# Detector Physics measurements in MicroBooNE

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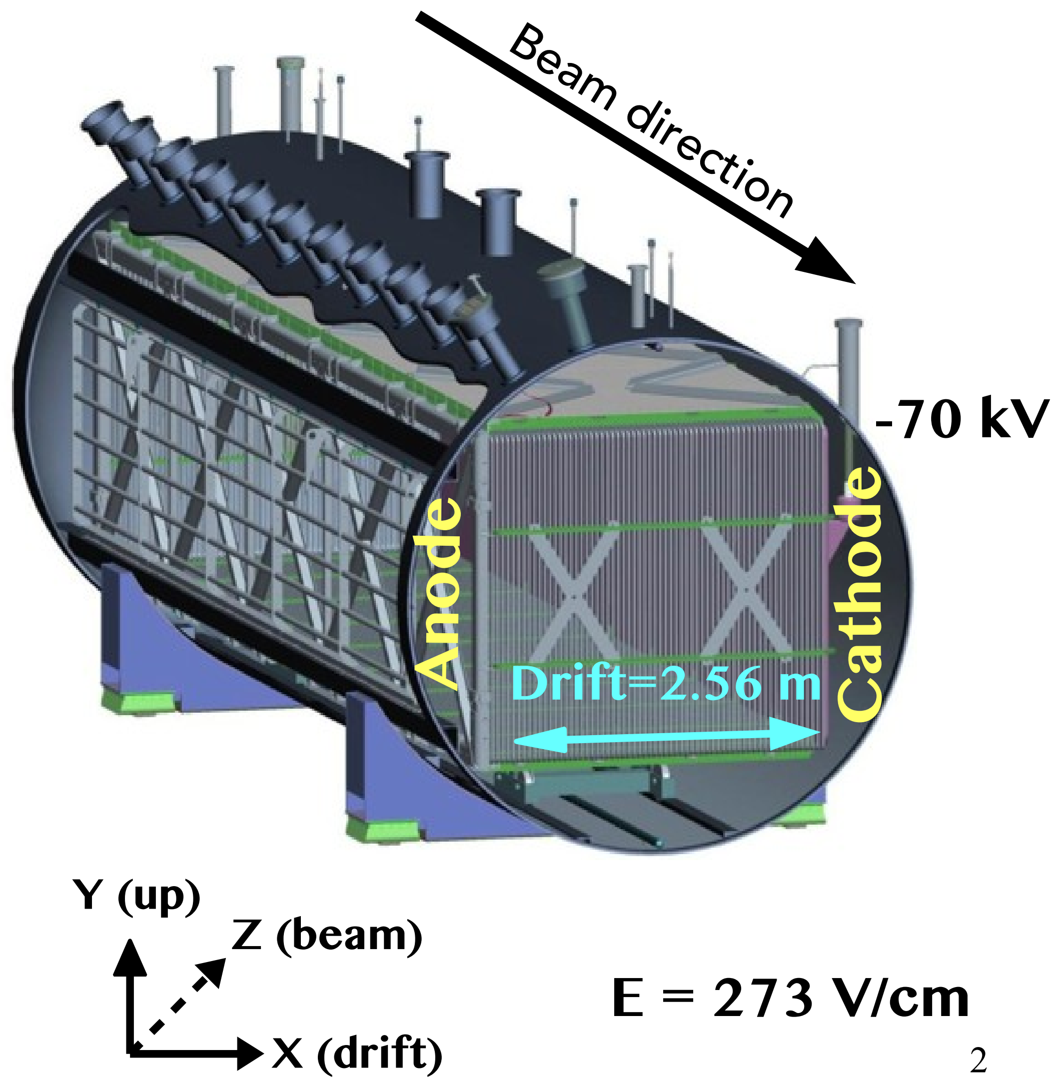
(for the MicroBooNE Collaboration)

**Joint DUNE/SBN Meeting: Lessons Learned,** Fermilab, May 15, 2017

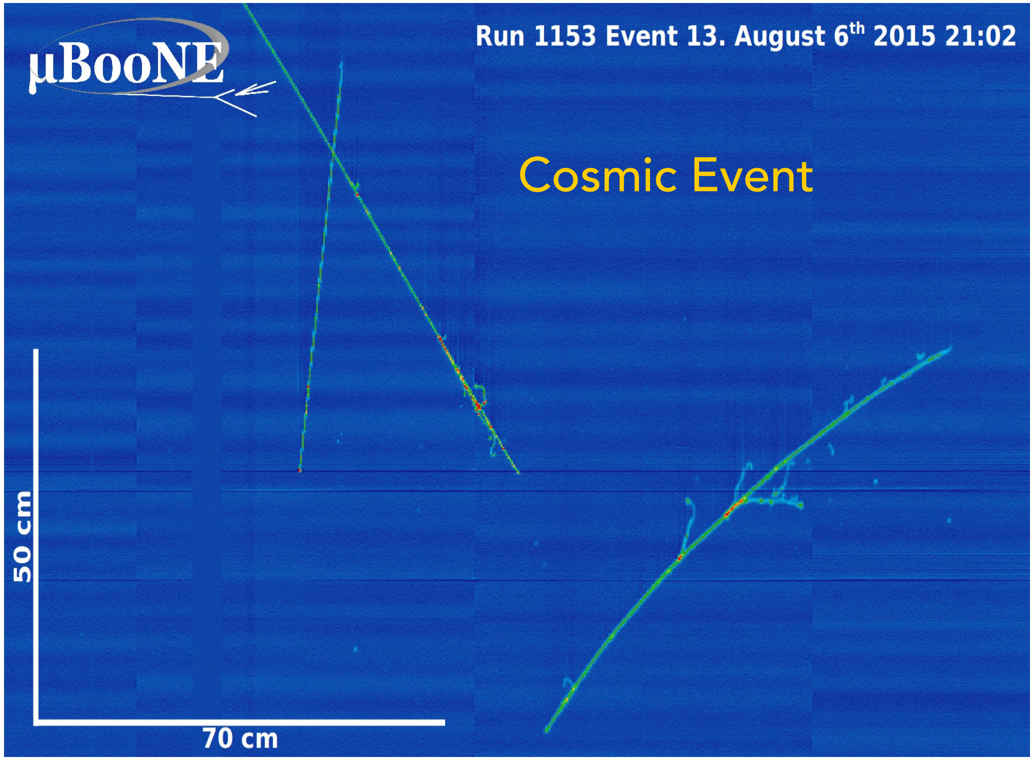
# The MicroBooNE LArTPC

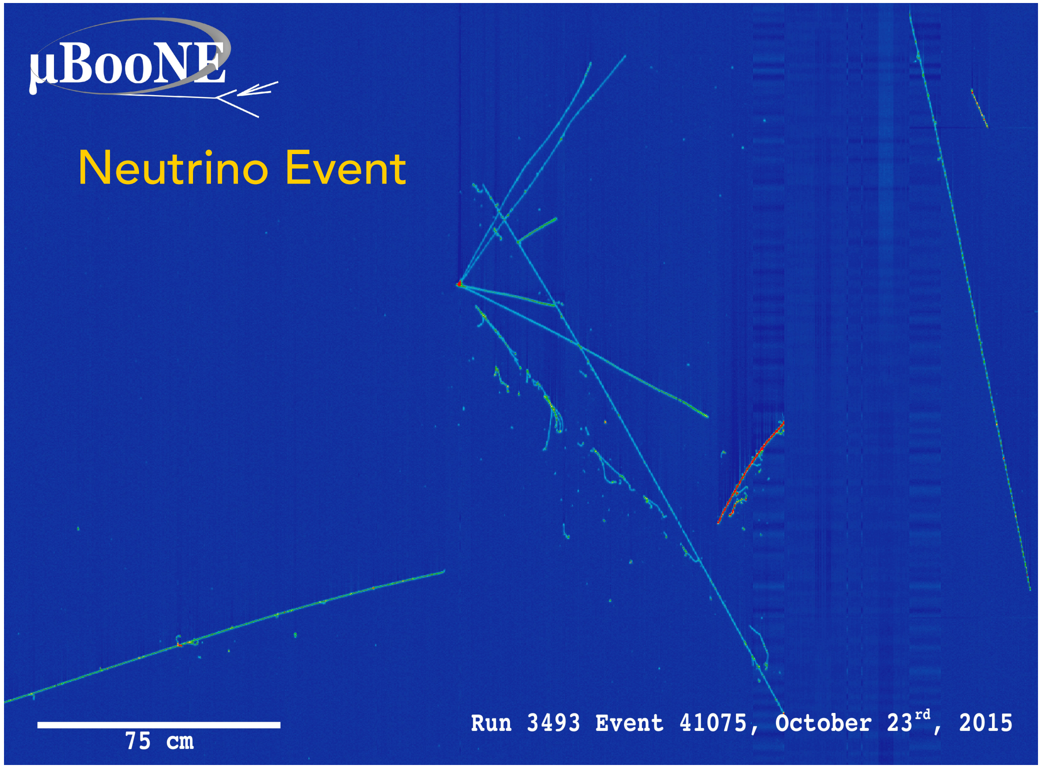
- Surface-based, 89-ton active volume liquid argon
- One drift chamber
  - Cathode at -70kV
  - Drift at 2.56 m
  - E-field at 273 V/cm
- Three wire planes
  - 2 induction, 1 collection
  - 3 mm wire pitch
  - 3 mm wire plane spacing
- PMT and UV Laser System
- Collecting cosmic and neutrino data since Fall 2015



# LArTPC Technology

- LArTPC technology provides particle interactions with unprecedented amount of detail and allows exceptional calorimetry and high resolution tracking
- However, complete understanding of the physics that surrounds the drifting electron and precise calibration are essential to achieve physics performance
  - Critical for the SBN and DUNE program
  - With plenty of data, MicroBooNE is making excellent progress towards this effort!

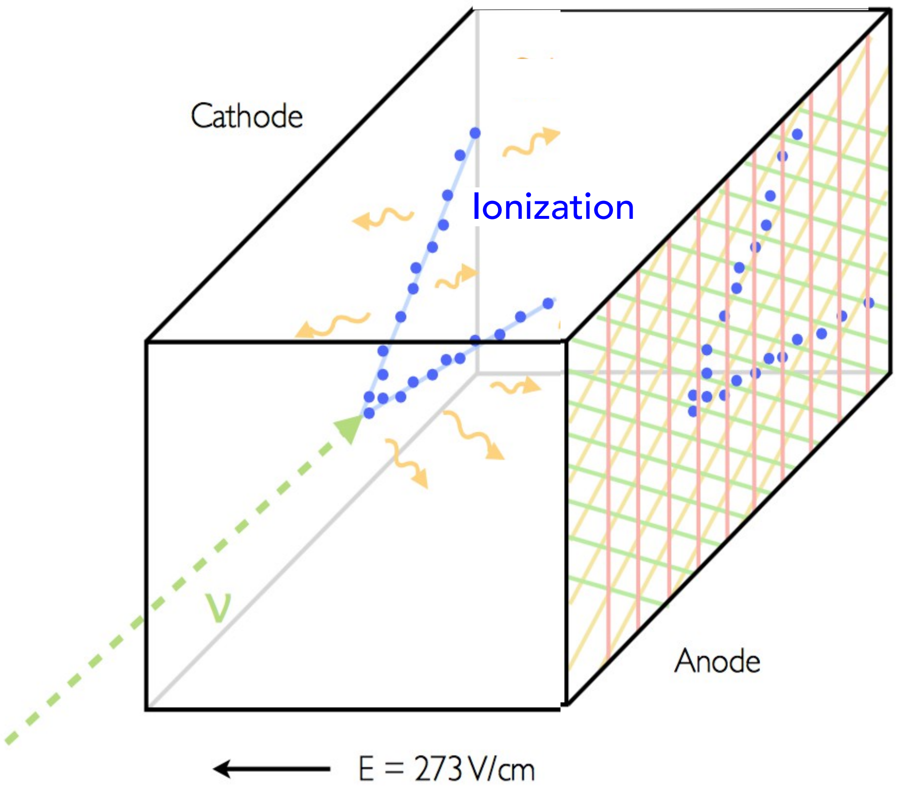


# Ionization charge in a LArTPC

- Precise determination of ionization charge and position, from the point of formation to the point of collection, with as less bias as possible is critical for both energy scale reconstruction and detector resolution
- There are many effects that can impact this

Image credit: Y.-T. Tsai



# Ionization charge in a LArTPC

- Precise determination of ionization charge and position, from the point of formation to the point of collection, with as less bias as possible is critical for both energy scale reconstruction and detector resolution

- There are many effects that can impact this, E.g.,

Energy scale

- Argon purity ($e^-$ lifetime)
- Electron-ion recombination
- Space charge
- Electronics calibration

Position/timing Resolution

- Diffusion
- Space charge
- Noise
- Wire response

These effects are not independent, everything effects everything – which is what makes this challenging!

