Testing the waters for the DUNE experiment

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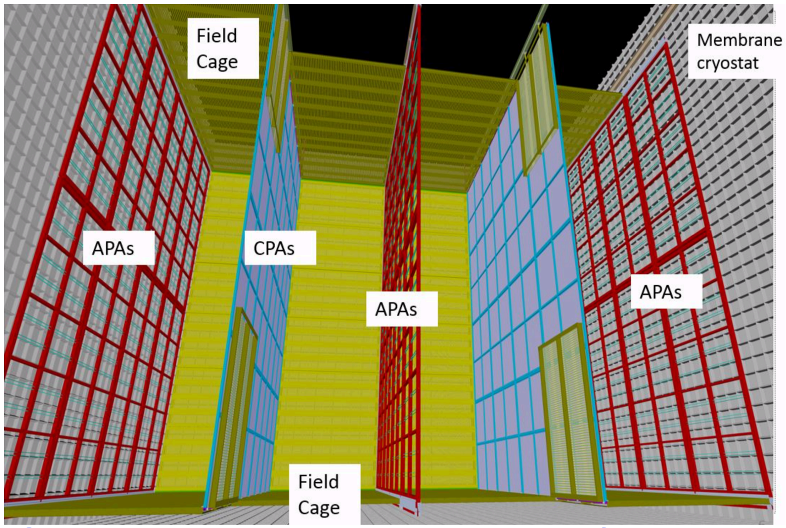
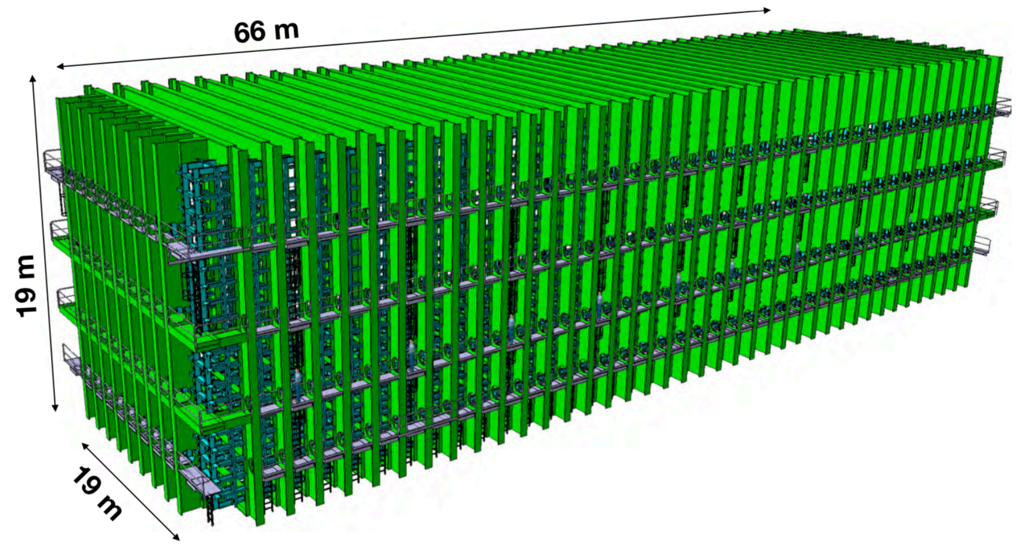
for the DUNE Collaboration

- ProtoDUNE aims
- Construction & timeline
- Operational experience
- Space charge effects
- Energy calibration

ProtoDUNE motivation





Single-phase Far Detector configuration

DUNE Far Detector module size requires “proper” validation

- full-scale validation of single-phase technology made possible by modular construction

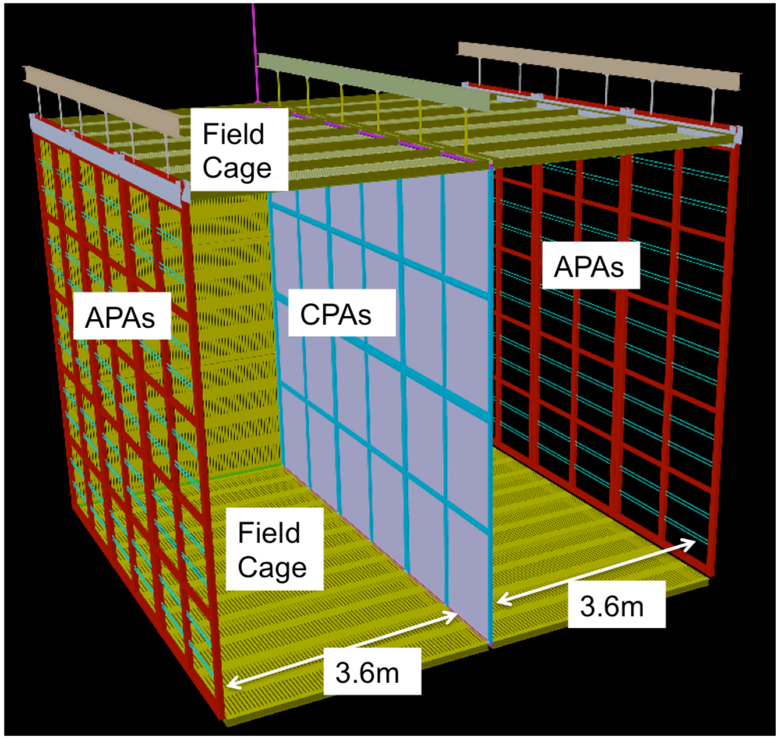
Proposal for a Full-Scale Prototype Single-Phase Liquid Argon Time Projection Chamber and Detector Beam Test at CERN

