Ionization electron signal processing in single-phase LArTPCs

Hanyu WEI
Brookhaven National Lab

Workshop on Calibration and Reconstruction for LArTPC detectors
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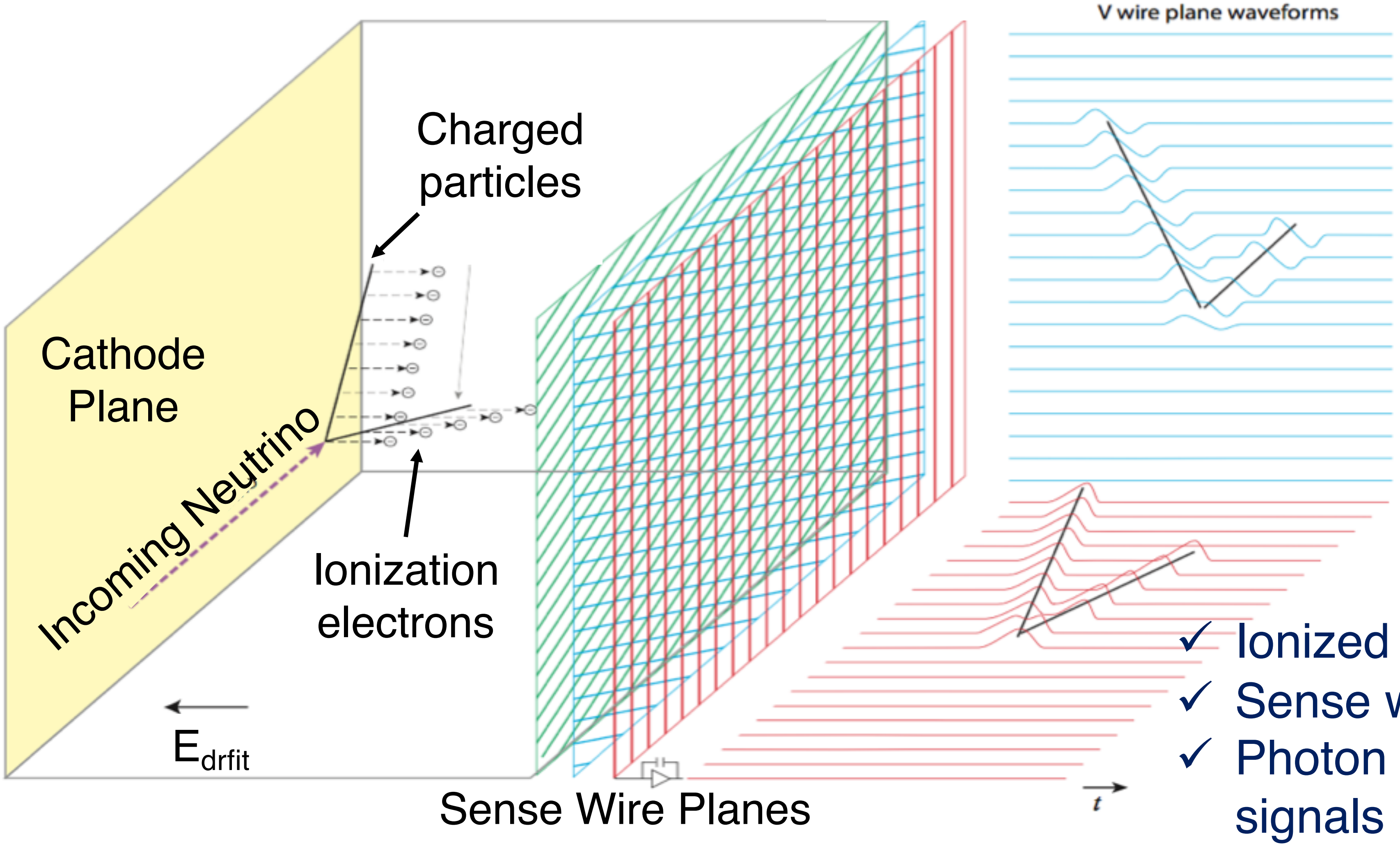
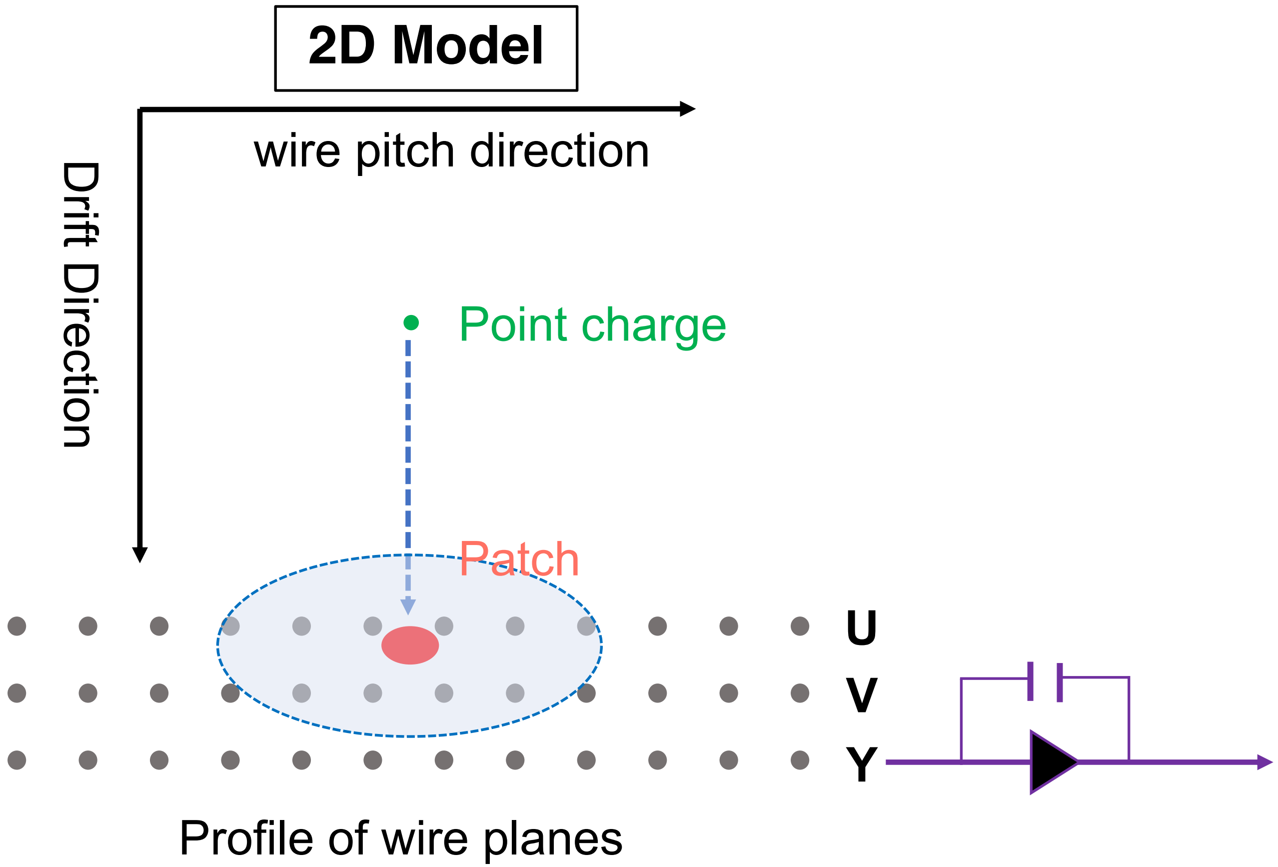
Single-phase LArTPC Detector



