MicroBooNE Calibrations

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DUNE Calibration Mini-Workshop – July 26th, 2017

Introduction

- Calibrations are an important part of MicroBooNE's physics program
- Two goals:
  - Ensure data/MC agreement
  - Maximize physics reach of detector technology
- First point above can in principle be realized by simulating certain effects, but the second requires calibration program
  - Desire is to produce unbiased physics measurements with maximal physics sensitivity
- Will focus on MicroBooNE today, drawing connections to DUNE FD and ProtoDUNEs where applicable
  - But majority of DUNE-related content will be saved for tomorrow (8:00-8:30 am CT talk by M. Mooney)

TPC Calibration Items

- Two fundamental ways in which adverse detector effects impact reconstruction of data events:
  - Reconstruction inefficiency
  - Misreconstruction (e.g. biased calorimetry)
- Often both result from a given effect (e.g. utilization of incorrect wire field response function in deconvolution)
- Primary TPC calibration topics at MicroBooNE:
  - Noise level
  - Electronics response
  - Wire field response
  - Space charge effect
  - Electron lifetime
- Overview of each in these slides (focus solely on TPC)

TPC Calibration Items

- Two fundamental ways in which adverse detector effects impact reconstruction of data events:
    - Reconstruction inefficiency
    - Misreconstruction (e.g. biased calorimetry)
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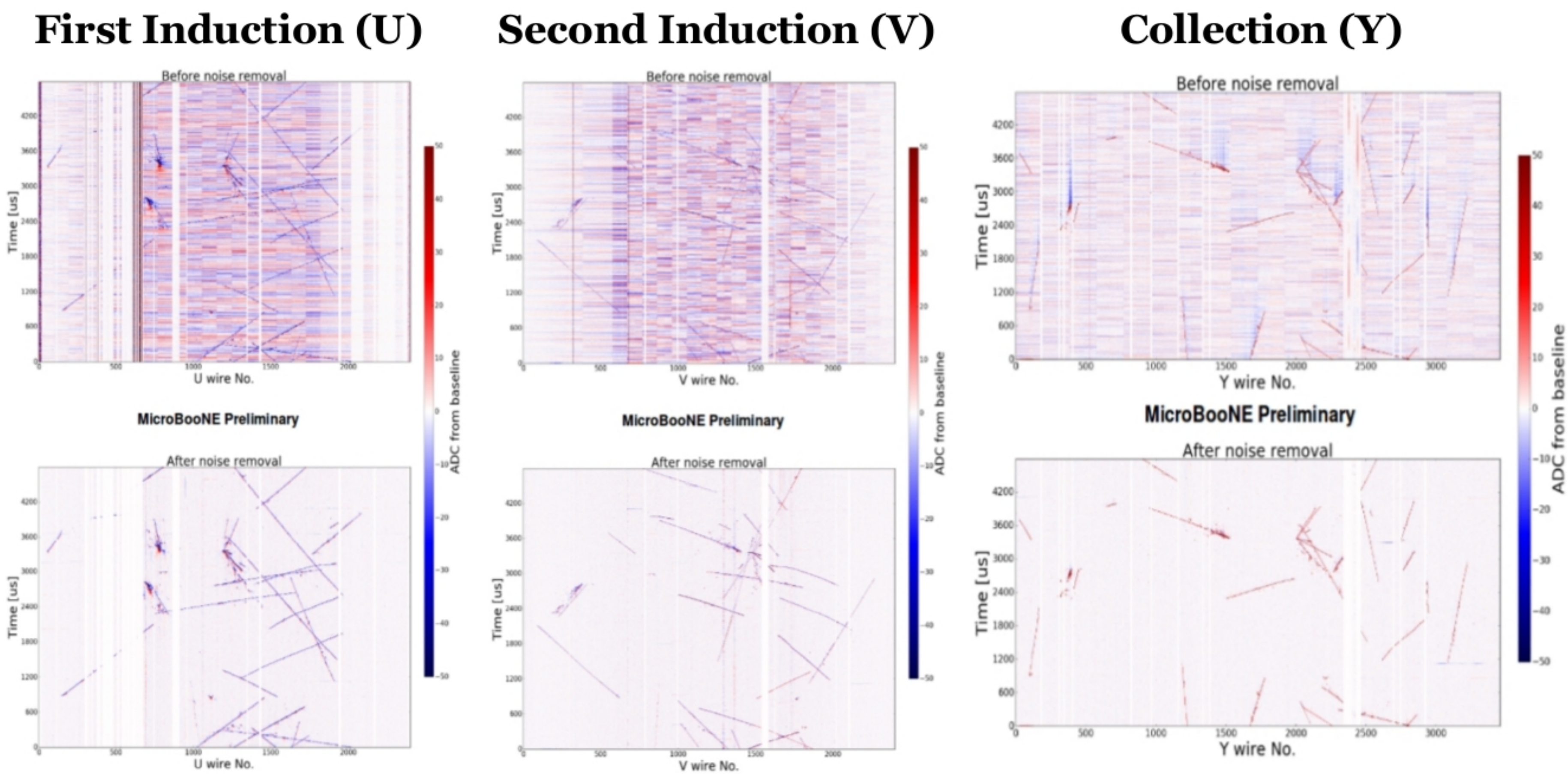
- Primary
    - Nois…
    - Electronic…
    - Wire field response
    - Space charge effect
    - Electron lifetime
- Overview of each in these slides (focus solely on TPC)

Not emphasizing measurements that can be done with other LArTPC experiments or at test stands

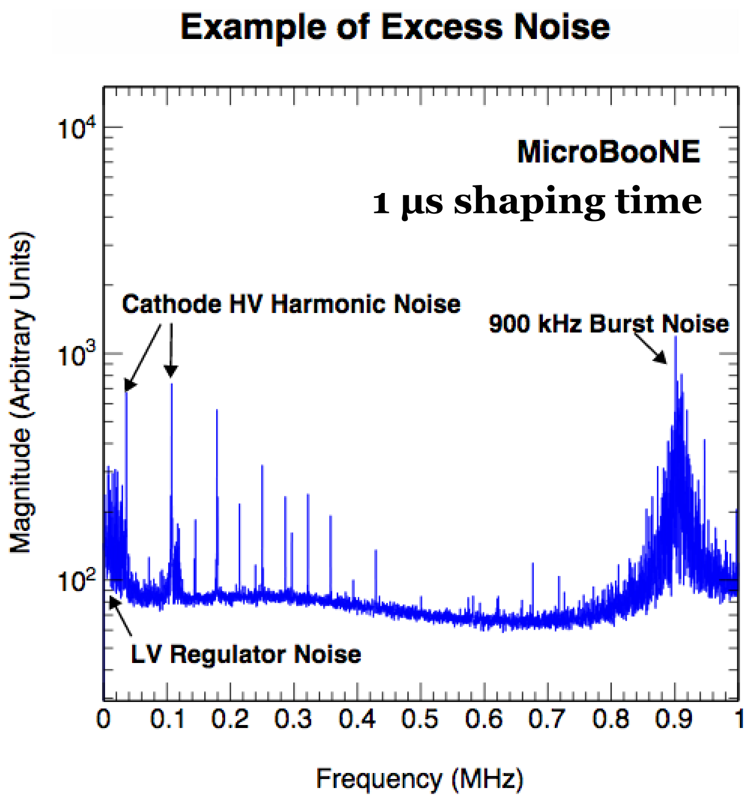
e.g. recombination, diffusion, etc.

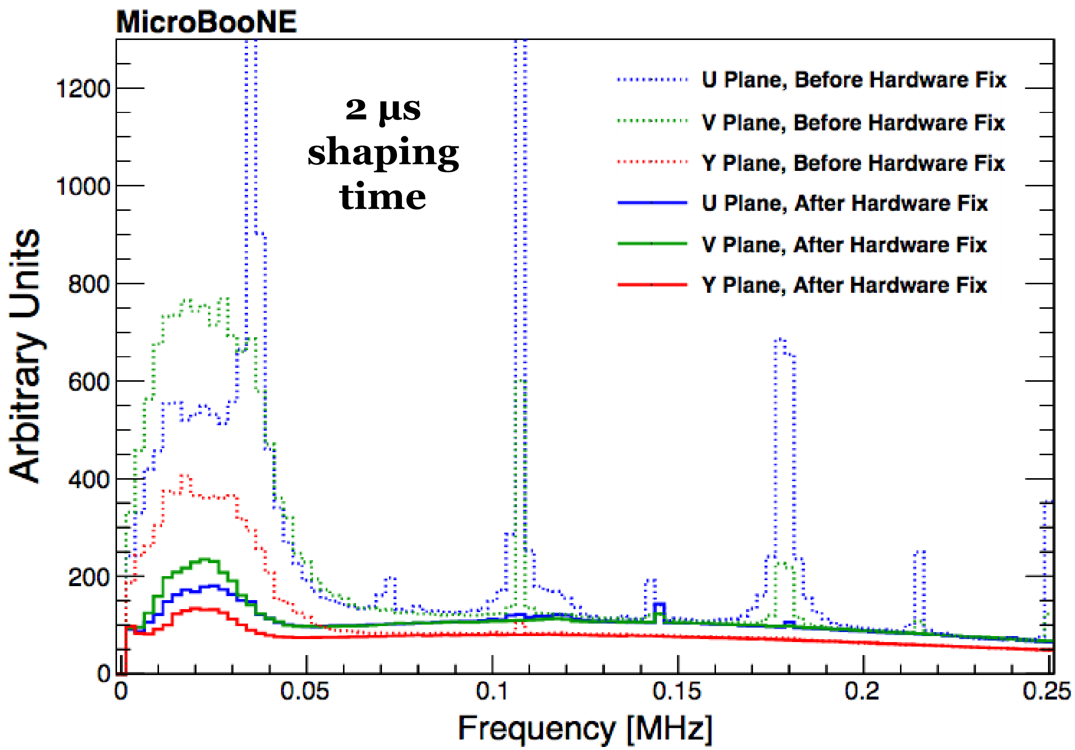
Noise Levels



- First things first: had to address noise level at beginning of operations due to various noise issues (w/ software filter)
    - Later addressed majority of noise issues in hardware

