# 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:
  - dQ/dx: Charge per step as reconstructed on the wires of the Anode Plane Array of the TPC.
  - $C_{cal}$: Gain to convert from wire response (ADC*tick) to electrons.
  - $W_{ion}$: Work function for argon ($23.6 \times 10^{-6}$ MeV/$e^-$)
  - $\xi$: Local electric field
  - $\alpha$: 0.93 g/cm$^3$ (from ArgoNeuT [1])
  - $\beta'$: 0.212 (kV*g)/(cm$^3$*MeV) (from ArgoNeuT [1])
  - $\rho$: 1.38 g/cm
- Measurements are needed for $C_{cal}$, $\xi$, and dQ/dx.

- Calibration is done to correct for:
  - Space charge effect
    - Due to bombardment of cosmic rays, the electric field is distorted due to an excess of positive argon ions.
  - Drift electron lifetime and diffusion
    - Impurities in the liquid argon and diffusion of charge causes changes in dQ/dx as a function
  - Recombination
    - Drifting electrons and recombine with positive argon ions, therefore, attenuating the charge read on the wires.
  - Electronics and other detector effects
    - Issues with the detector and its electronics, such as dead wires and electron diverters, can cause asymmetries in dQ/dx across the detector.

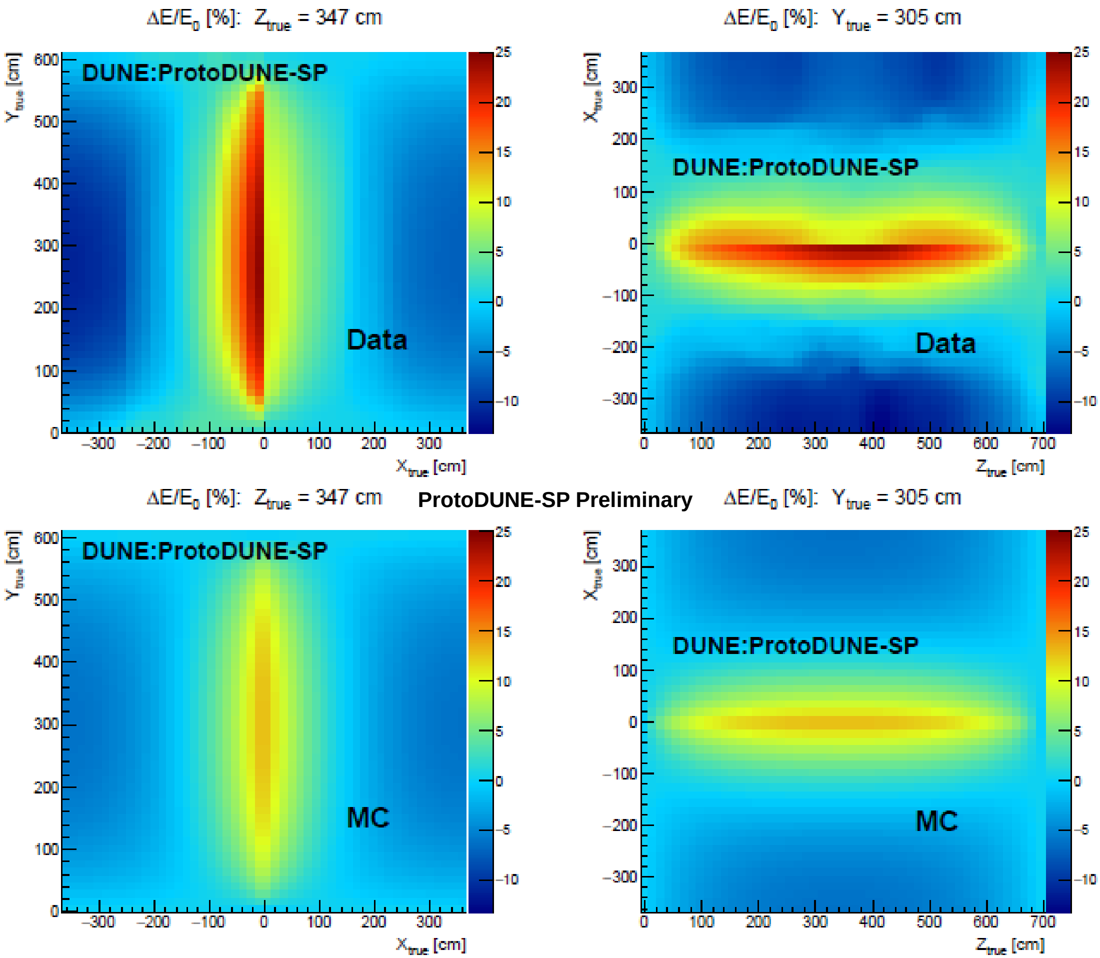
$$\left(\frac{dE}{dx}\right)_{\text{calibrated}} = \left(\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{\text{calibrated}}}{C_{\text{cal}}}\frac{\beta' W_{\text{ion}}}{\rho\mathscr{E}}\right) - \alpha\right)\left(\frac{\rho\mathscr{E}}{\beta'}\right)$$

