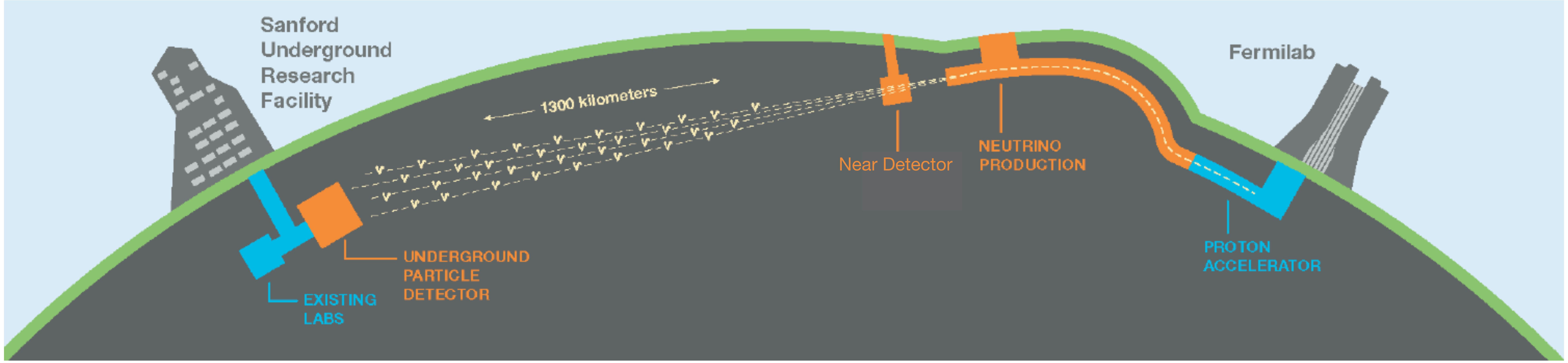
ProtoDUNE Physics and Results

Wenjie Wu (UCI), on behalf of the DUNE collaboration

APS DPF Meeting 2021

July 12, 2021

DUNE

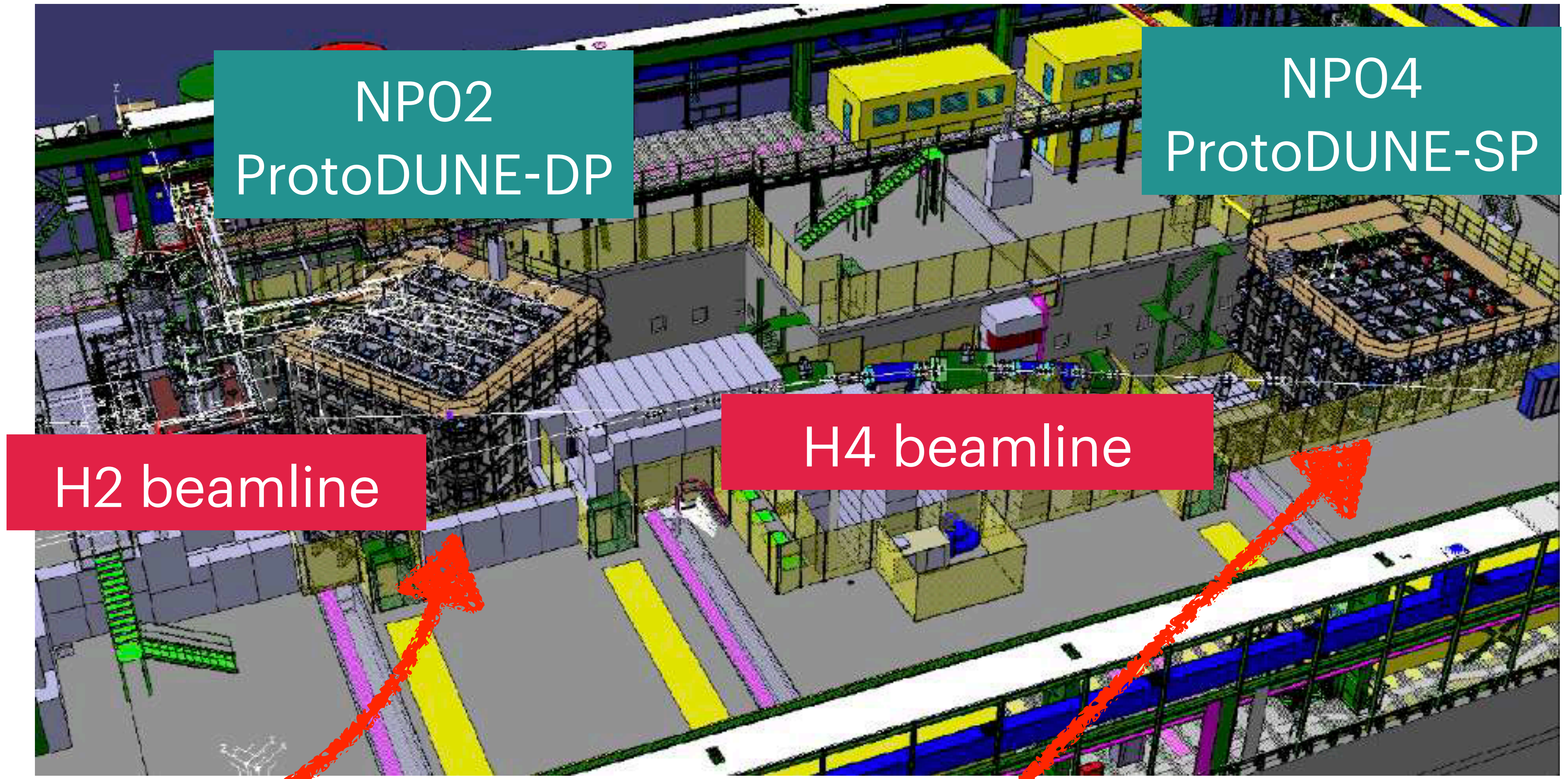


See Jose Maneira' s talk @ Plenary on 13 July

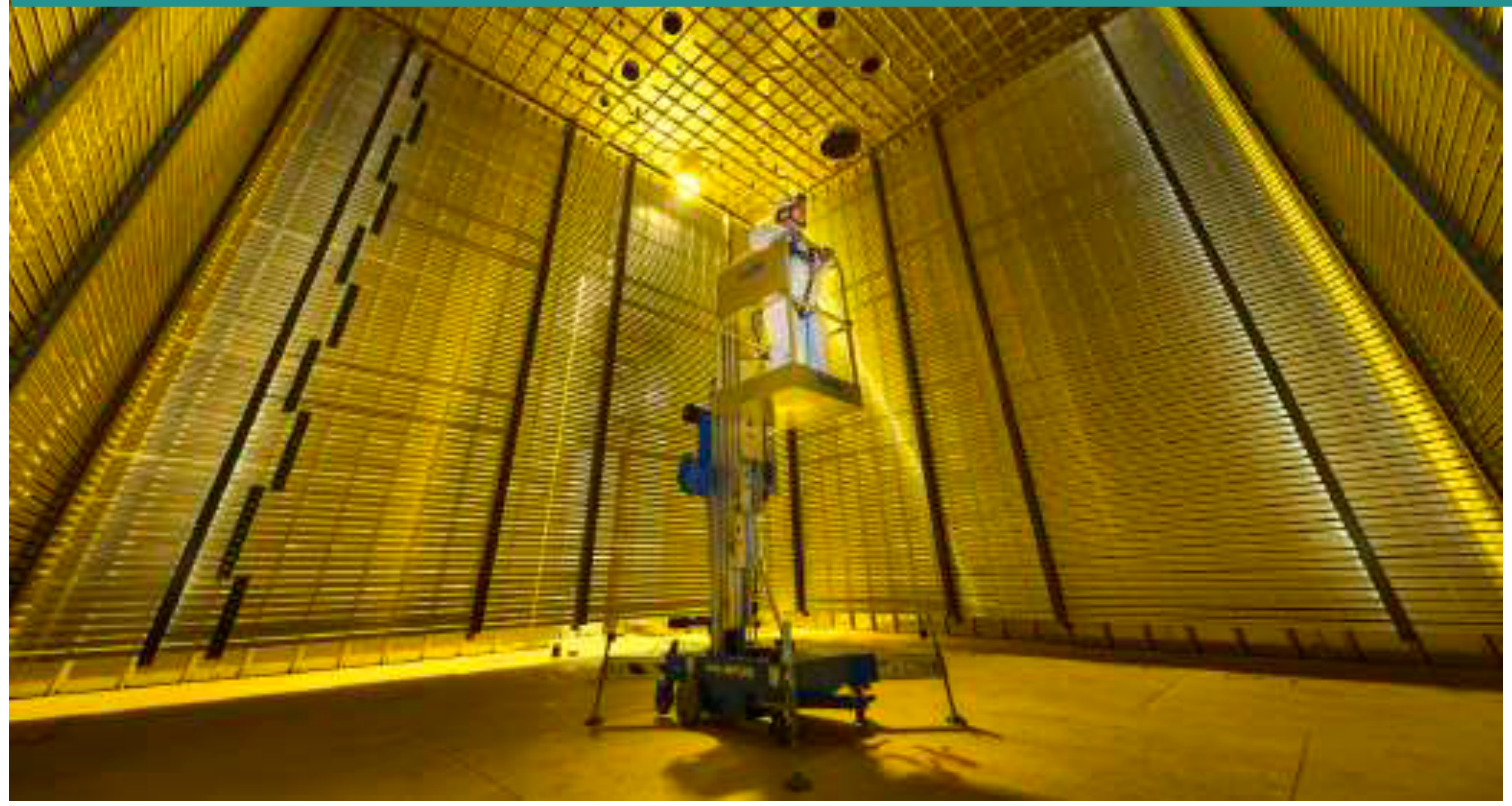
- DUNE: next generation neutrino experiment using LArTPC technology
  - New neutrino beam at Fermilab (1.2 MW, upgradeable to 2.4 MW), 1300 km baseline
  - 4 modules for Far Detector at Sanford Underground Research Facility, South Dakota, 1.5 km underground
  - Multiple technologies for the Near Detector (ND)
- $\nu_e/\bar{\nu}_e$ appearance and $\nu_\mu/\bar{\nu}_\mu$ disappearance → Neutrino CP violating phase and mass ordering
- Large detector, deep underground, high intensity beam → Supernova burst neutrinos, atmospheric neutrinos, nucleon decay and other BSM, etc
- Excavation started in 2017, start Far Detector installation in the middle of 2020s

ProtoDUNEs at CERN

- ProtoDUNE-SP and DP are DUNE's large scale prototypes (~1 kton-scale) of its far detector modules at CERN Neutrino Platform
  - Use components identical in size to those of the full-scale module
  - Critical to demonstrate viability of LArTPC technology

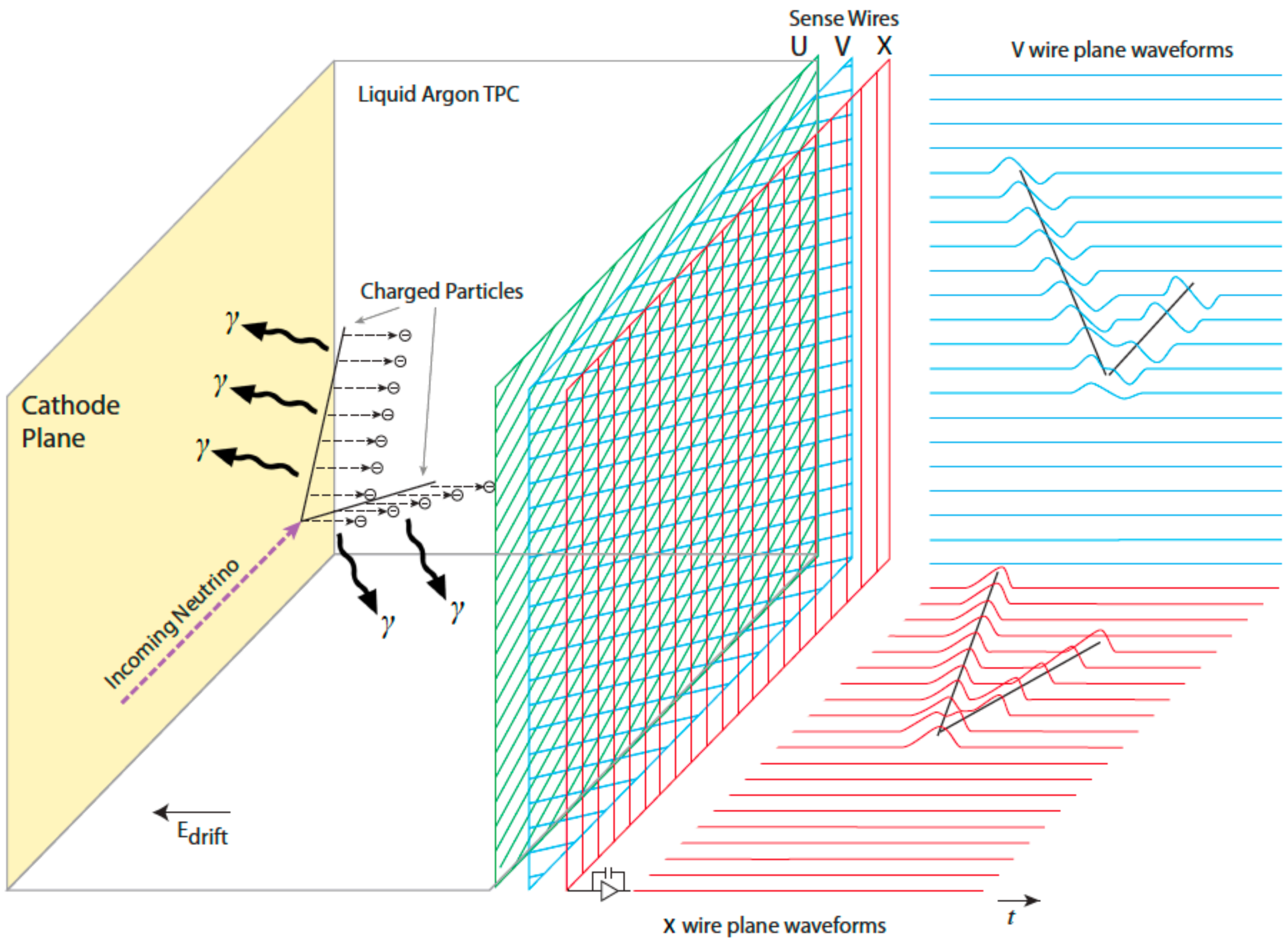


ProtoDUNE Dual Phase (DP)
- LArTPC 6 m vertical drift + charge amplification in gas Ar + photon detection
- Cosmic-muon data in 2019 - 2020



ProtoDUNE Single Phase (SP)
- LArTPC 3.6 m horizontal drift + photon detection
- Beam data taken in 2018 & cosmic data in 2018 - 2020
- ProtoDUNE-SP Phase II in 2022

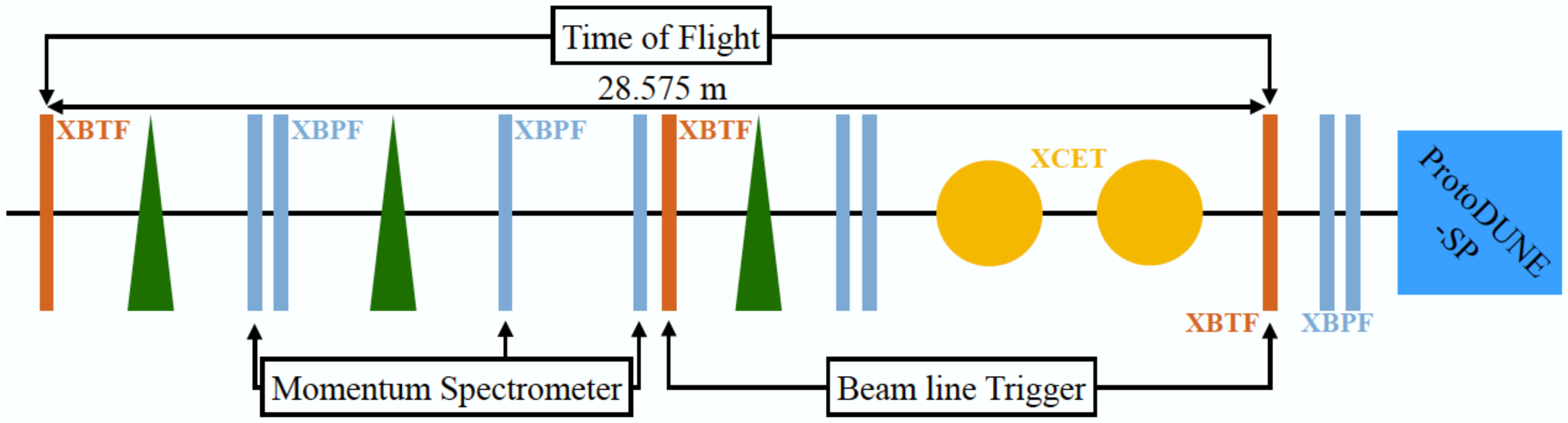
ProtoDUNE-SP: Operating Principle



- Charged particles ionize argon atoms
- Ionized electrons drift horizontally opposite to the E field in the LAr and are collected on the anode wire planes (~ ms) → 2D spatial location
- Electron drift time projection → enable 3D spatial location
- Argon scintillation light (~ ns) detected by photon detectors, providing event start time t_0
- Key factors: LAr purity and noise on the readout electronics

ProtoDUNE-SP at CERN Neutrino Platform

- Tertiary beam
- Spectrometer to measure the particle momenta
- Particle ID from time of flight and two Cerenkov detectors
- Over 4 million triggers over the momentum range 0.3 to 7.0 GeV (positrons, pions, muon, kaons and protons)



B. Abi *et al* 2020 *JINST* **15** P12004

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First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform

B. Abi[142], A. Abed Abud[21,118], R. Acciarri[61], M.A. Acero[8], G. Adamov[65], M. Adamowski[61], D. Adams[17], P. Adrien[21], M. Adinolfi[16], Z. Ahmad[182] + Show full author list

