Towards TPC Signal Simulation in Single Phase LArTPC

Hanyu WEI

Brookhaven National Lab

APA consortium meeting
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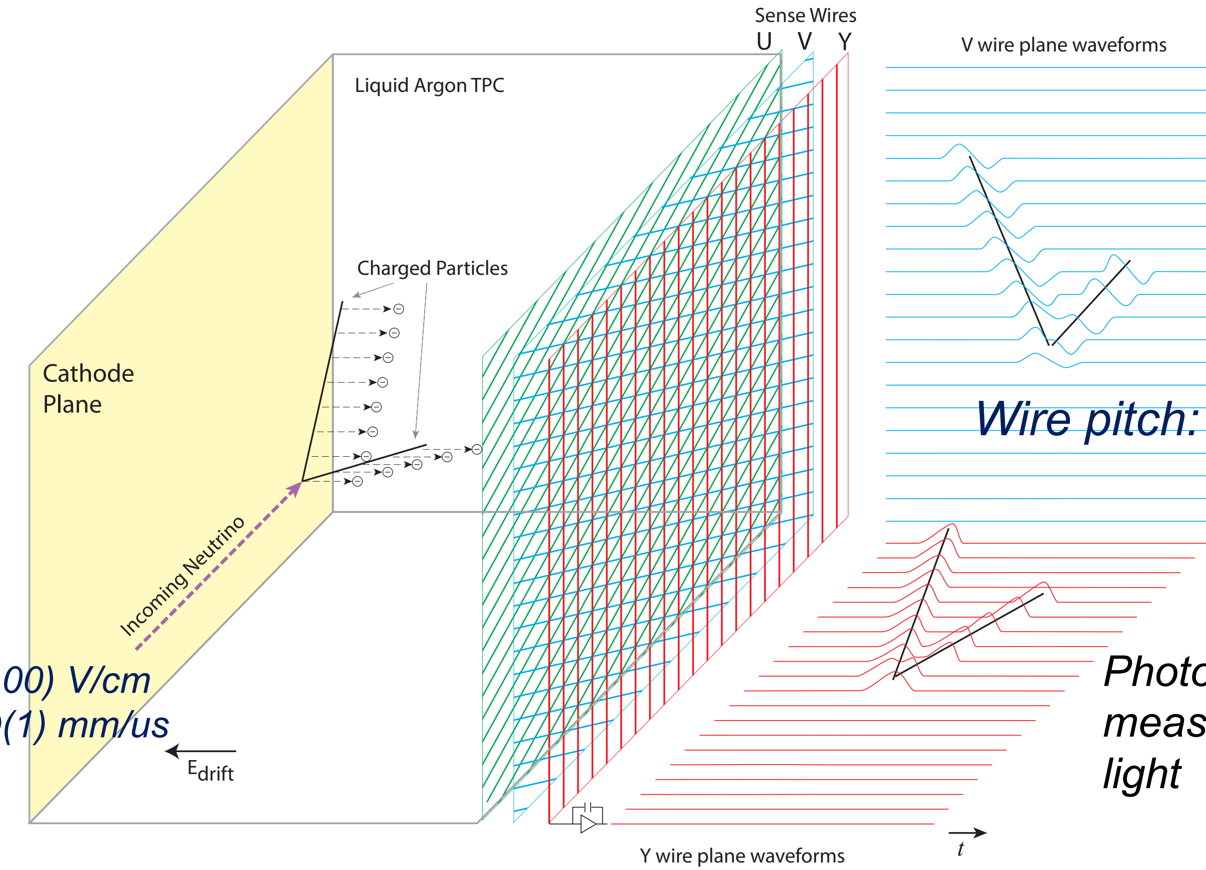
Single phase LArTPC



Wire pitch: 3-5 mm

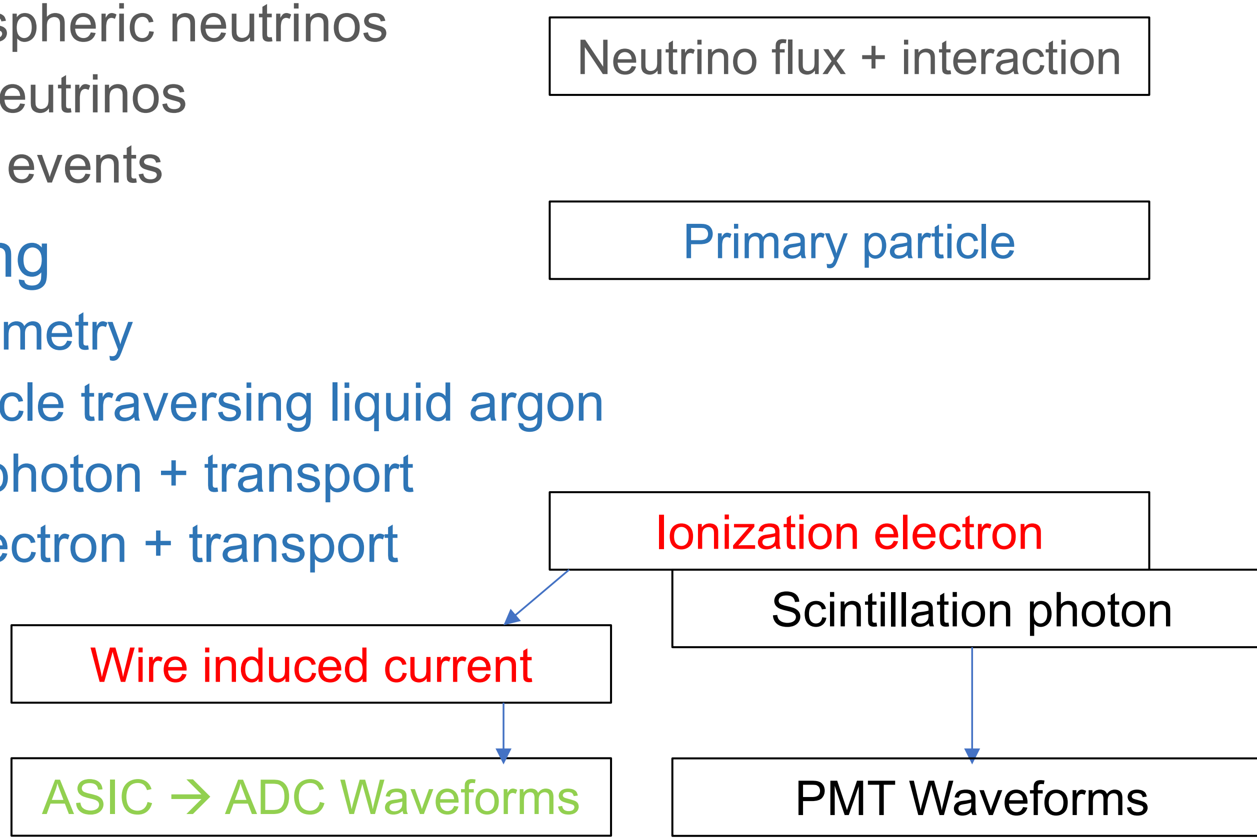
Drifting field: O(100) V/cm
Drifting speed: O(1) mm/us

Photon sensor to measure scintillation light

- ✓ Wire readout instead of pixel readout
- ✓ Three wire planes in general design sense the induced current signal

DUNE Far Detector Simulation

- Generation
  - Beam, atmospheric neutrinos
  - Supernova neutrinos
  - Cosmogenic events
- Geant4 tracking
  - Detector geometry
  - Primary particle traversing liquid argon
  - Scintillation photon + transport
  - Ionization electron + transport
- Wire signal
- Electronics



DUNE Far Detector Simulation

- Generation
  - Beam, atmospheric neutrinos
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  -
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  -
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  - Ionization electron + transport
- Wire signal
- Electronics

TPC Signal Simulation

Ionization electrons → ADC waveforms

Neutrino flux + interaction

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Ionization electron

Scintillation photon

Wire induced current

ASIC → ADC Waveforms

PMT Waveforms

Nominal TPC Signal Simulation

LAr

At production
- ✓ Ionization
- ✓ Recombination

In drifting
- ✓ Diffusion
- ✓ Attachment/absorption

Wire induced current (field response)

Short-range effect
- ✓ Time dimension
- ✓ Closest wire
- ✓ Average response

Integrated charge
+
One closet wire

Electronics

Cold electronics
- ✓ Preamplifier
- ✓ RC filter
- ✓ ADC

- ✓ Nominal TPC signal simulation in LArSoft (many LArTPC experiments share the core algorithms)
- ✓ Wrapped wire case in APA (either side: grid wire plane, 2 induction plane + 1 collection plane)

Improved TPC Signal Simulation

LAr

At production
- ✓ Ionization
- ✓ Recombination

In drifting
- ✓ Diffusion
- ✓ Attachment/absorption

Wire induced current (field response)

Long-range effect
- ✓ Time dimension
- ✓ Inter-wire
- ✓ Intra-wire

Each charge deposition
+
Intra- and inter- wire

Electronics

Cold electronics
- ✓ Preamplifier
- ✓ RC filter
- ✓ ADC

- ✓ This improved TPC signal simulation currently in WireCell Toolkit (https://github.com/WireCell/)
- ✓ Integration to LArSoft/local testing is on-going

Improved TPC Signal Simulation

LAr

At production
- ✓ Ionization
- ✓ Recombination

In drifting
- ✓ Diffusion
- ✓ Attachment/absorption

Wire induced current (field response)

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Electronics

Cold electronics
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- ✓ Thi
(htt
- ✓ Inte

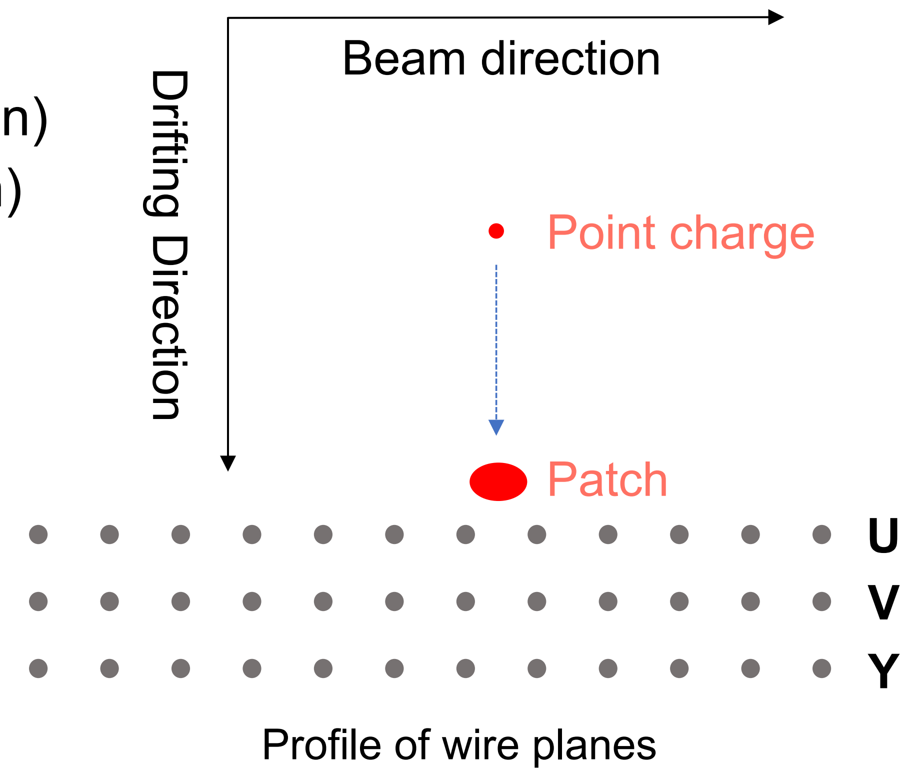
Field response ← input by external configuration + calculation (e.g. Garfield)

Signal formation in drifting

- Signal loss
  - 30-40% due to recombination (ionization electron + argon ion)
  - ~20 ms lifetime @16 ppt O_2 equivalent contamination (~5% absorption @1m drifting)
- Diffusion (shape change)
  - Longitudinal (time dimension)
  - Transverse (wire dimension)

Roughly a 3D **Gaussian diffusion**
$\sigma_{\parallel}$ (longitudinal) ~ 1.0 us @1 m drifting
$\sigma_{\perp}$ (transverse) ~ 1.5 mm @1 m drifting

$$\sigma \propto \sqrt{D_{drift}}$$



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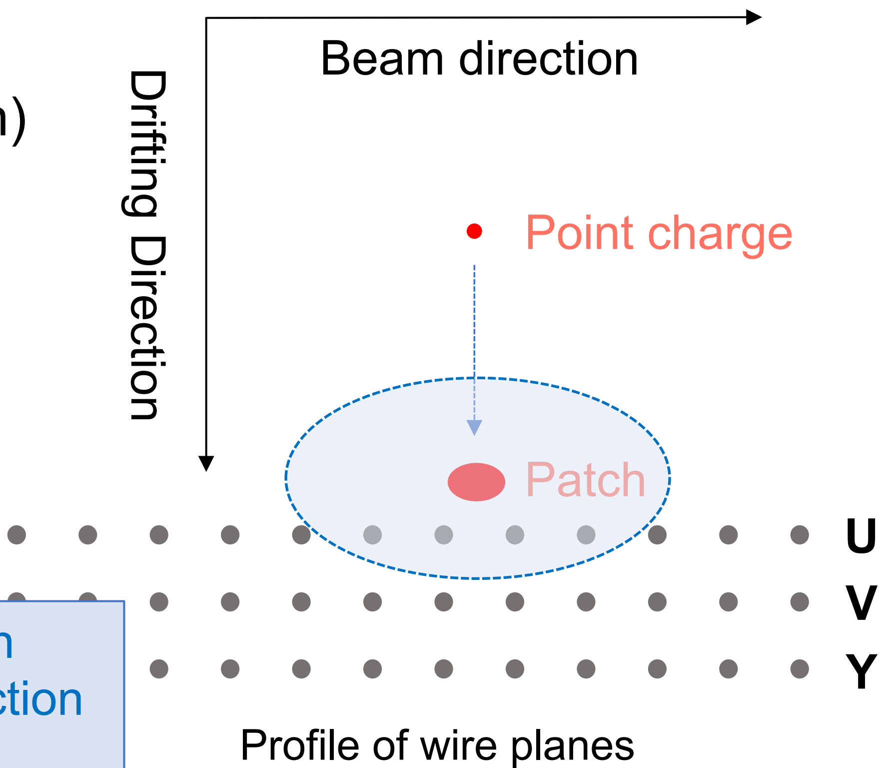
Insignificant in comparison with long-range wire induction field response



