Charge response and energy calibration of ProtoDUNE-SP

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Introduction

ProtoDUNE-SP is a test bed liquid argon time projection chamber (LArTPC) for the far detector of the Deep Underground Neutrino Experiment (DUNE). This LArTPC was calibrated using cosmic-ray cathode-crossing muons, electric field maps, and purity-monitor data to correct for nonuniformities in the detector response. Cosmic-ray stopping muons are used to perform the absolute energy scale calibration for further physics analysis.

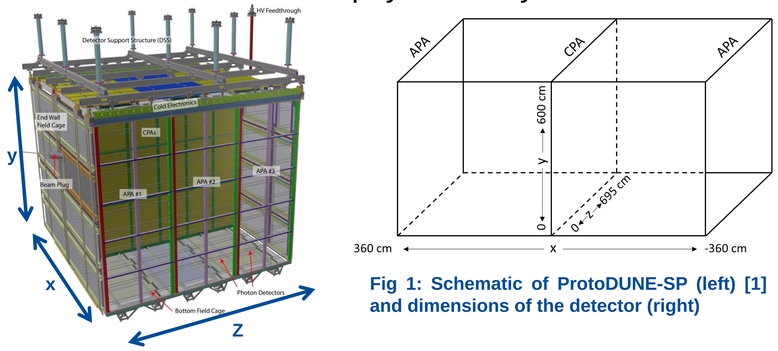
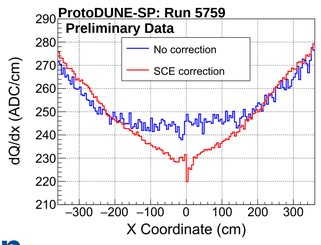


Fig 1: Schematic of ProtoDUNE-SP (left) [1] and dimensions of the detector (right)

Space Charge Effects

Fig 2: Charge deposition per unit length (*dQ/dx*) vs *x* coordinate with and without space charge effect (SCE) corrections applied in plane 2. Cosmic rays passing through the detector cause the accumulation of positive ions, leading to distortions in the electric field in the LArTPC. The SCE is corrected for using measured electric field maps.



Electron Lifetime Correction

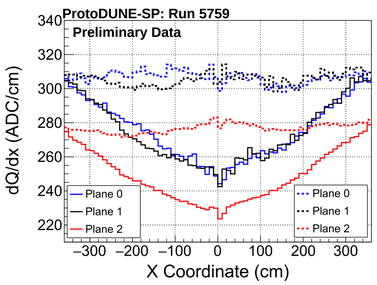


Fig 3: *dQ/dx* vs *x* coordinate without (solid) and with (dashed) an electron lifetime correction of 10.9747 ms. Electron lifetime measurements are based on purity-monitor data.

Reduced charge model:

$$Q(t) = Q_0 \exp(-(t_{\text{hit}} - t_0)/\tau)$$

$Q(t)$ is charge measured on wire, Q_0 is initial charge from ionization of argon, t_{hit} is time charge arrived at the APA, t_0 is time ionization occurred, and τ is drift electron lifetime.

YZ, X, and Normalization Corrections

- **Divide two volumes into 5x5 cm² bins for *yz* plane and 5 cm bins for *x* coordinate**
- **Correction factors calculated using global *dQ/dx* (median value across *x* coordinate or *yz* plane) and local *dQ/dx* (median value in bin)**
- **Normalization using median *dQ/dx* at anode and global *dQ/dx***

YZ correction factor:

$$C(y,z) = \frac{(dQ/dx)^{\text{global}}_{\text{YZ}}}{(dQ/dx)^{\text{local}}_{\text{YZ}}}$$

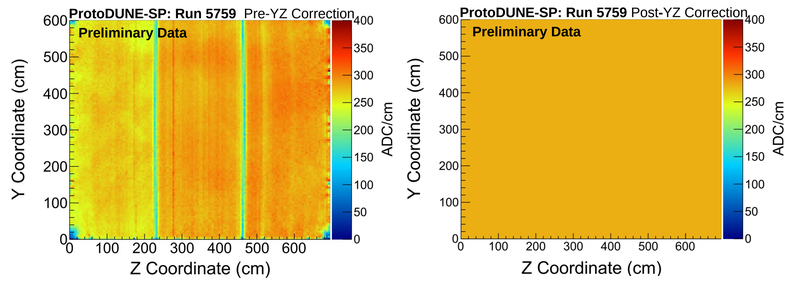
X correction factor:

$$C(x) = \frac{(dQ/dx)^{\text{global}}_{\text{x}}}{(dQ/dx)^{\text{local}}_{\text{x}}}$$

Normalization factor:

$$N_Q = \frac{(dQ/dx)^{\text{anode}}}{(dQ/dx)^{\text{global}}}$$

$$(dQ/dx)_{\text{calibrated}} = N_Q C(y,z) C(x) (dQ/dx)_{\text{reconstructed}}$$



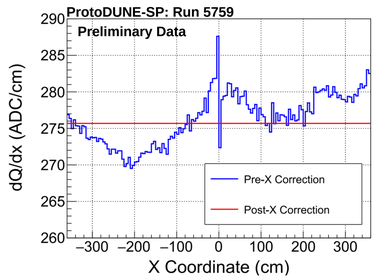


Fig 4: *dQ/dx* distribution in plane 2 for x < 0 before *yz* correction (top left) and after *yz* correction (top right). Corrections were performed in both drift volumes (x < 0 and x > 0).

