Energy calibration of the ProtoDUNE-SP TPC

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ICHEP 2020

FERMILAB-SLIDES-20-077-V

dE/dx in ProtoDUNE-SP

- Precise dE/dx measurements needed to make cross-section and Bragg peak measurements for pions, protons, muons, and kaons in ProtoDUNE.
- Use Modified Box Model
  - Formula pioneered by ICARUS that is a modification of Birks' Law

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

dQ/dx: Charge per step as reconstructed on the wires.

C_{cal}: Gain to convert from wire response (ADC*tick) to electrons.

ξ: Local electric field

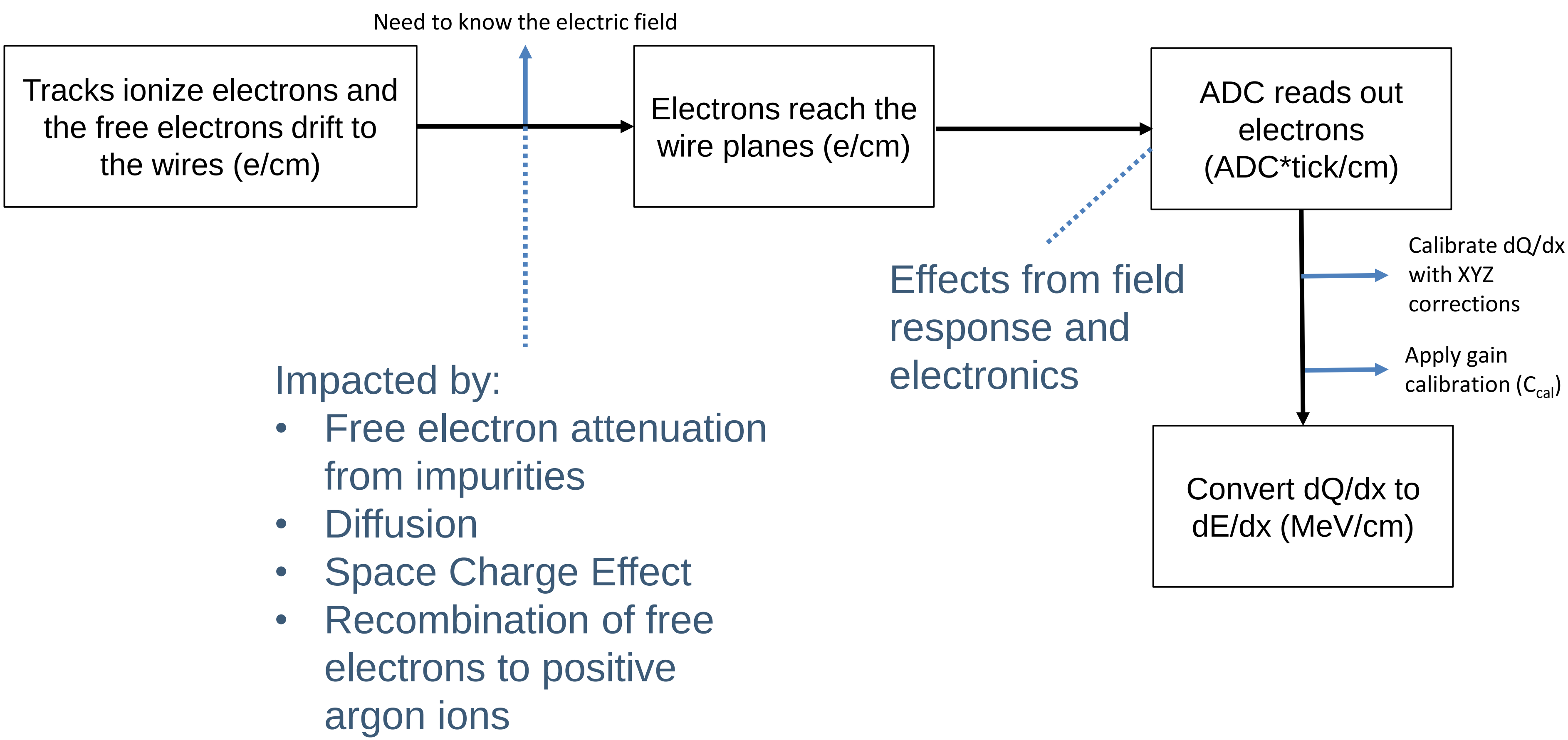
W_{ion}, ρ, α, β' are constants measured previously [1].