# This Talk

We will focus on,

- Space charge effect
- Electron lifetime measurement
- Electron-ion recombination
- Electron diffusion

Example of how these effects are connected: Calorimetry

dQ/dx (ADC/cm) → dQ/dx (e/cm) → dQ*/dx (e/cm) → dE/dx (MeV/cm)

Electronics calibration factor

Purity correction

Electron-ion Recombination Correction

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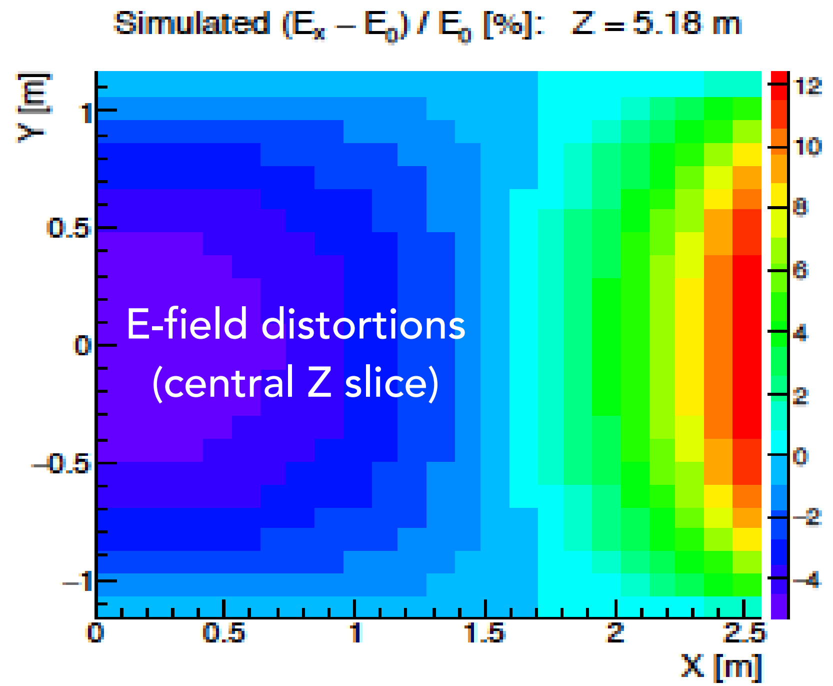
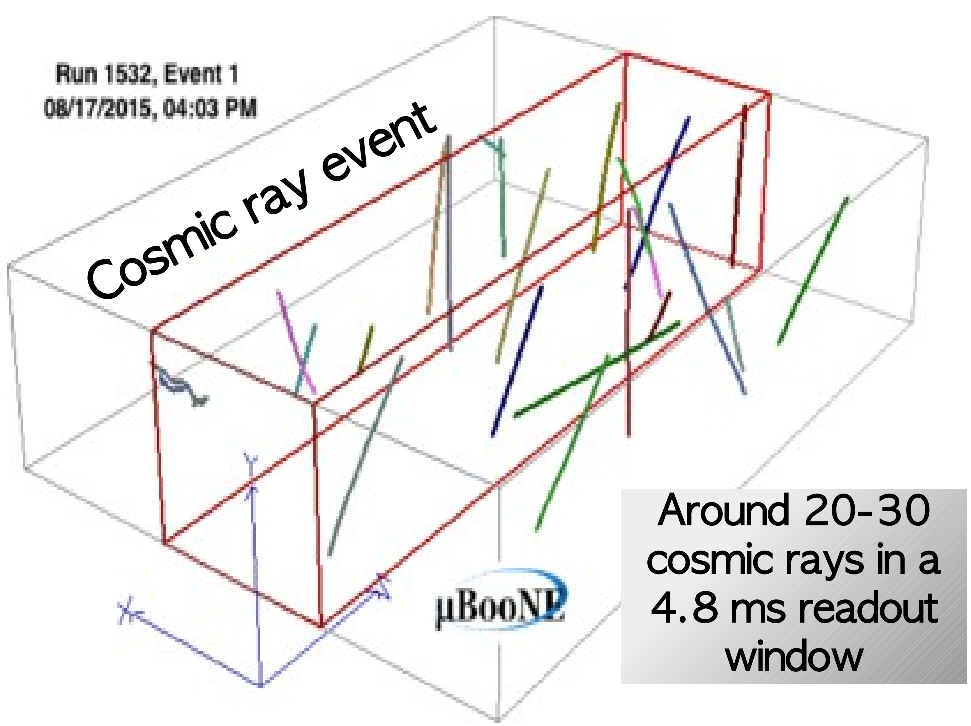
# Space charge effects in MicroBooNE

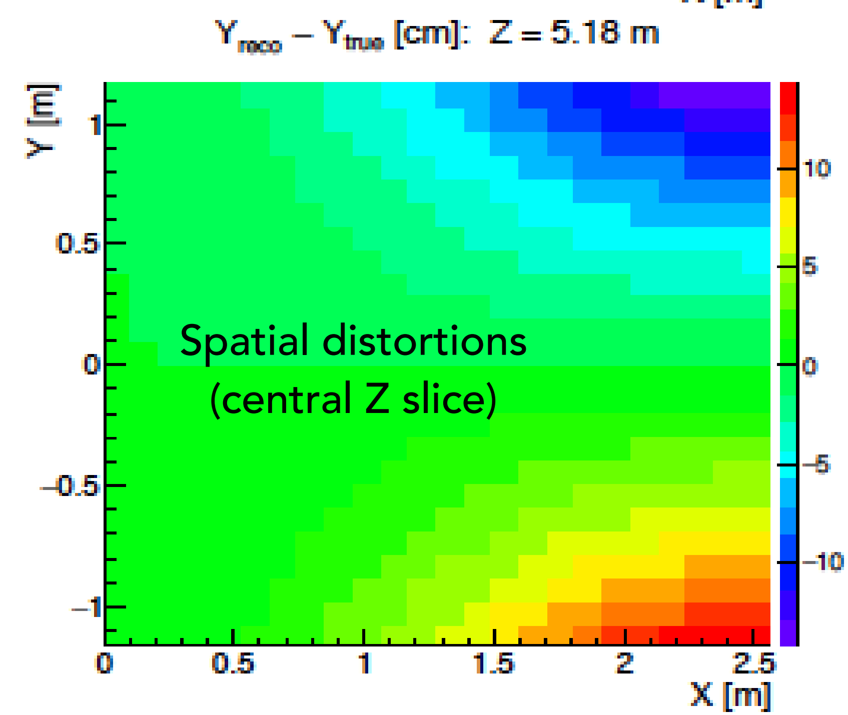
- MicroBooNE is surface detector → abundant cosmic rays
- Build up of slow moving $Ar^+$ ions in the detector due to, for example, cosmic rays, which results in:

  Local variations of E-field: 12% increase at Cathode; 5% decrease at Anode

  Spatial variations in ionization position: Around 5cm distortion along drift; Around 12 to 15 cm along non-drift directions

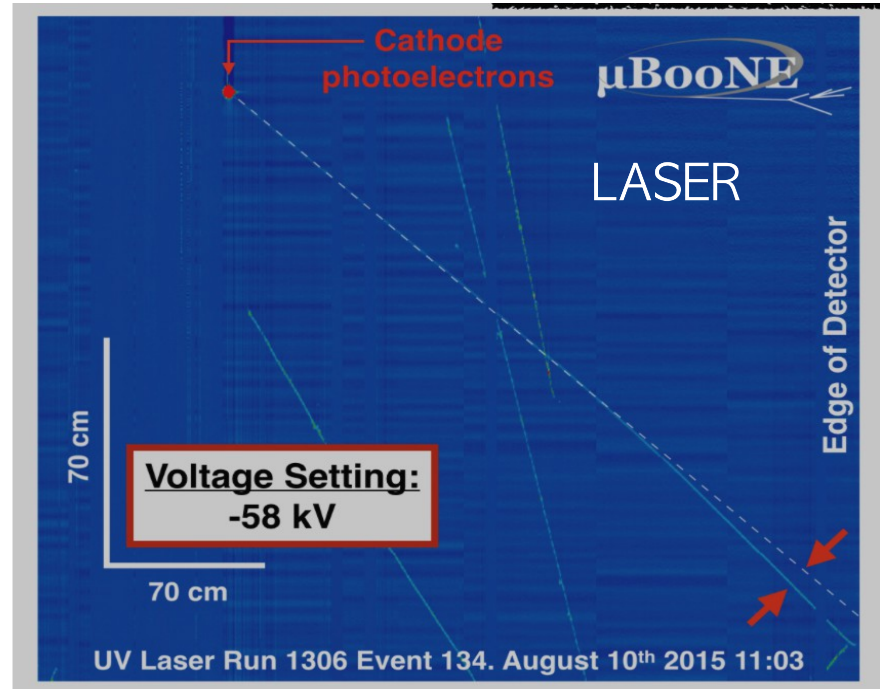


# Space charge effects in MicroBooNE

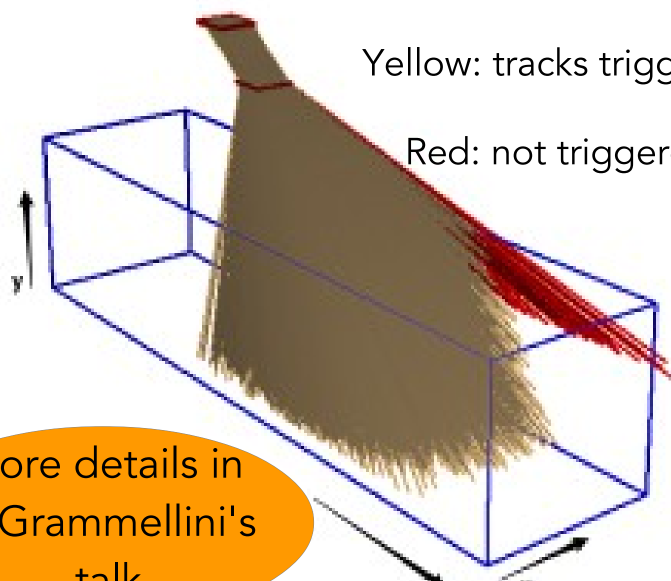
- Space charge effects (SCE) seen in
  - Laser data and muon tracks tagged by an external "small" muon counter (MuCS)
- Measurement using MuCS tagged tracks
  - Pros: "t0" known
  - Cons: limited angular coverage (this will improve with the full tagger system now in place)