SPSC 351, May 2015

ProtoDUNE: programme

Validation of the production technology using “full-scale” prototypes

- two 7×7×6 m^3 cryostats (active volume) at CERN
  - at surface ➠ bg from cosmic rays
  - this presentation: single phase
    - dual phase ➠ next talk



Demonstrate long-term operational stability

Measurements with beam

- towards demonstrating calibration
- 0.5 — 7 GeV particle beams (e, π, p, K)
- beam time limited by availability of CERN accelerator complex
  - August — November 2018

ProtoDUNE: detector construction

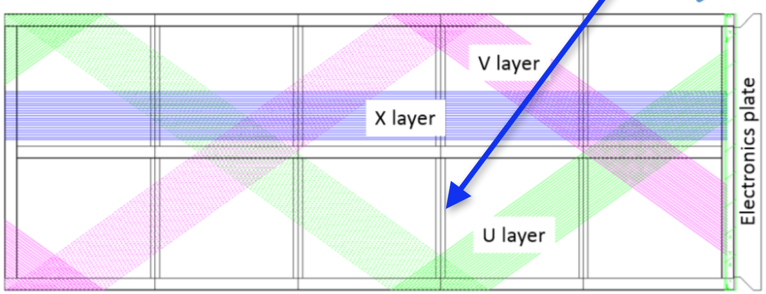
Example: anode plane arrays

- other elements: field cage, cathode plane

960(X)+800(U)+800(V) wires/APA

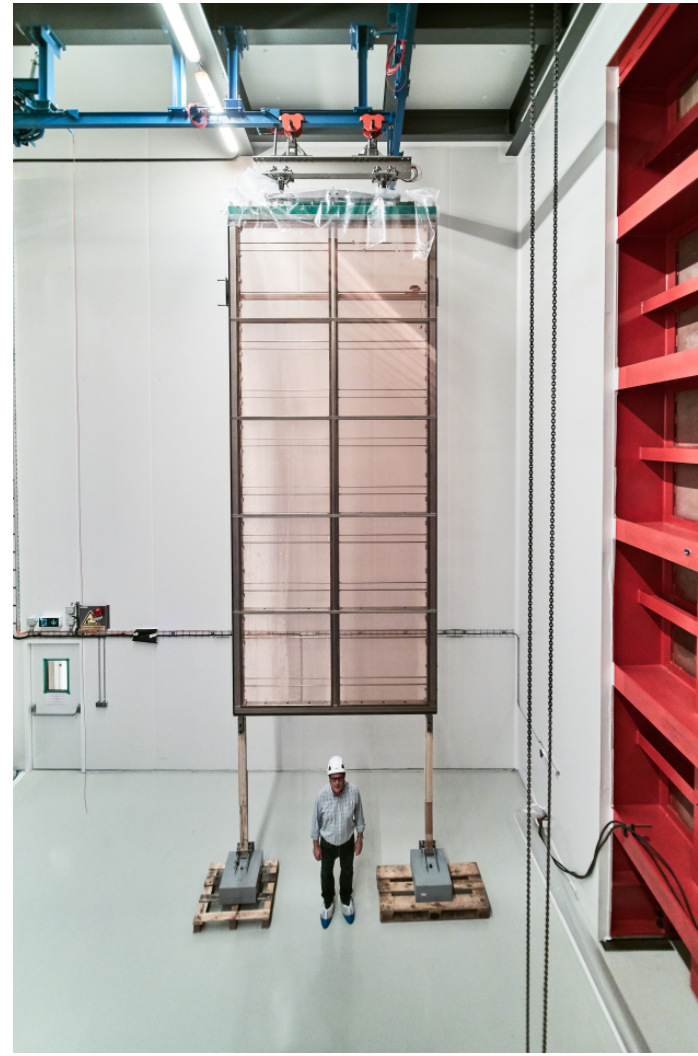
photodetector bars

6 m

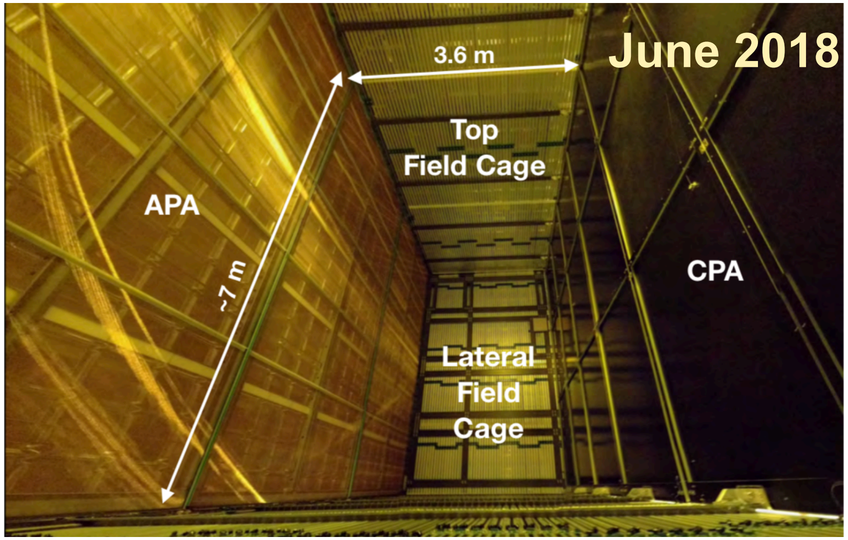


2.3 m

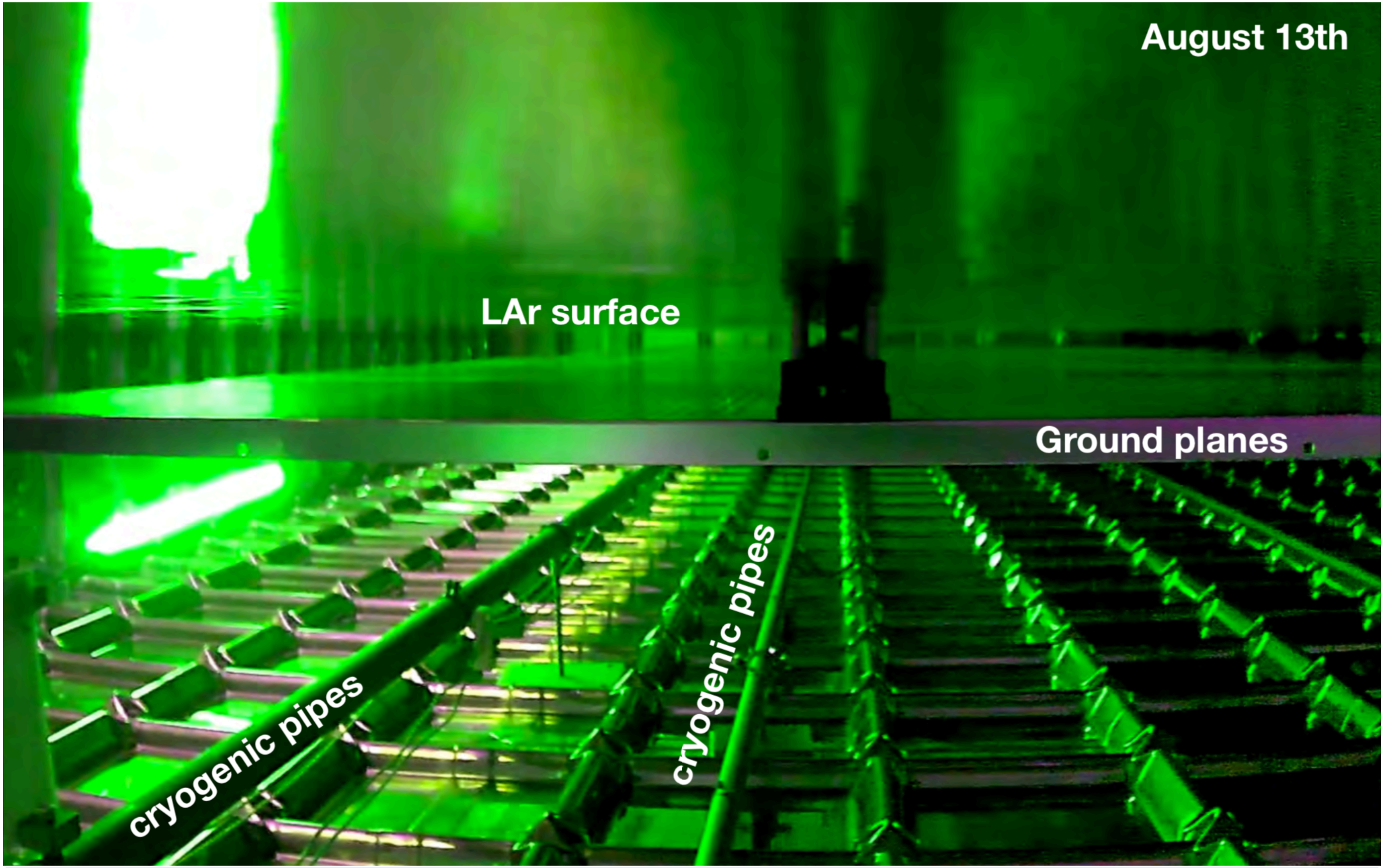
pitch ~ 4.7 mm



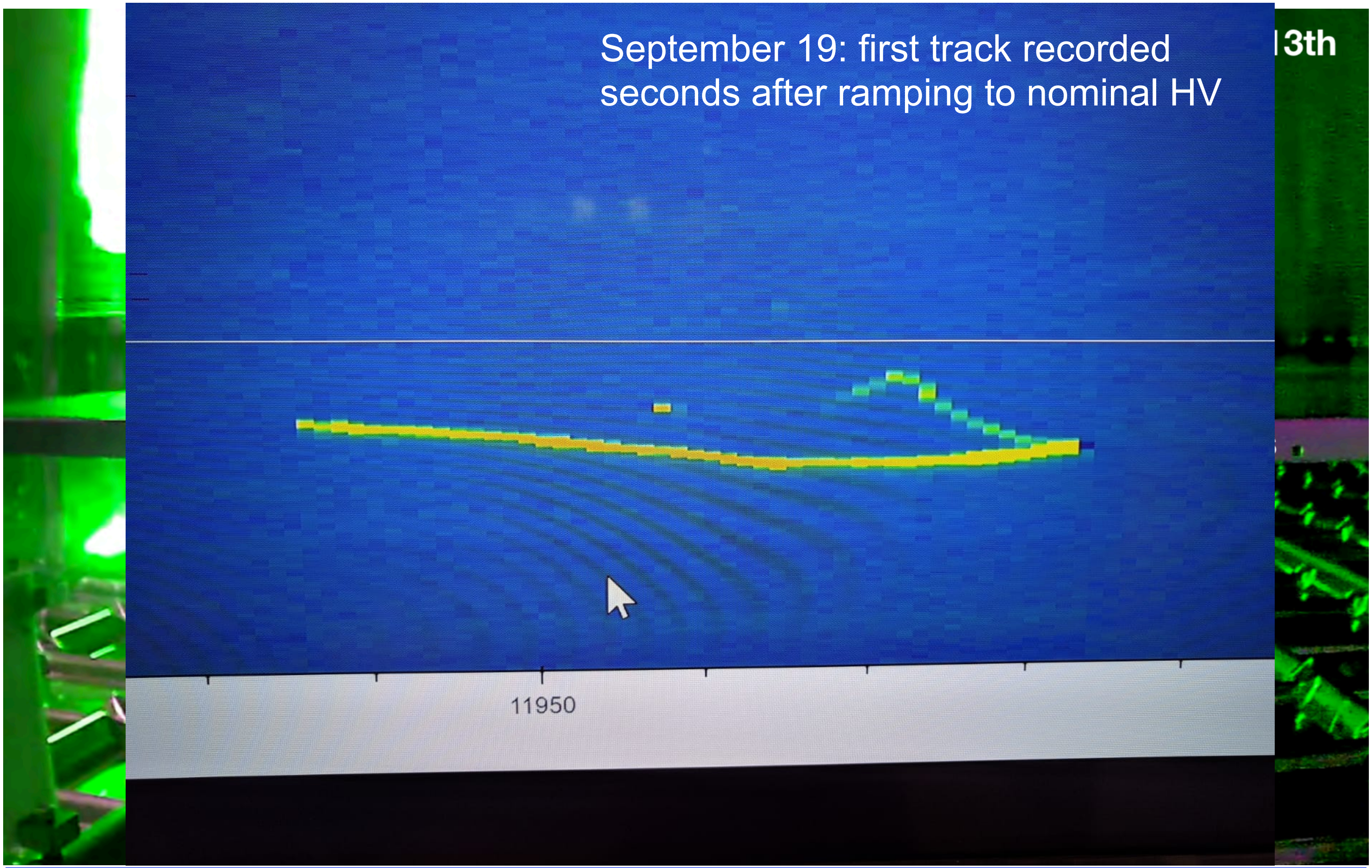
ProtoDUNE-SP construction



ProtoDUNE-SP construction



