First Results from Singe-Phase ProtoDUNE at CERN Neutrino Platform

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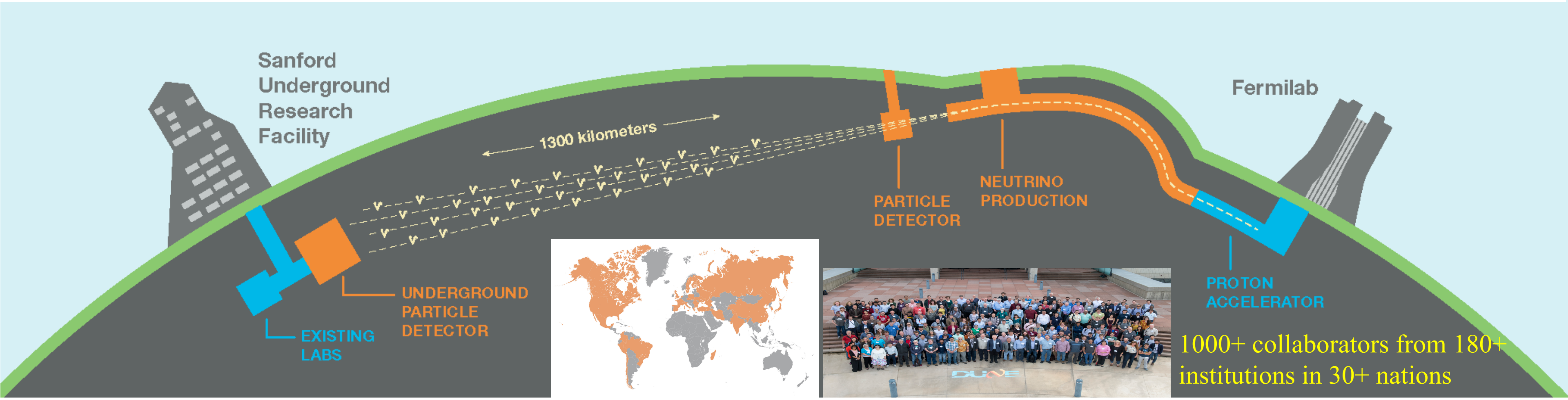
08-29-2019

NuFACT2019, Daegu, KOREA

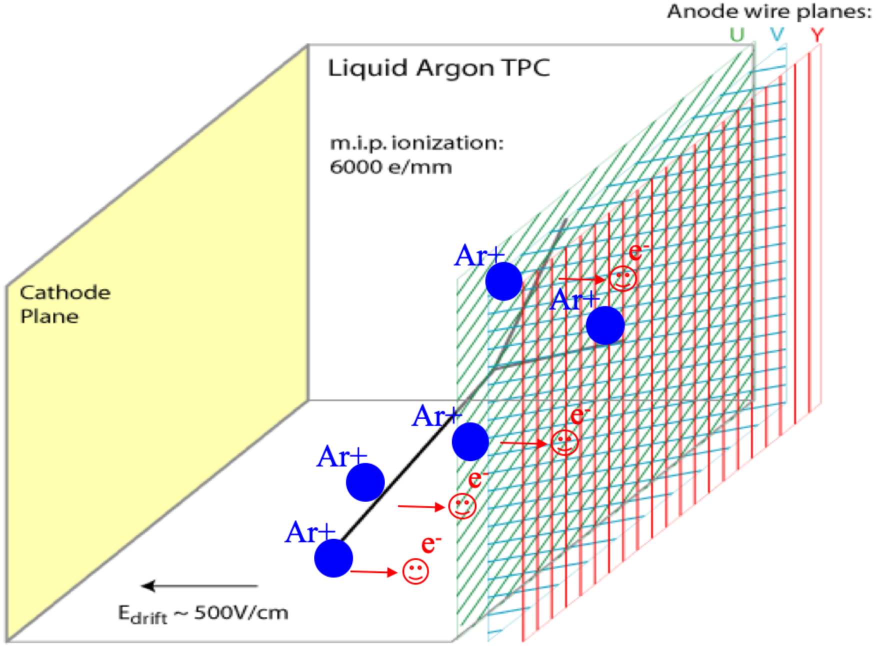
DEEP UNDERGROUND NEUTRINO EXPERIMENT

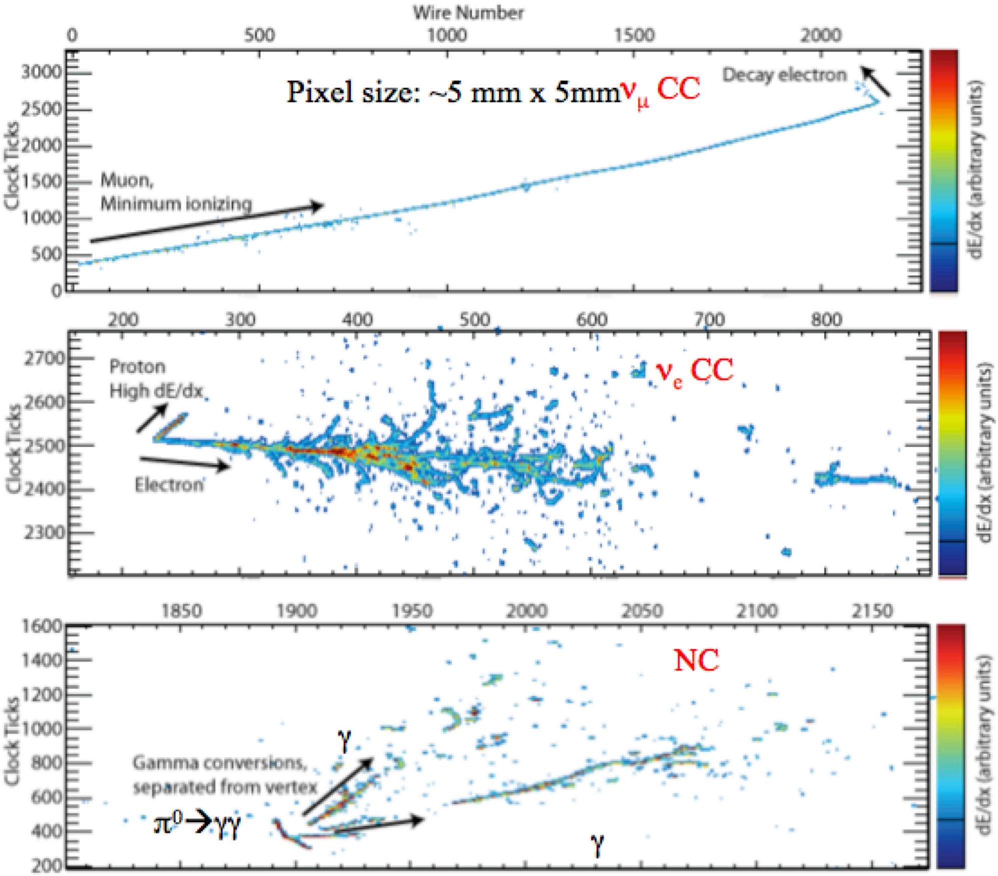


- New beam at Fermilab (1.2 MW@80 GeV protons, upgradeable to 2.4 MW), 1300 km baseline (Chris Densham's talk)
- On-Axis 40 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
- Highly-capable near detector at Fermilab (Alan Bross’s talk, Kim Siyeon/Sunwoo Gwon's poster)
- ν_e appearance and ν_μ disappearance → Measure MH, CPV and mixing angles (Kim Siyeon’s talk)
- Large detector, deep underground → Nucleon decay, supernova burst neutrinos, atmospheric neutrinos, etc (Kihyeon Cho's talk)

DUNE Overview: Jae Yu’s plenary tomorrow

Far Detectors: Liquid Argon Time Projection Chamber (LArTPC)

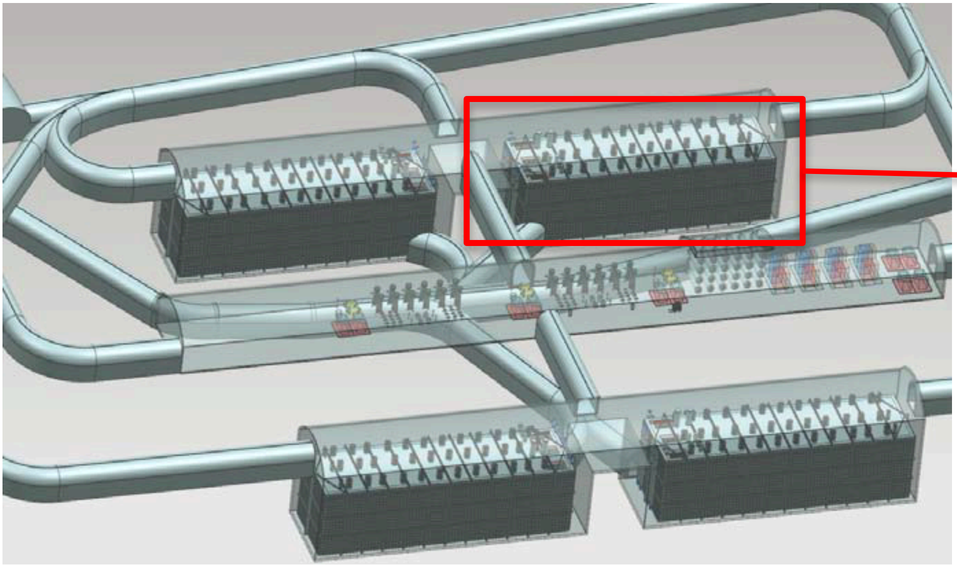


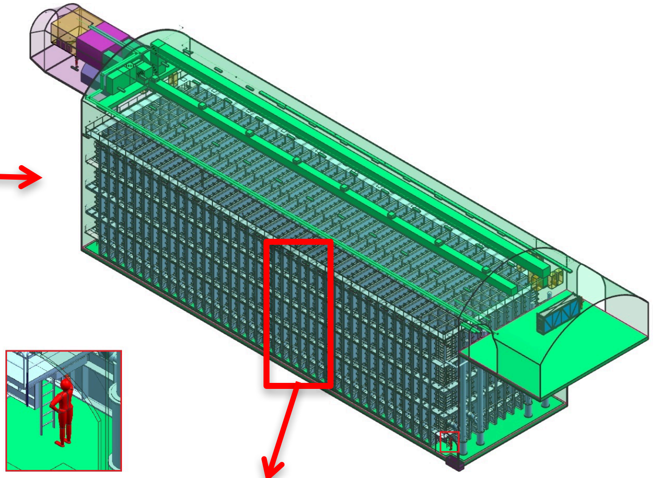


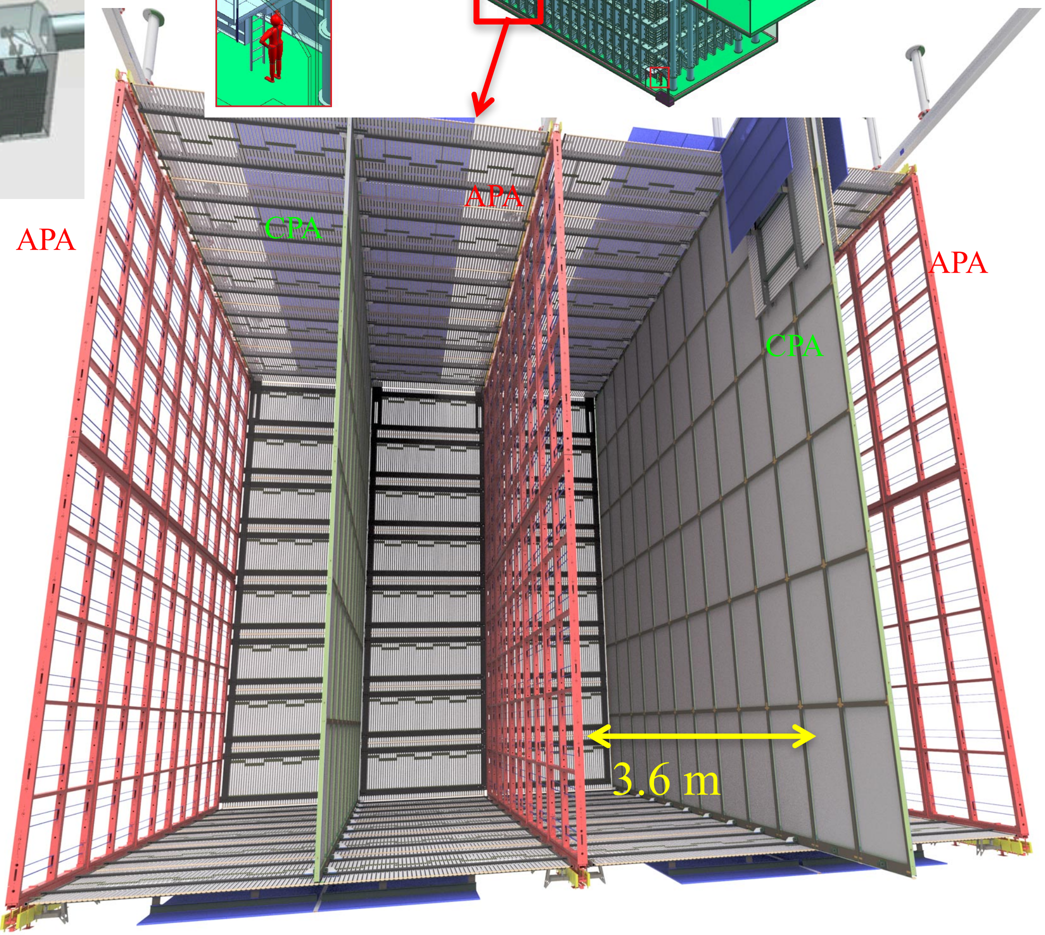
Event display in LArTPC (MicroBooNE MC)