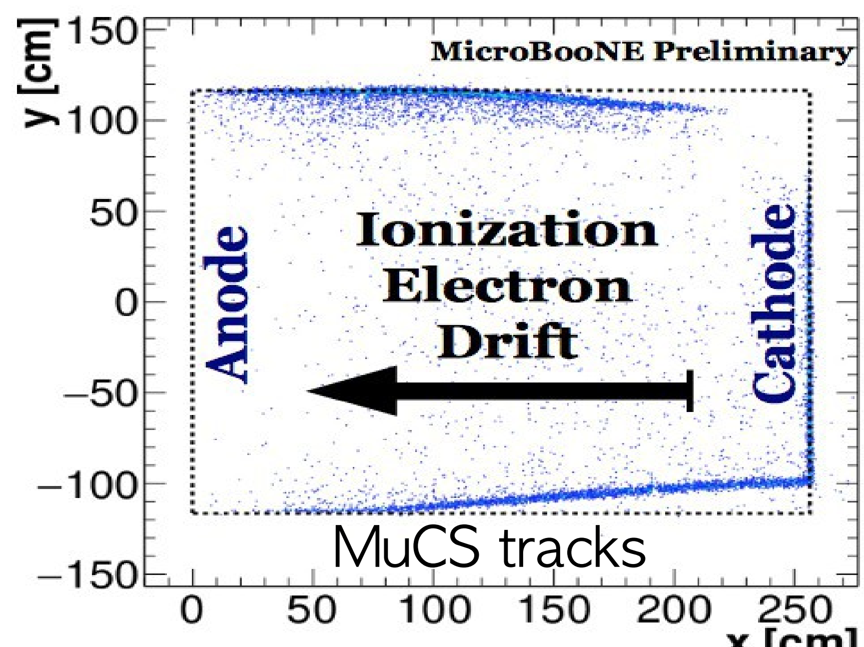



MuCS system coverage

Yellow: tracks triggered by MuCS

Red: not triggered by MuCS



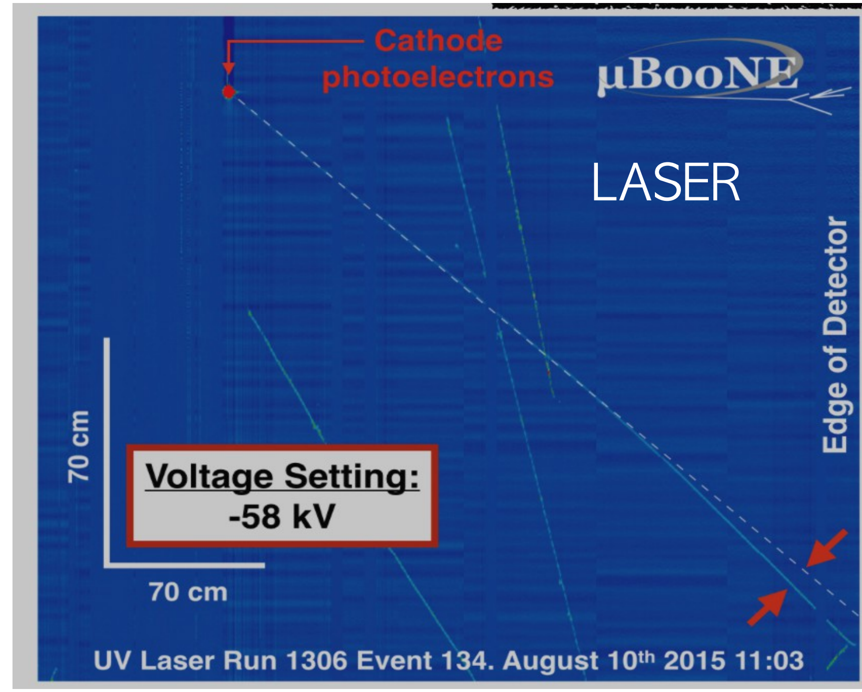



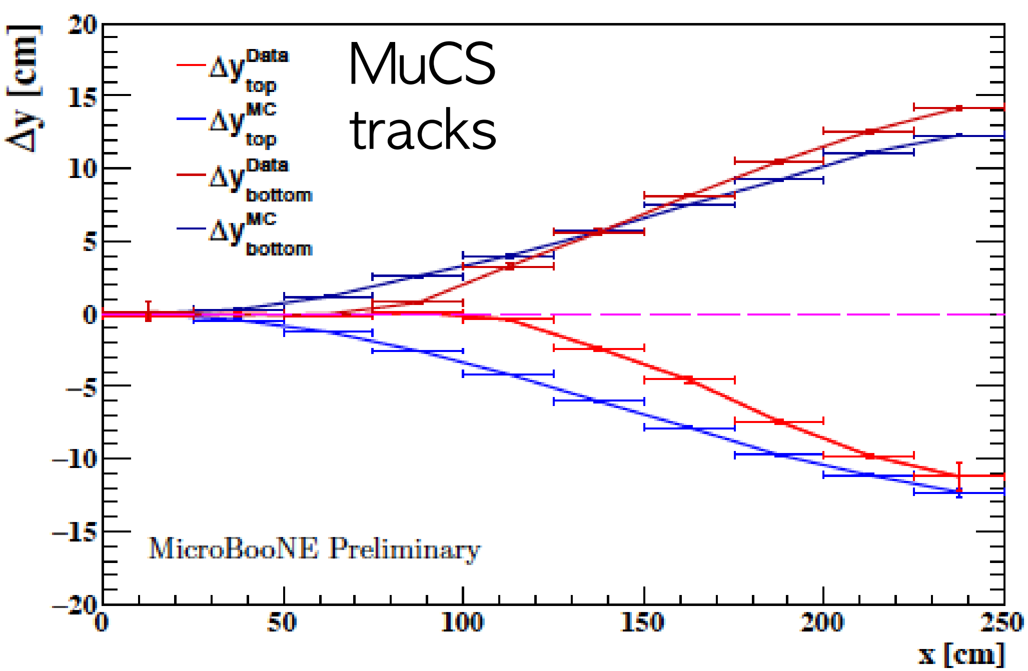

More details in E. Grammellini's talk

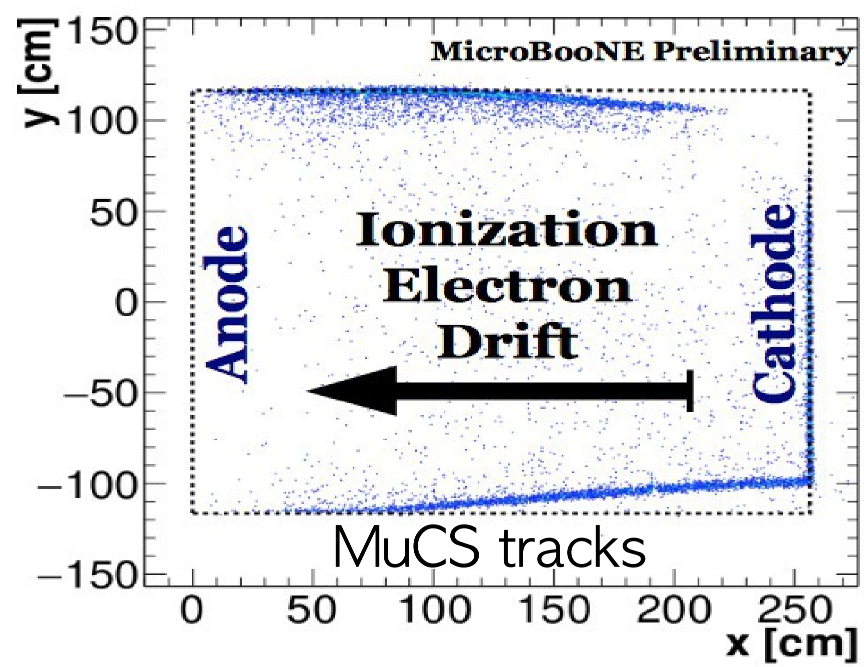
# Space charge effects in MicroBooNE

Measurement using MuCS tracks

- Data and MC reasonably agree in terms of basic shape and normalization
- Offset near anode in data:
  - Is liquid argon flow pushing the ions near the anode?
  - Interesting ideas on testing this theory: e.g. vary pump flow and see how it effects ion SCE



# Space charge effects in MicroBooNE: outlook

- Read all about our space charge preliminary results in our public note:
  - http://www-microboone.fnal.gov/publications/publicnotes/ MICROBOONE-NOTE-1018-PUB (November, 2016)
- On-going & Future work to fully characterize/calibrate the SCE in MicroBooNE
  - MuCS moved to various Z boundaries and data taken → data currently being analyzed
  - Using UV laser data to do 3D calibration for space charge
    - We have the laser data, current focus on developing end-to-end Laser data reconstruction
    - Laser system doesn't provide full coverage: plan to fill the gap with additional "t0 known" cosmic data such as A-C crossing tracks, A/C piercing tracks etc.
  - Great progress recently towards understanding time dependence of SCE
  - Stay tuned for more results soon!
- Later  we will see, SCE significantly impacts lifetime and recombination measurements

# Space charge effects in MicroBooNE

- Read all about our space charge preliminary results in our public note:

**Lessons learned for SBN/DUNE:**

- SCE a challenge for any surface-based LArTPCs
  - Effect will be worse for ProtoDUNE due to longer drift
- Availability of "t0-known" tracks with good phase space coverage critical to properly characterize and calibrate this effect in 3D
  - Importance of Laser system, Cosmic ray tagger system cannot be understated
  - Requires dedicated studies at the design stage to understand the phase space coverage from TPC tracks
  - Studies to understand (experimentally) how liquid argon flow impacts ion movement is important

  - Stay tuned for more results soon!
- Later  we will see, SCE significantly impacts lifetime and recombination measurements

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- Electron lifetime measurement
- Electron-ion recombination
- Electron diffusion

Example of how these effects are connected: Calorimetry

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Electronics calibration factor

Purity correction

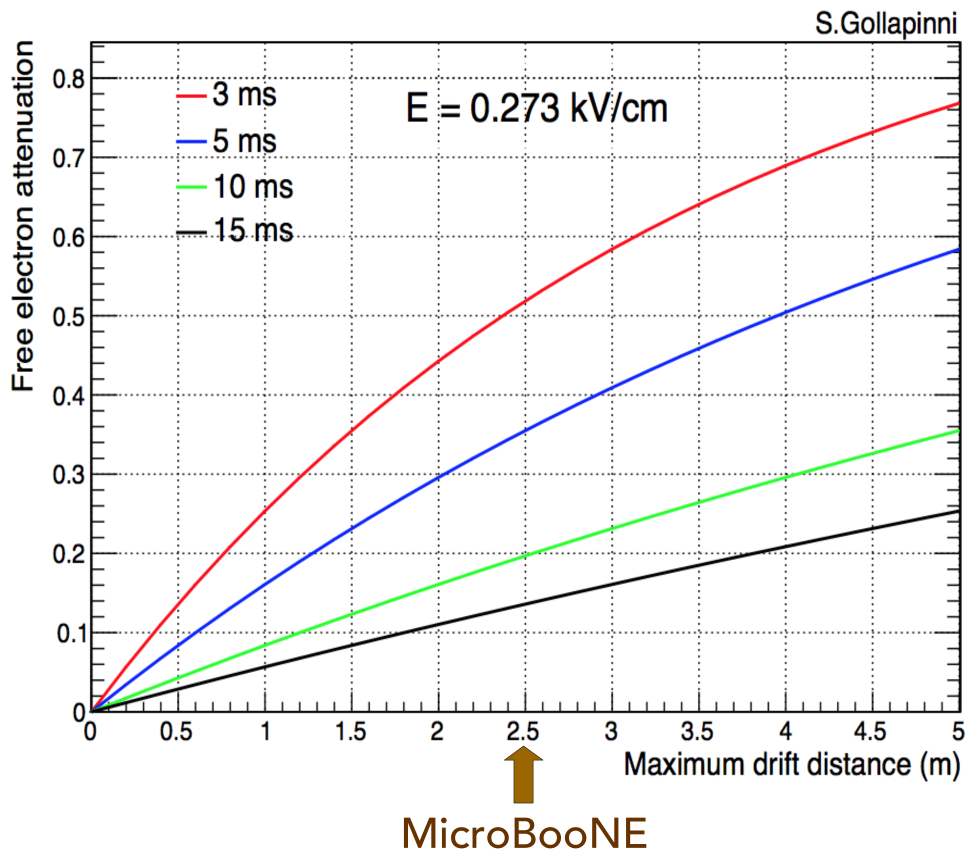
Electron-ion Recombination Correction

# Impurities in argon & charge loss

- Electro-negative impurities such as ($O_2$ and $H_2O$) can capture drifting electrons and result in signal loss

$$N_e(t_{drift}) = N_e(t_0) \times \exp(-t_{drift}/\tau)$$

electron drift-lifetime




- Measuring $e^-$ lifetime tells us
  - Ionization signal loss @ given E-field
  - $O_2$ contamination in argon
- Electron lifetime and $O_2$ impurity contamination are inversely proportional

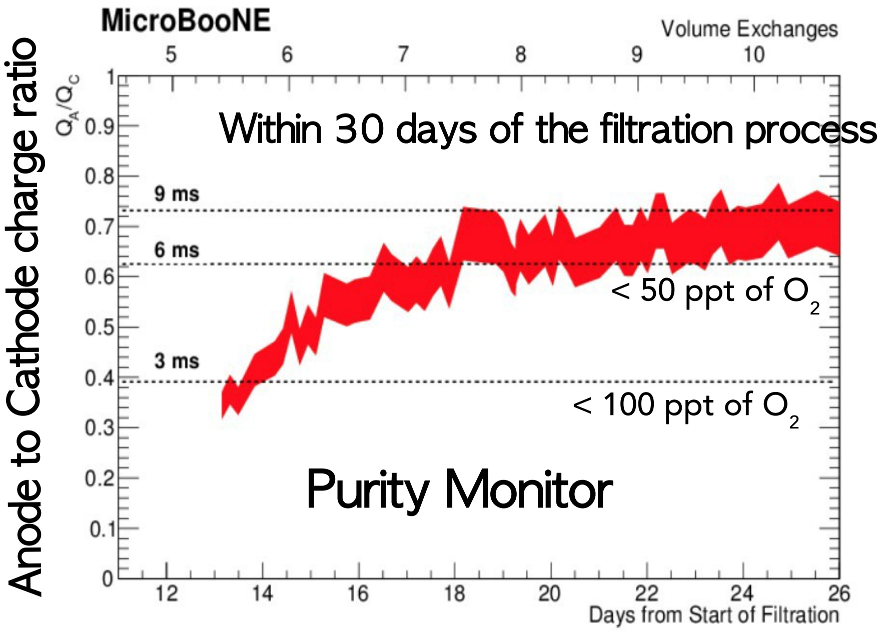
$O_2$ Contamination (in ppb) = 0.3/ $\tau$ (in ms)