Field Response

- Input to wire induced current signal
- Demonstrated using MicroBooNE anode plane design

Field response

- **Electrostatic induction on wires**
- **End by electron collection**

Shockley–Ramo theorem

$$i = -q \cdot \vec{E}_w \cdot \vec{v}_q$$

$$\int i dt = q \cdot (V_w^{end} - V_w^{start})$$

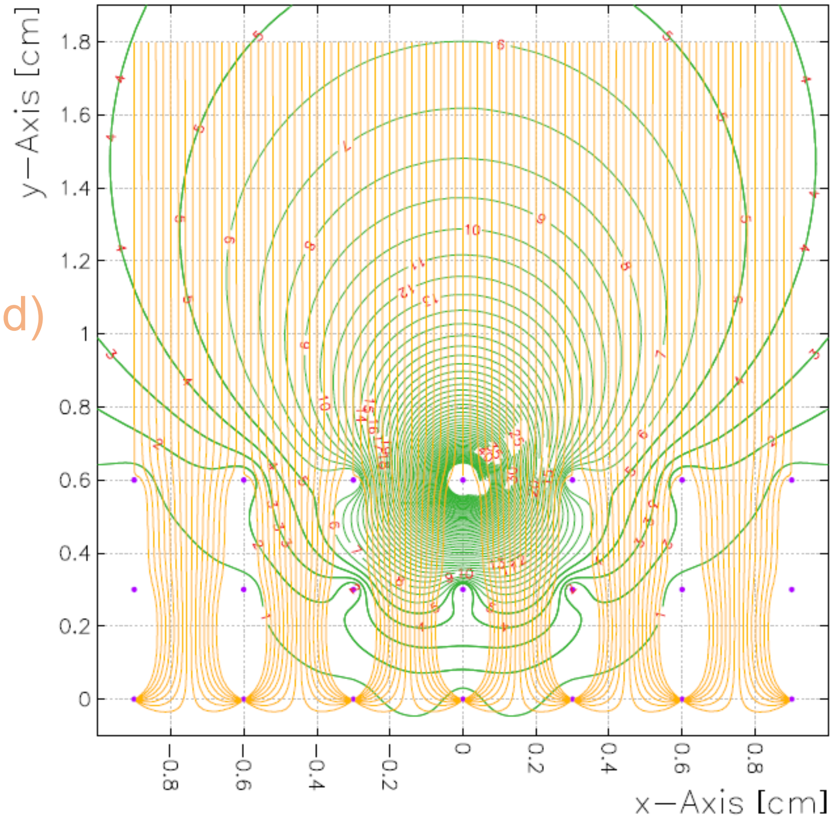
E_w/V_w: weighting electric field/potential

- *placing the target wire to the unity potential, and the rest to zero*
- *Long range effect*

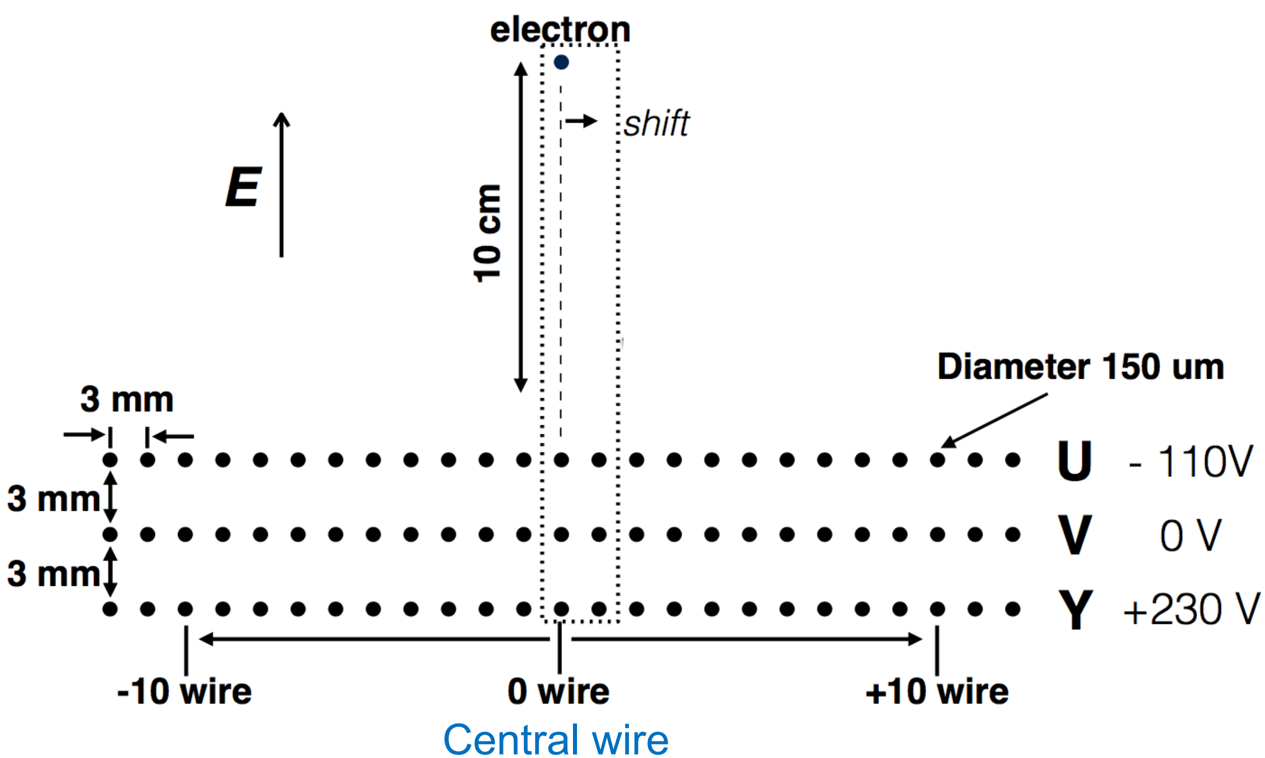
Electron track (E field)

+

Weighting potential

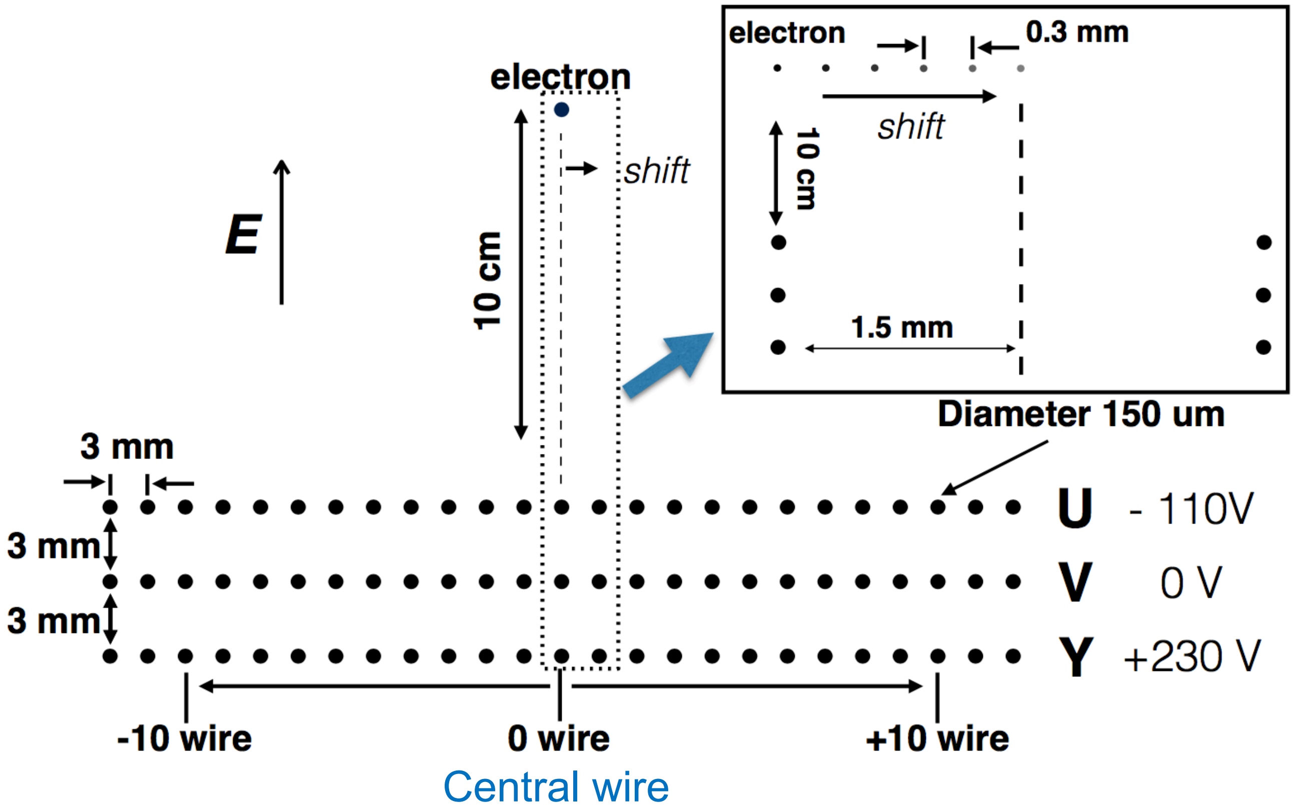


Field response -- 2D Garfield calculation



- ✓ A 2D configuration for MicroBooNE anode palne
- ✓ Average profile along wire orientation (ignore the dependency → residual 3D effect)

Field response -- 2D Garfield calculation

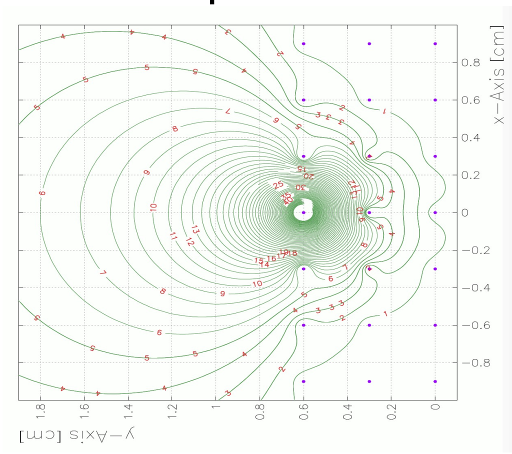


- ✓ 6 drifting paths (per 0.3 mm) for half wire pitch, the other half symmetrical
- ✓ 0 $\pm$ 10 wires
- ✓ 126 field responses are calculated

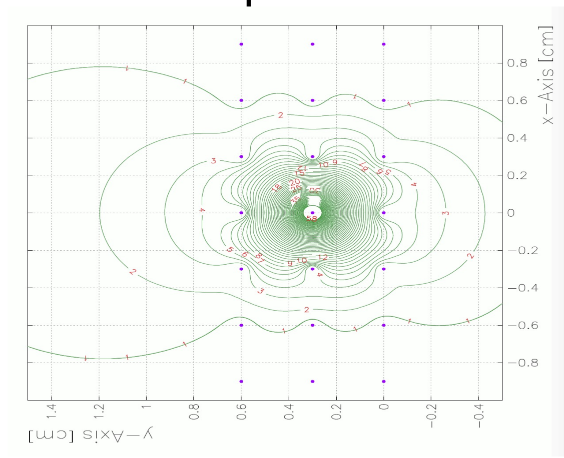
Field response -- 2D Garfield calculation