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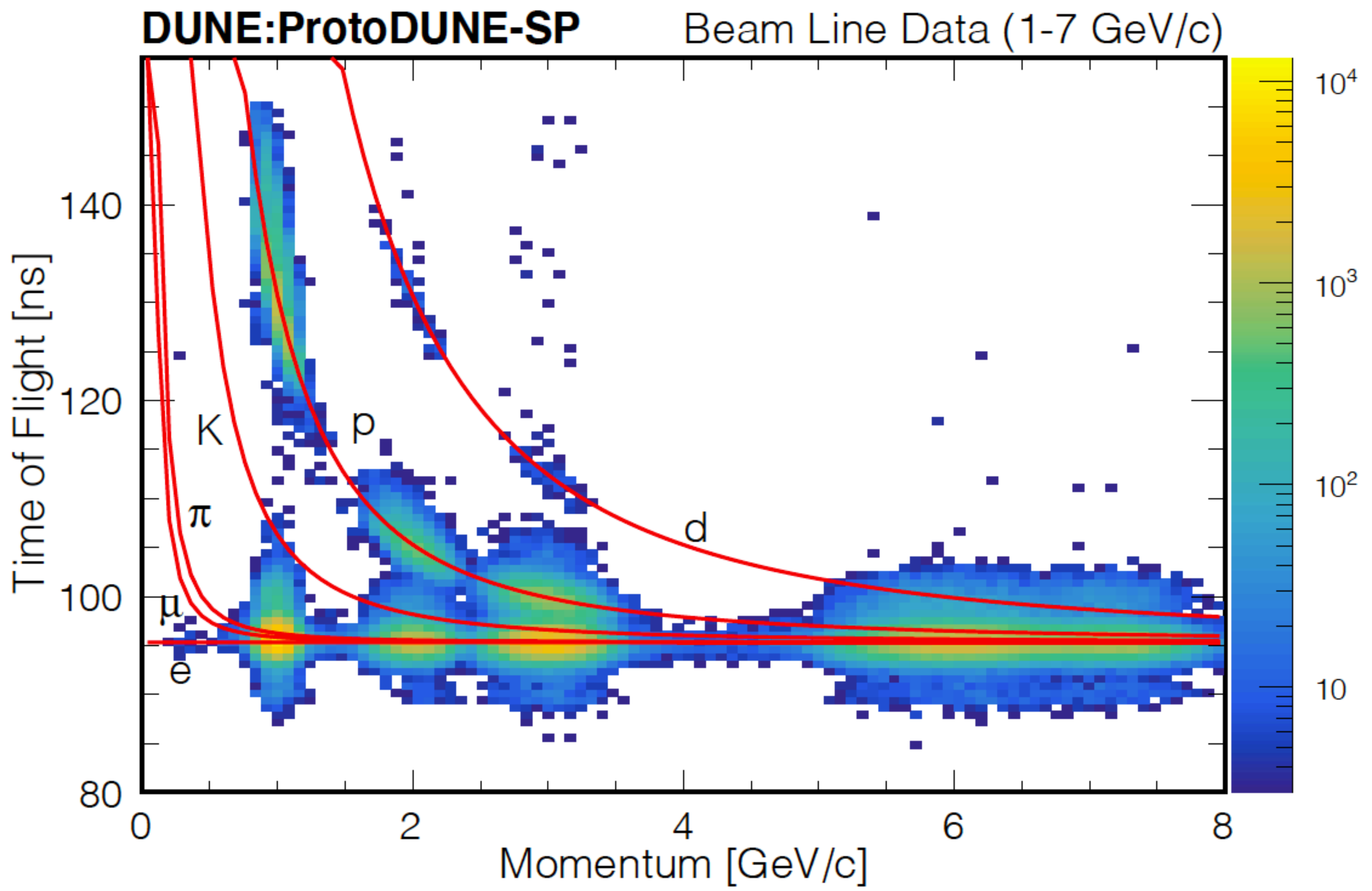
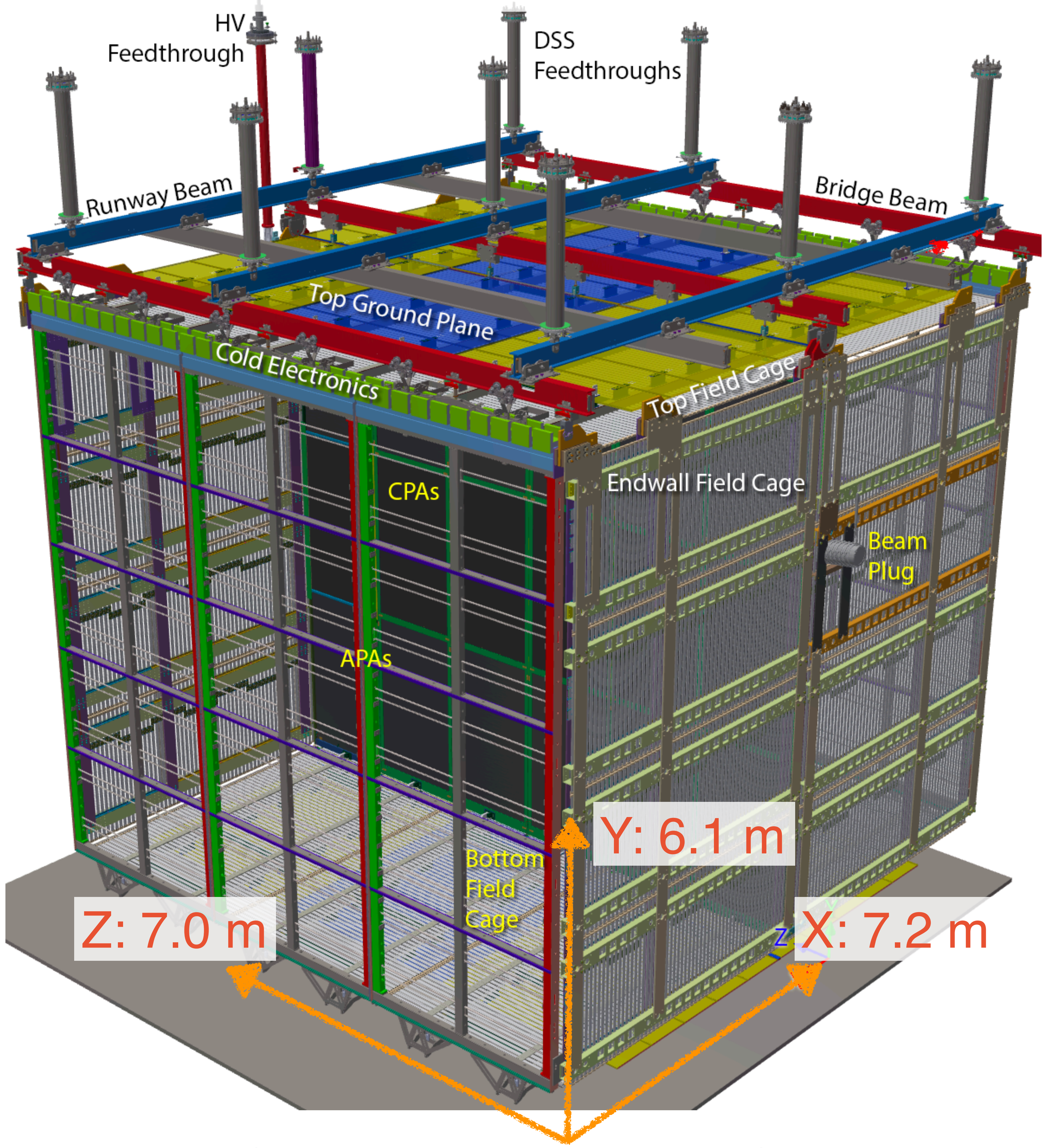


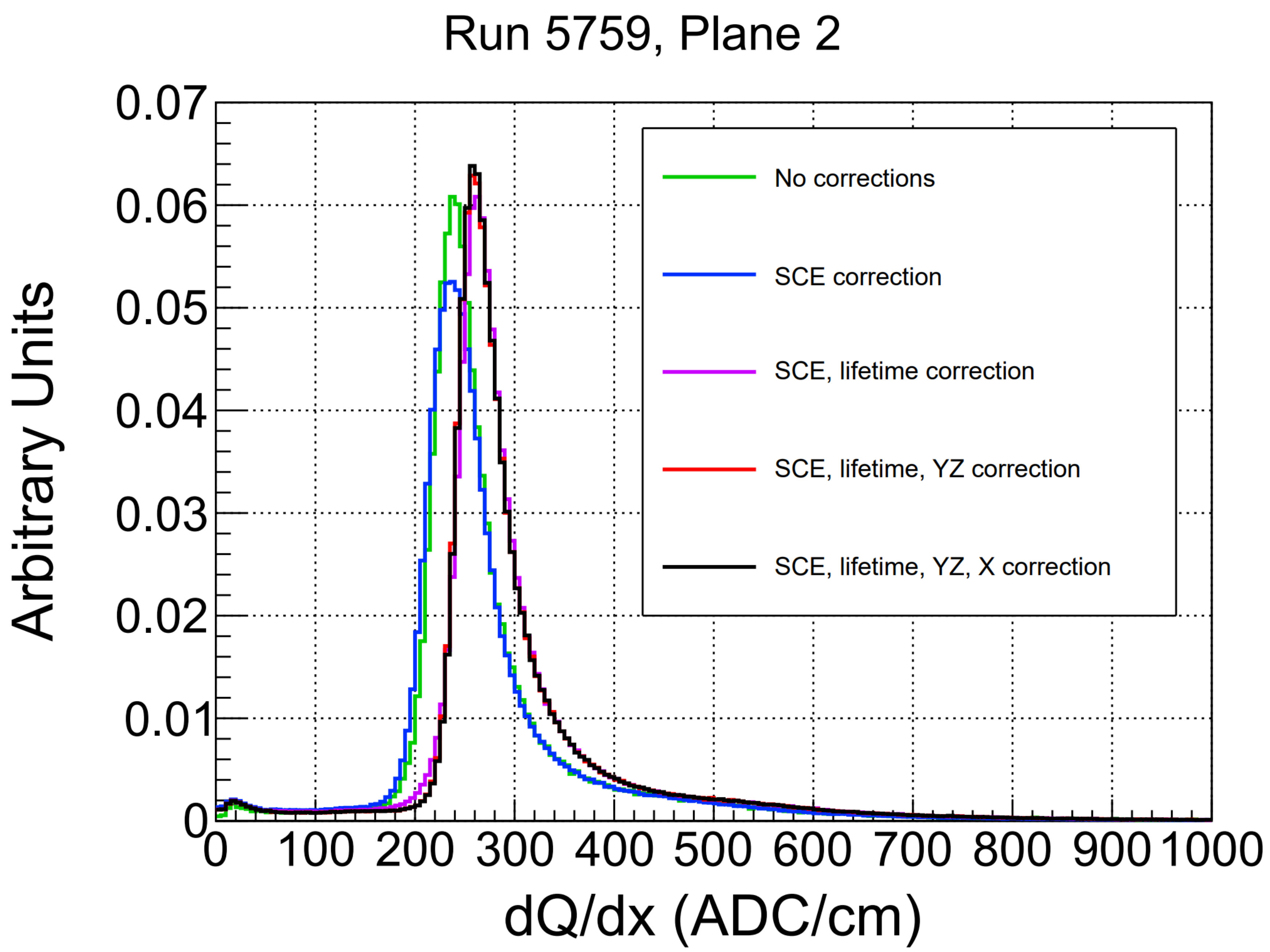
ProtoDUNE-SP Detector

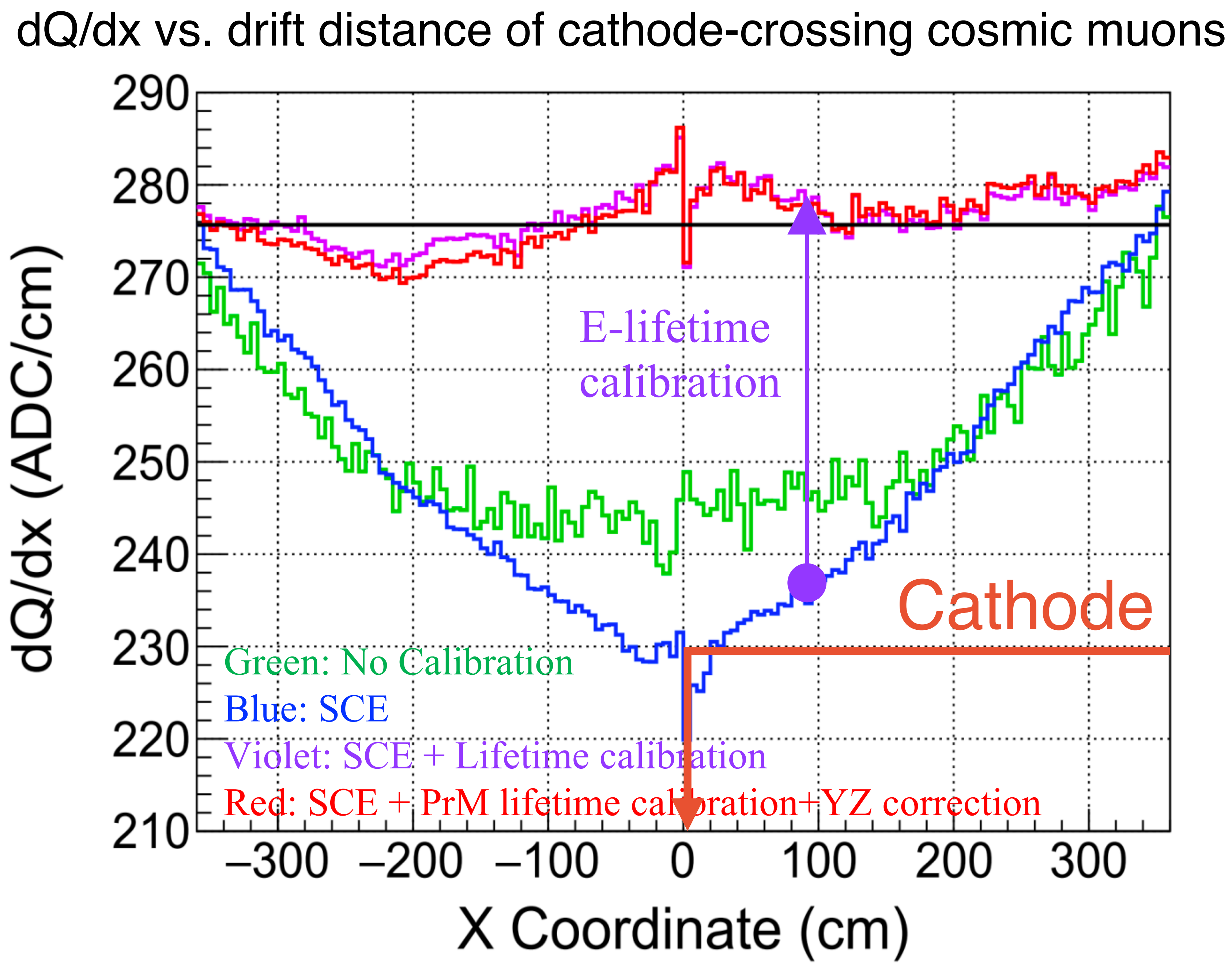
- TPC
  - Two drift volumes, 3.6 m drift distance (2.25 ms) @ 500 V/cm
  - Cathode Plane Assembly (CPA) on middle plane
  - Anode Plane Assembies (APAs) on both sides
  - Cold electronics attached to the top of APAs
- Photon detectors (PDS)
  - SiPM readouts
  - Wavelength shifter converts VUV to visible light
  - 3 designs integrated into APA frame bars
- Cryogenic instrumentations: measure argon purity, temperature, liquid level and tag cosmic rays