ProtoDUNE-SP construction

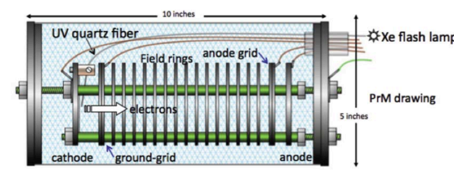


LAr purity

High purity (especially absence of O_2) is essential for long electron drift times ($t_{max} \approx 2.3$ ms)

- $1/\tau \sim O_2$ contamination, need ≲ ppb — achieved!

Adamowski et al., 2014

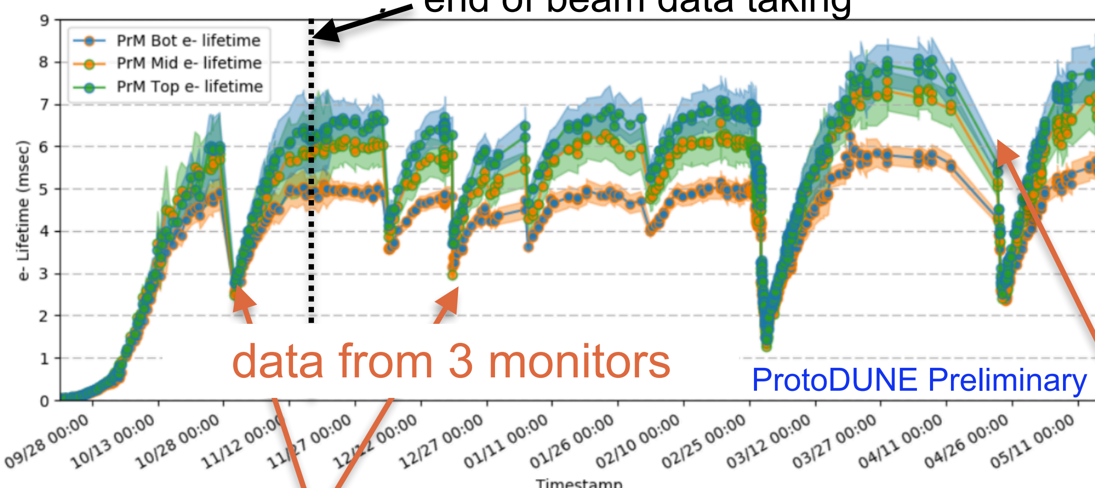


miniature TPC,

$$Q_a / Q_c = e^{-t/\tau}$$

(e⁻ liberated from photocathode after Xe flash)

end of beam data taking



essential means to provide quick feedback upon issues:

- saturation of O_2 filter during Ar filling
- pump stoppages

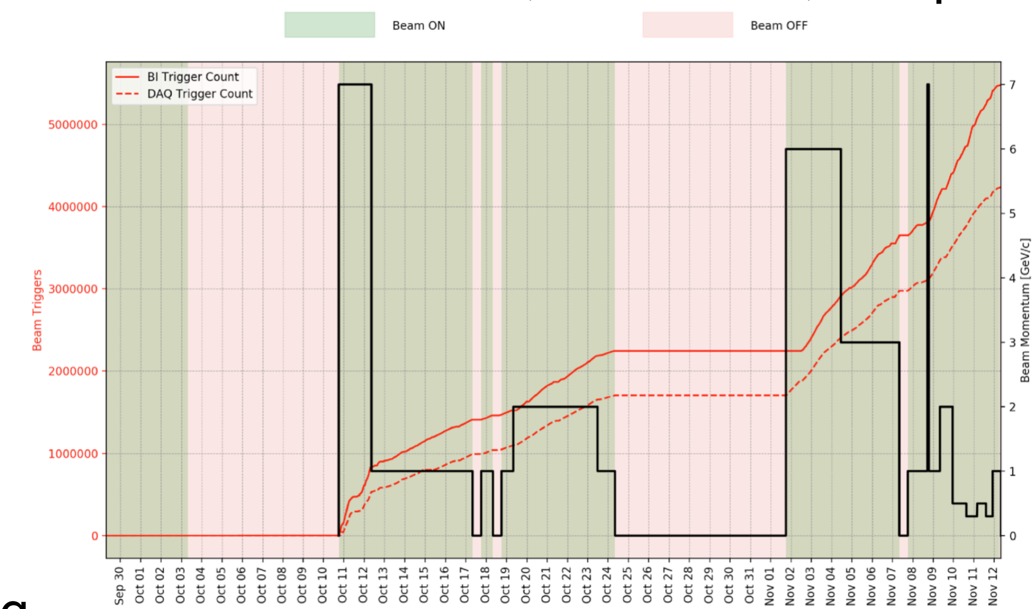
non-uniformities; saturation effects

- real value of τ likely higher

Measurement programme

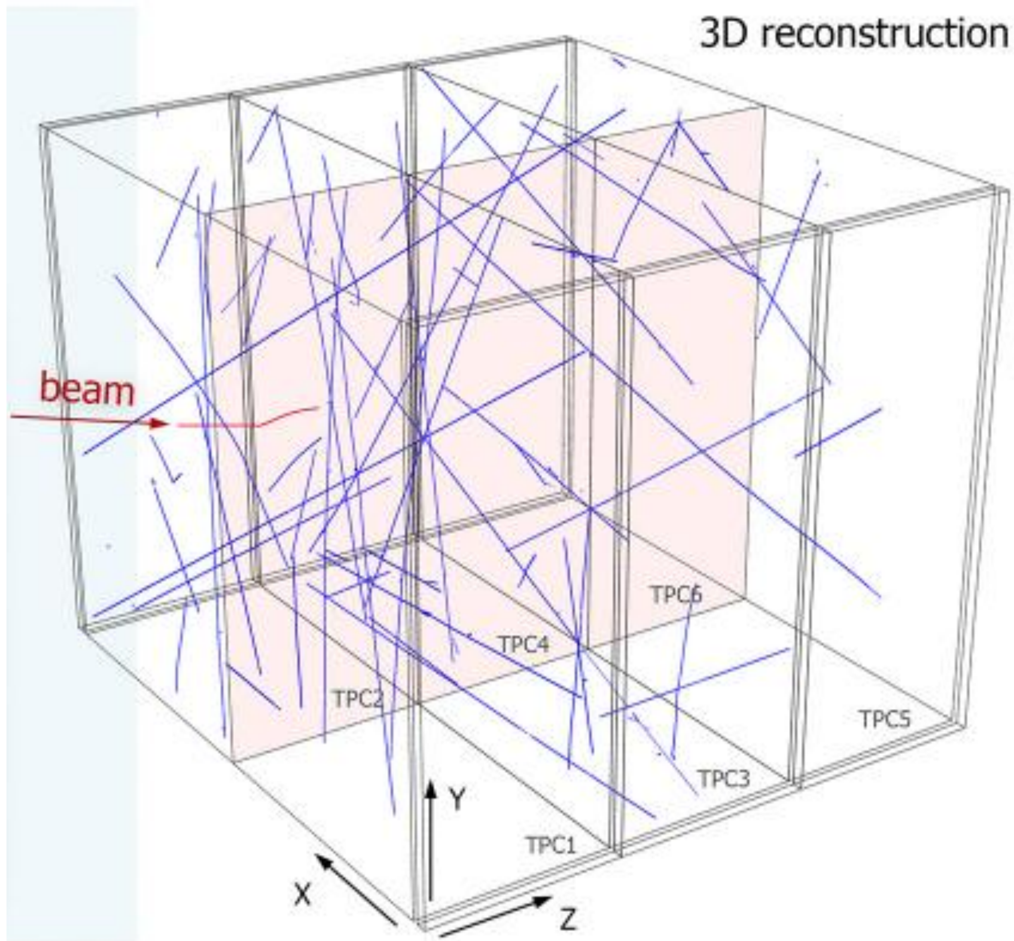
Plan: beam momenta from 500 MeV/c to 7 GeV/c; $3 \cdot 10^5$ π^+, 10^5 p for each setting

- achieved, with 300 MeV/c (e^+ only) beam to spare!
  - > 4M triggers in total
  - nominal trigger rate 25 Hz, limited by TPC bandwidth (raw data ~ 430 Gb/s) and storage
- composition estimated using beam instrumentation
  - Cherenkov & TOF counters