Measurements are needed for C_{cal}, ξ, and dQ/dx to calibrate dE/dx.

[1] R. Acciarri *et al.*, "A study of electron recombination using highly ionizing particles in the ArgoNeuT Liquid Argon TPC," *JINST* 8 (2013) P08005, arXiv:1306.1712 [physics.ins-det].

dE/dx and Calibration

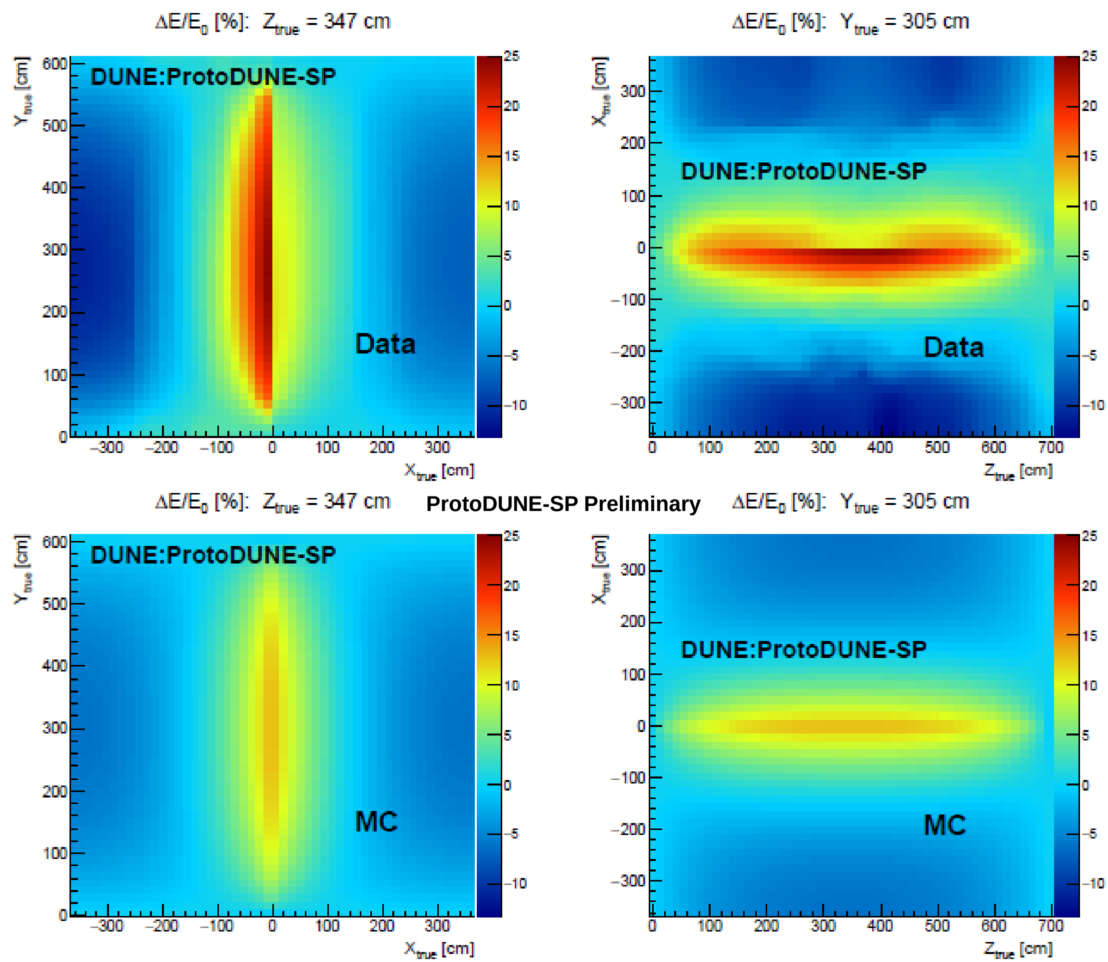
- Calibration is done to go from ionized electrons to a quantifiable dE/dx.



