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Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Overview of the MicroBooNE LArTPC Detector Calibration

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μBooNE

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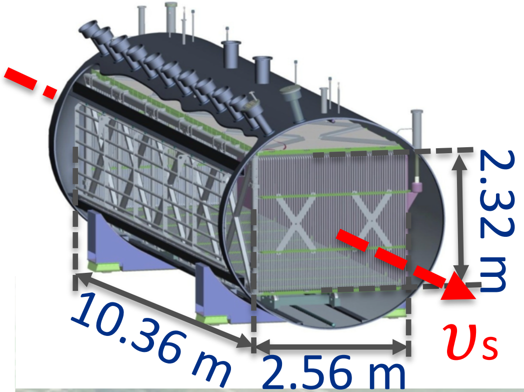
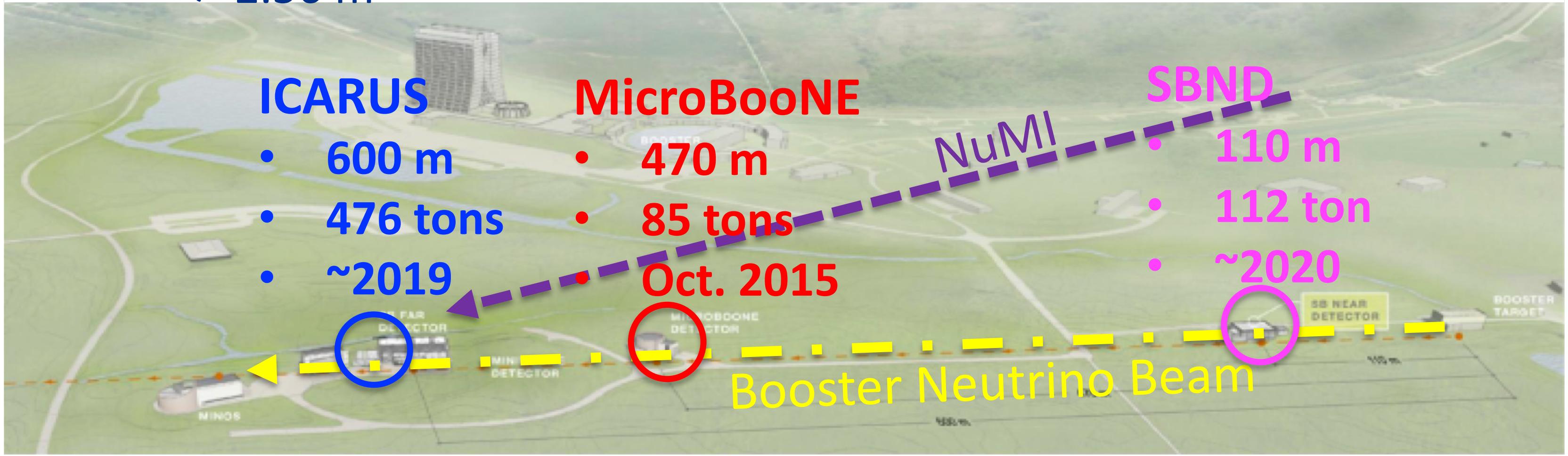
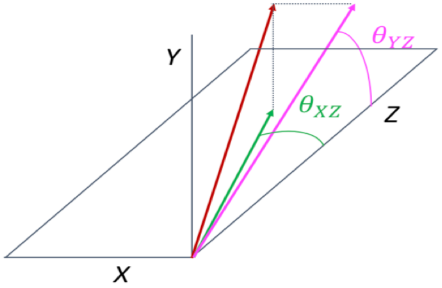
The MicroBooNE Experiment

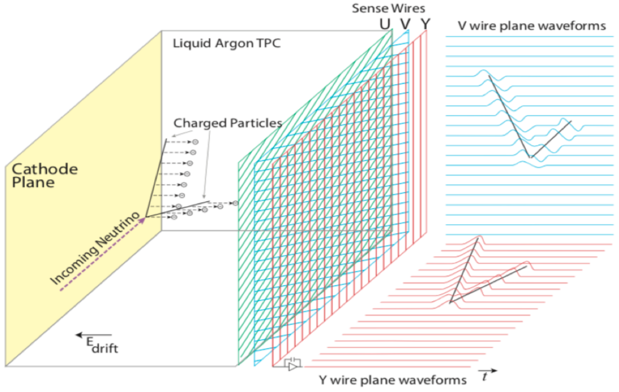


- Liquid Argon Time Projection Chamber (LArTPC)
- Investigate low-energy excess (LEE) of electron-like neutrino events observed by MiniBooNE in 2009
- Measure the low energy neutrino cross sections

