

# Energy calibration of the ProtoDUNE-SP TPC

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# 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

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

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

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

$\xi$ : Local electric field

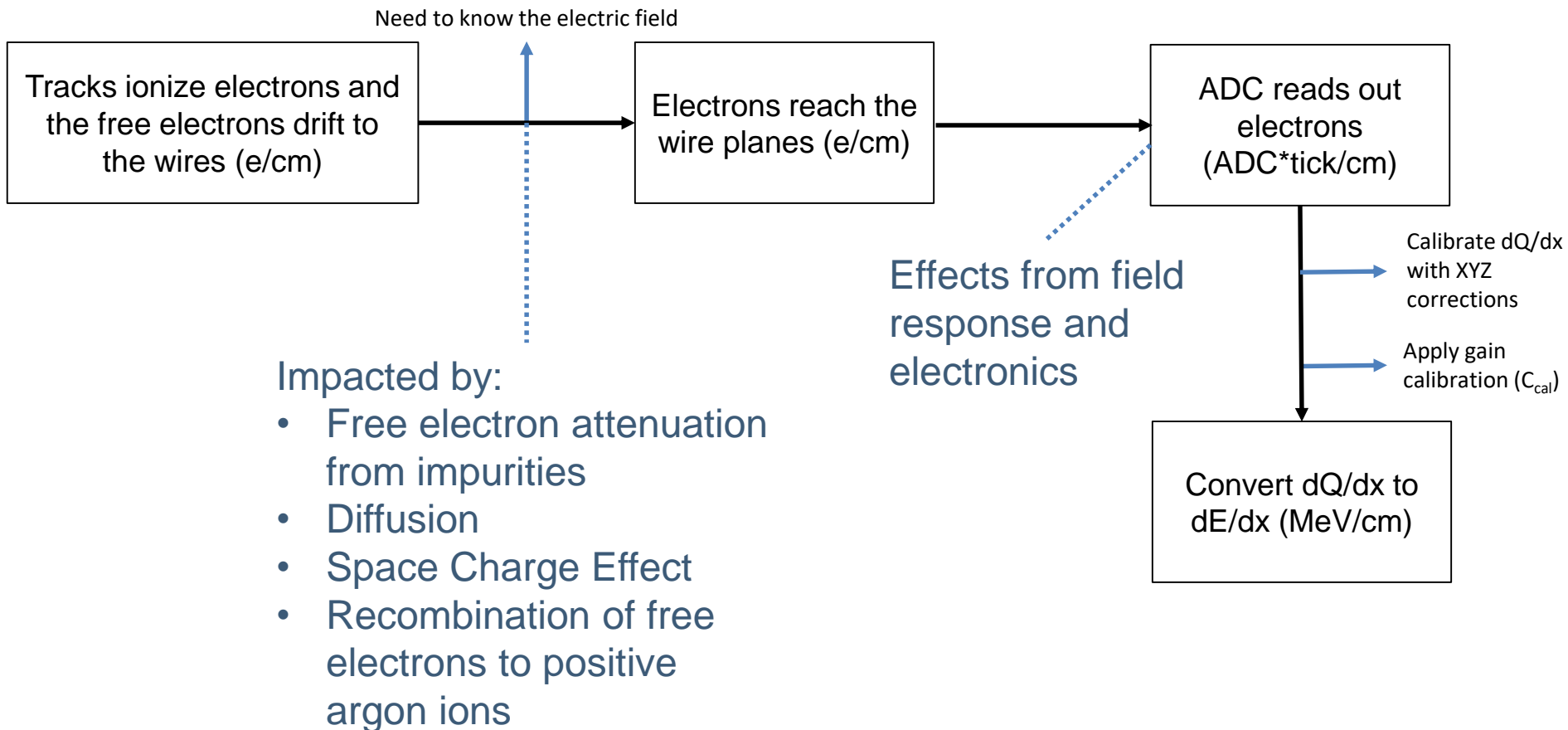
$W_{\text{ion}}$ ,  $\rho$ ,  $\alpha$ ,  $\beta'$  are constants measured previously [1].

