Towards TPC Signal Formation, Simulation in Single Phase LArTPC

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APA consortium meeting
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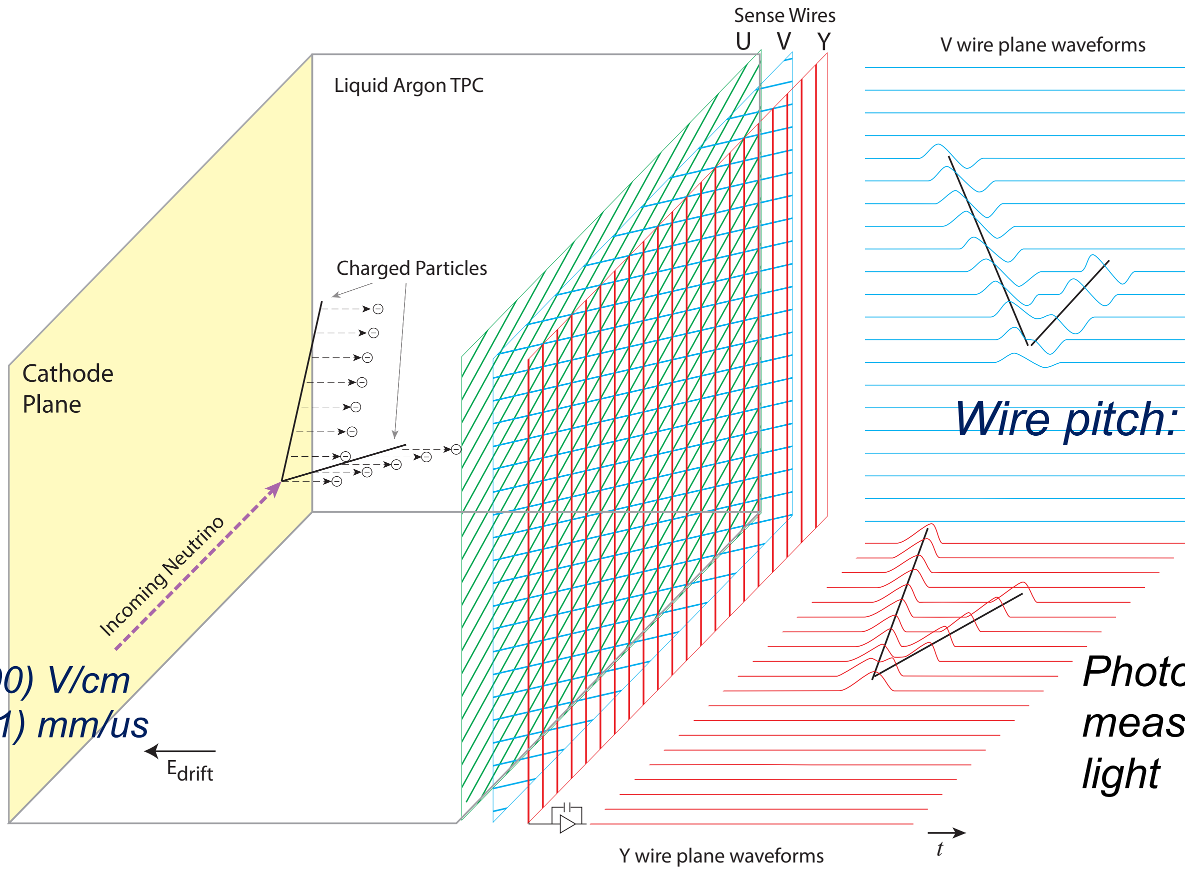
Outline

MicroBooNE detector context and experience.

- LArTPC introduction
- Signal formation (wire readout)
- Signal simulation (time & wire dimension)
- Noise simulation (analytic method)
- Summary

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

Signal Formation

- Definition: from ionization electrons to ADC waveforms

LAr

At production

✓ Ionization

✓ Recombination (signal loss)

In drifting

✓ Diffusion (signal shape change)

✓ Attachment/absorption (signal loss)

Wire induced current (field response)

Long-range effect

✓ Time dimension

✓ Wire dimension

Electronics

Cold electronics

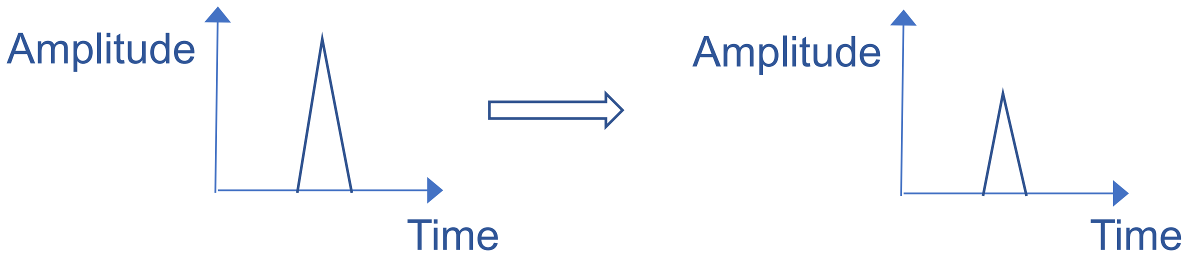
✓ Preamplifier

✓ RC filter

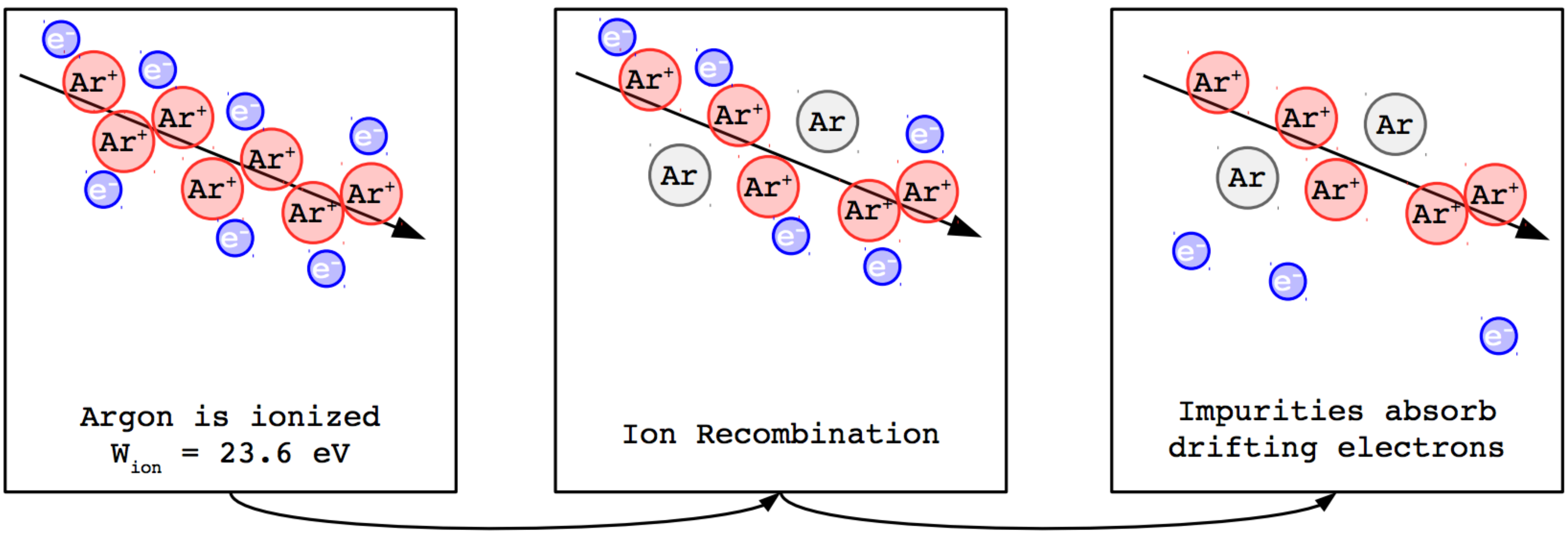
✓ ADC

In uBoone, only cold preamp
In future design, all in cold

Signal formation – signal loss in LAr



uBooNE DocDB 6866



Signal formation – signal loss in LAr

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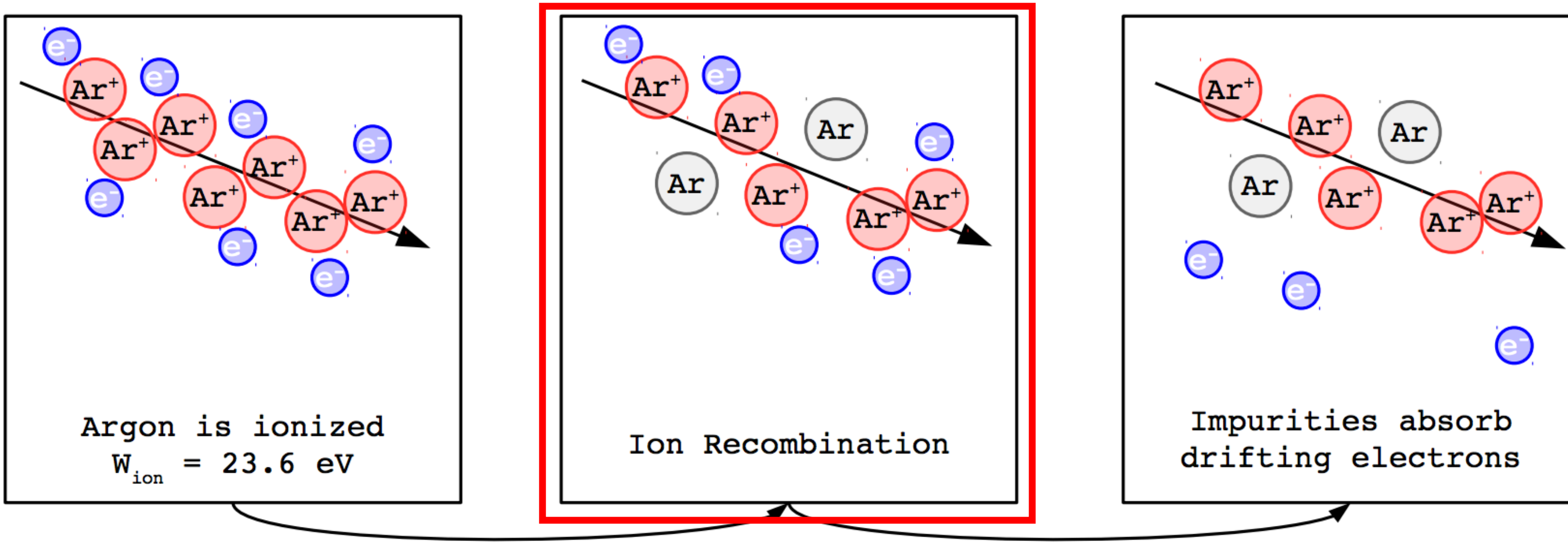

