Signal Processing & TPC simulation for single-phase LArTPCs

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Sep 16, 2019

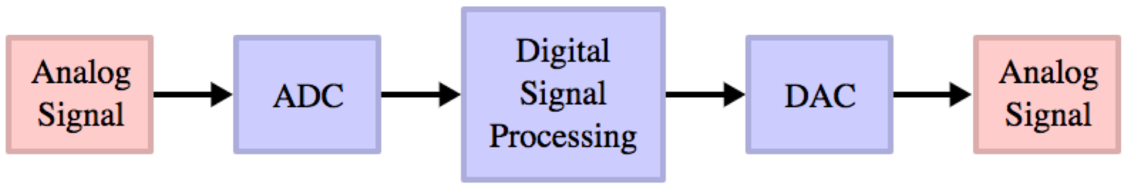
Workshop of Reconstruction and Machine Learning in Neutrino Experiments

@ DESY, Hamburg Germany

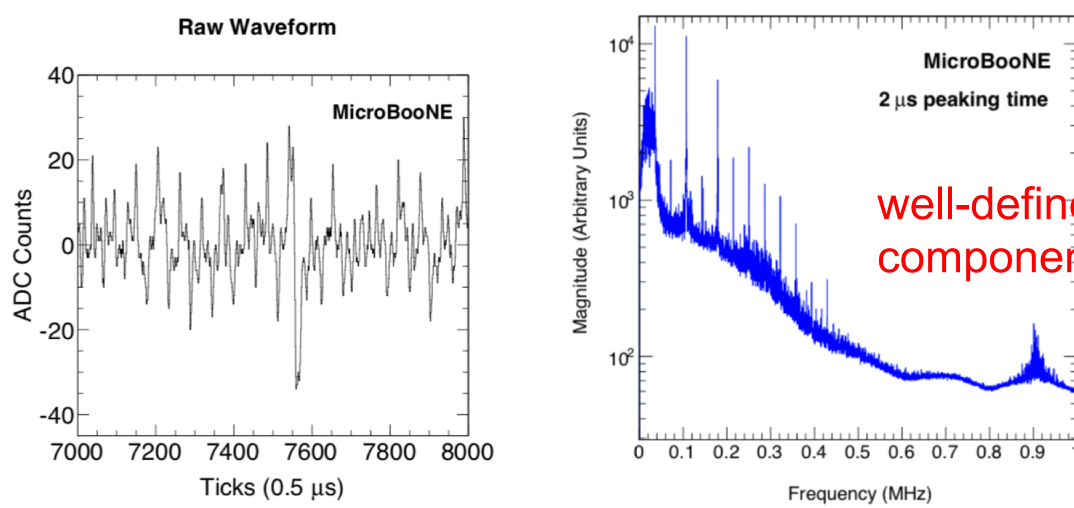
Signal Processing

An electrical engineering subfield that focuses on analyzing, modifying, and synthesizing signals.
The principles of signal processing can be found in the classical numerical analysis techniques of the 17th century.

A typical digital processing system
(hardware + software architectures)

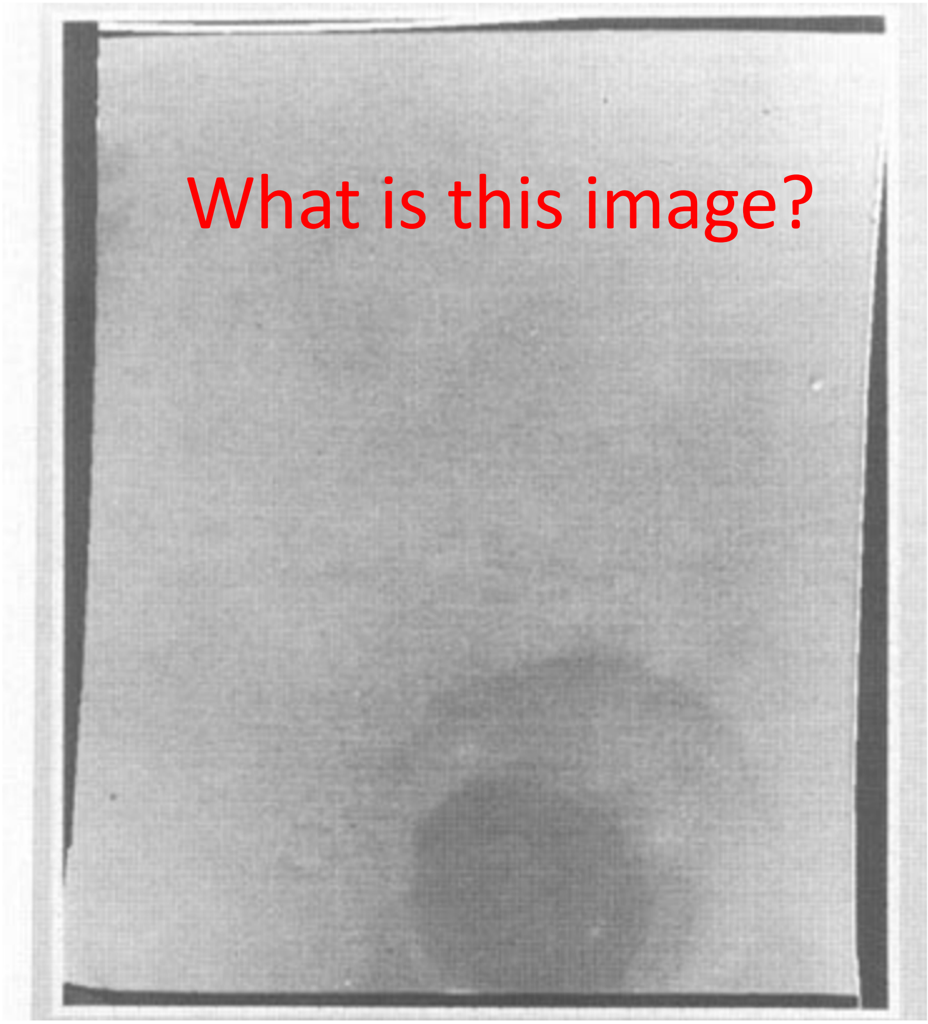


A typical signal processing technique in waveform analysis: Fourier Transform



Signal Processing

Widely used in image measurements and analyses such as medical imaging, astronomy imaging, …



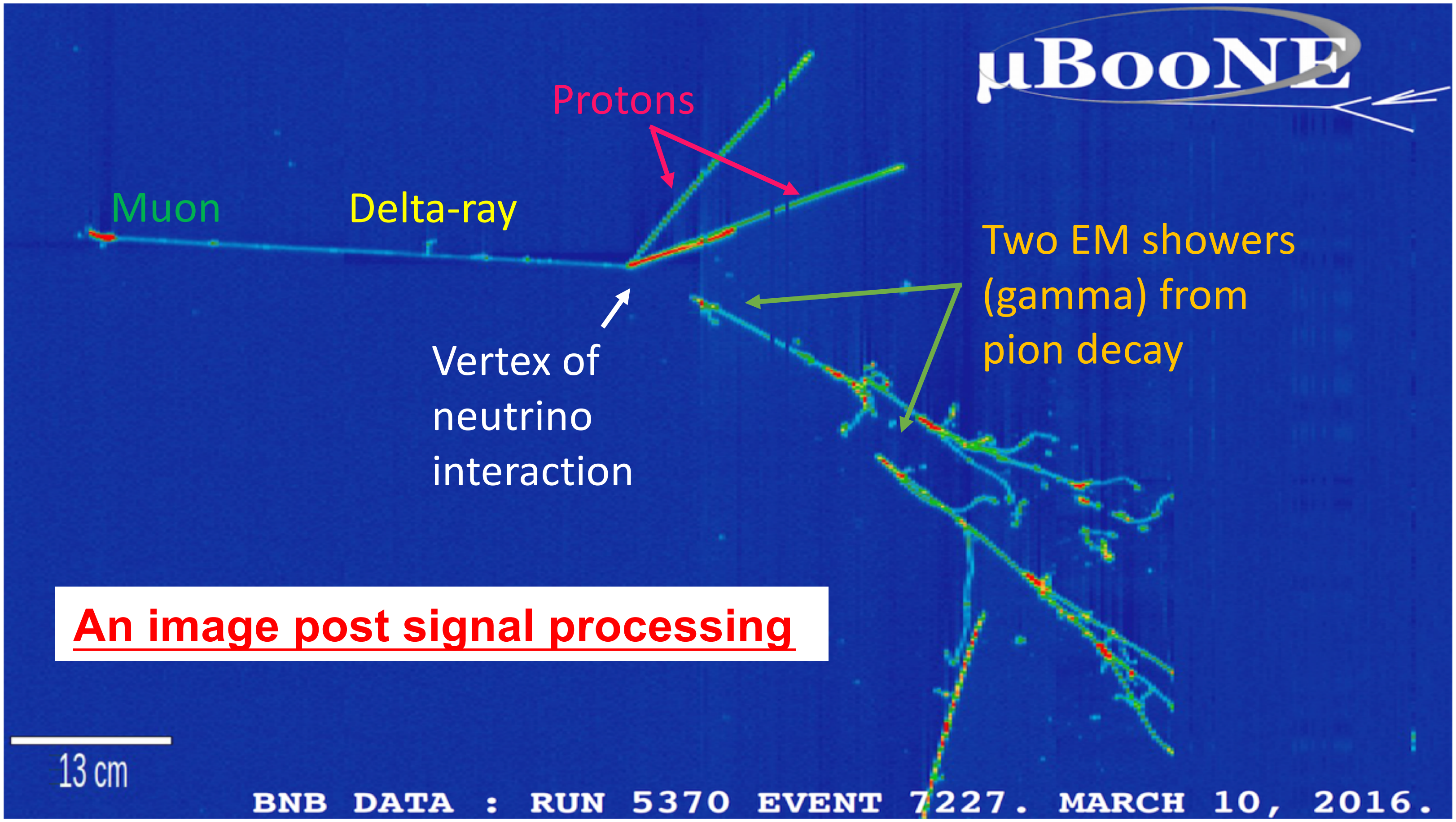
Signal Processing

Widely used in image measurements and analyses such as medical imaging, astronomy imaging, …

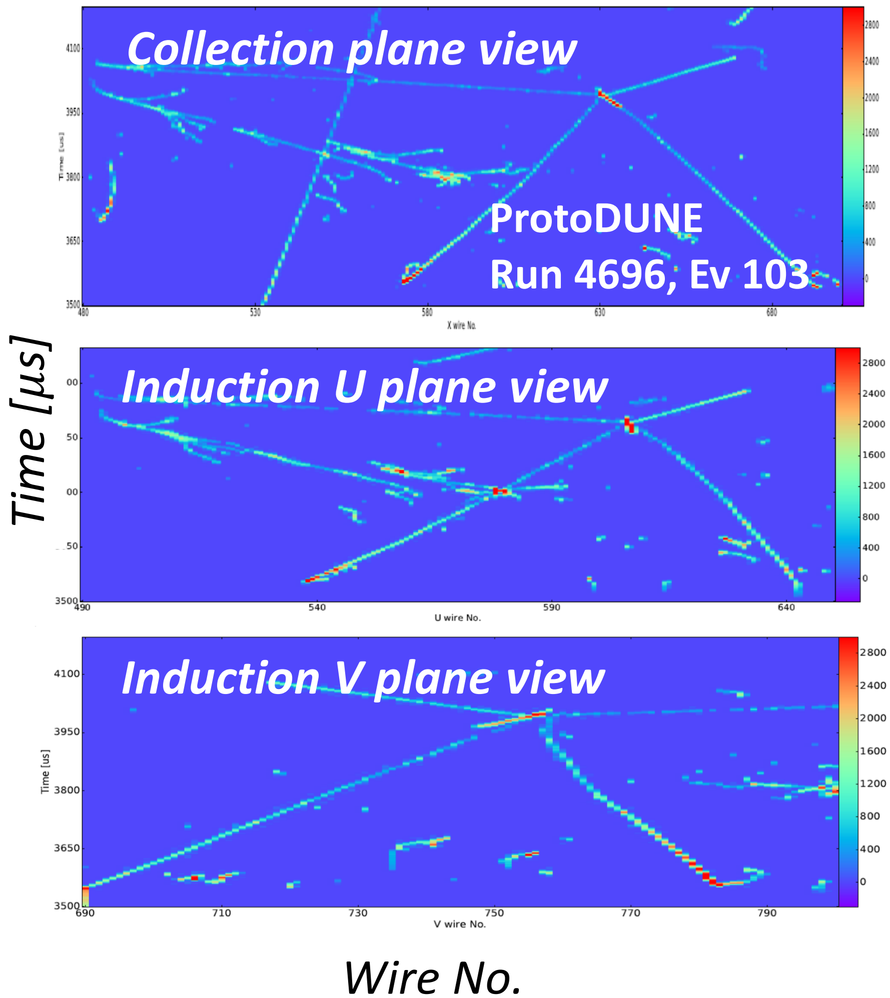
High-quality image with digital processing

Liquid Argon TPC (LArTPC)

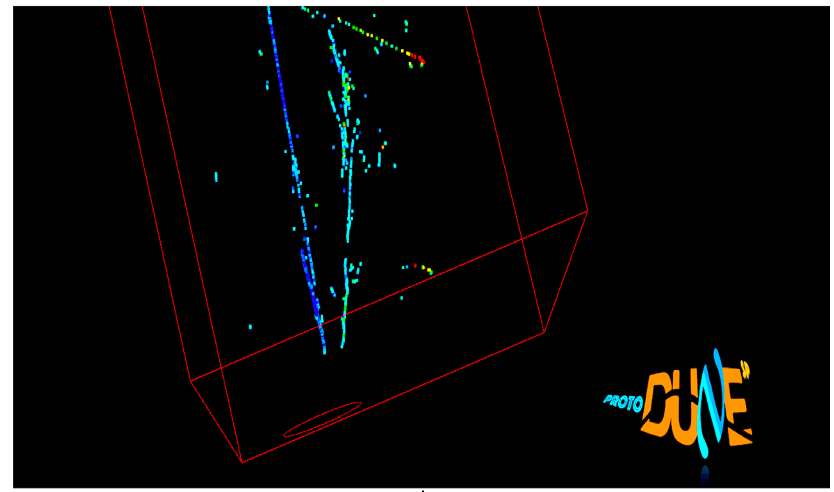
- A state-of-the-art neutrino detector technology with excellent **3D tracking** & **calorimetry** for charged final state particles of neutrino interactions
- LArTPC experiments: MicroBooNE, SBND, ICARUS, ProtoDUNE/DUNE
- **Particle imaging detector**