- For Example, In MicroBooNE, to achieve 36% signal loss (or 5 ms lifetime at 273 V/cm), require $O_2$ equivalent concentration to be less than 60 ppt

# Measuring electron lifetime

- Many ways to measure this:
  - Purity Monitors (e.g. ICARUS, MicroBooNE)
  - Long Cosmic muon tracks (e.g. ICARUS)
  - Laser (e.g. ArgonTube)

More details in M. Zuckerbrot's talk




MICROBOONE-NOTE-1003-PUB (May 2016)

# Measuring electron lifetime

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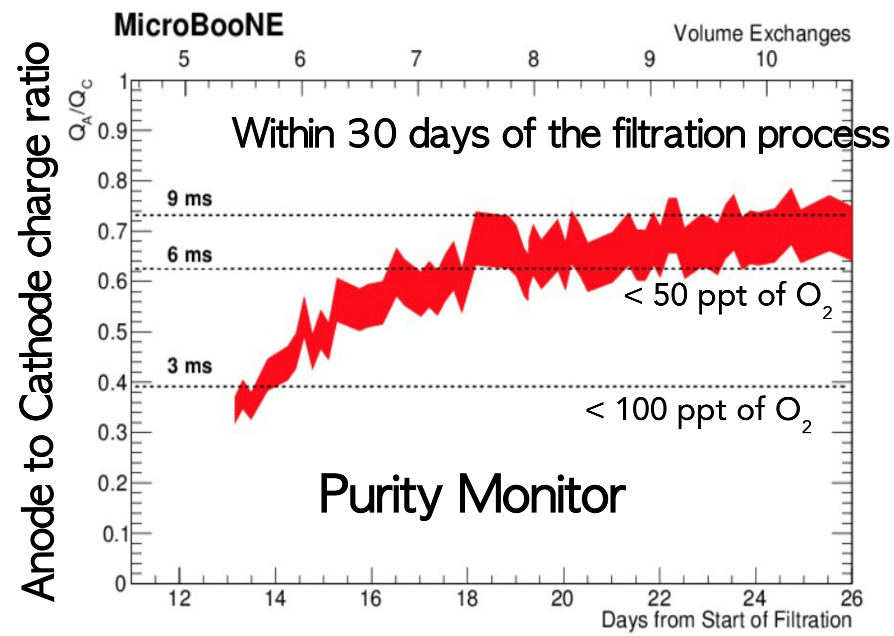
  - Long Cosmic muon tracks (e.g. ICARUS)
  - Laser (e.g. ArgonTube)

- **UV Laser: would be great if one can do it**
  - Uniformity of ionized charge along the track is important



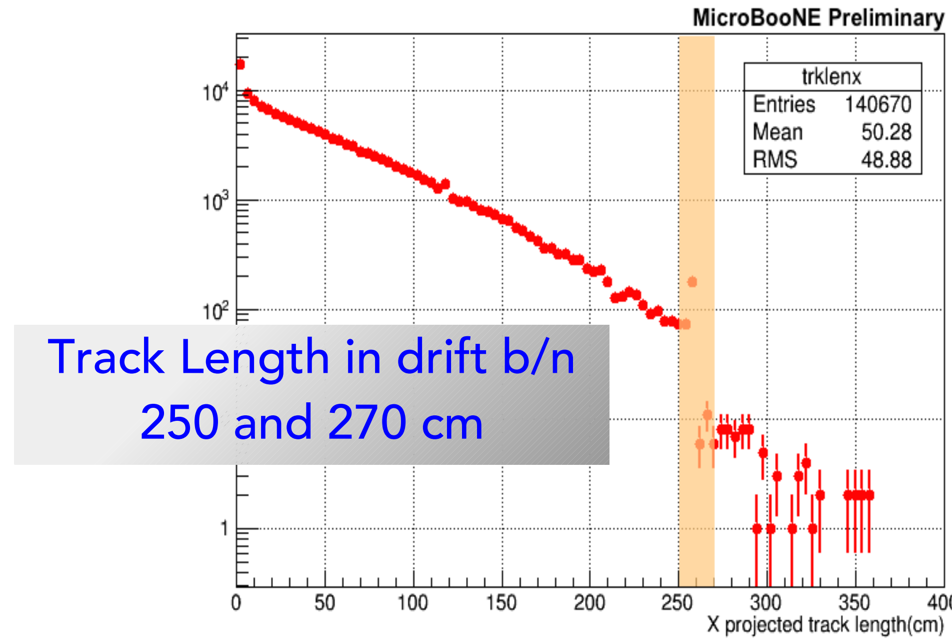

| Advantages | Disadvantages |
| --- | --- |
| • Quick (online) measurement<br>• Doesn't require reconstructed tracks<br>• Great for commissioning & initial data runs when reconstruction is still being worked out | • Localized measurement<br>• Cannot always be extrapolated to the entire TPC volume<br>• Cannot be used to study purity variations in the TPC<br>• Typically at lower E-fields<br>• Longevity is a problem |

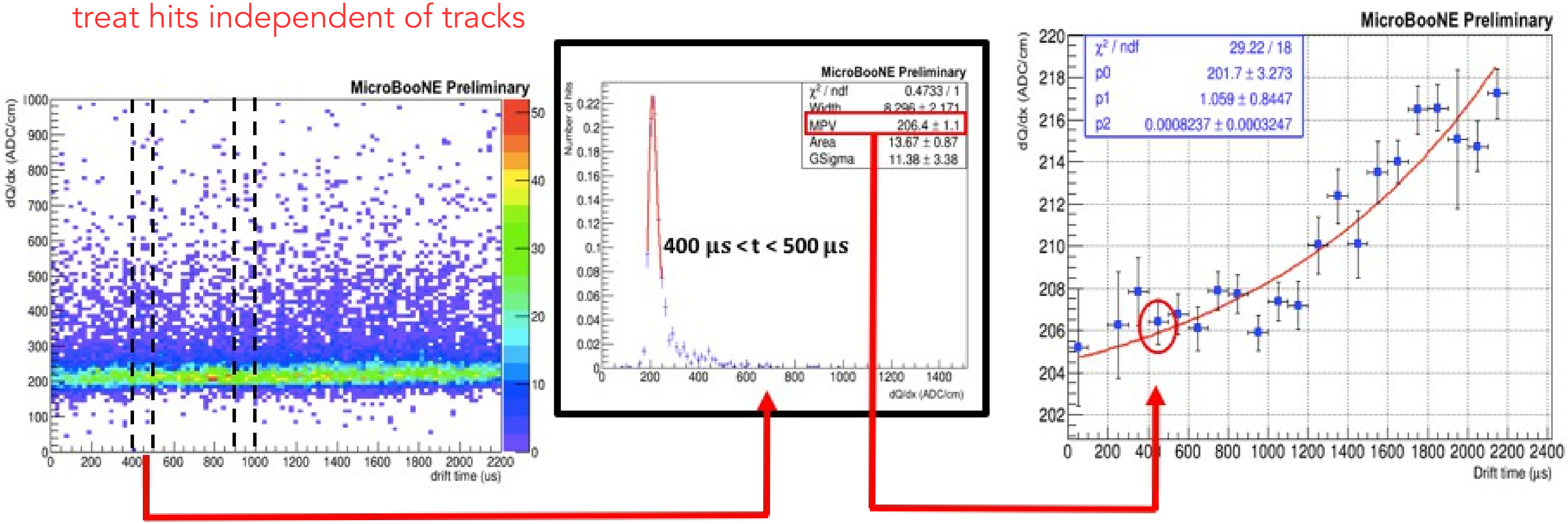
PURITY MONITORS

- By far the best way to measure purity is using long cosmic muon tracks
- Wide angular coverage
- Can represent purity through out the TPC and can be used to understand purity variations over the entire volume

# Electron lifetime using cosmic rays at MicroBooNE

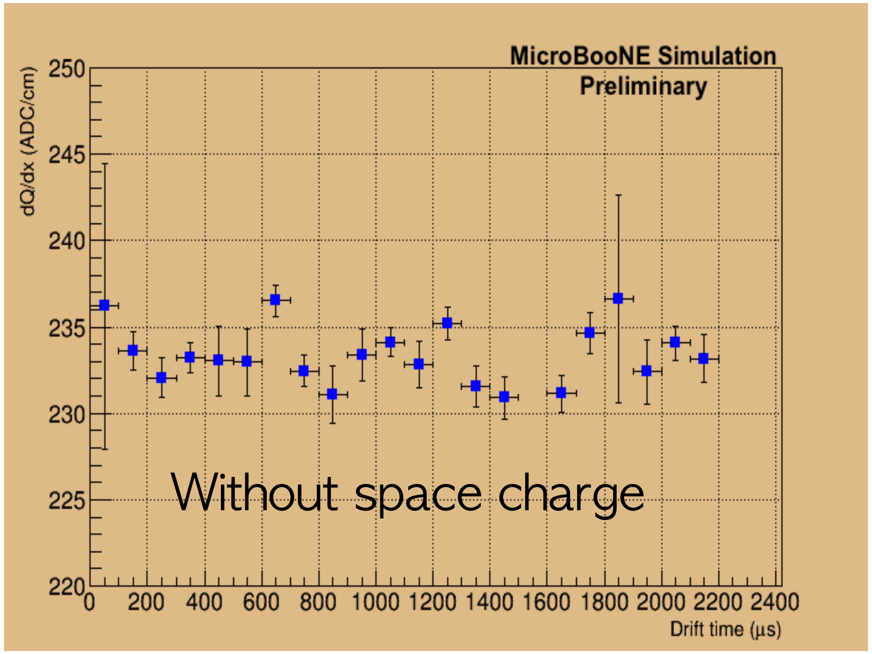
- This talk: measuring electron lifetime from TPC tracks that cross both anode and cathode → TPC crossing tracks
- In a 5k event sample, about 2% tracks are crossing tracks → rare
- Crossing tracks uniformly cover the full drift length
- **NOT a track-by-track approach;** instead treat hits independent of tracks

