules will be horizontal drift LArTPC
- The second module will be vertical drift LArTPC
- The technologies for the further modules have not been decided yet

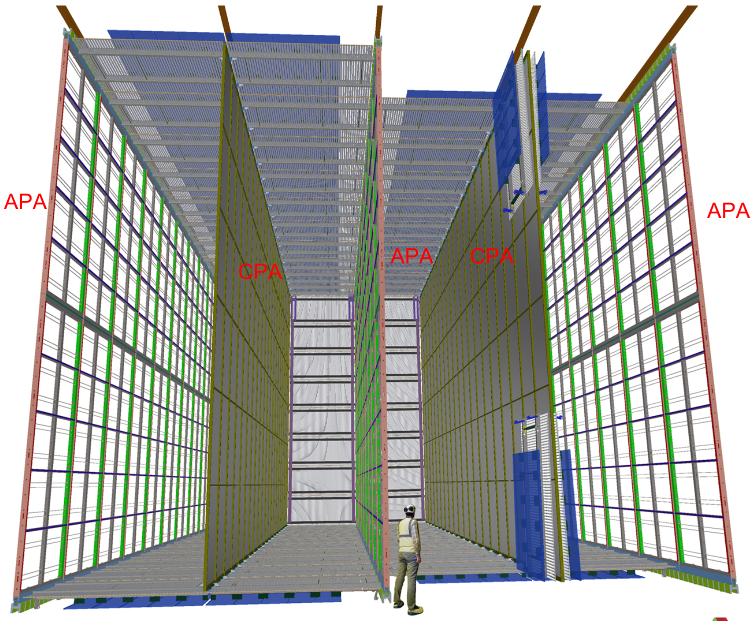


FAR DETECTOR (MOD-1)

Horizontal drift FD

- 18 x 19 x 66 m^3 total volume, 17 kT total mass
- Horizontal drift LArTPC with
  - Four 3.5 m long drift regions with 500 V/cm field
  - Anode plane with 3 planes of wire readout having 5 mm pitch
    - 2 Anode Plane Assemblies (APA) stacked vertically
  - 1500 ARAPUCA 209 x 12 x 2 cm^3 photon detection bars integrated into APAs

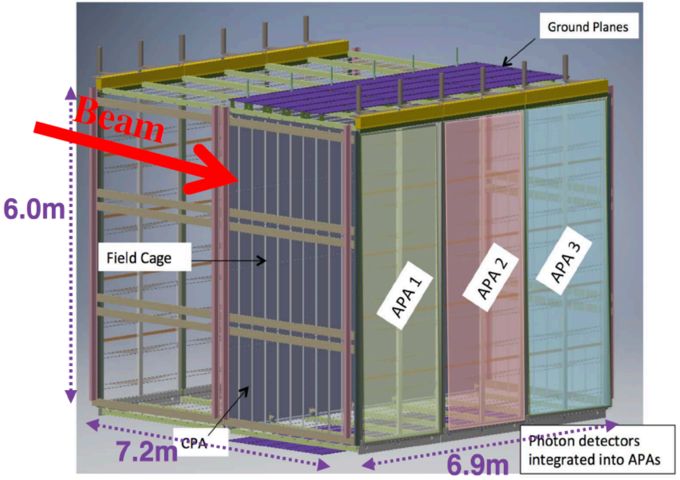




PROTODUNE SINGLE PHASE (SP)

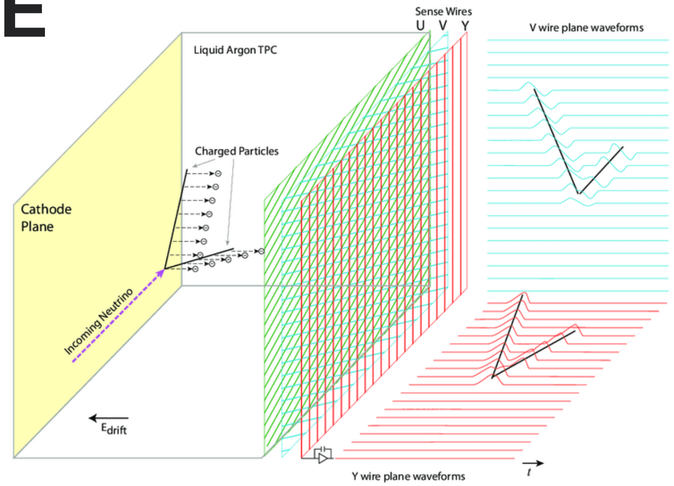
- Prototype of DUNE horizontal drift FD (Mod-1)
- 1-kt ProtoDUNE in charged test beam at CERN
- Active Volume: 6m (H) x 7m (L) x 2 x 3.6 m (W)
- Central Cathode Plane Assembly (CPA) :
  - 3.6 m drift distance @180 kV
  - 500 V/cm field in drift volume
- Anode Plane Assembly (APA):
  - 3 APAs on each side
  - Each APA module: 6m high, 2.3m wide
  - Two induction planes and one collection plane
- Photon detectors (PDS): 3 designs integrated into APA frame bars
- Test of component installation, commissioning, and performance
- First paper on ProtoDUNE-SP performance published
  - [JINST 15 (2020) 12, P12004]
- ProtoDUNE-SP Phase-I operated Sept. 2018 – July 2020, Phase-II data taking under preparation