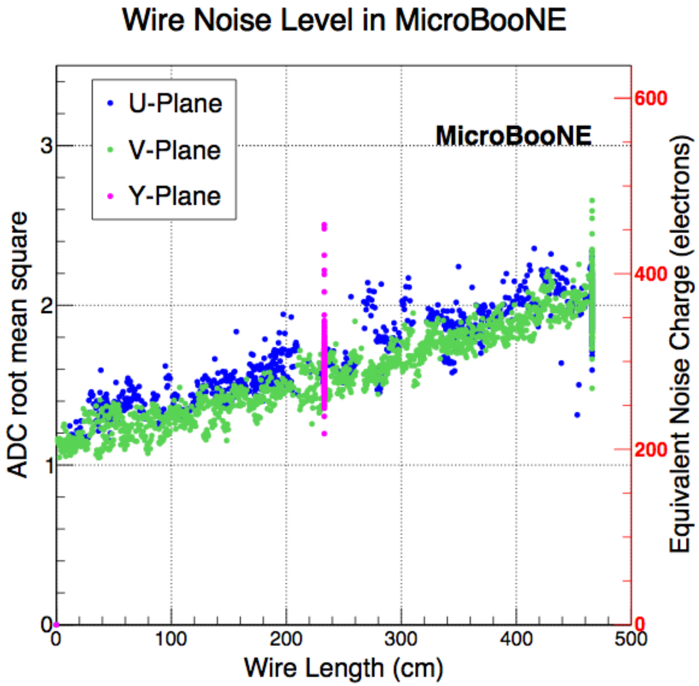
Sources of Noise

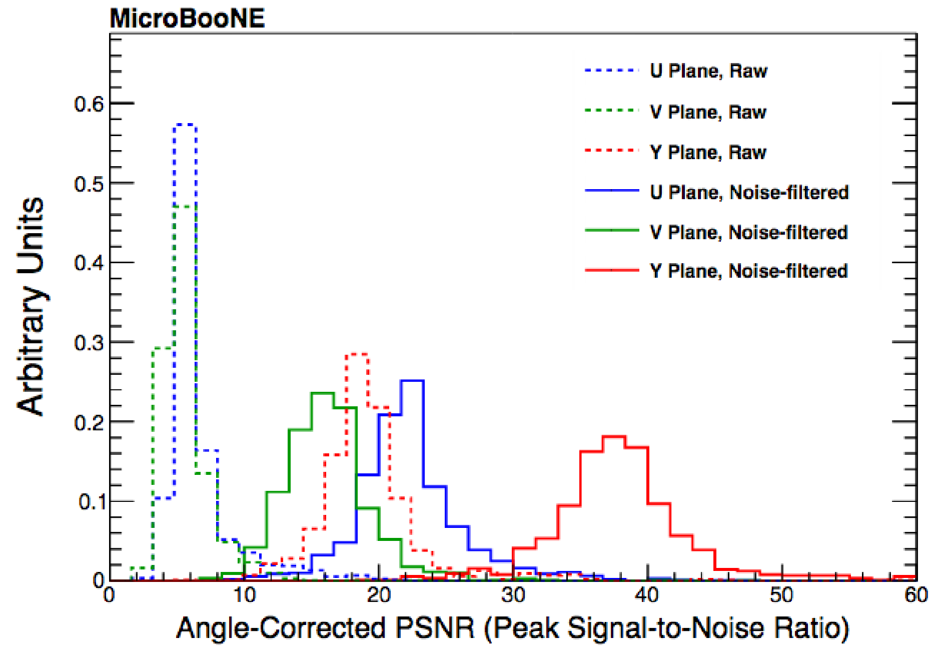




- Characterized noise sources impacting MicroBooNE – see **MicroBooNE noise paper** (recently accepted by JINST)
- Excess noise largely (~completely) removed in hardware (software)

Noise-filtering Performance





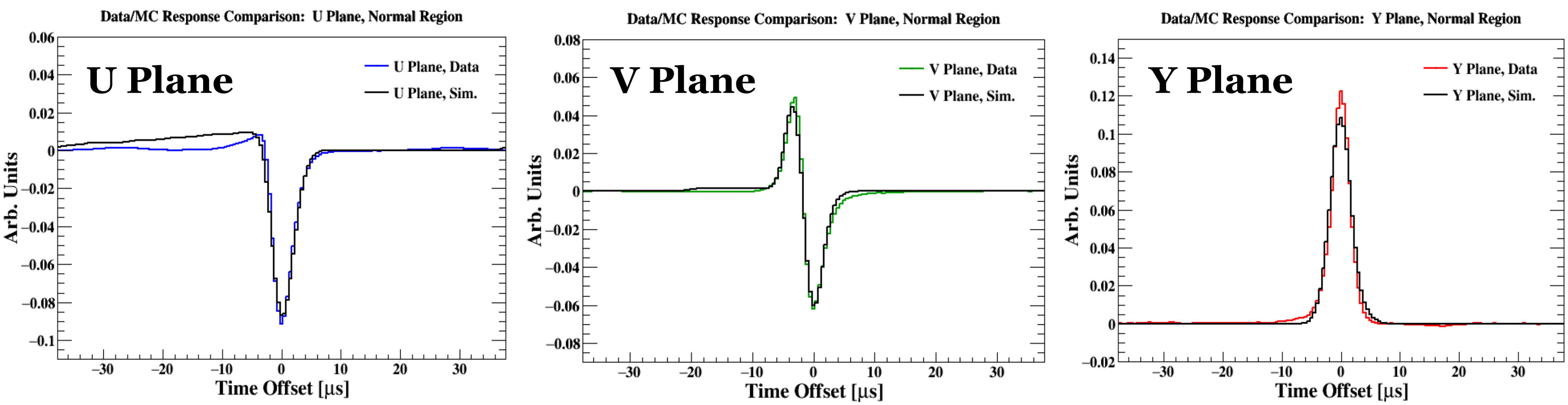
- Events visually clean and noise level scales with wire length
  - Post-filtering: PSNR > 15 (35) for induction (collection) planes
- Given near-complete removal of noise in data, **we do not simulate excess noise in MC**
  - Instead use **data-driven intrinsic noise spectrum**

Electronics Response

- Several things impact the front-end (FE) electronics response, necessitating calibration
  - Imperfect pole cancellation in shaping circuit (leads to dip after peak in shaping function)
  - Response/gain of intermediate amplifier
  - Different gain in-situ
  - Different shaping time in-situ
- Use **external pulser** to characterize electronics response
  - Gain and shaping times: 10% bias, uniform to 1%, time-independent
  - Incorporate into deconvolution kernel – could simulate as well
- (Warm) ADCs not perfect at MicroBooNE, but pretty close
  - Roughly 11.3 ENOB
  - Leads to slightly different amount of unshaped white noise which is accounted for in MC via data-driven noise spectrum