- High resolution 3D track reconstruction
  - Charged particle tracks ionize argon atoms
  - Ionized electrons drift to anode wires (~ms) for XY-coordinate
  - Electron drift time projected for Z-coordinate
- Argon scintillation light (~ns) detected by photon detectors, providing t_0

Far Detector: Single-Phase LArTPC



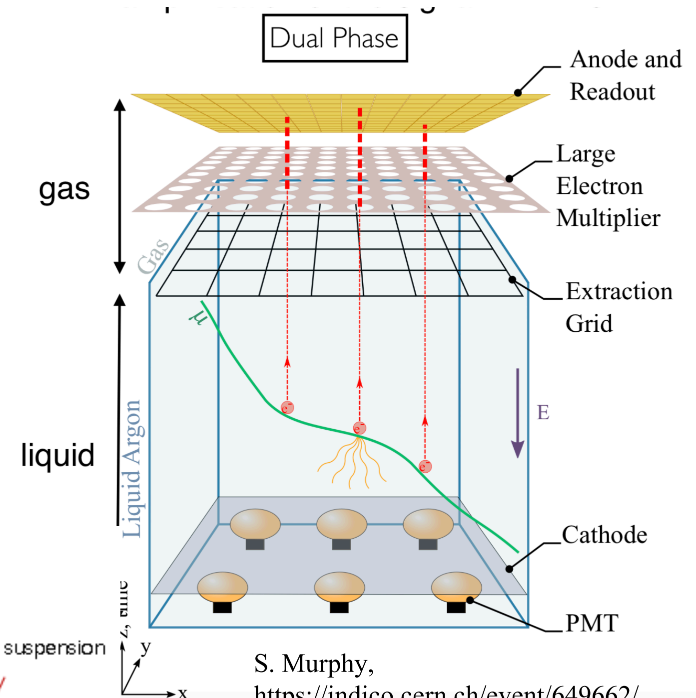




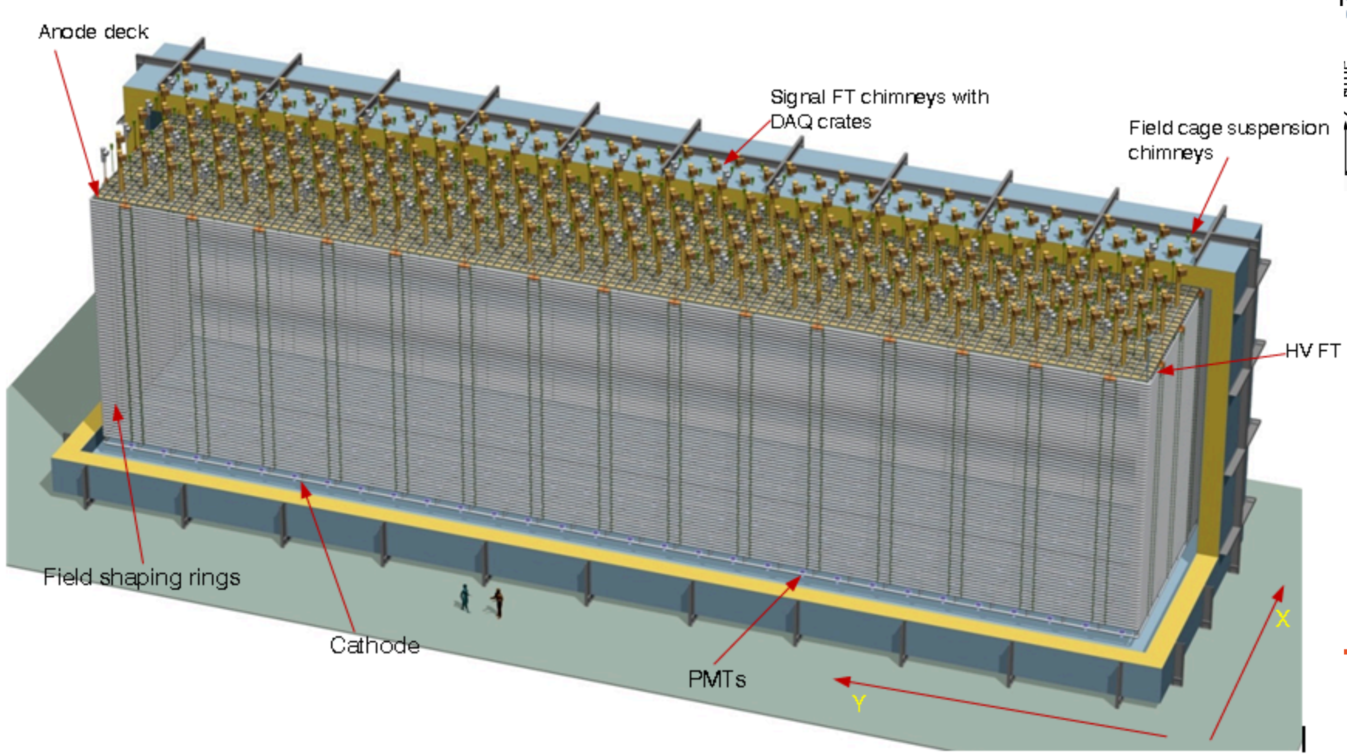
- Anode wire planes (2 induction, 1 collection) immersed in LAr
- Anode and Cathode Plane Assemblies (APA, CPA) suspended from ceiling
- Drift distance: 3.6 m, wire pitch: 5 mm
- Induction wires +-37.7^{o} to collection wires, wrapped around APA
- Photon detectors: light guides+SiPMs, embedded in APAs

Far Detector: Dual-Phase LArTPC

- Electrons extracted from LAr to gaseous volume
- Signal amplified by Large Electron Multiplier (LEM) in gas phase
- Charge collected and recorded on 2-D segmented anode
- Drift distance: 12 m (vertical)
- Accessible electronics, better Signal/Noise
- Photon detectors: PMT below cathode



S. Murphy, https://indico.cern.ch/event/649662/



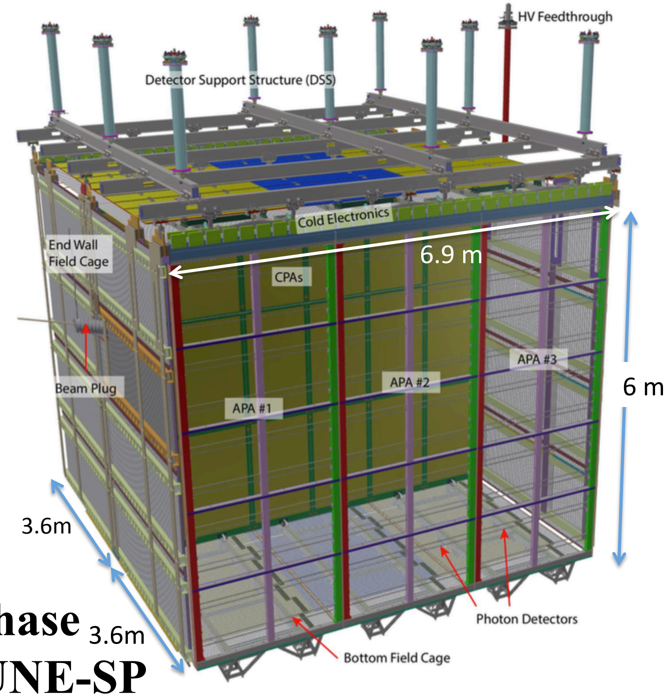
ProtoDUNEs at CERN

- Two major DUNE prototype LArTPCs at CERN
  - One single phase and one dual phase
  - 770 t LAr mass each
  - Exposed to H2 (DP) and H4 (SP) testbeams at CERN, momentum-dependent beam composition contains e, $K^{\pm}$, μ, p, $\pi^{\pm}$
- Strategic Goals
  - Prototyping production and installation procedures
  - Validating the design from basic detector performance
  - Accumulating large test-beam data for detector response understanding, calibration, dE/dx, PID etc.
  - Demonstrating long-term operational stability

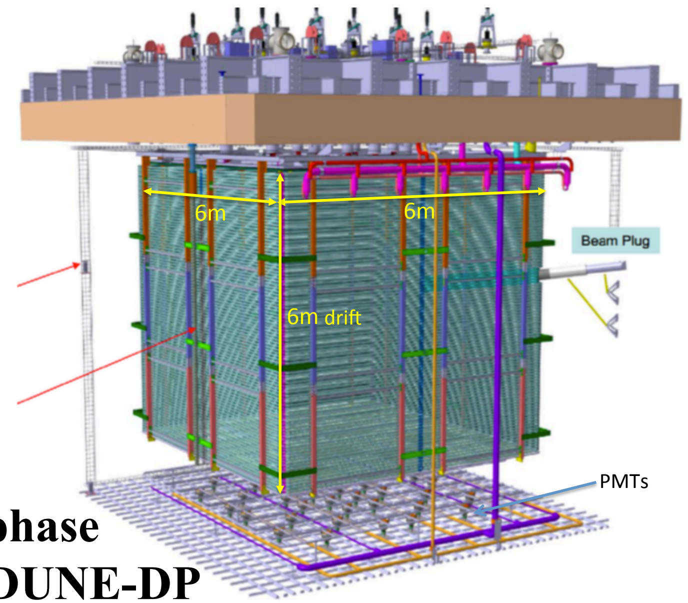
Status:

ProtoDUNE-SP: First test beam data took in Sep-Dec 2018 (This talk)

ProtoDUNE-DP: Taking first data



Single phase ProtoDUNE-SP



Dual phase ProtoDUNE-DP

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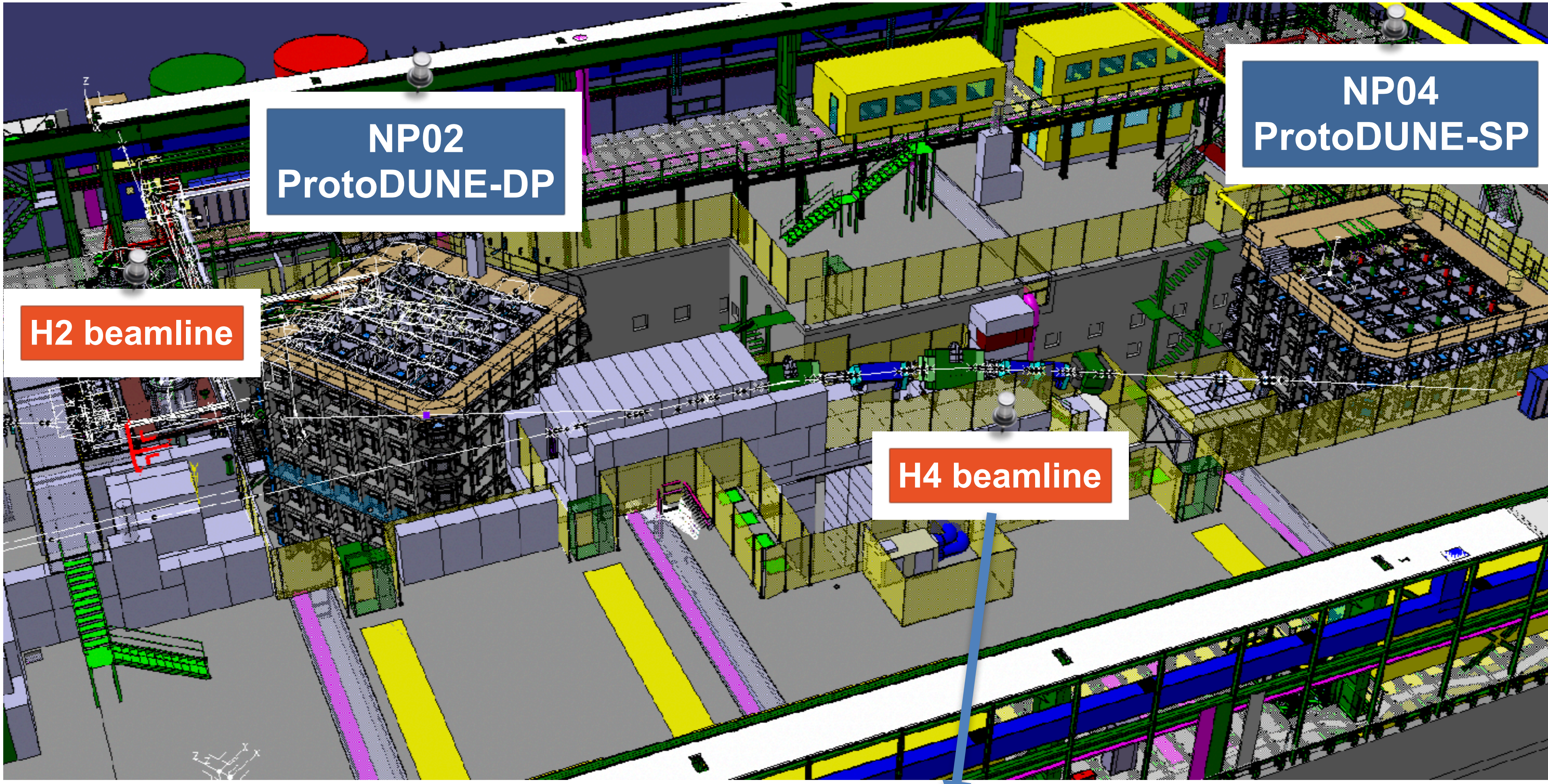
ProtoDUNE SP and DP at EHN1 (CERN)

