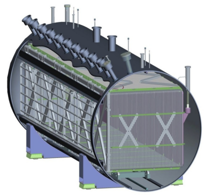
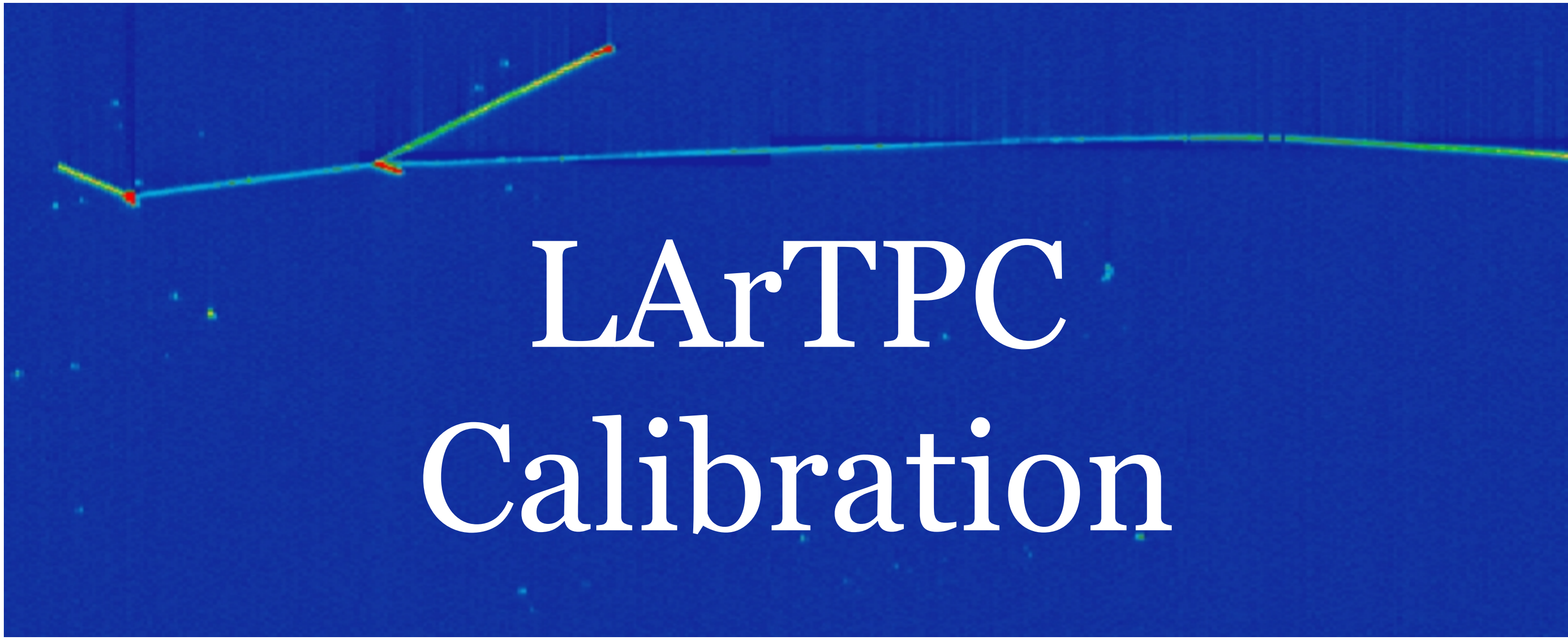




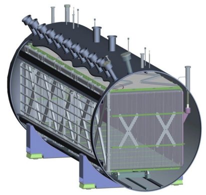
LArTPC Calibration

Michael Mooney

Brookhaven National Laboratory (BNL)

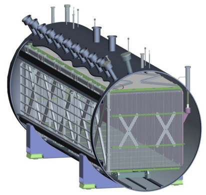
NNN16, IHEP, Beijing, China

November 3rd, 2016



Introduction

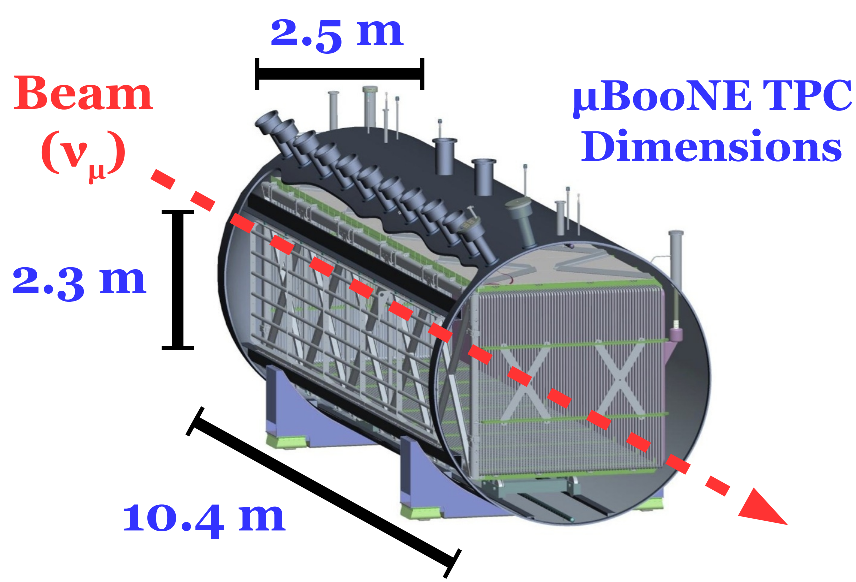
- <u>Goal of LArTPC calibration</u>: measure charge and position associated with ionization signal in unbiased manner and as precisely as possible
  - Noise, detector effects lead to bias, resolution loss
  - With calibrations in place, can then look at higher-level candles to study particle reconstruction (e.g. cosmic muons, Michel electrons, photons from π^o decays)
- Crucial for LArTPC experiments to reach physics goals!
- In what follows, will describe relevant detector effects and calibration techniques using **MicroBooNE** as an example
  - Operational single-phase LArTPC: plenty of data to begin looking at these effects
  - Also reference **test stand measurements** where relevant

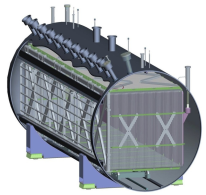


Case Study: MicroBooNE

- "Micro Booster Neutrino Experiment"
  - Accelerator ν experiment @ FNAL
  - LArTPC with 89 ton active mass
  - Non-evacuated liquid argon fill
  - Cold (in LAr) front-end electronics
  - Near-surface operation
  - UV laser calibration system

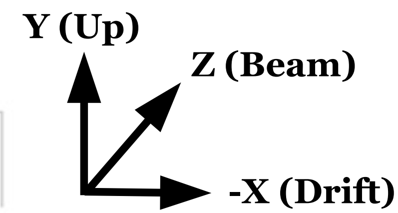
- Physics goals:
  - Investigate MiniBooNE low-energy excess
  - Measure first low-energy ν-Ar cross sections
  - R&D for future detectors
  - Key step for Short Baseline Neutrino (SBN) program

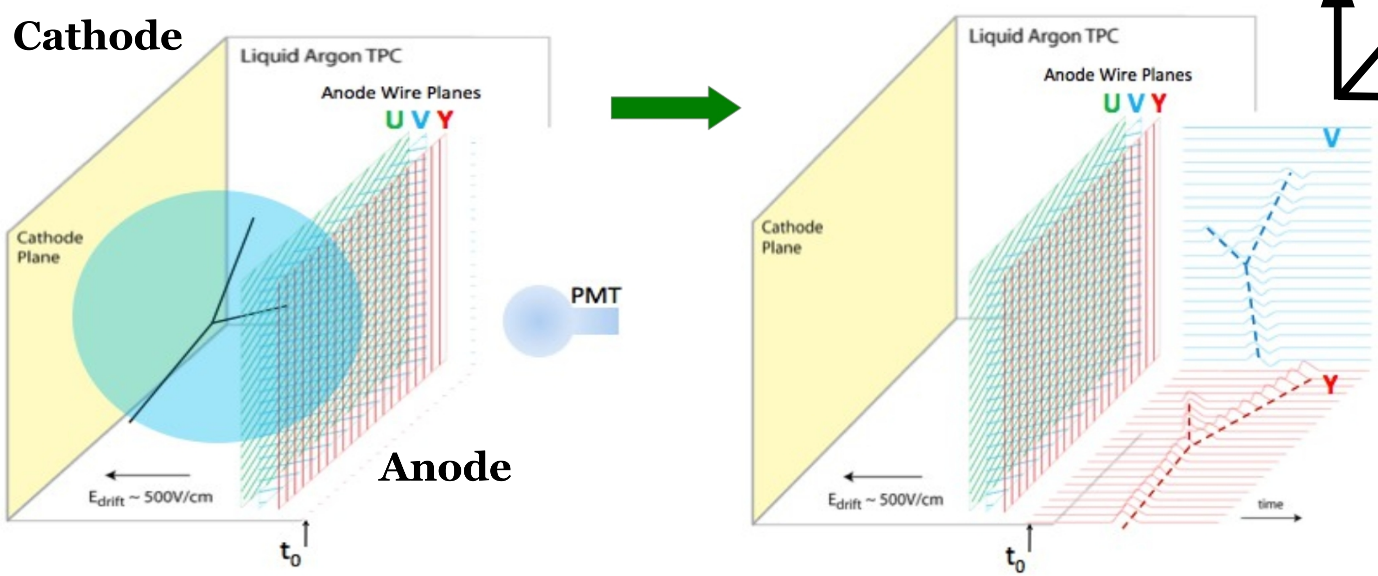




MicroBooNE TPC

- Two **induction** planes (U, V) and one **collection** plane (Y); drifted ionization in LAr puts signal on all three
  - Drift E field at 273 V/cm, ~uniform via surrounding field cage
  - 8000+ channels in total with front-end electronics in LAr
- 3D event reconstruction by combining signals from all three planes (minimum two needed), each with 3 mm wire pitch
  - **Millimeter-scale spatial resolution**

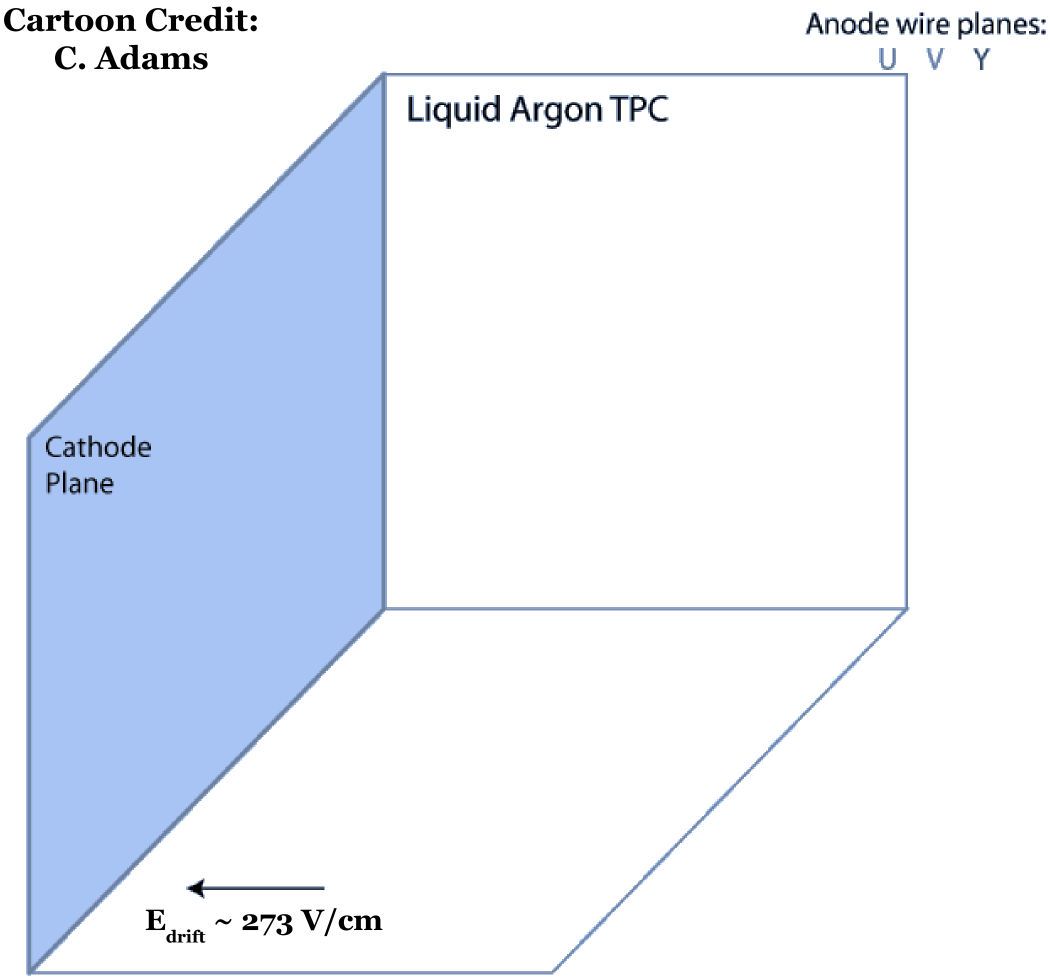




NIM 120 (1974), no. 2, 221-236

Signal Formation

Cartoon Credit:
C. Adams



Signal Formation

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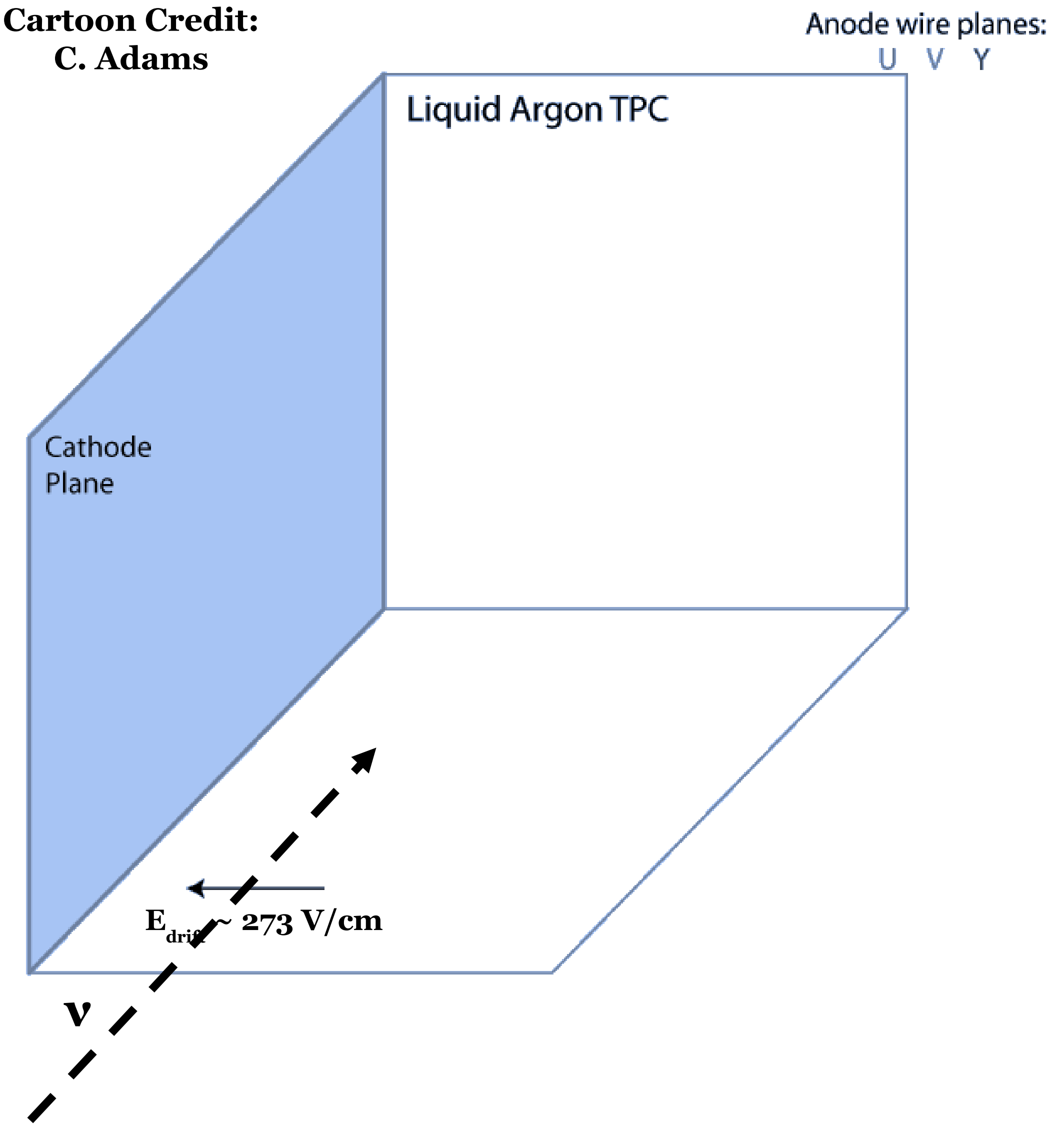

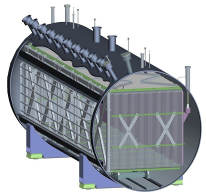

Signal Formation

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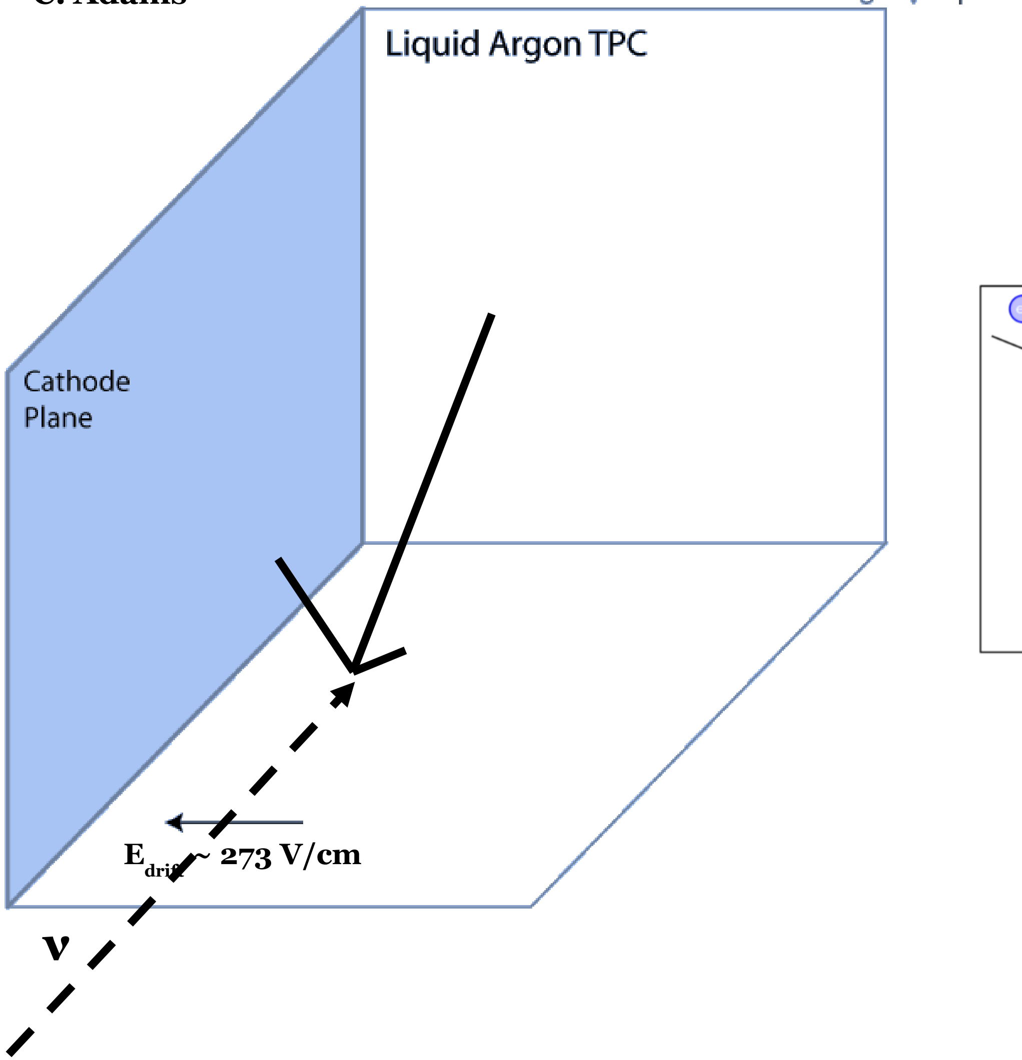
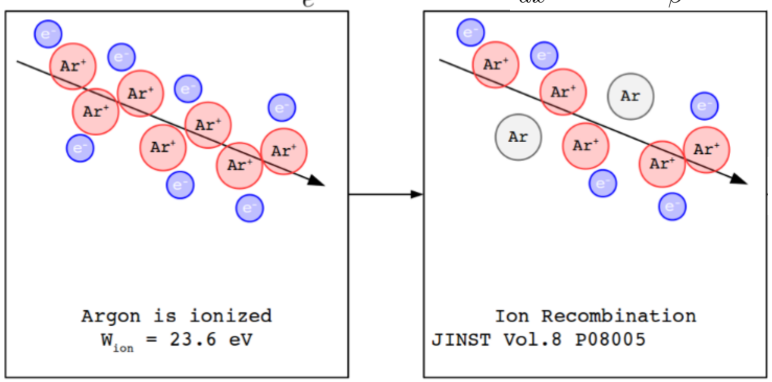
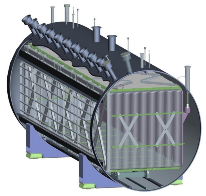


$$dQ = dE \times \frac{W_{ion}}{e^-}$$

$$\frac{dE}{dx} = \frac{e^{\beta \times \frac{W_{ion}}{e^-}\frac{dQ}{dx}} - \alpha}{\beta}$$





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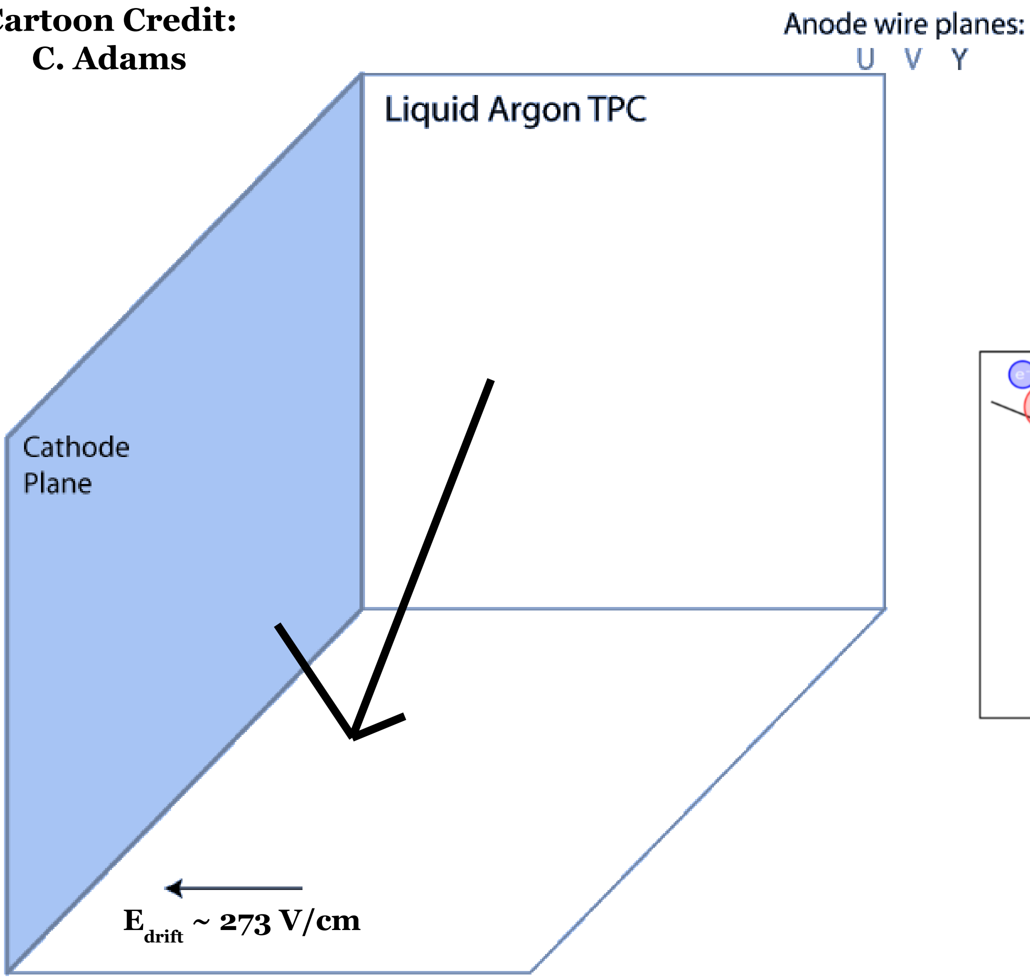

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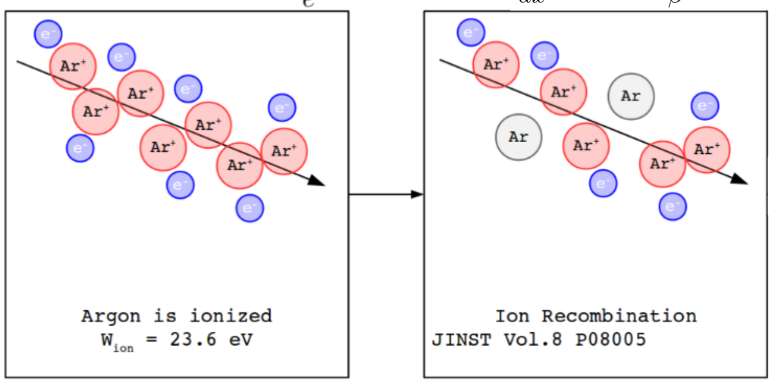

Signal Formation

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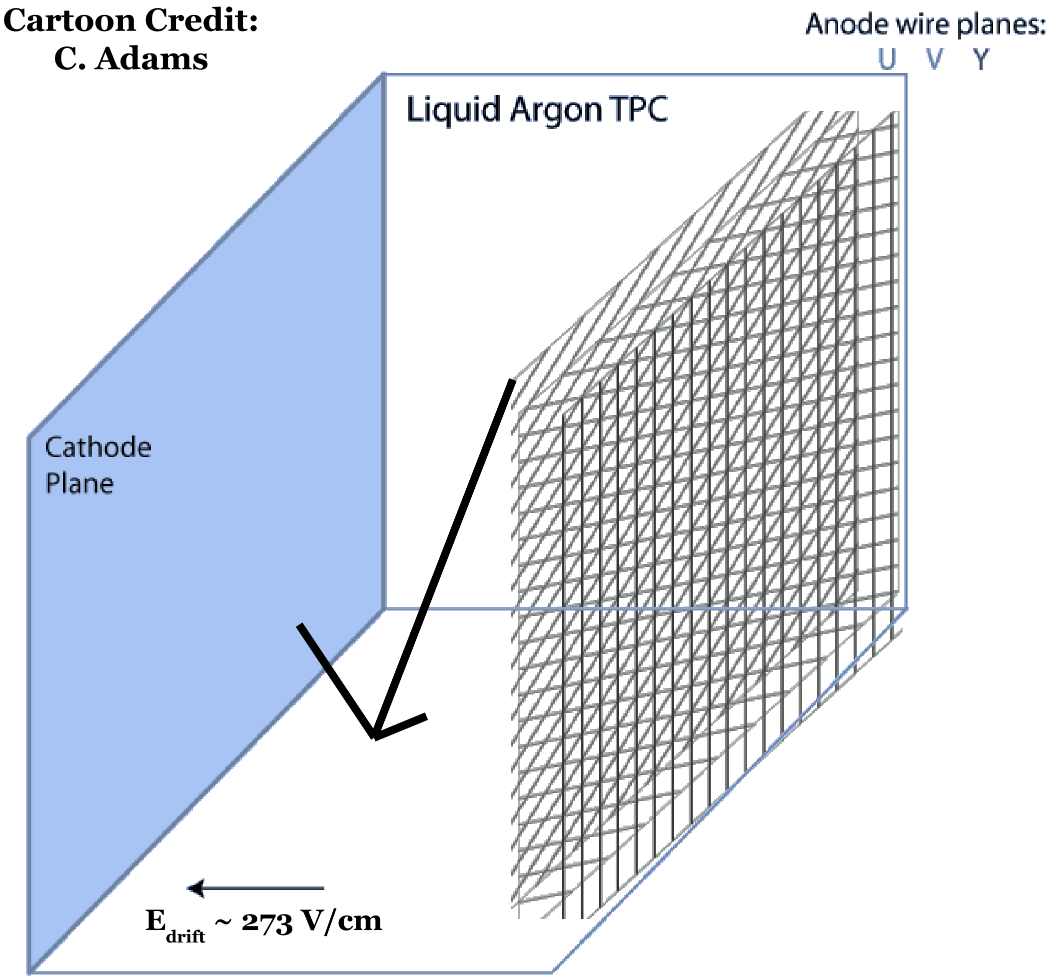

