Results on Physics Performance of ProtoDUNE-SP

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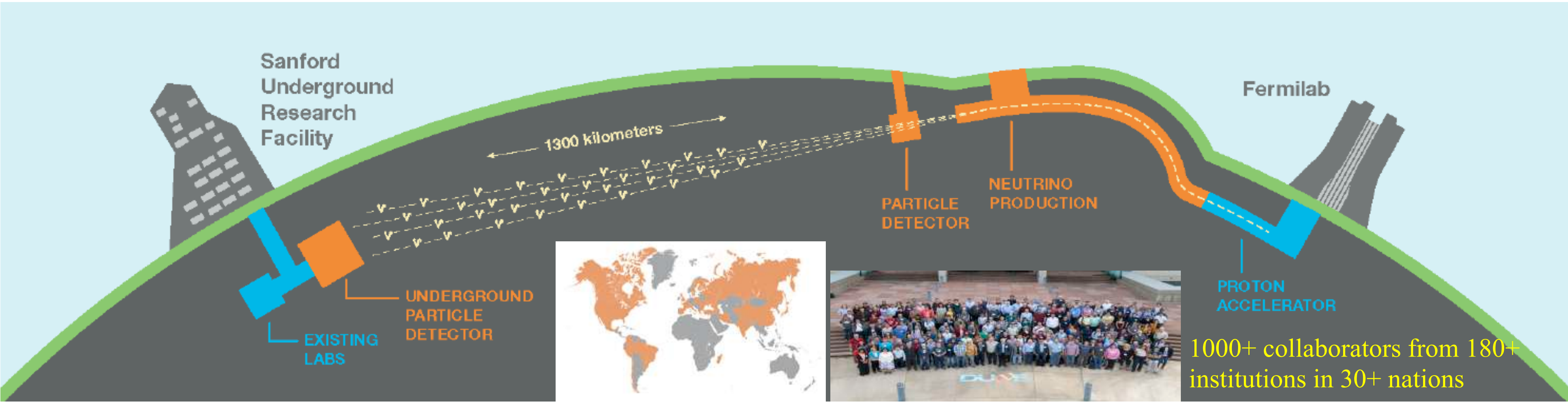
For the DUNE Collaboration

University of California, Irvine

02-25-2021

XIX International Workshop on Neutrino Telescopes, Online

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

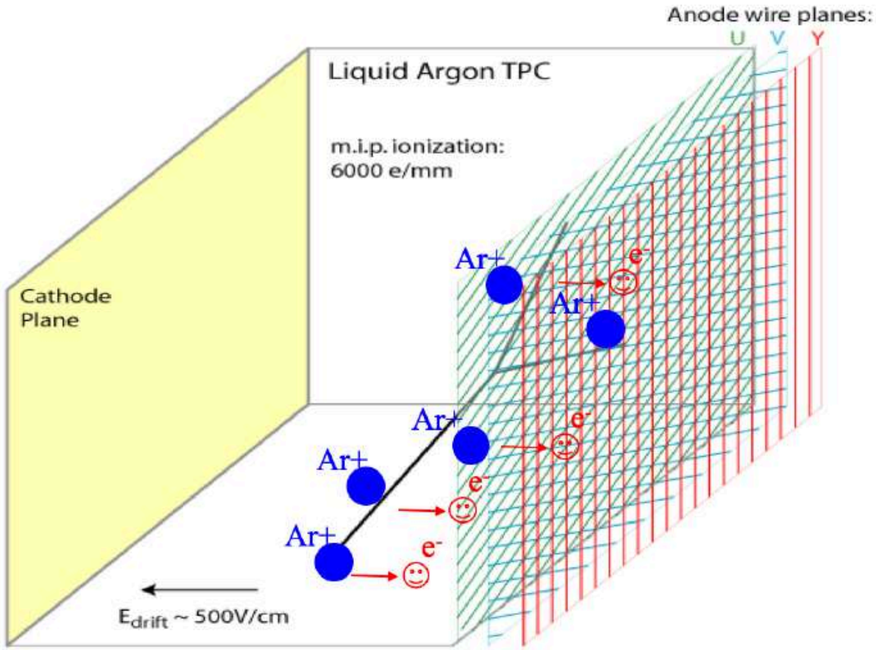


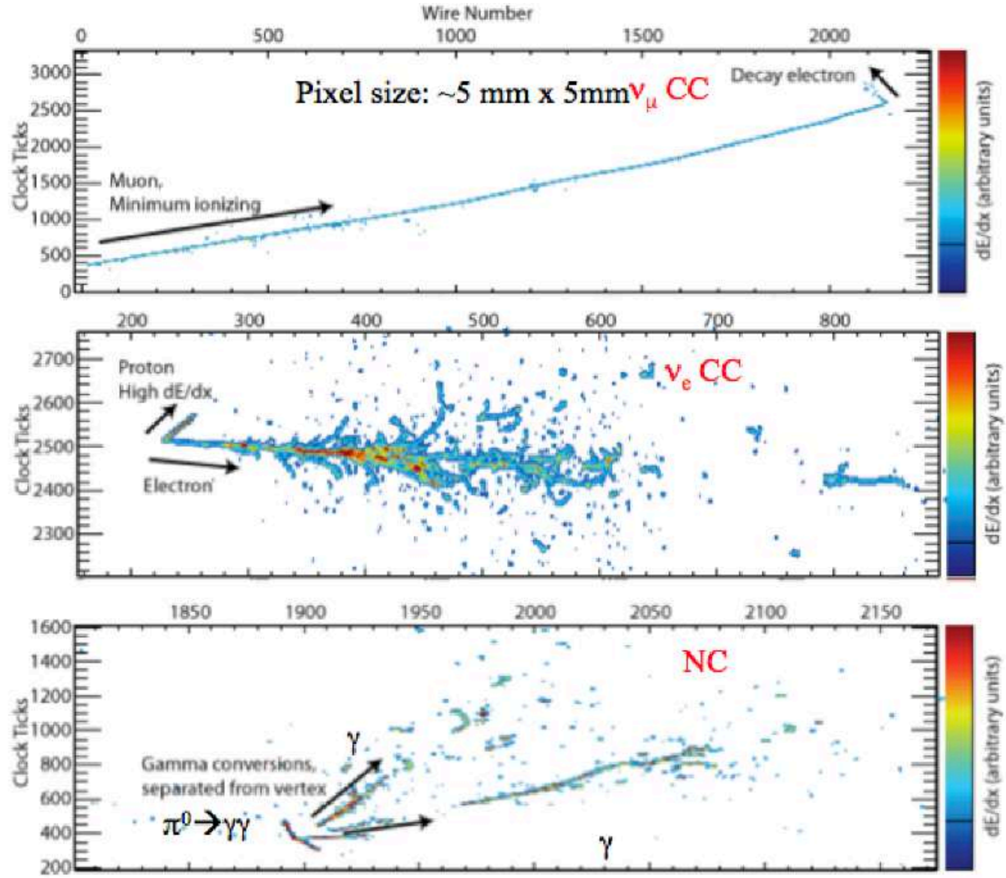
- DUNE: next generation neutrino experiment using LArTPC technology
  - New neutrino beam at Fermilab (1.2 MW@80 GeV protons, upgradeable to 2.4 MW), 1300 km baseline
  - 70 kton Liquid Argon Time Projection Chamber (LArTPC) Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
  - Multiple technologies for the Near Detector (ND)

(Karagiorgi, Battisti, Mohayai and Singh's talk in NuTel21)

- ν_e appearance and ν_μ disappearance → Neutrino mass ordering and CP violation
- Large detector, deep underground, high intensity beam → Supernova burst neutrinos, atmospheric neutrinos, nucleon decay and other BSM, etc
- Excavation started in 2017, begin taking data in late 2020s

Far Detectors: Liquid Argon Time Projection Chamber (LArTPC)

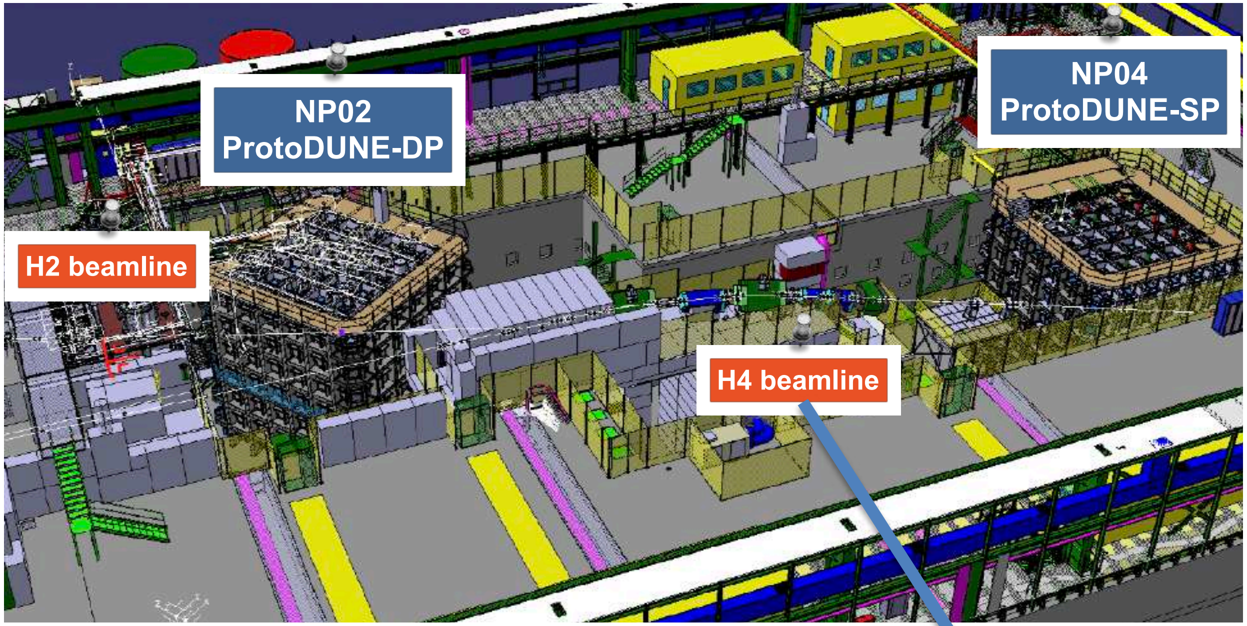




Event display in LArTPC (MicroBooNE MC)

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

ProtoDUNE SP and DP at EHN1 (CERN)

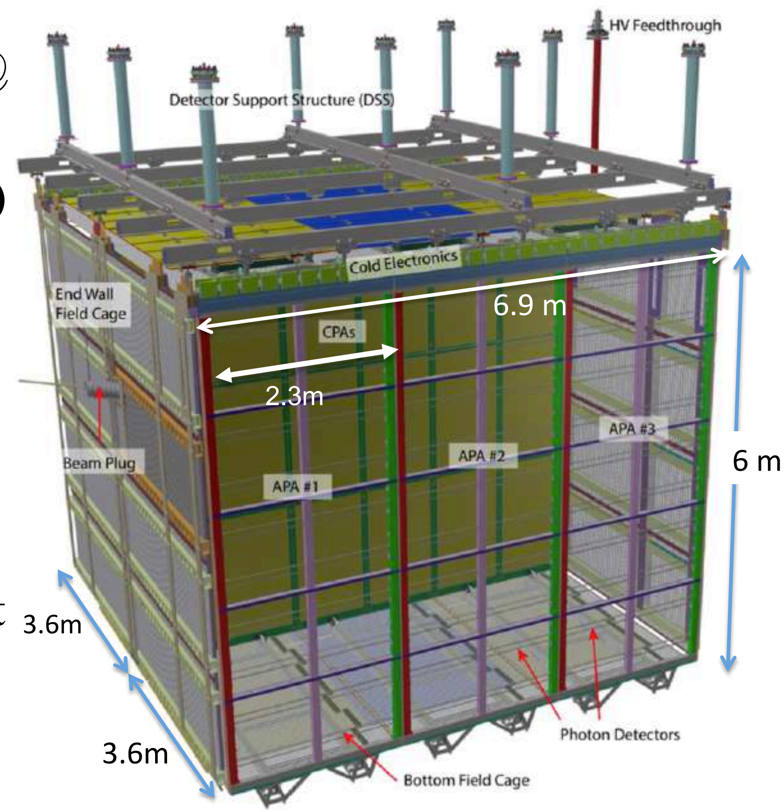


- ProtoDUNE-SP and DP are two large DUNE prototype detectors at CERN Neutrino Platform EHN1
- 770 tons LAr mass each
- Exposed to test beams H4(SP) and H2(DP), momentum-dependent beam composition contains $e, K^{\pm}, \mu, p, \pi^{\pm}$
- Also take cosmic ray data