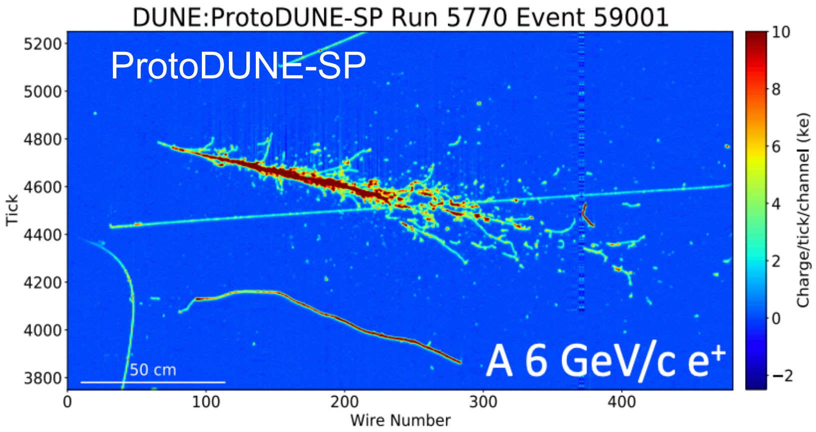
ProtoDUNE-SP TPC



LARTPC WORKING PRINCIPLE

- High resolution 3D track reconstruction
  - Charged particle tracks ionize argon atoms
  - Ionized electrons drift ~ms to anode wire planes → wire planes give 2D position information
  - The third dimension is obtained by combining different 2D views
- Argon scintillation light (~ns) detected by photon detectors, providing event start time t_0

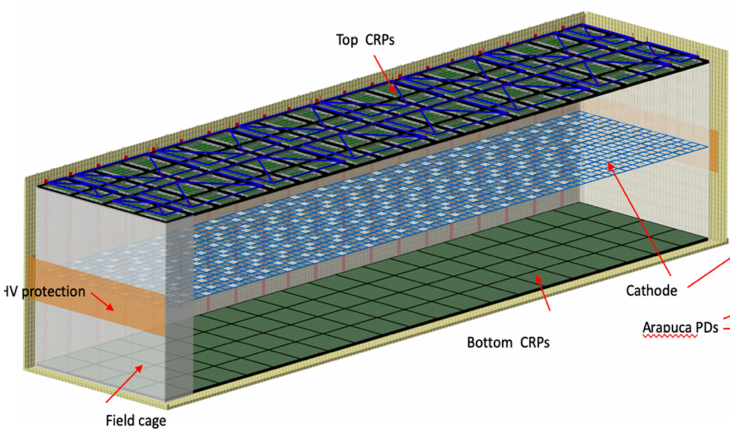


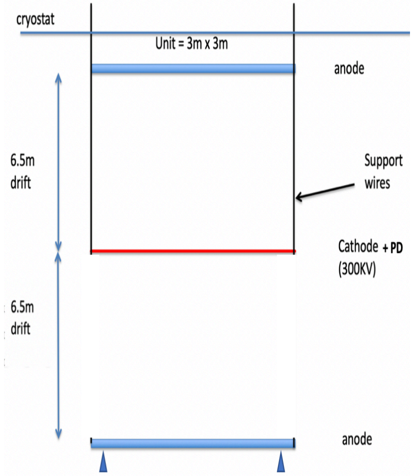


FAR DETECTOR (MOD-2)

Vertical Drift FD

- New detector scheme that includes:
  - 2-sided long vertical drift (VD) that maximizes active volume
  - Printed Circuit Board-based readout scheme makes detector assembly much simpler
  - Photodetection system deployed on the central cathode plane
- Combines the positive features from FD prototypes
- New approach to second FD module
  - Plan is to complete VD development and “ProtoDUNE-VD” in 2023