- ✓ Ionized electron drift along E-field
- ✓ Sense wire planes at anode
- ✓ Photon sensor to record prompt light signals

TPC Signal Formation



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

⊗

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

⊗

Field response (long-range induction ~ a few cm)

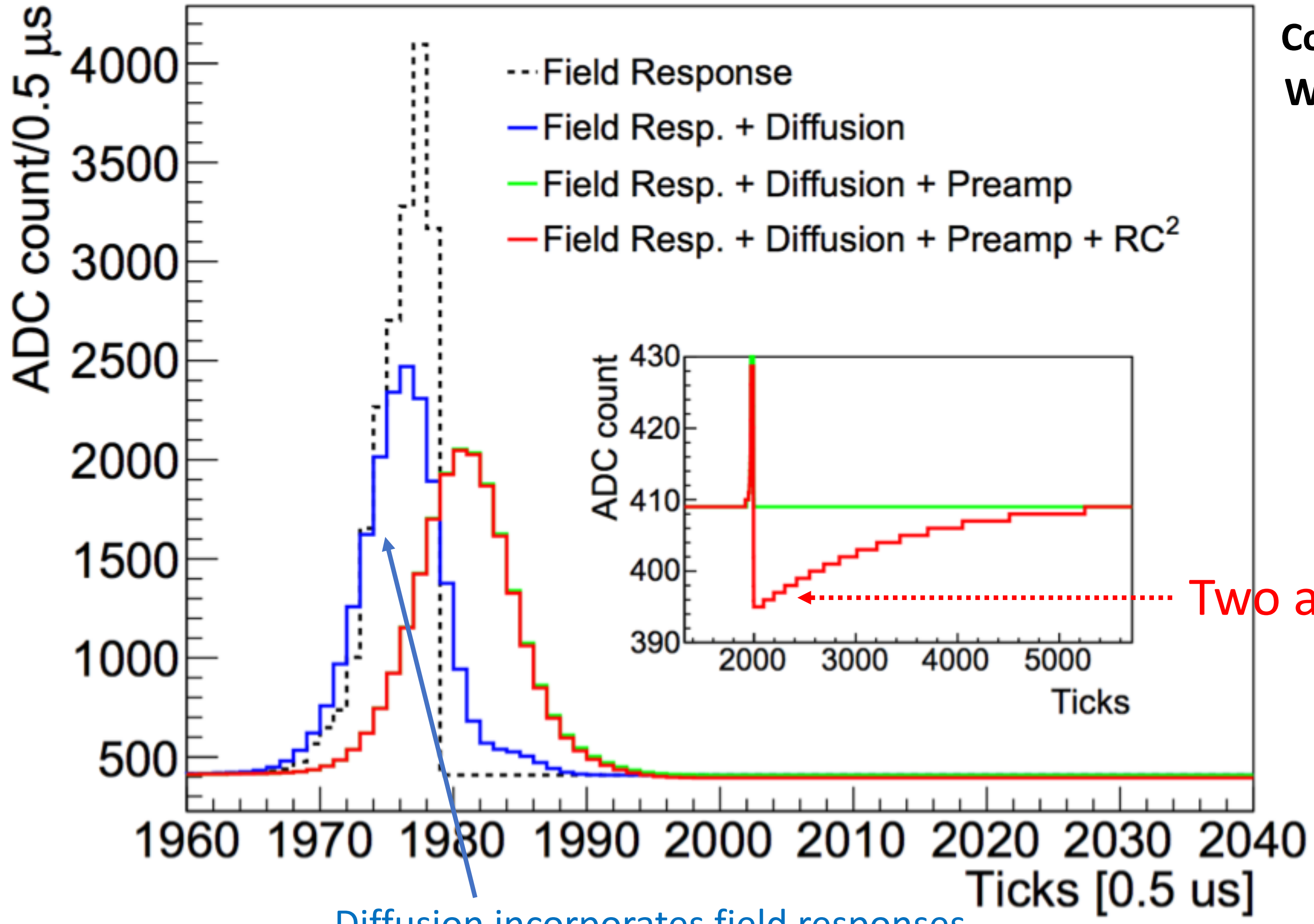
⊗

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

+

Electronics noise

TPC simulation of a point charge



Collection Plane

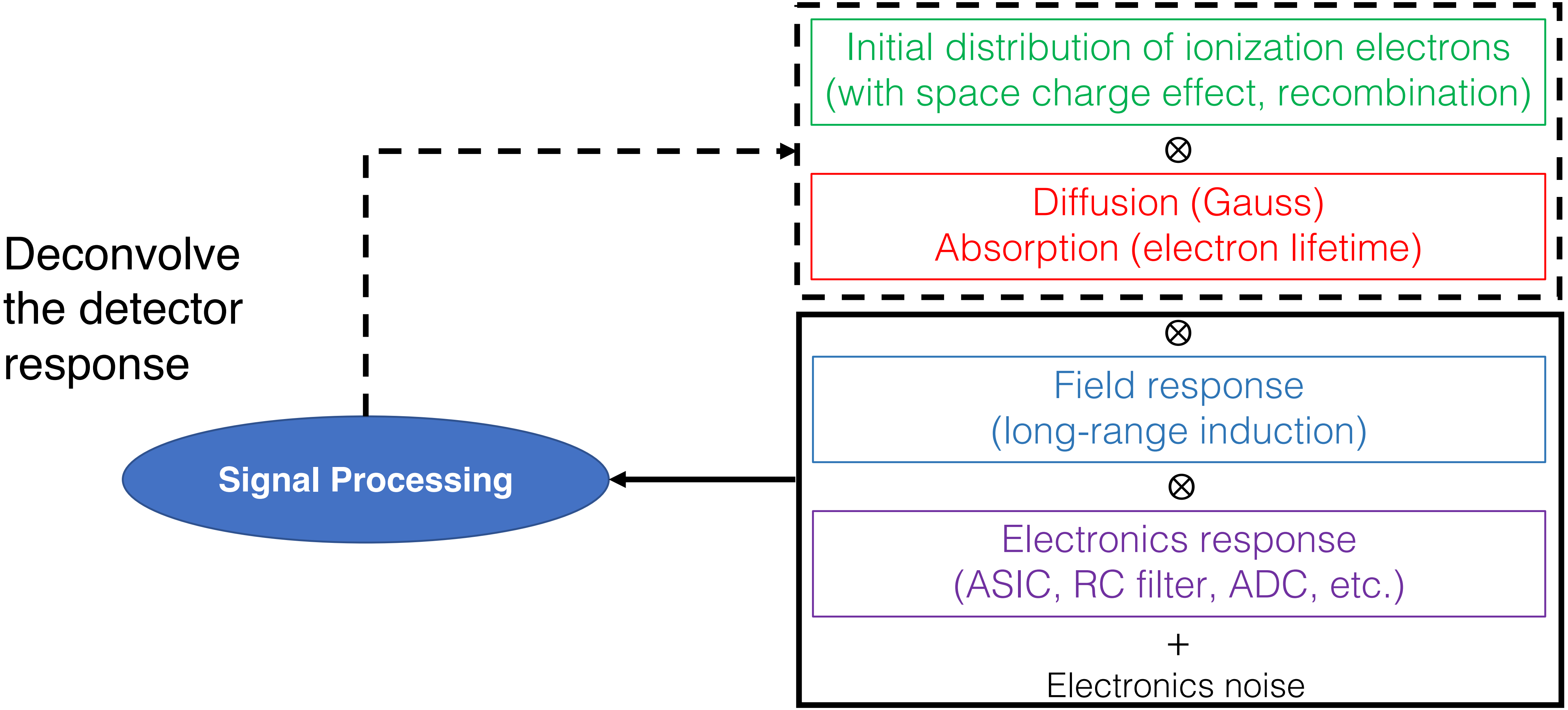
Wire-Cell drift simulation

Two additional RC filters

Diffusion incorporates field responses in adjacent wires (slightly time shift)

