FERMILAB-SLIDES-22-025-V

Energy reconstruction and calibration of the MicroBooNE LArTPC

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CALOR 2022

May 16th, 2022

UNIVERSITÄT BERN

μBooNE

MicroBooNE

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

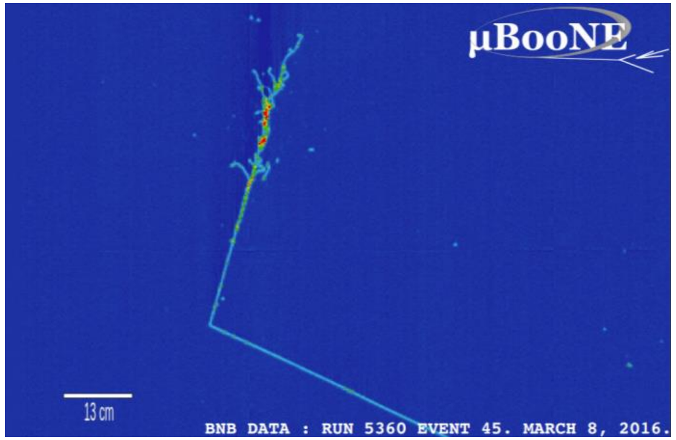
MicroBooNE cryostat without insulating foam.

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

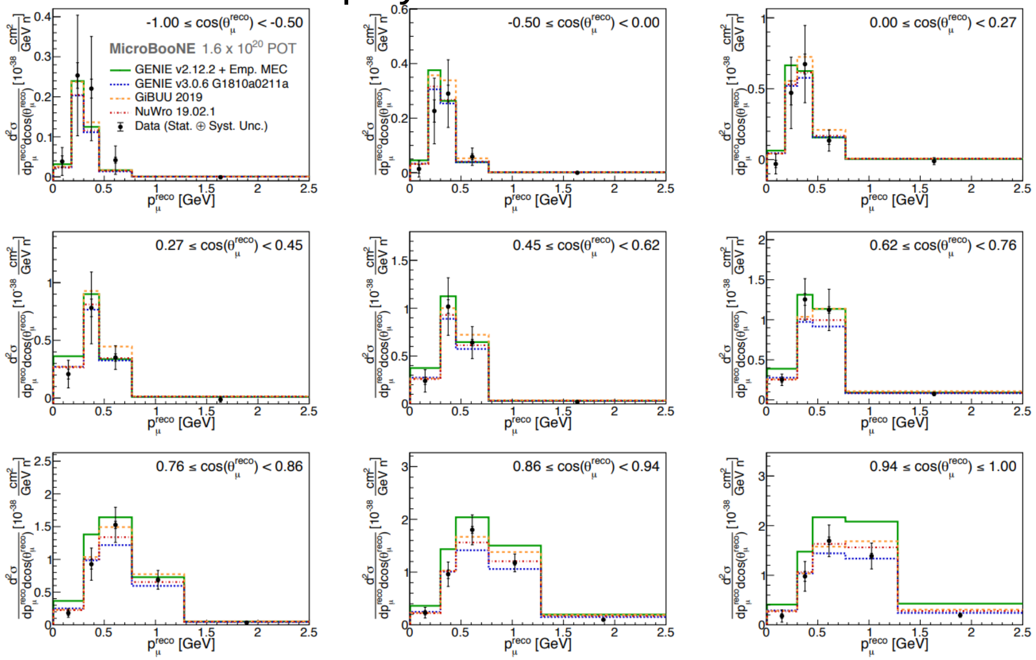
R. Acciarri *et al* 2017 *JINST* **12** P02017

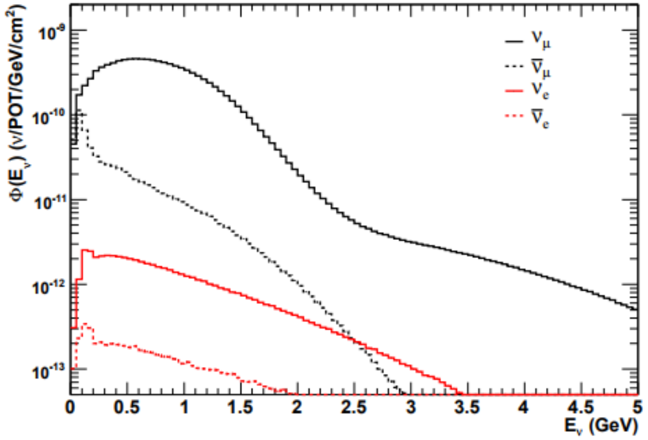
Motivation

- 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





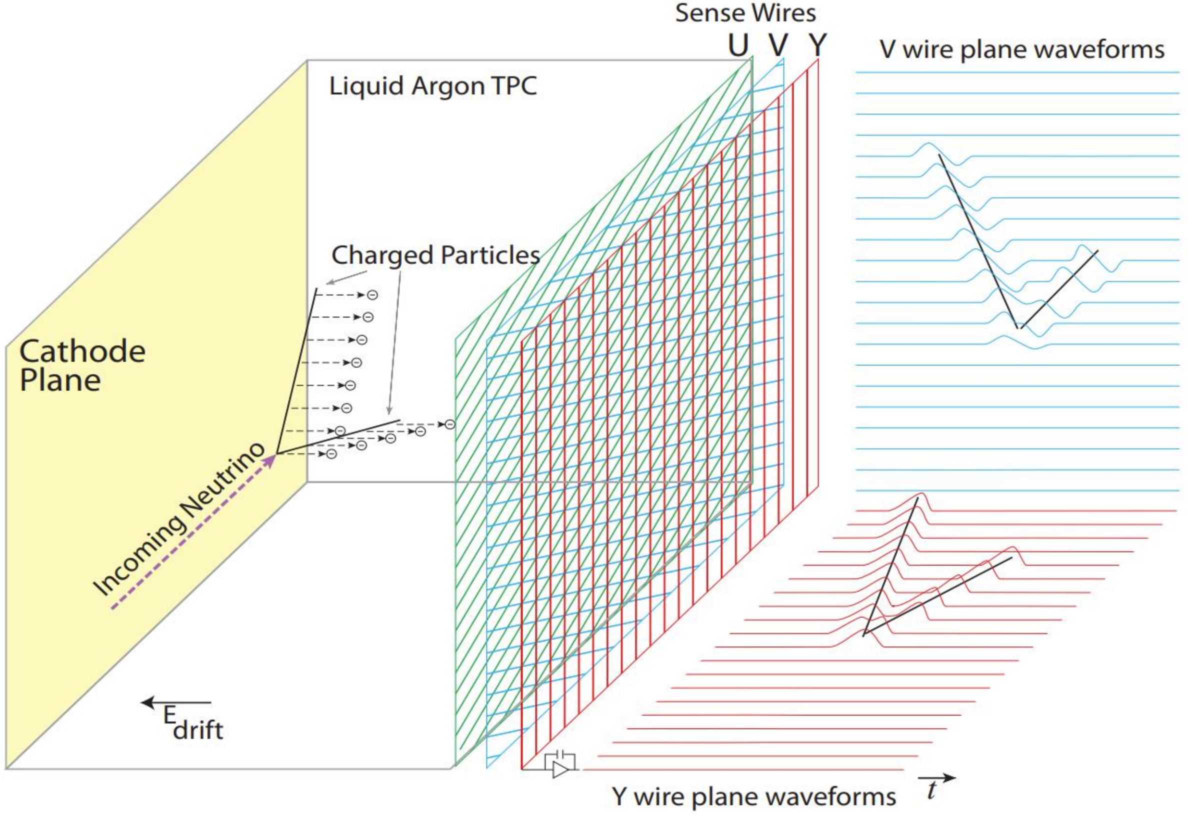
Predicted forward horn current flux of the BNB at MiniBooNE (*Phys. Rev. D* **79**, 072002).