LArTPC Signal Processing



2 EM showers and a pion interaction with 4 outgoing particles

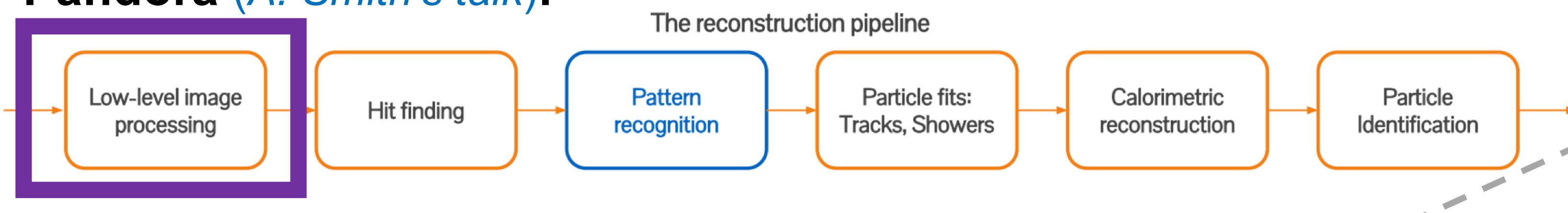


Foundation to high-level 3D event reconstruction

Three 2D images (time vs wire) from three wire planes post signal processing

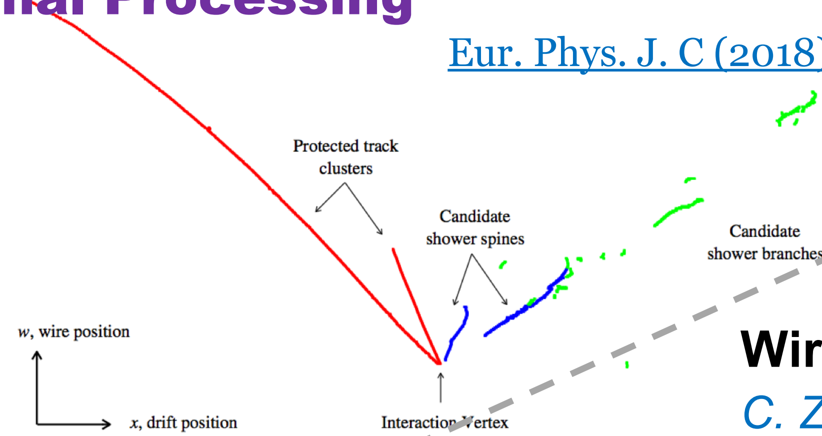
Connections to traditional approaches

Pandora *(A. Smith's talk)*:

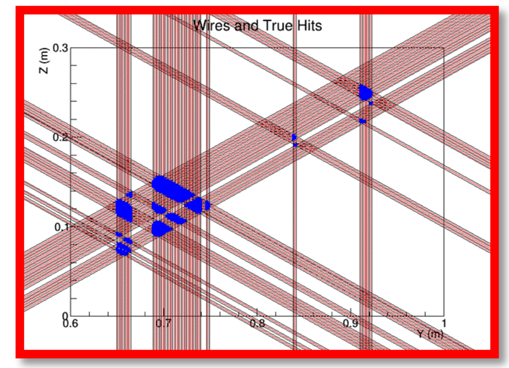


Signal Processing

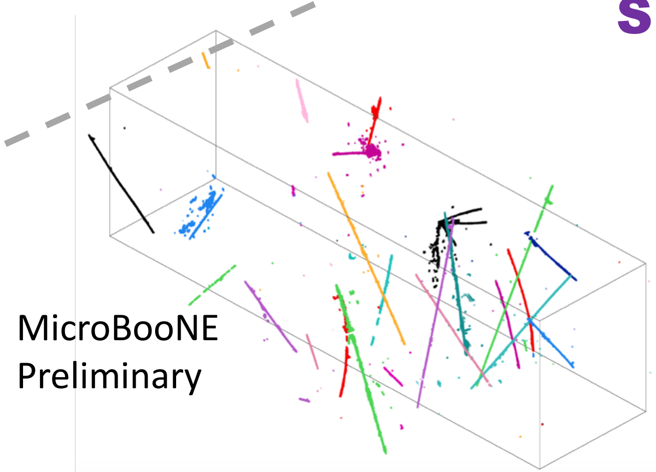
[Eur. Phys. J. C (2018) 78:82]



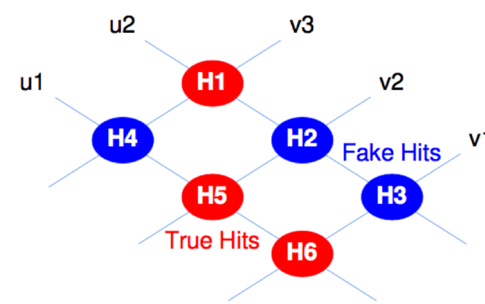
Wire-Cell *(C. Backhouse and C. Zhang's talks)*:



Signal Processing



$$\boxed{\begin{pmatrix} u1 \\ u2 \\ v1 \\ v2 \\ v3 \end{pmatrix}} = \begin{pmatrix} 0 & 0 & 0 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} H1 \\ H2 \\ H3 \\ H4 \\ H5 \\ H6 \end{pmatrix}$$

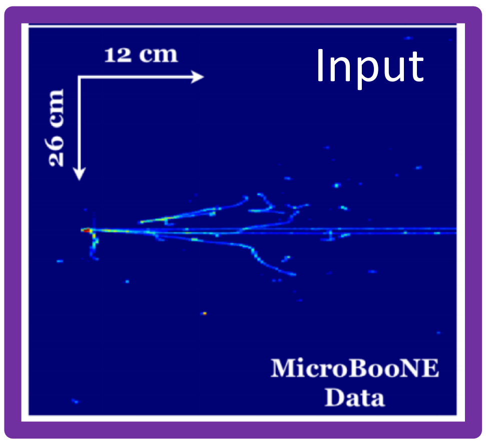


Under-determined linear equation

[JINST 13, P05032 (2018)]

Connections to machine learning

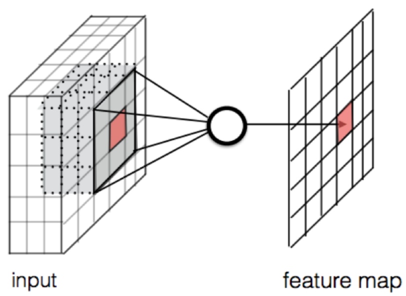
- Facilitate the feature engineering (fundamental to machine learning): robustly decouple the common features (detector response) in the input
- Signal processing (deconvolution) ↔ TPC simulation (convolution)
- The knowledge gained in the development of signal processing feeds back to the TPC simulation introducing a well-behaved machine-learning training samples



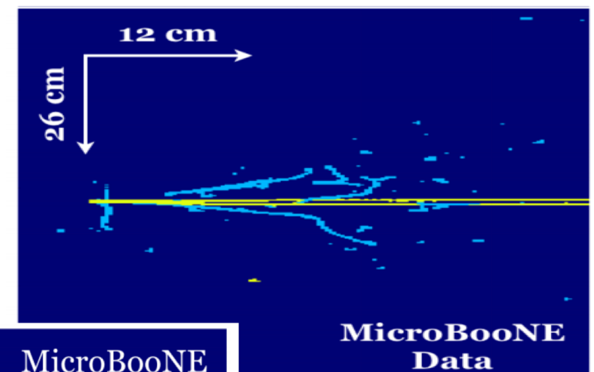
Signal Processing

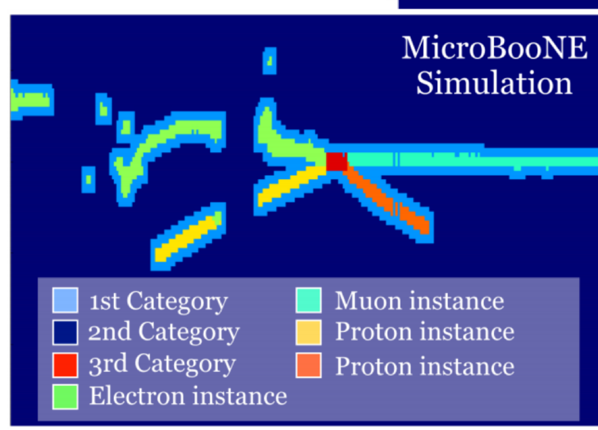
1. 2017 JINST 12 P03011
2. Phys. Rev. D 99, 092001

Deep learning (tomorrow's *talks*):



Track/Shower Identification

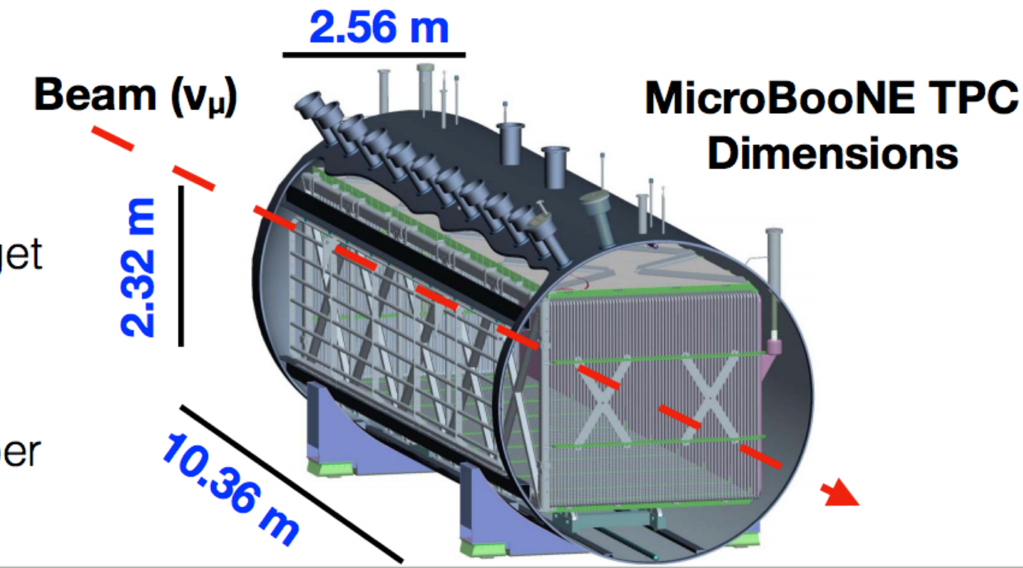




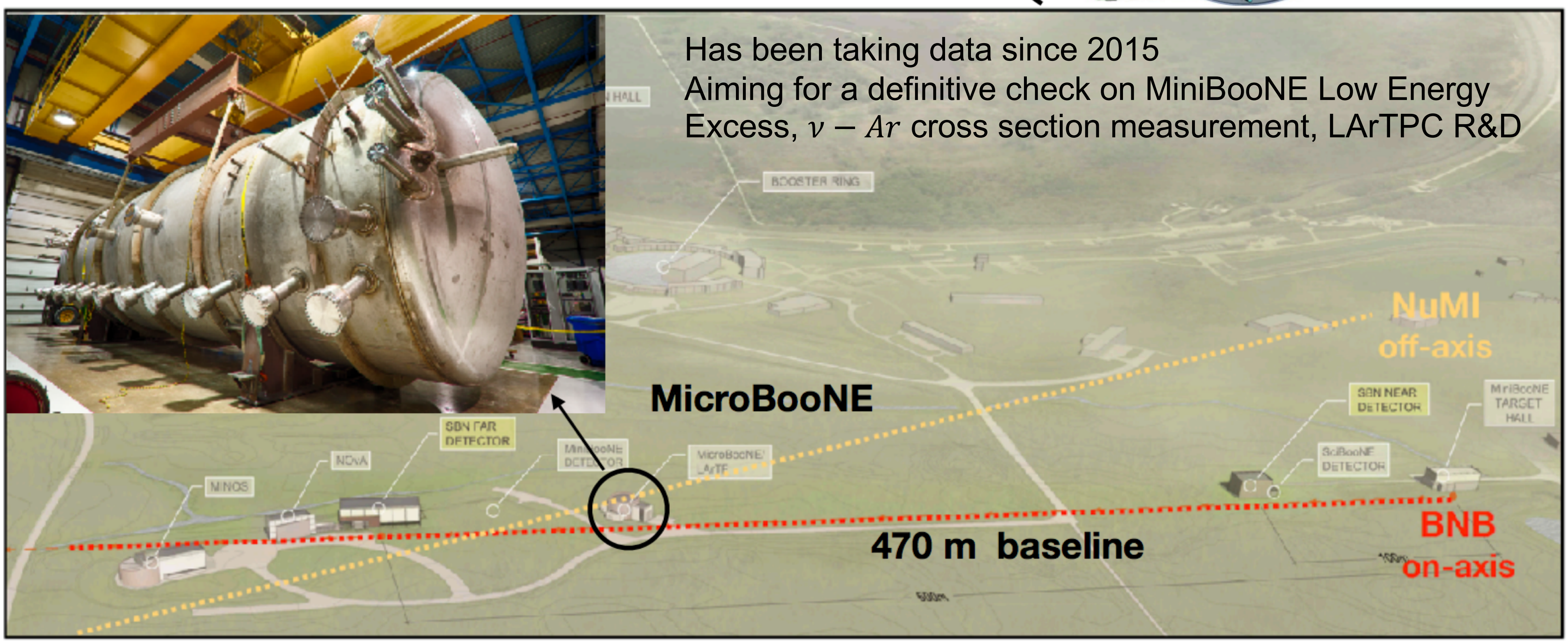
Particle Identification

The MicroBooNE Experiment

- Accelerator ν experiment
- 8 GeV proton beam on beryllium target
- 800 MeV ν energy on average
- 470 m baseline
- Liquid Argon Time Projection Chamber (LArTPC) with 85 ton active mass

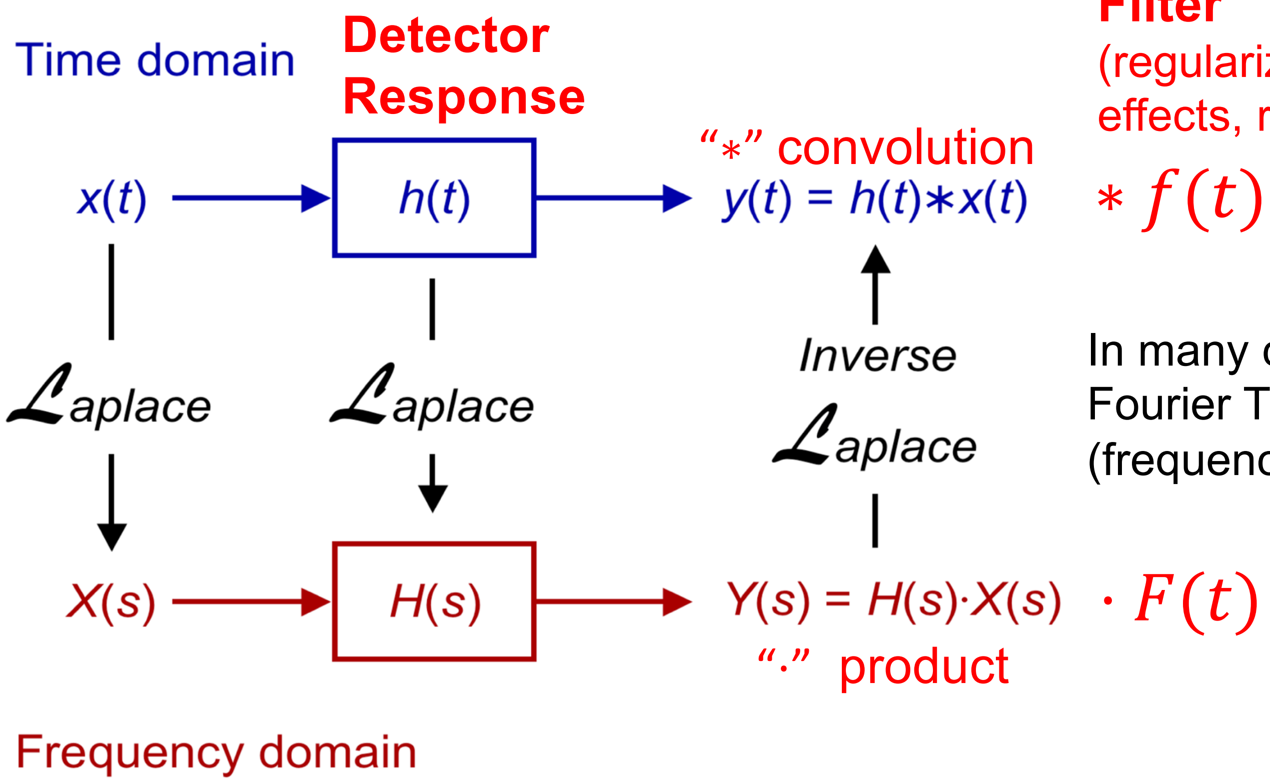


Has been taking data since 2015
Aiming for a definitive check on MiniBooNE Low Energy Excess, $\nu - Ar$ cross section measurement, LArTPC R&D



How Signal Processing Works

Linear time-invariant system (sensors, electronics, etc.)