TPC signal processing

Conversion of raw ADC waveform to ionization electron distribution at anode plane

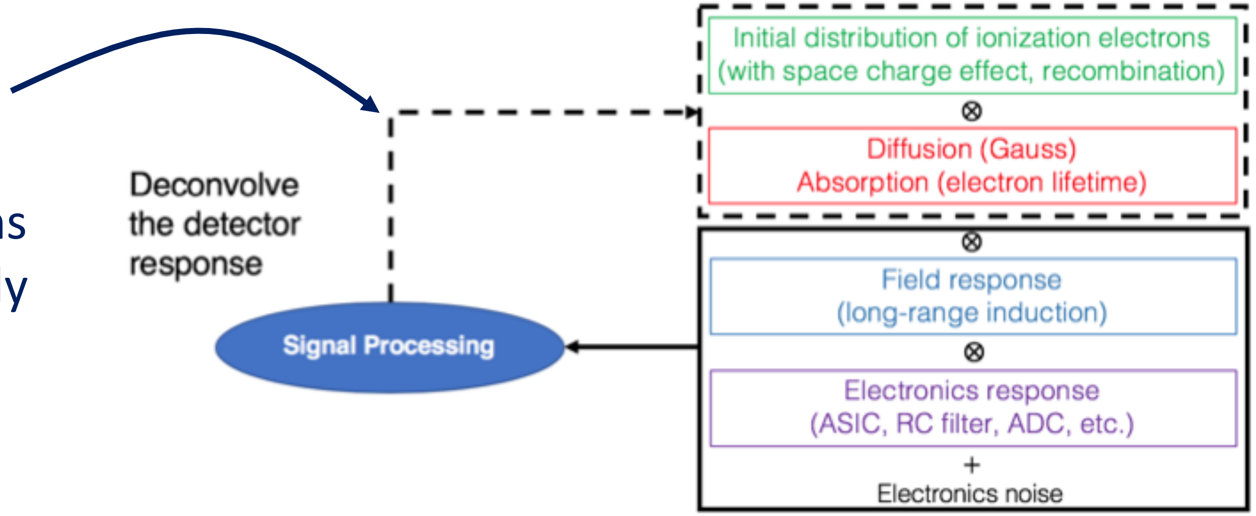


2D signal processing

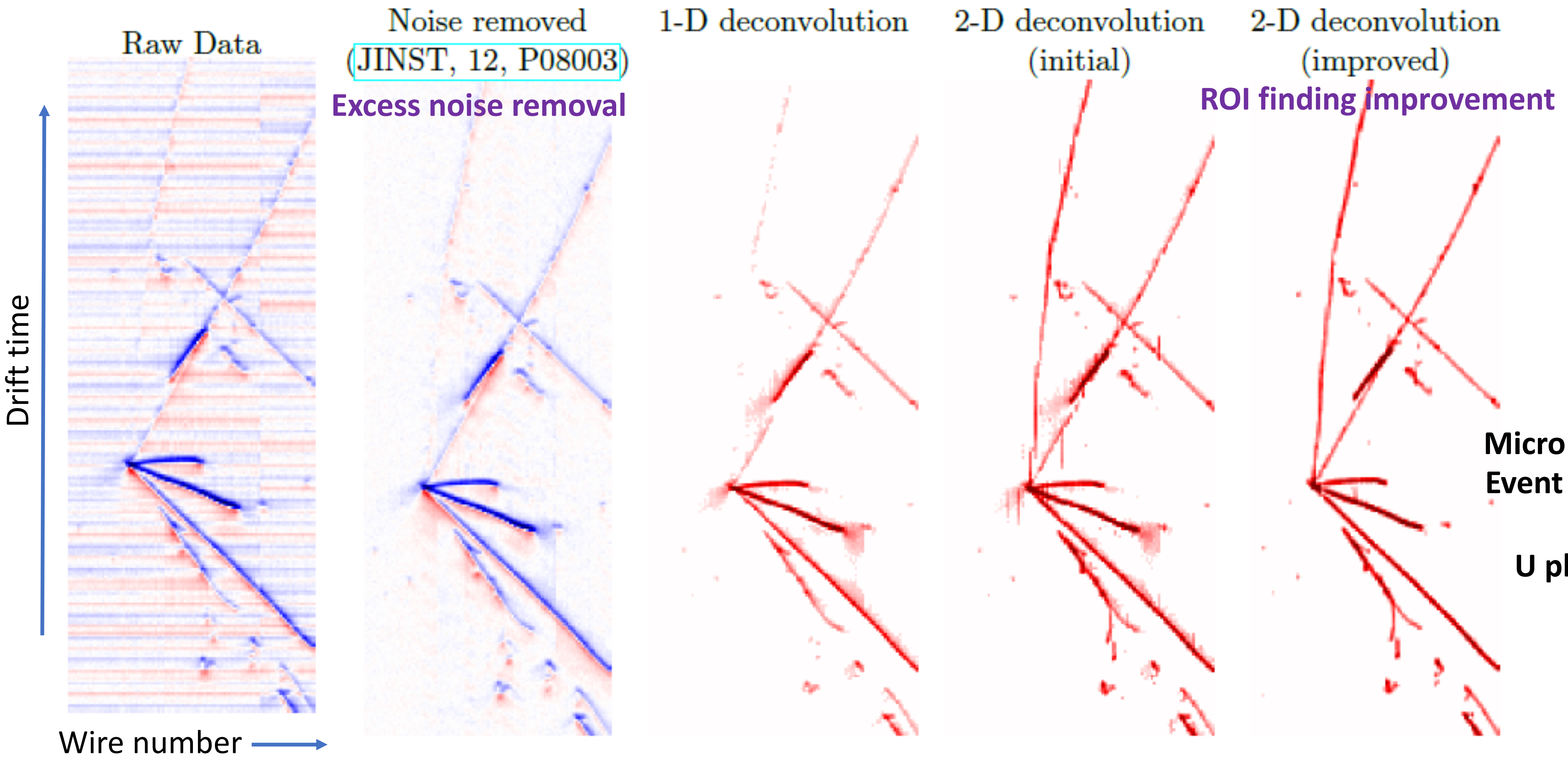
- Respect to the TPC signal formation (long-range induction)
- 2D deconvolution: to deconvolve the 2D field response + electronics response
- Intrinsic ROI finding: to mitigate the noise impact on the deconvolved spectrum, especially for induction planes