$$R = \frac{dQ/dx}{dE/dx}$$

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

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

Signal formation – signal loss in LAr

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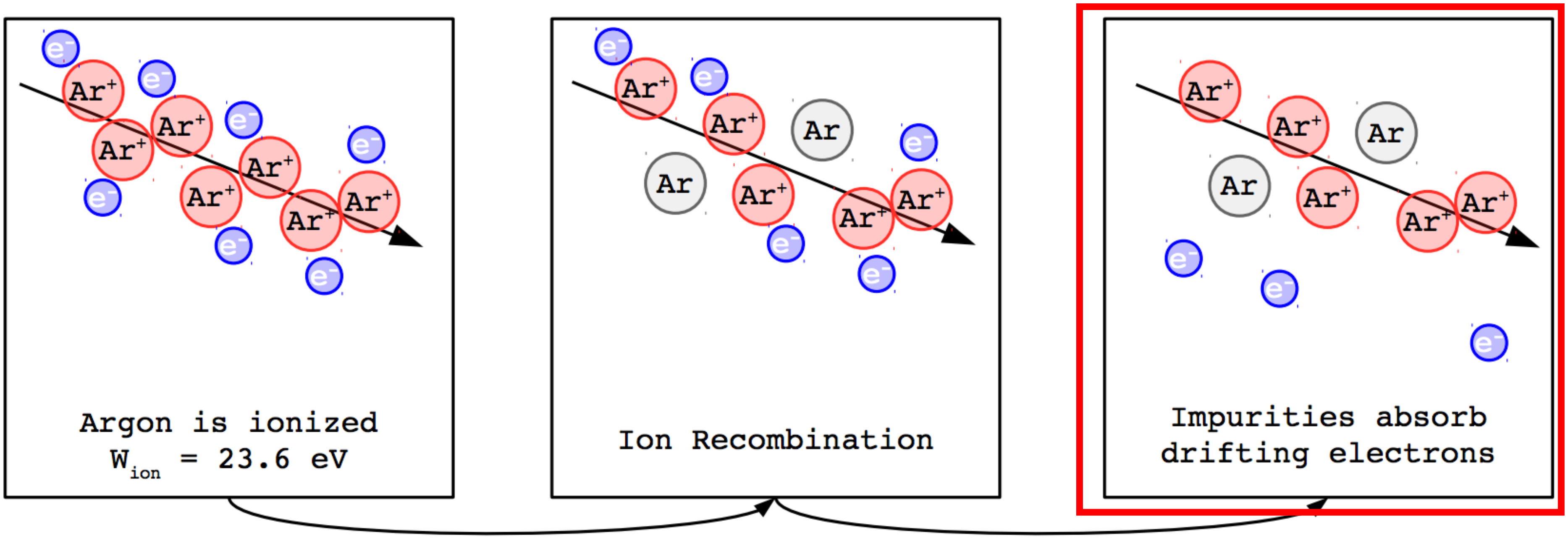
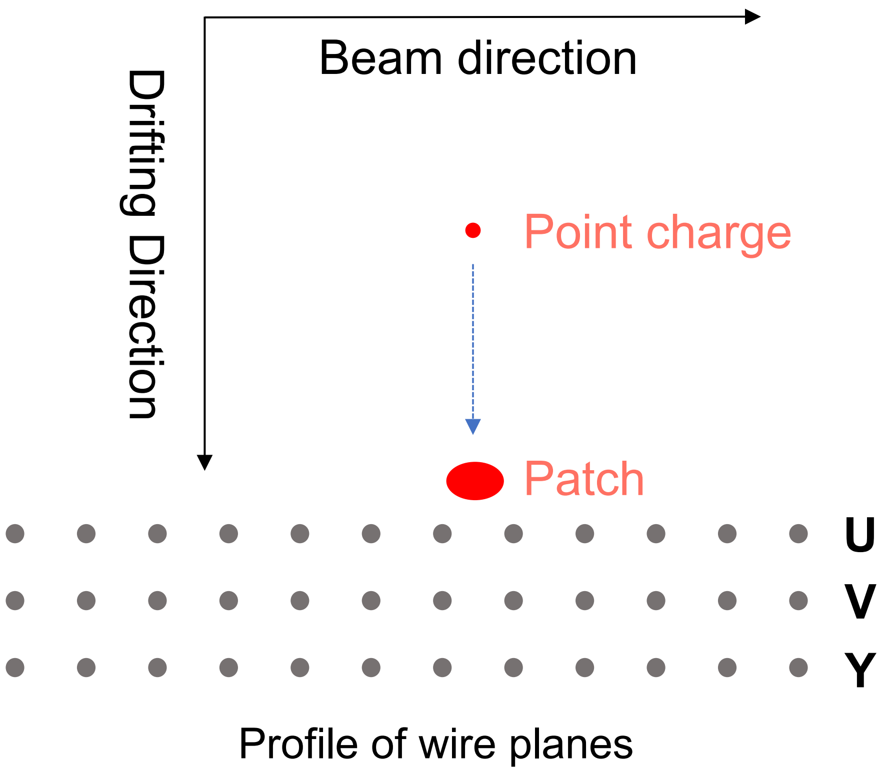


$L = e^{-t_{drift}/\tau}$, τ is defined as electron lifetime, τ > 18.5 ms (normal MicroBooNE operation, O_2 equivalent contamination < 16 ppt)
Maximum signal loss <12% at MicroBooNE (2.3 ms drift from anode to cathode).

Signal formation – diffusion in LAr

- Signal 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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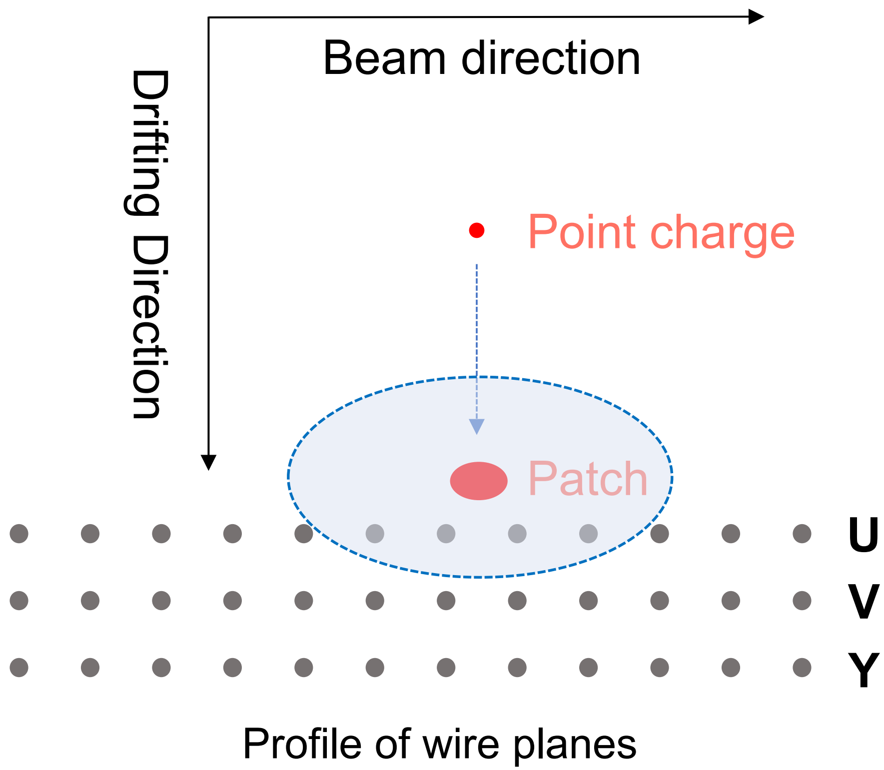

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$$\sigma \propto \sqrt{D_{drift}}$$

Insignificant in comparison with long-range wire induction field response (*signal expansion in time & wire dimensions*)

Field response

- Wire readout – **induced current signal**
  - All three wire planes (induced signal ceased at 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

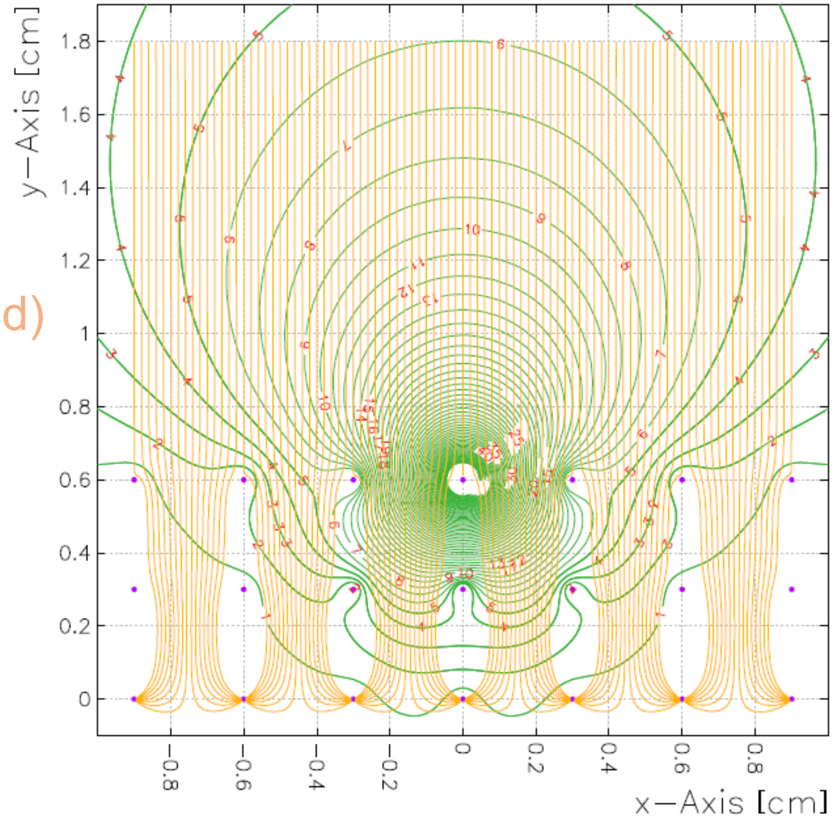
- *placing the target wire to the unity potential, and the rest to zero*
- *Long range effect*