Measurements are needed for  $C_{\text{cal}}$ ,  $\xi$ , 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

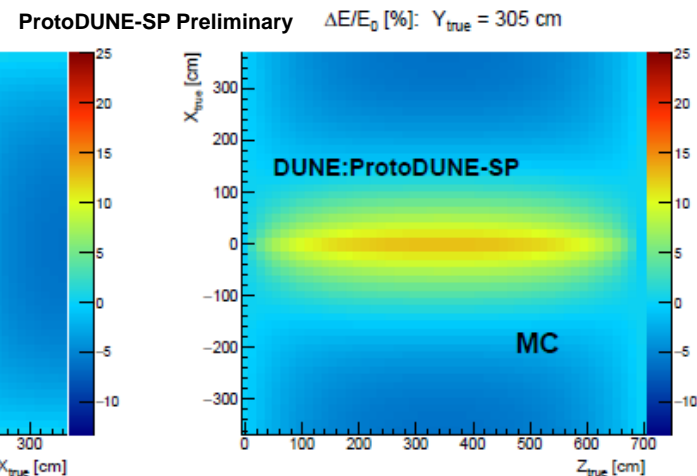
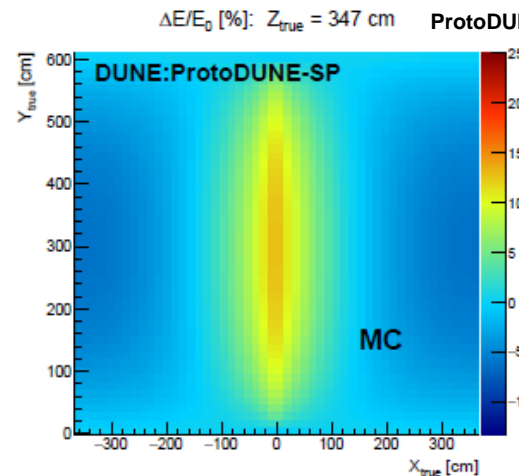
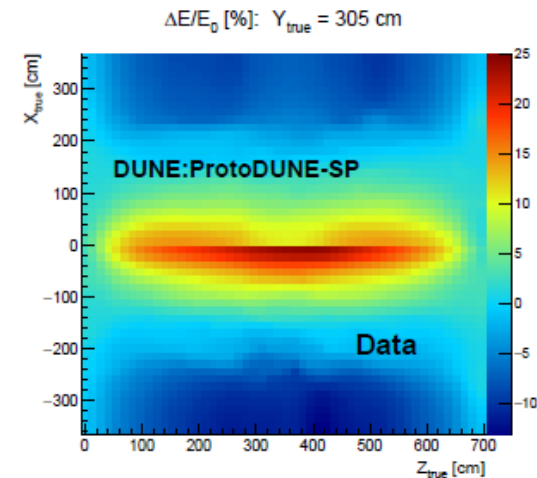
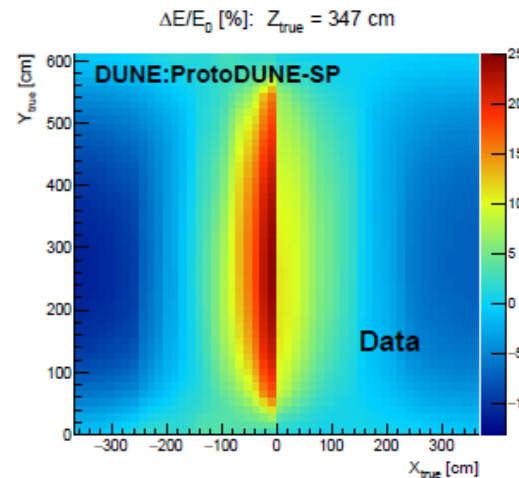
- Calibration is done to go from ionized electrons to a quantifiable dE/dx.



