

Measurement of Space Charge Effects in ProtoDUNE-SP

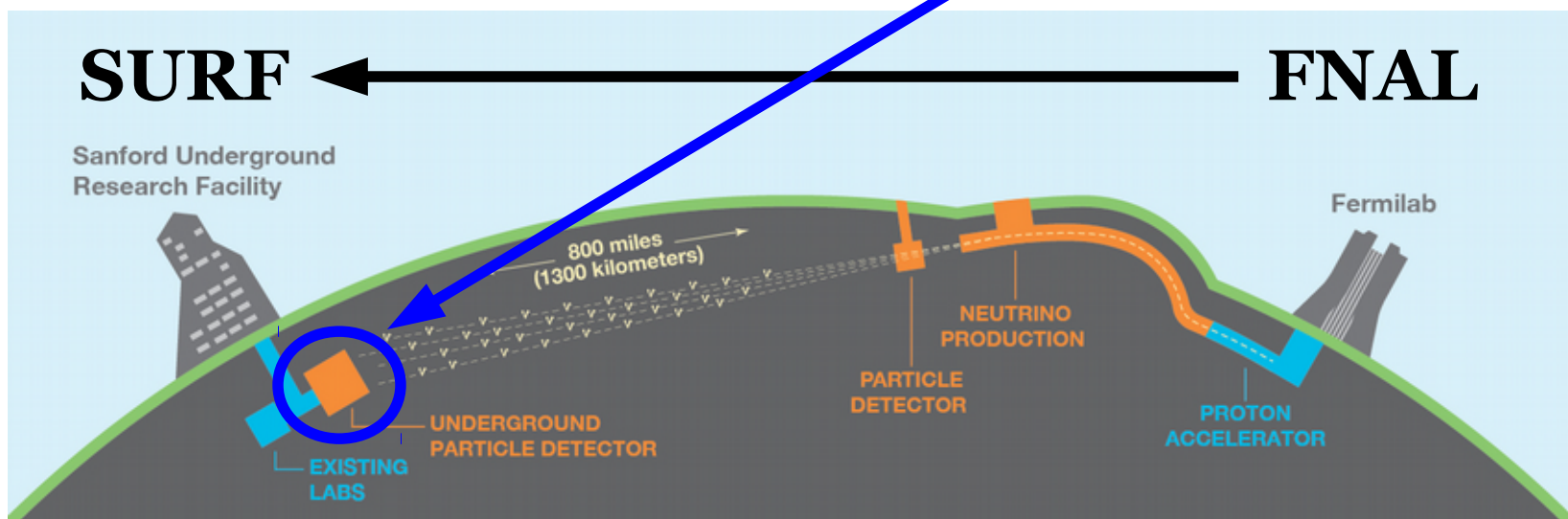
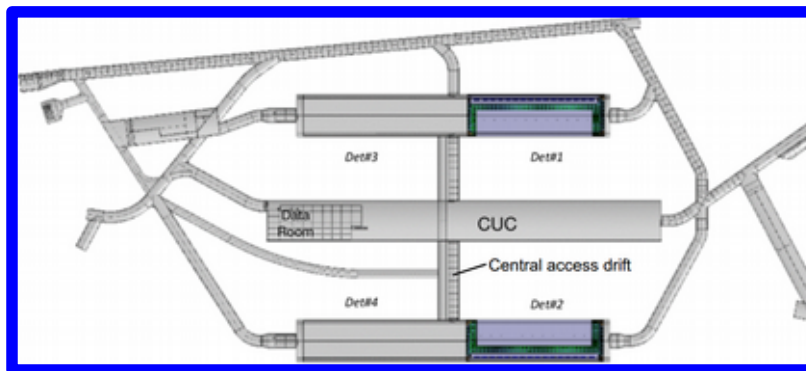
Michael Mooney (Colorado State University)

On behalf of the DUNE Collaboration

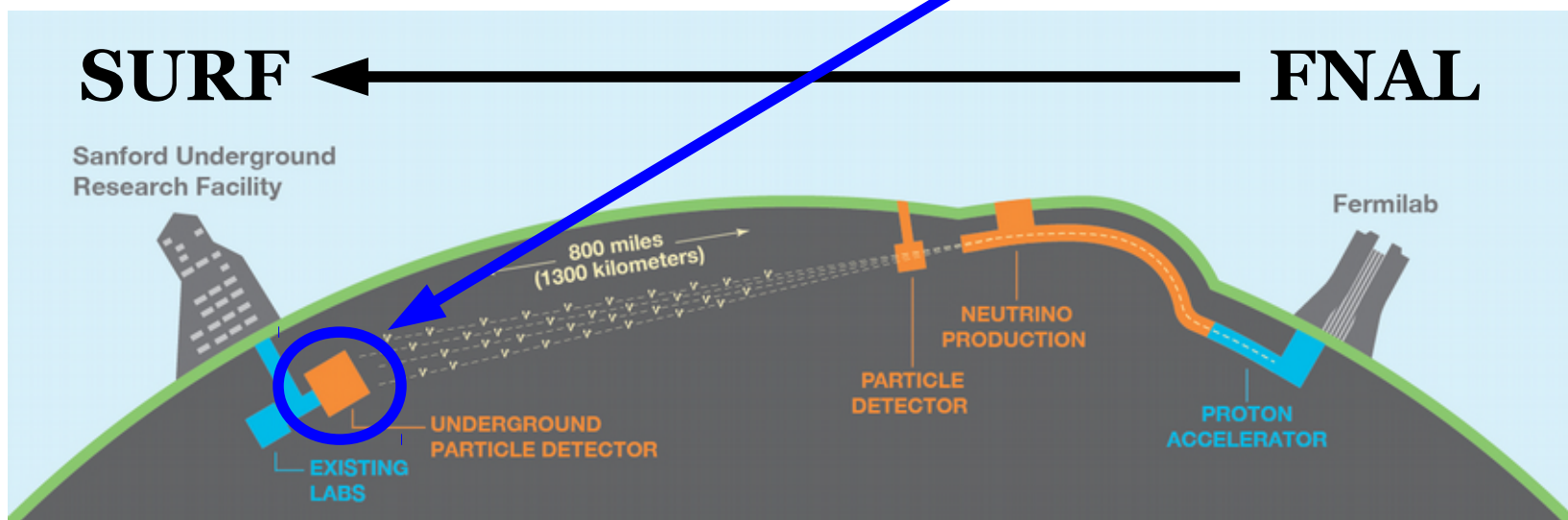
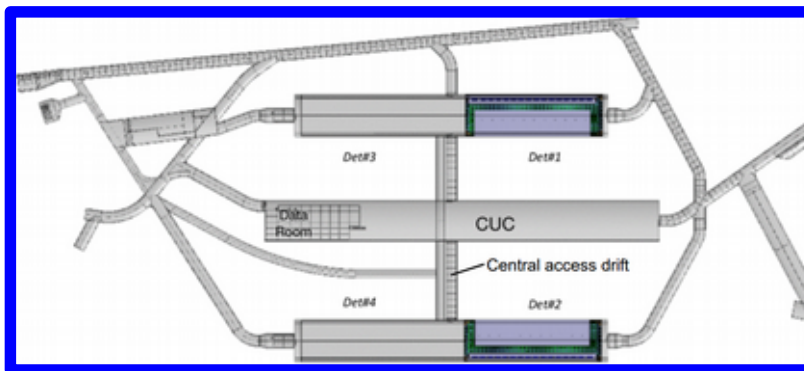
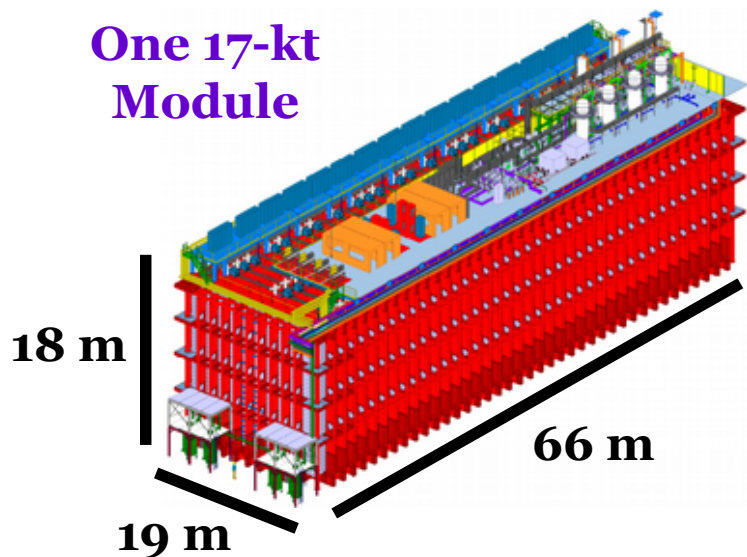
*40th International Conference on High Energy Physics
July 28th, 2020*

- ◆ Presented first measurement of space charge effects at ProtoDUNE-SP
 - Up to 35 cm of transverse spatial distortions from TPC edges
 - E field distortions as large as 25% of nominal E field near cathode
- ◆ SCE calibration for particle dE/dx presented – performs well
- ◆ Results presented here summarized in forthcoming paper
 - “First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform” – [arXiv:2007.06722](https://arxiv.org/abs/2007.06722) (submitting to JINST)
- ◆ Preparing dedicated SCE publication including improved 3D calibration, systematic uncertainty analysis, and time dependence studies

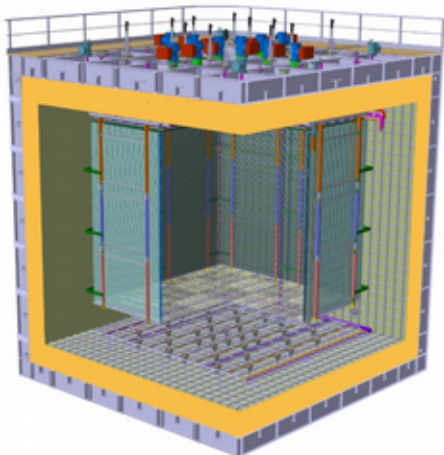
The DUNE Far Detector: Four LArTPC Detector Modules