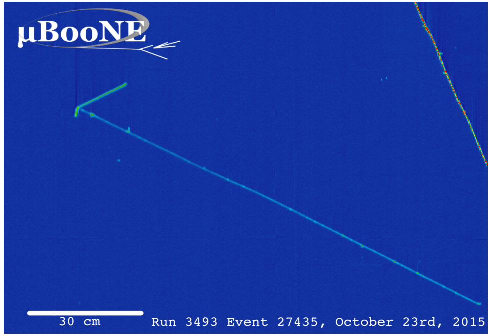


The MicroBooNE Experiment

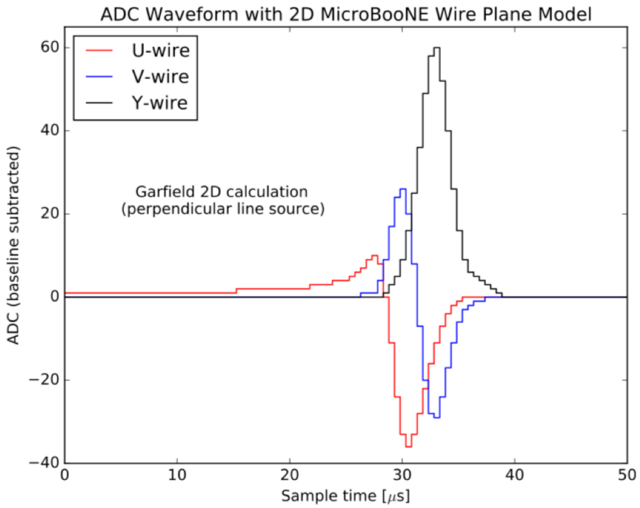




- 3 wire planes:
  - separated by 3 mm, with 3 mm wire spacing for each
  - to reconstruct the event, tracking and calorimetry
- 32 PMTs:
  - to detect scintillation light, mainly for trigger and event selection



Example of Simulated Digitized Signals

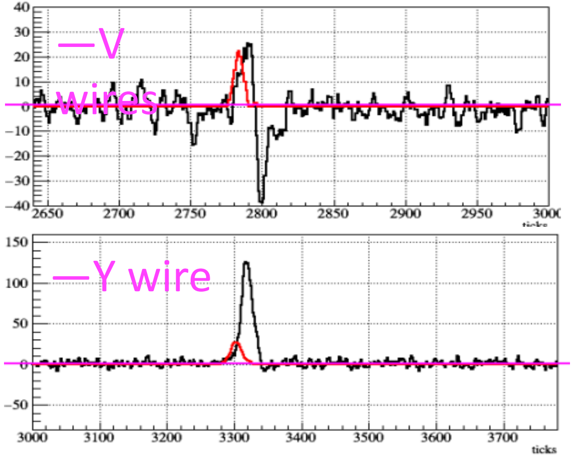


(ADC: Analog-to-digital converter)

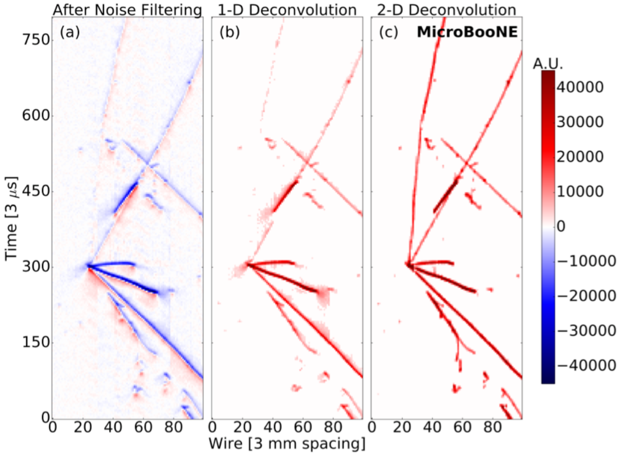
The digitized signals from a central wire from each plane that are induced by an ideal MIP track in a 2D model of the MicroBooNE TPC.

----Refer: JINST 12, P08003 (2017)

Reconstruction of Drifted Electrons



----Image from W. Gu



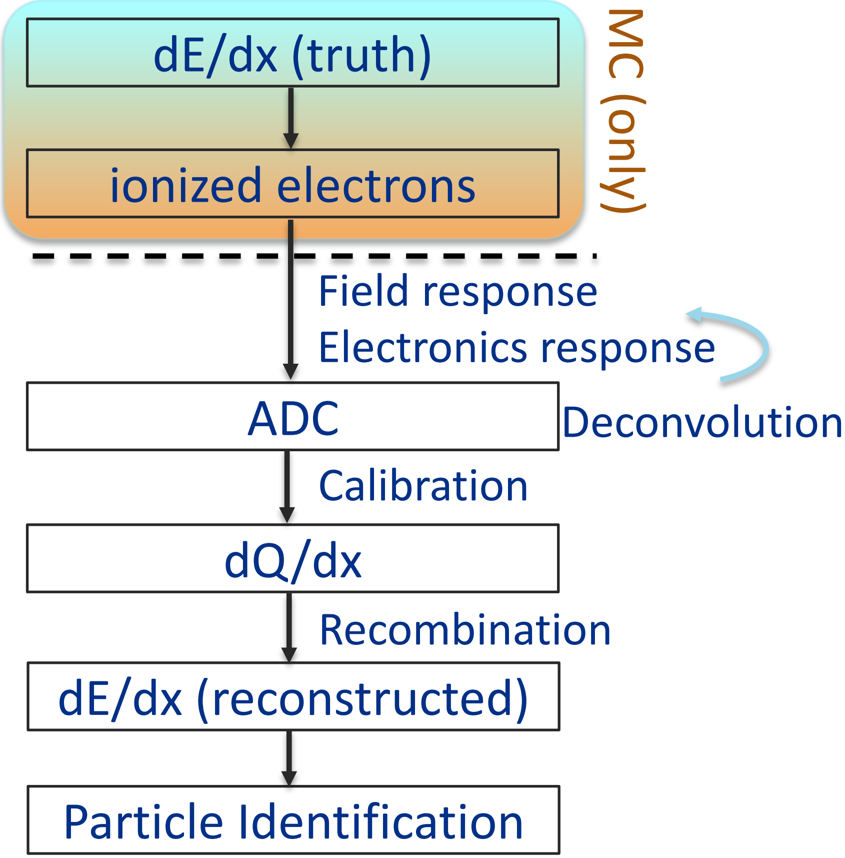
----Refer: JINST 13, P07006 (2018)