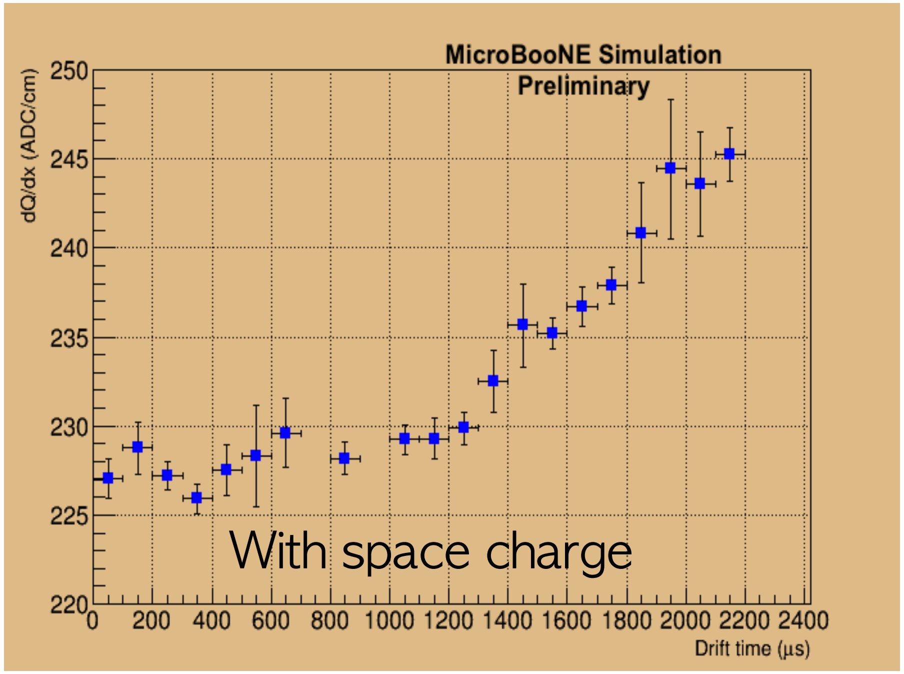


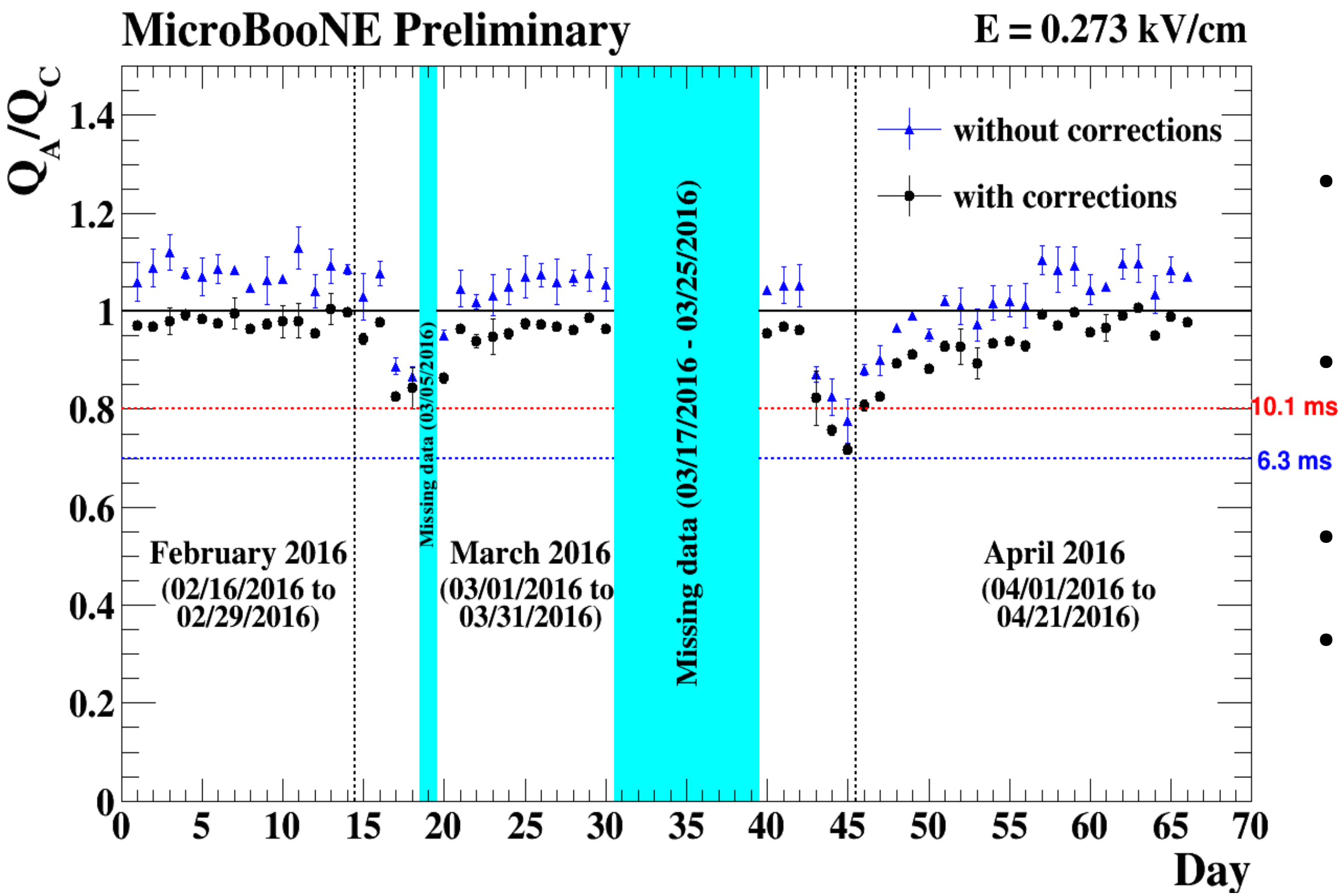
# Space charge & dQ/dx

- Space charge induced E-field distortions impact electron-ion recombination which in turn impacts dQ/dx
  - Recombination is suppressed at higher fields
  - Cathode: 12% increase in E-field → 3.55% increase in dQ/dx
  - Anode: 5% decrease in E-field → 1.2% decrease in dQ/dx
- 3D distortions in the ionization position can also impact dQ/dx
  - Example: tracks crossing the wire planes at 45 degrees will roughly see about 8% bias in dQ/dx
- Both of these effects result in a scenario where charge appears to be increasing with drift distance!



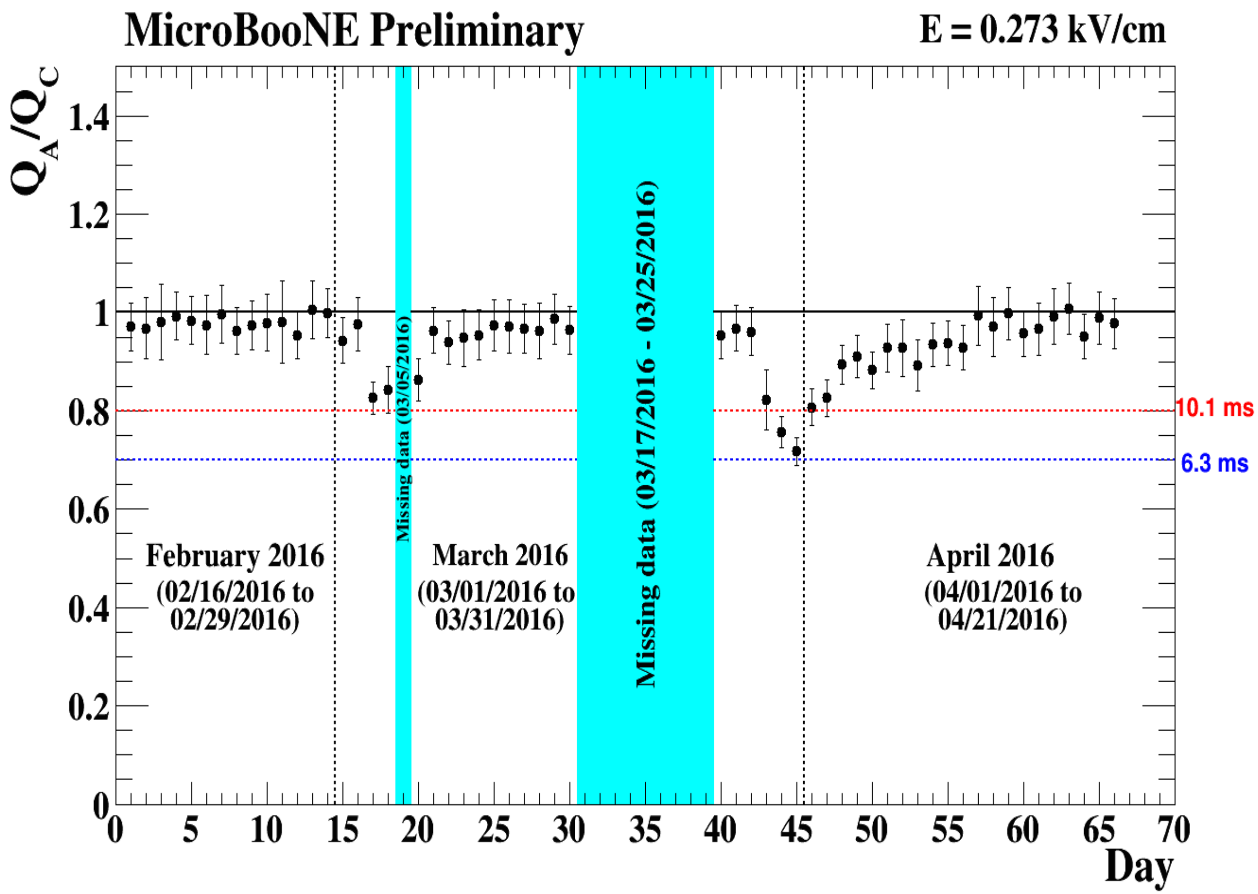
# Electron attenuation after space charge corrections




- Variation of $Q_A/Q_C$ over time (statistical errors only)
- Charge ratio values below 1 after space charge corrections
- Purity very high in MicroBooNE
- The two dips correspond to power outage and LAr top-up

- Space charge corrections extracted from models implemented in Simulation
  - Since data and MC doesn't agree completely, a large systematic error assigned to corrections
  - Future studies focused on extracting data-driven corrections

# Electron Attenuation after systematics




| Systematic name | Uncertainty (%) |
|---|---|
| Space charge correction | 5.0 |
| Recombination model | 1.0 |
| Diffusion | 2.0 |
| Total | 5.5 |

(% of final space-charge correction $Q_A/Q_C$ value)

Overall Period:

- $Q_A/Q_C$ > 0.72+/-0.04
- Lower bound
  - 6.8 ms electron lifetime
  - $O_2$ contamination < 44 ppt
  - Maximum charge loss 28%

Normal Operation:

- $Q_A/Q_C$ > 0.88+/-0.04
- Lower bound
  - 18.0 ms electron lifetime
  - $O_2$ contamination < 16 ppt
  - Maximum charge loss 12%

# Electron Attenuation measurement: Outlook

- Main message: The argon purification and recirculation system in MicroBooNE is performing exceptionally well
  - The maximum charge loss during normal operation is ~ 12%!
- Analysis presented at the APS "April" meeting → Public note coming out soon
- Future studies
  - Since space charge is our biggest effect, effort focused on deriving "data-driven" SCE and related systematics
  - Extending the analysis to a larger MicroBooNE dataset
  - Other systematics such as muon energy loss, dynamic induced charge, electronics gain and shaping time variations etc. will be studied in detail as well.
  - Stay tuned for updated results soon!

# Electron Attenuation measurement: Outlook

Lessons learned for SBN/DUNE:

- When the purity is very high, space charge has sizable effect on recombination which can result in the observed unexpected scenario
- Correctly simulating space charge (both spatial & E-field) and understanding how it impacts recombination and dQ/dx is important
- Effects even more important for long-drift detectors such as ProtoDUNE
- This effort should go hand in hand with the space charge and recombination topics
- Developing centrally available "t0" tagged samples (from various sources) early on will greatly benefit this analysis

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- **Electron-ion recombination**
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Electronics calibration factor

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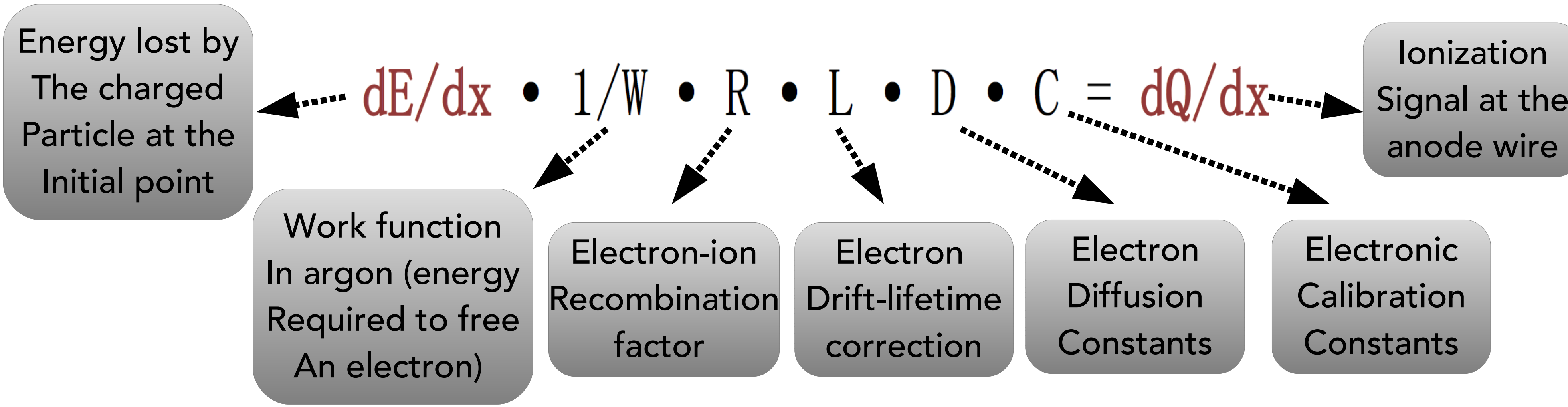
# Electron-ion Recombination