Weighting potential

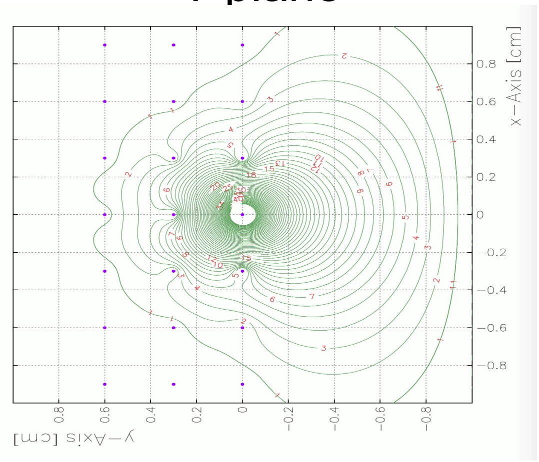
U plane



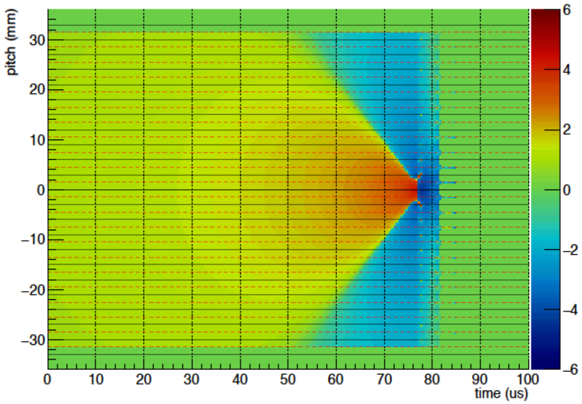
V plane

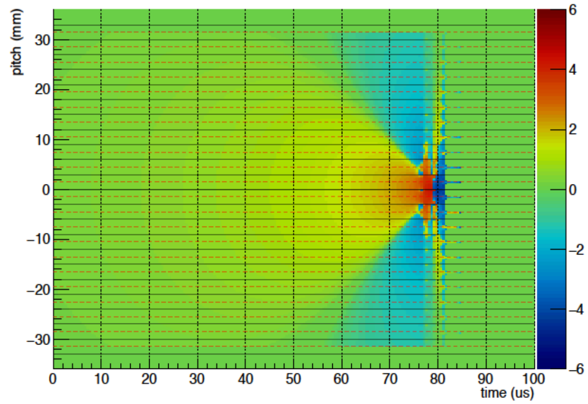


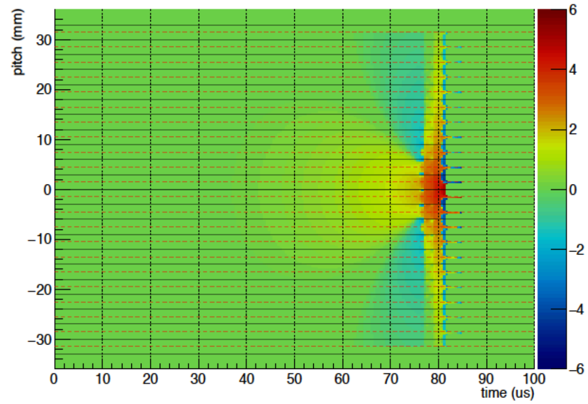
Y plane



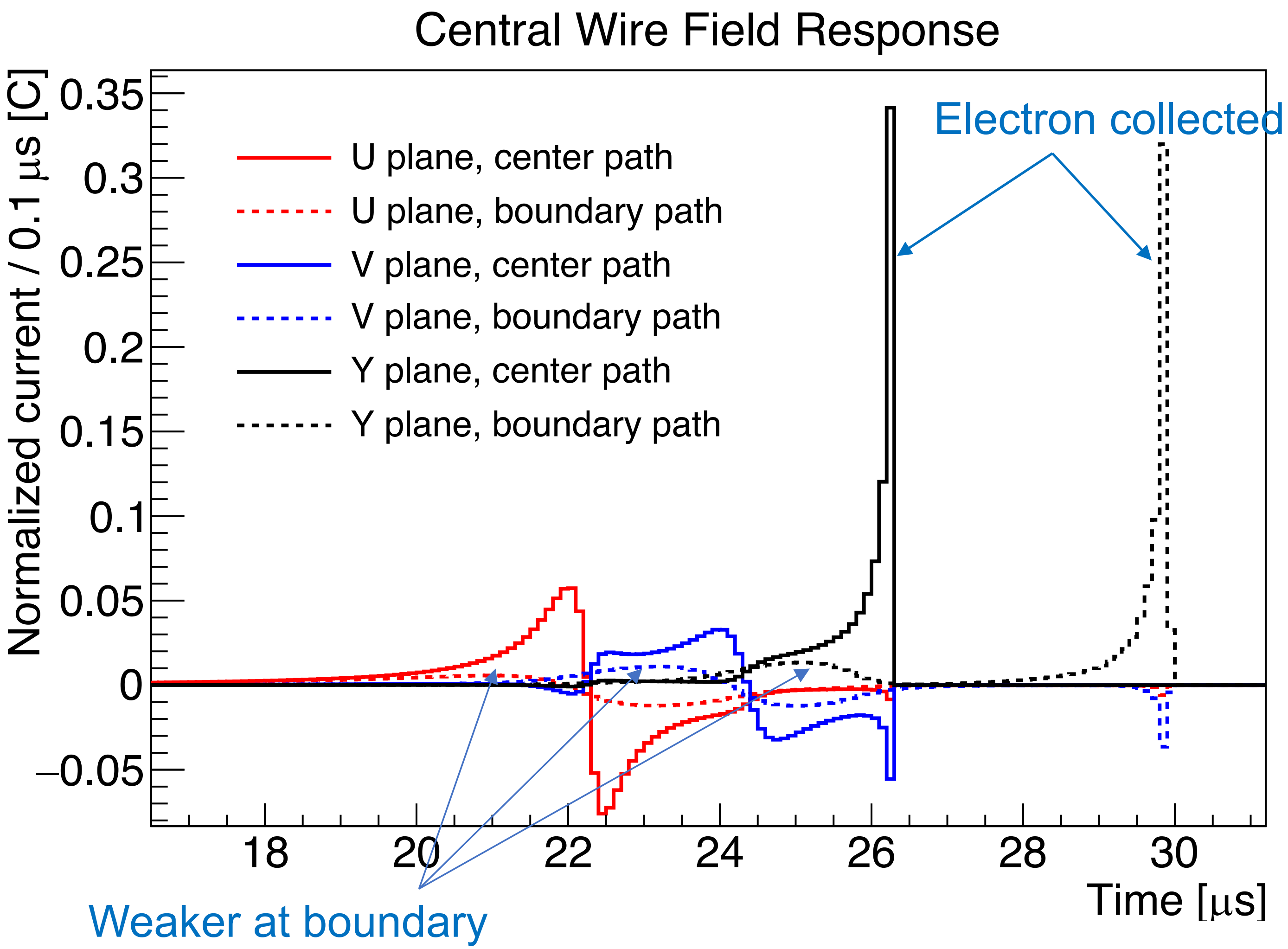
Field response (Plot in log scale, arbitrary unit)





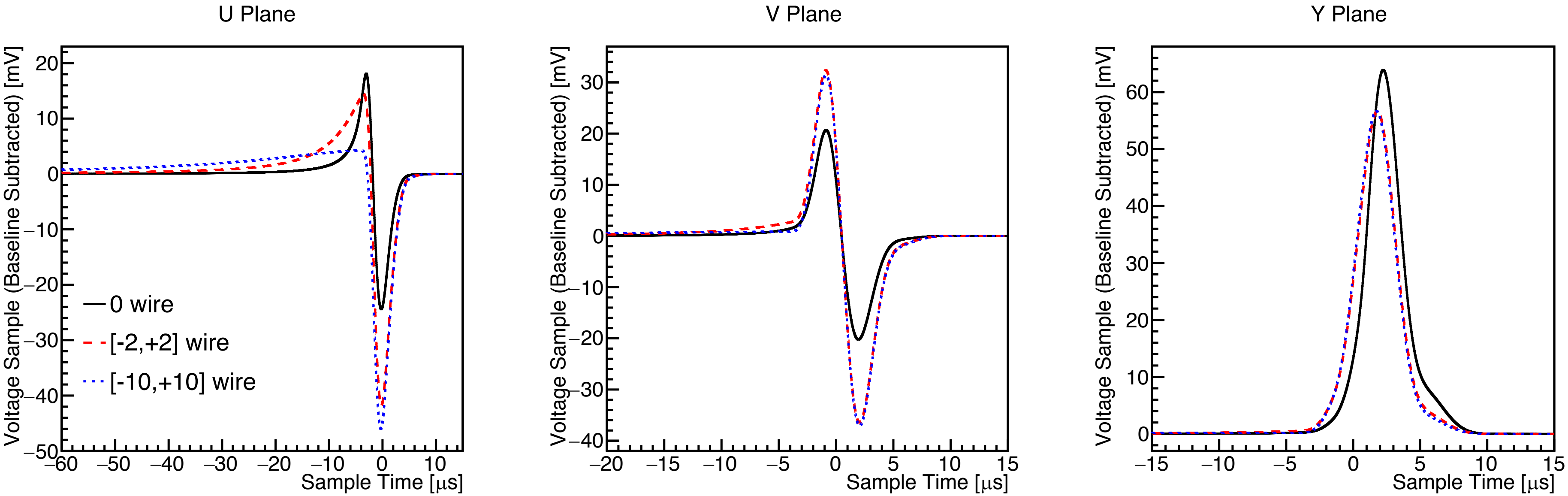


Field response shape

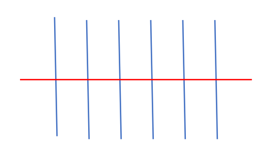


Responses over wires

Field response + Pre-amp response

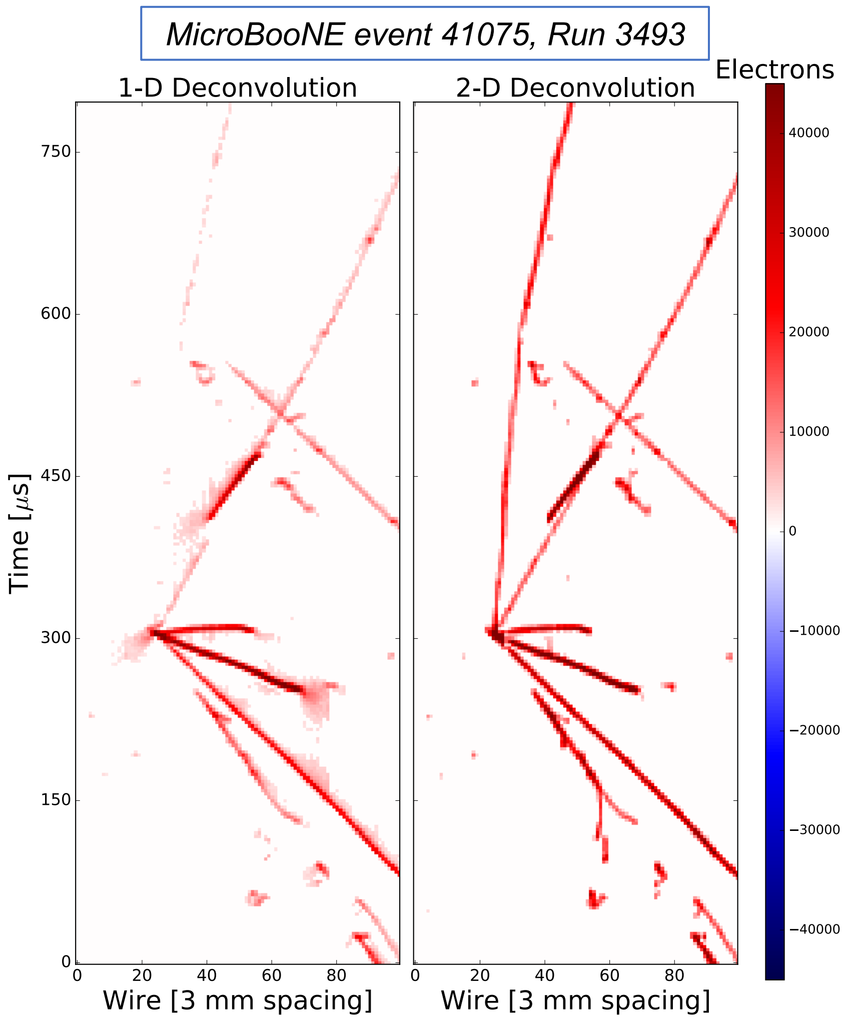


- ✓ Significant contribution from adjacent wires
  - ✓ [-10, 10] (21) wires for U plane (mitigated in DUNE design by a grid plane in front of U plane)
  - ✓ [-2, 2] (5) wires for V, Y planes (shield by U plane)
- ✓ Equivalent to an isochronous track (parallel to wire plane) and perpendicular to wire orientation (along wire pitch direction)



2D signal formation validation

- Largely by 2D (time + wire dimension) field response



Reconstructed charge after signal processing (kernel -- deconvolution)

2D decon has much better performance than 1D decon

- ✓ Significantly improved for large angle track
- ✓ Intense charge density along the track