[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].

# Electric Field Calibration

- Interpolate the electric field based on the positional biases for the interior of the detector.
- Use the location of each track hit to find the electric field of the TPC for the hit.
- The nominal electric field was measured at 0.487 kV/cm
- This only corrects for the space charge effects impact on the electric field. We still need to do dQ/dx and a gain calibration in order to "completely" calibrate out its effects.

See previous talk by M. Mooney



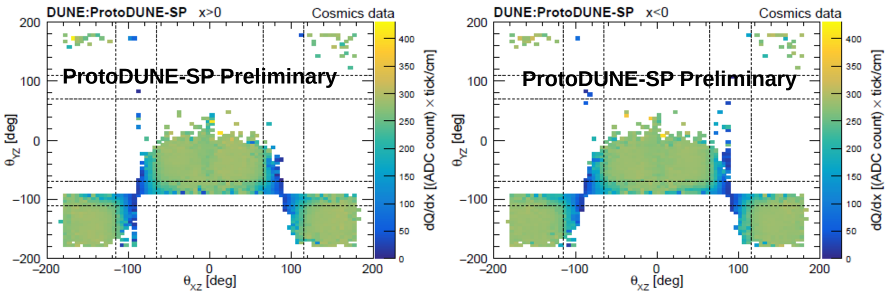

Electric field deviations measured using the end points of cathode-crossing tracks.

# dQ/dx and Energy ($C_{cal}$) Calibration

- Both dQ/dx and energy calibration rely on using cathode-crossing cosmic muons
  - This is because cosmic muons at high residual range have well-defined dE/dx that is known theoretically by less than 1% uncertainty using the Landau-Vavilov theory [2].
- dQ/dx calibration is done as a function of position before measuring $C_{cal}$ in order to ensure the energy gets scaled evenly across the detector.

Calibrating dQ/dx is done in three steps:

1. Select cathode-crossing tracks that start and end outside the detector by making a fiducial volume that avoids the edges of the detector.
2. Cut out cosmic muons that have certain track angles avoid geometrical effects from the way the readout wires are placed on the anode plane array. ($65^0<\theta xz<110^0$, $70^0<\theta yz<110^0$)
3. Measure fluctuations in dQ/dx as a function of YZ. These are likely caused by diffusion, gaps in the detector, dead wires, and issues with the electronics.
4. Measure dQ/dx as a function of drift distance (X) to calibrate out effects from diffusion, the drift electron lifetime and remaining offsets due to the space charge effect.
5. Normalize between drift volumes.