Electron track (E field)

\+

Weighting potential

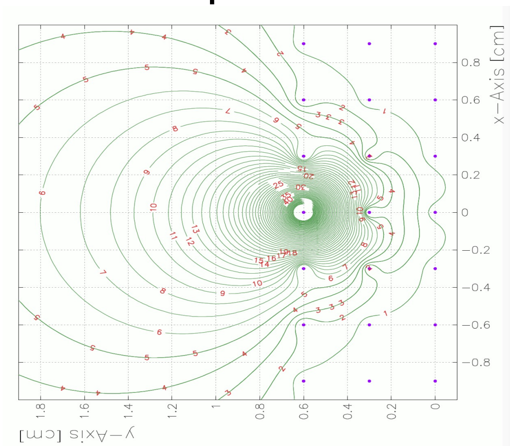
Weighting Field of a U Wire



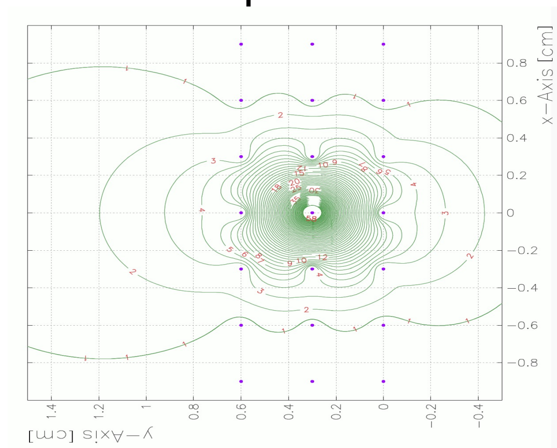
Field response -- 2D Garfield calculation

Weighting potential

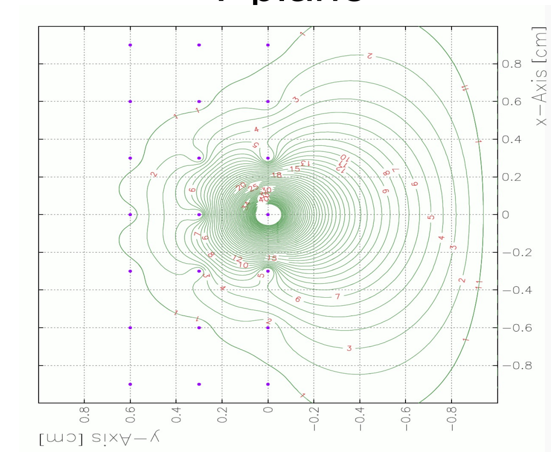
U plane



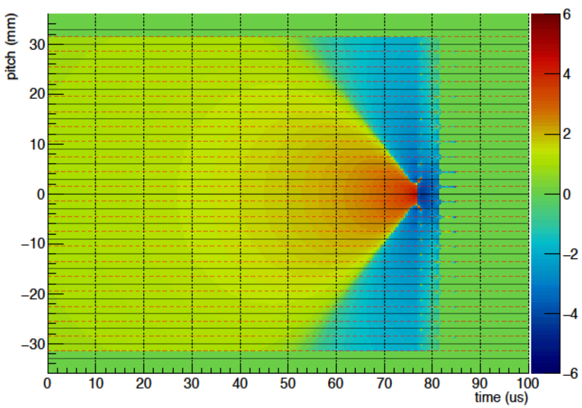
V plane

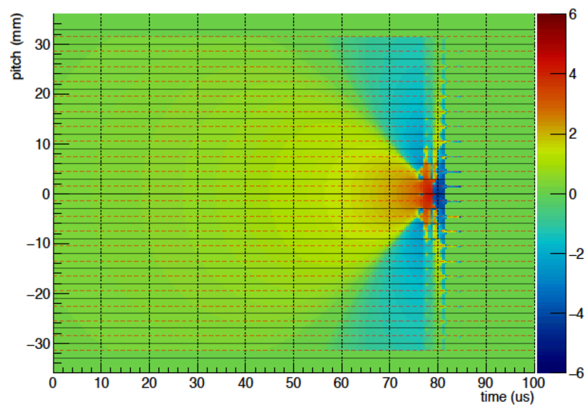


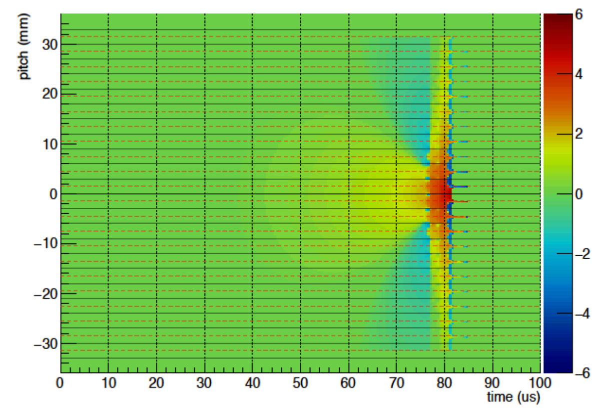
Y plane



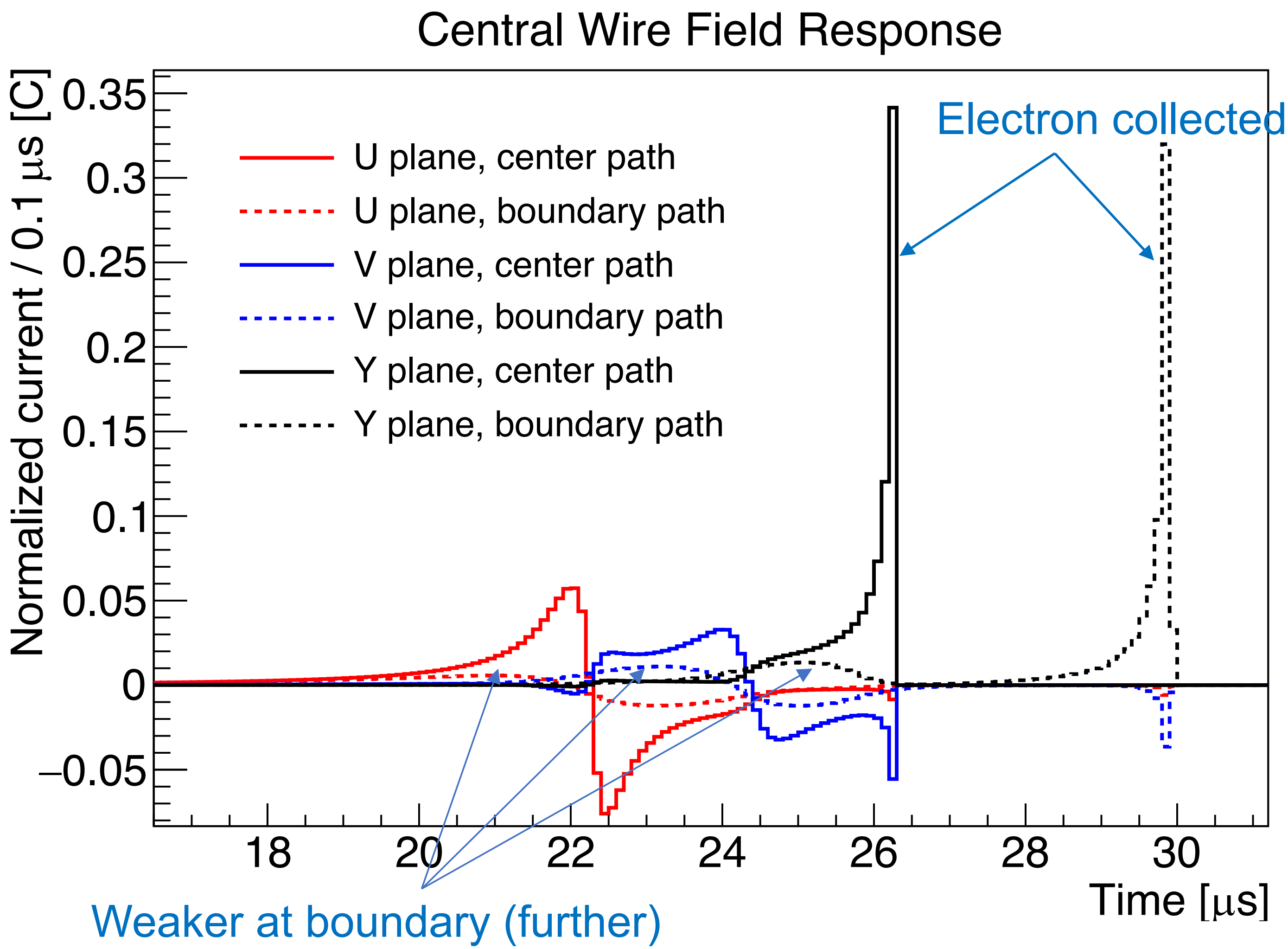
Field response (Plot in log scale, arbitrary unit)



