TPC Signal Formation and Processing

Xin Qian
BNL

APA Review

July 13th 2016

Outline

- TPC Signal Formation
- TPC Signal Processing
- Electronic Noise
- Ongoing Work

Single-Phase TPC Signal Formation

Number of ionized electrons

↓ Field Response

Signal on Wire Plane

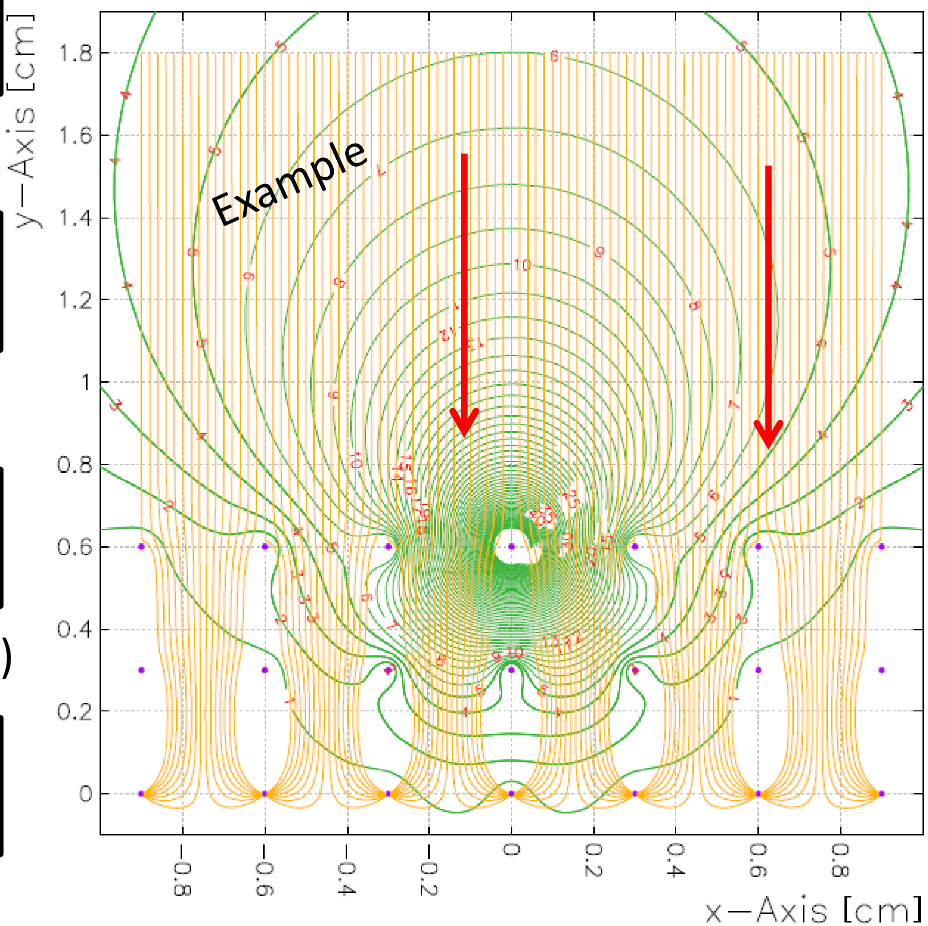
↓ Electronic Response

Signal to be digitized by ADC

↓ (Charge Extraction)

Number of ionized electrons

Weighting Potential of a U Wire



Shockley–Ramo theorem

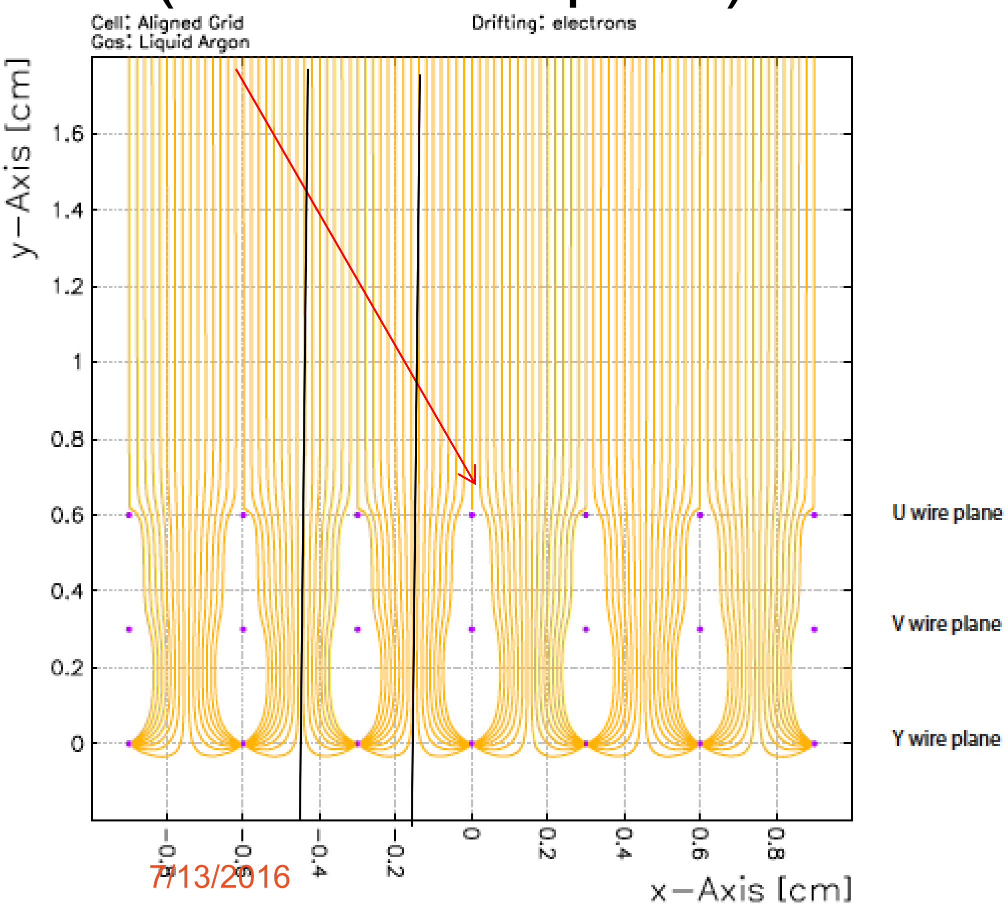
$$i = -q \cdot \vec{E}_w \cdot \vec{v}_q$$

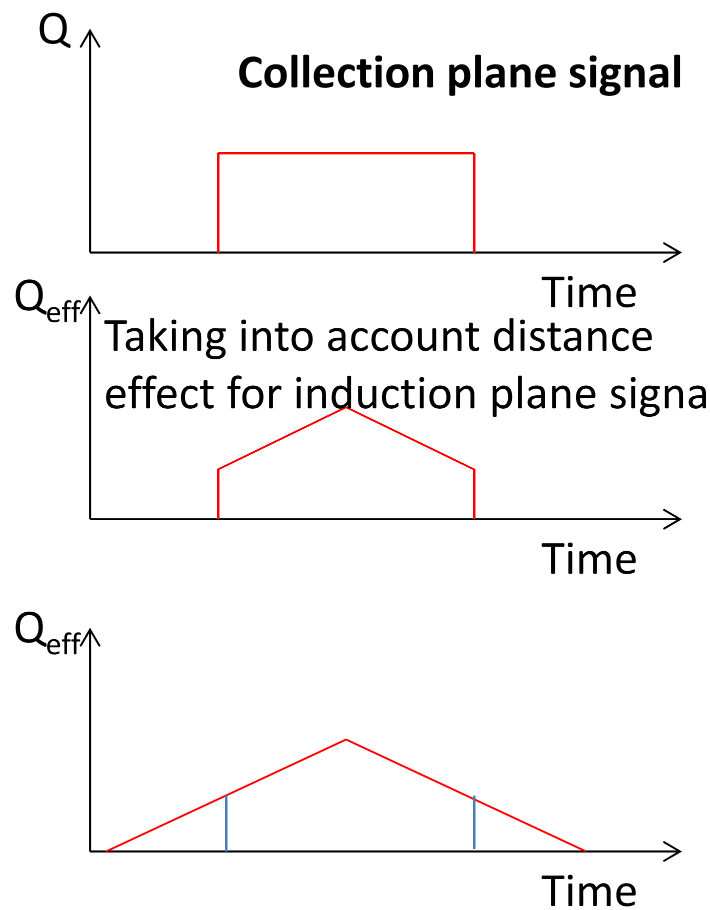
v_q: velocity
E_w: weighting field
q: charge

- Induction plane signal strongly depends on the local charge distribution, collection plane signal is much simpler

Example I: ideal track (uniform charge density)

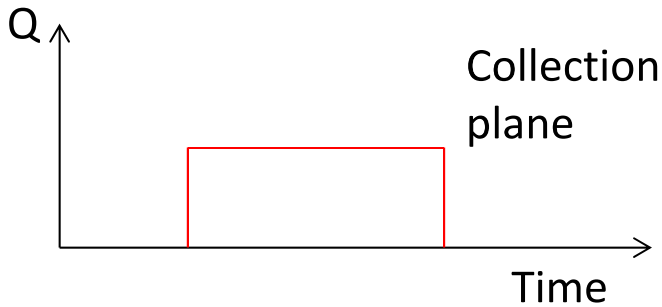
- Black lines are used to illustrate the wire boundary (+- half wire pitch)

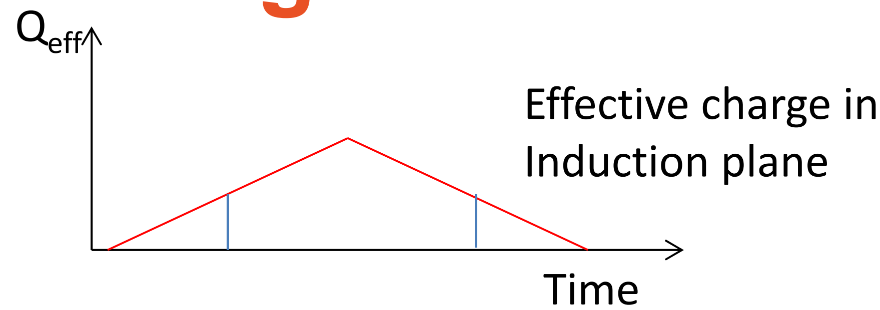


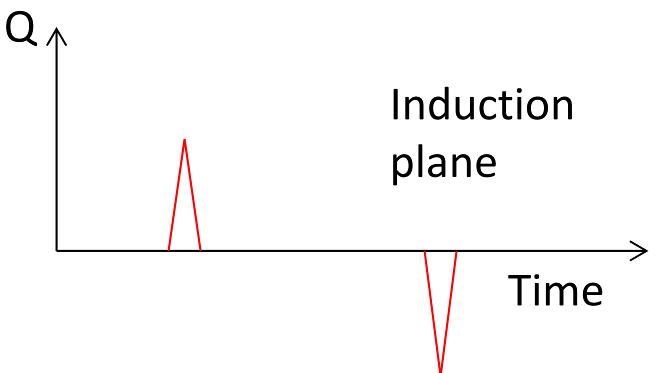


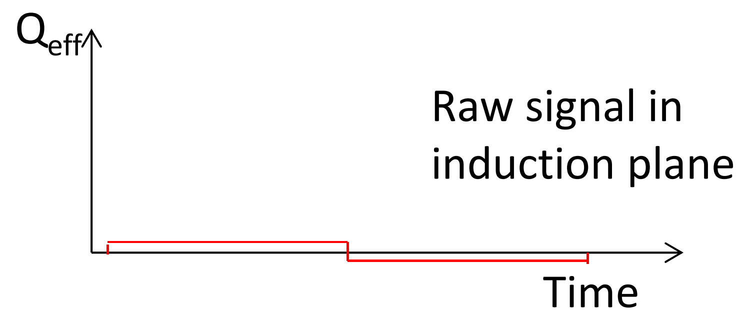
Taking into account induced signal from charge passing through next wire

Now look at the raw signal after convolute with bi-polar signal









In the middle, the raw signal will be close to zero due to the cancellation of bipolar response function

If the signal is rising slowly, the net contribution on the raw digit will be small, however the signal will be long

The induction plane signal can be very small in height → importance of data compression scheme

No such complication for collection plane

Outline

- TPC Signal Formation
- TPC Signal Processing
- Electronic Noise
- Ongoing Work

1-D Deconvolution

Time domain

$$\mathrm{M}(t_0) = \int_t R(t - t_0) \cdot S(t) \cdot dt$$

↓ Fourier transformation

$$M(\omega) = \mathrm{R}(\omega) \cdot \mathrm{S}(\omega)$$

Frequency domain

↓

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

↓ Anti-Fourier transformation

Back to time domain

$$\mathrm{S(t)}$$

- Good for Collection plane
- There is NO universal "average" response function for induction plane
- A deconvolution assuming universal response function would lead to gaps in the images which CANNOT be explained by the dead channels
  - Vertex activity
  - EM shower
  - Track with various angles

2-D Deconvolution

$$M_i(t_0) = \int_t \left(R_0(t-t_0) \cdot S_i(t) + R_1(t-t_0) \cdot S_{i+1}(t) + \ldots \right) \cdot dt$$

$$M_i(\omega) = R_0(\omega) \cdot S_i(\omega) + R_1(\omega) \cdot S_{i+1}(\omega) + \ldots$$

- With induced signals, the signal is still linear sum of direct signal and induced signal
  - R_1 represents the induced signal from i+1th wire signal to ith wire
  - S_i and S_{i+1} are not directly related