- We use deconvolution to extract original signals:
  - Noise filtering & Signal processing
  - Deconvolution is a mathematical technique to extract the original signal $S(t)$ from the measured signal $M(t')$.

$$M(t') = \int_{-\infty}^{\infty} R(t,t') \cdot S(t)dt$$

$R(t,t')$: detector response function

Detector Calibration



Many other effects need to be calibrated:

I. Detector uniformity calibration (dQ/dx)

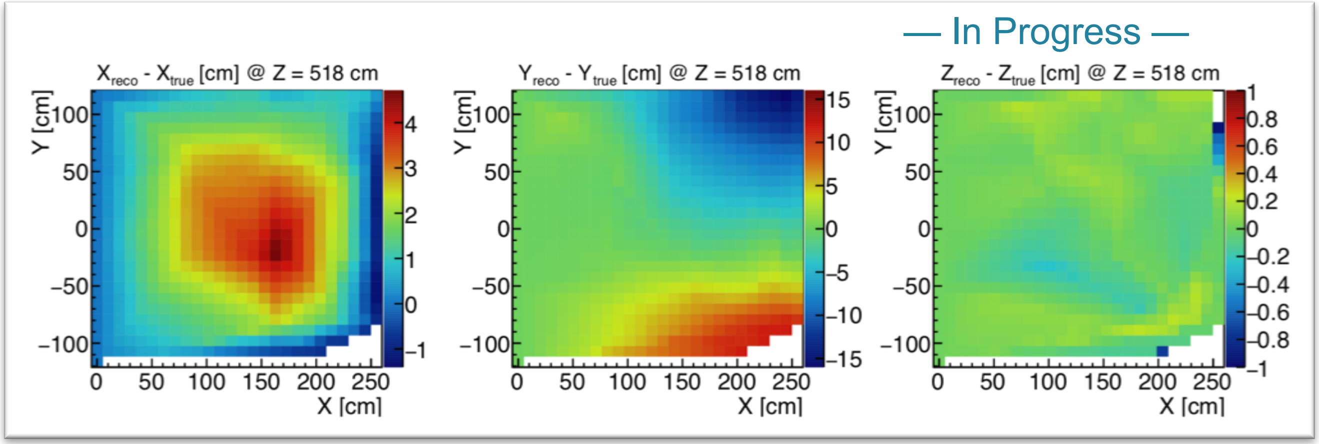
- Variation in electronics gains
- Electron attenuation (e lifetime)
- Nonuniform E field due to Space Charge Effects (SCE), diffusion, disconnected wires, TPC edges, etc.
- Temporal variations: i.e., change of run condition, temperature

II. Energy scale determination (dE/dx)

- Use the well-known energy loss profile

Space Charge Effects

- MicroBooNE detector is on the surface (~20-30 cosmic muons per 4.8 ms readout window)
- Distortion of E field and ionization drift trajectories due to accumulation of slow-moving argon ions produced from cosmic muons impinging TPC
- Calibration on the E-field can be done by using UV laser system and the cosmic muon tracks

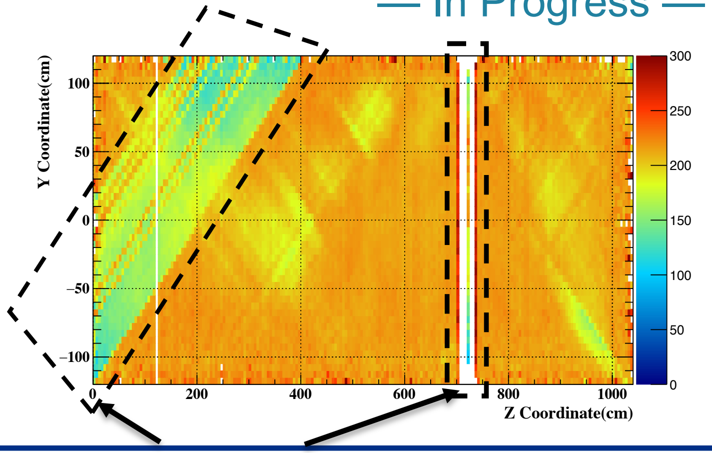


At central Z the spatial distortion of $dX = X_{reco} - X_{true}$ (left), $dY = Y_{reco} - Y_{true}$ and $dZ = Z_{reco} - Z_{true}$ from laser data.