- 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-SP Detector

- TPC:
  - Two drift volumes, 3.6m drift distance in each @ 500V/cm
  - Active Volume: 6m (H) x 7m (L) x 2 x 3.6m (W)
  - Cathode Plane Assembly (CPA) on middle plane
  - Anode Plane Assemblies (APAs) on both sides
  - Cold electronics attached to the top of APAs
- Photon detectors (PDS):
  - SiPM readouts
  - Wavelength shifter converts VUV to visible light
  - 3 designs integrated into APA frame bars
- Cryogenic instrumentations: measure argon purity, temperature, liquid level and tag cosmic rays
- ProtoDUNE-SP Phase-I was operated Sept. 2018 – July 2020, Run-II data taking is under preparation



CPA:
- 18 CPA modules
- HV=180 kV

APA:
- Each APA module: 6m high, 2.3m wide
- Two induction planes and one collection plane

Cold electronics
- 2560 wires/APA, 15360 total wires

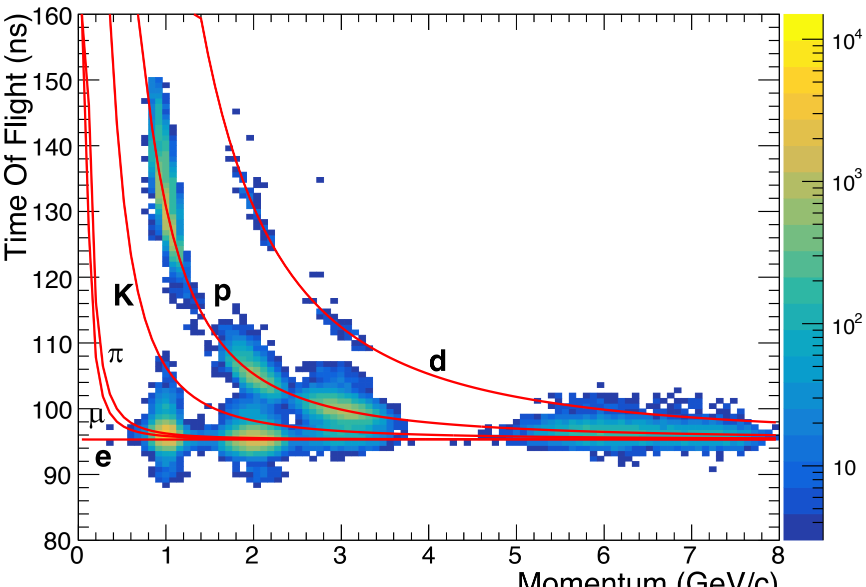
Field cage
- Surrounds the open sides of the drift region to ensure uniform electric field

Collected beam events: Oct-Dec 2018

Data taking time, total running time

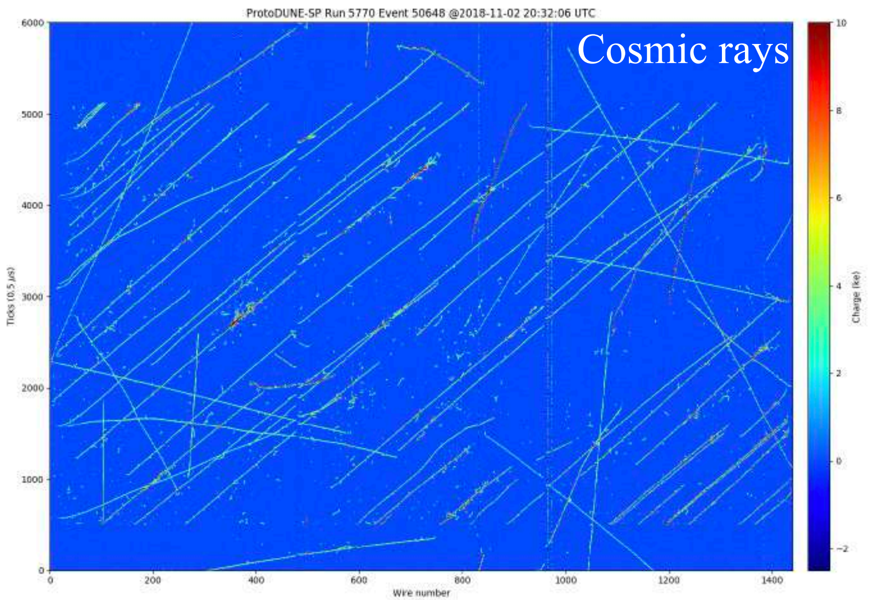
Momentum (GeV/c)	Total Triggers Recorded (K)	Total Triggers Expected (K)	Expected Pi trig. (K)	Expected Proton Trig. (K)	Expected Electron Trig. (K)	Expected Kaon Trig. (K)
0.3	269	242	0	0	242	0
0.5	340	299	1.5	1.5	296	0
1	1089	1064	382	420	262	0
2	728	639	333	128	173	5
3	568	519	284	107	113	15
6	702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

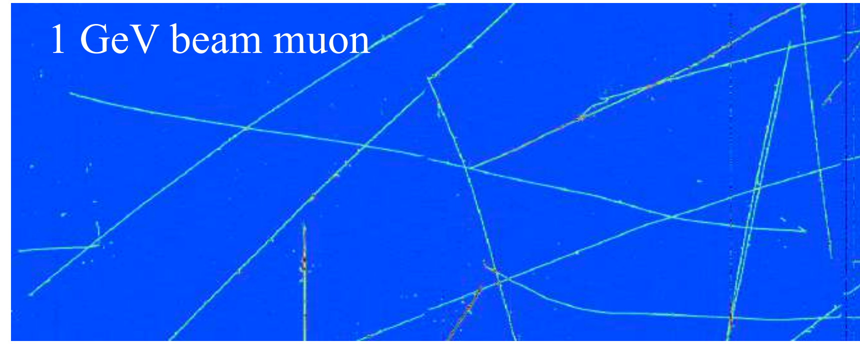
- Large statistics pion, proton, electron and kaon data at 1, 2, 3, 6, 7 GeV, data
- Beamline Time of Flight (TOF) and Cherenkov measurements for beam particle ID
- First paper on ProtoDUNE-SP performance published: JINST 15 (2020) 12, P12004

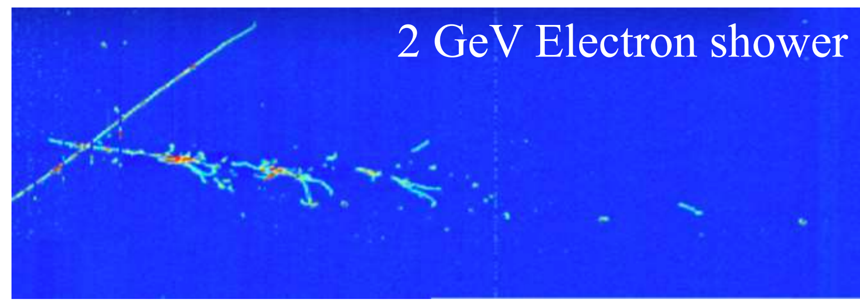


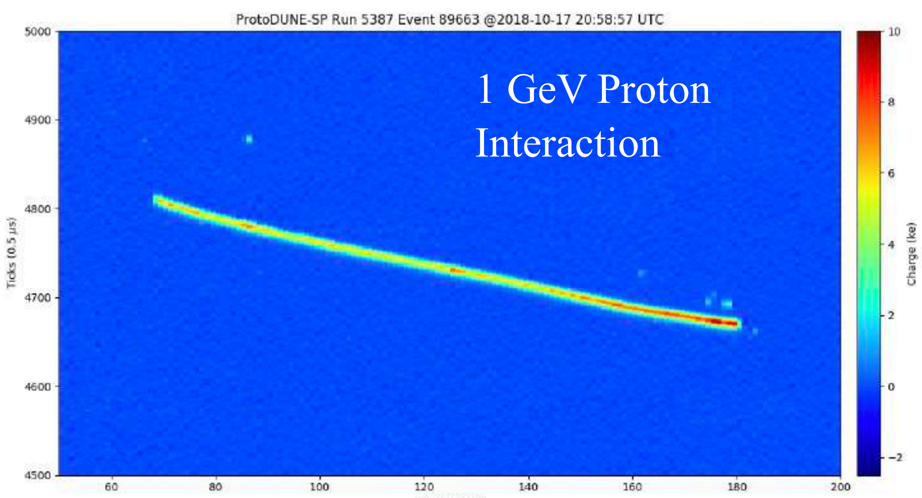
Event Displays in ProtoDUNE-SP Data

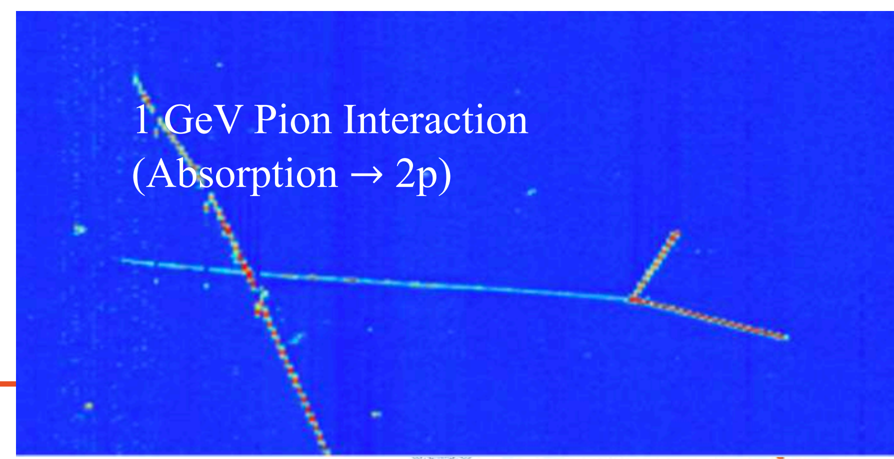
Resolution and data quality excellent → Liquid argon has high purity, Electronic noise under control