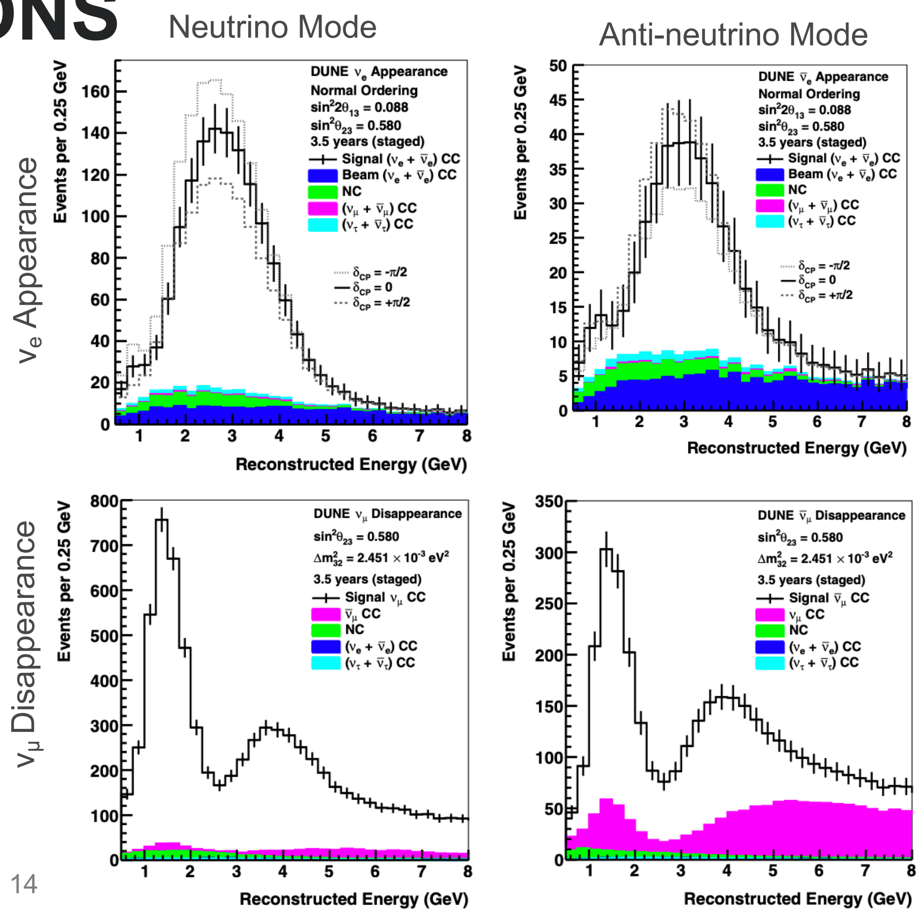




DUNE PHYSICS

NEUTRINO OSCILLATIONS

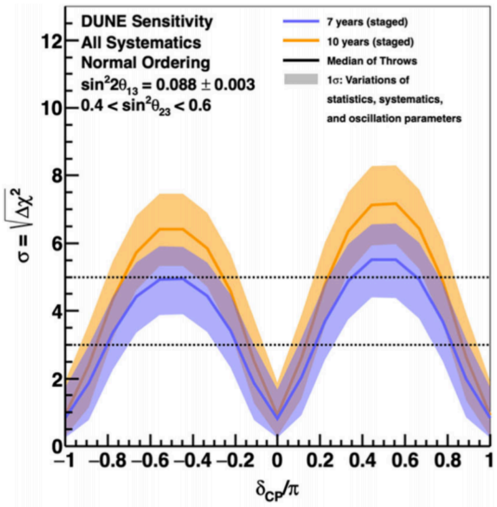
- Measurement and simultaneous fit over four components of FD data
- These are also observed prior to oscillation by the near detector (ND)
- Sensitivity assessment includes full systematics treatment (flux, cross section, and detector)
- EPJC (2020) 10, 978



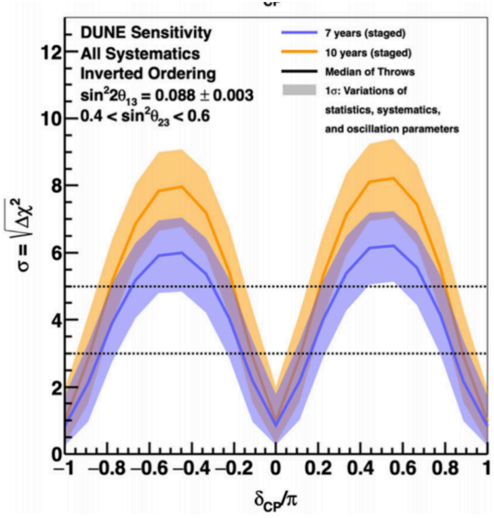
CP VIOLATION SENSITIVITY

- Significant CP violation discovery potential over a large range of possible true δ_{CP} values in 7-10 years of (staged) running