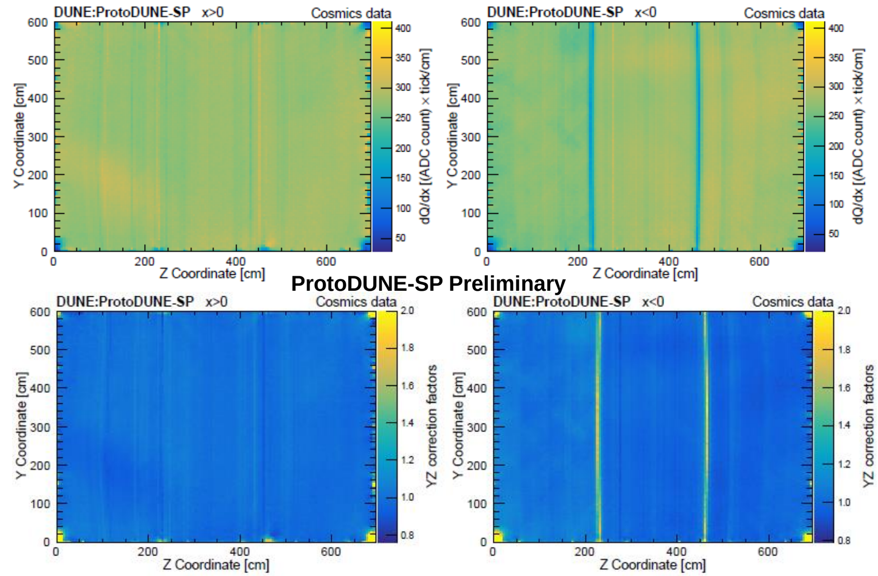

(a) $x > 0$ (b) $x < 0$

Track angles of cosmic muons selected. The cathode plane of the detector sits at X=0. The plot, therefore, shows the track angles for each drift volume of the detector.

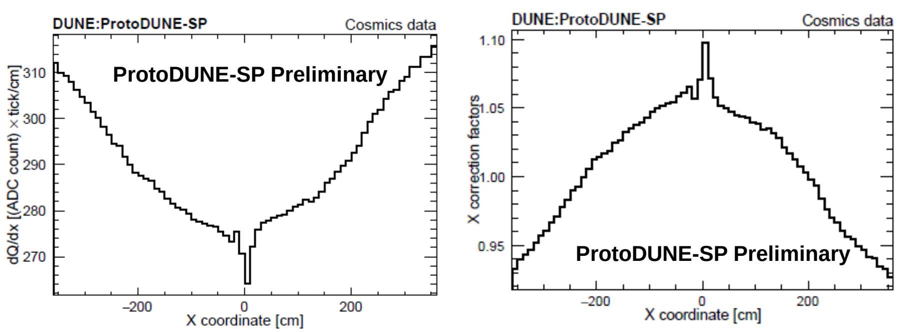
[2] Particle Data Group collaboration, M. Tanabashi, K. Hagiwara, K. Hikasa, K. Nakamura, Y. Sumino, F. Takahashi et al., *Review of particle physics*, *Phys. Rev. D* **98** (Aug, 2018) 030001

# XYZ Calibration of dQ/dx

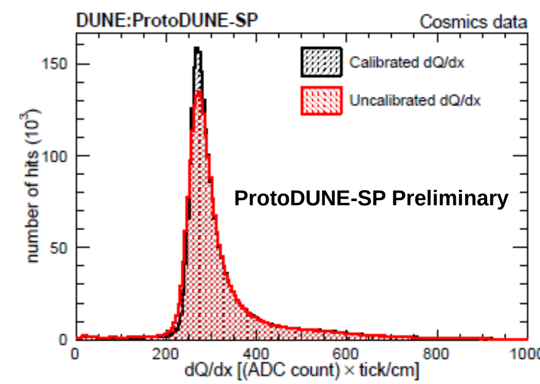
- YZ calibration
  - $C(y,z)=\frac{dQ/dx_{global\,yz}}{dQ/dx(Y,Z)}$
- X Calibration
  - $C(x)=\frac{dQ/dx_{global\,x}}{dQ/dx(X)}$
- Normalization
  - $N_Q=\frac{dQ/dx(anode)}{dQ/dx_{global}}$
- Full dQ/dx calibration
  - $dQ/dx_{cal}=C(x)C(y,z)N_Q dQ/dx$




dQ/dx as a function of YZ (top) and the correction factors as a function of YZ (bottom)




dQ/dx as a function of X (left) and the correction factors as a function of X (right)

