ProtoDUNE-Single Phase

Prototyping the next generation of neutrino detectors

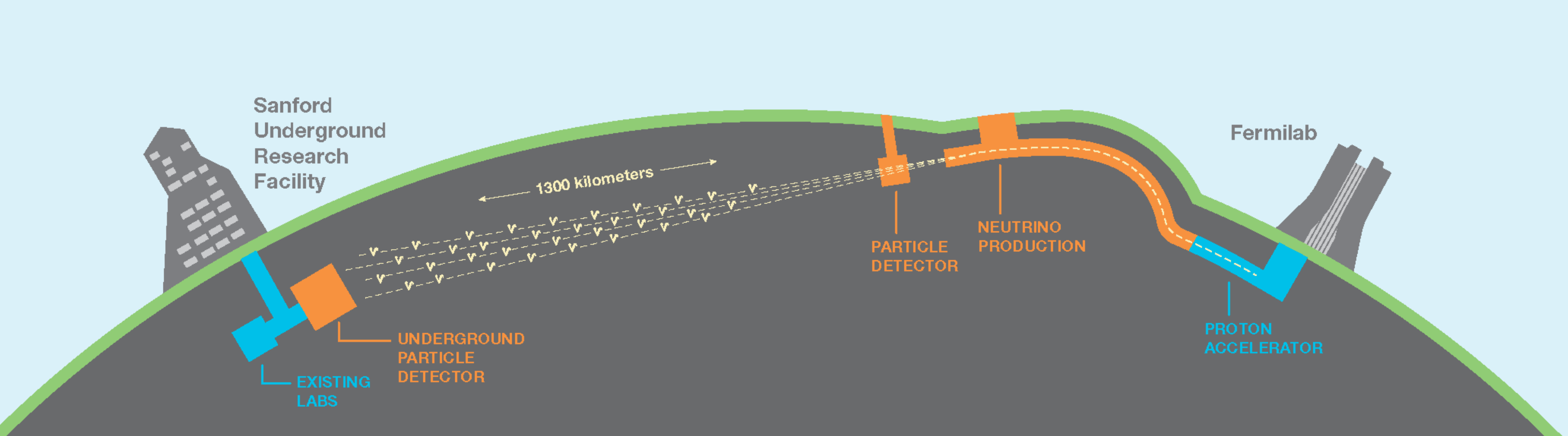
Aidan Reynolds

The DUNE Experiment

The Deep Underground Neutrino Experiment

Future long baseline neutrino oscillation experiment

- Physics goals:
  - Precise measurement of neutrino oscillations from a neutrino beam
  - Measurement of supernova burst neutrinos
  - Proton decay and other BSM physics searches
- Muon neutrino beam
- Far Detector: 4 x 10kt liquid argon TPC’s
- Near Detector: Multi component detector including LArTPC

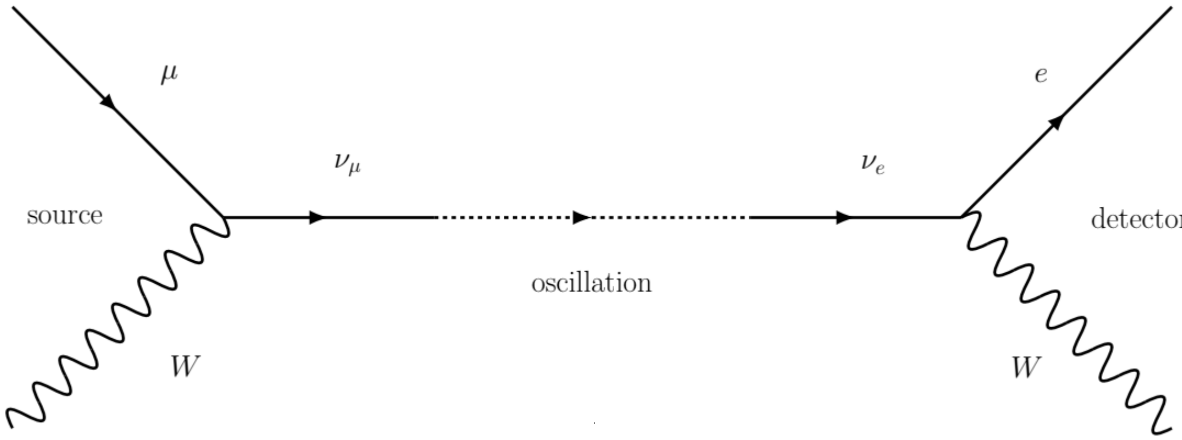


The DUNE Experiment

Physics goals

Neutrino Oscillations

Neutrinos are created in one flavour but detected in another



Flavour states are a superposition of different mass states

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$\mathrm{P}_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

3-flavour Oscillation

3-flavour mixing matrix

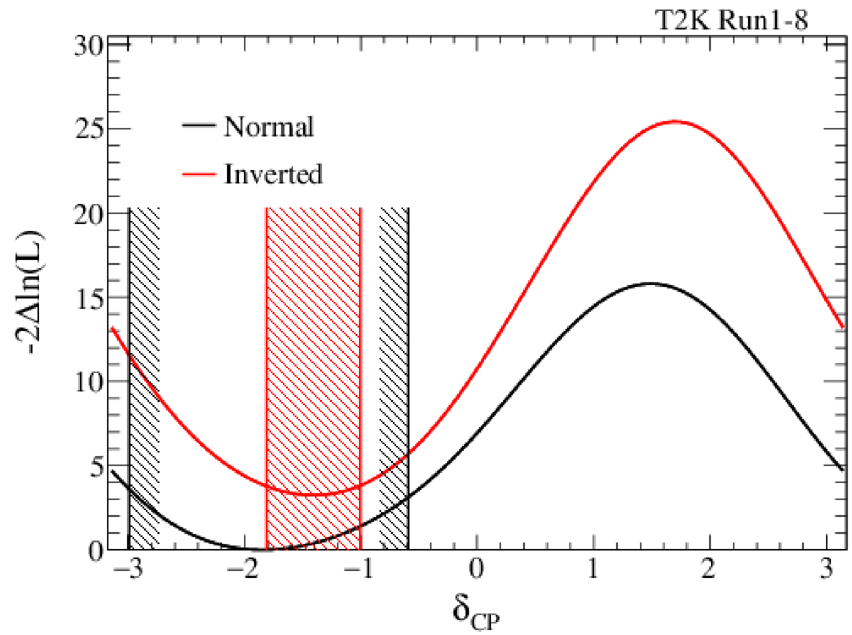
$$
\begin{array}{cccc}
 & \text{Atmos \& Accel} & \text{Reactor} & \text{Solar \& Reactor} \\
 & \text{SK, T2K, Minos, Nova...} & \text{Double Chooz, Daya Bay, Reno,...} & \text{Homestake, SNO, SK, KamLAND,...} \\
\mathrm{U}_{PMNS} = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}
\end{array}
$$

CP violating phase

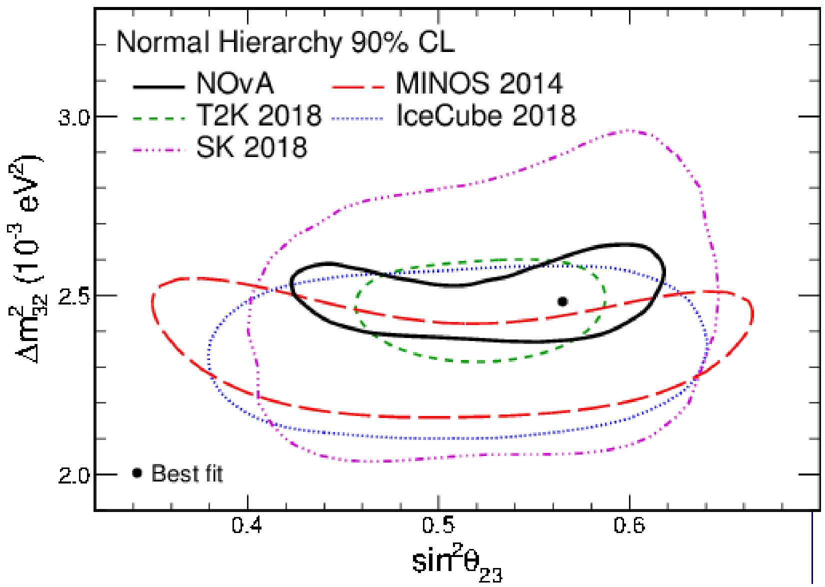
Oscillation depends on

- Mixing matrix
  - θ_{12}, θ_{13}, θ_{23}
  - δ_{CP}
- Mass Differences
  - Δm^2_{32}, Δm^2_{21}

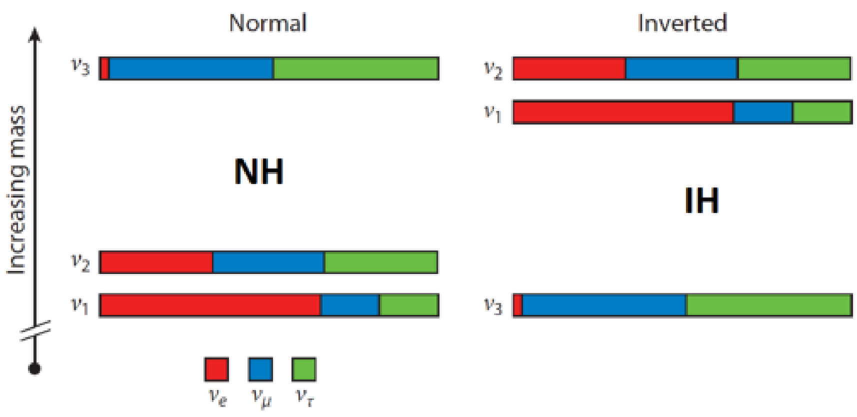
Neutrino Oscillations
Open Questions and Current Status



T2K: arXiv:1807.07891



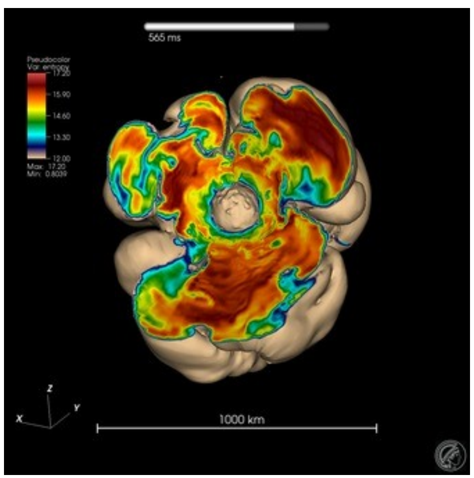
NOvA: arXiv:1906.04907

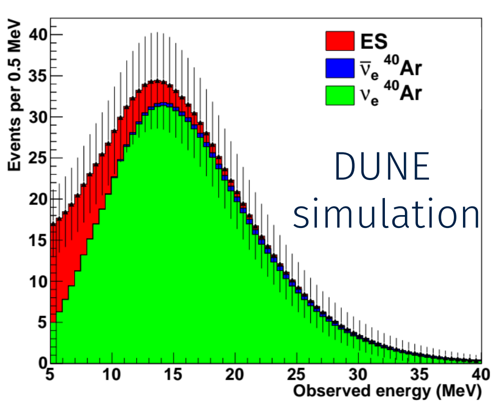


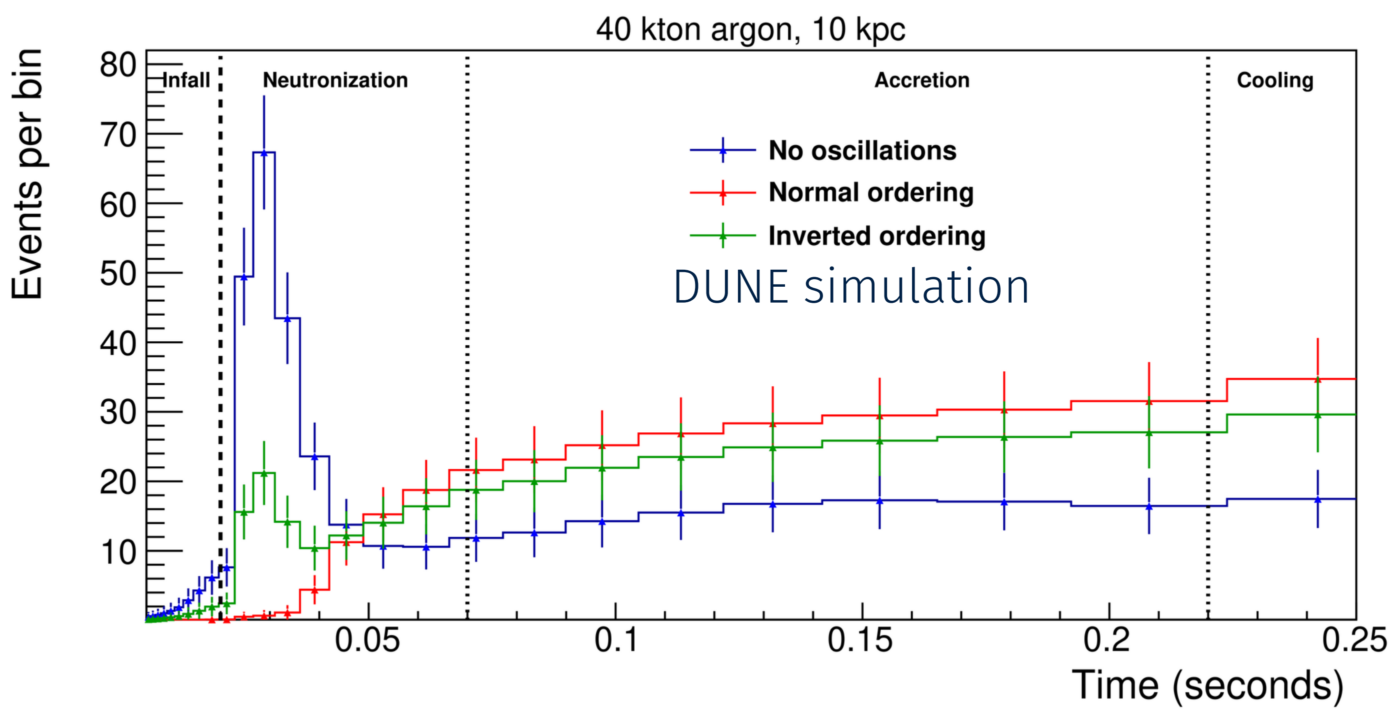
- CP violation
- Octant
- Mass hierarchy

Supernova Neutrinos

- Neutrinos can offer unique insights into the mechanics of supernova bursts
  - Only a few core collapse supernovae per century in the milky way
- Liquid argon is particularly sensitive to the ν_e signal (complementary to water cerenkov)
  - ~3,000 events over a period of 10s for a 10kpc supernova
- The energy and time structure of the neutrino signal gives information about the core collapse mechanism and neutrino properties





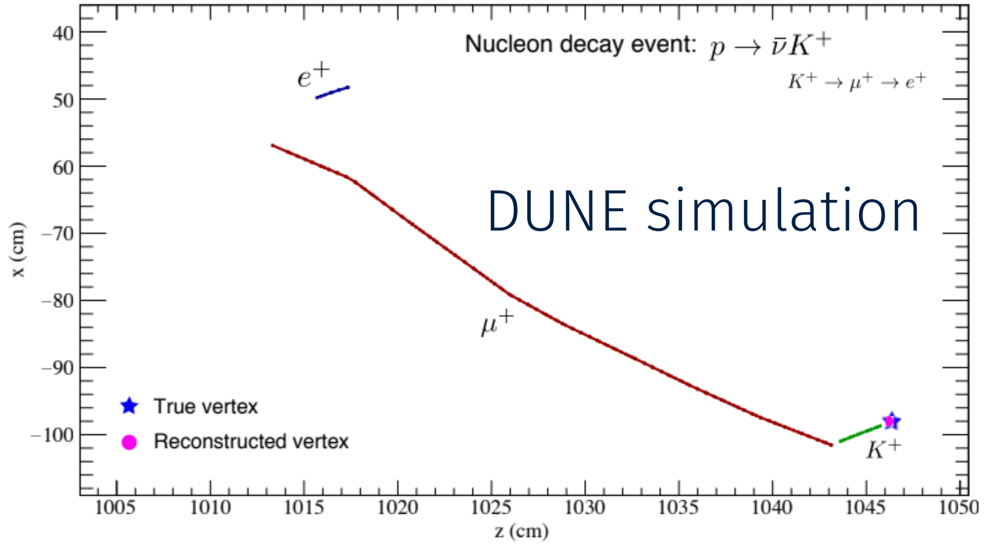


Beyond Standard Model Physics

- Baryon number violation in the far detector
  - Predicted in many BSM theories
  - Particularly sensitive to certain channels ($p \rightarrow K\nu$)
  - $\Delta(B\text{-}L) \neq 0$ channels ($n\bar{n}$ oscillations)

- Non-standard oscillation phenomena
  - Sterile neutrinos, non-standard interactions, non-unitarity, CPT violation

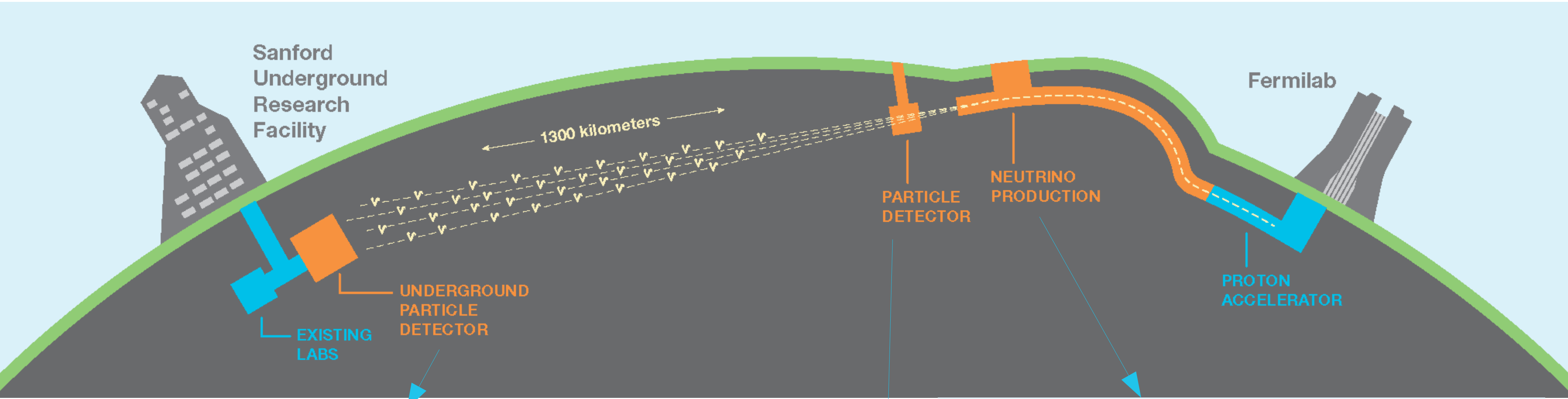
- New phenomena at the near detector
  - Trident interactions, heavy neutral leptons, low mass dark matter