Filter
(regularization, remove artificial effects, reduce noise)

In many cases,
Fourier Transform utilized
(frequency analysis)

Signal Processing always refer to a deconvolution

$$X(s) = \frac{Y(s)}{H(s)} \qquad S(\omega) = \frac{M(\omega)}{R(\omega)}$$

(In physics analysis)

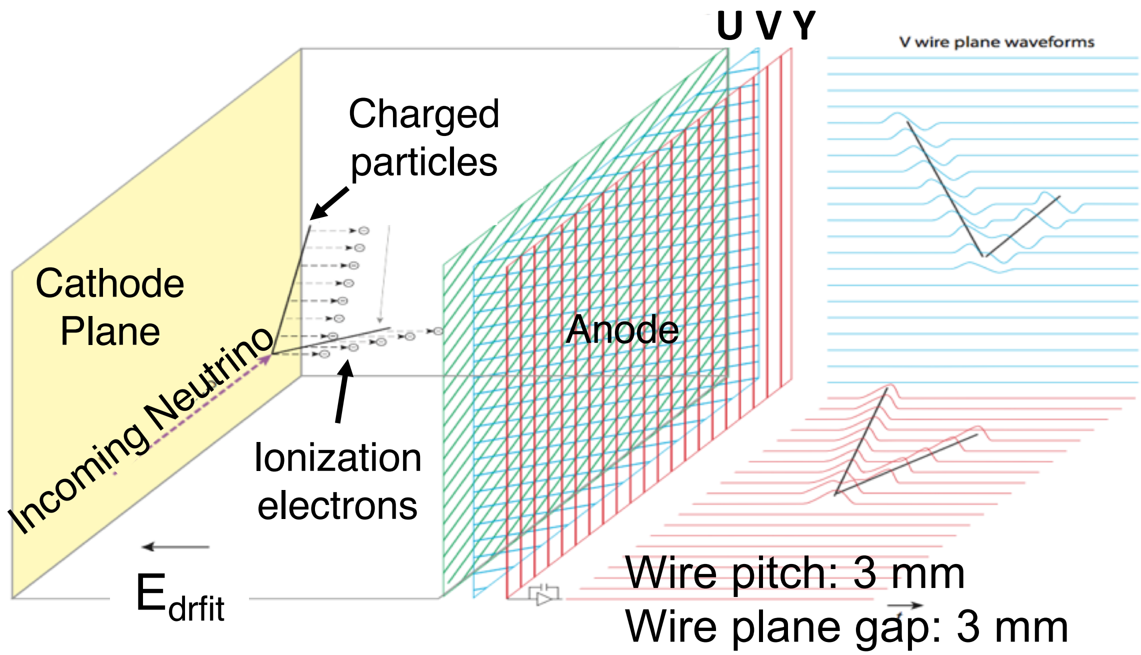
LArTPC Signal Processing

$$S = \frac{M}{R}$$

S: ionization electrons arriving at the anode plane (post attenuation & diffusion)

M: ADC waveforms from all wires

R: sense wire response (field response), electronics response



Photon sensors to detect scintillation light (t0 tagging)

LArTPC Signal Processing

$$\boldsymbol{S} = \frac{\boldsymbol{M}}{\boldsymbol{R}}$$

$\boldsymbol{S}$: ionization electrons arriving at the anode plane (post attenuation & diffusion)

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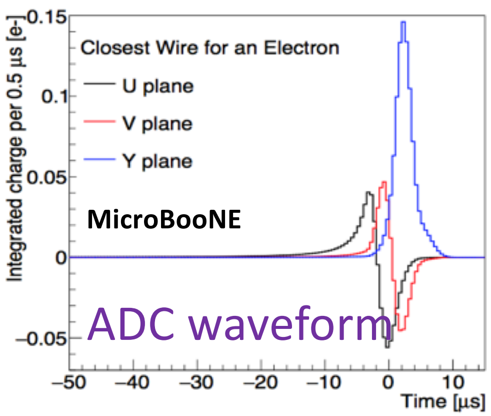
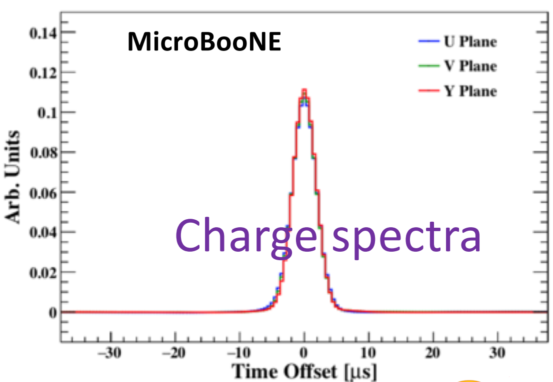
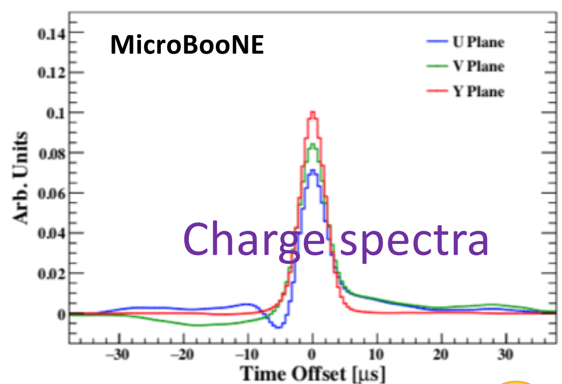


Typical waveform for a wire

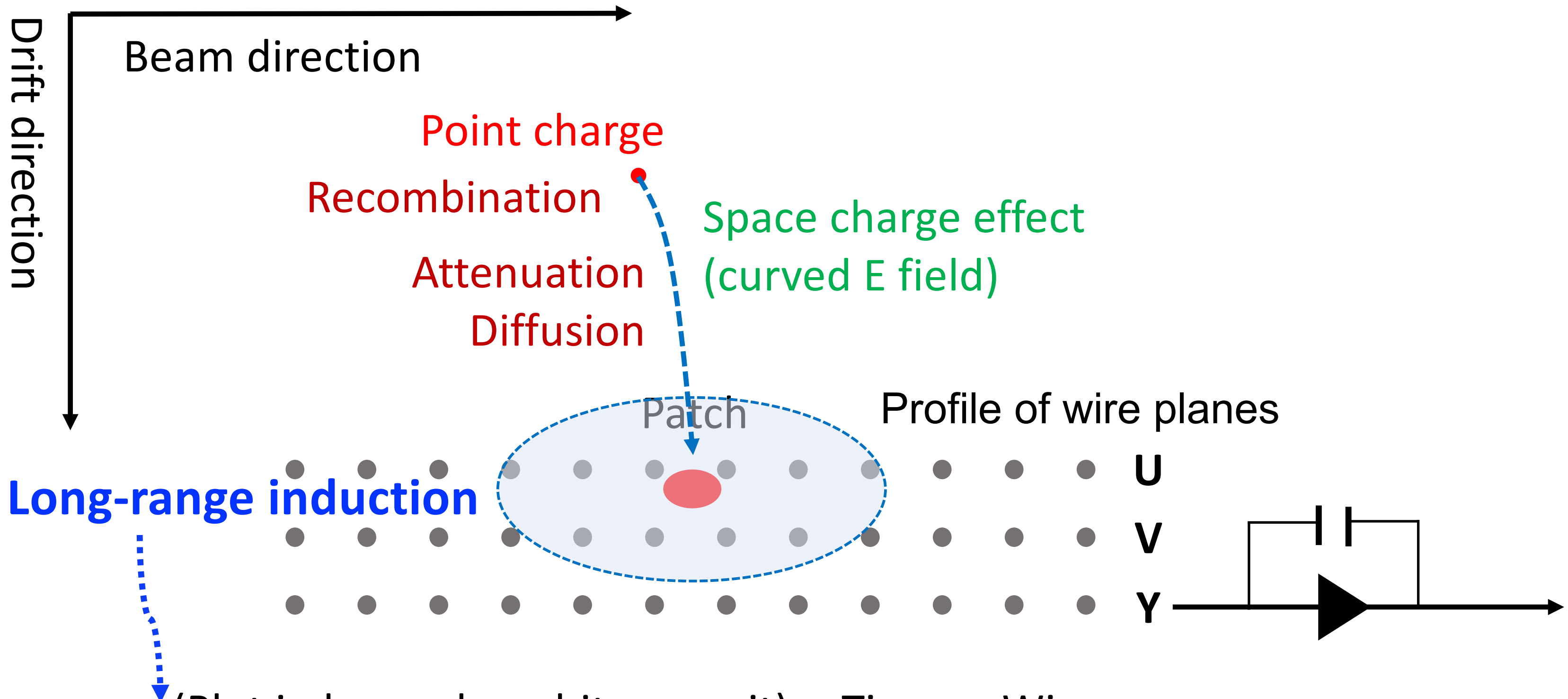


What we expect 😀

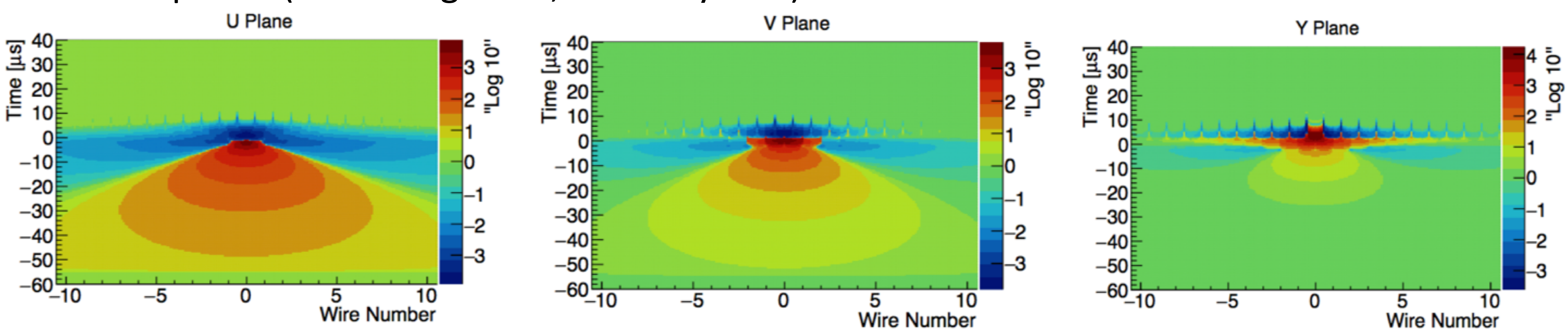


What we obtained 😟?

TPC Signal Formation



Field response (Plot in log scale, arbitrary unit) -- Time vs Wire



From Garfield 2D simulation

LArTPC Signal Processing

$$\boldsymbol{S} = \frac{\boldsymbol{M}}{\boldsymbol{R}}$$

$\boldsymbol{S}$: ionization electrons arriving at the anode plane (post attenuation & diffusion)

$\boldsymbol{M}$: ADC waveforms from all wires

$\boldsymbol{R}$**: sense wire response (field response)**, electronics response

$$\boldsymbol{M} = \boldsymbol{R} \cdot \boldsymbol{S}$$

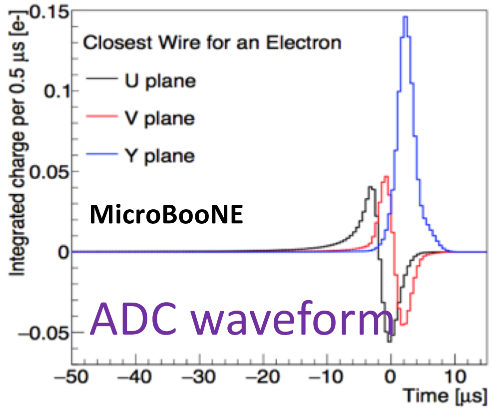
$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \vdots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \dots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \dots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{n-2}(\omega) & R_{n-3}(\omega) & \dots & R_0(\omega) & R_1(\omega) \\ R_{n-1}(\omega) & R_{n-2}(\omega) & \dots & R_1(\omega) & R_0(\omega) \end{pmatrix} \cdot \begin{pmatrix} S_1(\omega) \\ S_2(\omega) \\ \vdots \\ S_{n-1}(\omega) \\ S_n(\omega) \end{pmatrix}$$

Wire dimension

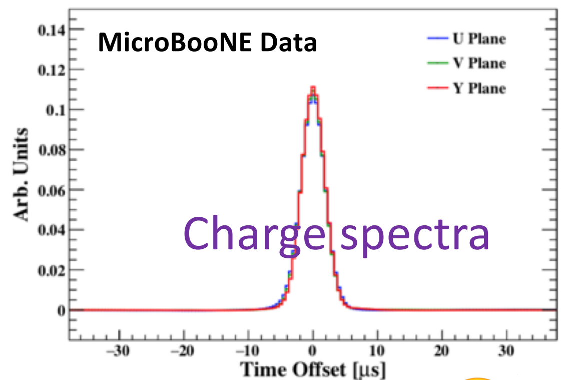
M_i, S_i: waveform, charge on the ith wire

R_j: response on the jth adjacent wire (**field response ⊗ electronics response**)