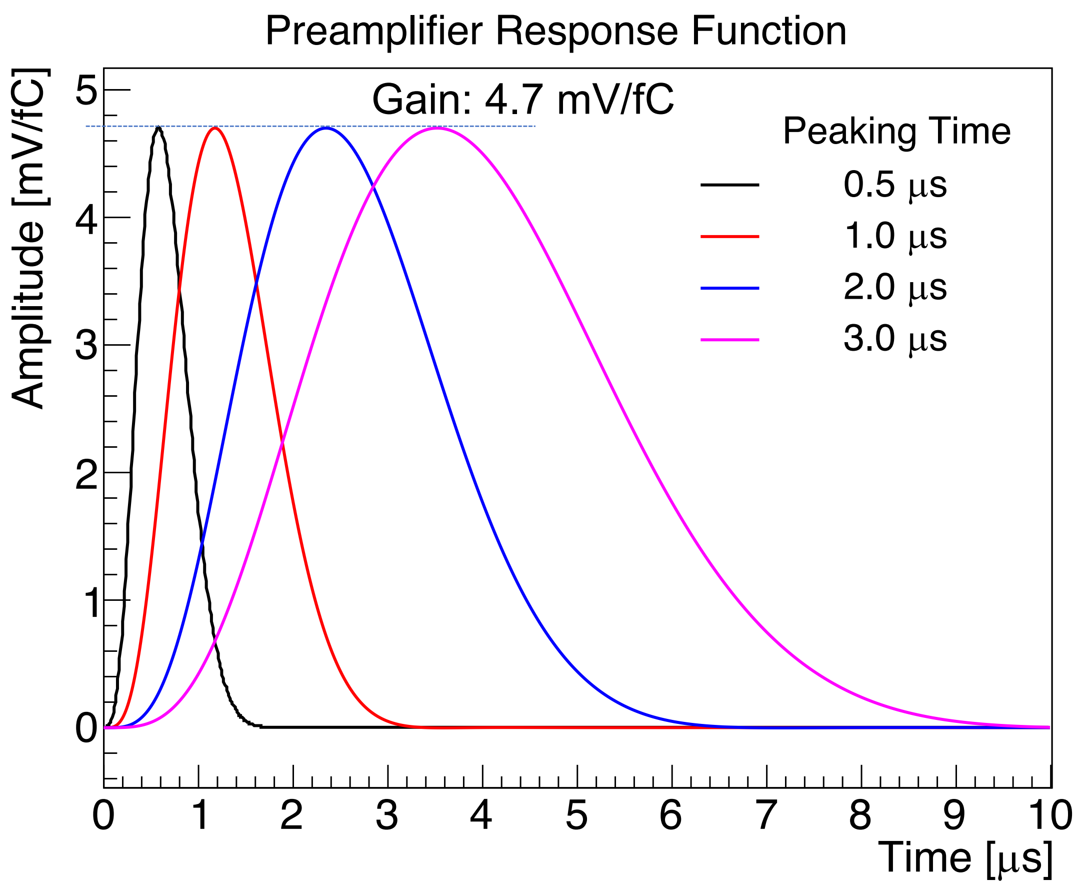




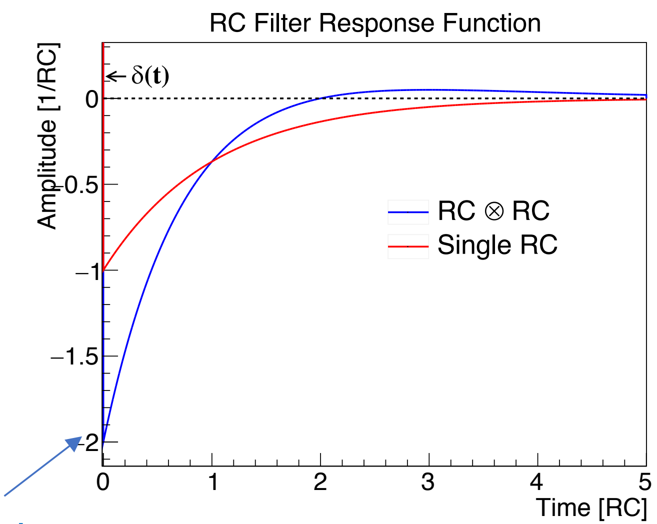
Field response shape



Electronics responses

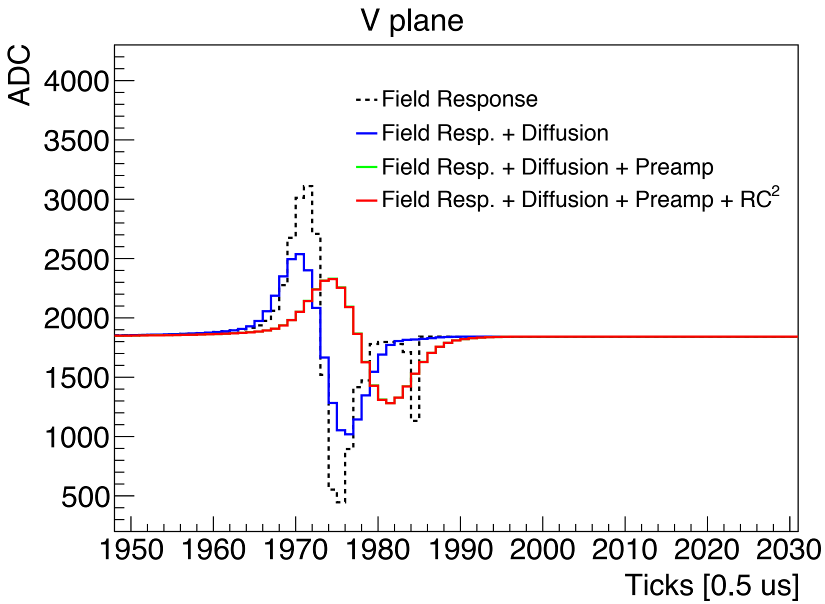


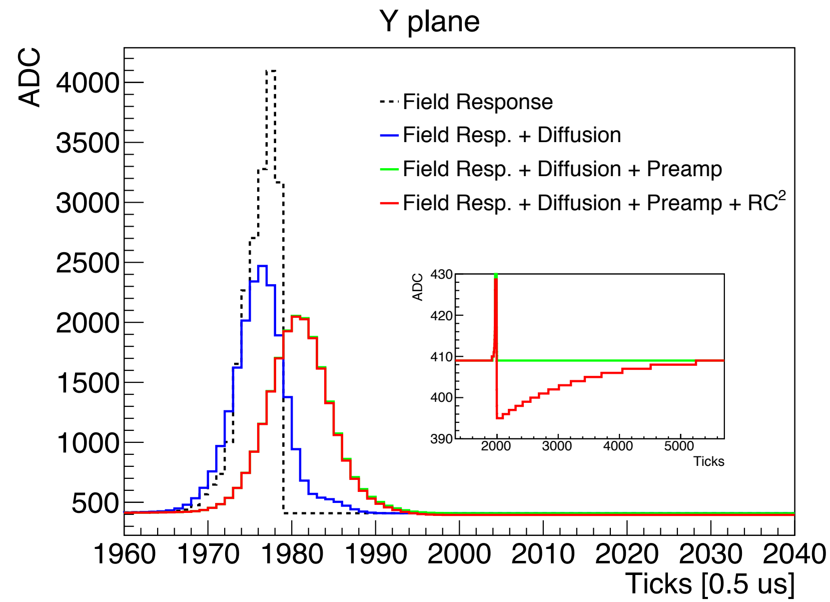
In MicroBooNE, two additional RC filters (RC =1 ms, remove baselines)



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

Overall response





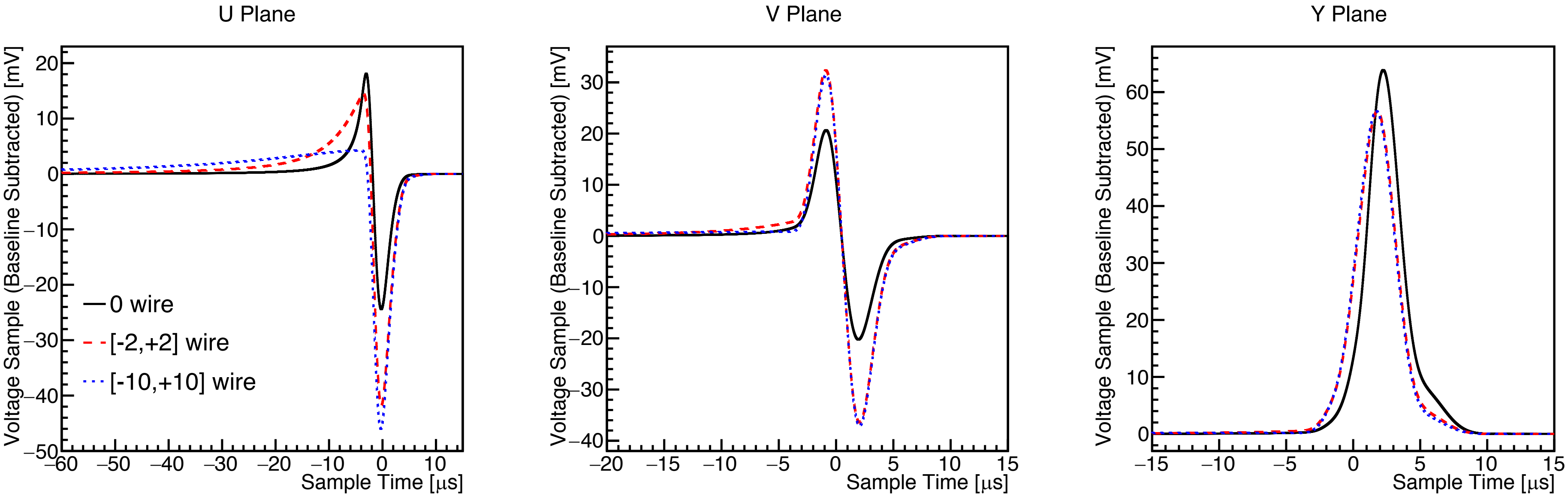
- ✓ Effects/Responses changing the signal shape (from a point source of charge)
- ✓ In time dimension

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

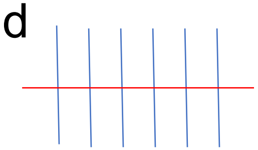
- **Diffusion**
- **Field response**

Responses over wires

Field response + Pre-amp response

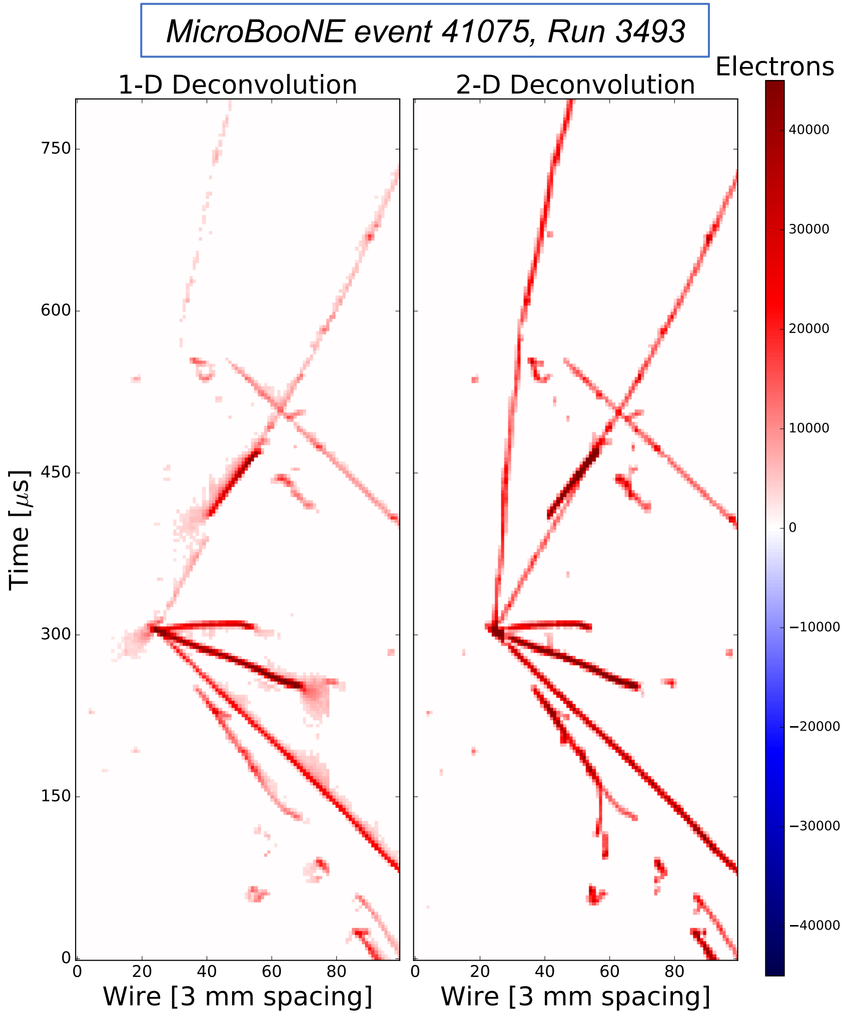


- ✓ Significant contribution from adjacent wires
  - ✓ [-10, 10] (21) wires for U plane
  - ✓ [-2, 2] (5) wires for V, Y planes (shield by U plane)
- ✓ Equivalent to an isochronous track (parallel to wire plane) and perpendicular to wire orientation (along wire pitch direction)