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.

R. Acciarri *et al* 2017 *JINST* **12** P02017

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



Cartoon of the liquid argon readout system with sample waveforms for an induction plane (V) and collection plane (Y).

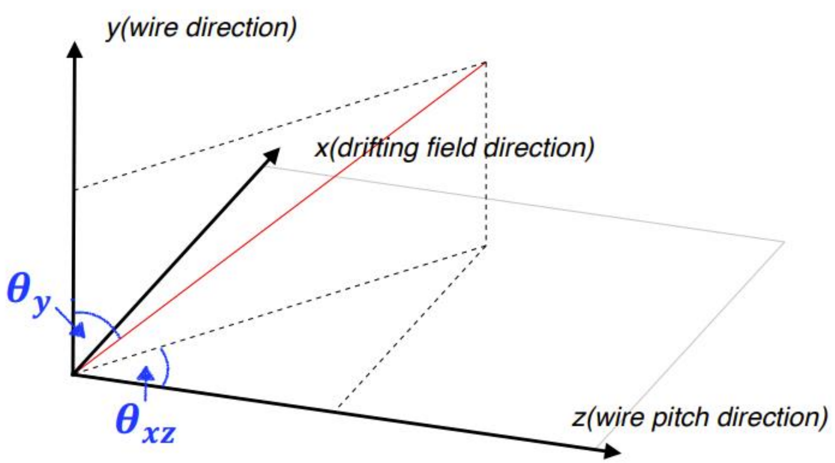


Diagram of the coordinate system.

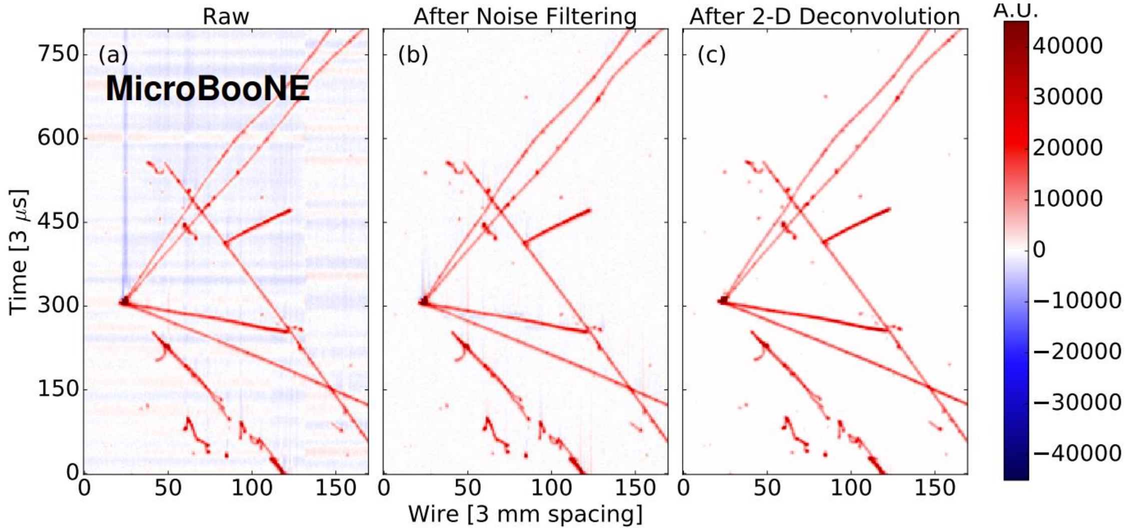
- Coordinate system has:
  - x-coordinate as the drift direction
  - y-coordinate as the height
  - z-coordinate as the length of the detector

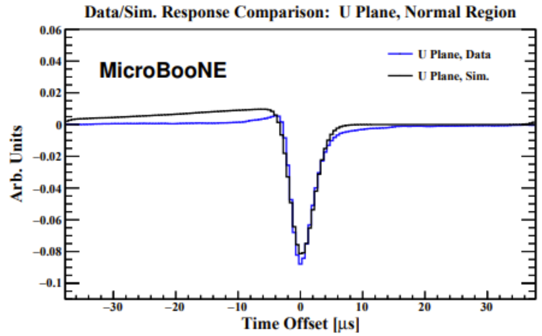
C. Adams *et al* 2018 *JINST* **13** P07006

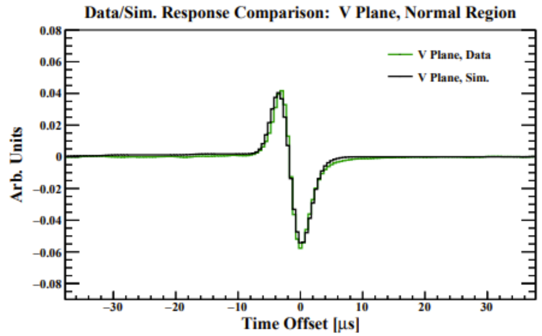
Signal processing: Waveforms for Charge Extraction

- 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.

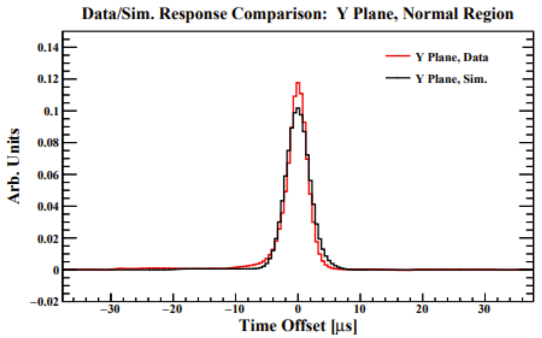
Event display of candidate neutrino event from data through each stage of signal processing.