True normal ordering

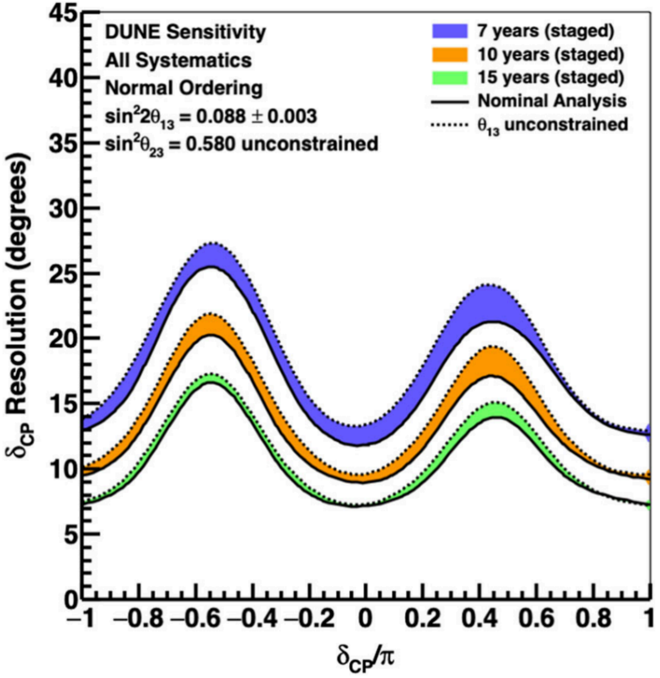


True inverted ordering



DELTA-CP RESOLUTION

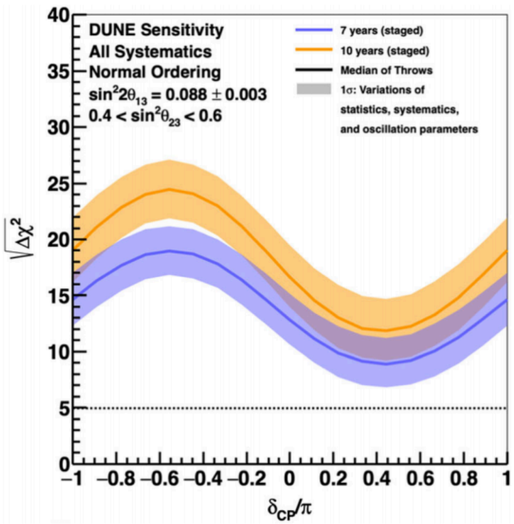
- After 10 years running, δ_{CP} resolution is (10 − 20) degrees
- Moving to longer exposures, resolution drops to even lower levels



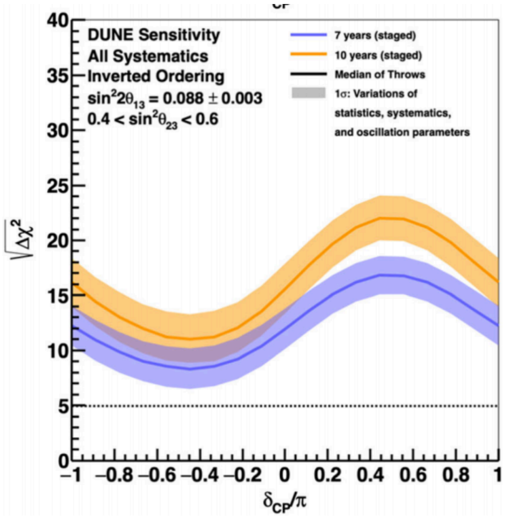
MASS HIERARCHY SENSITIVITY

- Definitive determination of neutrino mass hierarchy (normal or inverted) for all possible parameters

True normal ordering



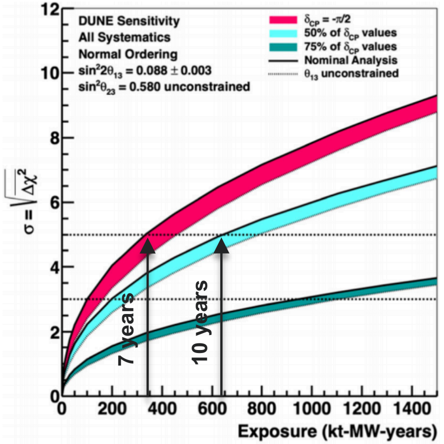
True inverted ordering



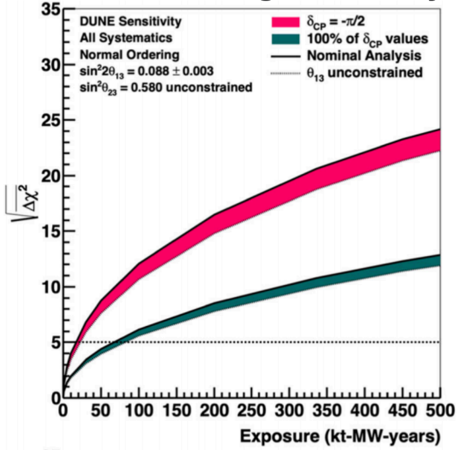
TIME-PROJECTED SENSITIVITY

- Significant milestones throughout the DUNE physics program
  - CPV discovery if true δ_{CP} = -π/2 in ~7 years
  - CPV discovery for 50% of true δ_{CP} values in ~10 years
- Determination of mass hierarchy within the first 2-3 years