# Electric Field Calibration

See previous talk by M. Mooney

- 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



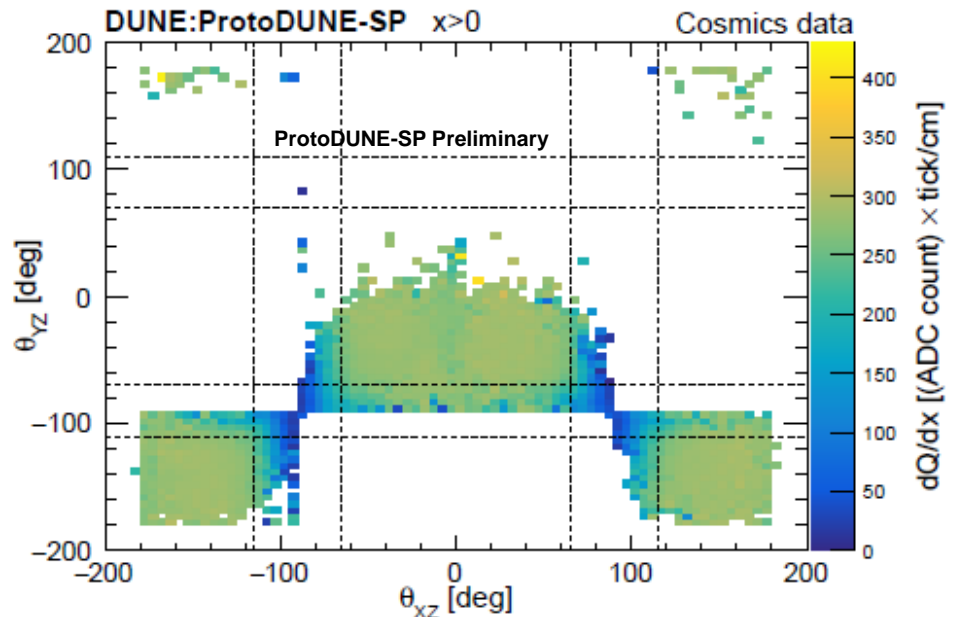
Electric field deviations measured using the end points of cathode-crossing tracks.

# 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  $65^\circ < \theta_{xz} < 110^\circ$  or  $70^\circ < \theta_{yz} < 110^\circ$ )
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

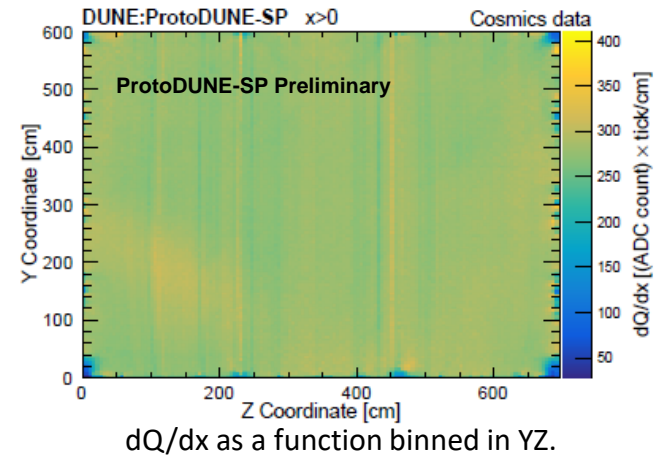
$$- C(x) = \frac{dQ/dx_{global\ x}}{dQ/dx(X)}$$

## 3. Normalization

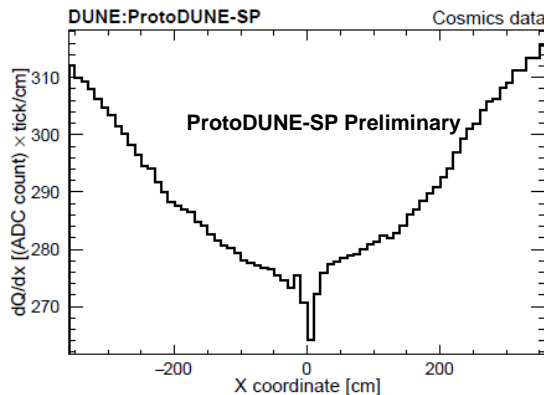
$$- N_Q = \frac{dQ/dx(anode)}{dQ/dx_{global}}$$