Detector Uniformity Calibration–dQ/dx

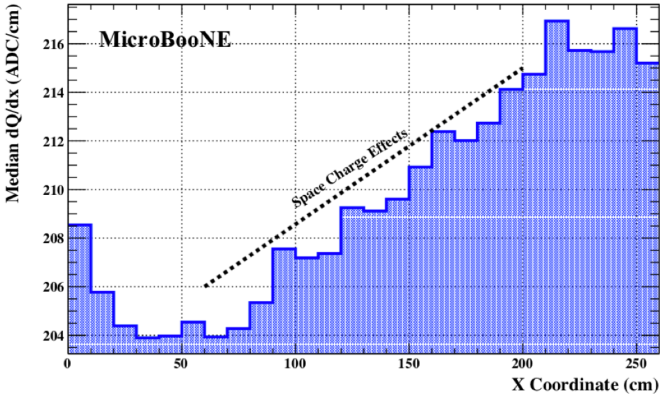
- **dQ/dx calibration** (dQ/dx: ionization charge per unit length)
  - make the detector response to ionization charge uniformly throughout the detector and in time: *YZ plane, X direction, T*
  - use anode-cathode crossing cosmic muons to cover whole drift distance
- Variation of detector response (dQ/dx) in YZ plane and in the drift direction X

— In Progress —



Misconfigured/cross-connected TPC channels

— In Progress —

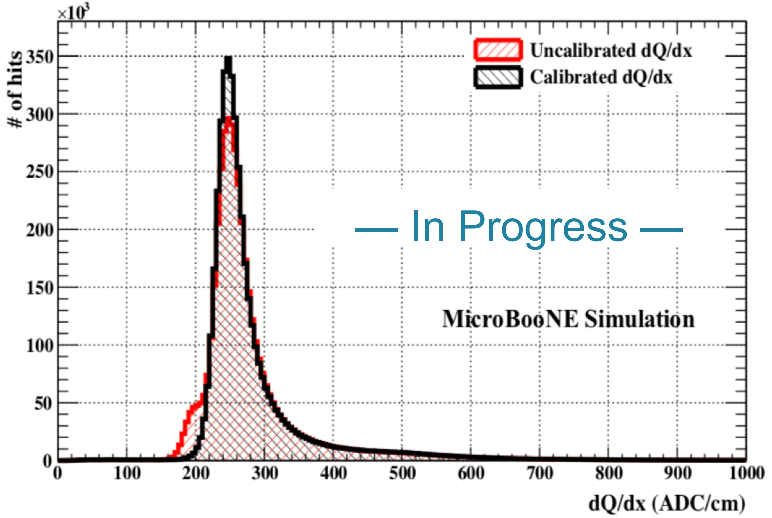


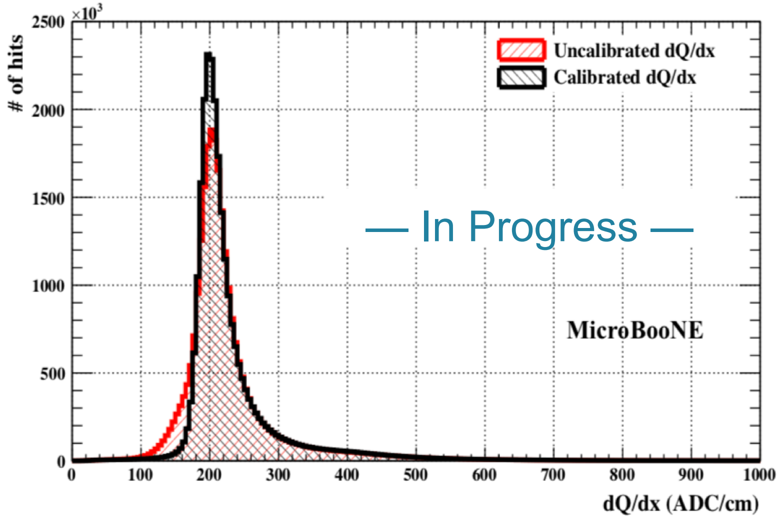
----Refer: MICROBOONE-NOTE-1048-PUB

Detector Uniformity Calibration–dQ/dx

μBooNE

- Results (MC does not have time dependence):
  - Data: $(dQ/dx)^{data}_{corr.} = C(t) \cdot C(x) \cdot C(y,z) \cdot (dQ/dx)_{uncorr.}$
  - Monte Carlo (MC): $(dQ/dx)^{MC}_{corr.} = C(x) \cdot C(y,z) \cdot (dQ/dx)_{uncorr.}$
- Comparisons between calibrated and uncalibrated dQ/dx for both MC and data

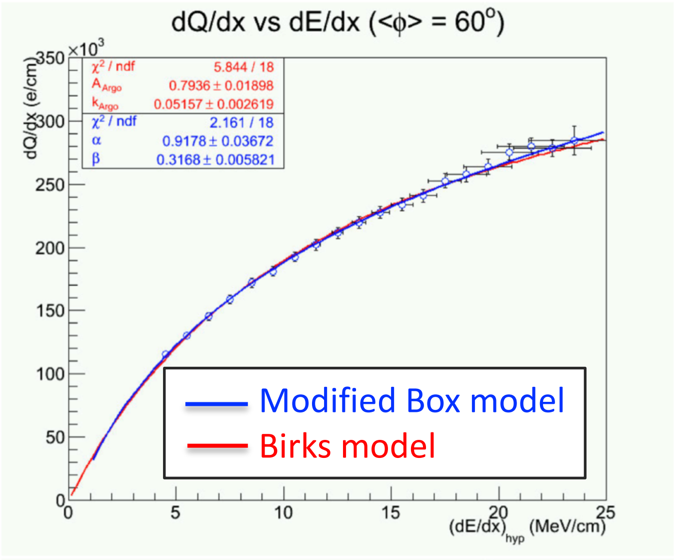




Energy Scale Determination—dE/dx

- Determine the calibration constant *C* (unit: ADC/e), which translates the corrected dQ/dx (ADC/cm) to dQ/dx (e/cm).
- Stopping muons from neutrino interactions or cosmic rays are used to study the measured and predicted Most Probable dE/dx Value (MPV):

$$\left(\frac{dE}{dx}\right)_{corr.} = \frac{\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{corr.}}{C} \cdot \frac{\beta' W_{ion}}{\rho\xi}\right) - \alpha}{\frac{\beta'}{\rho\xi}}$$