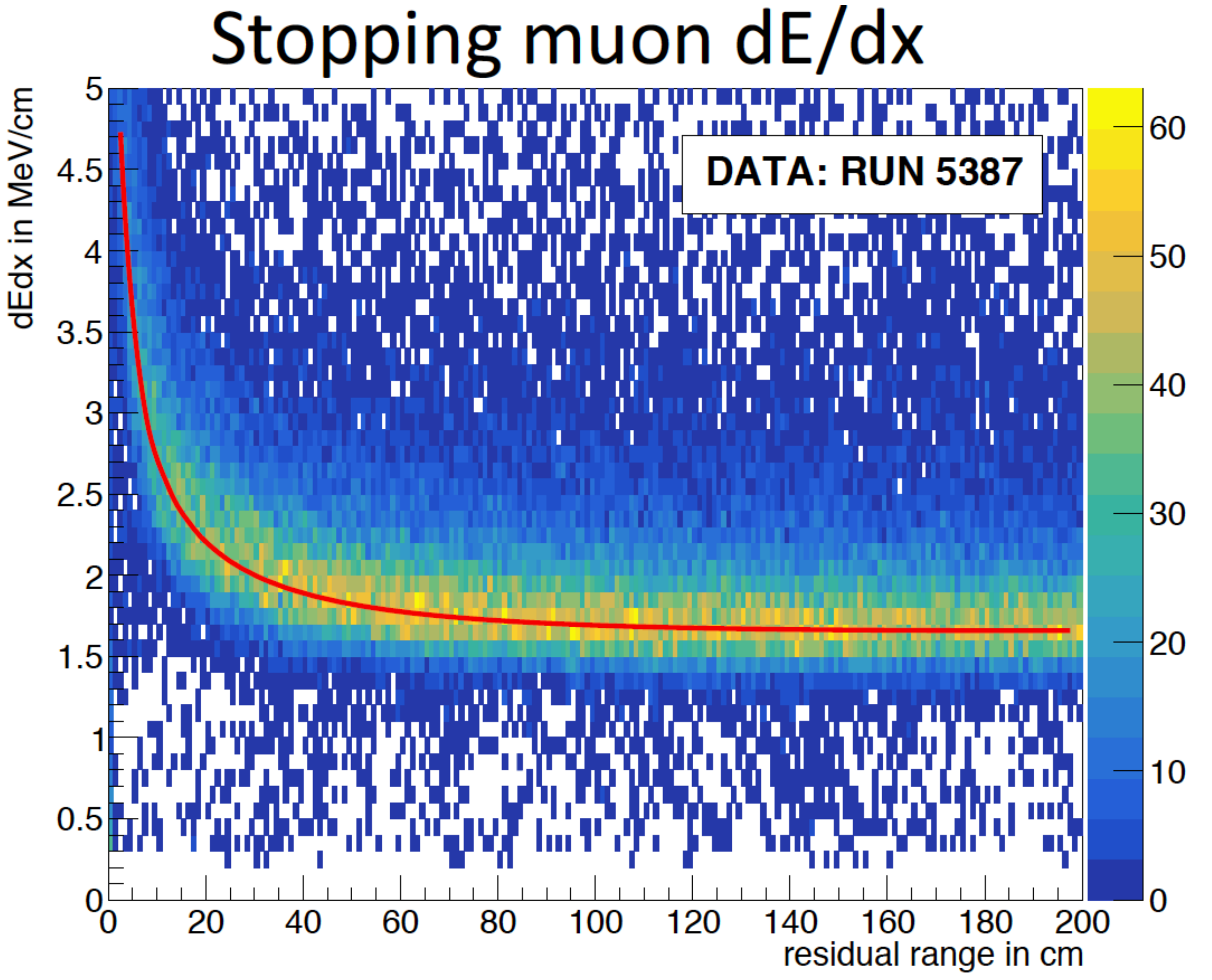


Schematic of ProtoDUNE-SP

ProtoDUNE-SP: Detector Calibration

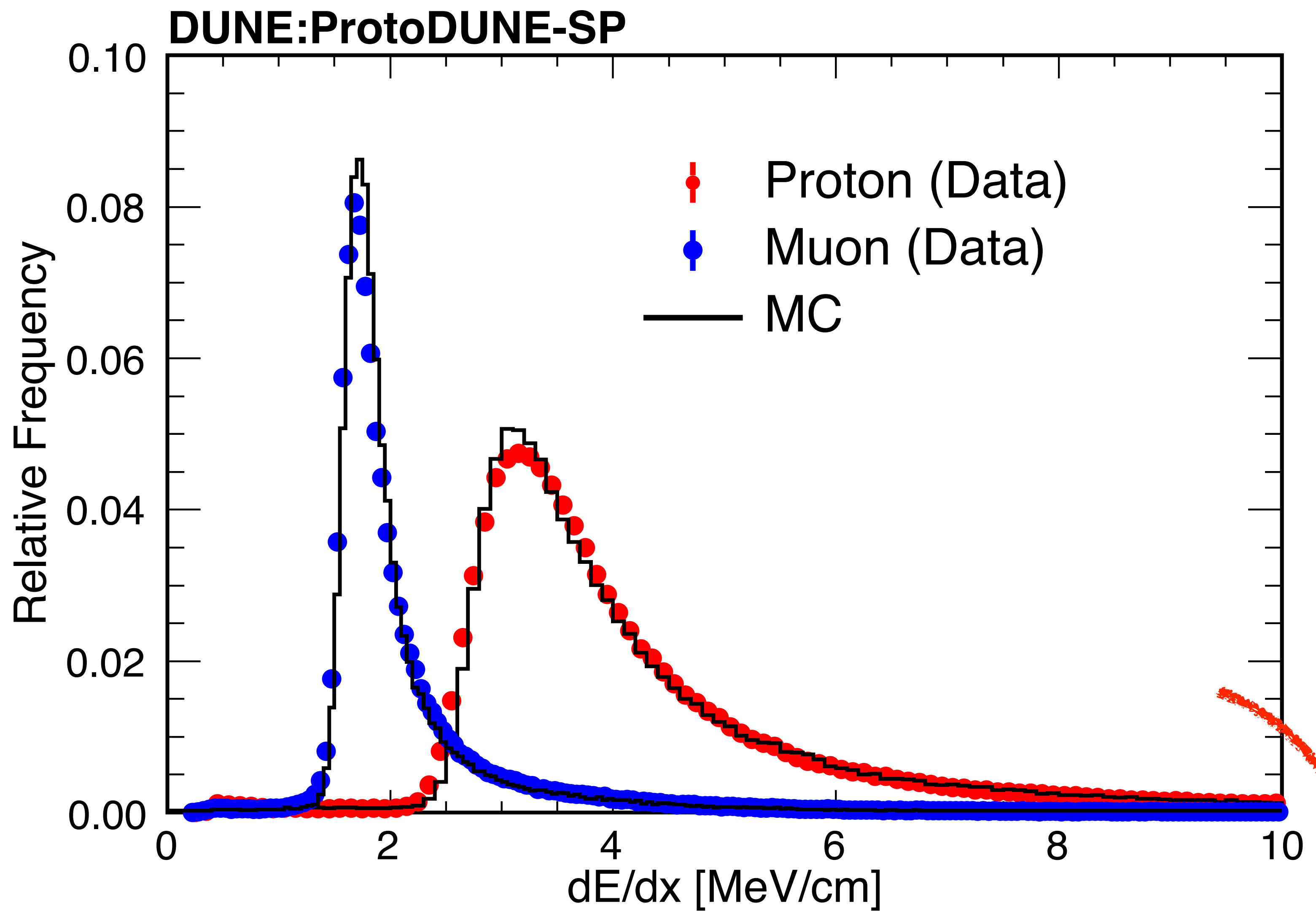




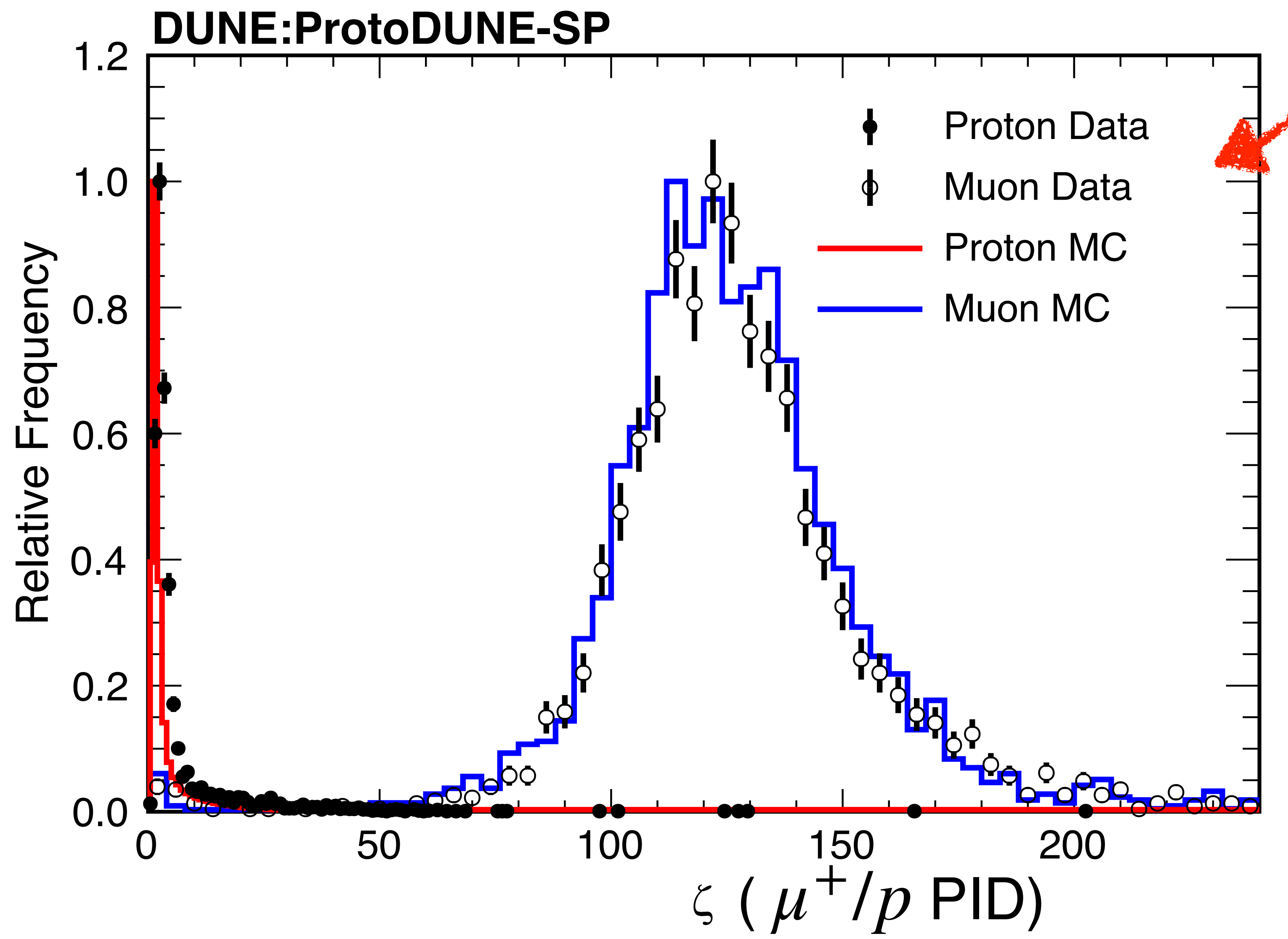


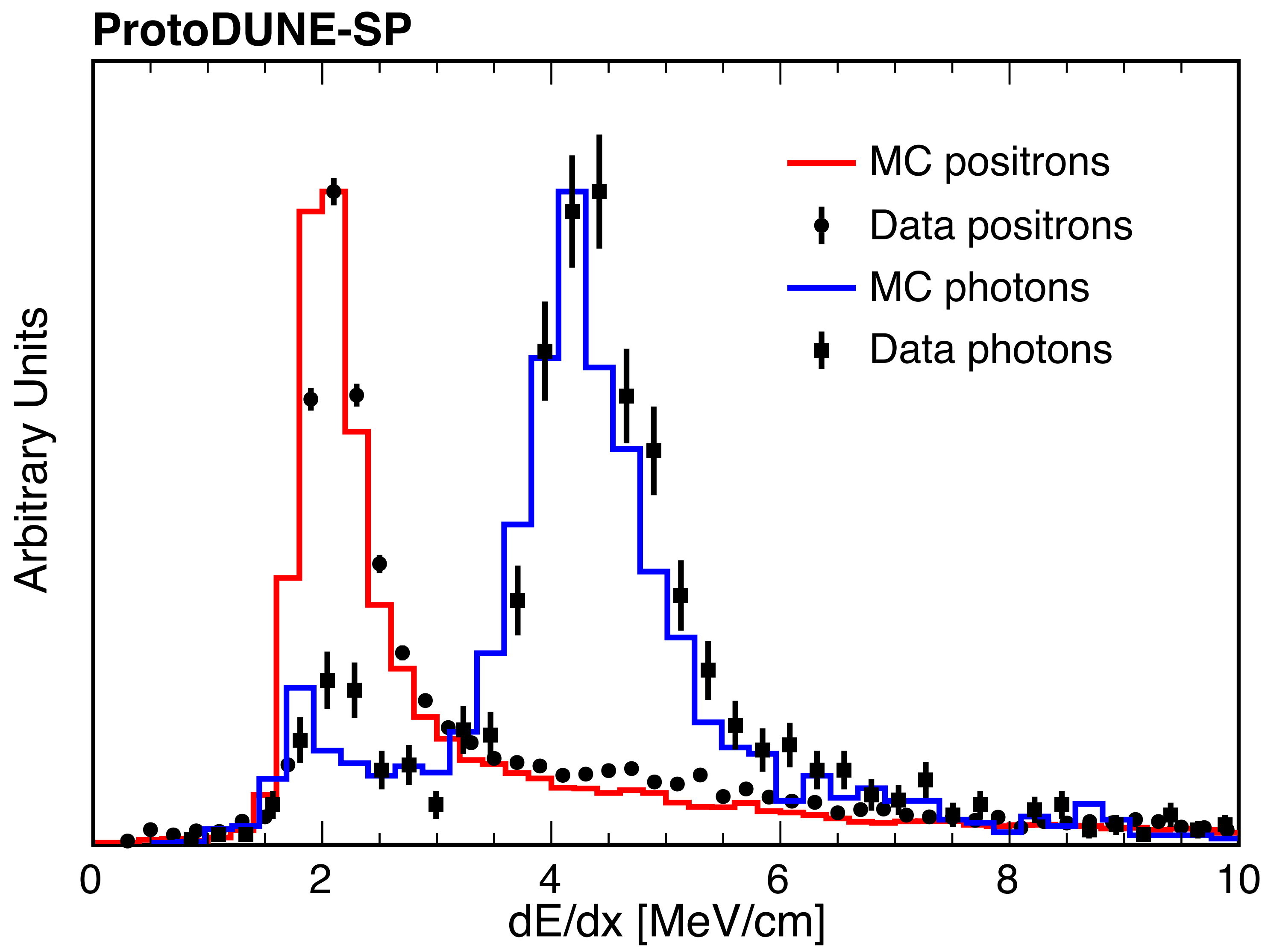
- Individual effects are measured and corrected for
  - SCE (Space charge effect), attenuation, electronic gain, diffusion, recombination, etc
  - Detector response is uniform in space and over time after the corrections
- Absolute energy scale is determined using stopping muons

ProtoDUNE-SP: dE/dx Measurements



Precise dE/dx leads to excellent μ^+/p separation

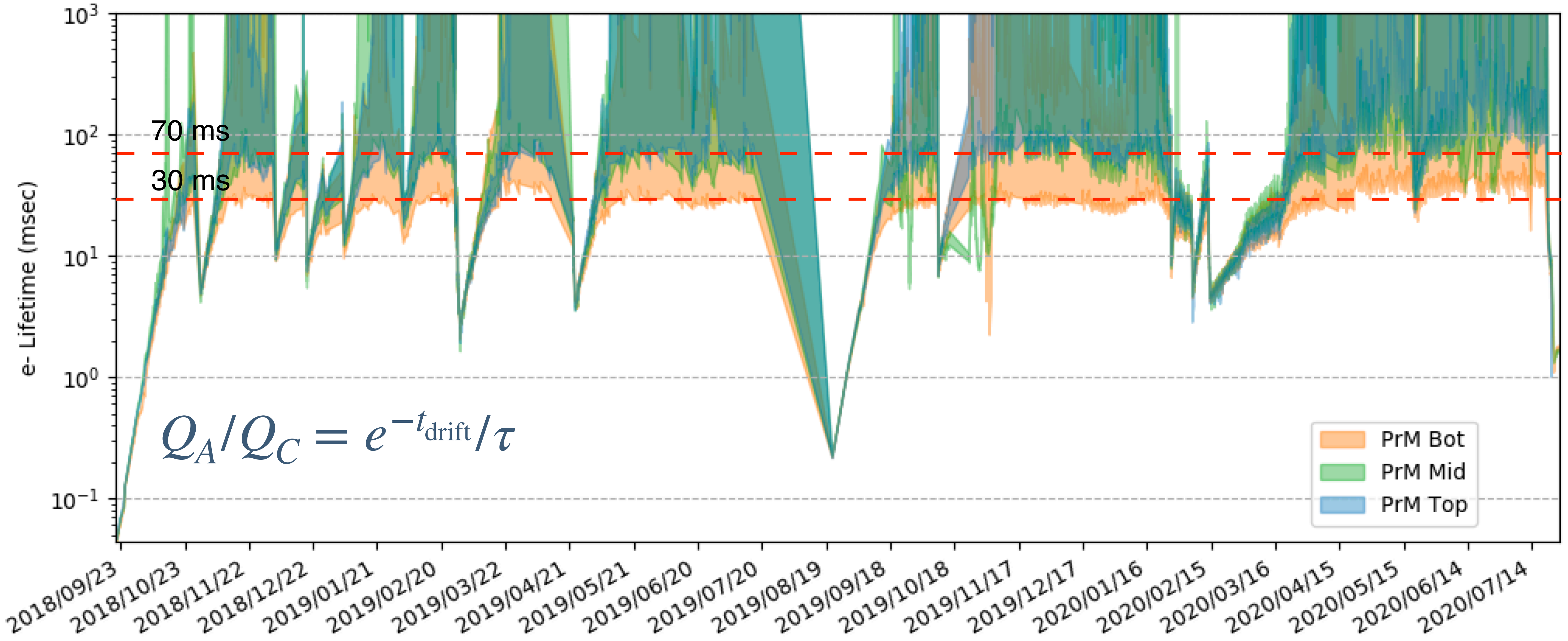




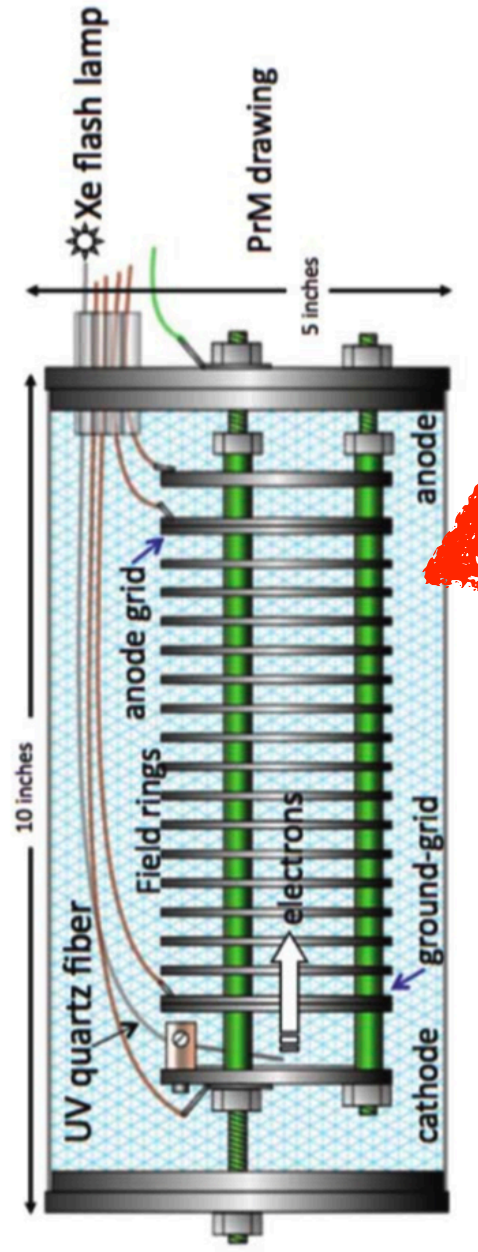
Good e/γ separation crucial for electron neutrino ID