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

TPC signal simulation

- Consist with abovementioned 2D signal formation

Overview of full TPC simulation

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

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

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

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

Key convolution (signal shape):

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

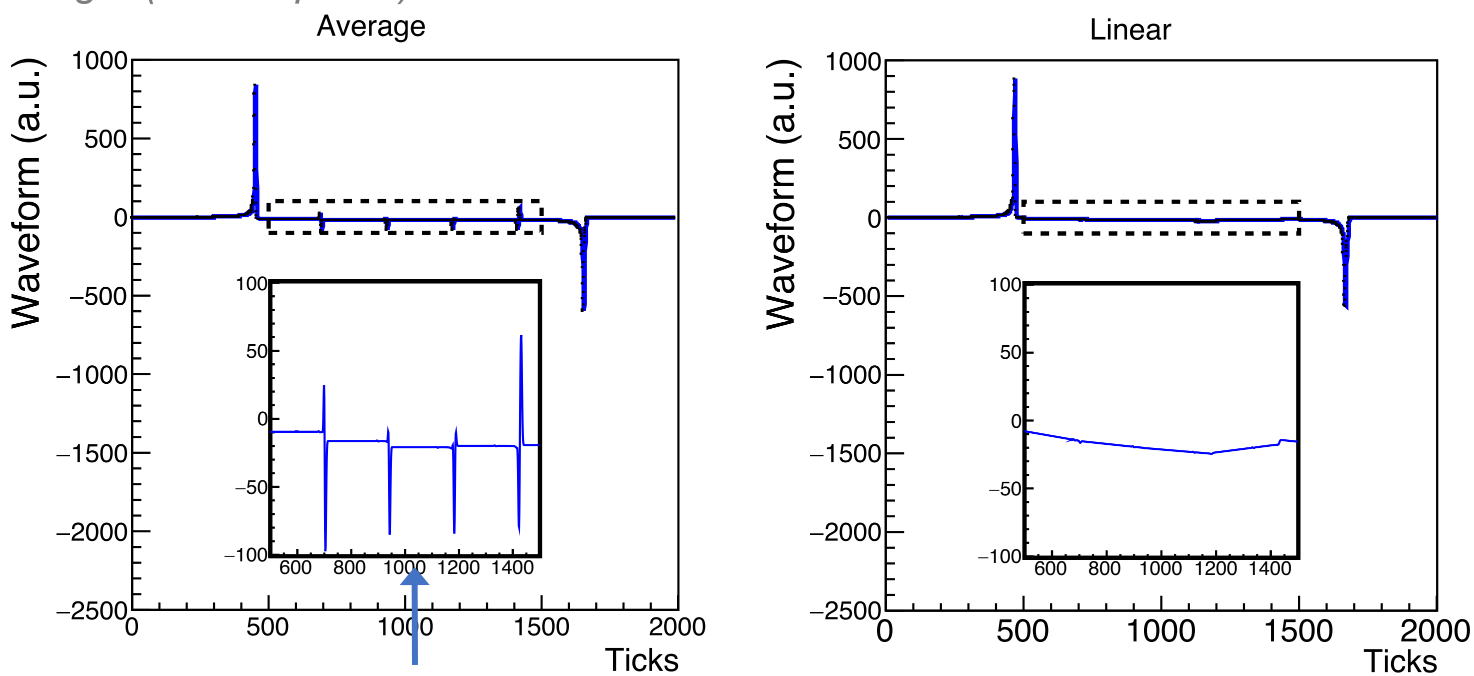
Interpolation of field response

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

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

Linear interpolation performed

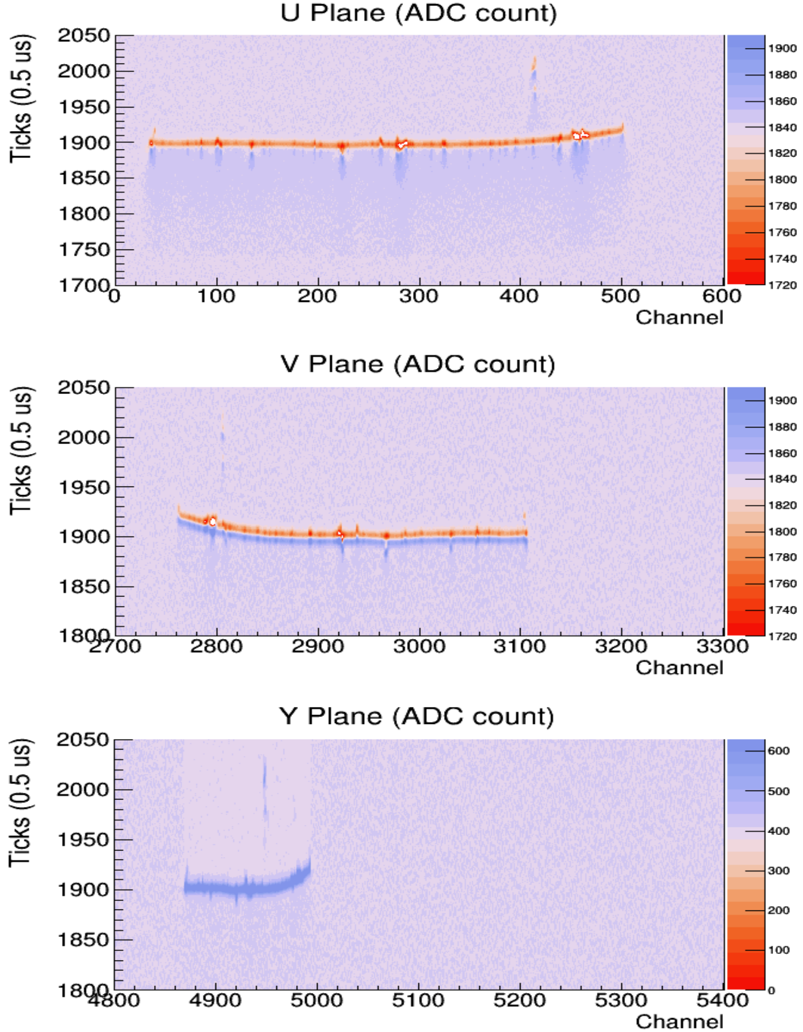
A large angle (to wire plane) track



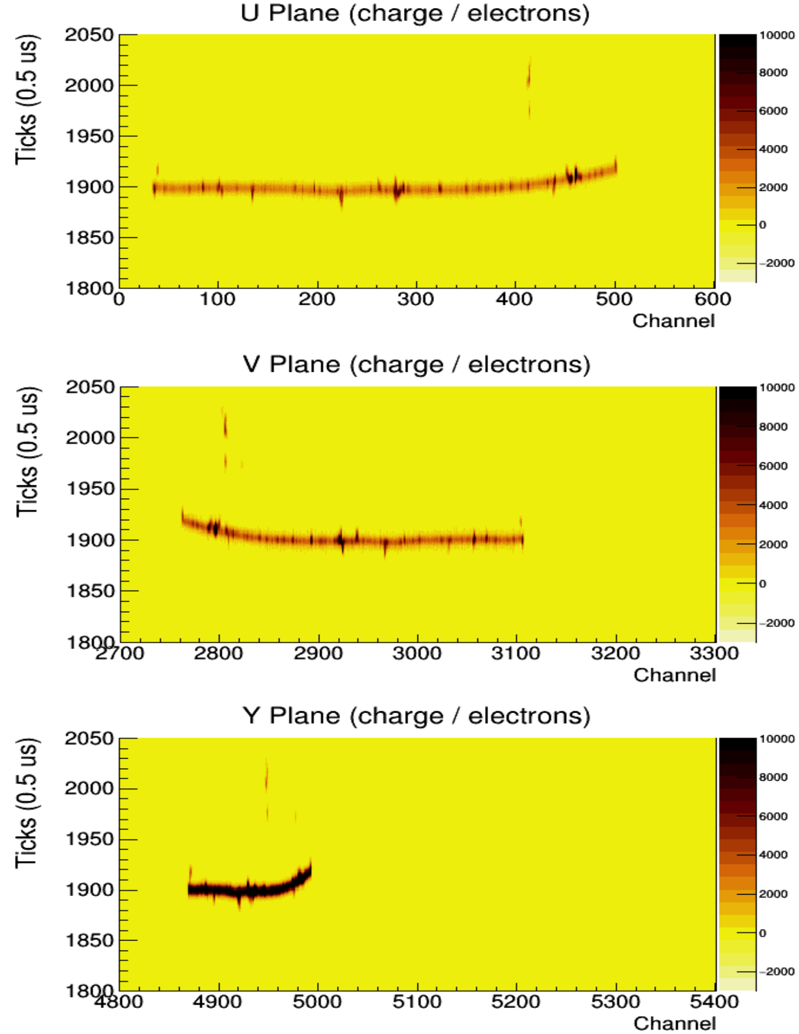
Non-proper bipolar cancellation at boundary of 0.3 mm sub-pitch