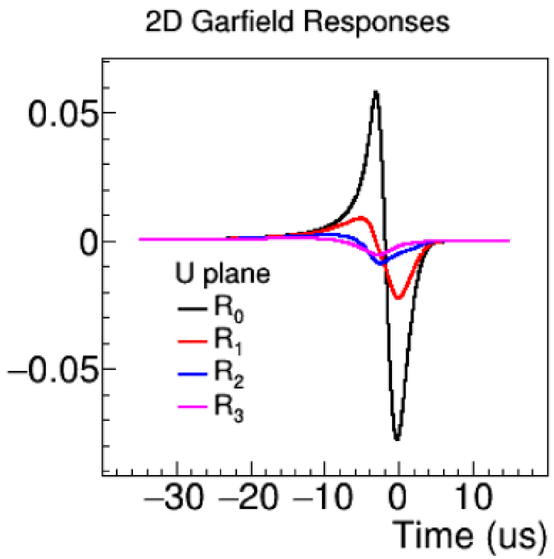
Wire Field Response

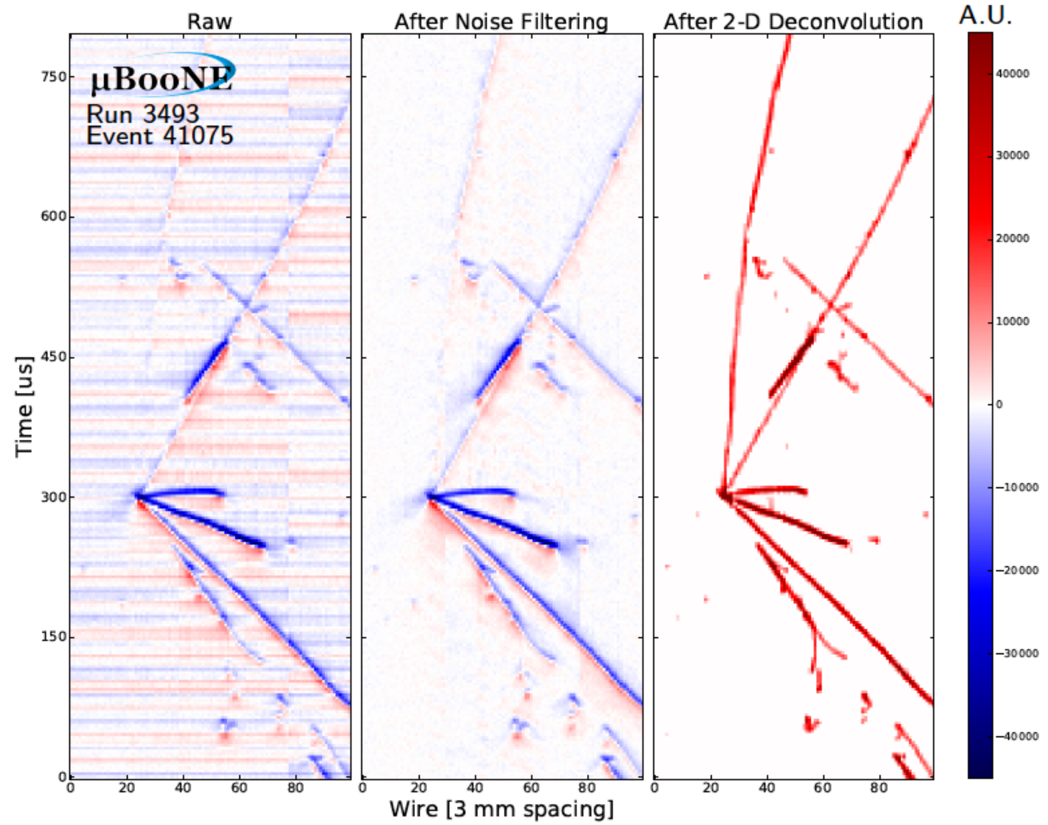
- Wire field response represents induced/collected charge due to ionization electron drift past wires
- Calculate using Garfield-2D, use in simulation
  - However, simulation may not represent data perfectly
  - Use comparison to data-driven response (obtained by utilizing t_0-tagged cosmic tracks) to **tune simulated responses**
- Vary residual differences as systematic in physics analyses



2D Deconvolution

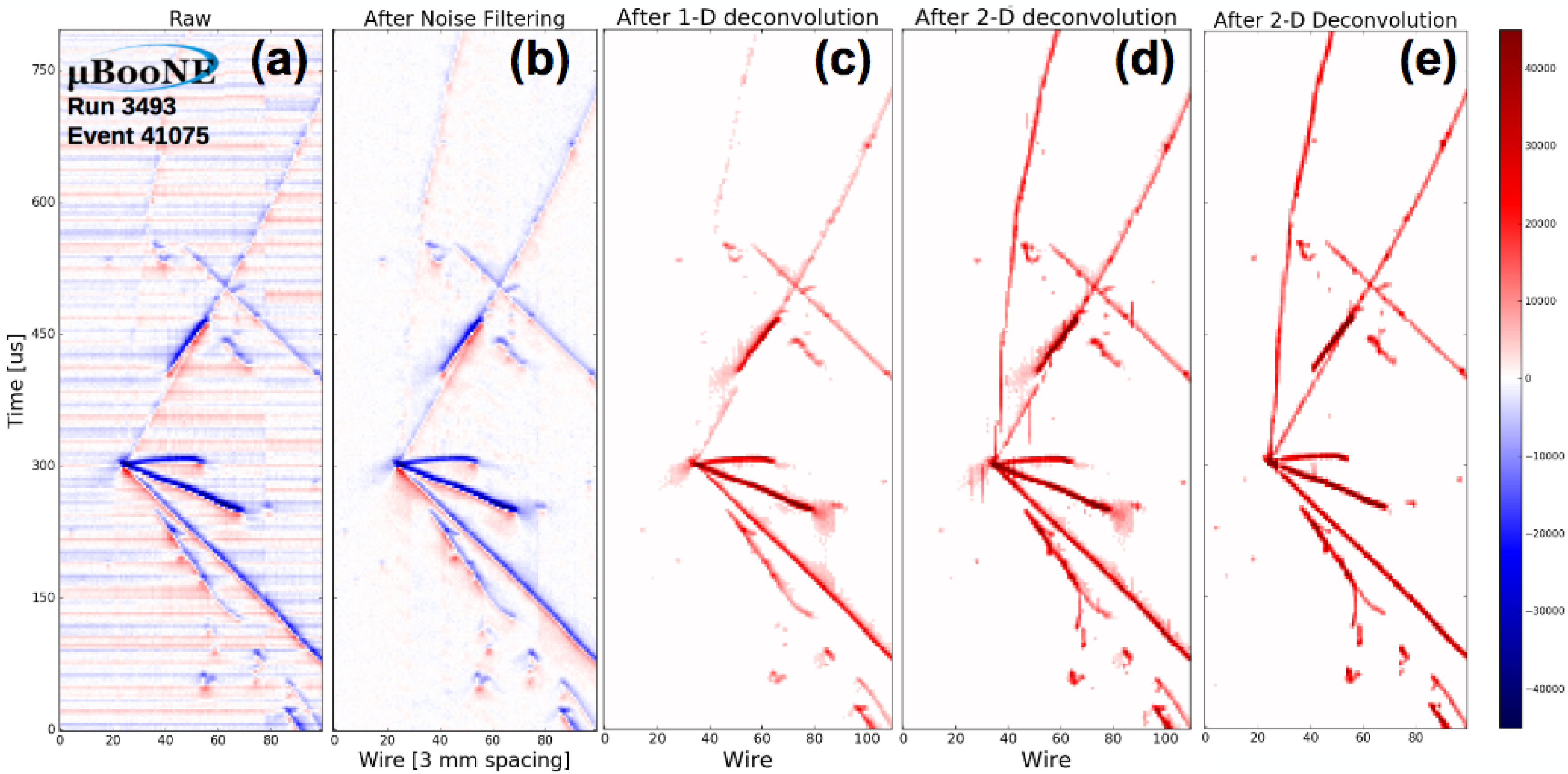
First Induction (U) Plane





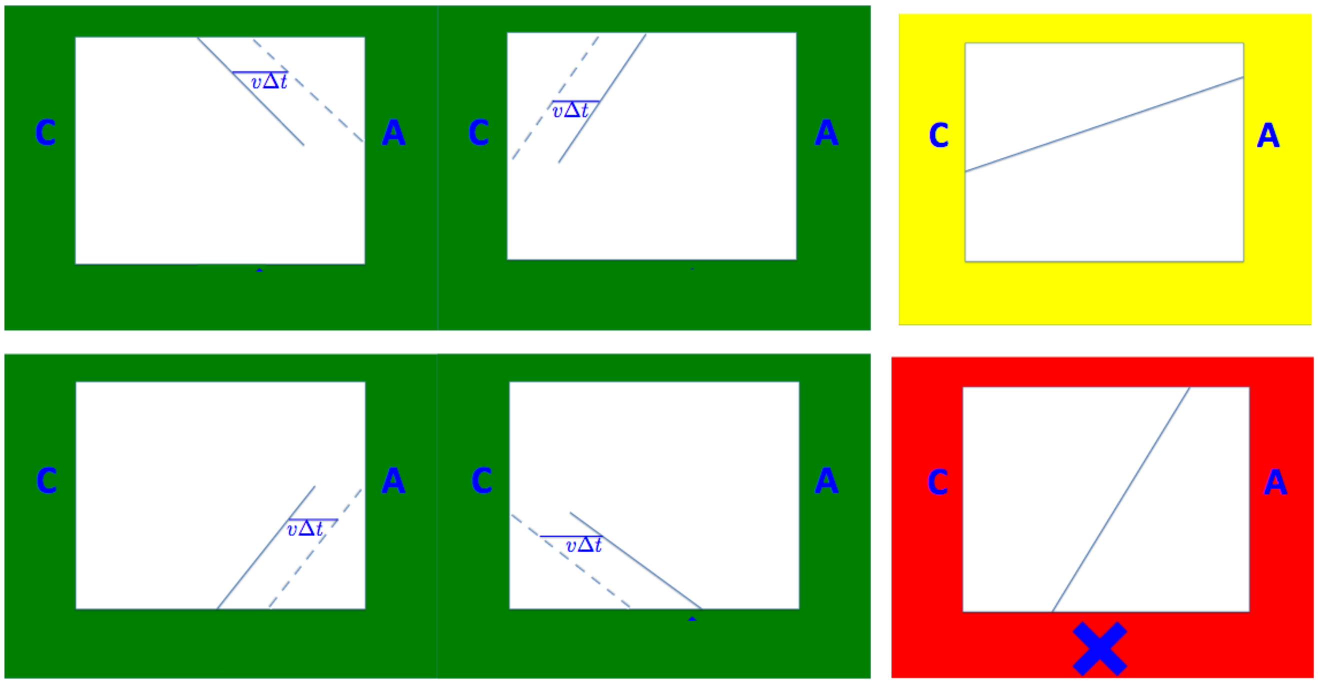
- "Remove" wire response in deconvolution using tuned sim.
  - Includes charge induced on wires neighboring the wire closest to ionization electrons (mainly U/V planes) → "2D deconvolution"
  - See **MicroBooNE public note on signal processing**

2D Deconvolution (cont.)