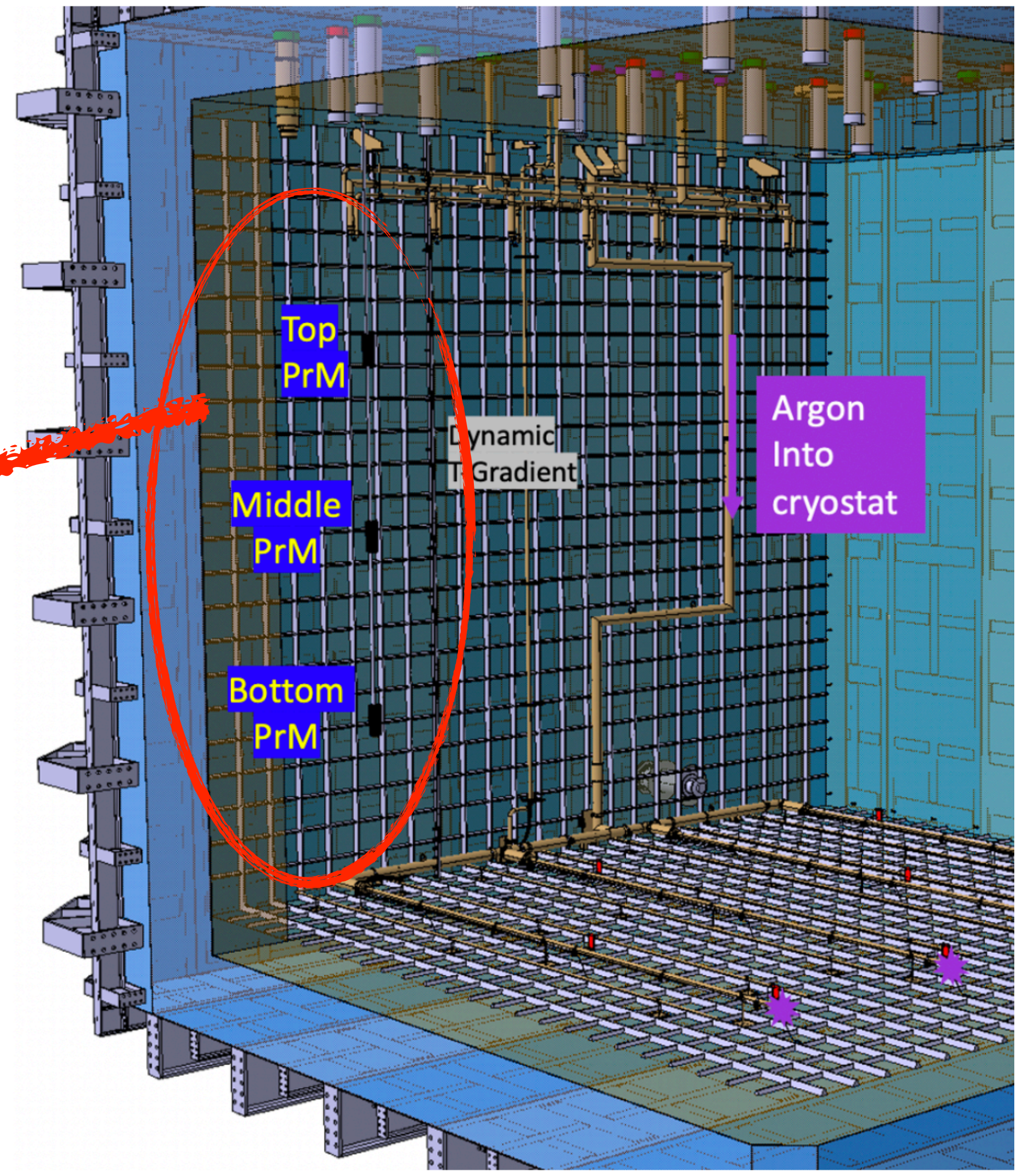
- The calibration constants applied to test beam particles and yielded good data and MC agreements
  - Excellent μ^+/p separation: crucial for cross section measurements
  - Good e/γ separation: crucial for DUNE's neutrino oscillation measurements

ProtoDUNE-SP: LAr Purity



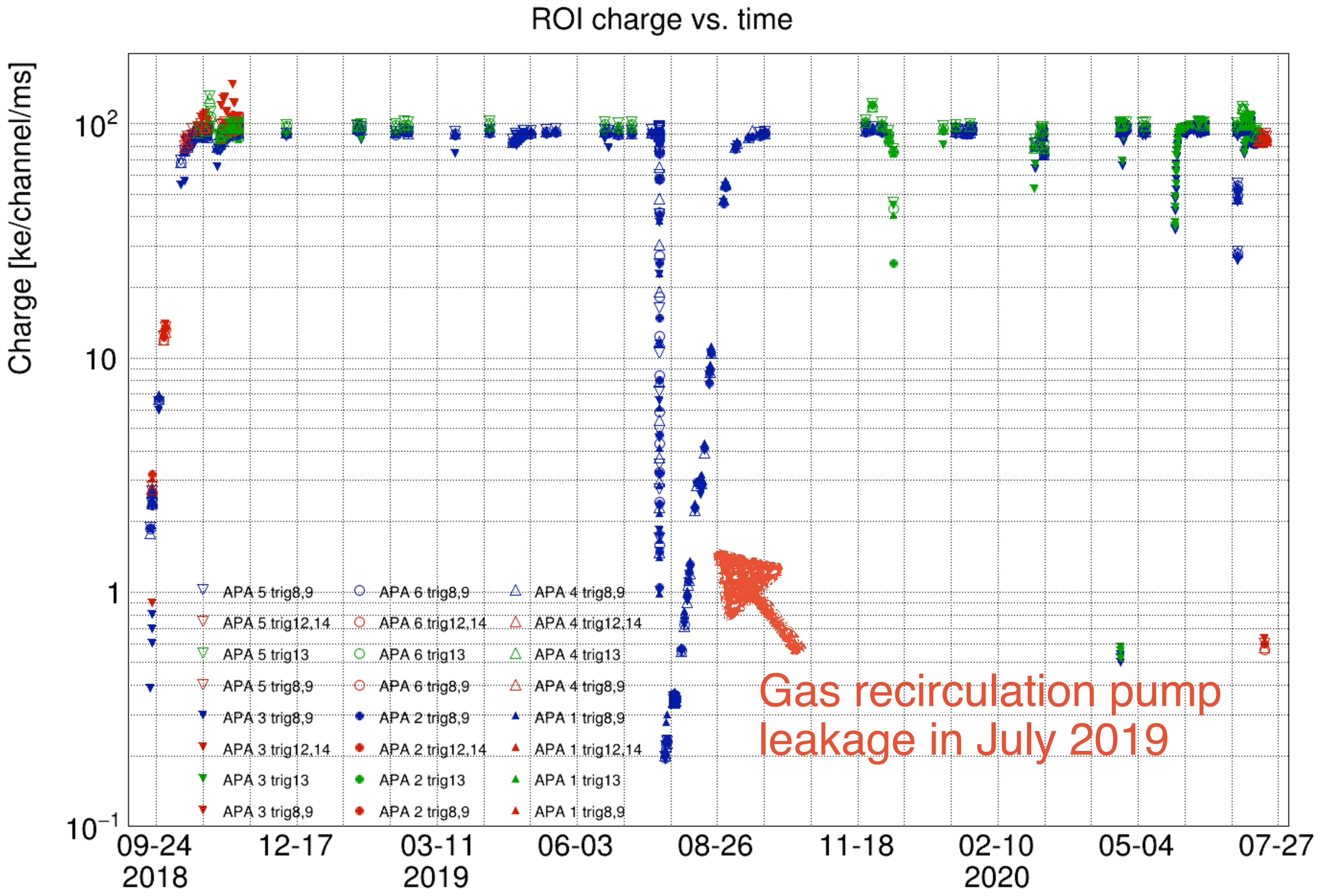
3 purity monitors at different heights to measure LAr purity





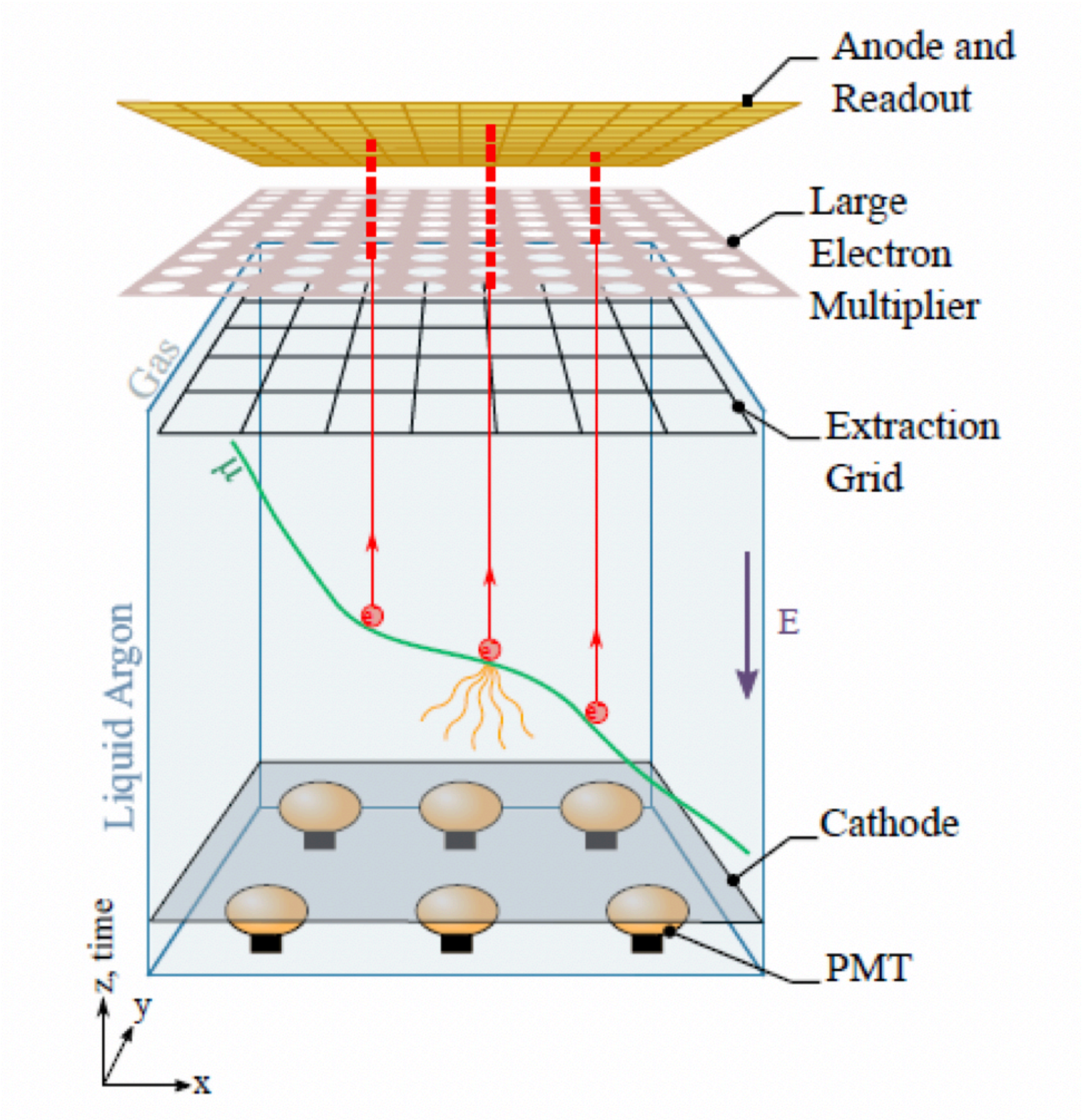
- Liquid Argon purity is routinely measured by three Purity Monitors
- High purity reached thanks to the gas/liquid recirculation & filtering
  - Lower limit of 30 ms lifetime over the majority of run period → 7% signal reduction over the entire 3.6 m drift distance (2.25 ms drift time)

ProtoDUNE-SP: Detector stability



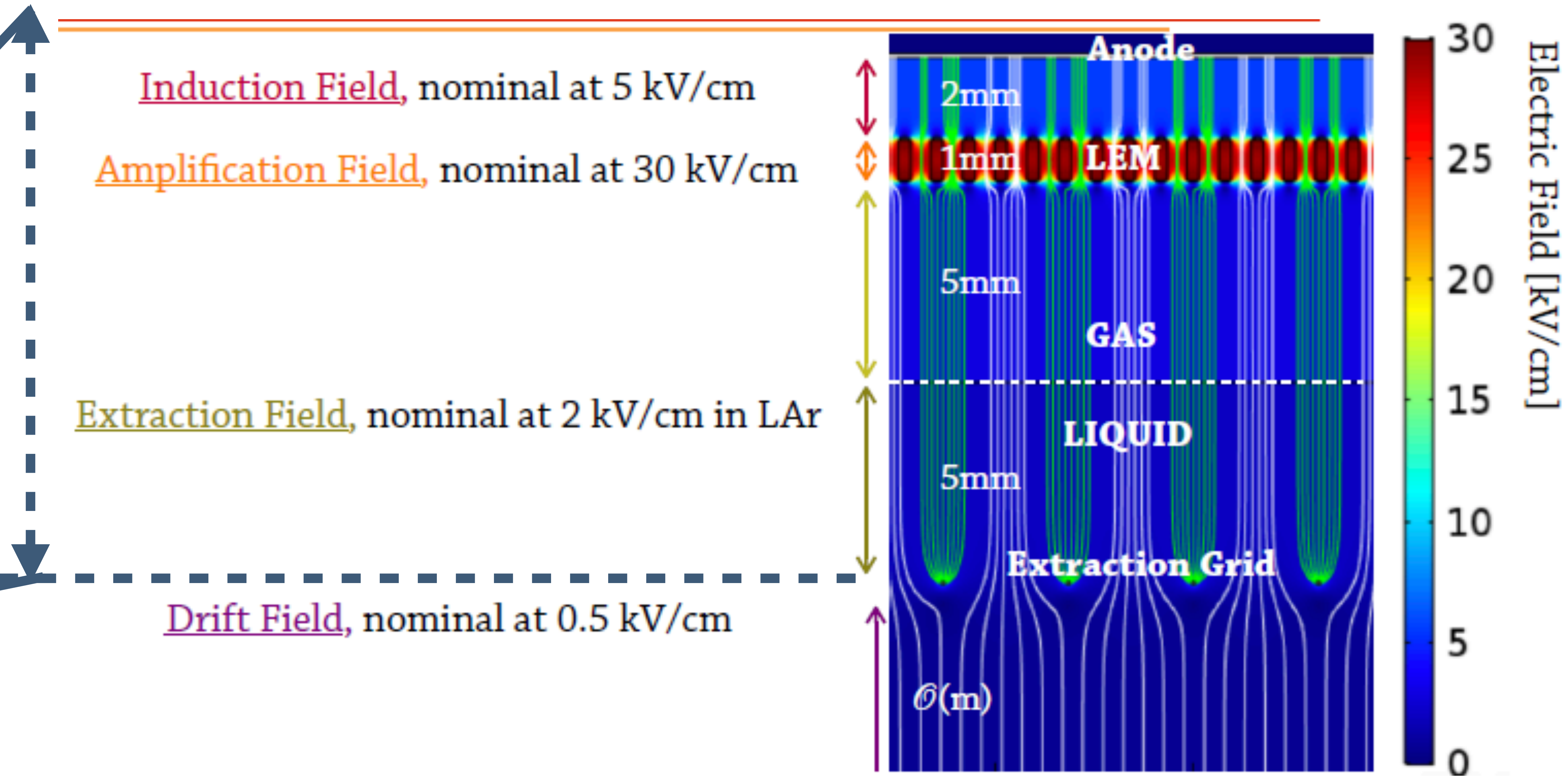
- TPC signal strength: The average charge per channel from cosmics
  - A monitor of overall detector response
  - Sensitive to amplifier/digitizer response, cathode voltage, LAr purity and other detector conditions
- Response has been stable over the 22 months of operation