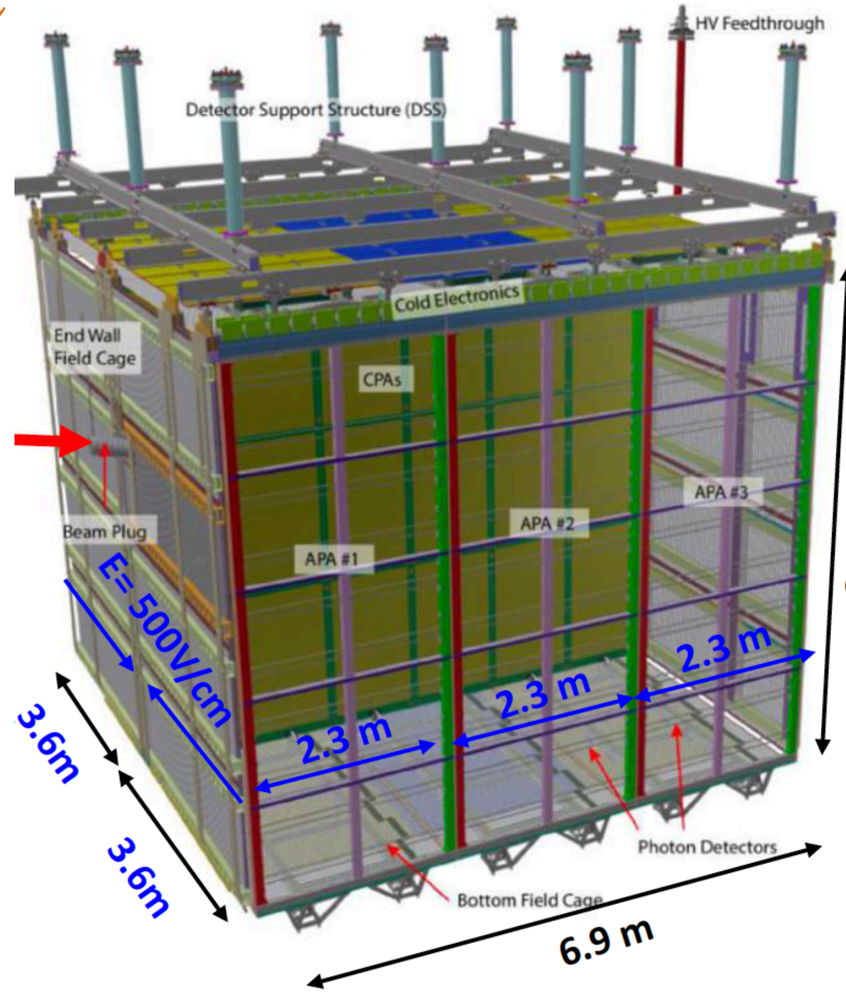


- Both ProtoDUNE cryostats and their beamlines are located near to each other in the EHN1 building at CERN

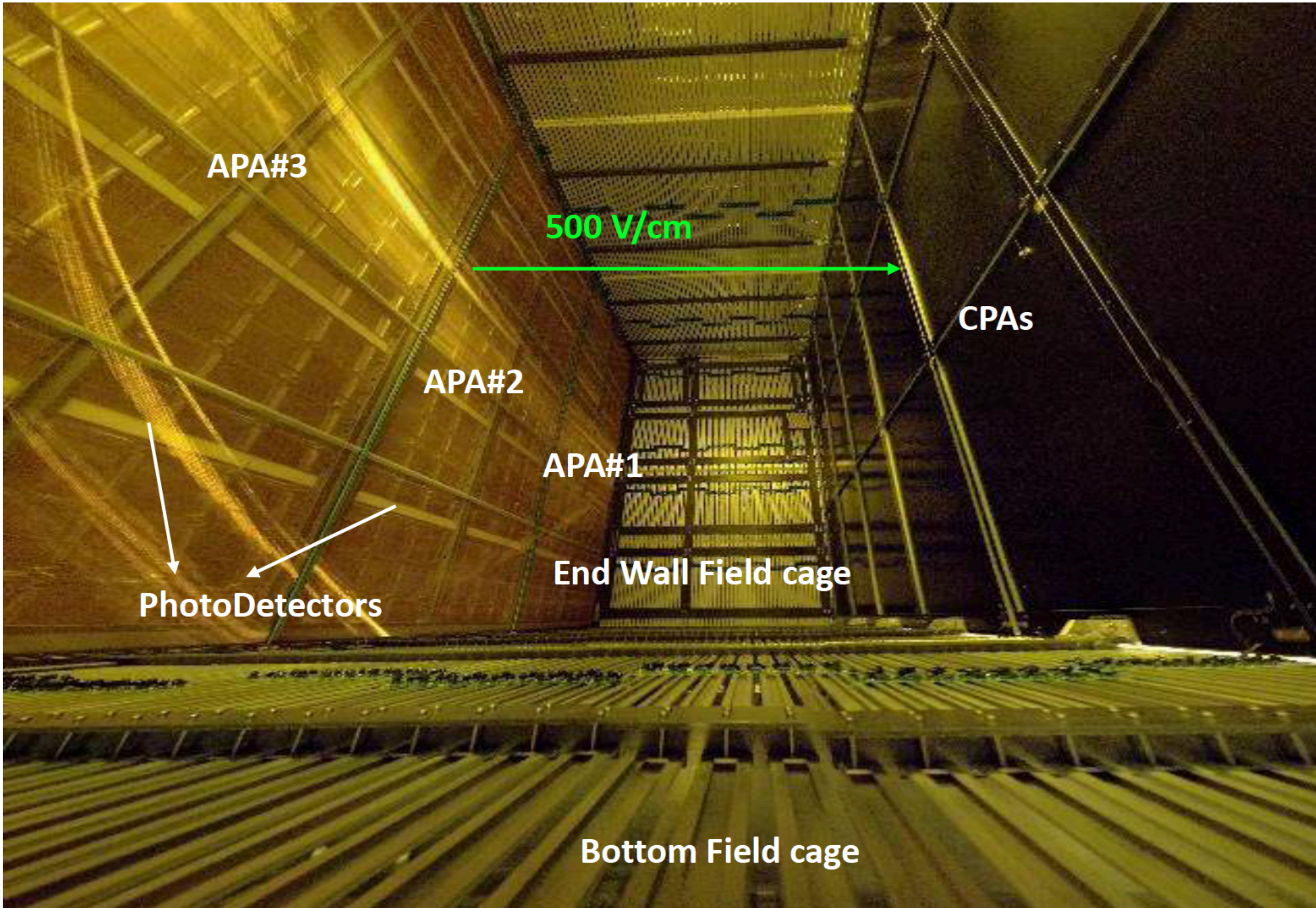
- H4-VLE beam line [Phys. Rev. Accel. Beams 22, 061003 (2019)]
    - New tertiary, low-mom beam line; 2 secondary targets
    - W for lower momenta (0-3 GeV/c); Cu for higher momenta (4-7 GeV/c)
    - TOF and Cherenkov counters for PID

ProtoDUNE Single Phase

- Active Volume: 6m (H) x 7m (L) x 2x3.6m (W)
- Central Cathode Plane Assembly (CPA) :
  - 18 CPA modules
  - 3.6 m drift distance @180 kV
  - 500 V/cm field in drift volume
- Anode Plane Assembly (APA):
  - 2 APA planes, each with 3 APAs
  - APA module: 6m high, 2.3m wide
  - Photodetectors integrated in APA
- Field cage: surrounds the open sides of the drift region, ensuring uniform electric field
- Cold electronics: directly attached to the top of the APA (2560 wires/APA, 15360 total wires)
- Photon detectors (PDS): 3 designs integrated into APA frame bars

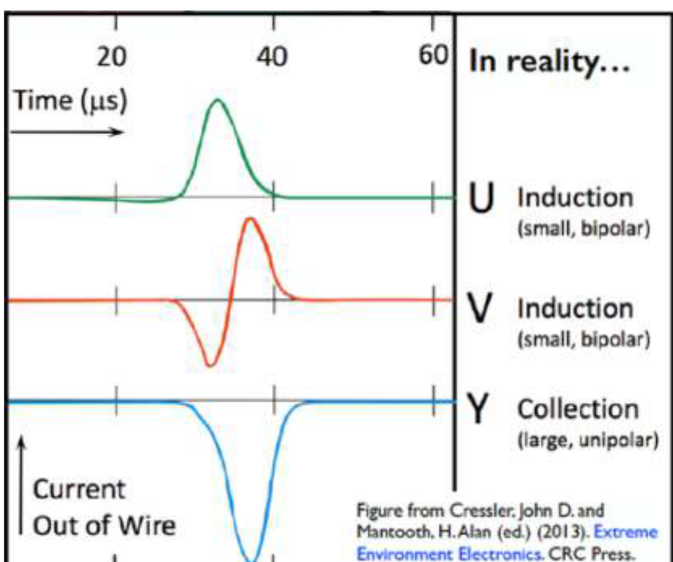


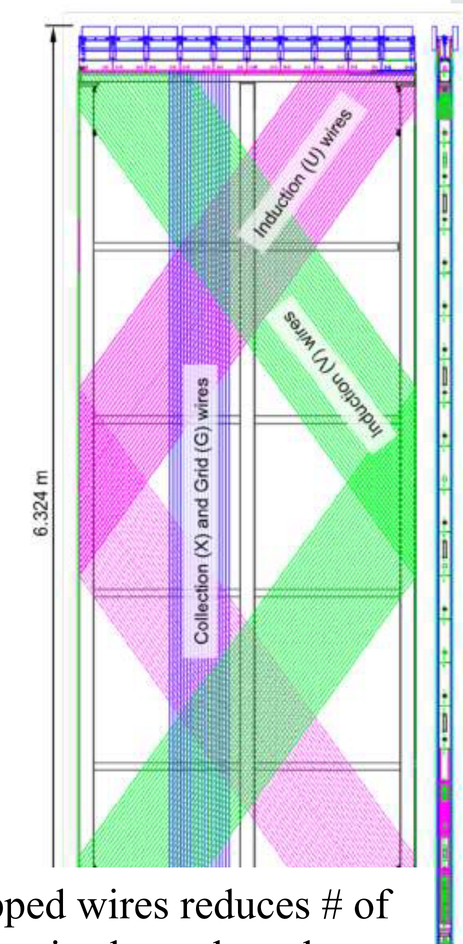
ProtoDUNE-SP Field Cage



ProtoDUNE-SP: Anode Plane Assembly(APA)

- APA: 3 wire planes (U/V,X) + 1grid plane(G)
  - Grid plane prevents induction currents from drifting charge in drift volume
  - Induction wires (U, V): inclined at +/- 35.7°, transparent to charges
  - Collection wires (X): collect charge forming unipolar signal
  - Grounding Mesh shields photon detectors

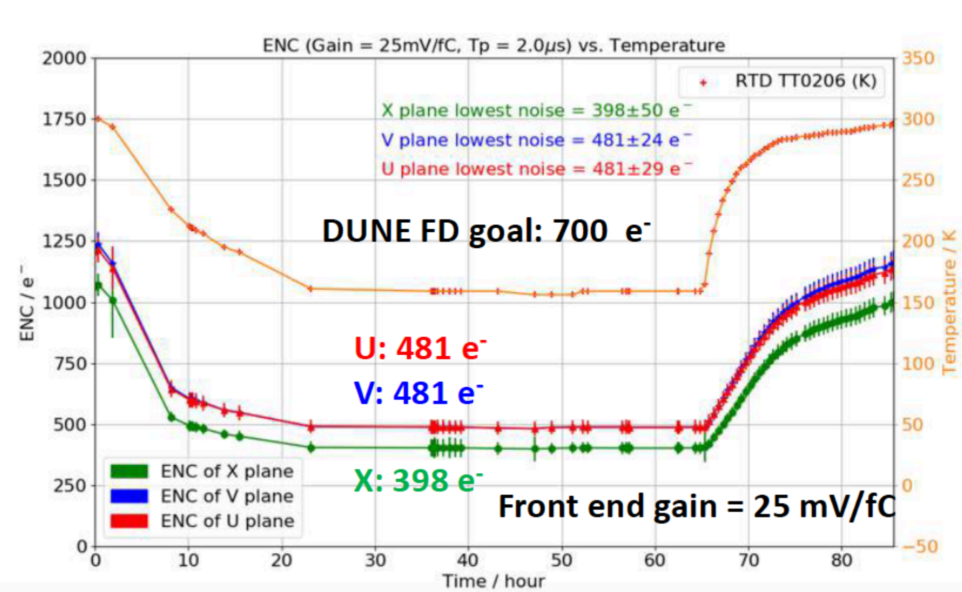


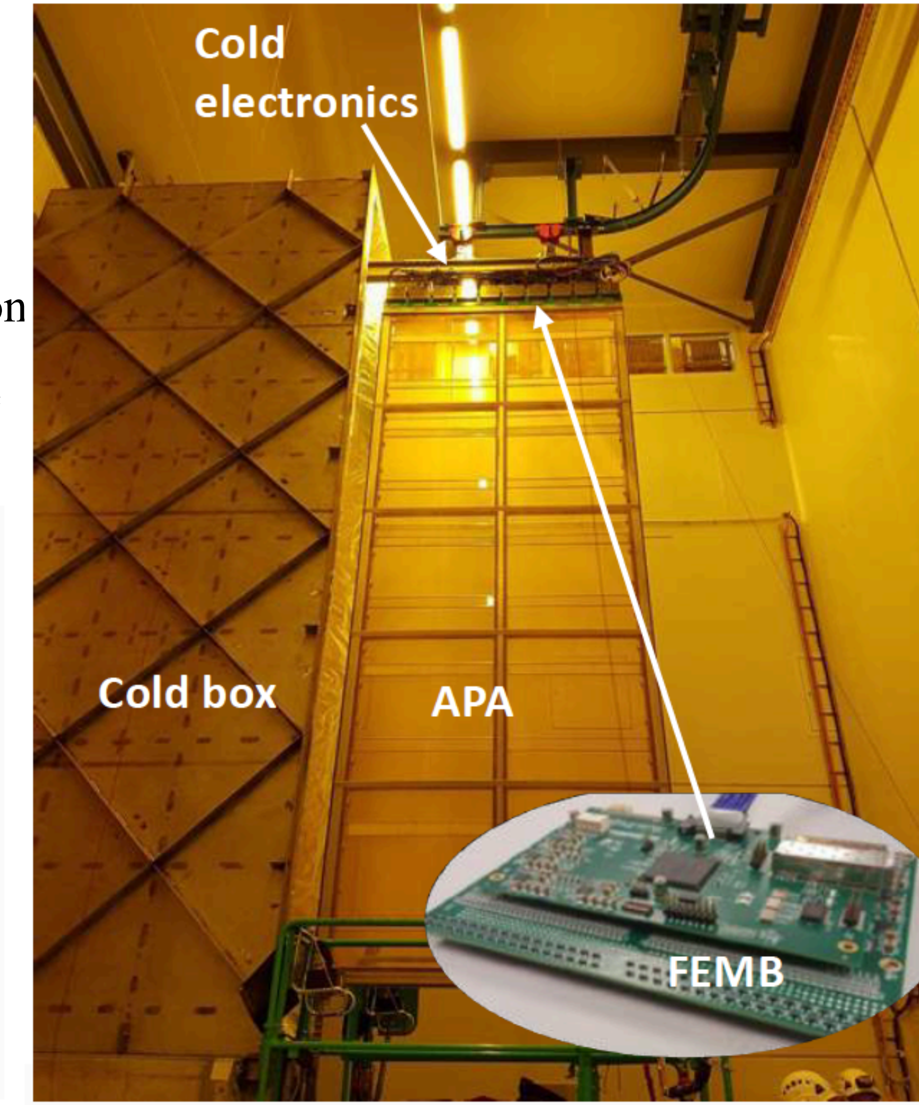


Wrapped wires reduces # of electronic channels and allows more active volume, all electronics on top