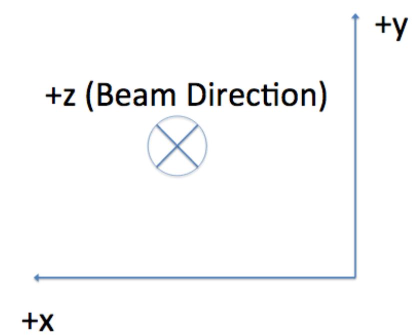


U plane from Event 41075, Run 3493. (a) Raw digits. (b) Raw digits after noise filtering[2]. (c) 1-D Deconvolved signal. (d) 2-D Deconvolved signal. (e) 2-D Deconvolved signal with improvements

Interlude: t_o-tagged Tracks



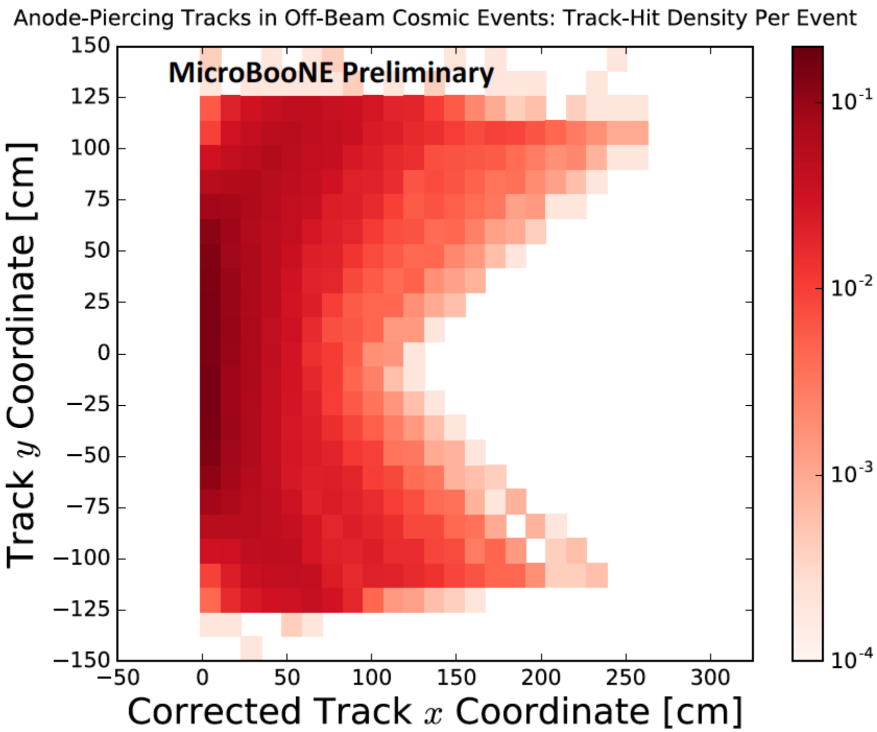
C. Barnes,
D. Caratelli,
M. Mooney



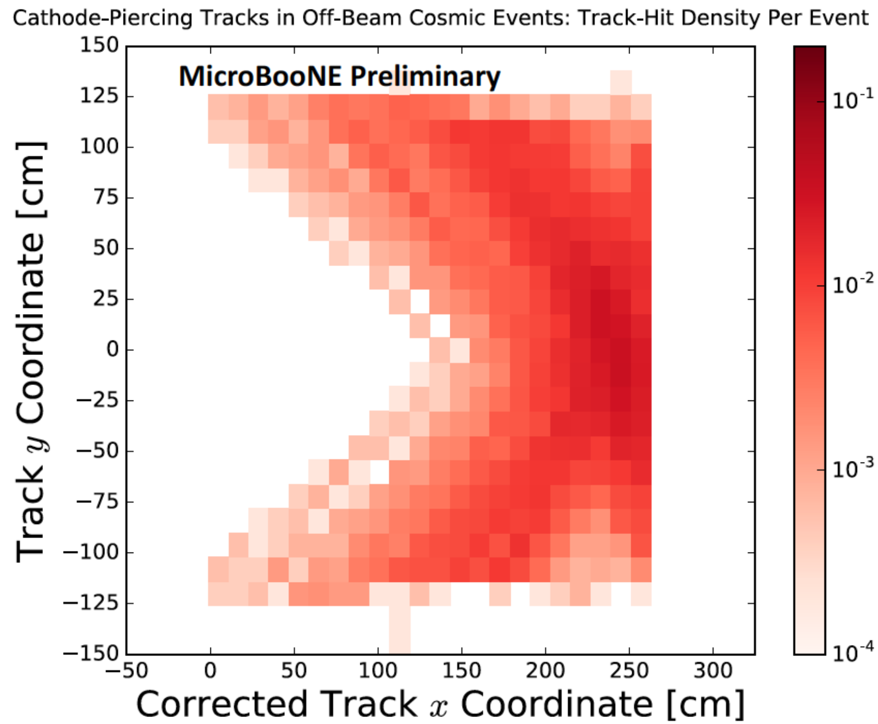
- Can tag cosmic muon t_o with TPC info (purify with PMTs)
  - Side-piercing tracks: assume through-going, use geometry
  - Cathode-anode crossers: projected *x* distance is full drift length
  - ProtoDUNEs and DUNE FD also get cathode-crossers
- Public note from MicroBooNE coming out on this soon

t_0-tagged Track Coverage

Anode-Piercing Tracks



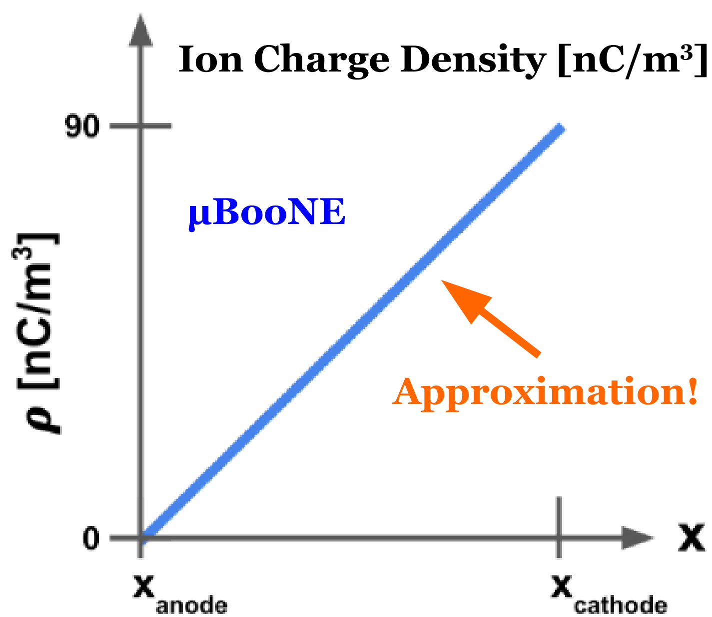
Cathode-Piercing Tracks

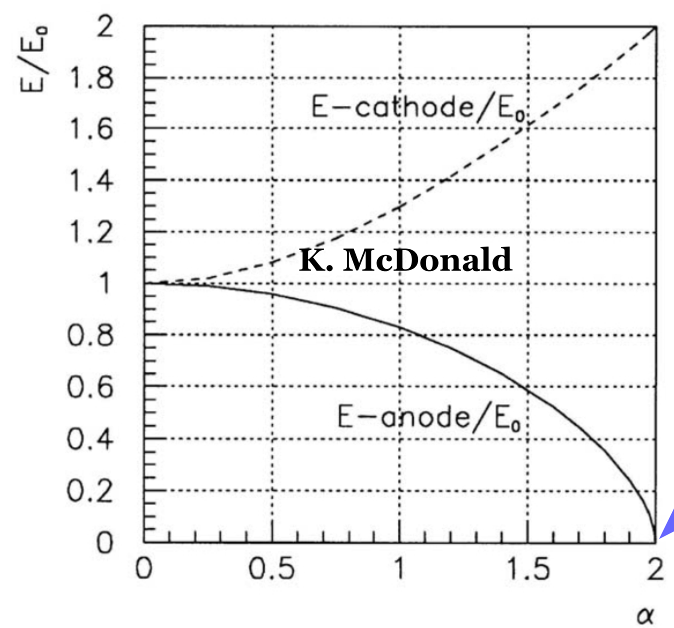


- Obtain O(1) t_0-tagged track per event, ~98% purity
  - Tracks crossing Y faces shown (sample also exists for Z faces)
- Gap in center of TPC – CRT will significantly add coverage

Space Charge Effects

- MicroBooNE is on surface $\rightarrow$ space charge effects (SCE)
- Space charge (slow moving argon ions) will pull drifting ionization electrons inward toward the center of the drift volume
  - Modifies E field in TPC, thus recombination level (dQ/dx)
  - Modifies spatial information, thus track/shower direction, dQ/dx
  - Magnitude of spatial distortions scales with D^3, $E^{-1.7}$