Electric Field Calibration

- Measure space charge effect field distortions using positional distortions on the edges of the detector.
- Interpolate the electric field at a specific hit measured using the map of the electric field generated by the space charge effect calibration.
- The dE/dx measurement also corrects for the squeezing and stretching of the step length (dx) using the space charge effect distortion measurements.
- The nominal electric field was measured at 0.487 kV/cm

See previous talk by M. Mooney



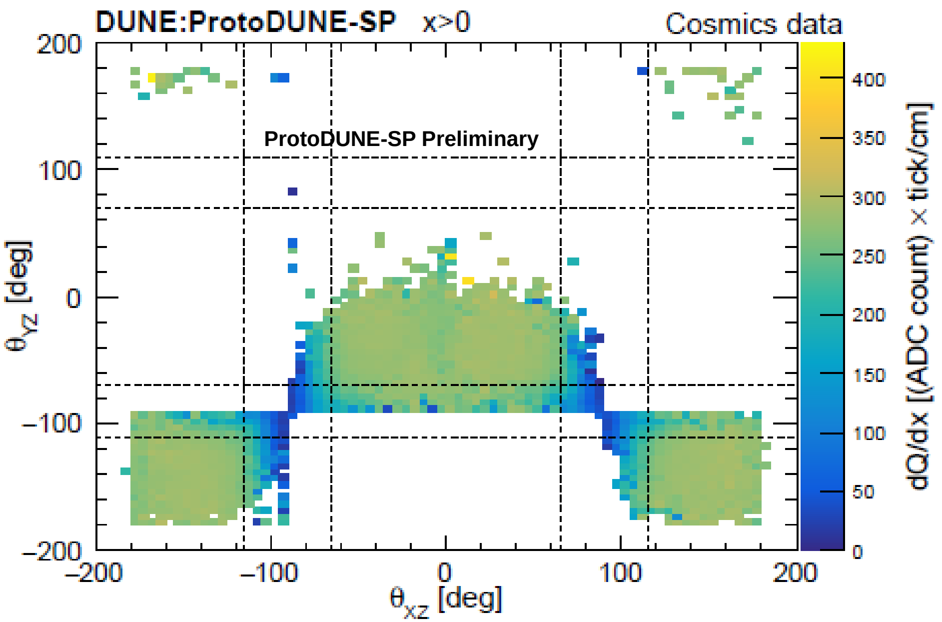
Electric field deviations measured using the end points of cathode-crossing tracks.

dQ/dx Calibration

- Use cosmic muons at high residual range as they have well-defined dE/dx that is known theoretically by less than 1% uncertainty using the Landau-Vavilov theory [2].

Calibrating dQ/dx:

1. Select cathode-crossing cosmic tracks enter and exit detector.
2. Cut out cosmic muons that have certain track angles to avoid geometrical effects. (Cut if $65^0<\theta xz<110^0$ or $70^0<\theta yz<110^0$)
3. Measure fluctuations in dQ/dx as a function of YZ, then measure dQ/dx as a function of drift distance (X).
4. Normalize dQ/dx between drift volumes.



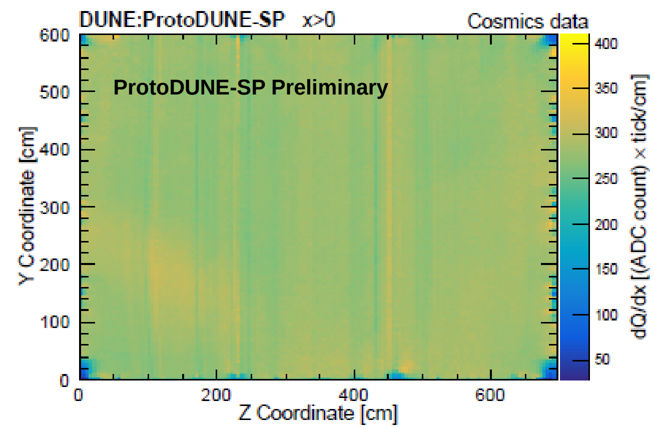
Track angles of cosmic muons for the non-beam side drift volume. The cathode plane of the detector sits at X=0.