## 4. Full dQ/dx calibration

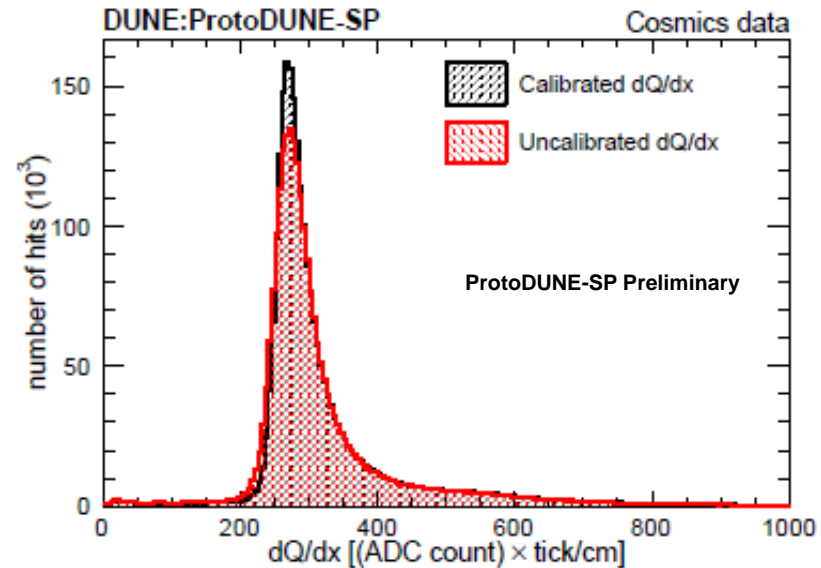
$$- dQ/dx_{cal} = C(x)C(y,z)N_Q dQ/dx$$



dQ/dx as a function binned in YZ.



dQ/dx as a function of X.

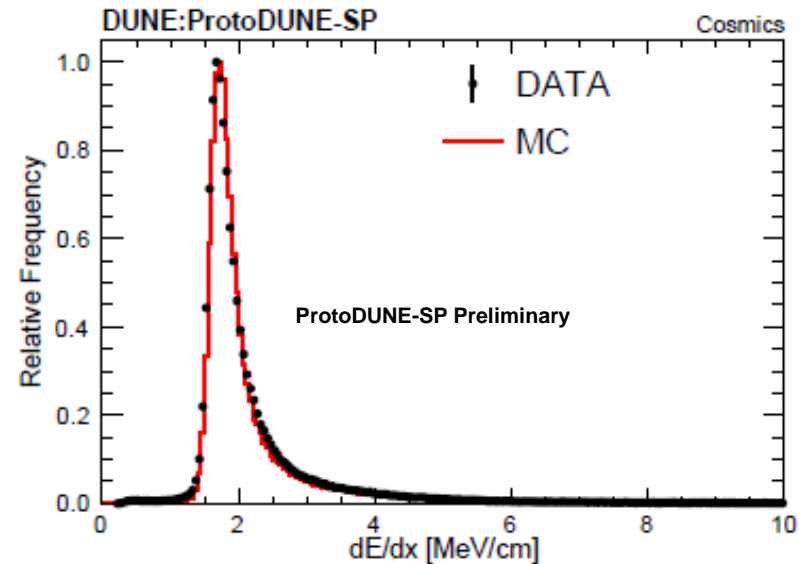
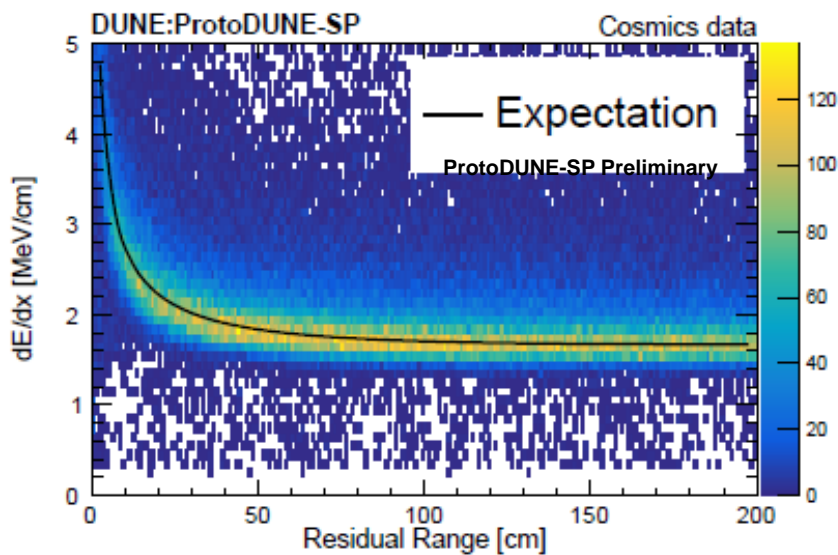


Final calibrated dQ/dx

# 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  $\chi^2$  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  $5 \cdot 10^{-3}$  ADCxtick/e.