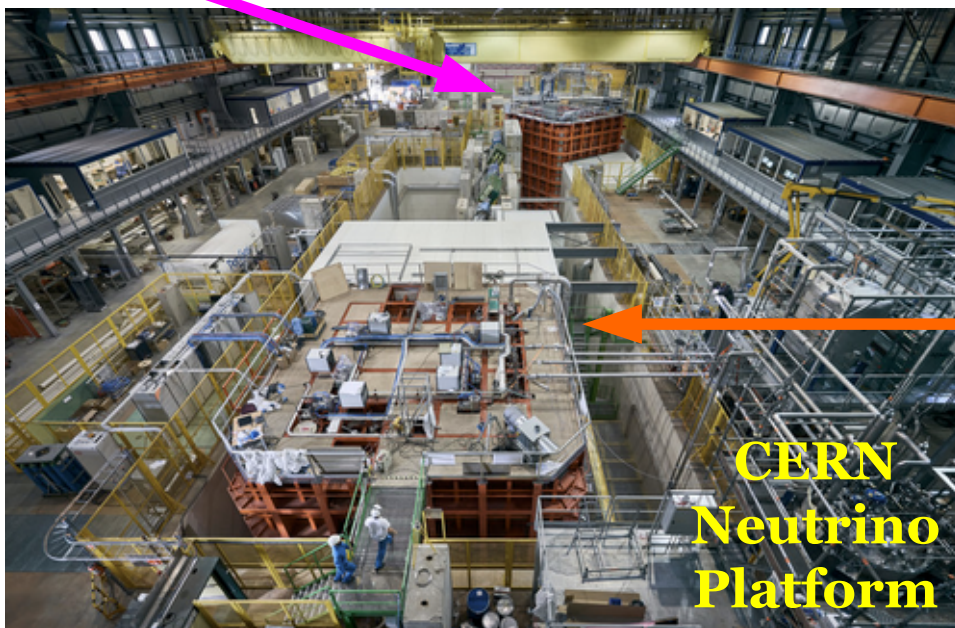
One 17-kt Module



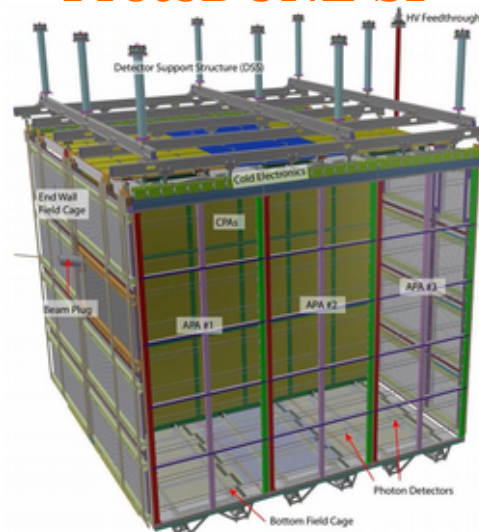
ProtoDUNE-DP

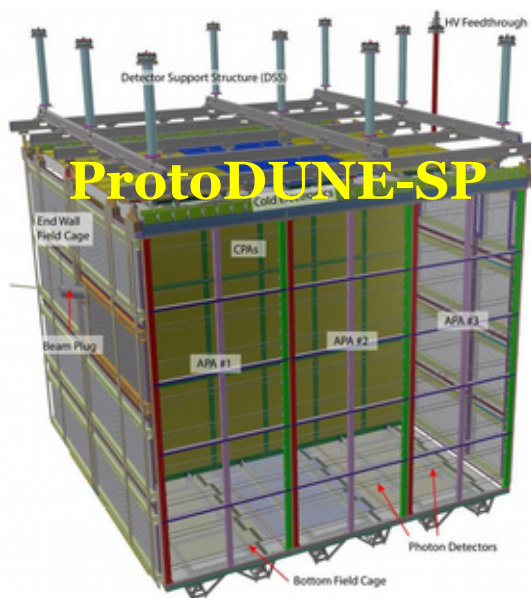


- ◆ Two 1-kt “ProtoDUNE_s” in charged test beam at CERN (one per FD design)
- ◆ Test of component installation, commissioning, and performance
- ◆ ProtoDUNE-SP operating since 2018; ProtoDUNE-DP since 2019

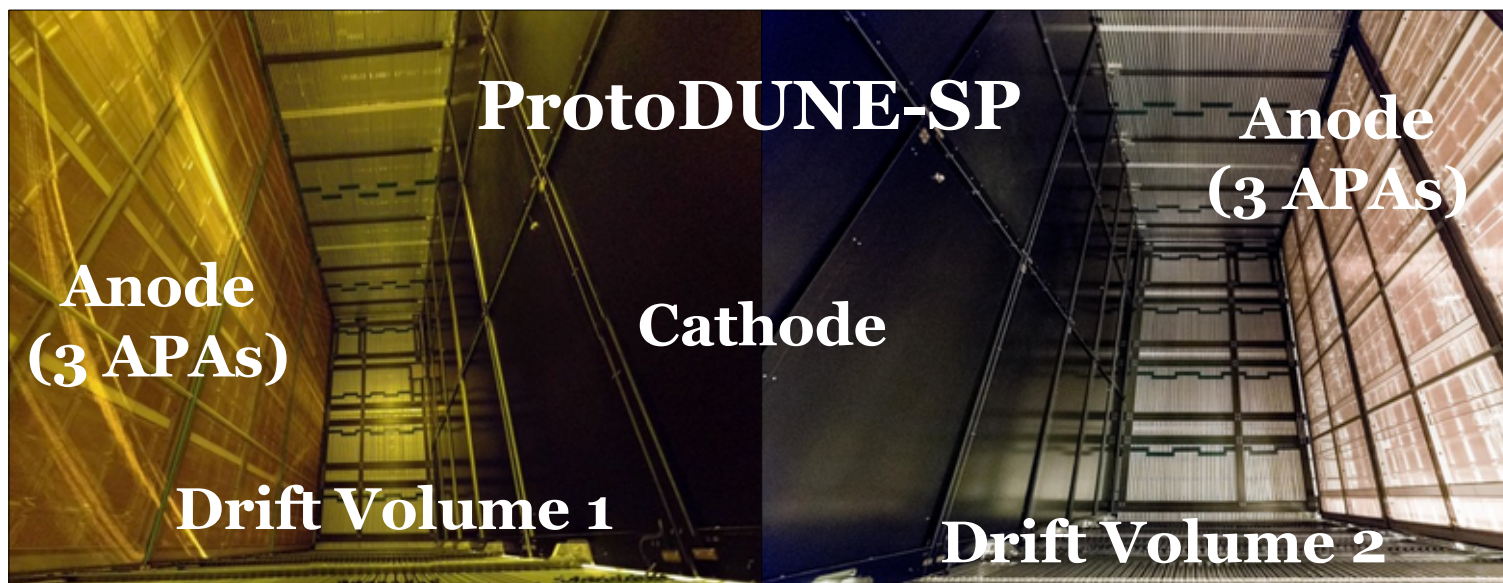


ProtoDUNE-SP

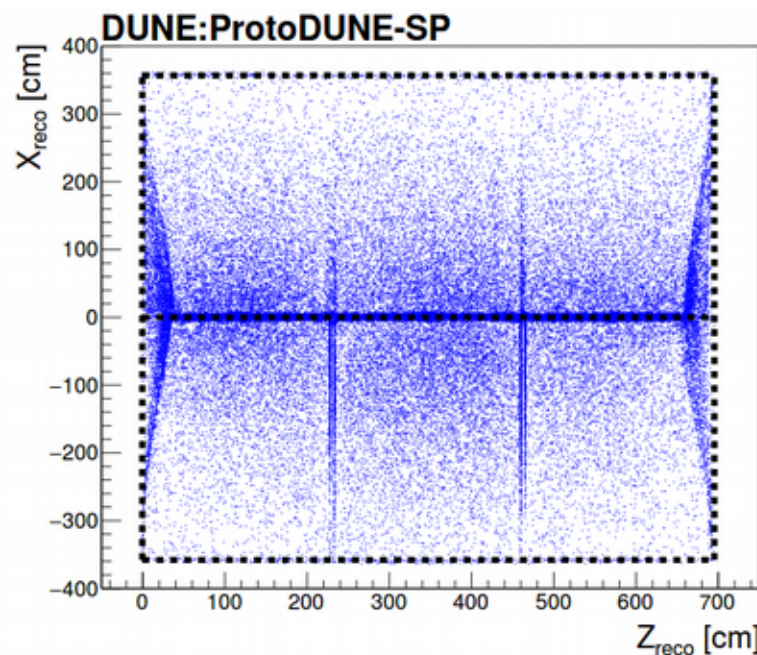
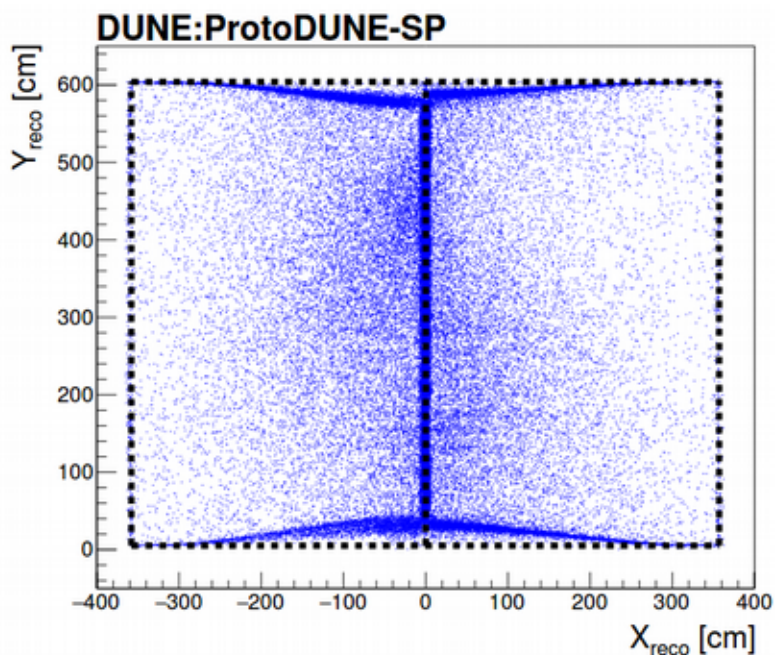




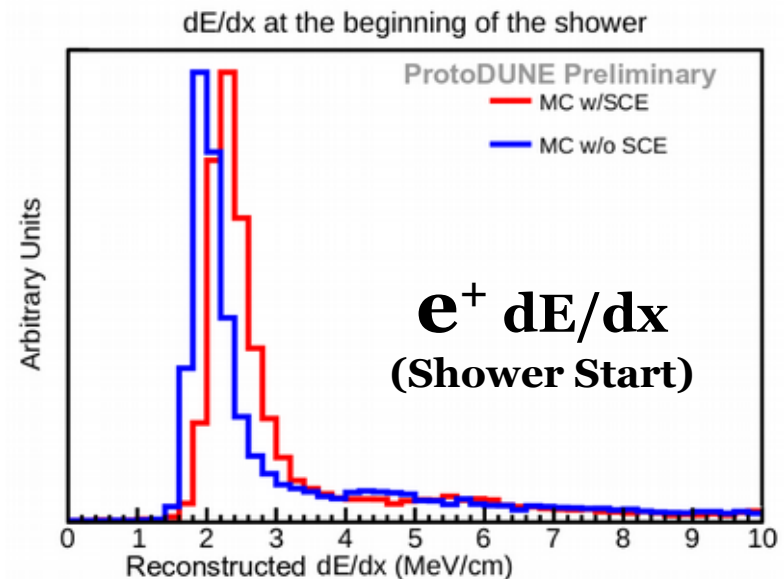
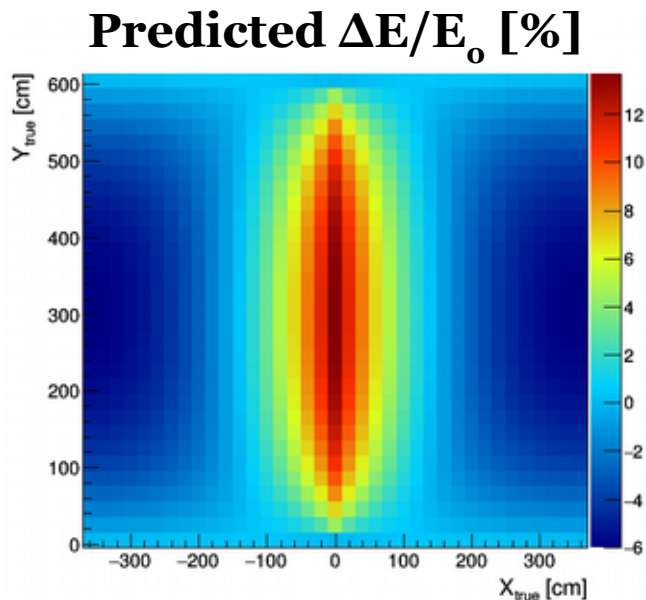
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- ◆ Looking at first cosmic data, notice offsets in track entry/exit points from top/bottom of TPC
 - Very suggestive of space charge effects (SCE) **as expected** given that ProtoDUNE-SP is located near the surface
 - **Space charge:** build-up of slow-moving Ar^+ ions due to e.g. cosmic muons impinging active volume of TPC (via ionization)



- ◆ SCE leads to E field distortions, distortions in reconstructed ionization position
- ◆ Can bias particle reconstruction in several ways:
 - Location of reconstructed charge – from spatial distortions
 - Particle energies – from E field distortions (recombination impact)
 - Particle dE/dx – from both E field and spatial distortions