Signal Formation

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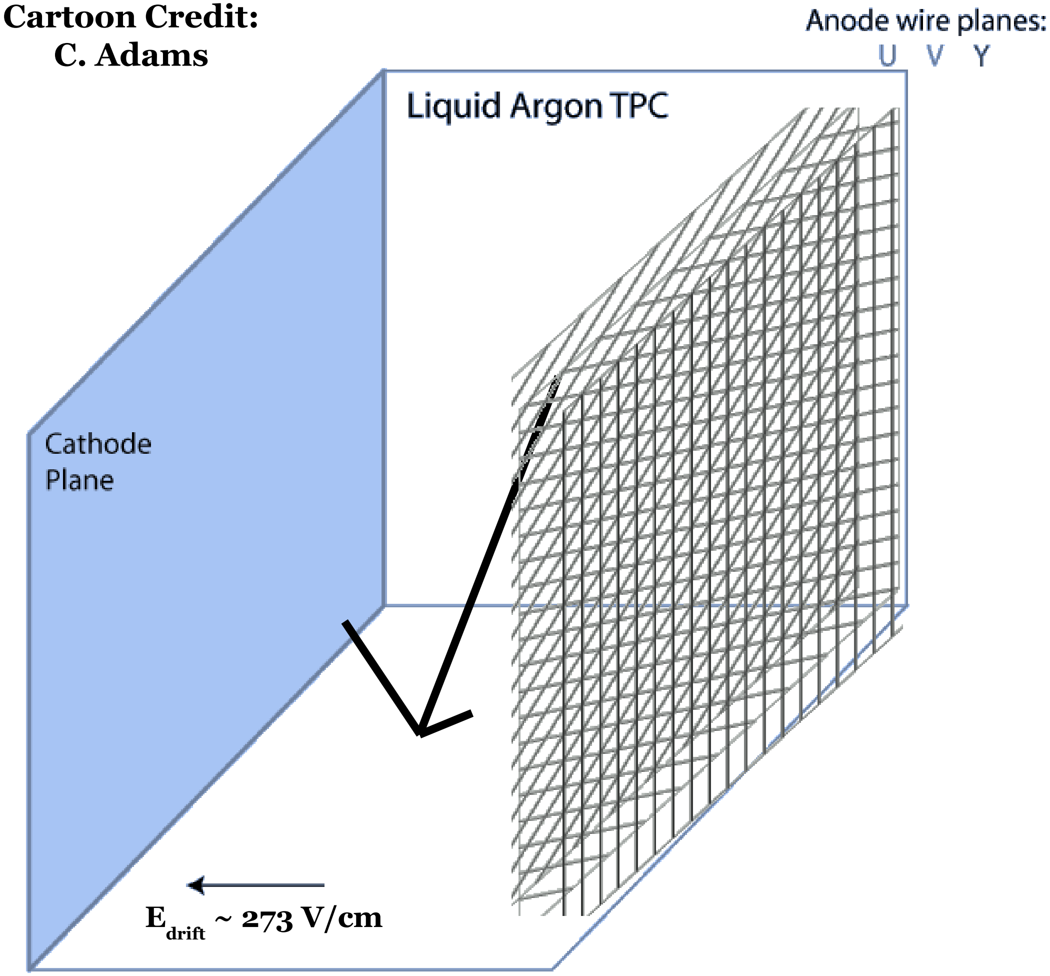
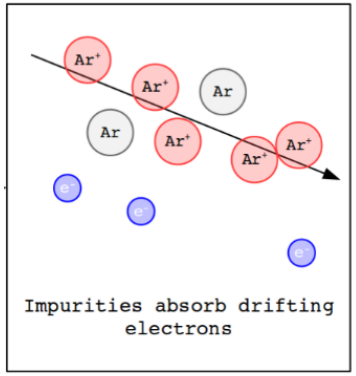
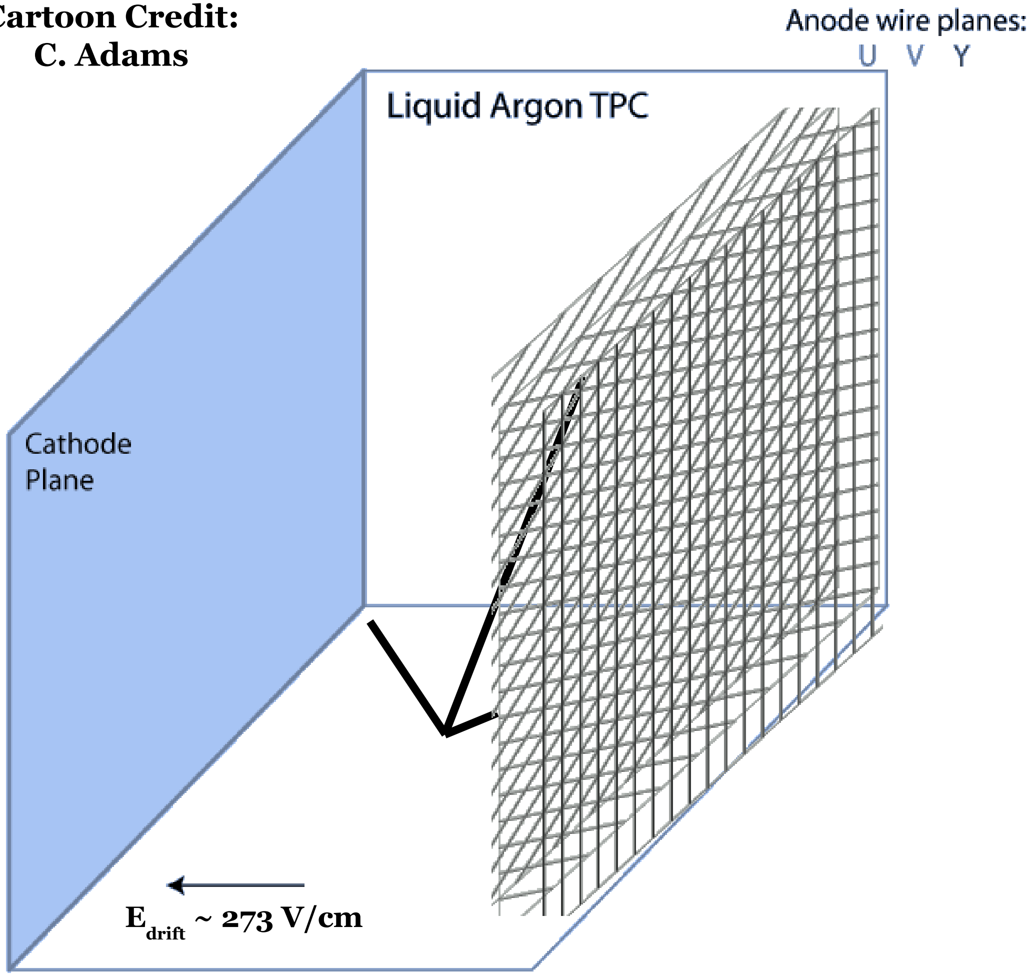


$Q = Q_0 e^{-t/\tau}$

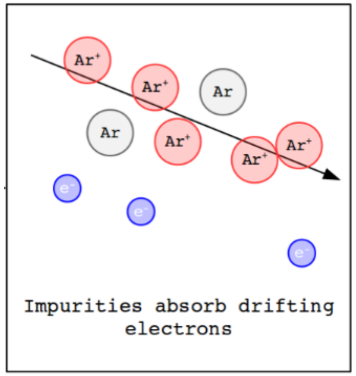


Signal Formation

Cartoon Credit:
C. Adams



$Q = Q_0 e^{-t/\tau}$



Signal Formation

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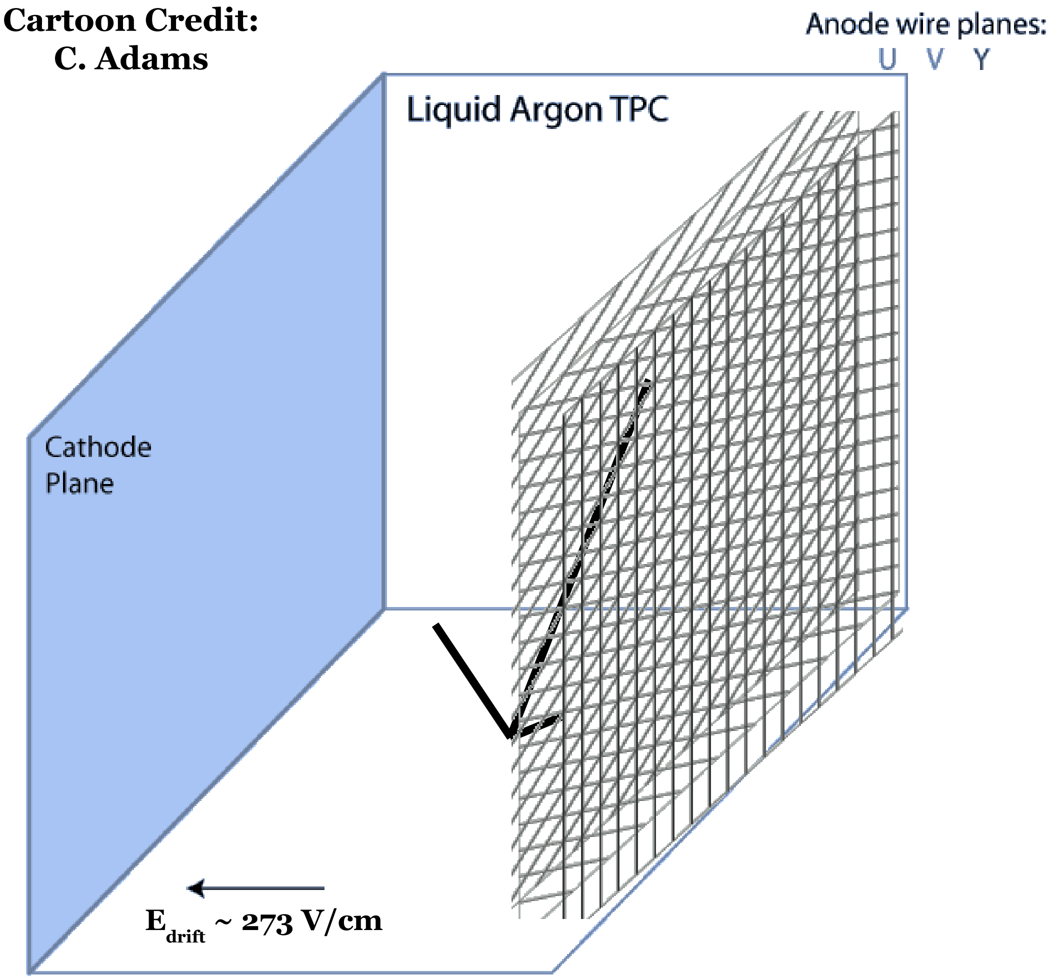

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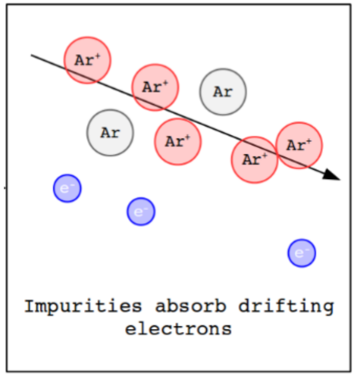

Signal Formation

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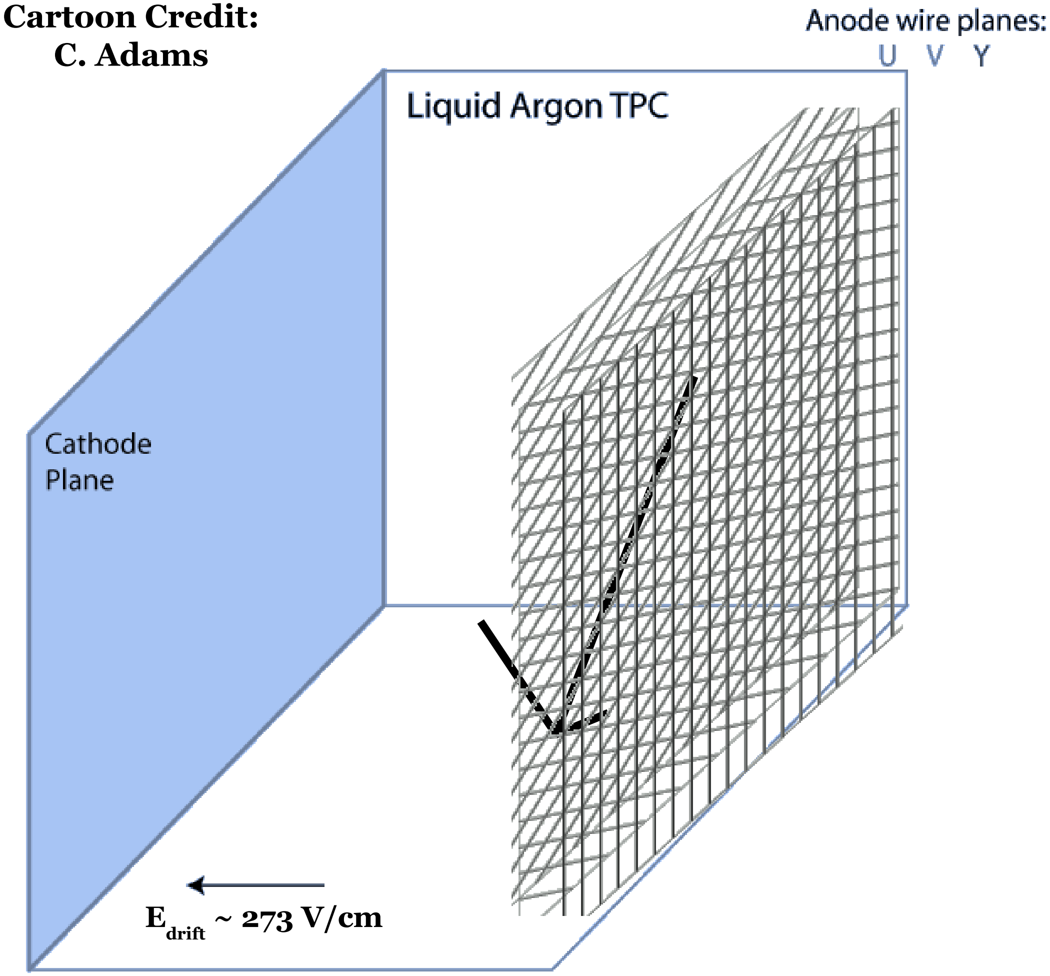
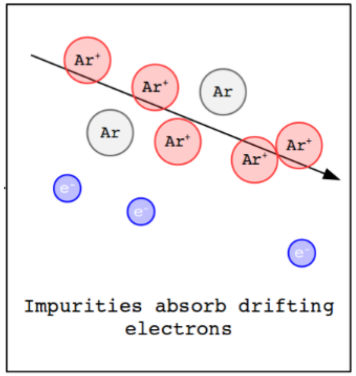


$$Q = Q_0 e^{-t/\tau}$$



Signal Formation

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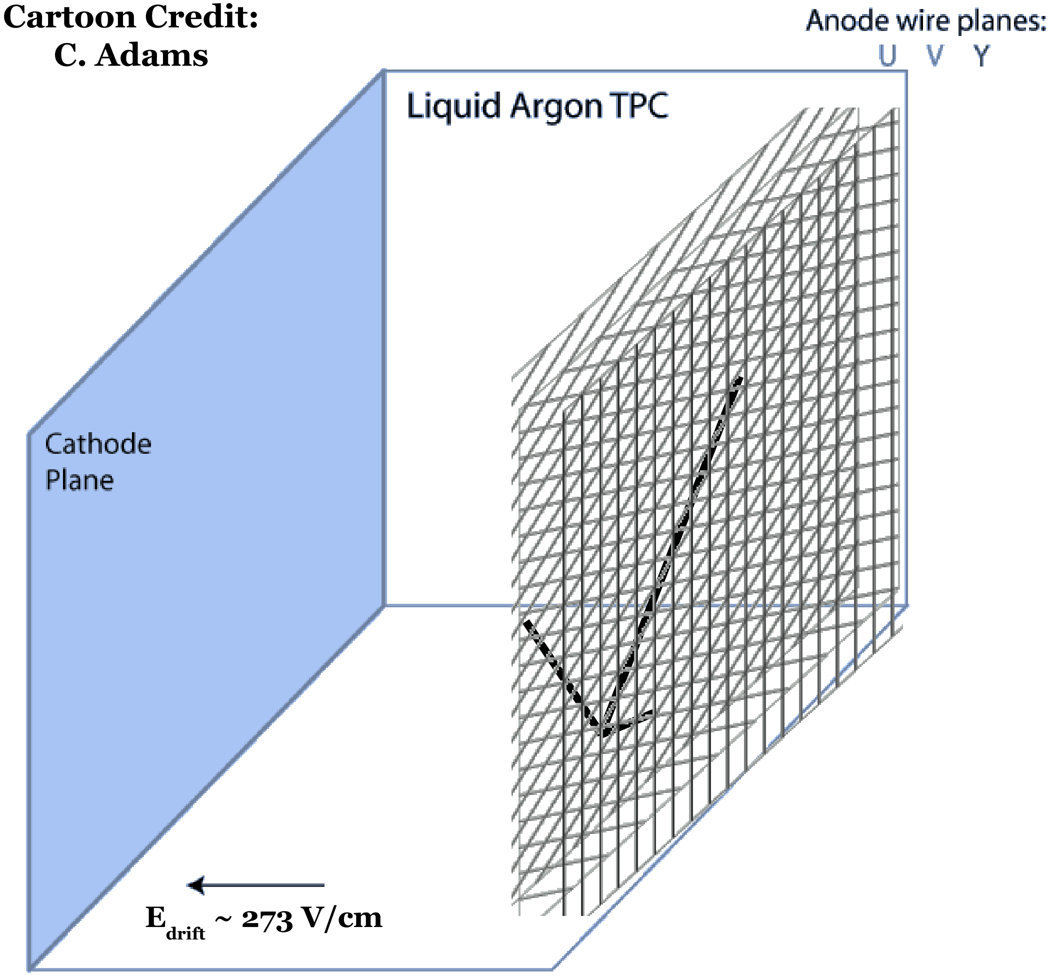
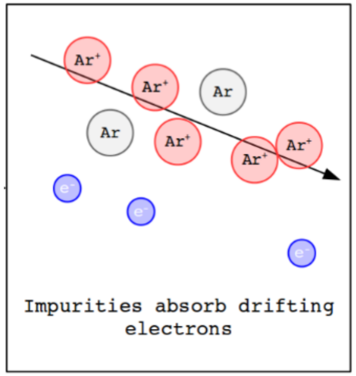
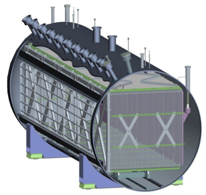


$Q = Q_0 e^{-t/\tau}$





Signal Formation

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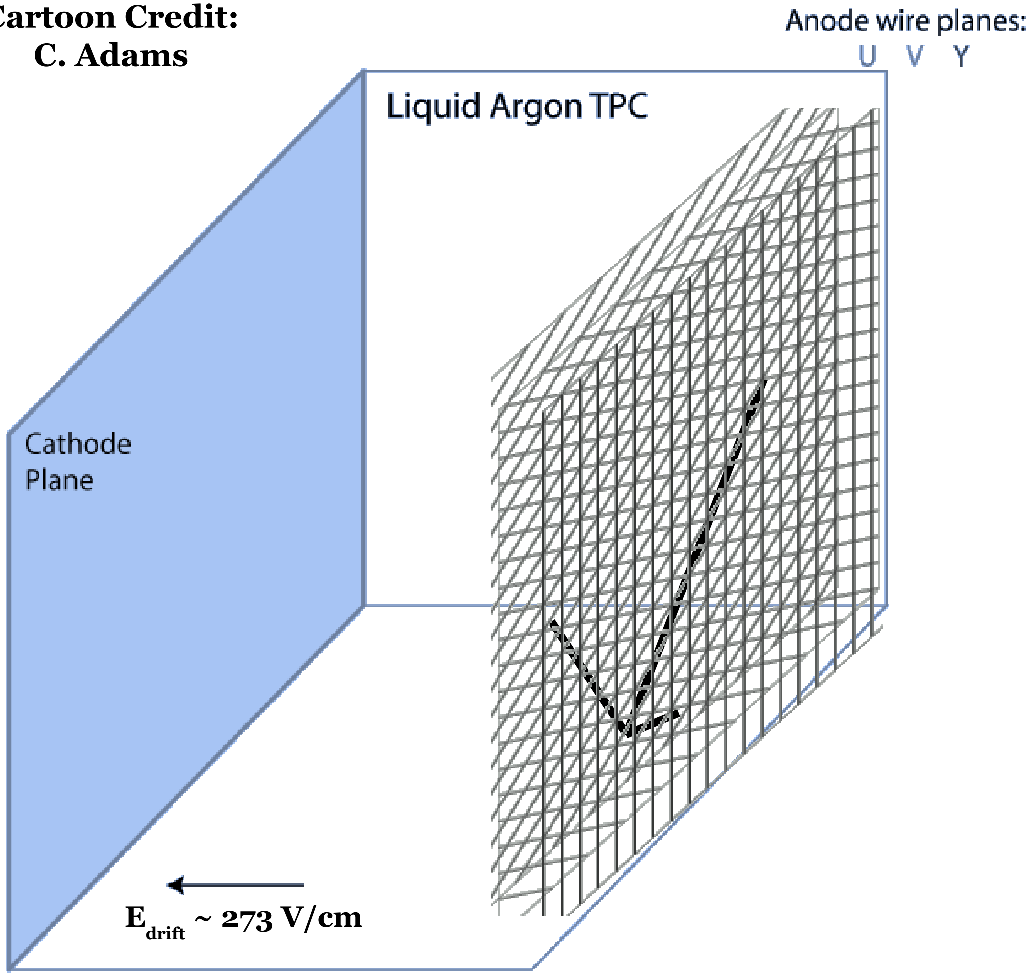

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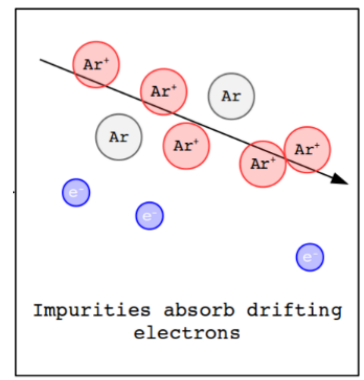

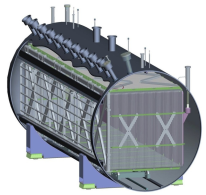

Signal Formation

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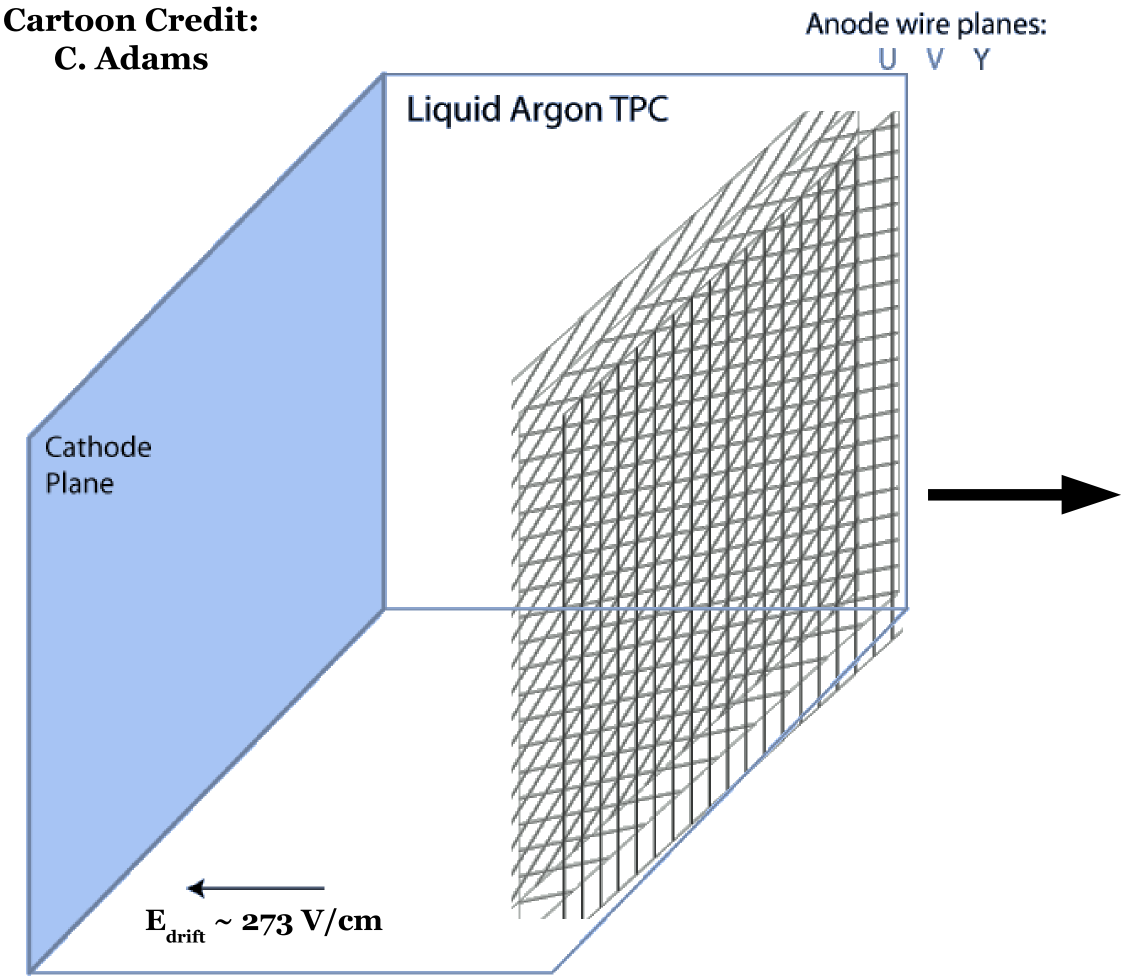
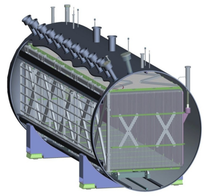
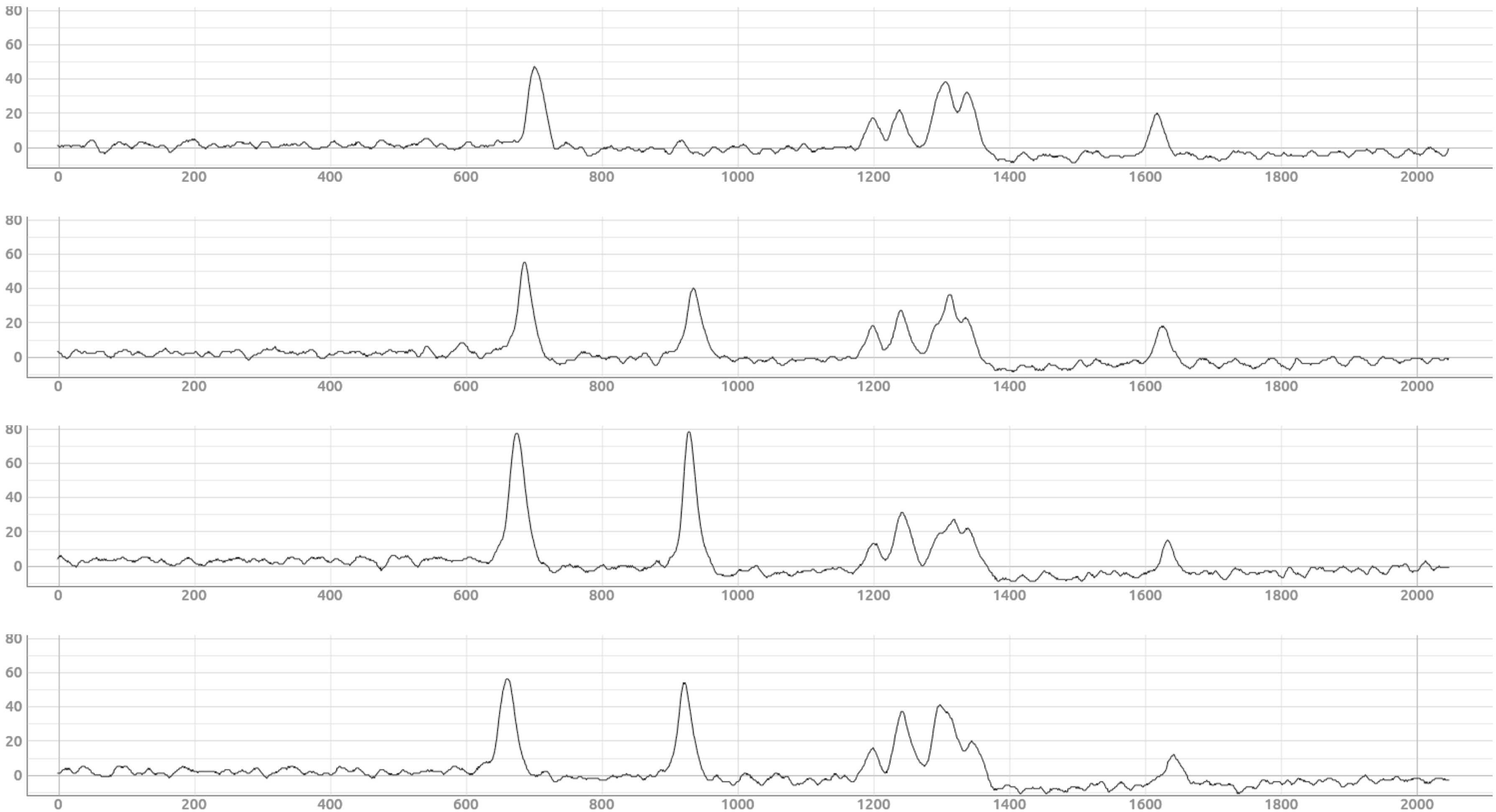




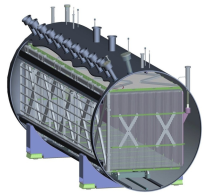
Raw Waveform Output

Image Credit: C. Adams



Increasing Wire

Increasing Time



Raw Waveform Output

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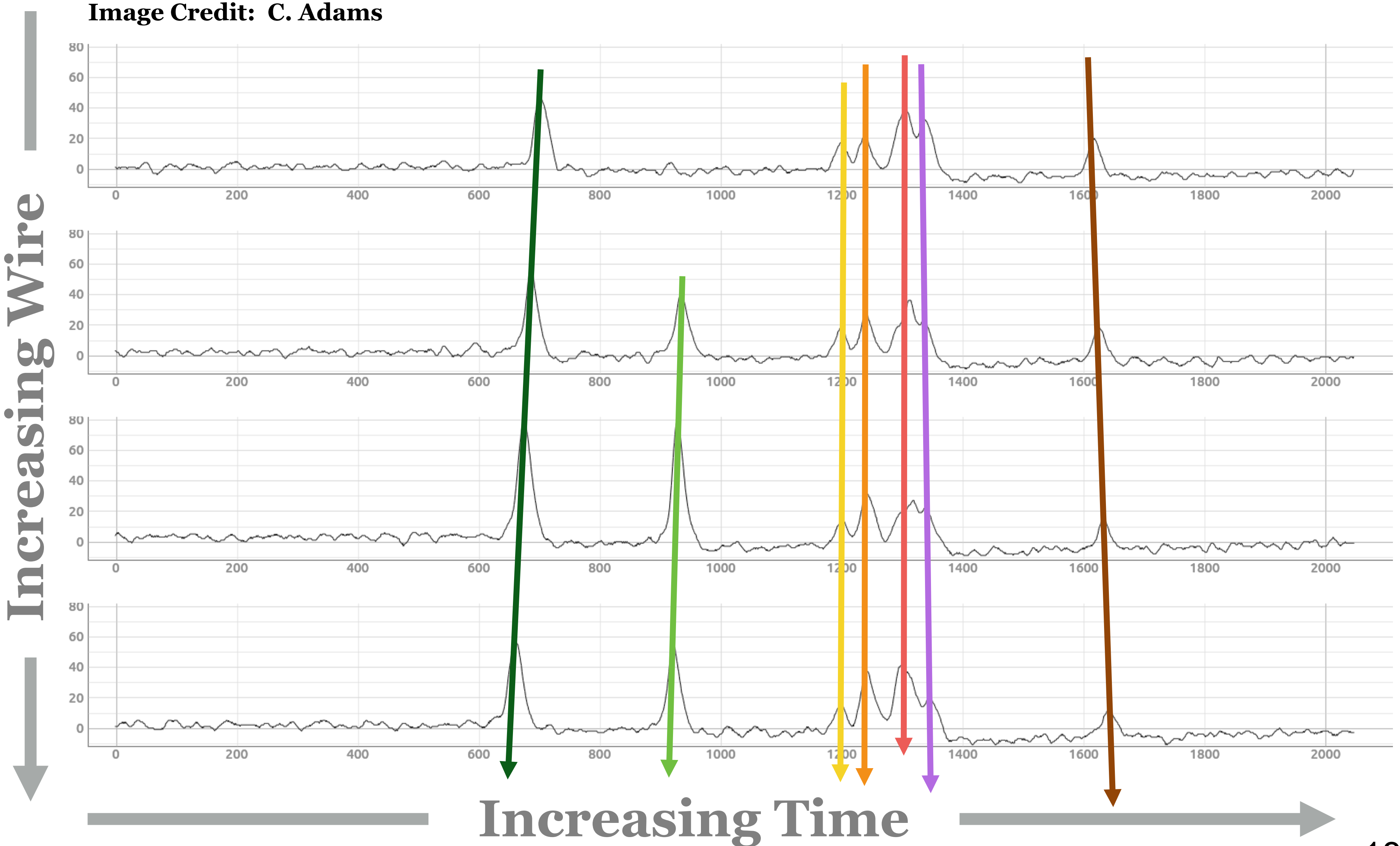
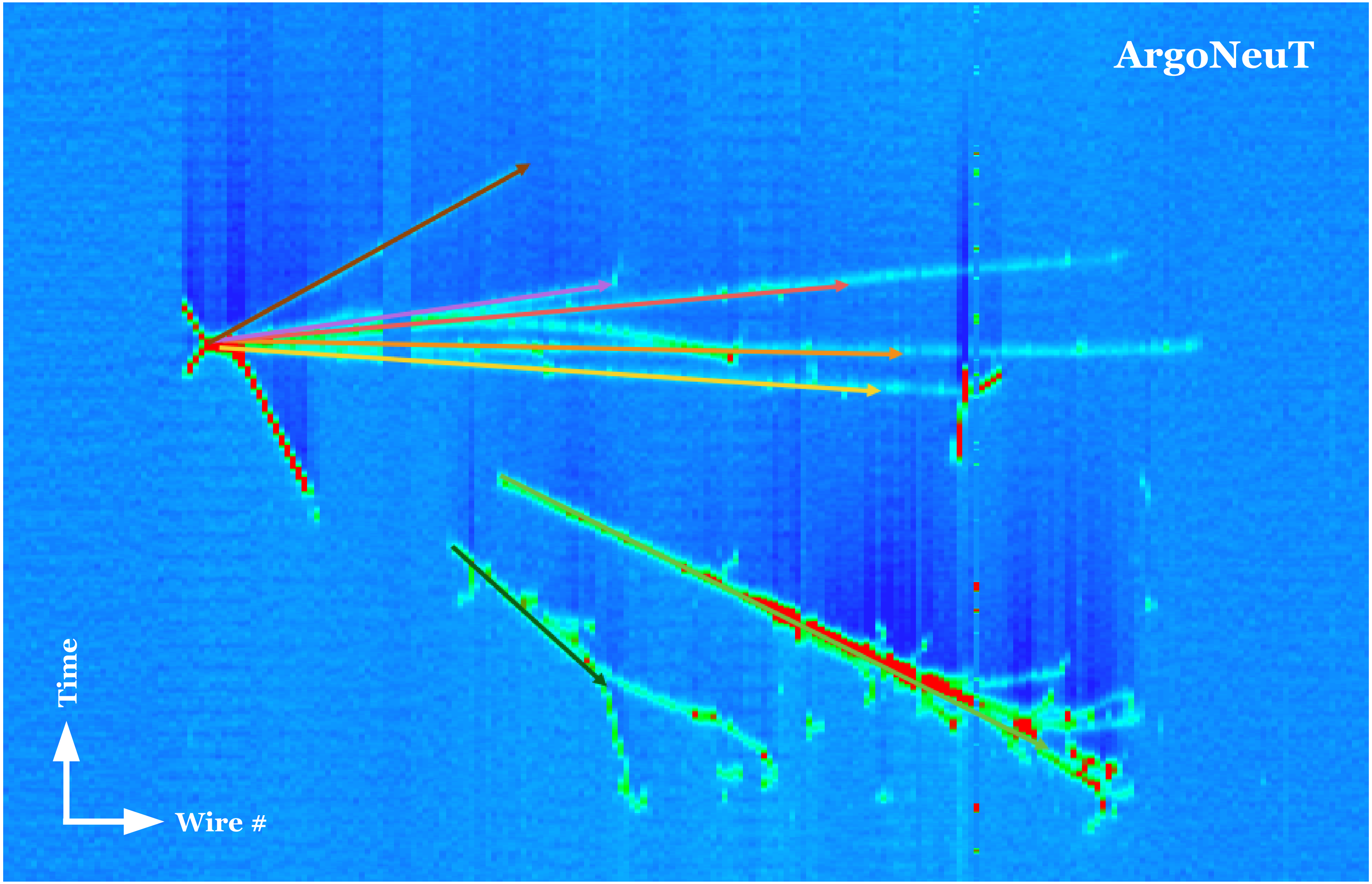
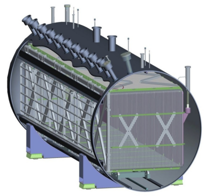
Image Credit: C. Adams