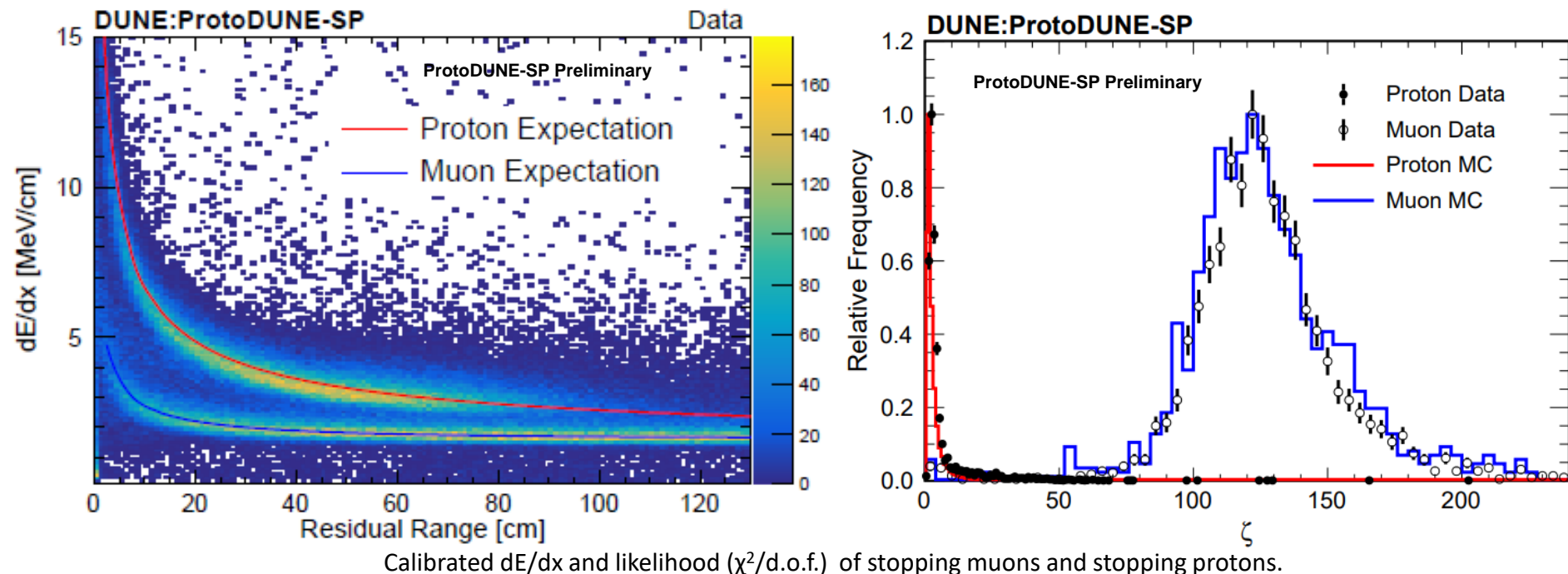
Calibrated dE/dx for cosmic muons

For this run:  $C_{cal} = (5.4 \pm 0.1) \cdot 10^{-3}$  ADCxtick/e

High residual range area

# 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).

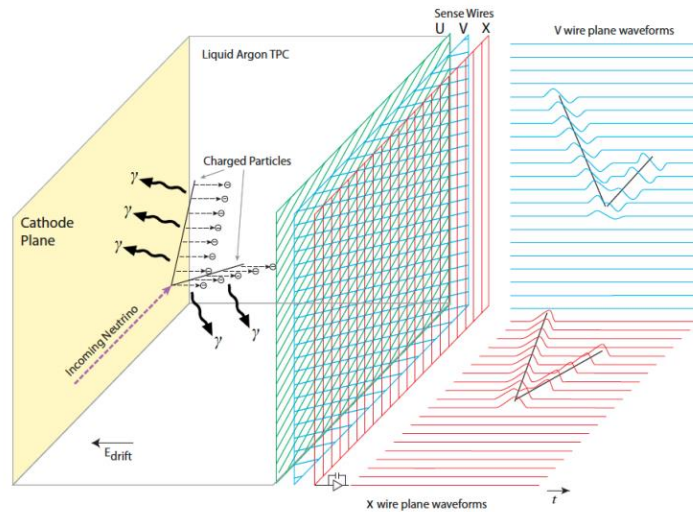