A simulation of 5-GeV muon

ADC Waveform



Charge



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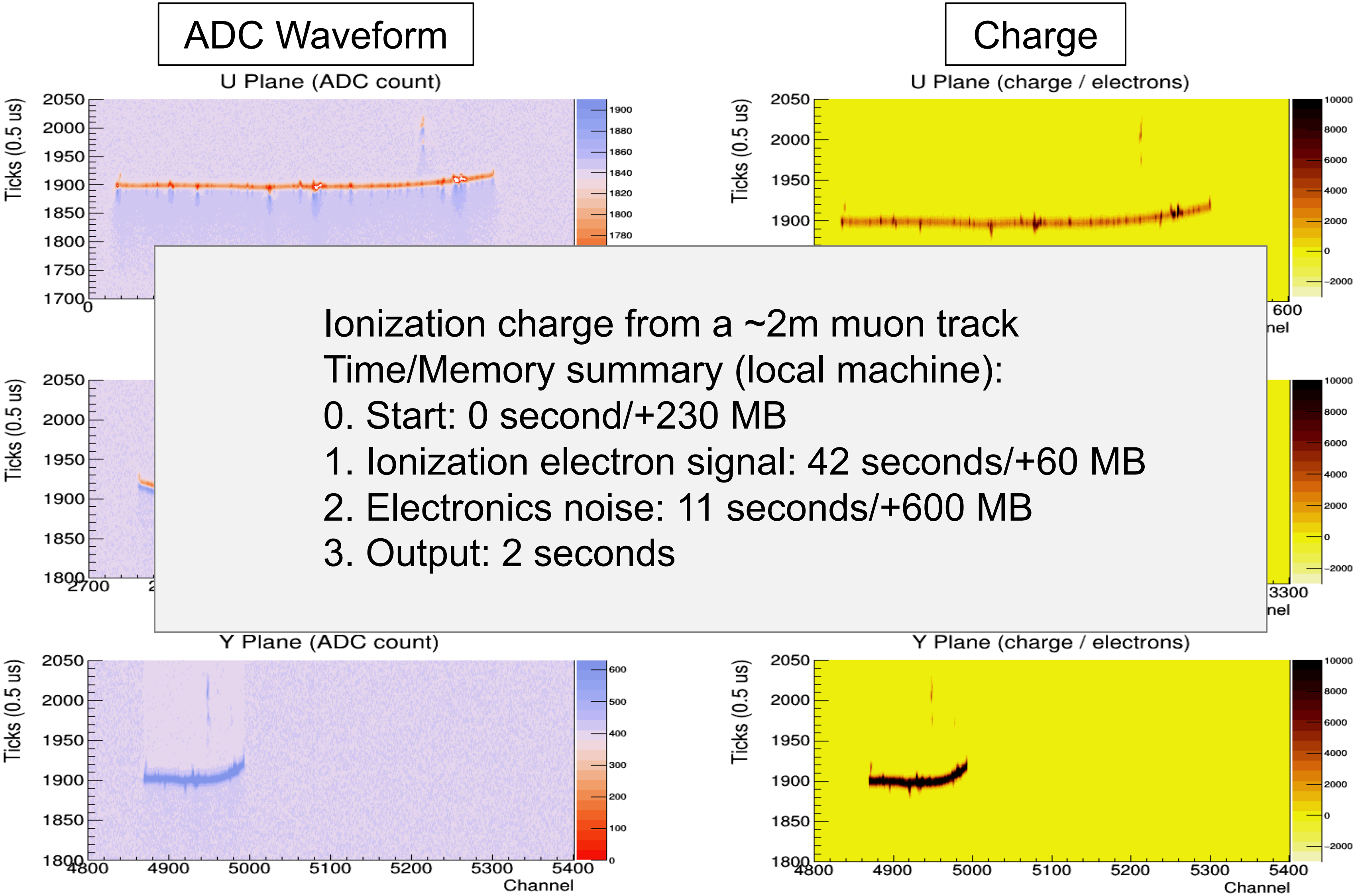


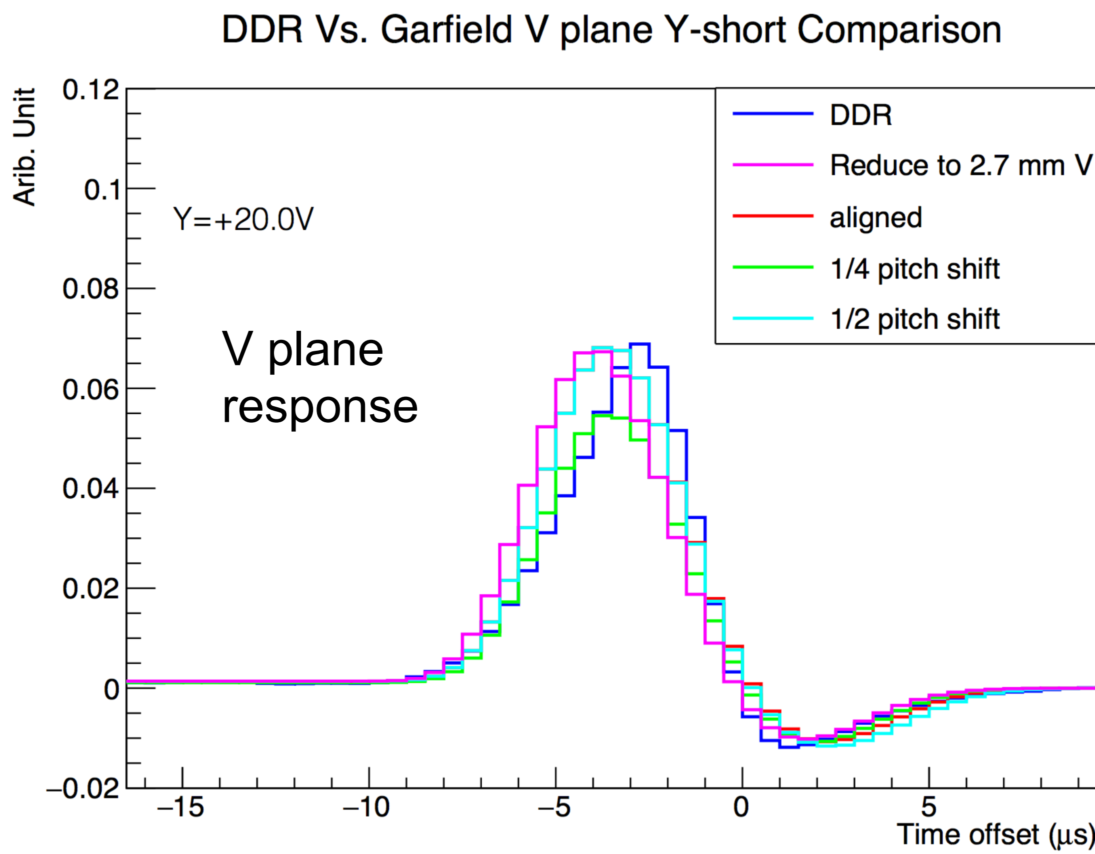
Ionization charge from a ~2m muon track

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

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)

Noise simulation

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

Pre-amplifier inherent noise

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.		

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

Thermal fluctuation in the input transistor

Transistor bias current and resistors providing the bias voltage

Charge trapping and de-trapping in the input transistor

- 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:

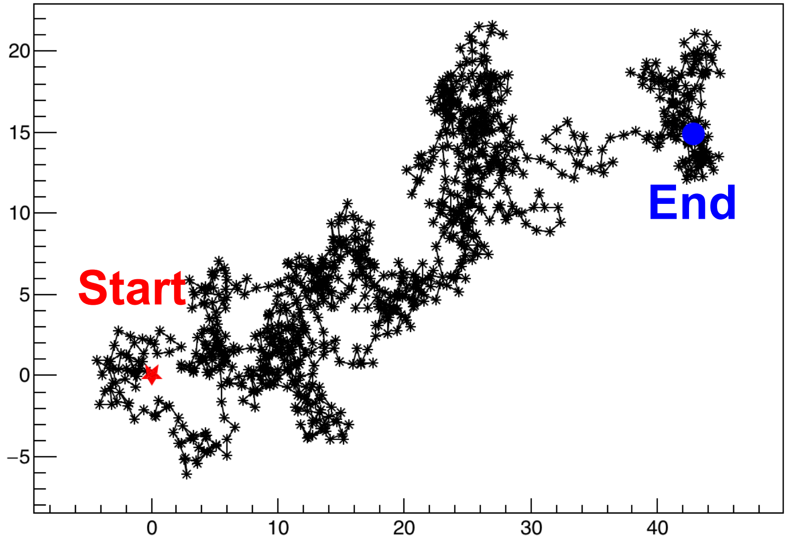
$$F(\omega) \propto \sum_{i=1}^{N} q_i(\omega) \cdot e^{-i\omega t_i} = \sum_{i=1}^{N} L(\omega) \cdot e^{-i\cdot\alpha}$$