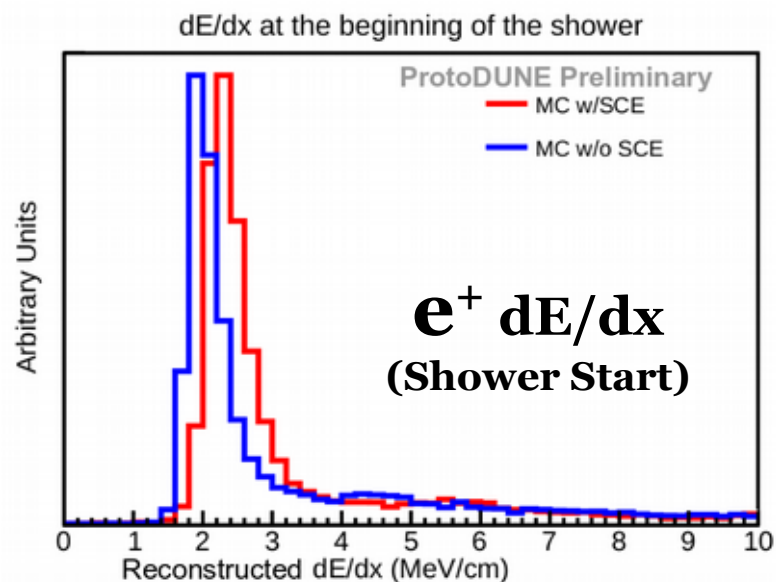
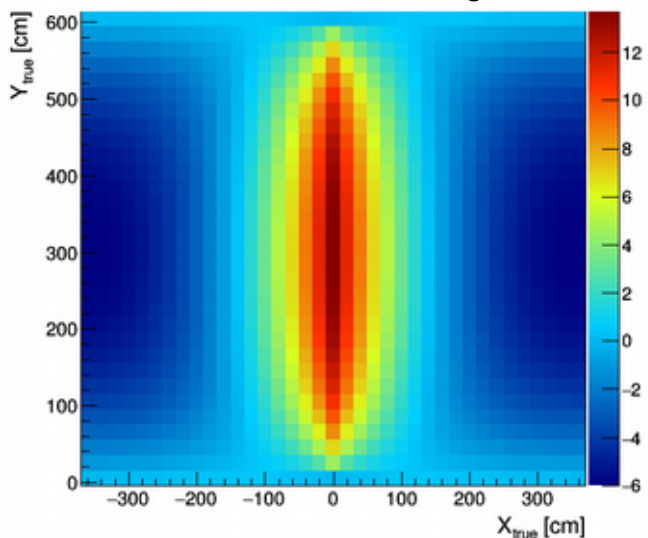
Impact of SCE

$$\frac{dE}{dx} = f \left(\frac{dQ}{dx}, |\vec{E}| \right)$$

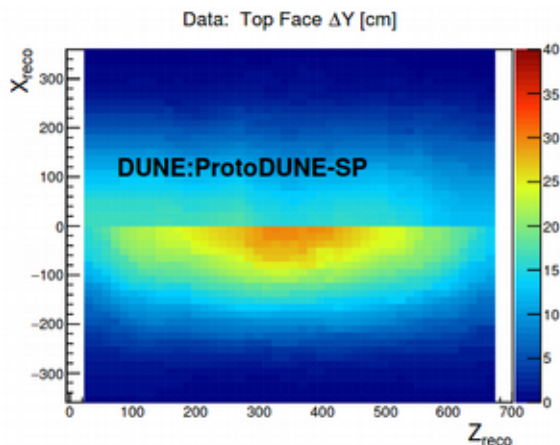
Impacted by SCE via
Spatial Distortions

Impacted by SCE via
E Field Distortions

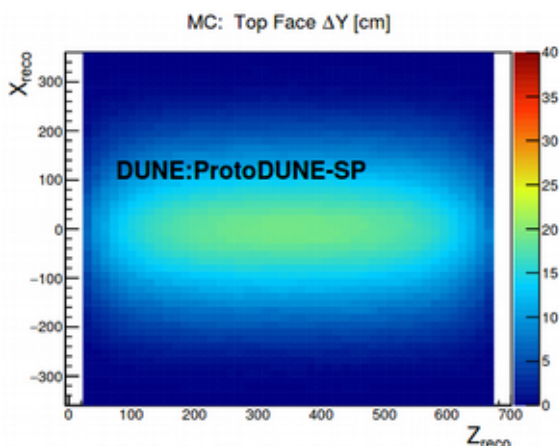
Predicted $\Delta E/E_0$ [%]



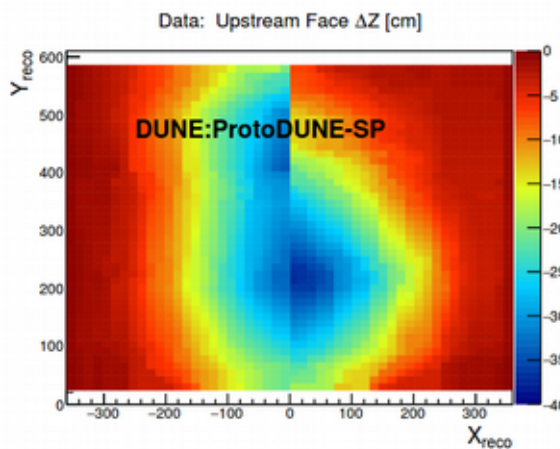
Data:
TPC Top



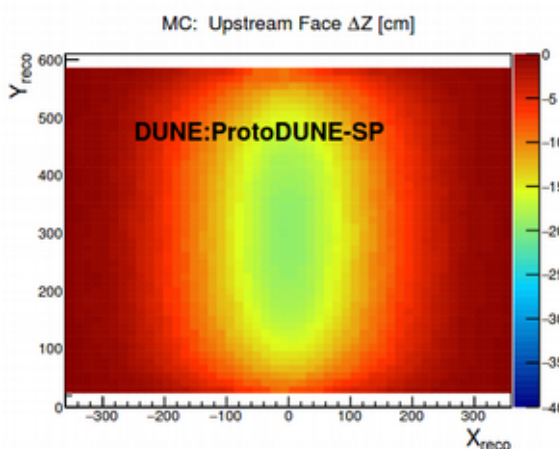
Prediction:
TPC Top



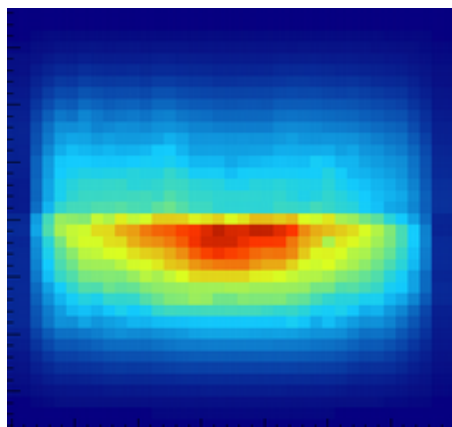
Data:
TPC Front



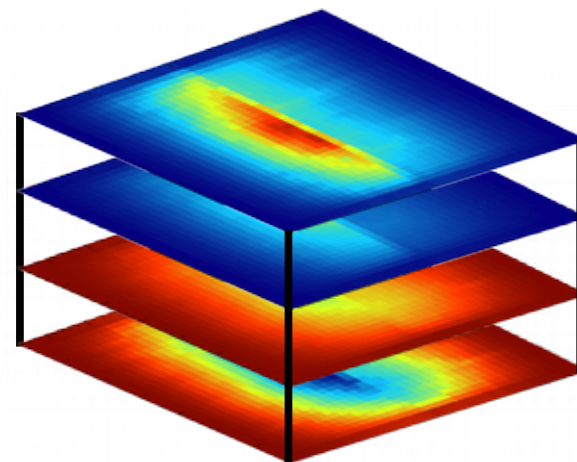
Prediction:
TPC Front



- ◆ Probe spatial offsets at TPC faces w/ cosmic track entry/exit points
- ◆ SCE **50-75% larger** than initial prediction – up to 35 cm
 - Asymmetries likely due to argon flow (not included in prediction)

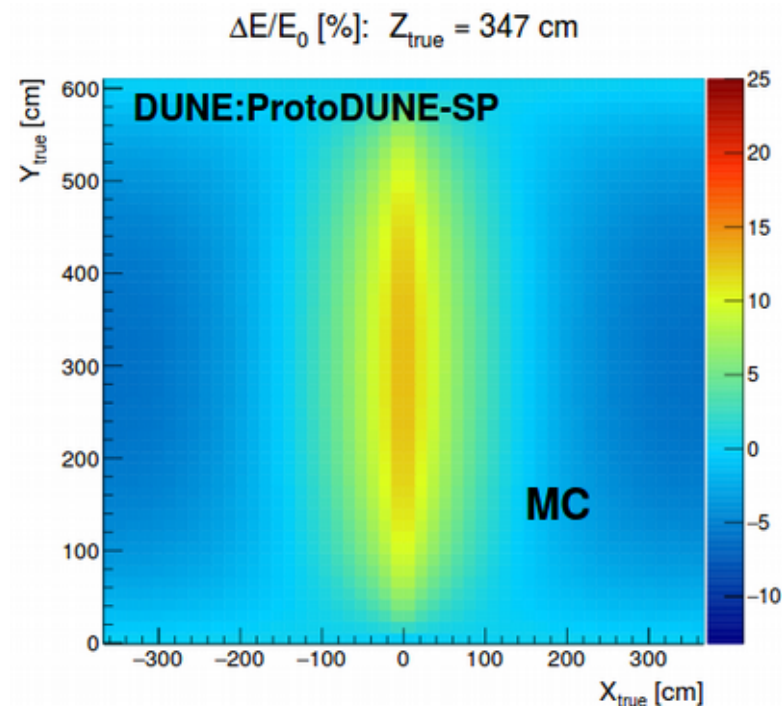
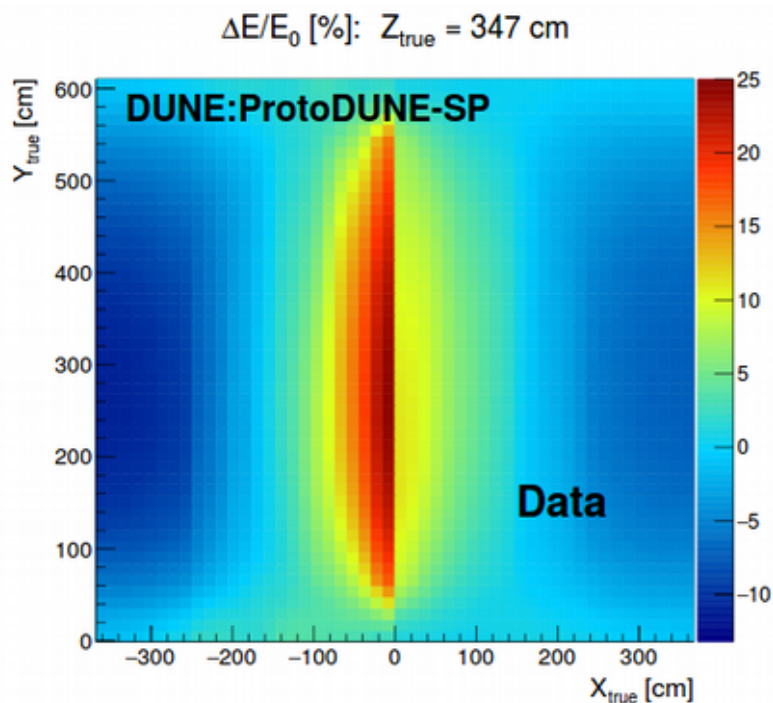