# Backup Slides



# Detector Basics



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

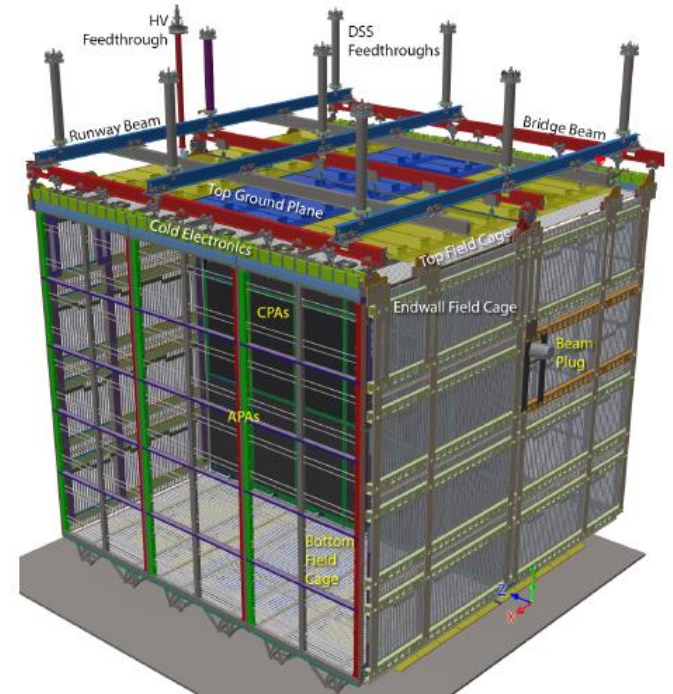


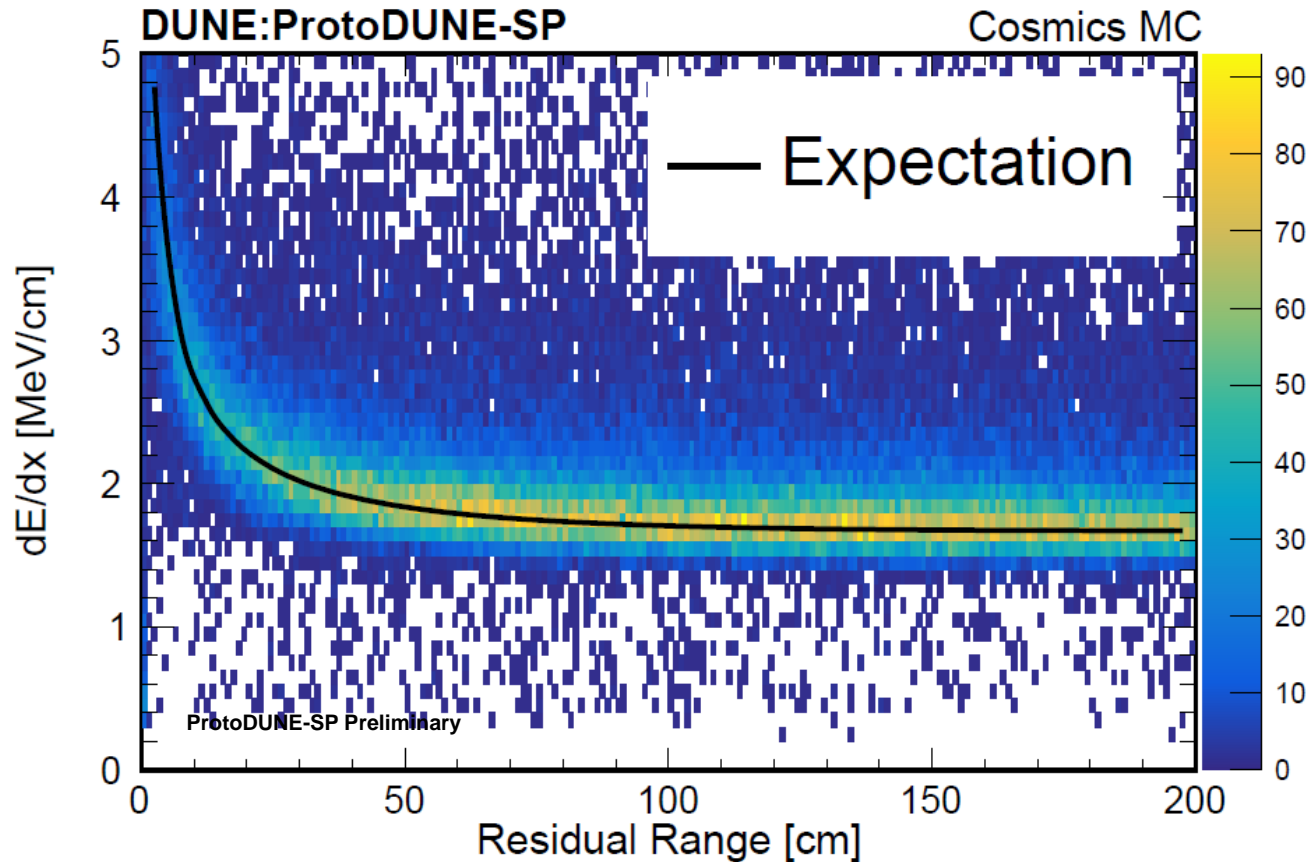
Diagram of the ProtoDUNE-SP detector. The 2<sup>nd</sup> set of APAs is on the other wall of the detector.