Main residual effects in the signal processing

1. Two software filters (suppress high frequency noise) in time and wire domains
2. Distortion and bias due to noise, especially low frequency noise amplification for induction planes



Evolution of Signal Processing in MicroBooNE



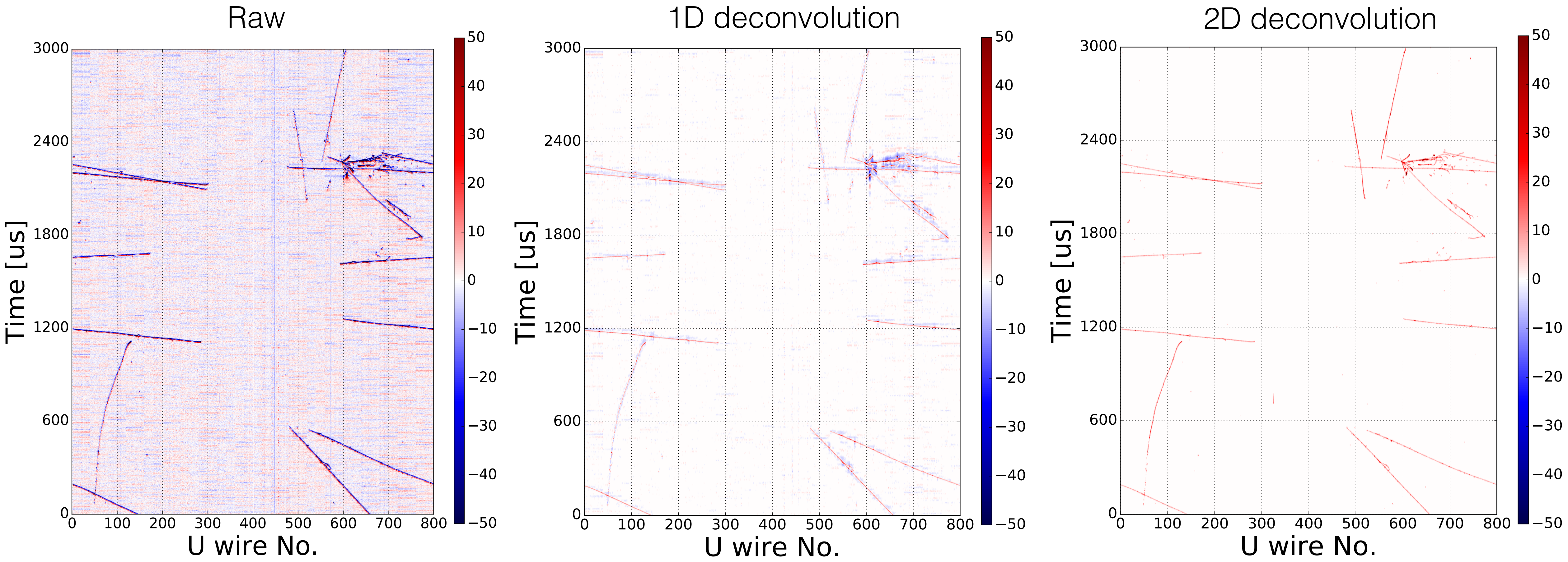
MicroBooNE data
Event 41075, Run 3493
U plane view

Two years efforts summarized in [JINST 13 P07006](#) (60 pages) and [JINST 13 P07007](#) (54 pages)

Recent progress on protoDUNE

protoDUNE data, Run 5141, Event 23865, APA3, U plane

Plots from W. Gu



Highlights of the 2D signal processing

More technical details can be found in
2018_JINST_13_P07006
2018_JINST_13_P07007

2D deconvolution

Frequency domain linear equation of the signal formation considering the contribution from all neighboring wires

S_i: initial charge distribution within the ith wire

R_j: average detector response from the jth adjacent wire to the central/target wire

M_i: waveform on the ith wire

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

- ✓ The 1st "D" corresponds to the Fourier transform on the time domain
- ✓ The 2nd "D" corresponds to the technique used to solve the linear equation above, which is equivalent to do a Fourier transform on the wire domain (the index i of S_i, M_i and R_j) given a certain frequency
- ✓ Commonly, filters (one for time domain, one for wire domain) are needed to suppress the "catastrophic oscillation" of the direction inverse solution

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

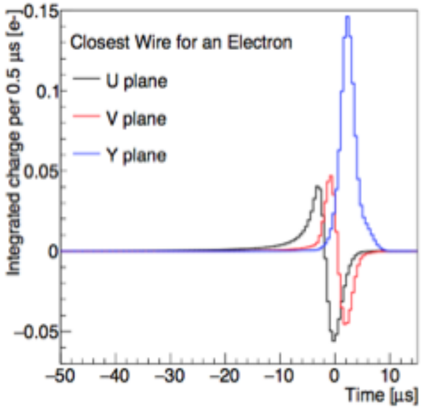
(Deconvolution, unfolding, compressed sensing, hypothesis + fitting, etc)

ROI (Region of Interest) finding

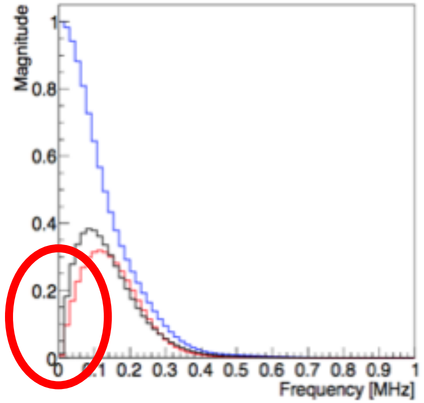
✓ Applied on the deconvolved (charge) waveform.
✓ To select the signal with the smallest time window, and further suppress the noise.

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

- 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 → a direct ROI finding largely fails



(a) Average response in time domain.

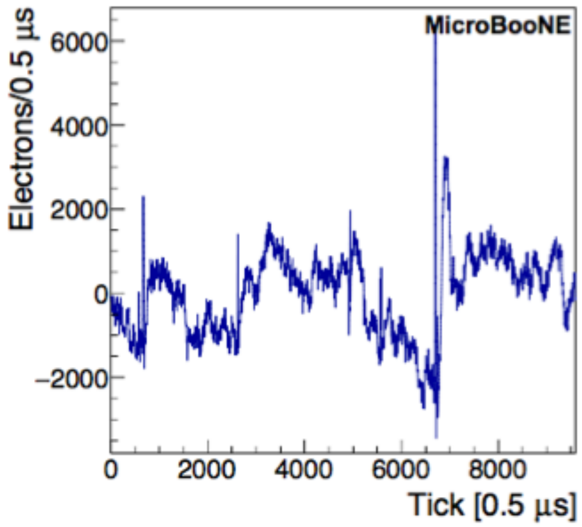


(b) Average response in frequency domain.