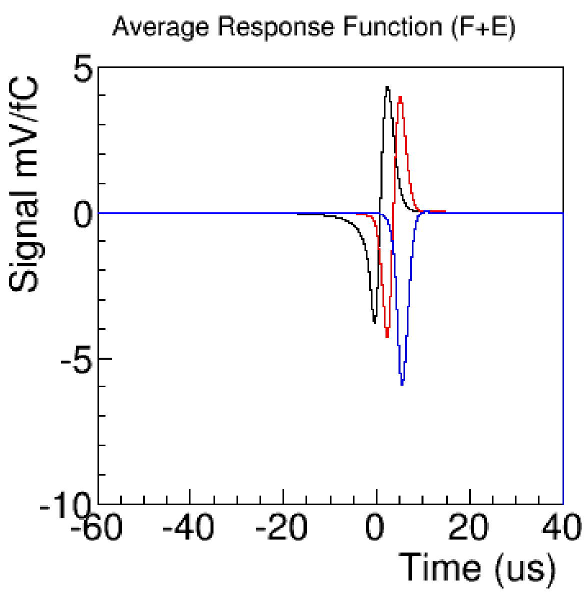
$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \ldots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \ldots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \ldots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \ldots & \ldots & \ldots & \ldots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

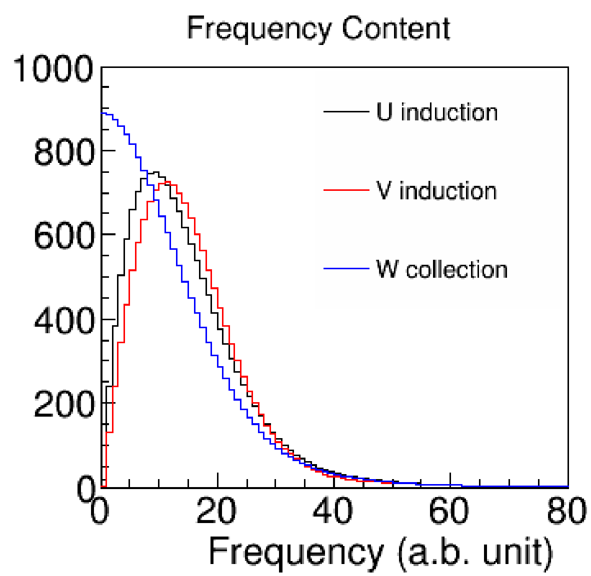
The inversion of matrix R can again be done with deconvolution through 2-D FFT

Just 2D deconvolution will not be enough → ROI + Adaptive Baseline

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

- The bi-polar nature of induction signal amplify the low-frequency noise during deconvolution
- One can improve the situation through ROI (Bruce Baller, Robert Sulej) and adaptive baseline technique (M. Mooney)

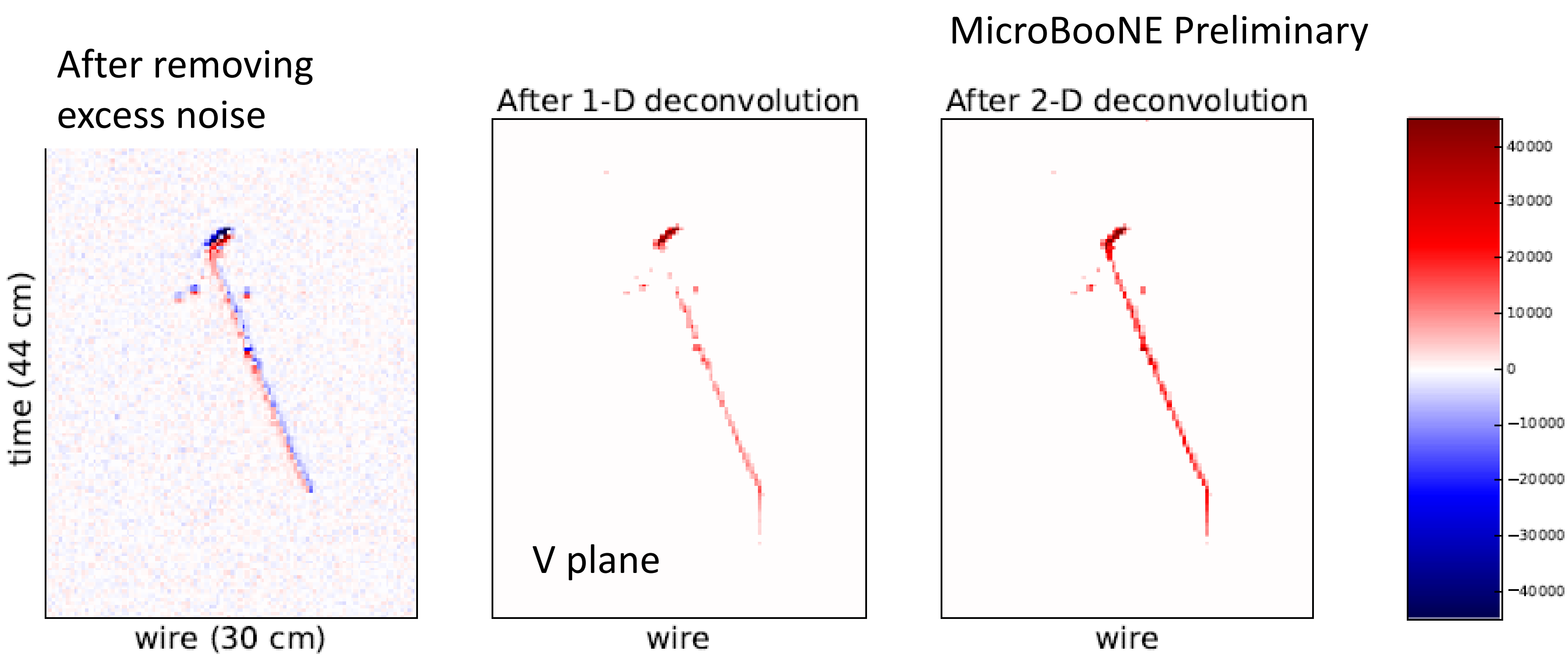




Given N time bins with 2 MHz digitization frequency,

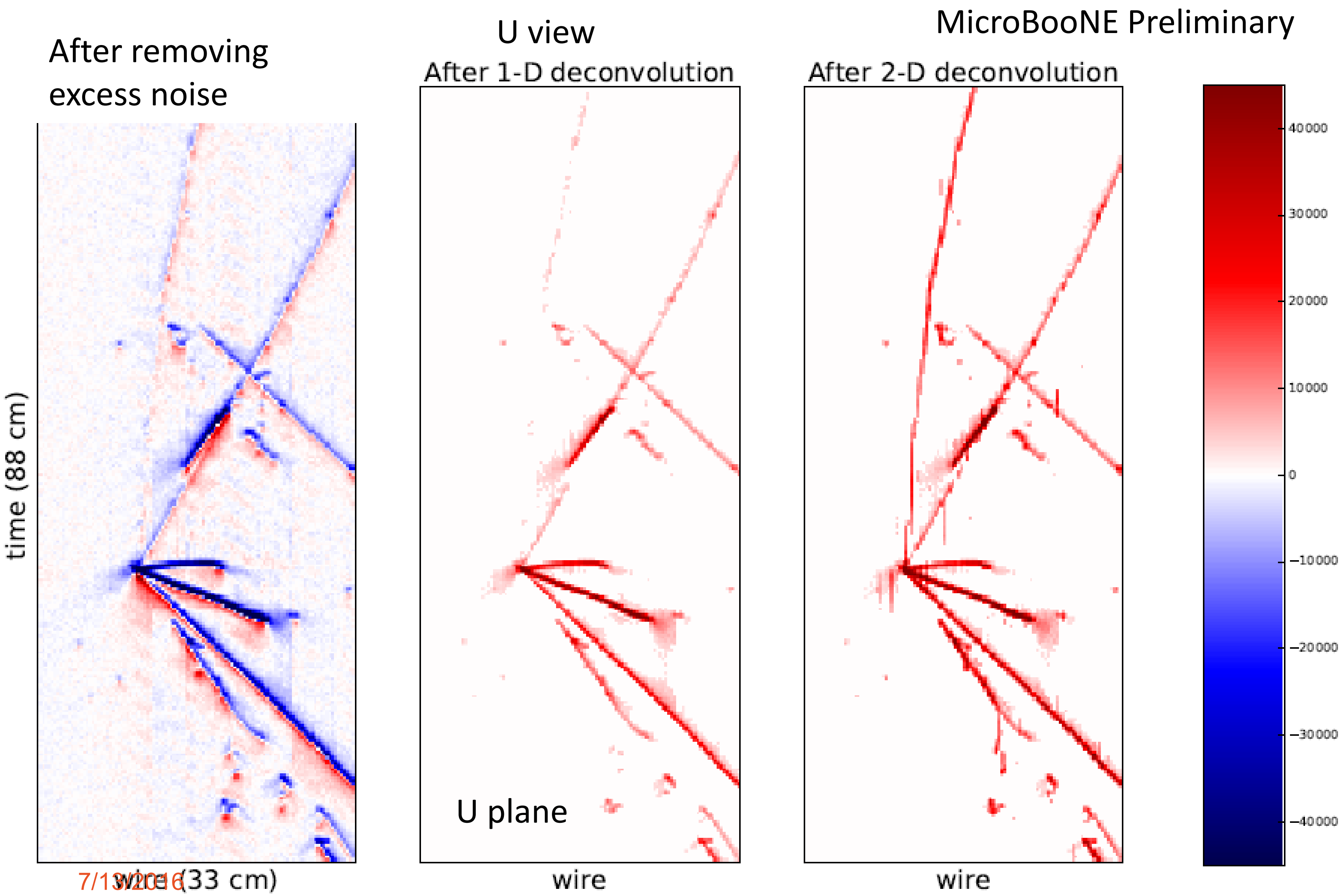
- The highest freq. is 1 MHz
- The lowest freq. (above 0) is 2/N MHz
  200 bins → 10 kHz
- Obviously not sensitive to noise < 2/N MHz
- Adaptive baseline → linear baseline correction instead of flat baseline correction