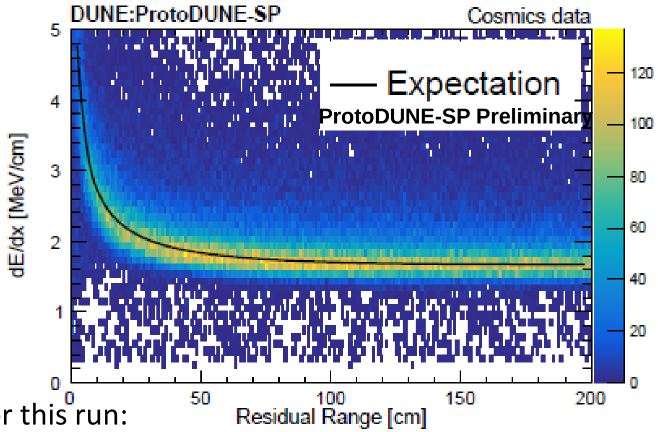



Final calibrated dQ/dx

# Energy Calibration ($C_{cal}$)

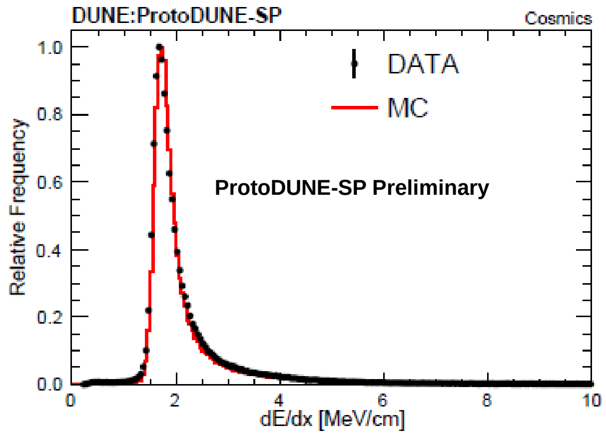
Cathode-crossing tracks are again selected but with the following cuts:

1. Select tracks that start outside the fiducial volume but stop somewhere within a fiducial volume that is 30 cm from either anode and 50 cm away from the edge across the length of the detector.
2. Again cut out cosmic muons that have certain track angles. ($65^0<\theta xz<110^0$, $70^0<\theta yz<110^0$)
3. Remove broken tracks by eliminating tracks that have endpoints within 30 cm of the endpoints of another track and an angle between them of $30^0$.
4. Remove tracks that are measured during the beginning and end of readout. Sometimes hits measured near the beginning and end of readout mimic a stopping muon.
5. Remove tracks that have Michel electrons attached to them incorrectly by the track reconstruction.
6. Fit track hits of dQ/dx with a residual range between 120-200 cm to the Landau-Vavilov dE/dx for muons and use a $\chi^2$ optimization to measure $C_{cal}$. Use the modified box model to convert from dQ/dx to dE/dx.




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

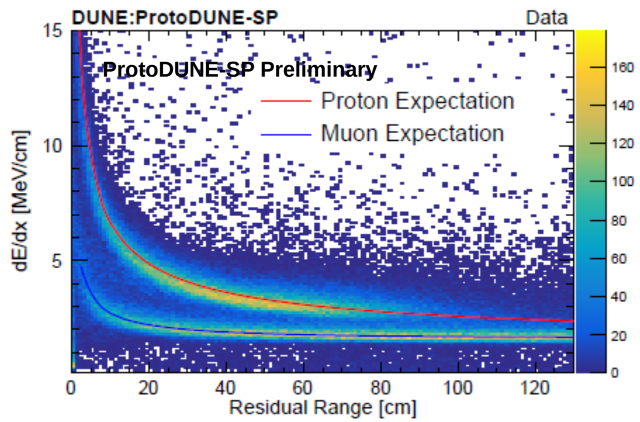
High residual range area




Calibrated dE/dx for cosmic muons

# Conclusion

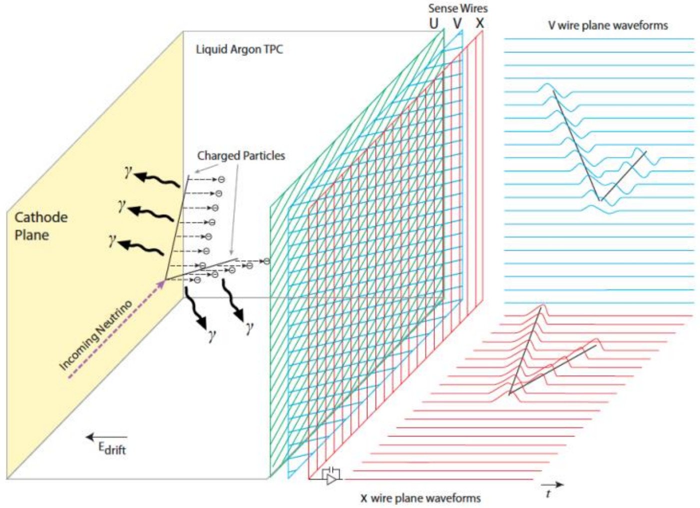
- Calorimetric hits in ProtoDUNE-SP undergoes distortions due to detector effects, such as the space charge effect, the electron lifetime, and dead readout wires.
- Calibrations of dE/dx were made by first calibrating out the dQ/dx and then scaling the gain calibration based on the dE/dx of muons using the Landau-Vavilov theory.
- Results show good agreement between Monte Carlo and data.
- These results are included in the ProtoDUNE-SP upcoming paper “First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform”, which is currently on the arXiv (arXiv:2007.06722).