## Recombination is obtained using the equation



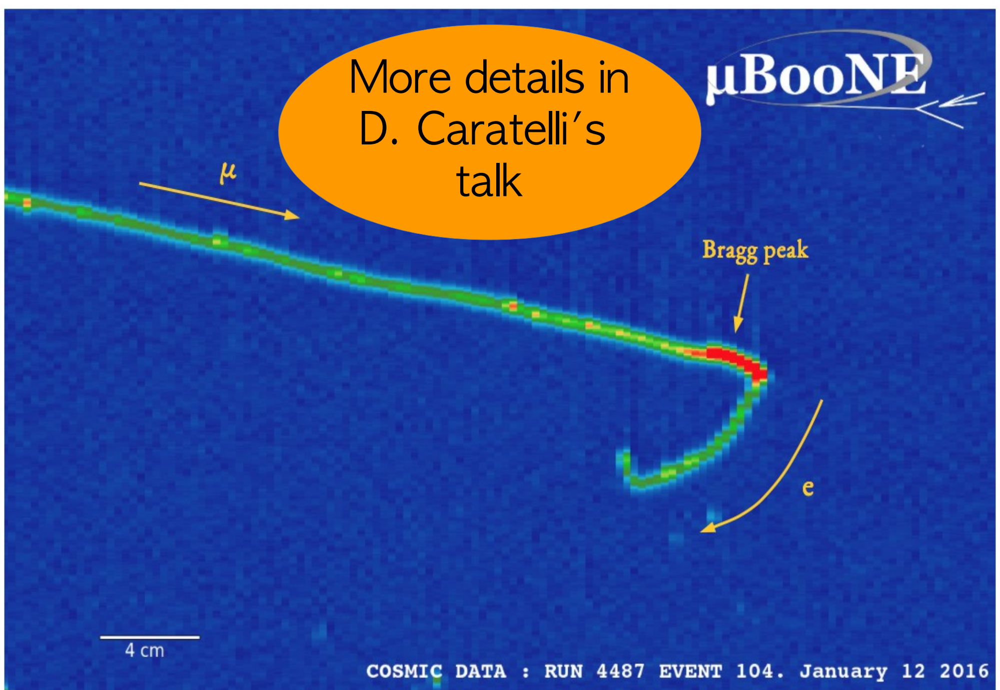

- Two recombination models exist:
  - Birk's Model and Modified Box Model

$$R_{Birk's} = \frac{A_B}{1 + \frac{k_B}{\rho} \cdot \frac{dE}{dx} \cdot \frac{1}{\mathcal{E}}} \qquad R_{ModBox} = \frac{\ln(\alpha + \frac{\beta_P}{\rho\mathcal{E}} \cdot \frac{dE}{dx})}{\frac{\beta_p}{\rho\mathcal{E}} \cdot \frac{dE}{dx}}$$

- These models are tested by previous experiments (ICARUS, ArgoNeuT)
- Goal: using stopping muons/protons obtain theoretical parameters for MicroBooNE

# Stopping muons/protons for Recombination

- Stopping muons/protons an excellent source to measure recombination
- An **"in-progress" analysis presented at APS** mainly to introduce analysis methodology
  - Signature: decay to Michel electrons (combine topology & calorimetry to select events)
  - Michel electron paper, arXiv: 1704.02927, submitted to JINST, April 2017!
  - Cosmic muons decay into Michel electron roughly 2/3$^{rd}$ of the time
  - Recombination analysis performed using 2000 stopping muon candidates




- **On-going studies:**
  - Validate analysis methodology
  - include other systematic effects (e.g. space charge)
  - Extend scope with stopping protons from cosmics and possibly also from BNB interactions

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  - 
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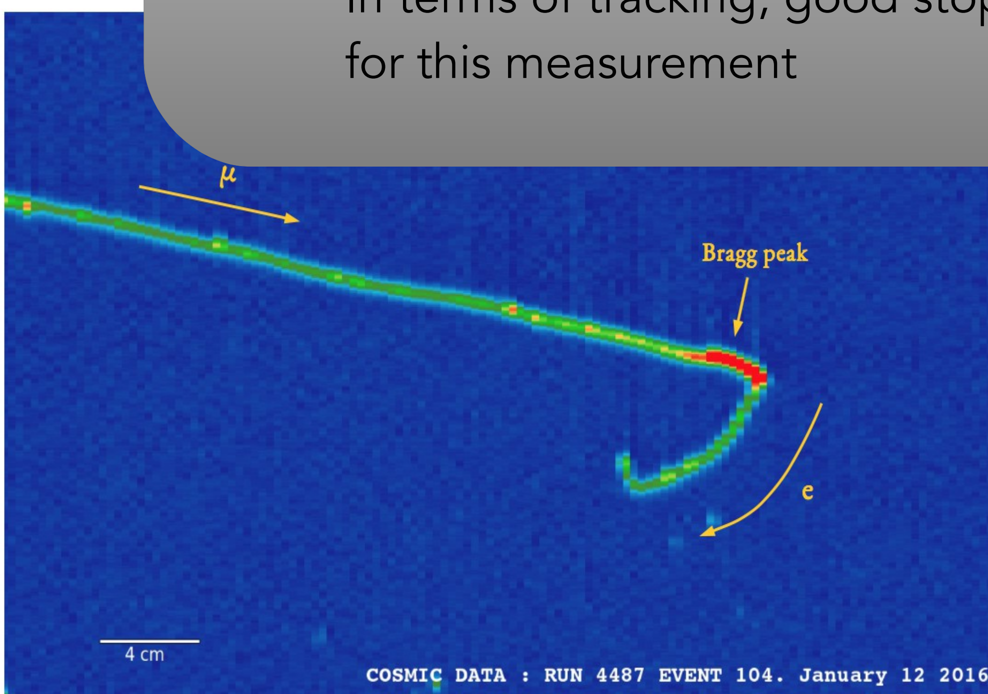
**Lessons learned for SBN/DUNE:**

- Developing strategies to identify and prepare stopping muon/proton sample and making them centrally available will be very useful to many analyses such as recombination, Michel electrons etc.
- In terms of tracking, good stopping point reconstruction is critical for this measurement

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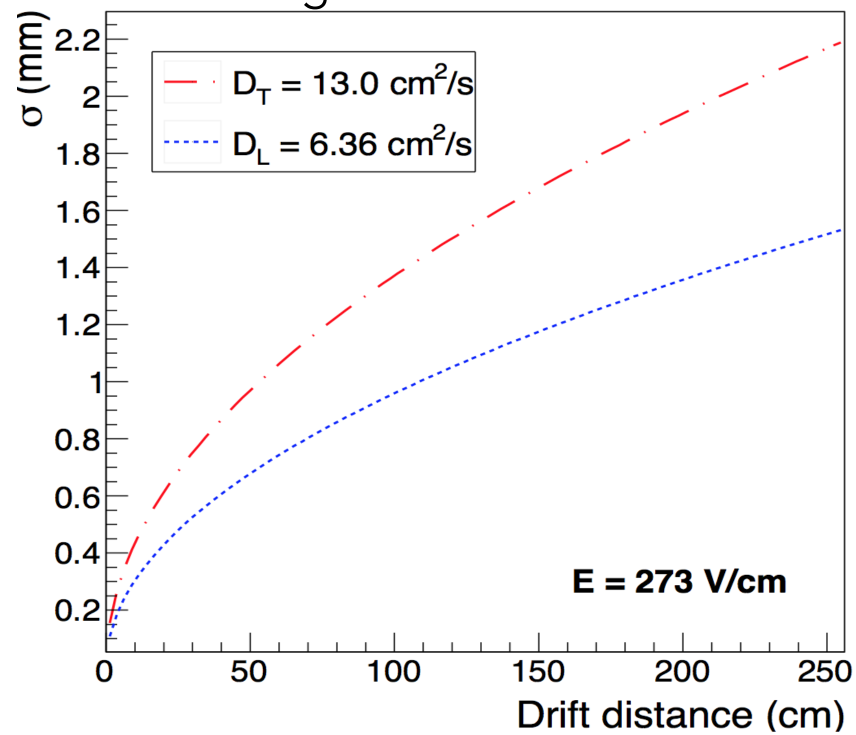
# Electron Diffusion

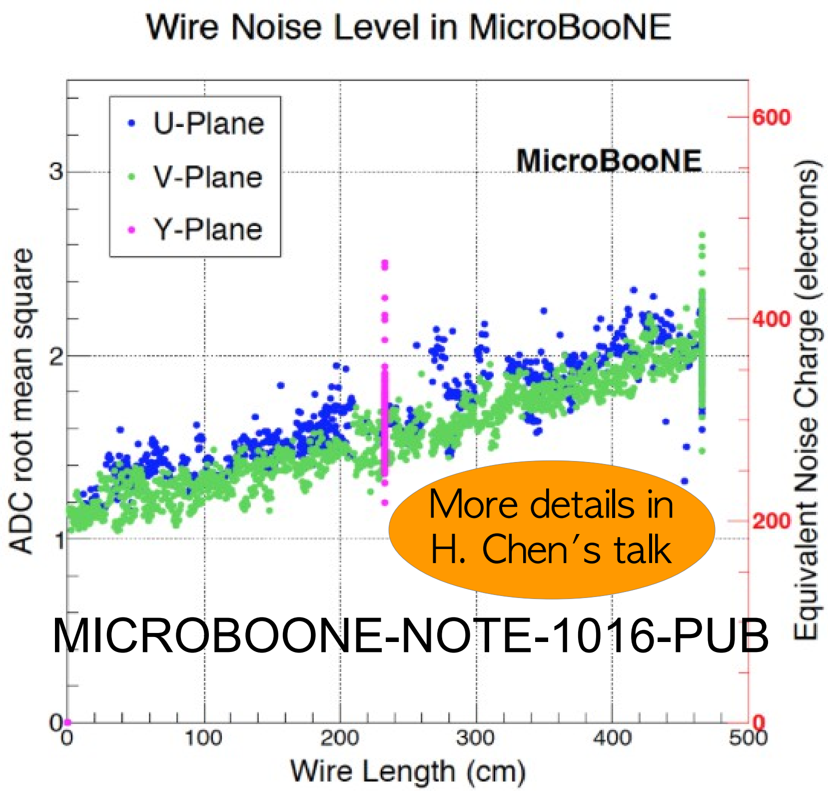
Image credit: A. Lister




- Knowledge of transport properties, such as diffusion and drift velocity of electrons in liquid argon → essential for LArTPC performance
- In strong electric fields, Diffusion is not isotropic → measure longitudinal and Transverse components separately
- Transverse Diffusion: perpendicular to drift
  ? affects spatial resolution
- Longitudinal Diffusion: parallel to drift
  → affects timing resolution
- Longitudinal diffusion can also be used to tag "t0" of tracks in a TPC (from 35-ton)
- Only few measurements on diffusion so far
  - Transverse diffusion for fields above 1500 V/cm
    NIM122 (1974) 319; PRA20 (1979) 2547.)
  - Longitudinal diffusion for fields b/n 100 and 2000 V/cm
    NIMA816 (2016) 160; NIM A345 (1994)230.

# Longitudinal Electron Diffusion in MicroBooNE

- Diffusion is a very challenging measurement since it is impacted by almost anything
  - Noise → noise in MicroBooNE at the expected level currently not a problem for Diffusion
  - ADC threshold
  - Electronics gain and shaping time
  - Transverse diffusion
  - Raw detector signal vs deconvoluted signal vs hits what stage analysis is being performed matters!
  - Space charge/ recombination
  - Track angle, charge induced on to neighboring wires etc.