2D signal formation validation

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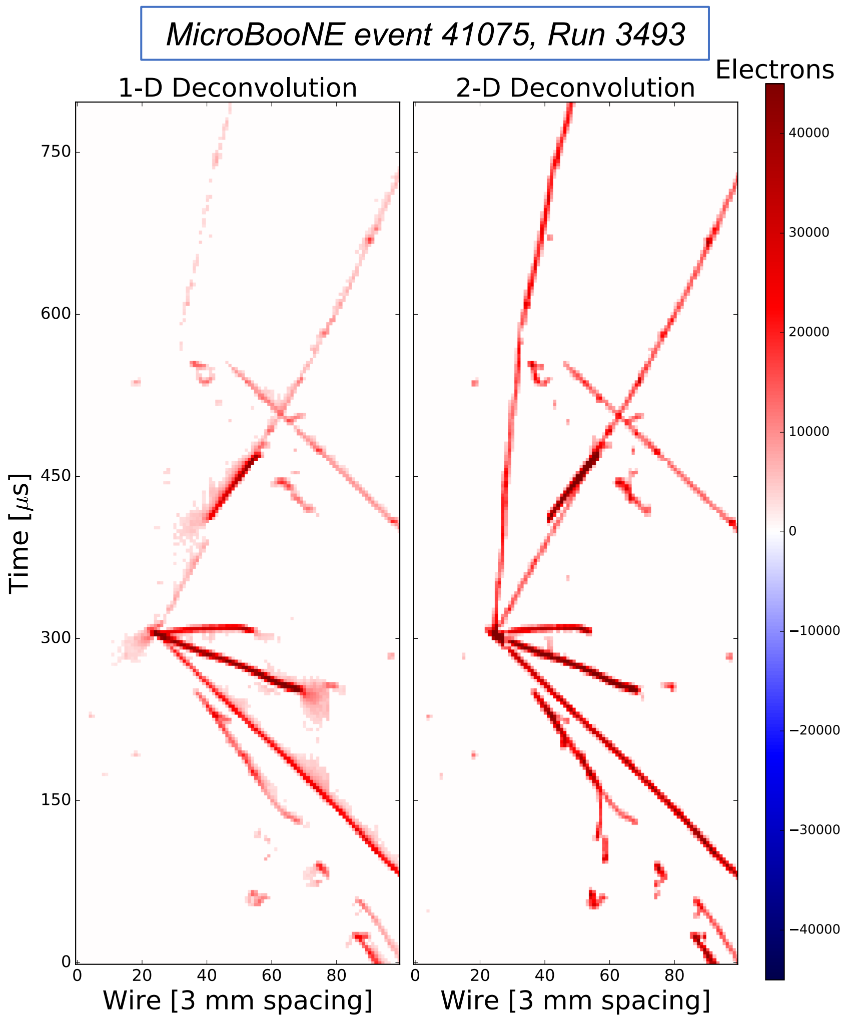

Reconstructed charge after signal processing (kernel -- deconvolution)

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Validation of Inter-wire effect

2D signal formation validation

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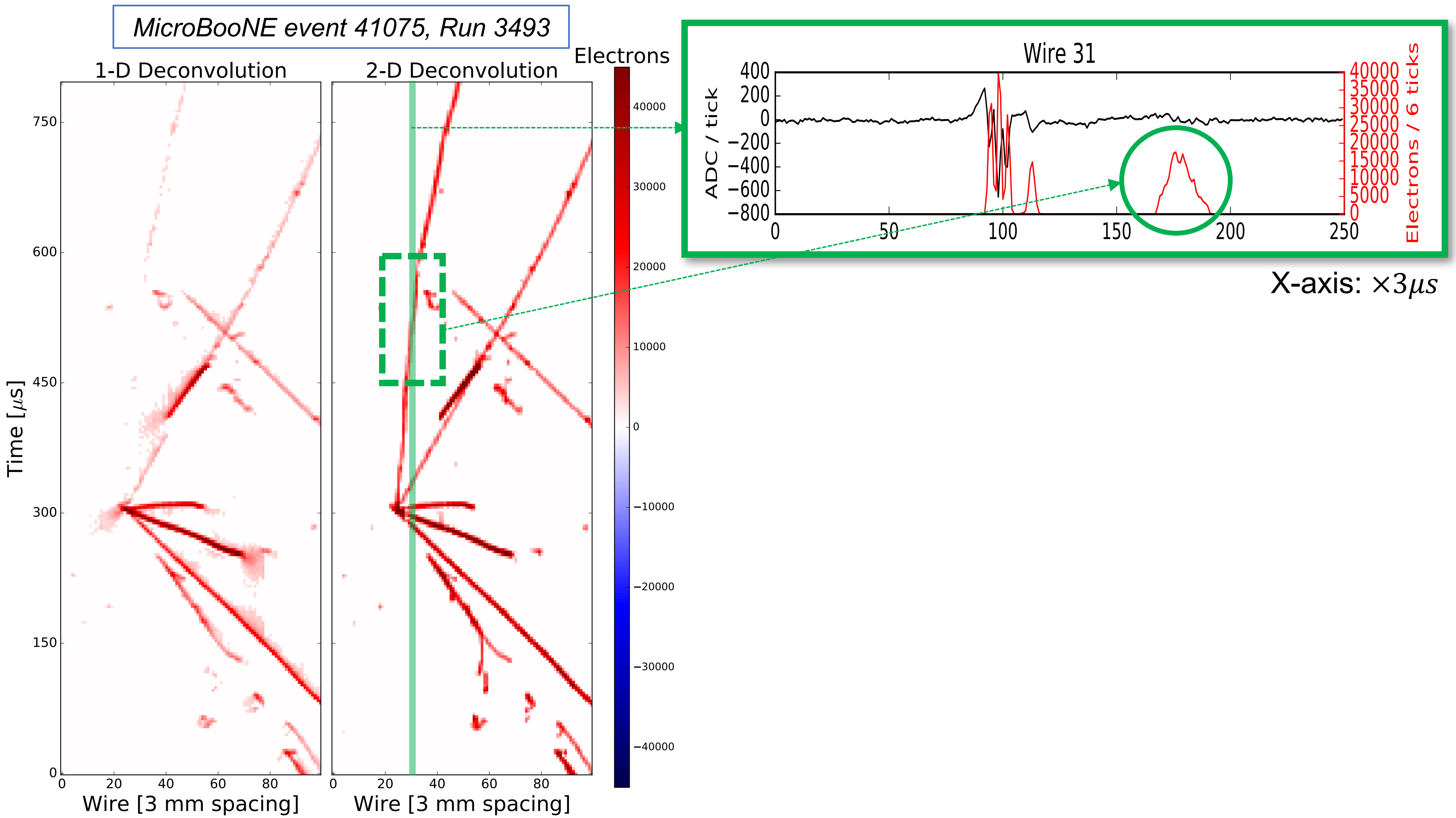
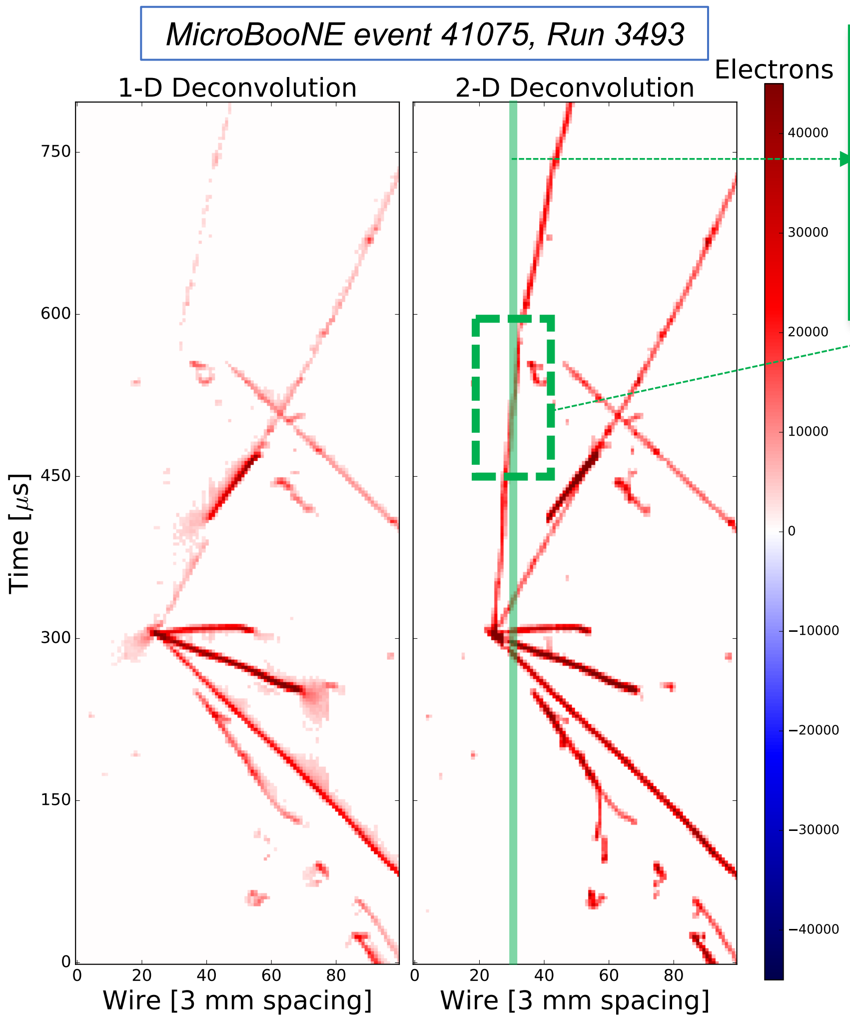
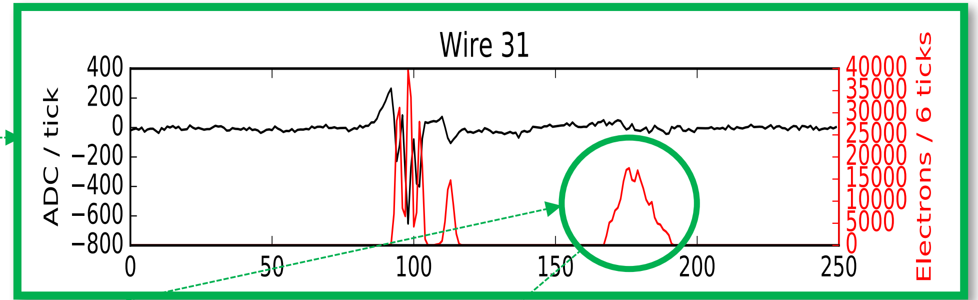


X-axis: $\times 3\mu s$

2D signal formation validation

- Largely by 2D (time + wire dimension) field response





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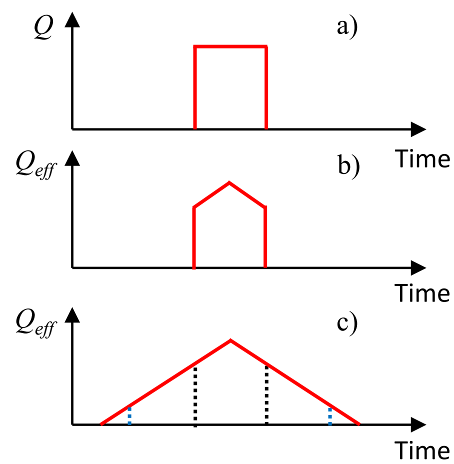


True charge in one wire

Recon charge (average response in deconvolution)

Contribution from adjacent wires

Validation of Intra- + inter-wire effect

TPC signal simulation

- Consist with abovementioned 2D signal formation

Overview of full TPC simulation

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

INPUT:
✓Geant4-based charge deposition
✓Simple point/track of charge deposition

Analytic method (shown at last)

Blue: input

✓Field response (2D garfield calculation)
✓Pre-amplifier electronic response (gain, peaking time)
✓Additional two independent RC filter response (RC constant)

Key convolution (signal shape):

$$[Gaus(t) \cdot Gaus(x)] \otimes Field(x,t) \otimes Preamp\,(t) \otimes RC(t) \otimes RC(t)$$

✓Ionization (W-value, fano factor)
✓Recombination (Birks & Modified box models)
✓Ionizing electron attachment (electron lifetime in LAr)
✓Gaussian diffusion (longitudinal / transverse)
✓Fluctuation (each step)

Interpolation of field response

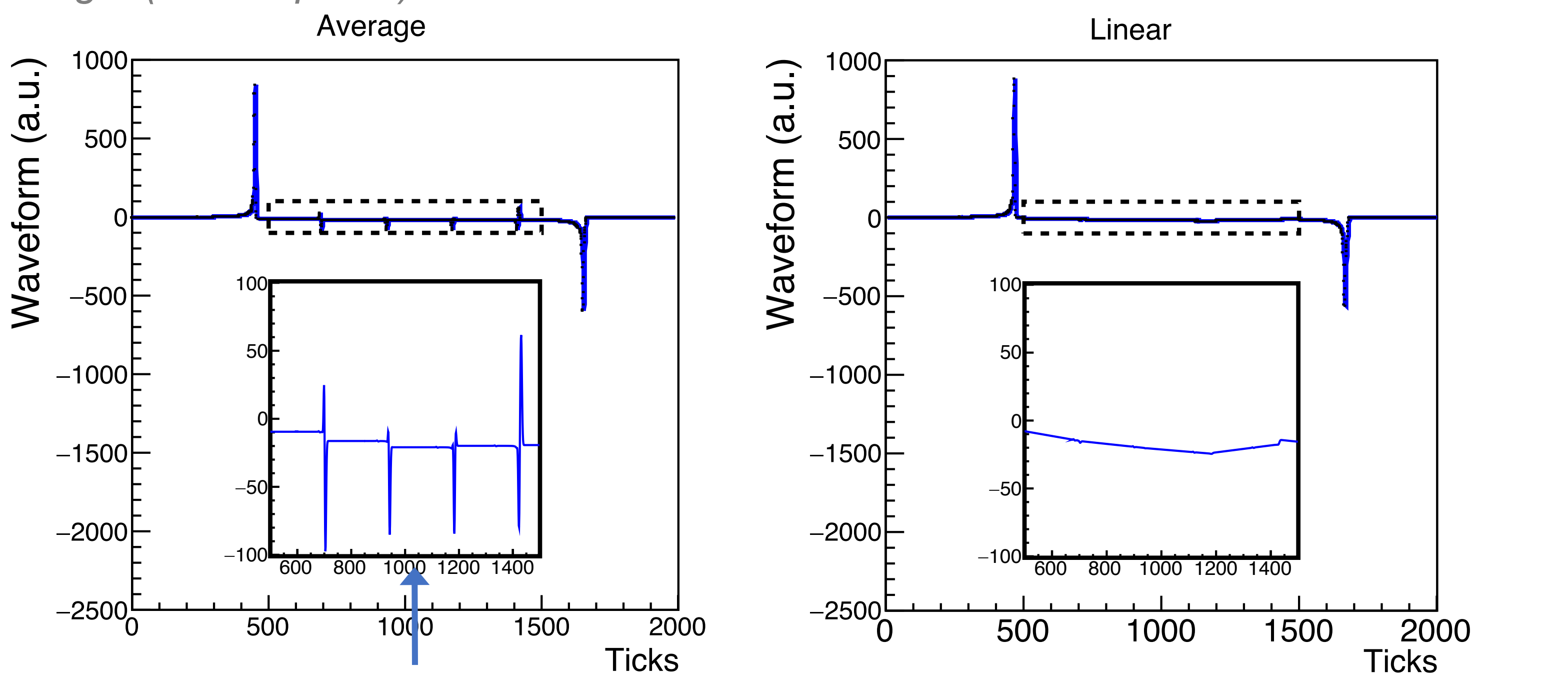
$$Diffusion[Gaus(t) \cdot Gaus(x)]$$
$$\otimes Field(x,t)$$
$$\otimes Preamp\ (t) \otimes RC(t) \otimes RC(t)$$