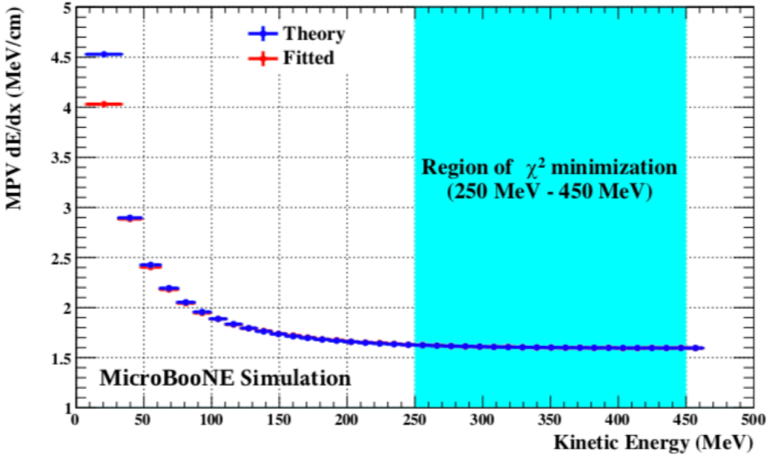


----Refer: [ArgoNeuT JINST 8, P08005 (2013)]()

Energy Scale Determination—dE/dx

- Once we find the calibration constants, we would expect the calibrated dE/dx matches expectation.

— In Progress —



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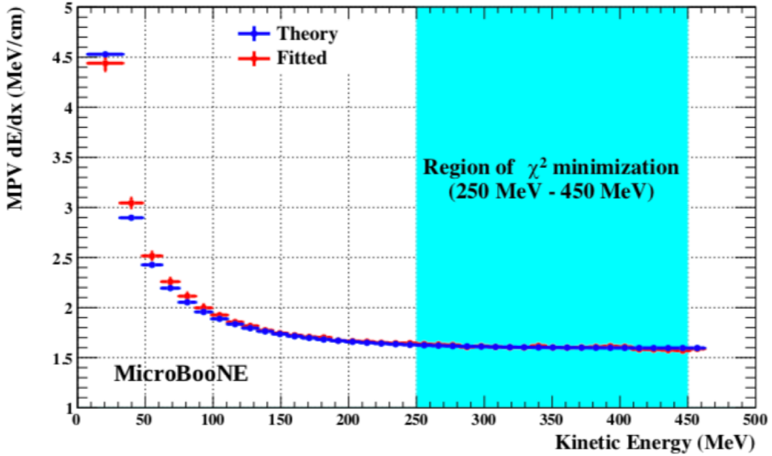


- Kinetic Energy (K.E.) $= \sum \frac{dE}{dx} dx$, where dx is the track pitch.

