PROCEEDINGS OF SCIENCE

Energy calibration of the ProtoDUNE-SP TPC

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The single-phase liquid argon prototype at CERN (ProtoDUNE-SP) acts as a validation of the design for the DUNE single-phase far detector. With a total mass of 770 tons, it is the largest monolithic liquid argon single-phase time projection chamber in the world. ProtoDUNE-SP collected test-beam in autumn of 2018 and has been collecting cosmic and special calibration data since the end of 2018. To analyze data from the test-beam, a calibration plan using cosmic muons passing through the detector was developed. An outline of this plan and its impact on the calorimetric measurements of the detector will be discussed.

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1. Introduction

ProtoDUNE Single-Phase (ProtoDUNE-SP) is a surface-level 770-ton single-phase liquid argon time projection chamber (TPC) at the CERN Neutrino Platform. The detector serves as a prototype for the single-phase DUNE Far Detector module design and sits under a charged particle test-beam from the CERN Super Proton Synchotron.

Currently, ProtoDUNE-SP is analyzing charged particle test-beam events to better understand reconstruction and liquid argon-hadron cross sections for the DUNE neutrino program. Detector effects need to be compensated for to fix distortions and attenuation of TPC signals. ProtoDUNE-SP utilizes the large flux of cosmic-ray muons that bombard the ProtoDUNE-SP detector as a sample of tracks to correct for these effects. The following discussion will talk about how ProtoDUNE-SP measures energy deposits in the detector and how the detector calibration is implemented to ensure precision calorimetric measurements of charged particles.

2. Calorimetry Measurements in ProtoDUNE-SP

ProtoDUNE-SP uses the signal size from charged particles ionizing the liquid argon to determine the energy deposited from wire-to-wire. Measuring dE/dx is accomplished using the modified Box model in ProtoDUNE-SP, shown in Equation 1 [1].

$$\mathrm{dE/dx} = \frac{\rho\mathscr{E}}{\beta'}\left(\exp\left(\frac{\beta' \mathrm{W_{ion}}(\frac{\mathrm{dQ}}{\mathrm{dx}})_{\mathrm{calibrated}}}{\rho\mathscr{E}\mathrm{C_{cal}}}\right) - \alpha\right) \tag{1}$$

where

$\mathrm{C_{cal}}$ = Gain constant for converting analog-to-digital converter (ADC) values to number of electrons,
$\mathrm{W_{ion}}$ = 23.6×10^{-6} MeV/electron (Work function of liquid argon),
$\mathscr{E}$ = Electric field,
ρ = 1.38 g/cm (Density of liquid argon at 124.106 kPa),
α = 0.93 (recombination factor), and
β' = 0.212 (kV/cm)(g/cm^2)/MeV (recombination factor) [1].

In Equation 1, the electric field at the location of the energy deposit ($\mathscr{E}$), the total charge deposition per unit length ($\mathrm{dQ/dx_{calibrated}}$), and gain value converting a TPC hit's ADC integral to units of ionized electrons ($\mathrm{C_{cal}}$) come from measurements made within the ProtoDUNE-SP TPC. The rest of the variables are coming from external measurements, such as the recombination factors α and β' measured by ArgoNeut [1]. The subsequent sections explain how ProtoDUNE-SP arrives at a measured electric field, calibrated dQ/dx, and gain calibration constant to quantify the dE/dx in the TPC.

3. Correcting for the Space Charge Effect

Complicating the challenge of measuring the electric field, ProtoDUNE-SP sits on the surface with no overburden. Therefore, it receives an immense flux of cosmic muons. These cosmic muons

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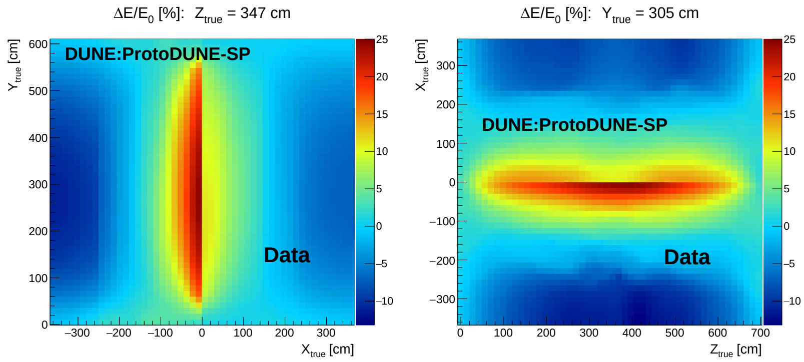

Figure 1: Electric field distortion maps as seen through a slice in XY of the detector (left) and XZ of the detector (right) [2].

create a build-up of positive argon ions, as the cosmic muons zip through the detector and ionize the argon. The positive ions distort the electric field of the TPC's drift, which causes discrepancies between the true position and deposited energy and the reconstructed position and deposited energy. This effect, known as the space charge effect (SCE), requires calibration of the whole detector to offset these electric field fluctuations that lead to calorimetric and tracking distortions.