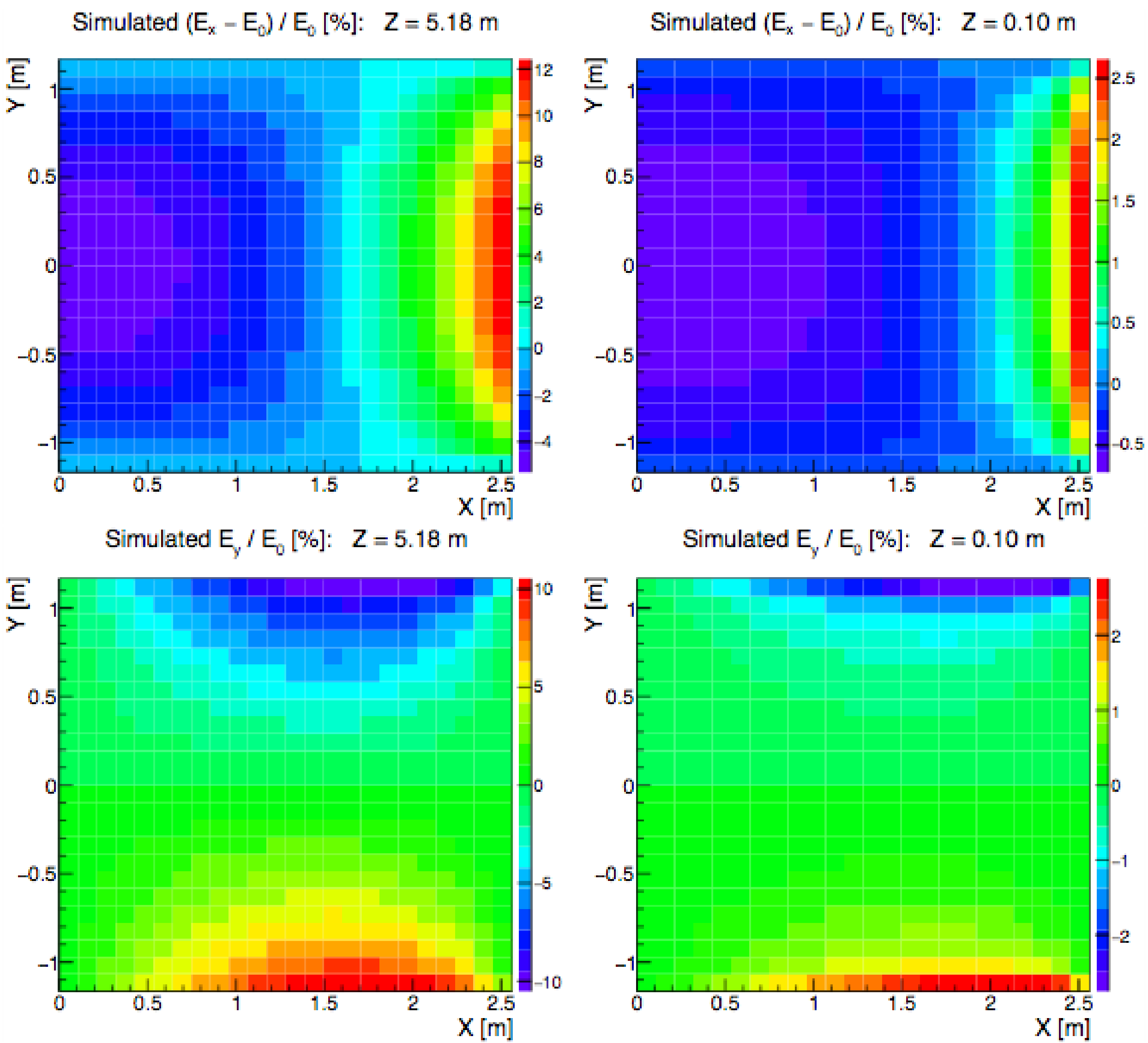


$$\alpha = \frac{D}{E_0}\sqrt{\frac{K}{\epsilon\mu}}$$

$$\mathbf{v} = \mu\mathbf{E}$$

No Drift!

SCE Simulation – E Field



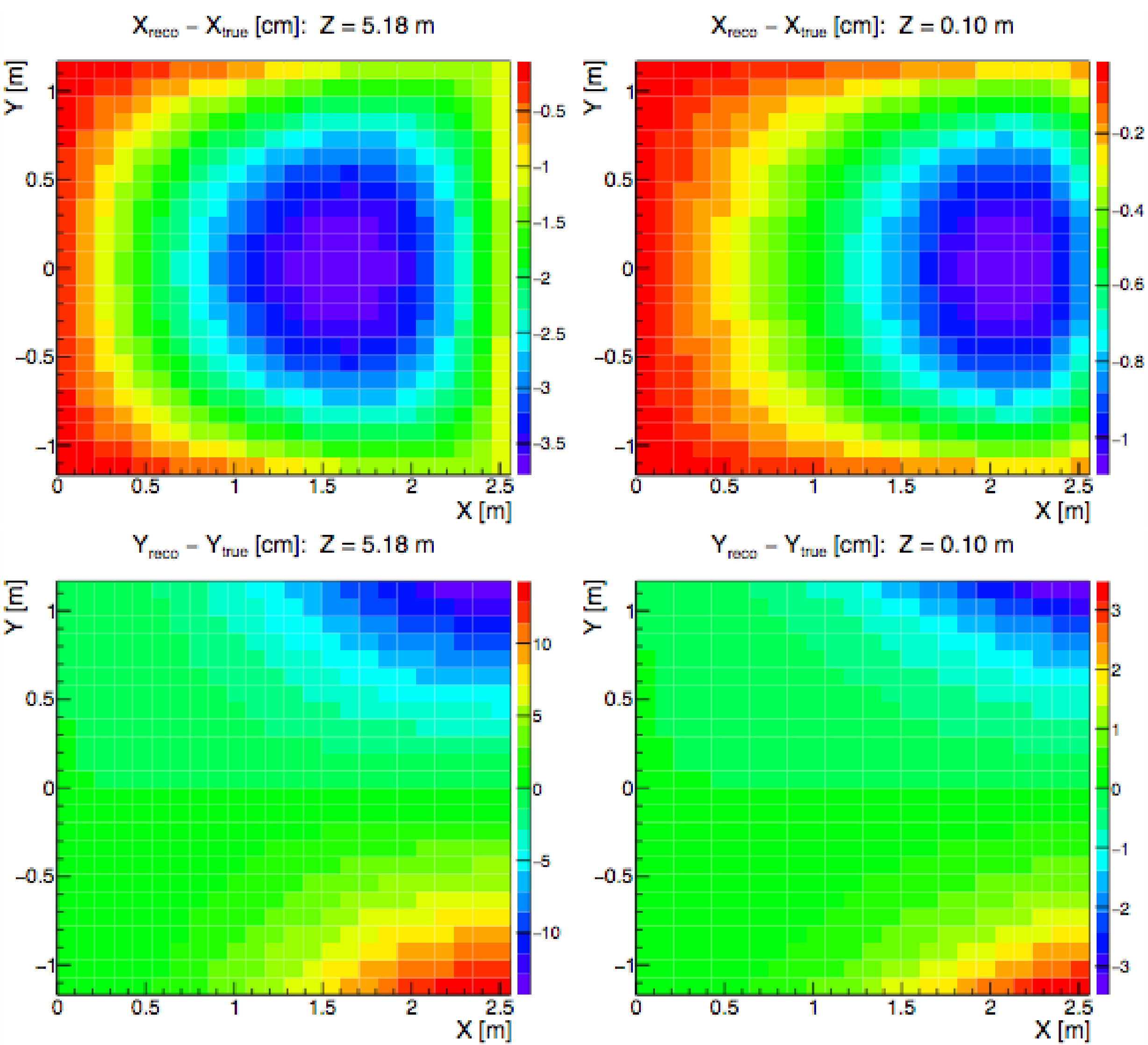
273 V/cm

Central Z Slice (Max Effect)

Cathode On Right (One Drift Volume)

Drift Coordinate: X
Beam Direction: +Z (Into Page)

SCE Simulation – Spatial



273 V/cm

Central Z Slice (Max Effect)