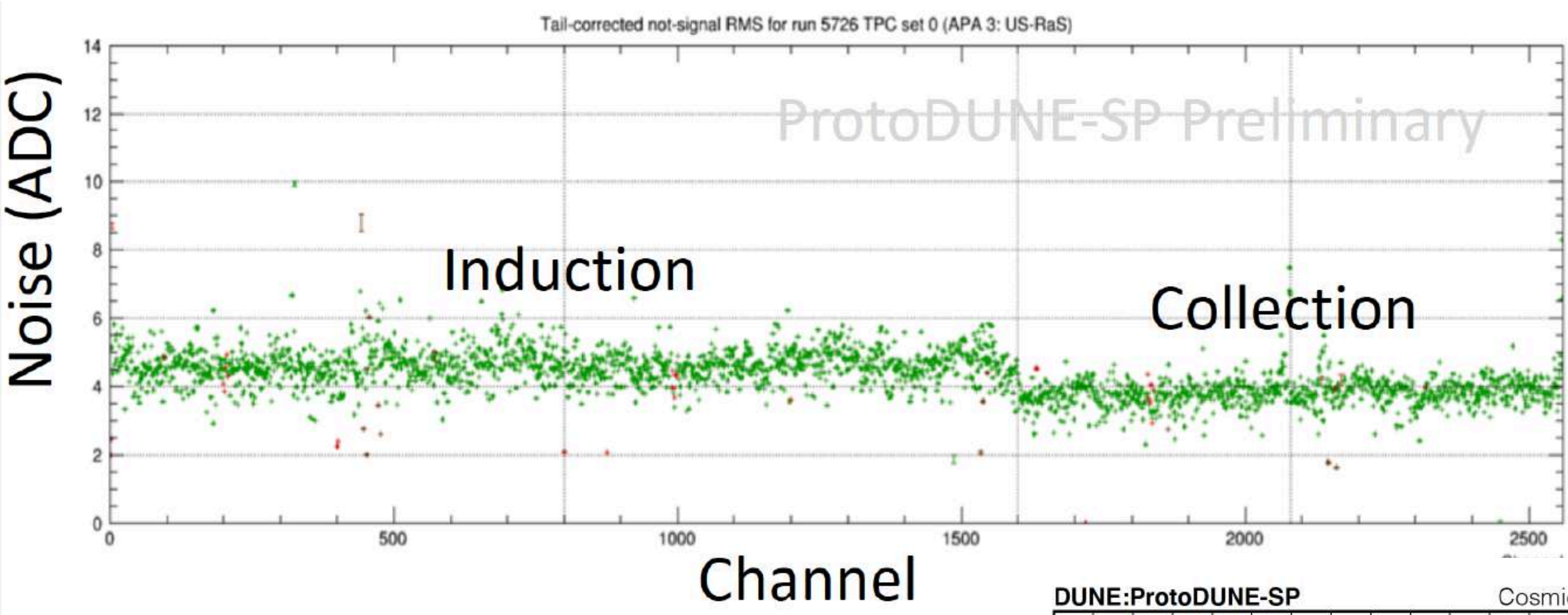


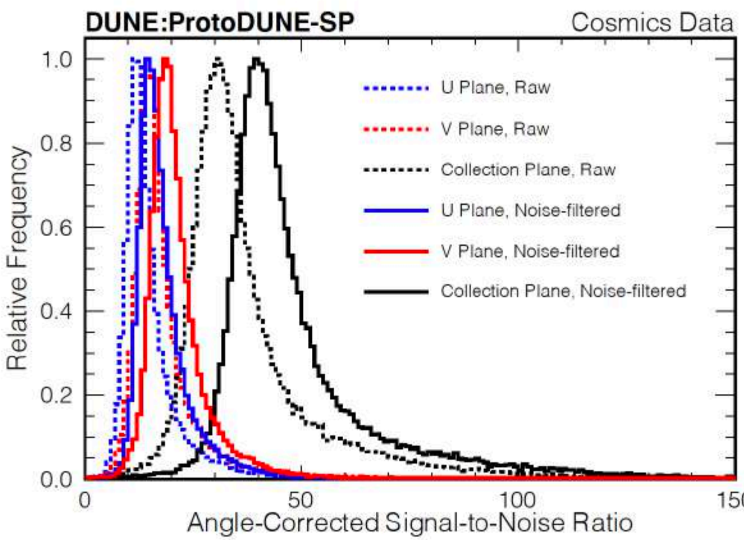






Electronic noise and S/N ratios

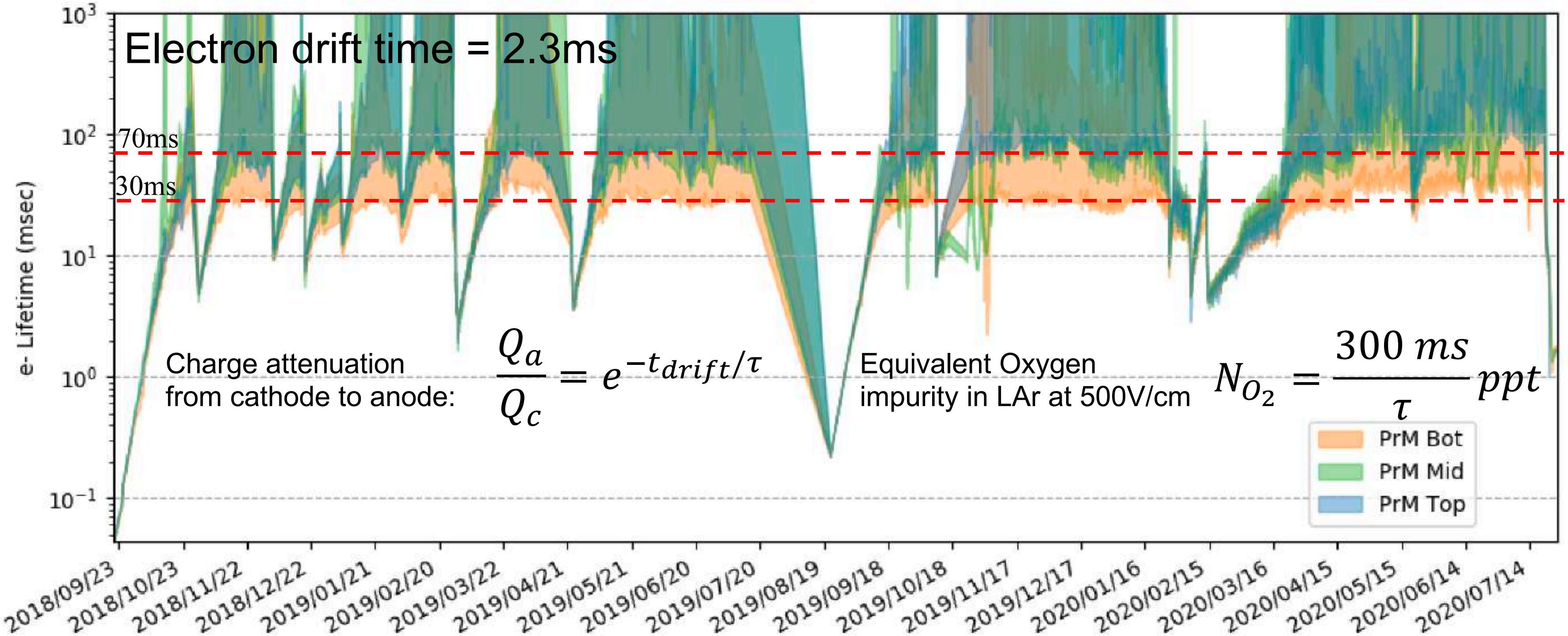




- Electronic noise level measured by pedestal ENC (equivalent noise charge) before noise filtering: Collection (X): 550 e-, Induction: 650 e- (DUNE goal <1000 e-)
- Noise filter reduces both by ~100 e-
- Noise-filtered signal-to-noise ratio measured by cosmic muons: Collection: 48.7:1, Induction : 21.2:1

Jianming Bian - UCI

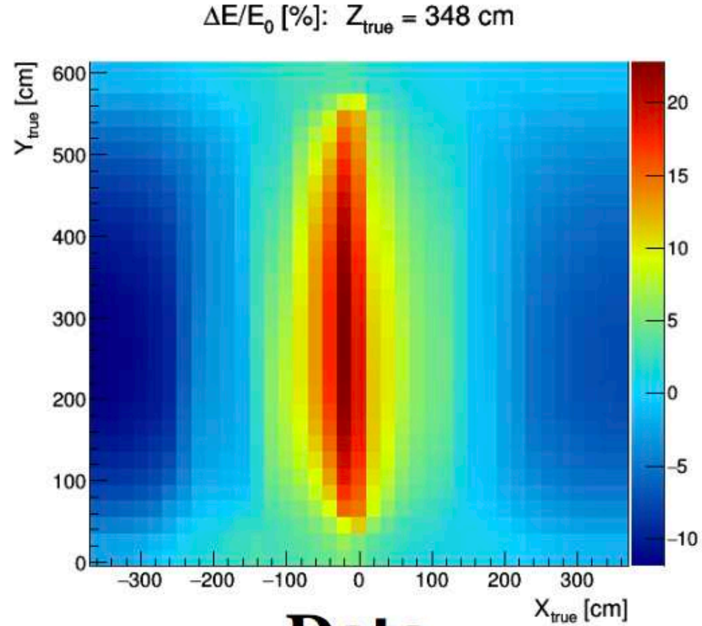
Drift electron lifetime from Purity Monitors

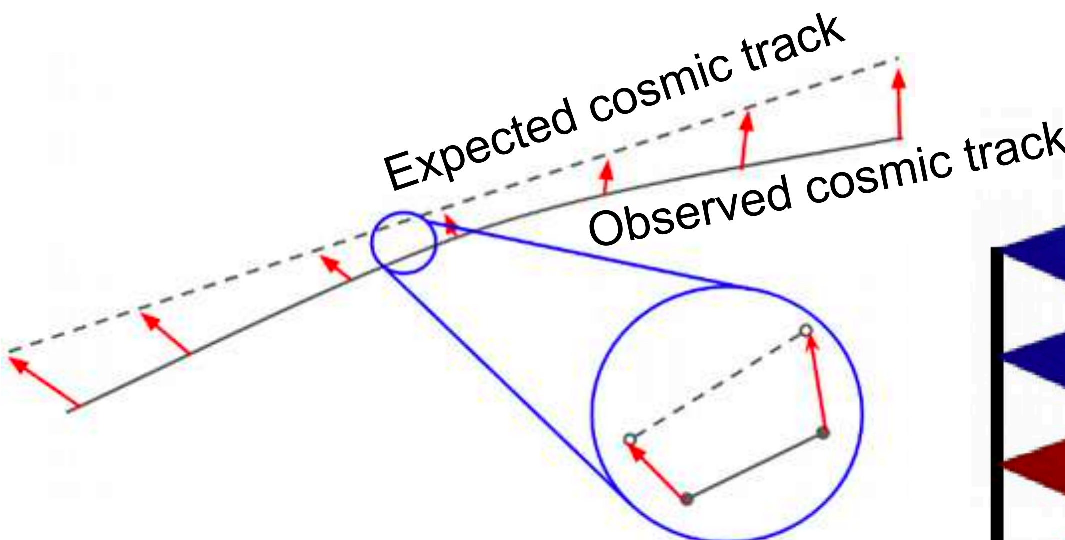


- Drift electron lifetime (τ): average drift time of electrons before captured by LAr impurities
- Key component of LArTPC calibration - corrects charge loss caused by LAr impurities
- Electron lifetime measured by purity monitors (small TPCs which measure e-lifetime with photoelectrons from a UV light source)
- Validated with cosmic ray tagger (CRT, Diurba's talk at NuTel21) data.
- High LAr purity and electron lifetime (>30ms) achieved at ProtoDUNE-SP

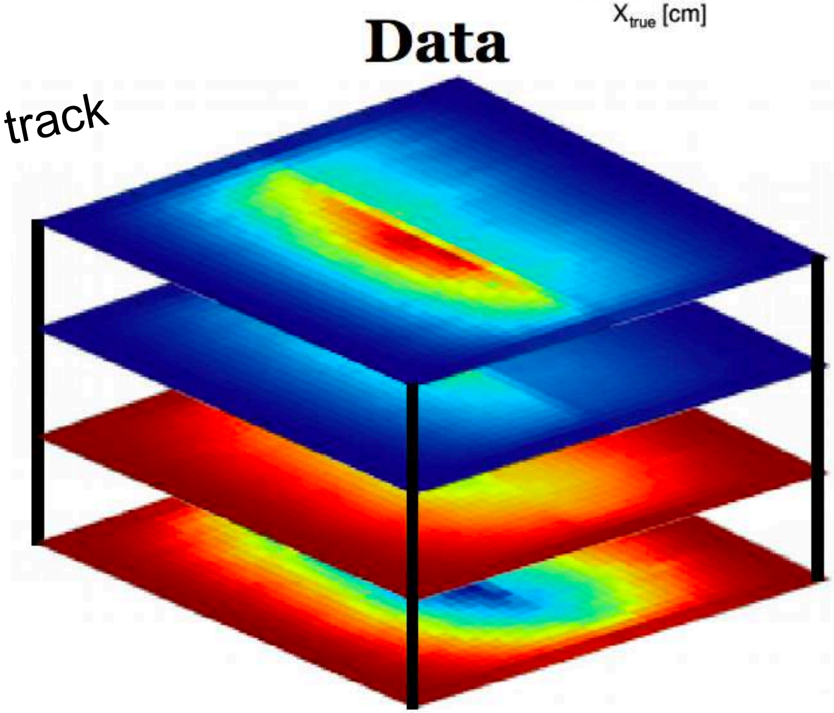
Space Charge Effect Correction with cosmic rays

- Space Charge Effect (SCE): E-field distortions due to accumulation of slow drifting ions induced by cosmic rays
- Key effect to charge and position calibration for on-surface LArTPC experiments
- Solve for E-field distortion from spatial distortion observed in cosmic ray tracks
- Map and correct E-field for calibration ~+20% at cathode, ~-10% at anode due to SCE



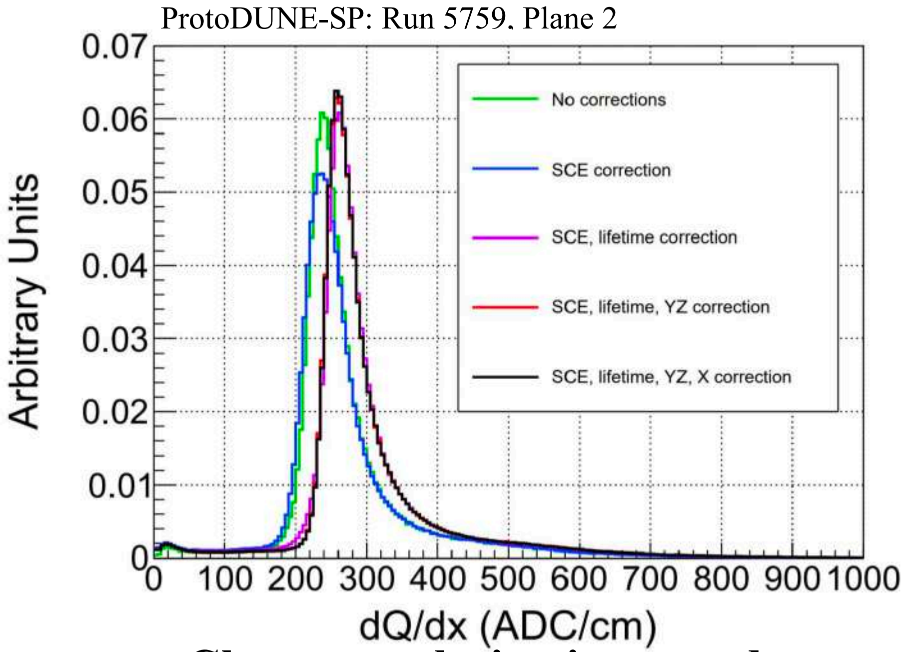


(Michael Mooney, ICHEP20)