Input (126 paths):
0 ± 10 wires (63 mm)
Fine-grained calculation (per 0.3 mm)

\+

Linear interpolation performed

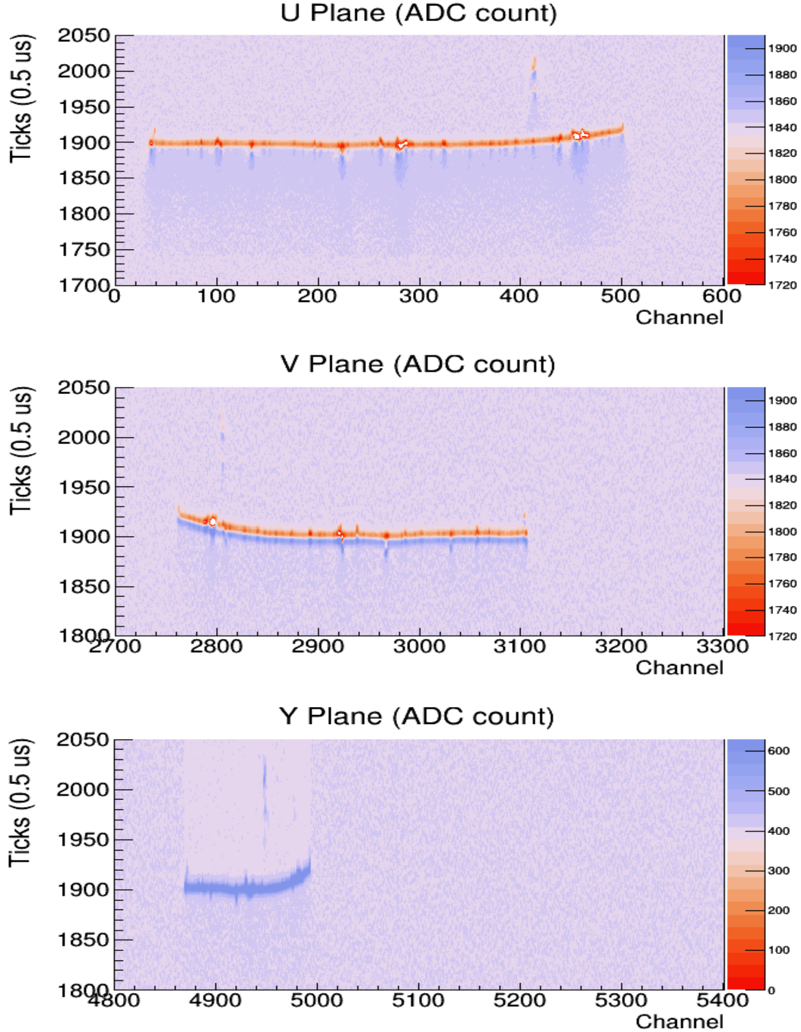
A large angle (to wire plane) track



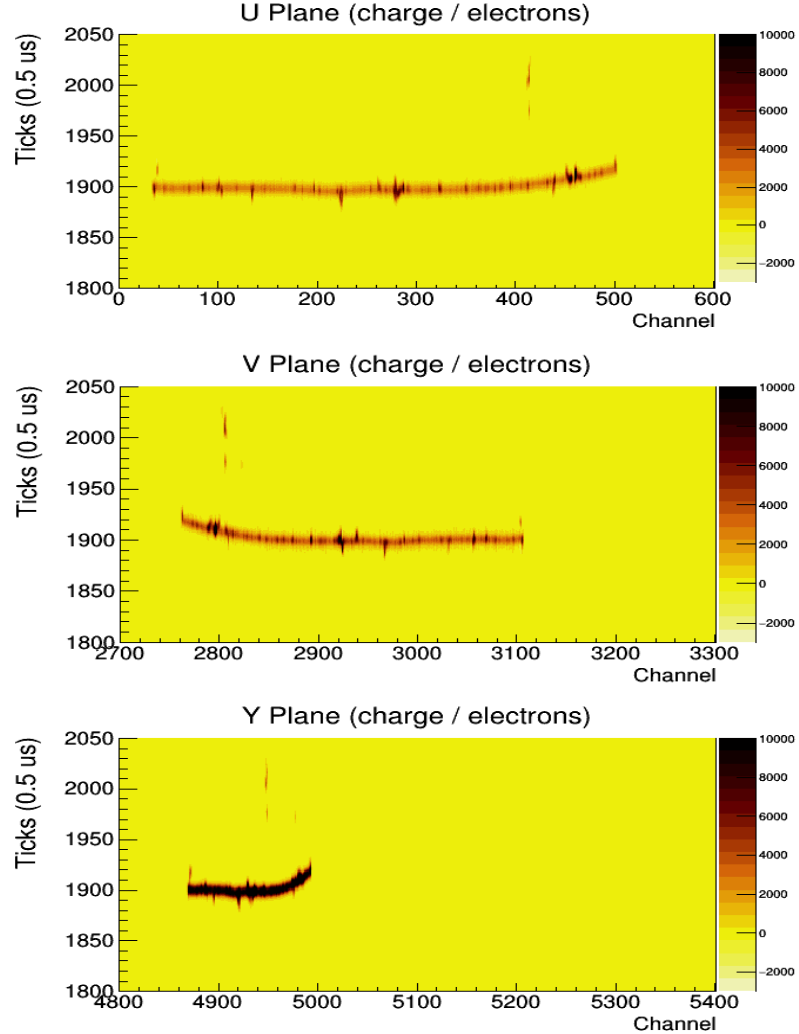
Non-proper bipolar cancellation at boundary of 0.3 mm sub-pitch

A simulation of 5-GeV muon

ADC Waveform



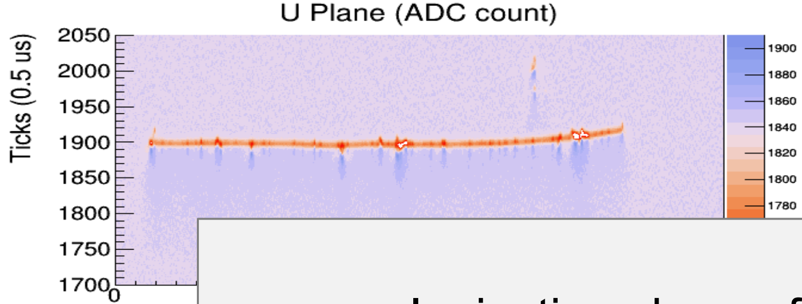
Charge

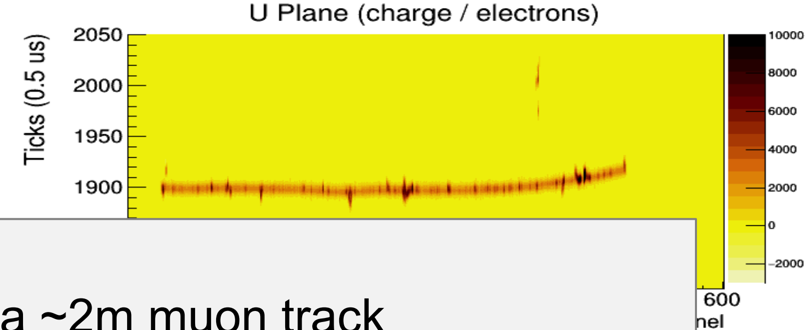


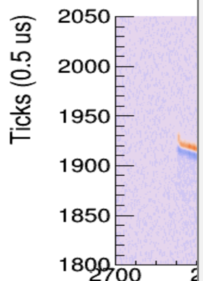
A simulation of 5-GeV muon

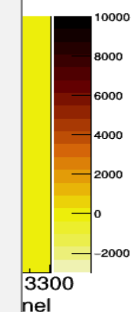
ADC Waveform

Charge





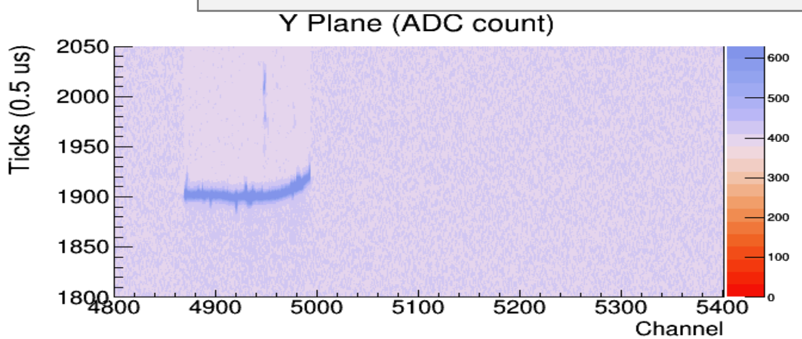


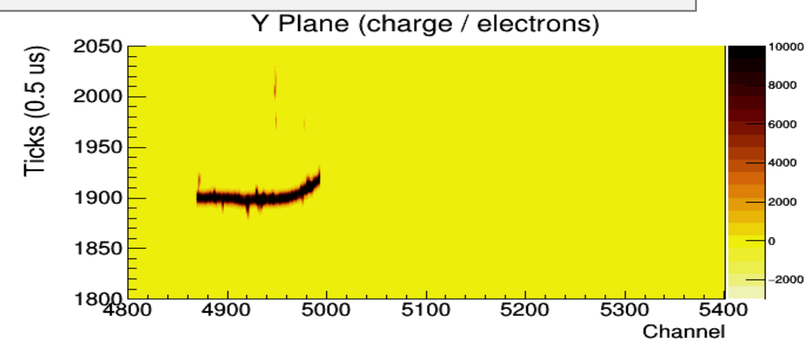


Ionization charge from a ~2m muon track

Time/Memory summary (local machine):

0. Start: 0 second/+230 MB
1. Ionization electron signal: 42 seconds/+60 MB
2. Electronics noise: 11 seconds/+600 MB
3. Output: 2 seconds





Noise simulation

- Inevitable in the electronics
- Critical to the signal processing (ADC waveforms to ionization charge)

Pre-amplifier inherent noise

"Noise Characterization and Filtering in the MicroBooNE Liquid Argon TPC", JINST 12 (2017) P08003

noise type	also called	normalization	Time Domain pulse	s domain
Thermal 1	series white	$\sqrt{2k_B T_{temp} R_S} \times C_{\det}$	$\times G \cdot \delta(t - t_j)$	$\times G \cdot e^{-st_j}$
Thermal 2	parallel white	$\sqrt{2k_B T_{temp} / R_F}$	$\times G \cdot u(t - t_j)$	$\times \frac{G}{S} \cdot e^{-st_j}$
Shot noise	parallel white	$\sqrt{qI_{leakage}}$	$\times G \cdot u(t - t_j)$	$\times \frac{G}{S} \cdot e^{-st_j}$
Flicker noise (1/f or pink)	series 1/f	$C_{\det} \sqrt{2\pi a_F}$	$\times \frac{G}{\sqrt{\pi \cdot (t - t_j)}}$	$\times \frac{G}{\sqrt{s}} e^{-st_j}$
Man made noise	Various couplings	Usually has discrete frequency spectrum. Ignored here, could be modeled.		