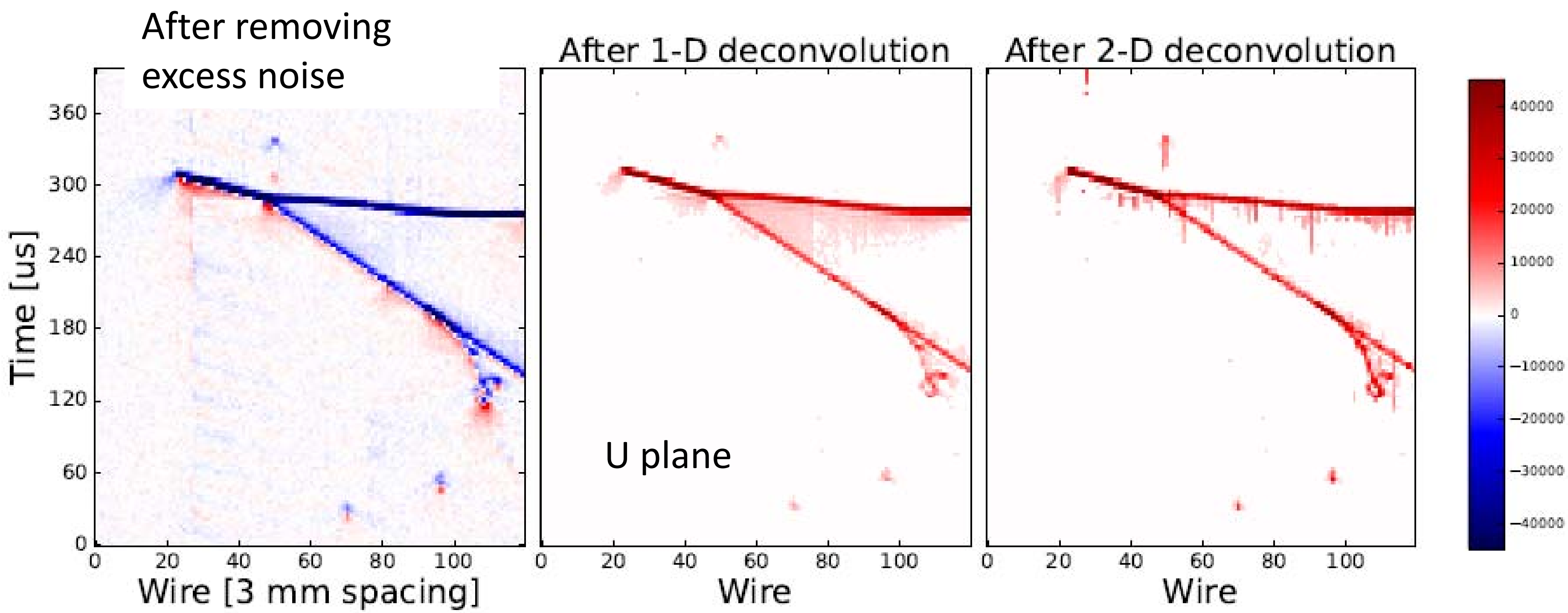
Example Event Display

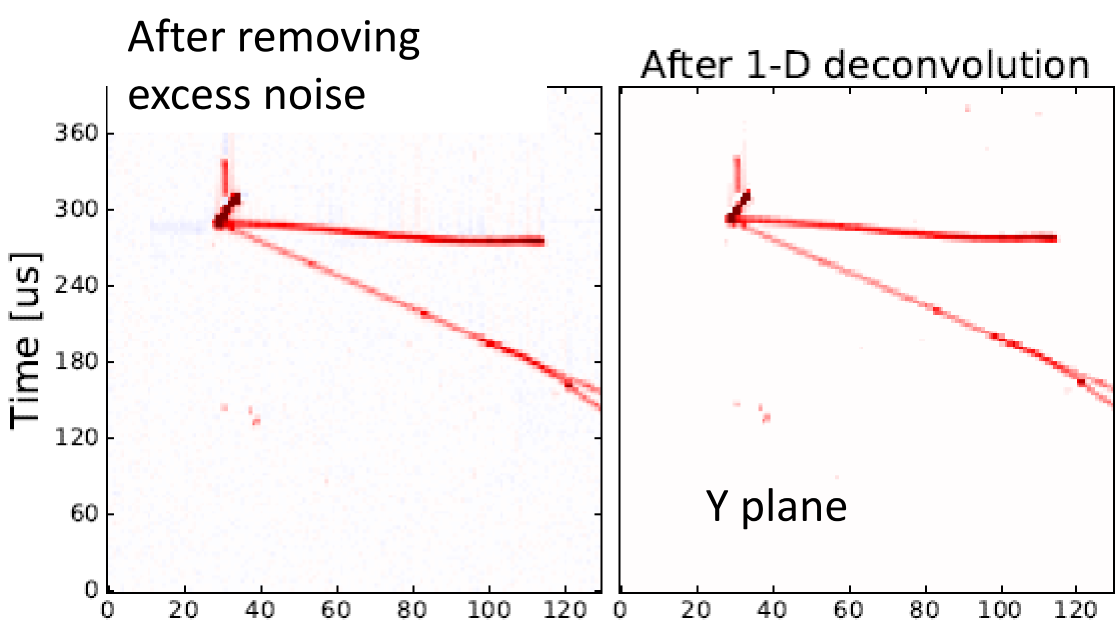


- Significant improvements achieved in the signal processing

Example Event Display







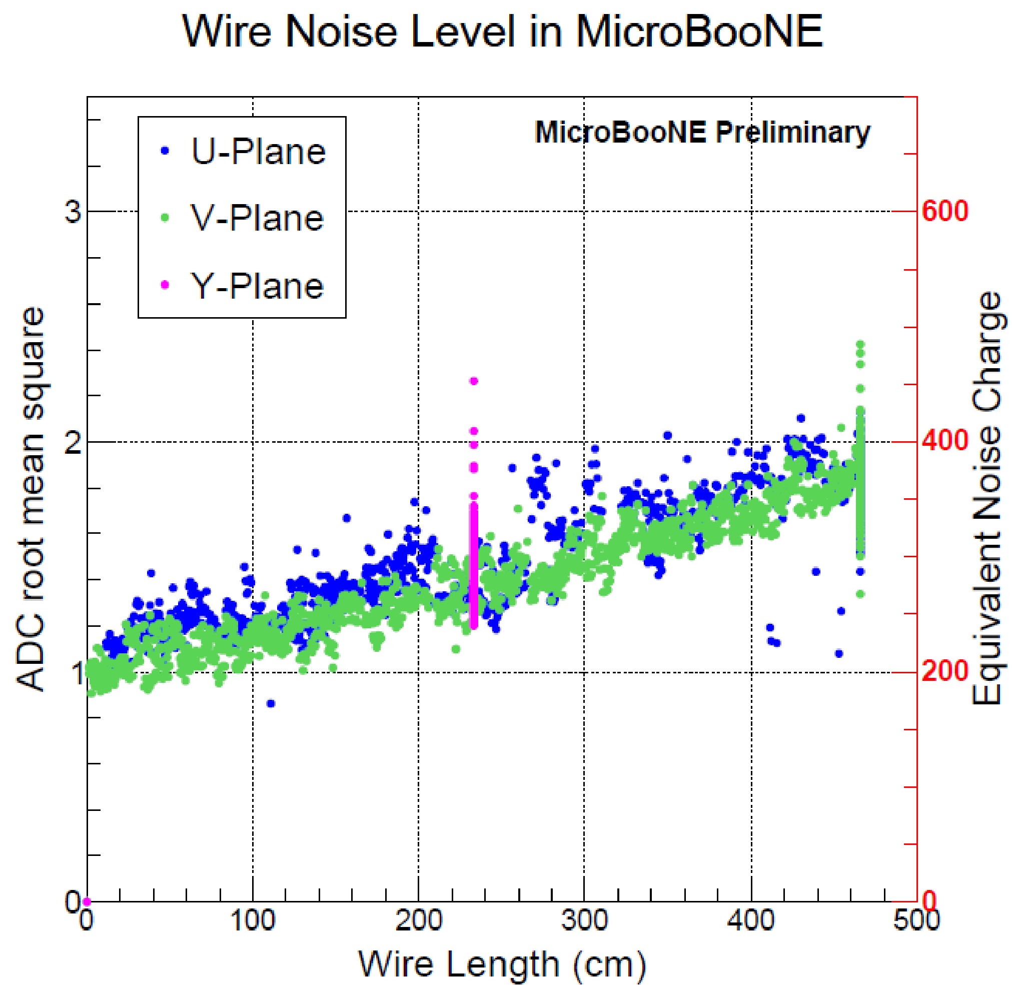
MicroBooNE Preliminary

- 2D deconvolution is not needed for the collection plane signal

Outline

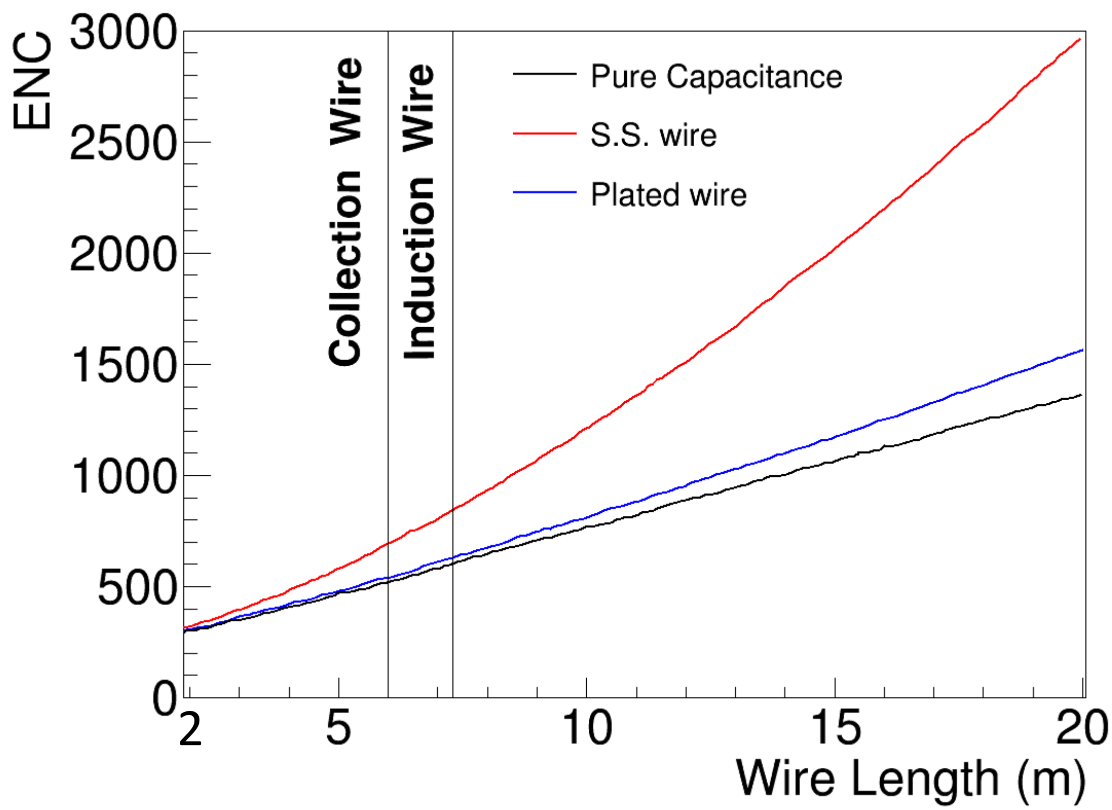
- TPC Signal Formation
- TPC Signal Processing
- Electronic Noise
- Ongoing Work

Noise Performance in MicroBooNE



ENC after (excess) noise filtering is consistent with the expectation!
Projected protoDUNE noise 500-600 e^- due to longer wire length

Projected Noise Performance in ProtoDUNE



- MicroBooNE: Cu-Au plated stainless wire
  - Much lower resistance than stainless wire
- DUNE: Copper-beryllium wire
  - Similar resistance as Cu-Au wire
  - Much lower cost
  - Slight worse strength, but mitigated by the mechanical structures (i.e. spacers)

Excess Noise in LArTPC

- Beyond intrinsic electronic noise

- Noise from power supplies
  - Noise from LV regulator (MicroBooNE + 35 ton) → hardware fix is in order
  - Noise from HV power supply (MicroBooNE), existing filter is not enough, additional filter is in order
- Pick up noise → better shielding and grounding
  - 900 kHz noise in MicroBooNE (burst noise outside cryostat)

Microphonics

- Wire motion inside E-field due to liquid motion (< 20 Hz)
- Beyond the dynamic range of the signal → not contributing to the noise level
- However, can lead to periodic ASIC saturations
  - O(10) channels in MicroBooNE at 500 pA leakage current setting

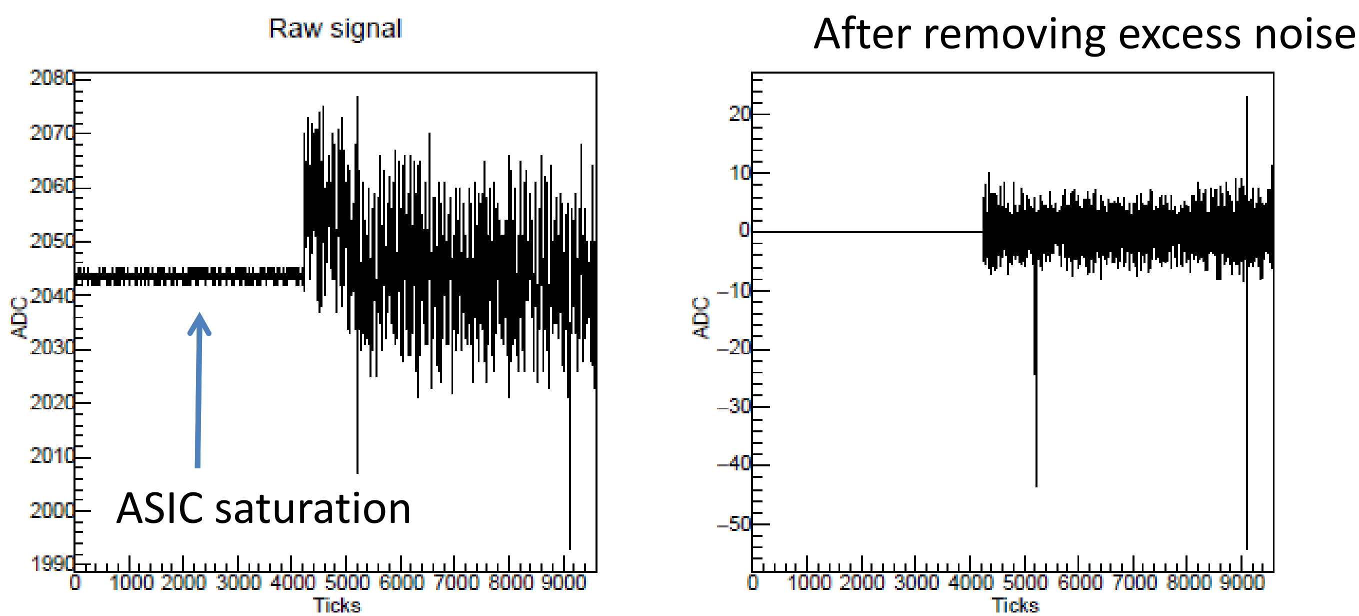


FIG. 8. An example U-plane raw waveform after the recovery of an ASIC from saturation (left). The same waveform after the noise filter (right). The region corresponding to the ASIC saturation (low RMS region) is identified. The distortion of the baseline after the ASIC saturation is removed. The DC baseline is moved to 0 after the noise filtration (right).