Cold Electronics (CE)

- Cold Electronics (CE): Both Front-End and ADC ASICs submerged in liquid argon
- FEMB (Front End Mother Board) mounted on top of the APA
- Assembled APA and cold electronics tested in Cold Box (150K nitrogen gas) before installation
- Front-End ASIC worked well, R&D to improve ADC ASIC for DUNE



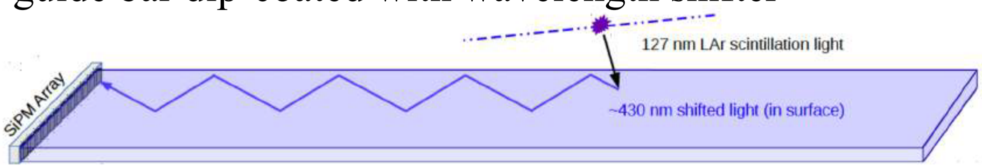


ENC (Equivalent Noise Charge): charge injected to detector capacitance which produces on the output side a signal with amplitude equals the output RMS noise

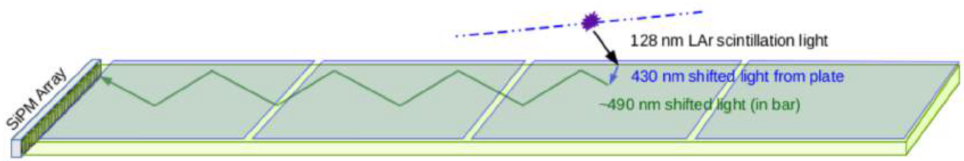
Photon Detection System (PDS)

- LAr is excellent scintillating medium: 20,000 photons/MeV @ 500 V/cm, wavelength=128 nm
- Wavelength shifter converts VUV to visible light readout by SiPMs
- 3 PDS designs being tested in ProtoDUNE-SP:

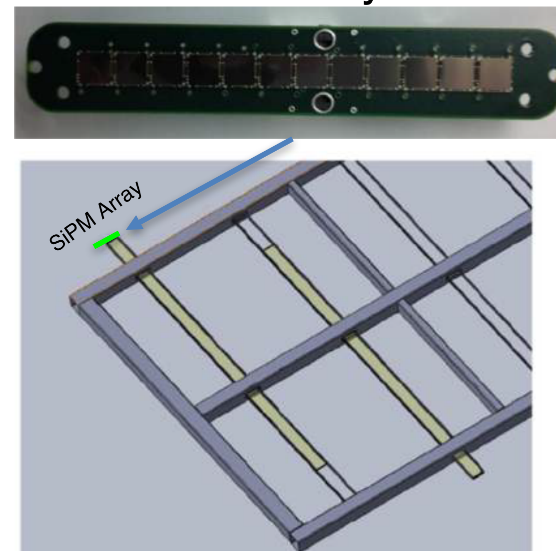
Design 1: Dip-coated light guide (MIT and Fermilab): Acrylic light guide bar dip-coated with wavelength shifter



Design 2: Double-shift light guide (Indiana University): Wavelength shifting plates + wavelength shifting light guide

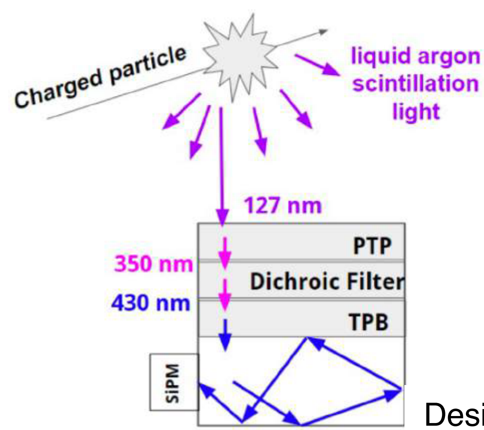


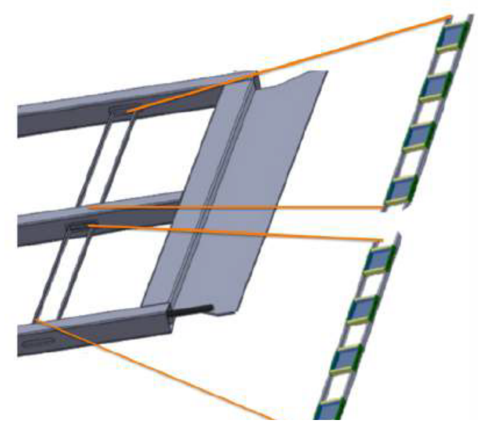
SiPM Array



Design 1&2 PDS module inserted APA frame

Design 3: ARAPUCA (Campinas University and Fermilab):
Light trapped and wavelength-shifted by dichroic filter, 5 ~10x light yield increase



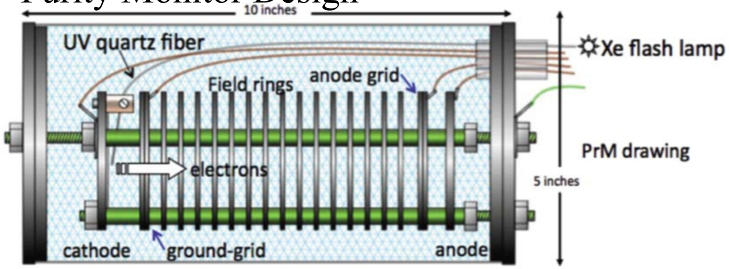


Design 3 PDS module inserted APA frame

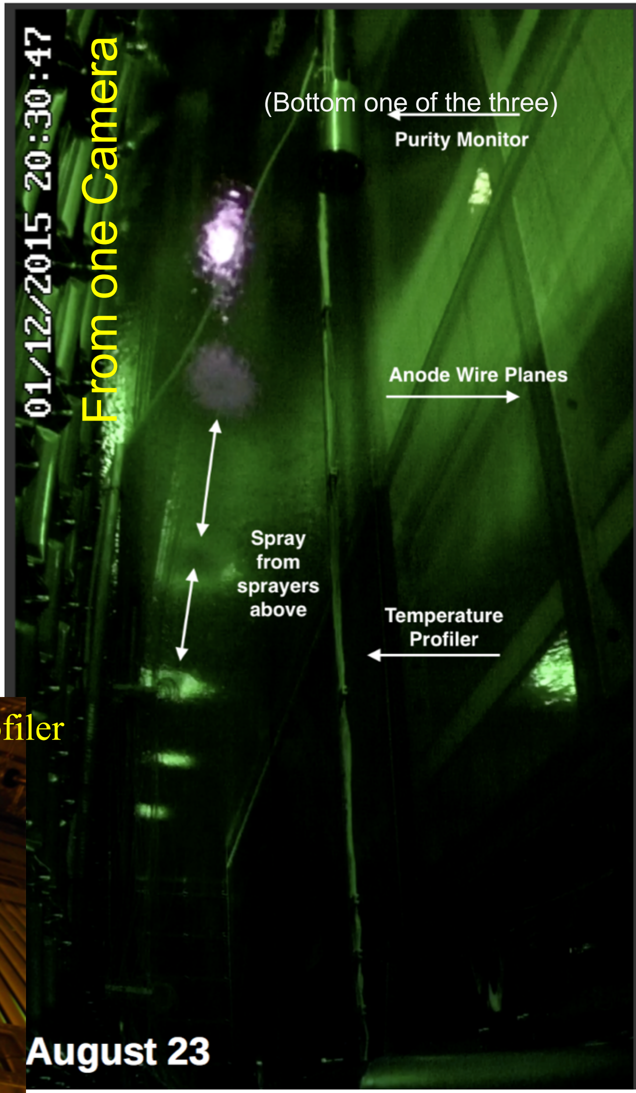
Detector Instrumentation and Cosmic Ray Trigger

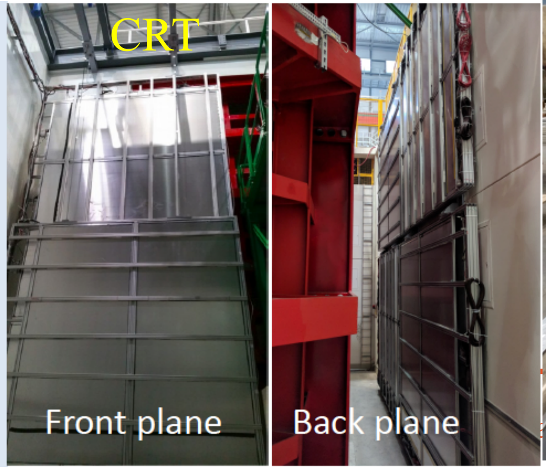
- Purity monitors (PrM): electron lifetime (LAr purity) measurement
- Gas analyzers analyzers: check argon gas purity
- Temperature sensors: Static and Dynamic sensors to measure temperature maps
- LAr level meters: keep LAr level constant
- Cameras: Observe visible for detector operation
- Cosmic ray tagger (CRT): scintillator panels upstream/downstream

Purity Monitor Design



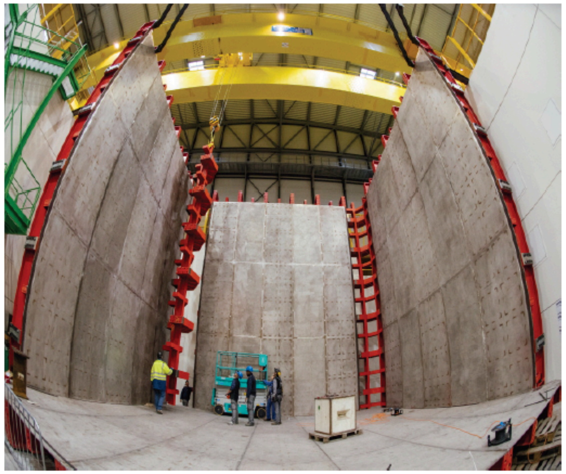
M. Adamowski et al., JINST 9, P07005 (2014).