2D Maps at TPC Faces



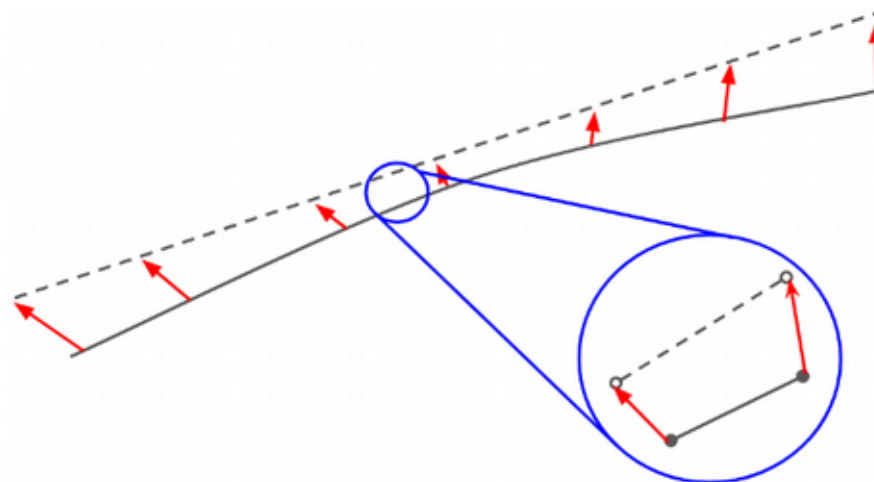
3D Maps in TPC Bulk

- ◆ Have robust estimation of spatial offsets at TPC faces (2D) using cosmic muon entry/exit points
- ◆ Scale **predicted** 3D spatial distortion map with data/MC scale factors at TPC faces, linearly interpolated across TPC
- ◆ With 3D spatial distortion map in hand, simple to calculate local drift velocity everywhere (ADD REFERENCE)
 - Then use drift velocity model, $v(E)$, to extract E field distortions



- ◆ Product of 3D calibration: E field map throughout TPC
 - Use this “data-driven” E field map in **improved MC simulation**
- ◆ Nearly 25% higher E field near cathode than nominal E field
 - Reminder: nominal E field is 500 V/cm
 - That means E field near cathode **greater than 600 V/cm!**

- ◆ Case study: SCE corrections to particle dE/dx
 - dE/dx vs. residual range used for particle ID – important to eliminate bias in this quantity
- ◆ Correct two separate impacts of SCE:
 - **Spatial distortions** – correct for spatial “squeezing/stretching” of reconstructed charge (impacts “ dx ” in calculation)
 - **E field distortions** – correct for E field dependence of electron-ion recombination (reduces “free charge” that drifts to wire)



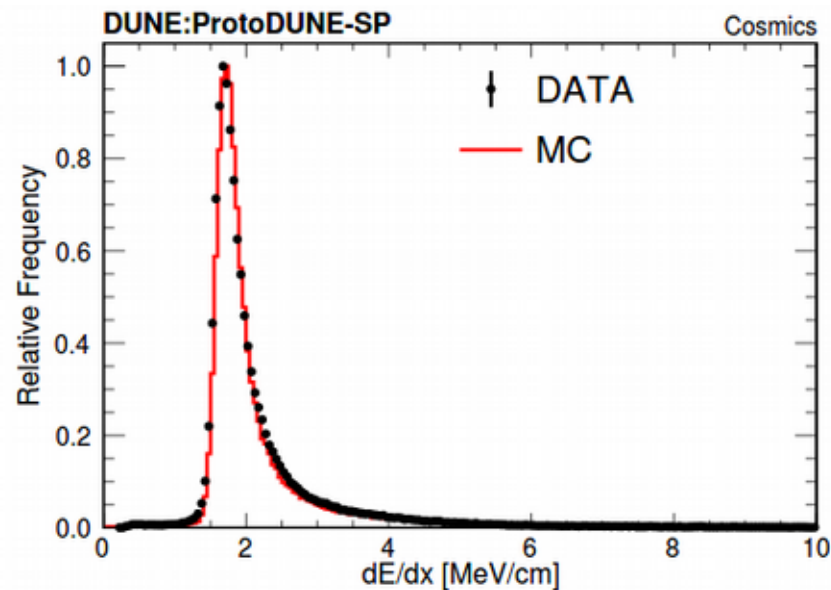
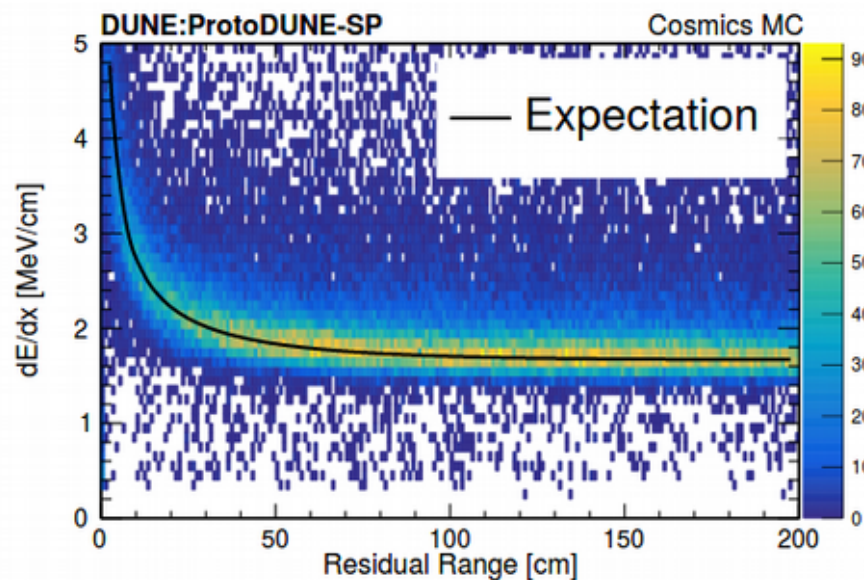
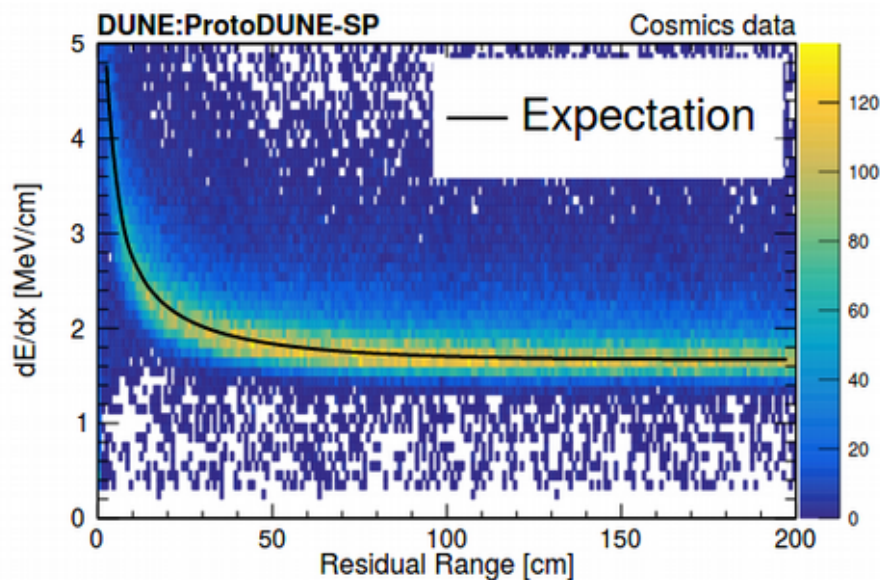
**Spatial
Distortion
Correction**