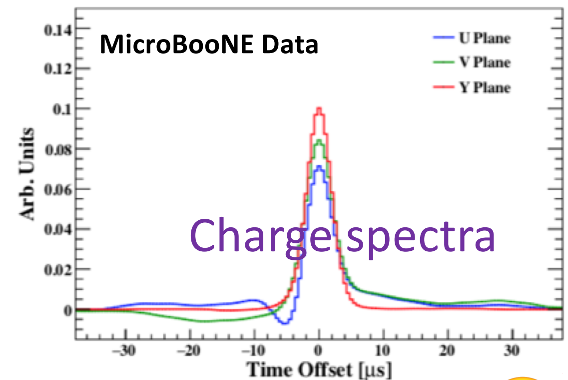
2D vs 1D signal processing



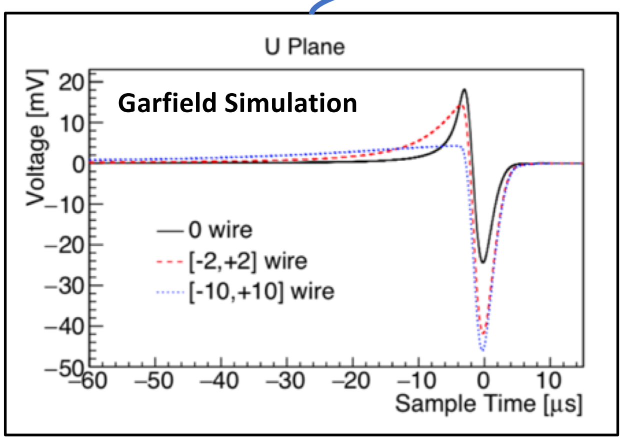
Typical waveform for a wire



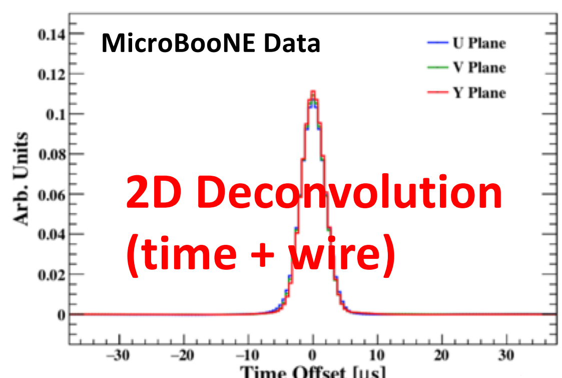
What we expect

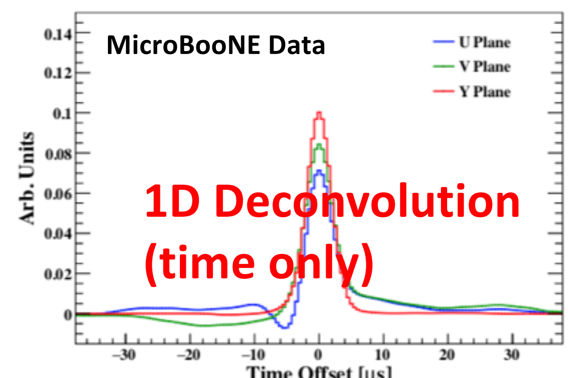


What we obtained

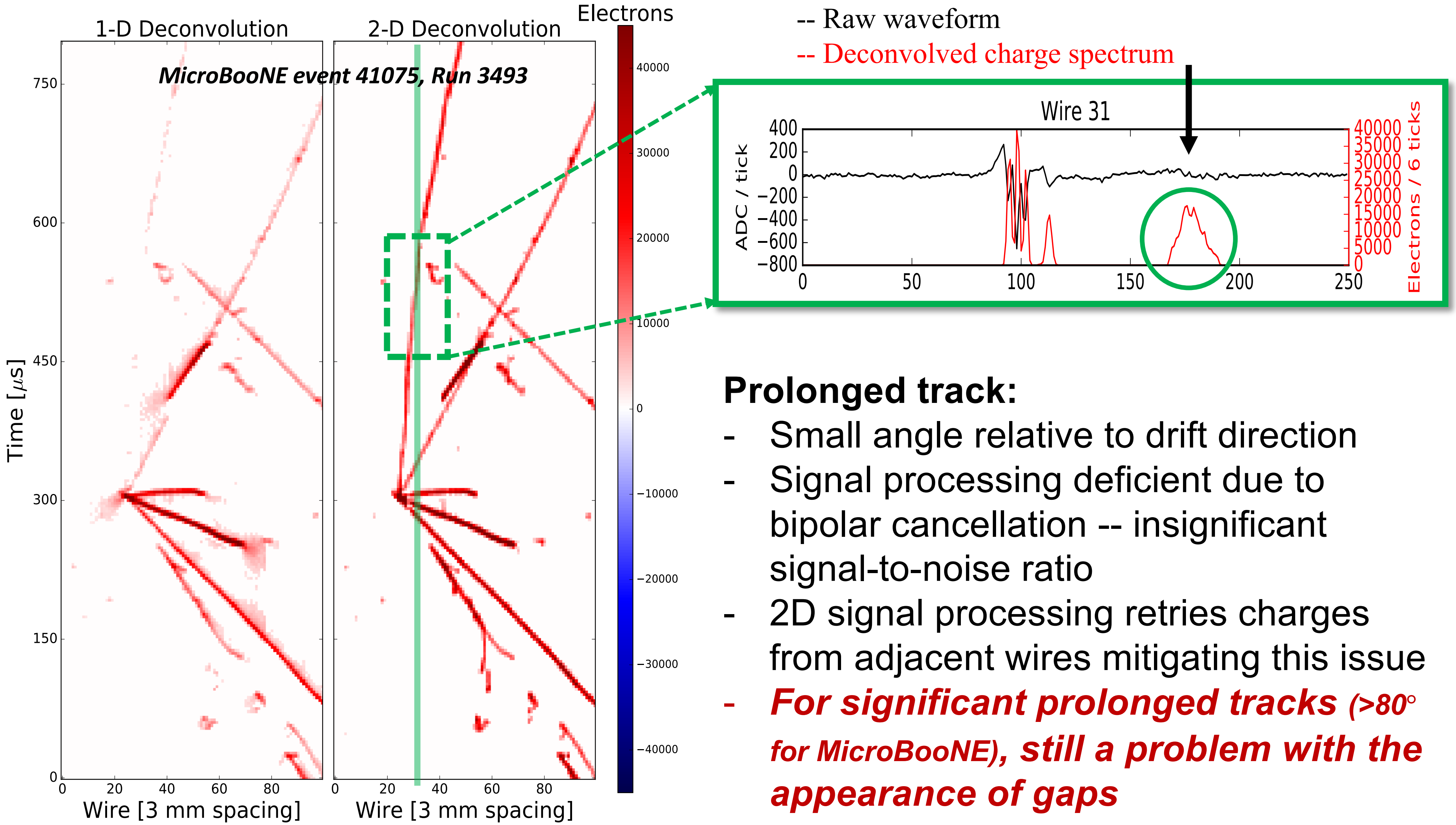


Adjacent wire contribution
(U plane as an example)





2D vs 1D signal processing



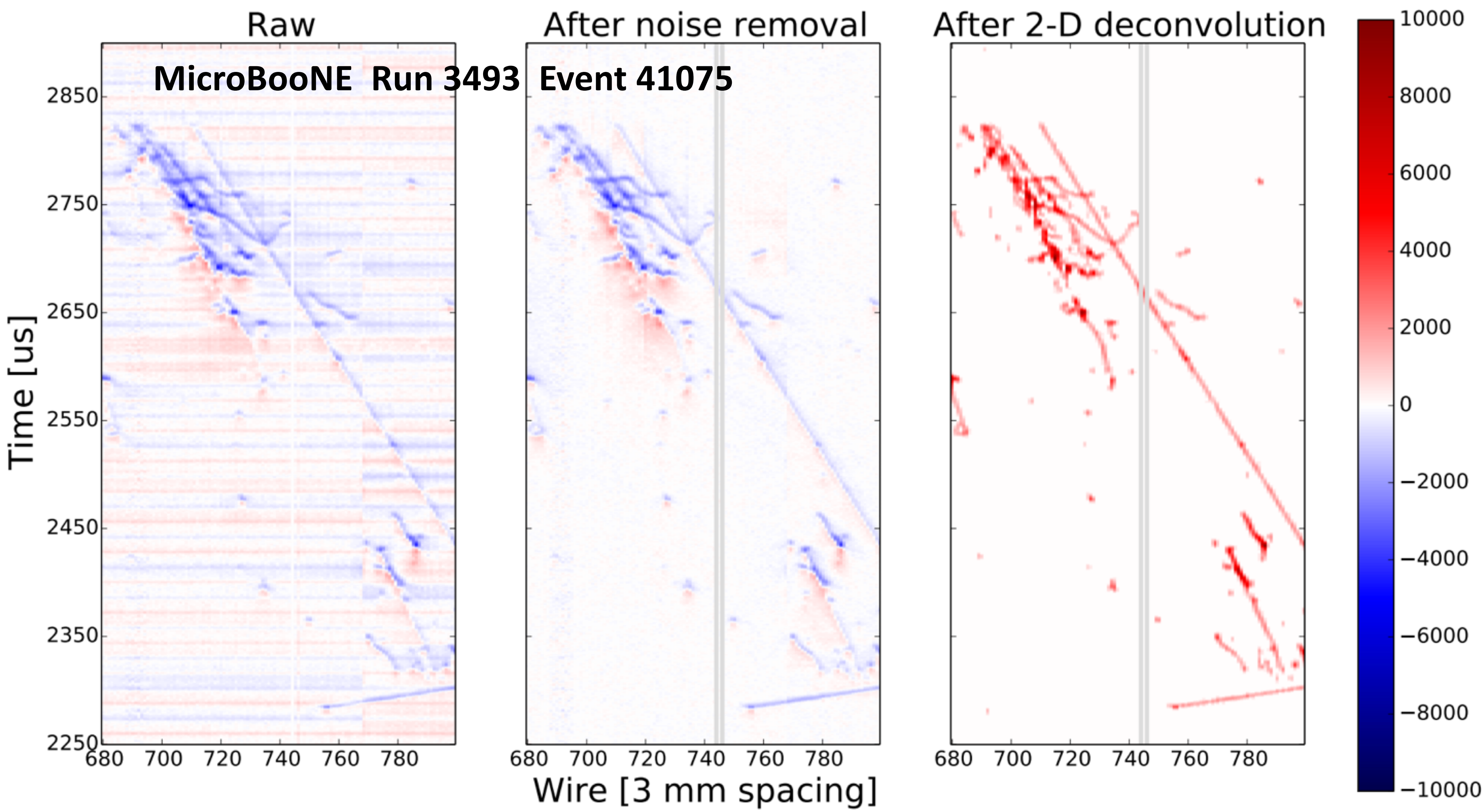
Prolonged track:

- Small angle relative to drift direction
- Signal processing deficient due to bipolar cancellation -- insignificant signal-to-noise ratio
- 2D signal processing retries charges from adjacent wires mitigating this issue
- ***For significant prolonged tracks (>80° for MicroBooNE), still a problem with the appearance of gaps***

Event display of an EM shower

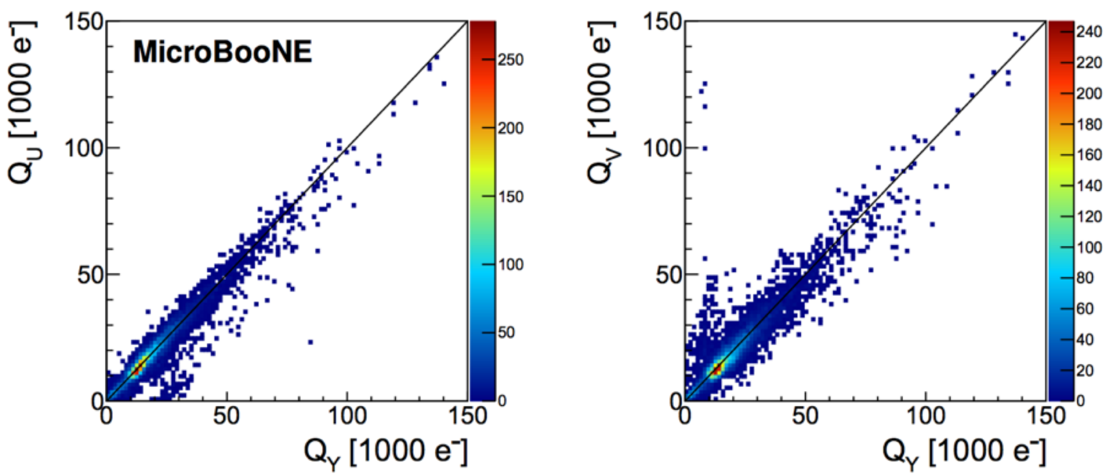
Data

https://lar.bnl.gov/magnify/#/event/uboone-3493-041075



Merits of 2D signal processing

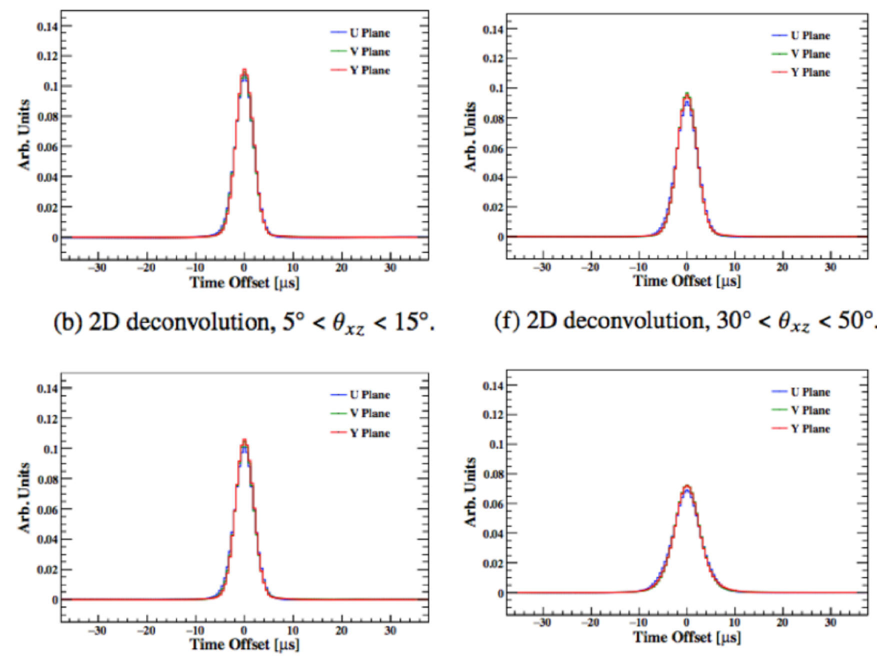
Induction plane = collection plane
Realize the identical “sense” of charge for all wire planes



~10% smear originating from electronics noise
Deviation due to the imperfection of detector

Consistent amount of charge.