TPC Calibration Scheme

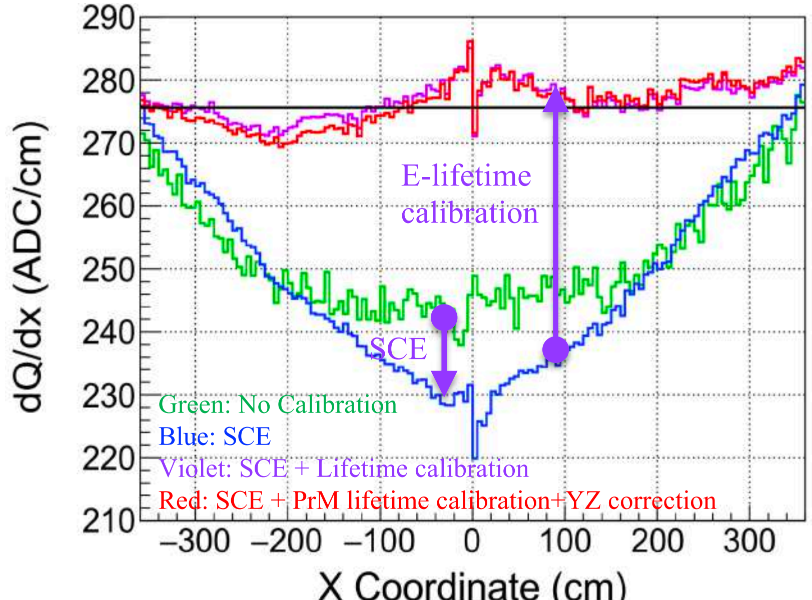
- Electron lifetime calibrated with purity monitors (validated with cosmic ray tagger data, Diurba's talk at NuTel21)
- Space charge effect corrected with cosmic rays
- Position calibration based on cosmic rays
- Absolute energy calibration: stopping muons in cosmic rays
- Other calibration methods under development: Ar39, neutron source, laser, radioactive source (Bezawada, Huang, Dvornikov and Fani's talk in NuTel21)



Charge resolution improved

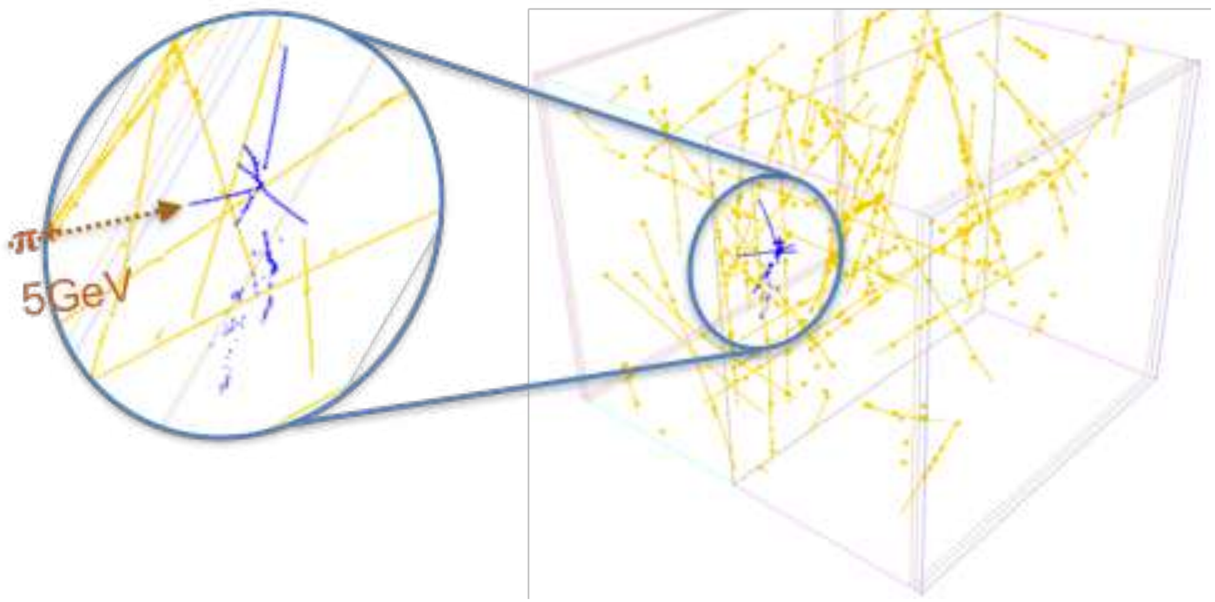
(Graham Chambers-Wall, Fermilab User's meeting 2020)

dQ/dx vs. drift distance of cathode-crossing cosmic muons

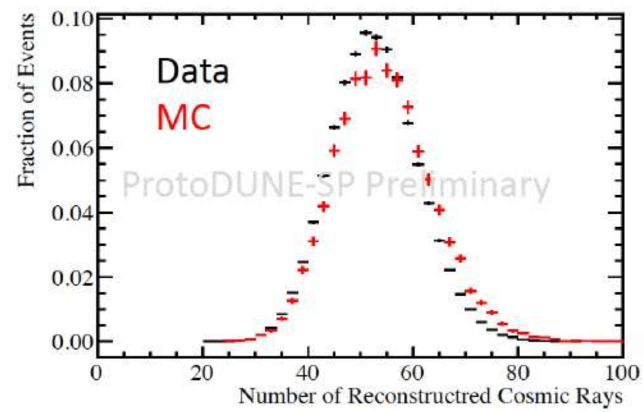


Charge attenuation and non-uniformity on TPC signal mostly corrected

Beam Event and Cosmic Ray Reconstruction



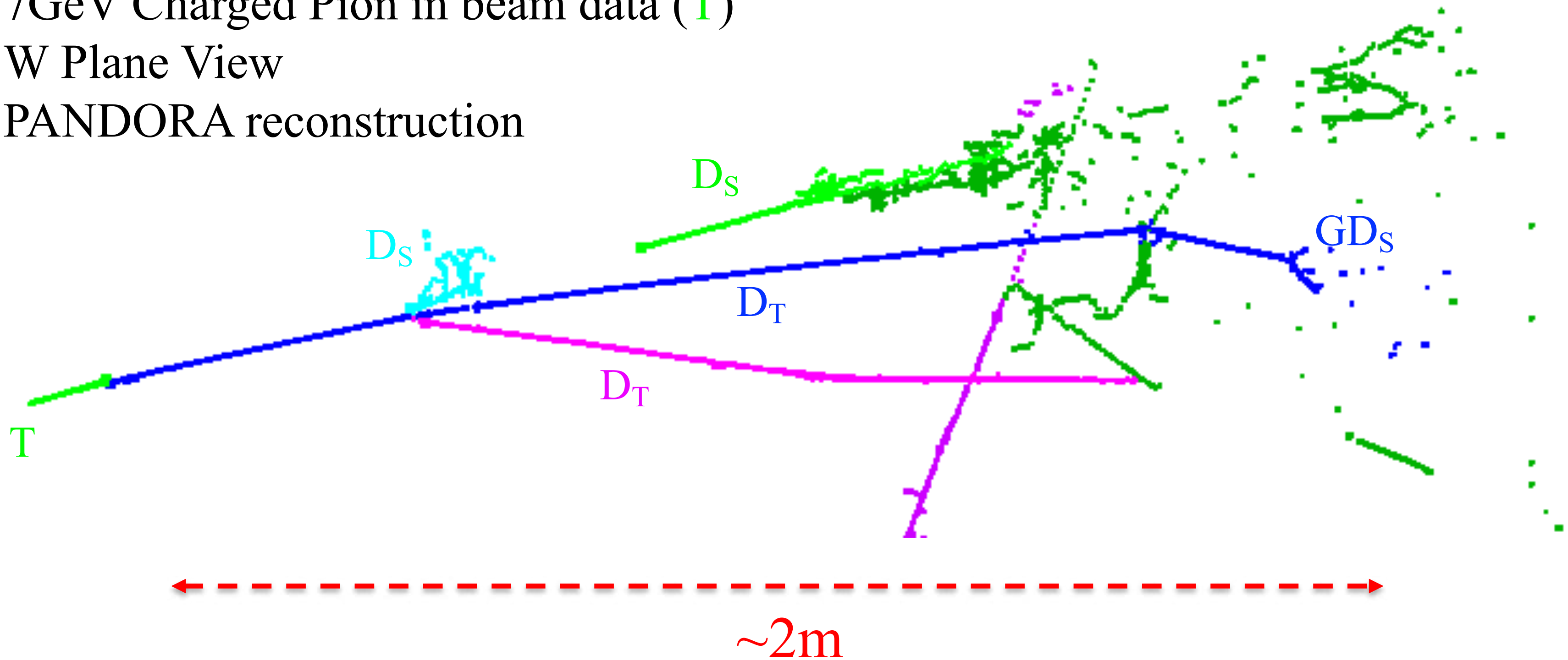
Number of reconstructed cosmic ray tracks in the 3 ms readout window



- PANDORA pattern recognition (Eur. Phys. J. C 78, no.1, 82 (2018)) to reconstruct and classify beam events and cosmic muon tracks in 3 ms TPC readout window
- Subsequent off-line analysis deals with beam events and cosmic rays separately

Beam Event Reconstruction in Data

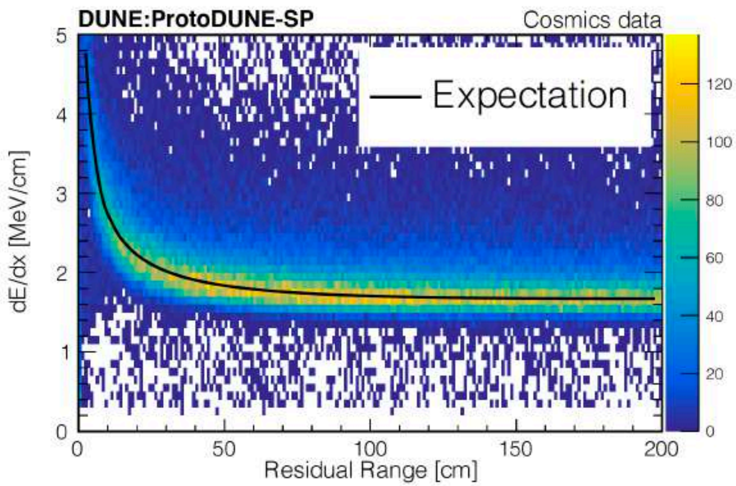
7GeV Charged Pion in beam data (T)
W Plane View
PANDORA reconstruction



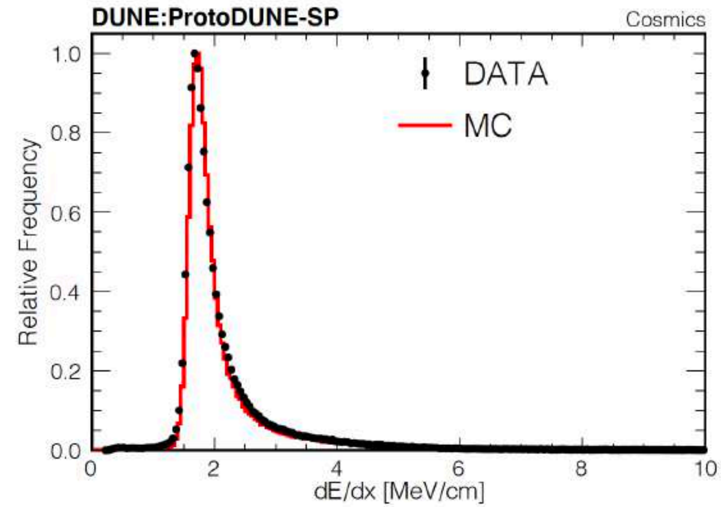
TPC reconstruction chain tested with real test beam data