Bipolar field response
→ small low freq component

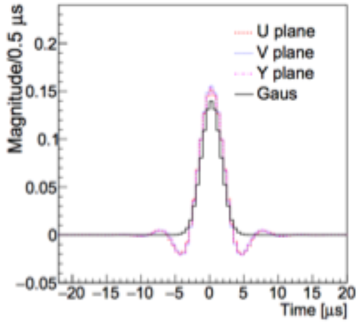
$$S(\omega) = \frac{M(\omega)}{R(\omega)}$$

→ amplify the low freq noise

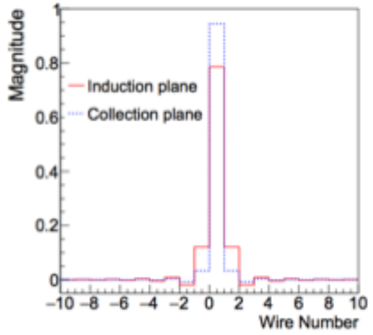


(a) Without low-frequency filter.

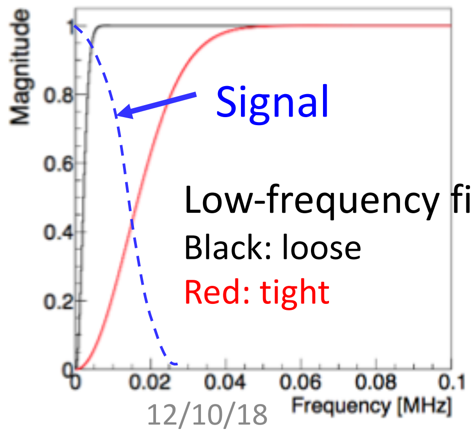
Actual Signal Processing Flow Chart



Two types of time domain filters

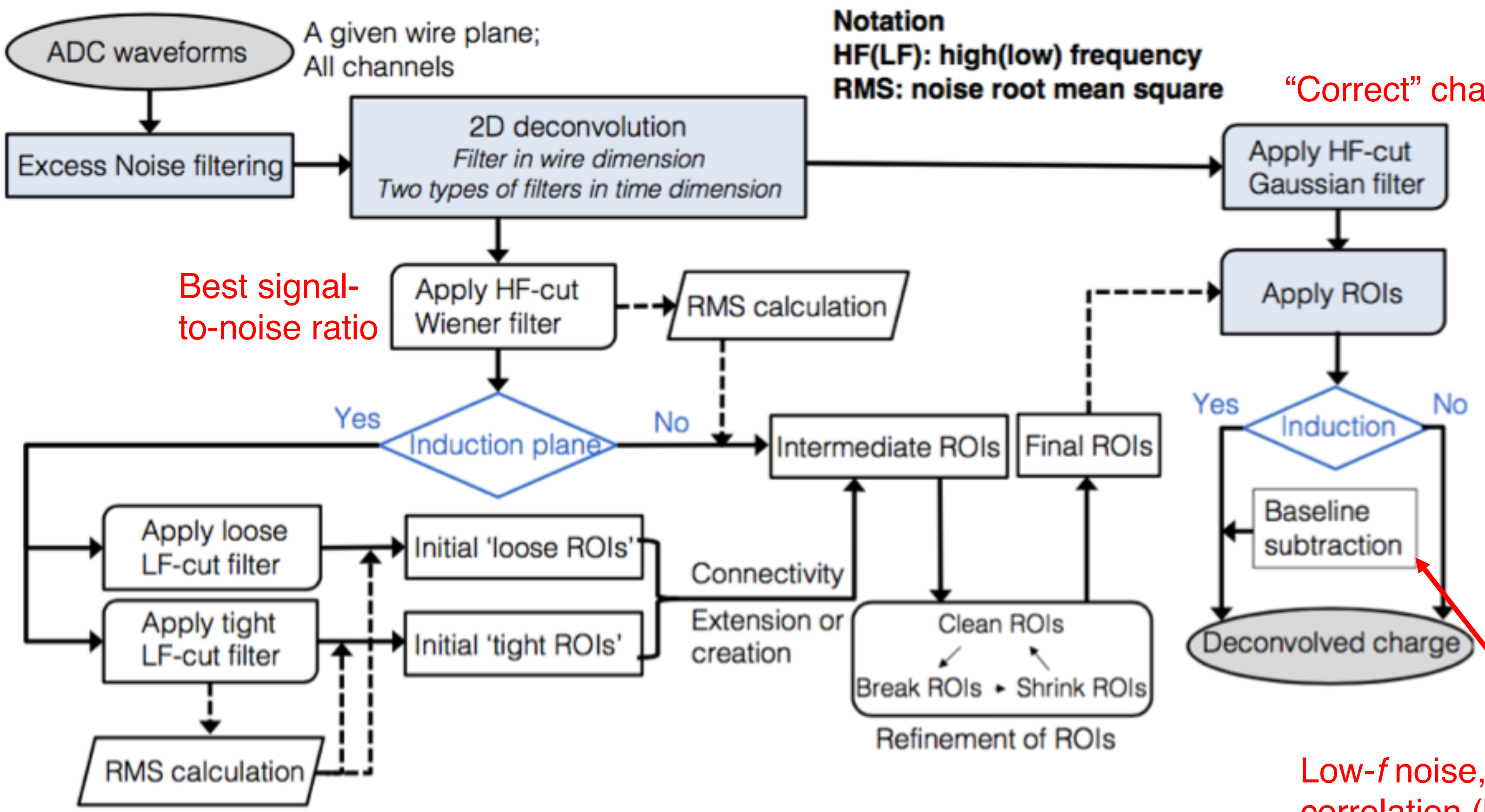


Wire domain filters



Signal

Low-frequency filter