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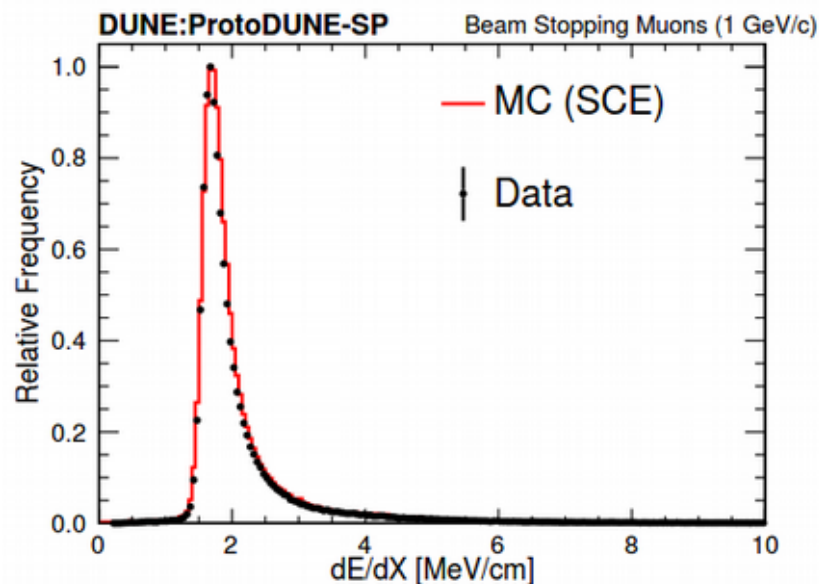
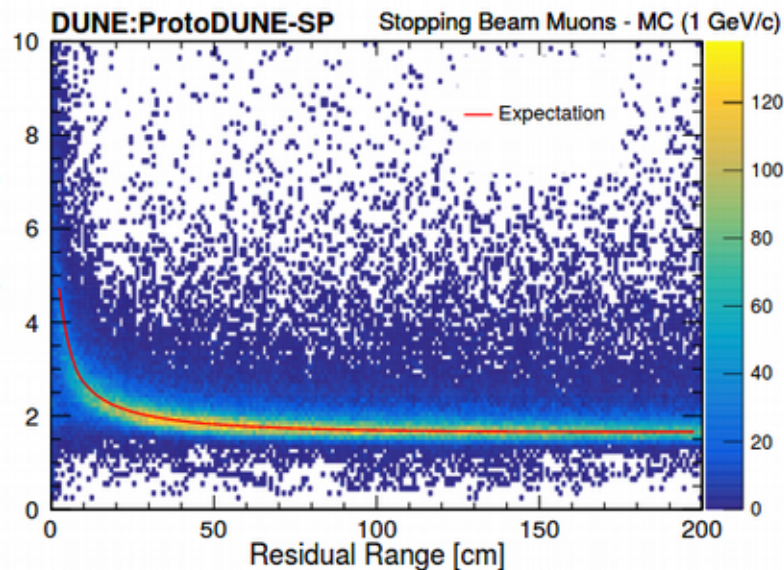
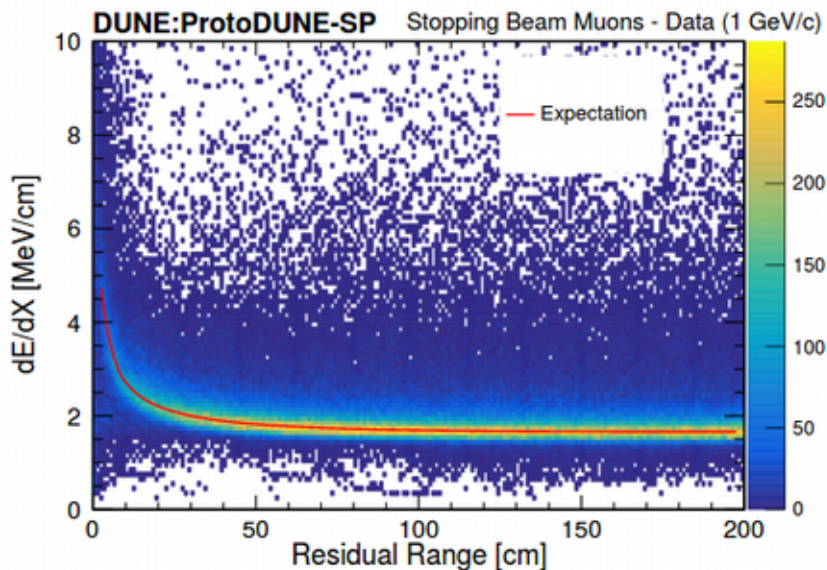
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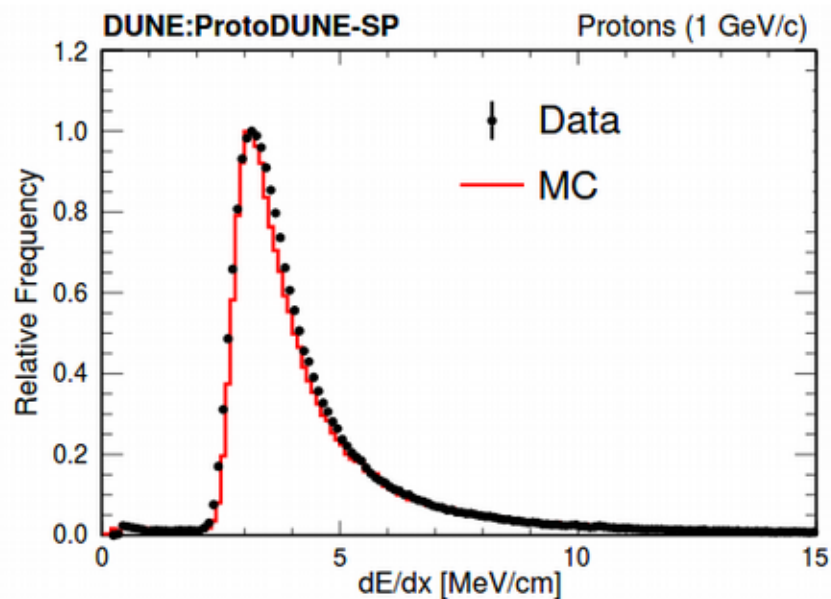
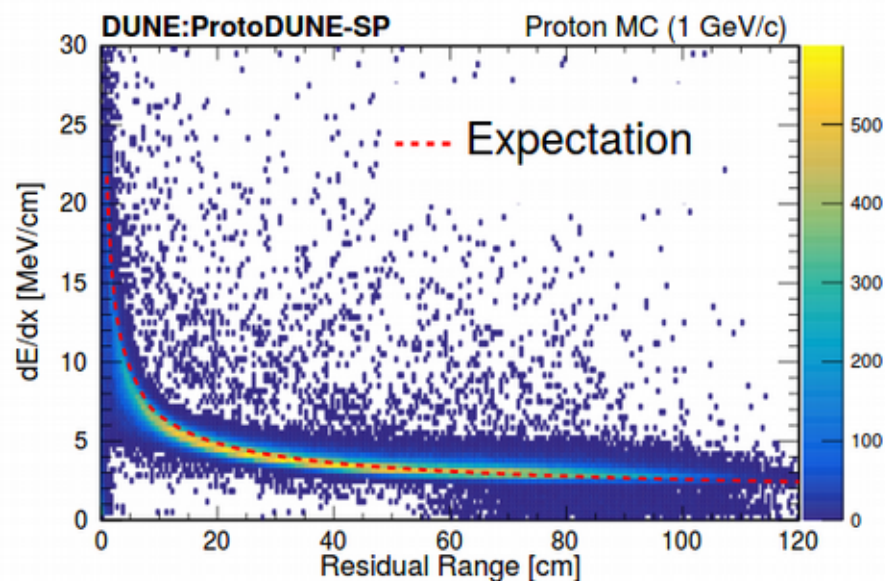
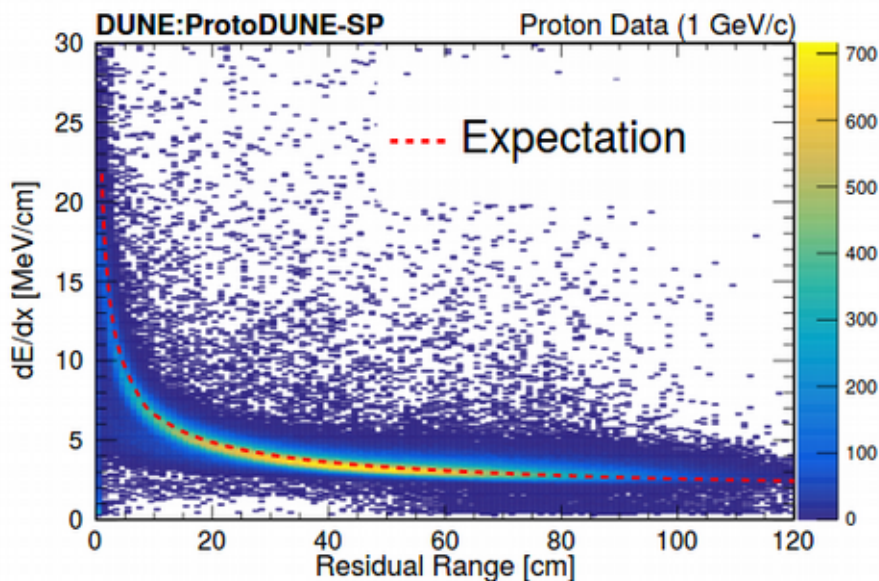
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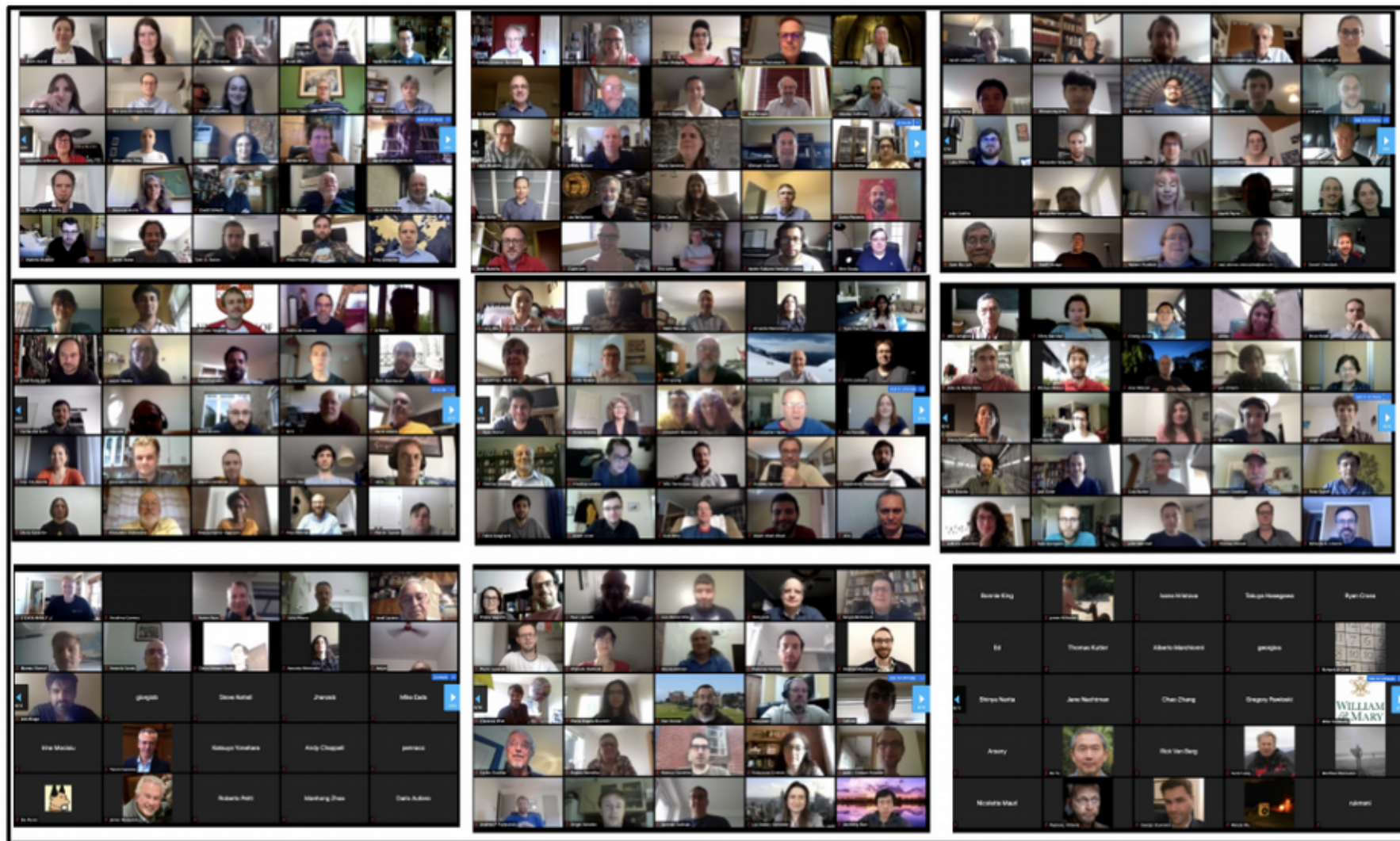