Summary

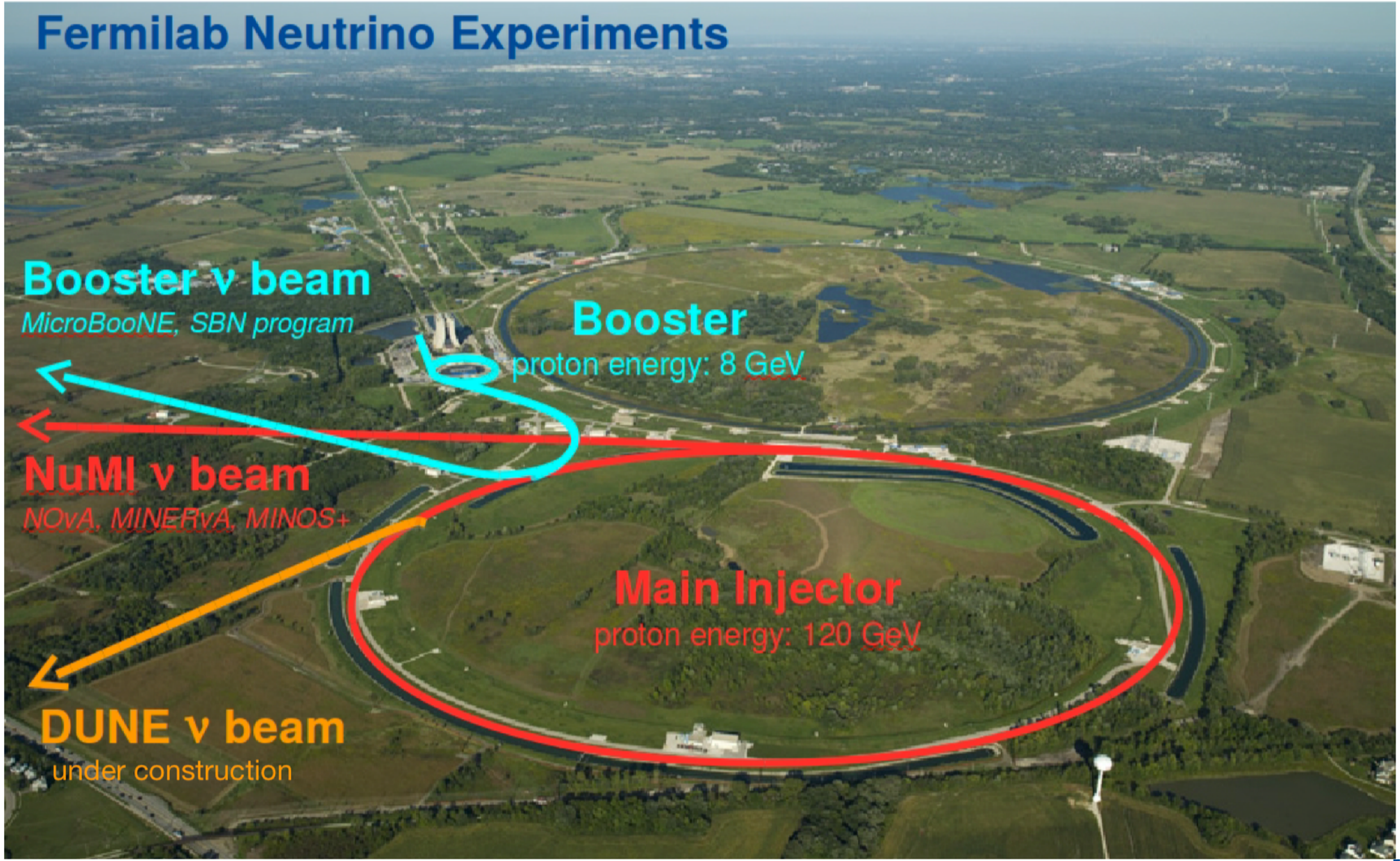
- In this talk, we present a briefly overview of the MicroBooNE LArTPC detector calibration.
- MicroBooNE detector performs at a high signal-to-noise ratio.
- Deconvolution is used to extract the charge signal after removing noise.
- Many detector effects will affect the measurement and need to be addressed appropriately.
- The detector calibration can correct most of the detector effects and improve the energy reconstruction and particle identification.
- The calibration strategy carried out here can be used by other LArTPC experiments to calibration their detectors.

Acknowledgement

- The calibration method is developed by the MicroBooNE Calibration Group. I would like to express my gratitude and appreciation to the team, especially *Tingjun Yang, Glenn Horton-Smith, Mike Mooney, Yifan Chen, Varuna Meddage* and *Marianette Wospakrik*. Without their effort and help, this talk would not have been possible.
- MicroBooNE is supported by the following: the U.S. Department of Energy, Office of Science, Offices of High Energy Physics and Nuclear Physics; the U.S. National Science Foundation; the Swiss National Science Foundation; the Science and Technology Facilities Council of the United Kingdom; and The Royal Society (United Kingdom).

—Thank you!

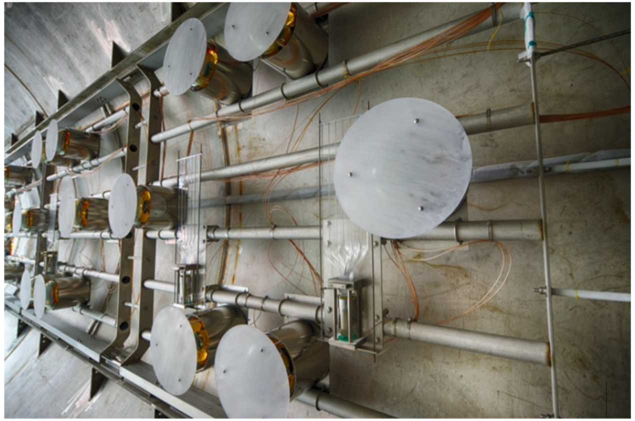
Backup—Fermilab Neutrino Programs



Backup—PMT and Trigger Systems

μBooNE

- 32 TPB-coated PMTs behind wires
- Two gains: 1.8% and 18%
- Shaping: 60 ns rise time
- 64 MHz ADC (ADS5272): accurate determination of event t_0

