Energy reconstruction and calibration of the MicroBooNE LArTPC

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MicroBooNE

- Operated from 2015 to 2021
- 85 active tonne liquid argon TPC with three wire planes

An installed MicroBooNE detector covered in insulating foam (left) and a picture of the MicroBooNE wire readout planes (right).

R. Acciarri et al 2017 JINST 12 P02017
Motivation

- Approximately 500 meters from the Booster Neutrino Beam (BNB).
- Energy range of neutrino interactions in detector typically between 0.2-2.5 GeV.
- Intended to:
  - Develop LAr detector R&D.
  - Measure neutrino cross sections on argon.
  - Search for an excess of low-energy neutrinos with electromagnetic showers (MiniBooNE anomaly).

Event display from data with an EM shower


Muon neutrino charged current inclusive cross section published by MicroBooNE (Phys. Rev. Lett. 123, 131801). These distributions were published in 2019, before many of the results included in this presentation.
Liquid Argon TPC

- Uses wire-based readout with three wire planes (U, V, Y).
  - U and V planes are 60 degrees rotated relative to Y plane.
  - Operates at 273 V/cm

- Coordinate system has:
  - x-coordinate as the drift direction
  - y-coordinate as the height
  - z-coordinate as the length of the detector
Signal processing: Waveforms for Charge Extraction

- U and V wire planes measure ionized electrons through induction as they move towards and away from the wires (bipolar).
- Y wire plane measures via collection (unipolar).
- Signal processing uses noise filtering and 2D deconvolution to go from raw to deconvolved waveforms. Hits formed from deconvolved waveforms.

Event display of candidate neutrino event from data through each stage of signal processing.

Data and simulation comparisons of the waveforms for each plane.

C. Adams et al 2018 JINST 13 P07006
C. Adams et al 2018 JINST 13 P07007
Calibration of $dQ/dx$

Hit-by-hit calorimetry is one method of many used by MicroBooNE.
• Starts with hit $dQ/dx$, the ionization per unit length (e/cm) collected.
• Use cosmic ray muons as calib. sample.
• Calib. process has four steps:
  1. Apply corrections for non-uniformities in the electric field \((JINST\ 15\ P12037)\).
  2. Calibrate $dQ/dx$ as a function of YZ.
  3. Calibrate $dQ/dx$ as a function of drift distance.
  4. Normalize the event $dQ/dx$ to a global median.
Each step is applied to the proceeding step.

d$Q$/d$x$ as a function of YZ (height, length) for the collection plane

Measured correction to the global median, higher correction factor corresponds to lower liquid argon purity.

C. Adams et al 2020 JINST 15 P03022
Calibration of dE/dx

- Step converts ADC/cm -> e/cm -> MeV/cm.
- Calculate dE/dx with the modified Box model for recombination (see bottom left).
- Use hits from stopping cosmic muons at high residual range (MIP range, see bottom plot).
- Calibrate dE/dx by measuring $C_{\text{cal}}$ by fitting values to the predicted dE/dx based on the residual range.

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

$W_{\text{CM}} = 23.6 \times 10^{-6}$ MeV/electron (work function of argon),
$E = 0.273$ kV/cm (MicroBooNE drift electric field),
$\rho = 1.38$ g/cm$^3$ (liquid argon density at a pressure 124.106 kPa),
$\beta' = 0.212$ (kV/cm)(g/cm$^3$/MeV), and
$\alpha = 0.93$.

Modified Box model of dE/dx

Some analyses measure energy by range. Both methods, summing up hits and by range, agree within a small bias (top).

Stopping muon curve for data compared to prediction ($(4.113 \pm 0.011) \times 10^{-3}$ ADC/e, chi2/ndof~0.28). Blue shaded region is the high residual range considered.

C. Adams et al 2020 JINST 15 P03022
Effective Recombination Measurements

- Stopping protons used to measure recombination parameters and verify them.
- Compare the dQ/dx with the dE/dx obtained from the residual range of the stopping proton.
- Fit the distribution with modified Box model or the Birks model.
  - Extract effective recombination parameters from this fit.
  - Note: Not all uncertainties applied in reported fit uncertainties.