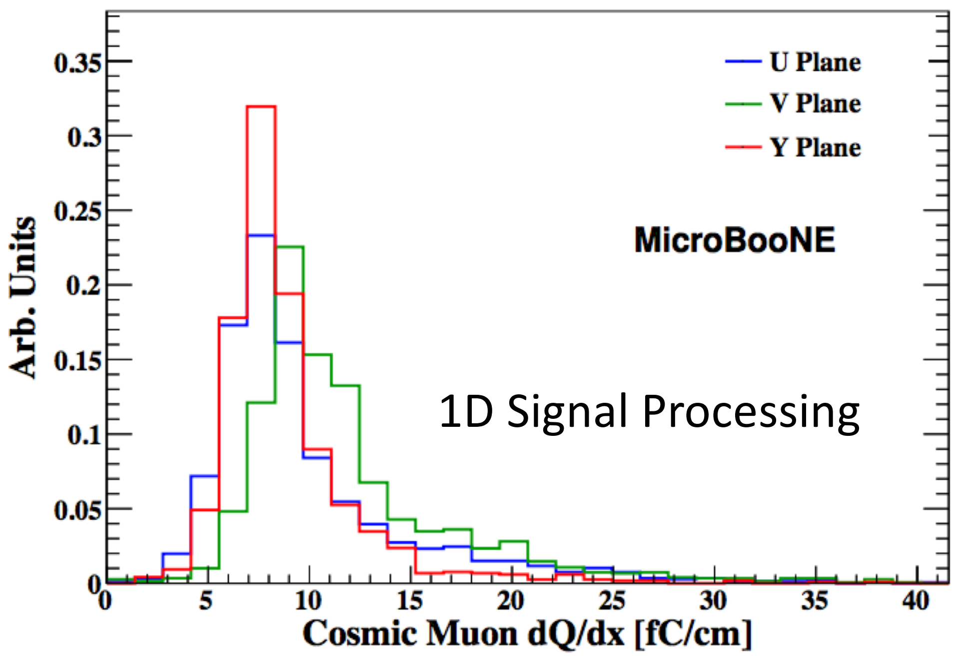
Consistent shape.



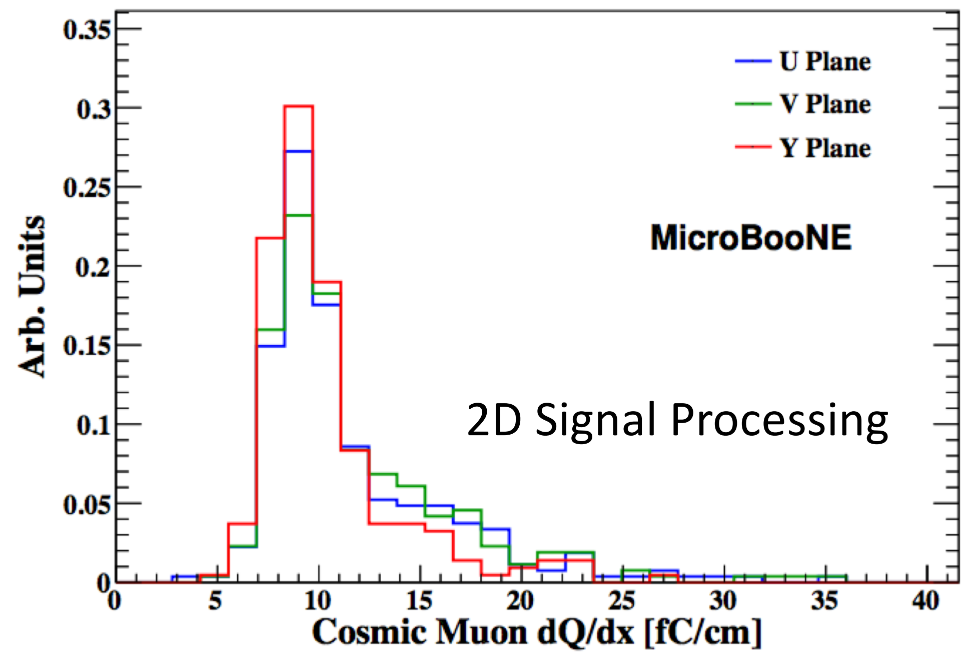
(b) 2D deconvolution, $5° < \theta_{xz} < 15°$.
(f) 2D deconvolution, $30° < \theta_{xz} < 50°$.
(d) 2D deconvolution, $15° < \theta_{xz} < 30°$.
(h) 2D deconvolution, $50° < \theta_{xz} < 70°$.

Data

Cosmic-muon dQ/dx

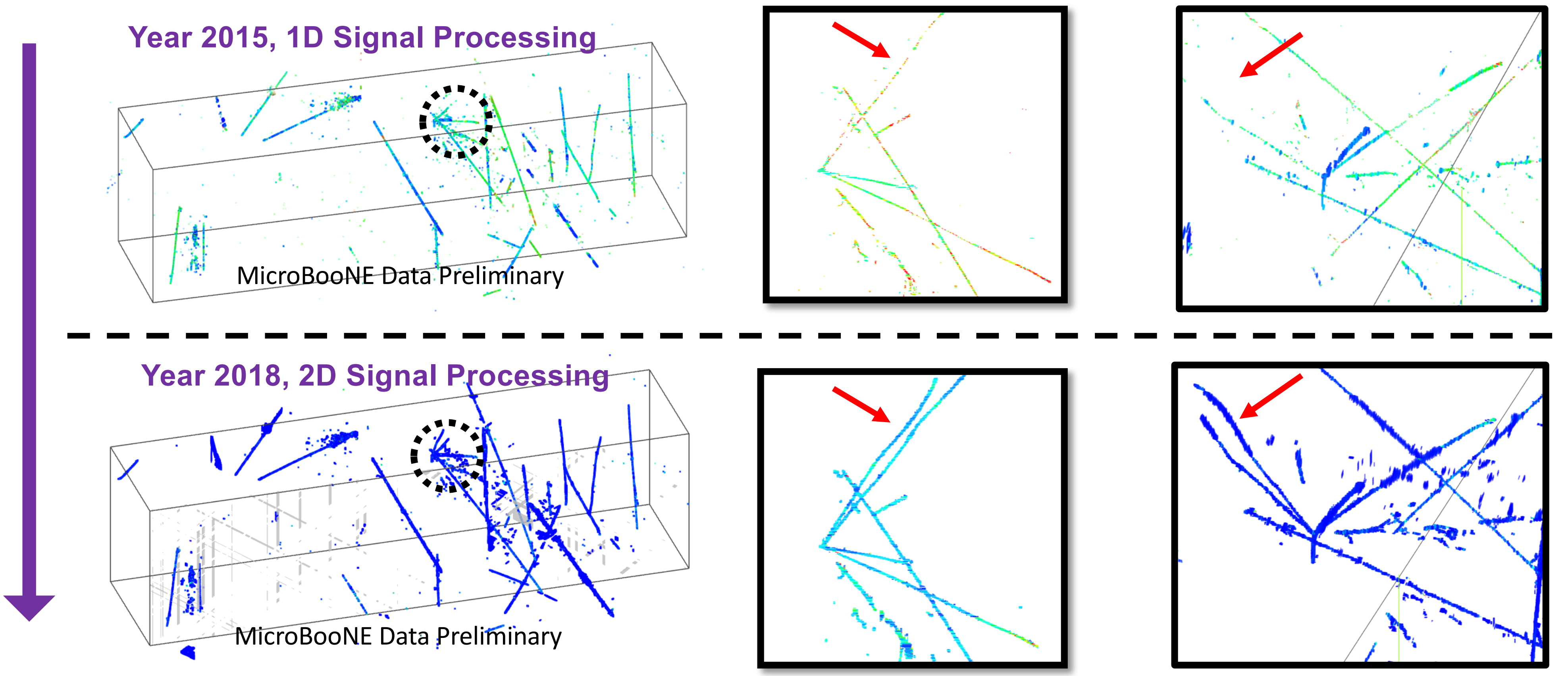


(a) Cosmic muon dQ/dx distribution for the case of the 1D deconvolution.



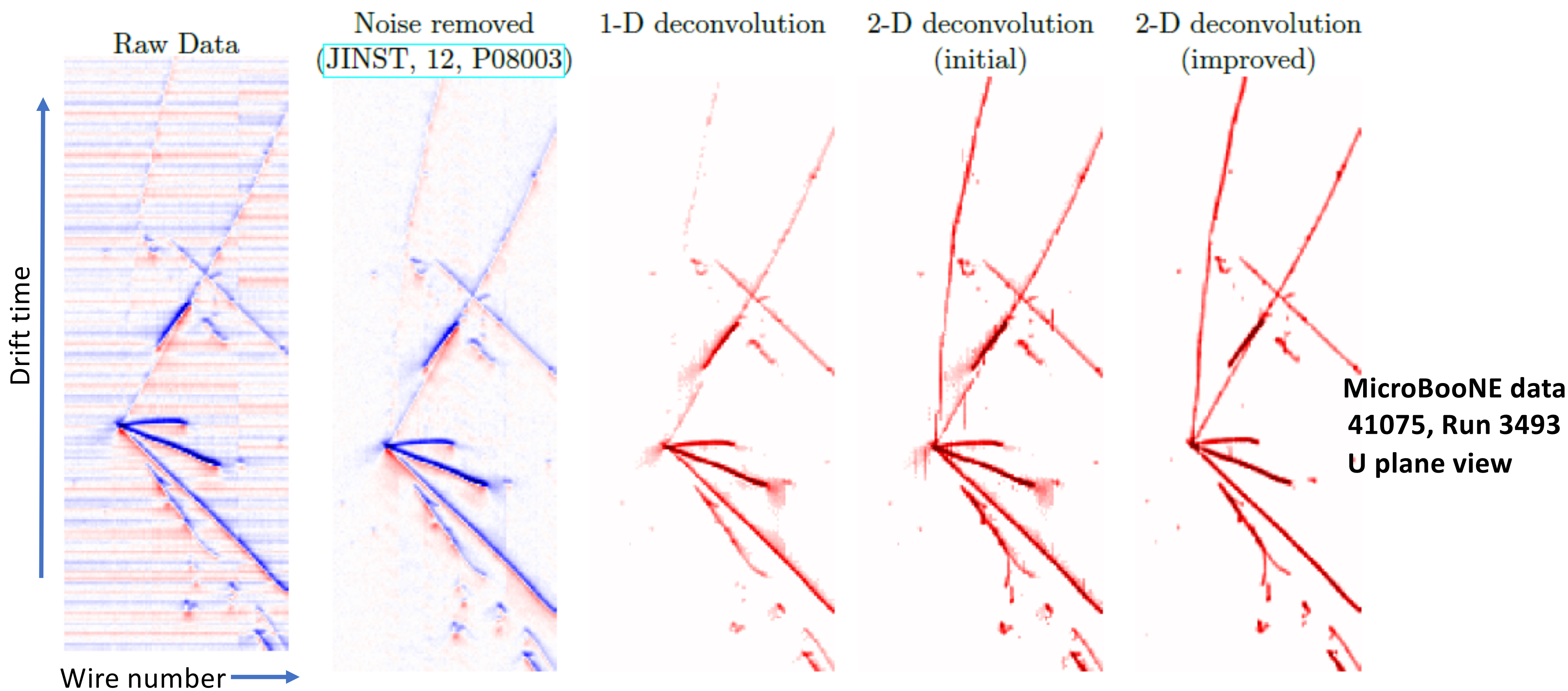
(b) Cosmic muon dQ/dx distribution for the case of the 2D deconvolution.

Wire-Cell 3D Imaging (see C. Zhang's talk)



- 2D Signal Processing significantly enhanced the efficiency (continuous & uniform lines)

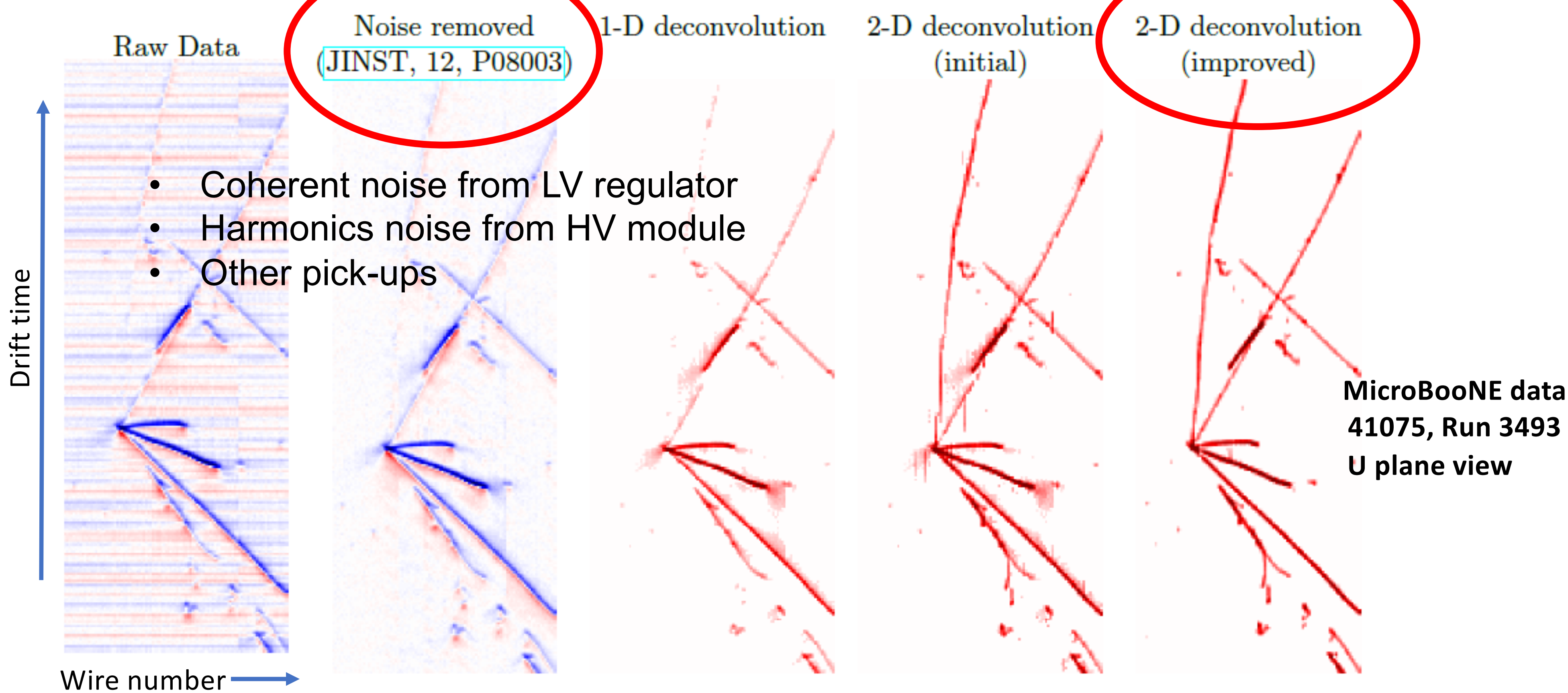
Evolution of Signal Processing



Summarized in JINST 13 P07006 and JINST 13 P07007

Evolution of Signal Processing

Excess noise removal **ROI finding improvement**



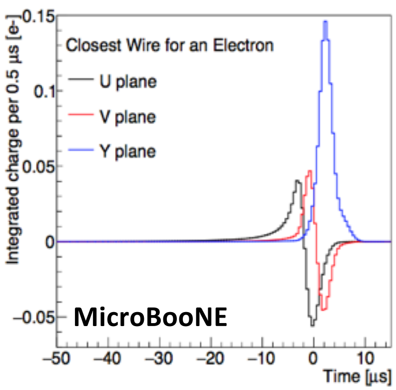
- Coherent noise from LV regulator
- Harmonics noise from HV module
- Other pick-ups

Summarized in JINST 13 P07006 and JINST 13 P07007

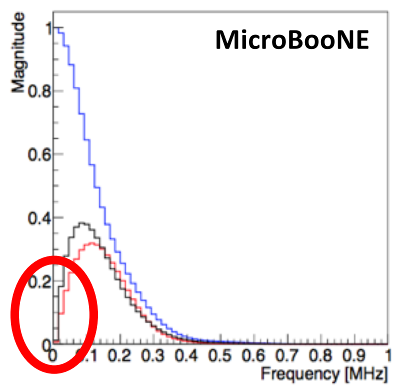
ROI (Region of Interest) finding

$$R^{-1} \cdot M \cdot Filter = \boldsymbol{S \cdot Filter} + (R^{-1} \cdot Noise \cdot Filter)$$

- For collection plane, ROI finding is trivial which bases on the threshold determined by noise RMS
- Unfortunately, for induction planes, the second term ($R^{-1} \cdot Noise \cdot Filter$) is still significant due the low-frequency noise amplification. Various low-freq filters are jointly applied to suppress the noise and obtain an efficient signal ROI finding



(a) Average response in time domain.