Black: loose
Red: tight

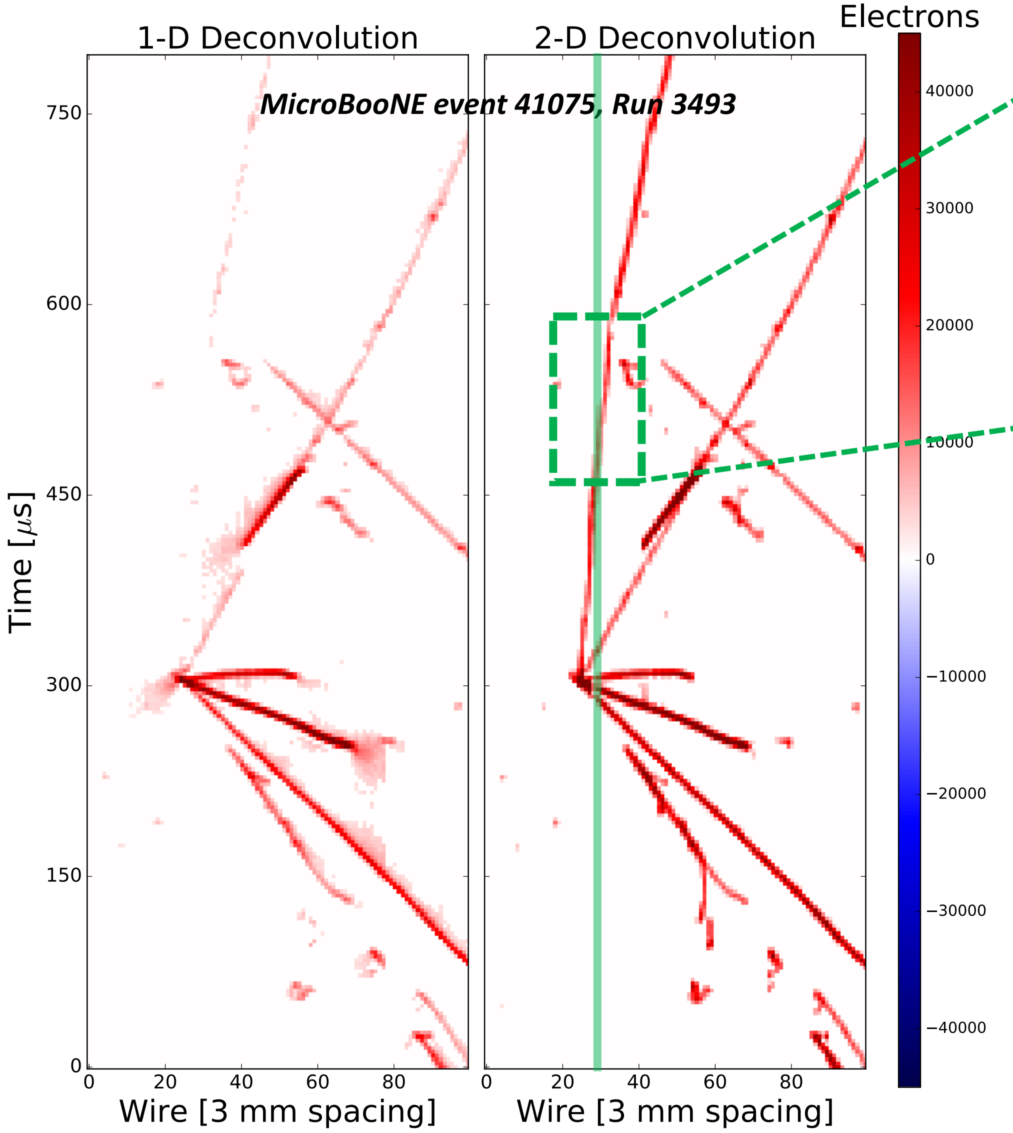


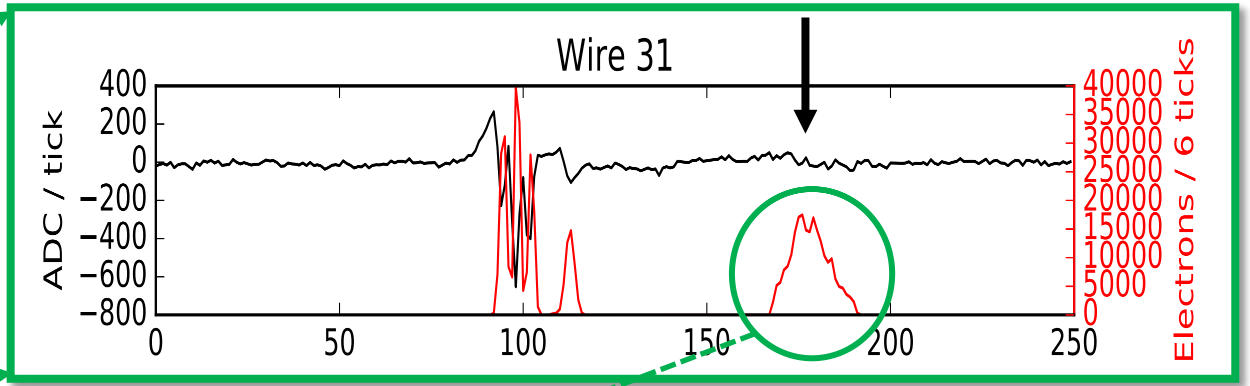
"Correct" charge

Best signal-to-noise ratio

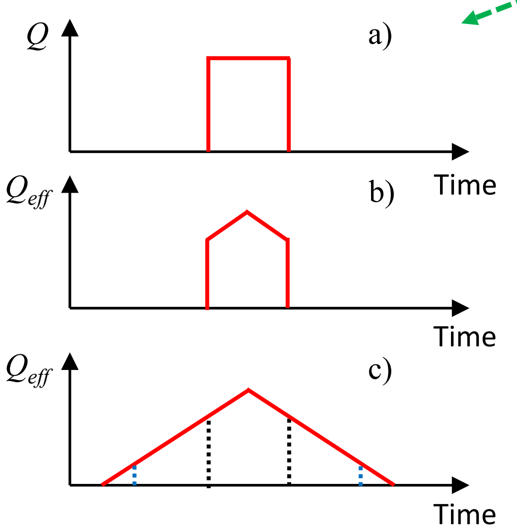
Low-*f* noise, strong correlation (baseline-like) within ROI

Charge spectrum with 2D signal processing





X-axis: $\times 3\mu s$



True charge in one wire

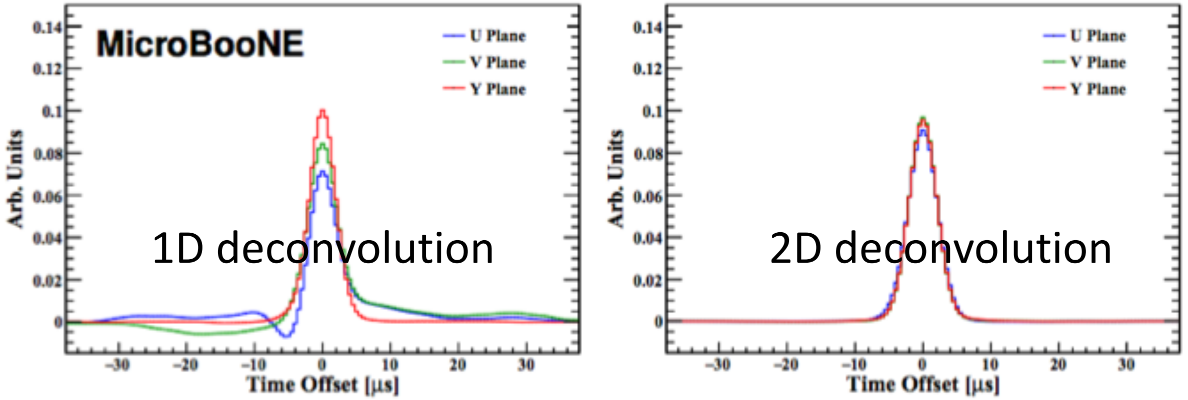
Recon charge (average response in deconvolution)