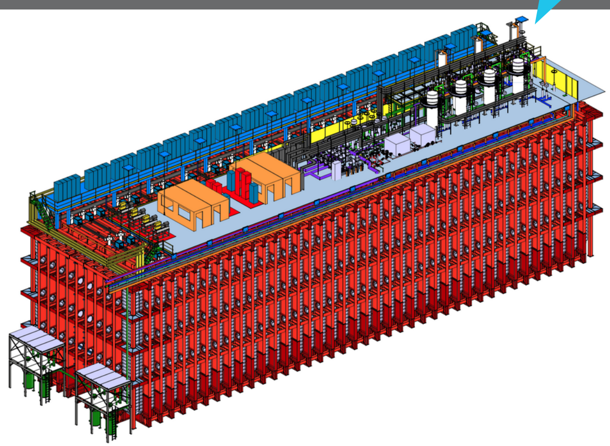


The DUNE Experiment

The Detectors

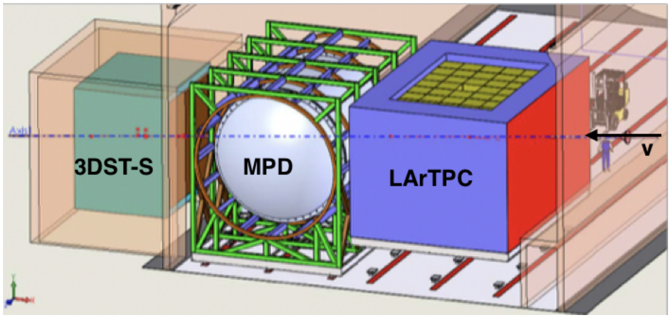
Multi-detector Oscillation Experiment

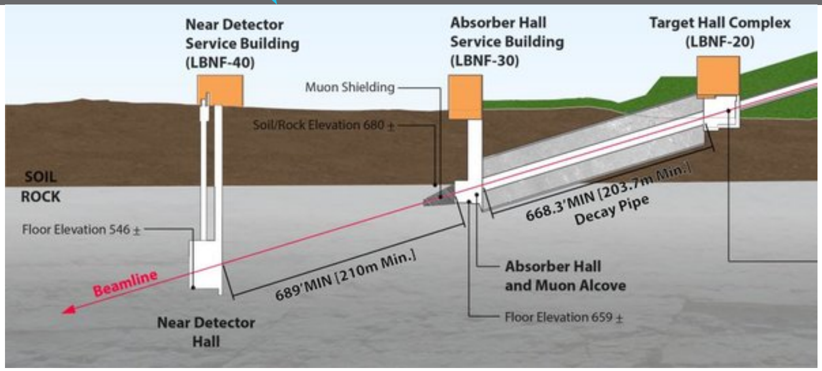




Far Detector

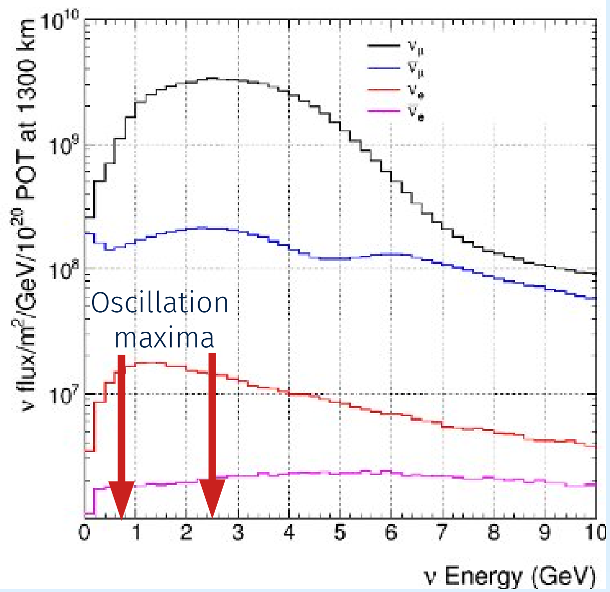
Near Detector





Neutrino Beam (LBNF)

The Long Baseline Neutrino Facility



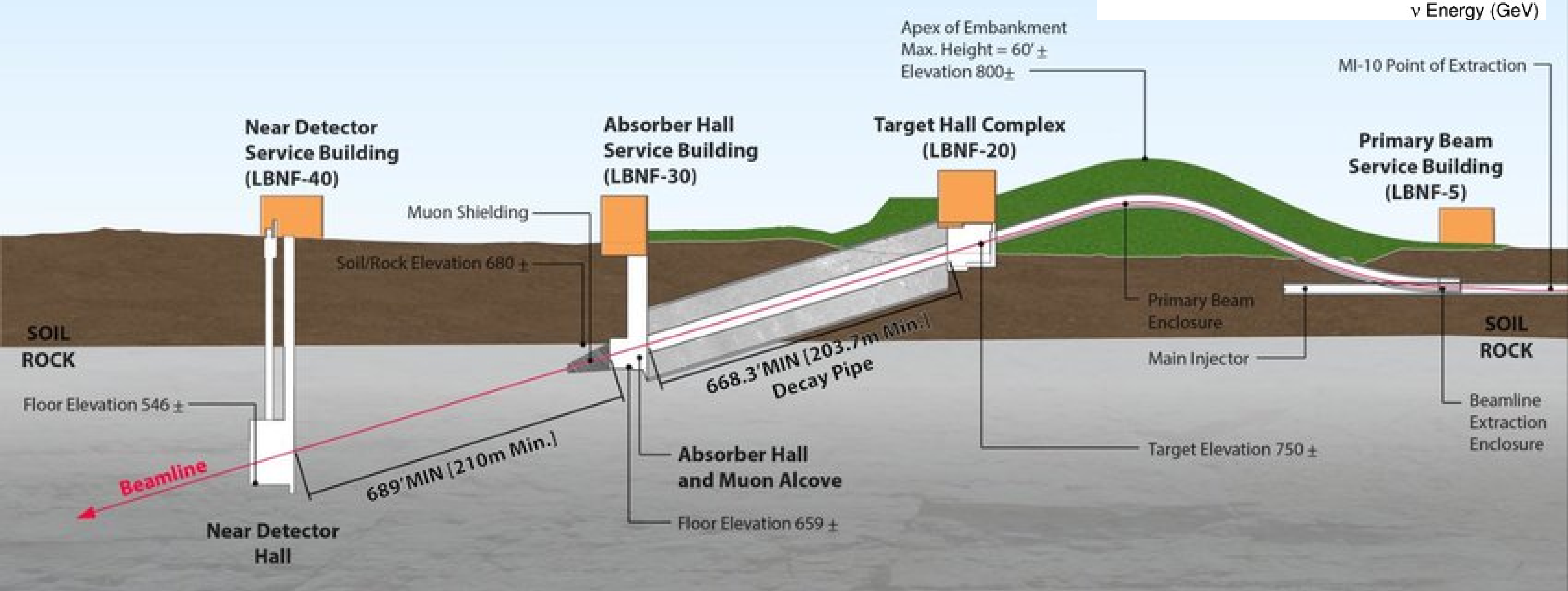
Protons (60-120 GeV) provided by Fermilab's main injector

- It will be the most powerful neutrino beam ever constructed

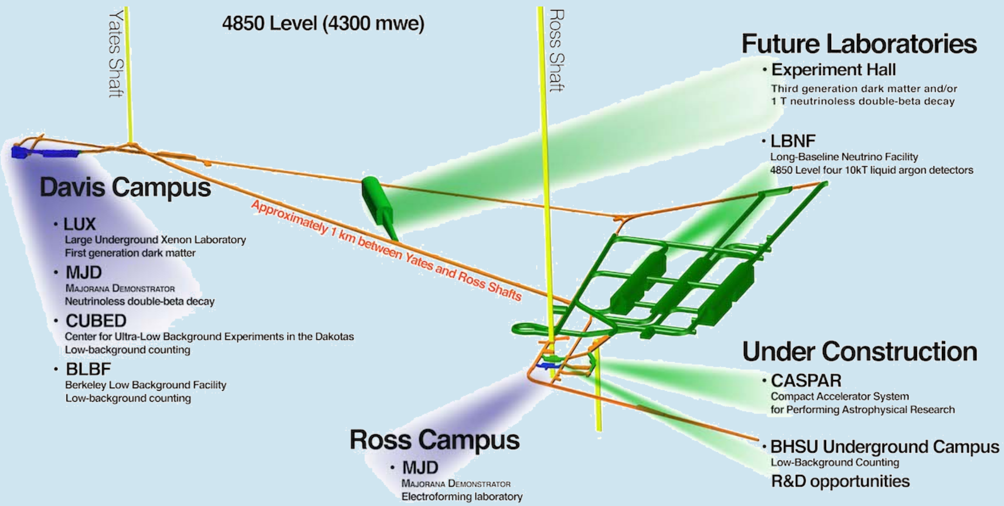
It will run in both neutrino and anti-neutrino modes by switching the polarity of the focussing horns

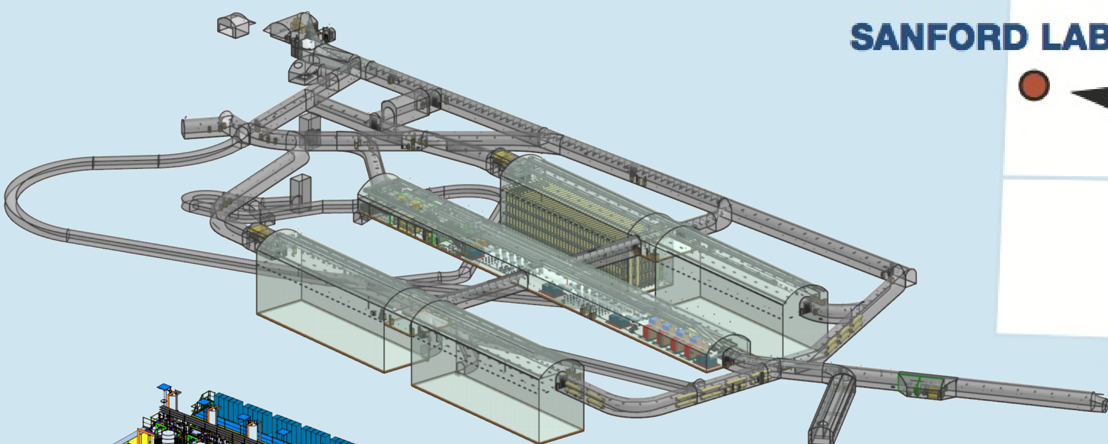
Wide band beam incorporates both the first and second oscillation maxima

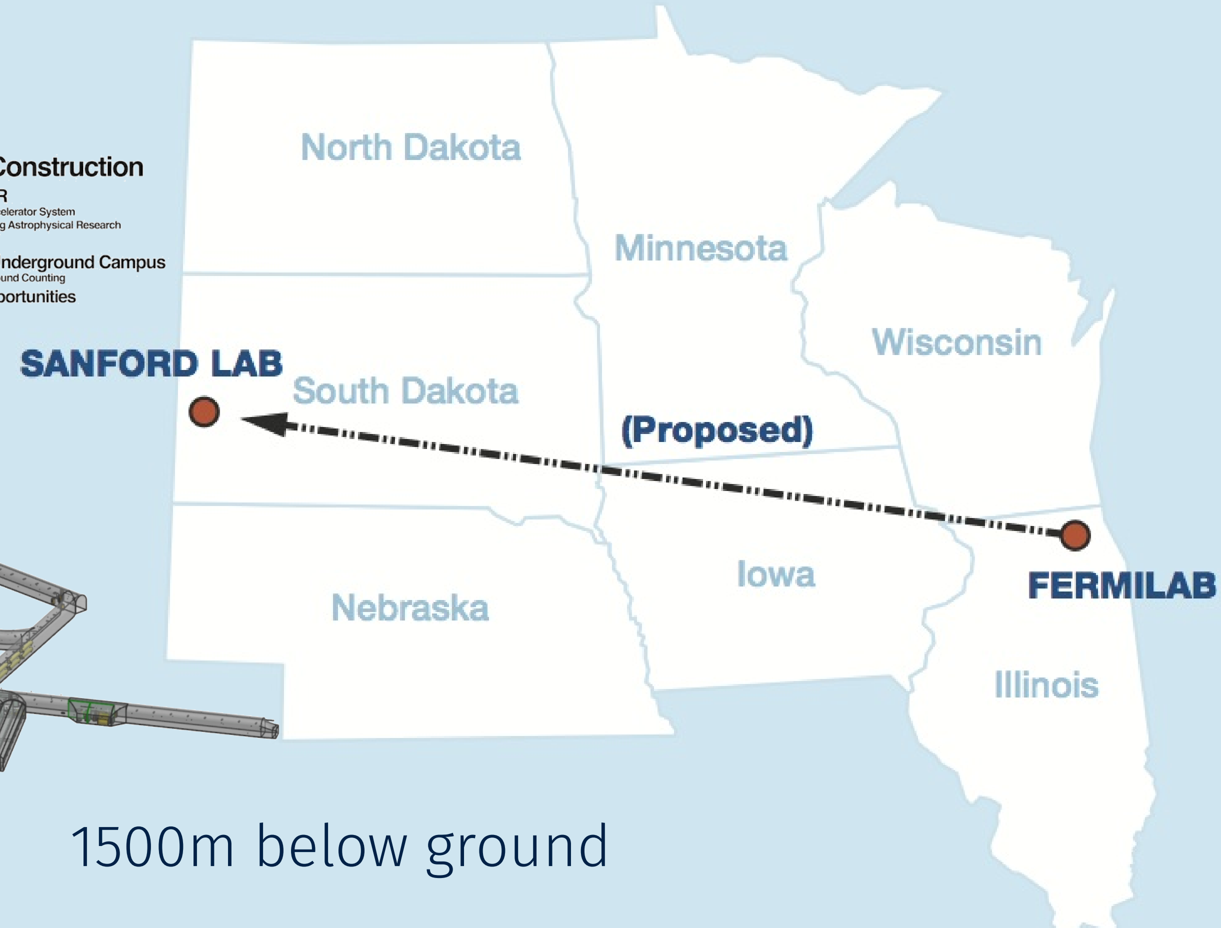
- Enhances both oscillation and BSM physics potential

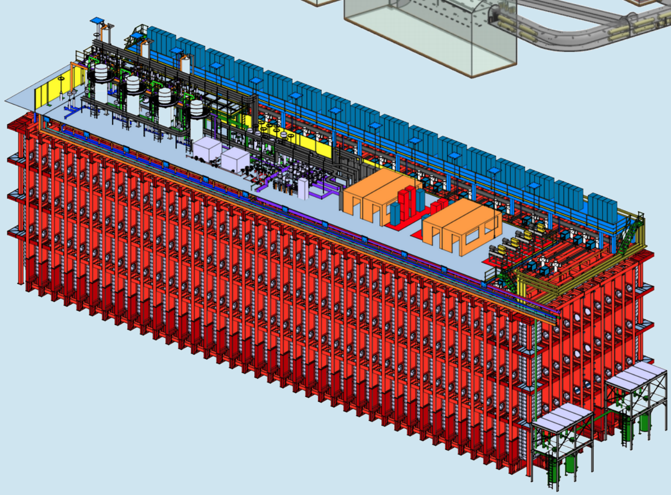


The Far Detector





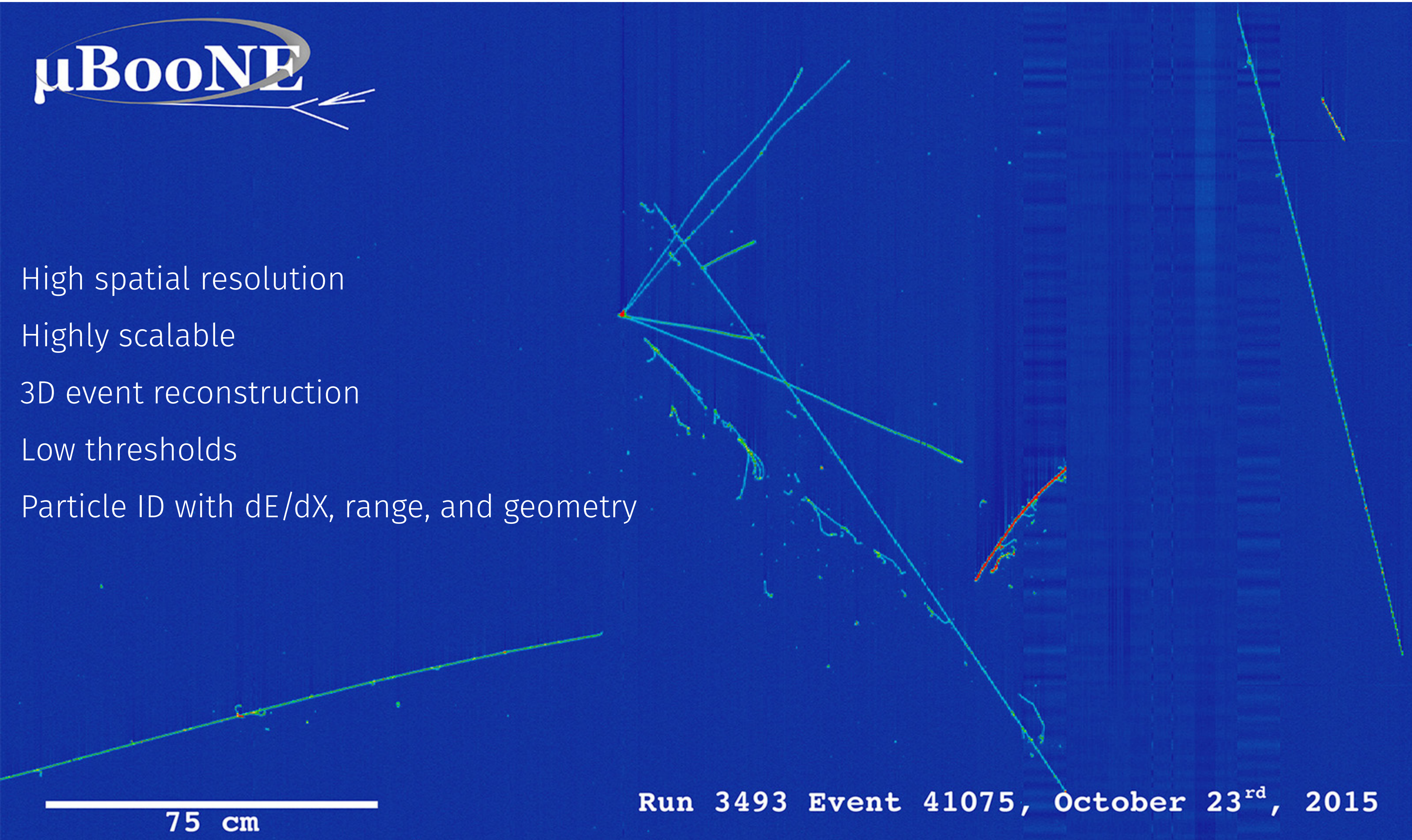




1500m below ground

Modular design
- 4 x 10KT active volume LArTPC's
- Single and dual phase options

Far Detector: Liquid Argon TPC (LArTPC)