CP Violation Sensitivity



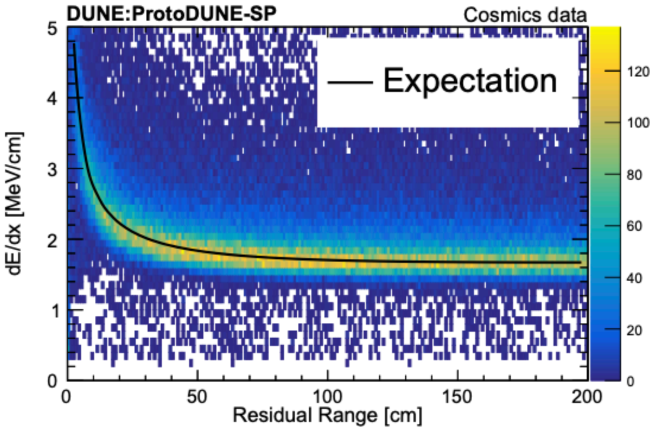
Mass ordering Sensitivity

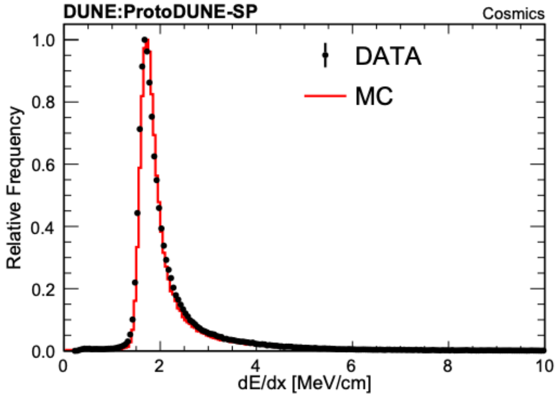


PROTODUNE-SP PHYSICS

FIRST PROTODUNE-SP RESULTS

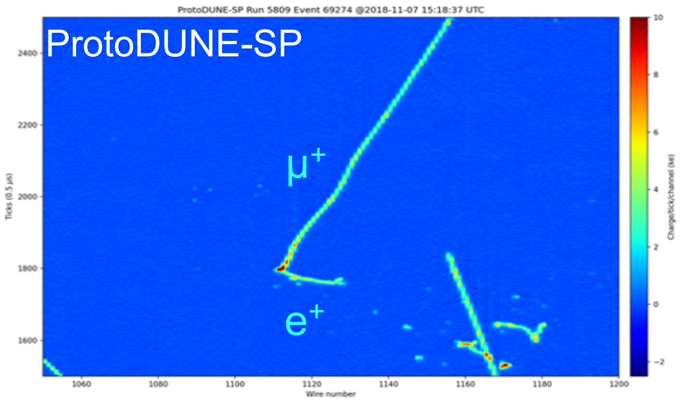
- First results from ProtoDUNE-SP informing calibrations and reconstruction for single phase DUNE FD
- Top plot: dE/dx vs. residual range for ProtoDUNE cosmic ray muons (data)
- Bottom plot: dE/dx distribution of cosmic ray (data vs. MC)
- First paper on ProtoDUNE-SP performance published
  - [JINST 15 (2020) 12, P12004]

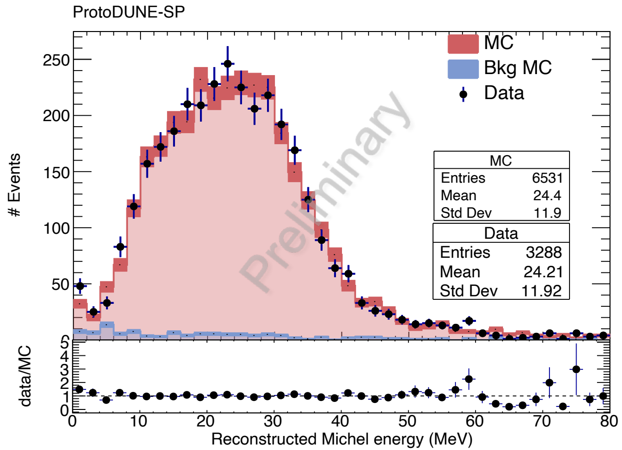




MICHEL ELECTRON ANALYSIS

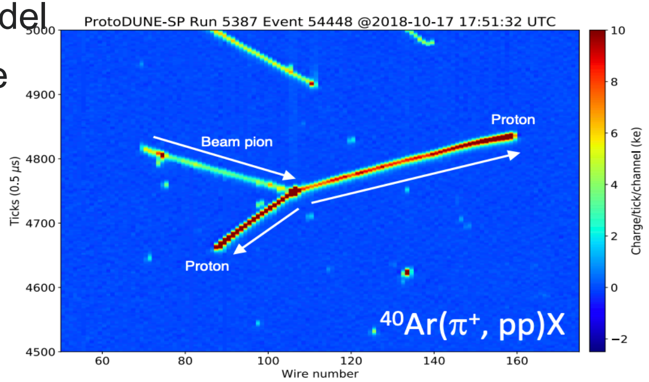
- A calibration sample to measure detector response to 10’s MeV electrons
- Deliver selection and reconstruction framework to isolate muons and its Michel electrons to calibrate electron energy scale at DUNE Far Detector
- Developed selection, reconstruction, and energy calibration tools for ProtoDUNE-SP
  - Achieved 95% event purity
  - Variation in Michel electron energy energy is <2%
- Paper is coming soon
  - Stay tuned!