An average ProtoDUNE beam event

On average, ~ 70 cosmic-ray muons within 3 ms readout window

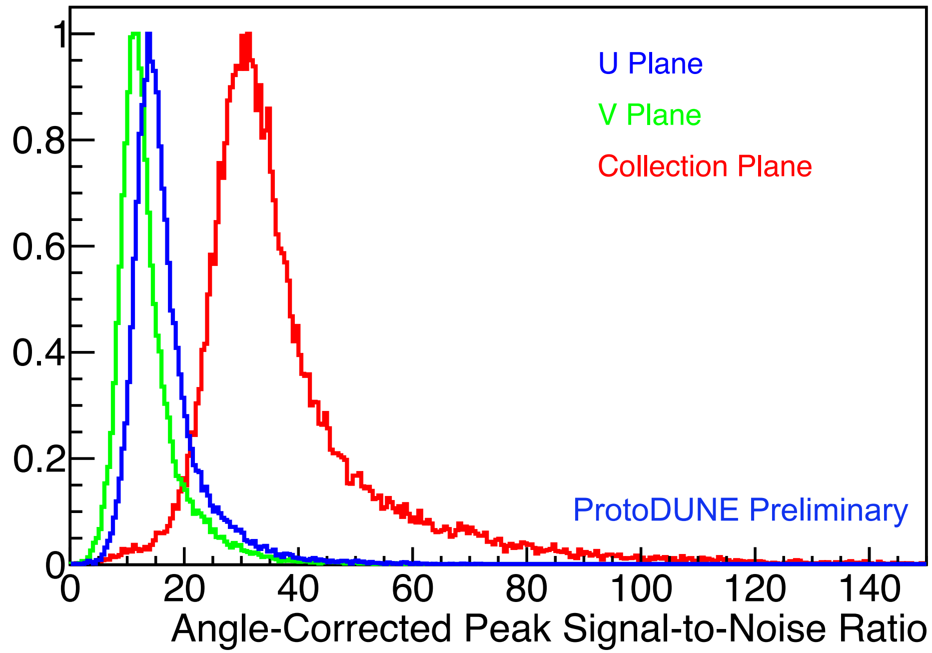


Signal/Noise ratio

Tiny (unamplified) signals seen by wires

- minimise cable lengths ➠ front-end electronics immersed in LAr
- extensive campaign to avoid ground loops

- Signal measured on cosmic-ray muons: maximum of raw waveform
- Noise obtained from σ of Gaussian fit to each wire's pedestal distribution
- Only tracks ~ perpendicular to wire planes used

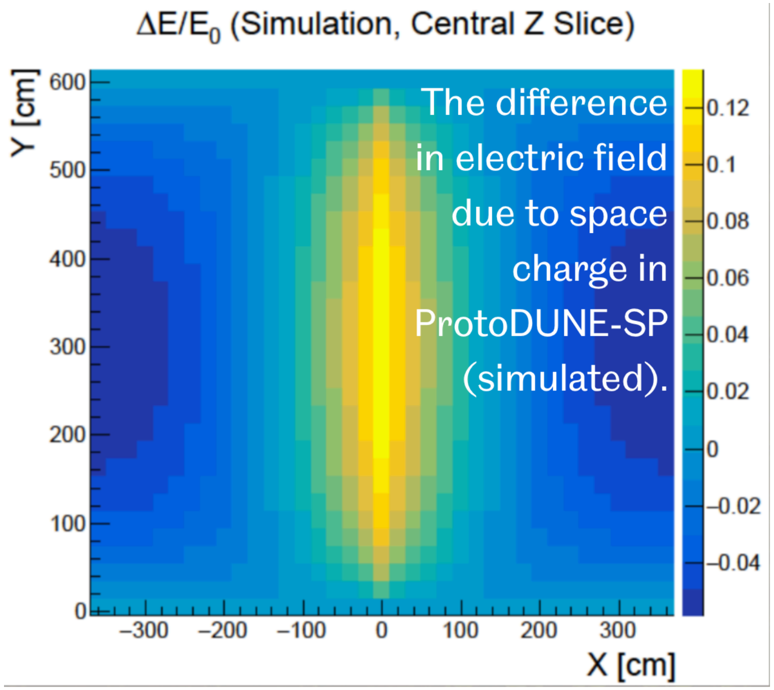


Space charge effects

Adverse effect of high cosmic-ray muon flux: low Ar ion drift velocity (~ 8 μm/ms) ➠ ion cloud

- E field modification
  - affects drift velocity ➠ apparent displacements (up to ~ 30 cm!) and changes to length scales
- electron-Ar recombination
- affected by LAr recirculation