Improvement in DUNE APA design

- A grid plane is added in front of the first induction wire plane (Mitch's talk)
  - Reduce impact of long-range induced signal
  - Reduce impact of potential noise from HV power supply
- Spacers are added to support wires to reduce the vibration of the wires
  - 1.5 m in DUNE instead of 5 m long wires in MicroBooNE
- A mesh plane is added behind the collection plane to suppress signal from behind (Mitch's talk)

- Also more leakage current settings are added to the frontend ASIC (1 nA and 5 nA) for ASIC saturation due to wire motion
  - 500 pA one is still the likely one to use

Summary of TPC Signal Processing

	Longitudinal (Drift)	Transverse
Digitization length	0.8 mm	3-5 mm
Diffusion (σ)	<1.7 mm	<2.4 mm
Electronic Shaping (σ)	1.3 mm	N/A
Field Response Function	~1.1 mm (derived)	3-5 mm

Based on MicroBooNE, we estimate DUNE with change in wire length and wire pitch

- MIP (2.1 MeV/cm) moves parallel to wire plane and perpendicular to wire@anode
  - (Peak Height)/(Noise σ) ratio for collection plane ~ 68:1 (~40:1 based on 35-ton experience)
  - (Peak Height)/(Noise σ) ratio for induction plane ~ 17:1
- For Induction plane, the above ratio
  - Decrease with angle to the wire plane (0 degrees for parallel)
  - Increase with smaller angle to the wire (90 degrees for perpendicular)
- Finite electron lifetime will reduce the above ratio

A word about unusable channels

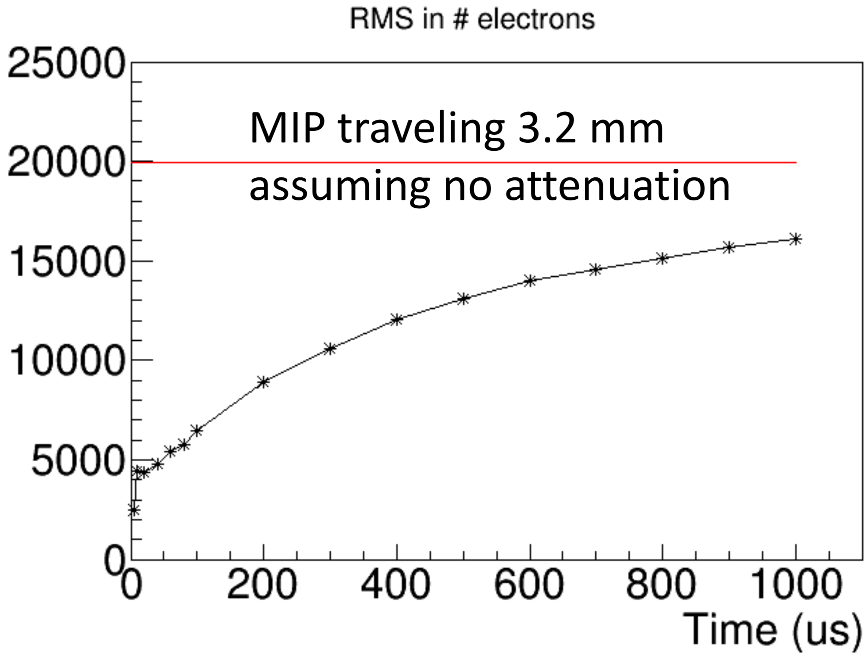
- The expectation of dead electronics is O(0.1%) (ATLAS, Lariat)
  - Currently, MicroBooNE have ~4% cold preamplifier dead due to startup problem, ~6% of cold ADC having problem in 35 ton, expected to be improved with improved design, rest of dead channels are due to disconnected wires or integration issues
- In Single-phase APA, the dead region is dominated by APA gap (2 cm / 2.3 m + 7.5 cm/ 7.2 m) with about 1.9%
- The volume efficiency due to unusable channels can be estimated as ~ ε^3

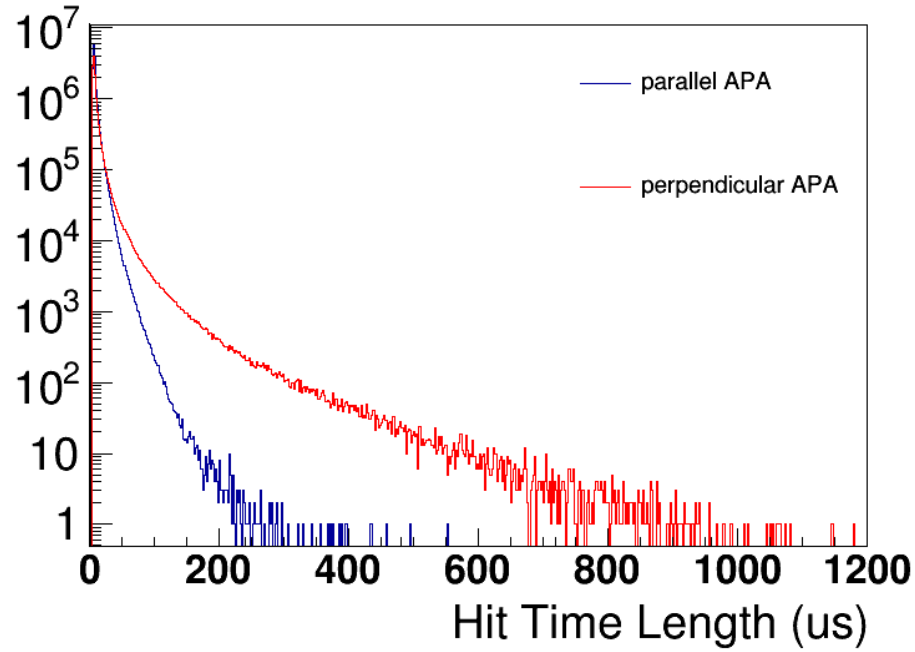
- **The goal of unusable channels is O(0.1%)**
- **The requirement of unusable channels is < ~0.6%**

Metrics for Signal Processing

- There are only two solid metrics can be used to evaluate the noise and signal processing
  - **<u>ENC</u>** (equivalent noise charge) → basically proportional to the pedestal RMS in terms of ADC
    - Straight forward for collection plane, but not enough for induction plane
  - **<u>DNC</u>** (deconvoluted noise charge) for induction plane, can be compared with the number of ionized electrons from real signal, it depends on
    - ENC (noise level) and frequency content
    - Response function used for deconvolution (field response for the real signal)
    - Time window (band width)

Simulated Induction DNC Results



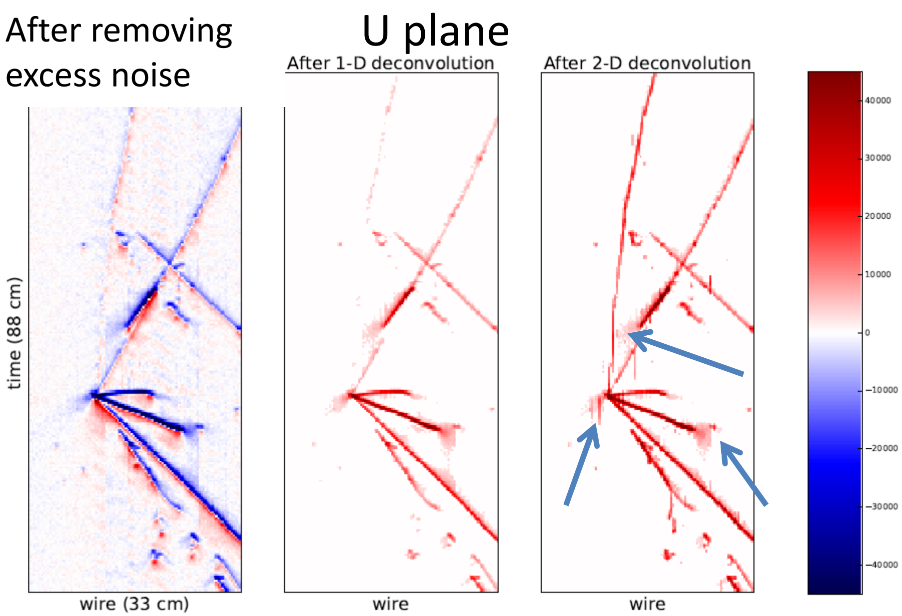


- Smallest signal is a MIP 3.2 mm (2 us) track segment perpendicular to the wire plane (i.e. wire pitch is ~ 5 mm)
- Given the expected signal length, for **<u>the smallest signal</u>** that we can have for induction, expect a **4~8:1** signal to noise ratio
- Factor of **~2** margin exists for electron lifetime and electronic noise before hit inefficiency entering

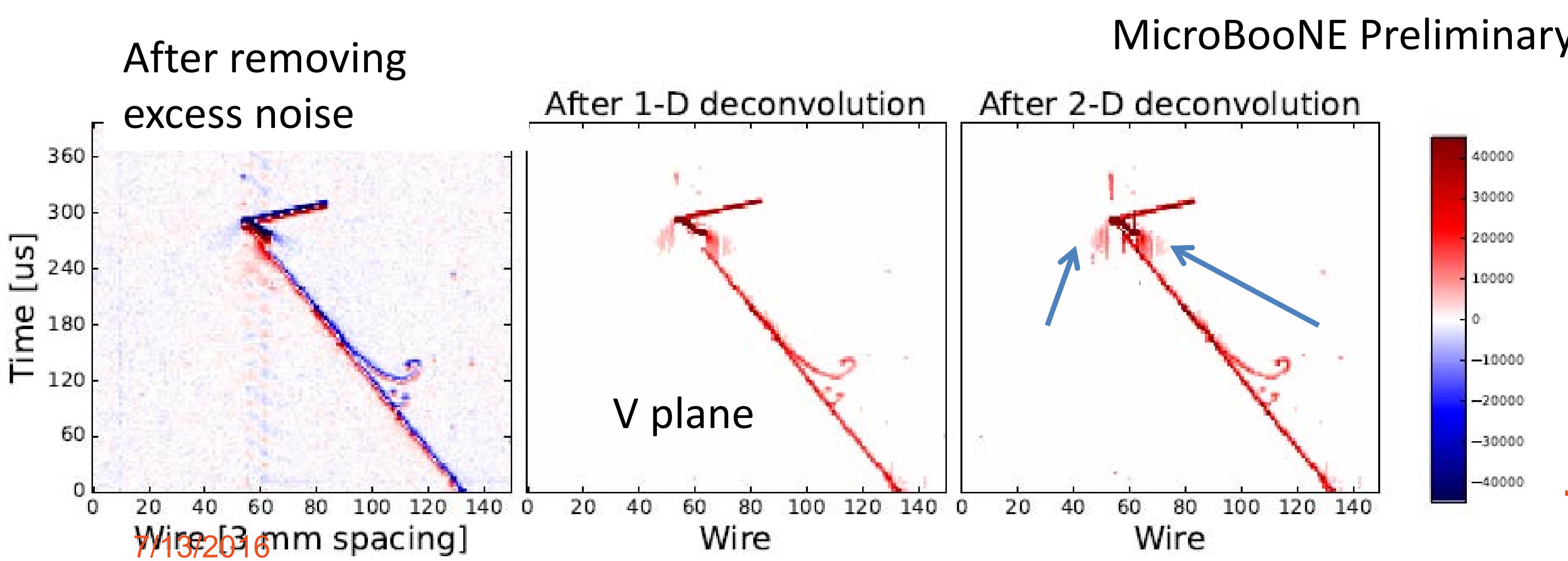
Outline

- TPC Signal Formation
- TPC Signal Processing
- Electronic Noise
- Ongoing work

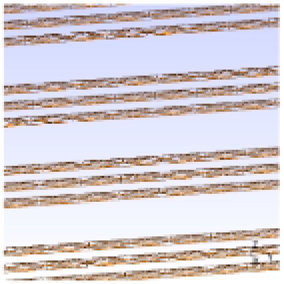
What are these shadows?



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

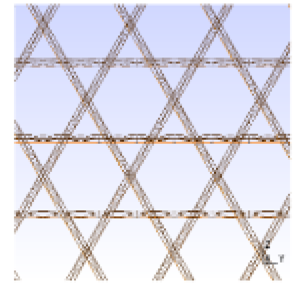


3D Field Calculation using Boundary Element Method

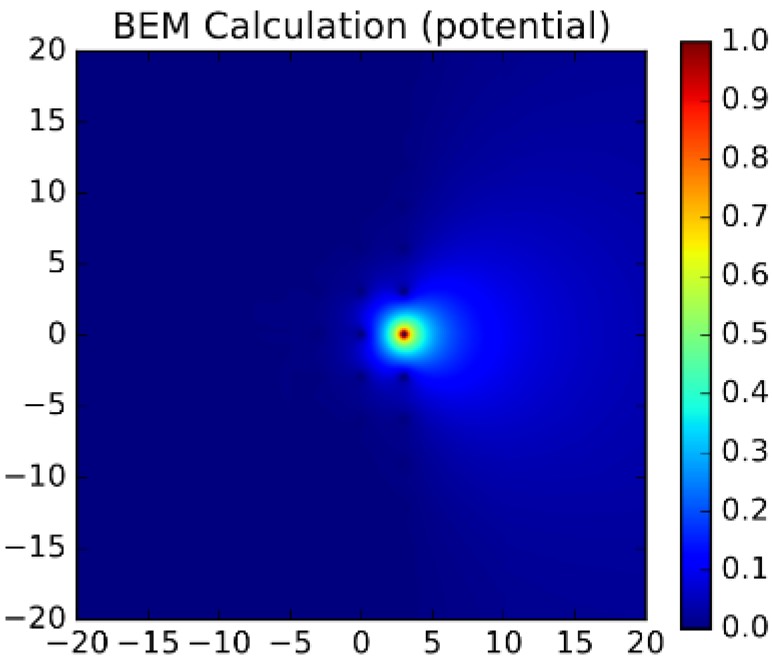


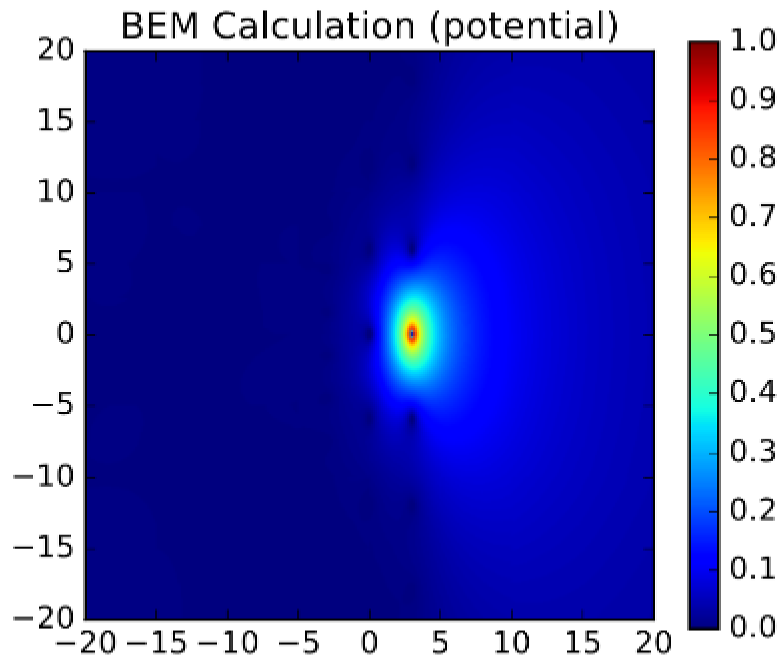
fully-parallel wire planes

- So far just Shockley-Ramo *weighting potentials*.
- Meshes with custom code + GMSH and BEM with BEM++.
- Fully-parallel wires for checking with prior Garfield 2D.
- Initial, full-3D using a MicroBooNE-like geometry.
- To do: drift field, ray tracing, average response functions.
- BEM seems to perform well as alternative to FEM.