Data and simulation comparisons of the waveforms for each plane.



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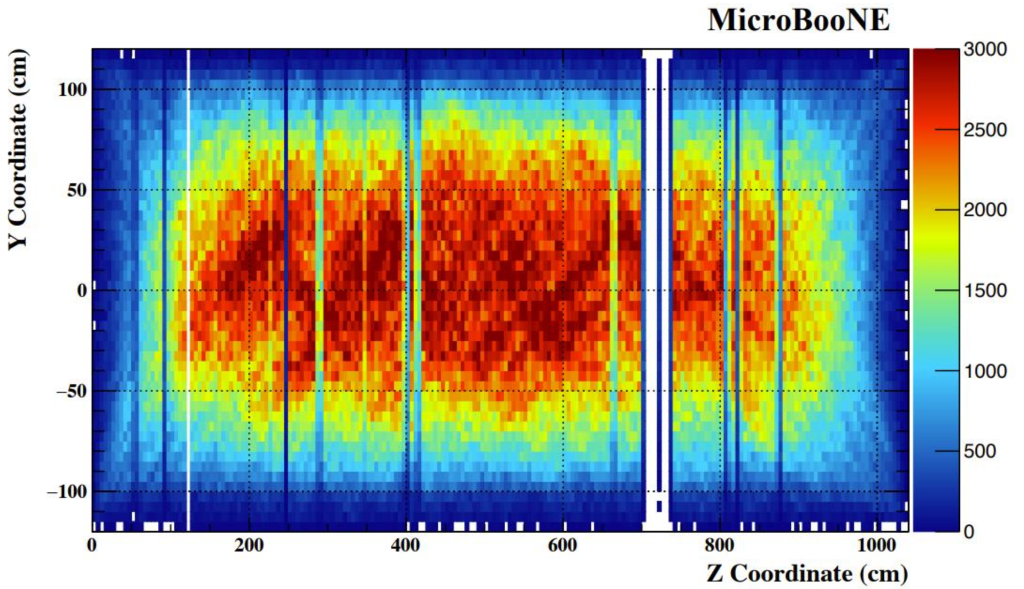
Calibration of dQ/dx

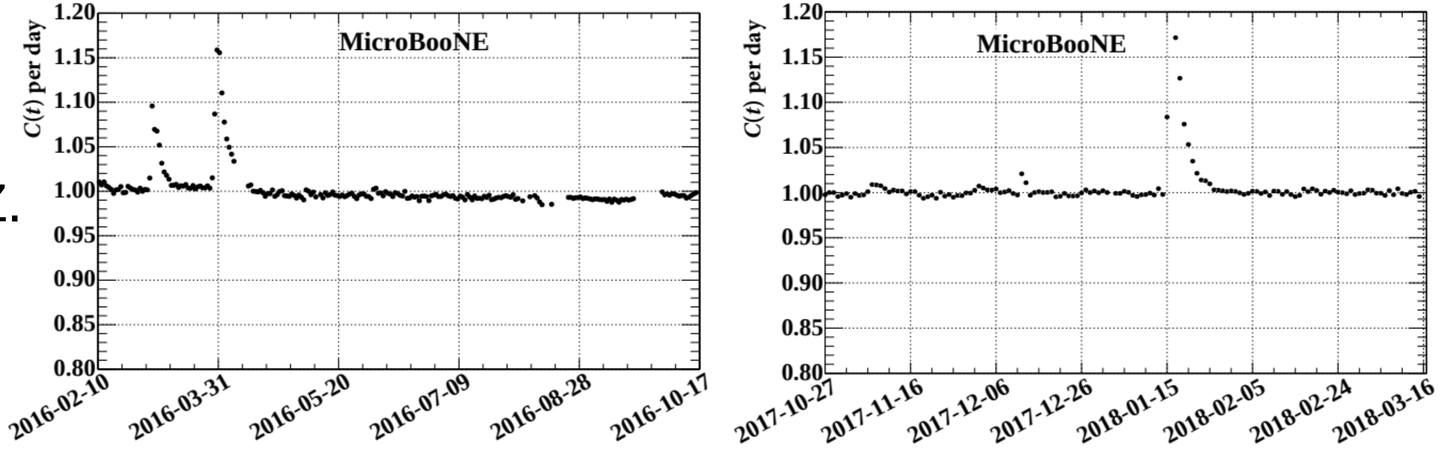
Hit-by-hit calorimetry is one method of many used by MicroBooNE.

- 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.



dQ/dx as a function of YZ (heigh, length) for the collection plane



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

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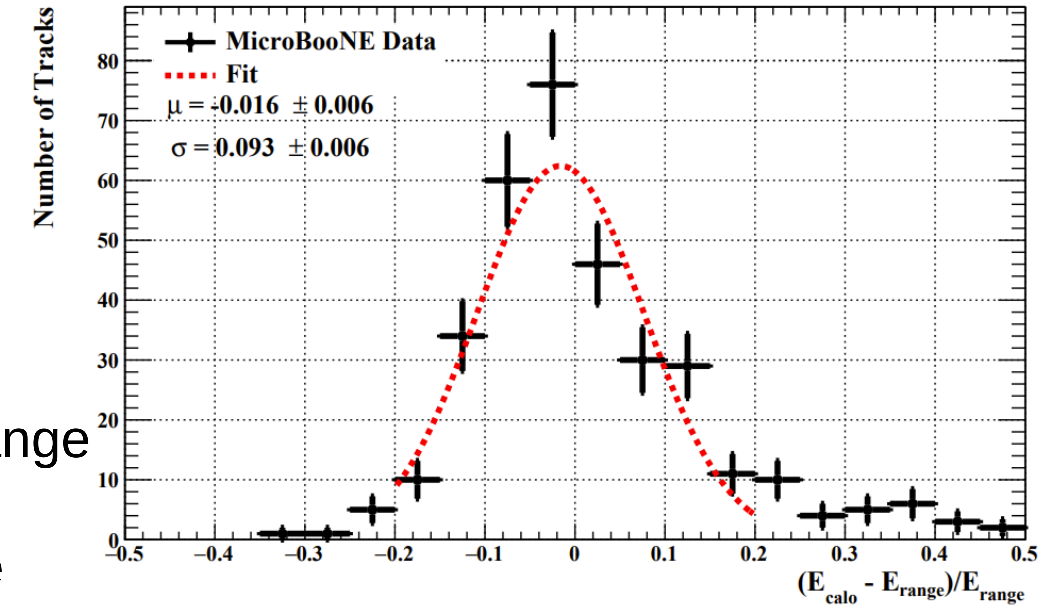
Calibration of dE/dx

- 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_{cal} by fitting values to the predicted dE/dx based on the residual range.