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

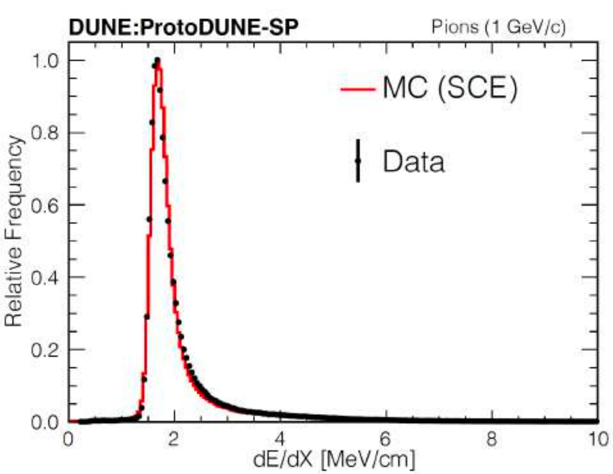
dE/dx Reconstruction

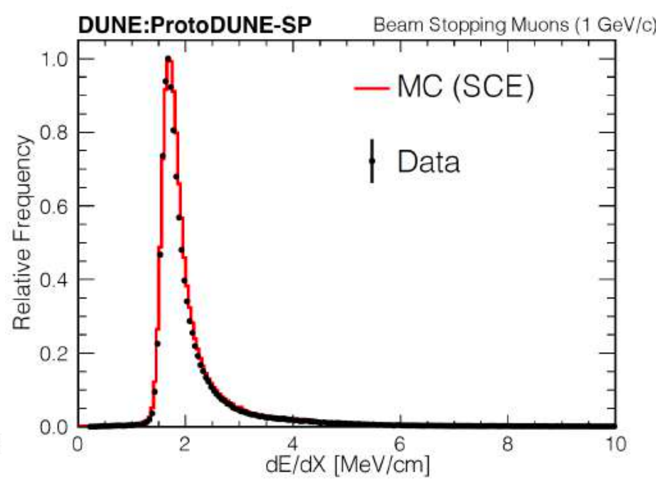


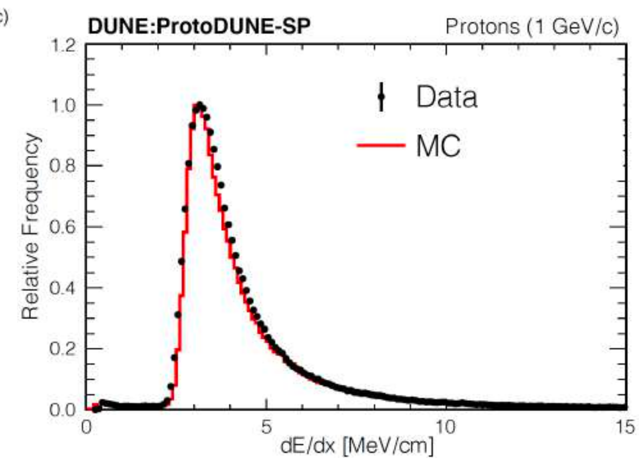
Use stopping muons in cosmic ray data to determine absolute dE/dx scale



Same stopping muon absolute calibration works well for beam data





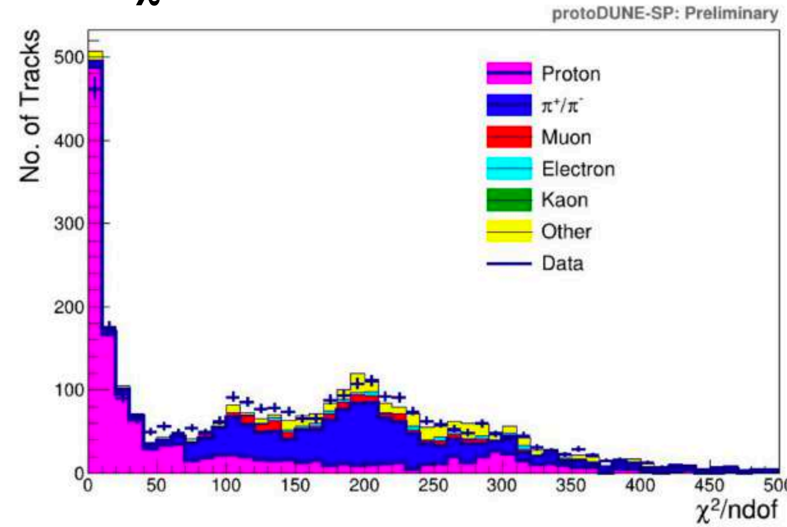


UCIRVINE DUNE

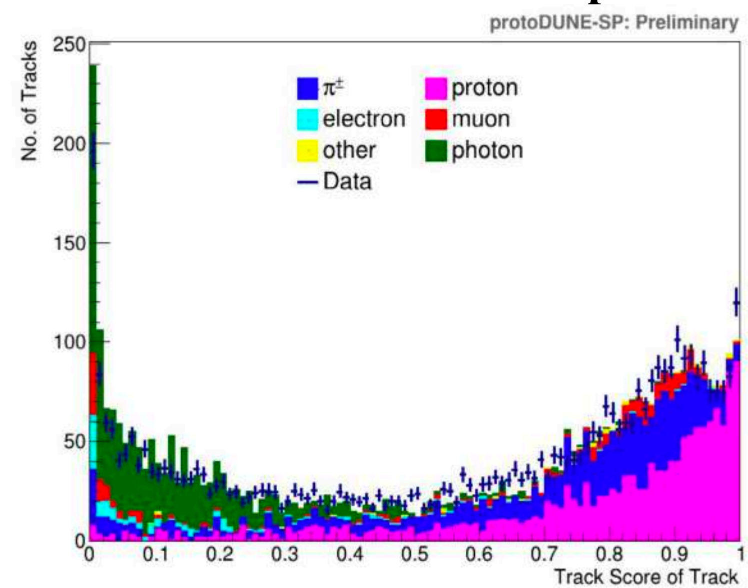
Particle Identification (PID)

- Well understood and calibrated detector response for different types of particles
- Developed traditional dE/dx/χ^2-based particle identification and deep-learning (CNN) based particle identification
- EM-shower and proton identification purity ~ 90%
- PID distributions show good data/MC consistency

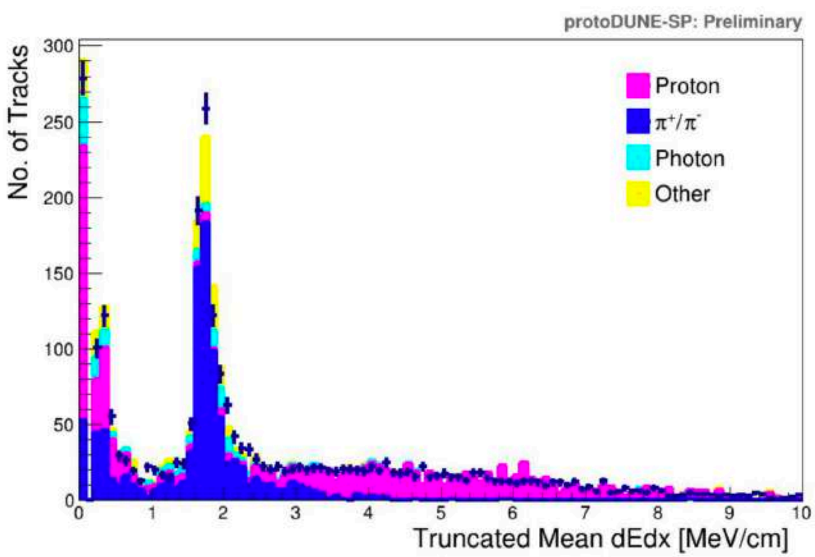
dE/dx χ^2 for Proton-Pion identification



