Calibration of the ProtoDUNE-SP detector using cosmic muons

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Overview

- ProtoDUNE-SP data charge and energy calibration
  - Corrections for space charge effects (SCE) and electron lifetime corrections
- Analysis follows calibration technique developed by Ajib Paudel and Tingjun Yang using Ajib’s calibration code
- Examined $\frac{dQ}{dx}$ distribution with and without lifetime corrections
- Determined calibration constants ($\frac{dE}{dx}$) for ProtoDUNE-SP data (run 5759, 5770, and 5841)

Calibration code by Ajib Paudel:
https://wiki.dunescience.org/wiki/DQdx_and_dEdx_calibration_instructions
Detector Calibration Corrections

• **Space Charge Effects**
  – Electric field distortion due to ions
  – Distortion alters particle reconstruction
  – Space charge effects removed based on electric field map measured from cosmic muons

• **Electron Lifetime Corrections**
  – Ionized electrons captured by impurities (H$_2$O and O$_2$) and Ar$^{2+}$
  – Corrections make detector response ($\frac{dQ}{dx}$) uniform
  – Measured electron lifetime from purity monitor data and recorded in the ProtoDUNE-SP calibration database

ProtoDUNE-SP Calibration Database:
https://wiki.dunescience.org/wiki/ProtoDUNE-SP_Calibration_Database
Crossing Muon Selection

- Track must pass through cathode plane array
- Track must start and end 10 cm from anodes, 50 cm from top or bottom, or 50 cm from sides
- **Plane 2:**
  - Remove tracks with $60^\circ < |\theta_{xz}| < 120^\circ$ or $|\theta_{xz}| < 10^\circ$ or $80^\circ < |\theta_{yz}| < 100^\circ$
- **Plane 1:**
  - If x position is between -360 and 0 cm, remove tracks with $|\theta_{xz}| < 130^\circ$ or $80^\circ < |\theta_{yz}| < 100^\circ$
  - If x position is between 0 and 360 cm, remove tracks with $|\theta_{xz}| > 40^\circ$ or $80^\circ < |\theta_{yz}| < 100^\circ$
- **Plane 0:**
  - If x position is between -360 and 0 cm, remove tracks with $|\theta_{xz}| > 40^\circ$ or $80^\circ < |\theta_{yz}| < 100^\circ$
  - If x position is between 0 and 360 cm, remove tracks with $|\theta_{xz}| < 130^\circ$ or $80^\circ < |\theta_{yz}| < 100^\circ$
Stopping Muon Selection

- **Angles:** removed $65° < |\Theta_{xz}| < 115°$ and $70° < |\Theta_{yz}| < 110°$
- **Early/late hits:** removed tracks with peak time $< 250$ ticks and peak time $> 5900$ ticks
- **Track length:** removed tracks with length $< 100$ cm or $> 700$ cm
- **Position:** removed tracks with start or end $z$ coordinate between 226 and 236 cm or $z$ coordinate between 456 and 472 cm

Angular cuts and early/late hits changed from Ajib’s code to match selection from https://indico.fnal.gov/event/23989/contributions/74784/attachments/46641/56015/APS_April_meeting_2020.pdf

Figures showing geometry of ProtoDUNE-SP detector and definitions of $\theta_{xz}$ and $\theta_{yz}$
Figures of $\frac{dQ}{dx}$ as a function of $x$ without lifetime correction (top row) and with lifetime correction (bottom row) for runs 5759 (left), 5770 (middle), and 5841 (right)
Calibration Constants

Modified Box Model:

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

where,

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

Minimum calibration constant (10^{-3} ADC/electron)

<table>
<thead>
<tr>
<th>Plane</th>
<th>Run 5759</th>
<th>Run 5770</th>
<th>Run 5841</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5.414±0.0064</td>
<td>5.375±0.0061</td>
<td>5.516±0.0064</td>
</tr>
<tr>
<td>1</td>
<td>5.387±0.0065</td>
<td>5.345±0.0061</td>
<td>5.517±0.0063</td>
</tr>
<tr>
<td>2</td>
<td>4.935±0.0068</td>
<td>4.884±0.0053</td>
<td>5.033±0.0076</td>
</tr>
</tbody>
</table>

Uncertainty of \( C_{\text{cal}} \) is given by \( \Delta \chi^2 = \chi^2 - \chi^2_{\text{Min}} = 1 \)

\[ \text{arxiv 1907.11736} \]
Absolute Energy Calibration

Run 5759 dE/dx vs Residual Range

Figures of $\frac{dE}{dx}$ as a function of residual range of stopping muons as predicted by Landau-Vavilov theory from collection planes. *Left: run 5759, top: run 5770, bottom: run 5841*
Summary

• Applied lifetime corrections
  – $\frac{dQ}{dx}$ distribution is relatively flat after correction

• Determined calibration constants
  – Constants for runs 5759 and 5770 are consistent with each other

• Absolute energy calibration
  – Theoretical $\frac{dE}{dx}$ vs residual range fits well with data
Backup