- High spatial resolution
- Highly scalable
- 3D event reconstruction
- Low thresholds
- Particle ID with dE/dX, range, and geometry

The Near Detector

The near detector is essential to control uncertainties in the oscillation analysis by making precise flux and cross section measurements

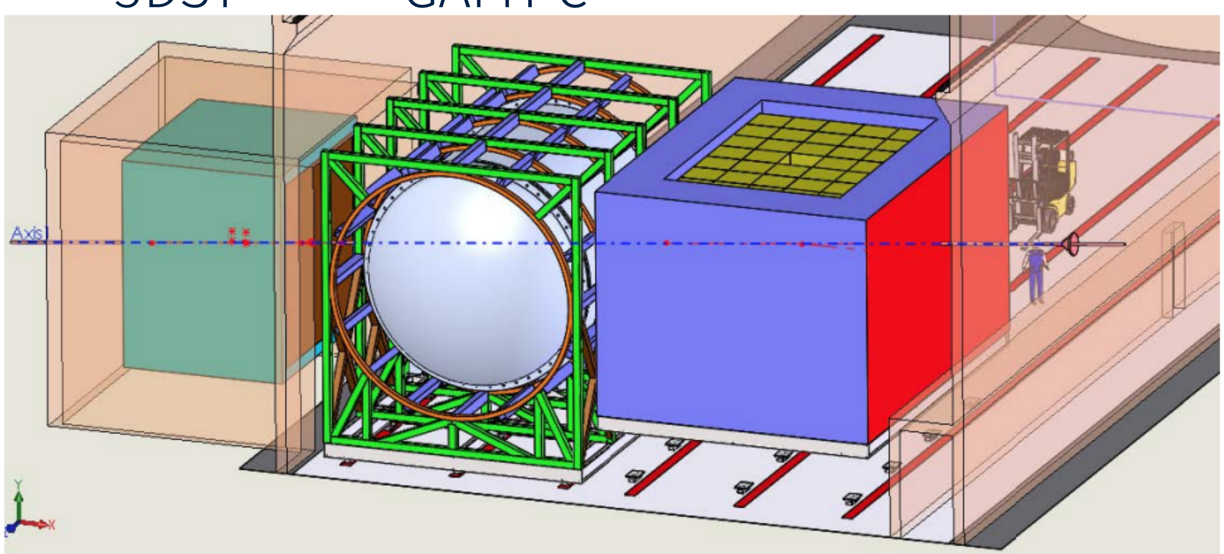
The conceptual design includes 3 detectors

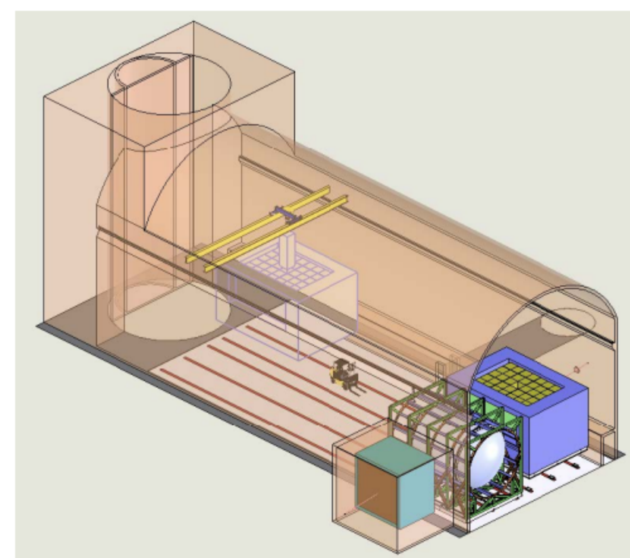
- A LArTPC with pixelated readout
- A high presure gas argon TPC in a magnetic field
- A 3D scintillator tracker in a magnetic field

In addition the design allows for data taking at varying off axis angles

- Variable neutrino flux to help deconvolving flux and cross section

3DST GArTPC LArTPC

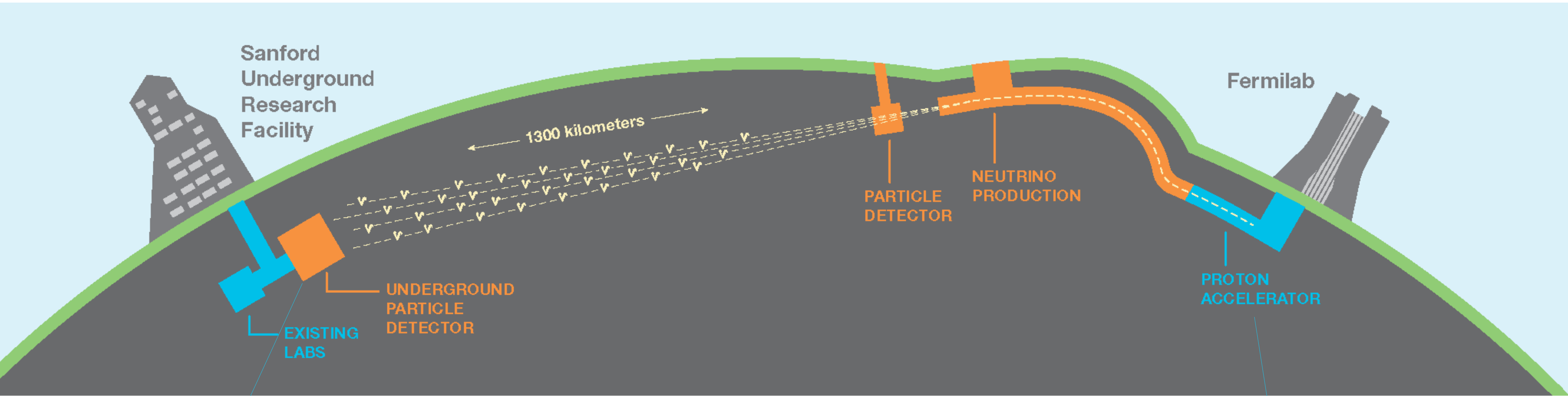


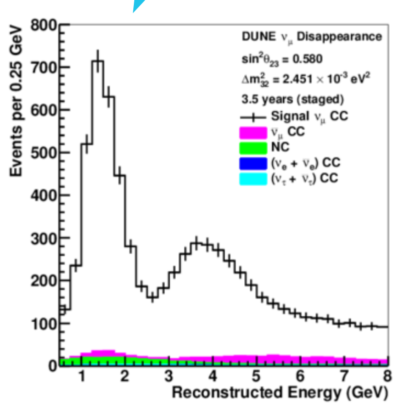


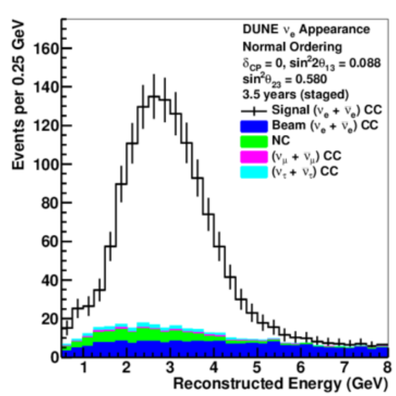
The DUNE Experiment

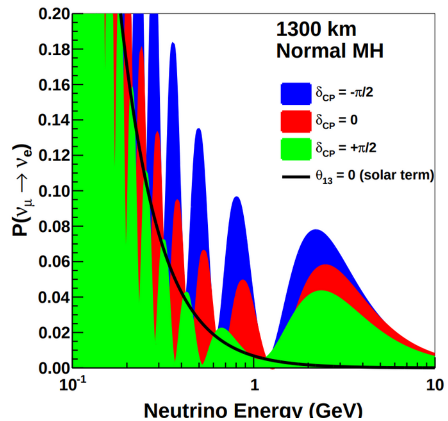
Sensitivity

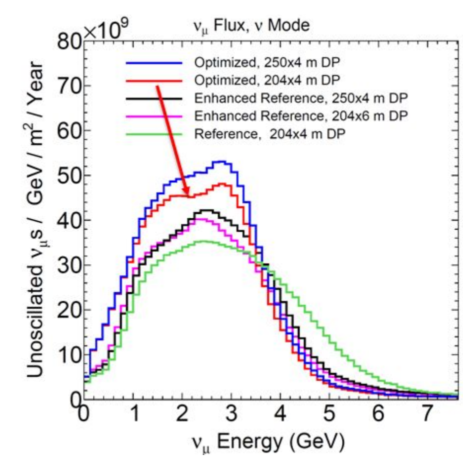
The Oscillation Measurement



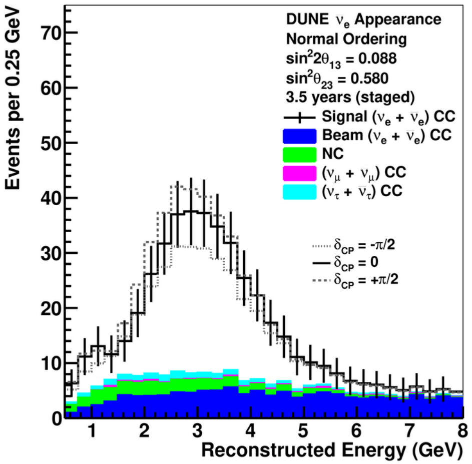


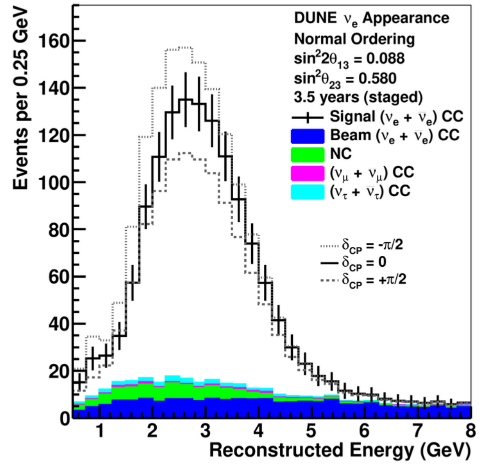






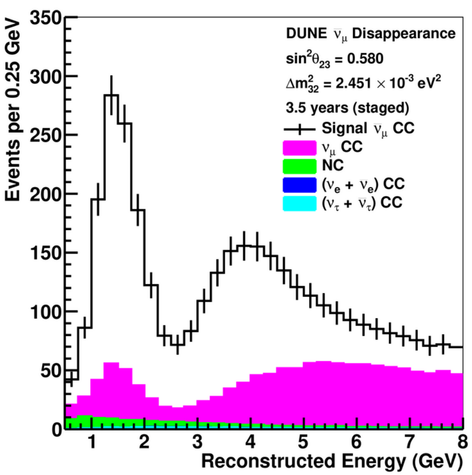
Analysis Strategy

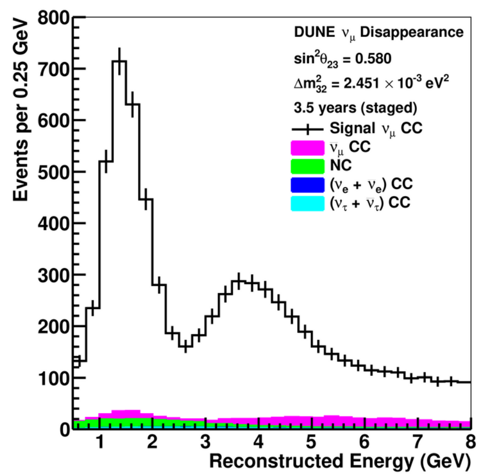




~1,000 ν_e / $\bar{\nu}_e$ appearance events in 7 years (NO)

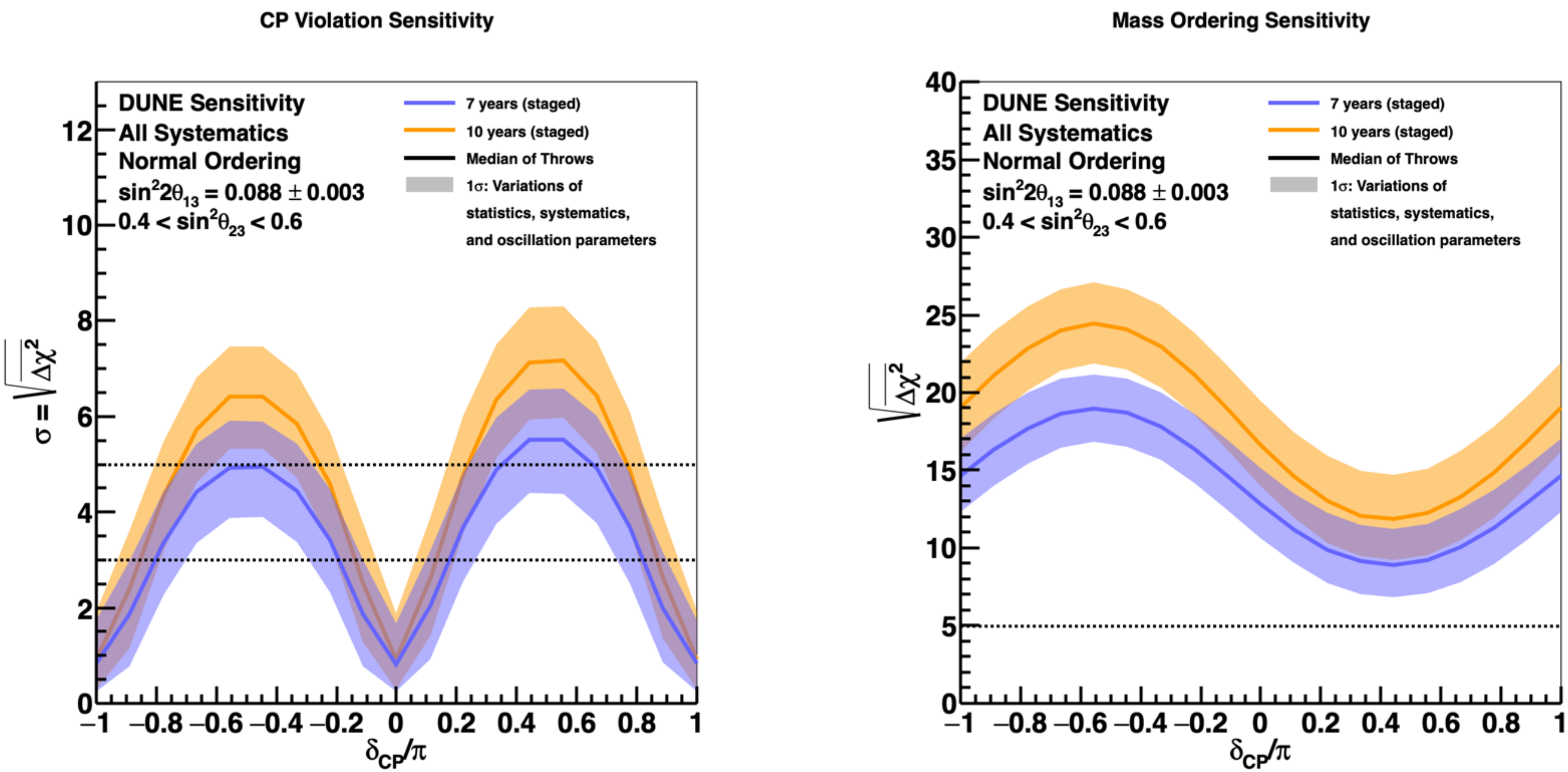
ND Constraints → Global Fit → Oscillation Parameters





~10,000 ν_μ / $\bar{\nu}_\mu$ events

CPV and Mass Ordering Sensitivity



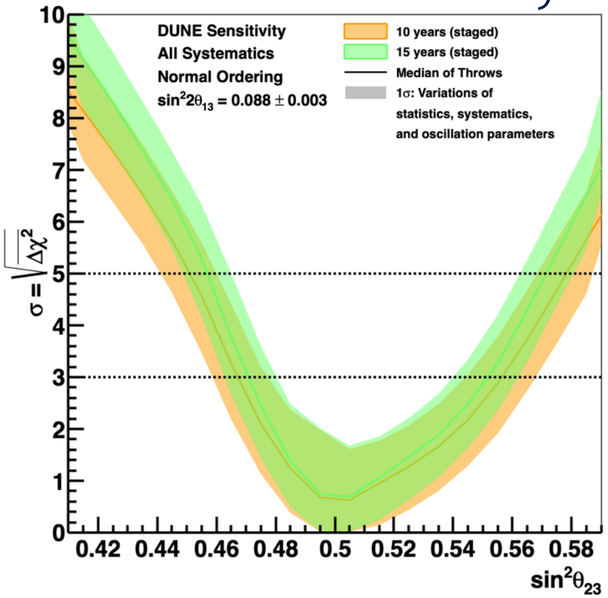
Updated sensitivities with realistic systematics and reconstruction

- 50% of CP values covered to 5σ within 10 years for NO
- Mass ordering determined to 5σ within 2-3 years for all CP values

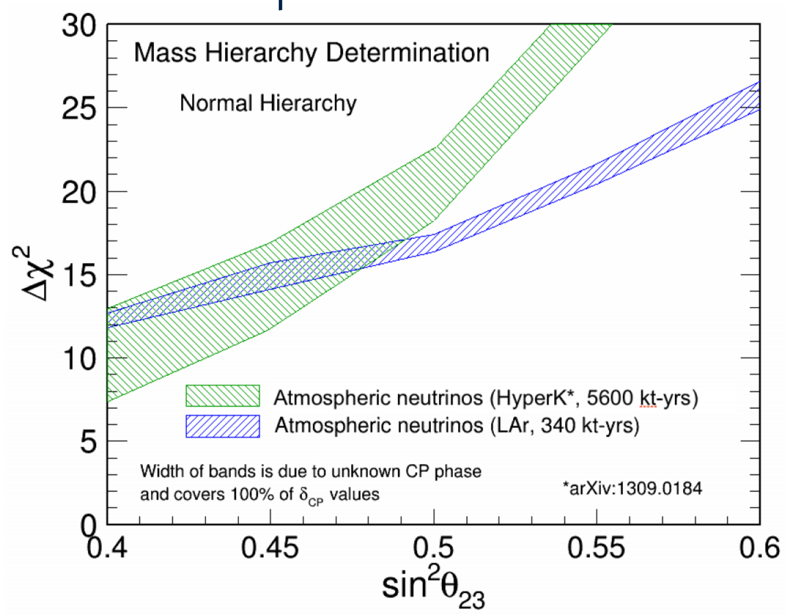
For detailed discussion of analysis see the DUNE TDR (published soon)