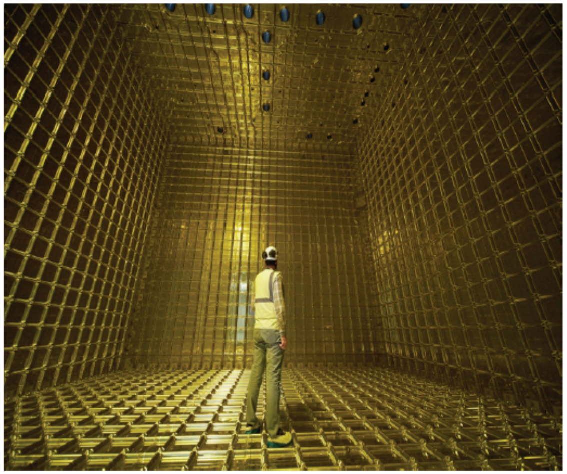


Milestones of ProtoDUNE-SP construction in EHN1

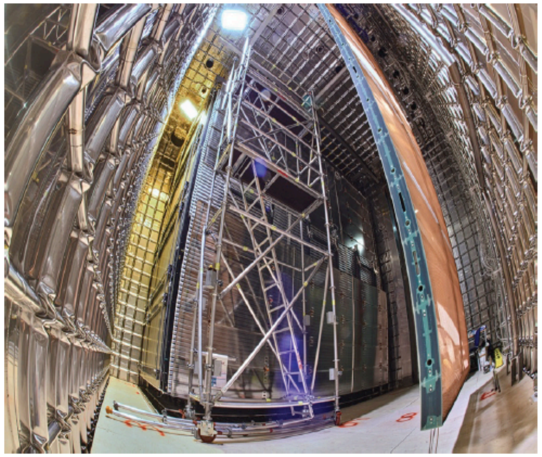
March 2016, construction of EHN1 extension



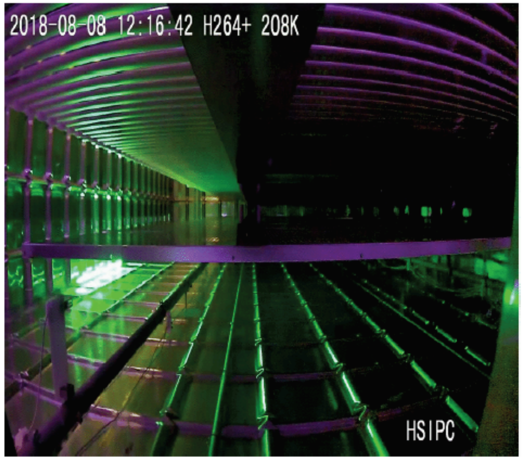
November 2016, cryostat structure assembly



September 2017, cryostat completion



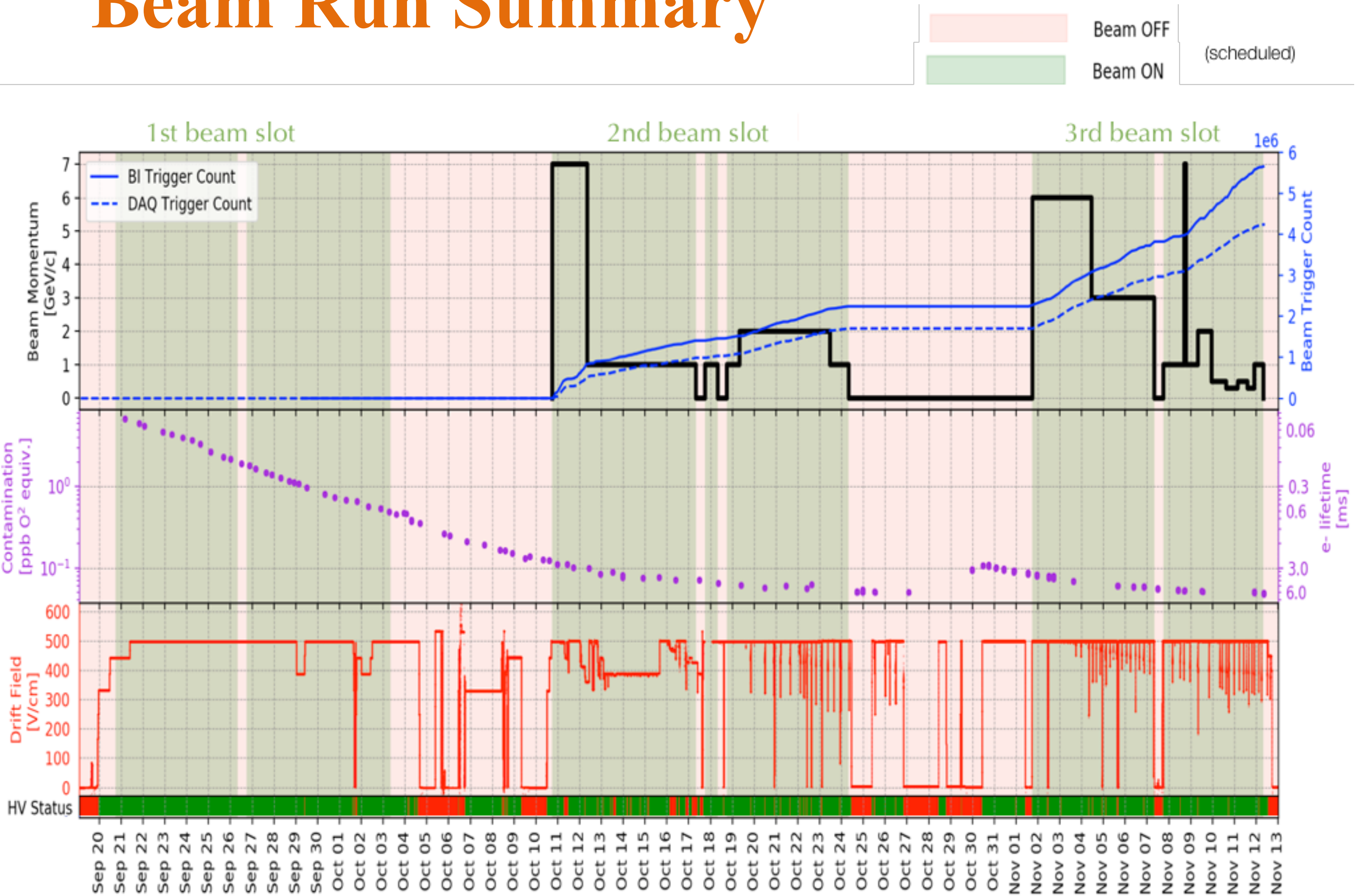
February 2018, detector assembly



August 2018, LAr filling

September 19, 2018 – HV @ 180 kV ready for beam!

Beam Run Summary

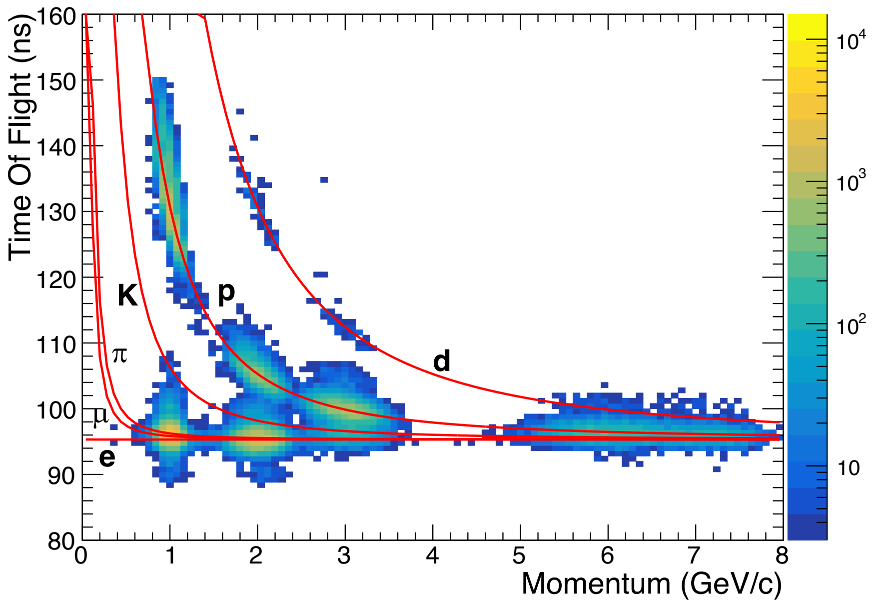


Jianming Bian - UCI

Collected beam events: Oct-Nov 2018

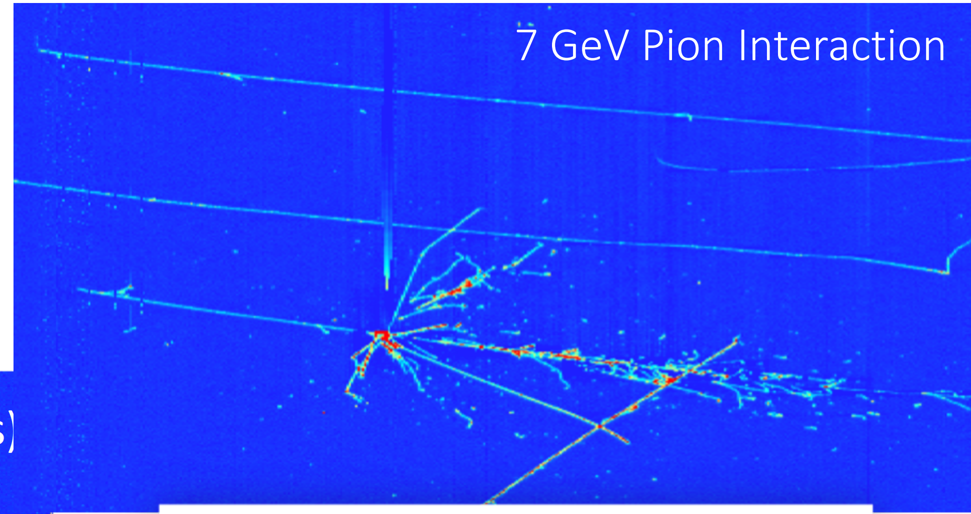
Momentum (GeV/c)	Total Triggers Recorded (K)	Total Triggers Expected (K)	Expected Pi trig. (K)	Expected Proton Trig. (K)	Expected Electron Trig. (K)	Expected Kaon Trig. (K)
0.3	269	242	0	0	242	0
0.5	340	299	1.5	1.5	296	0
1	1089	1064	382	420	262	0
2	728	639	333	128	173	5
3	568	519	284	107	113	15
6	702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

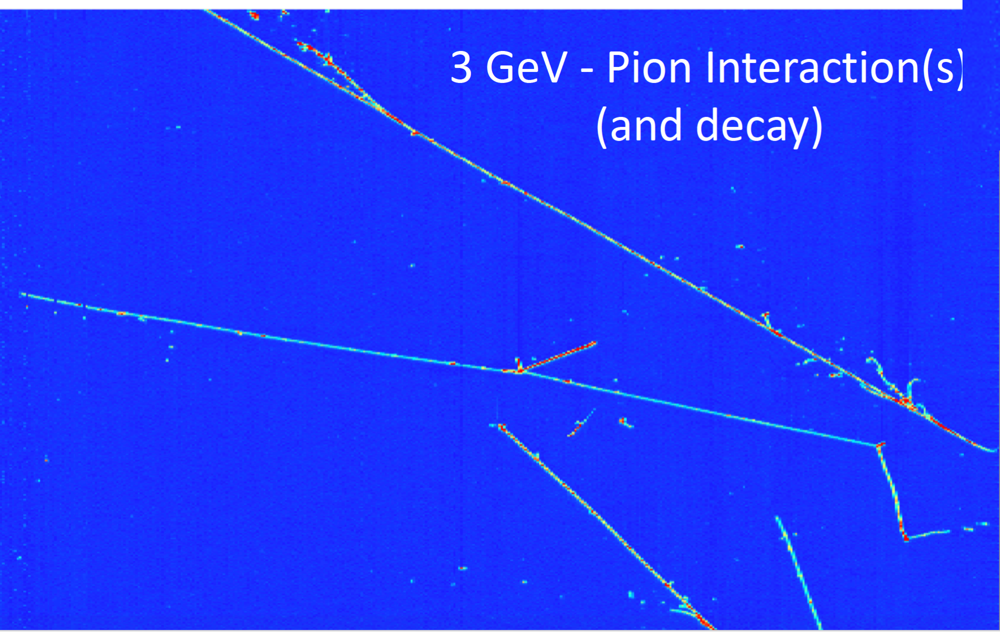
- 300k pion events at 1, 2, 3, 6, 7 GeV, enough for small cross section measurements
- Large statistics proton and electron data
- Some high energy kaon data
- Beamline Time of Flight (TOF) and Cherenkov measurements for PID.