MicroBooNE-like geometry





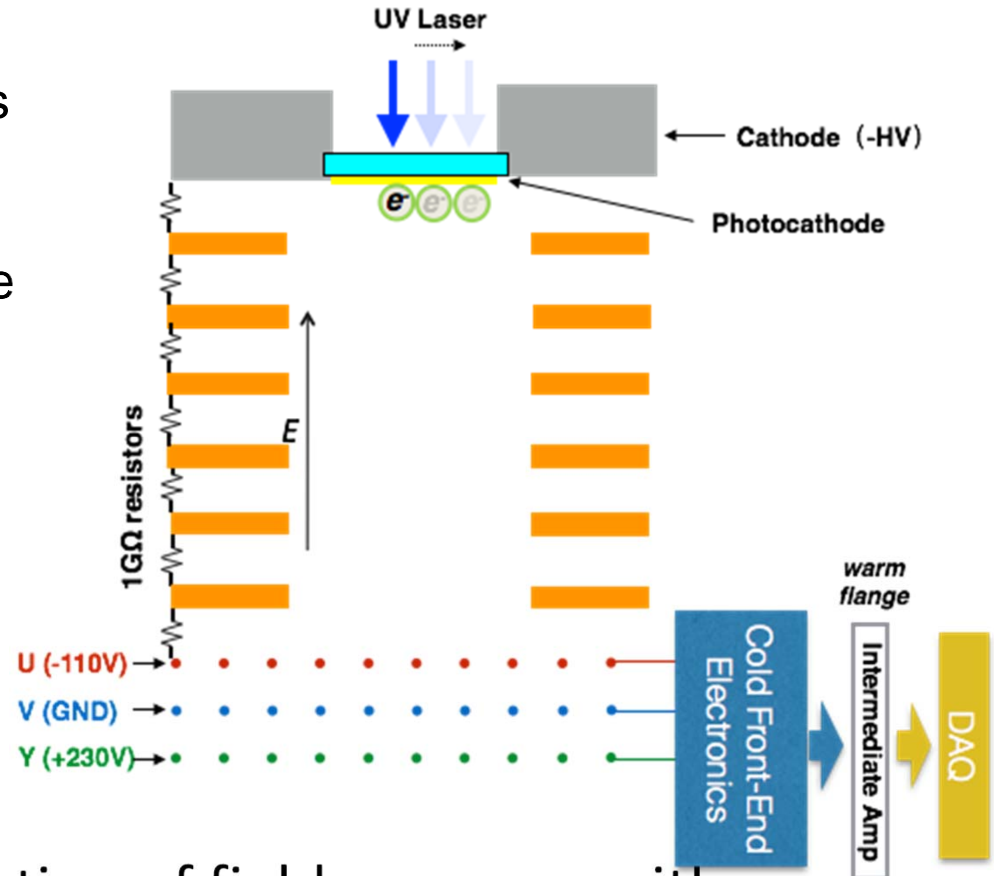
Weighting potentials, units are mm.

Brett Viren (BNL) , also Leon Rochester (SLAC)

Requirements of a Field Response Calibration System

Yichen Li

- A bright point-like electron source is favored
- The multiple known source positions are crucial
- The electron spot is close to the wire plane to limit diffusions
- Averaging is needed to minimize electronic noise → trigger is desired
- Distortion by digitization must be minimized
- Negligible influence on the drift field



- We will perform direct calibration of field response with photocathode driven by pulsed laser → better understanding the induction signal

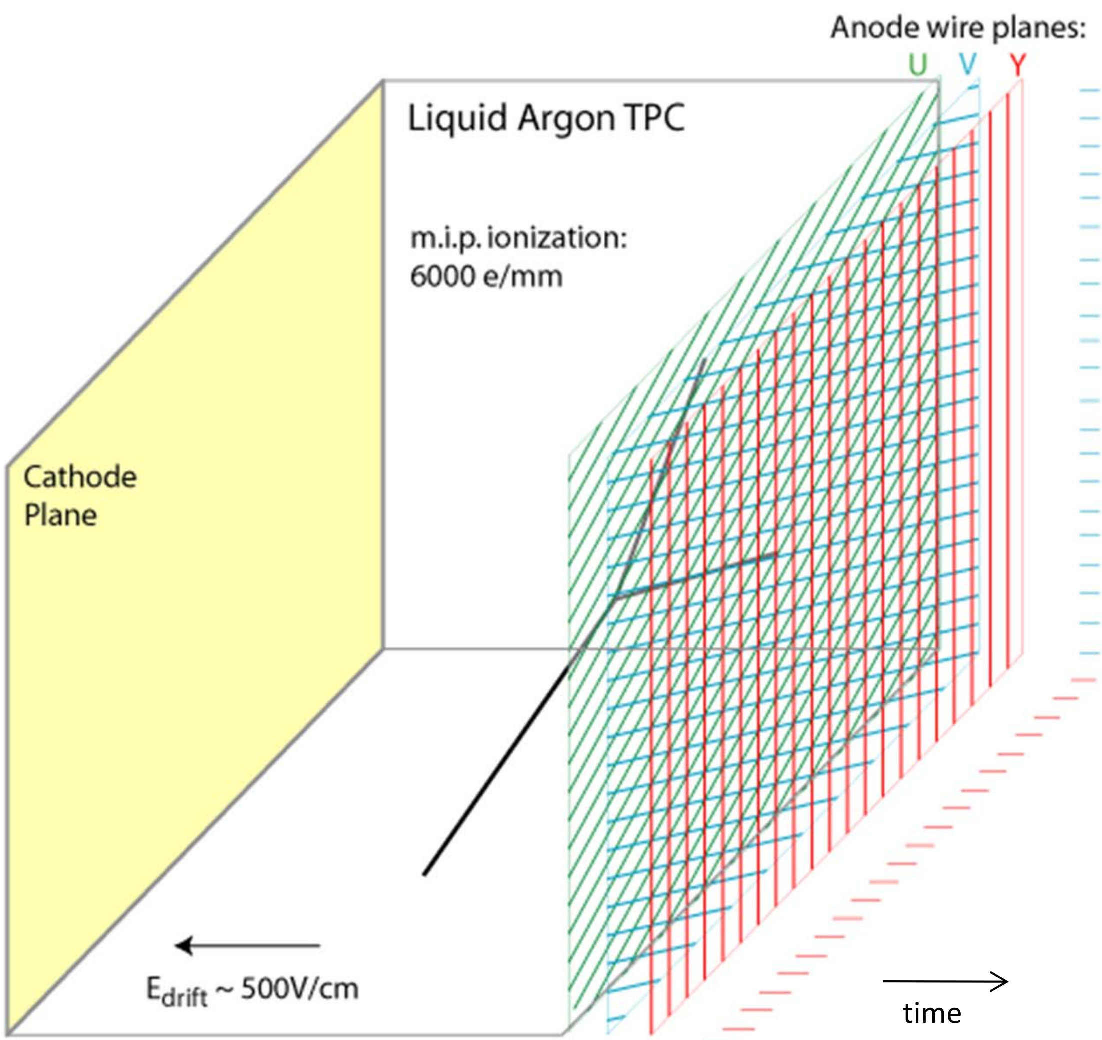
Summary

- The design of DUNE APA benefits from the experience of noise and TPC signal processing from MicroBooNE and ICARUS
  - We have figured out a robust way to do TPC signal processing to extract time and charge information from both collection and induction wire planes
  - 3D field calculation and direct calibration of the field response are in progress → better understanding the induction signal
- Minimizing noise and disconnected wires is the key to success!
  - Aim at O(0.1%) unusable channels (requirement < 0.5%)
  - Reaching expected noise level is the key to reach high quality performance for the induction plane signal (collection is much better)
  - Need to evaluate revising the 3 ms lifetime requirement for ProtoDUNE-SP (aiming for ~10 ms)

Response to Charge

- Are the requirements/justifications sufficiently complete and clear?
  - Choice of grid plane, mesh plane, TPC wire length, wire material, and wire spacer are clearly justified
  - Requirement of number of unusable channels is clearly justified
- Does the design provide adequate signal response characteristics ?
  - Yes, signal to noise ratio for both collection (ENC) and induction (DNC) wire planes are sufficient at expected noise level
- Is it optimized for the proposed electronics?
  - Choice of bias voltage fit the proposed electronics, various event topology can be properly processed with electronics and recovered by the TPC signal processing procedure

Principle of Single-Phase LArTPC



Number of ionized electrons

↓ Field Response

Signal on Wire Plane

↓ Electronic Response

Signal to be digitized by ADC

↓ Noise Filter, Charge Extraction

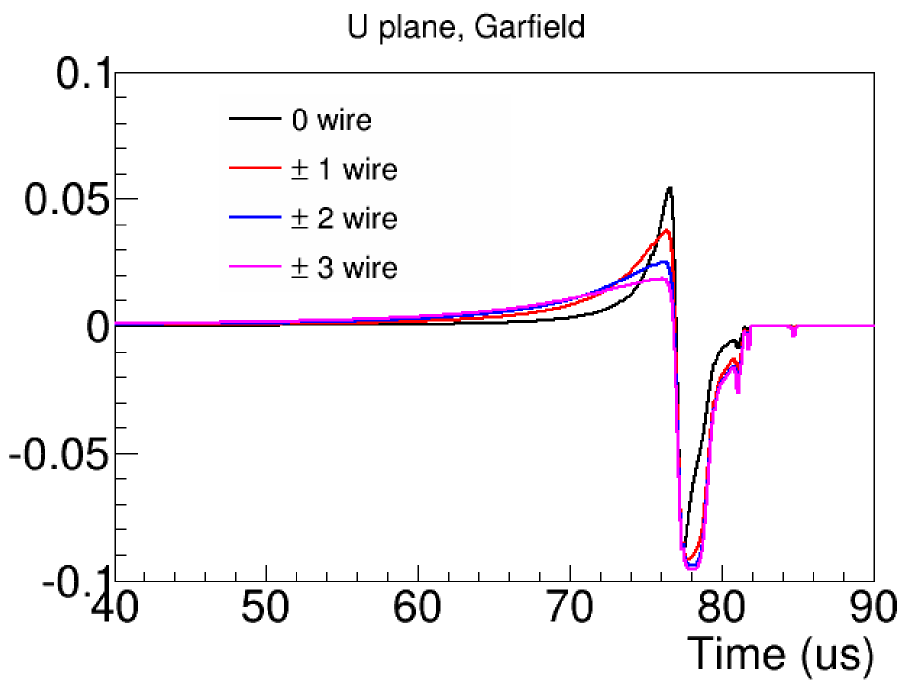
Number of Ionized electrons

↓

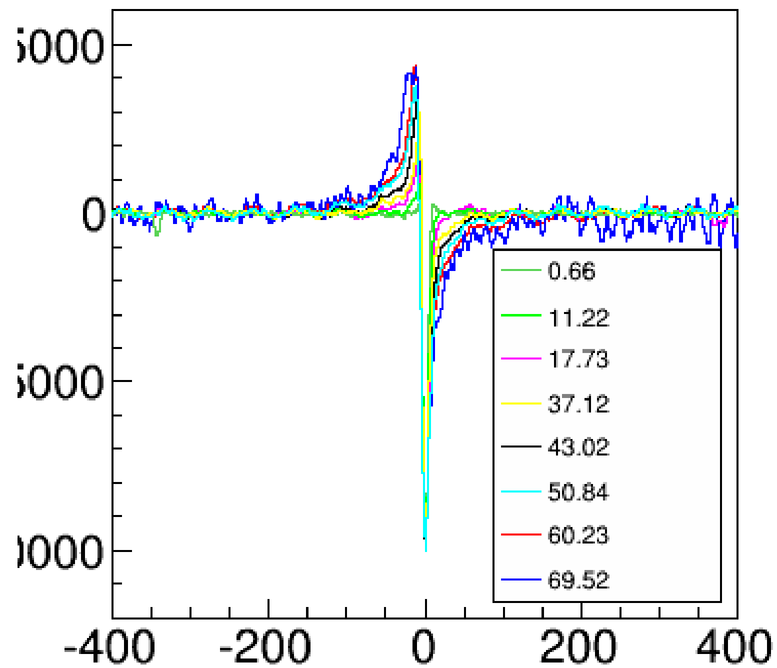
High-level tracking …

(Induction) wires are essential due to i) lack of electron amplification in liquid, ii) **power consumption** of electronics, and iii) **costs**

Example II: Parallel Track seen by U



MicroBooNE Preliminary



When we include the contribution from the near by wires, the field response is further deviated from the simple bipolar signal

→0 : close to parallel to wire plane (perpendicular to drift E field)
→ 90 : close to perpendicular to the wire plane (parallel to the drift E field)

What do we know for sure

- Cold preamplifier can reach expected ENC (MicroBooNE and LARIAT)
  - The remaining excess noise in MicroBooNE are reducible with hardware solutions
  - No software filter is needed for LARIAT

- We have figured out a robust way to do TPC signal processing
  - There are some problems with our current modeling of the induction field response → need this better understood for the induction plane

What do we want to know?