LArTPC Imaging

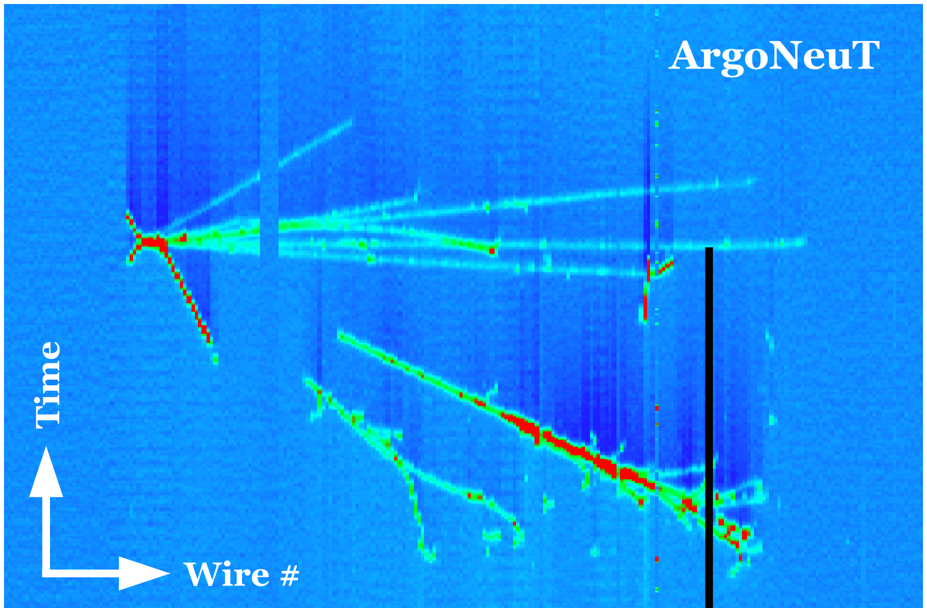
Image Credit: C. Adams



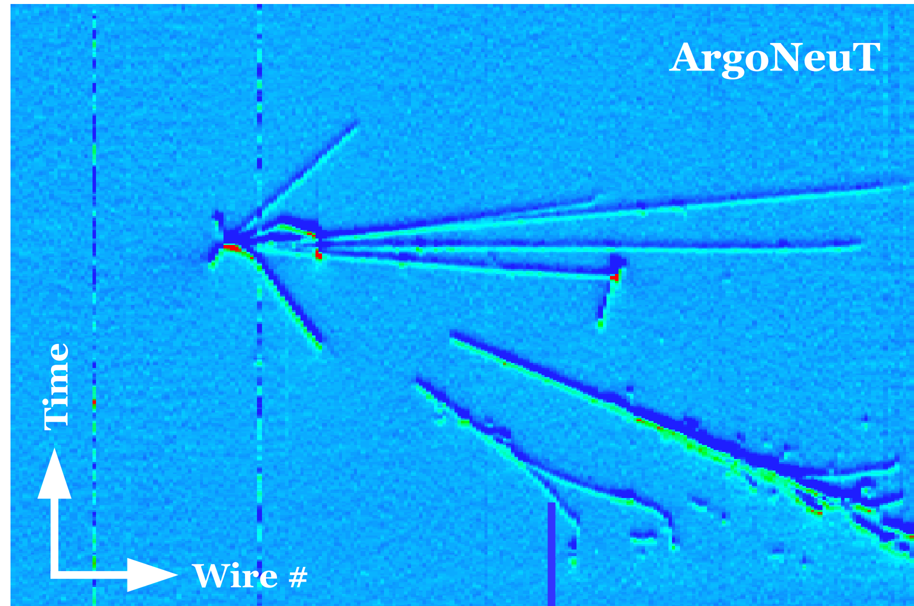


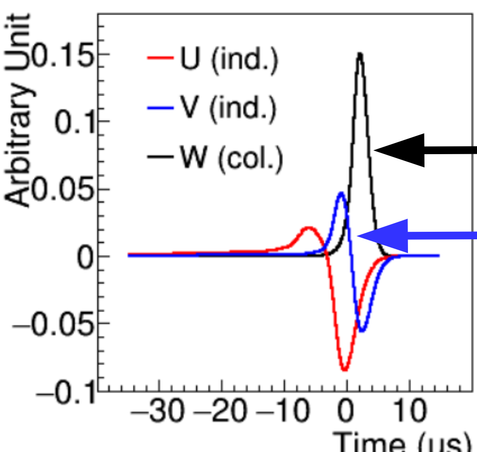
Different Plane Views

"Collection" Plane (Y)



"Induction" Plane (U, V)

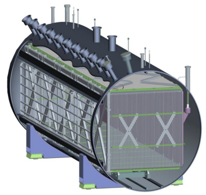




<u>Collection Wire Response</u>:
Unipolar Signal

<u>Induction Wire Response</u>:
Bipolar Signal

In order efficiently find ionization signal and correctly determine charge, must first *remove detector response* → **deconvolution**



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

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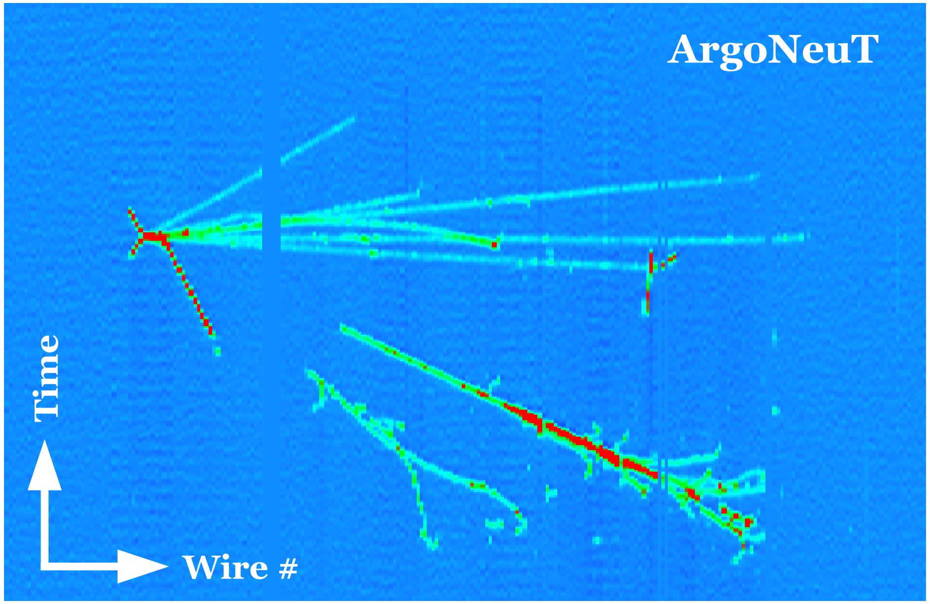
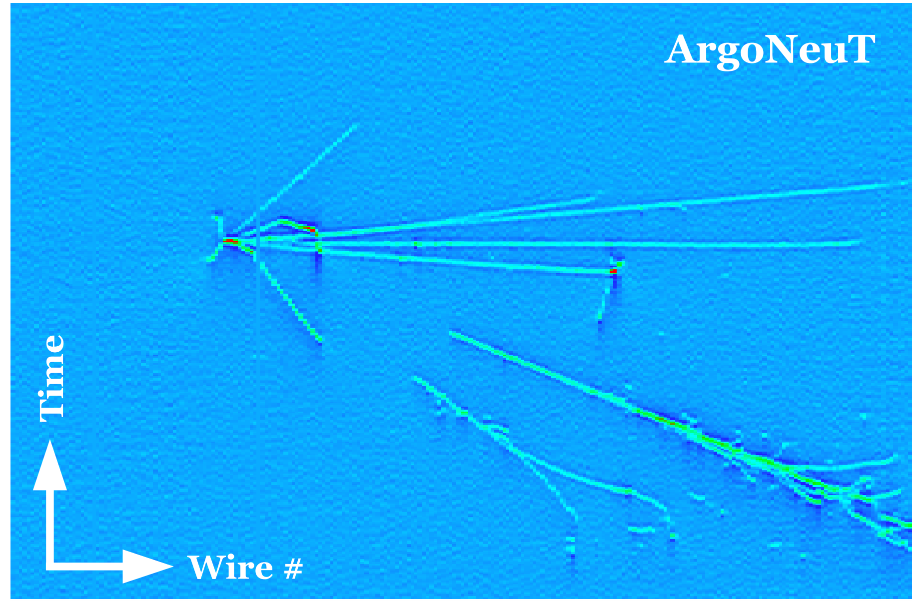
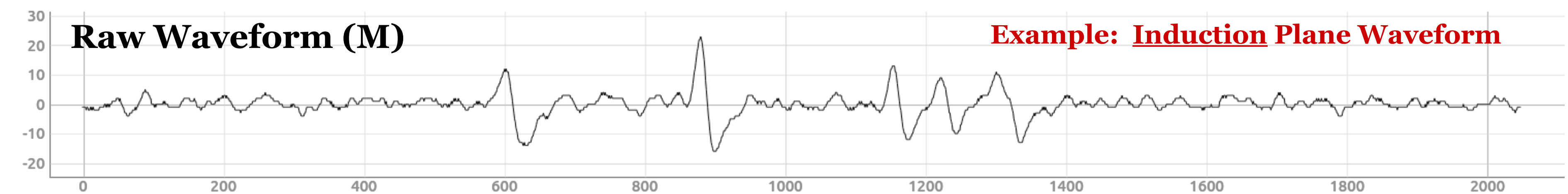
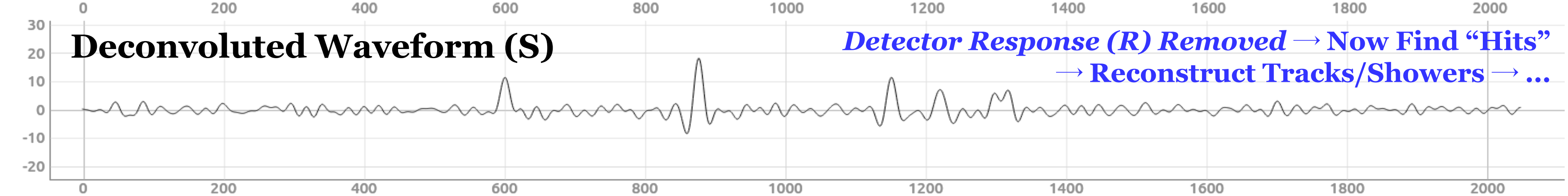
"Collection" Plane (Y)



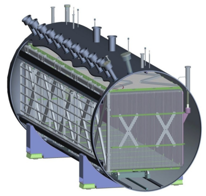
"Induction" Plane (U, V)





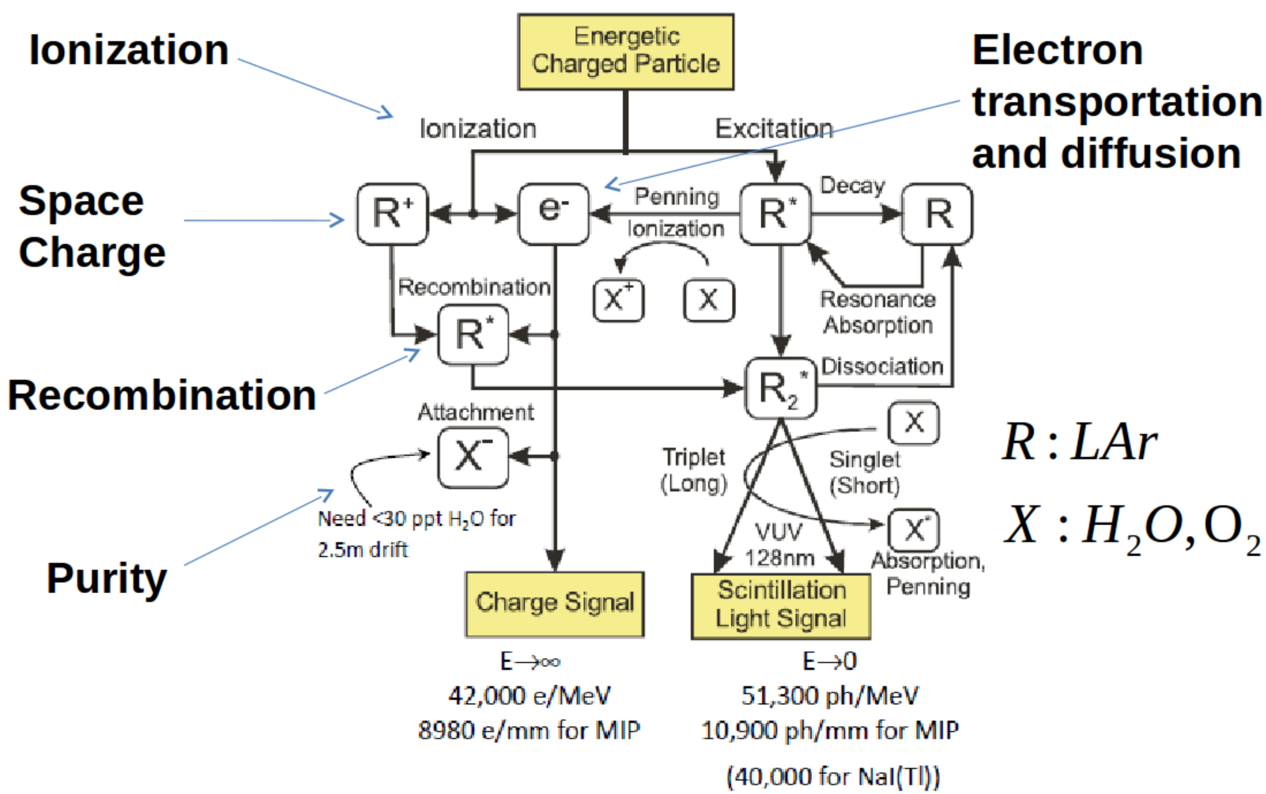


Filter (F): Prevents Blow-up of Noise During Deconvolution



Calibration Scheme

- Must understand detector effects to develop LArTPC technology
  - Essential for SBN and DUNE
  - Noise removal, space charge effects (SCE), wire response, energy scale, diffusion, e^- lifetime, etc.



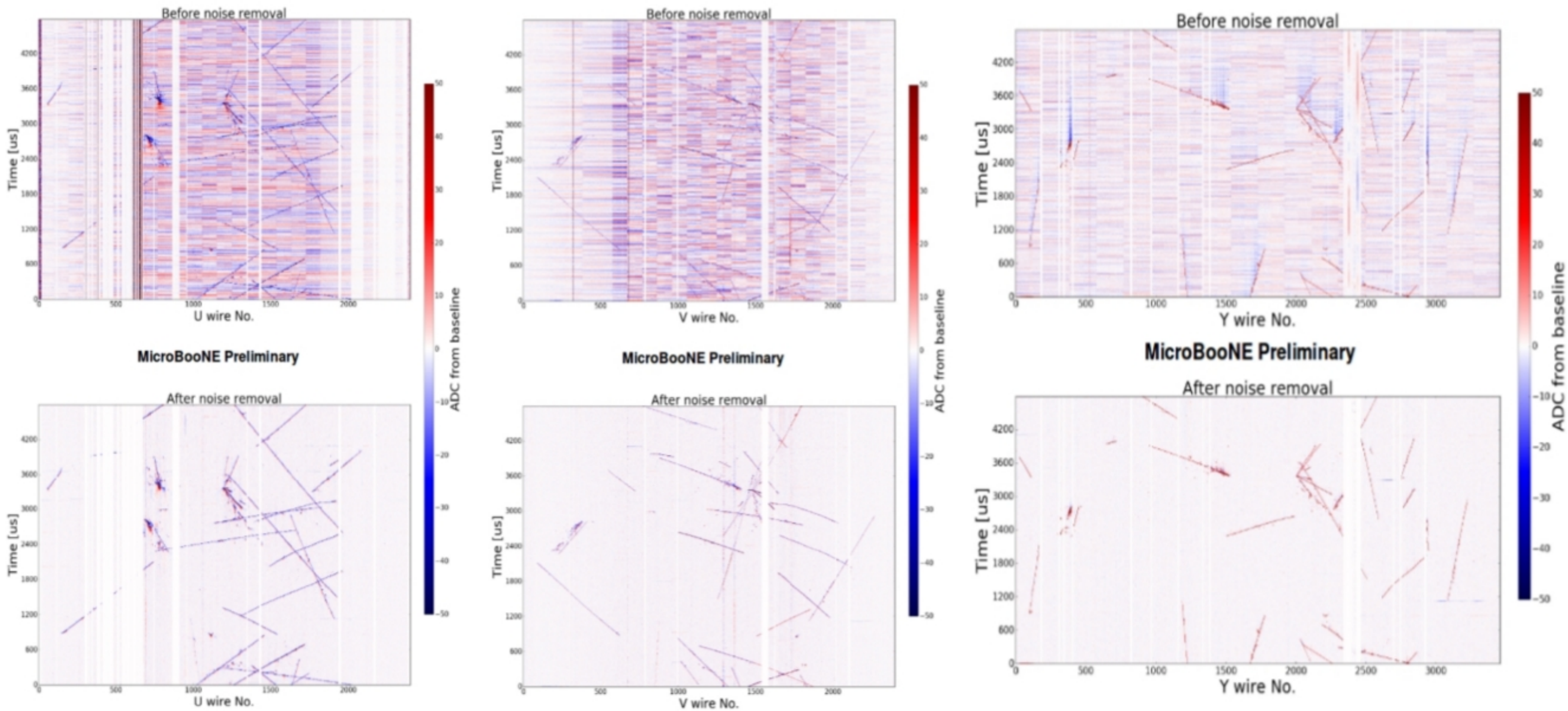
$R: LAr$

$X: H_2O, O_2$

Important to understand detector effects and develop calibration scheme for unbiased, precise determination of ionization charge.

Reducing Noise Levels

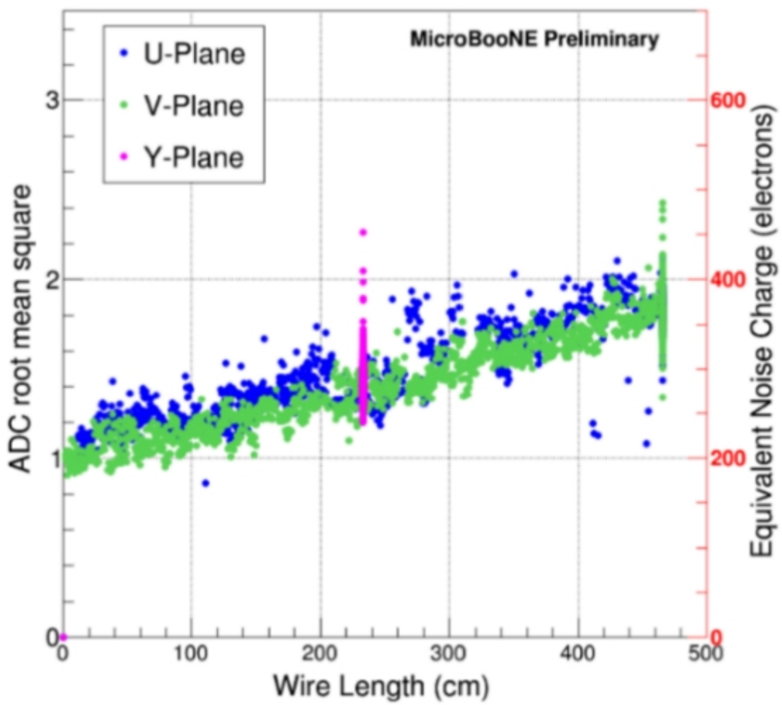
First Induction (U) | **Second Induction (V)** | **Collection (Y)**

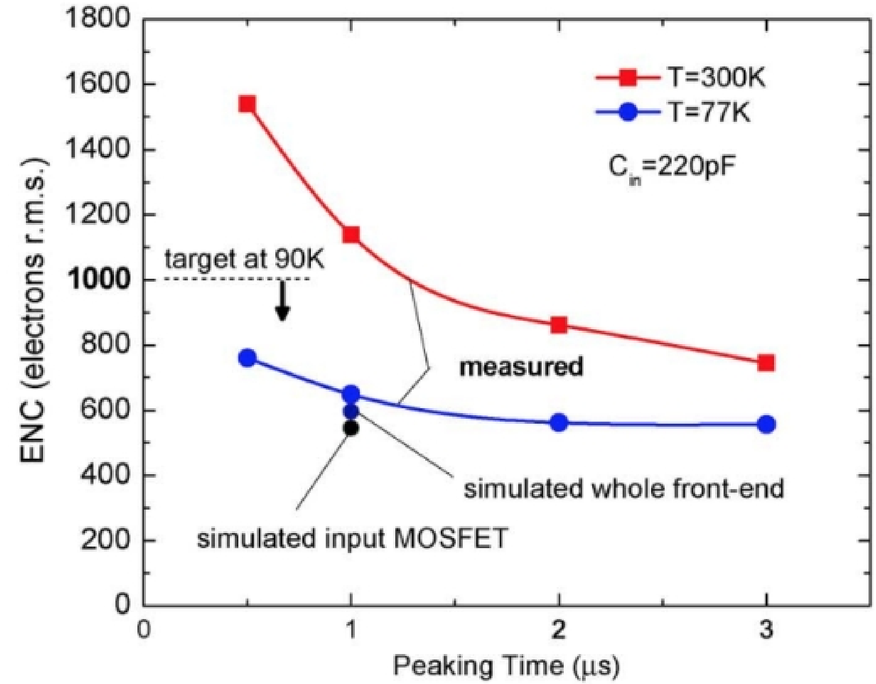


- Significantly more noise "out of the box" on induction planes (top row)
- All planes look very clean after software noise filtering (bottom row)

Final Noise Levels

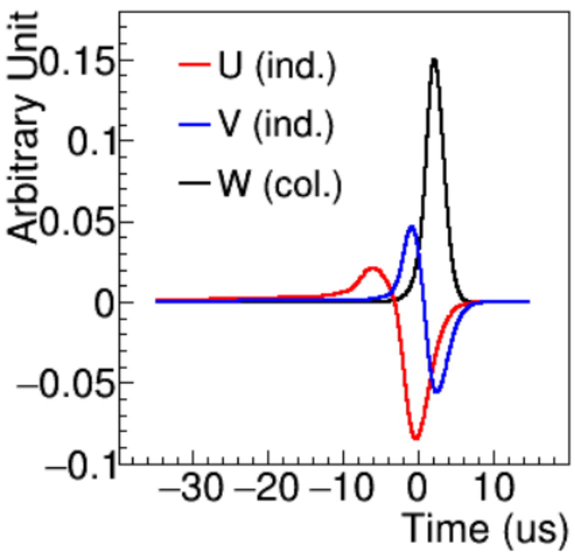
Wire Noise Level in MicroBooNE

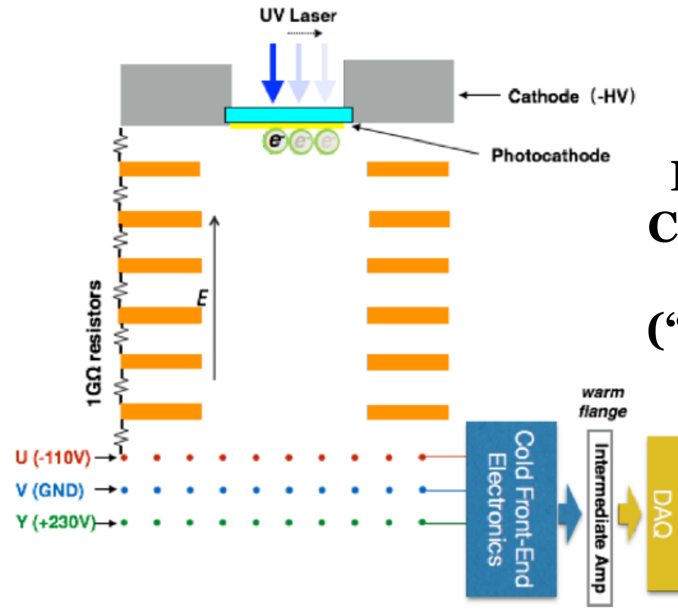




- After software noise filtering on MicroBooNE data, see noise levels expected from bench measurements of cold front-end electronics
  - Scales linearly with wire length (capacitance)
  - Thanks to cold front-end electronics and noise-filtering techniques, low ENC achievable in 100-ton-scale LArTPC: **ENC < 400 e^-**

Field Response Measurement



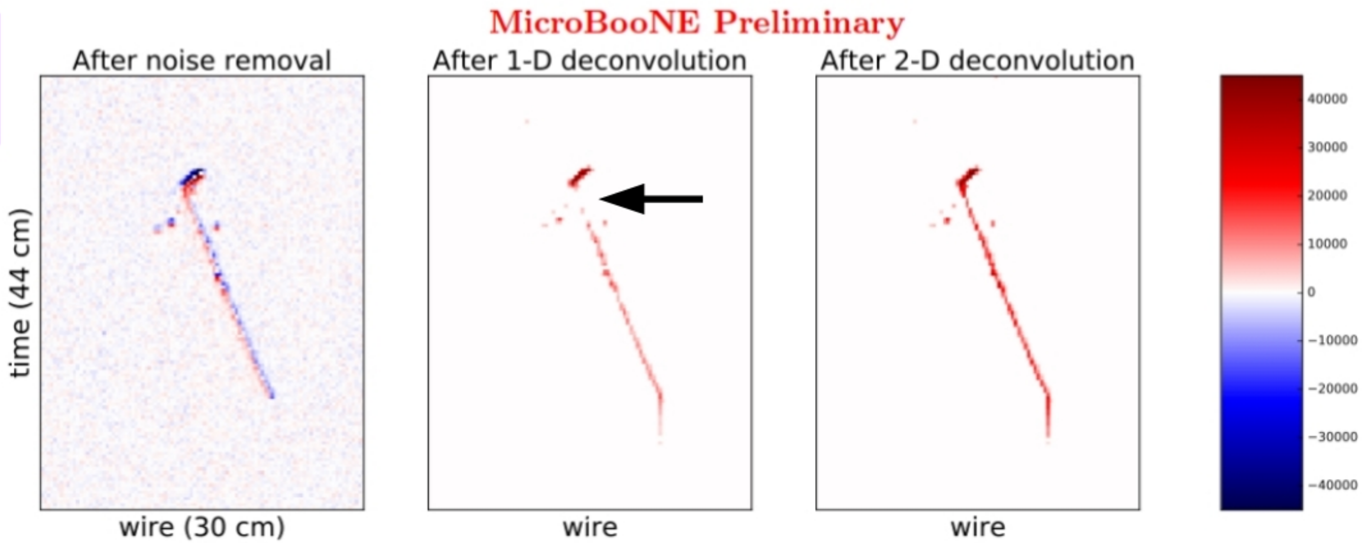


LAr Field Calibration System (“LArFCS”)

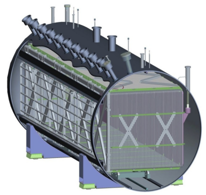
- Must remove correct field response of wires in deconvolution to enable unbiased charge estimation
- Simulated field response (Garfield) needs verification with **data**
- Measurement with MIPs in situ folds in track extent across wire pitch
- **BNL test stand** aiming to make measurement with point-like source from laser pulsed on photocathode – **“LArFCS”**

Dynamic Induced Charge

Second Induction Plane



- Nominally assume ionization leads to signal on only one wire
- In reality, nearby wires also see some signal
  - Characteristics of this induced signal dynamically dependent on track angle – "Dynamic Induced Charge" or DIC
  - Effect leads to cancellation of signals on waveform for tracks at high angles → **hits lost** → **problems in track/shower reconstruction**
- Solution is to account for DIC when removing detector response in deconvolution to extract charge – improves imaging



Another DIC Example

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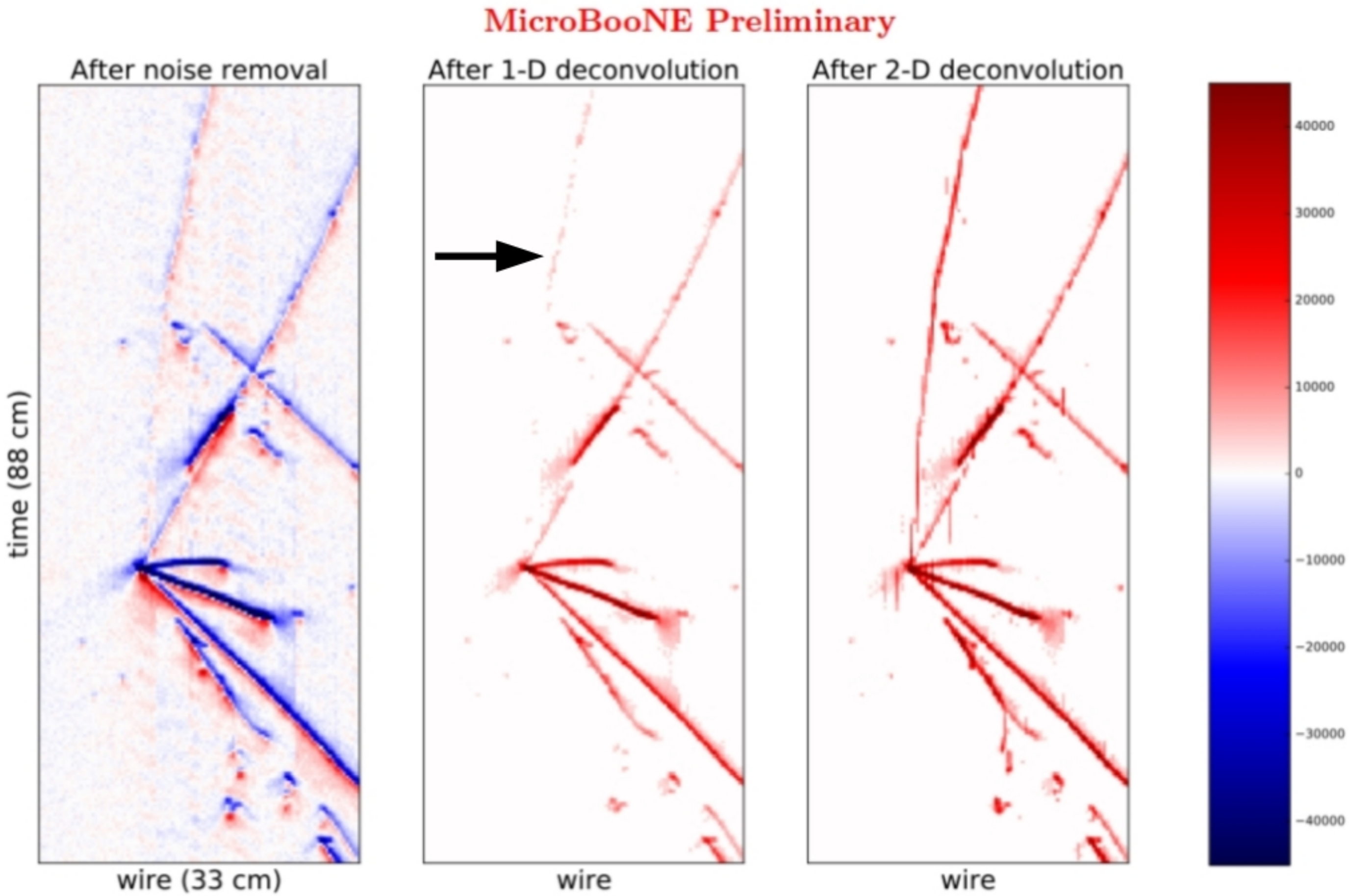
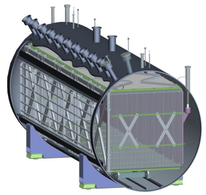
First Induction Plane