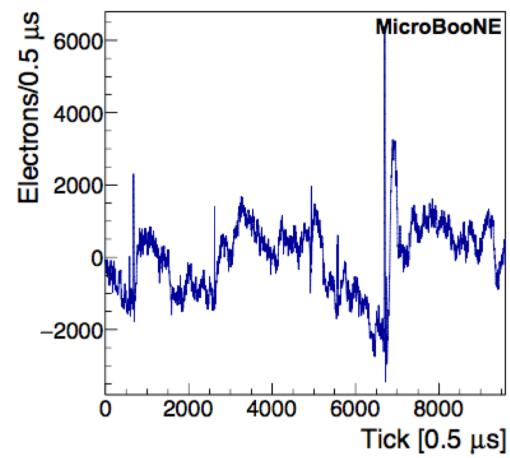
(b) Average response in frequency domain.

Bipolar field response

→ small low freq component

$$S(\omega) = \frac{M(\omega)}{R(\omega)}$$

→ amplify the low freq noise



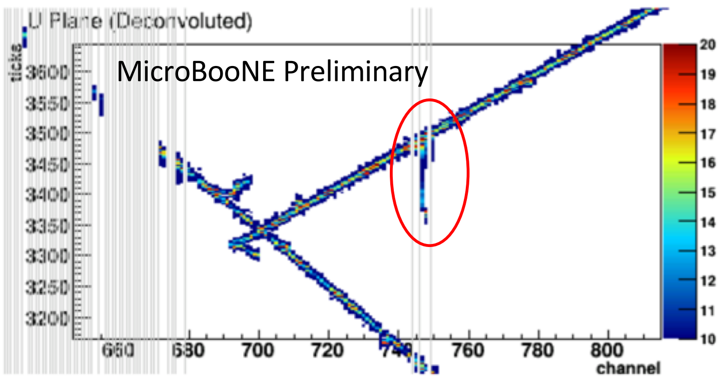
(a) Without low-frequency filter.

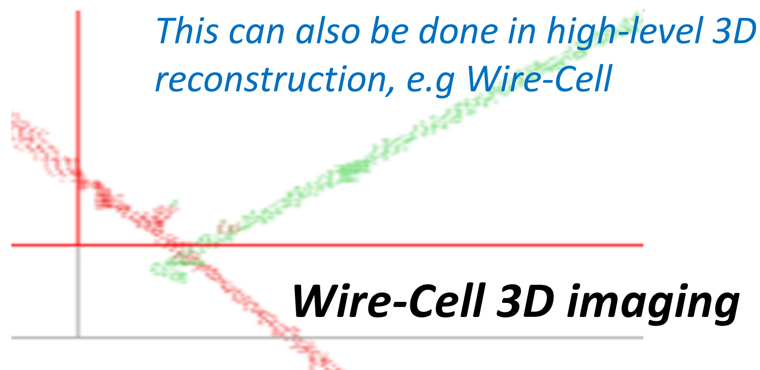
Further improvements (ongoing)

Match ROIs from all wire planes to suppress the “fake” charge hits

In one wire plane (2D view) the artificial effects are less likely to appear in the other wire plane views

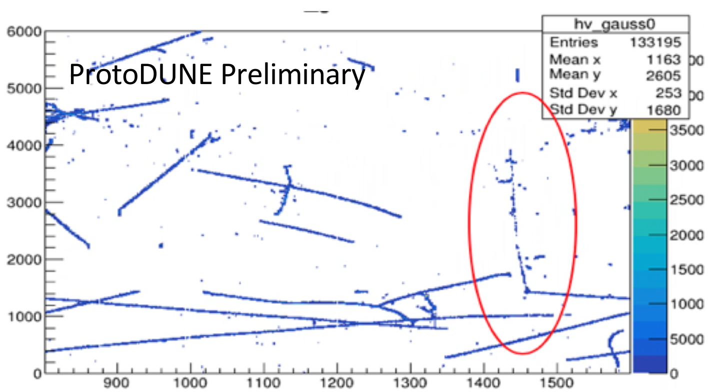
Tear drops – dead channel boundary effect or noise

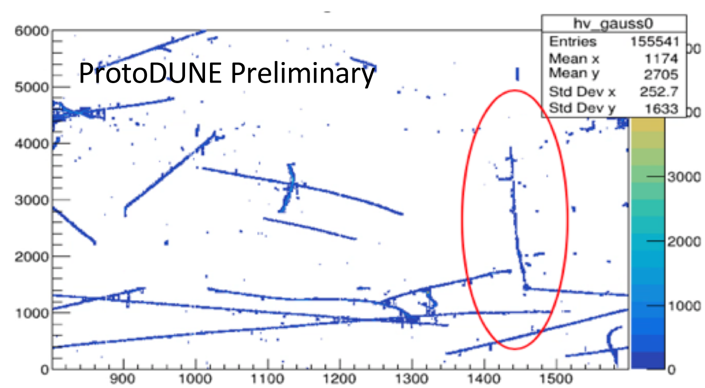




This can also be done in high-level 3D reconstruction, e.g Wire-Cell

Prolonged tracks – low signal-to-noise ratio in one wire plane view





TPC simulation

Initial distribution of ionization electrons
(with space charge effect, recombination)

dE/dx → dQ/dx

$\otimes$

Diffusion (Gauss, ~mm)
Absorption (electron lifetime ~ms)

TPC Simulation
-- input charge deposition
output ADC raw waveforms

$\otimes$

Signal Processing

Field response
(long-range induction ~cm)

$\otimes$

Electronics response
(ASIC, RC filter, ADC, etc.)

+

Inherent Noise (ASIC) + Excess Noise

TPC simulation

Initial distribution of ionization electrons
(with space charge effect, recombination)

dE/dx → dQ/dx

⊗

Diffusion (Gauss, ~mm)
Absorption (electron lifetime ~ms)

TPC Simulation
-- input charge deposition
output ADC raw waveforms

⊗

Signal Processing

Field response
(long-range induction ~cm)

⊗

Electronics response
(ASIC, RC filter, ADC, etc.)

+

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TPC simulation

Initial distribution of ionization electrons
(with space charge effect, recombination)

dE/dx → dQ/dx

$\otimes$

Diffusion (Gauss, ~mm)
Absorption (electron lifetime ~ms)

$\otimes$

Signal Processing
2D deconvolution

2D (time + wire) Field response
(long-range induction ~cm)

TPC Simulation
2D convolution

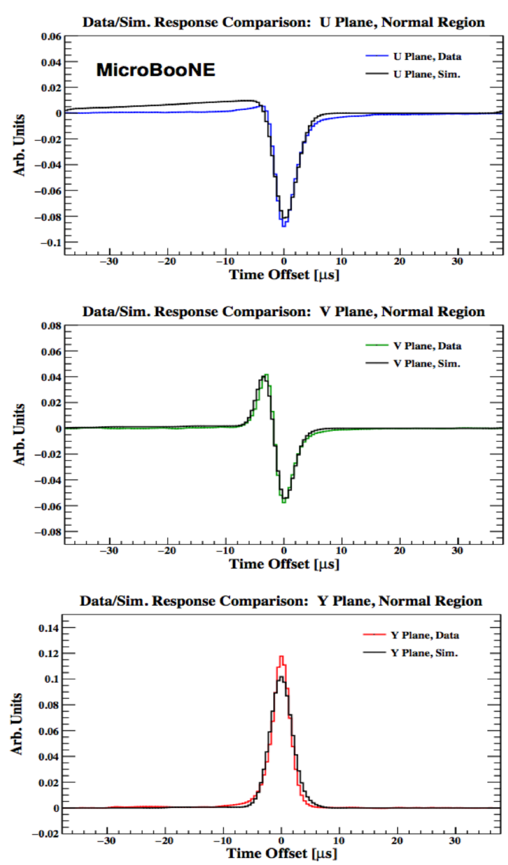
$\otimes$

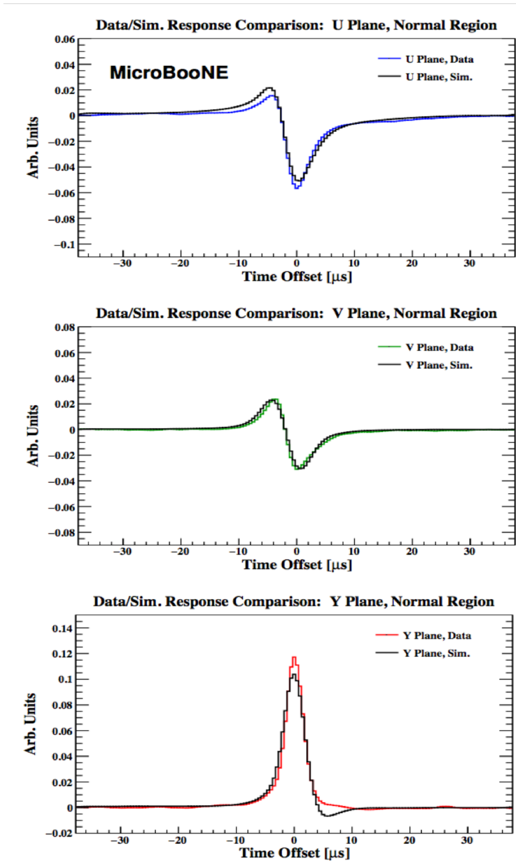
$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \vdots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \ldots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \ldots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{n-2}(\omega) & R_{n-3}(\omega) & \ldots & R_0(\omega) & R_1(\omega) \\ R_{n-1}(\omega) & R_{n-2}(\omega) & \ldots & R_1(\omega) & R_0(\omega) \end{pmatrix} \cdot \begin{pmatrix} S_1(\omega) \\ S_2(\omega) \\ \vdots \\ S_{n-1}(\omega) \\ S_n(\omega) \end{pmatrix}$$

TPC Simulation

- Facts of 2D TPC simulation
  - Point charge → 2D Gaussian cloud → 0.5 us × 0.3 mm pixelization post diffusion ~100 pixels
  - Long-range & fine-grained 2D field response → 21 × 10 = 210 sub-pitch field responses
- Speed & Memory optimization
- A practical & reliable TPC simulation consistent with data (field response validation)

Isochronous track





Moderate angle track $(40 - 50°)$

Summary

- The signal processing (2D deconvolution + ROI finding) provides a solid foundation to fully utilize the capabilities of LArTPC
  - ✓ Improves the correlation of signals between multiple 1D projective wire readout and helps to resolve the degeneracies (where the charge is along the wire) and remove the noise (e.g. tear drops)
  - ✓ Is essential for 3D event reconstruction using tomographic concept (e.g. Wire-Cell, *see C. Zhang & X. Qian's talk*) and is expected to further enhance 3D reconstruction for techniques (Pandora, Deep-learning, etc.) that match the image in different 2D projection views.
- A TPC simulation with fine-grained 2D field response has been implemented to match the 2D signal processing and respects the long-range induction in real data
- Developed and applied in MicroBooNE
- Stay tuned for ProtoDUNE/DUNE, other LArTPCs
- Further improvements are underway

Main References

[1] MicroBooNE collaboration, R. Acciarri et al., *Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC*, JINST 12 (2017) P08003

[2] MicroBooNE collaboration, C. Adams et al. *Ionization Electron Signal Processing in Single Phase LArTPCs. I. Algorithm Description and Quantitative Evaluation with MicroBooNE Simulation*, JINST 13 (2018) P07006

[3] MicroBooNE collaboration, C. Adams et al., *Ionization Electron Signal Processing in Single Phase LArTPCs. II. Data/Simulation Comparison and Performance in MicroBooNE*, JINST 13 (2018) P07007

Backup slides

Overview of full TPC simulation

$$\boldsymbol{Wave} = (\boldsymbol{Depo} \circledast \boxed{\boldsymbol{Drift} \circledast \boldsymbol{Duct}} + \boxed{\boldsymbol{Noise}}) \circledast \boldsymbol{Digit}$$

# of ionization electrons in 3D space

Diffusion (longitudinal, transverse) $\propto \sqrt{D_{drift}}$
Attenuation (exponential lifetime)

Key (2D) convolution in two dimensions
Time domain + Wire domain

Data-driven frequency spectra
In complex plane (frequency domain)
Noise follows a random walk

https://indico.fnal.gov/event/12345/session/12/material/slides/0?contribId=30

Sampling & linear scaling from voltage to ADC

TPC Simulation Speed

- Facts of 2D TPC simulation
  - Point charge → 2D Gaussian cloud → 0.5 us × 0.3 mm pixelization post diffusion ~100 pixels
  - Long-range & fine-grained 2D field response → 21 × 10 = 210 sub-pitch field responses
- 2D convolution in wire domain in a minimal range of time vs wire (a factor of 10)
  - Compared to 1D convolution in time domain + loop in wire dimension
- Symmetry in field response (a factor of 2)
  - Use complex FFT to incorporate half convolution in the real part and the symmetrical/mirror half in the imaginary part
- "Magic" length of array (e.g. number of ticks) in FFT (a factor of >2)
  - Power-of-two length → faster
  - Prime factorization → more factors, faster
  - E.g. *n=10240* is 30% faster than *n=9600, n=9600* is twice faster than *n=9595*
  - A table is created to contain all the local minimal "magic" numbers and used in the FFT (need additional padding)
    - Local minimal: Input N_0, magic number $N_1 \geq N_0$ but time(N_1) is minimal
    - In total **78** "magic" numbers from 1 to $2^{14} = 16384$

2D Signal Processing

A Toeplitz matrix
(a matrix in which each descending diagonal from left to right is constant.)