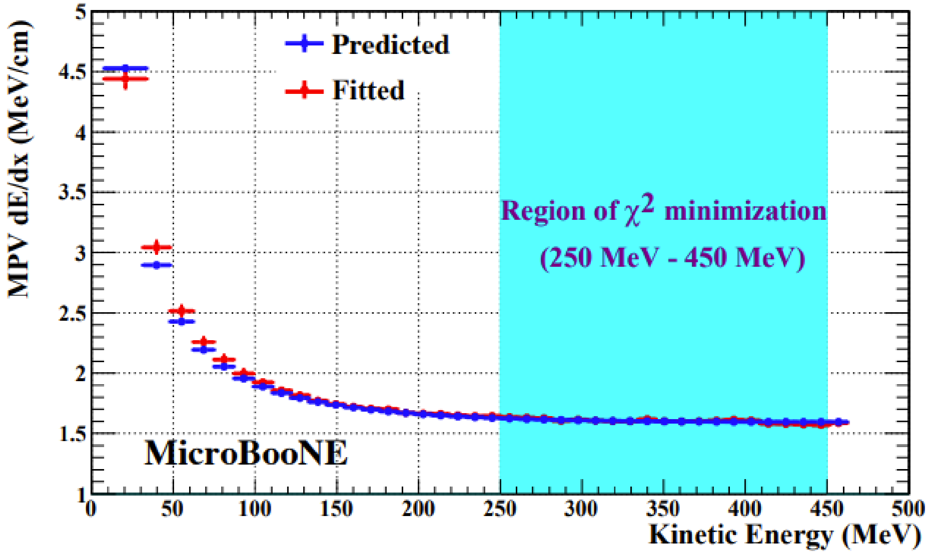


Some analyses measure energy by range. Both methods, summing up hits and by range, agree within a small bias (top).

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

$W_{\text{ion}} = 23.6 \times 10^{-6}$ MeV/electron (work function of argon),
$\mathcal{E} = 0.273$ 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^2)/MeV, and
$\alpha = 0.93$.

Modified Box model of dE/dx



Stopping muon curve for data compared to prediction ((4.113 ± 0.011) × 10E−3 ADC/e, chi2/ndof~0.28). Blue shaded region is the high residual range considered.

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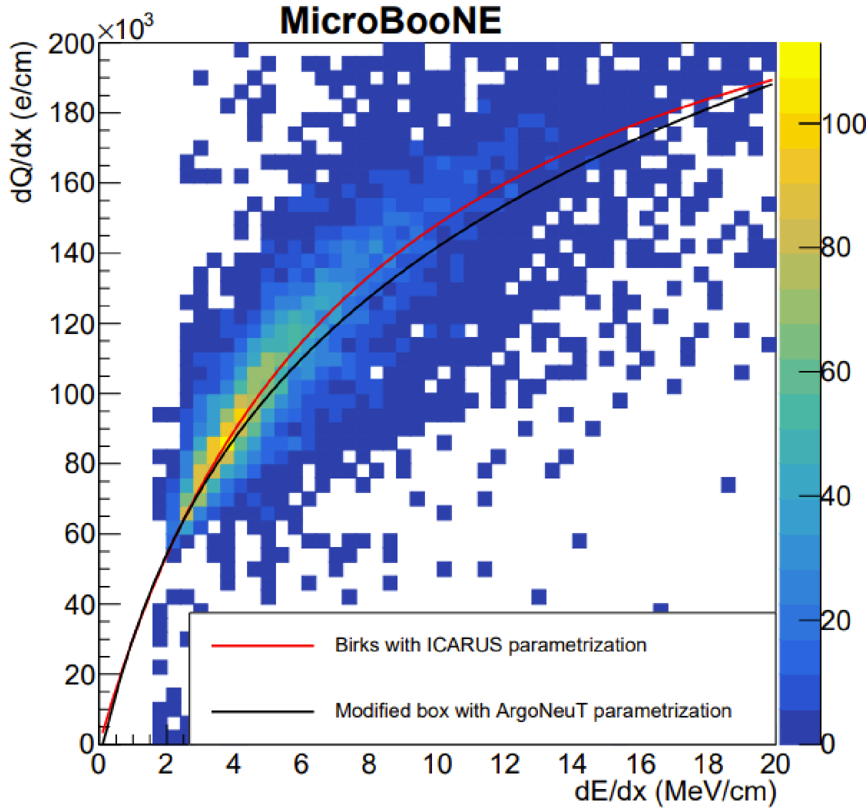
J.B. Birks, *The Theory and practice of scintillation counting.*

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.

Modified Box parameters	ArgonNeuT measurement (*JINST* **8** P08005)	MicroBooNE
α	0.93 ± 0.02	0.92 ± 0.02
β\` (kV/cm)(g/cm^2)/MeV	0.212 ± 0.002	0.184 ± 0.002

Birks' law parameters	ICARUS measurement (*NIM* **A 523** (2004) 275)	MicroBooNE
A_B	0.800 ± 0.003	0.816 ± 0.012
k (kV/cm)(g/cm^2)/MeV	0.0486 ± 0.0006	0.045 ± 0.001



Measurement of stopping protons parametrized with the two recombination models.

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Tool: Particle Identification Algorithm with Log-Likelihood Ratio

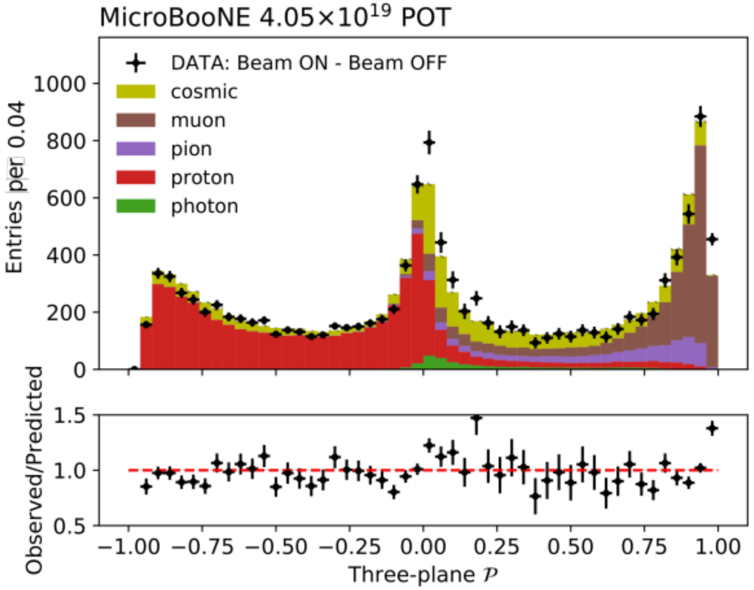
$$\mathcal{L}_{\text{plane}}(\text{type}|\text{plane}, \{dE/dx\}_{i=1,\ldots,N}, \{\text{rr}\}_{i=1,\ldots,N}, \{\text{local pitch}\}_{i=1,\ldots,N}) = \prod_{i=1}^{N} \mathcal{L}_{\text{hit}}(\text{type}|\text{plane}, dE/dx_i, \text{rr}_i, \text{local pitch}_i),$$

Problem: How to select proton tracks from muon tracks?