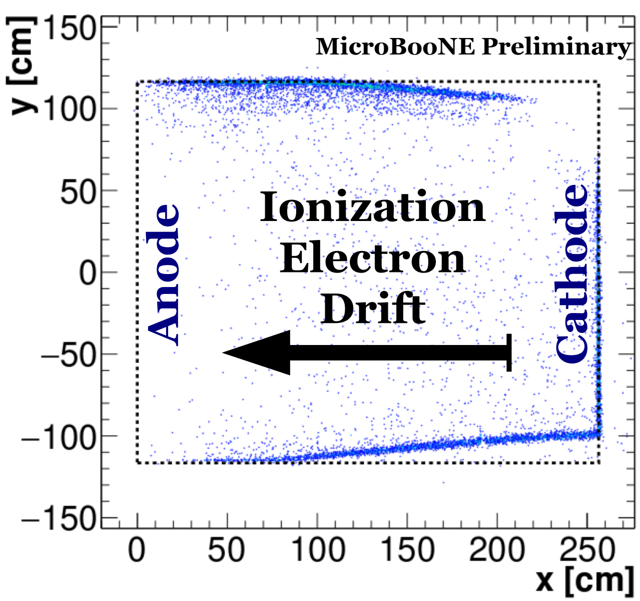


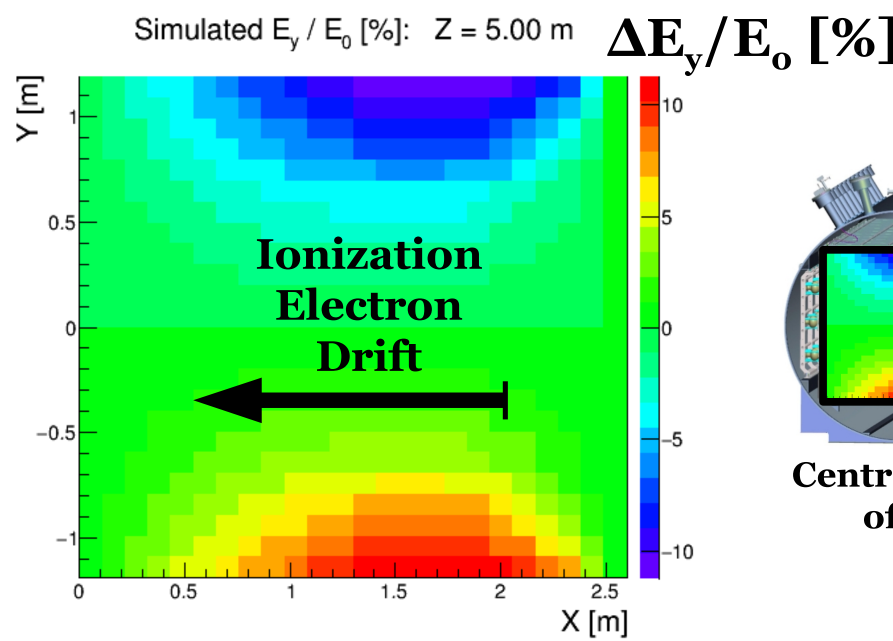
- Effect can be studied in depth at **LArFCS** with point-like source
- Smaller effect for larger wire spacing (e.g. 5 mm for DUNE)

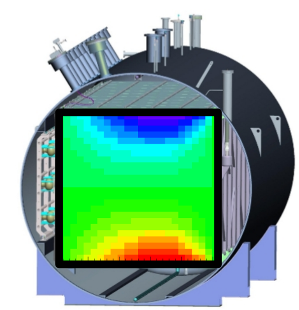


Space Charge Effects

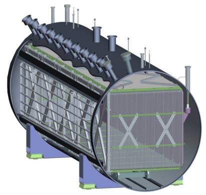
- Looking at cosmic data, noticed offsets in track start/end points from top/bottom of TPC
  - Very suggestive of space charge effects (SCE) at MicroBooNE, a near-surface experiment (20-30 cosmics per 4.8 ms readout window)
  - **Space charge**: build-up of slow-moving Ar^{+} ions due to e.g. cosmic muons impinging active volume of TPC (via ionization)
  - Leads to E field distortions, spatial distortions in ionization position



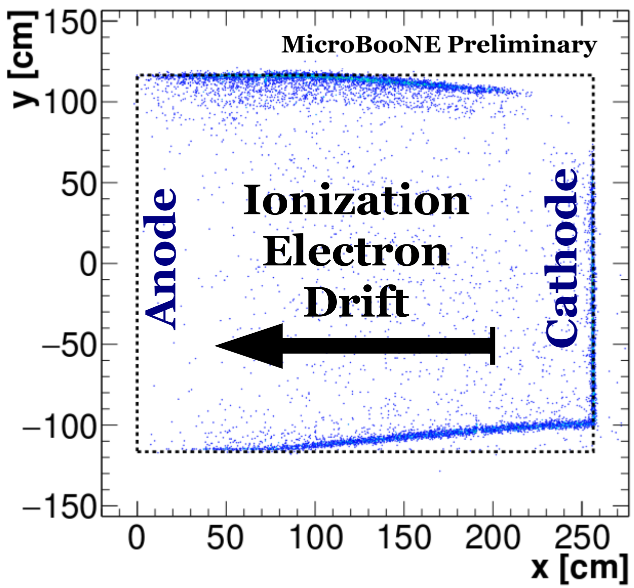


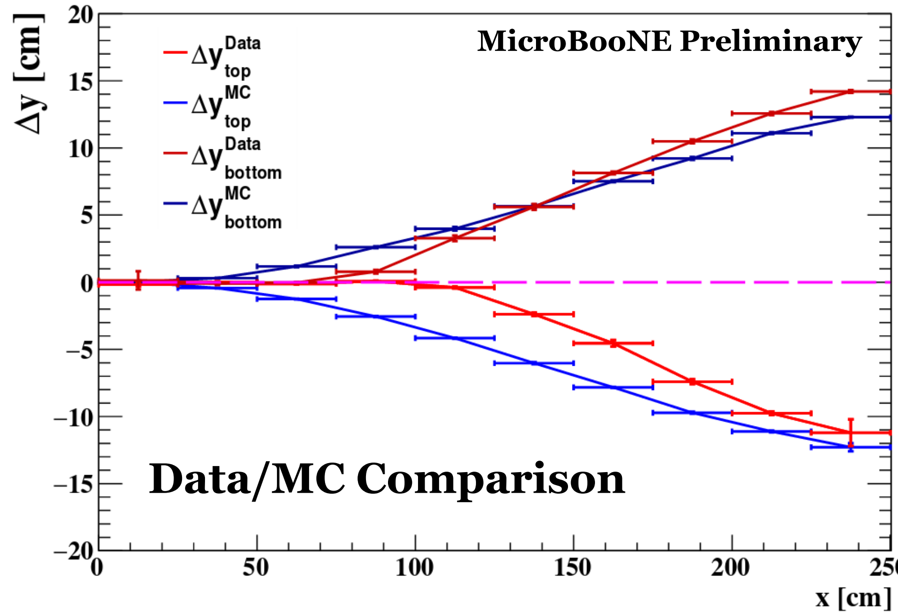


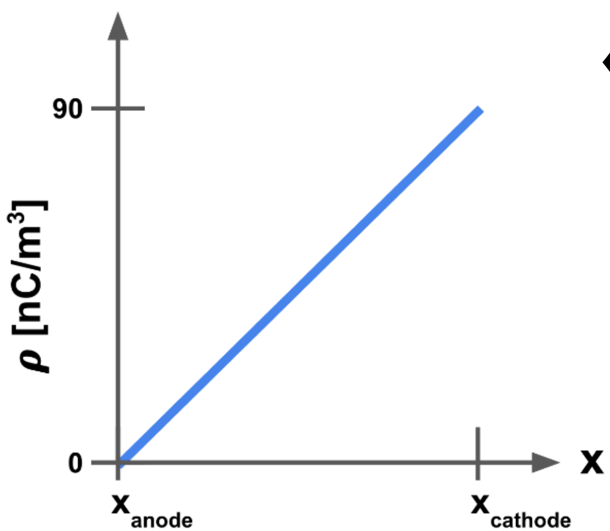
Central Z Slice of TPC



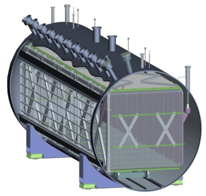
SCE Data/MC Comparison







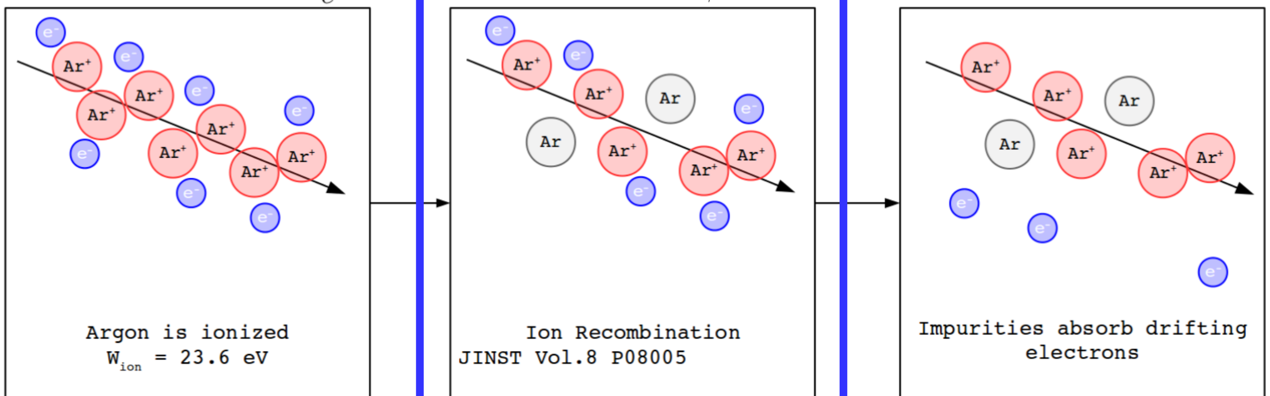
- SCE simulation qualitatively reproduces effect
  - Assumes linear space charge profile
  - Agreement in normalization, basic shape features, but offset near anode in data… consistent with impact from **liquid argon flow**
  - Can impact track/shower reconstruction and calorimetry – calibrate out **in 3D** using **UV laser system**, cosmic muon tracks

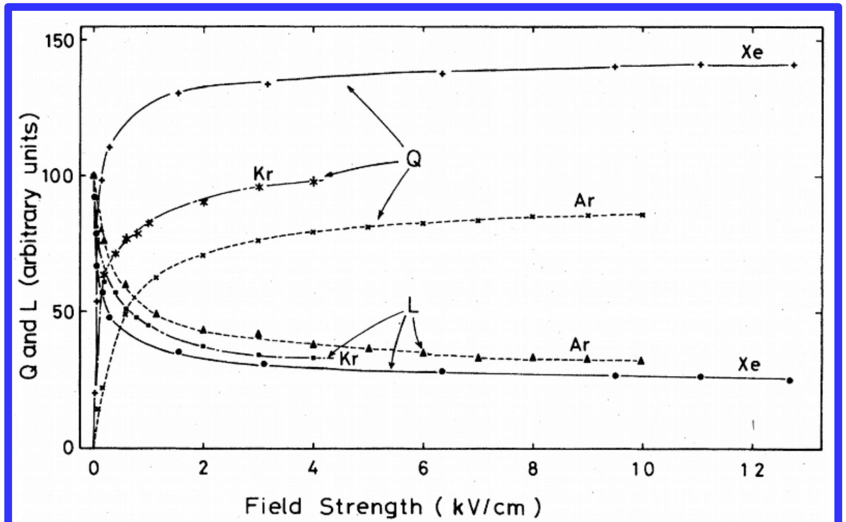


Ion Recombination

Image Credit:
D. Caratelli

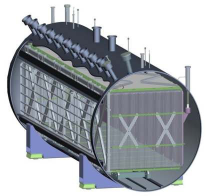
$$dQ = dE \times \frac{W_{ion}}{e^-} \qquad \frac{dE}{dx} = \frac{e^{\beta \times \frac{W_{ion}}{e^-}\frac{dQ}{dx}} - \alpha}{\beta} \qquad Q = Q_0 e^{-t/\tau}$$





S. Kubota et al., Phys. Rev. B, 20, 8 (1979)

- Charge quenching from prompt recombination of ionization electrons with argon ions leads to charge loss
  - Sizable: **~50%** Q loss (@ 273 V/cm)
- Correction depends on E field, dE/dx
  - Tracks (muon, proton, etc.): **simple**
  - Electromagnetic showers: apply to individual charge depositions based on dE/dx – **more complicated**



Electron Lifetime

Image Credit: D. Caratelli

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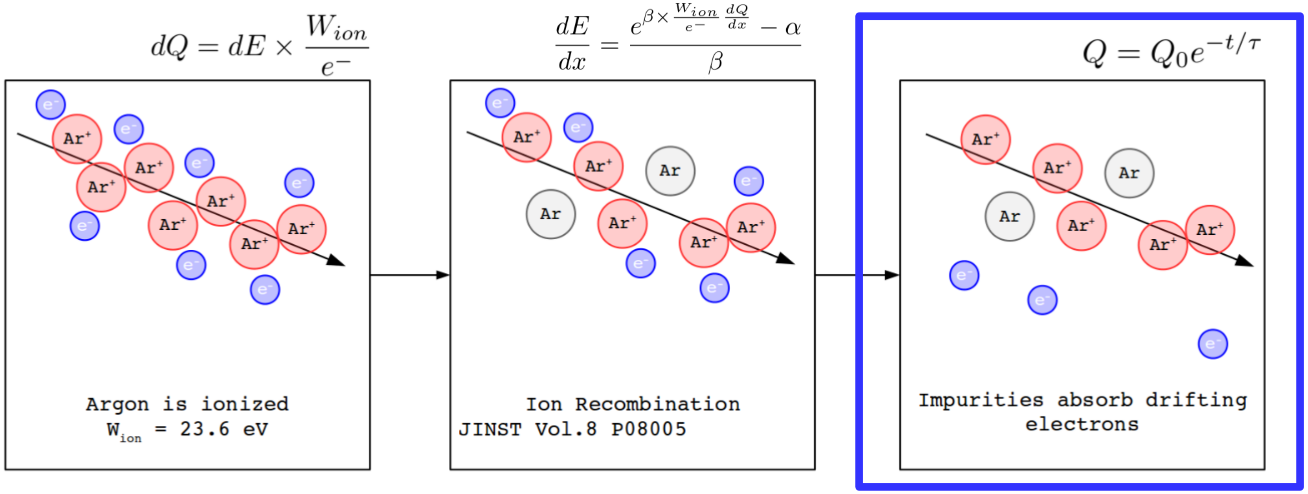
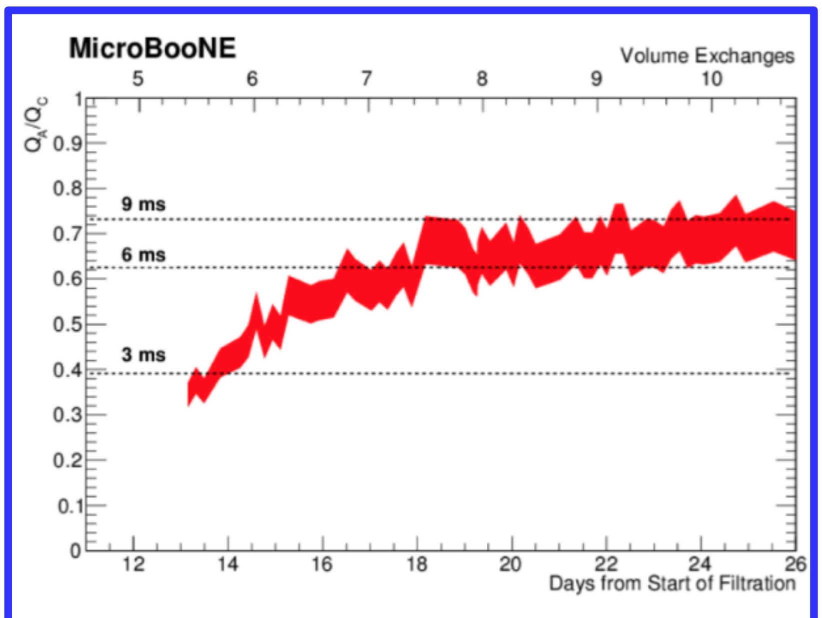
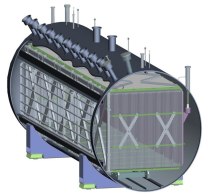


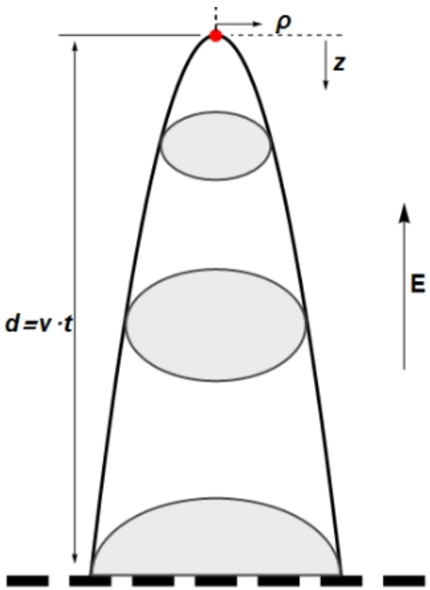


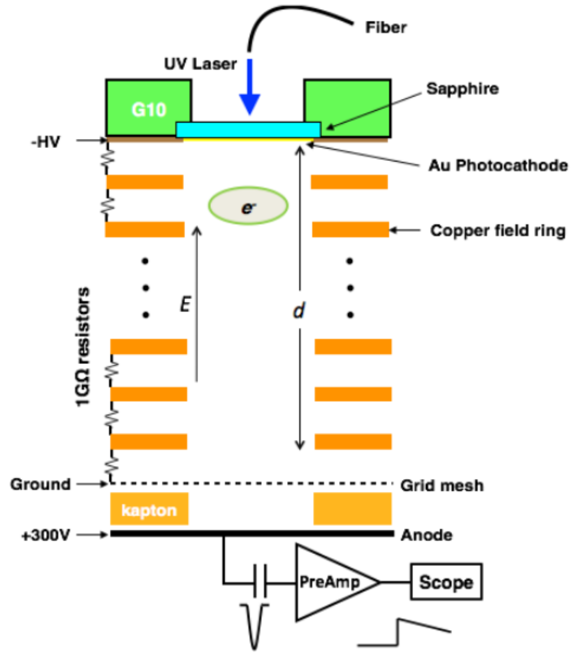
- Electron lifetime, as measured by purity monitors, consistently **above 6 ms** for majority of run thus far – design: **3 ms**
  - **6 ms**: conservative lower bound
- <u>Important conclusion</u>: can operate LArTPCs in non-evacuated cryostats with high electron lifetime
- Calibrate out via measurement of charge from TPC tracks vs. drift distance



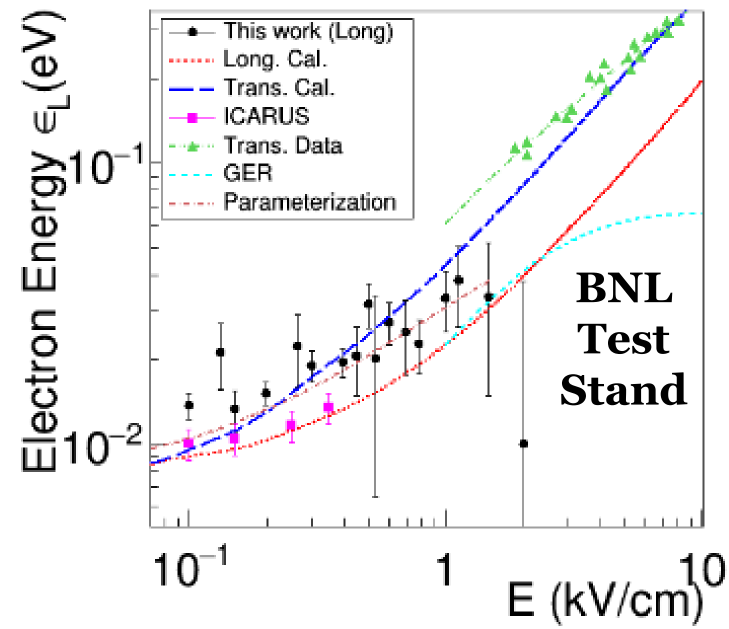
Diffusion

BROOKHAVEN NATIONAL LABORATORY





See Y. Li et al. NIMA 816 160 (2016)



- Diffusion can reduce the spatial resolution of reconstructed particle trajectories, especially for longer drift times → **must measure, simulate**
- Important for e.g. supernova neutrinos vs. alpha/beta decays (track-like vs. point-like)
- Measure longitudinal diffusion at **BNL test stand**

$$\sigma_{L/T} = \sqrt{\frac{2\cdot \varepsilon_{L/T}\cdot d}{E}\cdot\frac{t}{d}}$$

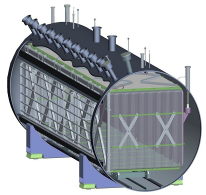
E: electric field

d: drift distance

t: drift time

σ: width of electron cloud

ε: electron energy



Diffusion

BROOKHAVEN NATIONAL LABORATORY

$$\epsilon_L = \frac{b_0 + b_1 E + b_2 E^2}{1 + (b_1/b_0)E + b_3 E^2}\left(\frac{T}{T_1}\right)$$

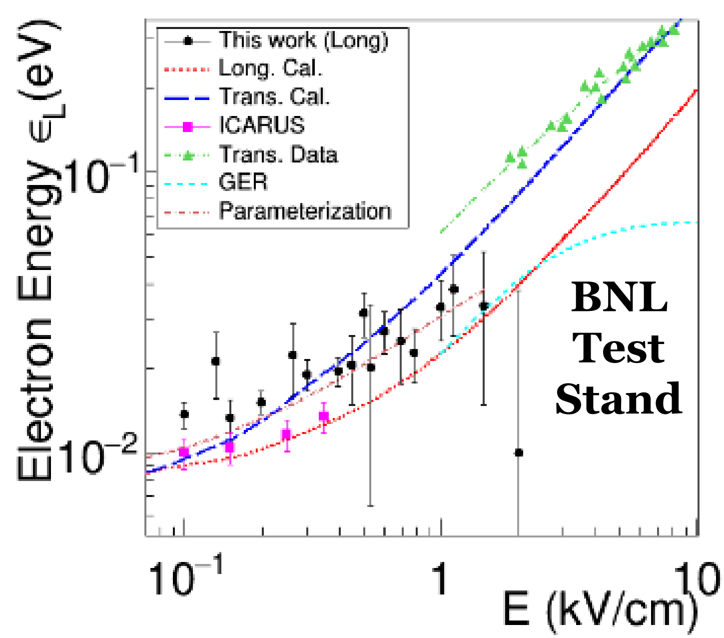
$$\begin{aligned} b_0 &= 0.0075 \\ b_1 &= 742.9 \\ b_2 &= 3269.6 \\ b_3 &= 31678.2 \end{aligned}$$

500 V/cm

Drift Field

Drift Length	σ_L	σ_T
1.8 m	**1.2** mm	**1.7** mm
3.6 m	**1.8** mm	**2.5** mm
6.0 m	**2.3** mm	**3.1** mm
20.0 m	**4.2** mm	**5.7** mm

See Y. Li et al. NIMA 816 160 (2016)



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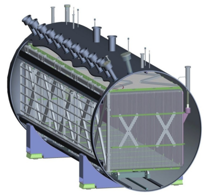
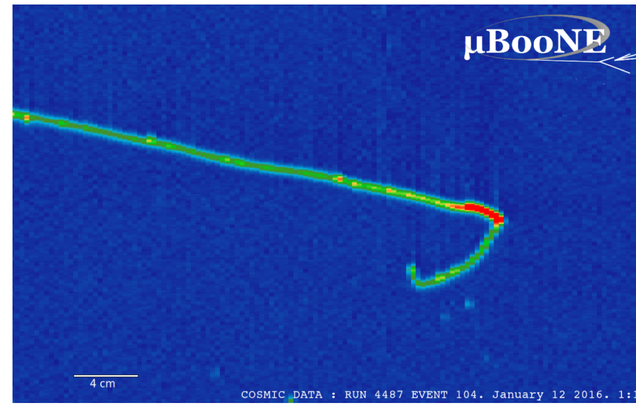
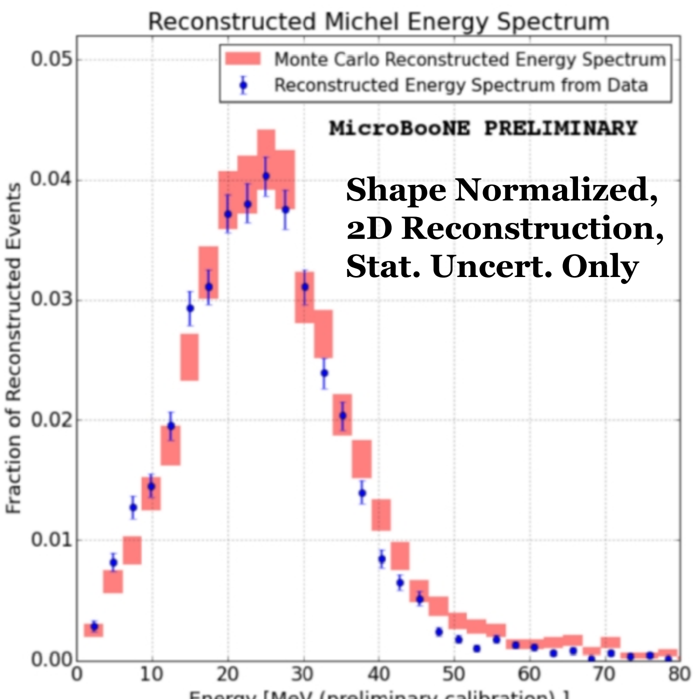
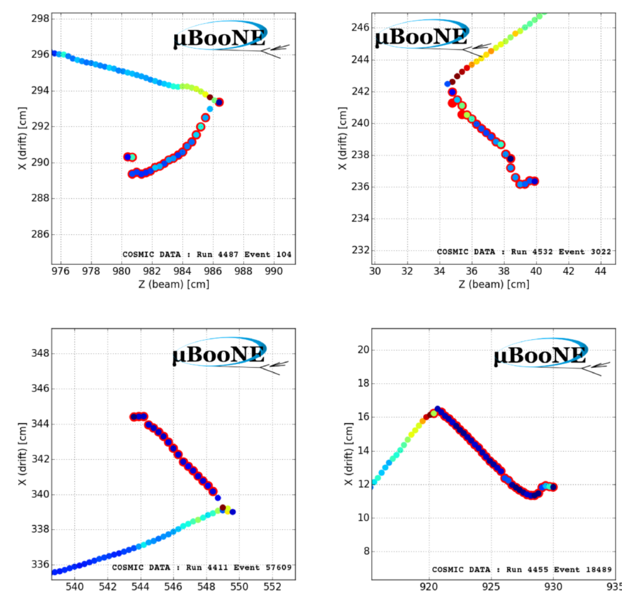


Michel e⁻ Spectrum

- ♦ Tag Michel electrons from cosmic muon decay using “kink” topology and muon Bragg peak
  - Uses automated reconstruction
  - Important calibration sample for **energy scale**, tuning **e$^-$, γ reconstruction** (charge clustering)







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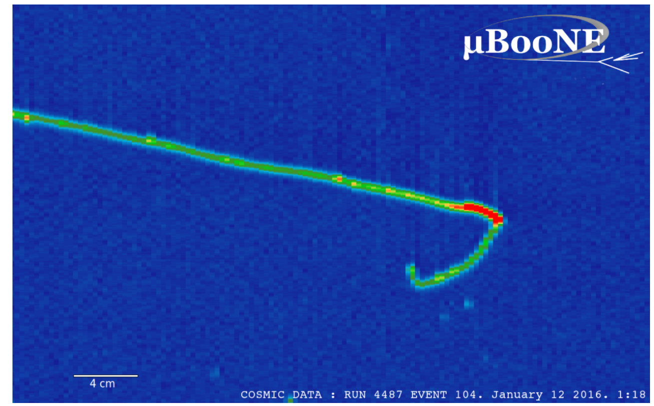