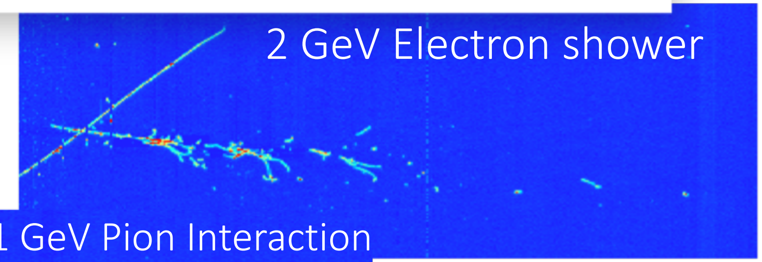


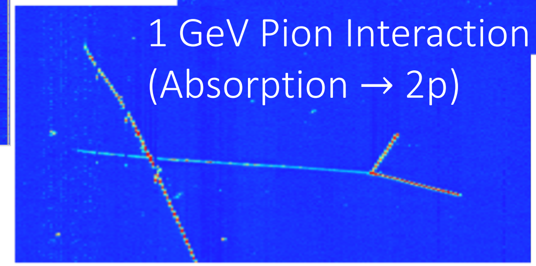
Event Displays

Resolution and data quality excellent
Electronic noise under control

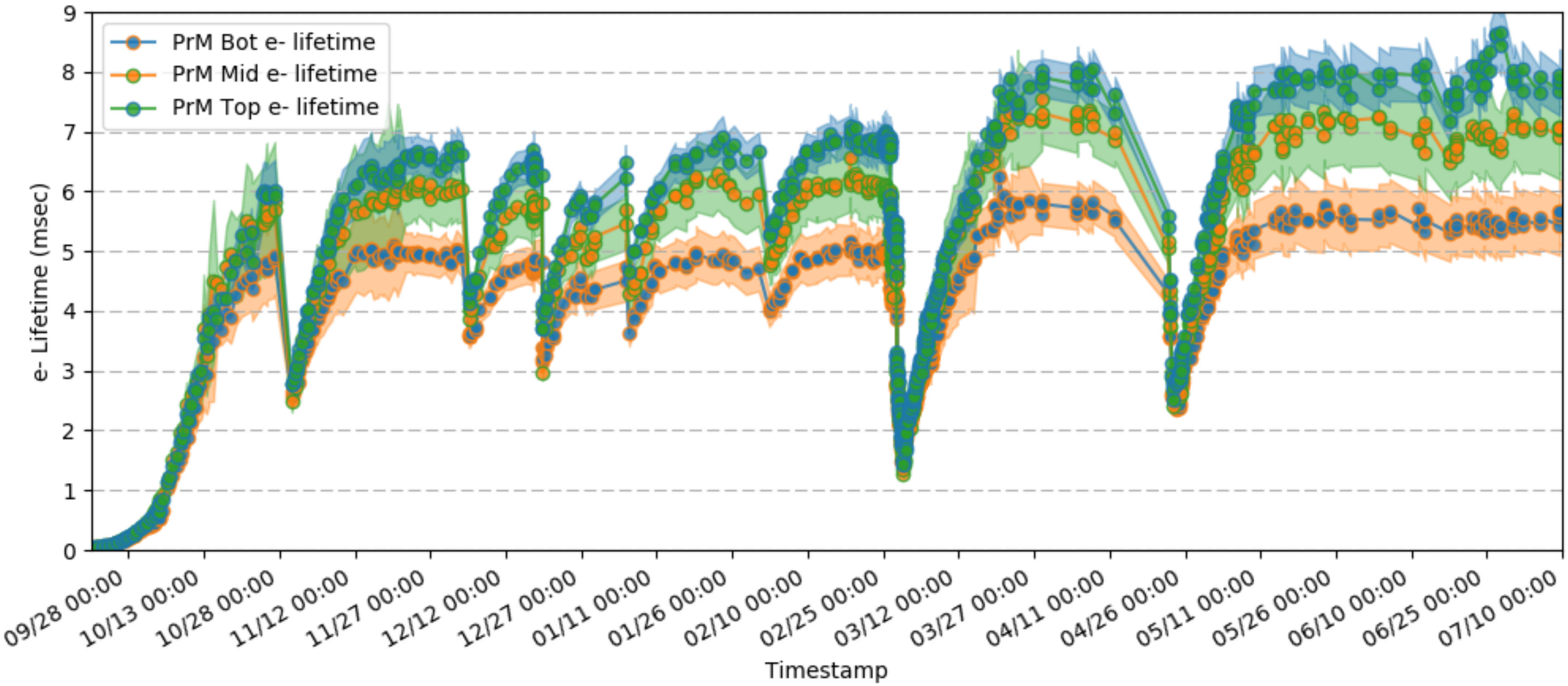








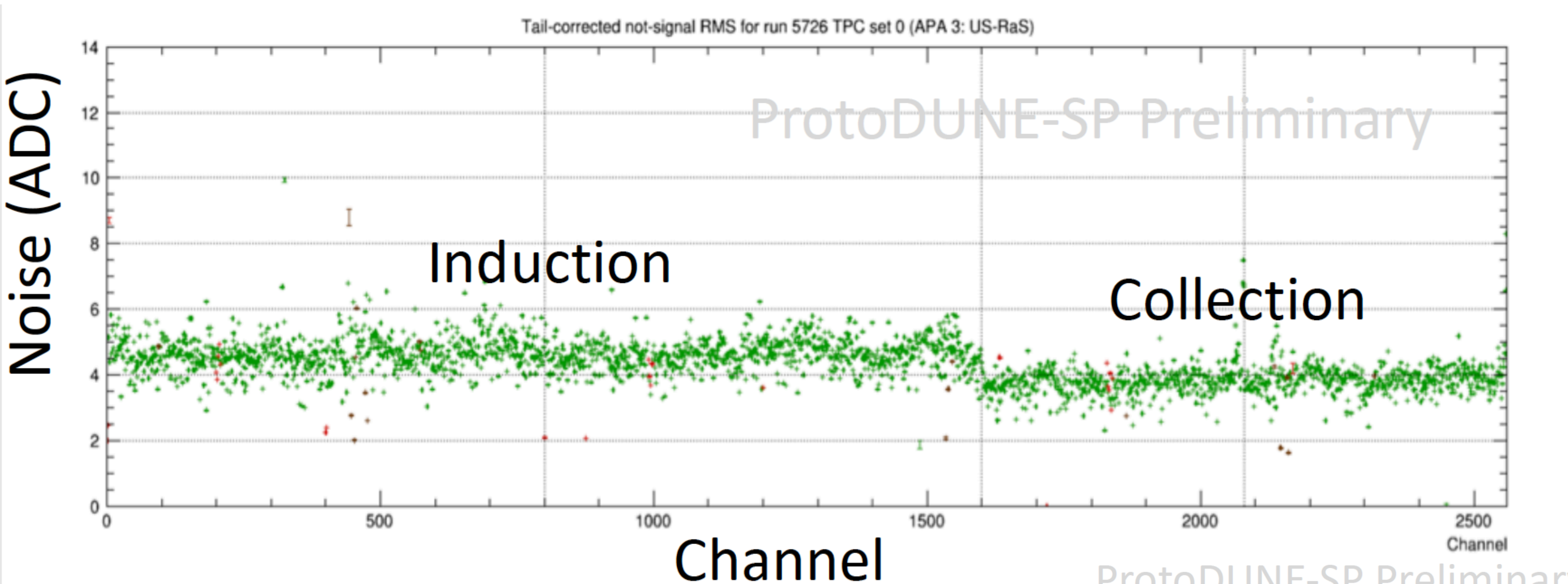
LAr Purity from Purity Monitors



- Liquid Argon purity routinely measured by the three Purity Monitors (PrM) at 1.8 m, 3.7 m, and 5.6 m from the bottom of the cryostat
- PrM: UV driven small TPC for electron lifetime measurement $Q_{anode}/Q_{cathode} = e^{-t_{drift}/\tau}$
- Gas/liquid recirculation & filtering rate ~ 1 volume/4.5 days, high purity reached
- Ar circulation pumps stoppage (electron lifetime dips) caught and alerted in time

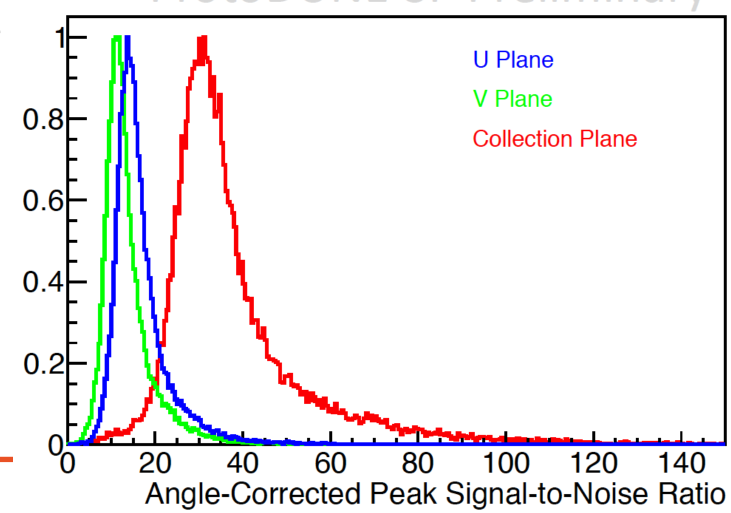
UCIRVINE DUNE

Electronic noise and S/N ratios

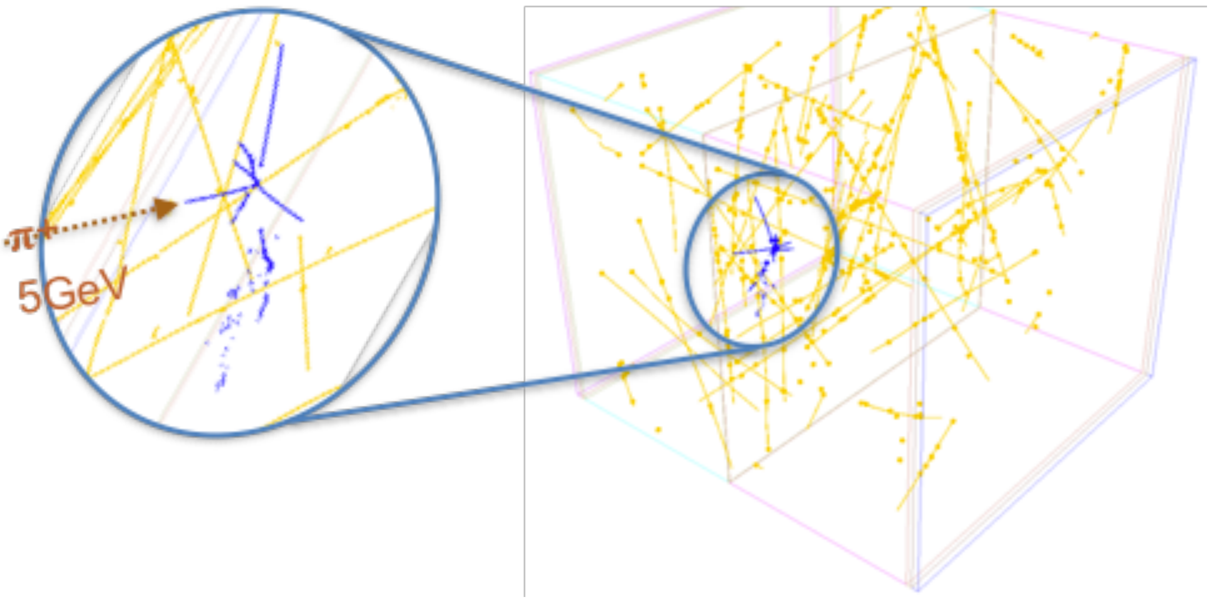


Noise level measured by pedestal RMS before noise filtering: Collection (X): 550 e-, Induction: 650 e- (DUNE goal 700 e-)
Noise filter reduces both by 100 e-

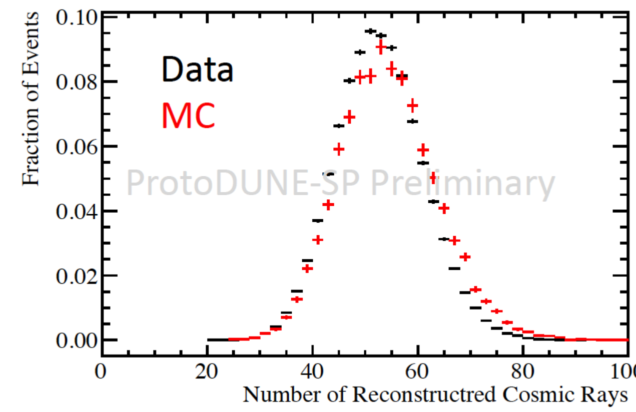
Signal-to-noise ratio measured by cosmic muons
Collection: 38:1, Induction U: 14:1, Induction V: 17:1



Beam Event and Cosmic Ray Reconstruction



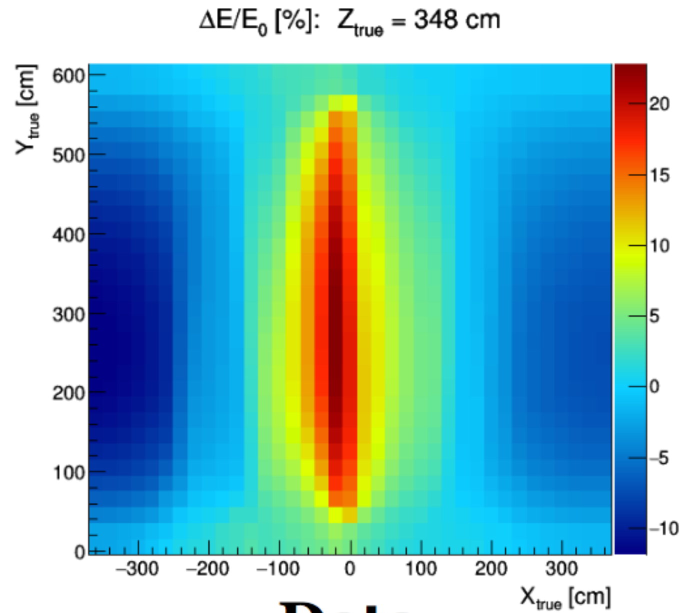
Number of reconstructed cosmic ray tracks in the 3 ms readout window



- PANDORA pattern recognition (arXiv:1708.03135) reconstructs, separates and classifies beam events and cosmic muons tracks in 3 ms TPC readout window
- Subsequent off-line analysis treats beam events and for the cosmic ray muon tracks separately