dE/dx Results: Beam Muons



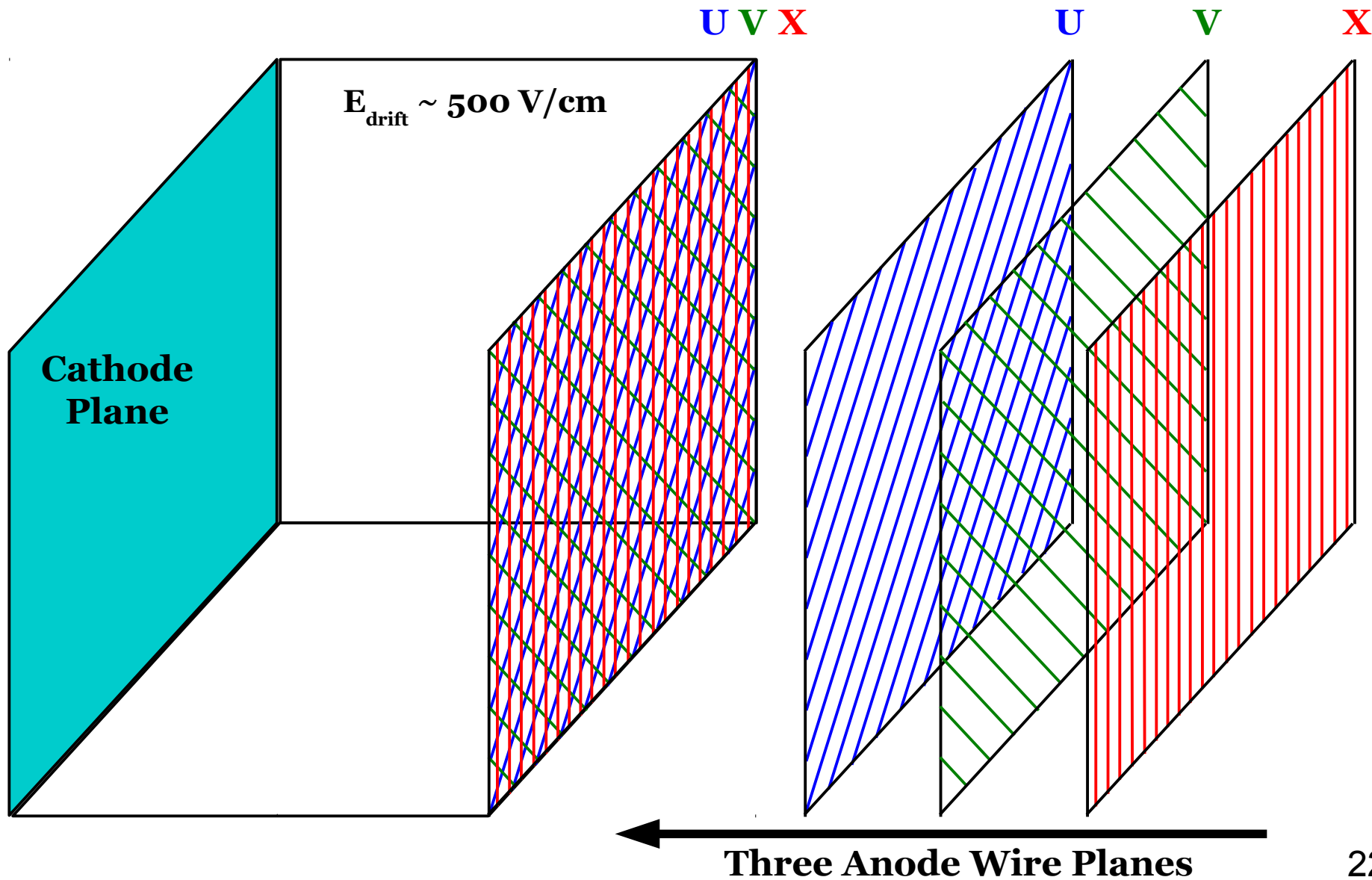


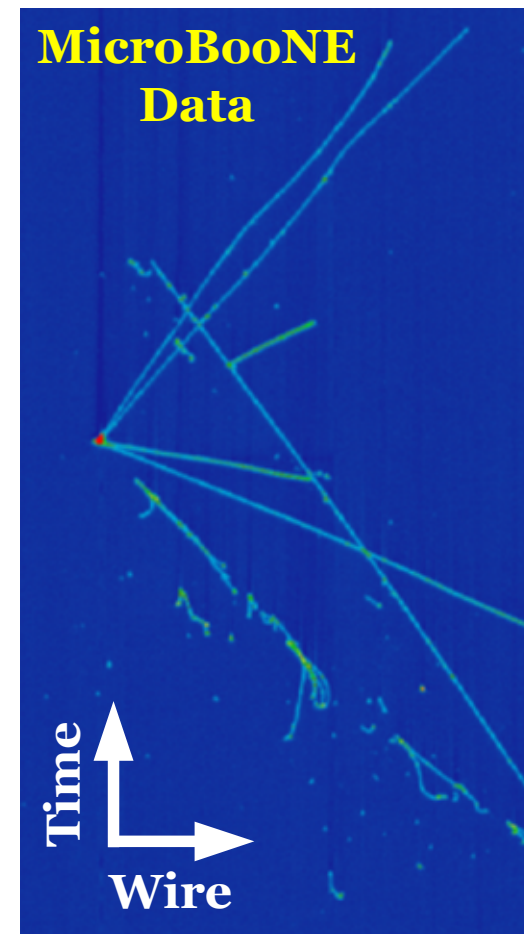
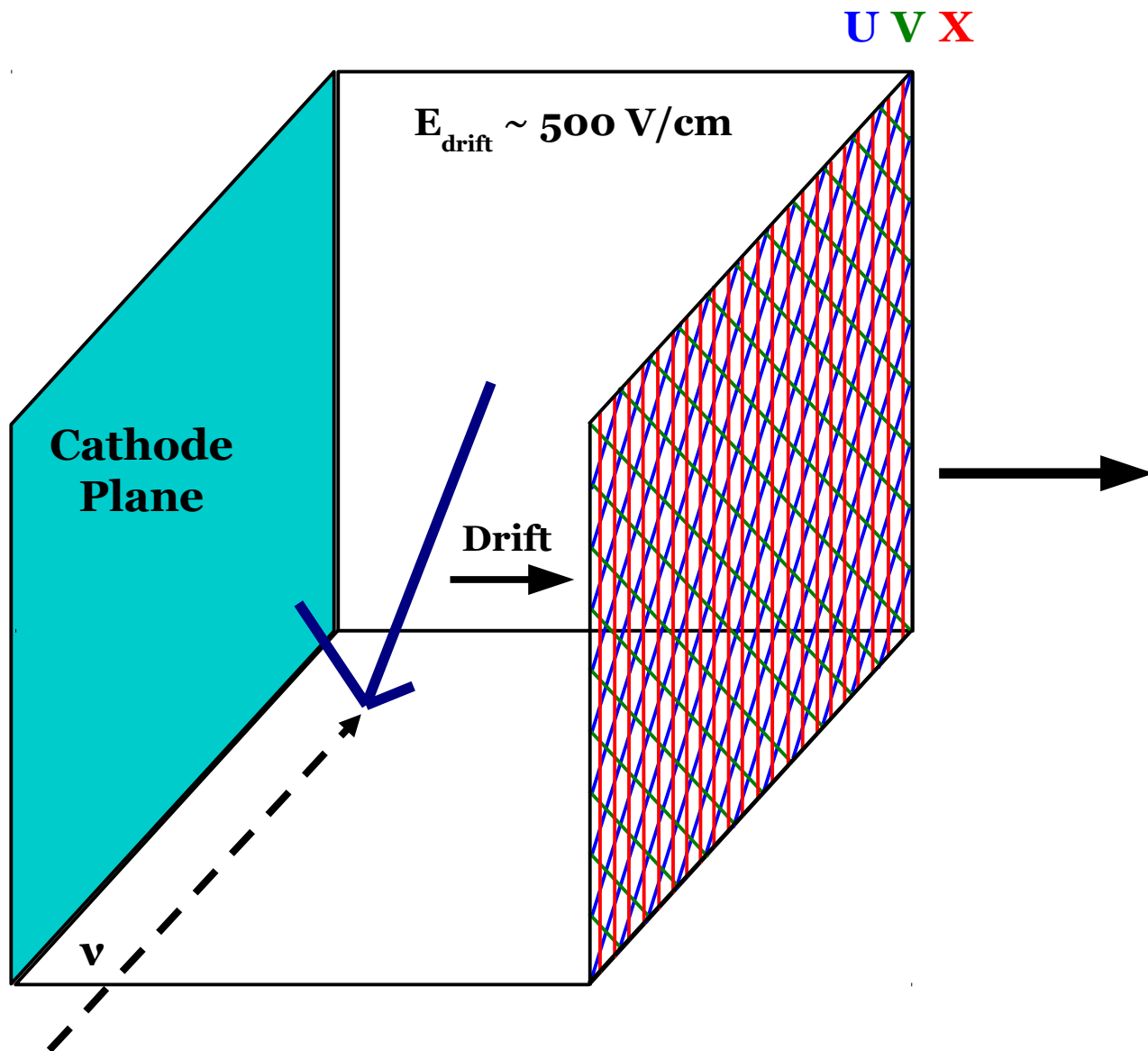
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Backup

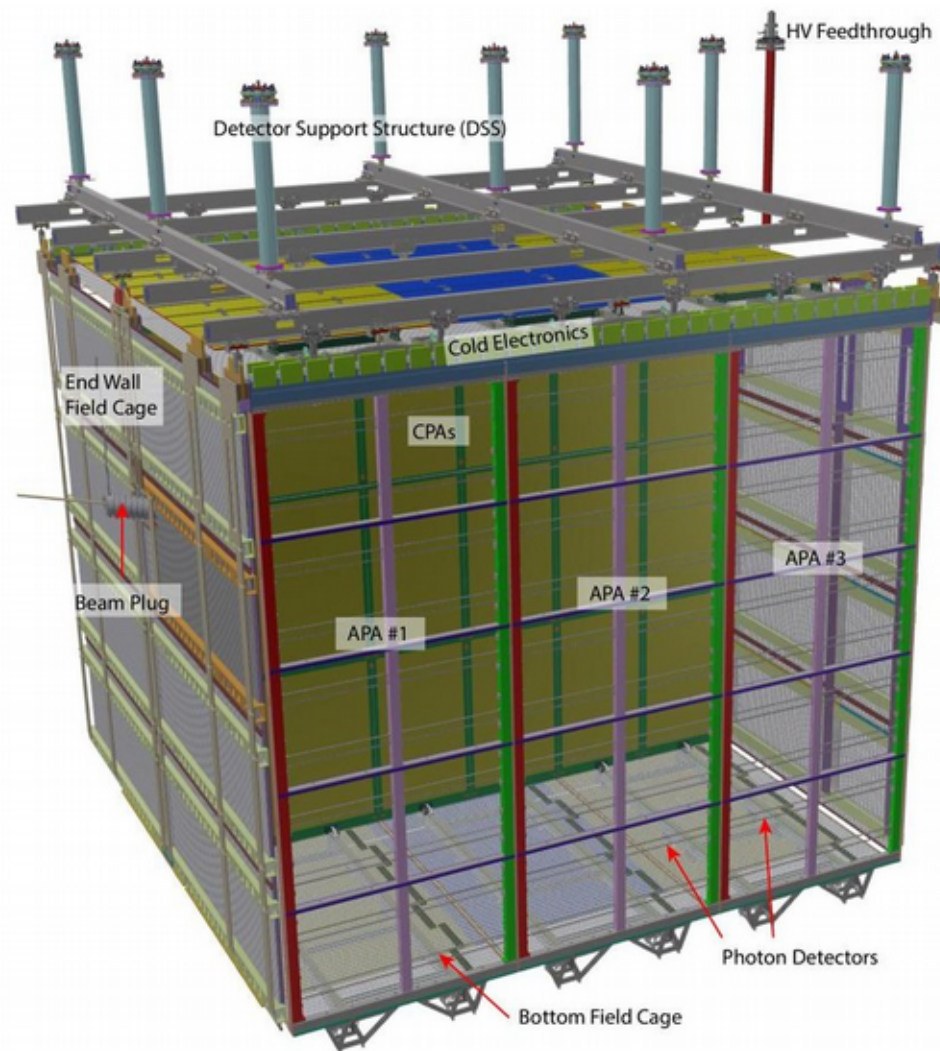
Signal Formation

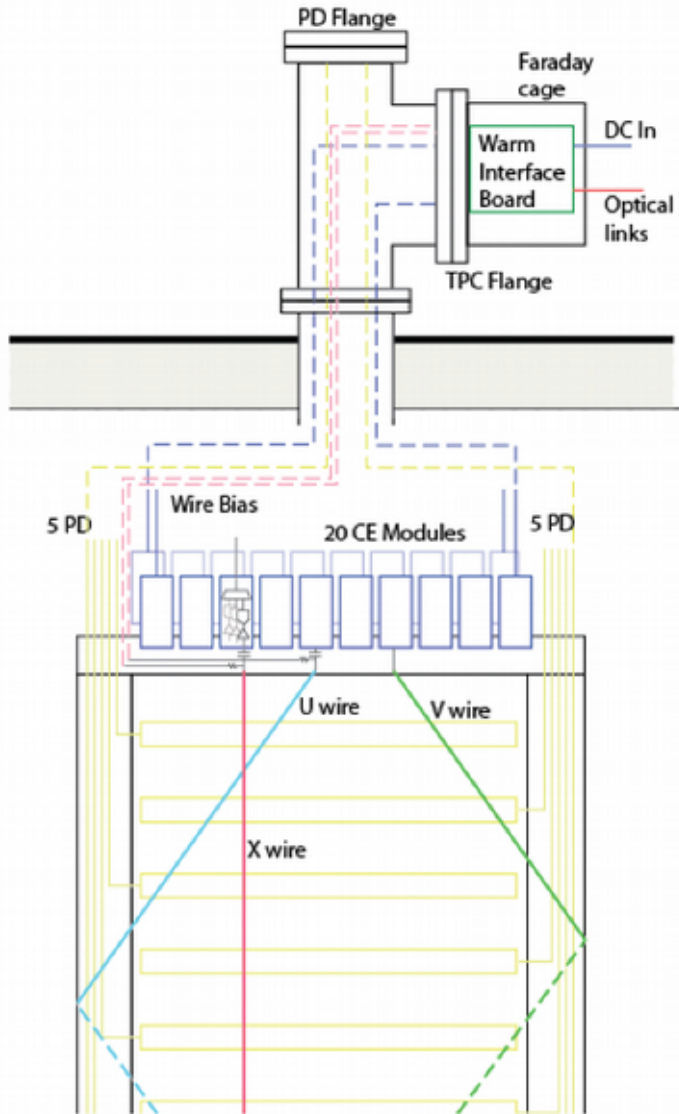




Three Images
(One Per Wire Plane)

- ◆ 1/20 of full 10-kt FD module
 - 0.77 kt total LAr mass
 - Components are 1:1 scale
- ◆ Six APAs (three per side)
 - 2,560 channels per APA
- ◆ Central cathode plane (CPAs) divides active volume into two separate drift volumes
 - 3.6 m max drift length
 - E field of 500 V/cm
- ◆ Field cage for keeping E field uniform (up to space charge)
- ◆ Cryogenic TPC electronics