- Reliable calculation and calibration of field response function
  - 3D field calculation
  - Direct calibration of field response
- How can we control the unusable channel to O(0.1%)?
  - Fix the cold ASICs issue in the new design (~3% ASICs with the startup problem)
  - Fix the stuck bits problem in cold ADC
  - Eliminate touching wires

Coupling Capacitance

- For V plane wire, it crosses with ~ 870 collection wire, so the induced signal due to coupling capacitance will be suppressed by about O(1000)
- For Collection wire, it crosses with ~ 720 V plane wires, so the induced signal will be suppressed by O(700)
- For U plane wire, it crosses with ~800 V plane wires, so the induces signal will be suppressed by O(800)

- Based on charge calibration study in MicroBooNE, the cross talk is at about 2% level before the suppression above

- Effect is expected to be negligible

Summary of 35-ton Noise

- Known problems:
  - Low voltage regulator ~ 11 kHz noise (seen in uBooNE)
  - Remnant startup ~4% of the preamplifier ASIC (seen in uBooNE)
  - ADC ASIC "stuck bits"
- Unknown problems:
  - Origin of the High Noise State (ENC ~ 4 fC)
    - Not likely due to ASIC oscillation
    - Observation of HNS with spectrum analyzer and photo detector readout suggest noise source outside the cryostat
- What worked (next slide)
- Some observations (next two slides)

From Veljko's talk

3.1. What worked:

- Readout functionality. All FEMBs performed data collection.
- APA1 has been working well with the lowest noise and not entering into (HNS) by itself (without the power turned on to all APAs, in particular to APA3).
- *All cold FPGAs (16) in 35 ton have functioned as expected. This is a first and a milestone in R&D on cold electronics.* FPGAs' functioning did not affect the noise.
- With software filter for low frequency LVR noise, ENC is comparable to ~ ***one half* of ICARUS noise**, ~ ***twice*** the **MicroBooNE noise**.
- Noise increase with bias, drift HV and PD turned ON was significant.
- Detail on the above points in slides 6-10.

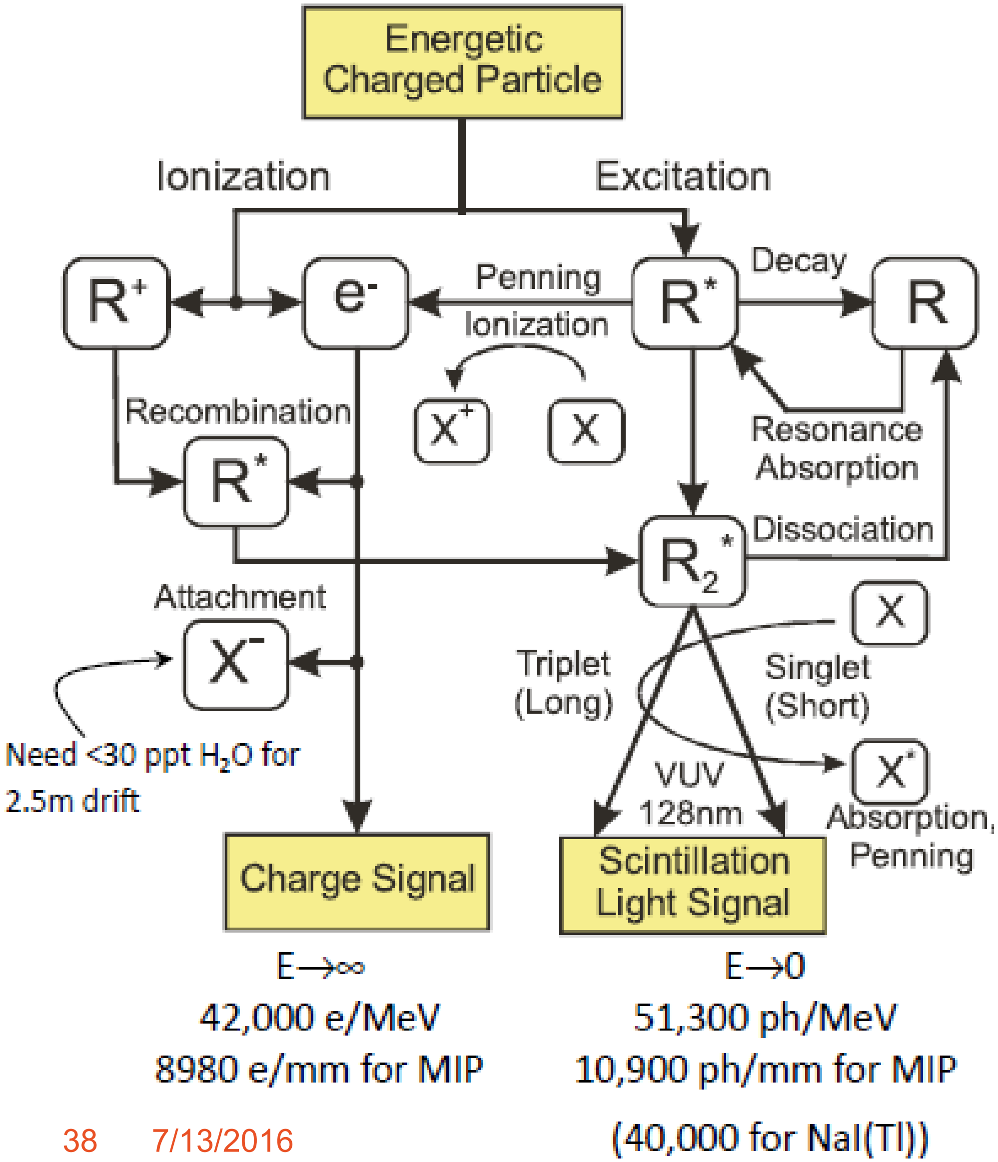
5

From Veljko's talk

3.6. Noise in "normal" state (no HNS)
- Some observations:

- Wide range of ENC among the APAs under normal cosmic data taking conditions (slide 7). APA1 the lowest.
- Non-readout TPC system noise contributions are very significant and most apparent at the lowest noise locations, increasing ENC from 610e- to 1070e-, and from 1210e- to 1950e-, for collection and induction wires respectively.
- Induction wire ENC ~ 1200e-~ twice the collection wire ENC ~ 600e-, at lowest ENC values, is higher than accounted for by different wire capacitances. Induction wires are more exposed to pick-up noise.
- The lowest noise values are also most uniform (slide 6). *Note*: All FE ASICs showed a very small ENC dispersion (<5% RMS) in the pre-assembly tests (all ASICs had been tested).

Charged Particle Traveling in LAr



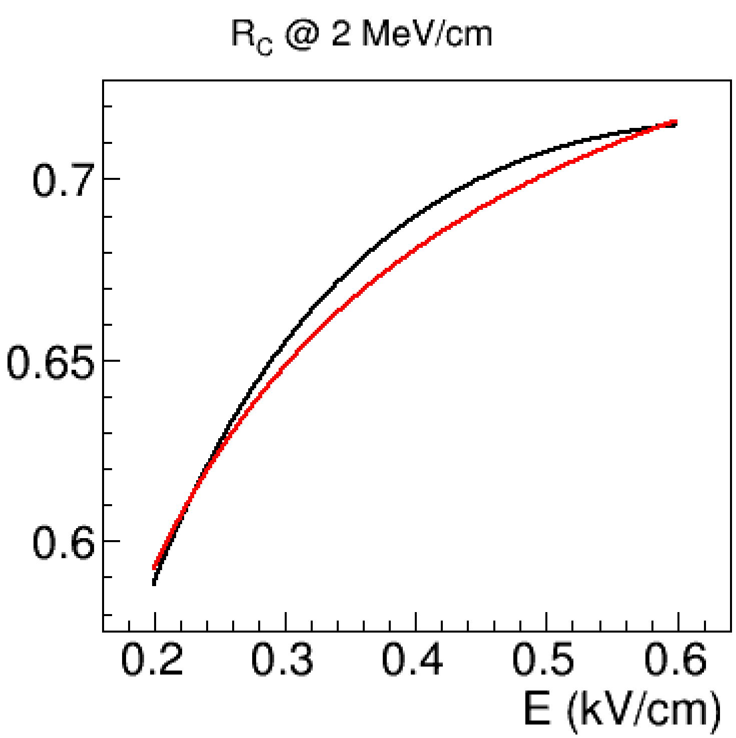
- Number of ionized electrons
  - Recombination effect
  - Electron lifetime due to impurities
- Ionized electron transportation
  - Drift Velocity
  - Diffusion

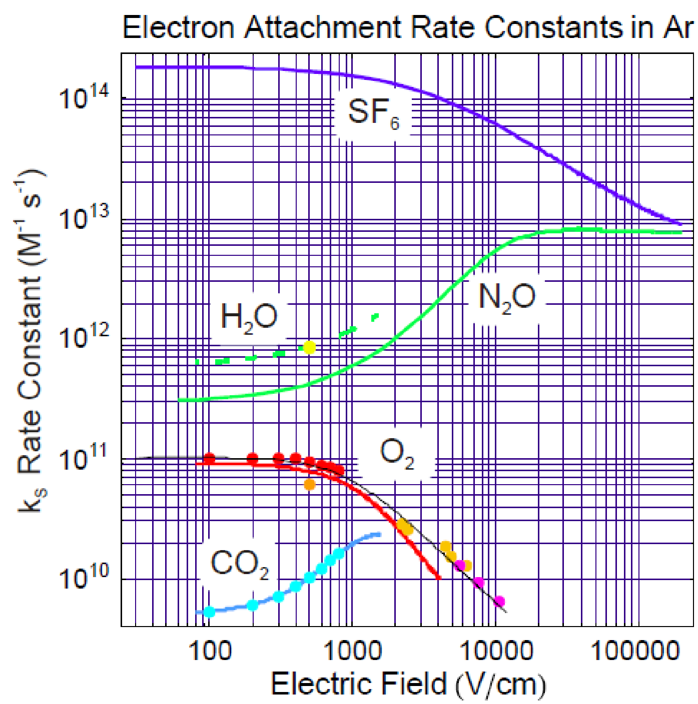
Recombination and Electron Lifetime

- Recombination:
  - Modified Box Model vs. Birks Model
  - Large dE/dx → more recombination
  - Large E-field → less recombination

- Electron lifetime
  - 1012 times collisions with atoms every second

$$Q_{collect} = Q_{drift} \cdot e^{-t_{drift}/T_{lifetime}}$$



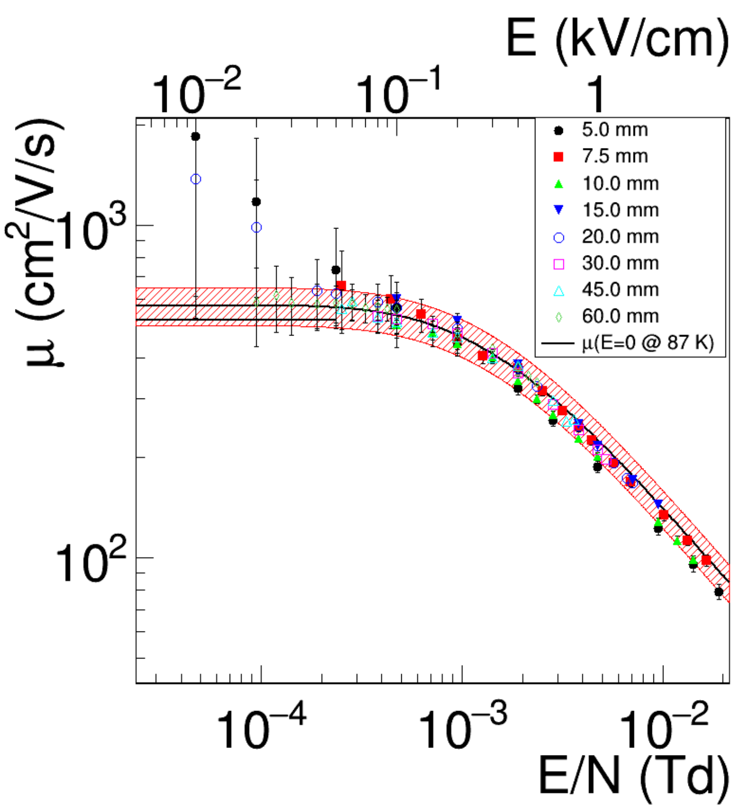


Electron Drift Velocity and Diffusion

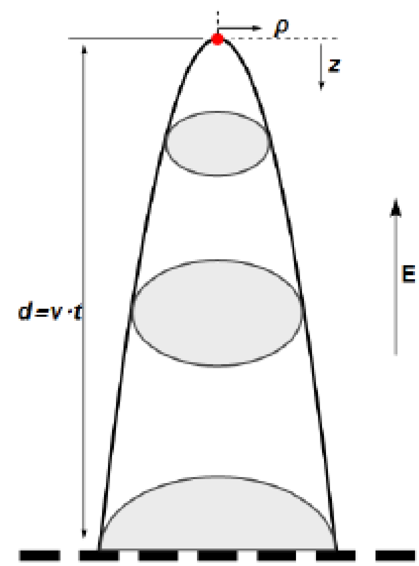
- Drift velocity

$$v \text{ (drift velocity)} = \mu \text{ (mobility)} \cdot E \text{ (electric field)}$$

- ~1.6 mm/us @ 500 V/cm
  - 2.3 ms for 3.6 m travel distance



- Diffusions: Y. Li et al. NIMA 816 160 (2016)