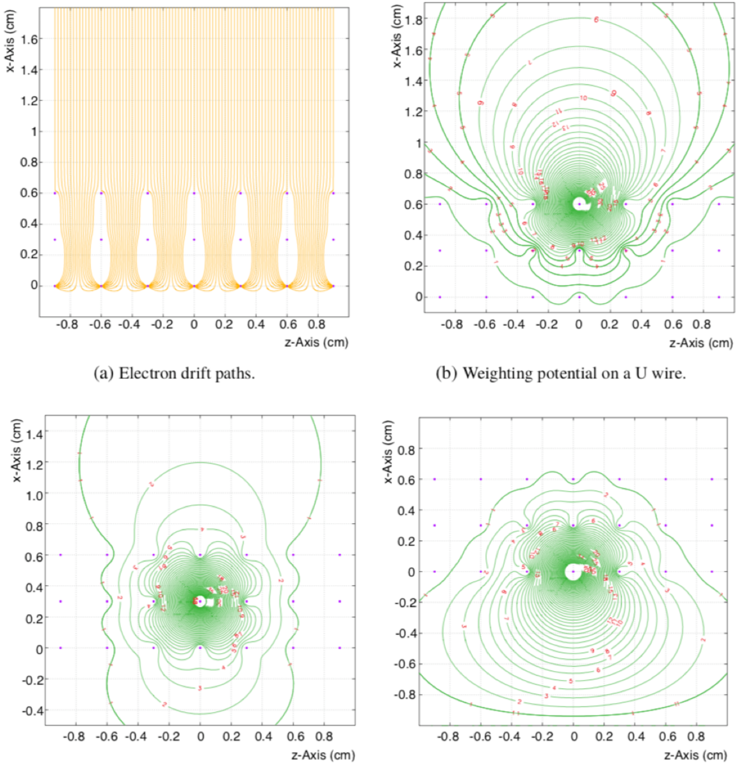


- Level-1 trigger: accelerator gates (BNB and NuMI) and random triggers (for cosmics)
- Level-2 trigger: PMT information in the beam window (in software)

MicroBooNE: JINST 10, T06001 (2015); JINST 8, T07005 (2013)

Backup—Drift Electron Path

μBooNE



(a) Electron drift paths. (b) Weighting potential on a U wire.

(c) Weighting potential on a V wire. (d) Weighting potential on a Y wire.

----Refer: [JINST 13, P07006 (2018)]

Backup — Deconvolution

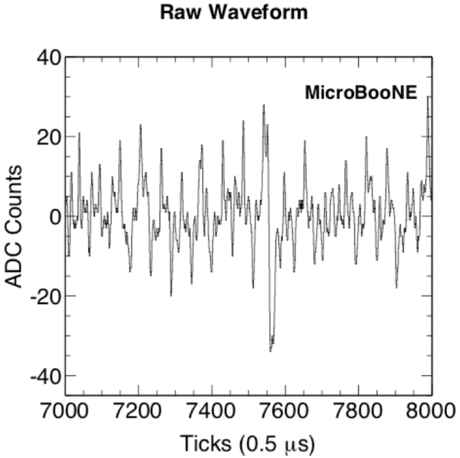
The principal method to extract charge is deconvolution. This procedure in its one-dimensional (1D) form has been used in the data analysis of previous liquid argon experiments [29, 30]. This technique has the advantages of being robust and fast. It is an essential step in the overall drifted-charge profiling process.

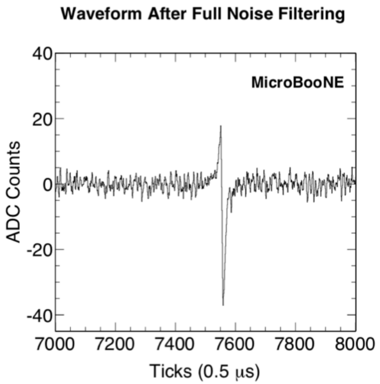
Deconvolution is a mathematical technique to extract the *original signal* $S(t)$ from the *measured signal* $M(t')$. The measured signal is modeled as a convolution integral over the original signal $S(t)$ and a given detector *response function* $R(t, t')$, which gives the instantaneous portion of the measured signal at some time t' due to an element of original signal at time t:

$$M(t') = \int_{-\infty}^{\infty} R(t, t') \cdot S(t) dt. \qquad (3.1)$$

----Refer: JINST 13, P07006 (2018)

Backup—Noise Filter





----Refer: [JINST 12, P08003 (2017)]

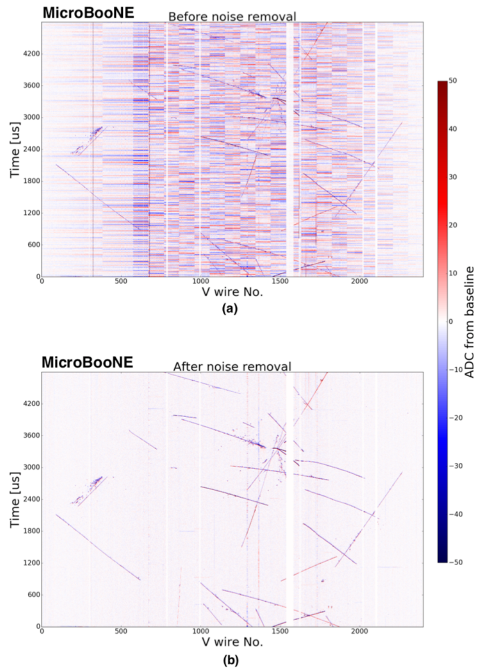
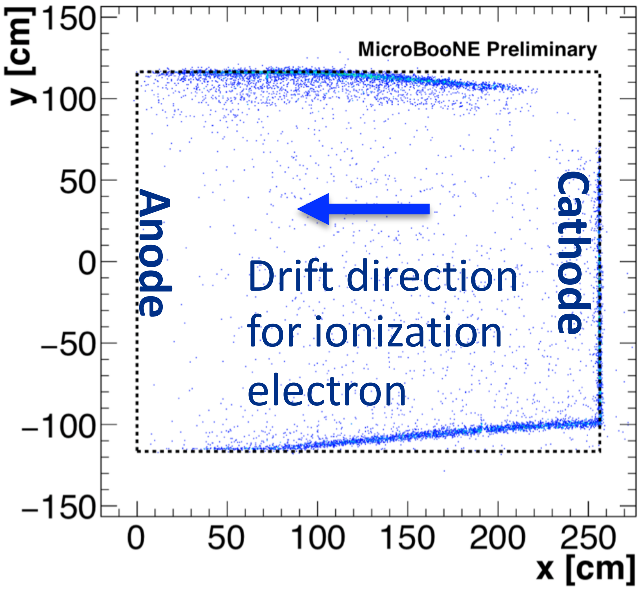


Figure 14. 2-D event display of the V plane from run 3493 event 41075 showing the raw signal (a) before and (b) after offline noise filtering. A clean event signature is recovered once all the identified noise sources are subtracted.