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



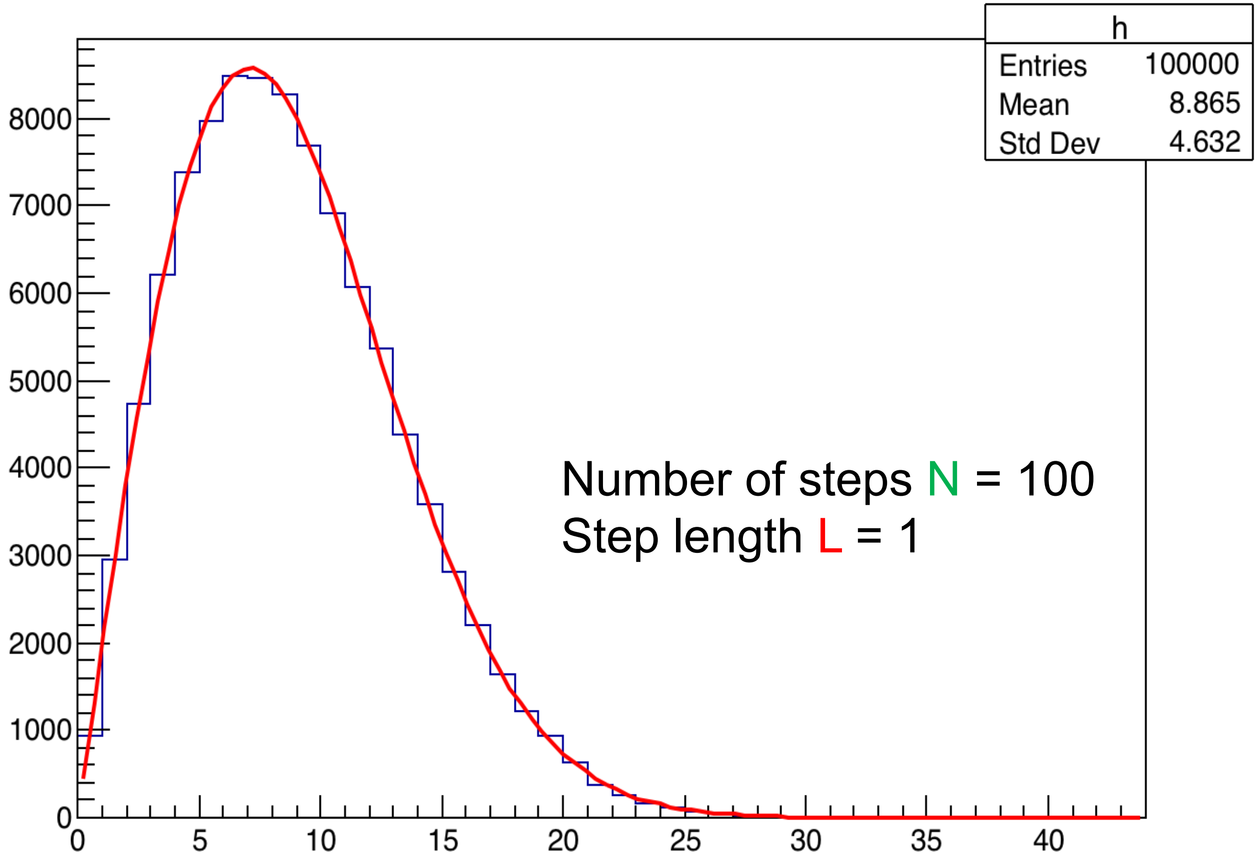
$F(\omega)$ follows a random walk in the complex plane with the step length $L(\omega)$

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

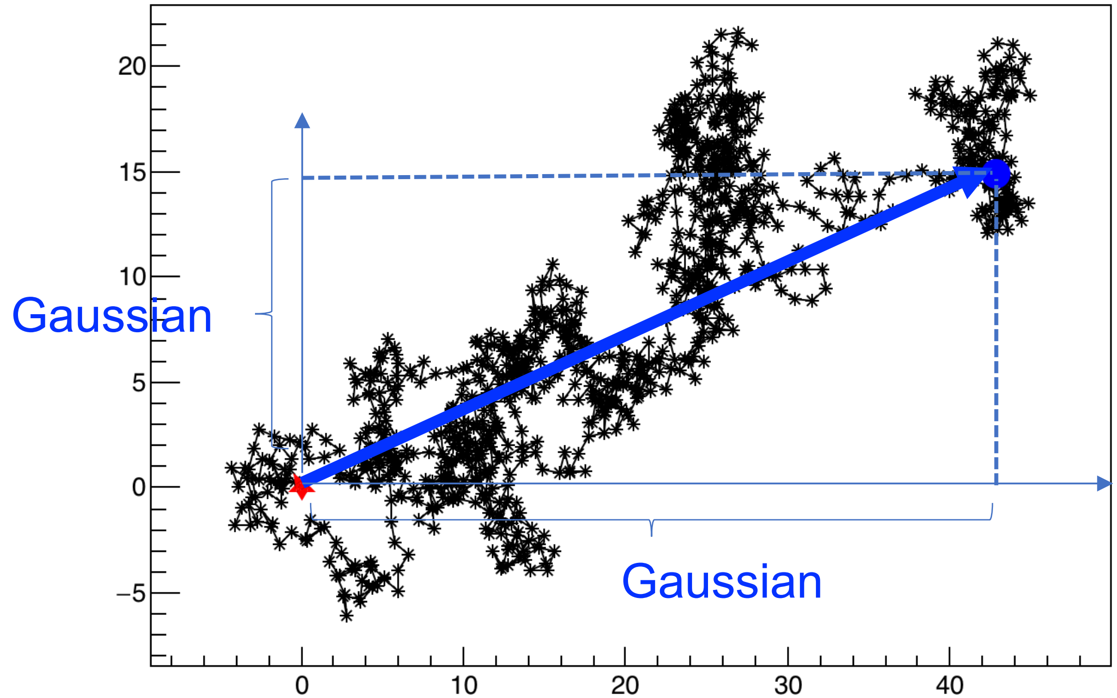
Random Walk (Rayleigh distribution + uniform phase):
Two independent Gaussian distributions with same deviation (the only parameter σ in Rayleigh distribution)

↓

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)



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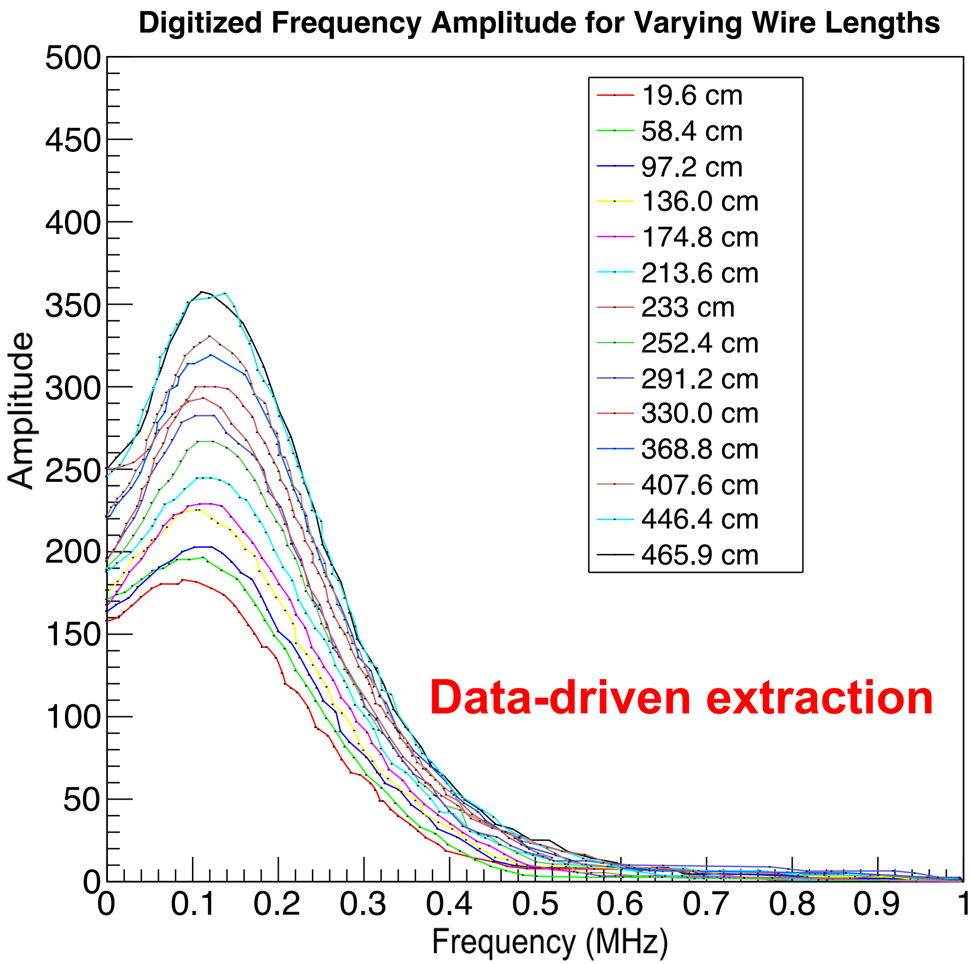
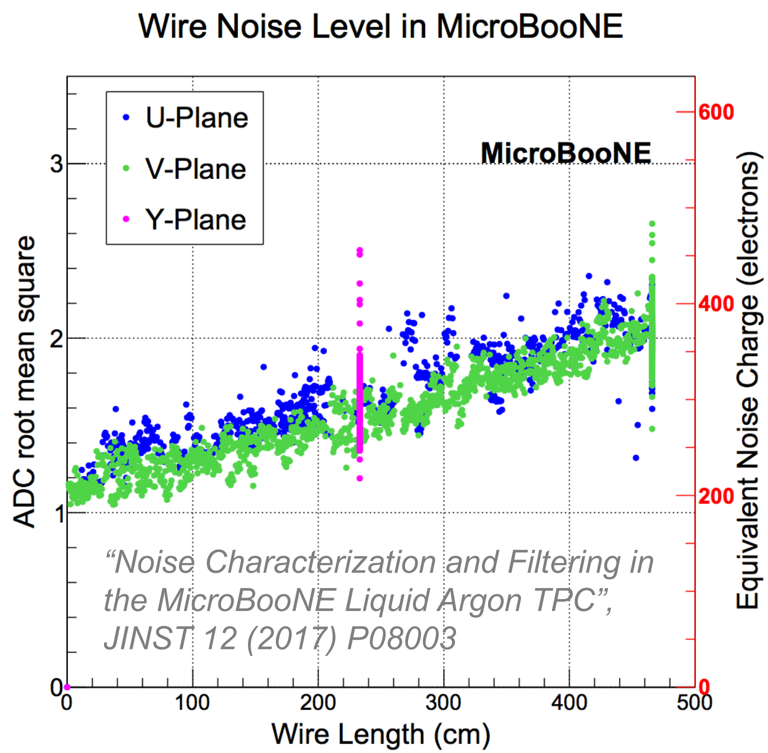
Only the mean amplitude of $F(\omega) = \sqrt{\pi/2} \cdot \sigma$ is needed

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.