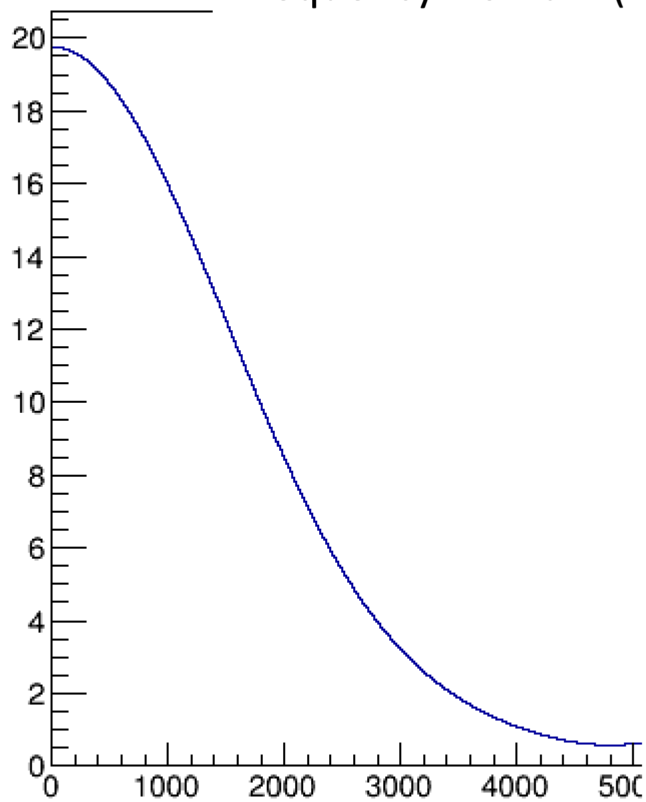


Drift Dis.	Longitudinal σ	Transverse σ
1.8 m	~1.2 mm	~1.7 mm
6.0 m	~2.3 mm	~3.1 mm

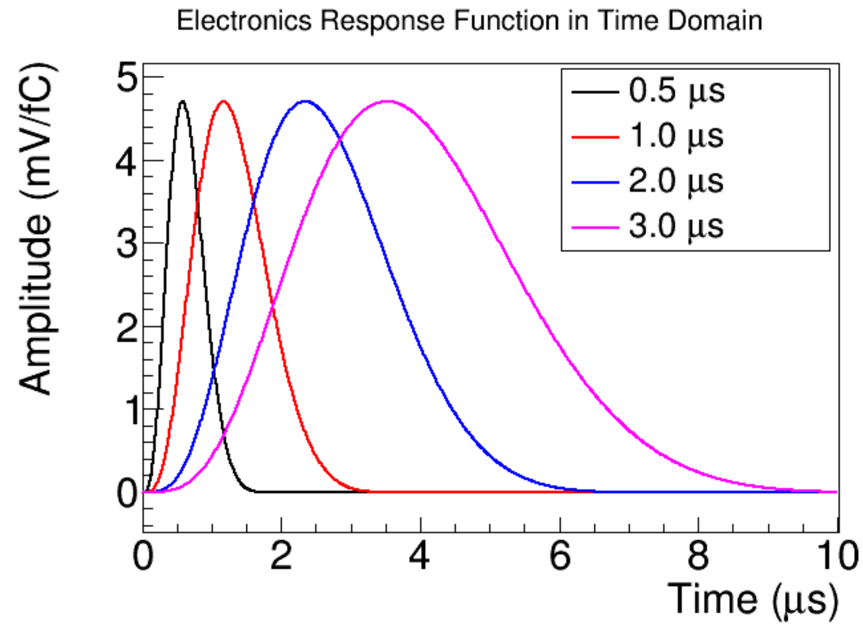
http://lar.bnl.gov/properties/

Electronic Response

Electronic Response in Frequency Domain (2 us)



0 Hz 1 MHz



Cold electronic:

- 4 shaping time (0.5, 1.0, 2.0, 3.0 us)
- 4 gain (4.7, 7.8, 14, 25 mV/fC)

$$[\text{Digitized (ADC)}] = [\#\ \text{of}\ e^-] \times [\text{Field res. (fC/}e^-)] \times [\text{Ele. res. (mV/fC)}] \times 2.5 (\text{ADC/ mV})$$

Impact of hardware filter on LV filter regulator

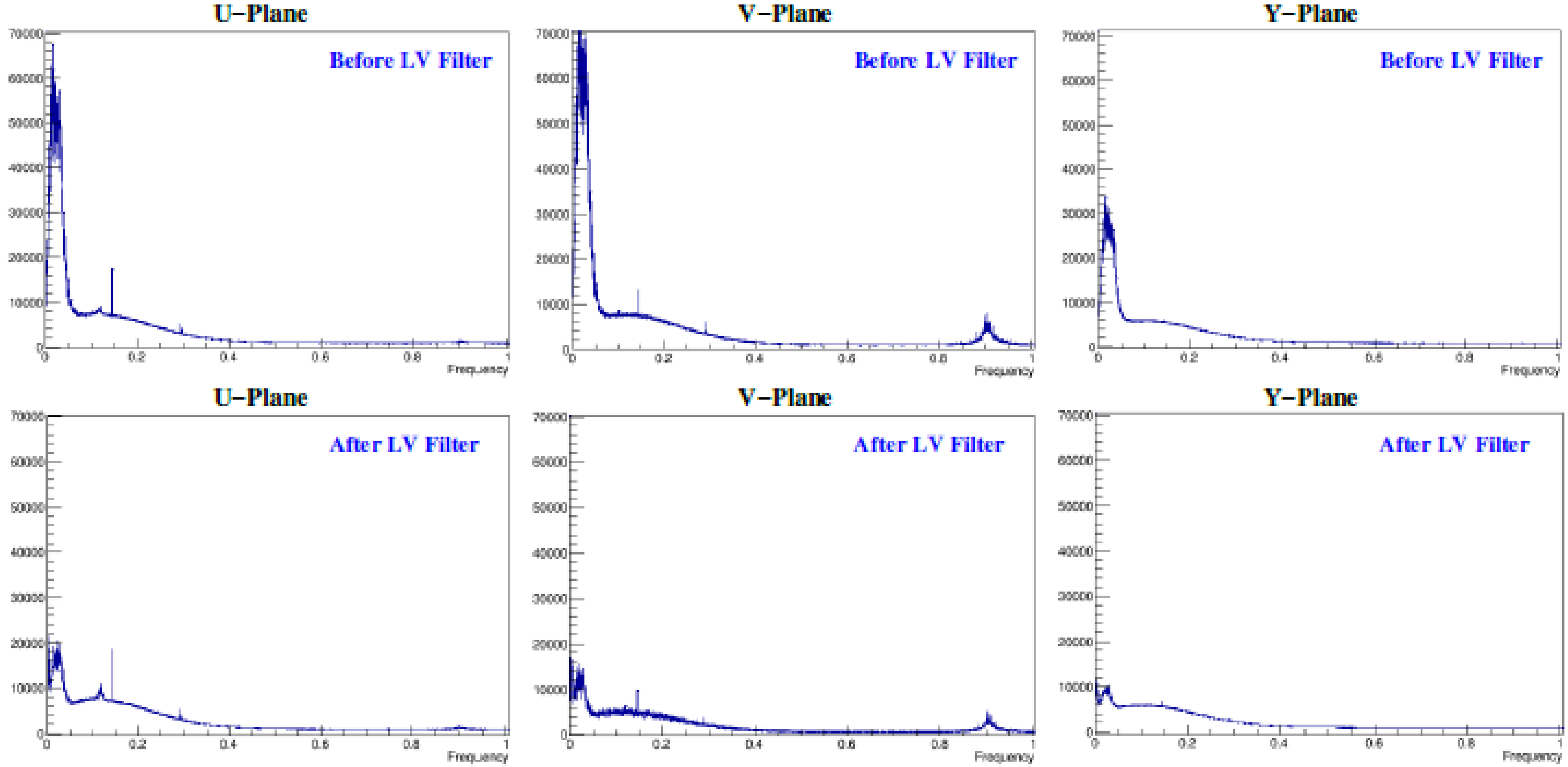
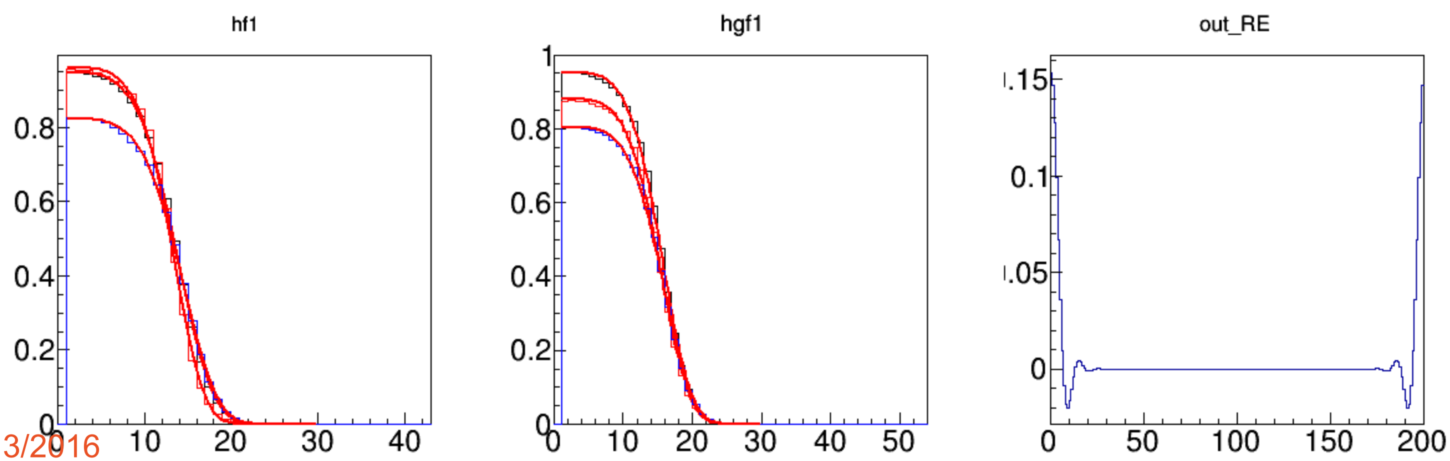


FIG. 12. The FFT of the data on the U (left), V(center) and Y (right) planes before (top) and after (bottom) the hardware filter was added to the low-voltage service board on feedthrough 5.

Use the Following "Wiener-like" Deconvolution Filter Functions

$$(x>0)\times[0]\times e^{-\frac{(x/[1])^{[2]}}{2}}$$

- To implement in, set [0] = 1, so that the filter will normalize to 1
- Filter (in frequency domain) is essential a smearing function (in time domain)



Electronic Shaping Function for cold ASIC

- Transfer function is obtained from Hucheng

Out[5]= $$\left\{ \frac{\text{Ao cAo}}{(p0 + s)\ \left(ip1^2 + (rp1 + s)^2\right)\ \left(ip2^2 + (rp2 + s)^2\right)} \right\}$$

p0 = {1.477/To/cTo}
rp1 = {1.417/To/cTo}
ip1 = {0.598/To/cTo}
rp2 = {1.204/To/cTo}
ip2 = {1.299/To/cTo}
cAo = {2.7433/(pwr(To*cTo,4))}
cTo = {1/1.996}
Ao = 1.4
To = 0.5us

Transfer function is Laplace transformation of the shaping function in the time domain

Example Field Response Functions

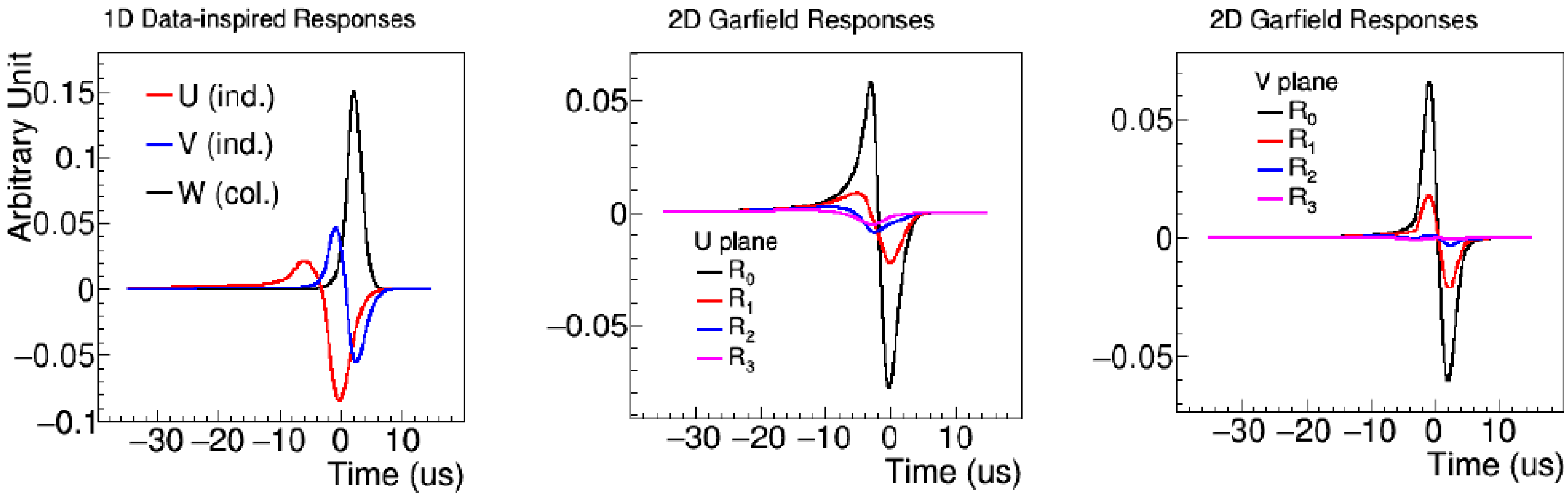
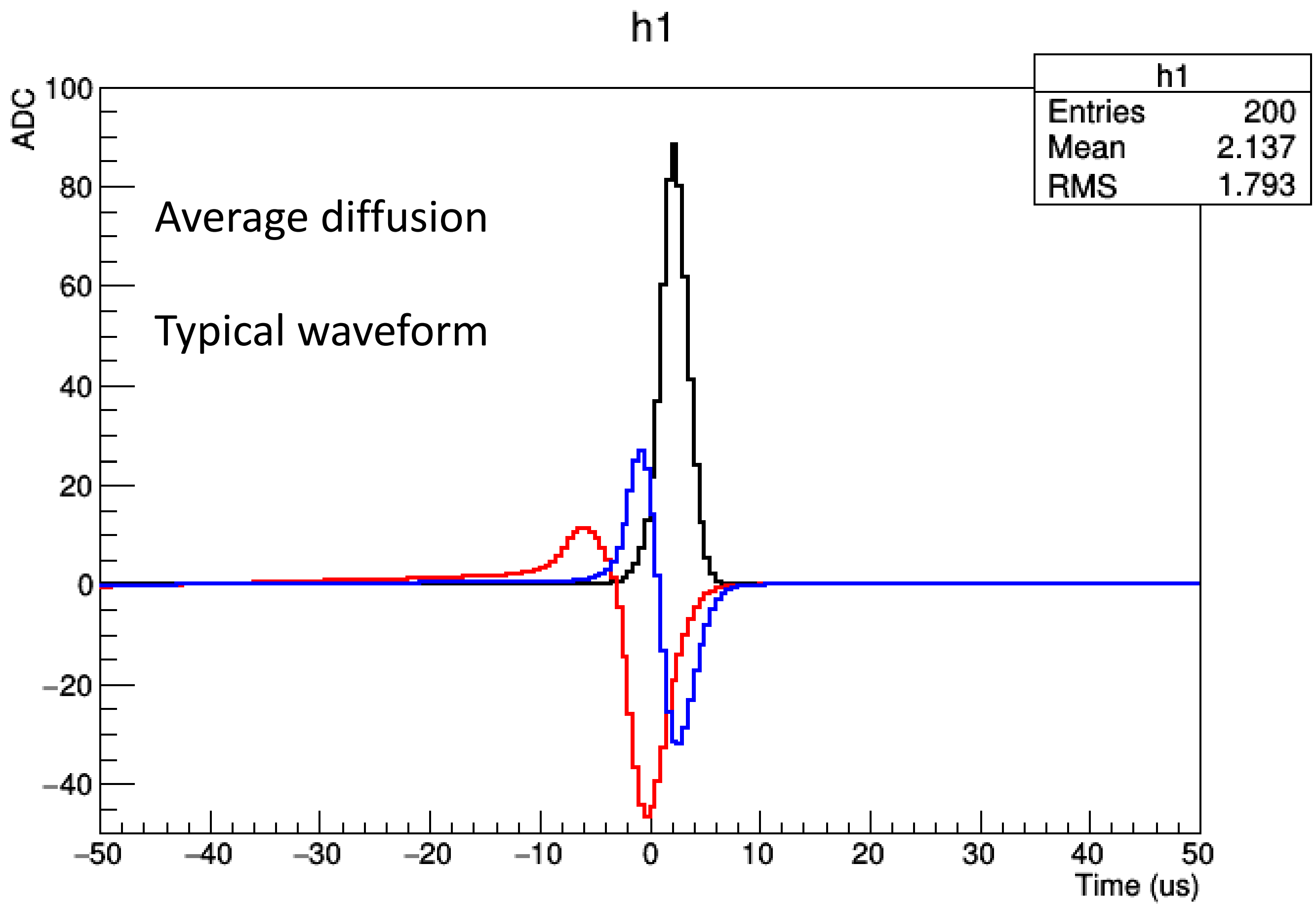