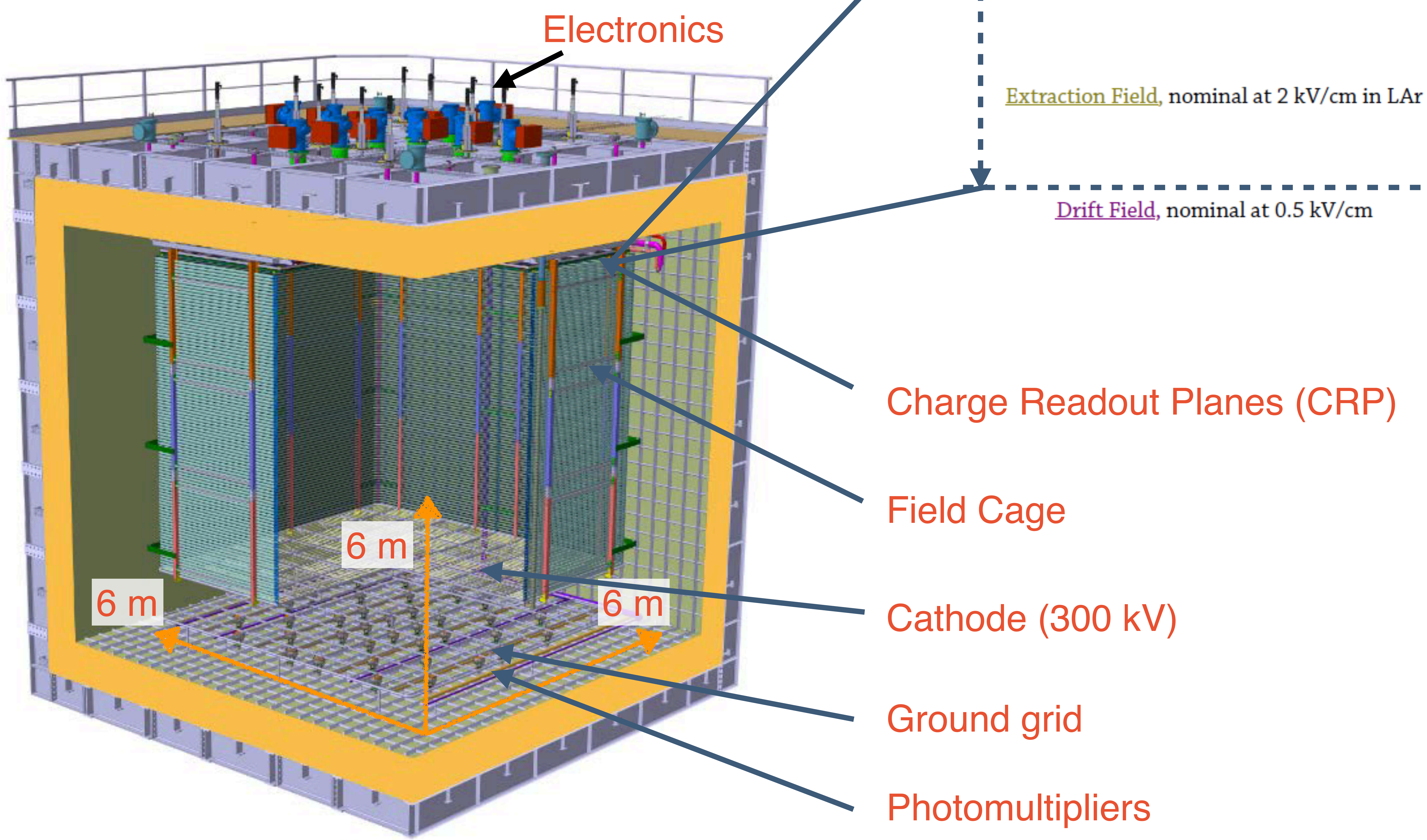
ProtoDUNE-DP: Operating Principle



- Ionized electrons drift vertically upward in LAr
- Electrons are extracted from liquid into gas phase above the liquid
- Charge signal amplified and read out at the top
- PMTs detect scintillation light at the bottom
- Challenge: the overall design increases the possible drift length which requires a correspondingly higher voltage

ProtoDUNE-DP Detector

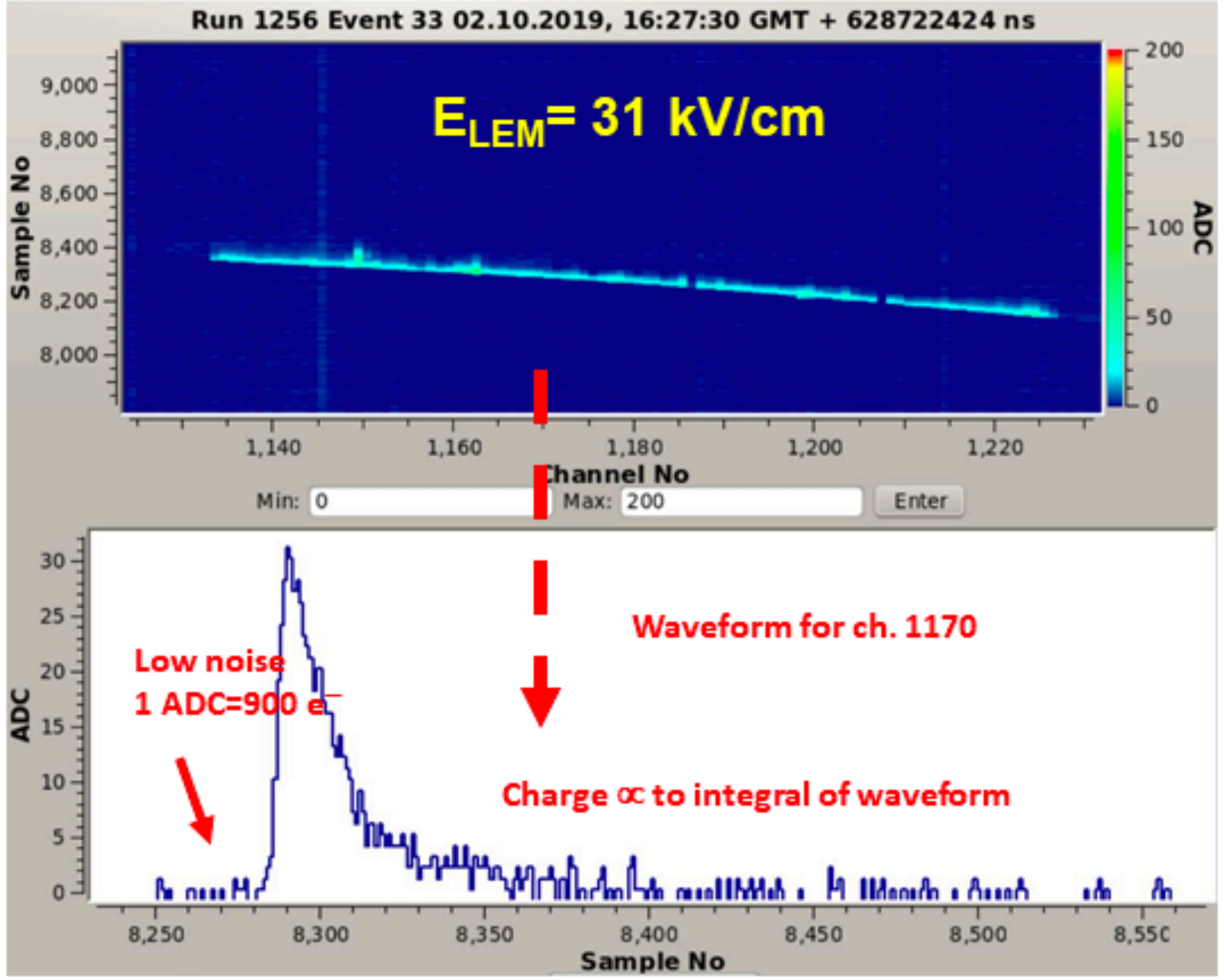




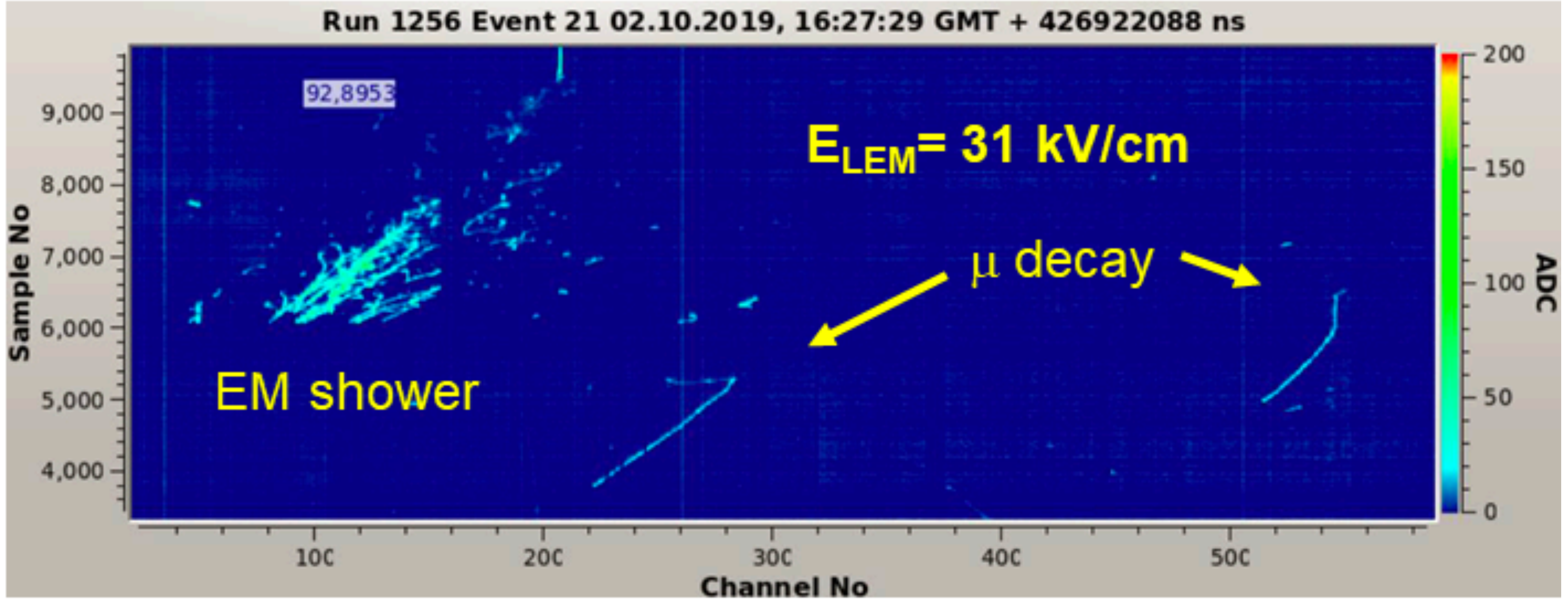
ProtoDUNE-DP: Cosmic Ray Events

- Events with LEM ΔV of 31–32 kV (Oct. 2019)