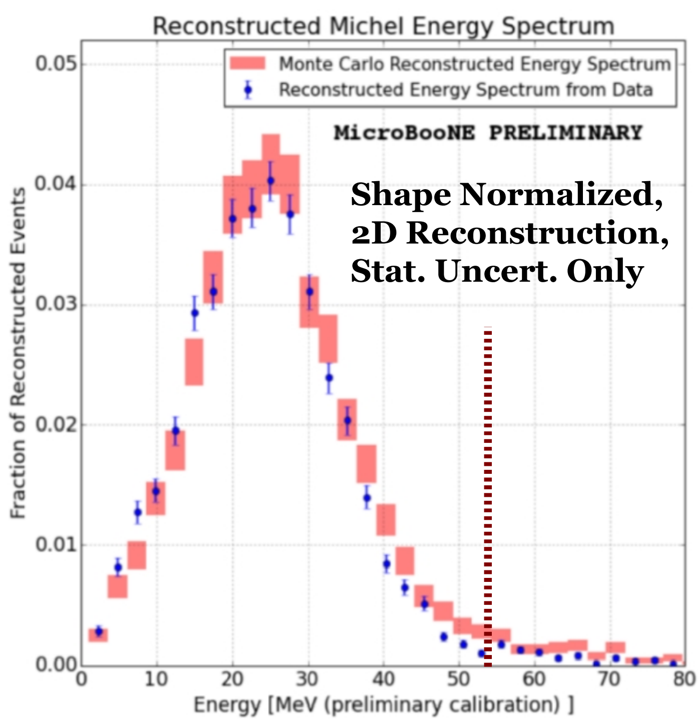

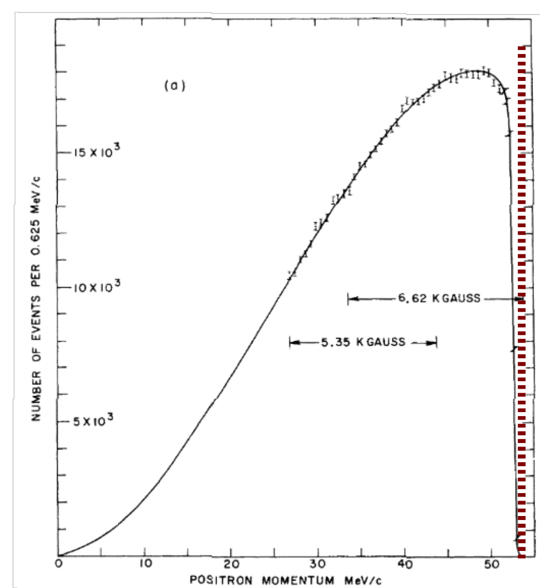

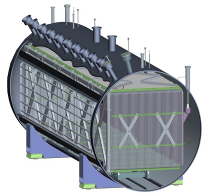

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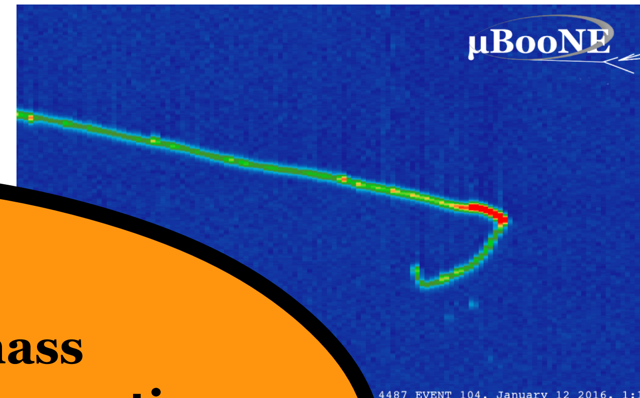
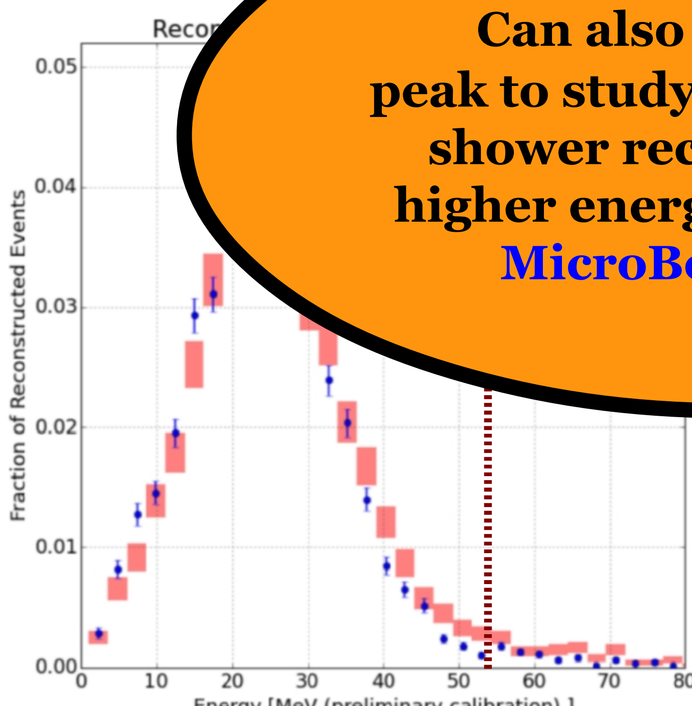
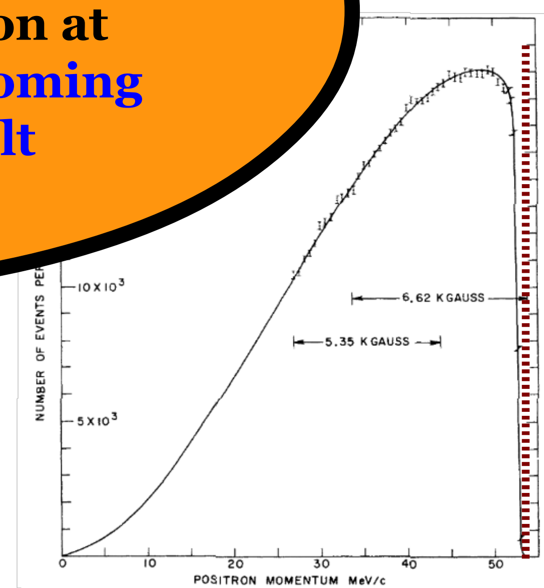
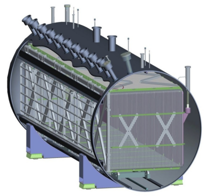


Can also use π^0 mass peak to study electromagnetic shower reconstruction at higher energies – upcoming MicroBooNE result

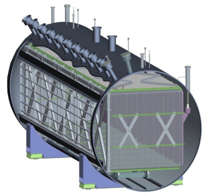






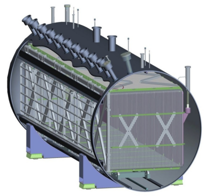
Summary

- LArTPC calibration essential for unbiased, precise determination of ionization charge
- This requires first **removing noise** to **find signals**
- Then **account for detector effects**, including wire response, to **obtain charge information** correctly
- Finally use **high-level candles** (e.g. Michel electrons) to **tune particle trajectory/energy reconstruction**
- Extensive process, but necessary before producing robust physics measurements




Thanks!

Backup

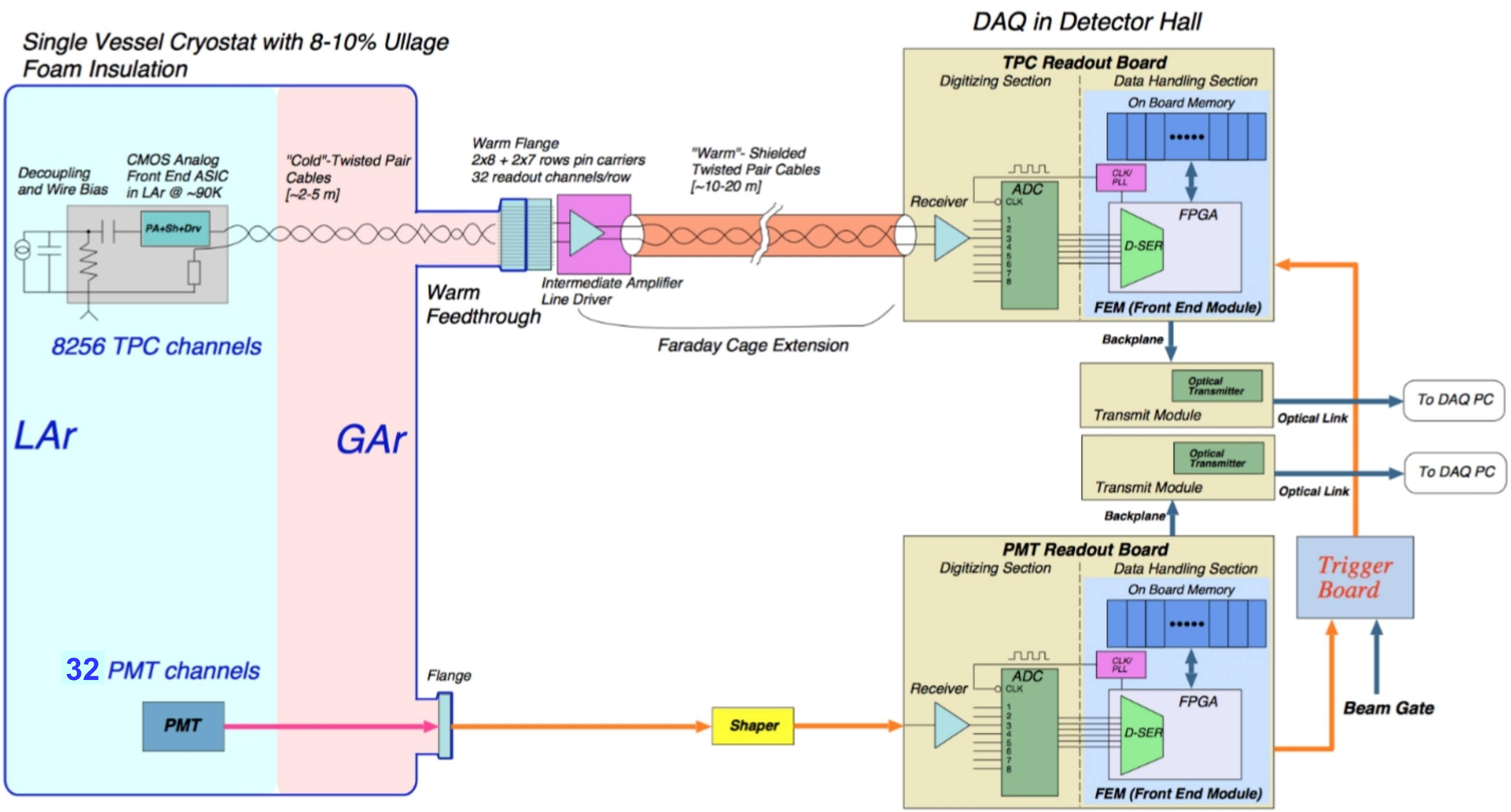


Why Liquid Argon?

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3	1
Radiation Length [cm]	755.2	24	14	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	
Approx. Cost [$/kg]	52	330	5	330	1200	

- Argon is cheap: **~1%** of atmosphere
- Dense target (more ν-N interactions per unit time)
- High scintillation light yield, argon transparent to own light
- Relatively small radiation length for EM shower containment

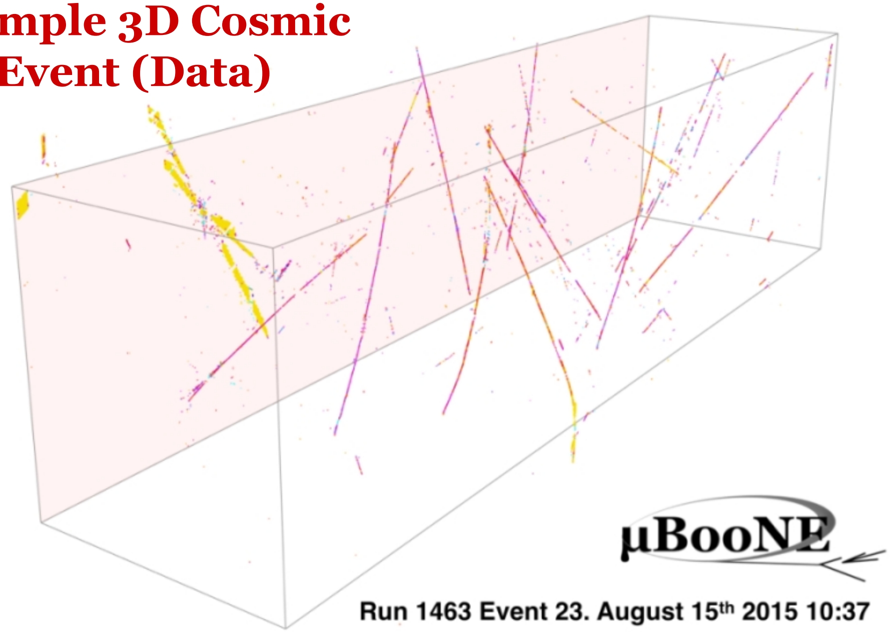
Electronics Chain



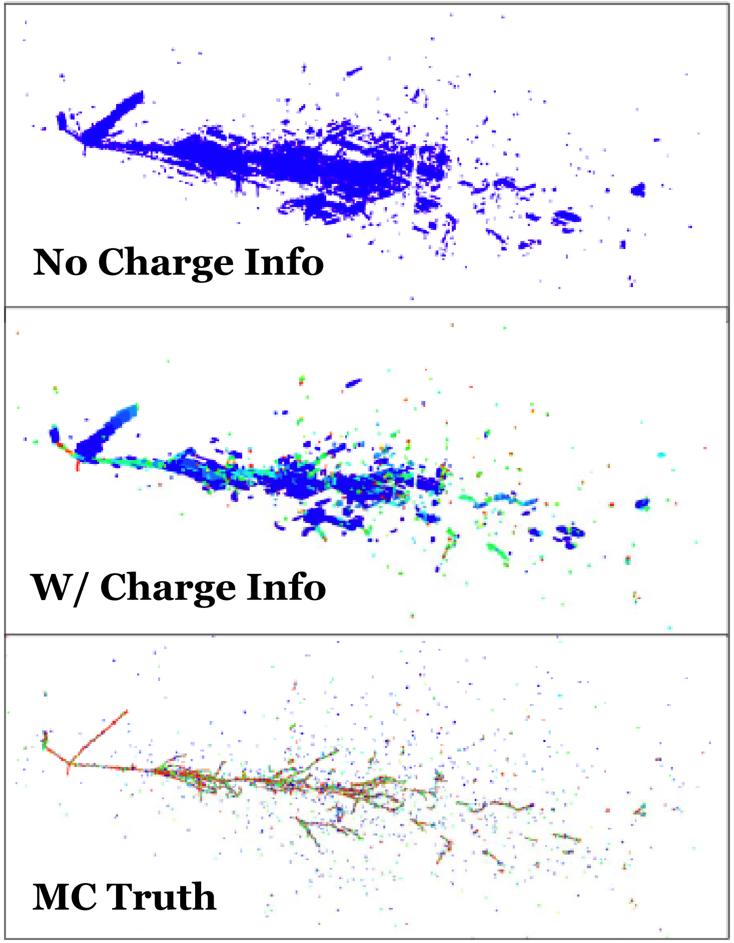
Event Reconstruction

- Multiple ways to get to 3D:
  - Identify clustered tracks/showers in 2D, match across planes
  - Create 3D hits from wire triplets (matching charge) and directly cluster tracks/showers
    - "Wire-Cell" method (see images)

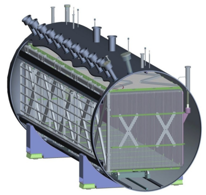
Example 3D Cosmic Event (Data)



Example MC Interaction Event (2D Projection of 3D)

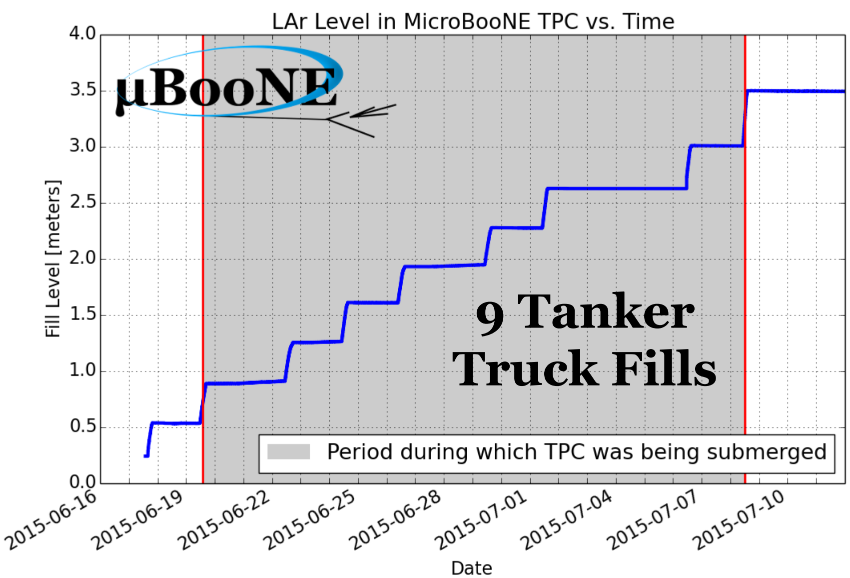


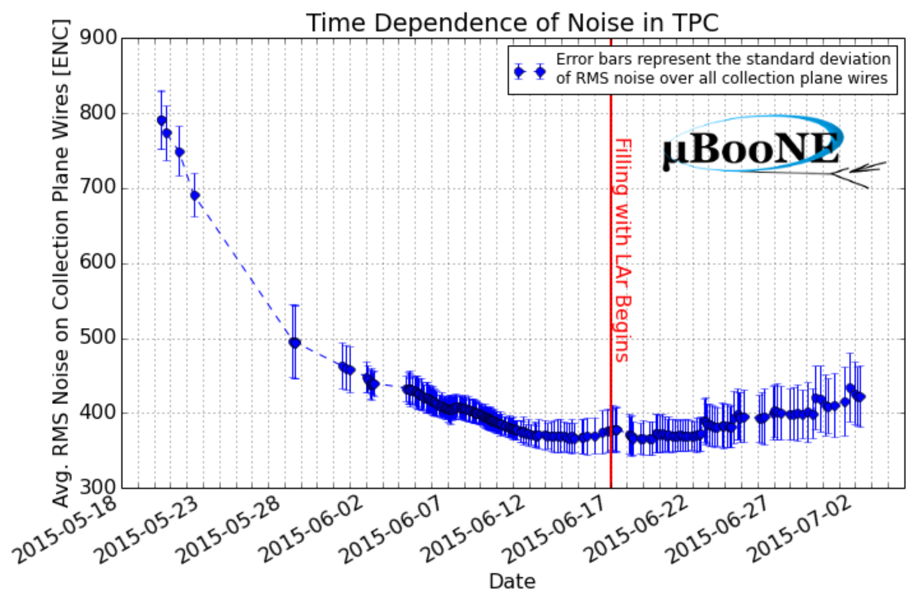
http://www.phy.bnl.gov/wire-cell/bee/



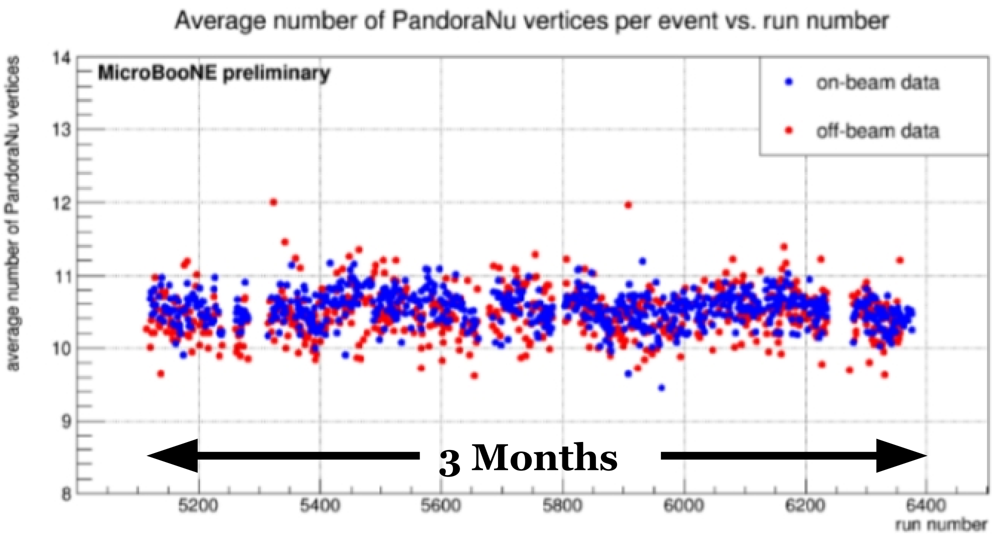
Looking at Noise Data

- First look at **noise data**: during TPC and cryogenics commissioning (April-July 2015)
- TPC noise level dropped during purge/cool-down
  - Expected (desired) feature of cold electronics; noise level as expected from design
- TPC noise level slowly rose with LAr fill
  - Increased capacitance w/ LAr





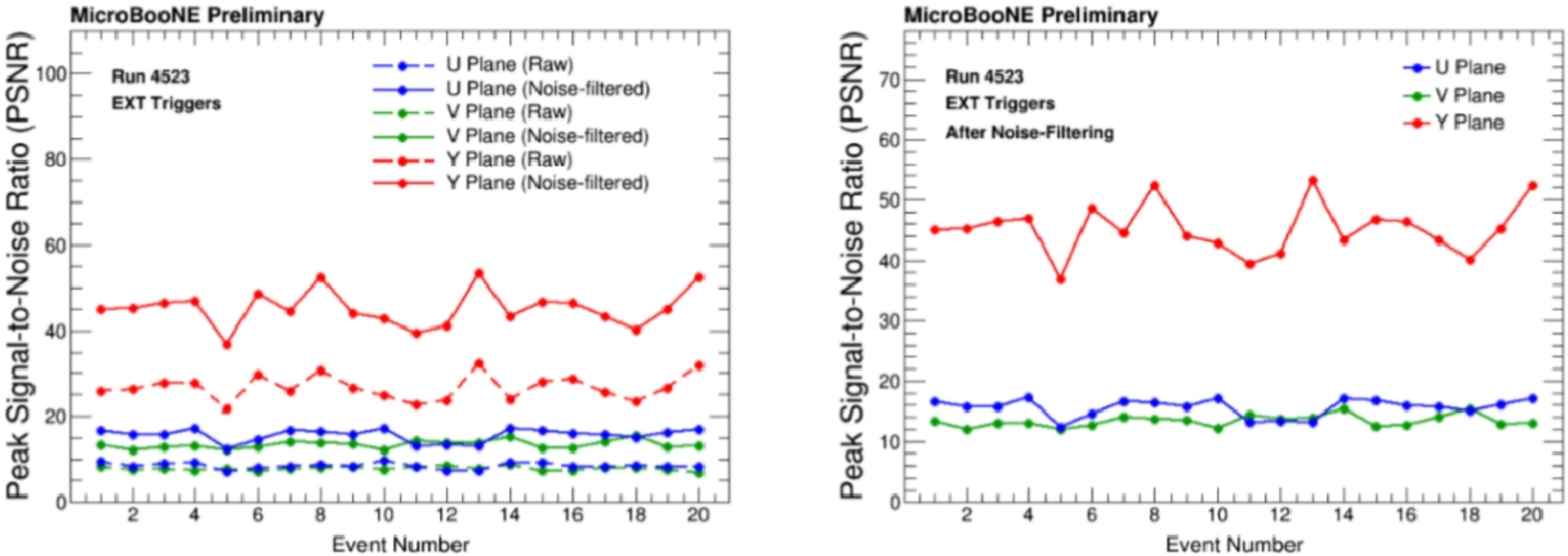
Detector Stability



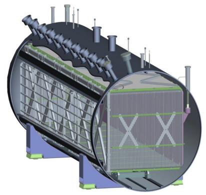
Issue	# Channels Affected
Unresponsive ASICs	~300
Shorted Wires	~400
Noisy Channels	~50
Uninstrumented	~100

- High detector uptime – only handful of cathode, pump trips in first year of operations
  - Gaining operational experience with large LArTPCs – essential for running **future LArTPC experiments**
- Both high-level and low-level features in data stable over time
- Number of unresponsive/noisy channels very stable w.r.t. time
  - 10% unresponsive/noisy, but **97%** of detector volume has **at least two planes operational** (minimum needed for 3D reco.)

Peak Signal-to-Noise Ratio

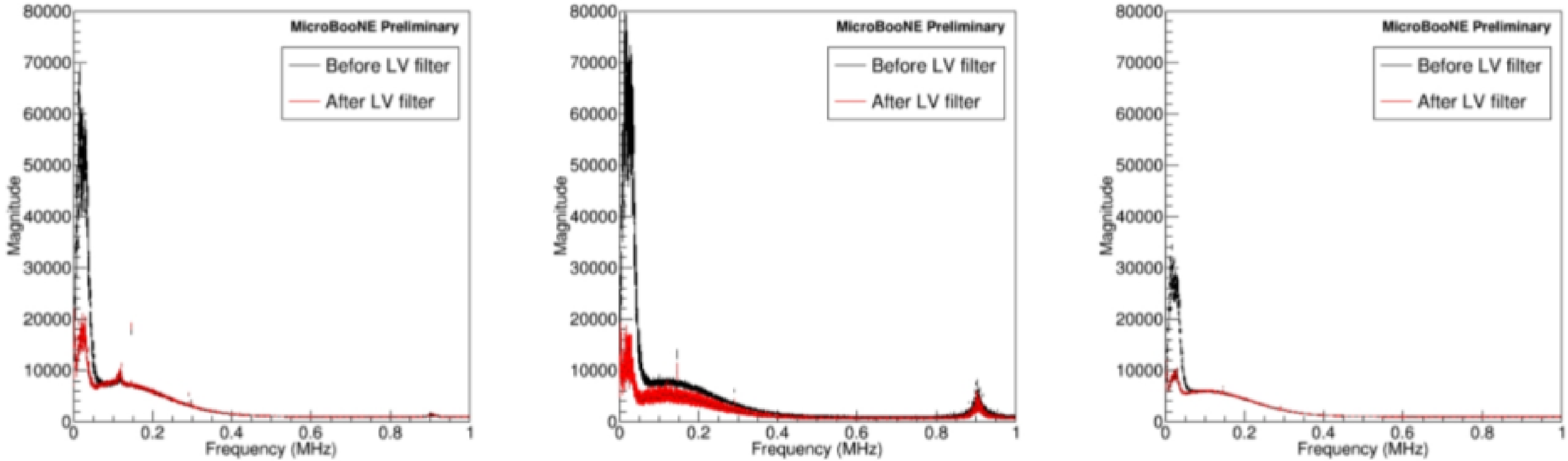


- Peak Signal-to-Noise Ratio (PSNR – signal height divided by noise RMS) very high after software noise filtering
  - Note: here calculated for all signals in event (not just MIPs)
  - Collection plane: **PSNR > 40**
  - Induction planes: **PSNR > 12** (note bipolar nature of signal)
- Higher PSNR post-filtering → charge resolution improves

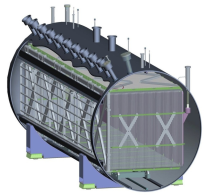


Low-Frequency Noise

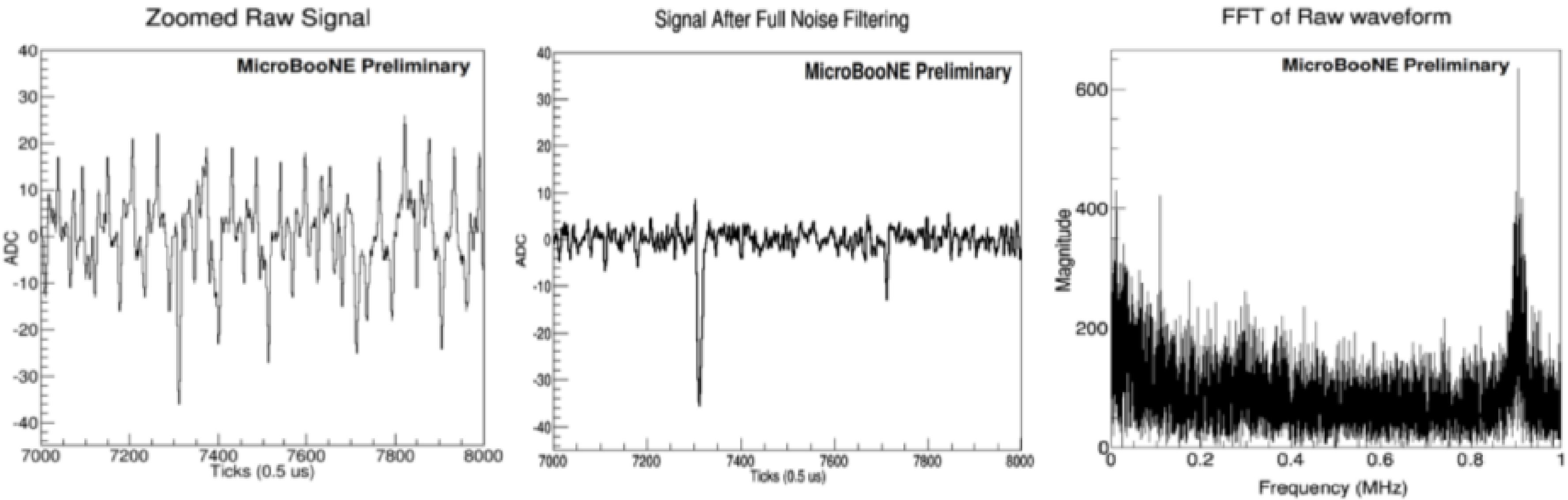
First Induction (U) **Second Induction (V)** **Collection (Y)**



- Majority of noise present before filtering is due to low-frequency (10-30 kHz) noise coherent across all channels on a cold motherboard pair – thought to be associated with voltage regulators
- Almost completely filtered out with software algorithm that takes advantage of coherent nature of noise
- Hardware fix: upgrade service boards (this summer)

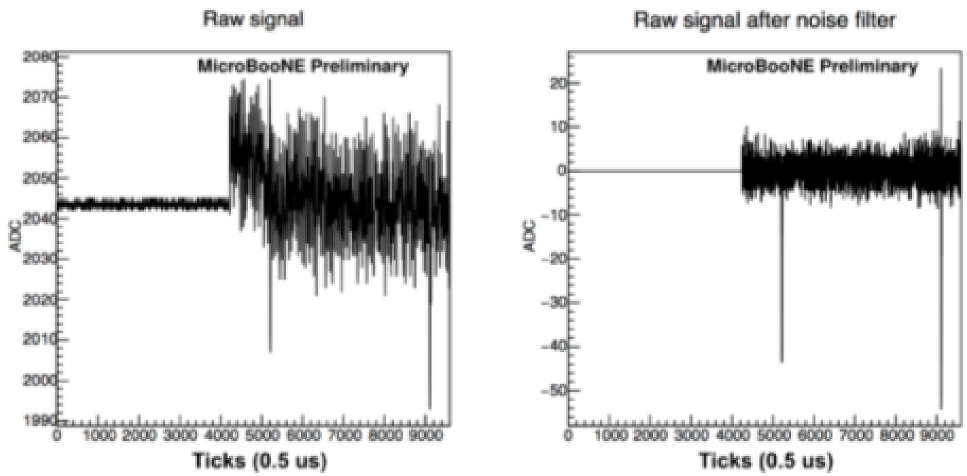


Other TPC Noise Features



- Another major noise source primarily on first induction plane: narrow-band noise associated with cathode HV power supply
  - Can filter out easily in software (compare left to middle)
  - Hardware fix: install second filter pot for cathode HV (this summer)
- High-frequency pick-up noise on downstream side of TPC (right)
  - Suppressed by higher shaping time, easily filtered out with low-pass filter

Effects of ASIC Saturation



- Occasionally ASICs found to "saturate" leading to dead regions of TPC waveforms
  - Charge builds up too fast on capacitor in ASIC circuit
  - Current source believed to be from vibrating wires – worse for longer wires
- Solution is to use higher bias current ("leakage current") setting in ASIC – occurrence small in MicroBooNE, but accounted for in software noise filtering step
  - New ASIC design includes higher leakage current settings