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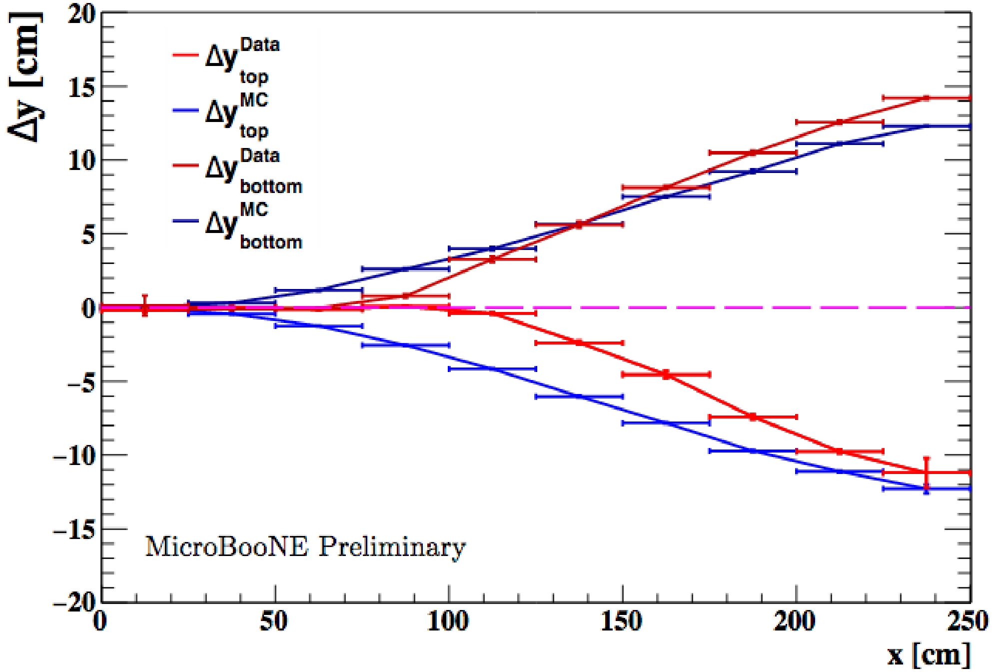
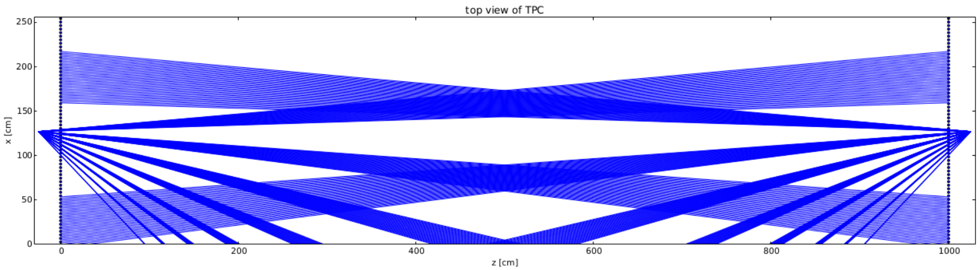
μBooNE SCE Data/MC Comp.



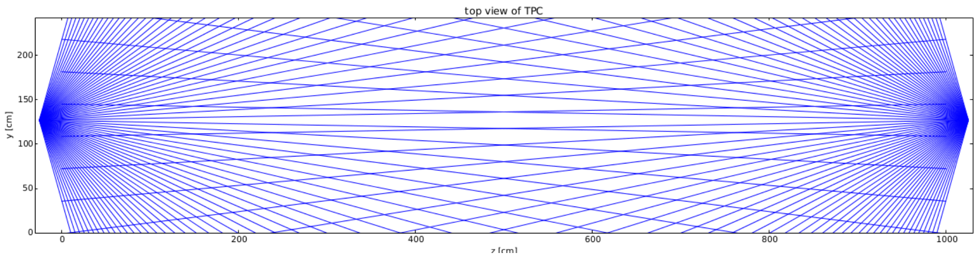
- Compare data to SCE simulation at top/bottom of TPC
  - See **MicroBooNE space charge effect public note**
  - Good agreement, small shape deviations (liquid argon flow?)
- Calibrate out of data with laser/cosmic tracks, vary residual differences as systematic in physics analyses