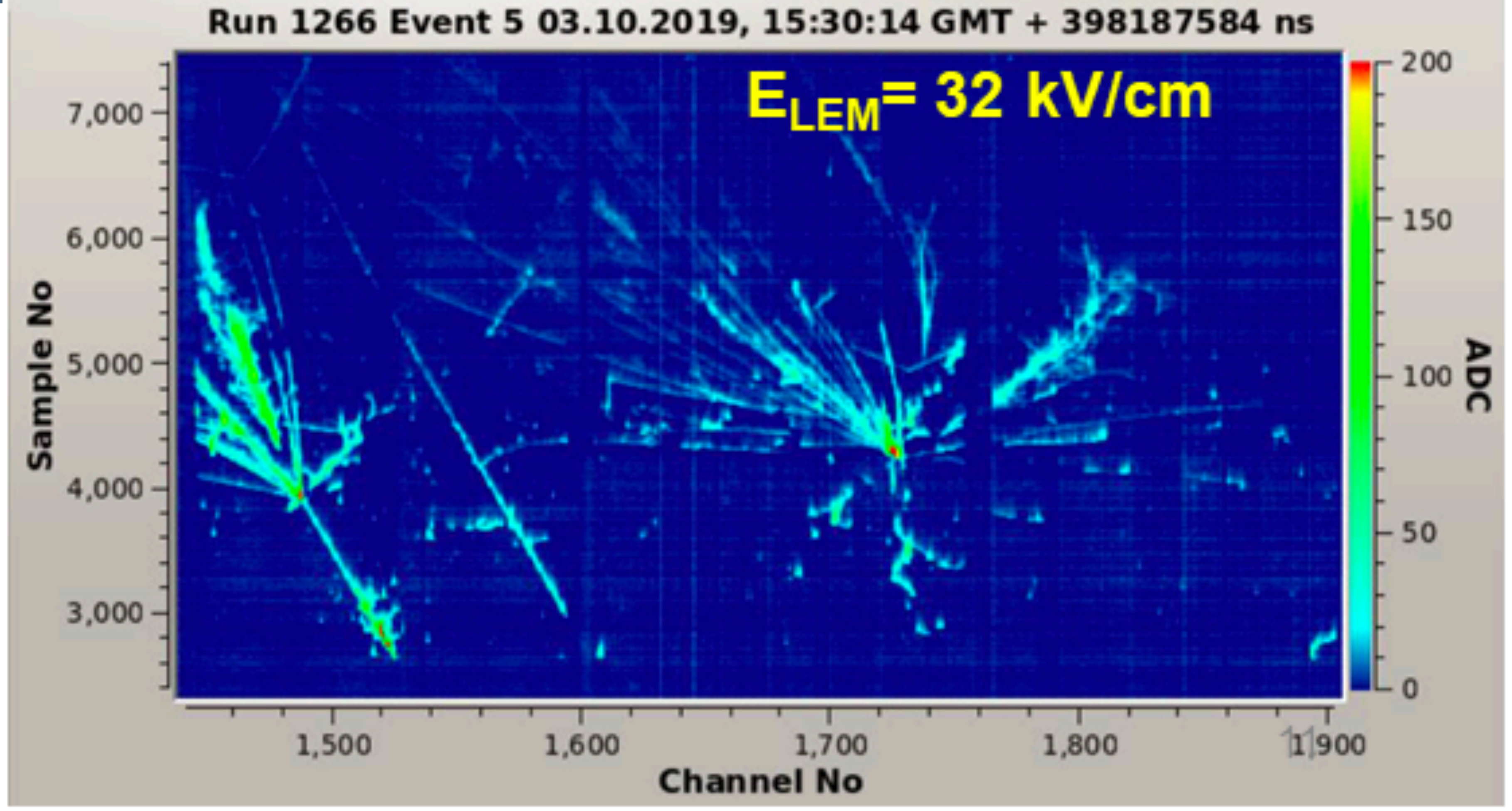
- Horizontal muon track



- Electromagnetic shower + 2 muon decays



- Multiple hadronic interactions in a shower



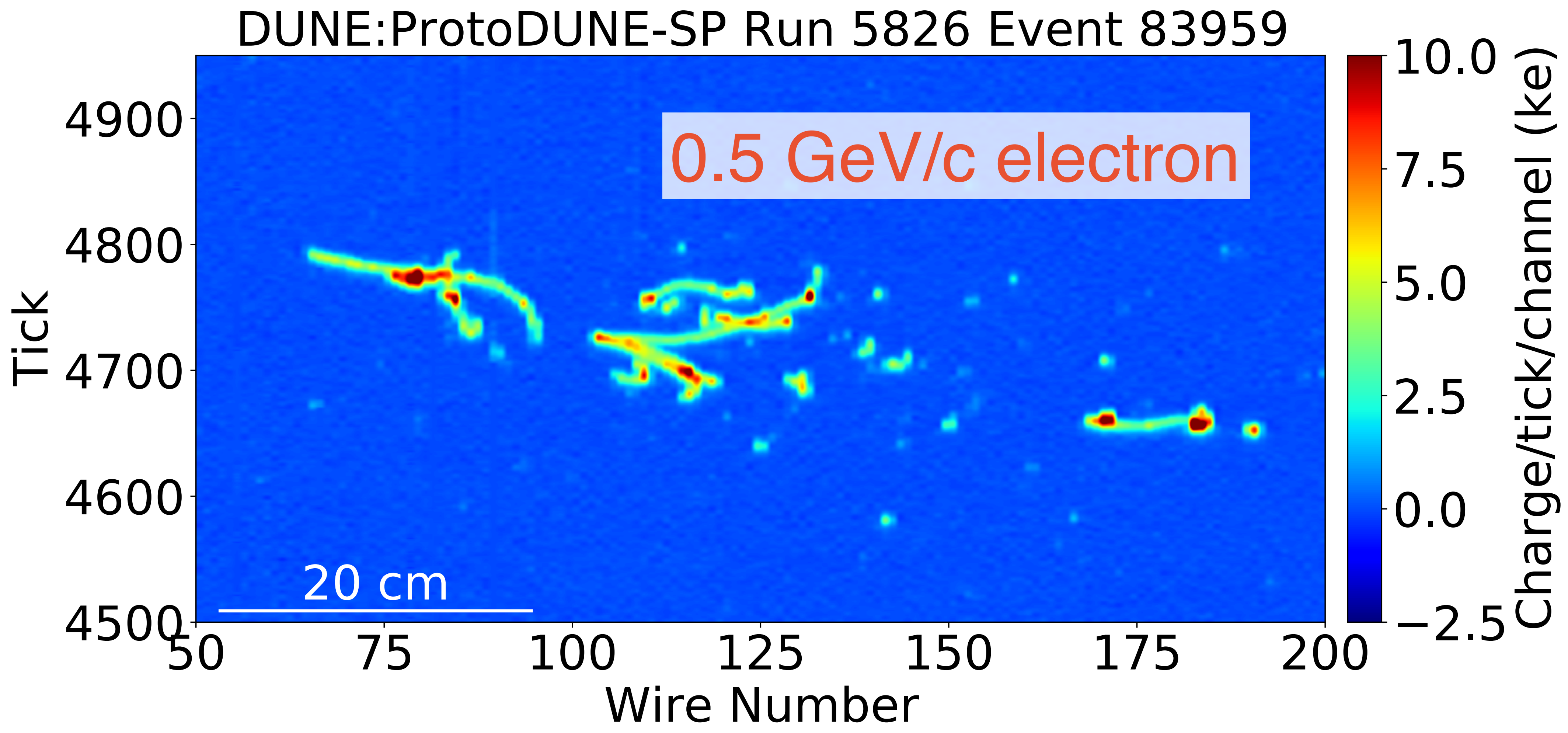
Summary and Prospect

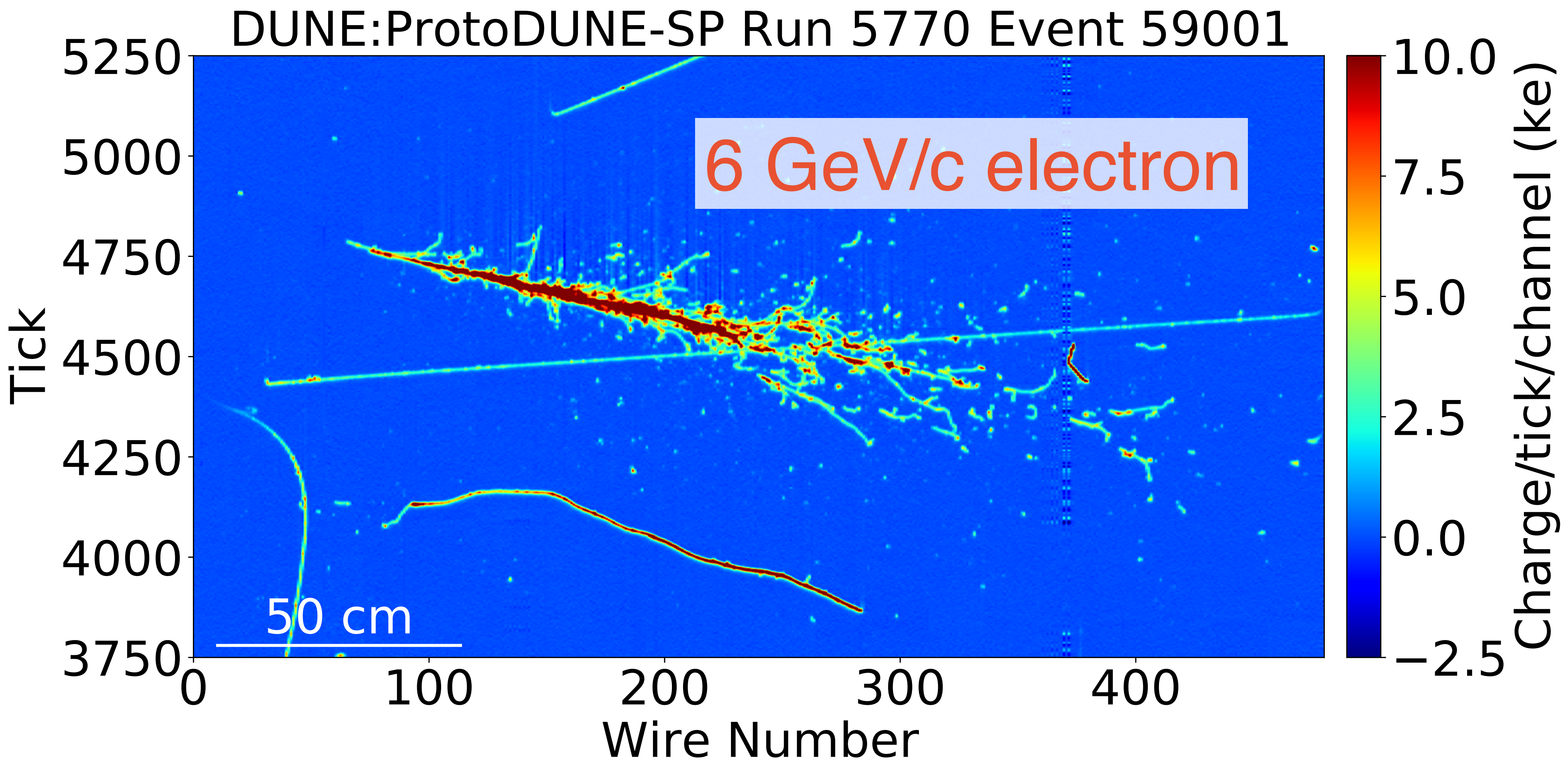
- The successful performance of ProtoDUNE-SP LArTPC using large samples of data from a test-beam run at the CERN Neutrino Platform demonstrates the effectiveness of the single-phase detector design and the execution of the fabrication, assembly, installation, commissioning, and operation
    - The data collected by ProtoDUNE-SP during beam runs and cosmic-ray runs will allow more detailed studies of detector characteristics and the measurement of argon-hadron cross sections
    - ProtoDUNE-SP Phase II, to improve detector with lesson learned from Phase I, is expected to start in late 2022
- ProtoDUNE-DP is the largest dual-phase TPC ever built and operated
    - Plenty of data to be analyzed and many interesting results to be share with a wider community interested in large LAr TPCs

Stay tuned!

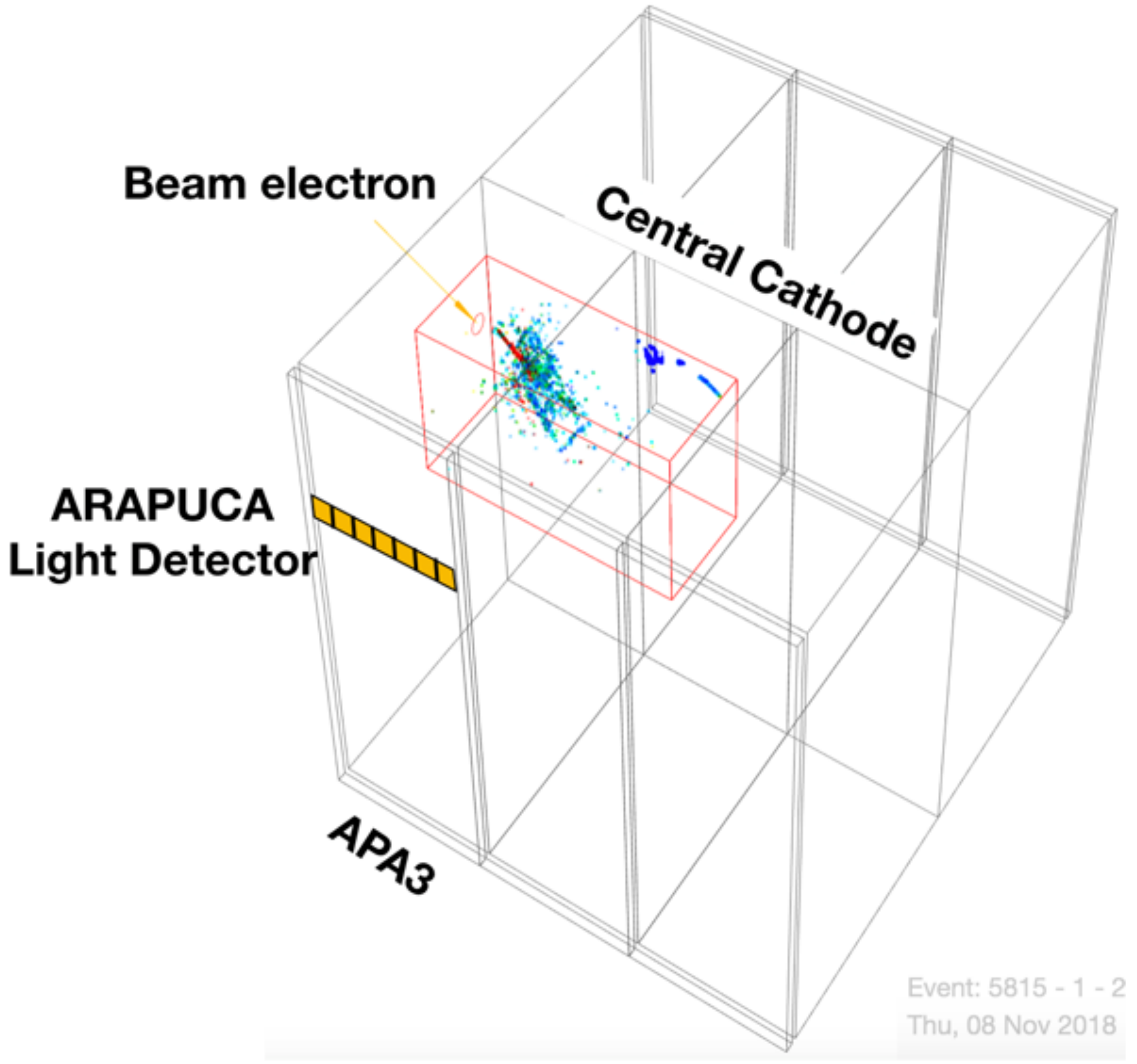
Backup

SP: Beam electron energy reconstruction



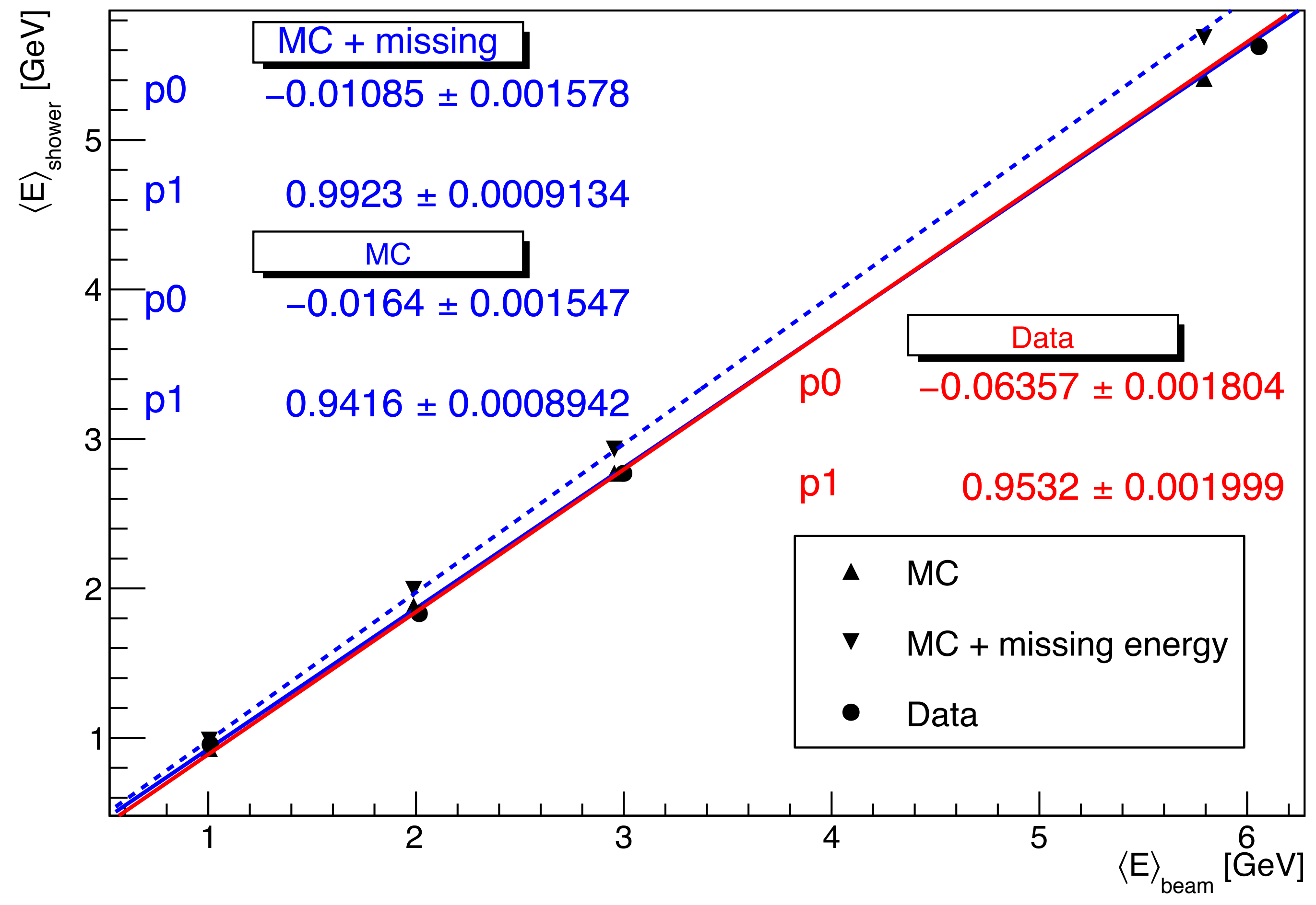


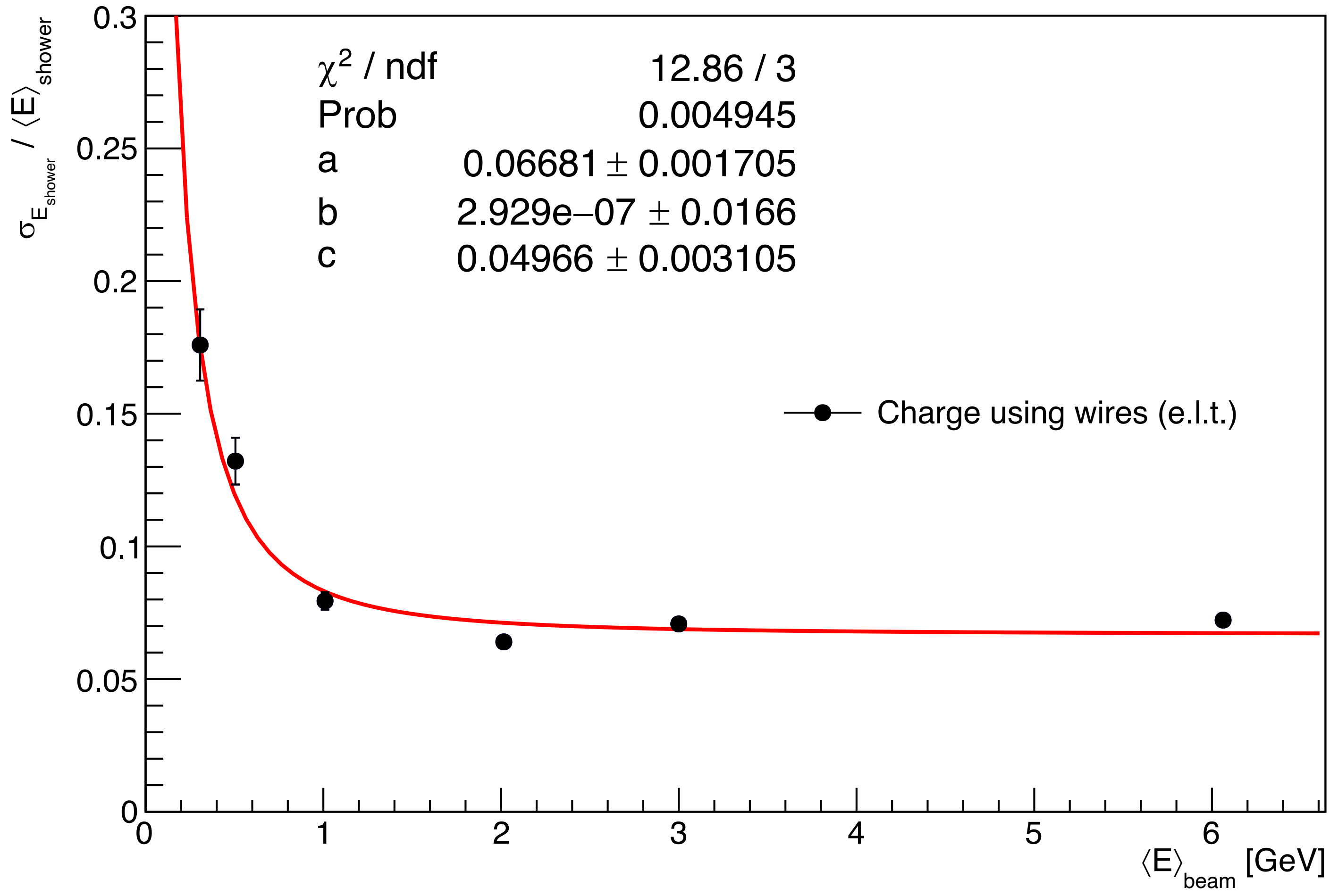
- Electron energy resolution is crucial for DUNE's oscillation measurements
  - $E_{\nu_e} = E_e + E_{had}$
- Two analyses to measure beam electron energy resolution
  - TPC charge information
  - Photon detector information with only one ARAPUCA bar