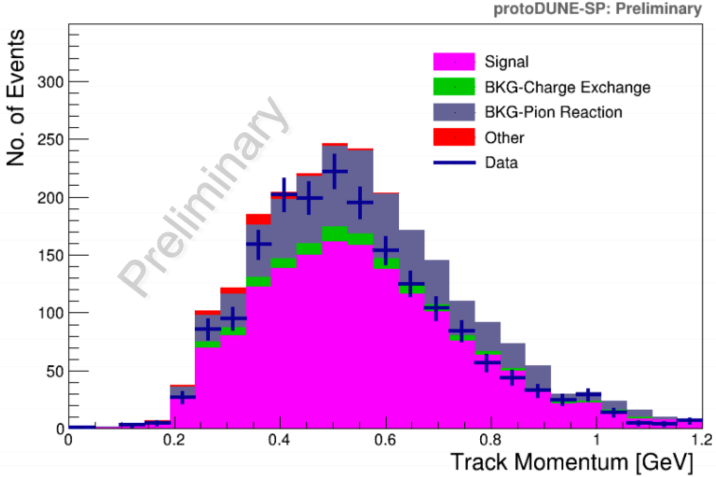


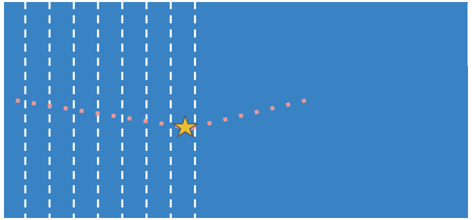
PROTODUNE ONGOING CROSS SECTION STUDIES

PION ABSORPTION CROSS SECTION



- Useful to measure FSI in neutrino interaction with better data-driven model
- A process where only protons or neutrons are produced in the final state
  - $\pi^+ pn \rightarrow pp$
  - $\pi^+ nn \rightarrow pn$
- Used the thin slice method to extract the pion cross section for 1 GeV beam
  - First measure the cross-section as a function of slice ID, and then convert the slice ID to pion KE.
- Future work
  - Include full detector
  - Systematic studies

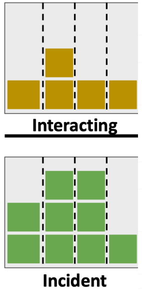




$$\sigma = (M_{Ar}/\rho t N_A) * (N_{Int}/N_{Inc})$$

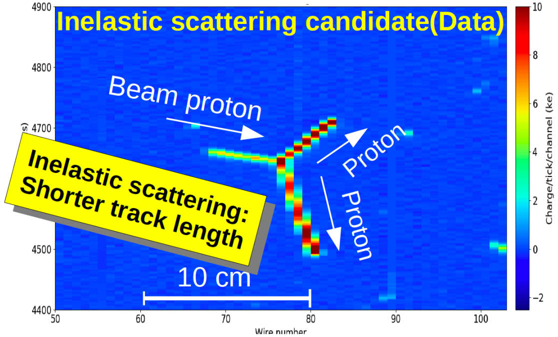
M_{Ar} -- Mass of Ar
t -- Thickness of slice
ρ -- Density of Ar

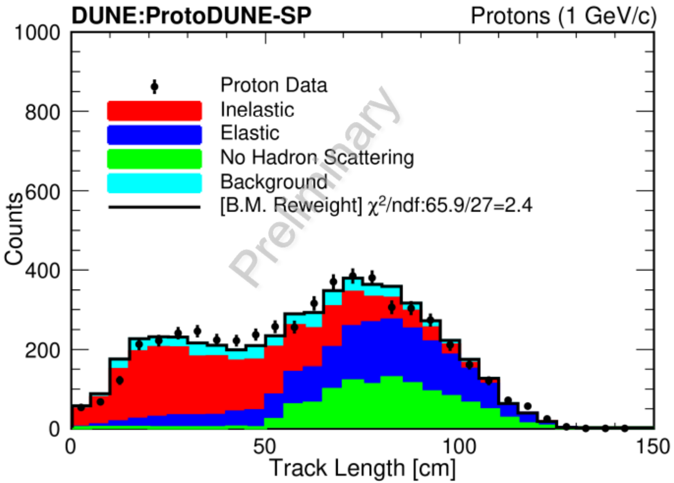
$\sigma \sim$

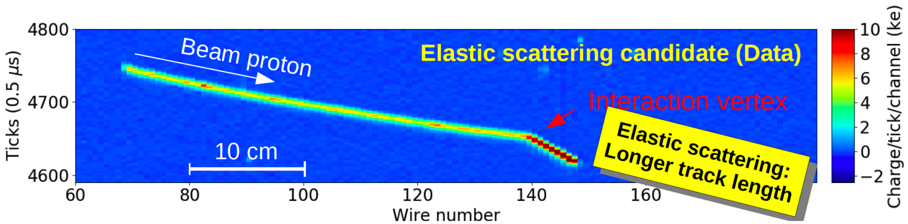


INCLUSIVE PROTON CROSS SECTION

- Provide critical information on hadron scattering and useful in tuning simulations for DUNE
- Track length distribution is sensitive to both elastic scattering and inelastic scattering cross section
- Analysis strategy is finalized
  - Adjust beam momentum using stopping protons
  - Fit track length distribution by scaling p-Ar cross sections
- Future work
  - Evaluation of cross section
  - Evaluation of systematic uncertainties