Two MicroBooNE papers

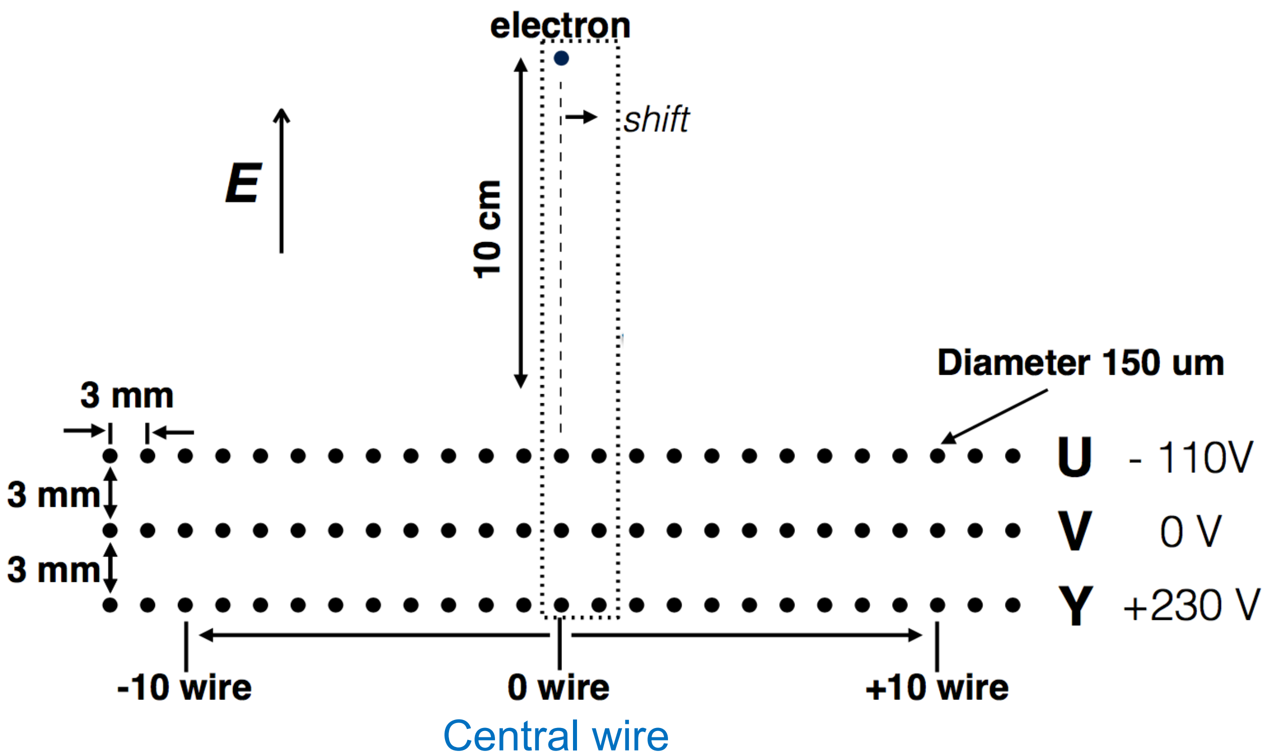
- Ionization signal analysis and processing in single phase LArTPCs
  - Paper 1: signal formation, simulation, extraction (signal processing)

    Starting review.
    B. Russell will give a talk about the signal processing.

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

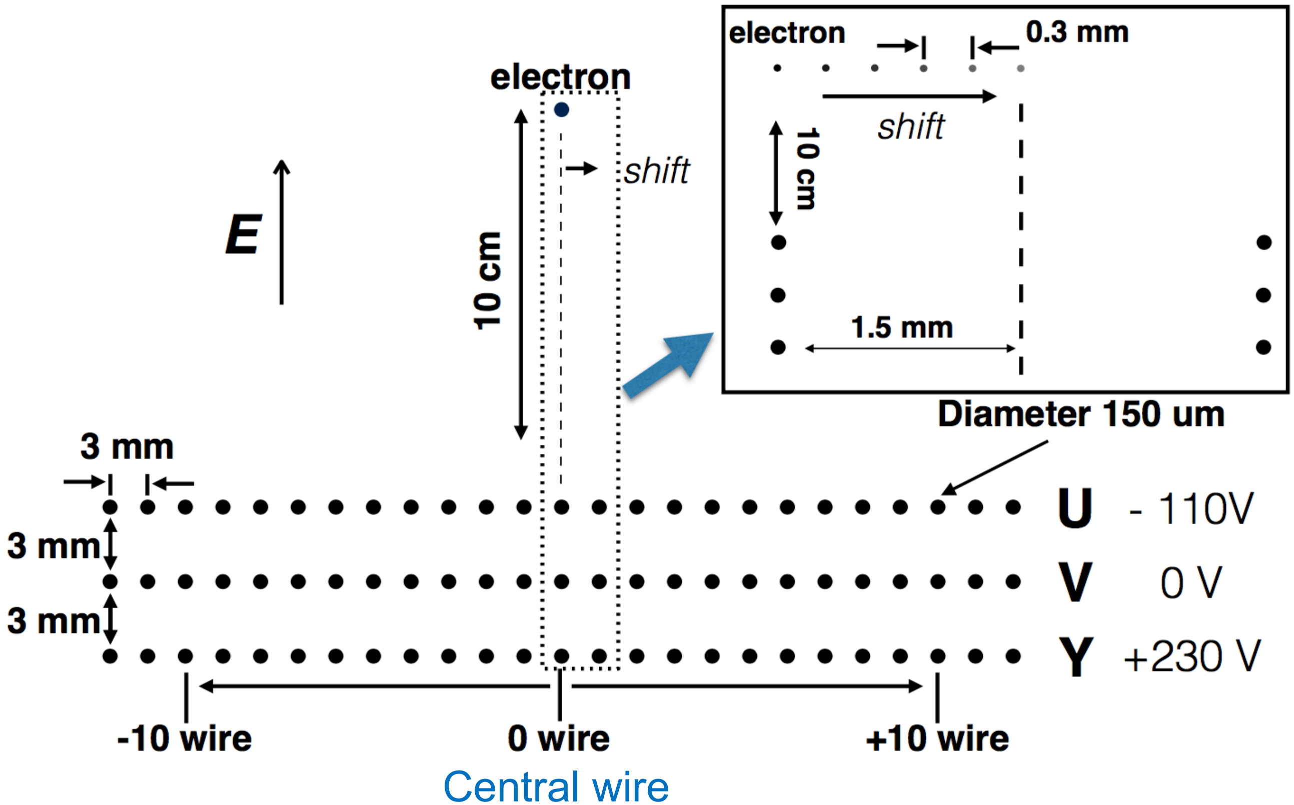
    Be ready soon.

Field response -- 2D Garfield calculation



- ✓ A 2D configuration for MicroBooNE
- ✓ Average crosscut (ignore the dependency, residual 3D effect) along wire orientation

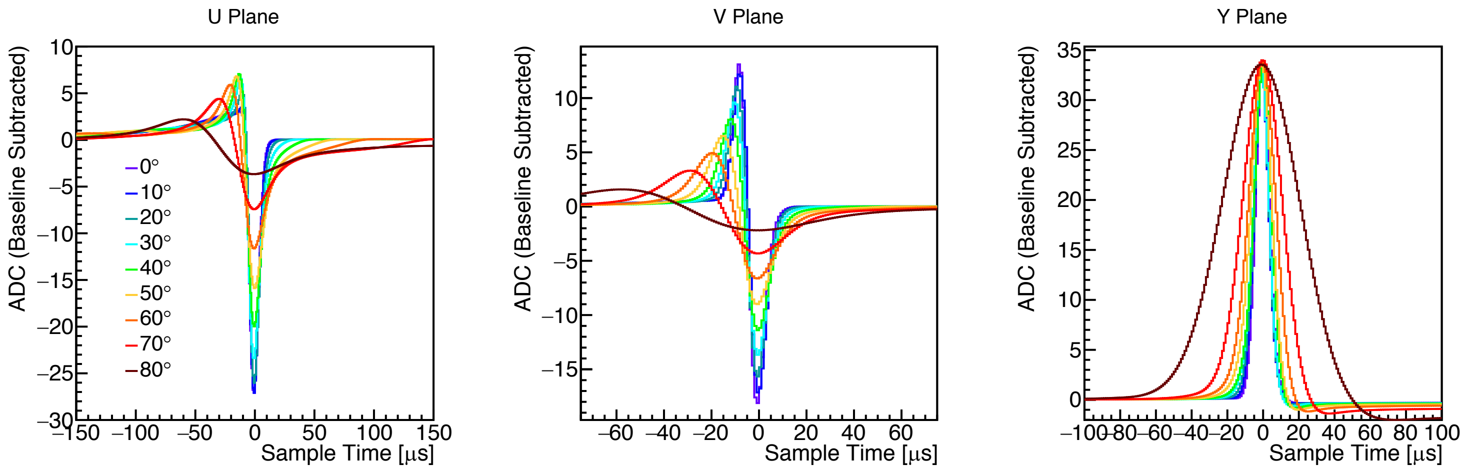
Field response -- 2D Garfield calculation

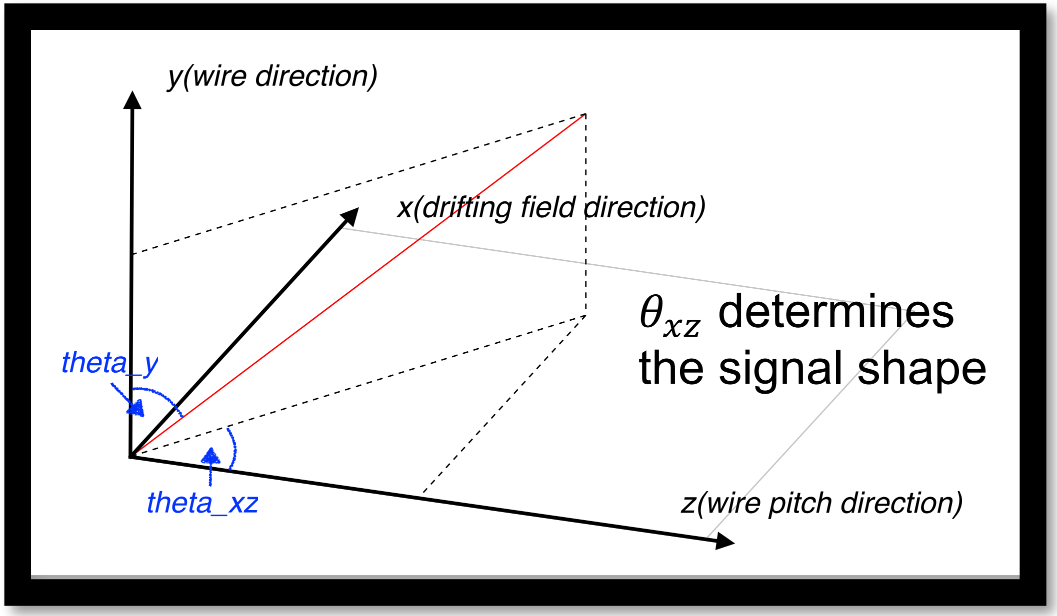


- ✓ 6 drifting paths (per 0.3 mm) for half wire pitch, the other half symmetrical
- ✓ 0 $\pm$ 10 wires
- ✓ 126 field responses are calculated

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)