Calibrated dE/dx for stopping muons and stopping protons.

# Backup Slides

# Detector Basics




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

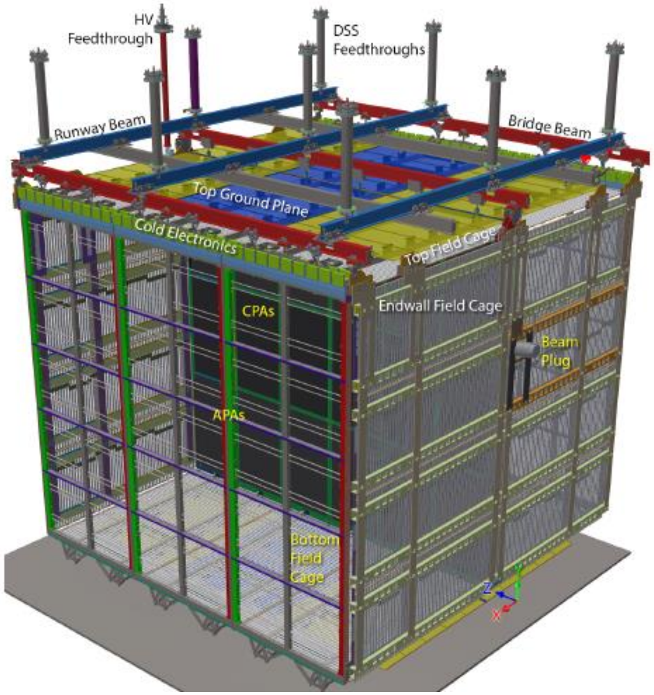
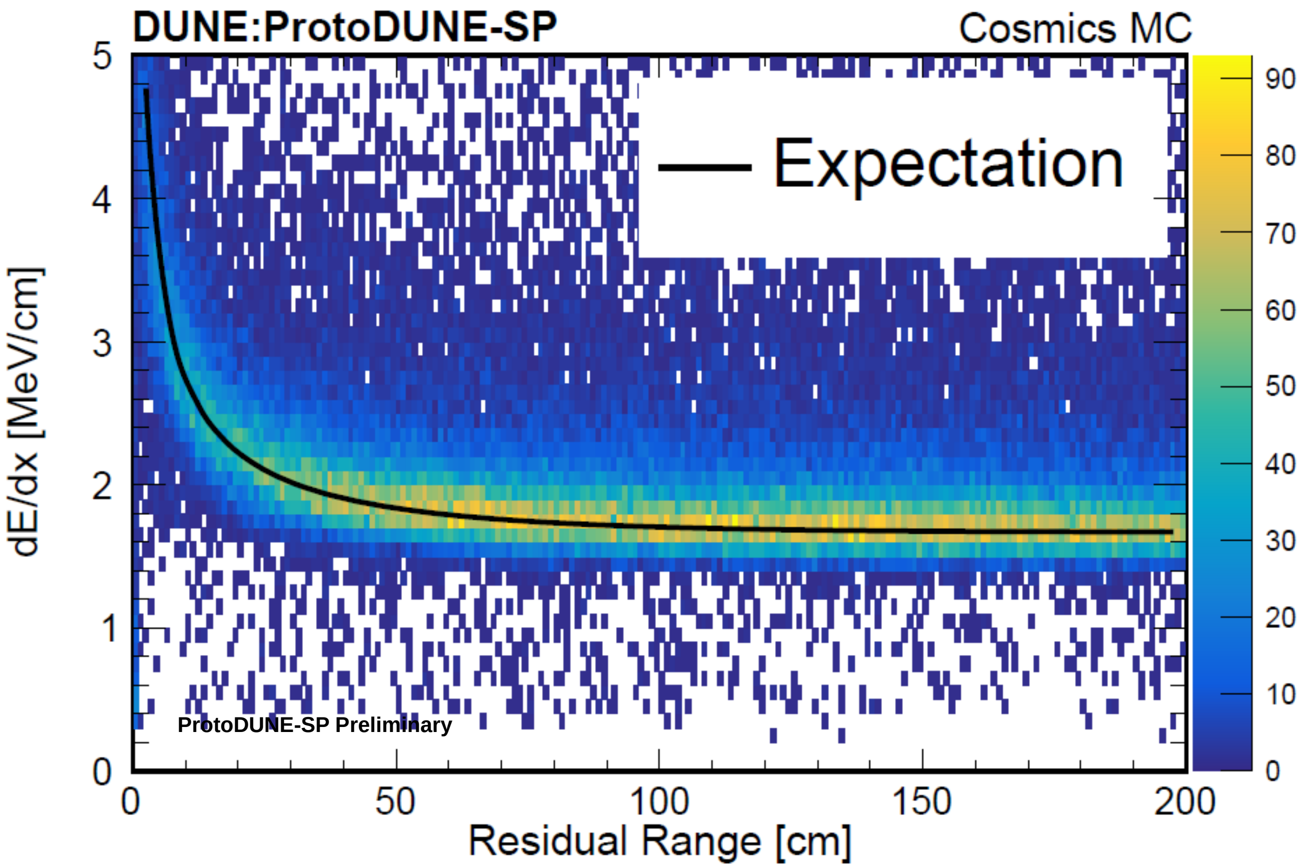