[2] Particle Data Group collaboration, M. Tanabashi, K. Hagiwara, K. Hikasa, K. Nakamura, Y. Sumino, F. Takahashi et al., *Review of particle physics*, *Phys. Rev. D* **98** (Aug, 2018) 030001

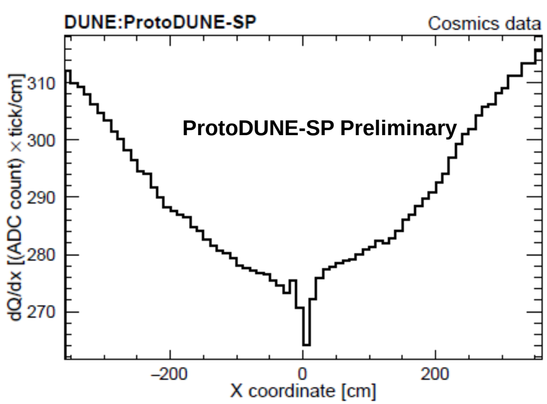
XYZ Calibration of dQ/dx

Each step is applied to the next.

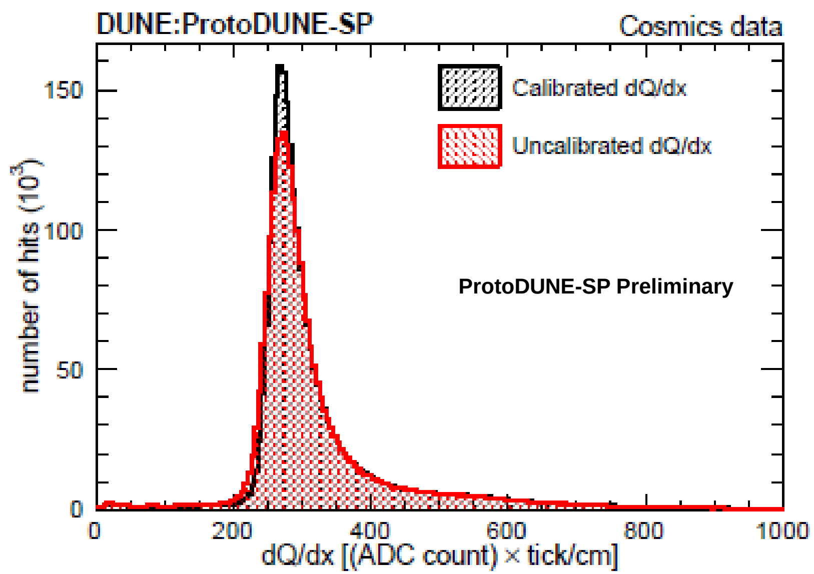
1. YZ calibration
   - $C(y,z)=\frac{dQ/dx_{global\,yz}}{dQ/dx(Y,Z)}$
2. X Calibration
   - $C(x)=\frac{dQ/dx_{global\,x}}{dQ/dx(X)}$
3. Normalization
   - $N_Q=\frac{dQ/dx(anode)}{dQ/dx_{global}}$
4. Full dQ/dx calibration
   - $dQ/dx_{cal}=C(x)C(y,z)N_Q dQ/dx$



dQ/dx as a function binned in YZ.



dQ/dx as a function of X.