$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \vdots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \boxed{\begin{pmatrix} R_0(\omega) & R_1(\omega) & \dots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \dots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{n-2}(\omega) & R_{n-3}(\omega) & \dots & R_0(\omega) & R_1(\omega) \\ R_{n-1}(\omega) & R_{n-2}(\omega) & \dots & R_1(\omega) & R_0(\omega) \end{pmatrix}} \cdot \begin{pmatrix} S_1(\omega) \\ S_2(\omega) \\ \vdots \\ S_{n-1}(\omega) \\ S_n(\omega) \end{pmatrix}$$

Linear discrete convolution = multiplication by a Toeplitz matrix.

- ✓ Core deconvolution [wire domain]: inverse (division) of the response matrix R given a ω
- ✓ FFT & IFFT [time domain ↔ frequency domain ↔ wire domain]
- ✓ Commonly, filters (one for time domain, one for wire domain) are needed to suppress the “catastrophic oscillation” of the direction inverse solution

2D Deconvolution

freqeuncies →

wires ↓

$$\begin{pmatrix} S_1(\omega_1) & S_1(\omega_2) & \dots & S_1(\omega_m) \\ S_2(\omega_1) & S_2(\omega_2) & \dots & S_2(\omega_m) \\ \vdots & \vdots & \vdots & \vdots \\ S_n(\omega_1) & S_n(\omega_2) & \dots & S_n(\omega_m) \end{pmatrix}$$

3

Inverse Fourier transform on each row vector → final result

2

Deconvolution to obtain each column vector first

Two Filters

$$\mathcal{F}^w\left[S(\omega_j)\right]_k = \frac{\mathcal{F}^w\left[M(\omega_j)\right]_k}{\mathcal{F}^w\left[R(\omega_j)\right]_k} \cdot WireFreq(k) \cdot Freq\,(j)$$

$\mathcal{F}^w$: Fourier transform w.r.t. wire

$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \vdots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \dots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \dots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ R_{n-2}(\omega) & R_{n-3}(\omega) & \dots & R_0(\omega) & R_1(\omega) \\ R_{n-1}(\omega) & R_{n-2}(\omega) & \dots & R_1(\omega) & R_0(\omega) \end{pmatrix} \cdot \begin{pmatrix} S_1(\omega) \\ S_2(\omega) \\ \vdots \\ S_{n-1}(\omega) \\ S_n(\omega) \end{pmatrix}$$

Convolution in frequency domain

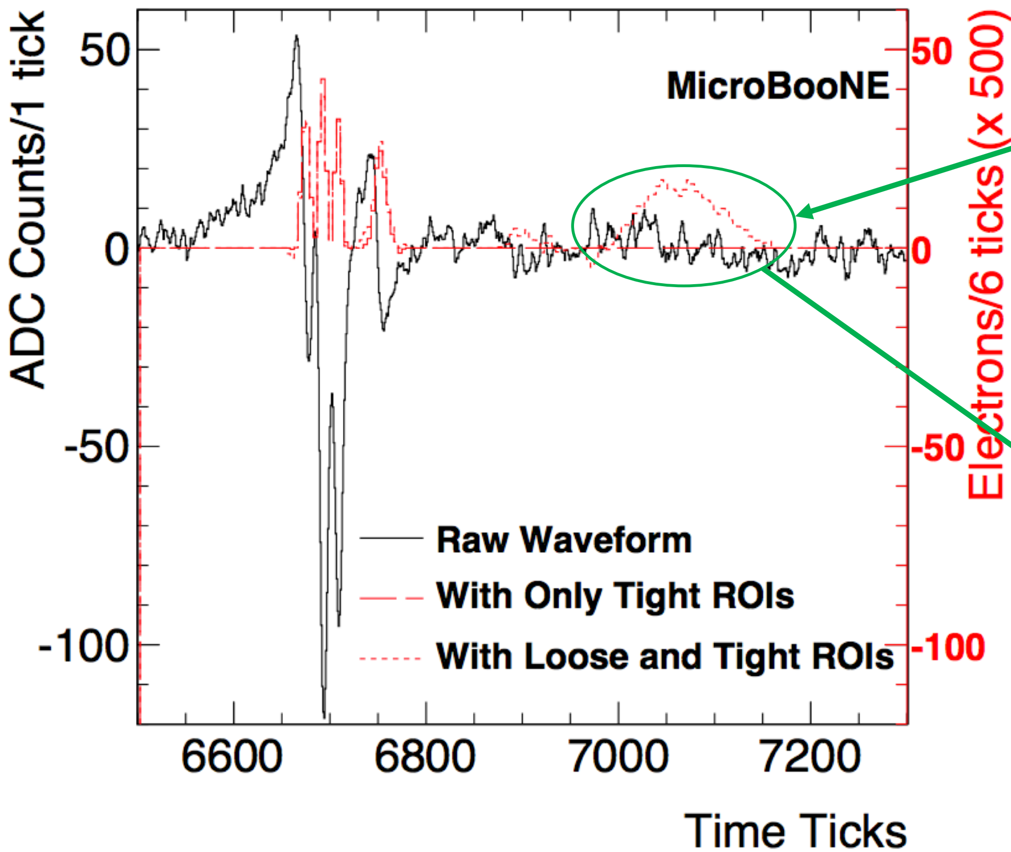
1

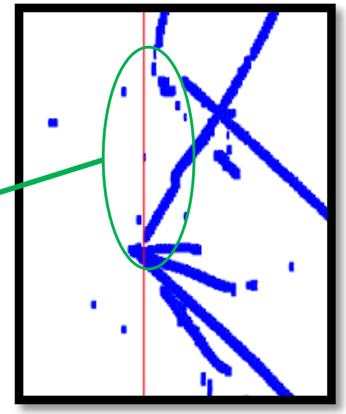
$\mathcal{F}^t$: Fourier transform w.r.t. time

$R_i(\omega) = \mathcal{F}^t[r_i(t)]$, response on the ith adjacent wire

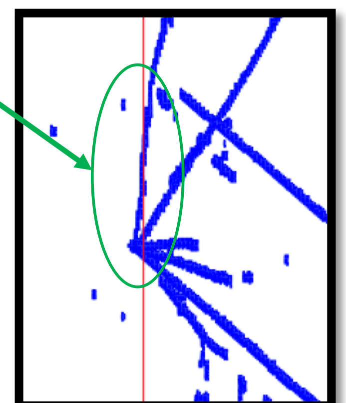
$M_i(\omega) = \mathcal{F}^t[m_i(t)]$, ADC waveform on the ith wire

Loose + Tight ROIs

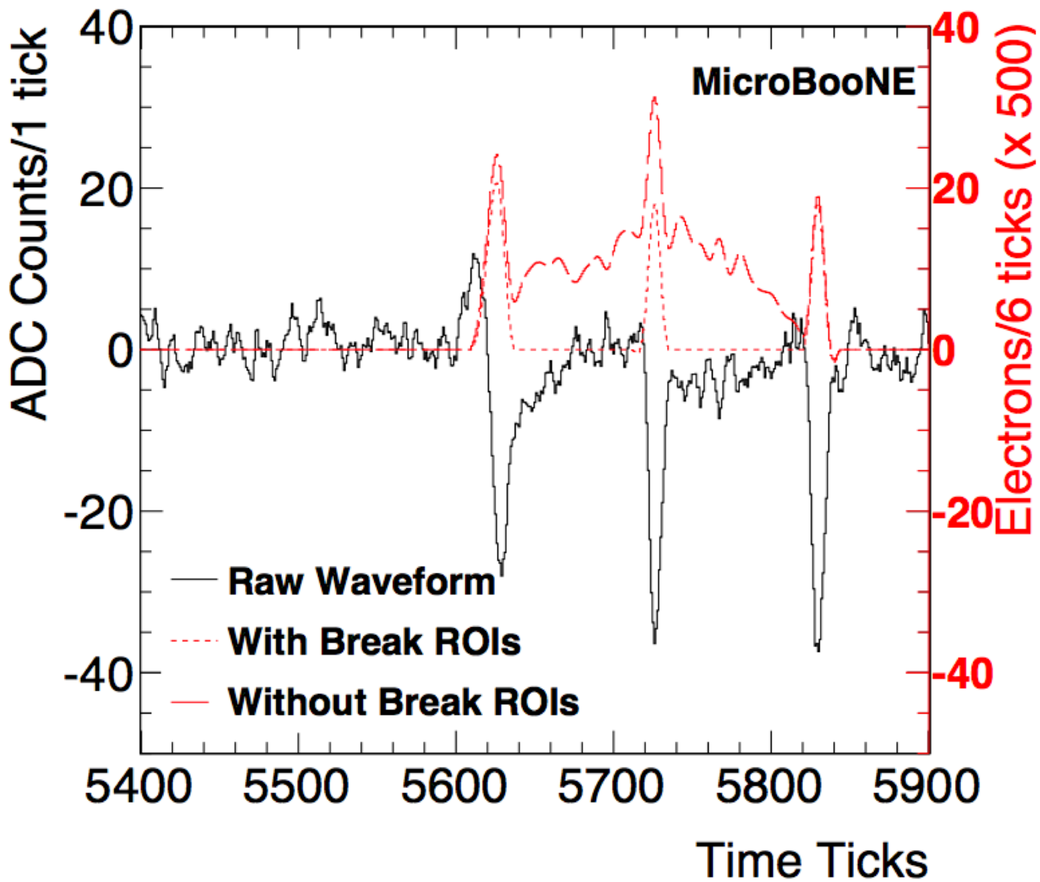




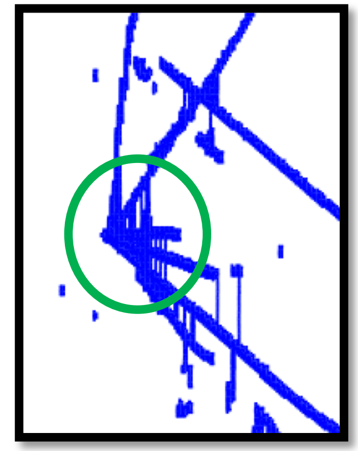
Missing part of this large θ_{xz} track

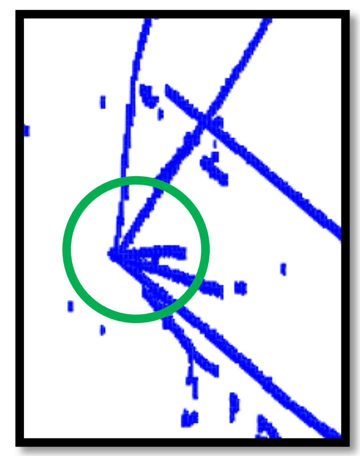


Break ROIs

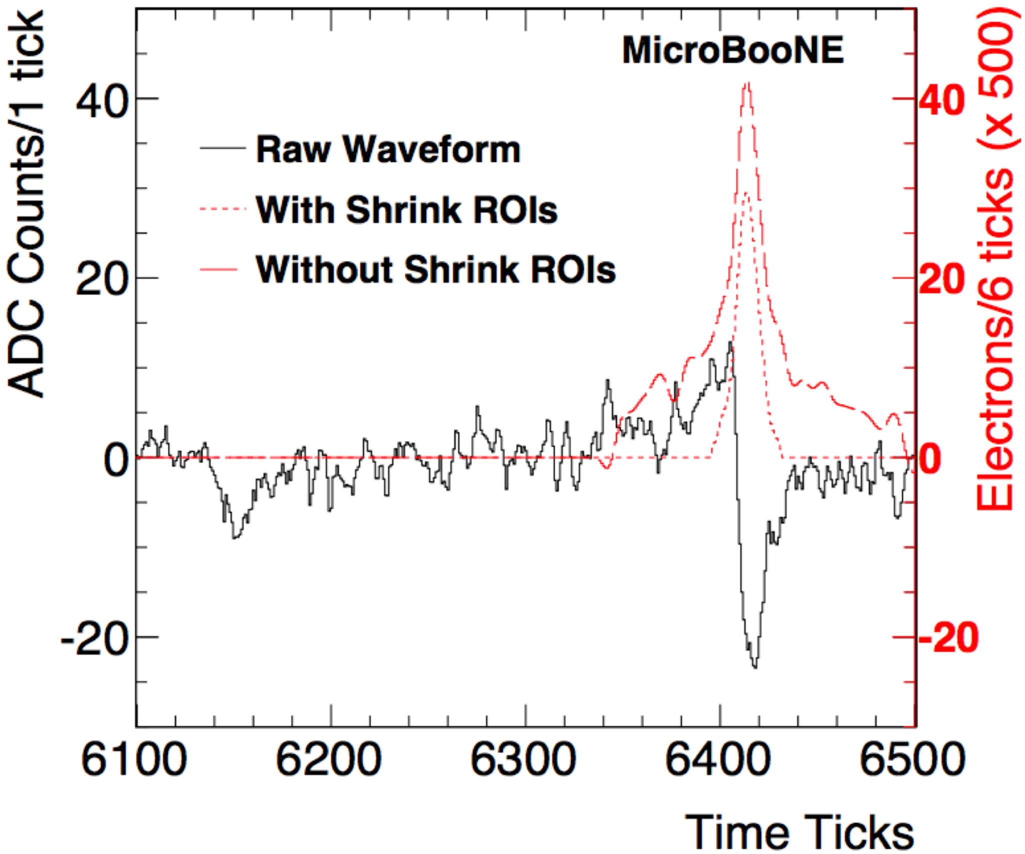


MicroBooNE
ADC Counts/1 tick
Electrons/6 ticks (x 500)
40
20
0
-20
-40
5400
5500
5600
5700
5800
5900
Time Ticks
Raw Waveform
With Break ROIs
Without Break ROIs