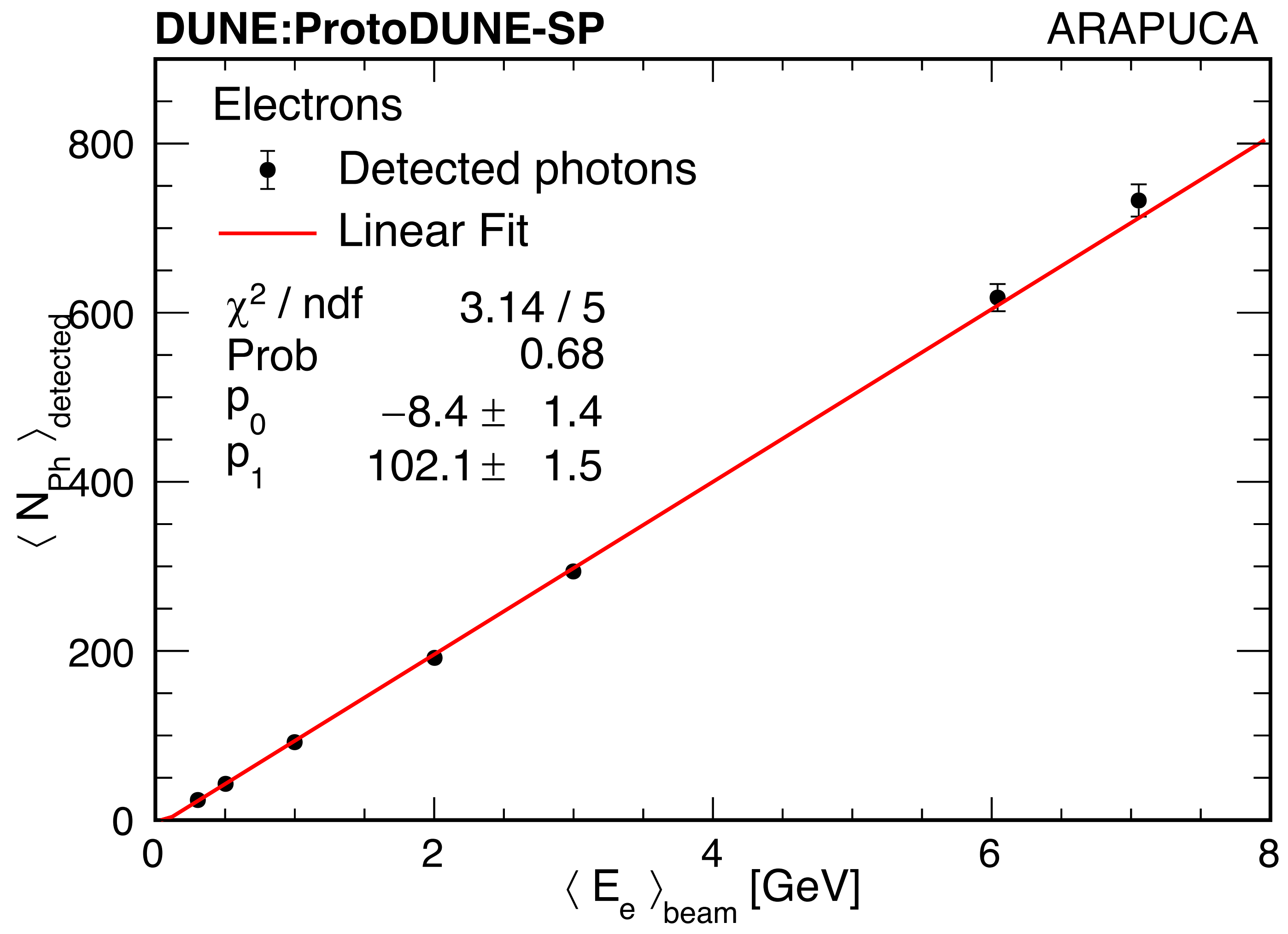
SP: Beam electron energy resolution

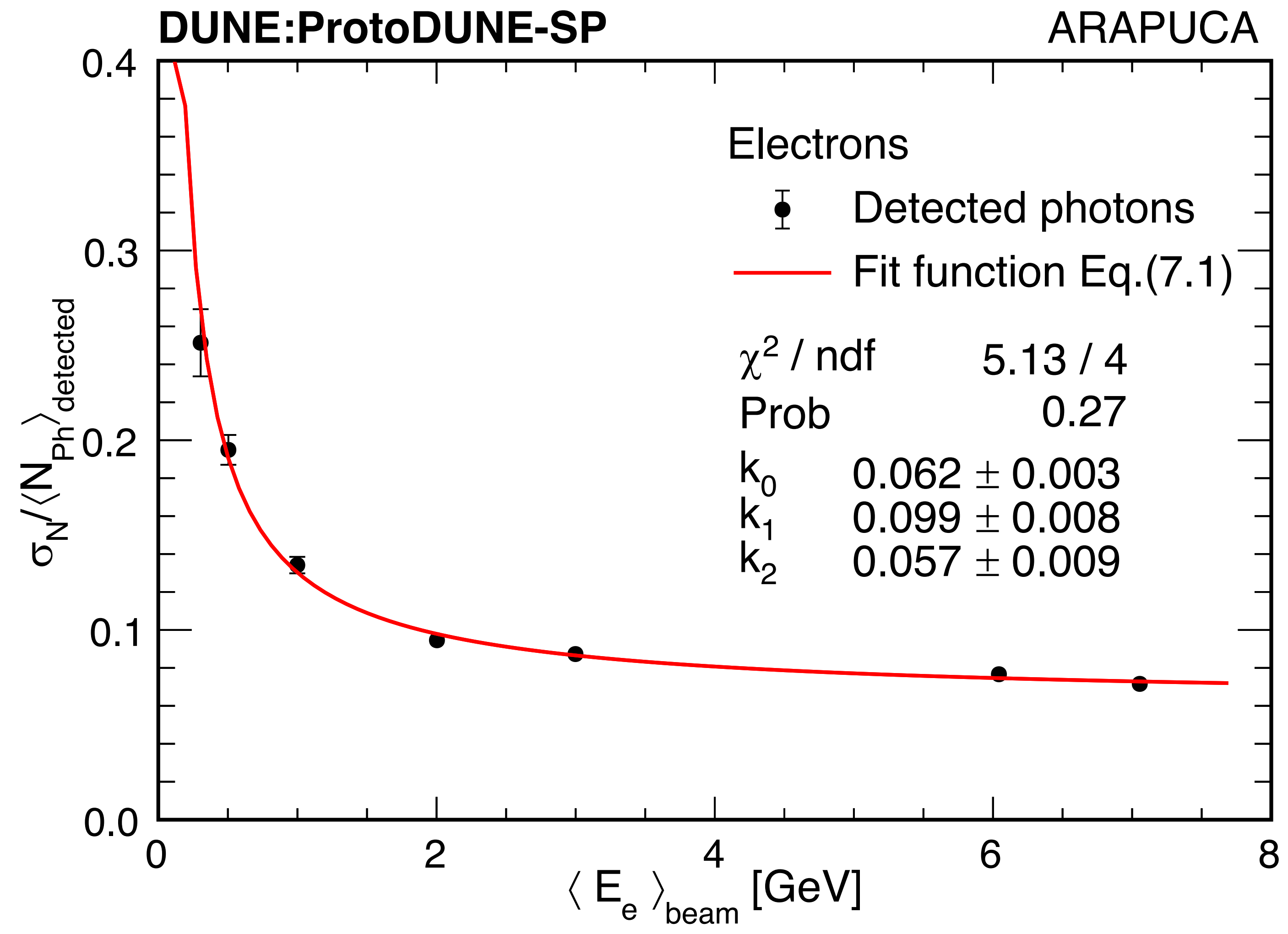
TPC





Photon Detector



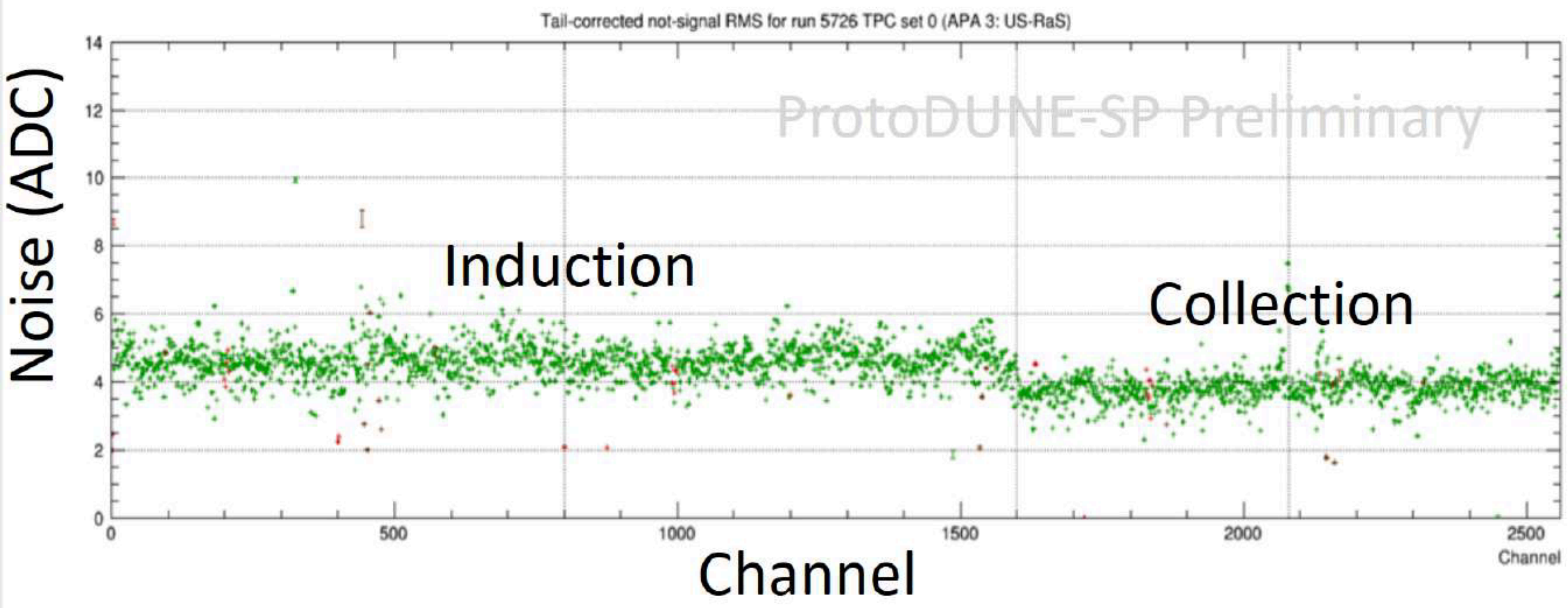


$$\sigma_E/\langle E\rangle = \sqrt{a^2 + (b/\sqrt{E})^2 + (c/\langle E\rangle)^2}$$

- Good linearity seen in both analyses
- Constant term dominated by spread of beam momenta
- Noise term dominated by fluctuation in the energy loss upstream
- Stochastic term characterizes the intrinsic detector resolution
  - ~ 2% for TPC and 9.9% for PD
  - Better than the design requirements

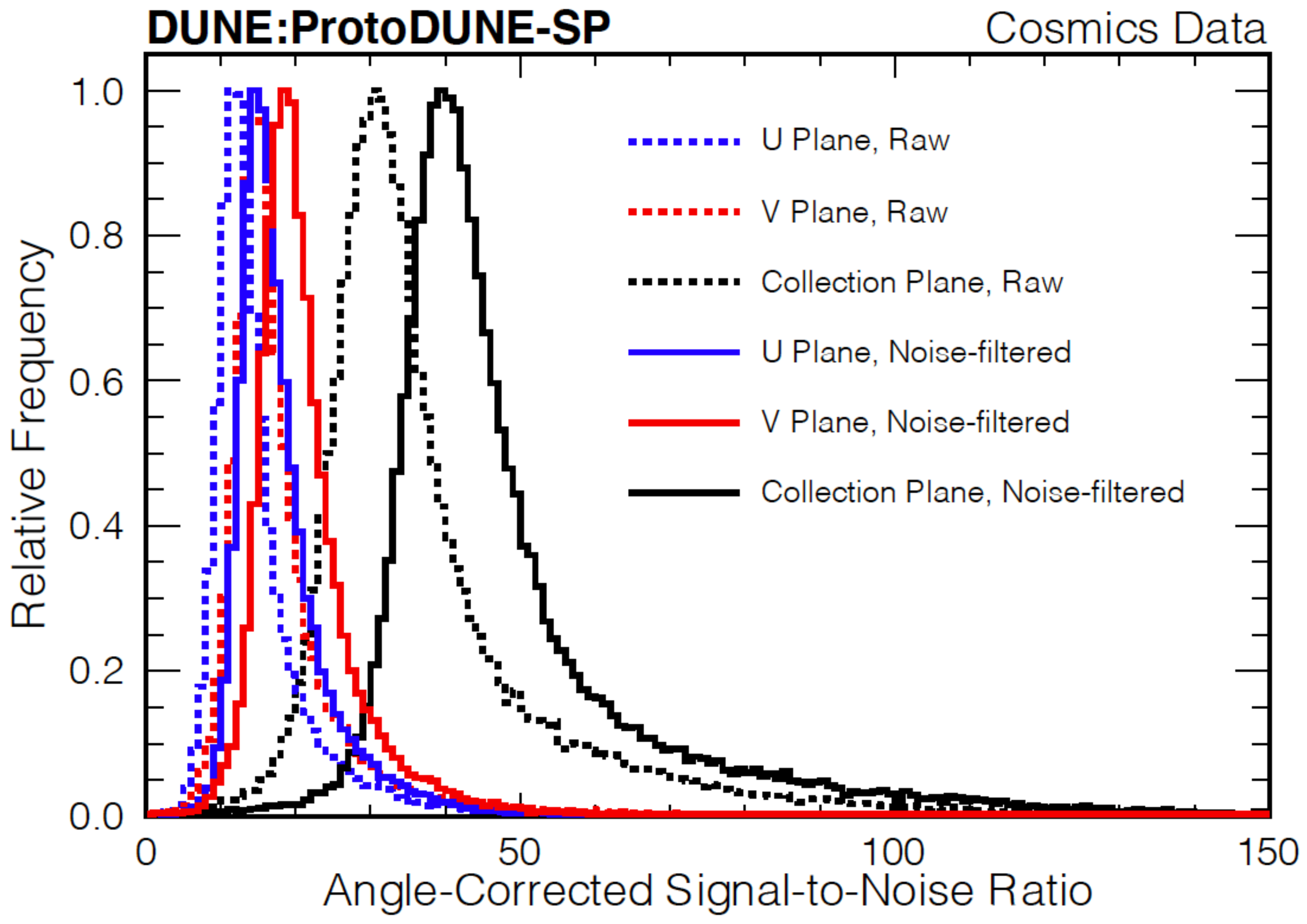
SP: Electronic noise and S/N ratios

- Electronic noise level measured by pedestal ENC (equivalent noise charge) before noise filtering: Collection (X): 550 e-, Induction: 650 e- (DUNE goal < 1000 e-)

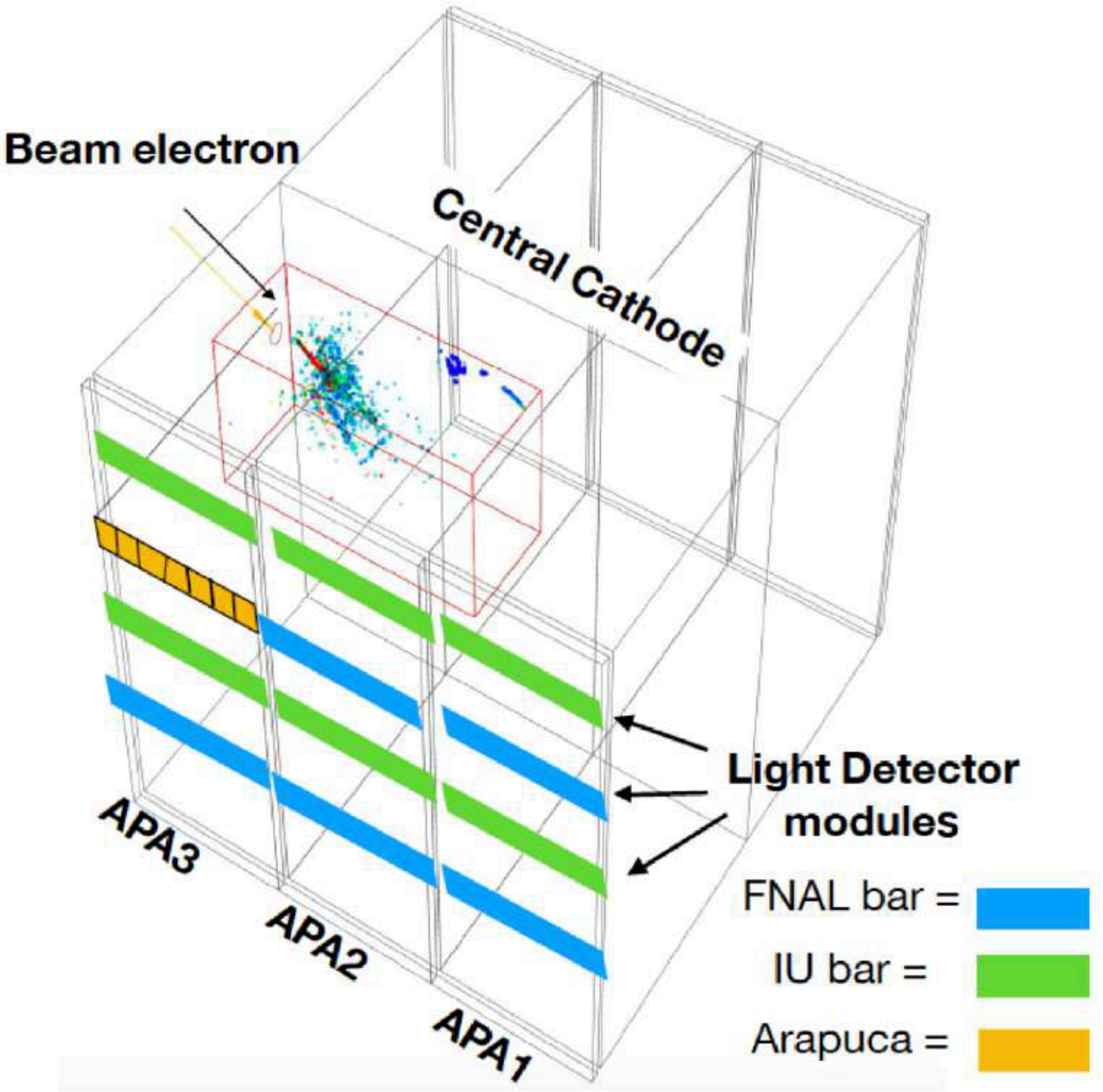


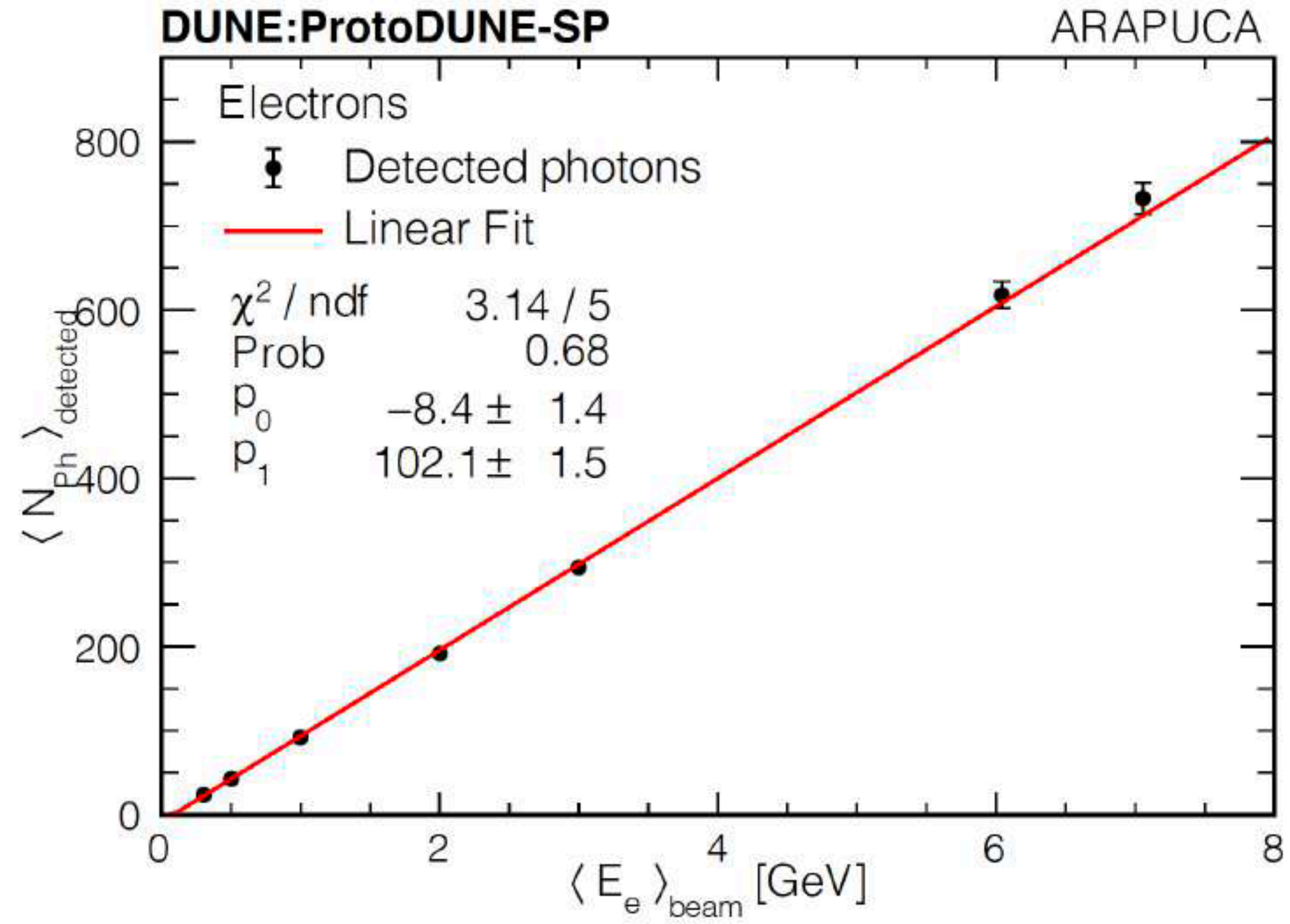
- Noise filter reduces both by ~ 100 e-

- Noise-filtered signal-to-noise ratio measured by cosmic muons: Collection: 48.7:1, Induction: 21.2:1