Thermal fluctuation in the input transistor (Thermal 1)

Transistor bias current and resistors providing the bias voltage (Thermal 2, Shot noise)

Charge trapping and de-trapping in the input transistor (Flicker noise)

- Noise occurring time t_j is uniformly distributed (origin of the fluctuations)
- In frequency domain, given a ω_0, the stochastic effect just in phase term $e^{-i\omega_0 t_j}$ (delta function at t_j in time domain)

Noise -- Random Walk

Noise in frequency domain:

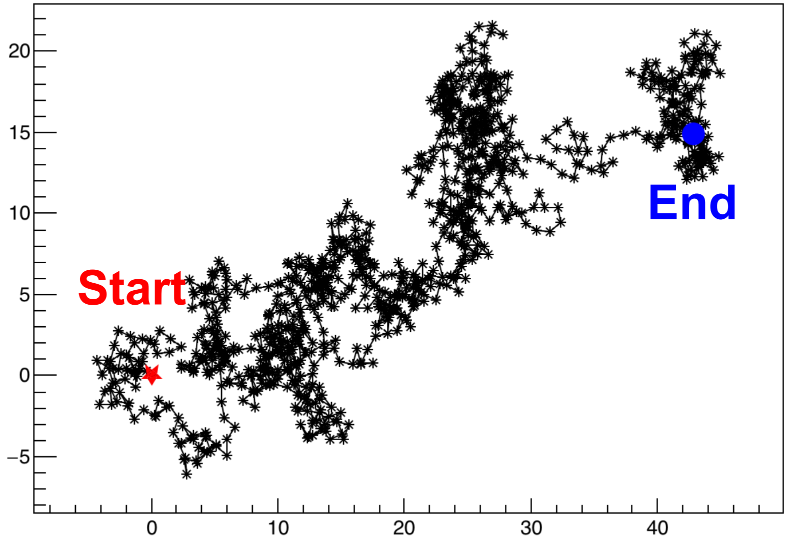
$$F(\omega) \propto \sum_{i=1}^{N} q_i(\omega) \cdot e^{-i\omega t_i} = \sum_{i=1}^{N} L(\omega) \cdot e^{-i \cdot \alpha}$$

Sign of q_i (Bernoulli variable)

- unnecessary to be 50% + (-)
- absorbed into phase term

α is uniformly distributed in [0, 2π)

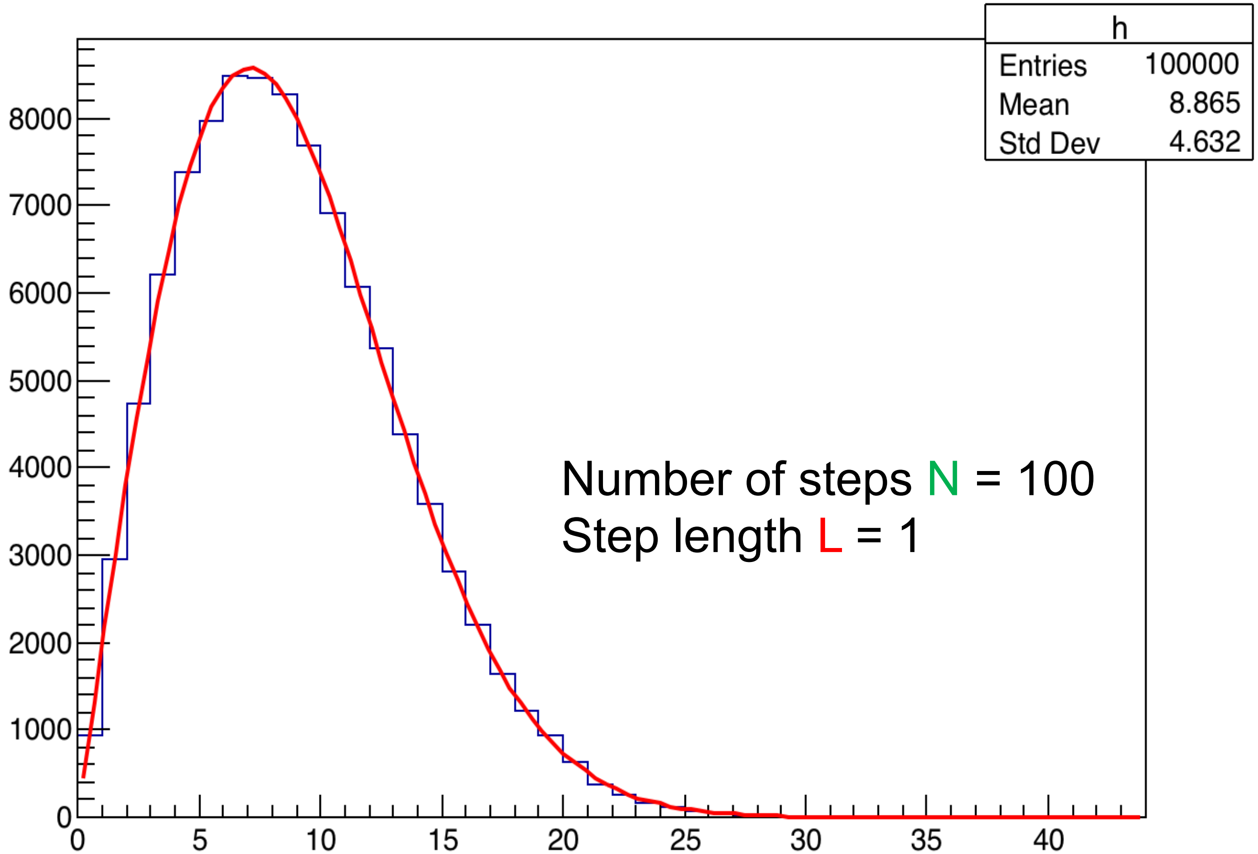
- N needs to be large enough



$F(\omega)$ follows a random walk in the complex plane with the step length $L(\omega)$

How to describe vector 'End – Start'?
Amplitude: Rayleigh distribution
Phase: uniform

Rayleigh distribution



$$f(x; \boldsymbol{\sigma}) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}$$

$$\text{Mean} = \sigma\sqrt{\pi/2}, \text{Mode} = \sigma$$

Only one parameter $\boldsymbol{\sigma}$

A simpler view

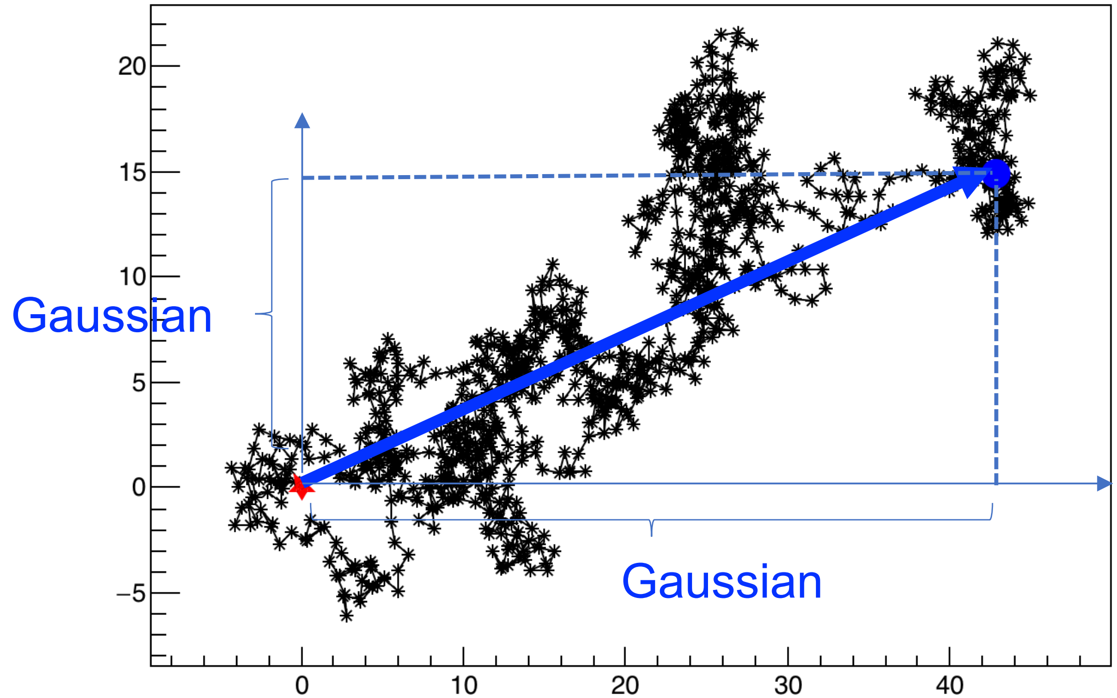
Random Walk (Rayleigh distribution + uniform phase):
Two independent Gaussian distributions with same deviation (the only parameter σ in Rayleigh distribution)

↓

Additivity property of Gaussian distribution

↓

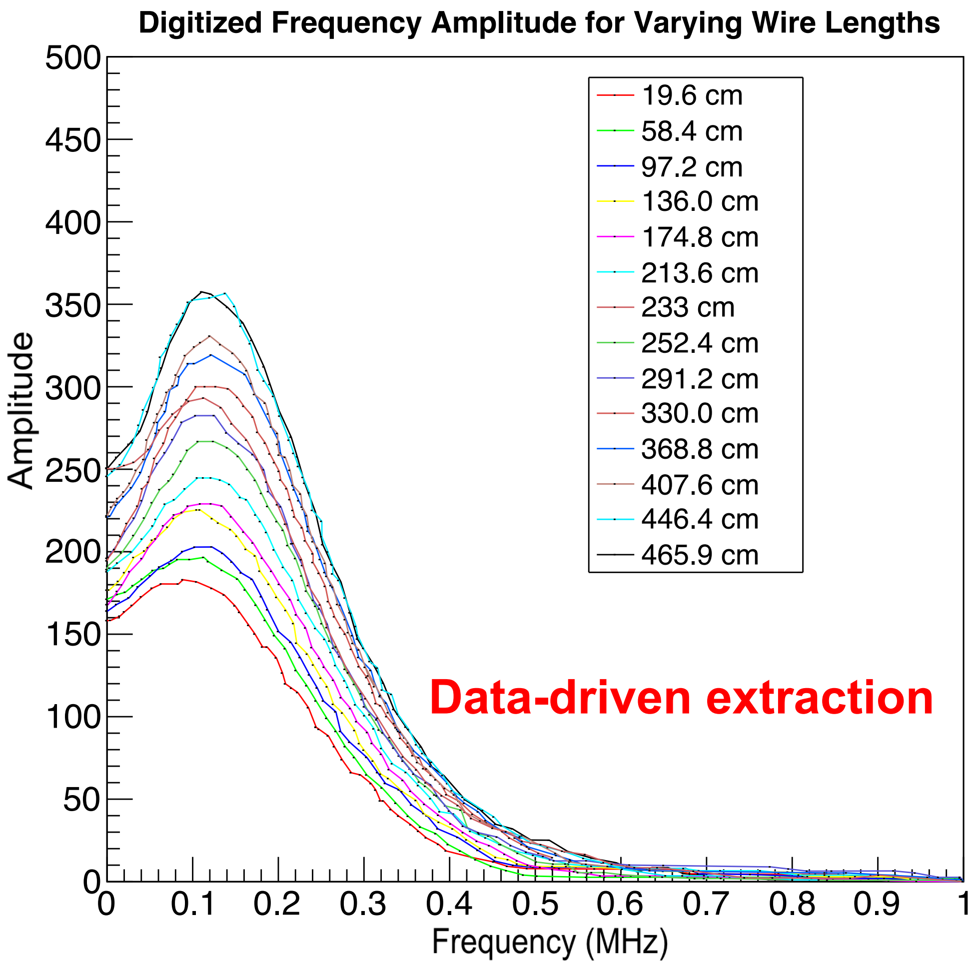
Summation of all sources of noise still can be described by only one parameter σ (the deviation of the two Gaussian distributions)

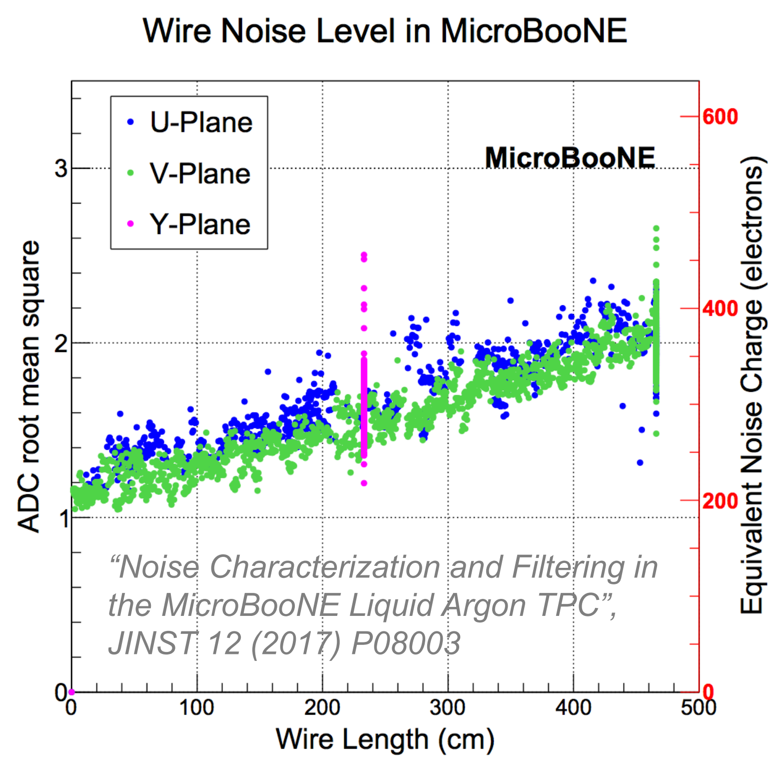


↓

Only the mean amplitude of $F(\omega) = \sqrt{\pi/2} \cdot \sigma$ is needed

Mean frequency amplitude





Summary

- The single phase LArTPC signal formation has been presented.
- 2D (time & wire) response is demonstrated.
- A corresponding/consistent signal simulation is introduced.
- A new analytic method of noise simulation is introduced.