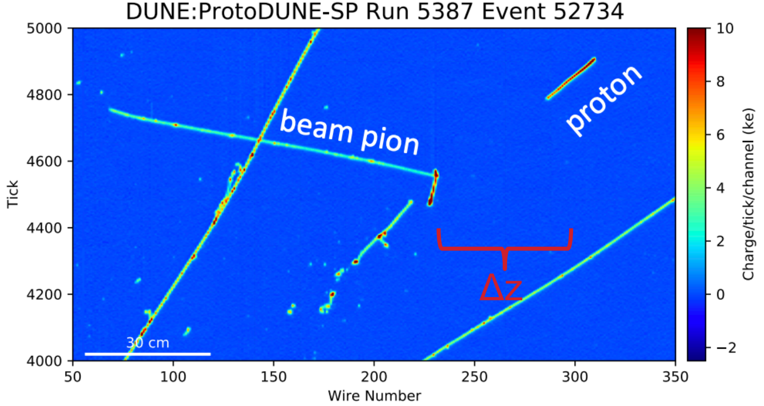


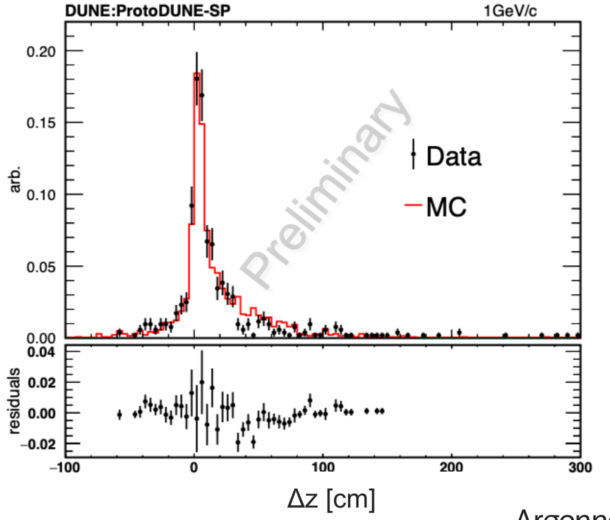




NEUTRON CROSS SECTION

- Neutrons can carry away a significant portion of the energy for an event
  – Understanding of the charged test beam momentum + PID helps to make this measurement possible
- Measure neutron inelastic cross section:
  – $\pi^+ + Ar \rightarrow n \rightarrow p$
- Good data/MC agreement for many variables
- Future work
  – Extract a neutron inelastic cross section
  – Perform systematic uncertainty studies





SUMMARY

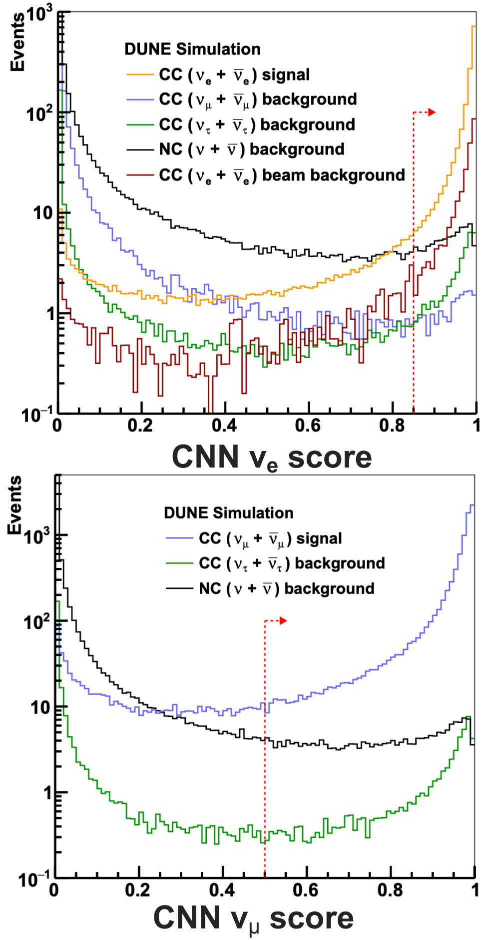
- DUNE will enable high-precision neutrino measurements in the next decade, and an exciting physics program, encompassing:
  - CP violation measurement and neutrino mass ordering determination
  - Studies of neutrinos from a galactic supernova burst, and potentially solar neutrinos
  - Many BSM searches, including sterile neutrinos, baryon number violation, non-standard interactions, etc.
- Excellent progress is being made on demonstrating detector technology and characterizing performance, towards realizing DUNE
  - Technical Design Report for DUNE FD completed in early 2020: Volume I, II, III, IV
  - PIP-II construction ground broken in July 2020
  - Site excavation continues
  - ProtoDUNE successfully operated at CERN with first R&D and physics results published [ref] → moving into phase II

THANK YOU FOR YOUR ATTENTION

BACKUP SLIDES

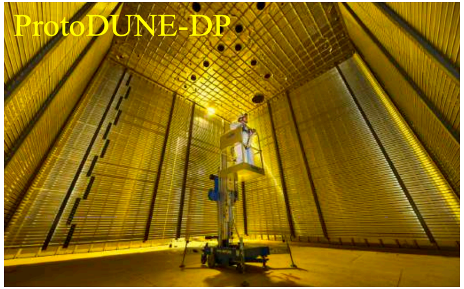
NEUTRINO EVENT RECONSTRUCTION AND SELECTION