Currently, ProtoDUNE-SP uses samples of cosmic tracks that cross the central Cathode Plane Assembly (CPA) as they have well-defined measurements of the time they crossed the detector (t_0). The precise t_0 comes from the fact that they existed in both of ProtoDUNE-SP's drift volumes allowing reconstruction to stitch them together and find a known drift time. To measure the space charge effect, the offset between the cosmic muon track's endpoints at the edge of the TPC and the TPC's true edges are evaluated and compared to the simulation of the space charge effect. The maps of electric field and positional offsets are then made from these measured offsets by scaling the simulated map of electric field and positional offsets of ProtoDUNE-SP based on the ratio of measured offsets between data and simulation. Figure 1 shows the electric field distortions at specific locations in the detector. The precise electric field of a TPC hit is then quantified by modulating the nominal electric field value by the electric field offset measured at the location of the liquid argon ionization.

4. dQ/dx Calibration and C_{cal} Measurements

The dQ/dx calibration focuses on ensuring that distributions of calibrated dQ/dx have minimal variations as a function of position in the detector. Cosmic muons that pass the CPA are used due to their defined position across the drift distance due to their known t_0. Some of these muons, however, are discarded if they have reconstruction irregularities or have angles relative to the TPC's readout wires that could complicate the measurement of dQ/dx. Figure 2 shows the distribution of CPA-crossing cosmic muons as a function of track angle.

The first step of calibration done to these tracks comes actually from the space charge effect calibration. During reconstruction, these tracks have the step size (dx) from hit to hit corrected for the squeezing and stretching that could happen due to positional reconstruction offsets from the space charge effect. The next step involves correcting for distortions as a function of the TPC's

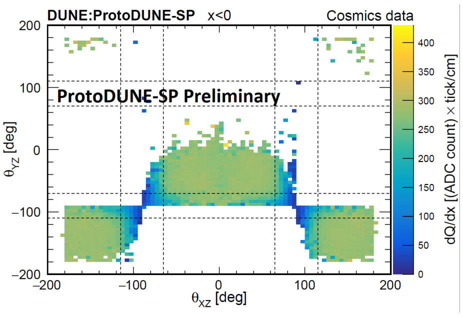

Figure 2: Distribution of track angles for muons that cross the CPA for the beam-side drift volume.

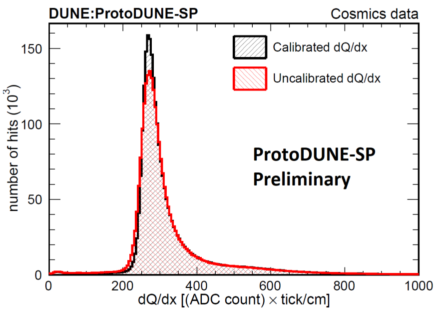

Figure 3: Histogram of the dQ/dx before and after calibration steps outlined in Equation 5.

vertical (Y) and longitudinal (Z) positions using Equation 2. After flattening dQ/dx distributions as a function of YZ, the dQ/dx fluctuations as a function of drift distance of the TPC (X) undergo calibration expressed in Equation 3. This step is done with YZ-corrections applied and calibrates offsets as a function of drift distance, which results from effects such as drift electron attenuation from impurities and longitudinal diffusion. The final portion of dQ/dx calibration normalizes the behavior between ProtoDUNE-SP's two drift volumes by altering the dQ/dx through a ratio seen in Equation 4. To calibrate a single hit, all dQ/dx corrections are multiplied together as seen in Equation 5 [2].

$$C(Y,Z) = \frac{(dQ/dx)^{global}_{YZ}}{(dQ/dx)^{local}_{YZ}} \tag{2}$$

$$C(X) = \frac{(dQ/dx)^{global}_{X}}{(dQ/dx)^{local}_{X}} \tag{3}$$

$$N_Q = \frac{(dQ/dx)_{anode}}{(dQ/dx)_{global}} \tag{4}$$

$$\frac{dQ}{dx}_{calibrated} = \frac{dQ}{dx}_{sce\ corrected} C(Y,Z)C(X)N_Q \tag{5}$$

By multiplying these factors to $\frac{dQ}{dx}_{sce\ corrected}$, the distribution of $\frac{dQ}{dx}$ narrows when compared to the uncalibrated sample in Figure 3, showing improvements of using this calibration scheme in TPC calorimetry.

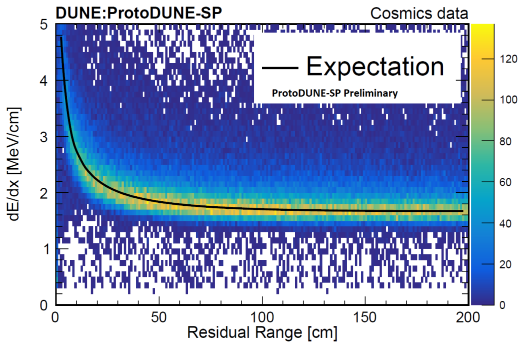

Figure 4: dE/dx for stopping cosmic muons for a data run taken in early November 2018.