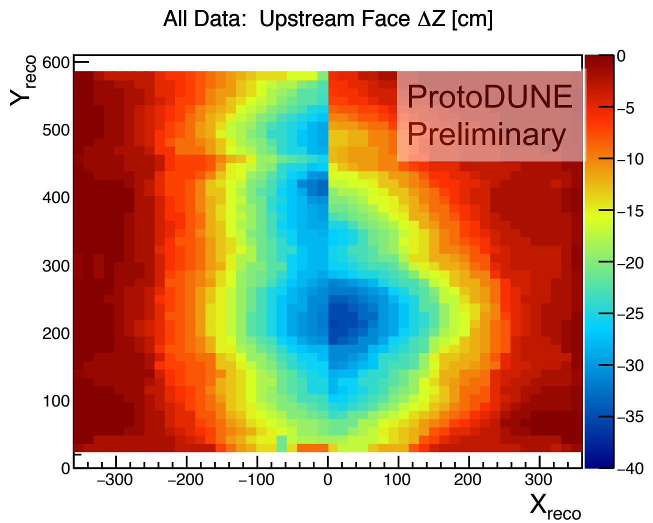
Needs measurement in data

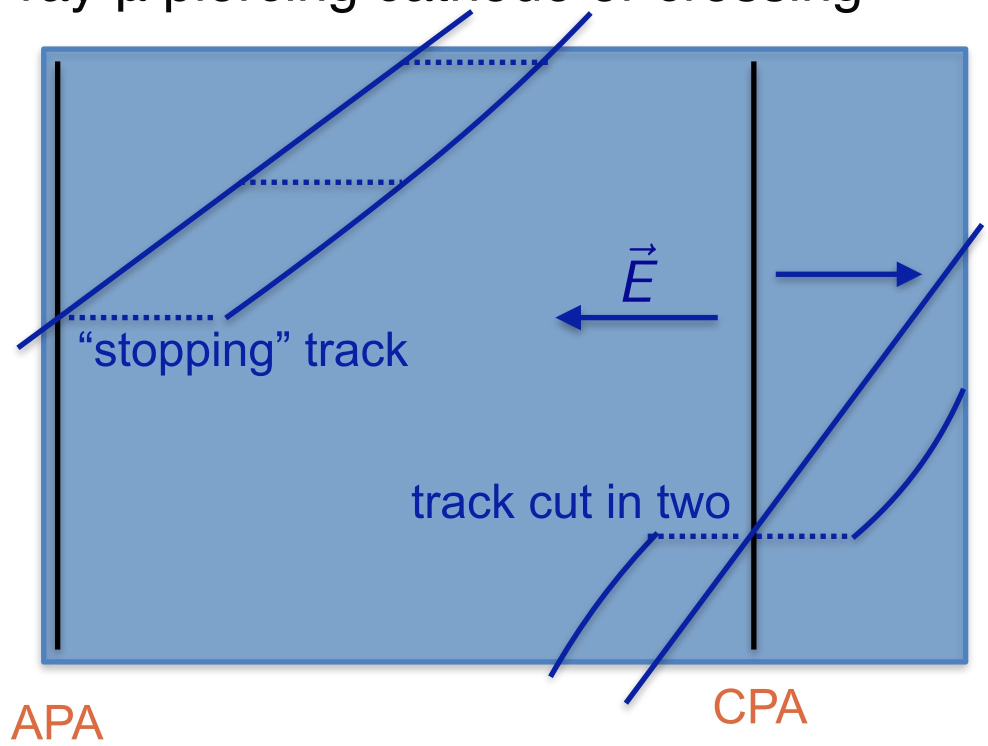


Space charge effects

Measure through-going cosmic-ray μ piercing cathode or crossing anode plane (providing t_0) and exiting one of the other faces (top/bottom/upstream/downstream)

- apparent offsets at faces
  - ex.: offset map at upstream face



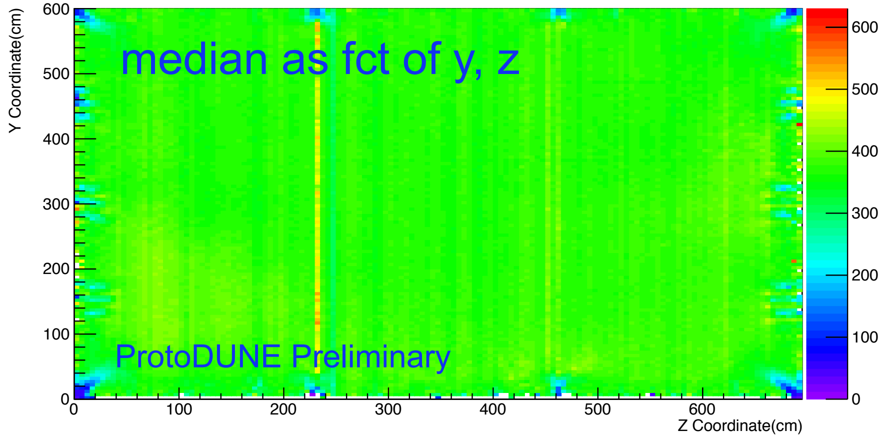


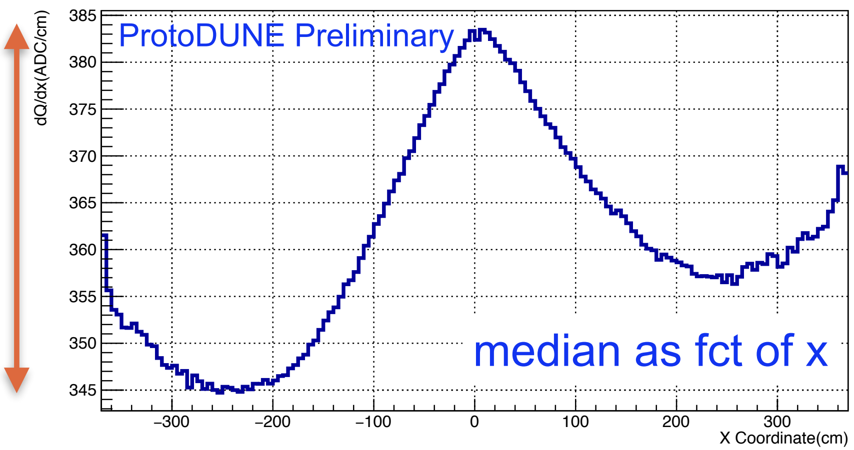
- interpolate to inside of TPC volume
  - data/MC correction factor in combination with detailed model from simulation

Response equalisation

Faster (even if more ad-hoc) way to arrive at an energy calibration (collection plane)

- response: ΔQ/Δs
- using through-going μ: piercing cathode (providing t_0) and traversing the full TPC (no Bragg peak from stopping muons)
- exclude tracks that may not be well reconstructed
  - within 25° from drift direction or within 20° from the collection plane wire direction
- correct to ΔQ/Δs near anode