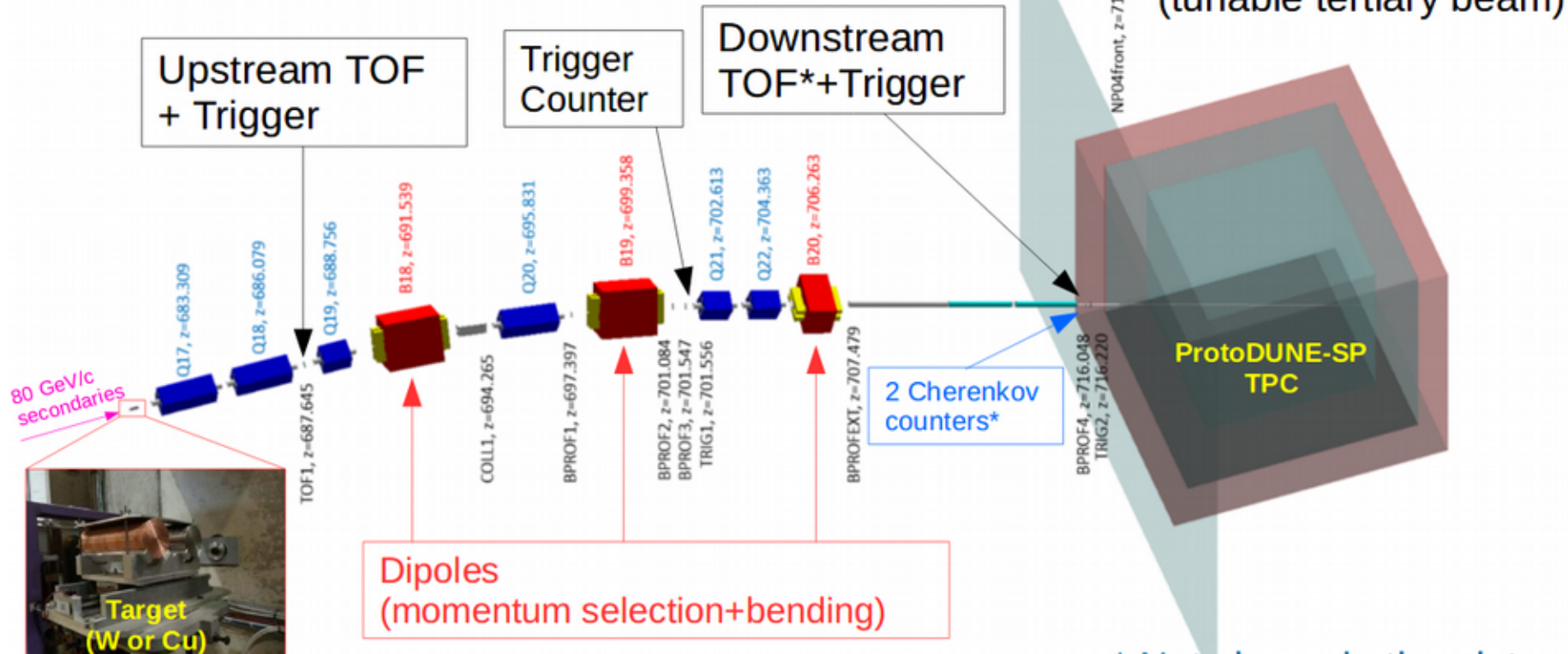




- ◆ Cold electronics (in LAr) directly attached to APA → low noise levels
- ◆ 1 APA → 20 Front-End Mother Boards (FEMBs)
 - 128 channels/FEMB
- ◆ FEMB holds 8 Front-End (FE) ASICs (16 channels/ASIC) and 8 ADC ASICs (16 channels/ASIC)
- ◆ FE ASIC performs two tasks:
 - Pre-amplification of signals
 - Signal shaping (0.5-3 μ s)
- ◆ Each FEMB multiplexed to 4 outputs (via FPGAs)

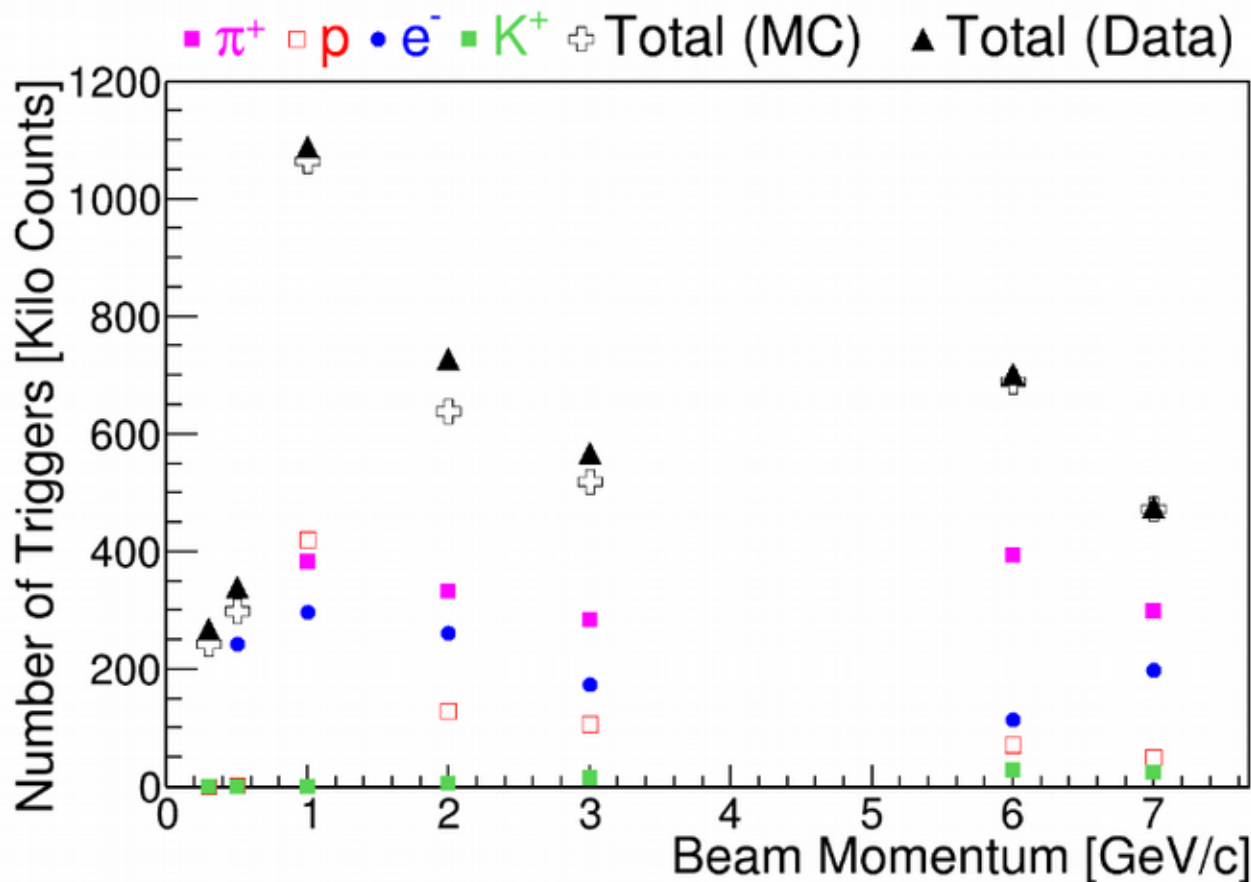
- CERN H4 beamline-extension & Beamline Instrumentation
 - Known particle type (hadrons and electrons) & incident energies

400 GeV/c protons → target → 80 GeV/c beam → target → **0.5 – 7 GeV/c**
 (primary beam) (secondary beam) **p/π⁺/K⁺/μ⁺/e⁻ beam**
 (tunable tertiary beam)



* Not shown in the plot 26

- Beam data taking: from 09/21/2019 to 11/12/2019
- Beam momentum: 0.5-7 GeV/c ($p/\pi^+/K^+/\mu^+/e^-$)
- Over 4 million beam events (all momenta) collected
- Successful data collection as designed