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

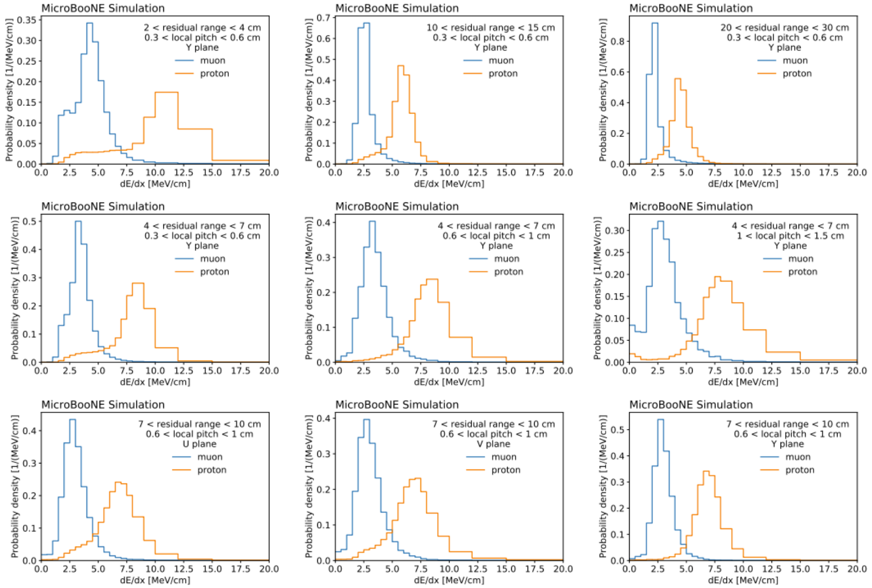
- Use calibrated calorimetry to make proton/muon discrimination.
- Build probabilities of each hit being a muon or proton based on simulation (see bottom).
- Compare the ratio of the probability between muons and protons (see right).

P = (2/π)*arctan(log(T)/100) where T is the log-likelihood ratio of muons to protons.



J. High Energ. Phys. **2021,** 153 (2021).

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



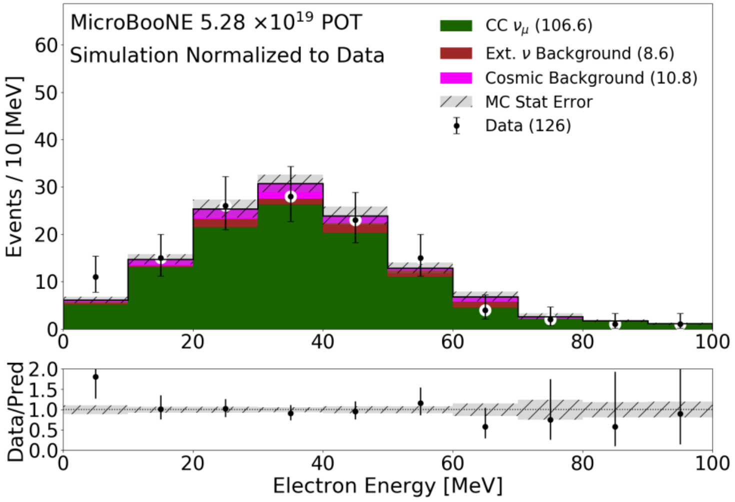
Tool: Using Deep Learning for Michels and π0s

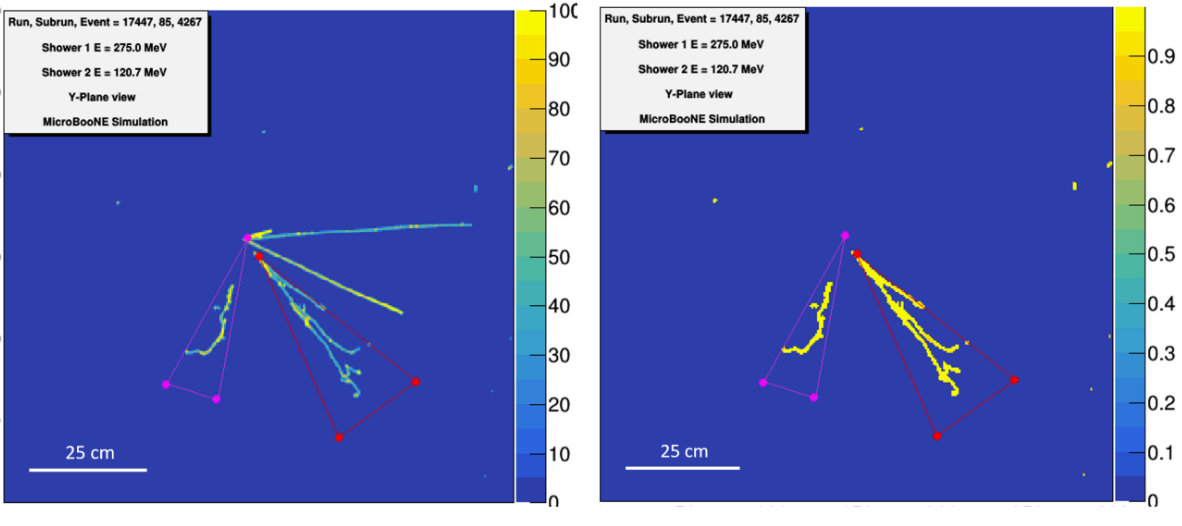
Problem: How to cluster deposits from a shower?
One method is to use a Kalman fitter (arXiv:2110.14065).

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.