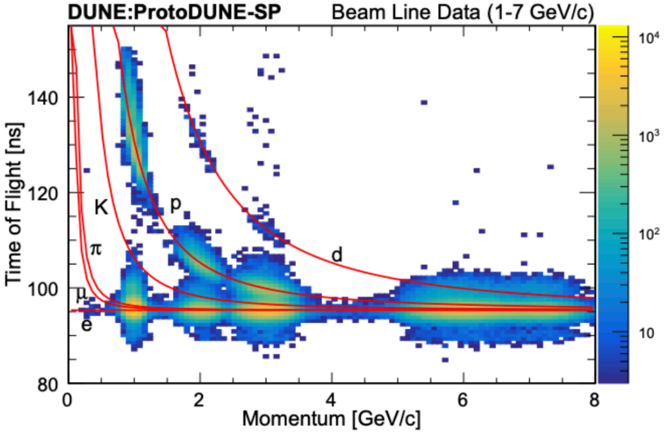
- Perform pattern recognition to reconstruct neutrino events in 3D
- Use convolution neural network (CNN) to classify events
  - Results: 80-90% efficiency for both ν_μ and ν_e selections
- Results published
  - [PRD 102 (2020), 9, 092003]



PROTODUNE SP AND DP AT CERN

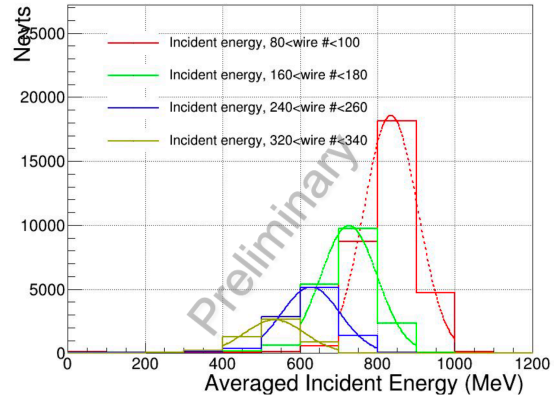
- Single-phase (SP) and dual-phase (DP) DUNE prototype LArTPCs at CERN
- 770 t LAr mass each
- Exposed to H2 (DP) and H4 (SP) test beams at CERN, momentum dependent beam composition contains *e*, $K^{\pm}$, $\mu^{\pm}$,*p* , $\pi^{\pm}$
- Also collect cosmic ray data

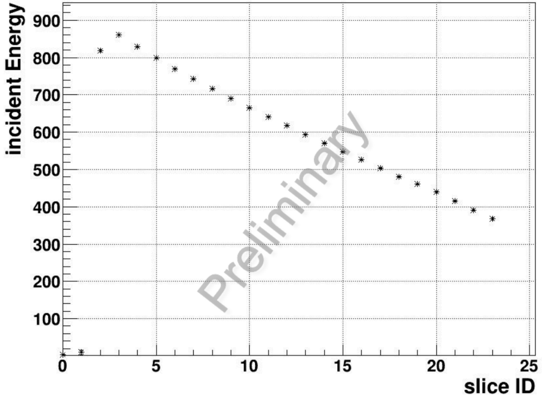


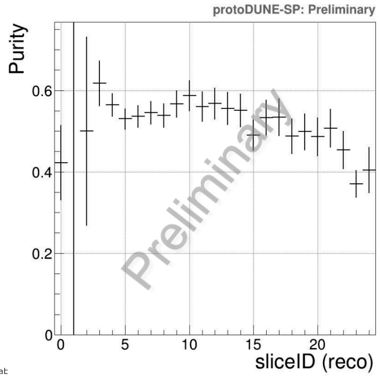


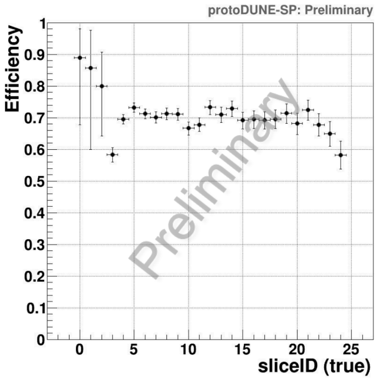
PION ABSORPTION CROSS SECTION

- (Averaged) Incident Energies in each slice are calculated in order to convert the cross sections as a function of slice ID into a function of averaged incident energy.
- Pion kinetic energy in each slice is calculated using calorimetry information: $KE = KE_0 - \sum \frac{dE}{dx} \Delta x$
  - KE_0 is the initial beam energy, dE/dx is the energy loss on each wire

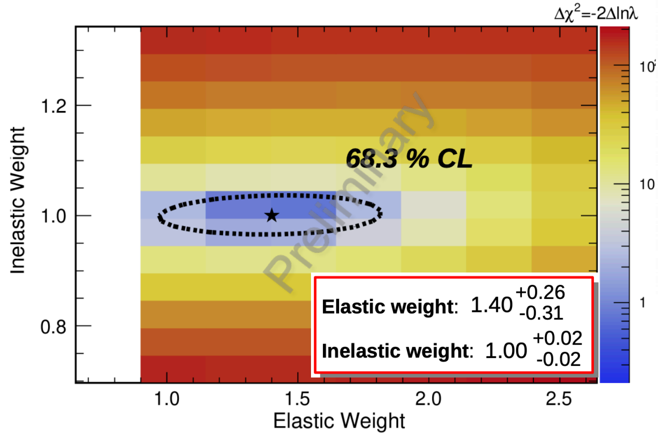








PROTON INCLUSIVE CROSS SECTION



NEUTRON CROSS SECTION

- Efficiency and purity