FIG. 10. The overall response functions, which is the convolution of the electronics response function (14 mV/fC gain and 2 μs shaping time) and the field response, are shown. See text for more discussion.

Example of the MIP (2.1 MeV/cm) traveling 3 mm parallel to the wire plane



Estimation of Peak to Noise Ratio

- Collection Wire plane

$$Signal: \quad 85 \times \frac{4.79\ mm}{3\ \text{mm}} \times 1.15 \sim 156\ ADC$$

$$Noise: \ 1+1\times\frac{6}{4.6} \sim 2.3\ ADC$$

$$S/N \sim 67.8:1$$

- Induction Wire plane

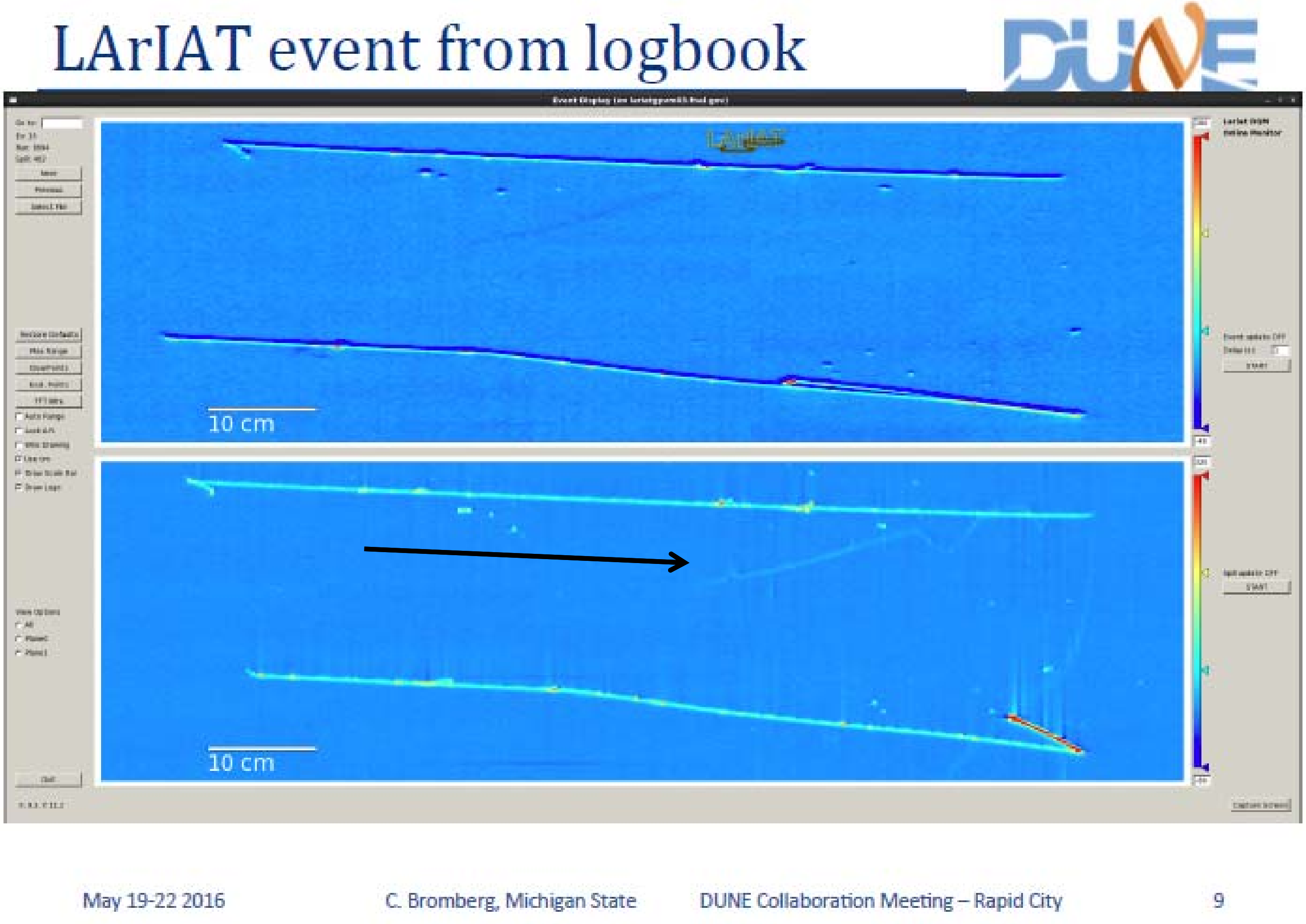
$$Signal: \quad 30 \times \frac{4.667\ mm}{3\ \text{mm}} \times \frac{1.4}{1.67} \times 1.1 \sim 43.0\ ADC$$

$$Noise: \ 1+1\times\frac{7.3}{4.6} \sim 2.6\ ADC$$

$$S/N \sim 16.5:1$$

- 1.4/1.67 from the field response function between 3 mm and 5 mm wire pitch
- 1.15 for collection (1.1 for induction) takes into account the different drift voltage (273 V/cm vs. 500 V/cm)

Signal from behind the collection



APA Design Parameters

Table 4.2: APA Design Parameters

Parameter	Value
Active Height	5.920 m
Active Width	2.295 m
Wire Pitch (U,V)	4.67 mm
Wire Pitch (X,G)	4.79 mm
Wire Position Tolerance	0.5 mm
Wire Plane Spacing	5 mm
Wire Angle (w.r.t. vertical) (U,V)	35.7°
Wire Angle (w.r.t. vertical) (X,G)	0°
Number Wires / APA	960 (X), 960 (G), 800 (U), 800 (V)
Number Electronic Channels / APA	2560
Wire Tension	5.0 N
Wire Material	Beryllium Copper
Wire Diameter	150 μm
Frame Planarity	5 mm
Photon Detector Slots	10

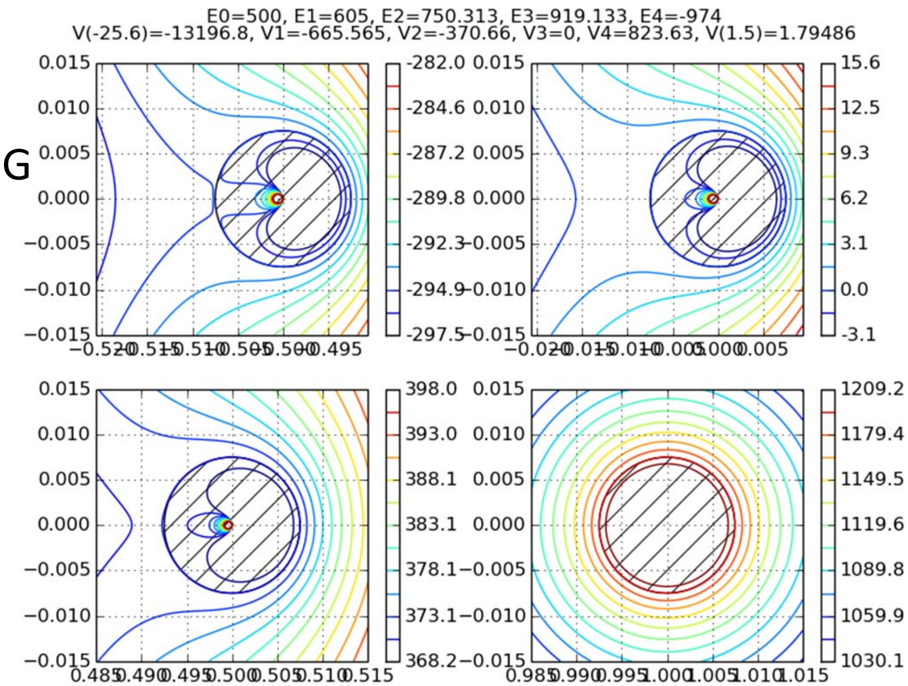
Anode Plane	Bias Voltage
Grid (G)	-665 V
Induction (U)	-370 V
Induction (V)	0 V
Collection (X)	820 V
Mesh (M)	0 V

FEM calculation

- 100% transparency checked with analytical calculation based on conformal representation theory (Glenn Horton-Smith, uBooNE db-4708)

G

U

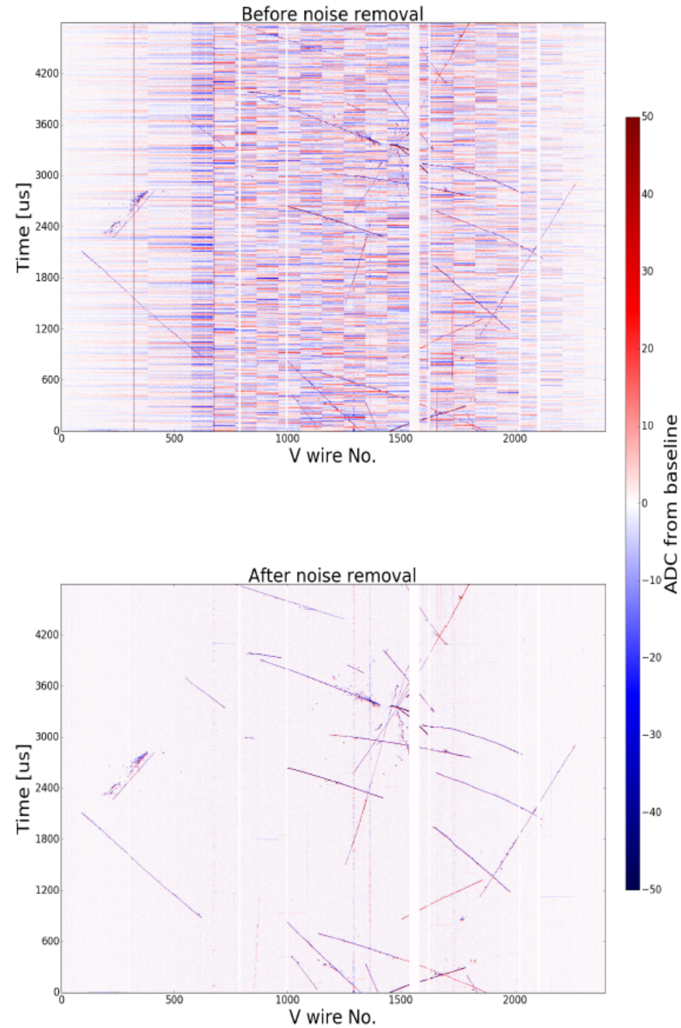


V

X

Noise in MicroBooNE

- There are three sources:
  - 10-30 kHz coherent noise → low voltage regulator on the mother board
    - Hardware fix in order
  - 900 kHz noise → some sort of pick-up noise due to its position dependence
    - Beyond signal bandwidth
  - 36 kHz harmonic noise → Drift high voltage power supply (mainly see in the first plane)
    - Hardware fix in order



All noise in MicroBooNE are accounted for and have hardware solutions