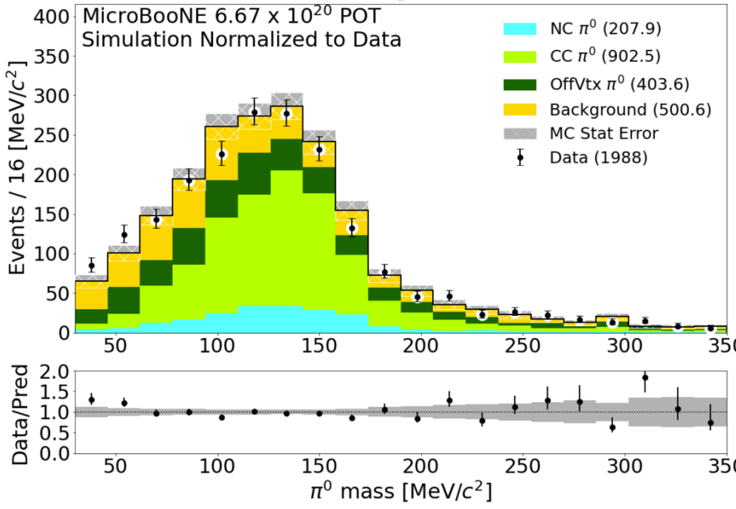




(a) Q Image (b) SparseSSNet Shower Image

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.

The calibration workflow is the same used for upcoming cross section papers (*Phys. Rev. D* **105**, L051102 and *Phys. Rev. Lett.* **128**, 151801) and publications searching for excesses of low energy electron-like neutrino events (*Phys. Rev. Lett.* **128**, 111801, arXiv:2110.14054 hep-ex).

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science NSF FNSNF SWISS NATIONAL SCIENCE FOUNDATION Science & Technology Facilities Council THE ROYAL SOCIETY European Commission Horizon 2020 European Union funding for Research & Innovation

Backup

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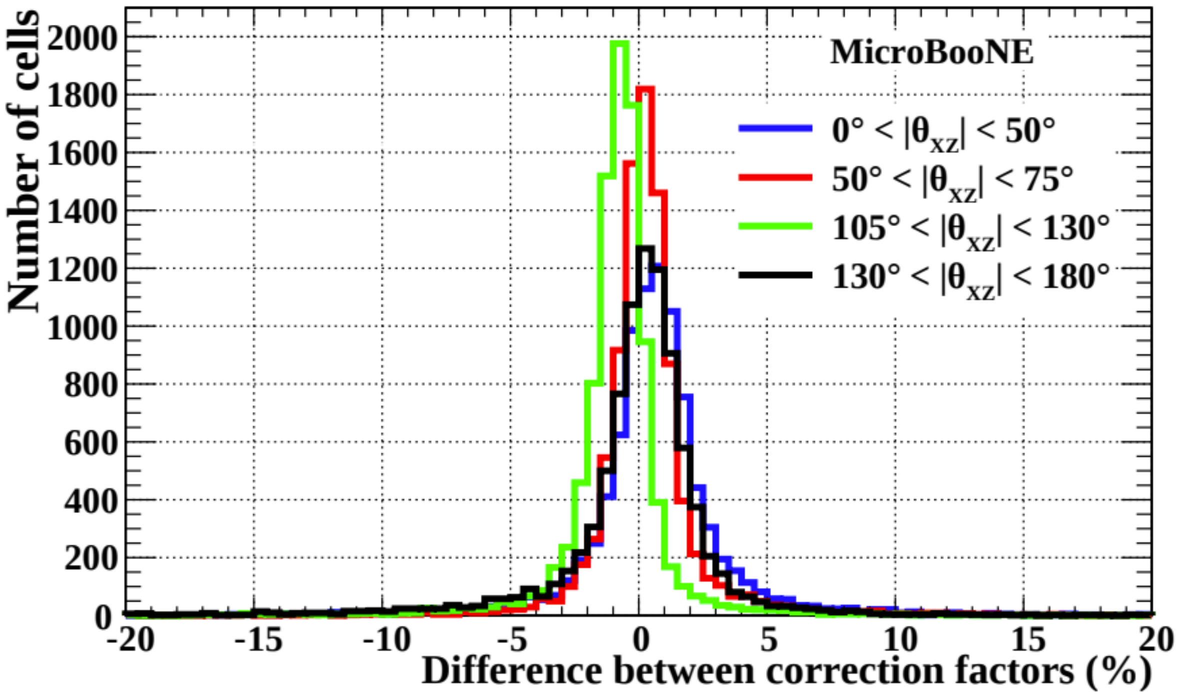
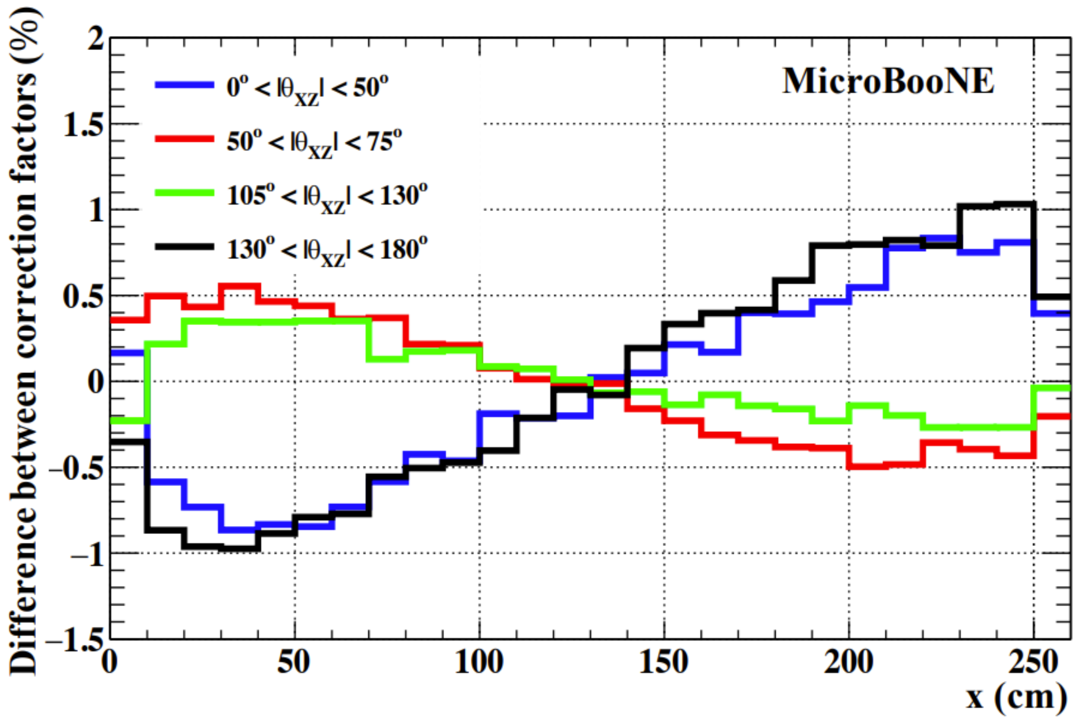
Uncertainties on dQ/dx and dE/dx Calibration

- 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.