[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%

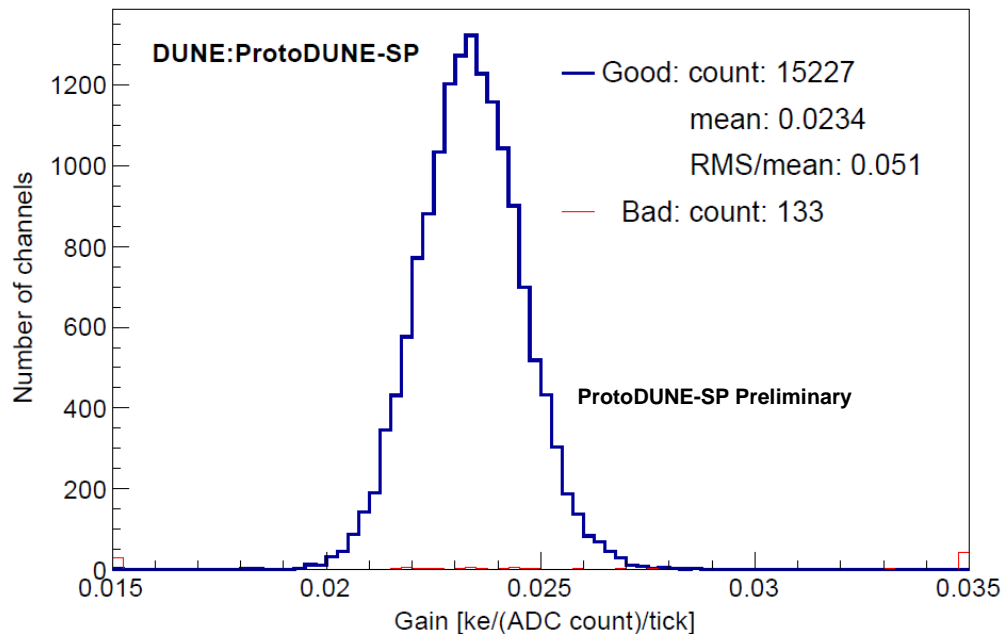
$$C_{\text{cal}} = (5.03 \pm 0.01) \cdot 10^{-3} \text{ ADCxtick/e}$$



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.