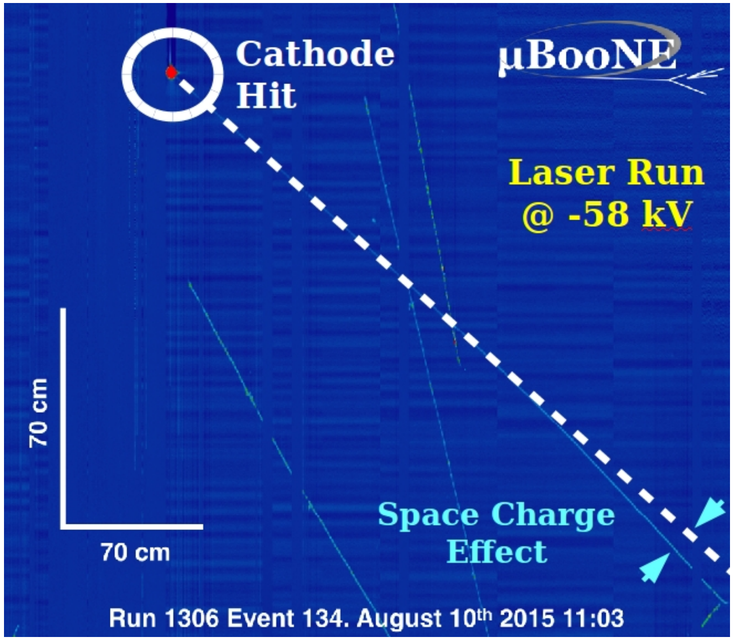
SCE Calib. via Laser System

Simulated Laser Coverage: X-Z Plane



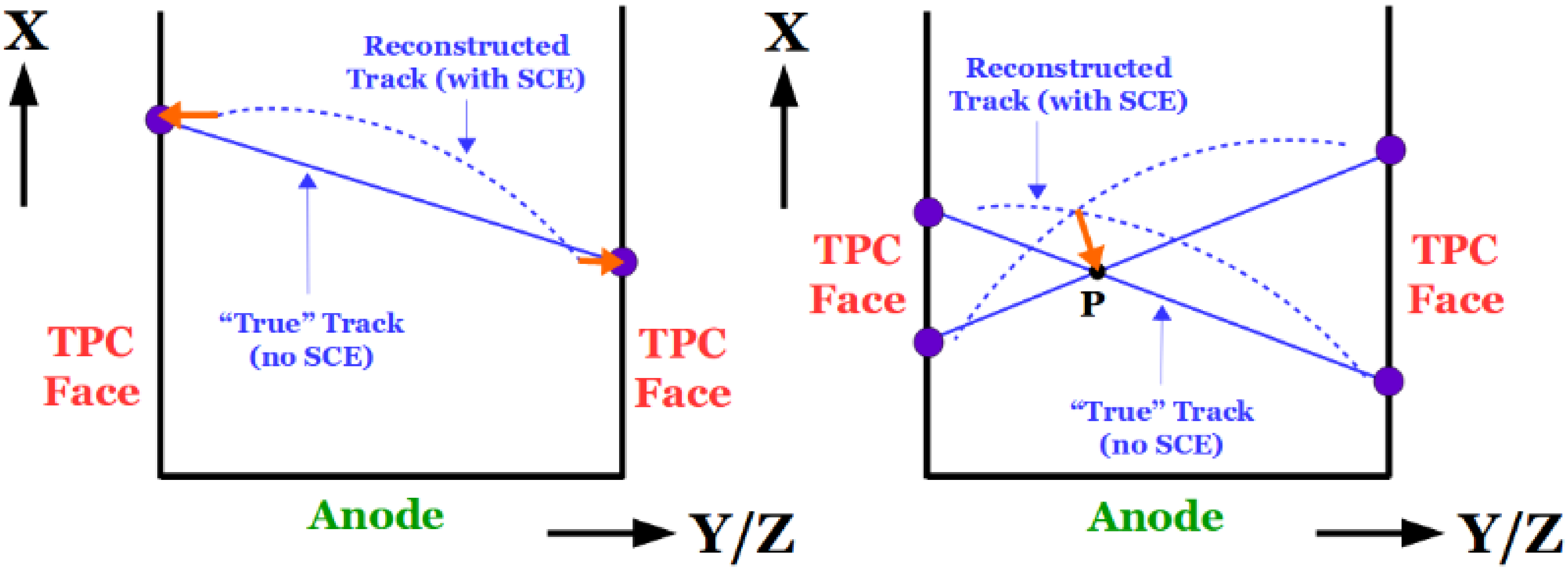
Simulated Laser Coverage: Y-Z Plane





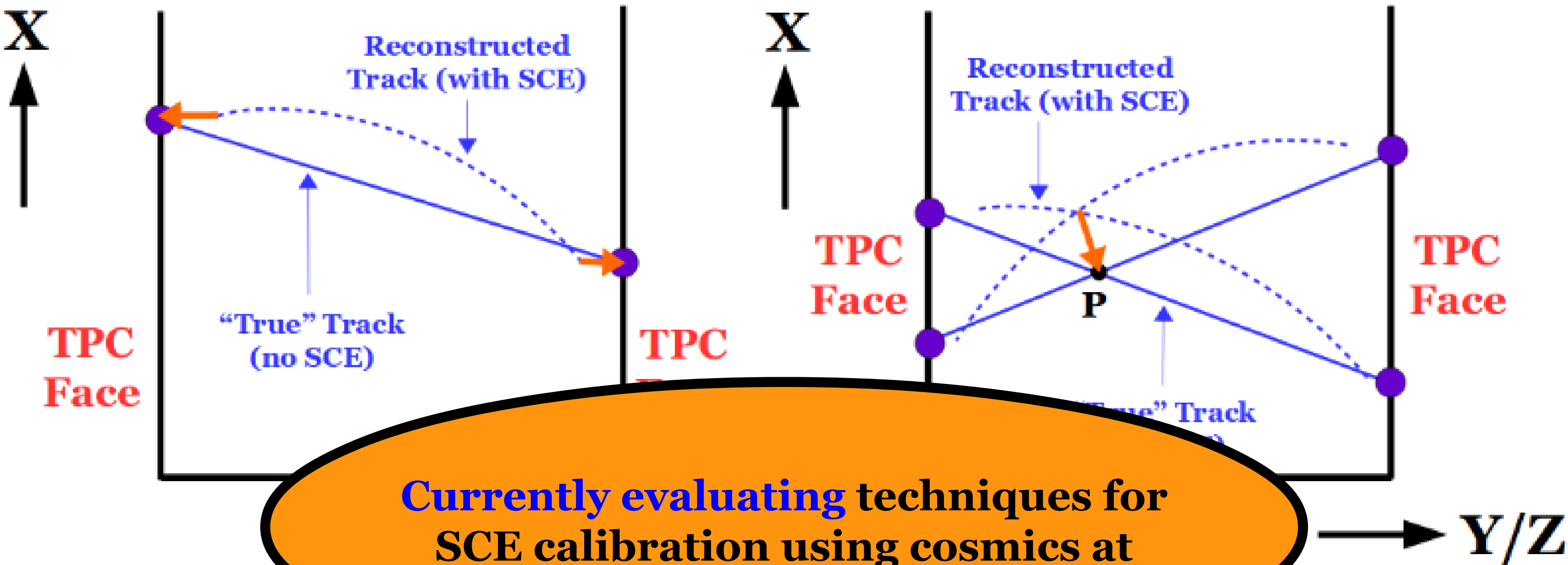
- Can calibrate out SCE with UV laser system quite well
  - Know true laser track position
- Complications due to gaps in coverage, potentially time-dependence → complementarity from cosmic muons

SCE Calibration w/ Tracks



- Two samples of t_o-tagged tracks can provide SCE corrections:
  - Single tracks – enable corrections at TPC faces by utilizing endpoints of tracks (correction vector approximately orthonormal to TPC face)
  - Pairs of tracks – enables corrections in TPC bulk by utilizing unambiguous point-to-point correction looking at track crossing points
- Require high-momentum tracks (plenty from cosmics, beam halo)

SCE Calibration w/ Tracks



Currently evaluating techniques for SCE calibration using cosmics at MicroBooNE

- Two samples of t_0 … corrections:
  - Single tracks – enable corrections at TPC faces by utilizing endpoints of tracks (correction vector approximately orthonormal to TPC face)
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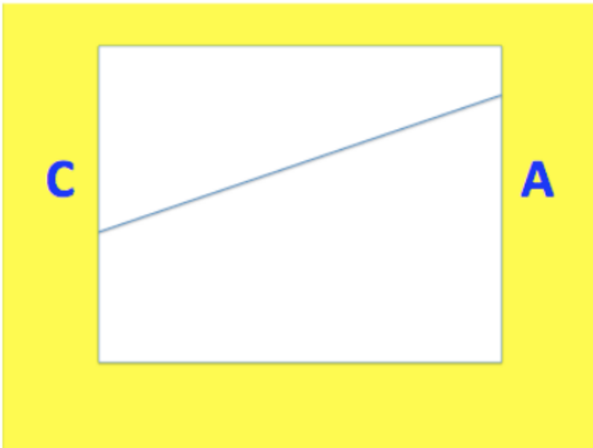
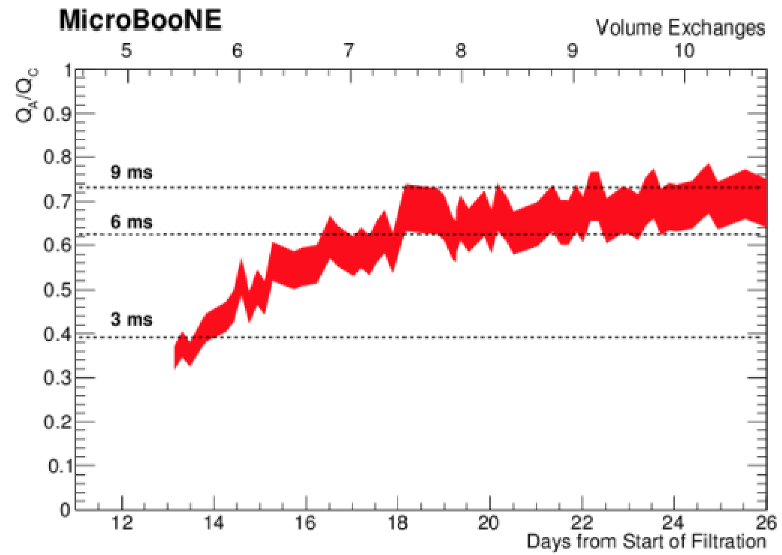
Electron Lifetime





- Natural to **calibrate out SCE first** before electron lifetime: SCE results in spatial **and** charge variations, while electron lifetime strictly influences amount of charge collected
- Measure in data using cathode-anode crossing tracks
- Electron lifetime known to be quite high at MicroBooNE since first operations (purity monitors, signal-to-noise ratio)
    - Likely small impact for physics – might not be the case for DUNE

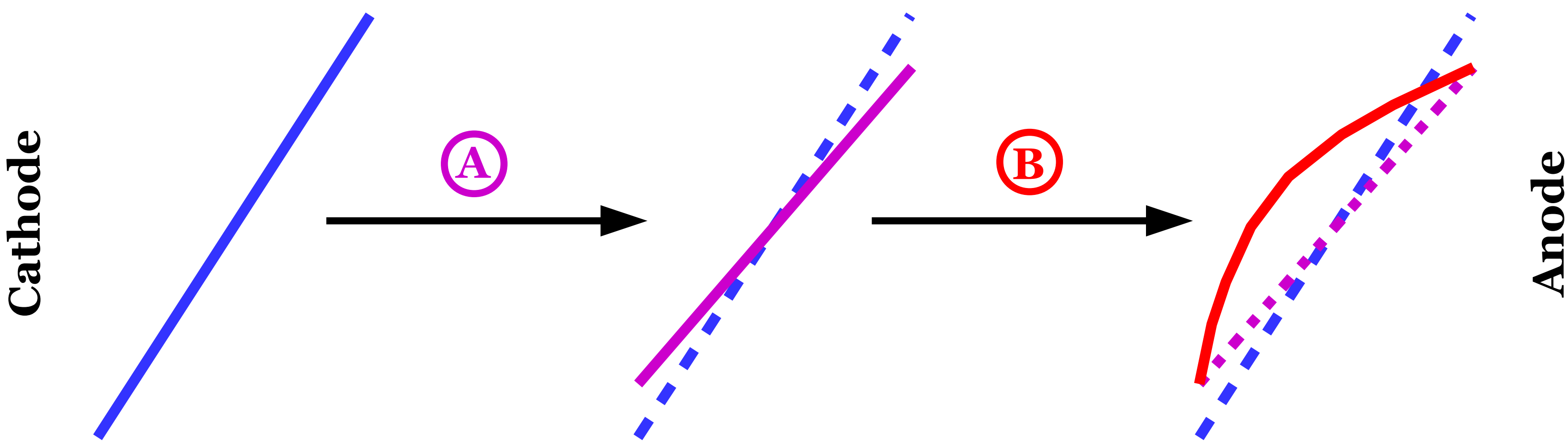
Summary

- Discussed calibrations utilizing TPC noise data, external pulser, t_o-tagged cosmic muons, and UV laser system
  - Did not cover CRT (for t0-tagging of cosmics) since not yet been integrated into our data stream – should be ready by end of year
  - CRT will especially aid calibration of space charge effects
- Calibration program at MicroBooNE **still in progress**
  - Limited people-power → must prioritize
- If I had to guess, biggest systematics at MicroBooNE due to electronics/field response shape and space charge effects
  - High electron lifetime means purity not much of an issue, and noise largely removed with hardware/software noise filtering
- For discussion: **MicroBooNE public notes**

BACKUP SLIDES

Impact on Track Reco.