- There is a lot of on-going work to measure longitudinal diffusion in MicroBooNE
  - First "in-progress" results for analysis methodology based on MC will be presented as a poster at the upcoming Users' meeting by A. Lister
  - The next step is to understand the various systematics by moving to a more realistic sample that is close to data

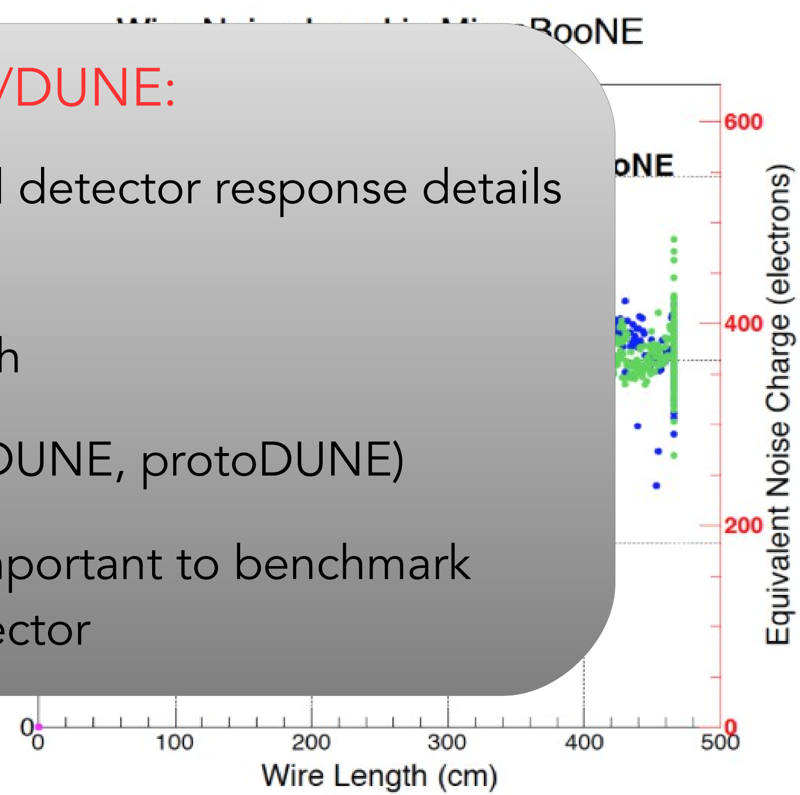
# Longitudinal Electron Diffusion in MicroBooNE

- Diffusion is a very challenging measurement since it is impacted by almost anything

**Lessons learned for SBN/DUNE:**

- Characterizing noise and other low level detector response details very important for this analysis
- Diffusion grows with growing drift length
- a concern for long-drift detectors (e.g. DUNE, protoDUNE)
- Accurate characterization of diffusion important to benchmark timing and spatial resolution of the detector

  - Track angle, Dynamic Induced charge etc.

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# Closing thoughts

- Many great results (especially detector physics related) from MicroBooNE over the last few months, check out our publics note page: http://www-microboone.fnal.gov/publications/publicnotes/
  - Many milestones achieved for a ~100-ton scale detector!
  - Many more results to come soon. Stay tuned!
  - With Laser and CRT reconstruction ramping up, more advanced studies are underway
- The importance of signal processing, understanding detector effects and developing a robust calibration scheme for LArTPCS cannot be understated
  - Higher level physics performance critically depends on how precisely we can reconstruct our ionization charge and position
  - One big lesson we learnt in MicroBooNE: given how all effects are connected, each of these detector effects require dedicated effort from early on and close collaboration to achieve best calibration possible
  - Keep in mind these effects can only get more complicated for longer drift detectors
  - MicroBooNE is in a unique position to inform future detectors of these challenges!

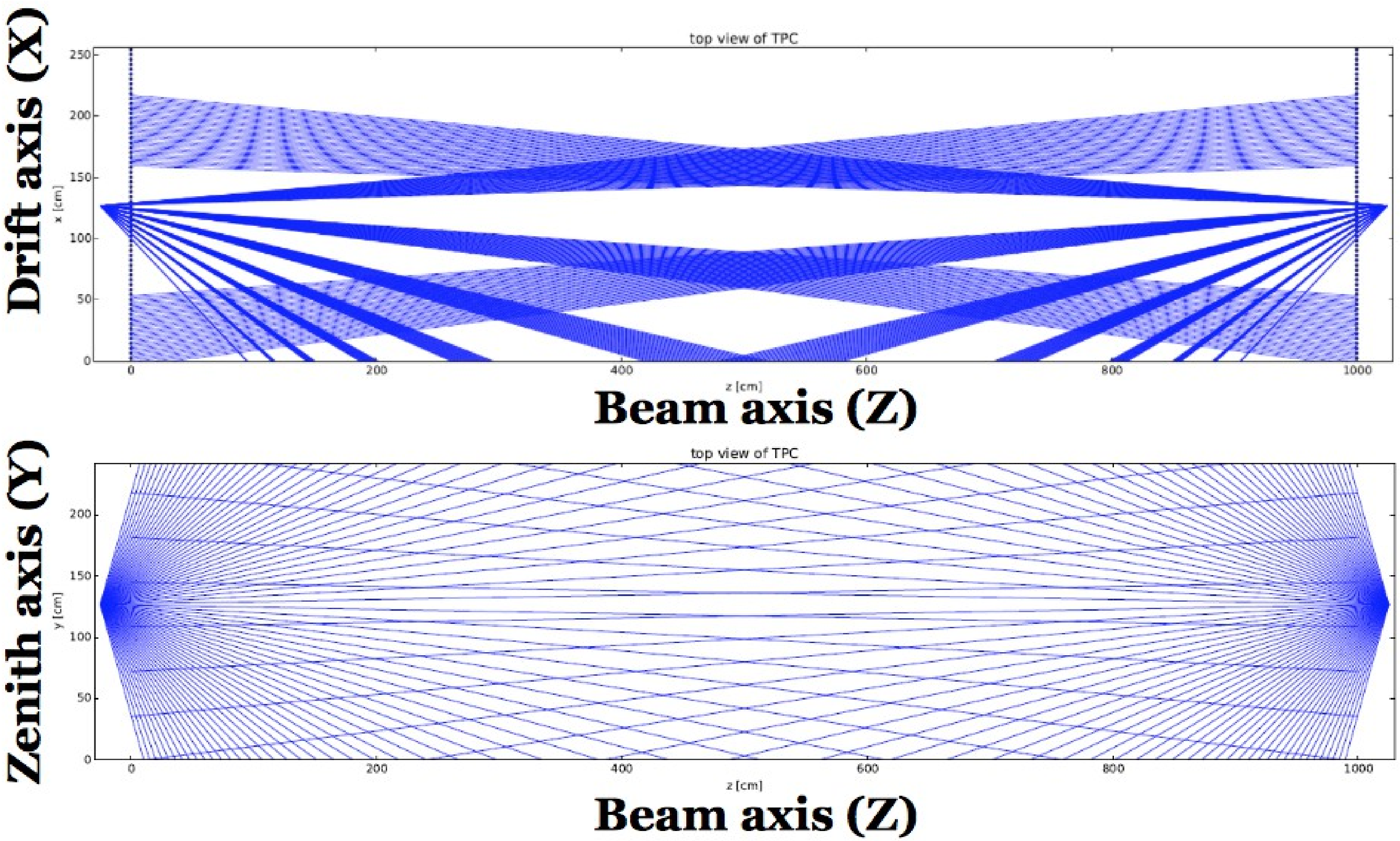
# Extras

# Calorimetric reconstruction

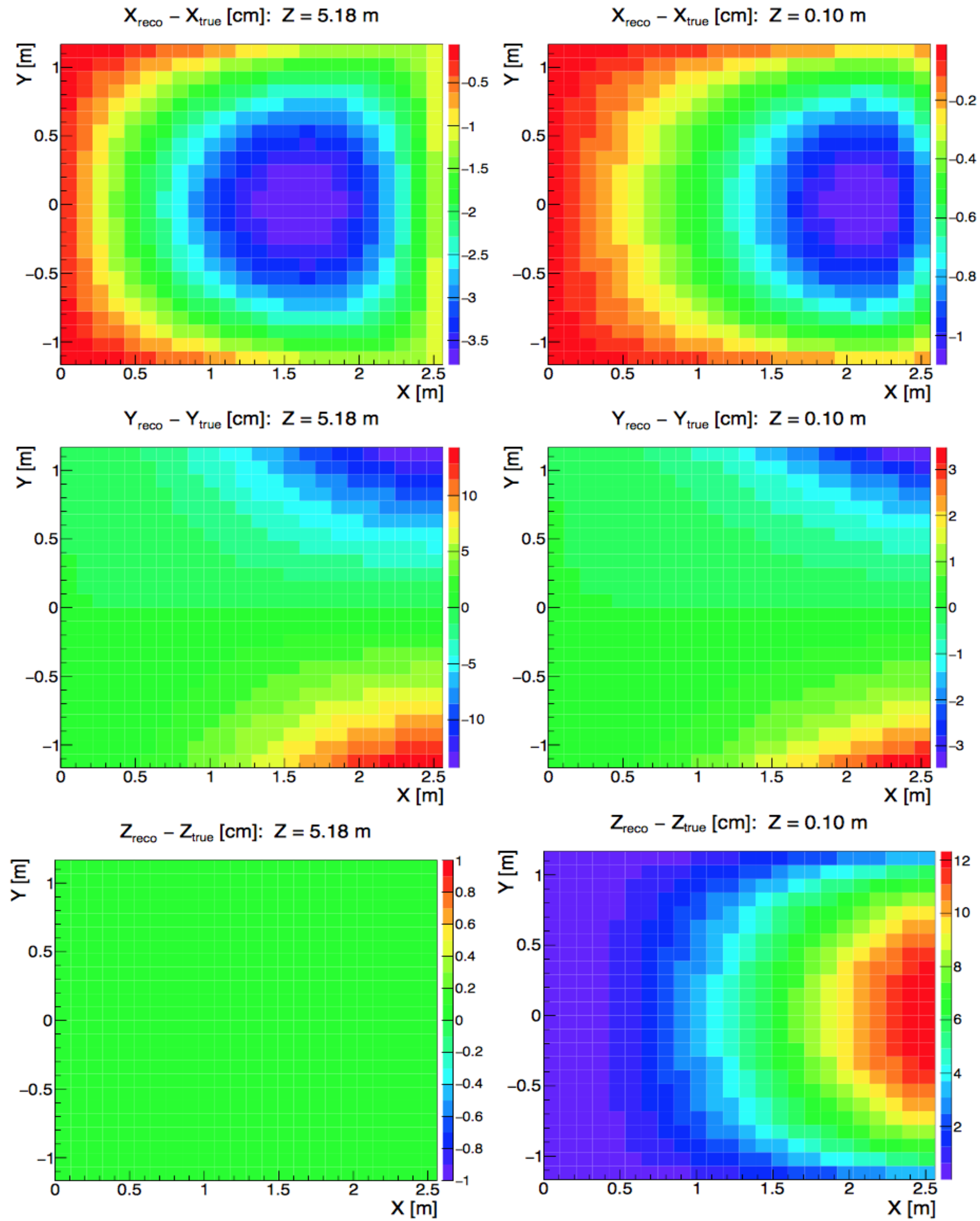
- Calorimetry requires knowing dE/dx as a function of residual range
- **The goal of calorimetry is to convert** dQ/dx (ADC/cm) → dE/dx (MeV/cm)
  - Step 1: dQ/dx (ADC/cm) → dQ/dx (e/cm)
    - Electronics calibration factor i.e., need to know electrons per ADC-tick
    - Can use stopping muons to determine this
  - Step 2: dQ/dx (e/cm) → dQ*/dx (e/cm)
    - Correct for charge lost due to impurities during transit (**electron lifetime**)
    - Many ways to measure this: cosmic muons, laser, purity monitors etc.
  - Step 3: dQ*/dx (e/cm) → dE/dx (MeV/cm)
    - Correct for the electrons lost due to **recombination** with argon ions
    - Can be done using stopped muons or protons
- **Space charge has a significant impact on all of this!**

# UV laser coverage for MicroBooNE

- UV Laser on both sides along the beam direction (Z)