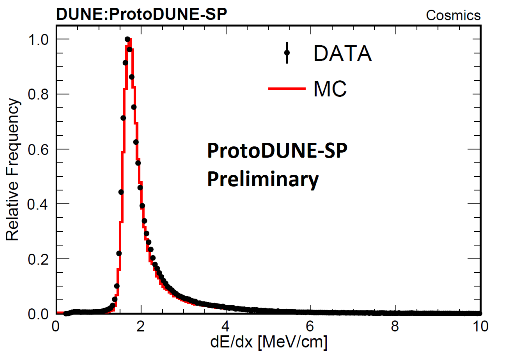

Figure 5: Comparison between calibrated simulation and data dE/dx of cosmic muons.

To measure the final calibration parameter, C_{cal}, ProtoDUNE-SP measures the dE/dx of stopping cosmic muons that cross the CPA at high residual range between 120-200 cm. The dE/dx values at these residual ranges is then compared to the Landau-Vavilov theory expectation of dE/dx at that residual range and, from these comparisons, the gain is evaluated in units of the ADC hit integral per ionized electron (ADCxtime tick/e^-) [3]. As an example, Figure 4 shows the dE/dx of cosmic muons in data as a function of residual range with the C_{cal} for that data run being measured as $(5.4 \pm 0.1) * 10^{-3}$ ADCxtime tick/e^-. Data and simulation were both calibrated using the method described and Figure 5 reveals the agreement of dE/dx of cosmic muons between data and simulation [2].

5. Evaluating dE/dx Calibration

With the TPC having calibrated dQ/dx measurements, measured the gain constant, and quantified the electric field throughout the detector, the dE/dx has been calibrated and can be used for particle identification and calorimetry. Stopping protons and muons were selected to test the ability of the dE/dx calibration to identify particles. A likelihood function (ζ) was employed to discern protons from muons using a stopping proton hypothesis in Equation 6, whereby j represents the j-th TPC hit before the last 26 cm of the track, n_T is the total number of collection plane hits for the last 26 cm of the track, and $\sigma(\frac{dE}{dx})_j$ is the width of the j-th dE/dx measurement. Figure 6 reveals

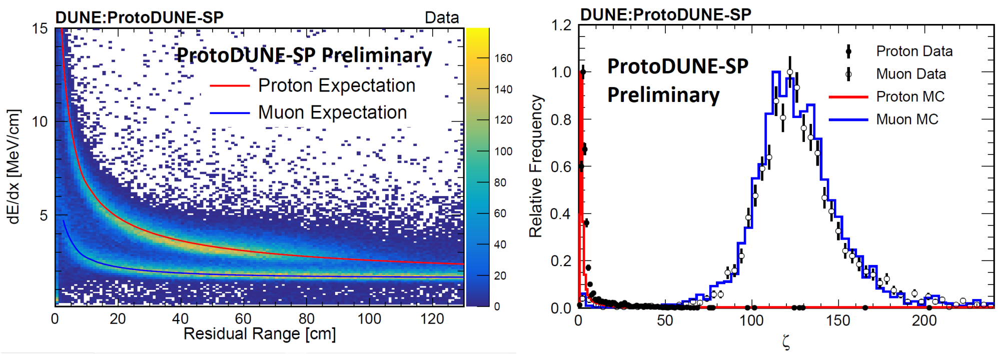

Figure 6: dE/dx Bragg peaks of muon and proton candidates compared to expectation (left) and a histogram of the likelihood parameter ζ (right).

that using the likelihood test on candidate particles leads to a clear separation between muon and proton candidates that could be implemented in analyses as a way to separate muons from protons [2]. Ultimately, this separation validates the dE/dx calibration and its ability to show two distinct Bragg peaks of two different particles, which is shown in Figure 6.

$$\zeta = \frac{1}{n_{\mathrm{T}}} \sum_j \frac{\left[(\frac{dE}{dx})_{j,\mathrm{data}} - (\frac{dE}{dx})_{j,\mathrm{mc\ proton}} \right]^2}{\sqrt{\left[\sigma(\frac{dE}{dx})_{j,\mathrm{data}} \right]^2 + \left[\sigma(\frac{dE}{dx})_{j,\mathrm{mc\ proton}} \right]^2}} \tag{6}$$

6. Conclusion

Liquid argon TPCs enable precision tracking and calorimetry. However, it requires a calibration scheme to offset detector effects like the space charge effect or drift electron attenuation from impurities. The ProtoDUNE-SP detector undergoes calibration through a set of sequential steps that includes quantifying the electric field, eliminating distortions in dQ/dx as a function of TPC location, and measuring the gain to convert from ADC hit integral to units of ionized electrons. Thanks to these calibrations, the dE/dx measurements on a track can be precisely calibrated and used for particle identification as seen in Figure 6.

References

[1] ArgoNeuT collaboration, R. Acciarri et al., *A Study of Electron Recombination Using Highly Ionizing Particles in the ArgoNeuT Liquid Argon TPC*, *JINST* **08** (2013), P08005, [1907.11736].

[2] DUNE collaboration, B. Abi et al., *First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform*, 2007.06722.

[3] 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.