Contribution from adjacent wires

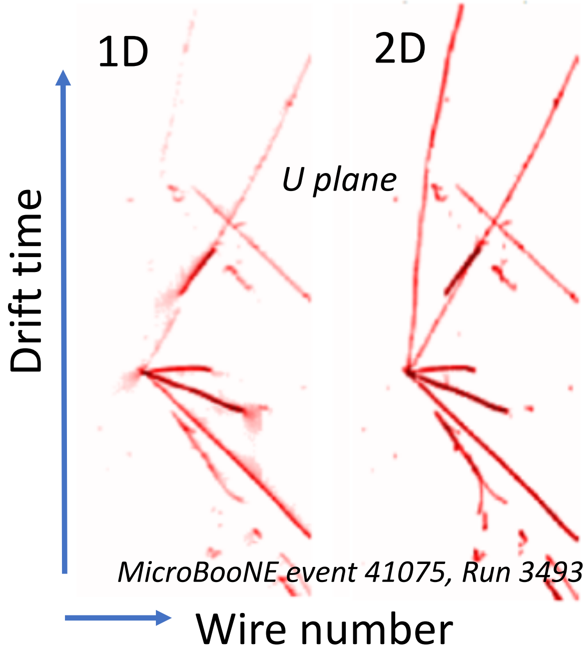
Intra- + inter-wire effect

Merits of the 2D Signal Processing

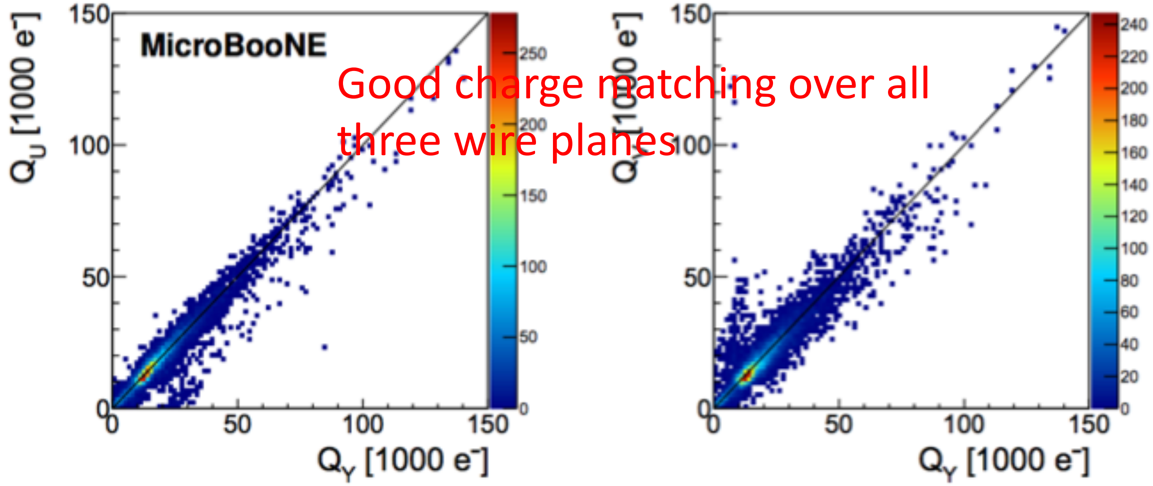
All plots for MicroBooNE data 2018_JINST_13_P07006



Cosmic muons given a certain range of angles to the wire plane

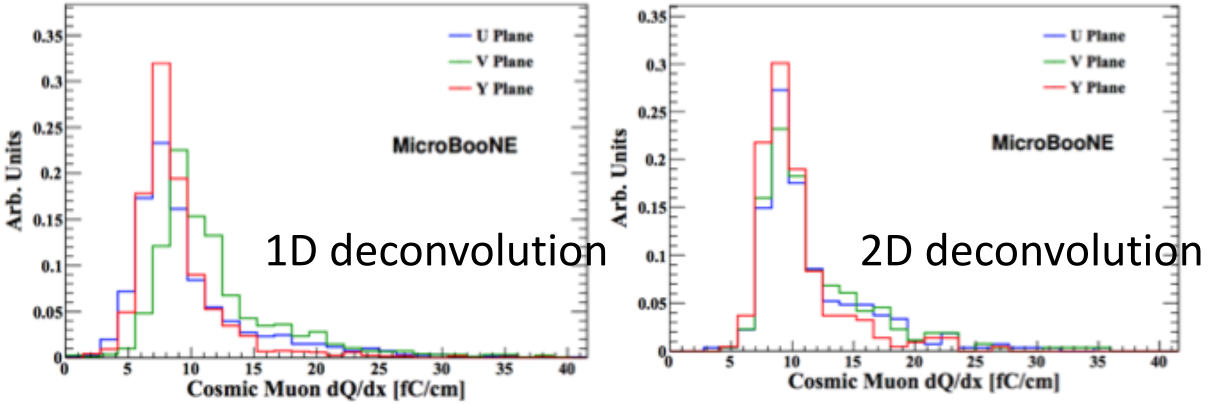


Significantly improved signal processing quality for induction plane



Good charge matching over all three wire planes

Charge after signal processing: U (V) plane vs Y plane



Impact on downstream event reconstruction

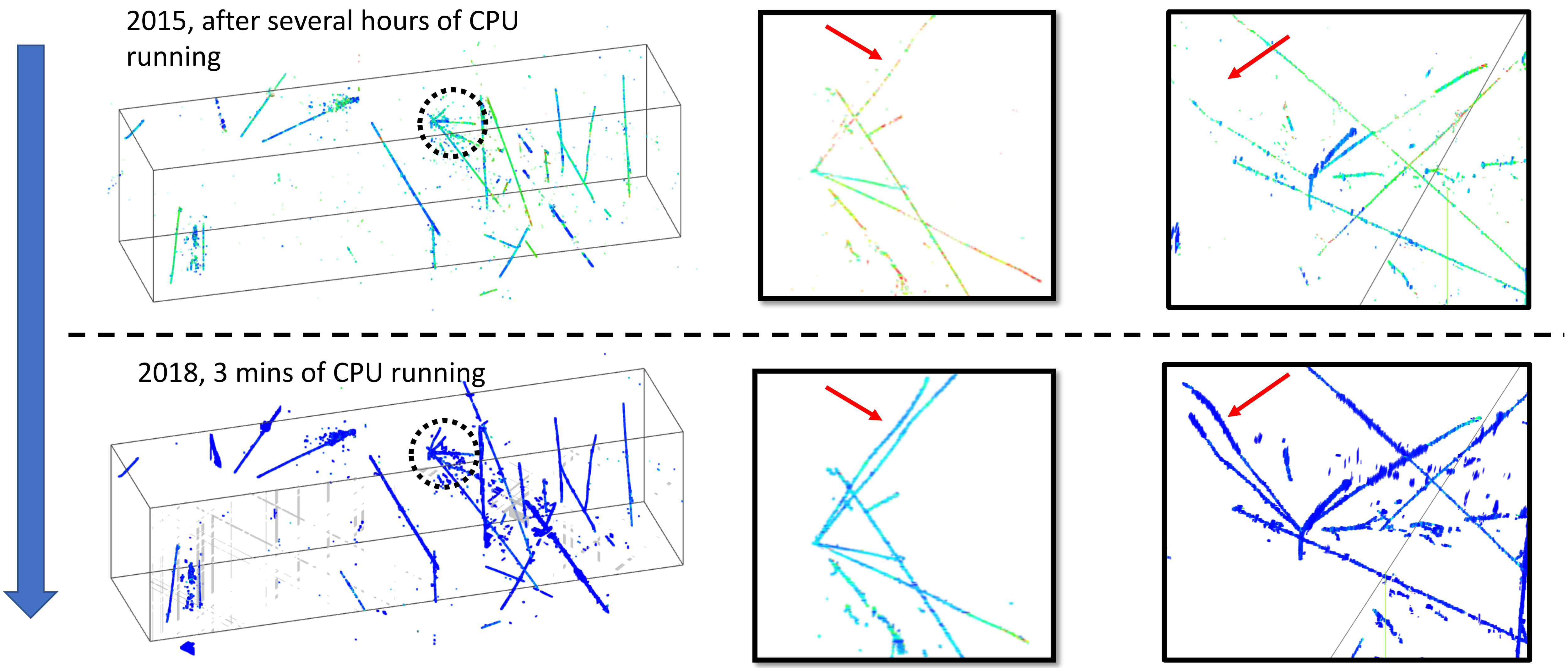
Good charge matching (i.e. significantly improved signal processing for induction planes) over all wire planes

✓Improves the correlation of signals between multiple 1D projective wire readout and helps to resolve the degeneracies (three 1D projective views ≠ 2D view on the anode plane, $\boldsymbol{n^2}$ vs $\boldsymbol{3 \cdot n}$)

✓Is essential for 3D event reconstruction in single-phase LArTPCs using tomographic reconstruction (e.g. Wire-Cell) and is expected to further enhance 3D reconstruction for techniques (Pandora, Deep-learning, etc.) that match the image in different 2D projection views.