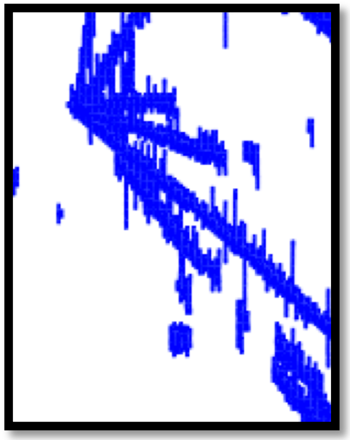




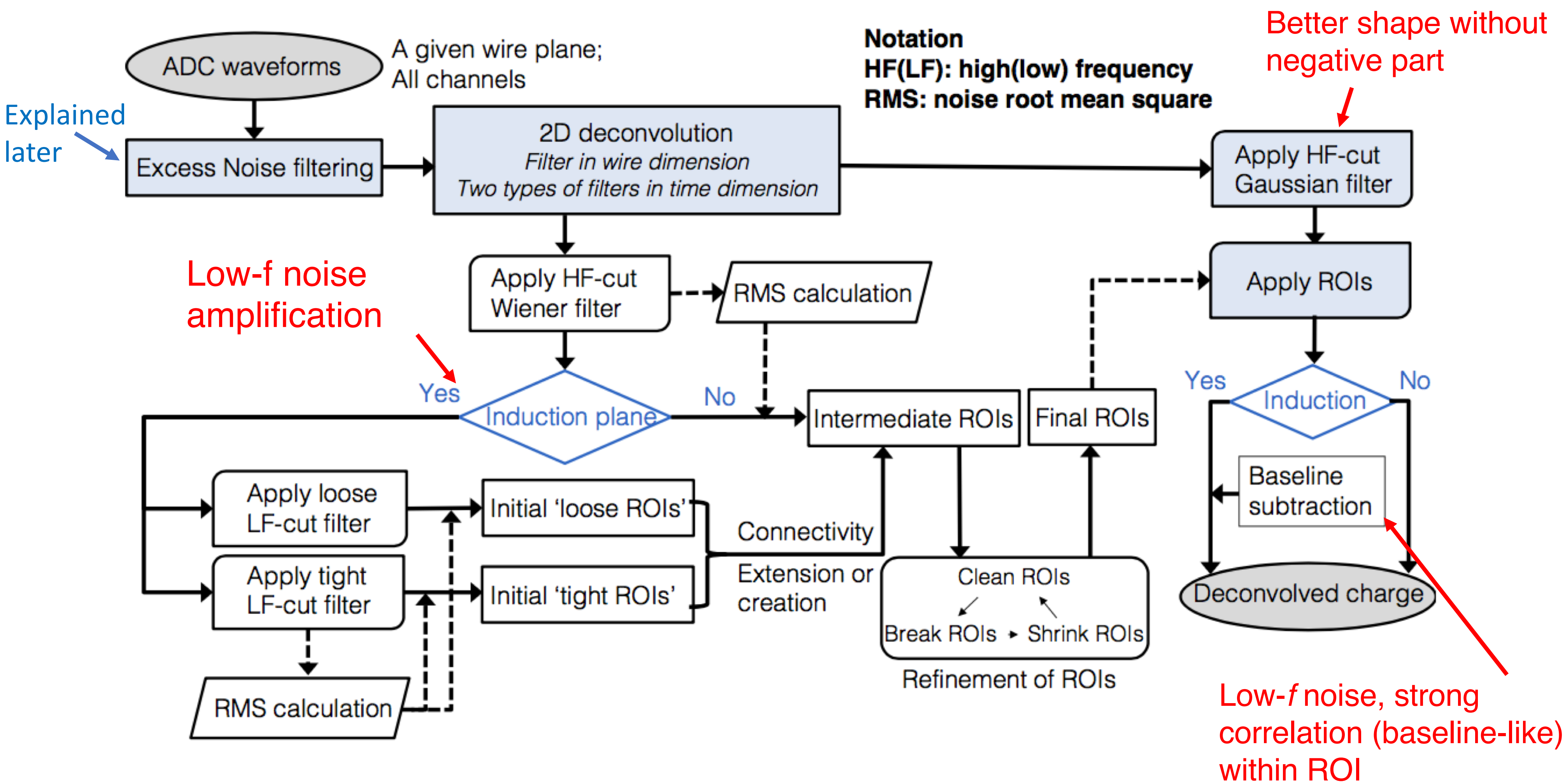
Shrink ROIs



MicroBooNE
Raw Waveform
With Shrink ROIs
Without Shrink ROIs
ADC Counts/1 tick
Electrons/6 ticks (x 500)
Time Ticks
40
20
0
-20
6100
6200
6300
6400
6500

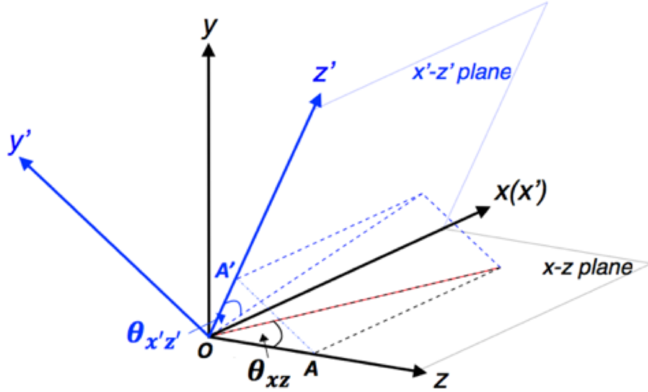


Signal Processing Flow Chart



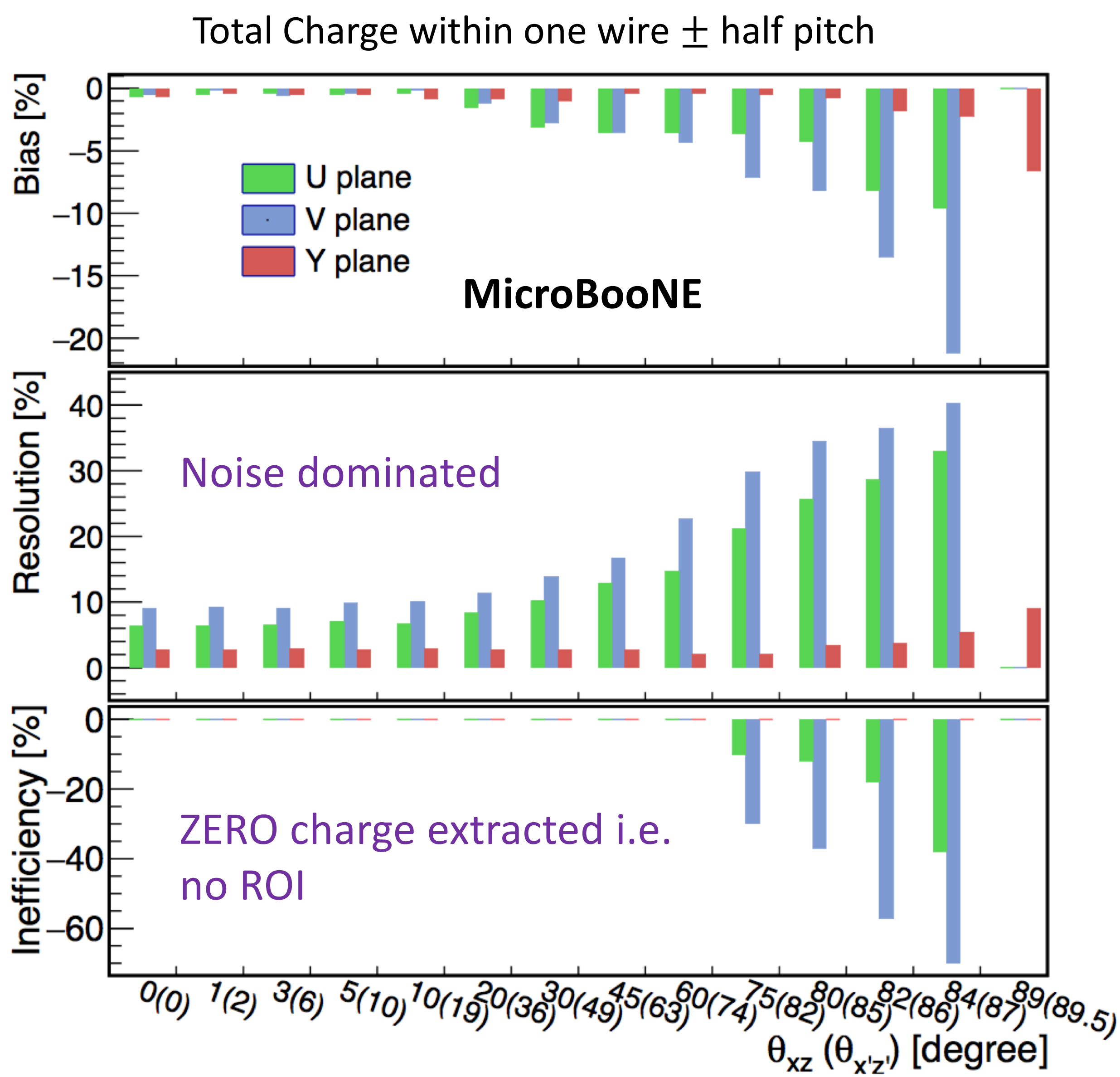
Signal Processing Evaluation

MIP line charge simulated as indicated by red line



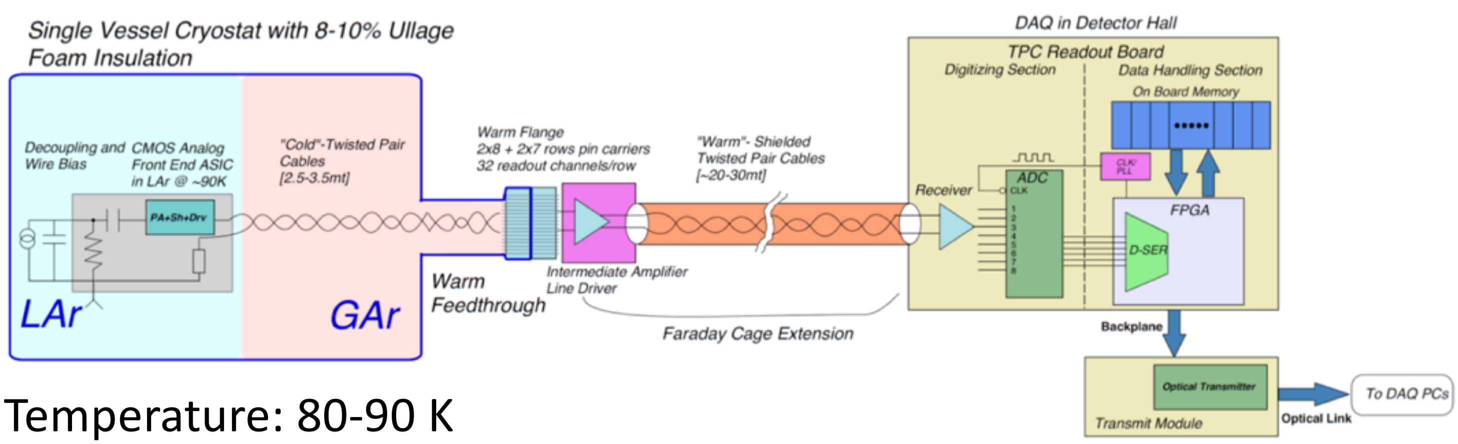
y (y'): collection (induction) wire direction
z (z'): wire pitch direction
x (x'): drifting field direction

- Good performance, but deteriorates with increasing θ_{xz}
- Induction plane considerably worse than collection plane



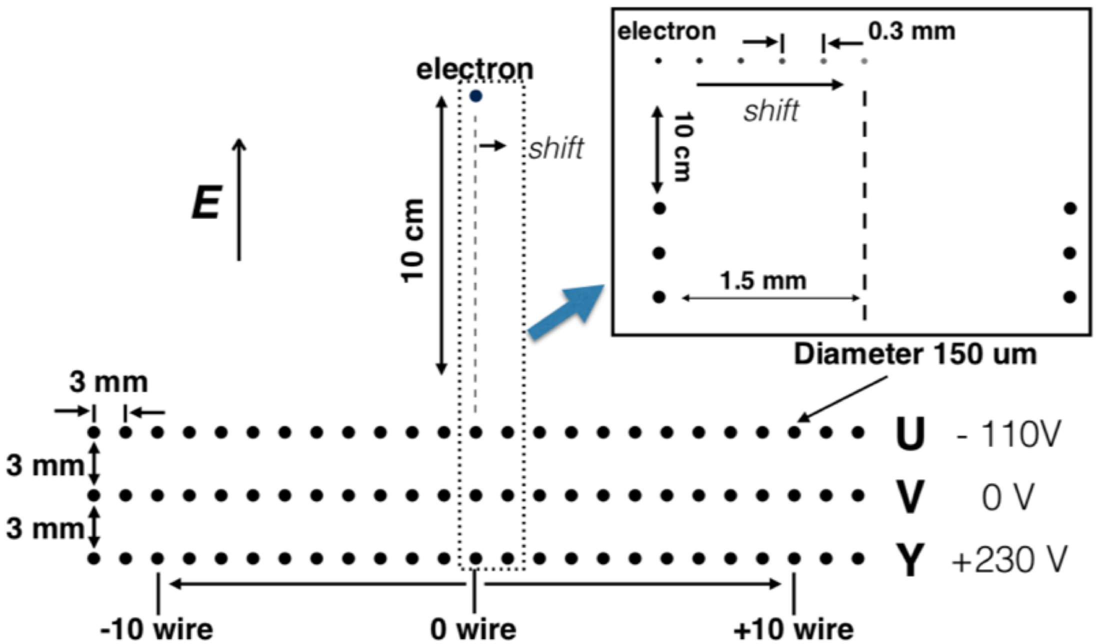
Necessity of Cold Electronics

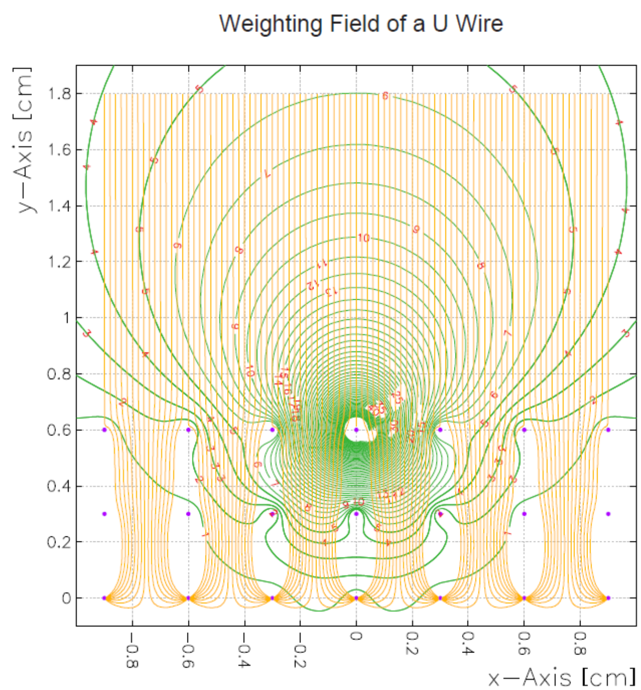
- Electronics noise dominates the charge resolution and has a big impact on the bias as well the inefficiency.
- MicroBooNE pioneered the usage of ultra-low noise cold electronics, which allows for the good performance of the signal processing
  - Simpler cryostat design + cabling, shorter signal cables
  - <u>Lower electronics noise: noise scales with temperature + length of cable</u>



Temperature: 80-90 K

Garfield calculation setup (MicroBooNE)





- ✓ **Fine-grained:** 10 drift paths (per 0.3 mm) per wire pitch
- ✓ **Long-range:** 0 (central wire) $\pm$ 10 wires
- ✓ 126 (21 wires $\times$ 6) field responses are calculated (considering symmetry)

Discussions – 3D calculation

- Finite Element Method (FEM)
  - Garfield: not support three dimensional structures
  - Detector edge effect
  - CPU/RAM requirements scale with "volume" of the problem
  - "Impossible"? to do 3D at LArTPC wire readout (mm) scale
  - Leon Rochester @ slac is braving this challenge with custom FEM
- Boundary Element Method (BEM) solves some problems
  - CPU/RAM requirements scale with "surface"
  - Fewer software implementations (compared to FEM)
  - Brett Viren @ BNL is exploring on this
- A dedicated test-stand facility would greatly aid in validating the residual 3D effect to a 2D field response calculation (LArFCS initiated by Chao Zhang @ BNL).