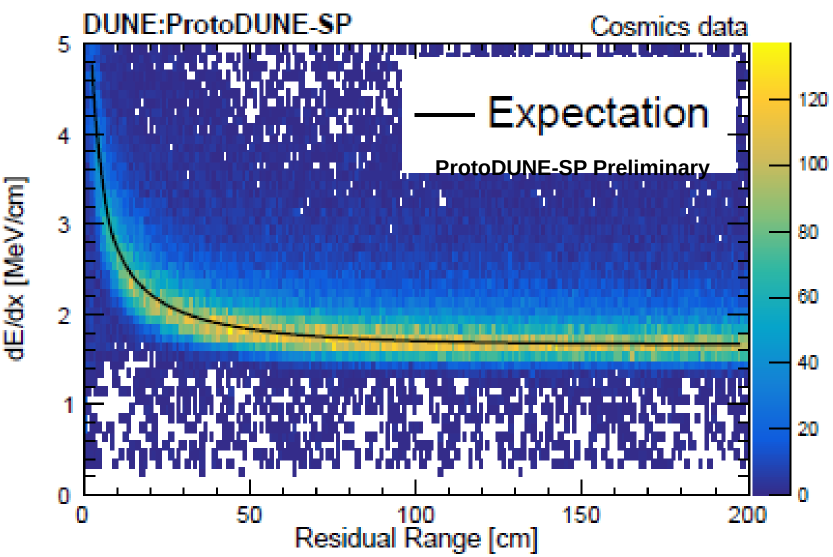


Final calibrated dQ/dx

Energy Calibration (C_{cal})

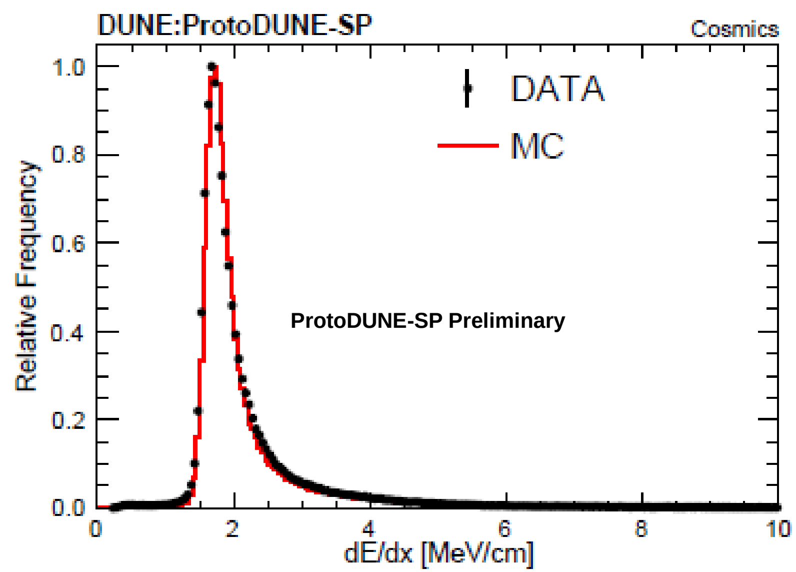
Cathode-crossing tracks are again selected but with the following cuts:

1. Cut tracks that stop too close from the edges and with angles parallel to the wire plane.
2. Remove tracks that have reconstruction errors, such as broken tracks.
3. Use a χ^2 optimization to measure C_{cal} using hits at high residual range (120-200 cm). Optimization is set that in a perfect detector C_{cal} would be set to $5*10^{-3}$ ADCxtick/e.