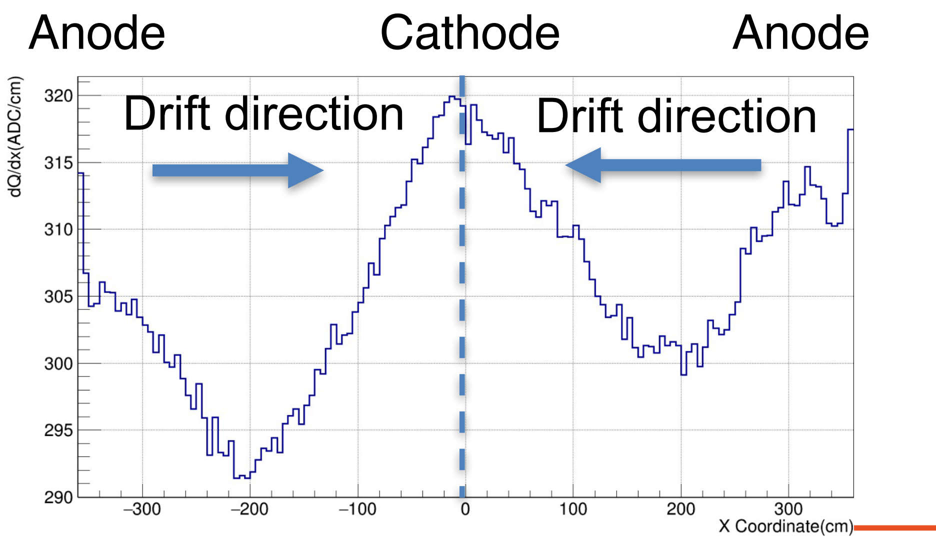
Space Charge Effects

E-field map: +20% at cathode, -10% at anode due to SCE

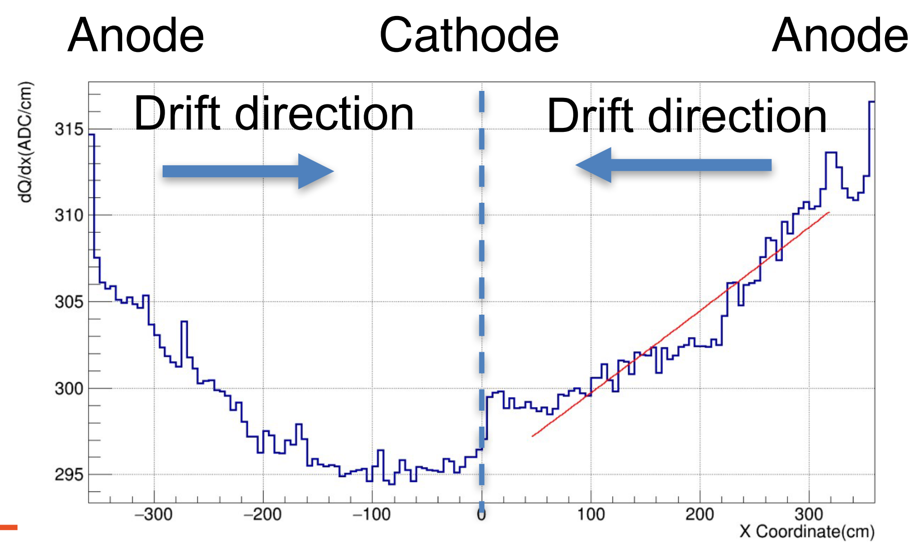


Data

- Space Charge Effect (SCE): E-field distortion due to accumulation of slow drifting ions induced by cosmic rays (Joshua Thompson's poster)
- Bias reconstructed dE/dx, particle trajectory and recombination
- Critical effects to energy and position calibration
- Can be removed by E-field map correction measured in cosmic data



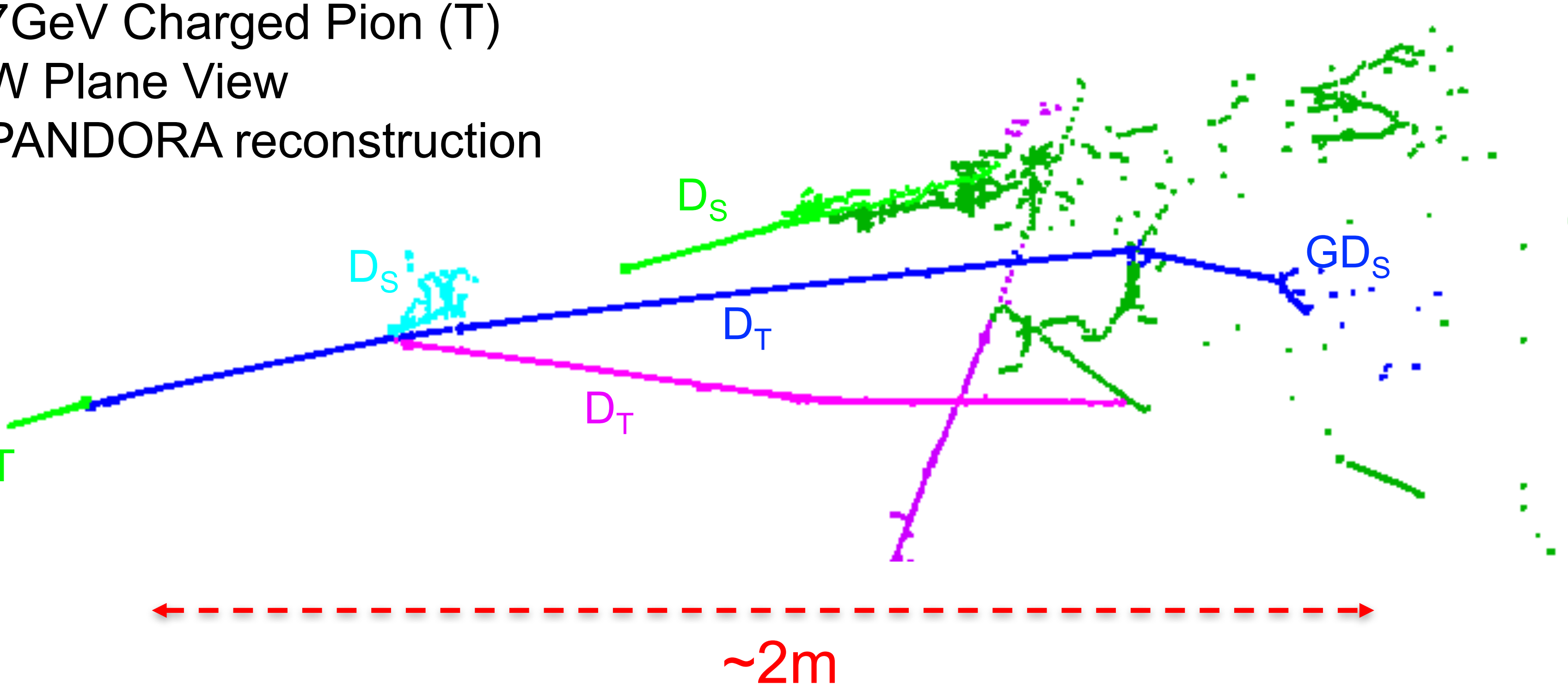
Before SCE correction



After SCE correction

Beam Data Events

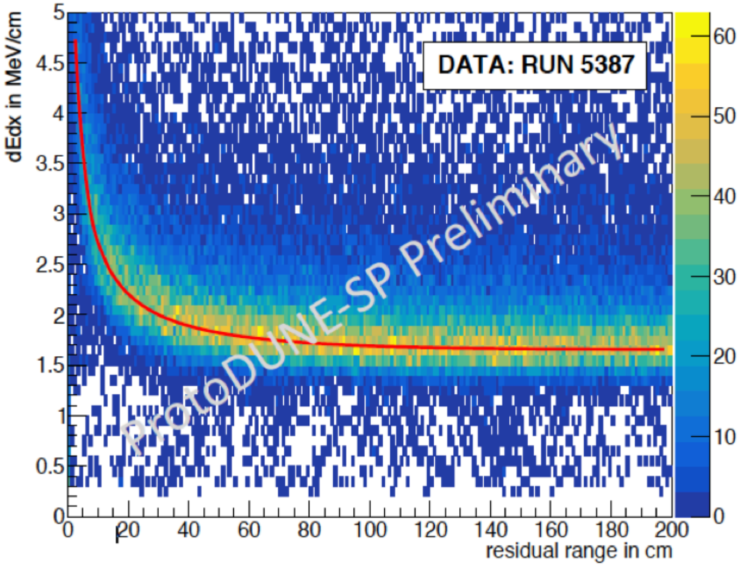
7GeV Charged Pion (T)
W Plane View
PANDORA reconstruction

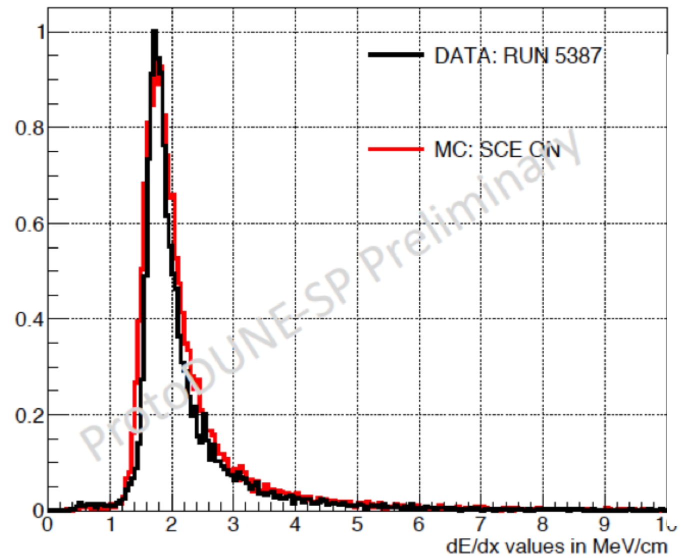


TPC reconstruction chain tested with real test beam data

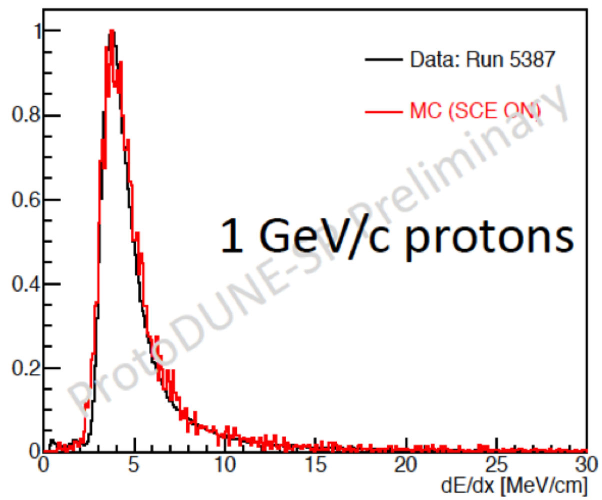
T = Trigger Parent Particle from test beam
D_T = Daughter Track
D_S= Daughter Shower
GD_T = Granddaughter Track
GD_S= Granddaughter Shower

dE/dx Reconstruction



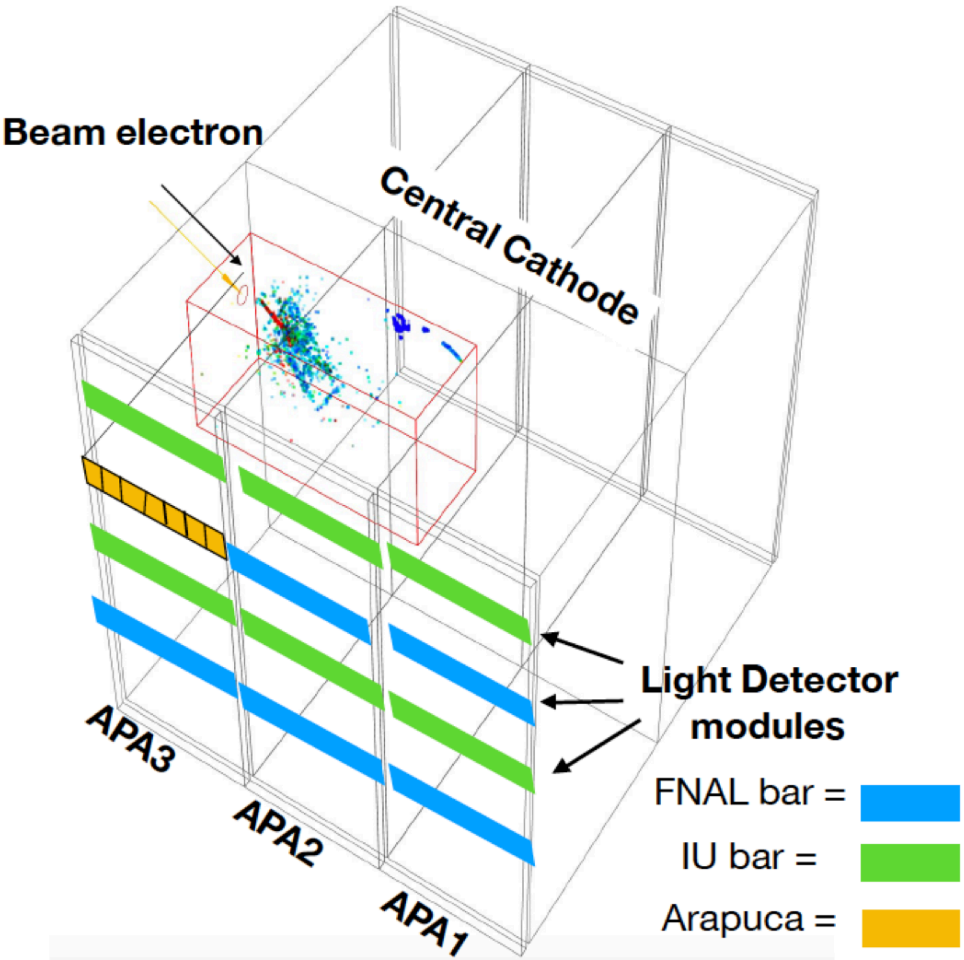


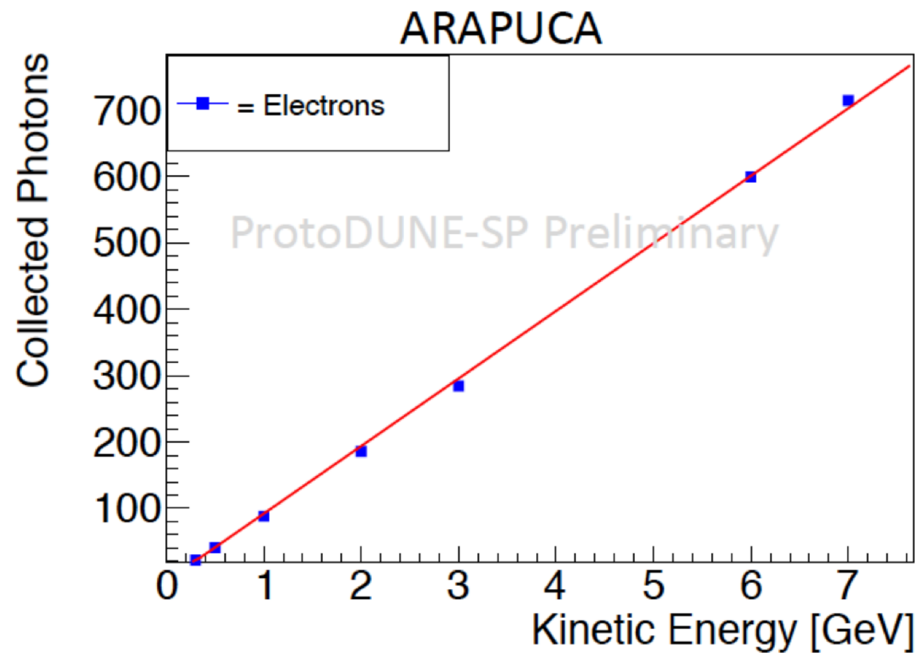
After SCE correction, use stopping muons to determine the absolute dE/dx scale



Same stopping muon absolute calibration works well for beam proton data

Photo Detector Performance





- Good energy linearity for contained beam electrons in the detector
- Working on geometry, attenuation and efficiency corrections

Summary

- First test beam data taken with the ProtoDUNE-SP LArTPC show excellent detector performance
- Calibration and reconstruction chain tested successfully with data:
  - Detector non-uniformity corrected
  - Energy scale determined
  - Excellent particle ID demonstrated
- Two papers under preparation on detector tech and performance
- Working on hadron cross section measurements to improve event generators and GEANT for DUNE
- Studying long-term operational stability
- Preparing round 2 beam test at CERN

Thank you!