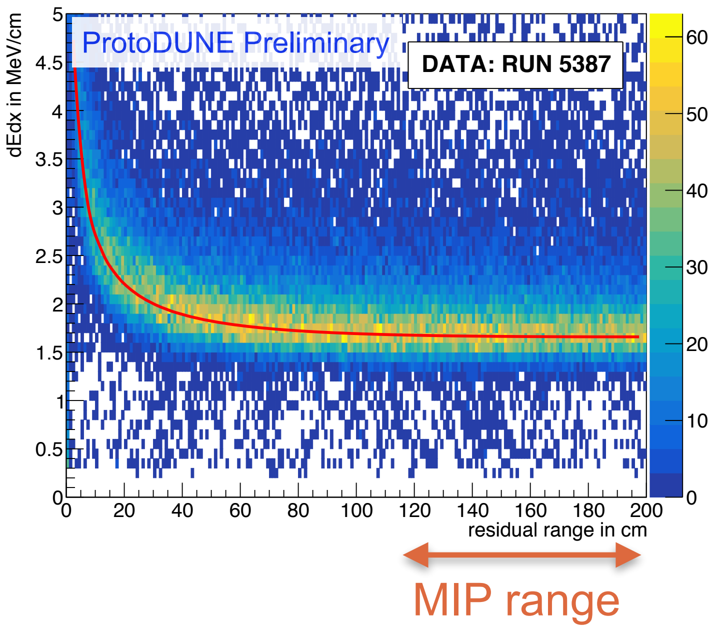


~ 10% effect: compatible with apparent length scale changes due to SCE

Energy calibration

Next, carry out calibration using stopping particles: energy loss given by Bethe-Bloch, Landau-Vavilov

- residual range: distance until endpoint
  - stopping muons: identify “clean” endpoint (e.g. no Michel electron)
    - otherwise selection as for response equalisation



$$\frac{\mathrm{d}E}{\mathrm{d}s} = \frac{\exp\left(\frac{\mathrm{d}Q}{\mathrm{d}s}\frac{W_{\mathrm{ion}}\beta'}{\rho|\vec{E}|C}\right) - \alpha}{\beta'/\rho|\vec{E}|}$$

C: calibration constant obtained from fit to data

- other parameters from detector settings or measured independently

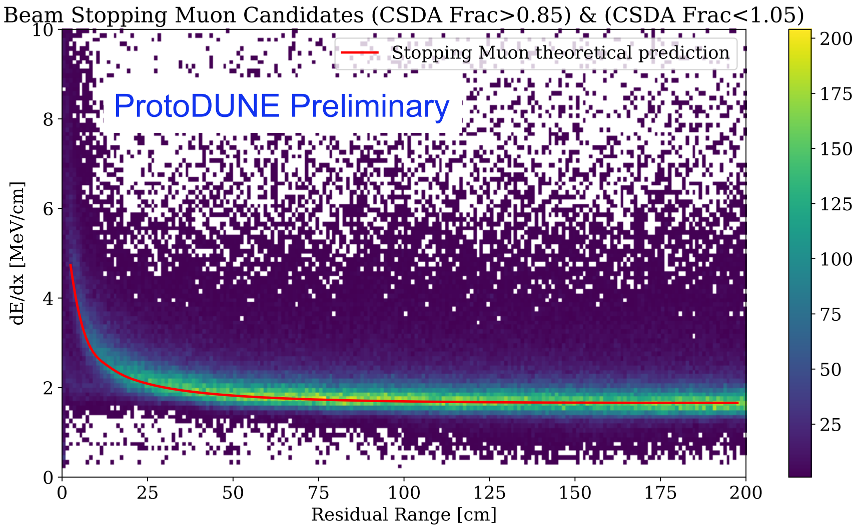
Energy calibration

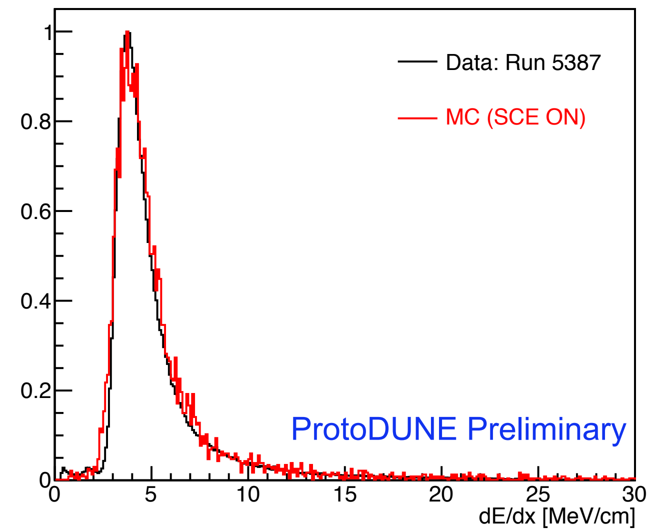
Same analysis can be carried out using beam μ, p

- t_0 from beam instrumentation

beam μ: good agreement with results from stopping cosmics

beam p: good agreement between data & MC for calibrated d*E*/ds in MIP range





Conclusions

ProtoDUNE: full-scale test of DUNE technolog. Crucial step towards full DUNE, with its own challenges (cosmics!)

- great opportunity to learn about physics & technology relevant for DUNE
- main goals achieved!
- now working towards more detailed understanding of detector — and first publication!
  - more to follow: π^+-Ar cross section, energy scale of electromagnetic & hadronic showers
- more beam data to be taken after present LHC shutdown!
  - improved front-end electronics & photon detection system

Backup

Beam triggers

Recorded and expected triggers (from simulation)

- also yields expected composition

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

Modified-Box formula

$$\left(\frac{dE}{dx}\right)_{calibrated} = \frac{\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{\text{calibrated}}}{C}\frac{\beta' W_{\text{ion}}}{\rho\mathcal{E}}\right)-\alpha}{\frac{\beta'}{\rho\mathcal{E}}}$$

where, C=Calibration constant, to be determined, which converts dQ/dx from ADC/cm to number of electrons/cm

ε=0.5kV/cm is the protoDUNE electric field

W_{ion} =23.6 x 10^{-6} MeV/electron (work function of argon)

ρ =1.38 g/cm3 (liquid argon density at a pressure 18.0 psia)

α =0.93

β'=0.212 (kV/cm)(g/cm2)/MeV

where, the last two parameters were measured by ArgoNeuT experiment at 0.481kV/cm.