For this run: $C_{cal}=(5.4\pm0.1)*10^{-3}$ ADCxtick/e

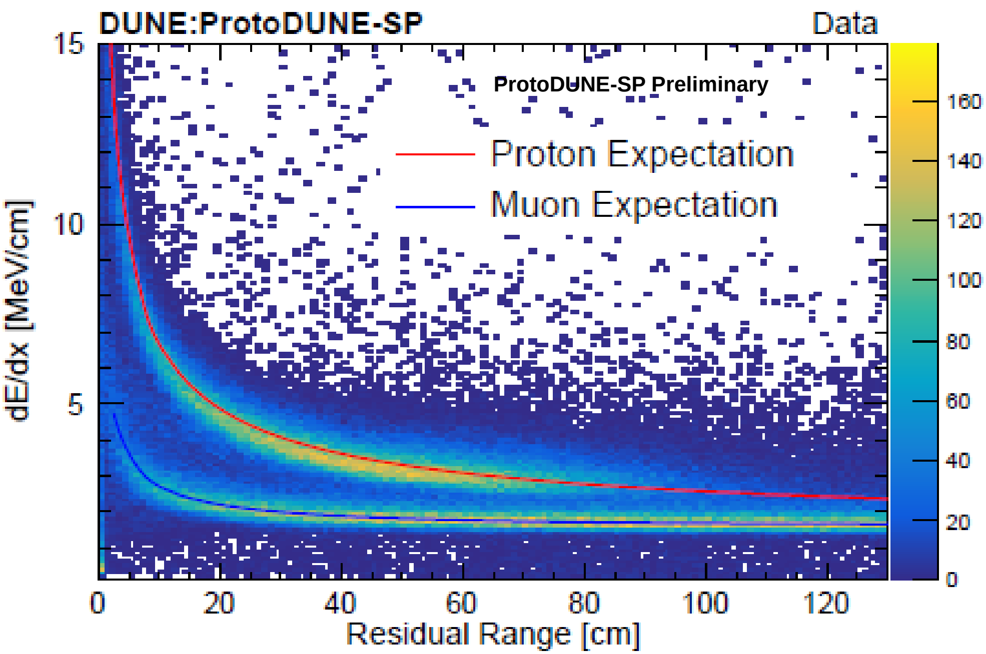
High residual range area

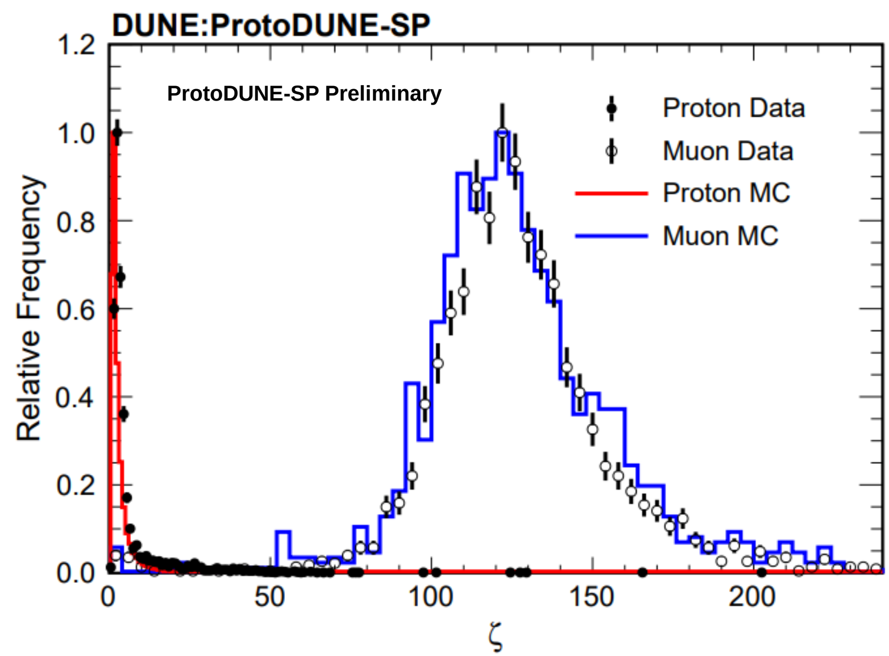


Calibrated dE/dx for cosmic muons

Conclusion

- Calibrations of dE/dx were made by calibrating dQ/dx across the detector and then scaling dE/dx using the Landau-Vavilov theoretical dE/dx.
- Results included in ProtoDUNE-SP paper currently on the arXiv (arXiv:2007.06722).

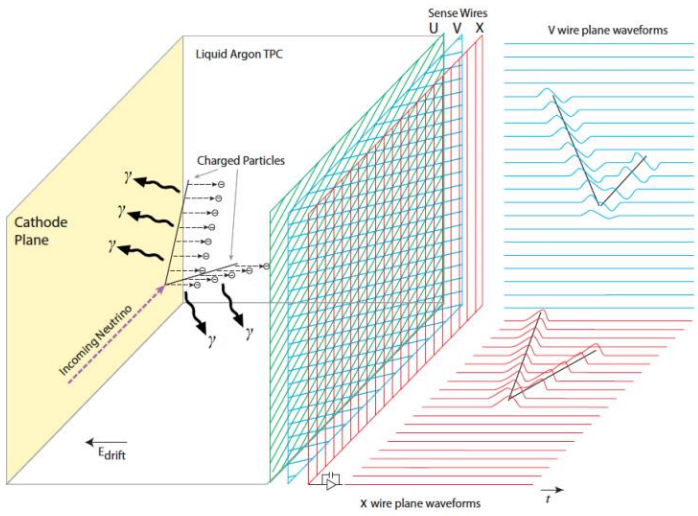




Calibrated dE/dx and likelihood (χ^2/d.o.f.) of stopping muons and stopping protons.