<table>
<thead>
<tr>
<th>Modified Box parameters</th>
<th>ArgonNeuT measurement (JINST 8 P08005)</th>
<th>MicroBooNE</th>
</tr>
</thead>
<tbody>
<tr>
<td>α</td>
<td>0.93 ± 0.02</td>
<td>0.92 ± 0.02</td>
</tr>
<tr>
<td>B' (kV/cm)(g/cm^2)/MeV</td>
<td>0.212 ± 0.002</td>
<td>0.184 ± 0.002</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Birks’ law parameters</th>
<th>ICARUS measurement (NIM A 523 (2004) 275)</th>
<th>MicroBooNE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_B</td>
<td>0.800 ± 0.003</td>
<td>0.816 ± 0.012</td>
</tr>
<tr>
<td>k (kV/cm)(g/cm^2)/MeV</td>
<td>0.0486 ± 0.0006</td>
<td>0.045 ± 0.001</td>
</tr>
</tbody>
</table>

Measurement of stopping protons parametrized with the two recombination models.

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Tool: Particle Identification Algorithm with Log-Likelihood Ratio

Problem: How to select proton tracks from muon tracks?

One method used by many analyses for muon/proton PID:

- Use calibrated calorimetry to make proton/muon discrimination.
- Build probabilities of each hit being a muon or proton based on simulation (see bottom).
- Compare the ratio of the probability between muons and protons (see right).

Distributions of muon and proton $dE/dx$ relative to residual range used to generate the likelihoods for each wire plane.

\[
L_{\text{plane}}(\text{type}|\text{plane}, \{dE/dx\}_{i=1,...,N}, \{rr\}_{i=1,...,N}, \{\text{local pitch}\}_{i=1,...,N})
\]

\[
= \prod_{i=1}^{N} L_{\text{hit}}(\text{type}|\text{plane}, dE/dx_i, rr_i, \text{local pitch}_i),
\]

\[
P = \frac{2}{\pi} \arctan(\log(T)/100)
\]

where $T$ is the log-likelihood ratio of muons to protons.

MicroBooNE 4.05 x $10^{19}$ POT

- DATA: Beam ON - Beam OFF
- cosmic
- muon
- pion
- proton
- photon

Problem: How to cluster deposits from a shower?
One method is to use a Kalman fitter (arXiv:2110.14065).

Another method used is to use SparseSSNet for shower clustering.
- Deep learning reconstruction identifies the shower(s) and clusters the hit.
  - Energy measured using calibrated hits.

Michel electron reconstruction using deep learning methods of stopped muons.
- Deep learning reconstruction identifies the shower(s) and clusters the hit.

Image of deep learning reconstruction (left).
Reconstruction using deep learning of the neutral pion reconstructed mass (right).
Conclusion

- MicroBooNE is an 85-tonne liquid argon TPC able to reconstruct wire hit-by-wire hit the calorimetry and tracking of tracks and showers.
- Signal processing and calorimetry calibration provide precision information to build dE/dx information that matches theory.
- MicroBooNE has developed tools to enable higher-lever reconstruction from muon/proton identification to shower reconstruction.

Backup
Uncertainties on dQ/dx and dE/dx Calibration

- Subdivides samples of cosmic rays used for dQ/dx calibration by track angle.
  - Compares the subsamples to the larger sample to determine the uncertainty from the deviations.
  - dE/dx calibration contains an uncertainty on the fit for the gain.

Deviations for data calibration in YZ (left) and X (right).
Detector Mismodeling Uncertainties

- Mismodeling of the detector can lead to different behavior in hits that can propagate to higher-level reconstruction (see slide 4 plot).
- Novel concept of modifying simulation waveforms based on ratios of hit reconstruction parameters as a function of position (X, Y, Z) and angle (XZ, YZ).
- Unisim samples for each of the five variables appears to cover simulation and data differences between data and simulation for pi0s (bottom right).

Hit charge and hit width ratios between simulation and data for the x-position (drift direction).
Stopping Proton and Stopping Muon $dE/dx$ as a function of residual range

C. Adams et al 2020 JINST 15 P03022
Space Charge Effect Calibration

- As a detector on the surface, cosmic ray muon flux is so high and ionizes so much argon that positive argon ions build in the detector and create field nonuniformities.
  - Known as the space charge effect.
  - Effect is most noticeable on edges (most noticeable for exiting tracks)
- MicroBooNE uses cosmic ray muons to create calibration maps (bottom diagram).
- UV laser corroborates results.

Methods of measuring the offsets on the TPC faces and inside the TPC using cosmic muons that pass the anode or cathode.