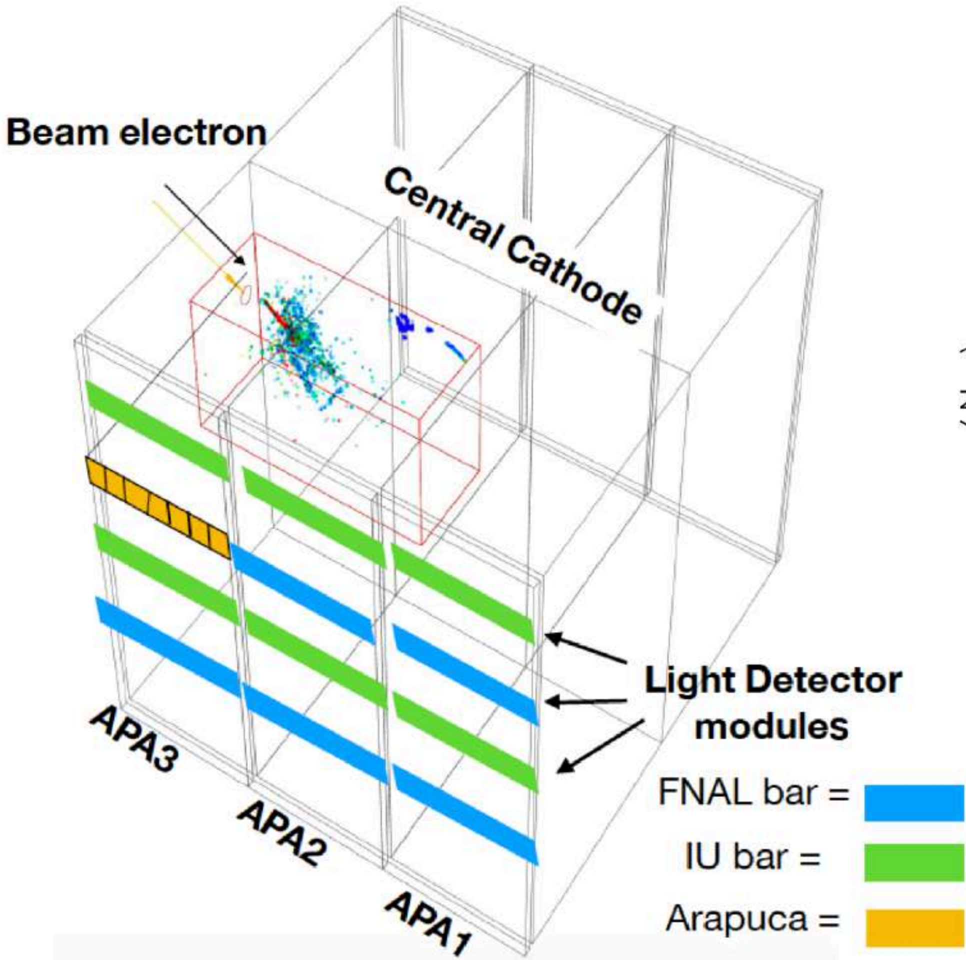
CNN based shower-track separation

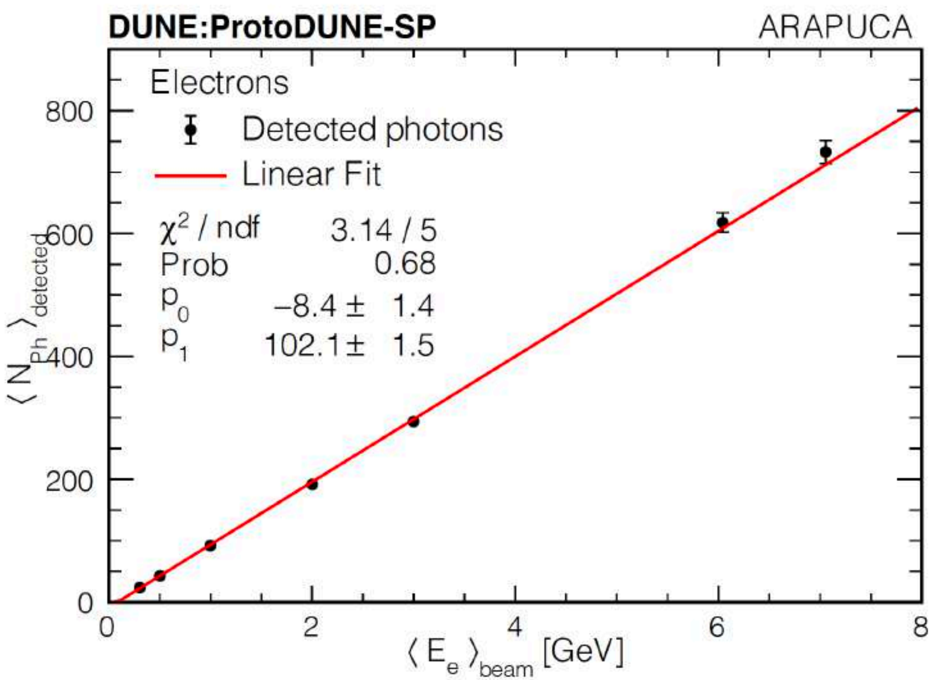


dE/dx for Proton-Pion identification



Photon Detector Performance





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

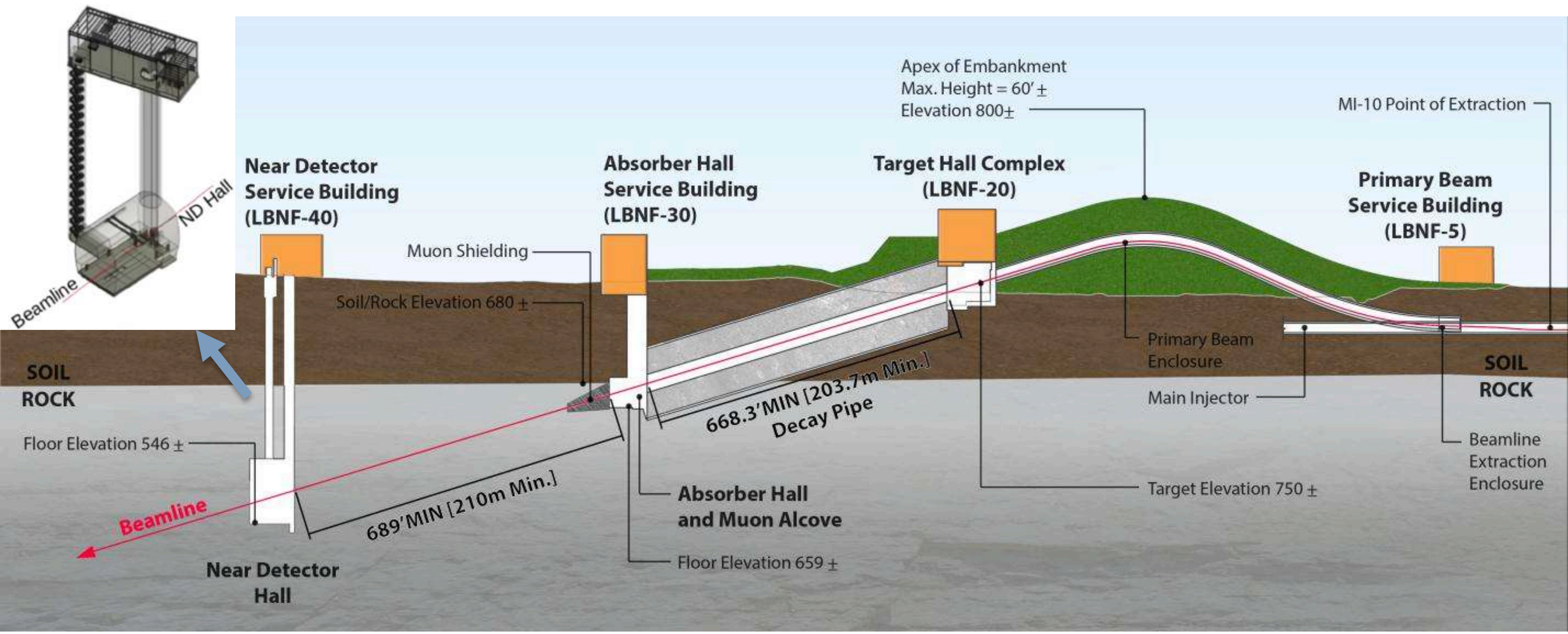
Summary

- ProtoDUNE-SP Phase-I successfully operated Sept. 2018 – July 2020, beam and cosmic data show excellent physics performance
- Excellent noise suppression and LAr purity achieved
- Calibration and reconstruction chain tested successfully with data:
  - Electron lifetime and detector non-uniformity calibrated
  - Absolute energy scale determined
  - Excellent dE/dx particle ID demonstrated
- First paper on ProtoDUNE-SP performance published: JINST 15 (2020) 12, P12004
- Working on physic analyses (pion, proton, Michel electron etc, Liao and Rafique's talks at NuTel) to improve event generators, GEANT, and calibration for DUNE
- Preparing ProtoDUNE-SP Phase-2 run expected to start in late 2022

Thank you!

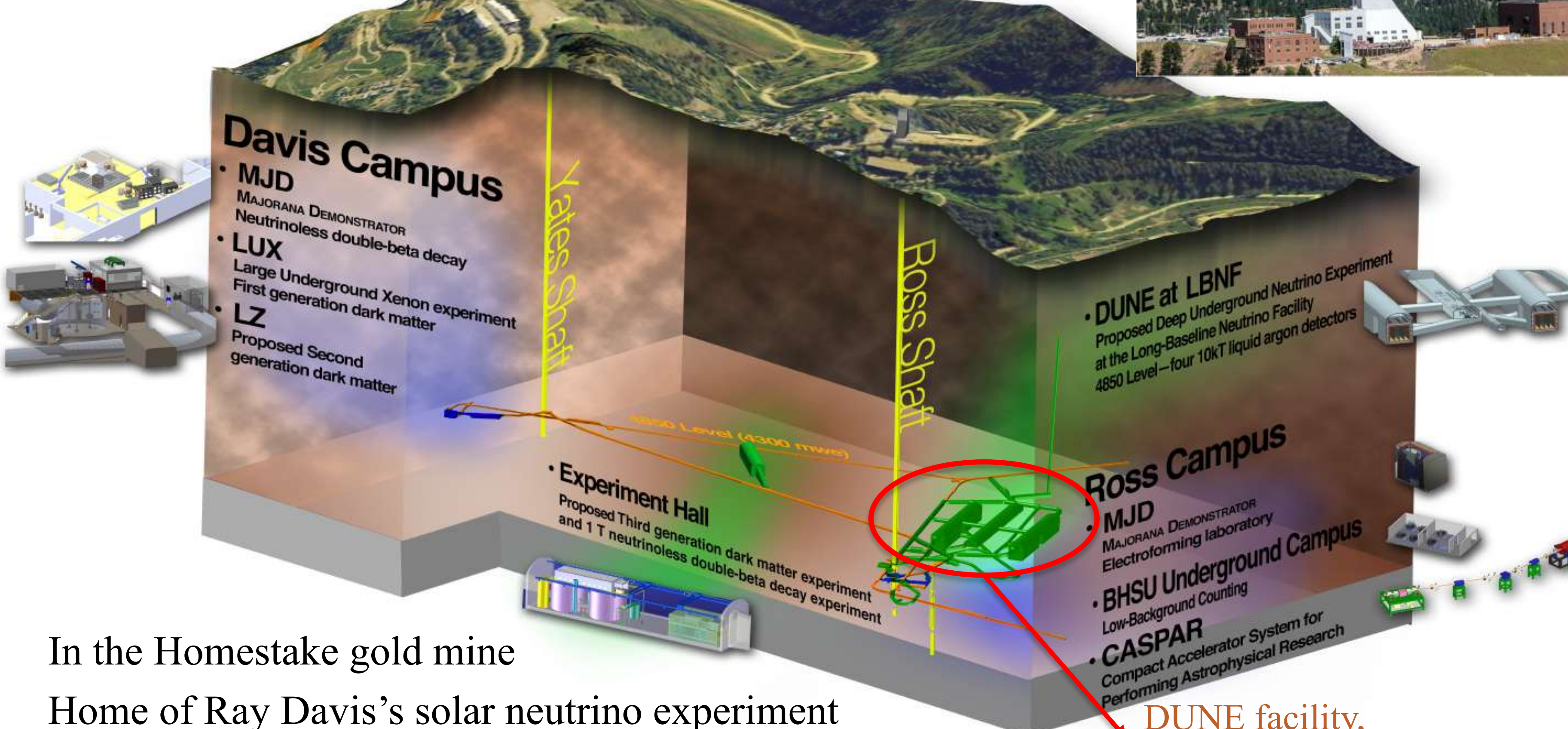
Backup

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)

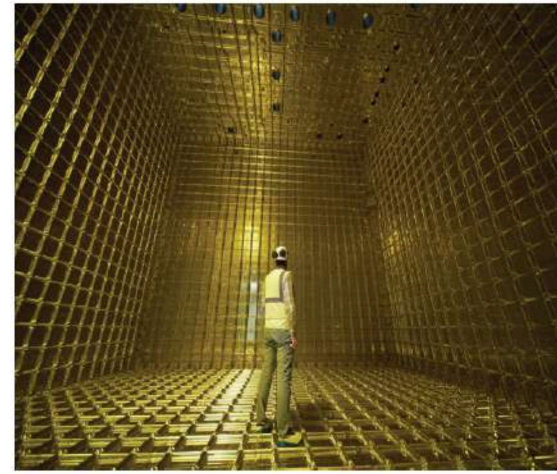
- In the Homestake gold mine
- Home of Ray Davis's solar neutrino experiment
- 4 caverns for detector and one utility hall for DUNE
- Blast vibration study has been done
- Excavation for the first two caverns started in FY2017

Groundbreaking: 21st July, 2017

Milestones of ProtoDUNE-SP construction in EHN1

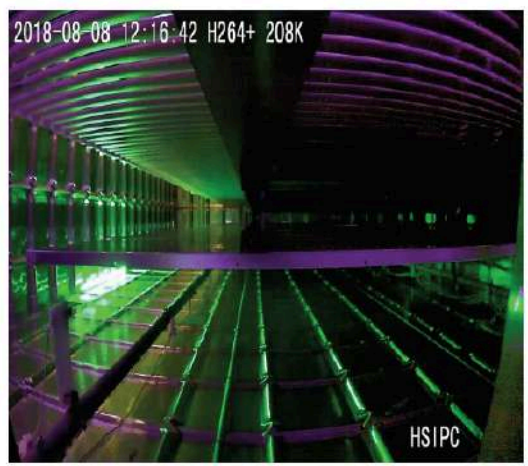
March 2016, construction of EHN1 extension

November 2016, cryostat structure assembly



September 2017, cryostat completion

February 2018, detector assembly

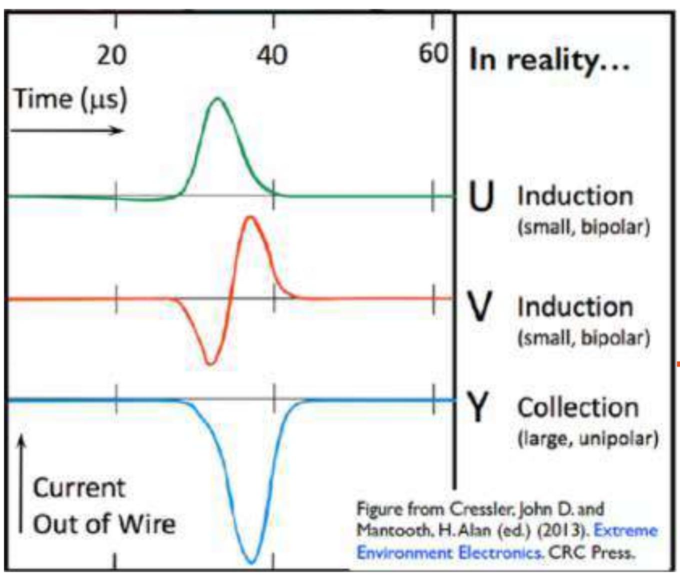


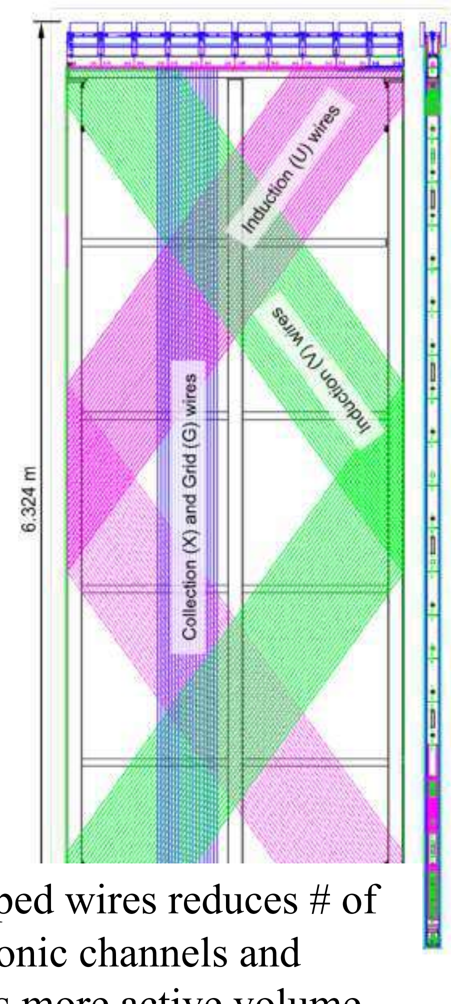
August 2018, LAr filling

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

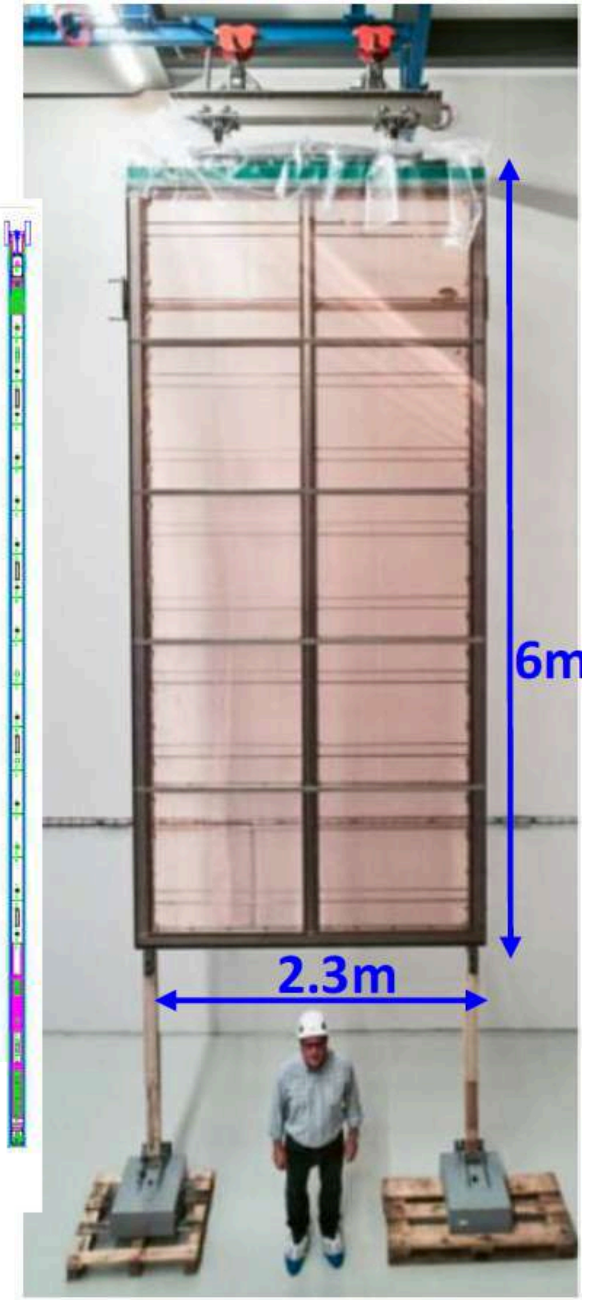
ProtoDUNE-SP: Anode Plane Assembly(APA)