Other Physics

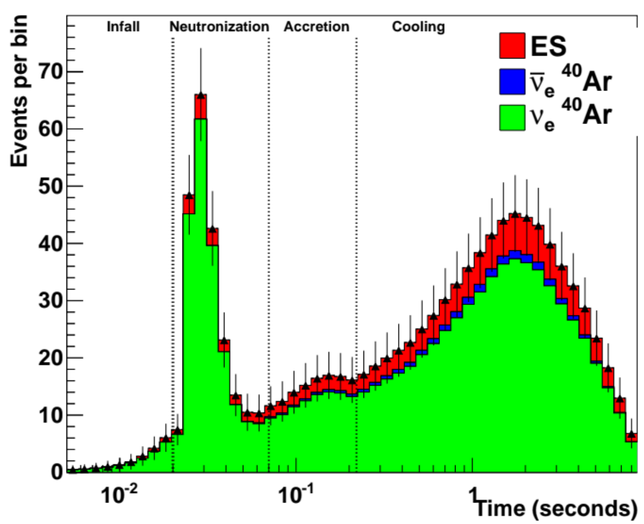
Octant Sensitivity



Atmospheric Neutrinos



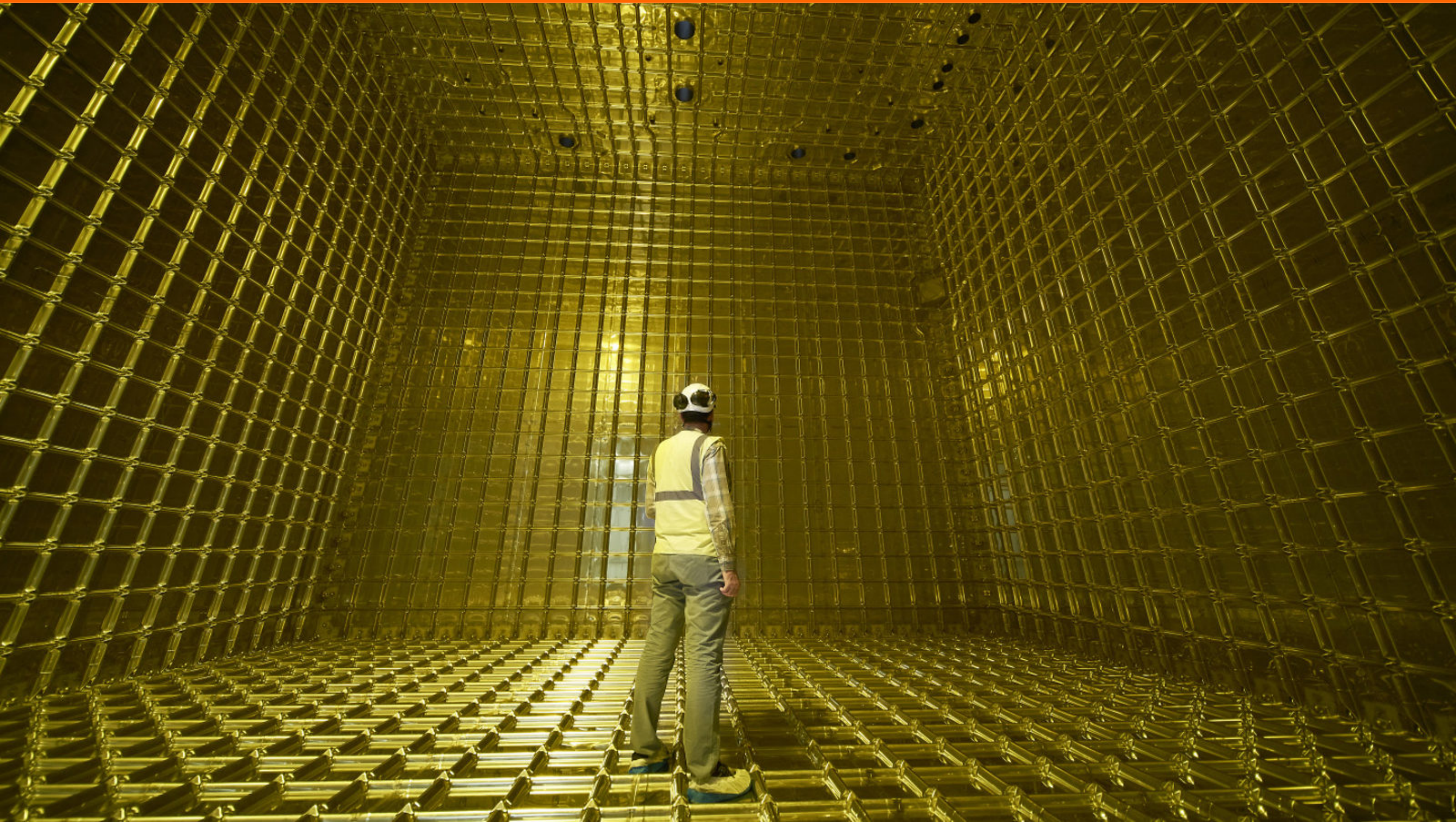
Supernova Neutrinos



- Proton Decay
- Neutrino cross sections
- BSM physics
- …

ProtoDUNE-SP

What is ProtoDUNE-SP?



ProtoDUNE-SP: ~1kt LArTPC at CERN

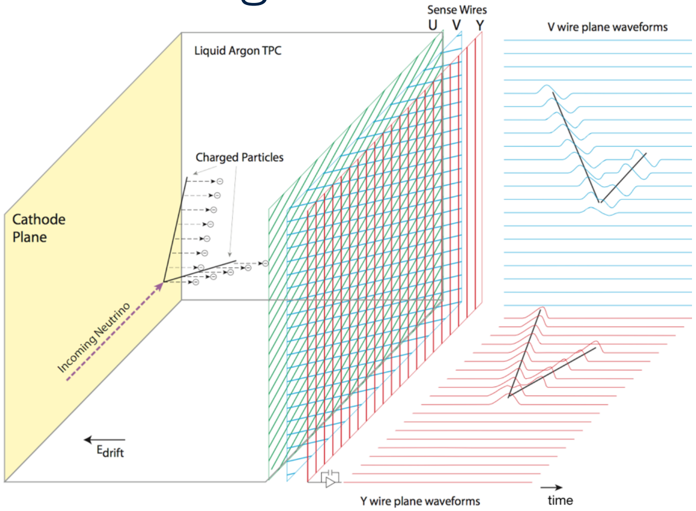
One of two prototypes for the DUNE far detector

The Far Detector TPC's

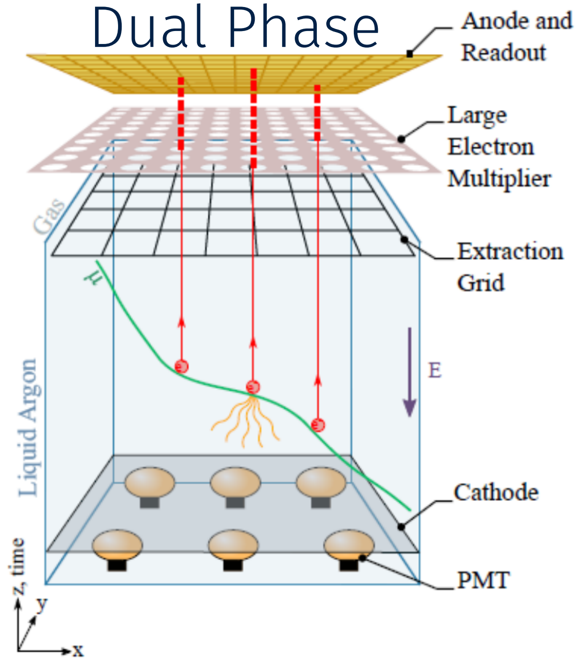
4 TPC's will make up the far detector

- 17.5kt LAr (10kt active) each
- Staged construction starting in 2021
  - 2 modules + beam by 2026
- Multiple readout technologies considered
  - Single phase
  - Dual phase
  - "Module of Opportunity"

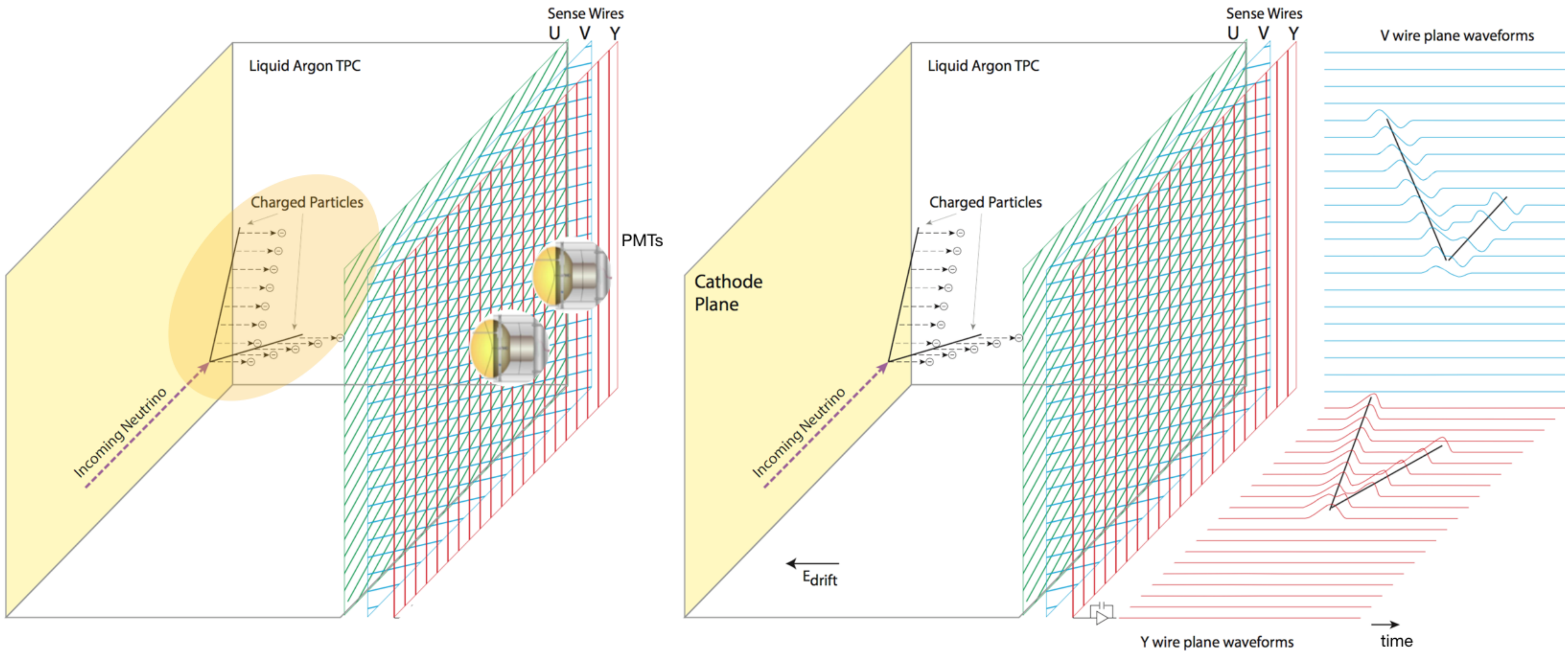
Single Phase



Dual Phase



Far Detector: Liquid Argon TPC (LArTPC)



ProtoDUNE-SP Goals

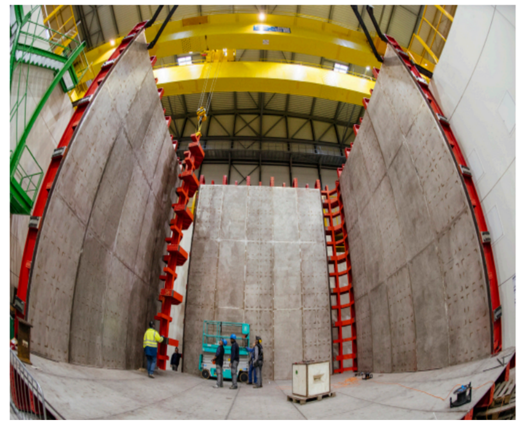
- Prototyping the production, installation and operation of the DUNE far detector
- Validate detector design in terms of basic detector performance
- Measure test beam data to understand/calibrate the detector response to different particle species
- Demonstrate long term operational stability