- Two separate effects on reconstructed **tracks**:
  - (A) Reconstructed track shortens laterally (looks rotated)
  - (B) Reconstructed track bows toward cathode (greater effect near center of detector)
- Can obtain straight track (or multiple-scattering track) by applying corrections derived from data-driven calibration



SpaCE: Space Charge Estimator

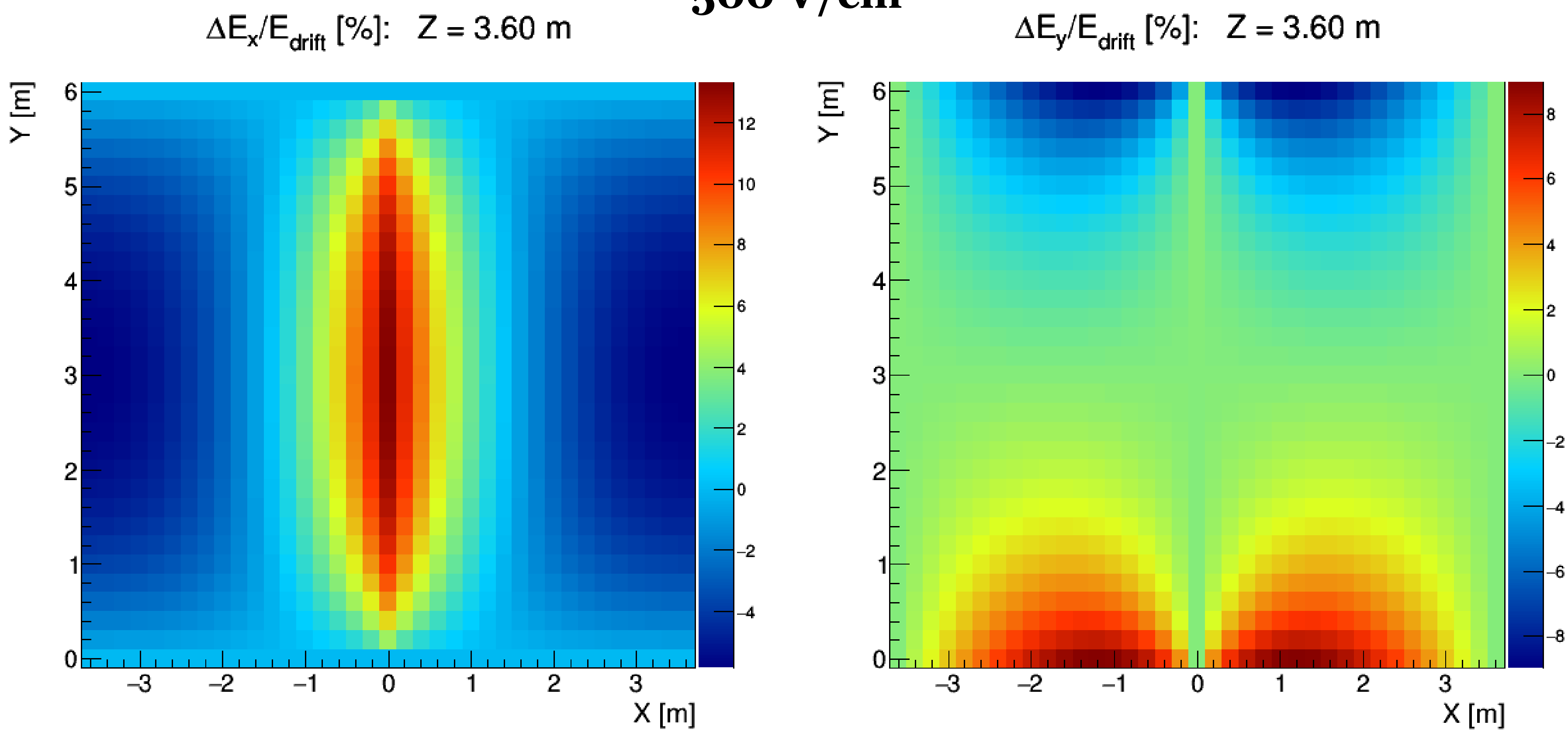
- Code written in C++ with ROOT libraries
- Also makes use of external libraries (ALGLIB)
- Primary features:
  - Obtain E fields analytically (on 3D grid) via **Fourier series**
  - Use **interpolation** scheme (RBF – radial basis functions) to obtain E fields in between solution points on grid
  - Generate tracks in volume – line of uniformly-spaced points
  - Employ **ray-tracing** to "read out" reconstructed {x,y,z} point for each track point – RKF45 method
- Can simulate arbitrary ion charge density profile if desired
  - Linear space charge density approximation for now
- Output: E field and spatial distortion maps (vs. {x,y,z})

SCE Simulation

- Can use SpaCE to produce displacement maps
  - **Forward transportation**: e.g. $\{x, y, z\}_{\textbf{true}} \longrightarrow \{x, y, z\}_{\textbf{reco}}$
    - Use to simulate effect in MC
    - Uncertainties describe accuracy of simulation
  - **Backward transportation**: e.g. $\{x, y, z\}_{\textbf{reco}} \longrightarrow \{x, y, z\}_{\textbf{true}}$
    - Derive from calibration and use in data or MC to correct reconstruction bias
    - Uncertainties describe remainder systematic after bias-correction
- Two principal methods to encode displacement maps:
  - **Parametric** representation (for now, $5^{th}/7^{th}$ order polynomials) – fewer parameters (thanks to Xin Qian for parametrization)
  - **Matrix** representation – more generic/flexible
- Module in LArSoft ready to utilize maps (E field, spatial)

ProtoDUNE-SP E Field SCE Dist.

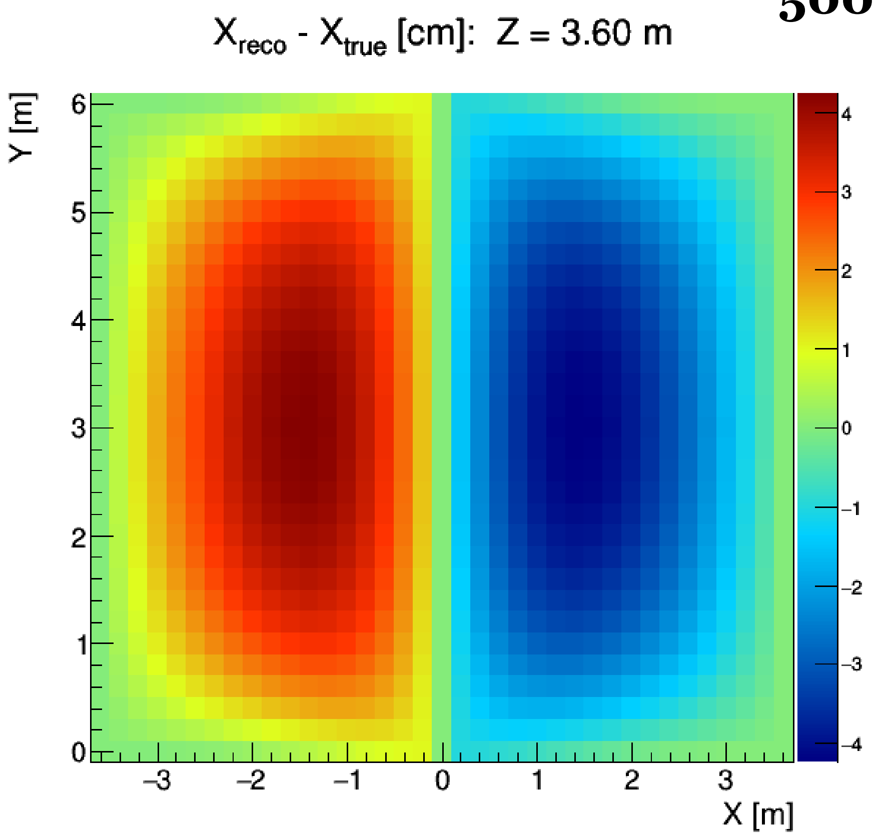
500 V/cm

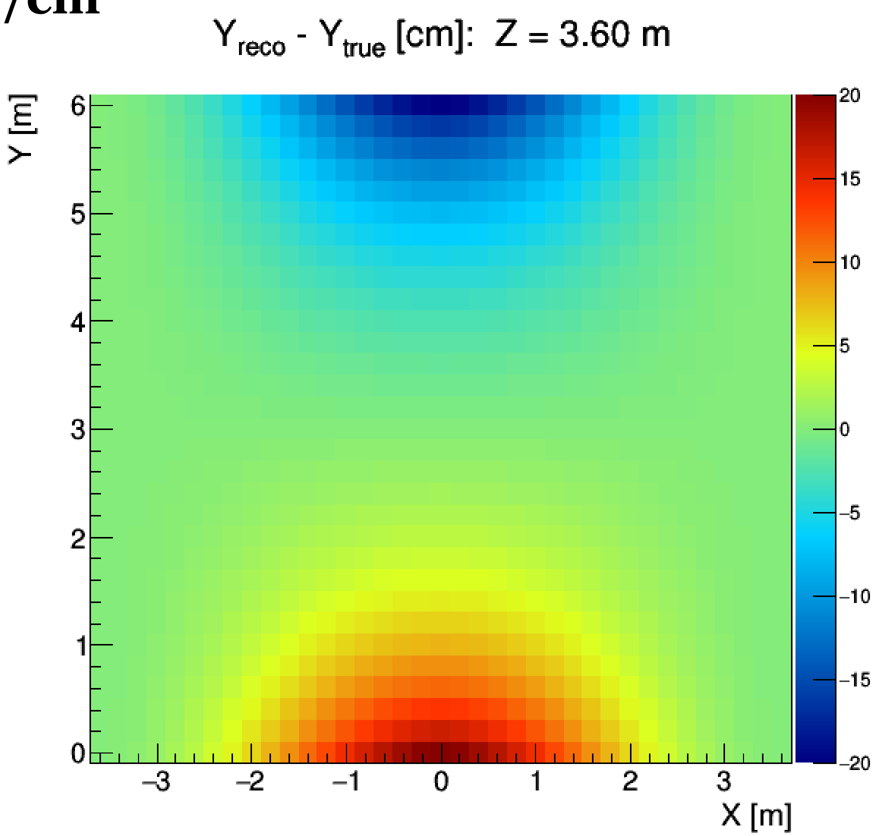


Central Z Slice (Max Effect)
Cathode In Middle (Two Drift Volumes)
Drift Coordinate: X
Beam Direction: +Z (Into Page)

ProtoDUNE-SP Spatial SCE Dist.

500 V/cm





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