Backup Slides

Detector Basics



Demonstration of a LAr TPC reading the drift ionized electrons of a neutrino interaction [3].

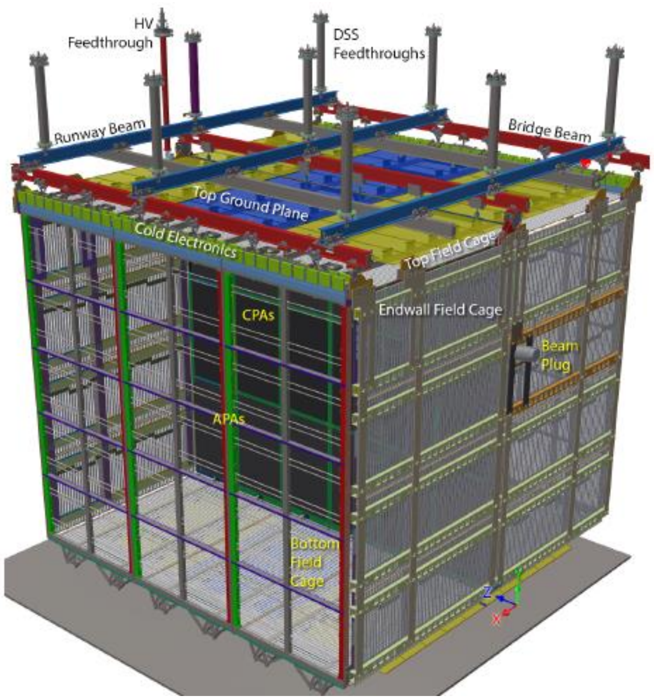
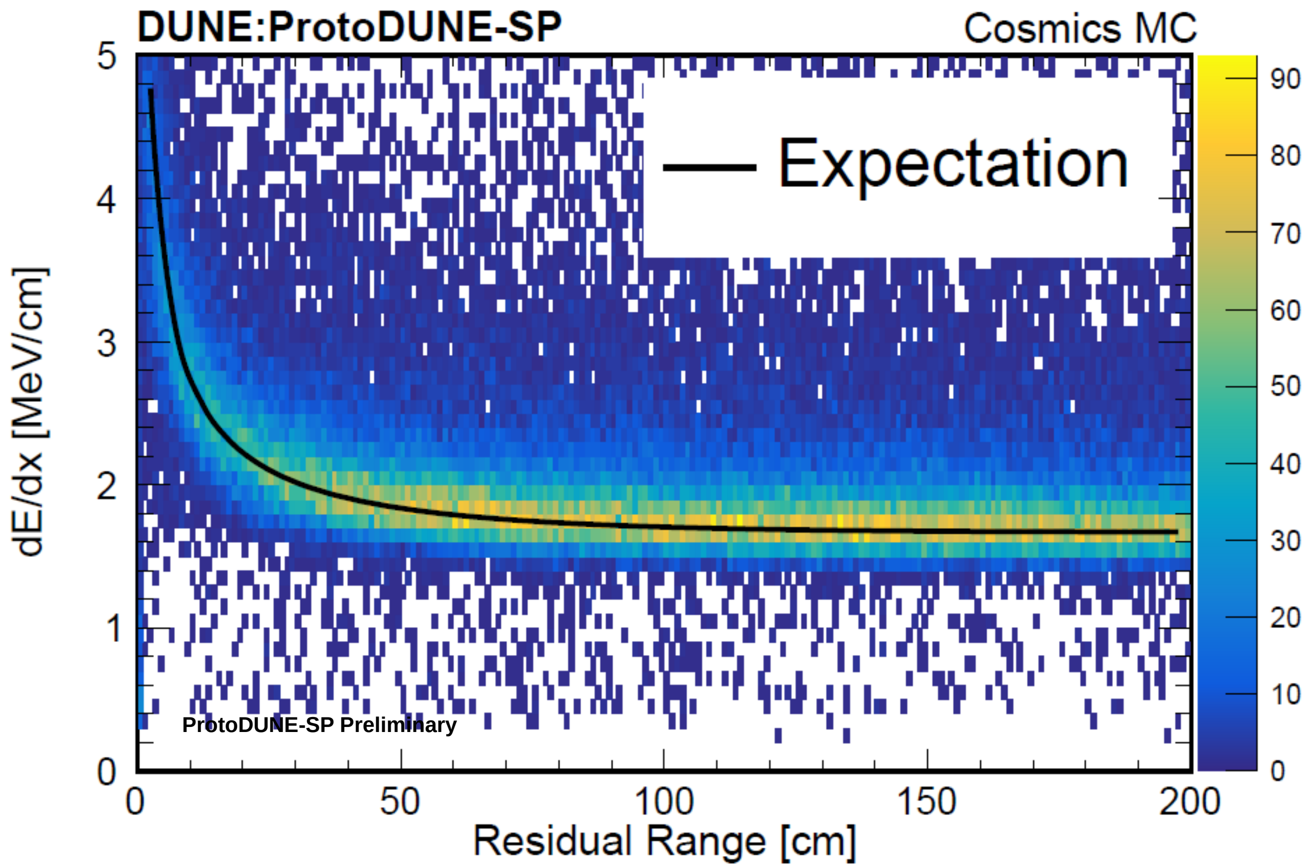