Signal Processing Chain

Number of Ionized electrons

↓ Field Response

Signal on Wire Plane

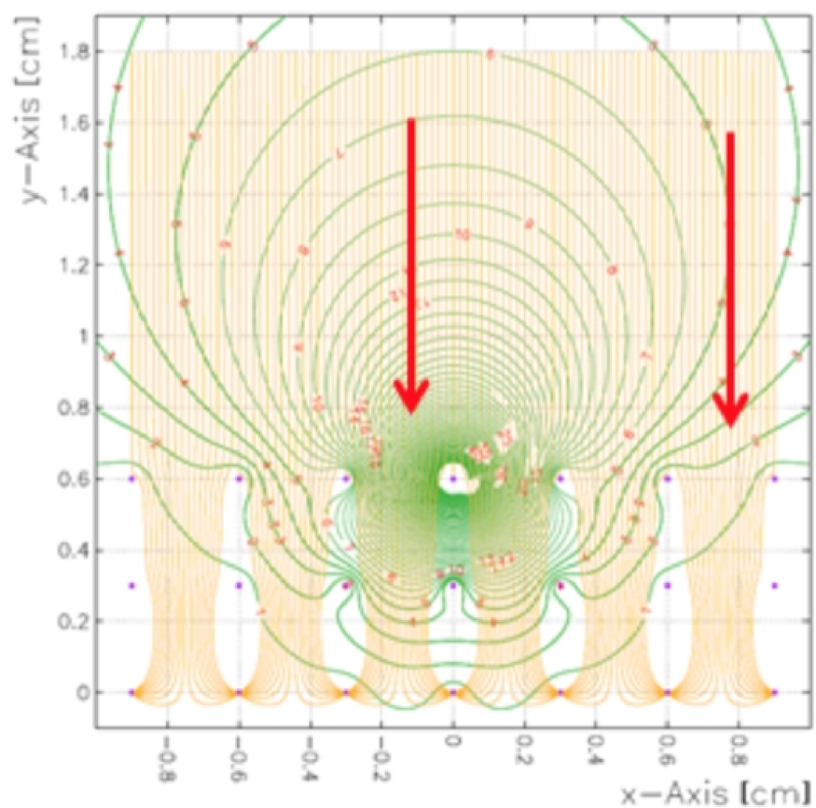
↓ Electronics Response

Signal to be digitized by ADC

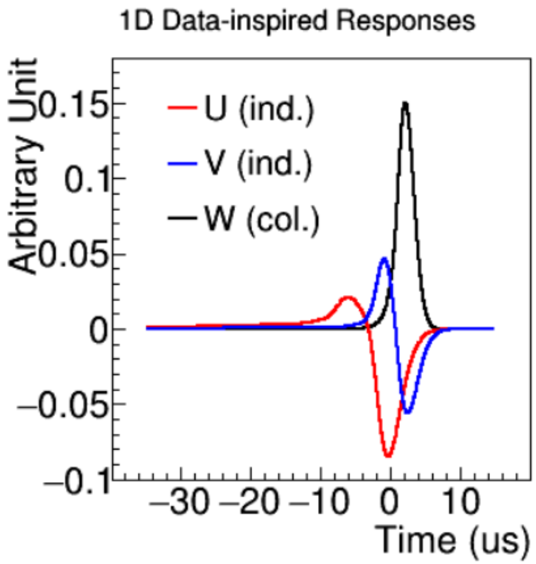
↓ Signal Calibration

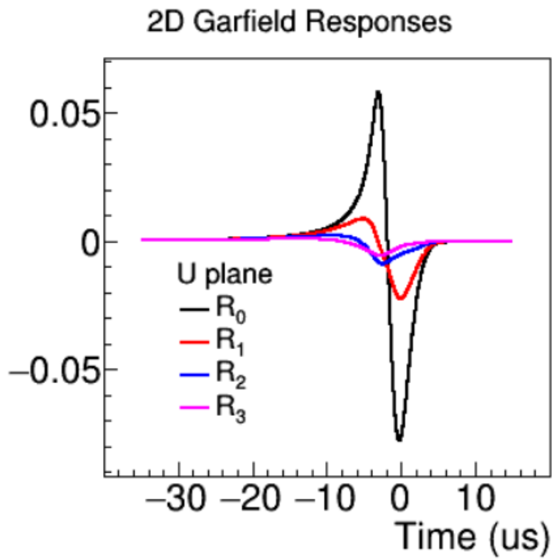
Number of Ionized electrons

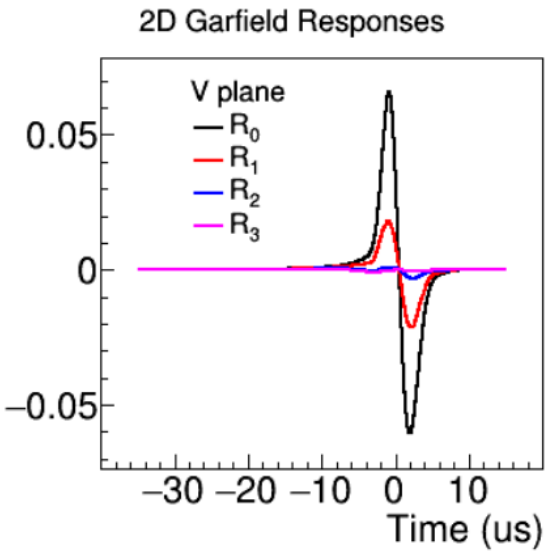
Weighting potential of a wire



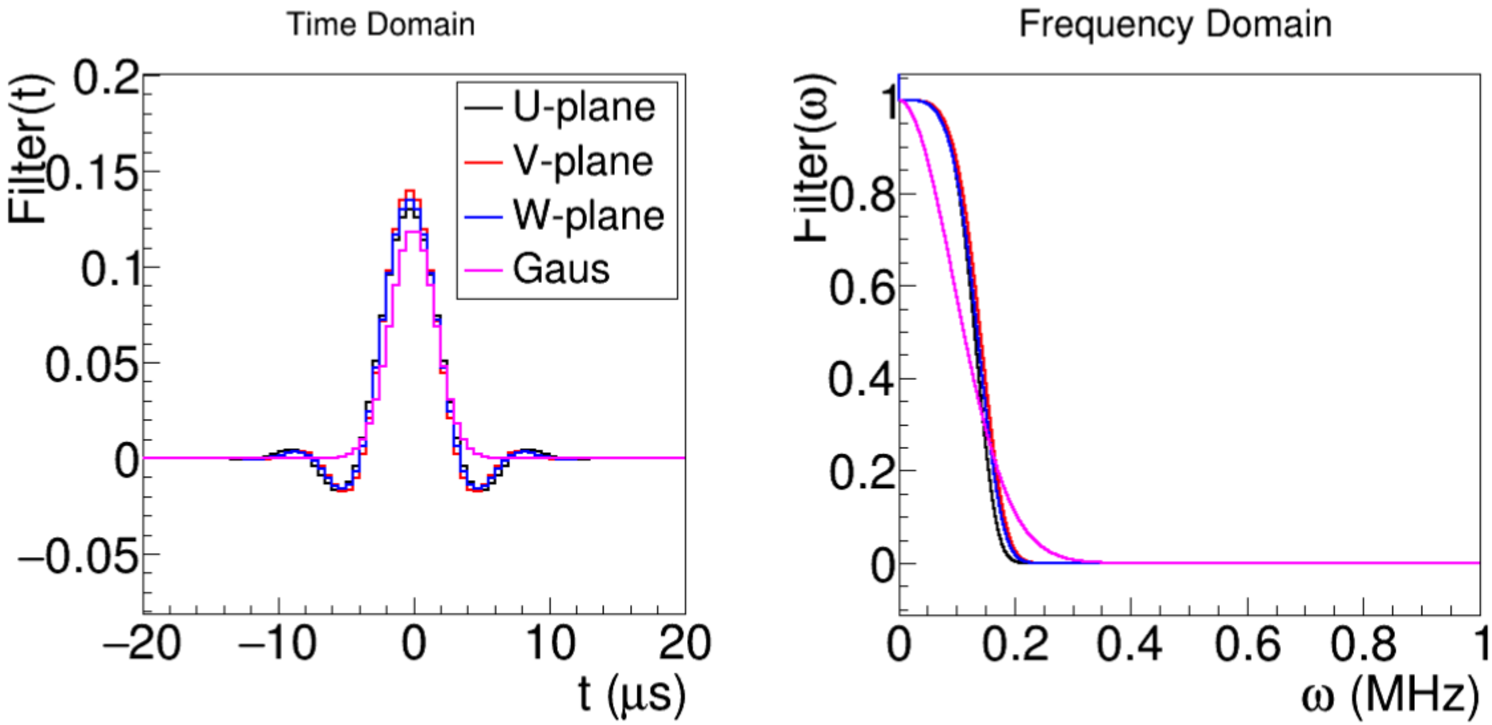
Response Functions

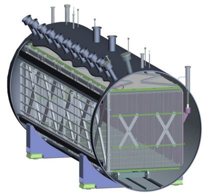




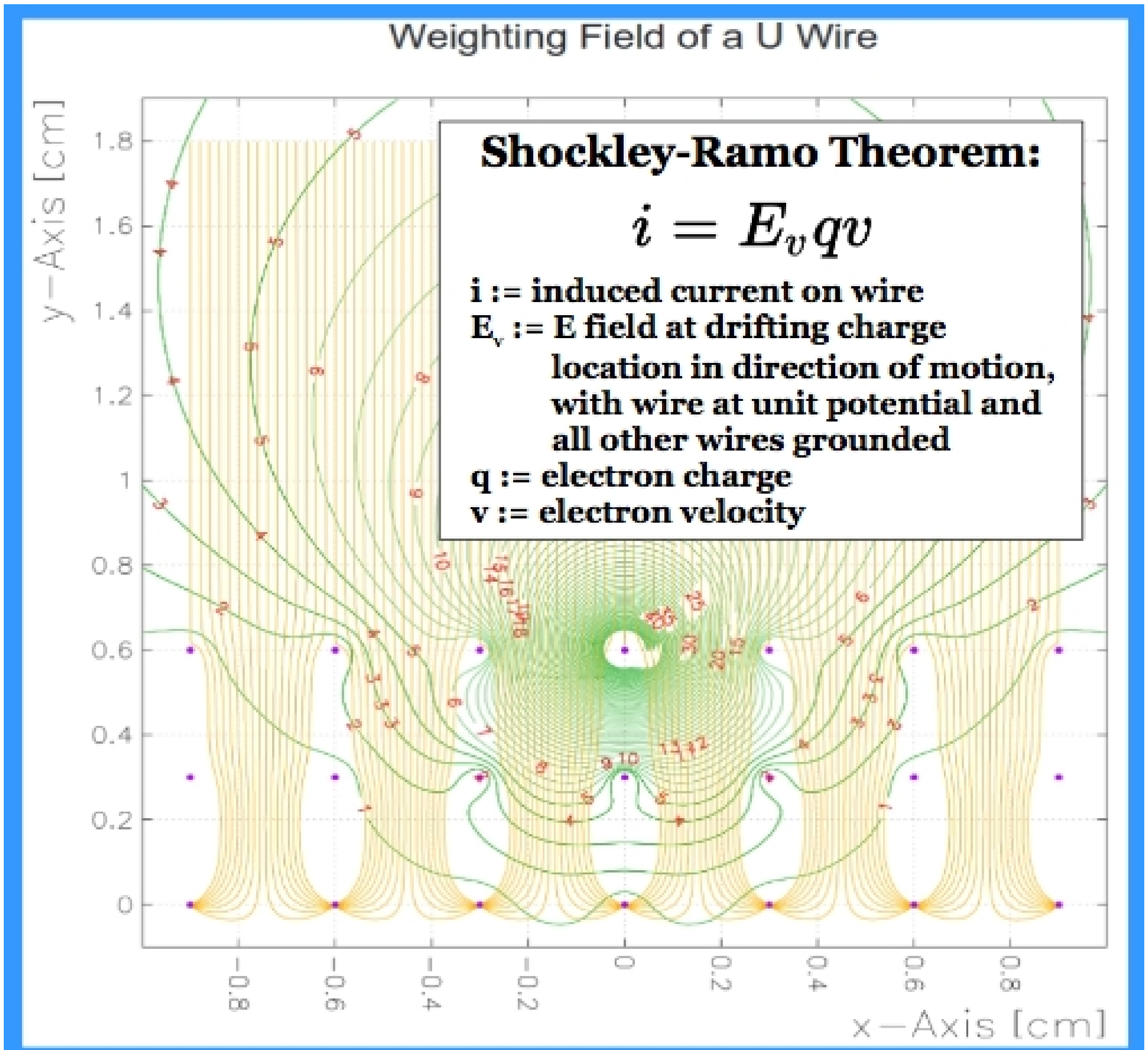


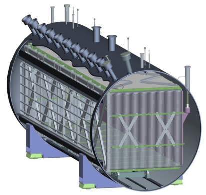
Deconvolution Filter





Shockley-Ramo Theorem





Deconvolution Procedure

The deconvolution is employed to estimate the true ionization signal *S* from the measured signal *M* on the raw waveform, with

$$R(t, t_0) \equiv R(t - t_0), \qquad M(t_0) = \int_{-\infty}^{\infty} R(t, t_0) \cdot S(t) \cdot dt.$$

This process is done in the frequency domain and utilizes a known full response *R* (field + electronics) and a filter *F*:

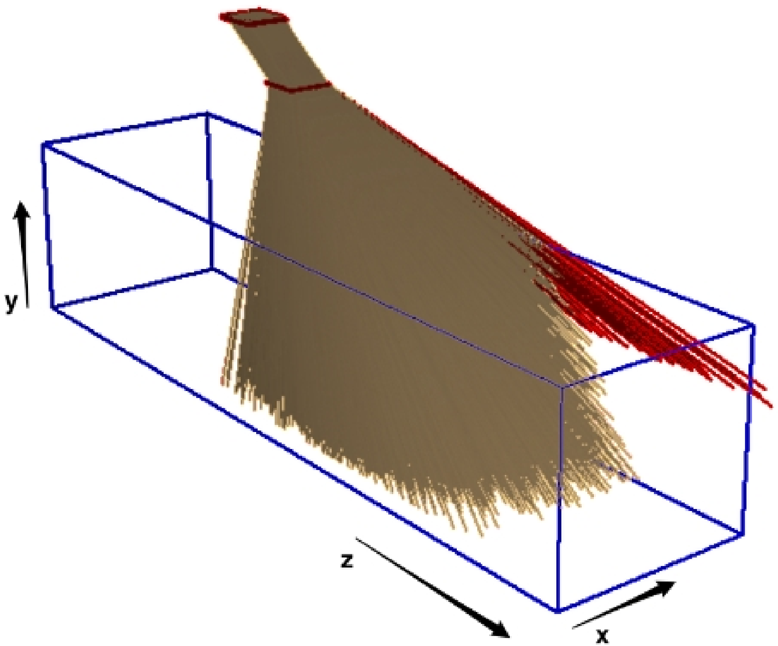
$$F(\omega) = \begin{cases} e^{-\frac{1}{2}\cdot\left(\frac{\omega}{a}\right)^b} & \omega > 0 \\ 0 & \omega = 0, \end{cases} \qquad S(\omega) = \frac{M(\omega)}{R(\omega)} \cdot F(\omega).$$

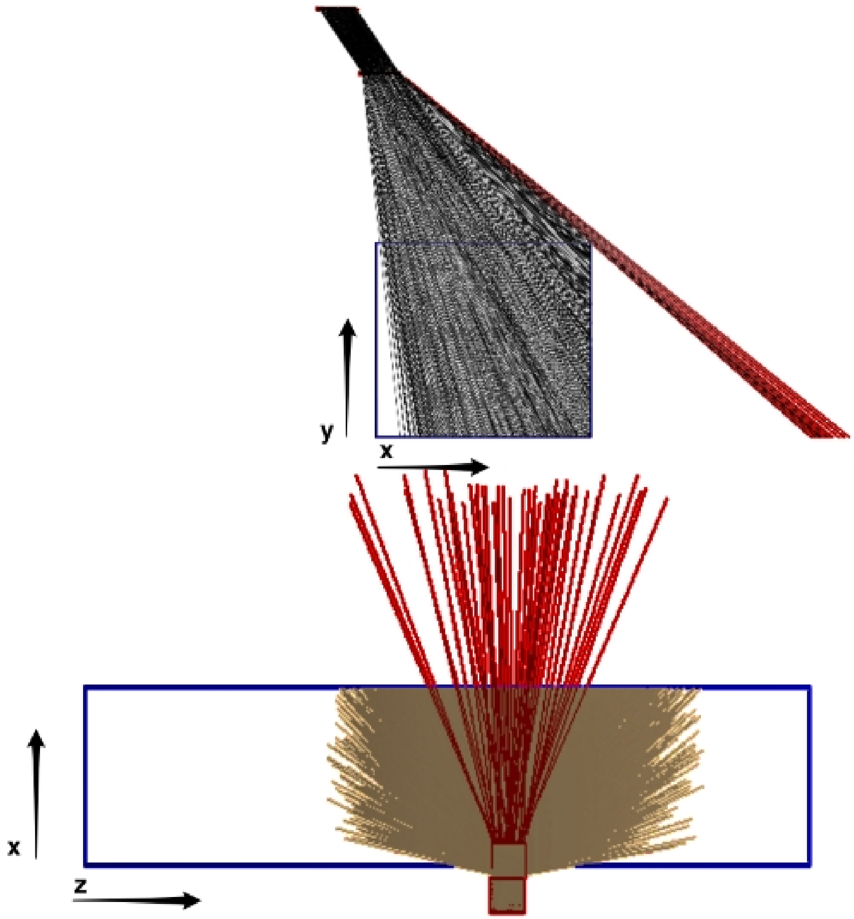
A 2D (time vs. wire) deconvolution is done for the U/V planes in order to account for different responses from nearby wires:

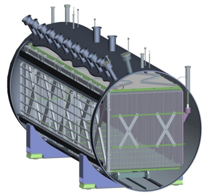
$$\begin{pmatrix} M_1(\omega) \\ M_2(\omega) \\ \vdots \\ M_{n-1}(\omega) \\ M_n(\omega) \end{pmatrix} = \begin{pmatrix} R_0(\omega) & R_1(\omega) & \ldots & R_{n-2}(\omega) & R_{n-1}(\omega) \\ R_1(\omega) & R_0(\omega) & \ldots & R_{n-3}(\omega) & R_{n-2}(\omega) \\ \vdots & \vdots & \ddots & \vdots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

The 2D version (*R* matrix inversion) recovers reconstructed tracks at high angles with respect to the anode plane.

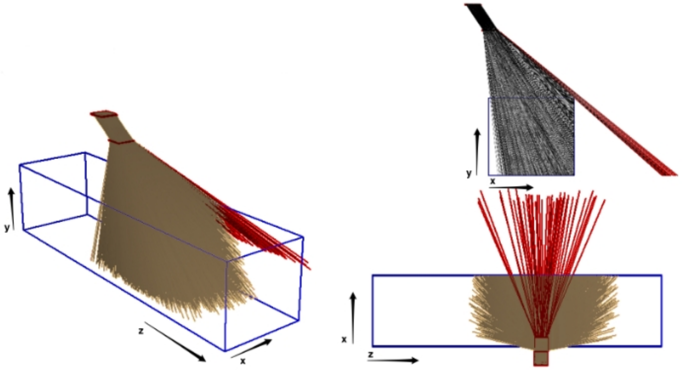
Muon Counter System

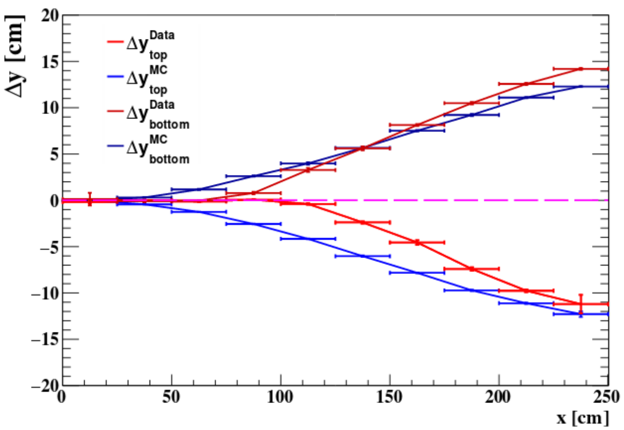


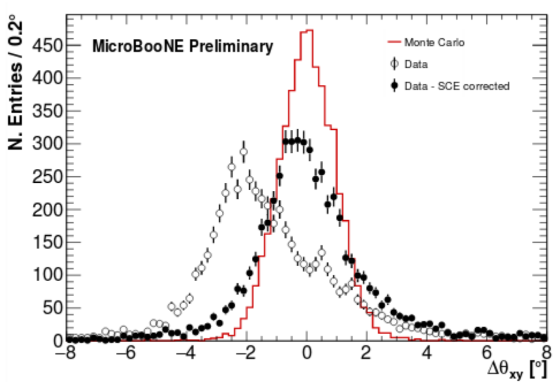


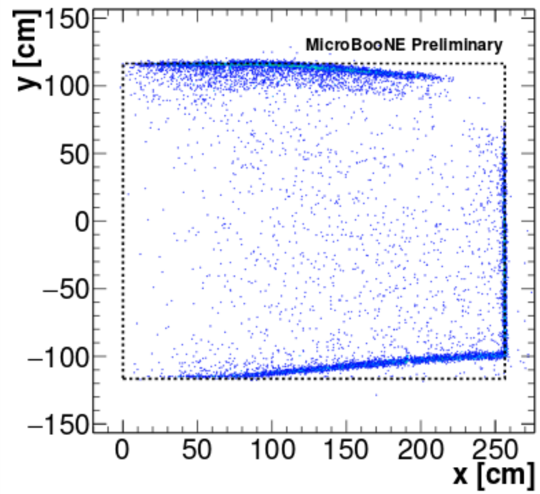


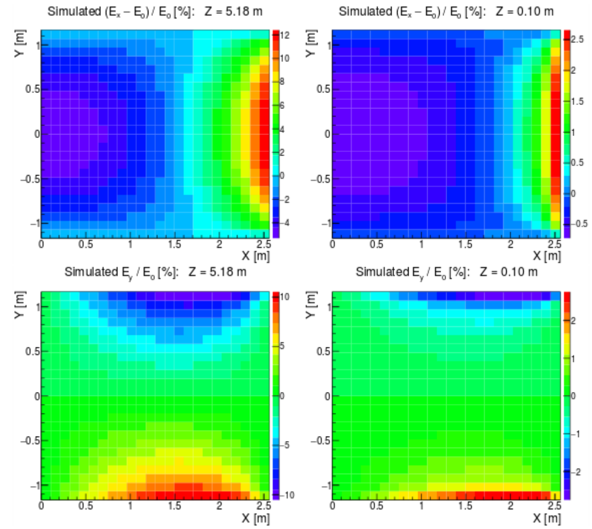
SCE Analysis Overview





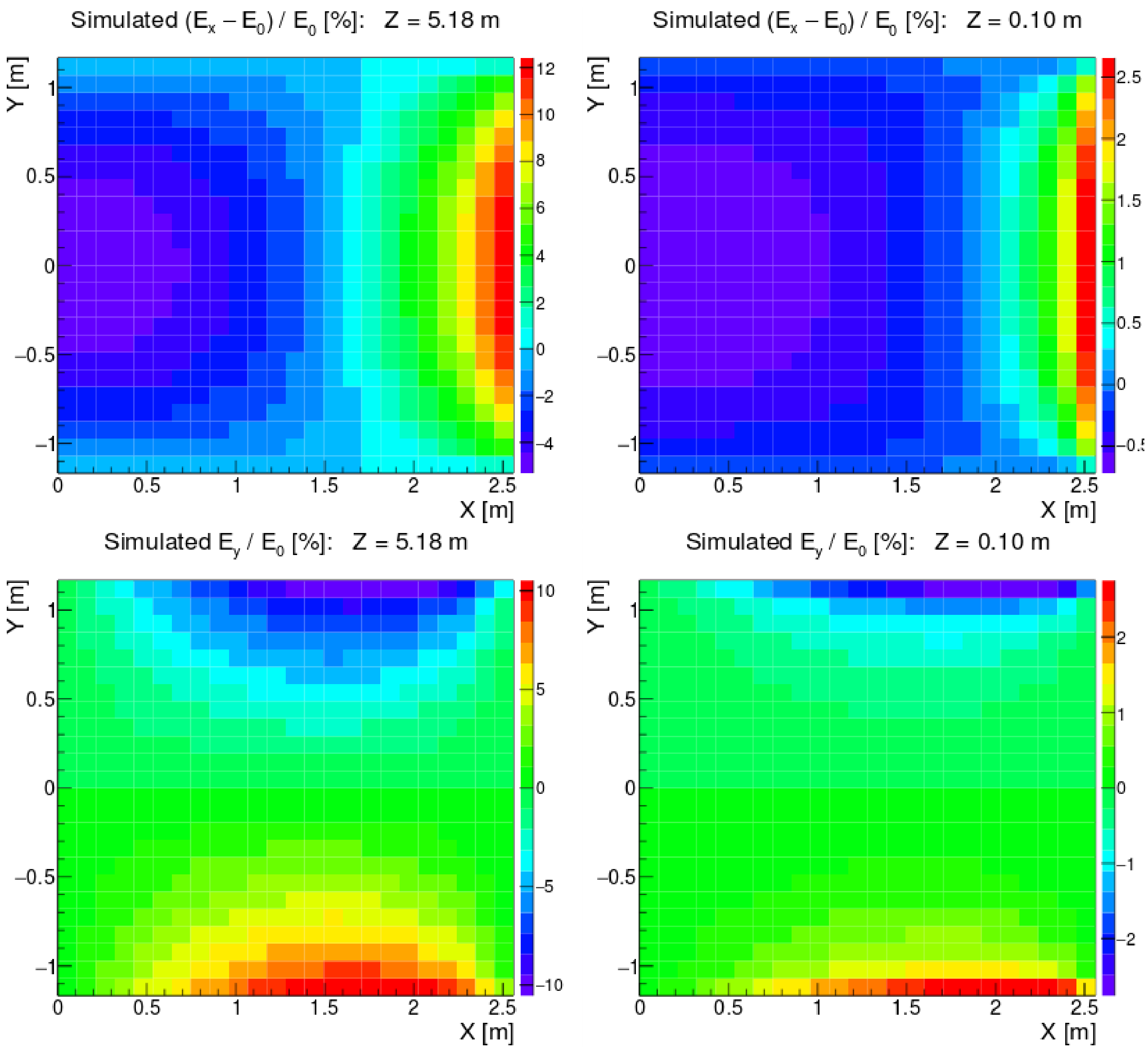




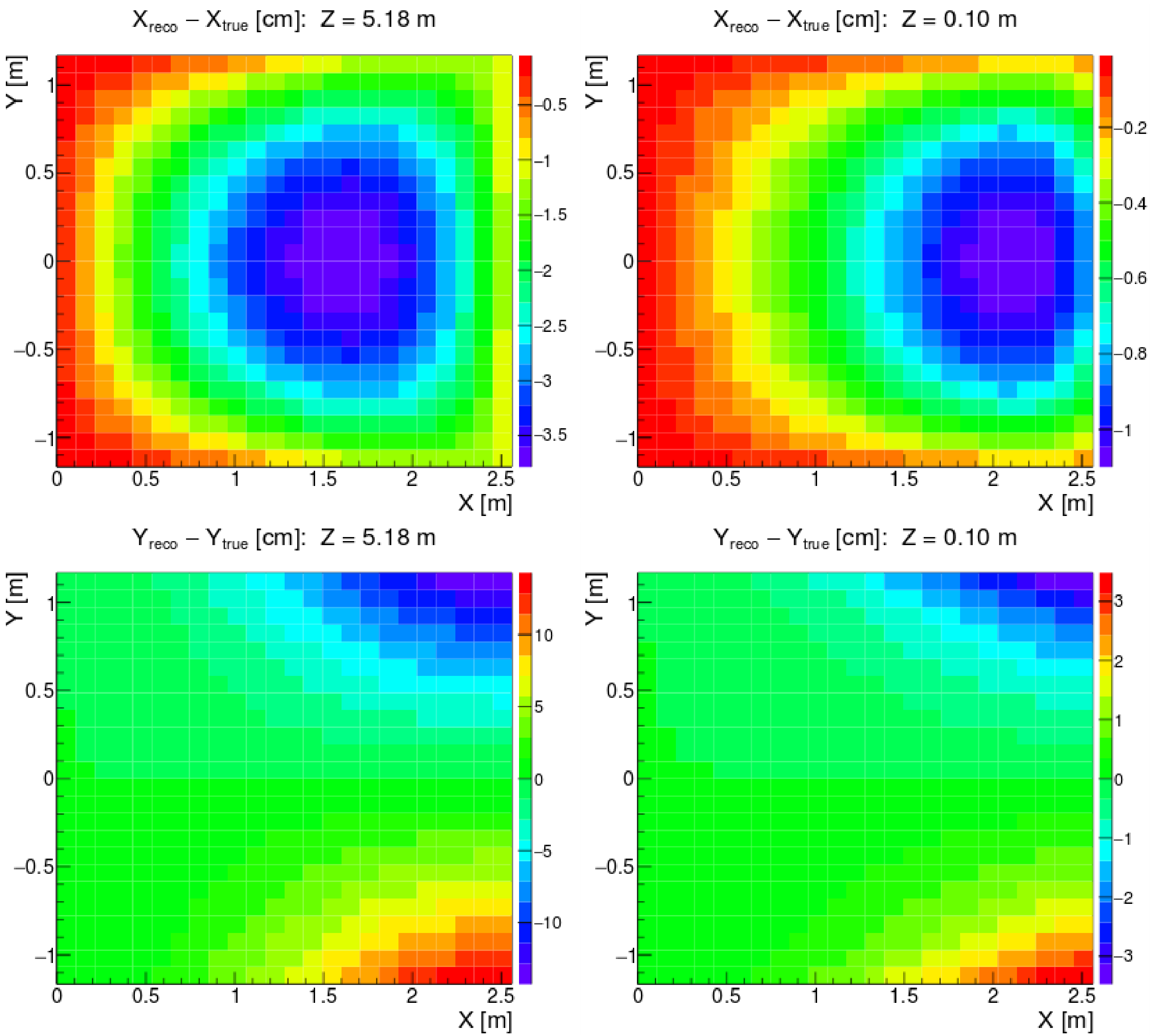


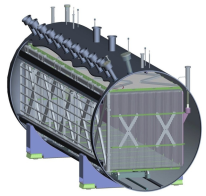
- Utilize MuCS for track t_o tags
  - Probe features in drift direction
- See strange feature in data
- Seems like SCE feature, so take a look at SCE simulation
- Data vs. MC: similar, but differences
- Attempt partial correction – can reduce impact of effect in data

SCE E Field Distortions



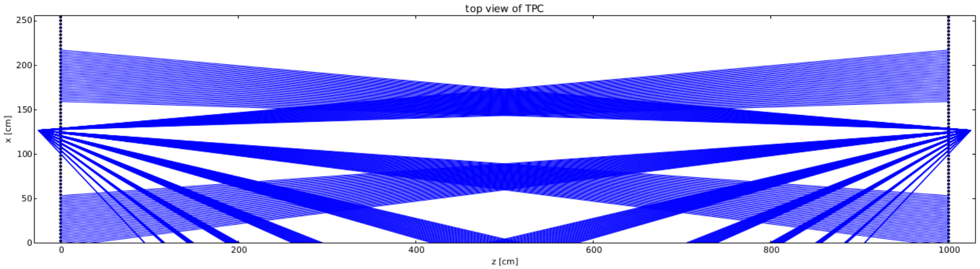
SCE Spatial Distortions





SCE Laser Calibration

Simulated Laser Coverage: X-Z Plane



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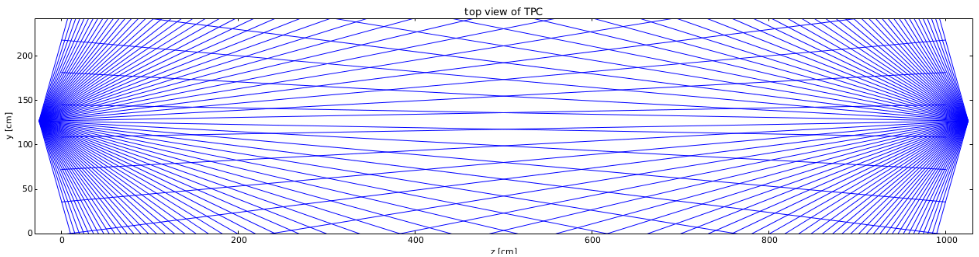
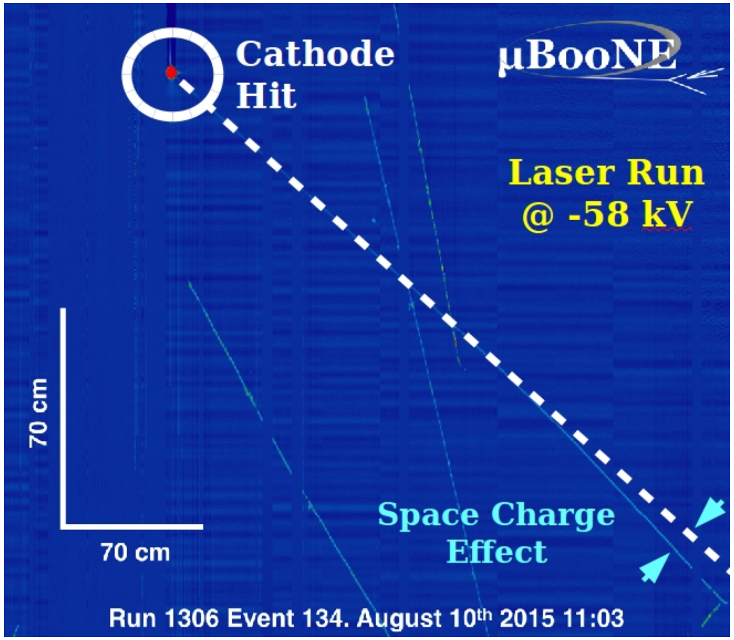
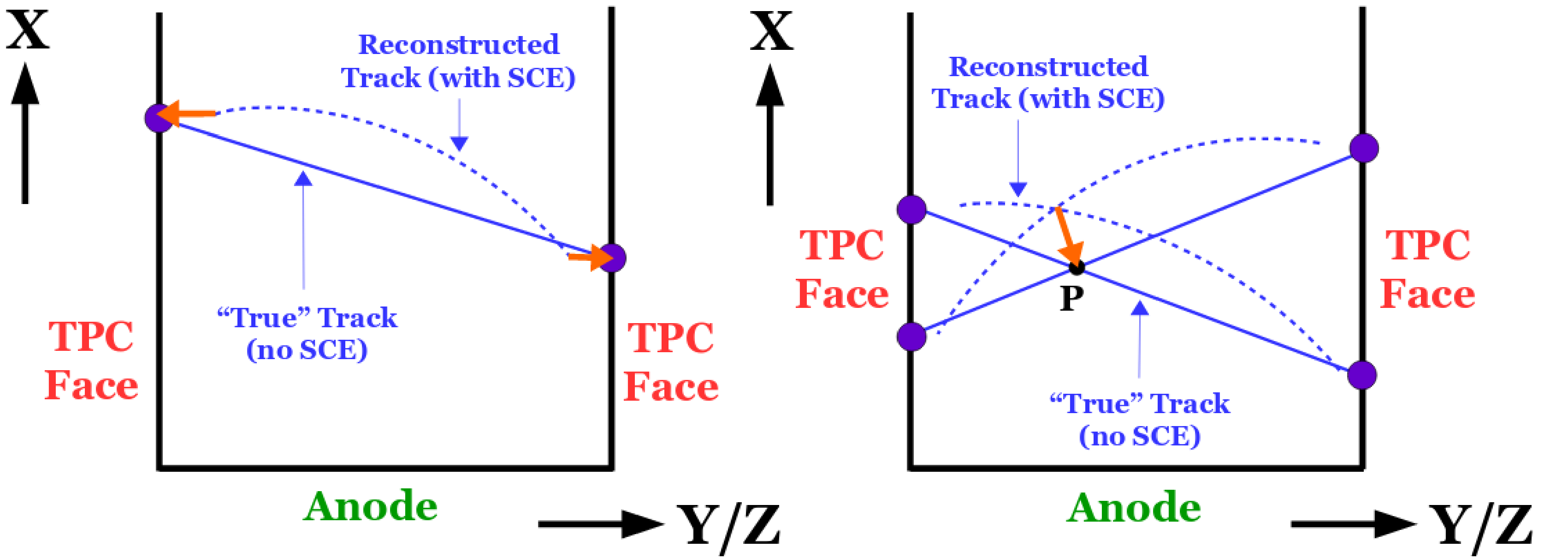