- 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

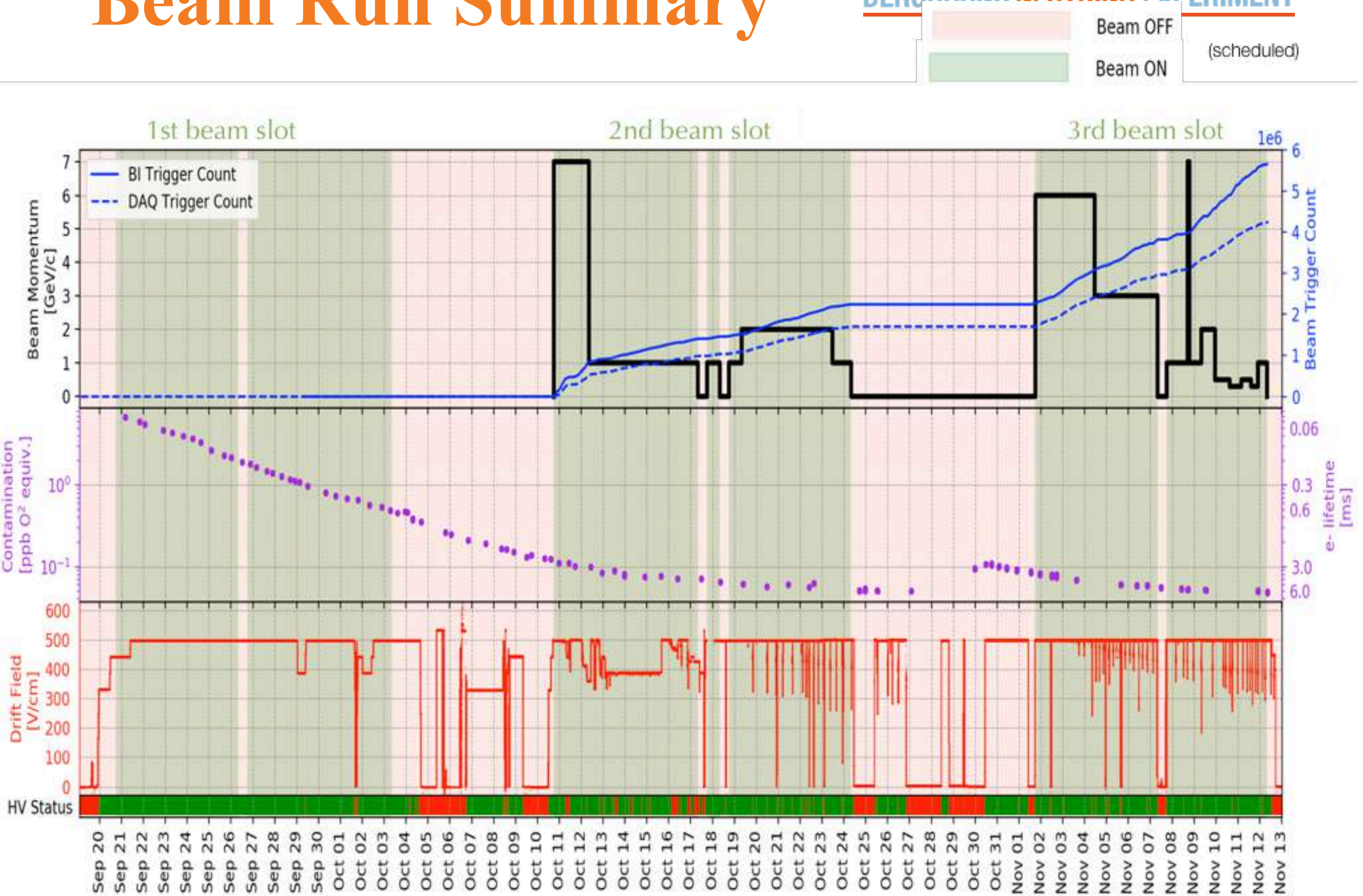




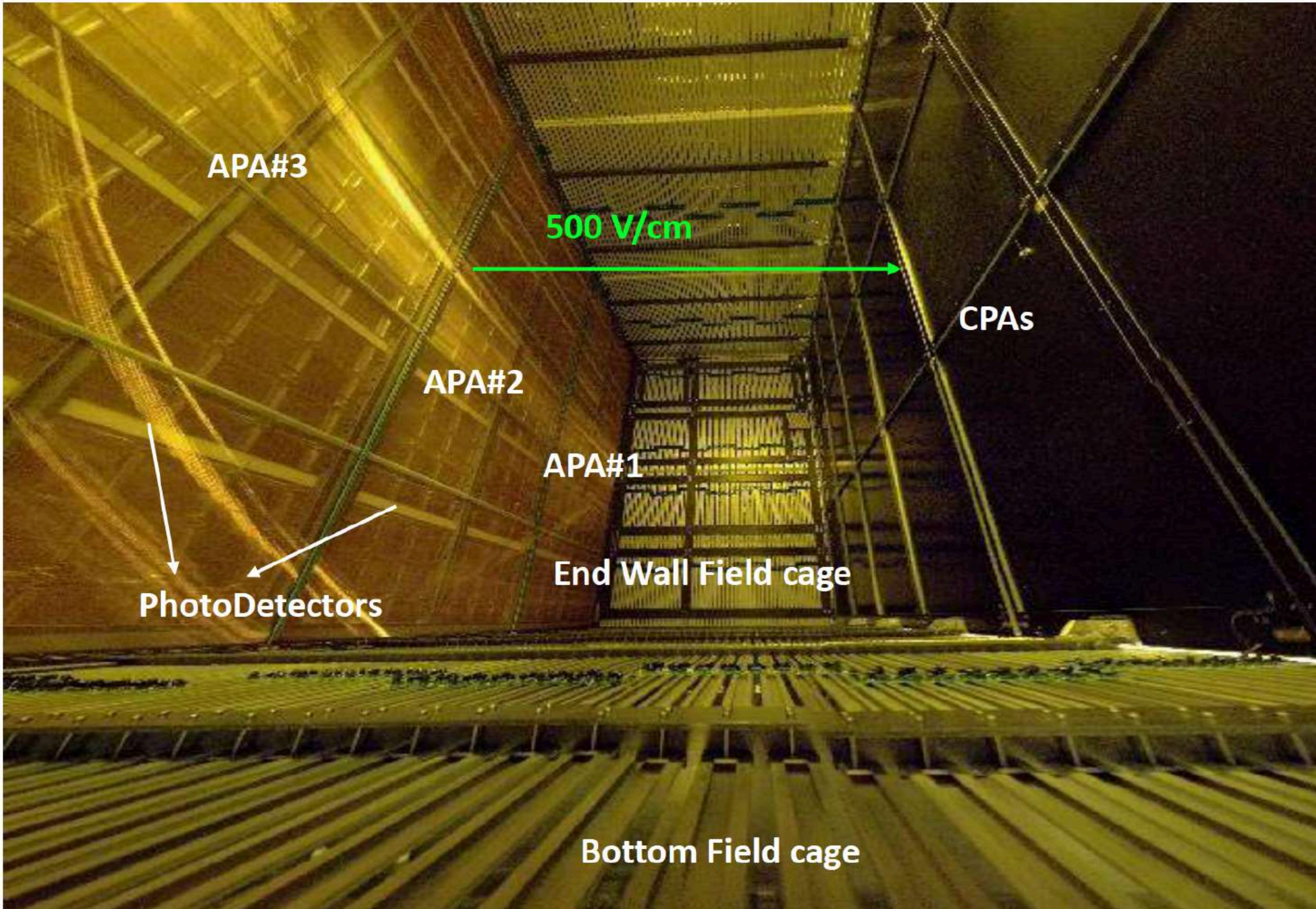
Wrapped wires reduces # of electronic channels and allows more active volume, all electronics on top