✓Would enable a truly 3D trajectory fitting and improves those PID that depends on the dQ/dx fitting along the trajectory (*see Xin's talk*)

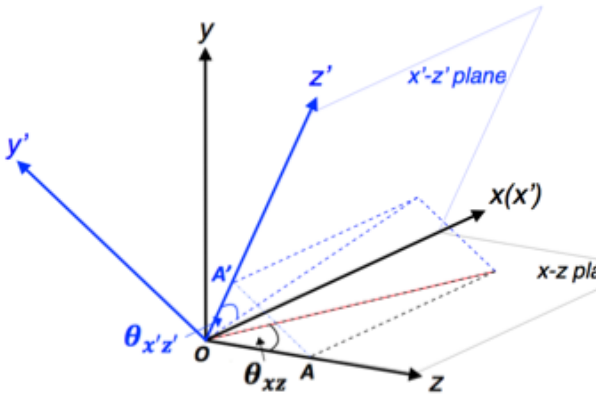
Wire-Cell on MicroBooNE Data (*see Xin's talk*)



- New Signal Processing chain significantly enhanced the efficiency (continuous lines)
- Advanced algorithms (compressed sensing) significantly reduced the running time

Evaluation of the 2D Signal Processing

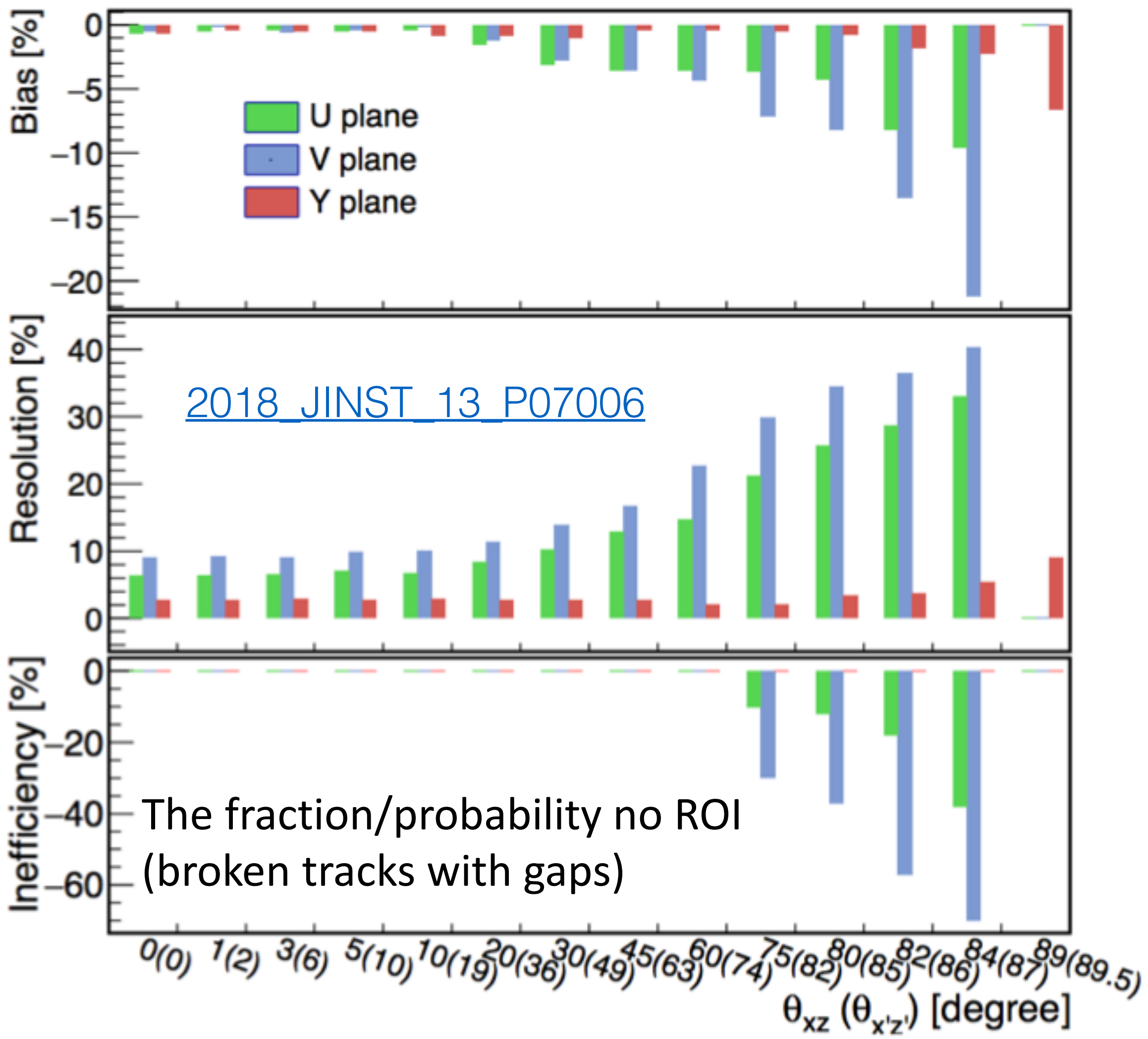
MIP line charge simulated as indicated by red line



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

Simulation of line charge

Total deconvolved charge on a wire



- Good performance, but deteriorates with increasing θ_{xz}, i.e. prolonged tracks

- Induction plane significantly worse than collection plane due to bipolar shape signals → worse signal-to-noise ratio

- Resolution (smearing) dominated by electronics noise RMS

- Bias and inefficiency largely affected by the thresholding in ROI finding

Summary

- 2D signal processing (2D deconvolution + special ROI finding) respects to the TPC signal formation
- A good understanding/calibration of the electronics response and the cold electronics design (low noise) are necessary for a successful signal processing
- Difficulties for induction plane mainly due to the bipolar field response
  - Bipolar cancellation for prolonged tracks
  - Amplification of low-frequency noise in the deconvolution procedure
- Good charge matching over all wire planes has been demonstrated in the MicroBooNE data
  - MicroBooNE new production campaign will shift 1D decon to 2D decon and accordingly adopt the Wire-Cell drift simulation, both of them use the 2D field response as the kernel
- High-performance 2D signal processing is essential or beneficial to the downstream 3D event reconstruction (3D hits, calorimetry, PID, etc) which suffers from degeneracies inherent from the wire readout ambiguity.