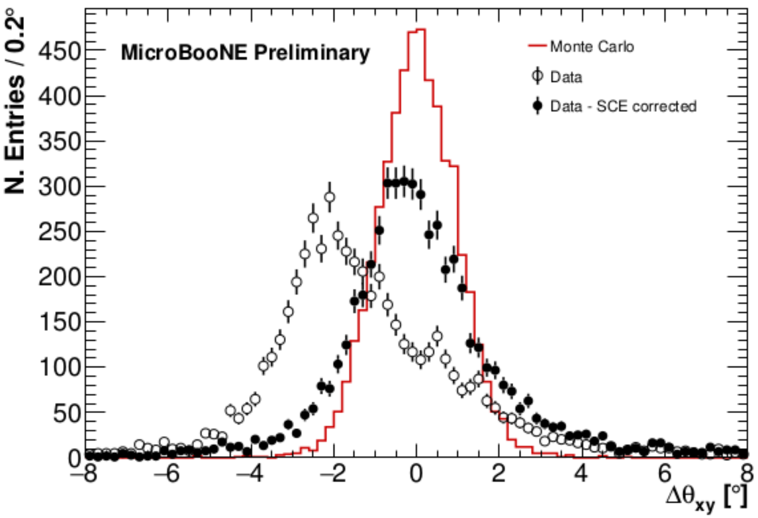
- ♦ Qualitatively, SCE very clear in laser event displays
- ♦ Can make point-to-point SCE correction throughout TPC using crossing point of two laser tracks

SCE Cosmic Muon Calibration

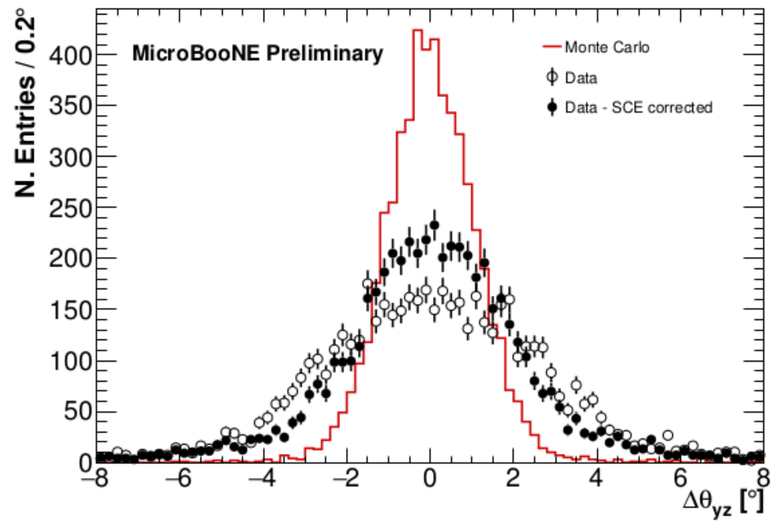


- Uses t_0-tagged tracks: anode-cathode crossing tracks, anode/cathode-piercing tracks and MuCS-tagged tracks
- Calibrate points in TPC using single tracks (TPC faces) and pairs of tracks (TPC bulk) – utilize ~straight tracks using MCS measurement (high momentum → ~straight)

SCE Corr. Validation



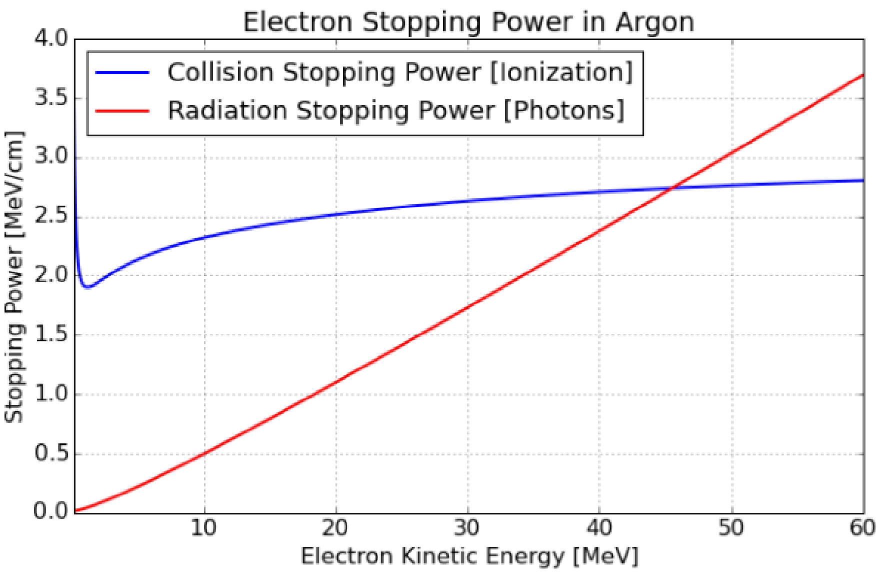
(a) $\Delta\theta_{xy}$ residual distribution

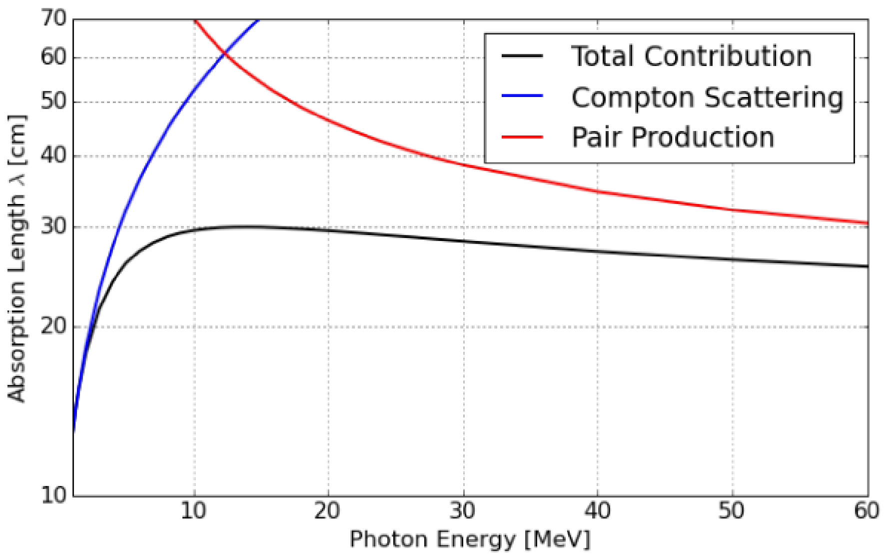


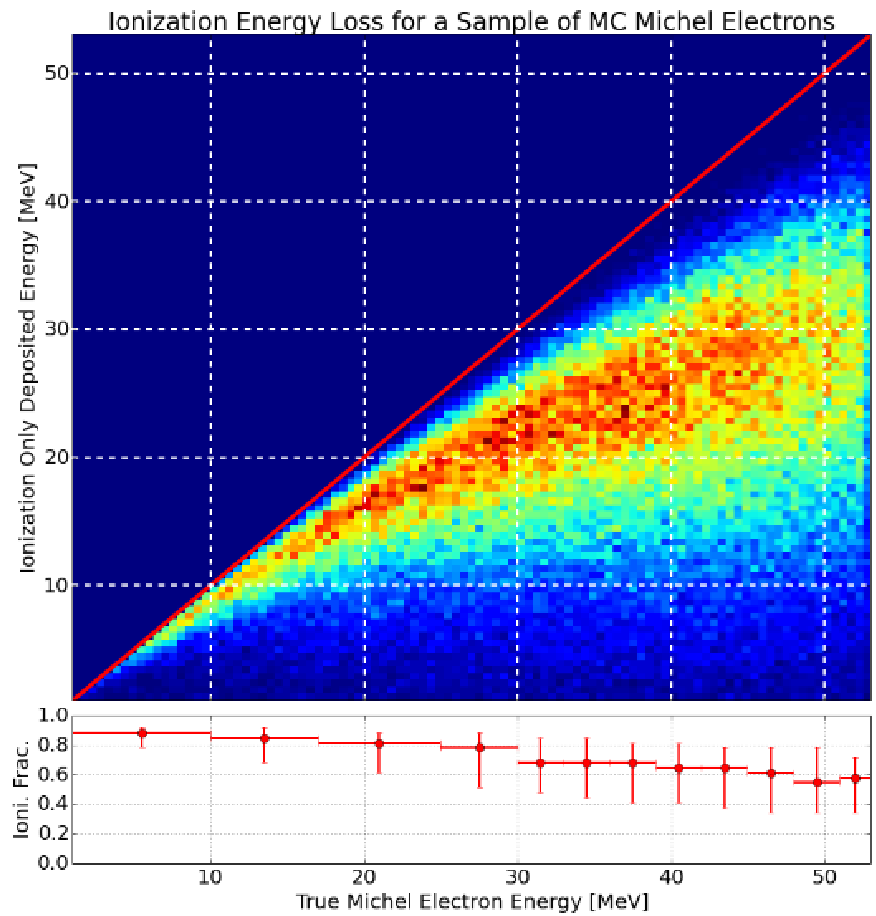
(b) $\Delta\theta_{yz}$ residual distribution

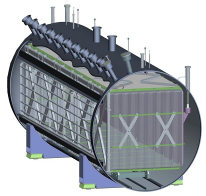
- Validate SCE calibration using separate sample of t_0-tagged tracks
  - Look at track angles, track hit density, etc.
  - Also characterize time-dependence of effect – **important!**
- MicroBooNE SCE public note gives example of this type of validation using MuCS-tagged tracks (angular residuals)

Michel e$^-$ Energy Loss



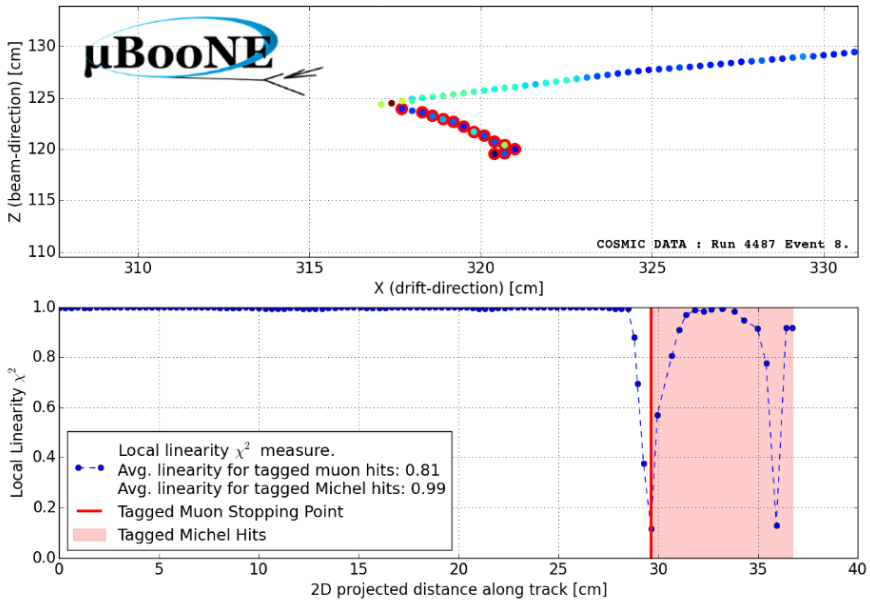




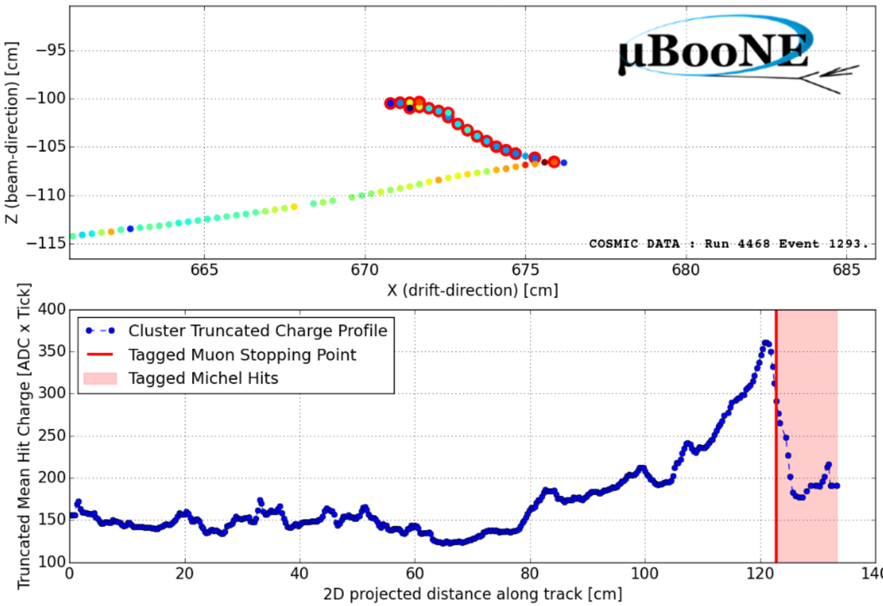


Michel e^- Reconstruction

Topology (“Kink”)

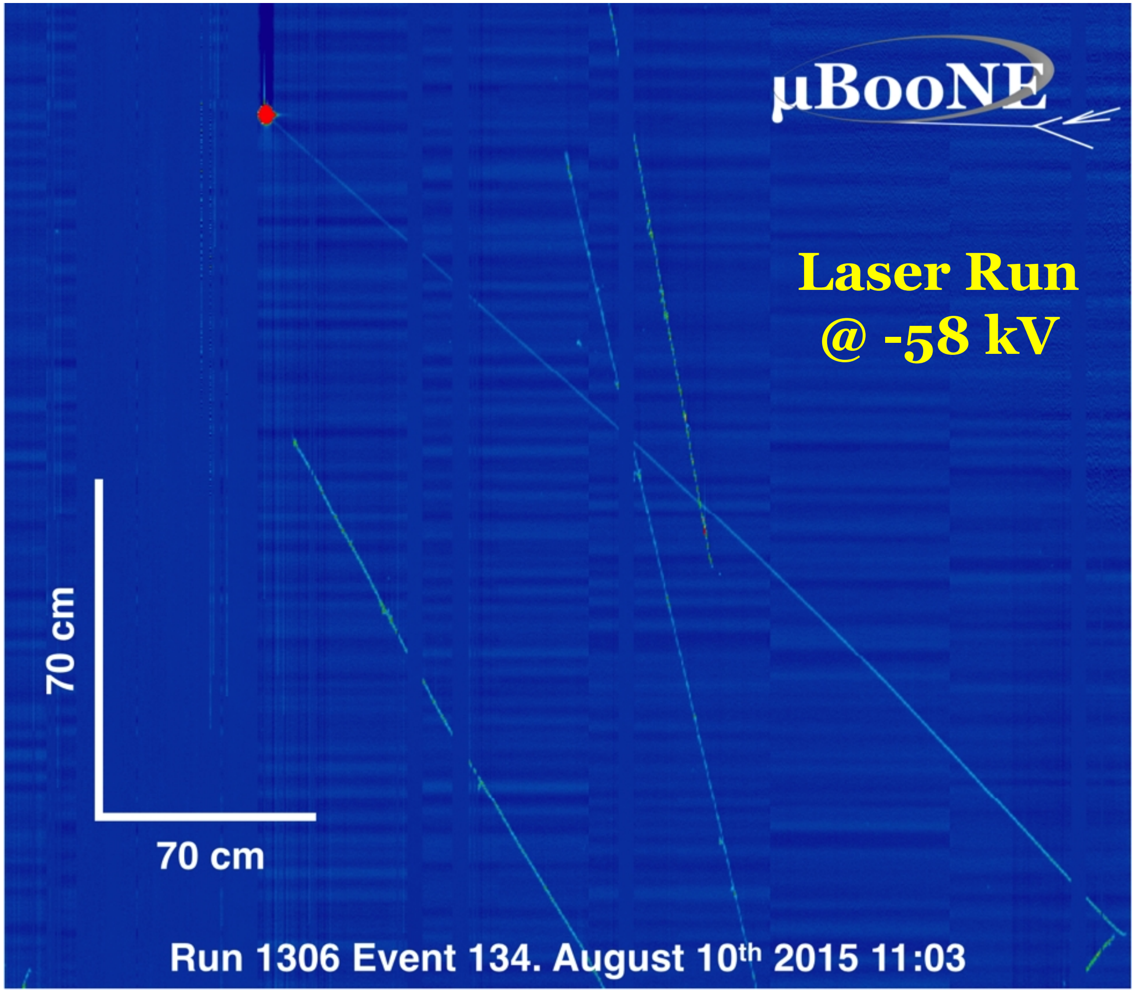


Calorimetry (Bragg Peak)



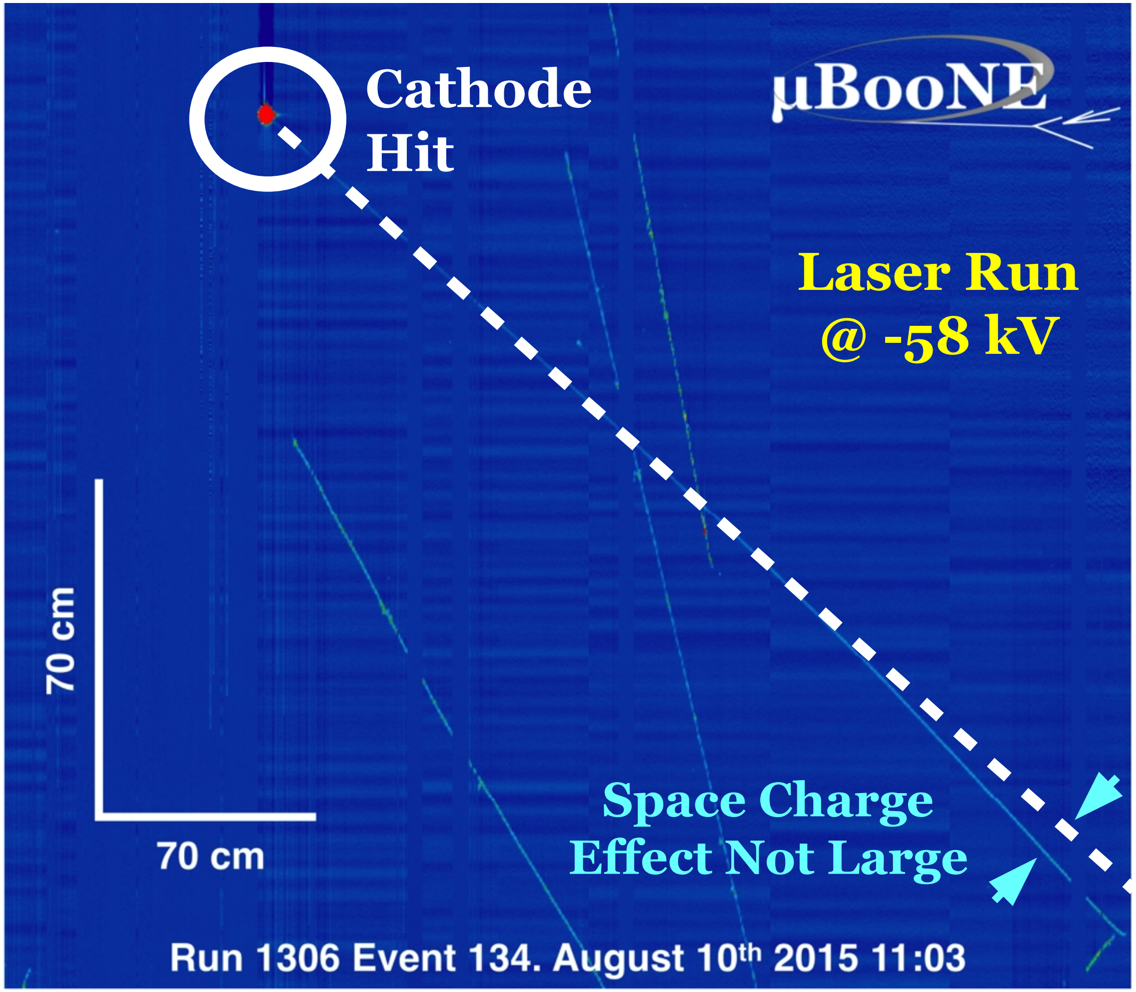
- Tag Michel electrons from cosmic muon decay using characteristic topology and calorimetric information
  - 2D reconstruction for now (collection plane only)
  - Yields a high purity (80-90%) and low efficiency (2-3%) sample of Michel electrons

Special Runs



♦ Also have taken special runs for calibrations and detector physics – laser, cosmic, special ASIC settings, etc.

Special Runs



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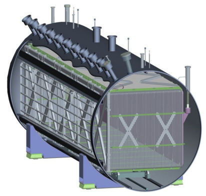
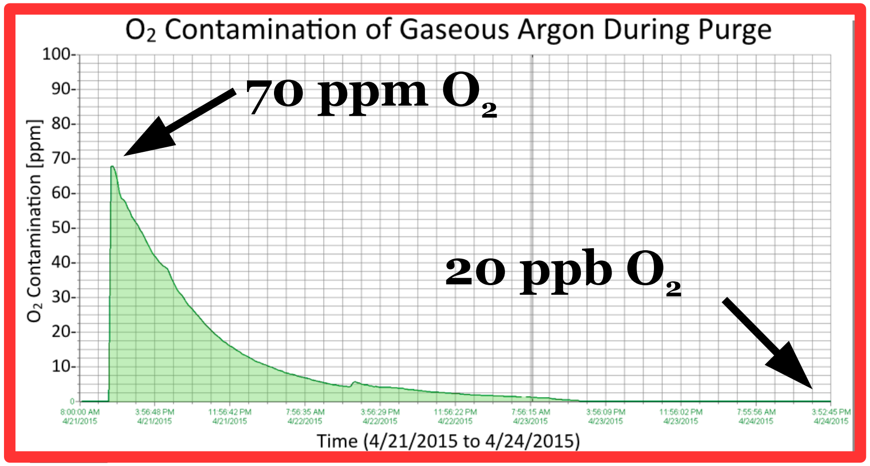
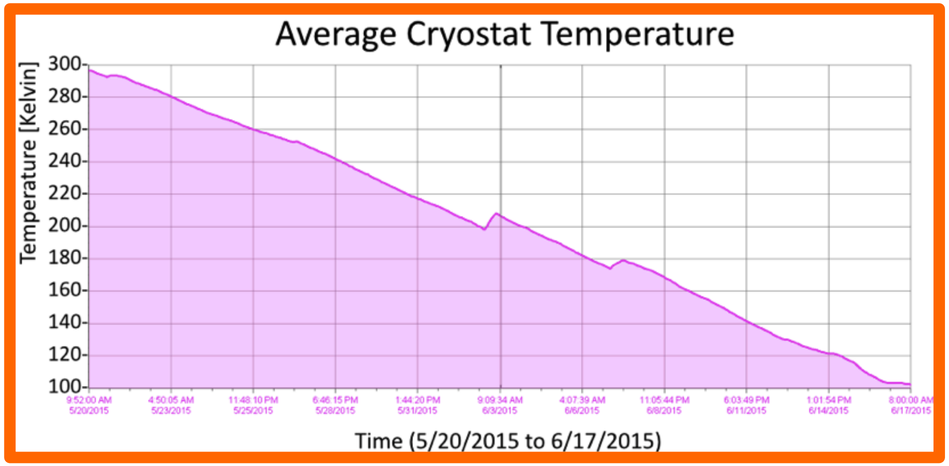
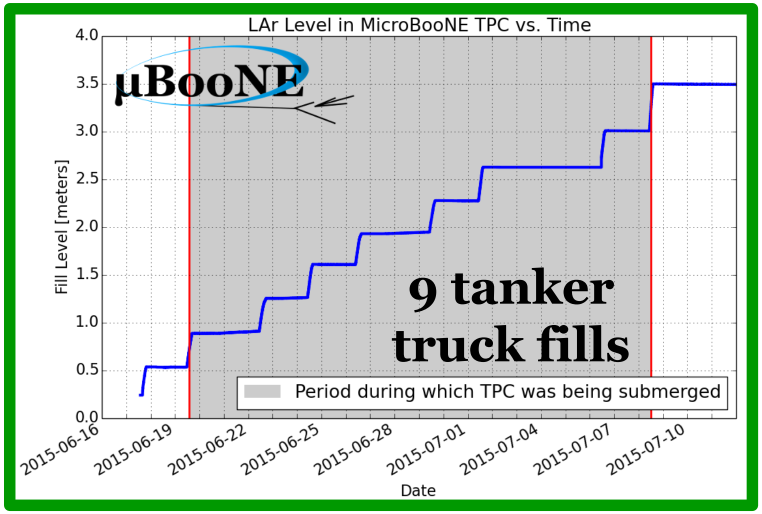


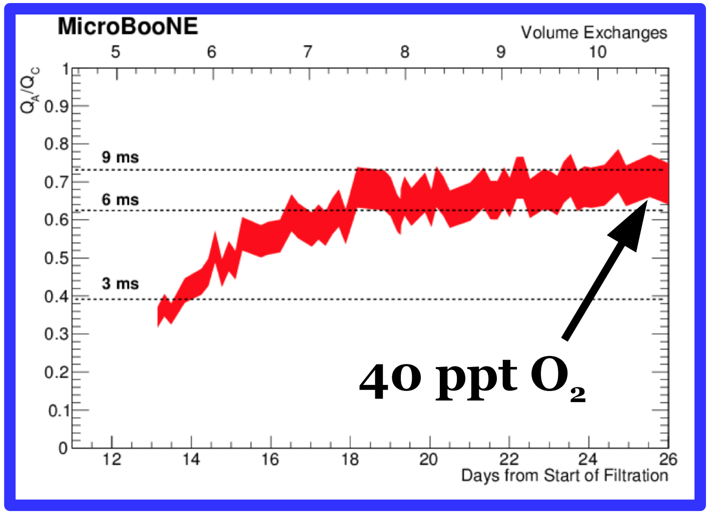
Cryogenics Commissioning

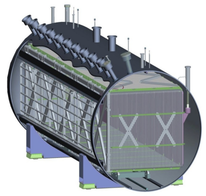
- <u>Four stages</u>: (1) purge (2) cool-down (3) LAr fill (4) recirculation and purification → **operating at least 2-3 times design purity!**











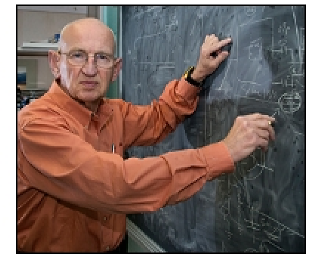
LArTPC: Early History

BROOKHAVEN NATIONAL LABORATORY

Early History of the Development of LArTPC

- W. Willis and V. Radeka, Liquid argon ionization chambers as total absorption detector, NIMA 120:221 (1974)
- D. R. Nygren, The Time Projection Chamber: A New 4π Detector for Charged Particles. eConf. C740805:58 (1974)
- H. H. Chen et al. A Neutrino detector sensitive to rare process. I. A study of neutrino electron reactions. FNAL-Proposal-0496 (1976)
- C. Rubbia, The liquid argon time projection chamber: a new concept for neutrino detector, CERN-EP/77-08 (1977)