Backup—MicroBooNE Calibration

- Challenges for MicroBooNE LArTPC detector:
  - Misconfigured or cross-connected TPC channels: change gain of electronic channels, distort field between wire planes
  - Space Charge Effects (SCE): cosmic rays, accumulation of slow moving Ar^+, causing distortion the magnitude and direction of drift E field
  - Electron attenuation: electronegative contaminants such as H2O and O2 can capture some of the drifting electrons
  - Diffusion: drifted electrons may get smeared out
  - Recombination: ionization electrons may not completely liberate from their parent argon ions and recombine back to form neutral argon atoms again, causing underestimation of particle energy loss
  - Temporal variations: change of temperature, run conditions…
  - …
- We want to measure the charge and position of ionization signal precisely and improve both the measurement of total deposited energy and particle identification (PID).

Backup—Space Charge Effects



Start/end points of reconstructed cosmic muon tracks tagged by an external muon counter in the x-y plane for off-beam (cosmic) events.

----Refer: MICROBOONE-NOTE-1018-PUB

Backup—dQ/dx

µBooNE

- $(\frac{dQ}{dx})_{uncorr.} \rightarrow YZ_{corr.} \rightarrow DriftDirection_{corr.} \rightarrow Time_{corr.} \rightarrow (\frac{dQ}{dx})_{corr.}$
  - Consists of 3 steps:
    1. YZ plane correction: remove effects from SCE, misconfigured or cross-connected TPC channels and transverse diffusion
    2. Drift direction correction: remove effects coming from electron attenuation, SCE and longitudinal diffusion
    3. Time correction: remove any temporal variations in detector response (for data only, MC does not have time dependence)
- $(\frac{dQ}{dx})_{uncorr.} \rightarrow YZ_{corr.} \rightarrow Lifetime_{corr.} \rightarrow (\frac{dQ}{dx})_{corr.}$
  - Consists of 2 steps:
    1. YZ plane correction: same as above
    2. Lifetime correction:
    - remove effects coming from electron attenuation, SCE and longitudinal diffusion, temporal variations
    - $Q = Q' \cdot e^{-(\frac{t}{\tau})}$ (t: drift time; τ: electron lifetime, determined by purity or TPC (laser system, muon count system)

In progress

Backup—dQ/dx: YZ Plane Correction

The YZ plane is segmented into 5 cm by 5 cm cells. The correction factor is defined by:

$$C(y,z) = \frac{(dQ/dx)_{Global}}{(dQ/dx)_{Local}}$$

$(dQ/dx)_{Global}$ – Global median dQ/dx in the collection plane

$(dQ/dx)_{Local}$ – Local median dQ/dx for a given YZ plane cell in the collection plane

Backup—dQ/dx: Drift Direction

After YZ plane calibration:

$$(dQ/dx)_{corr.} = C(y,z) \cdot (dQ/dx)_{uncorr.}$$

The drift direction is segmented into 10 cm in data (5 cm in MC). The correction factor is defined by:

$$C(x) = \frac{(dQ/dx)'_{Global}}{(dQ/dx)'_{Local}}$$

$(dQ/dx)'_{Global}$ – Global median dQ/dx value after correcting for YZ plane irregularities

$(dQ/dx)'_{Local}$ – Local median dQ/dx value after correcting for YZ plane irregularities

Backup—dQ/dx: Time Calibration

µBooNE

After YZ plane calibration and drift direction calibration:

$$(dQ/dx)_{corr.} = C(x) \cdot C(y,z) \cdot (dQ/dx)_{uncorr.}$$

The time dependent correction is determined for each day:

$$C(t) = \frac{(dQ/dx)_{Reference}}{(dQ/dx)_{Global}}$$

$(dQ/dx)_{Reference}$ – Selected reference *dQ*/*dx* value

$(dQ/dx)_{Global}$ – Global *dQ*/*dx* value in the anode wire plane after correcting for YZ plane and drift direction irregularities

Backup—dE/dx

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$$\left(\frac{dE}{dx}\right)_{corr.} = \frac{\exp\left(\frac{\left(\frac{dQ}{dx}\right)_{corr.}}{C} \cdot \frac{\beta' W_{ion}}{\rho \xi}\right) - \alpha}{\frac{\beta'}{\rho \xi}}$$

- C: Calibration constant to convert ADC values to number of electrons
- W_{ion}: 23.6×10^{-6} MeV/electron (work function of argon)
- ξ: 0.273 kV/cm (MicroBooNE drift electric field)
- ρ: 0.212 (kV/cm)(g/cm^2)/MeV
- α: 0.93

} ArgoNeuT: JINST 8, P08005 (2013)

$$\chi^2 = \Sigma\left(\frac{(MPV(dE/dx)_{prediction} - MPV(dE/dx)_{Measured})^2}{\sigma^2}\right)$$