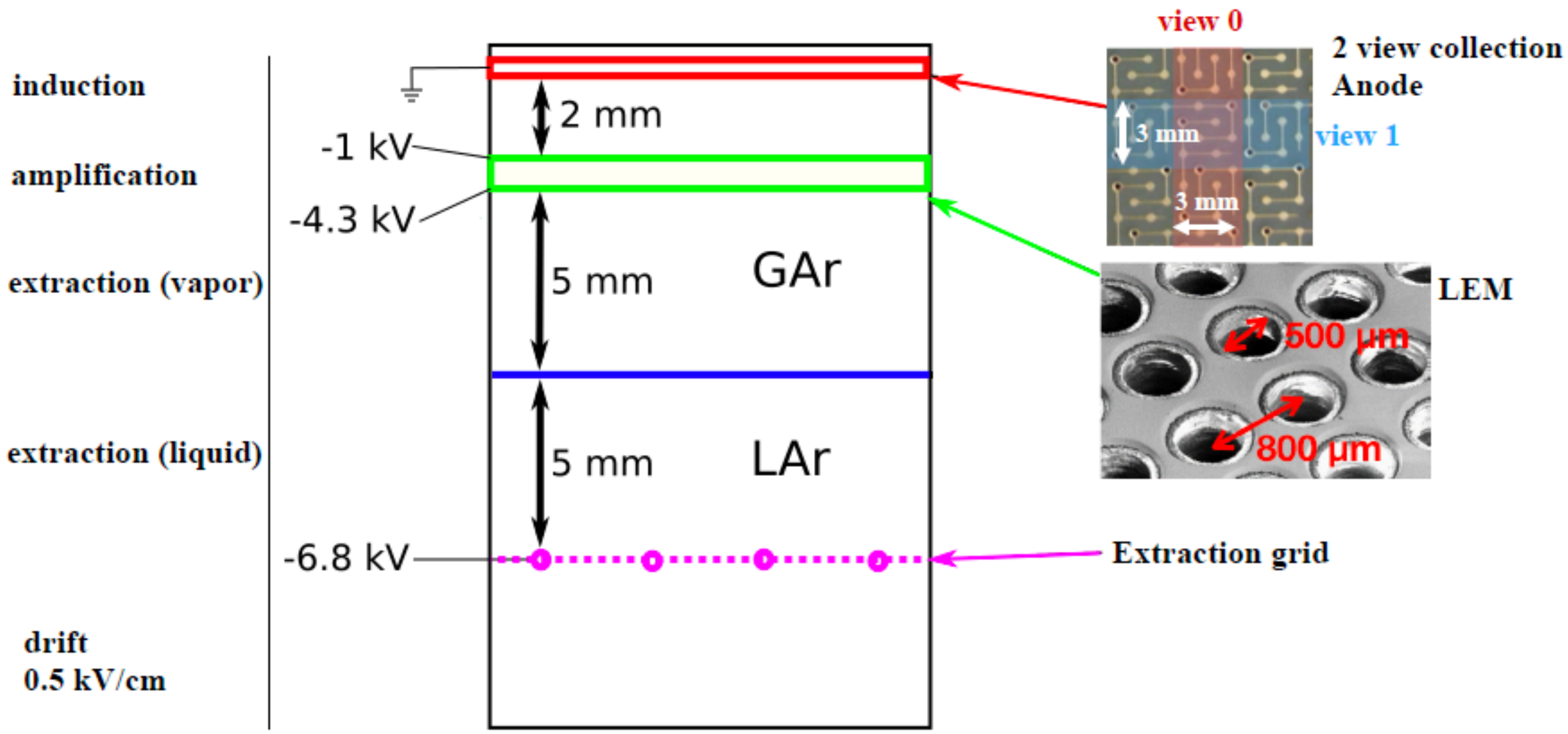
SP: Photon Detector Performance

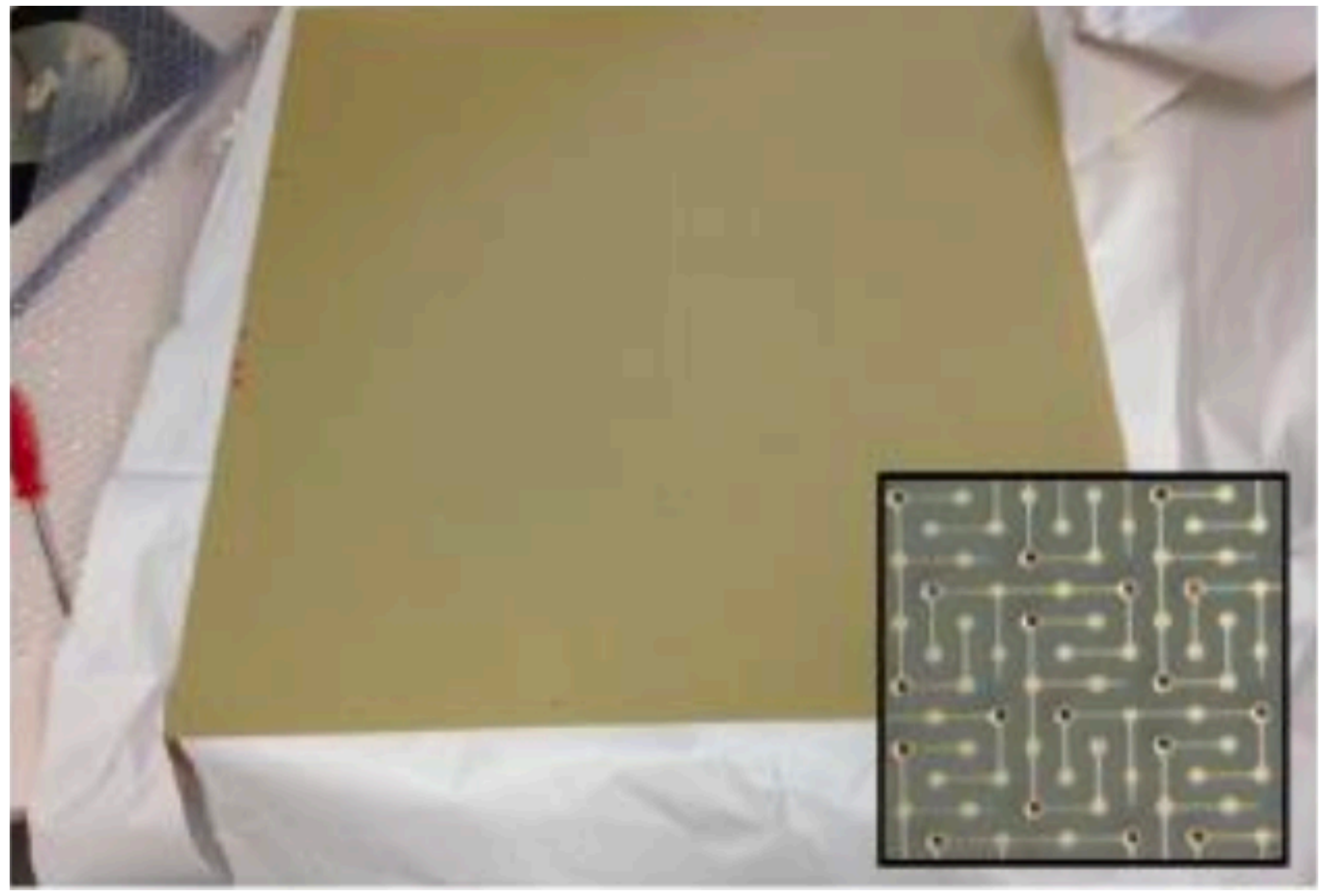


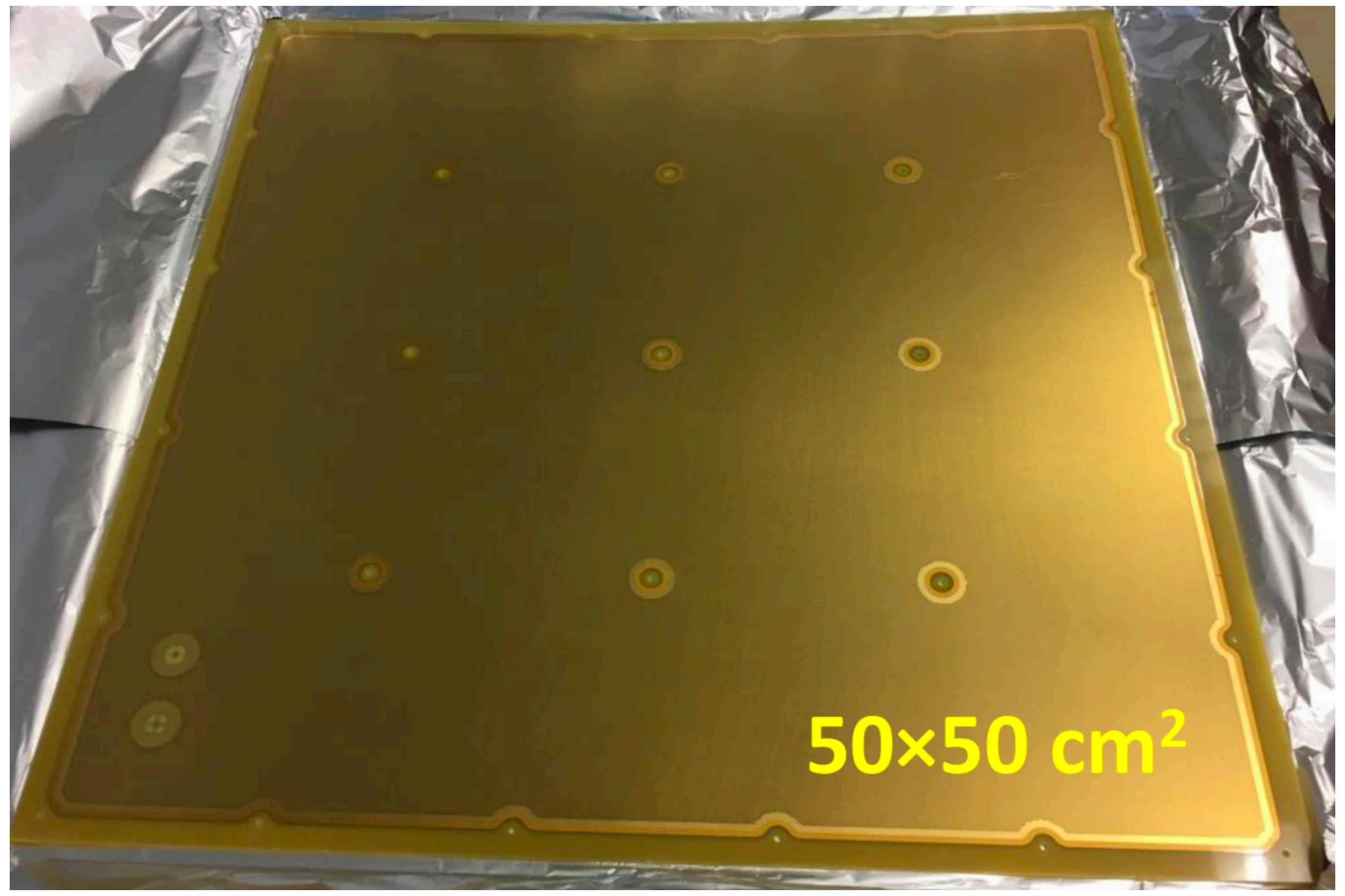


- Good energy linearity for contained beam electrons in the detector
- Working on geometry, attenuation and efficiency corrections

DP: Operating Principle



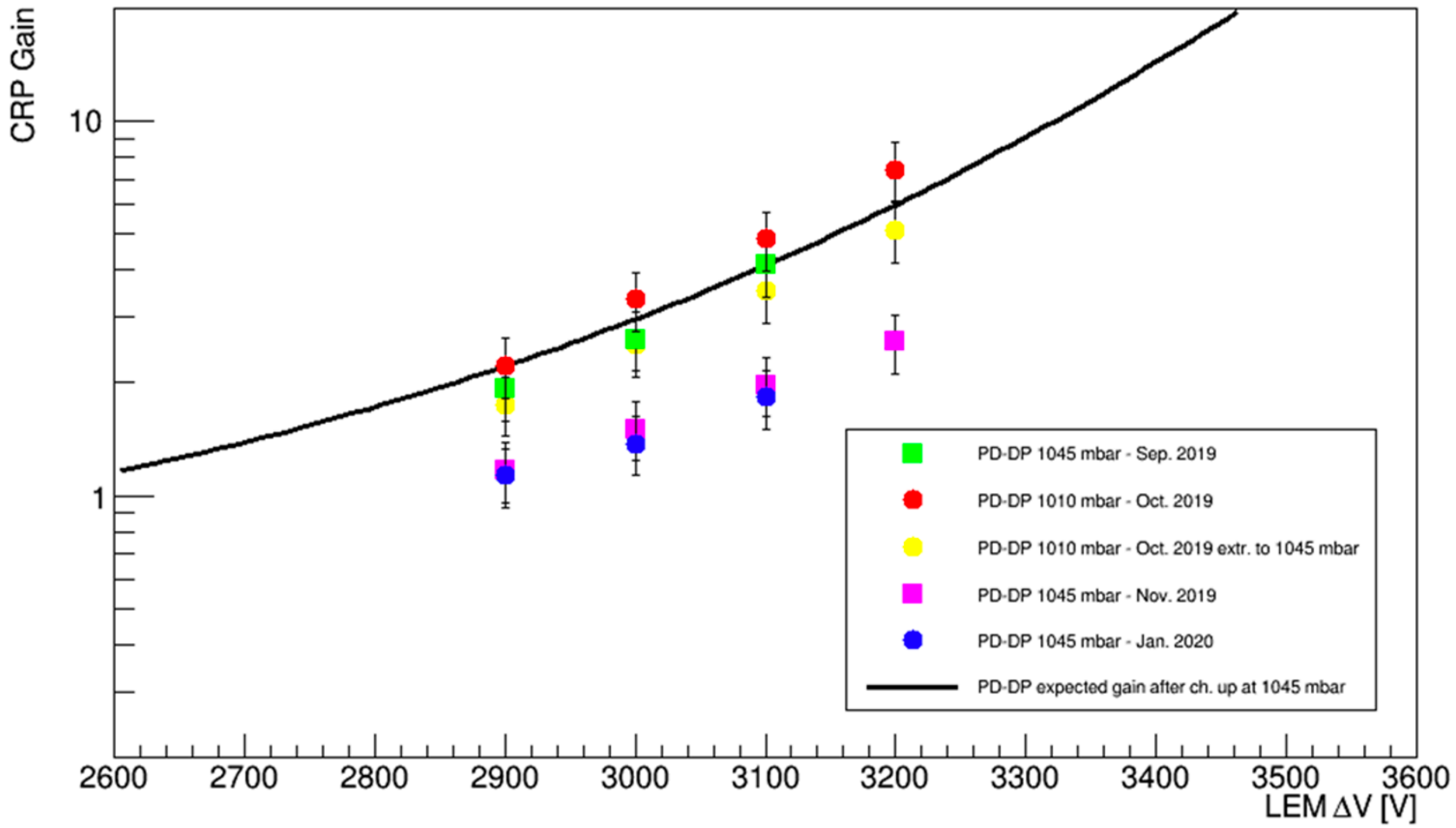




- Homogeneous 0.5 kV/cm drift field (cathode + field cage)
- Extraction field ~ 2.5 kV/cm between grid and LEM bottom
- Amplification ~ 20 in LEMs holes
- Readout in two directions (3.125 mm pitch) by collection on anode via field between LEM top electrode and anode

DP: Charge Readout Plane gain measurement

- Measurements between Sept. 2019 and Jan. 2020 with cosmics
- Operating conditions: 1045 mbar and ~ 90 K
- CRP gain: $\epsilon_{\text{extraction}} \times \epsilon_{\text{LEMs,amplification}} \times \epsilon_{\text{Qcollection}}(E_{\text{induction}})$
- $\epsilon_{\text{extraction}}$ estimated to be well above 90%



- Sept. → Nov: Reduction by at least a factor of 2 due to LEM charging up effects
- Nov. → Jan.: very small reduction, charging up completed
- Gain a factor of 2 lower than extrapolated from previous prototypes
- Discrepancy not yet understood, dedicated study to come