Diagram of the ProtoDUNE-SP detector. The 2nd set of APAs is on the other wall of the detector.

[3] B. Abi, et. al., "Deep Underground Neutrino Experiment (DUNE) Far Detector Technical Detector Report Volume 1" *arXiv:2002.02967*, 2020.

dE/dx in Monte Carlo

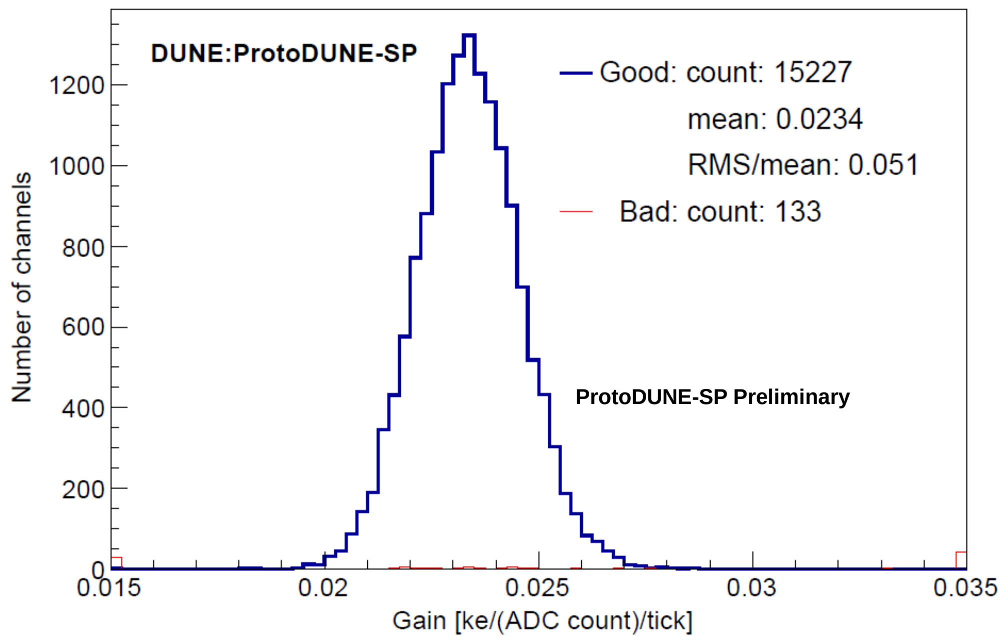
Purity of Hits in MC using Cuts Outlined: 99.74%
C_{cal}=(5.03±0.01)*10^{-3} ADCxtick/e



dE/dx as a function of residual range for Monte Carlo

ADC Calibration

- Measures the gain of the ADC to calibrate wire-to-wire differences in the readout.
- Uncertainty in the ADC calibration was considered to be at the few percent level.



Measurements of the ADC gain using the pulser on the front end electronics.