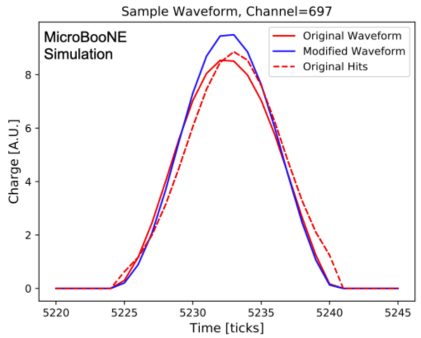


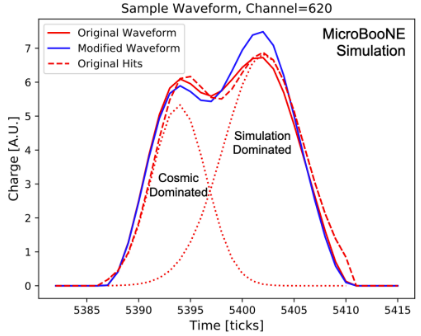
Deviations for data calibration in YZ (left) and X (right).

Detector Mismodeling Uncertainties

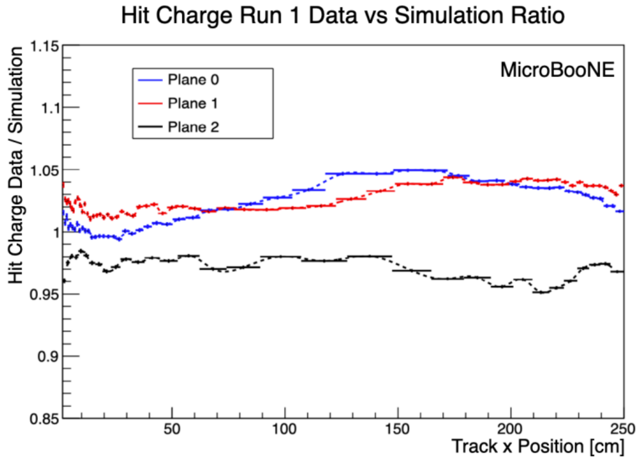
arXiv:2111.03556v1 [hep-ex] 5 Nov 2021
(Accepted by EJPC)

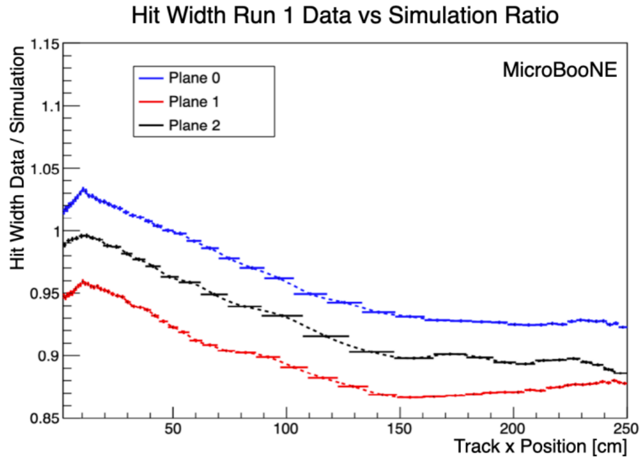
Sample wire modification.



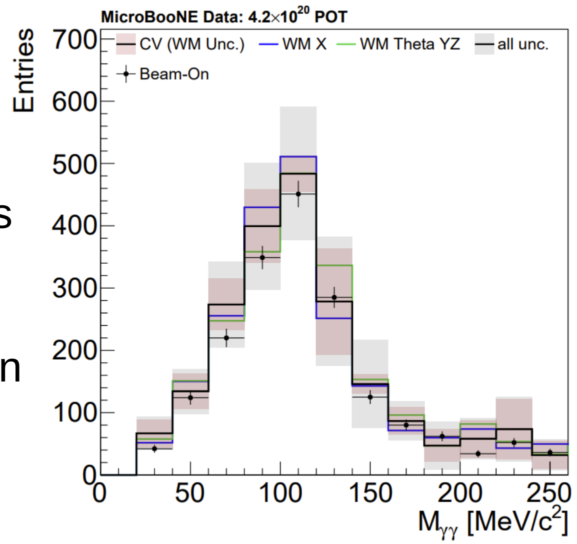


- Mismodeling of the detector can lead to different behavior in hits that can propagate to higher-level reconstruction (see slide 4 plot).
- Novel concept of modifying simulation waveforms based on ratios of hit reconstruction parameters as a function of position (X, Y, Z) and angle (XZ, YZ).
- Unisim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