ProtoDUNE-SP

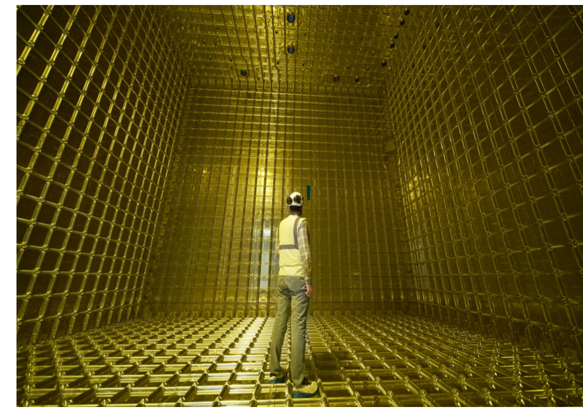
The Detector

The Journey

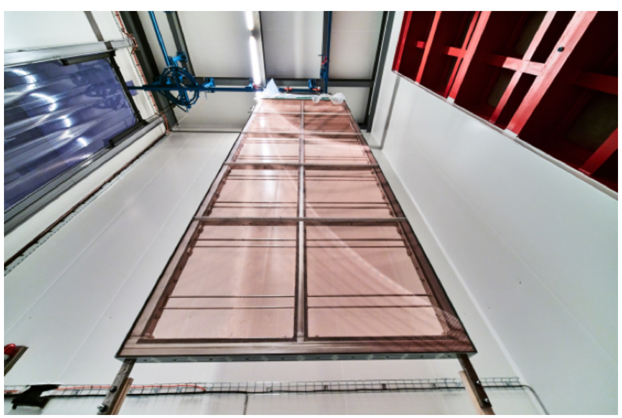
March 2016
EHN1 Extension



November 2016
Start Cryostat Assembly

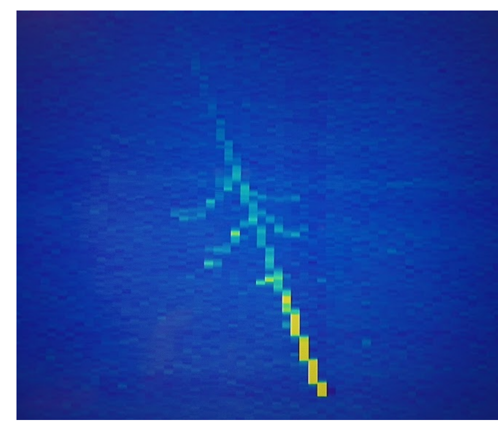


September 2017
Cryostat Completed



February 2018
Detector Assembly

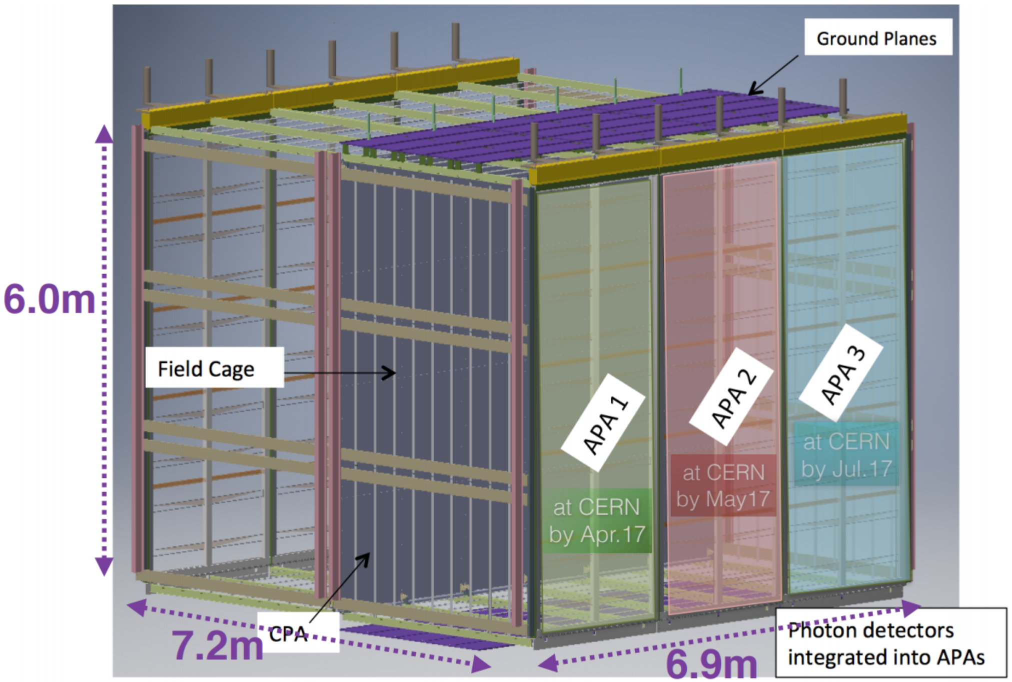
August 2018
Argon Filling

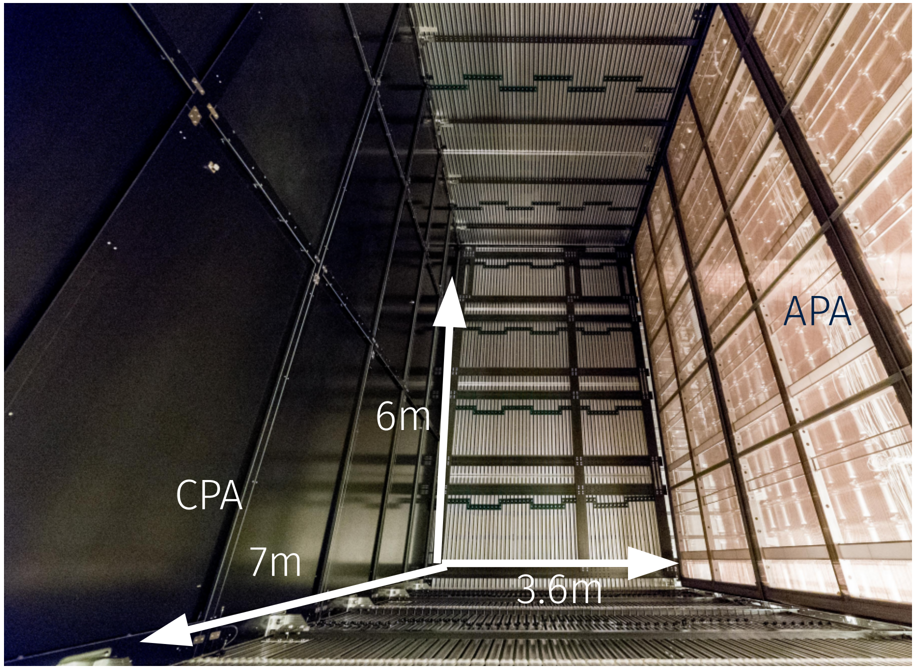


September 2018
First Tracks at 180kV
Ready for Beam

The TPC

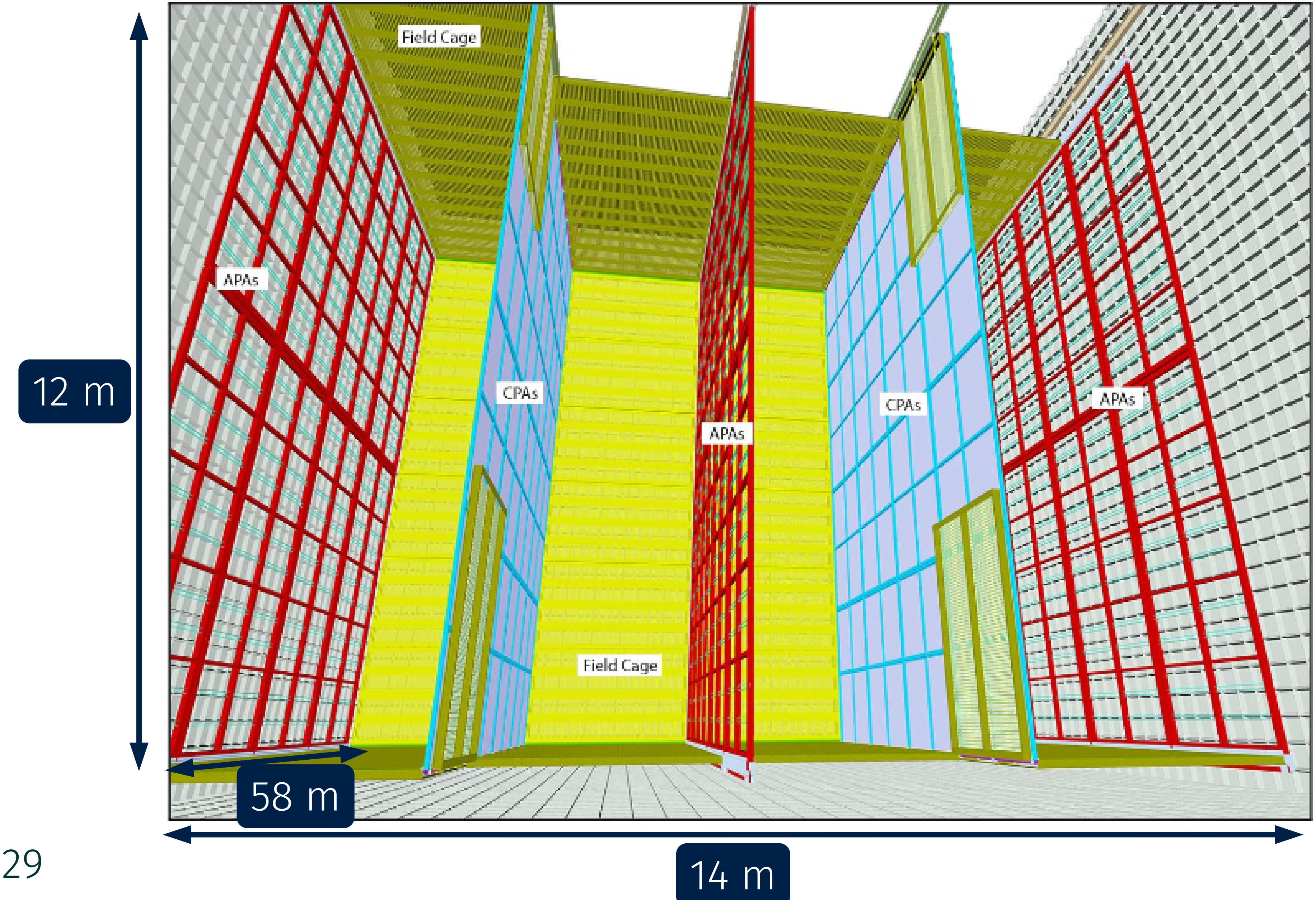
- Two 3.6m drift volumes
- 6 APA's (Modular far detector components)
- 0.42kt active volume
- 180kV high voltage, giving 500V/cm drift field





The worlds largest LArTPC

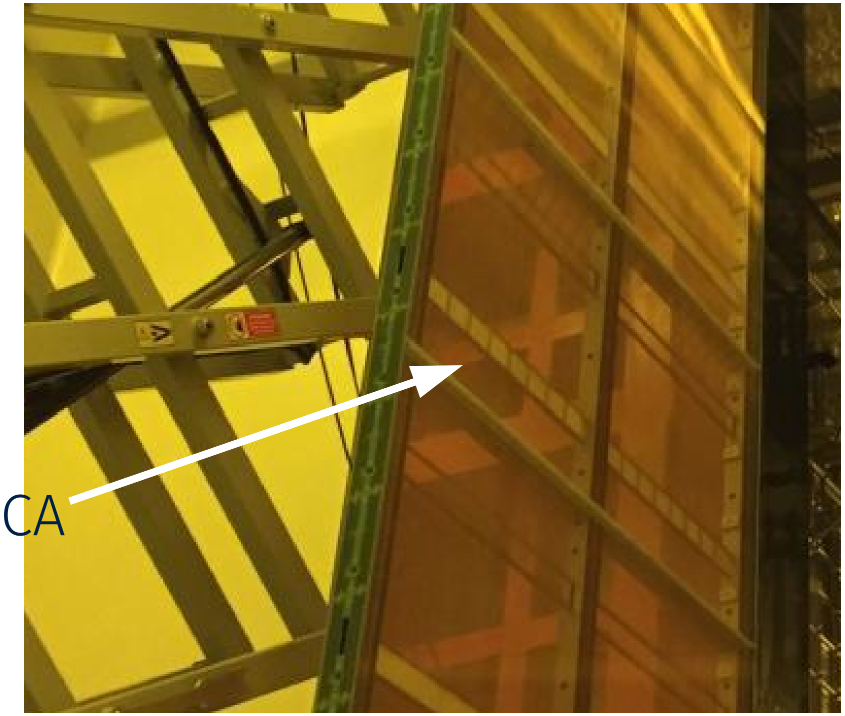
Far Detector: Liquid Argon TPC

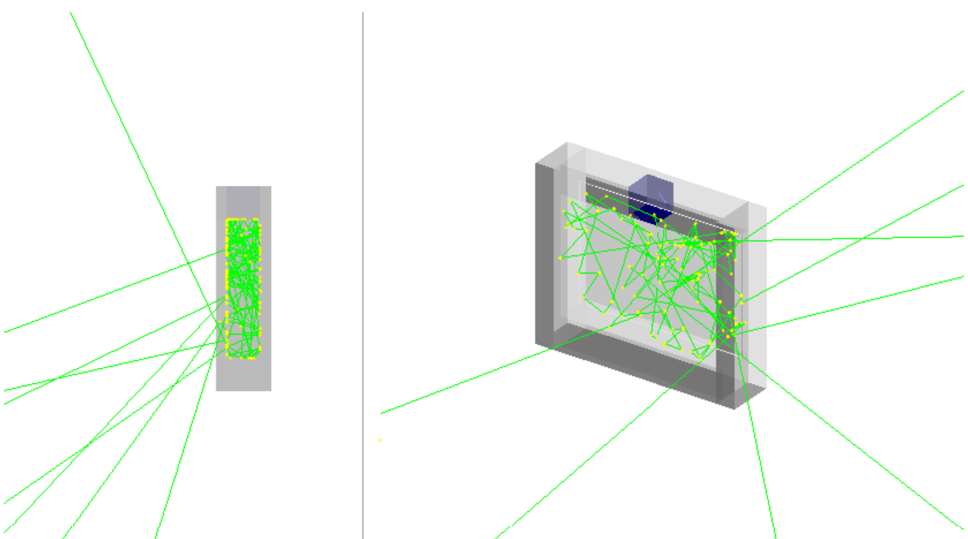


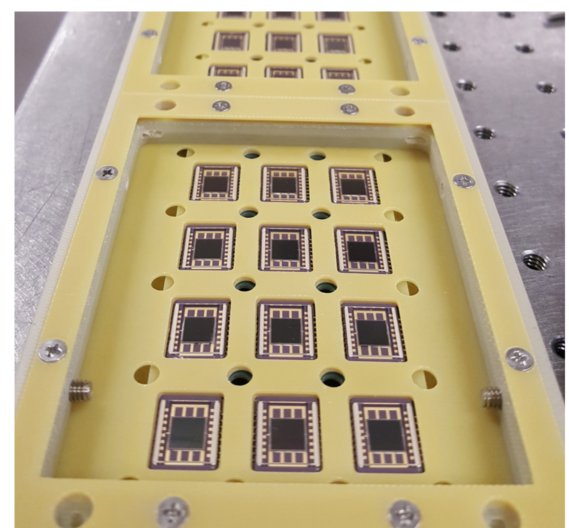
Photon Detectors

Photon detectors are integrated into the APA’s

- Wavelength shifting bars with SiPM’s
  - 60 bars in total
- 3 detector technologies
  - ARAPUCA light trap
  - Double shift light guide
  - Dip coated light guide



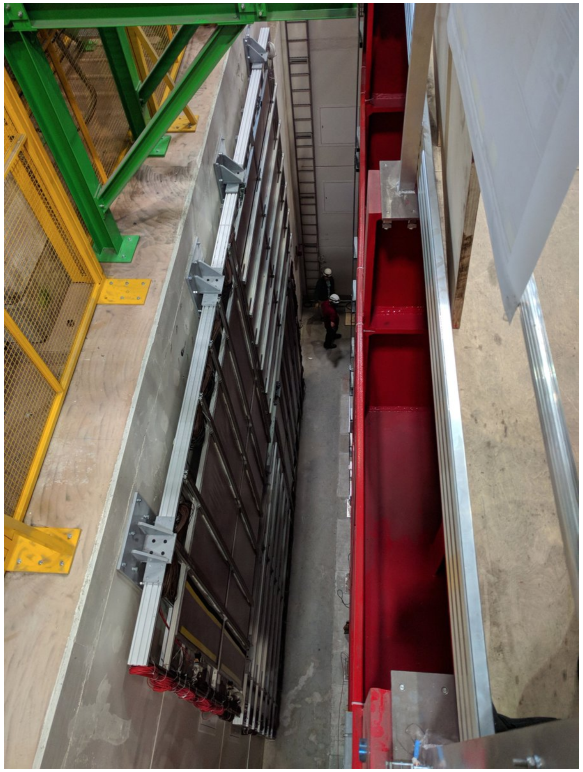




Other Systems

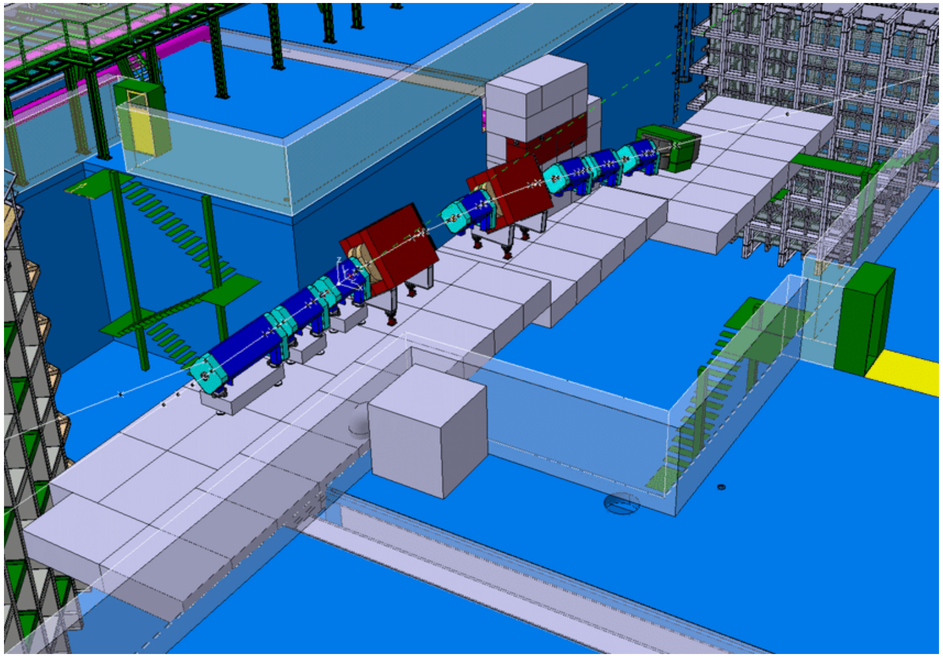
Cosmic Ray Tagger

- Upstream and down stream scintillator panels
- Provide “t0” to cosmic muons
- Trigger
- Space charge constraint



H4 Beamline

- Tertiary low energy beamline from SPS at CERN
- Provides a range of particles at 1-7GeV
- TOF and Cerenkov for PID



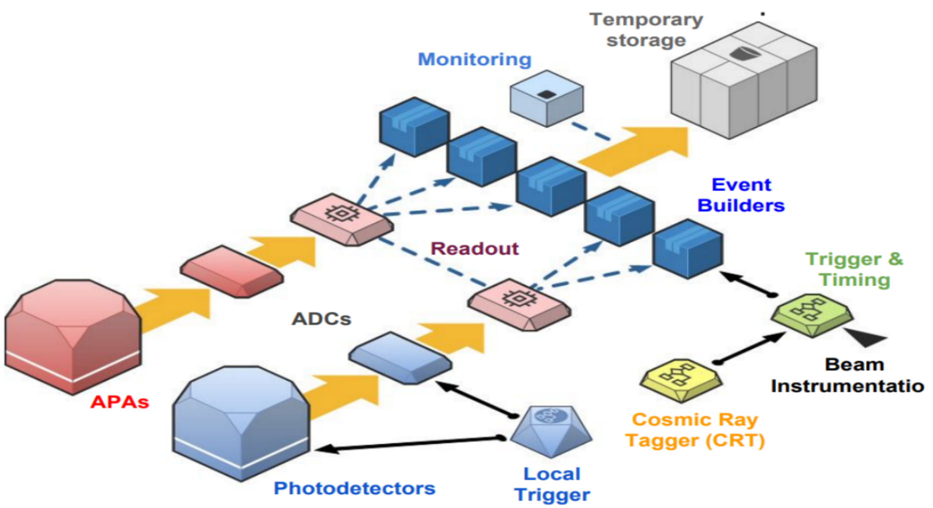
DAQ and Monitoring

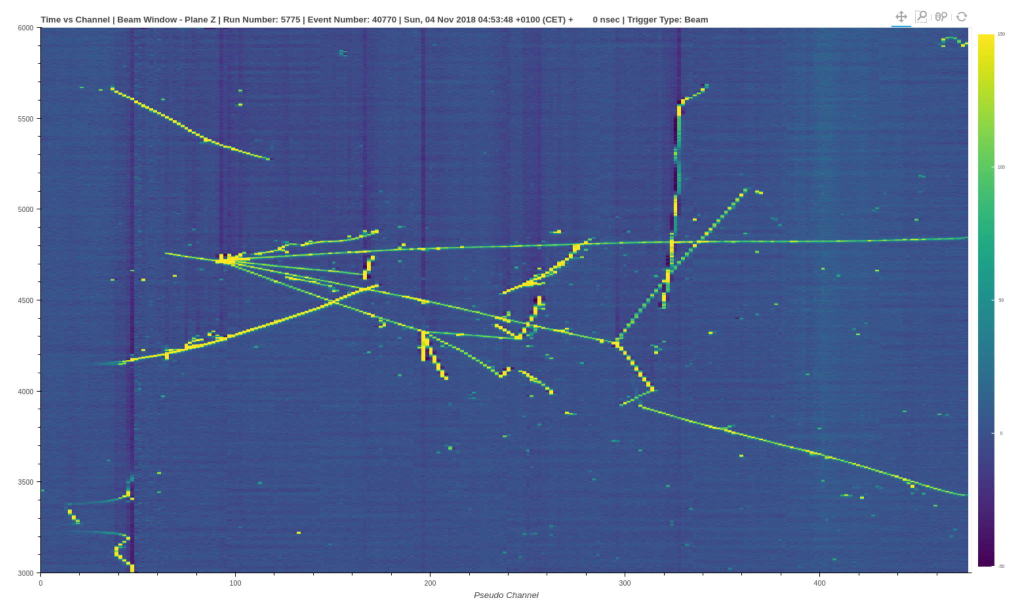
Full readout of around 450Gbit/s

- 20Gbit/s to disk

Readout system is able to successfully sustain full readout and up to 60Hz x 3ms triggered output