Diagram of the ProtoDUNE-SP detector. The $2^{nd}$ set of APAs is on the other wall of the detector.

[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

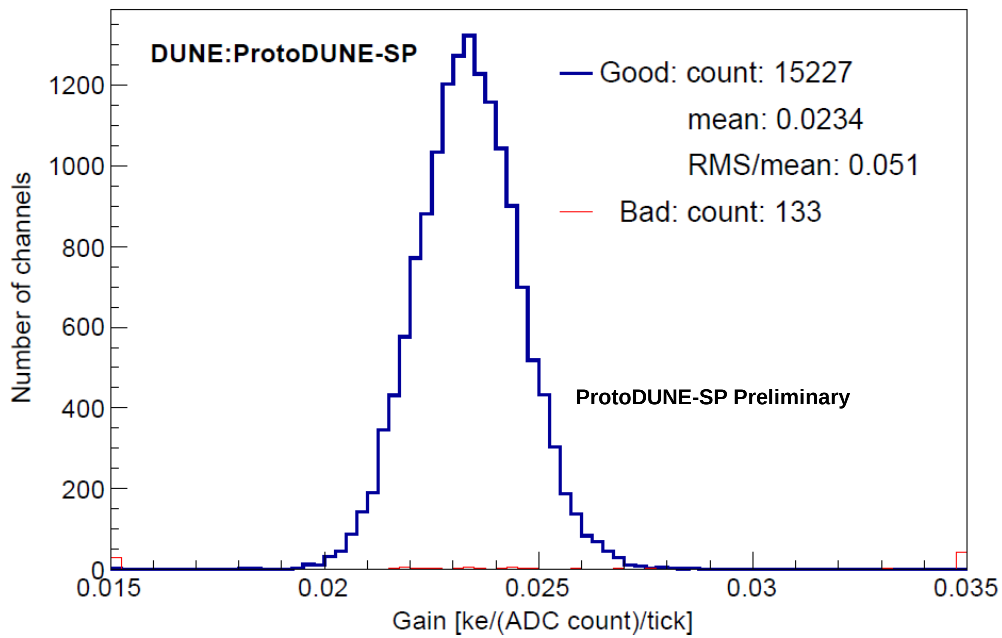
Purity Measured in MC: 99.74%
$C_{cal}$=(5.03±0.01)*$10^{-3}$ ADCxtick/e




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

# ADC Calibration

- Uncertainties for the ADC gain measurement using a pulser that are estimated at the few percent level.
- However, the measurement of dE/dx for cosmic muons is known to about 1%; therefore, we prefer to use the dE/dx to calibrate the gain.




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