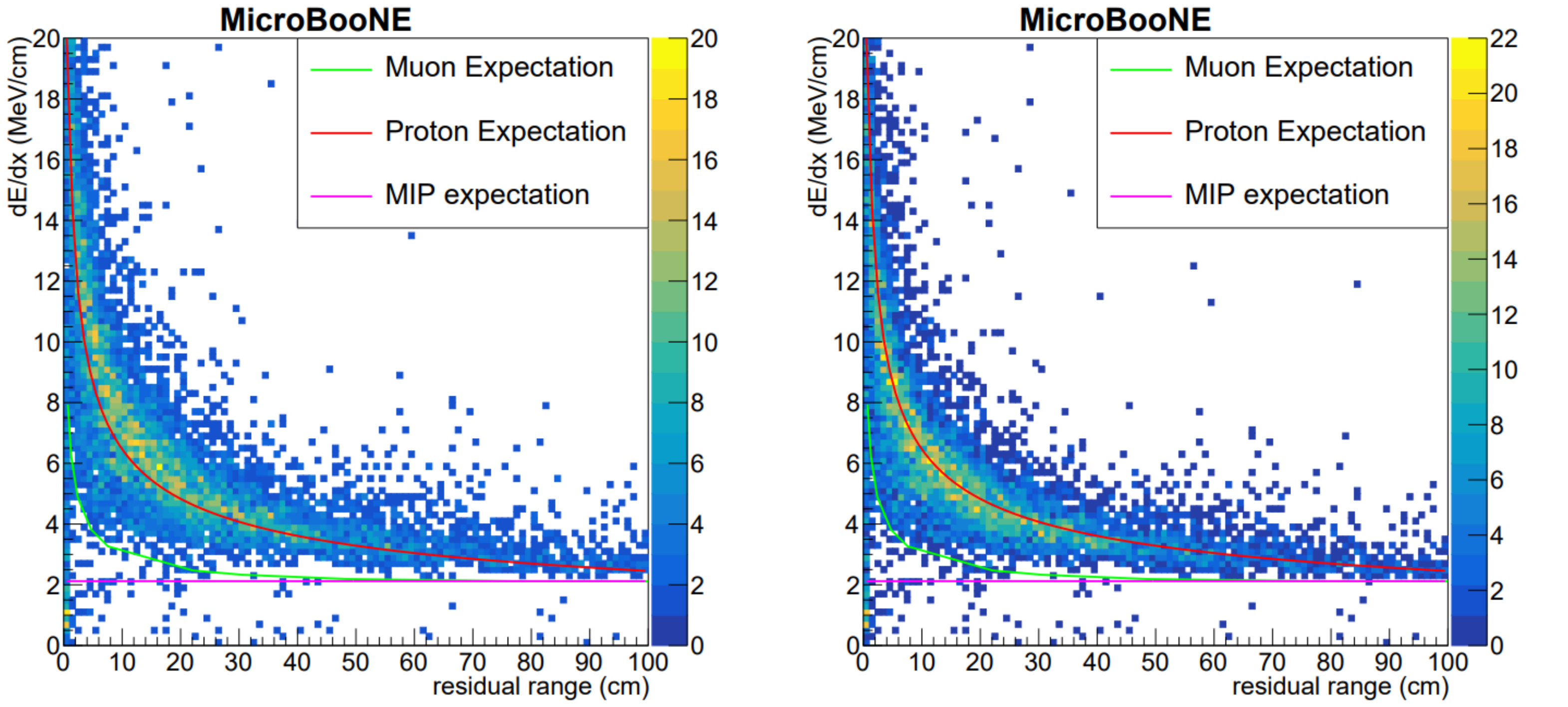


Reconstructed neutral pion mass distribution with the five unisim samples based on the ratios.



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



(a) With ArgoNeuT parameters (b) With MicroBooNE *effective recombination* parameters

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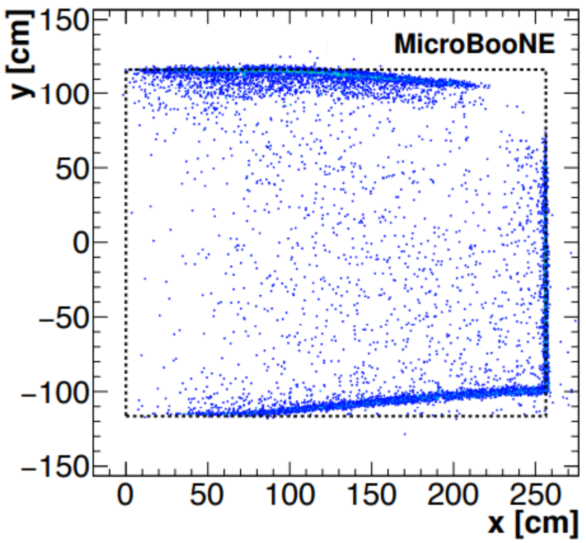
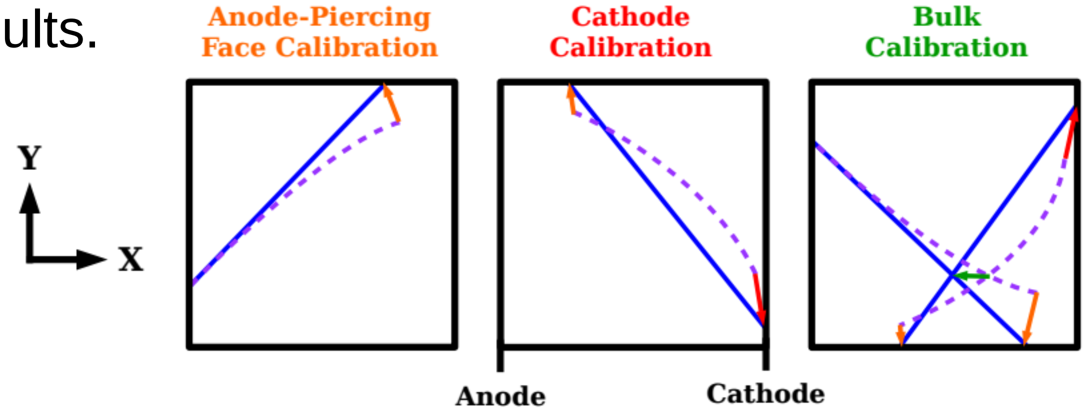
Space Charge Effect Calibration

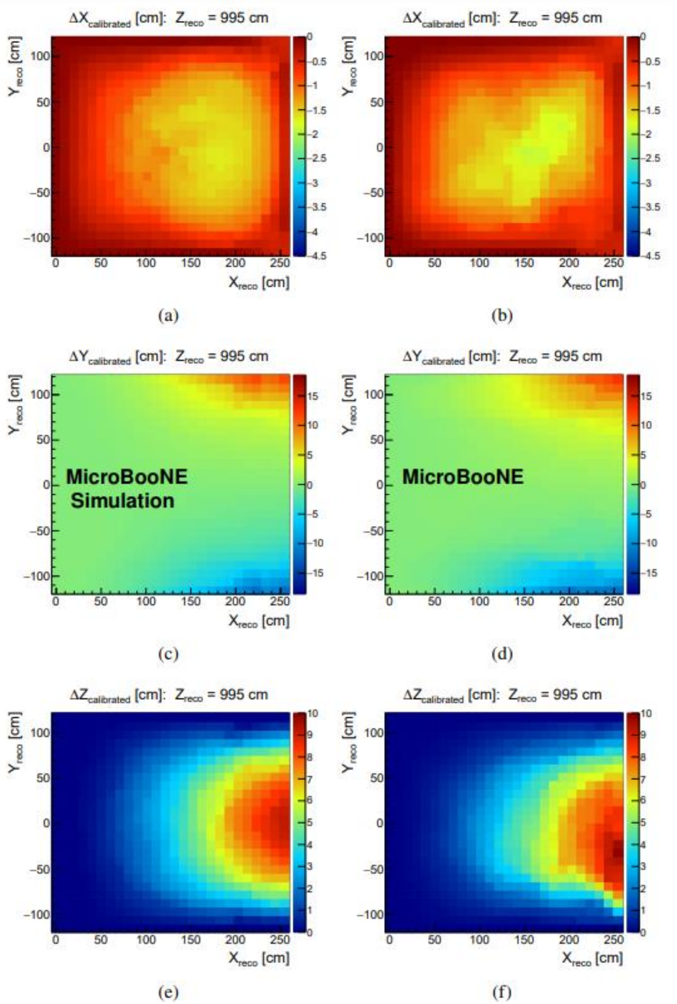
- As a detector on the surface, cosmic ray muon flux is so high and ionizes so much argon that positive argon ions build in the detector and create field nonuniformities.
    - Known as the space charge effect.
    - Effect is most noticeable on edges (most noticeable for exiting tracks)
- MicroBooNE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



Entry and exit points of cosmic muons. The dashed lines are the walls of the TPC.



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



Comparisons of the space charge effect measurements predicted in simulation (left) and data (right)

JINST **15** P12037