Fig 5: *dQ/dx* vs *x* coordinate (left) after *yz* corrections for plane 2 comparing before and after *x* correction.

Charge Distributions

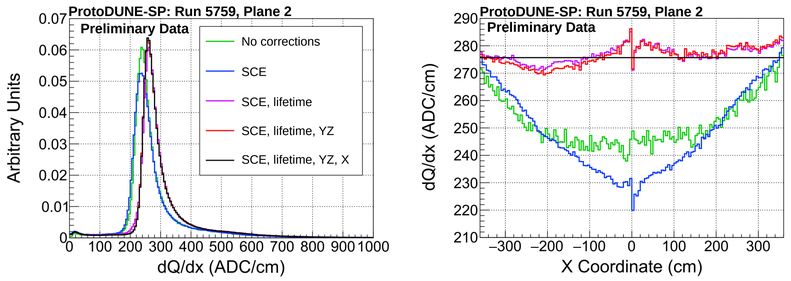


Fig 6: *dQ/dx* vs *x* (right) and *dQ/dx* distribution (left) of cathode-crossing muons comparing no corrections, SCE correction, SCE/lifetime corrections, SCE/lifetime/YZ corrections, and SCE/lifetime/YZ/X corrections.

Absolute Energy Calibration

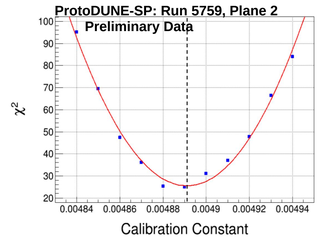
Modified Box Model:

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

C_{cal} = Constant used to convert ADC values to number of electrons,
W_{ion} = 23.6 x 10^{-6} MeV/electron (work function of argon),
$\mathcal{E}$ = ProtoDUNE-SP E field based on the space charge maps,
ρ = 1.38 g/cm³ (liquid argon density at a pressure of 105 kPa)
β' = 0.212 (kV/cm)(g/cm²)/MeV, and
α = 0.93.

The calibrated *dQ/dx* values of stopping muons are used in the Modified Box Model [2] to fit the *dE/dx* values.

Calibration Constants (10^{-3} ADC/electron)			
Plane	Run 5759	Run 5770	Run 5841
0	5.353±0.0065	5.325±0.0063	5.411±0.0062
1	5.328±0.0062	5.261±0.0057	5.403±0.0061
2	4.891±0.0063	4.828±0.0054	4.855±0.0071



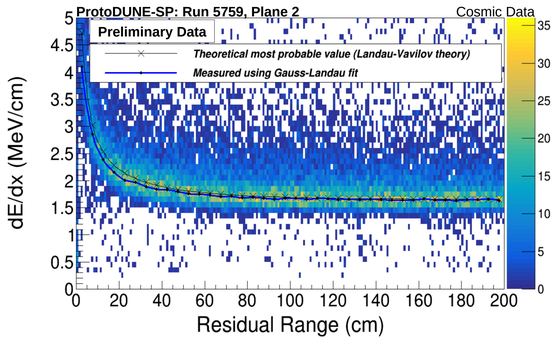


Fig 7: χ^2 vs calibration constant (above).

Fig 8: *dE/dx* vs residual range of stopping muons (left).

Conclusions

SCE, lifetime corrections, YZ corrections, X corrections, and normalization factors were applied to runs 5759, 5770, and 5841. Calibration constants were determined to convert *dQ/dx* to *dE/dx* for the absolute energy scale. These calibration factors were uploaded to a database for use in further physics analysis.

References

[1] B. Abi, et Al., "The Single-Phase ProtoDUNE Technical Design Report" arXiv:1706.07081, 2020.
[2] R. Acciarri et Al., "A Study of Electron Recombination Using Highly Ionizing Particles in the ArgoNeuT Liquid Argon TPC" arXiv:1306.1712, 2013.
[3] A. Paudel. "Charge and energy calibration of the ProtoDUNE-SP detector using cosmic muons" APS April Meeting 2020.
[4] A. Paudel. "dQdx and dEdx Calibration Instructions" DUNE Wiki Page, 2020.

Acknowledgements

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