Live data quality monitoring for all detector subsystems

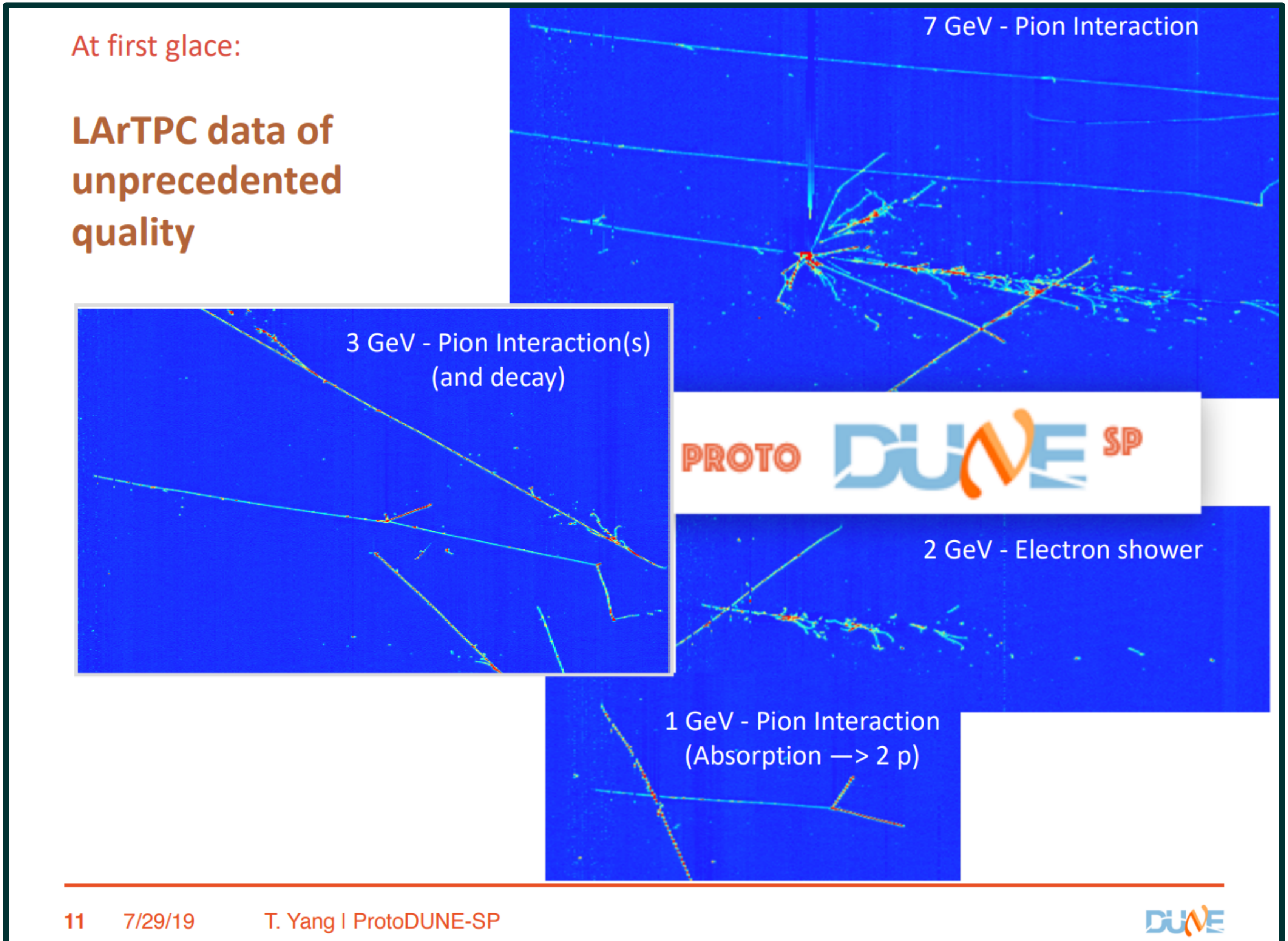




ProtoDUNE-SP

The Data

Events



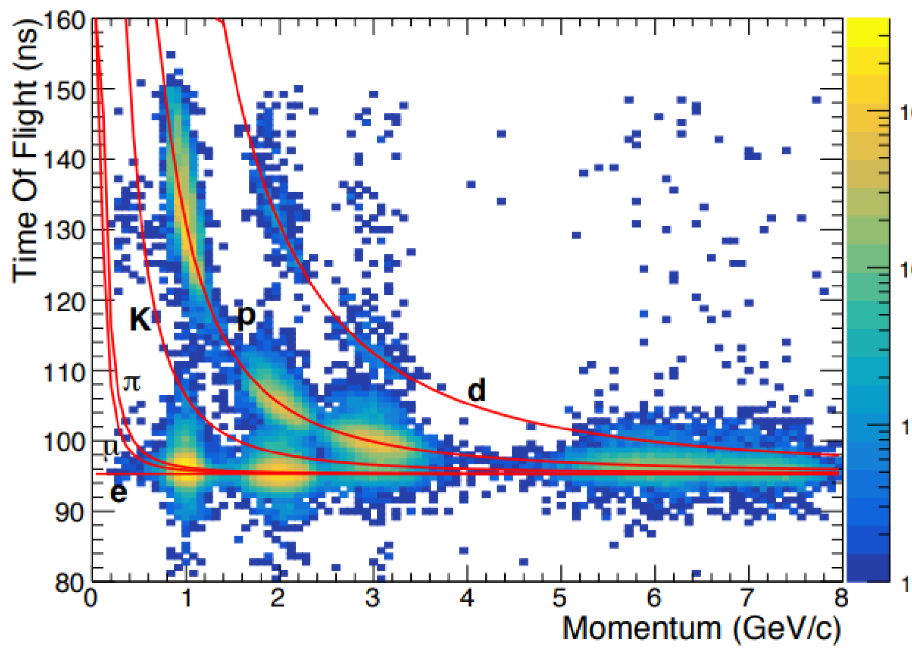
From Tingjun Yang's talk at DPF 2019

Data Taking Summary

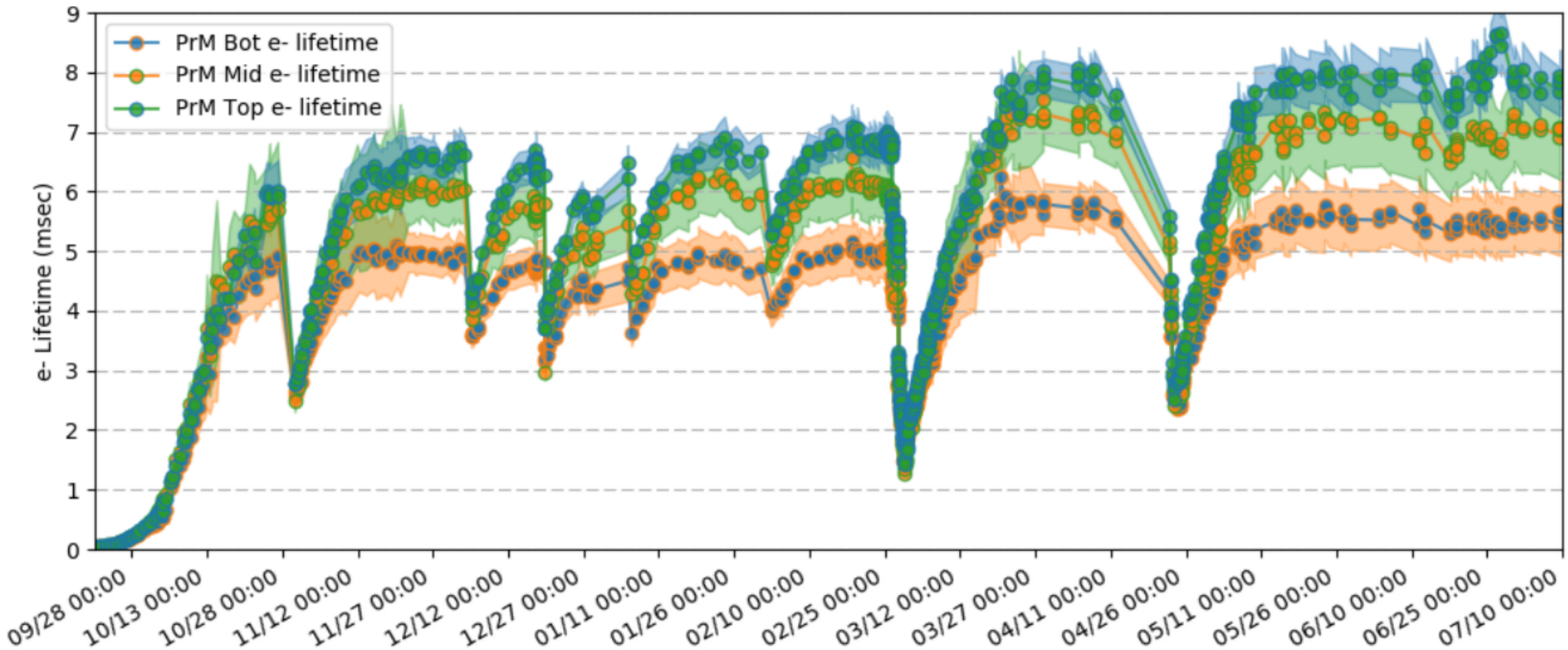
ProtoDUNE-SP collected beam data at CERN from Sep-Nov 2018

Momentum (GeV/c)	Total Triggers Recorded (K)	Total Triggers Expected (K)	Expected Pi trig. (K)	Expected Proton Trig. (K)	Expected Electron Trig. (K)	Expected Kaon Trig. (K)
0.3	269	242	0	0	242	0
0.5	340	299	1.5	1.5	296	0
1	1089	1064	382	420	262	0
2	728	639	333	128	173	5
3	568	519	284	107	113	15
6	702	689	394	70	197	28
7	477	472	299	51	98	24
All momenta	4173	3924	1693.5	777.5	1381	72

- ProtoDUNE-SP performance has been tested with the H4-VLE beam line as well as extended cosmic ray data taking
- Over 4M total beam events recorded and over 20M cosmic ray events
- Data taking is ongoing with an additional beam run planned after LS2 of the LHC
- Beamline PID provided by TOF and Cerenkov detectors



Detector Performance: LAr Purity

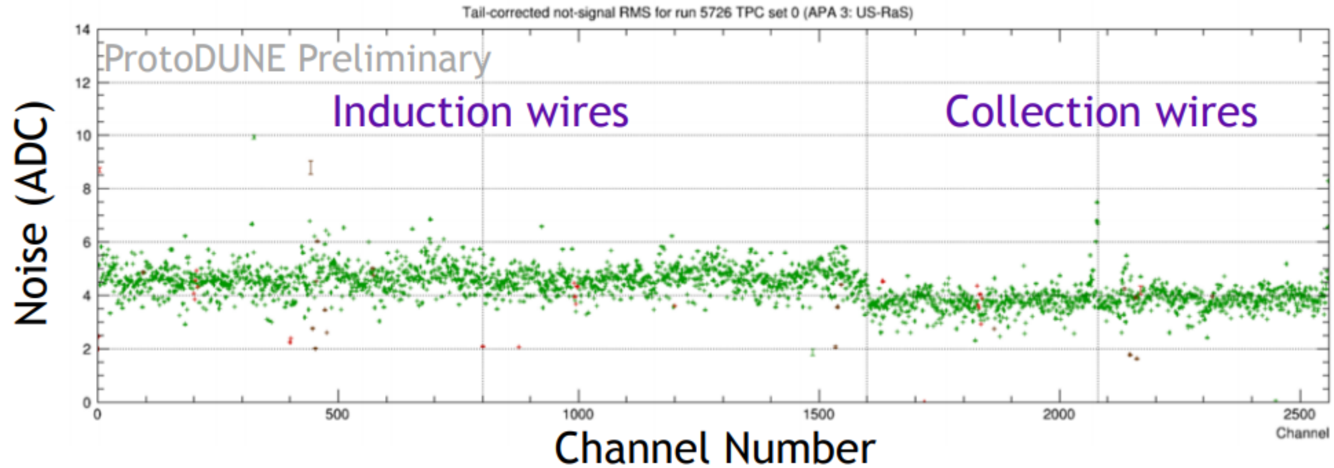


- High purity is critical for the operation of any LArTPC
  - Reduce charge attenuation for drifting electrons
- Purity is continually monitored by 3 purity monitors at varying heights in the cryostat
- The argon was maintained at a high purity (~500ppt Oxygen) due to recirculation and filtering (1kt/4.5 days)
- Purity dips when circulation is temporarily stopped

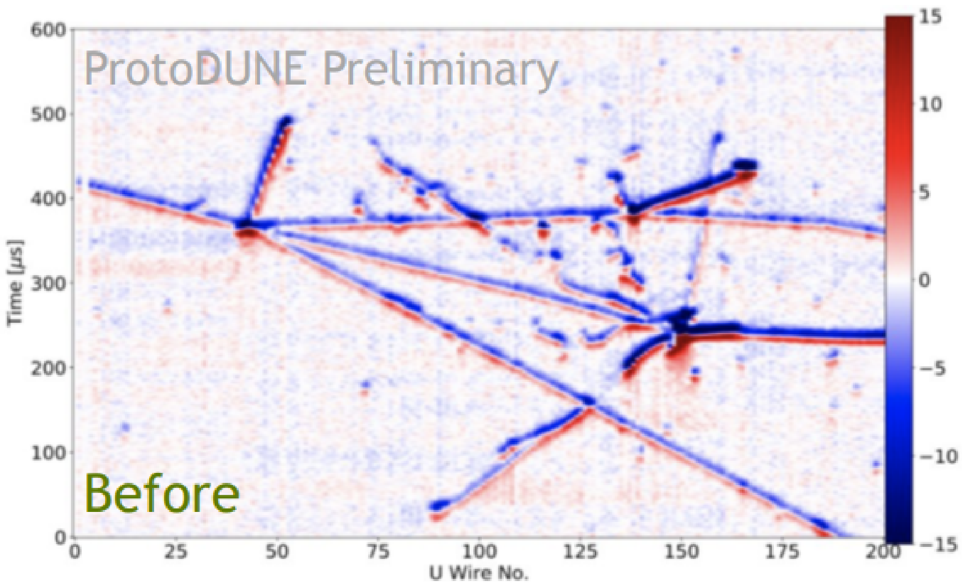
Data Quality: Noise Removal

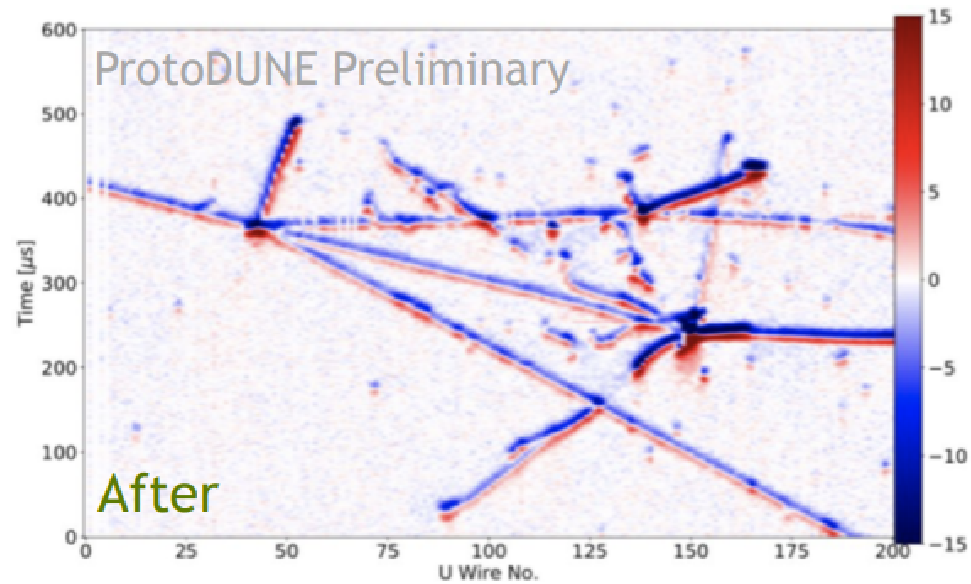
Electronics noise measured with RMS of pedestal before noise filtering

- Collection: 550e
- Induction: 650e



Coherent noise removal

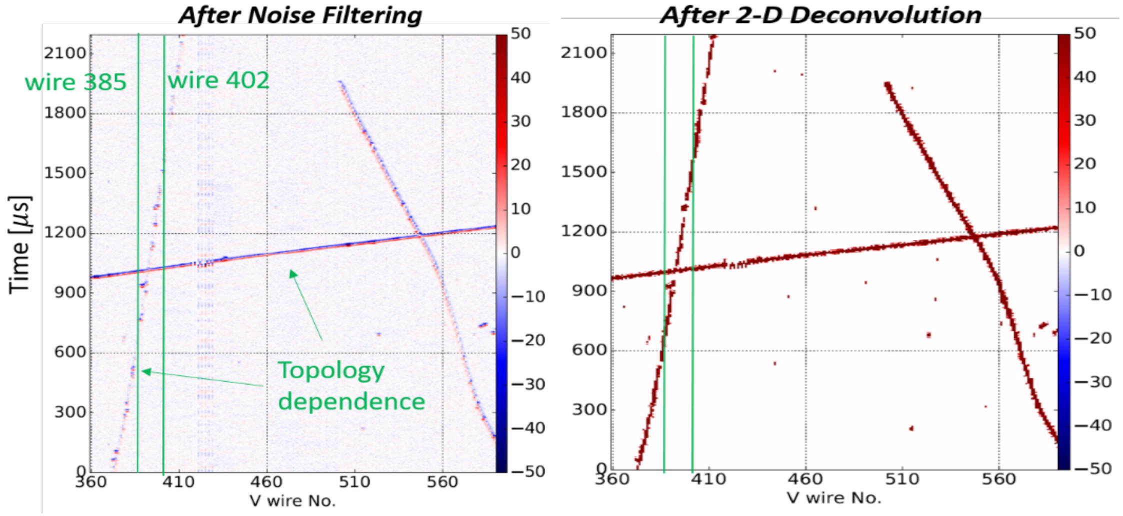


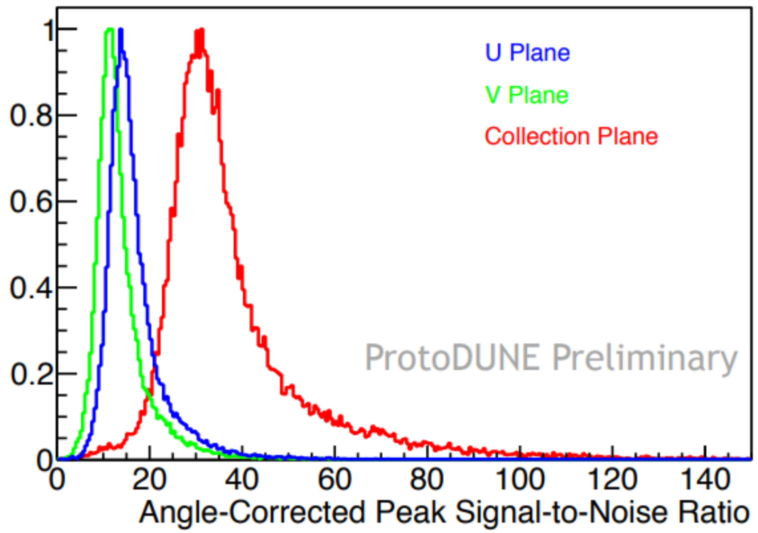


Data Quality: Signal to Noise Ratio

2D deconvolution applied to signal

- Helps with signal recovery for tracks close to parallel with wires
- Unipolar pulses in all planes





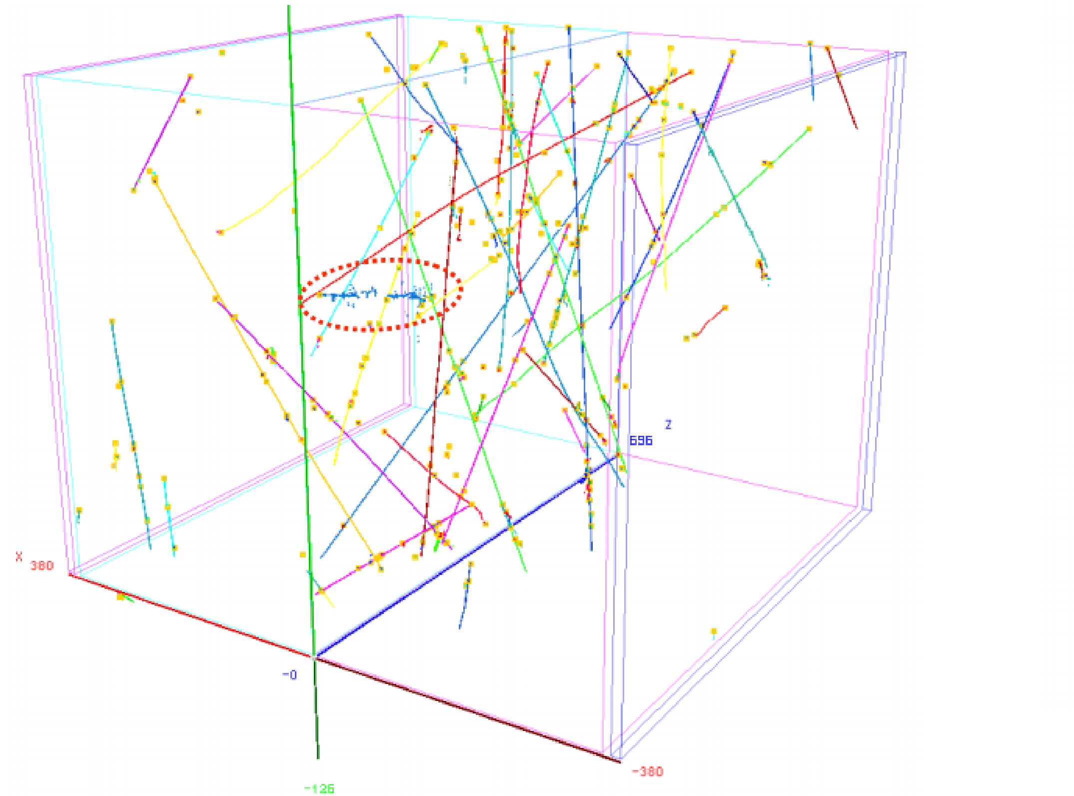
Signal to noise ratio from cosmic muons

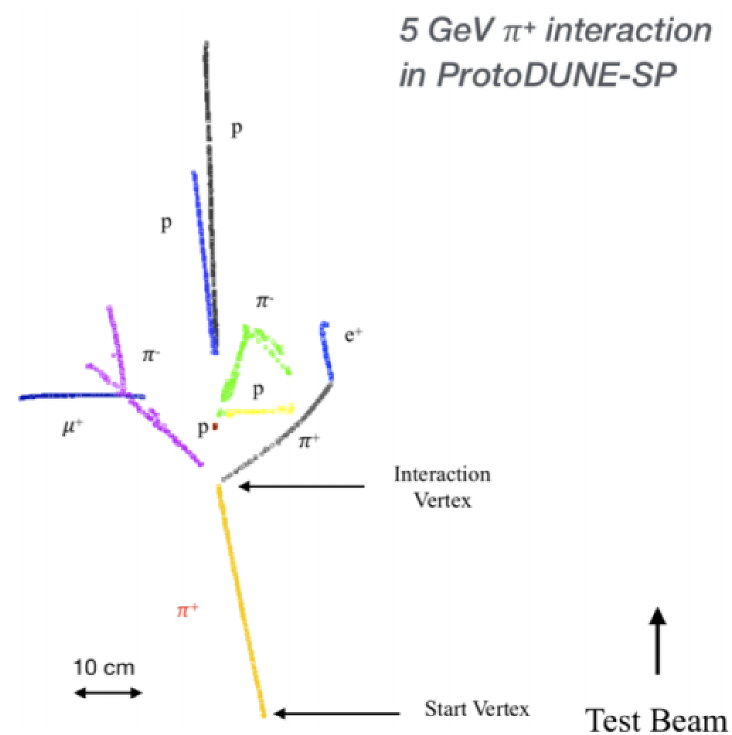
- Induction
  - U = 14:1, V = 17:1
- Collection: 38:1