Central Z slice | Edge of Z

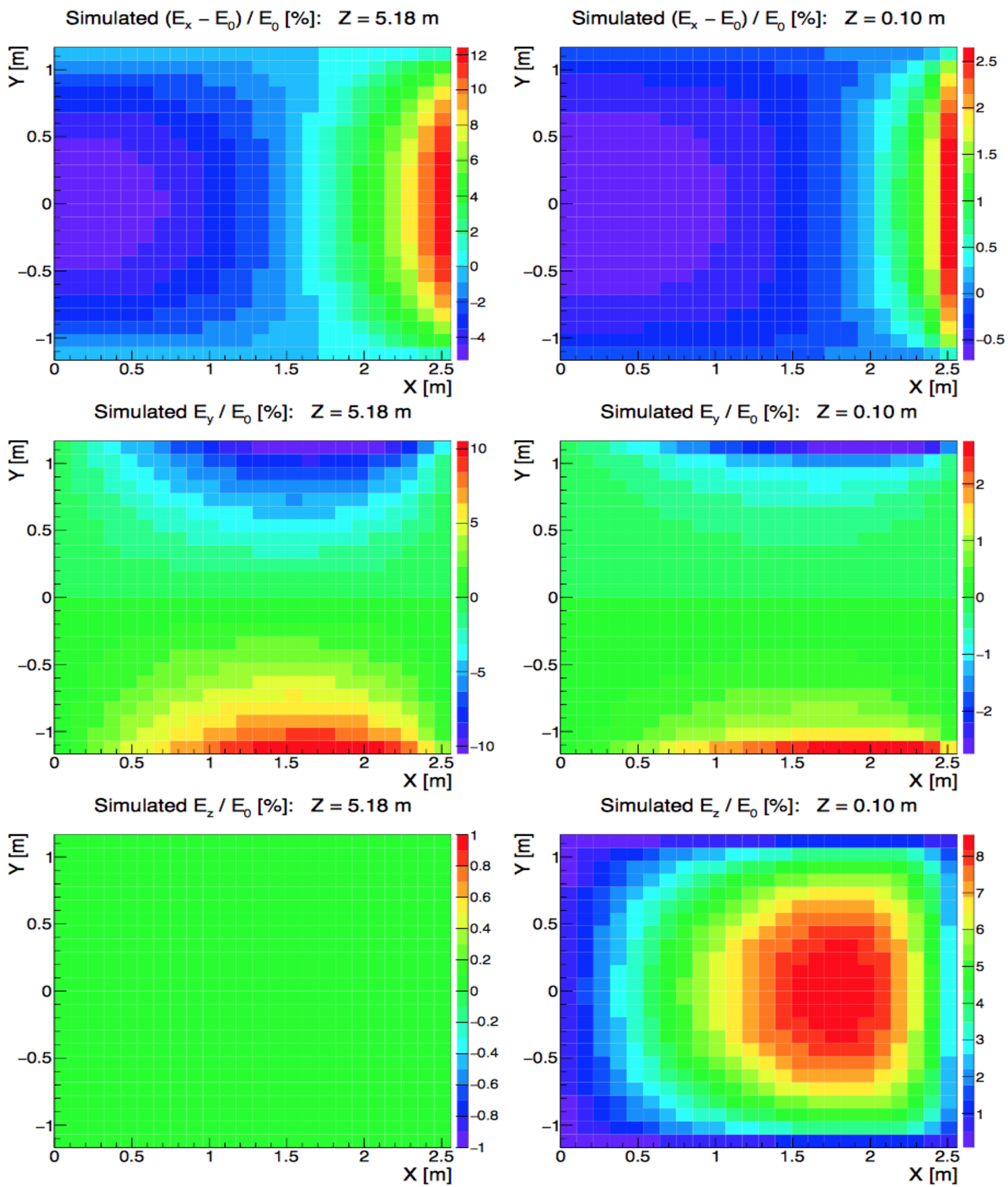



# SCE spatial distortions

Assumptions in Simulation

- No liquid argon flow
- Uniform charge deposition from cosmic rays throughout the TPC
- Linear space charge density along drift

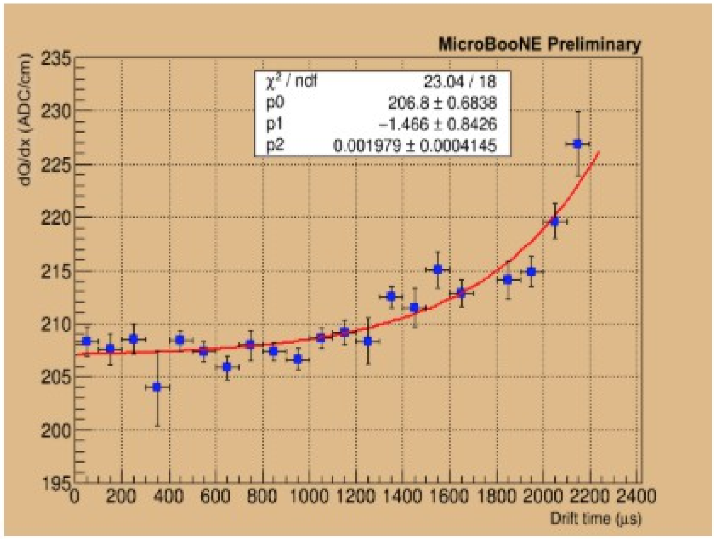
Central Z slice    Edge of Z



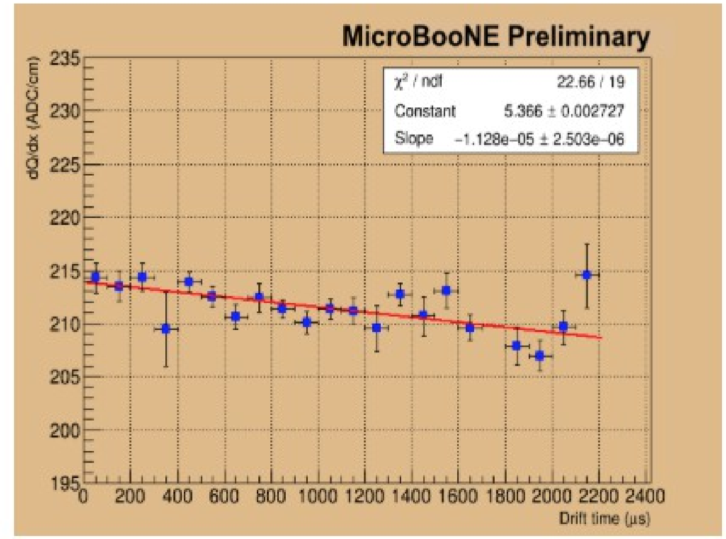

# SCE E-field distortions

# Electron attenuation before/after SCE

High purity

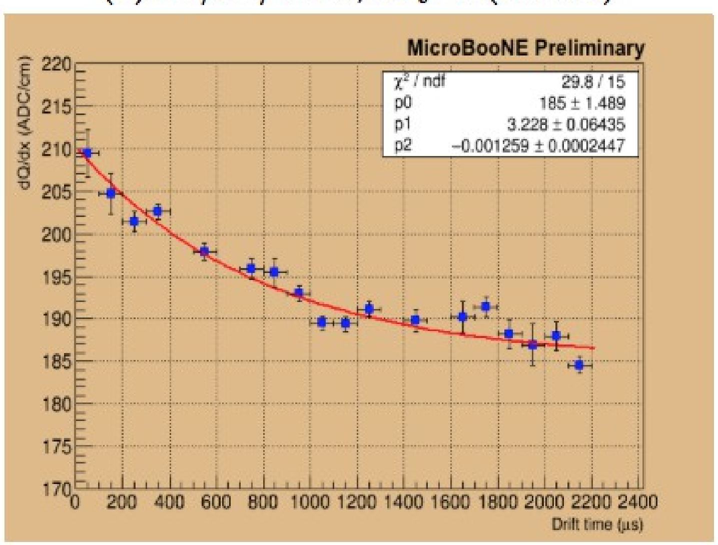



(a) 02/21/2016, day 6 (before)

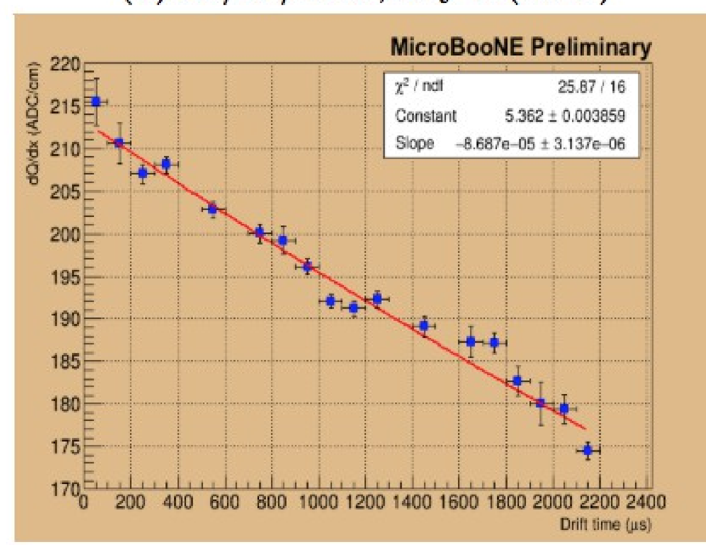



(b) 02/21/2016, day 6 (after)

Low purity

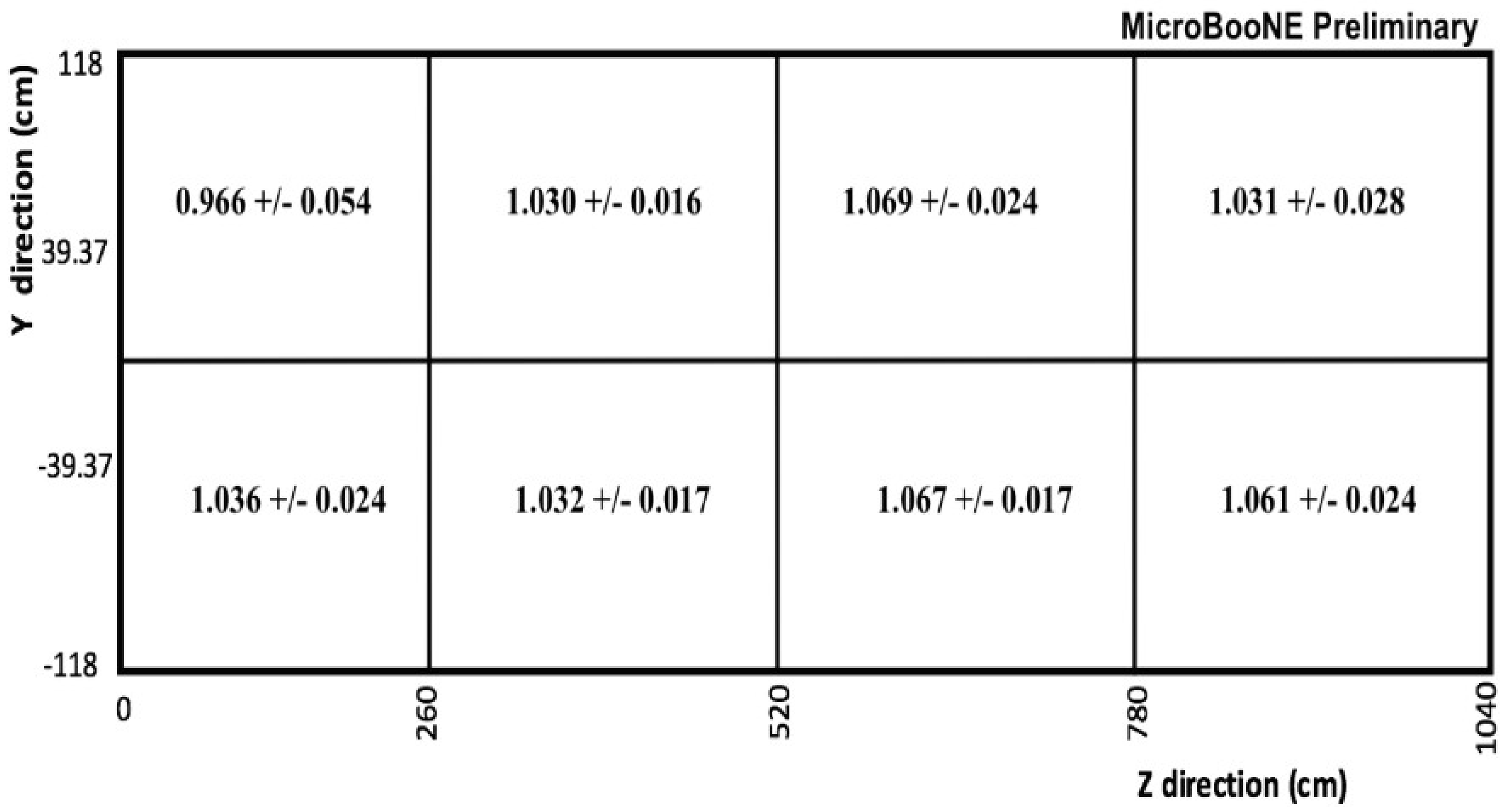



(e) 03/03/2016, day 17 (before)




(f) 03/03/2016, day 17 (after)

# Location dependence




- Location dependence charge ratio w/o SCE correction
- Chi2/ndf from an average charge ratio didn't yield significant deviation, no location dependence currently included.