William Willis

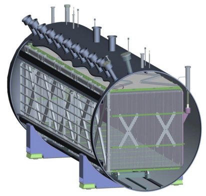


V. Radeka

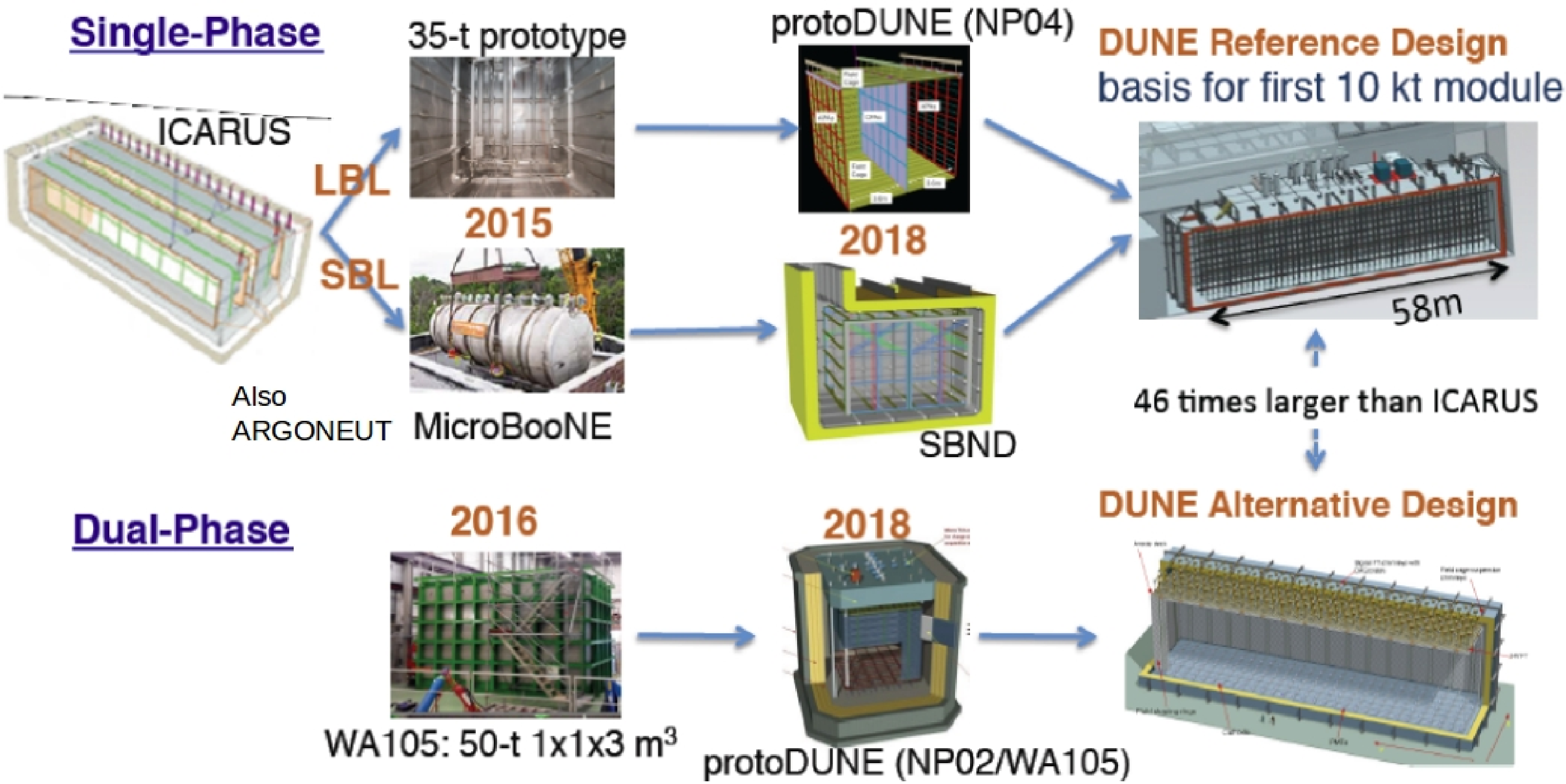
D. R. Nygren

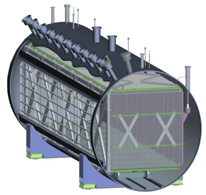
H. H. Chen

C. Rubbia



LArTPC Experiments



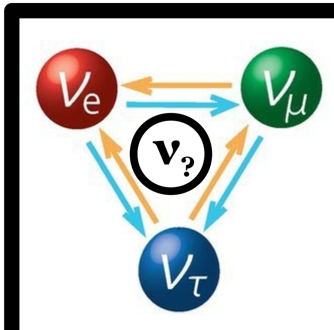


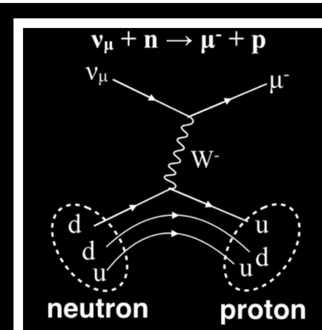
MicroBooNE Physics Goals

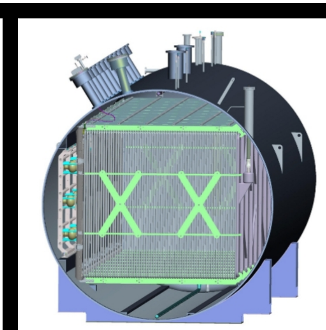
Oscillation Physics (Investigate MiniBooNE Low-Energy Excess)

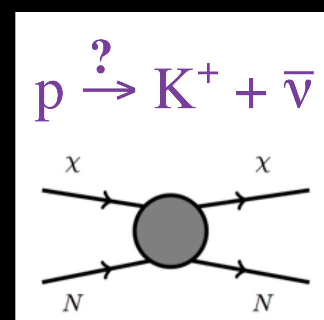
Cross-Section Measurements

Detector Physics for LArTPC R&D



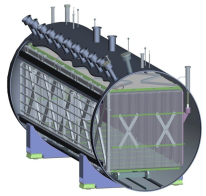




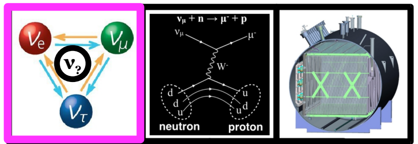


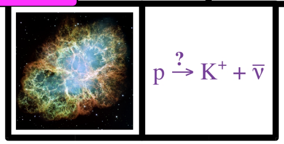
Supernova Neutrino Detection

Exotic Physics

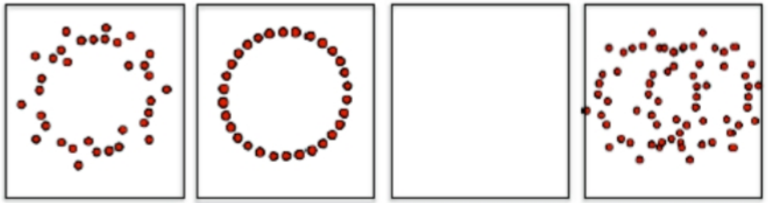


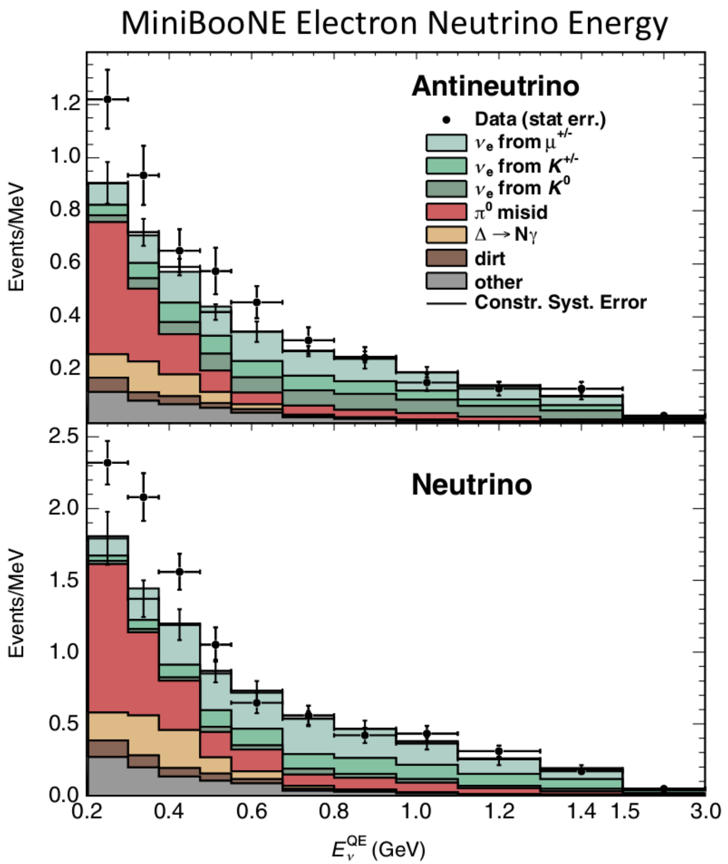
Low-Energy Excess

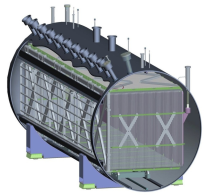




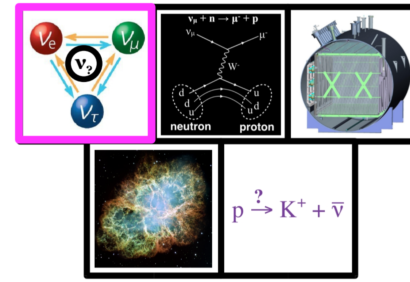
- Low-energy $\nu_e/\bar{\nu}_e$ candidate excess seen at MiniBooNE
  - MiniBooNE: Cherenkov detector (also on BNB)
  - Baseline too short (541 m) for 3-flavor $\nu_\mu \rightarrow \nu_e$ oscillation
- No e±/γ separation… is excess misunderstood background, sterile neutrino, or… ?



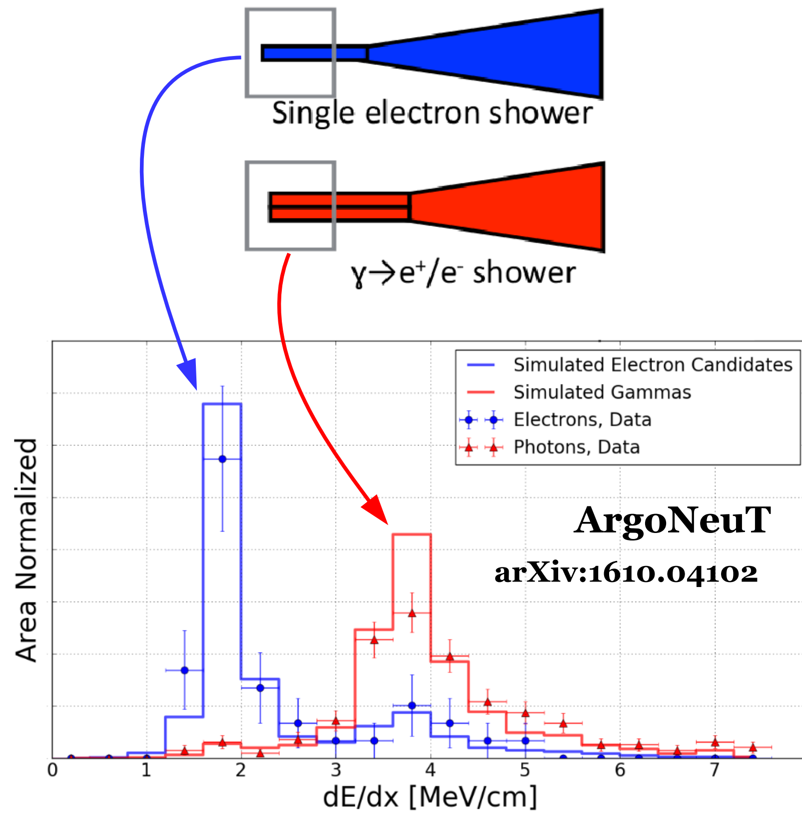


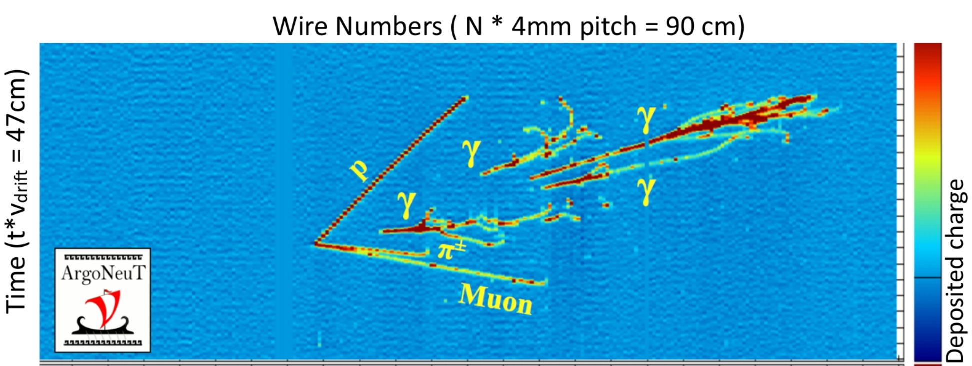


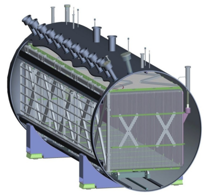
Low-Energy Excess (cont.)



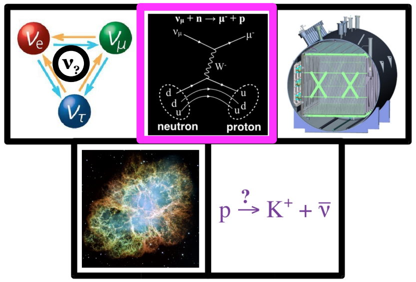
- Can discriminate $e^{\pm}/\gamma$ with MicroBooNE's LArTPC
  - Shower displacement from vertex ("gap") for γ also provides separation
  - Separation with dE/dx
- <u>End result</u>: either discover new particle or improve MC for future experiments



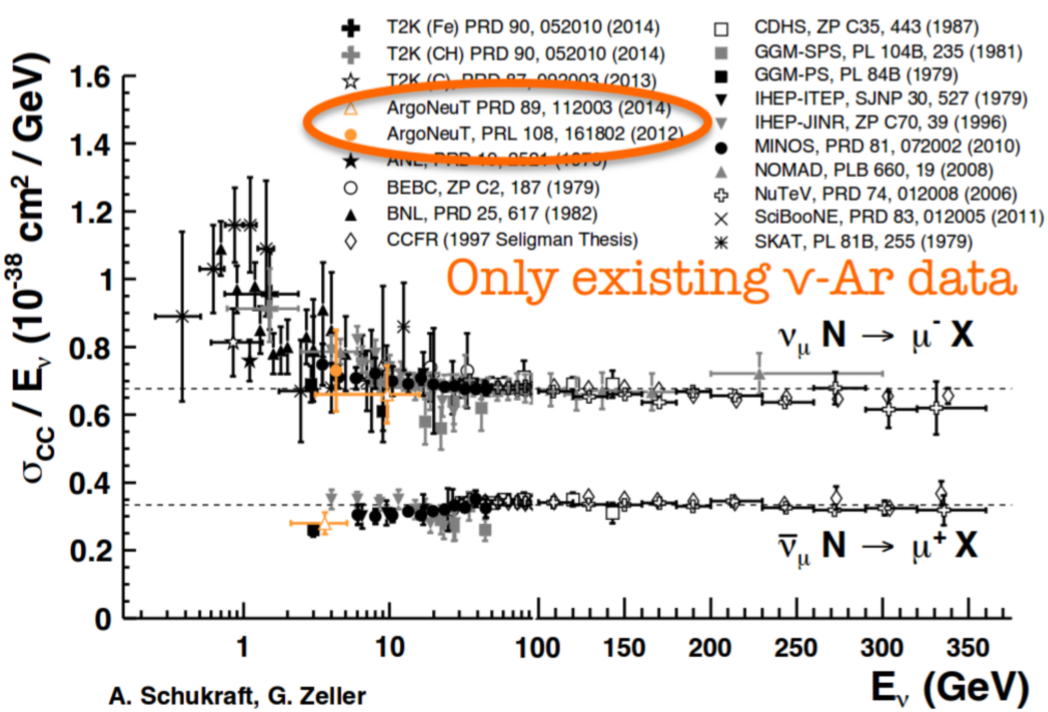


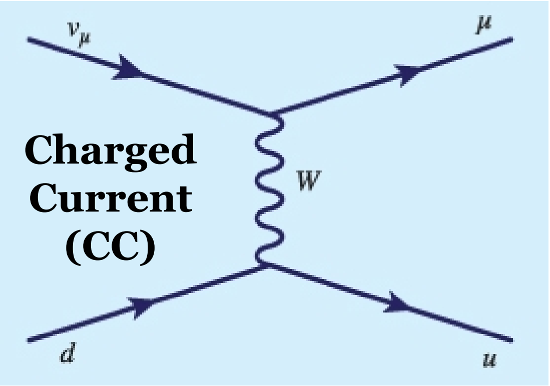


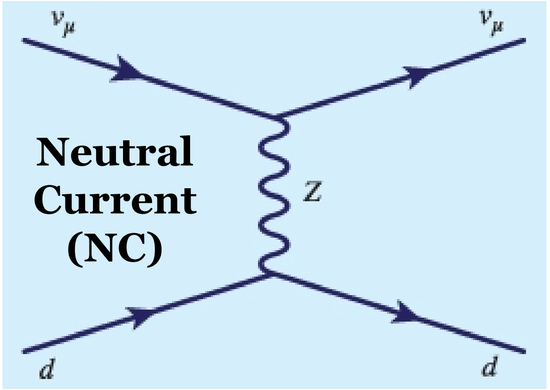
Cross Section Measurements

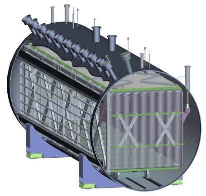


- Cross-section measurements at MicroBooNE will teach us more about nuclear effects, neutrino energy reconstruction, etc.
  - e.g. nucleon-nucleon correlations

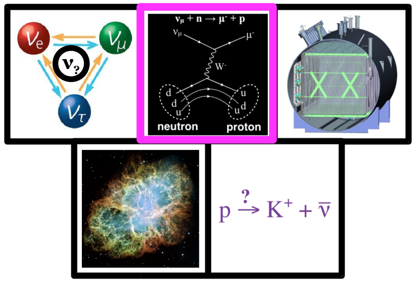








Cross Section Measurements



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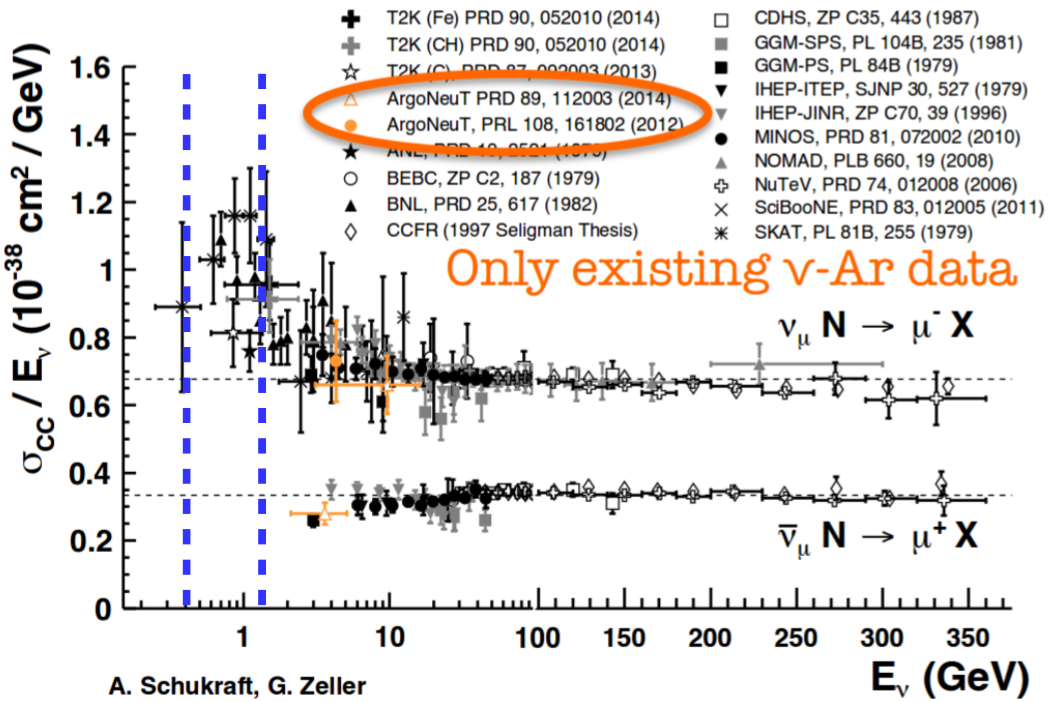
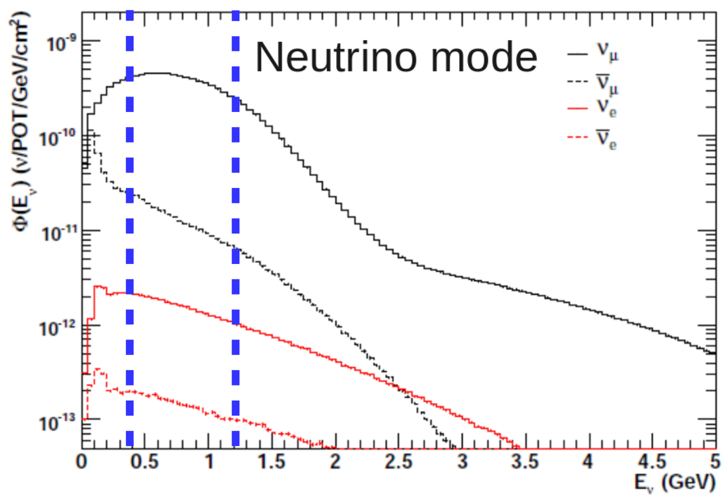
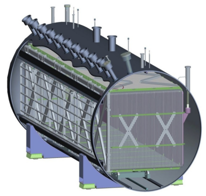
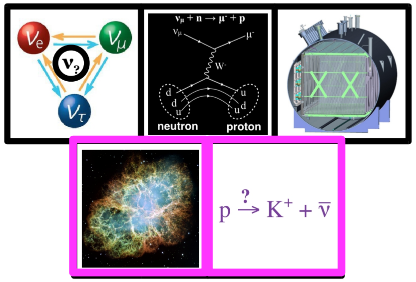


Energy Range:
DUNE's 2nd Osc. Maximum



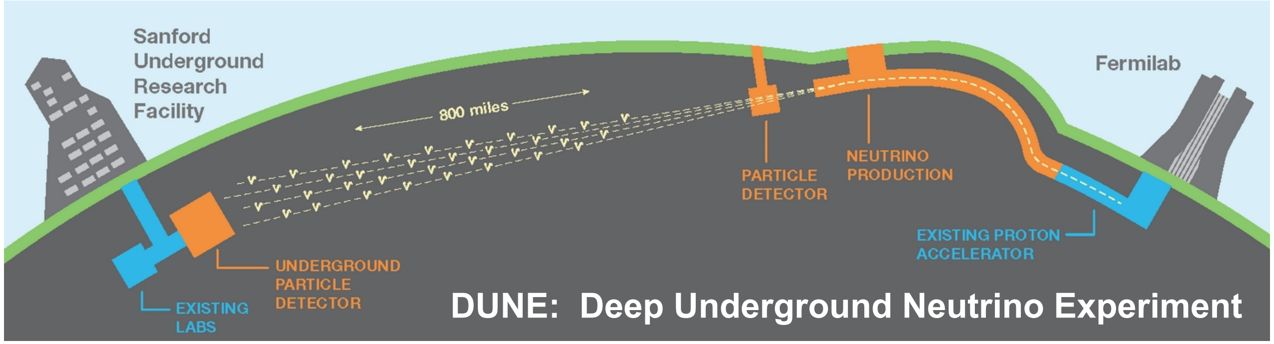


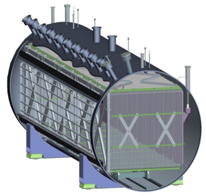
Supernova ν, Exotic Physics



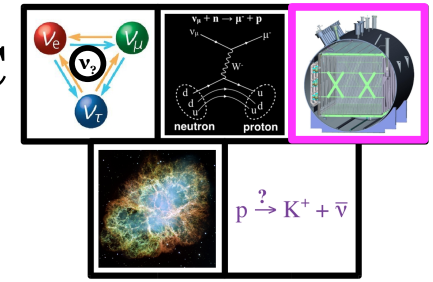
- Additional topics include studies related to supernova neutrinos and exotic physics
  - If we're lucky, supernova neutrinos (~10 MeV) captured using continuous readout stream and SNEWS alert system
    - Also study zero suppression, triggering schemes
  - Can study proton decay backgrounds in MicroBooNE's LArTPC
    - Signal: $\mathbf{p \rightarrow K^+ + \nu}$
    - Background (cosmogenic): $\mathbf{K^o_L + p \rightarrow K^+ + n}$
- Both helpful to DUNE physics program

SNEWS

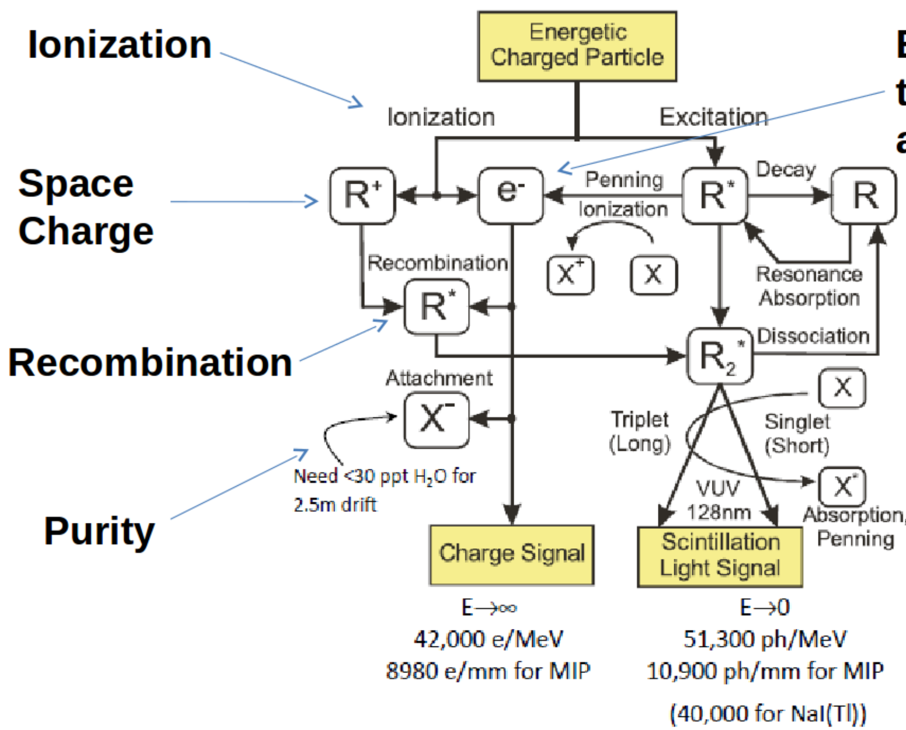


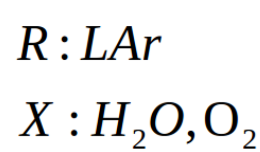


Detector Physics



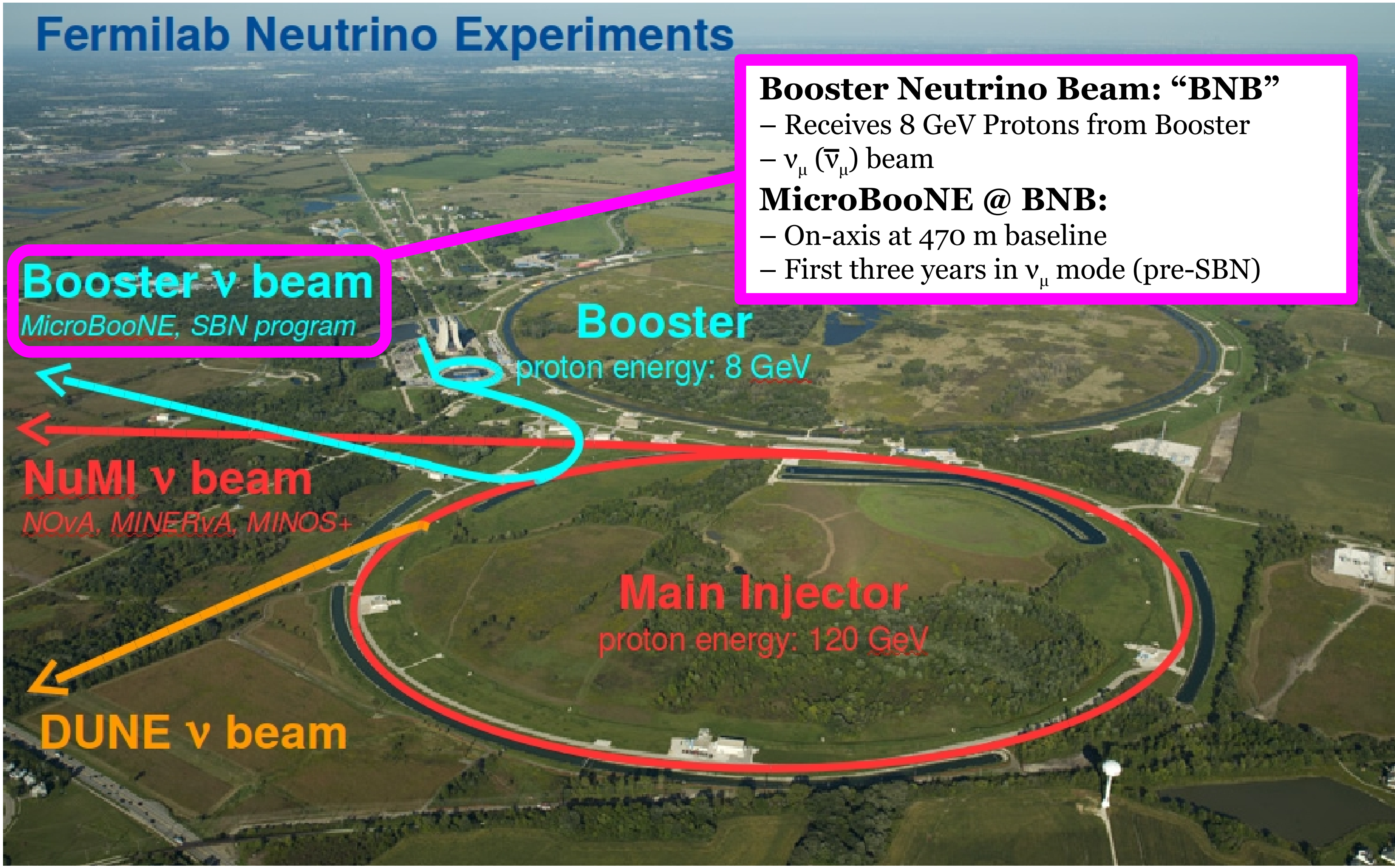
- Must understand detector effects to develop LArTPC technology
  - Essential for SBN and DUNE
  - Space charge effects (SCE), wire response, energy scale, noise studies, diffusion, e- lifetime, etc.





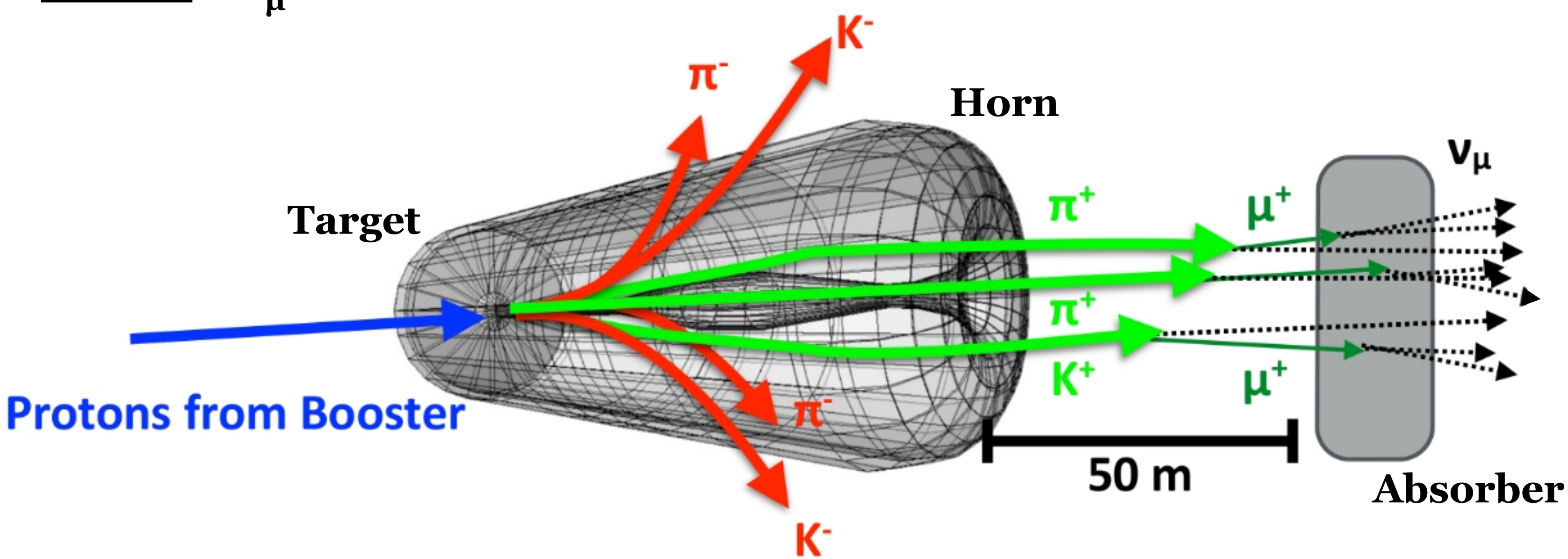
Important to understand detector effects and develop calibration scheme for unbiased, precise determination of ionization charge.

Booster Neutrino Beam



BNB Overview

- Protons hit beryllium target producing mesons
- Magnetic field of horn focuses positive mesons, defocuses negative mesons
- 50 m decay pipe for $\boldsymbol{\pi^+}$ and $\mathbf{K^+}$ decay to primarily $\boldsymbol{\mu^+}$ and $\boldsymbol{\nu_\mu}$
- Layers of steel and concrete absorb charged particles
- <u>Result</u>: $\boldsymbol{\nu_\mu}$ **beam**



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