ProtoDUNE-SP

Reconstruction

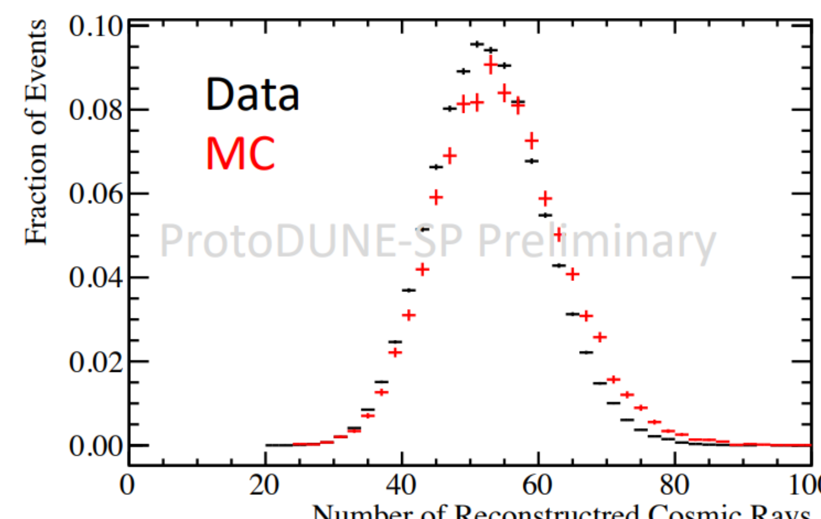
TPC Reconstruction with Pandora



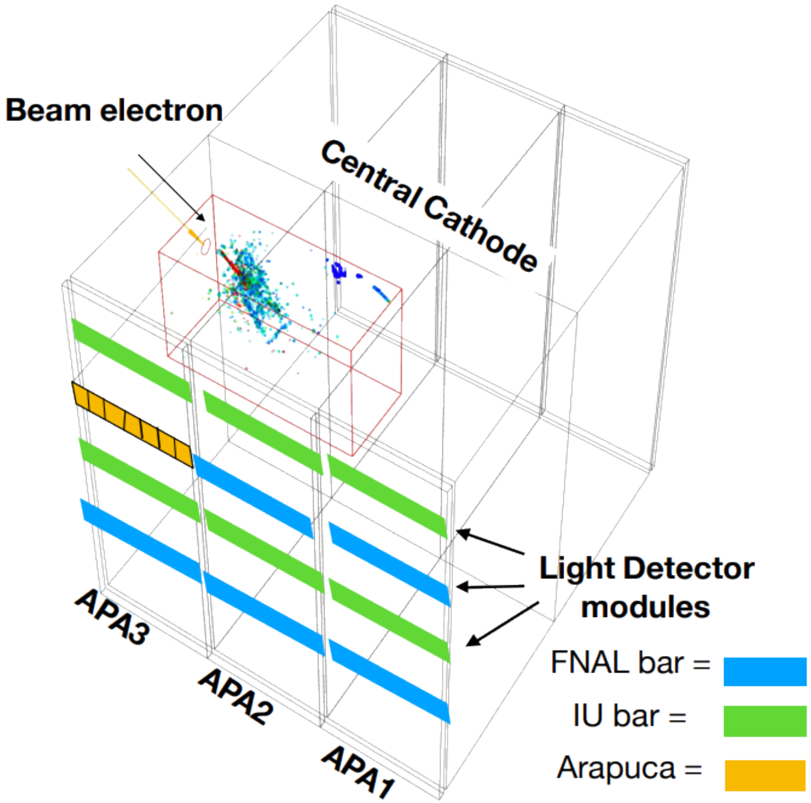


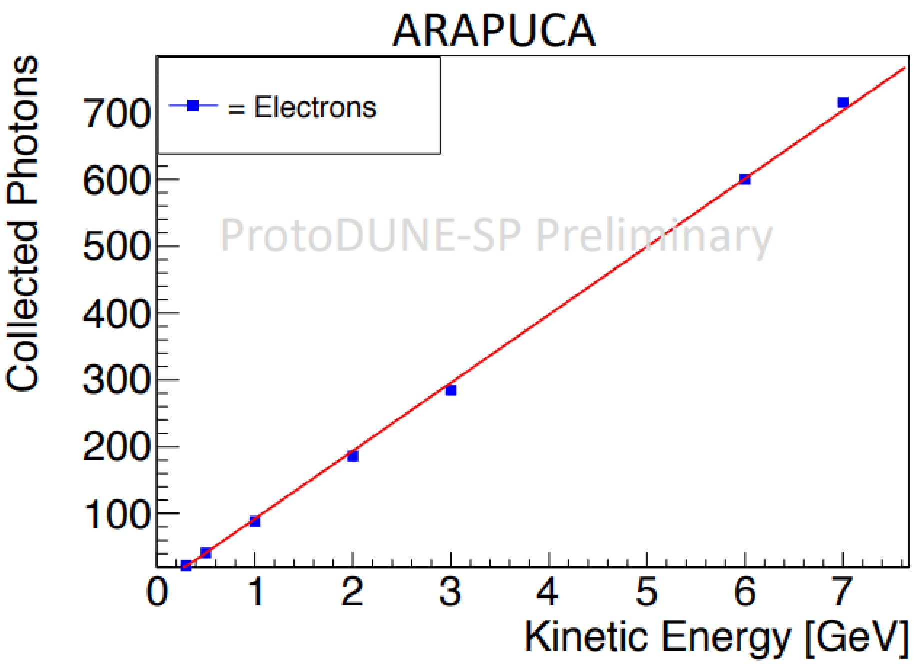
Pattern recognition performed by pandora

- Clear cosmics reconstructed and removed before looking for beam particles
  - Cosmic sample useful for calibration studies
- Test beam particles tagged
- Detailed particle hierarchy returned for analysis



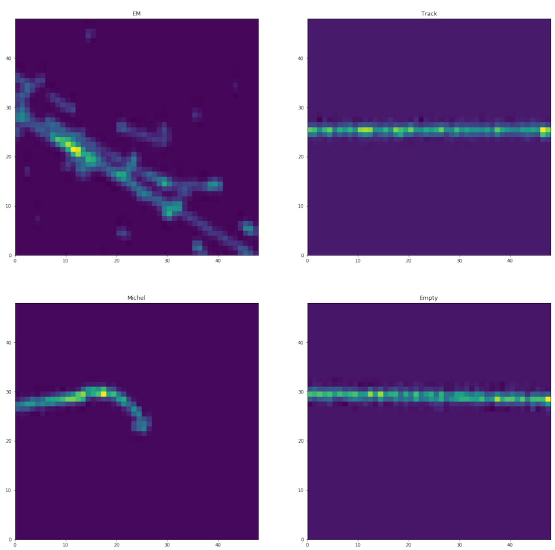
Photon Detector Performance

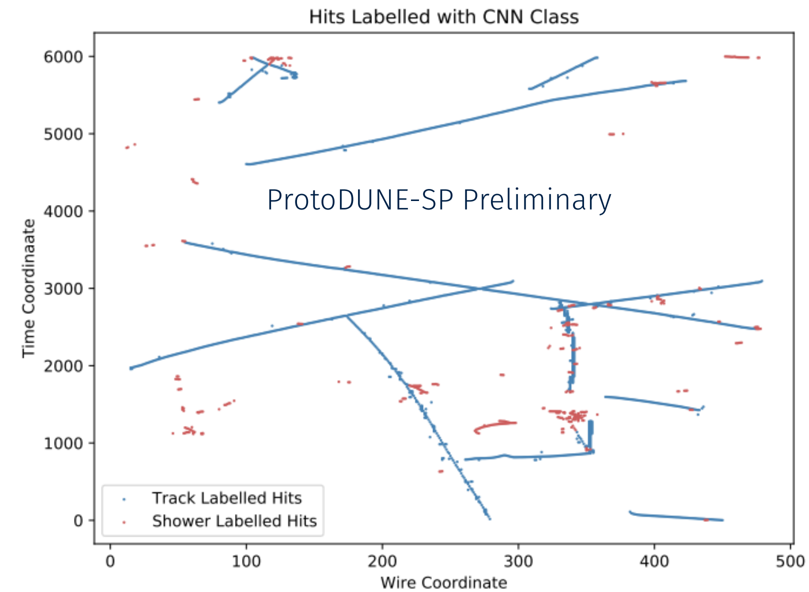




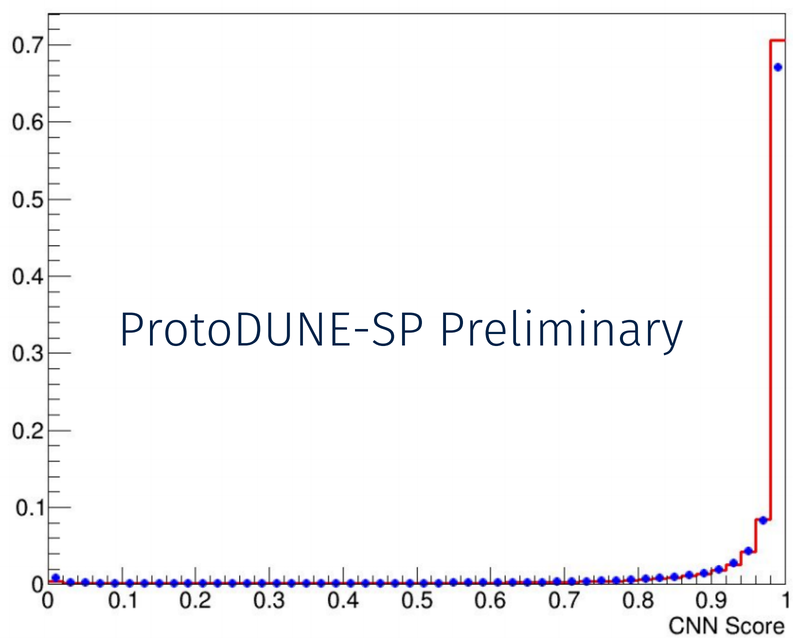
Energy linearity demonstrated for contained beam electron samples

Track and Shower Identification





Shower score for Beam Electrons



Track shower separation crucial in LAr TPC reconstruction

- Identifying ν flavour relies on identifying the charged lepton
- CNN based charge identification tested for track, shower, and Michel electron samples
  - Assists analysers with sample definitions/background removal
  - Potential to be incorporated into pattern recognition algorithms such as Pandora

ProtoDUNE-SP

Analysis

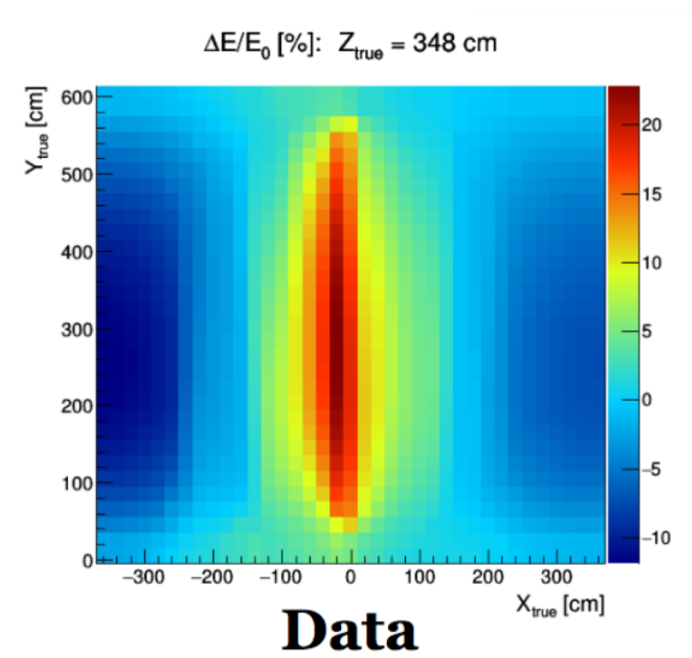
Space Charge Effect

Electric field distortion

- Build up of argon ions at cathode
- Distorts reconstructed tracks
- Modifies recombination

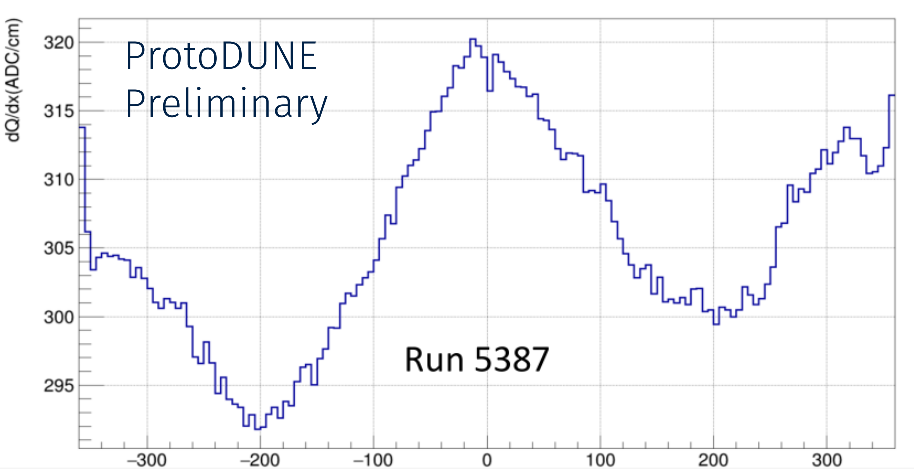
Distortion measured with cosmic muon tracks

- Corrected E-field map calculated

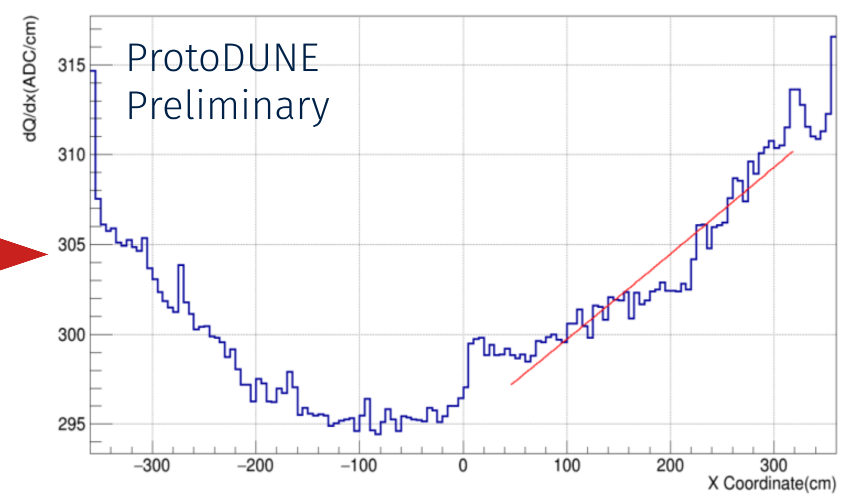


(Space charge effect not significant in DUNE far detector)

Anode Cathode Anode

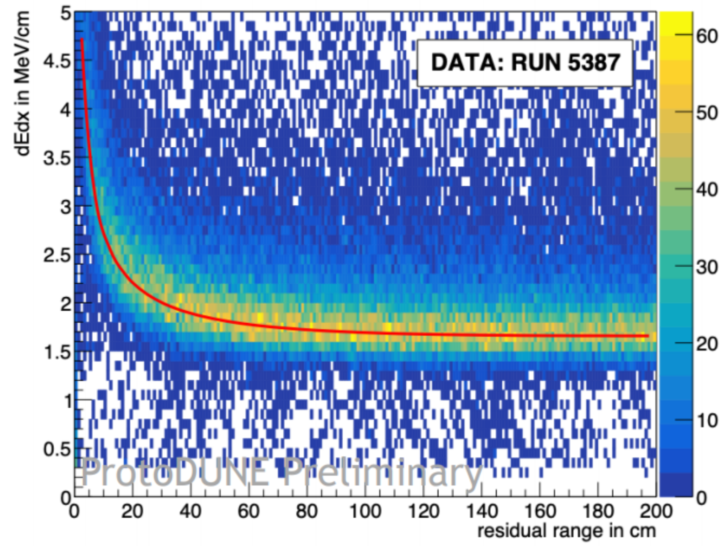


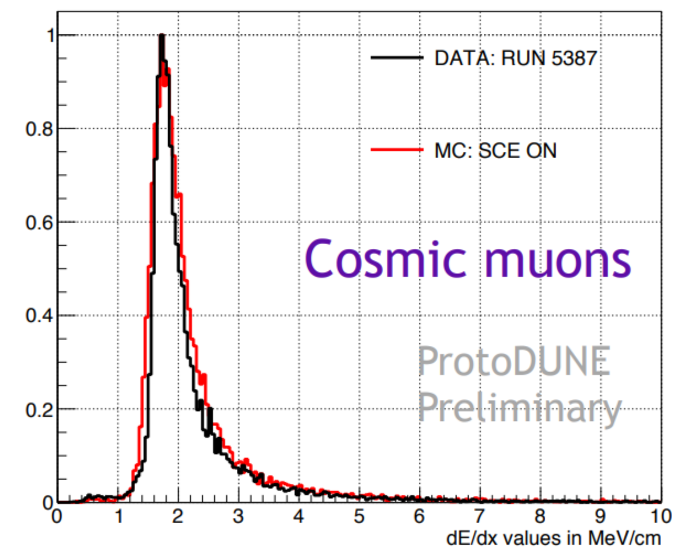
Anode Cathode Anode



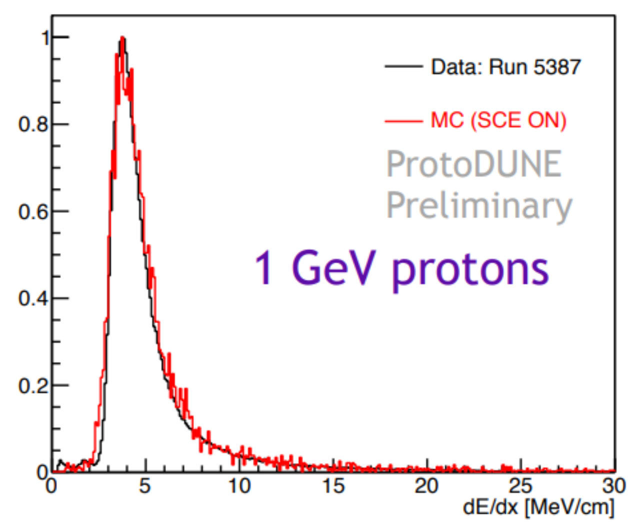
Cosmic Muon Calibration

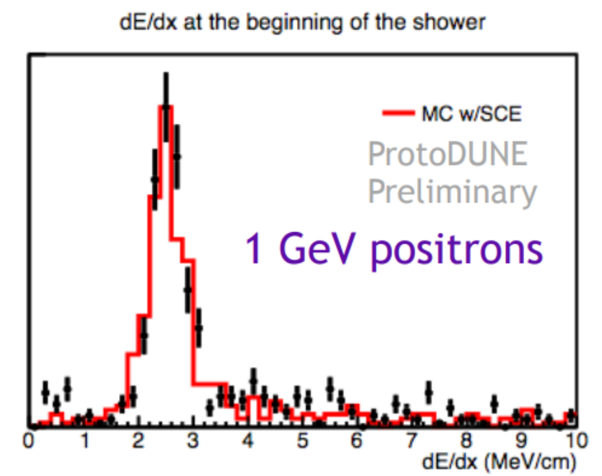
Energy scale is set using stopping muon sample