Backup

Neutrino Oscillation at DUNE

ν_e appearance

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

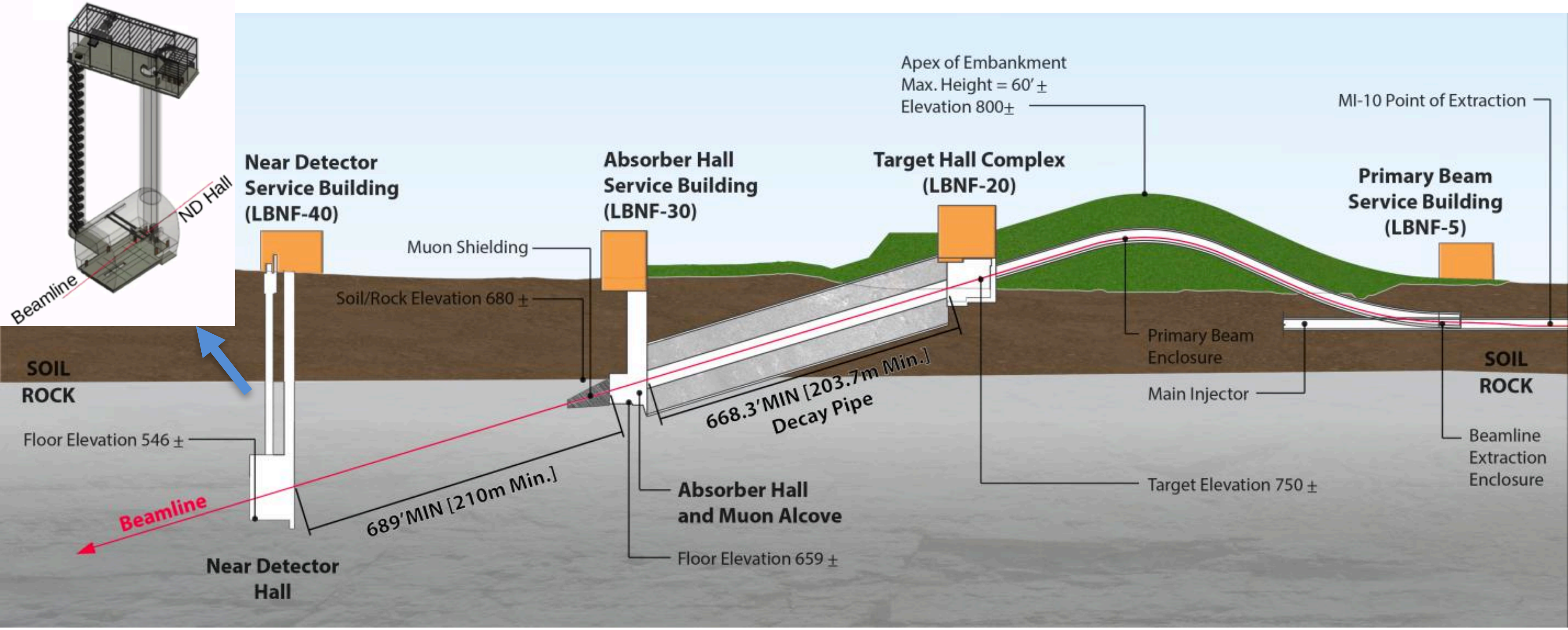
$$+ \ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta m^2_{31} L}{4E} \qquad A = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

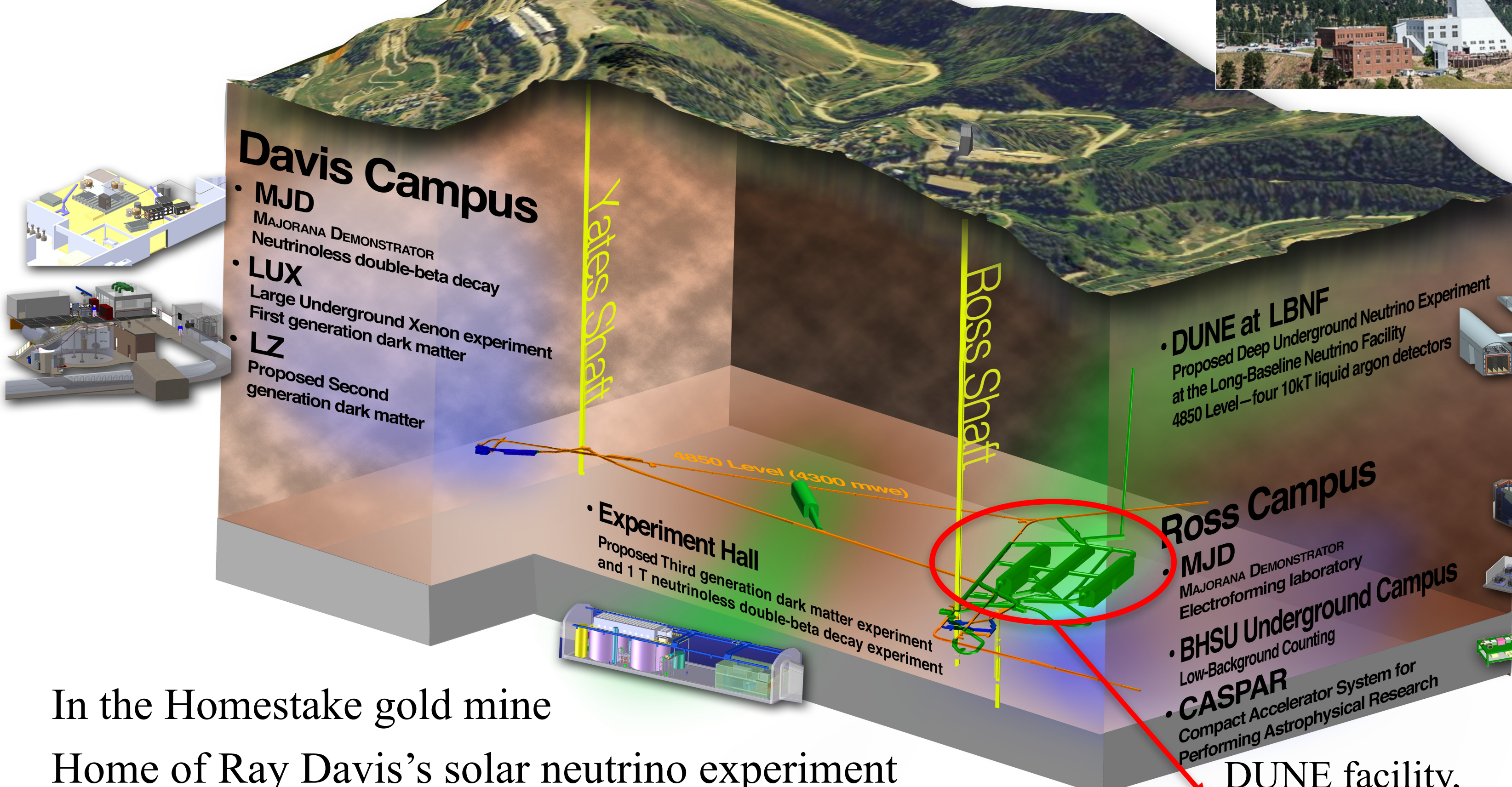
- DUNE measures ν_e appearance probability and ν_μ disappearance probability with ν_u and anti-ν_u beam.
- ν_e appearance: mass hierarchy, δ_{CP} and octant of θ_{23}
- ν_μ disappearance: high precision $|\Delta m_{32}|$ and $\sin^2 2\theta_{23}$, constrain octant

Long Baseline Neutrino Facility (LBNF)



- 60-120 GeV protons from Fermilab Main Injector
- Wide energy spectrum covers the 1st and 2nd oscillation maxima
- Initial upward pitch, 101 mrad pitch to get to S. Dakota
- Near Detector Hall at edge of Fermilab site
- Initially 1.2 MW @ 80GeV, upgradeable to 2.4 MW
- Reference design similar to NuMI, optimized to improve sensitivity to oscillation measurements

Sanford Underground Research Facility (SURF), Lead, S. Dakota



DUNE facility,
4850 ft (1.5km, 4300 mwe)

- In the Homestake gold mine
- Home of Ray Davis's solar neutrino experiment
- 4 caverns for detector and one utility hall for DUNE
- Blast vibration study has been done
- Excavation for the first two caverns started in FY2017

Groundbreaking: 21st July, 2017

Beamline TOF and Cherenkov for PID

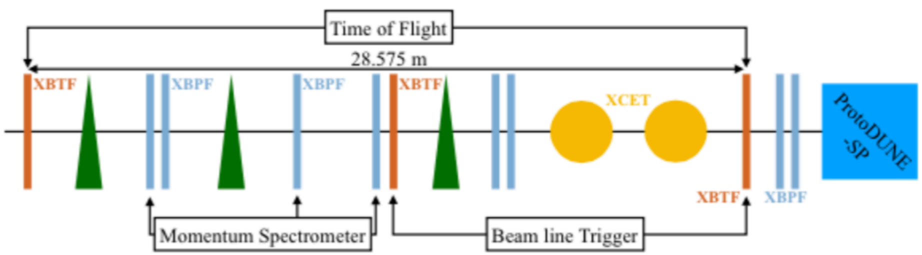


Figure 1: A schematic diagram showing the relative positions of XBTFs (orange), bending magnets (green), XBPFs (blue) and XCET (yellow) in the H4-VLE beam line. Combining data from different pieces of instrumentation can be used for triggering, reconstructing momentum and measuring time of flight, as discussed in the text.

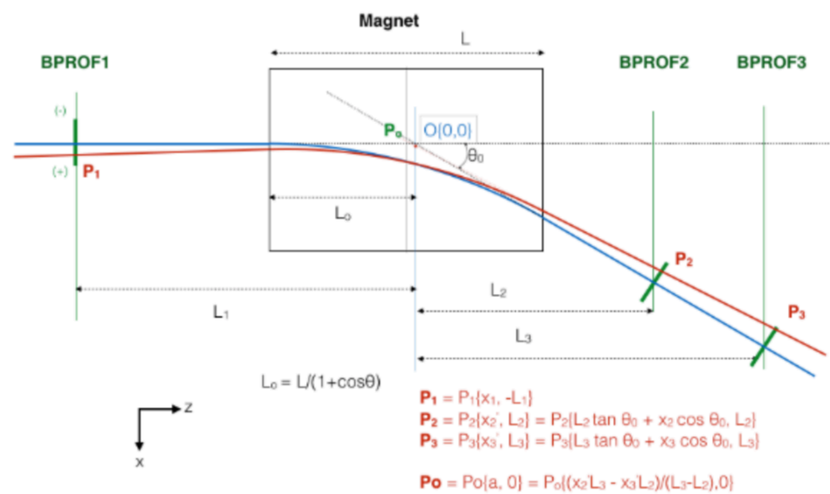


Figure 2: A schematic diagram showing the method by which momentum is reconstructed for a given beam particle (red), as discussed in the text. Taken from [4].

Alexander Booth and Jake Calcutt
(ProtoDUNE Beam Instrumentation Working Group)

ProtoDUNE-SP Analysis Plan & Goals

- Detector Performance – Information for DUNE TDR & first papers
  - ✓ LAr purity
  - ✓ Noise level, signal to noise ratio
  - ✓ Detector calibration, removing space charge effects etc.
  - ✓ dEdx of muons, protons, pions, kaons, electrons
  - ❑ Energy and momentum resolutions (w/ Charge-TPC and *(in progress)* Light-PDS)
- Physics measurements - physics publications
  - ❑ (*started*) Total pion cross section in [1-7] GeV range
  - ❑ (*started*) Exclusive channels Cross Section:
    - ➢ π absorption: $\pi^{\pm} \rightarrow$ 2p, 3p, 2p1n,..
    - ➢ $\pi^{\pm} \rightarrow \pi^{0}$ charge exchange, etc.

Tingjun Yang (Fermilab)

Detector calibration strategy

- Remove any nonuniformity in the detector response
  - ✓ **Space charge effects (SCE)** – removed using E-field map
  - ✓ Attenuation caused by impurities – removed using muon MIP map
  - ✓ Variations in electronics gain – removed using pulser data
  - ✓ Other effects (grounded electron diverters, floating grid plane, etc.) – removed using muon MIP map
- Determine the absolute energy scale
  - ✓ Using stopping muons
    - dE/dx in the MIP region is very well understood theoretically to better than 1%

Using the same method developed by MicroBooNE: **arXiv:1907.11736**

Tingjun Yang (Fermilab)