All Beam Momenta

Total (Data): 4173 K

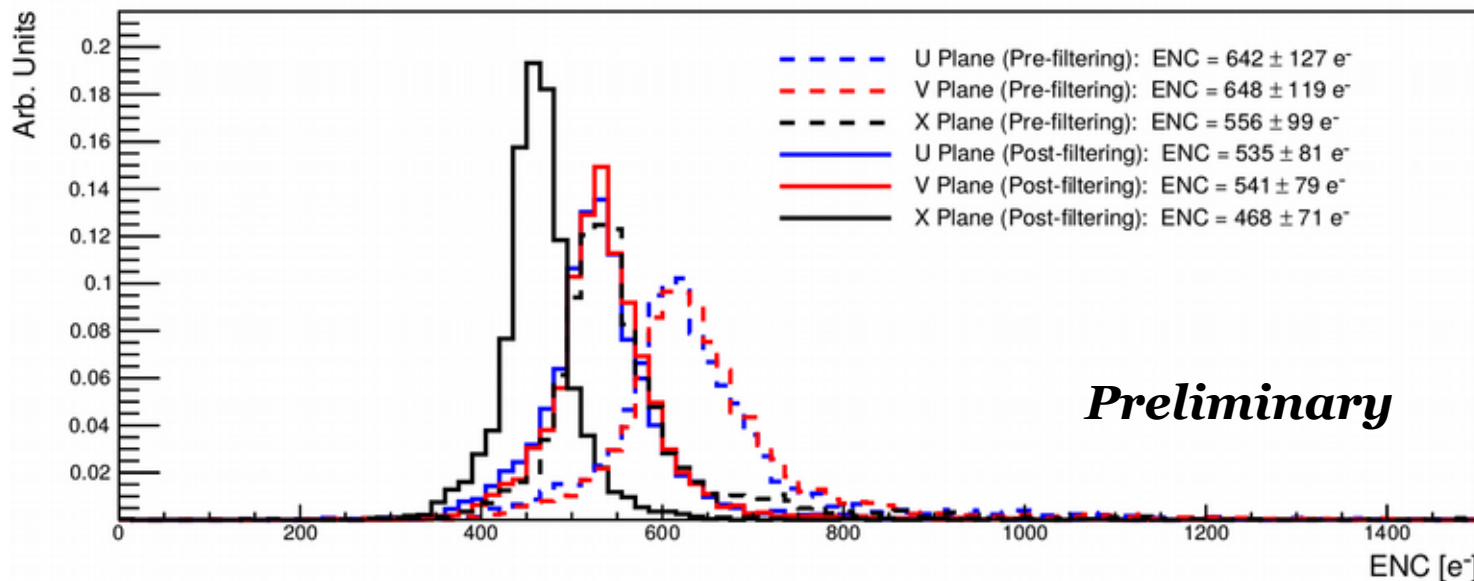
Total (MC): 3924 K

π^+ : 1694 K

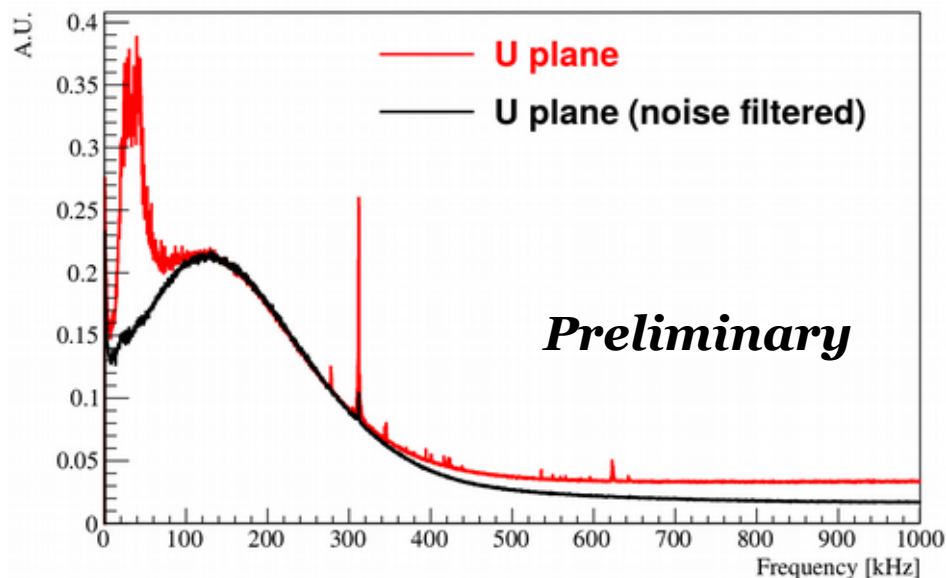
p : 779 K

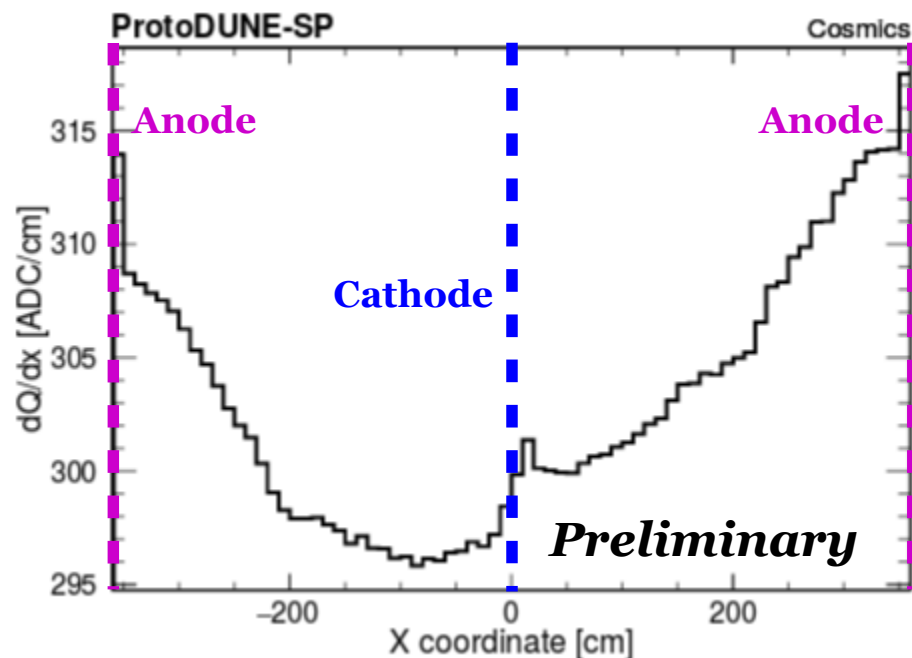
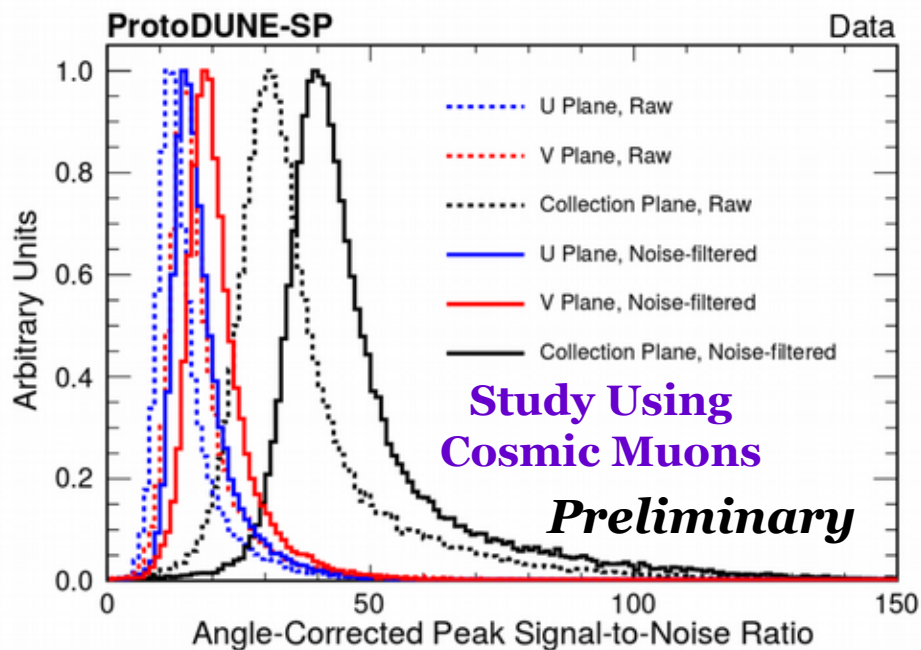
e^- : 1384 K

K^+ : 73 K



- ◆ Noise: 550 (480) e⁻ for collection plane, 650 (550) e⁻ for induction planes without (with) coherent noise filtering



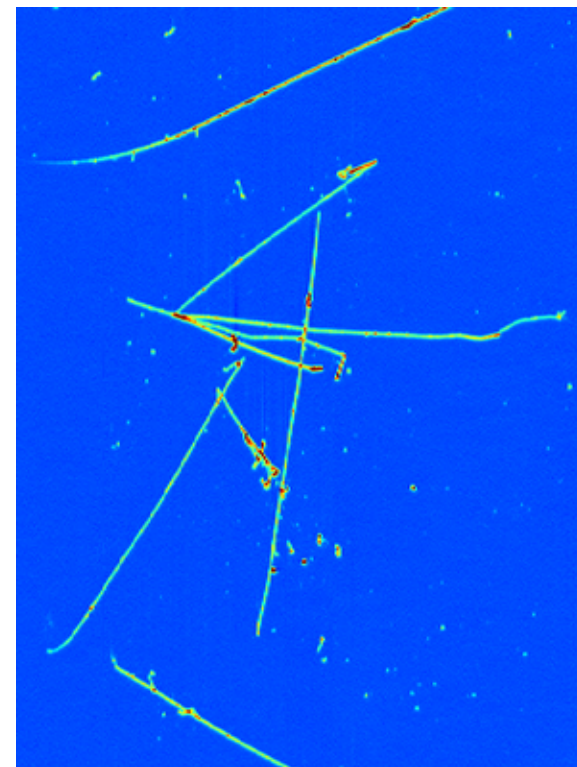
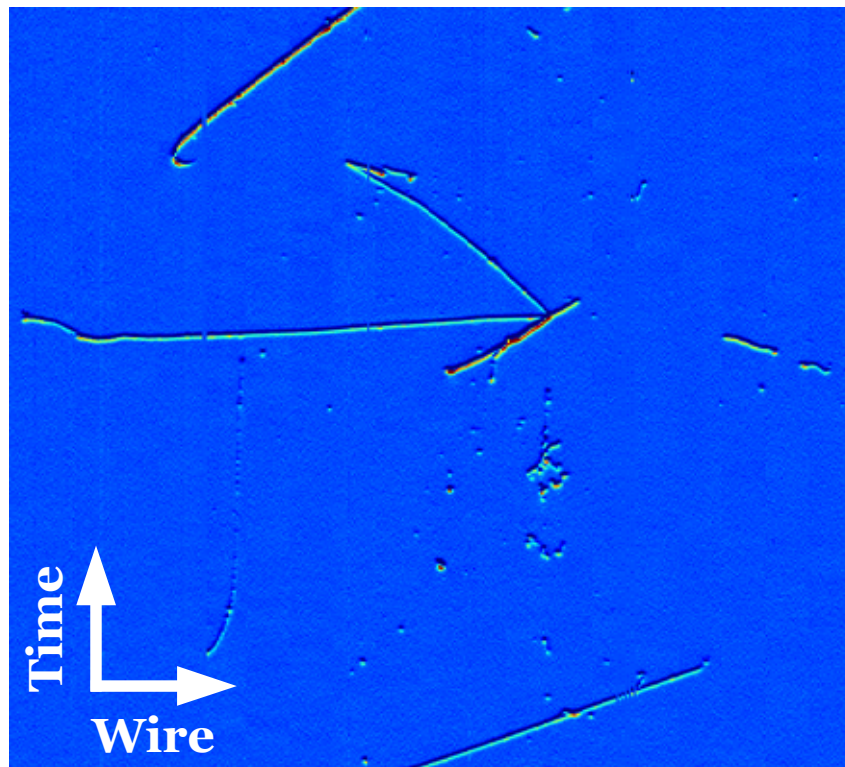
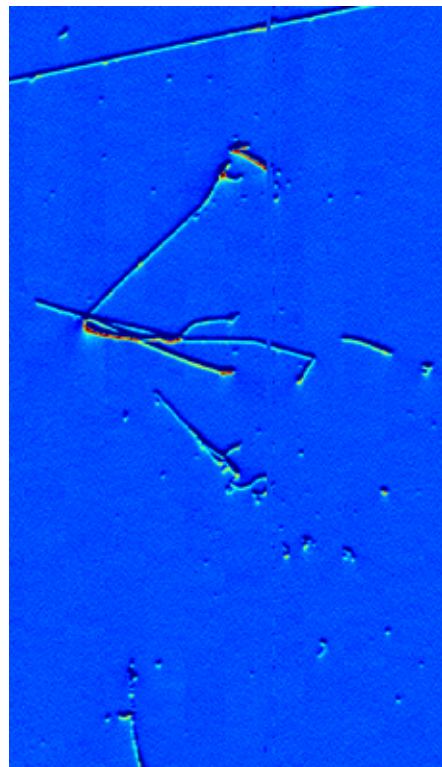


- ◆ Signal-to-noise ratio very high (**before** or **after** noise filtering)!
 - U Plane: **16** → **18**
 - V Plane: **19** → **21**
 - Y Plane: **38** → **49**
- ◆ After corrections for space charge effects, electron lifetime observed to be very high: **> 20 ms**

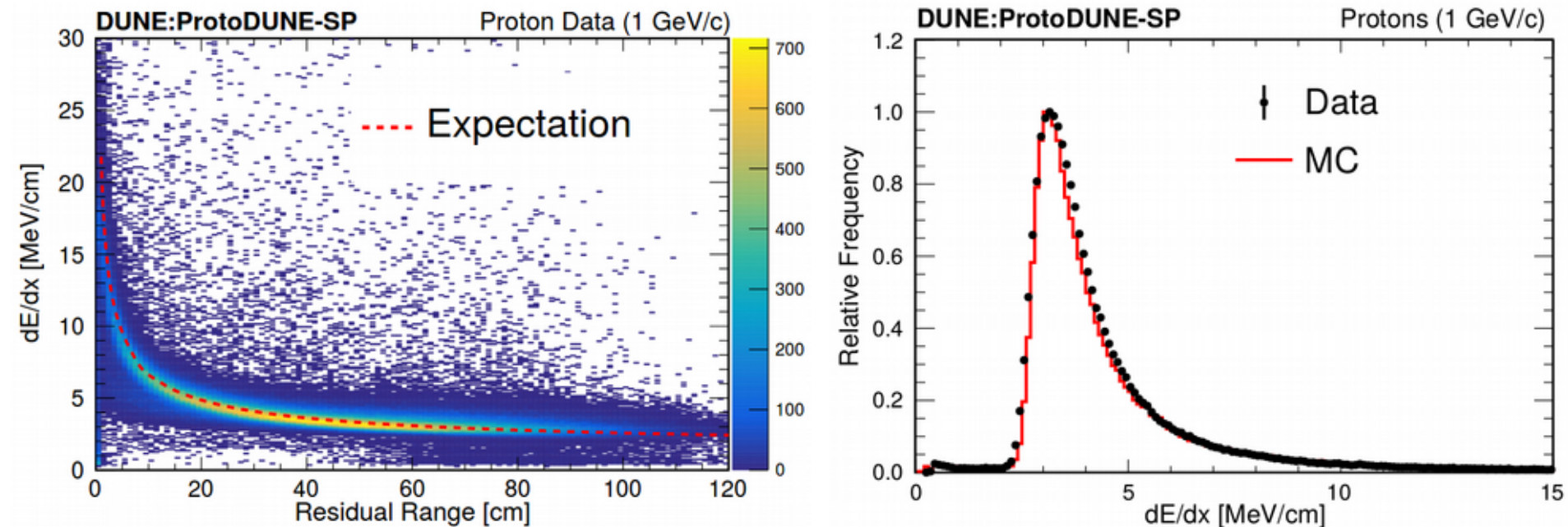
Induction 1

Induction 2

Collection



- ◆ First beam data events: **noise levels low** on all three planes
- ◆ S/N ratio > 10 in all cases (> 40 for collection plane)
- ◆ **Stable running** since first operations began in 2018



- ◆ First results from ProtoDUNE-SP informing **calibrations** and **reconstruction** for single phase DUNE FD
 - Above left: dE/dx vs. residual range for 1 GeV protons (data)
 - Above right: dE/dx distribution of 1 GeV protons (data vs. MC)
 - Upcoming paper on arXiv soon: “First results on ProtoDUNE-SP LArTPC performance from a beam test at the CERN Neutrino Platform”