- Special region response (e.g. shorted wire in MicroBooNE) stays tuned by data-driven result.
- An attempt on 3D calculation (boundary element method) is on-going.

Two MicroBooNE papers

- Ionization signal analysis and processing in single phase LArTPCs
  - Paper 1: signal formation, simulation, extraction (signal processing)

    Starting review.
    B. Russell will give a talk about the signal processing and evaluation with simulation.

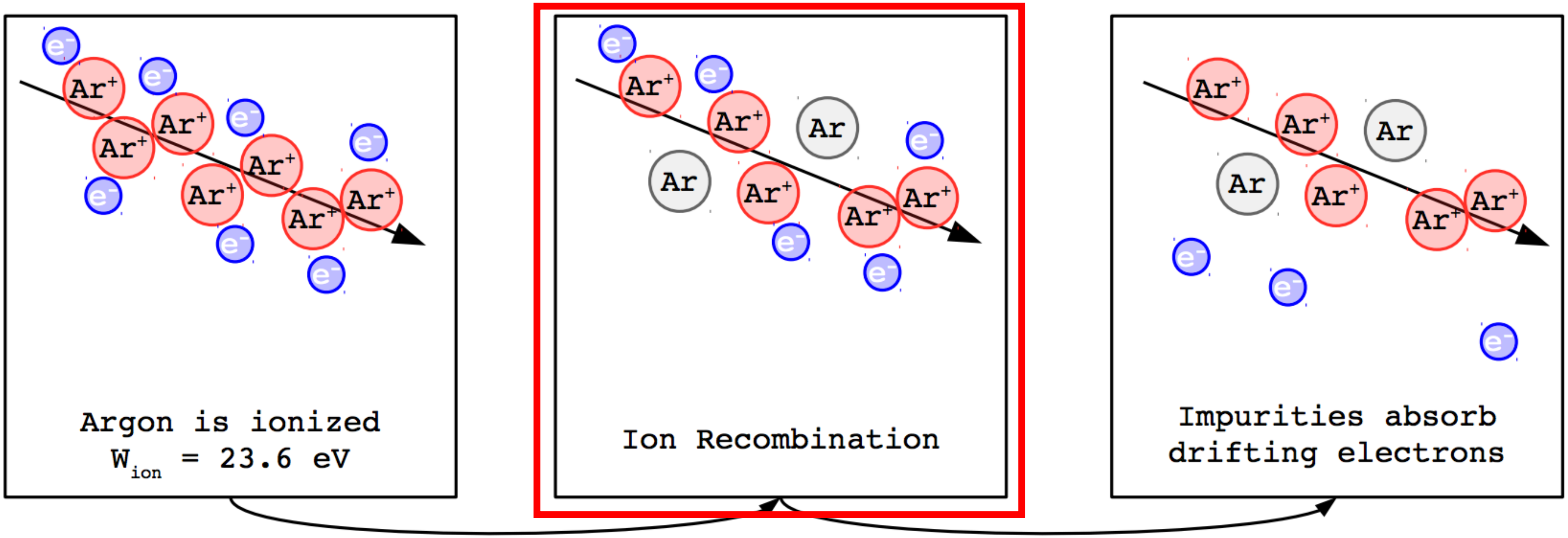
  - Paper 2: data/MC comparison and performance in MicroBooNE

    Be ready soon.

BACKUP

Signal loss in LAr -- recombination

uBooNE DocDB 6866



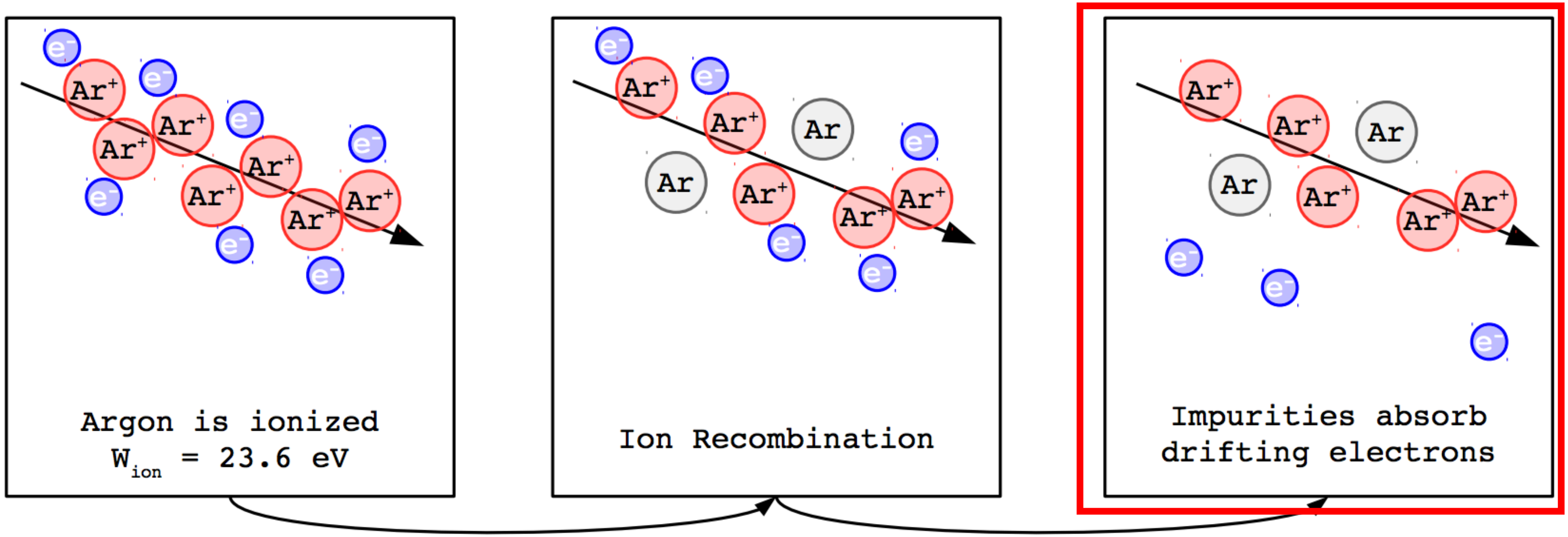
$$R = \frac{dQ/dx}{dE/dx}$$

$R \cong 60\%$ @87K, 273V/cm

$R \cong 70\%$ @87K, 500V/cm

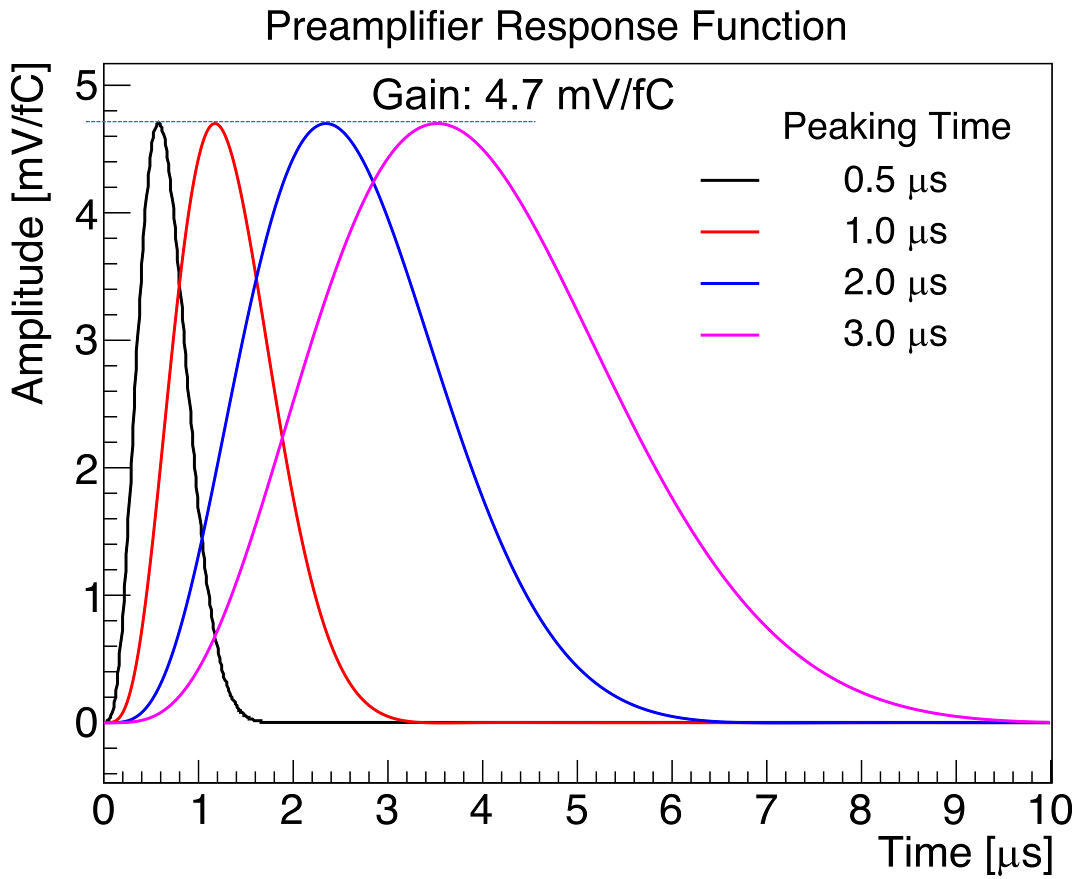
Signal loss in LAr -- absorption

uBooNE DocDB 6866

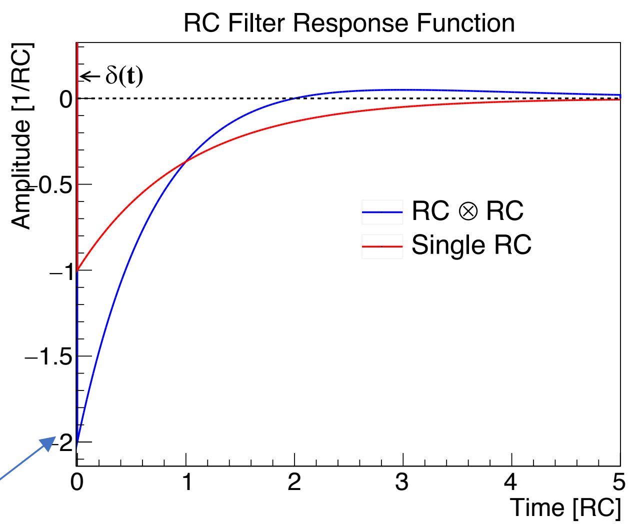


$L = e^{-t_{drift}/\tau}$, τ is defined as electron lifetime, τ > 18.5 ms (normal MicroBooNE operation, O_2 equivalent contamination < 16 ppt)
Maximum signal loss <12% at MicroBooNE (2.3 ms drift from anode to cathode).

Electronics responses



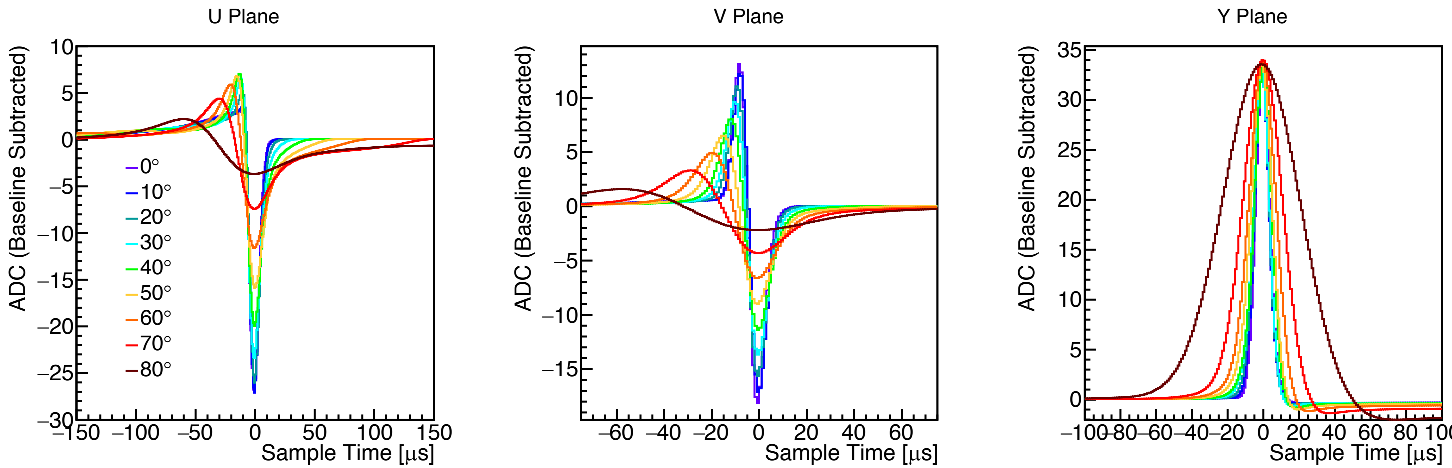
In MicroBooNE, two additional RC filters (RC =1 ms, remove baselines)

