Charge and energy calibration of the ProtoDUNE-SP detector using cosmic ray muons

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Cosmic ray muon based calibration is done in two steps:

- Charge \((dQ/dx)\) Calibration
- Energy \((dE/dx)\) Calibration
Charge Calibration

The charge deposition per unit length in a LArTPC (dQ/dx) is affected by several factors including:

- **Space-Charge Effect (SCE):** Which causes non-uniformity in Efield due to the accumulation of slowly moving positive ions in the detector.

- **Recombination Effect:** Some ionized electrons recombine with parent Ar2+ or is absorbed by other Ar2+ as it drifts towards the anode, thus affecting the measured dQ/dx values.

- **Electron attenuation:** Electronegative impurities such as O2 and H2O absorb drifting free electrons causing attenuation in the measured dQ/dx values.

- **Diffusion:** Smearing of charge along the drift direction and in direction transverse to drift direction.

Some of the effects causing non-uniform dQ/dx e.g., SCE and electronics gain variation are calibrated out using dedicated calibrations. The remaining non-uniformity is calibrated using the detector response for the energetic through-going cosmic muons as a data-driven correction, following the same method developed by the MicroBooNE collaboration*.

* https://arxiv.org/abs/1907.11736
Charge Calibration track selection:

- **Fiducial volume requirements:** FV1 = a rectangular prism with boundaries from anodes is 10cm, boundaries from top and bottom is 40cm and boundaries from upstream and downstream is 40cm. We require both track ends to be outside FV1.

- **Angular requirements:** The reconstruction capability of LArTPCs is limited for tracks that are parallel to the wire plane or contained in a plane containing a wire and the electric field direction. We remove tracks with $65 \text{ deg} < |\theta_{xz}| < 115 \text{ deg}$ and $70 \text{ deg} < |\theta_{yz}| < 110 \text{ deg}$.

Fig: Definition of $\theta_{xz}$ and $\theta_{yz}$

Fig: Mean $dQ/dx$ distribution as a function of track angles $\theta_{xz}$ and $\theta_{yz}$. Tracks within the dotted region are removed.
Charge calibration is carried out in two steps:

1. **YZ calibration**: $dQ/dx$ values in the $yz$ plane are affected by many factors including non-uniform wire response caused by nearby dead channels or disconnected wires, detector features such as the electron diverters and the wire support combs, and transverse diffusion.

We divide the $yz$ plane for $x>0$ and $x<0$ into several $5 \times 5 \text{ cm}^2$ bins. The median $dQ/dx$ value for each bin is denoted by $(dQ/dx)_{\text{local}YZ}$. Further, the median $dQ/dx$ value is calculated considering the hits throughout a drift volume (global median) which is denoted $(dQ/dx)_{\text{global}YZ}$. The YZ correction factor is then defined as

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

![Fig: Median $dQ/dx$ distribution for YZ plane for $x>0$ drift volume, left plot and $x<0$ drift volume, right plot](image-url)
The dQ/dx values along the drift direction are affected by factors including attenuation due to electronegative impurities and longitudinal diffusion. We divide drift distance into 5cm bins. The dQ/dx values are first corrected using YZ correction factors based on the y and z coordinates of the hit:

\[(dQ/dx)_{localX} = \text{median } dQ/dx \text{ for a bin.} \quad (dQ/dx)_{globalX} = \text{median } dQ/dx \text{ for the entire TPC}\]

**X correction factor,** \(C(x) = (dQ/dx)_{globalX} / (dQ/dx)_{localX}\)

The corrected dQ/dx values are then normalised to the dQ/dx at the anode \((dQ/dx)_{anode}\),

**normalization constant,** \(N = (dQ/dx)_{anode} / (dQ/dx)_{globalX}\)

\[(dQ/dx)_{corrected} = N \cdot C(x) \cdot C(y,z) \cdot (dQ/dx)_{reconstructed}\]

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**Fig:** dQ/dx distribution vs drift coordinate

**Fig:** dQ/dx before and after charge calibration
Energy Calibration

In the energy calibration we determine the calibration constant to convert ADC counts to the number of electrons. We use stopping muons for energy calibration.

Stopping muon Selection:

- **Fiducial Volume requirement:** Define FV2 = a rectangular prism with boundaries from anodes is 30cm, boundaries from top and bottom is 50cm and boundaries from upstream and downstream is 50cm. We require tracks to start outside FV1 and end inside FV2.

- **Angular Cuts:** We remove tracks with $65 \text{ deg} < |\theta_{xz}| < 115 \text{ deg}$ and $70 \text{ deg} < |\theta_{yz}| < 110 \text{ deg}$.

- **Removing broken tracks:** Some muons are reconstructed as two or more tracks, which mimic a stopping muon. If the end points of the two tracks is within 30 cm and the angle between them is less than 14 deg, both the tracks are removed.

- **Removing tracks with early and late hits:** Tracks that are cut off by the 6000-tick TPC readout window boundaries may mimic a stopping muon. If any hit associated with a track has a peak time less than 250 ticks or greater than 5900 ticks, the track is removed.
The most probable dE/dx value as a function of residual range for stopping muon tracks in LAr is accurately predicted by Landau-Vavilov* theory. From the calibrated dQ/dx values (in ADC/cm) along the muon track in its MIP region (120 to 200 cm from stopping point), the dE/dx (in MeV/cm) values are fitted using the Modified Box Model function with the charge calibration constant Ccal (ADC/cm → ADC/electron) as a free parameter in the χ2 minimization.

Modified Box Model**

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

where,

- \(C_{\text{cal}}\) = Calibration constant used to convert ADC values to number of electrons,
- \(W_{\text{ion}}\) = 23.6 x 10^-6 MeV/electron (the work function of argon),
- \(\epsilon\) = ProtoDUNE-SP E field based on the space charge maps,
- \(\rho\) = 1.38 g/cm^3 (liquid argon density at a pressure of 124.106 kPa),
- \(\beta'\) = 0.212 (kV/cm)(g/cm^2)/MeV, and
- \(\alpha\) = 0.93.

The last two parameters were measured by the ArgoNeuT experiment at an operational electric field strength of 0.481 kV/cm**.

Final, calibration factor \(C_{\text{cal}}=(5.395\pm0.0035)10^{-3}\) ADC/electron

Figure below shows χ2 vs Calibration factor(Ccal), based on the quadratic fit Calibration factor is the one corresponding to minimum χ2.

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*Particle Data Group

RESULTS: Plots below shows calibrated dE/dx vs prediction from Landau-Vavilov theory for stopping muons

Fig. dE/dx vs residual range, ProtoDUNE-SP data, left and ProtoDUNE-SP simulation, right

Fig aside shows calibrated dE/dx for stopping muons
SUMMARY:

• Cosmic ray muons has been used as a reliable calibration source for ProtoDUNE-SP detector.

• Monte-Carlo simulation agrees well with data.
Backup Slides
Liquid Argon Time Projection Chamber (LArTPC)

- Incident particle produces ionization electrons and scintillation light.
- Strong Electric field drifts the electrons towards anode, signals are visible on 3 wire planes. PMTs collect scintillation light giving timing information.
- Using charge and light information 3D trajectories are reconstructed.
- And using the charge information particle energy can be reconstructed.