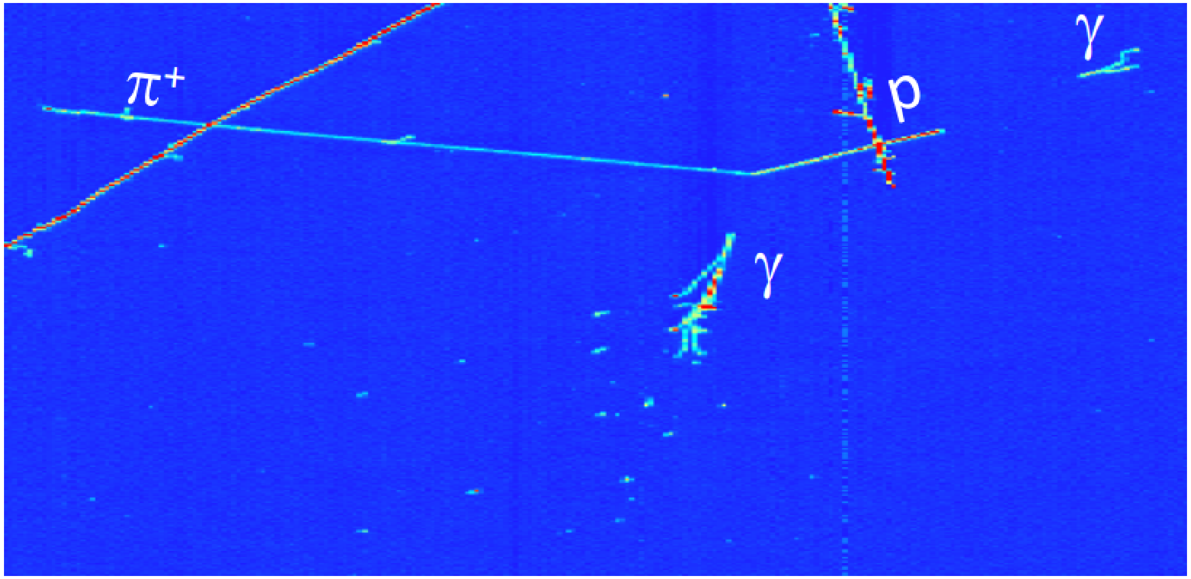


Muon calibration applied on other particle species



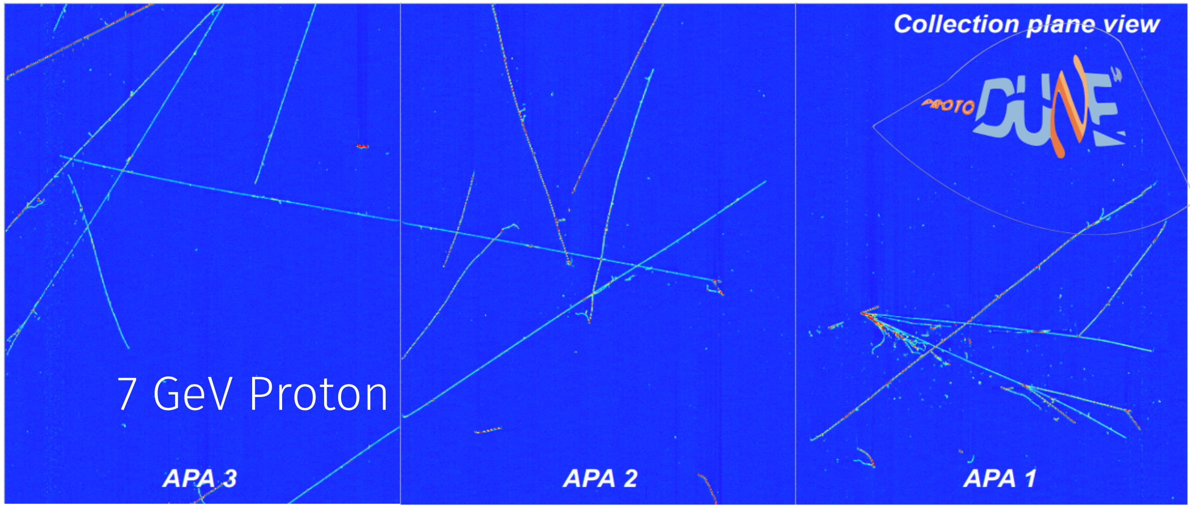


Ongoing Analyses



Charged pion cross sections from 1-7GeV

- Constraints are useful input for neutrino interaction models
- Inclusive
- Exclusive
  - Charge exchange, absorption, etc



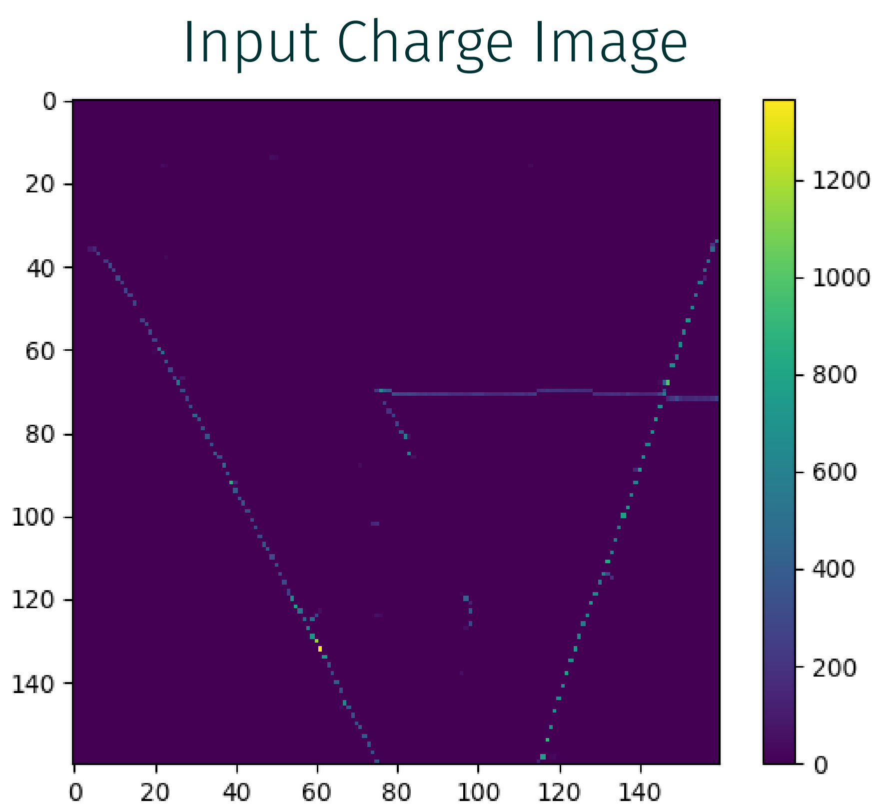
Other beam particle analyses

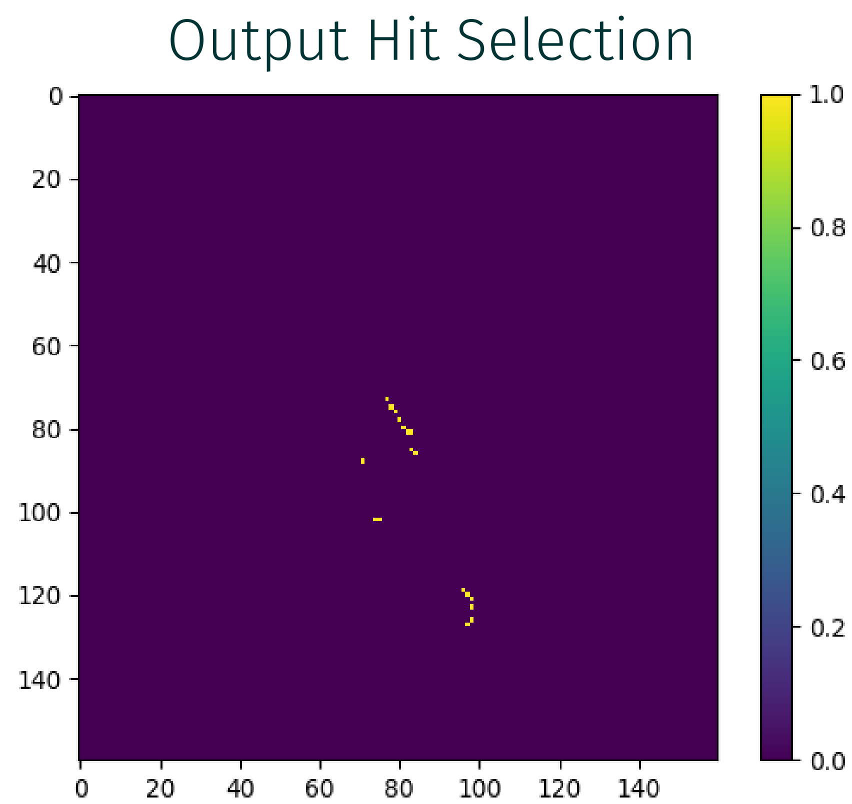
- Proton
- Kaon
- Electron

Ongoing Analyses

Michel electron reconstruction

- Calibration for electron energy scale at ~10's MeV
- Challenging topology ideal test for modern reconstruction techniques
  - CNN's, semantic segmentation

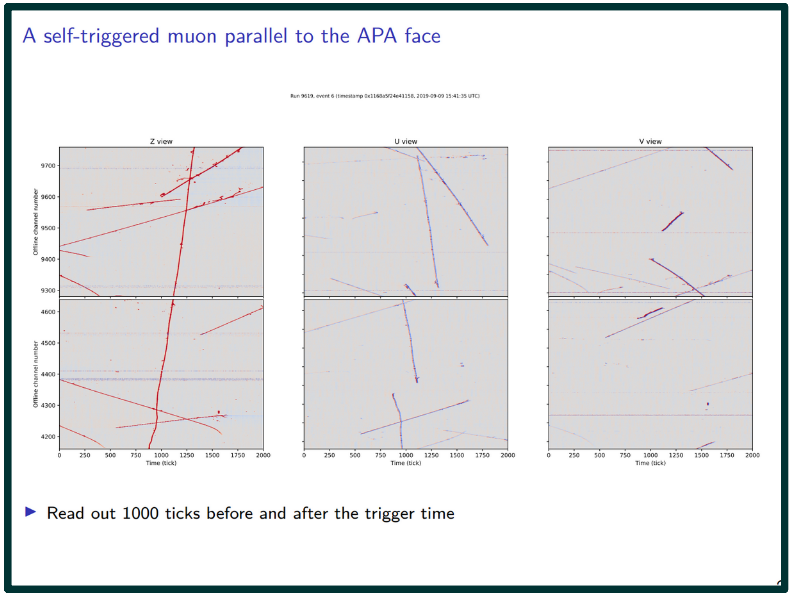




ProtoDUNE

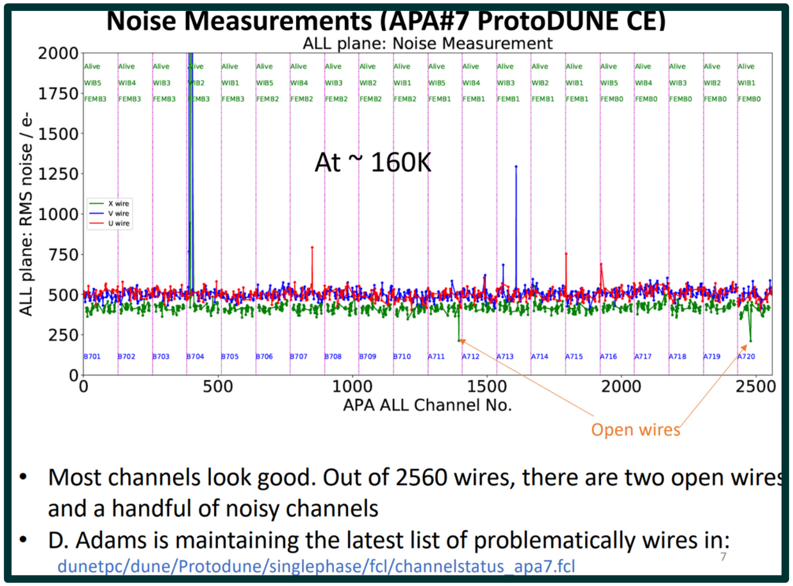
Future Plans

Ongoing R&D



TPC based self triggering

- Successfully tested in ProtoDUNE-SP
- Crucial step for the far detector
  - Get infrastructure in place for far detector self triggering

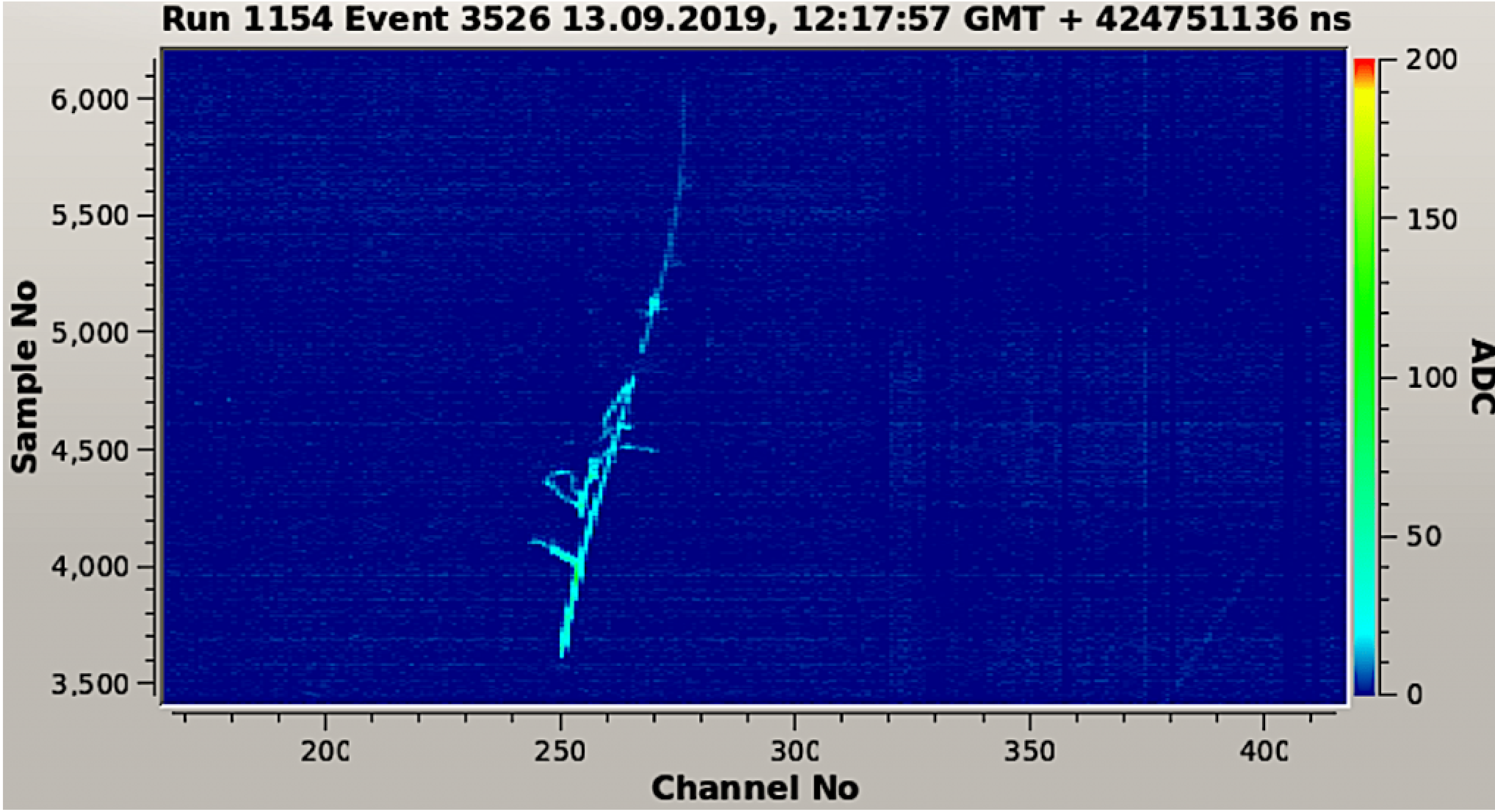


New APA testing

- Installed in coldbox
- APA noise level tested
  - Consistent with other APA's

Plus ongoing cosmic data taking, and more…

ProtoDUNE-DP



First tracks seen, lots more to come … more beam data for both ProtoDUNE’s after LS2

Summary

- The DUNE experiment is a next generation neutrino oscillation experiment which will study
  - Neutrino properties: CP violation, mass hierarchy, octant
  - Core collapse supernova neutrinos
  - BSM physics: Non-standard neutrino interactions, nucleon decay, …
- ProtoDUNE is a crucial step towards the success of the DUNE
  - Test bed for engineering, DAQ, reconstruction, and analysis
- ProtoDUNE-SP has demonstrated excellent performance in a test beam and with cosmic data
  - Important physics analyses to come
- ProtoDUNE-DP has started to see its first tracks
- Papers in the works for both ProtoDUNE's
- Stay tuned for more data from ProtoDUNE's after LS2

Thanks for listening!