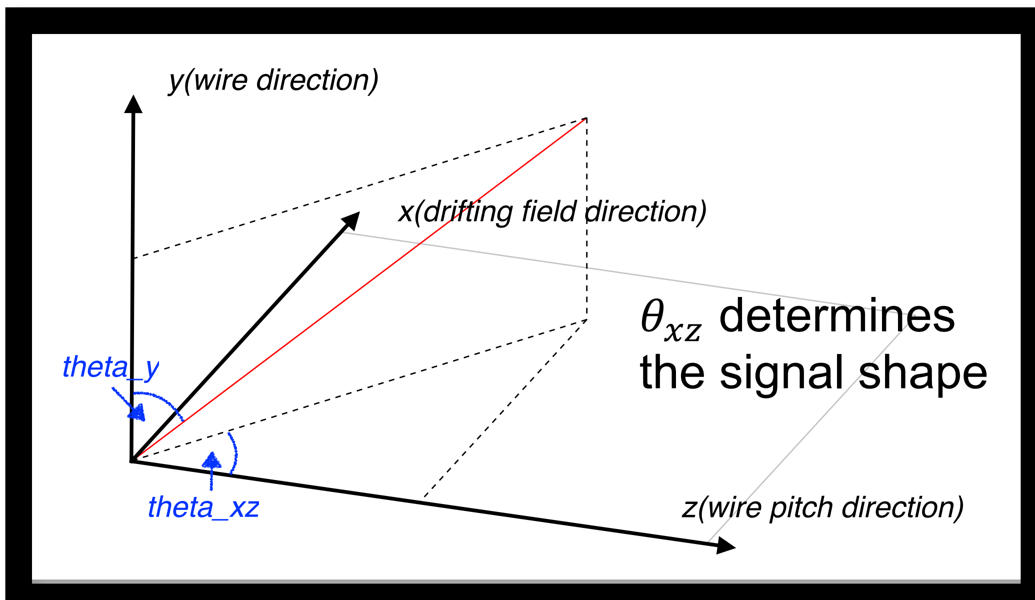


- ✓ Significant if long or large signal
- ✓ In general, <1% of the signal peak

Topology-dependent event

Varying θ_{xz}
given $\theta_y = 90°$
(perpendicular
to wire
orientation)

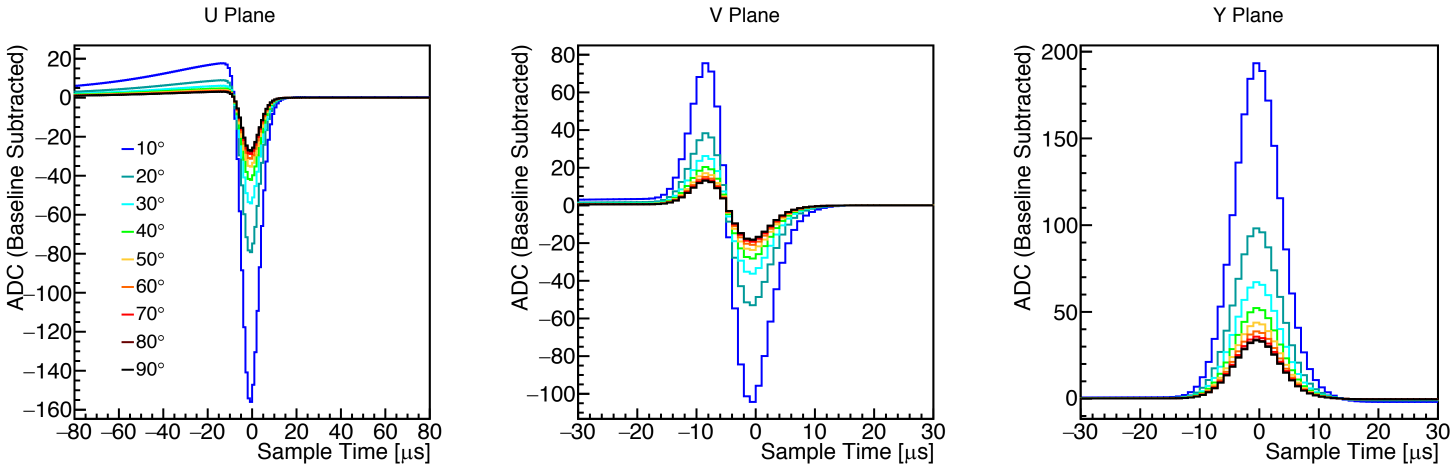


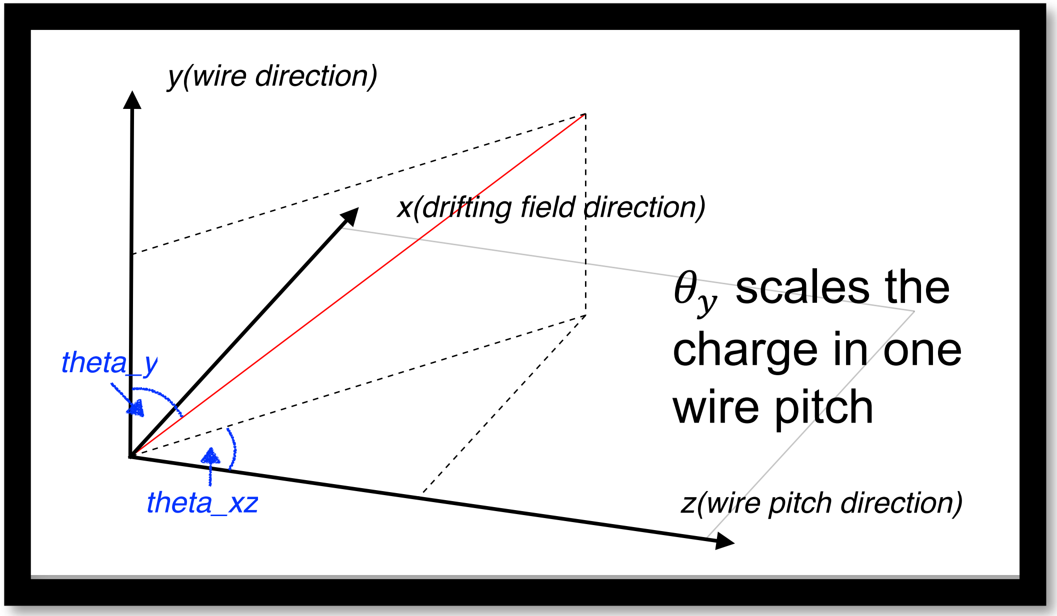


Topology-dependent event

Varying θ_y

given $\theta_{xz} = 0°$ (isochronous)

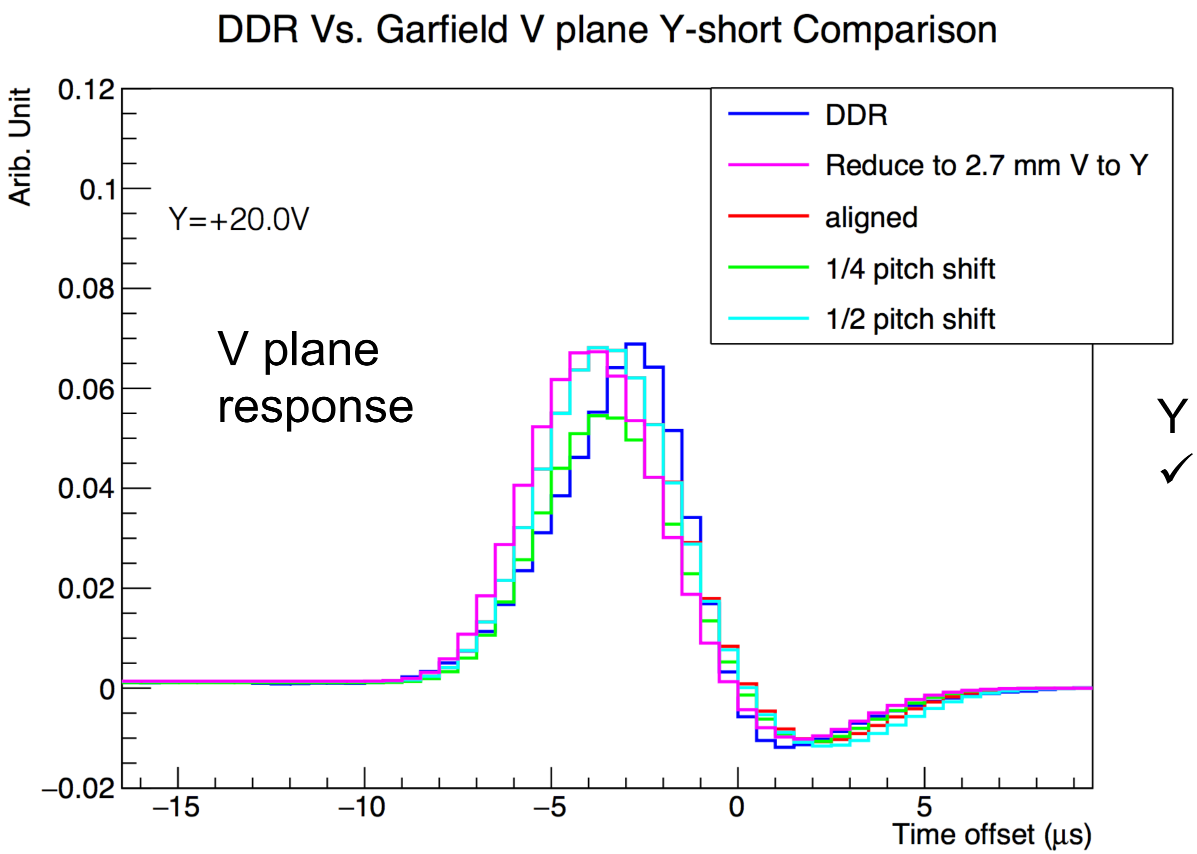




θ_y scales the charge in one wire pitch

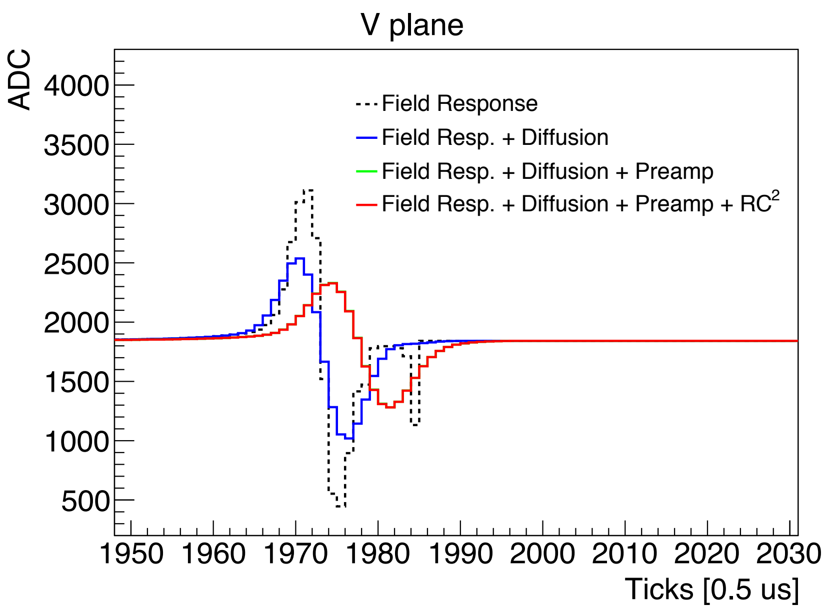
Shorted wire region

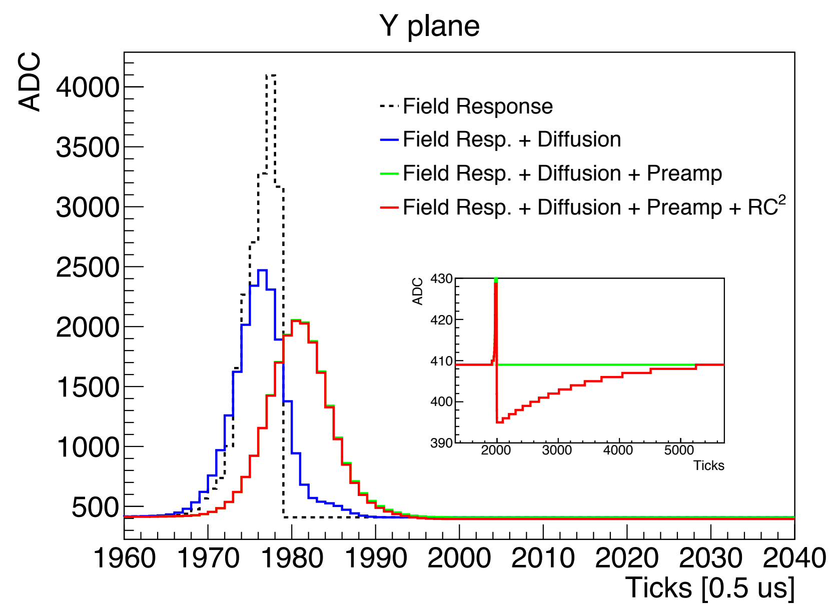
- Some special field response, e.g. shorted wire region of MicroBooNE detector, stays tuned by data-driven result.



Y shorted by V wire
✓ V plane has bipolar (electron bypass) + unipolar response (electron collected)

Overall TPC Response





- ✓ Effects/Responses changing the signal shape
- ✓ In time dimension

Do not forget about signal shape changes/smearing in wire dimension

- **Diffusion**
- **Field response**