Beam Run Summary

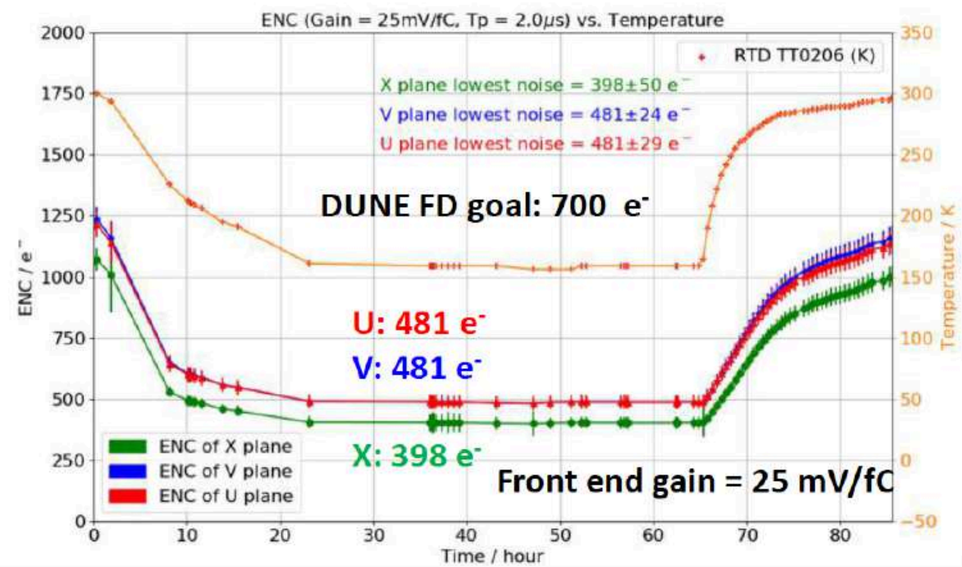


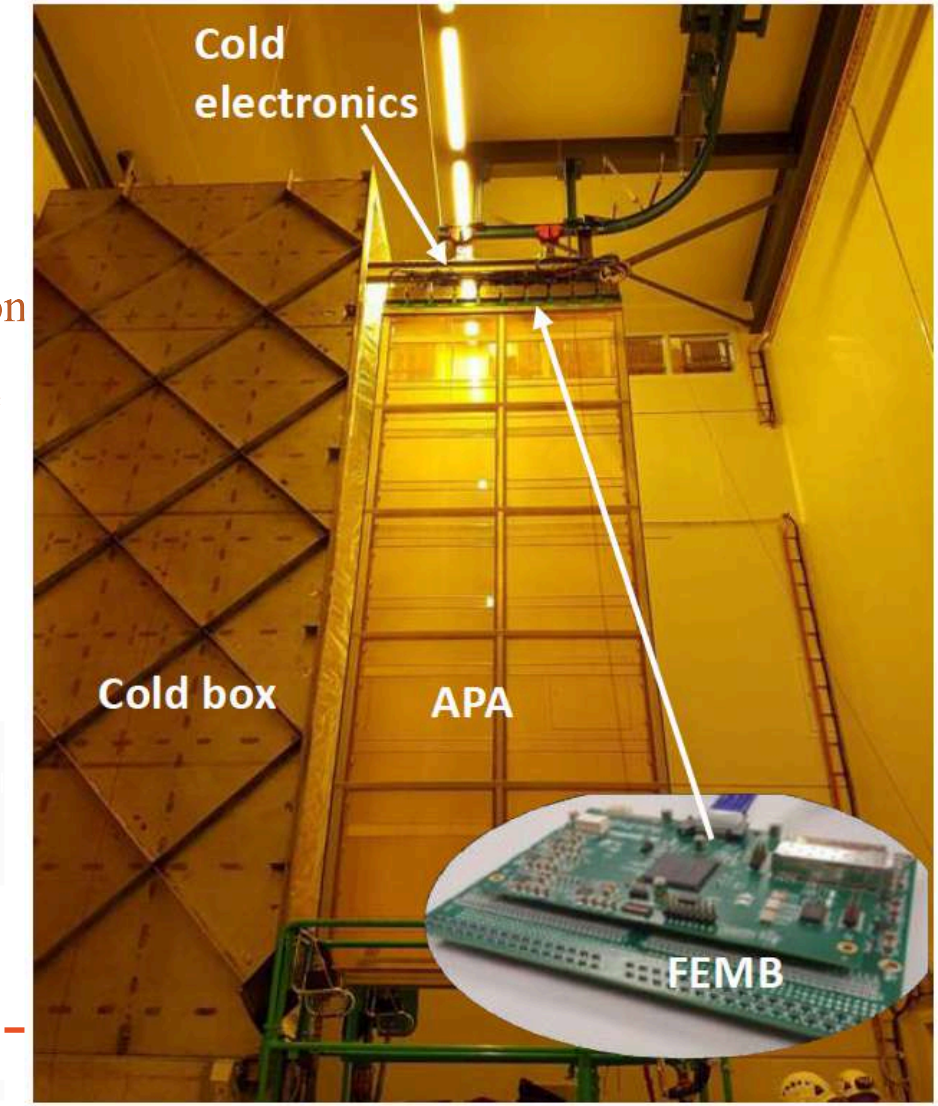
ProtoDUNE-SP Field Cage



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

DUNE
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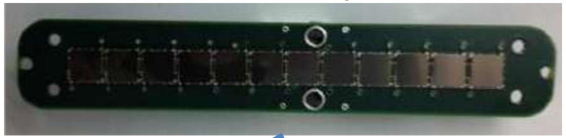
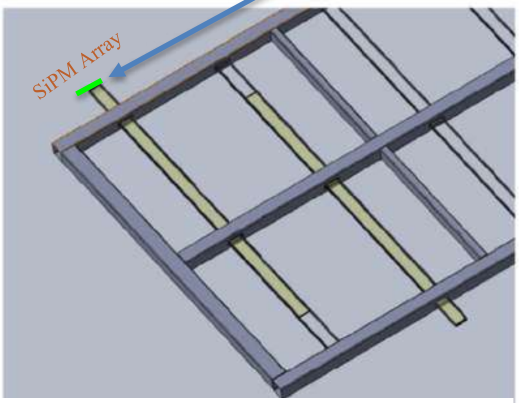
Photon Detection System (PDS)

- 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:

SiPM Array

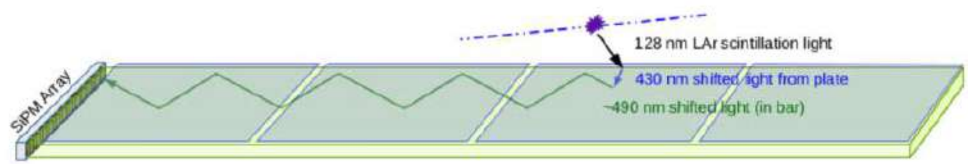




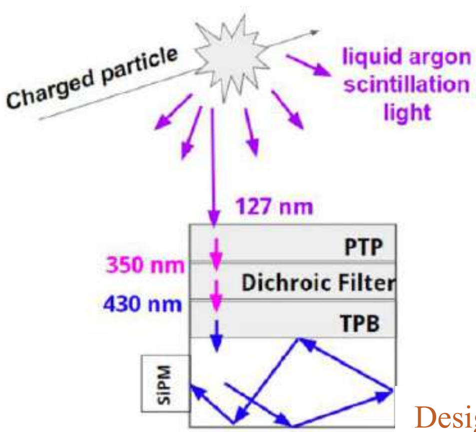
Design 1&2 PDS module inserted APA frame

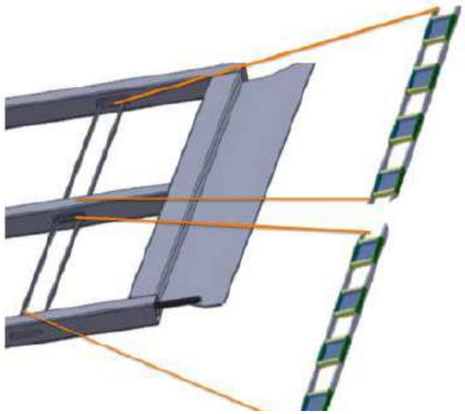
Design 1: Dip-coated light guide (MIT and Fermilab): Acrylic light guide bar dip-coated with wavelength shifter

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



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

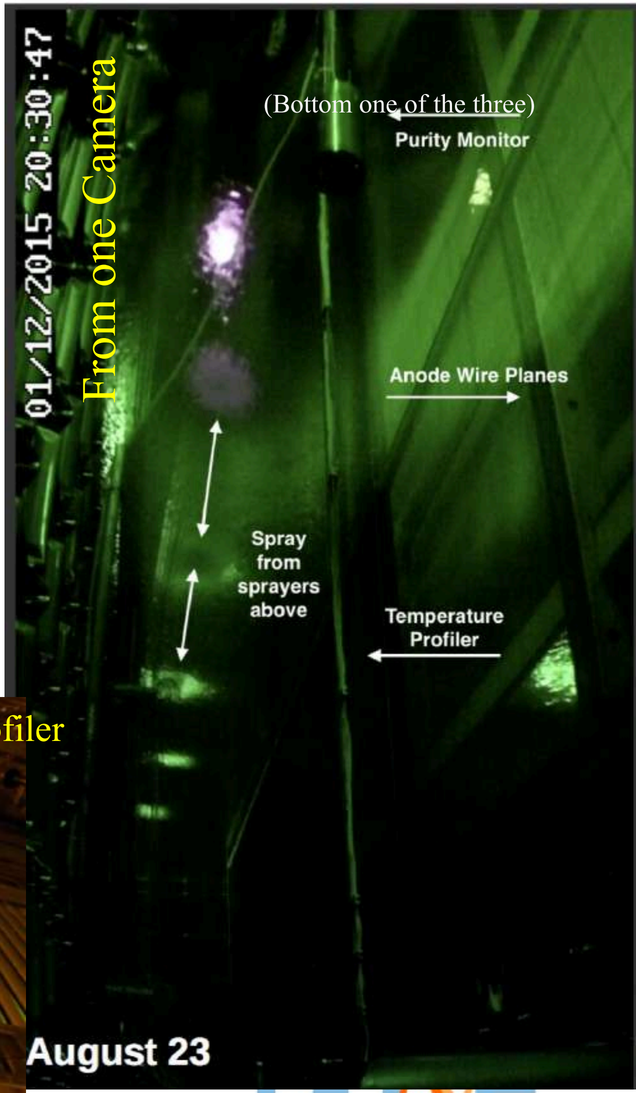




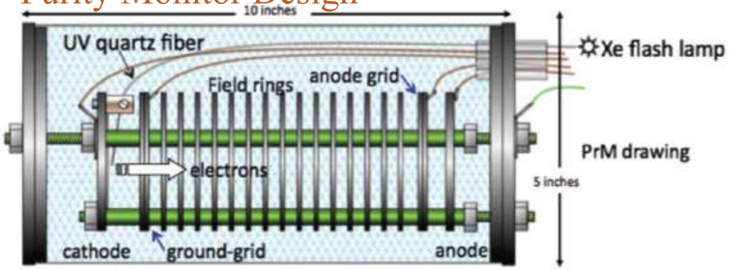
Design 3 PDS module inserted APA frame

Detector Instrumentation and Cosmic Ray Tagger

- 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).

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Beamline TOF and Cherenkov for PID

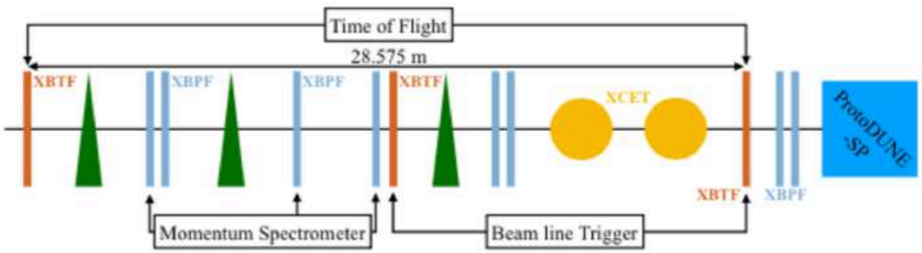

Figure 1: A schematic diagram showing the relative positions of XBTFs (orange), bending magnets (green), XBPFs (blue) and XCET (yellow) in the H4-VLE beam line. Combining data from different pieces of instrumentation can be used for triggering, reconstructing momentum and measuring time of flight, as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

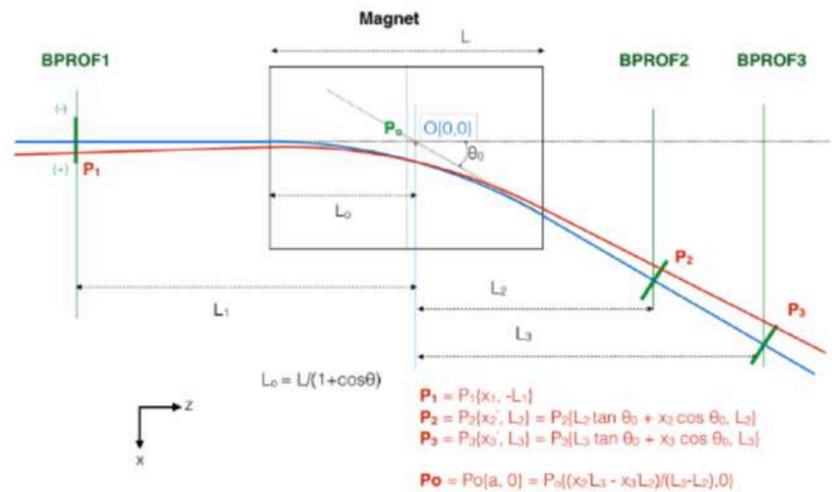

Figure 2: A schematic diagram showing the method by which momentum is reconstructed for a given beam particle (red), as discussed in the text. Taken from [4].

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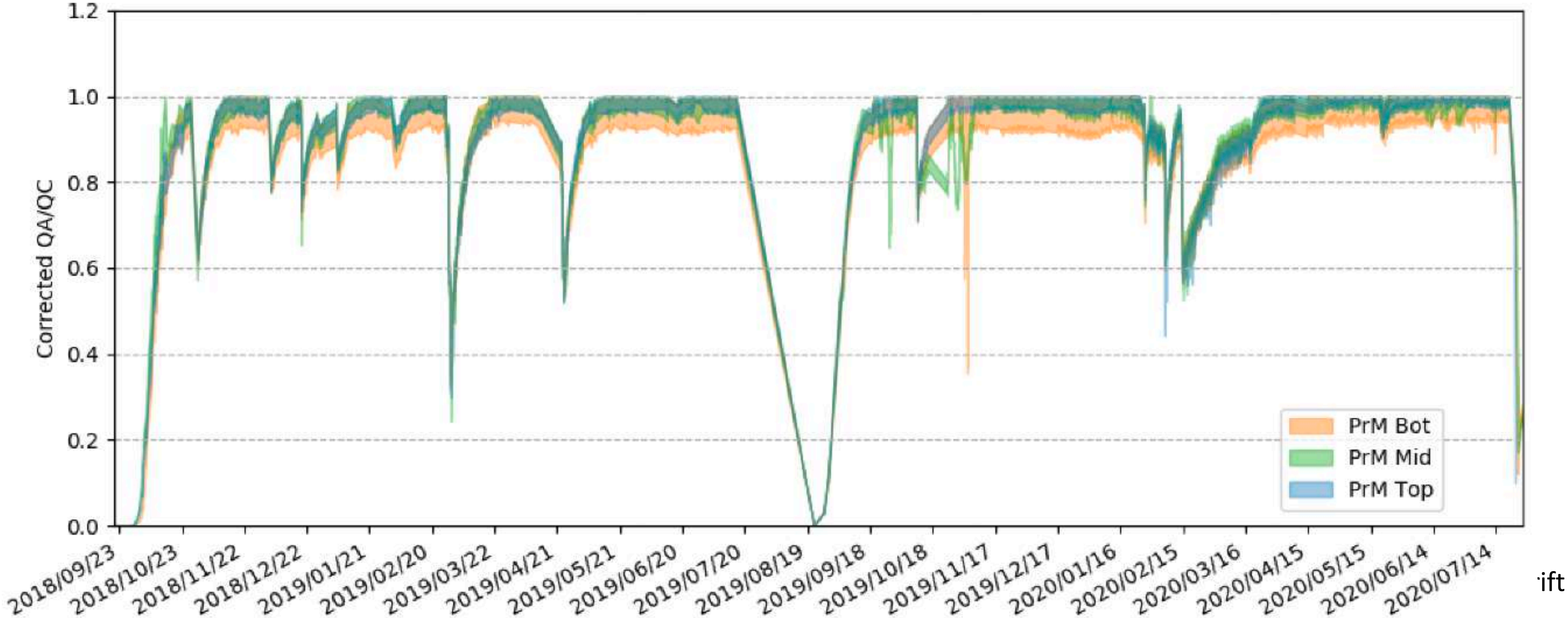
Electron lifetime from Purity Monitor and CRT



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