Impacts of Diffusion on High-Level Physics

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Fermilab

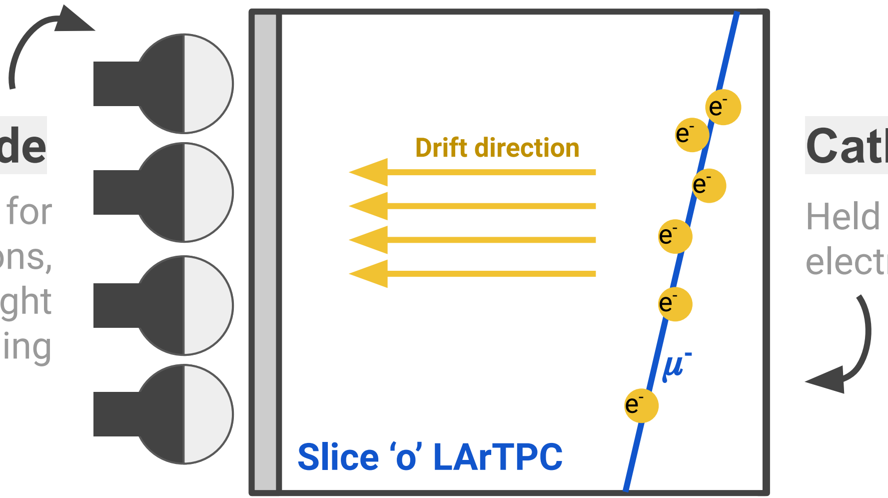
Introduction

- To do precision neutrino physics with LArTPCs, it's critical that we invest time in better understanding the physical process that go on inside of our detectors.
  - Junk in? Junk out!
- Here I'm going to focus on one specific process - ionization electron diffusion
  - Overview of why this is important to TPCs,
  - Brief overview of a measurement of longitudinal diffusion at MicroBooNE
  - How can diffusion impact calibrations and particle identification?

The (Single Phase) LArTPC in One Slide

Anode

Anode has some detector for detecting drifted electrons, generally paired with some light detection system for timing



Cathode

Held at high voltage to keep an electric field across volume

Charged particles → ionization electrons

- Drifted to anode for detection using E field

Detection technology varies

- Sense wires used extensively (eg ProtoDUNE, SBND, MicroBooNE, ICARUS, ArgoNeuT, LArIAT…)
- Lots of exciting work on using a pixel-based readout, CRPs for DUNE VD

If You Want To Build a LArTPC From Scratch

(First invent the universe, but then…)

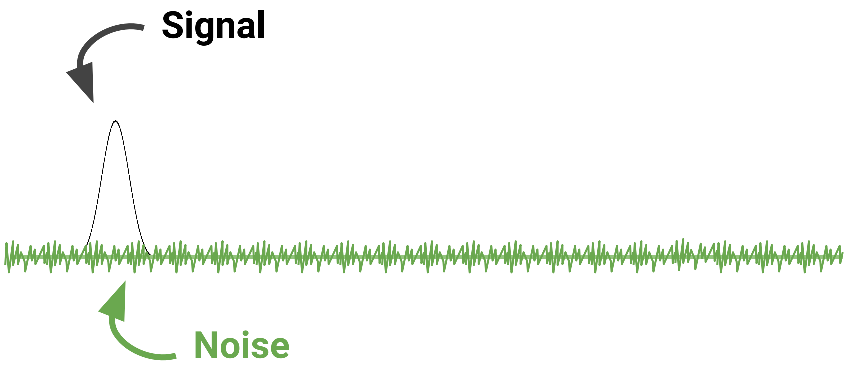
First step is to figure out the signal-to-noise ratio you need

$$\text{SNR} = f(\text{Noise}, \text{HV}, \text{Drift Length})$$

Essentially have two handles which determine everything else.

1. Noise

Driven by electronics, with some detection technology specific components. Mitigated by eg having cold electronics.



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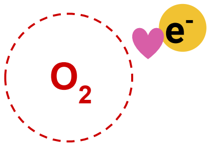
Essentially have two handles which determine everything else.

2. HV, Drift Length

HV + Drift Length →
ionization electron **drift velocity** and **drift time**→
Modifies physical processes that contribute to electron cloud.

Physical Processes

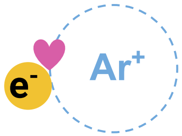
Lifetime



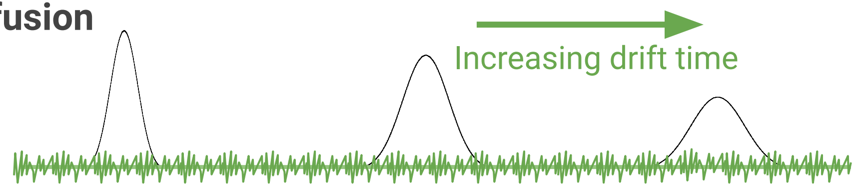
Electron capture on contaminants across volume

Recombination

Electrons recombine with argon ions at ionization point.



Diffusion



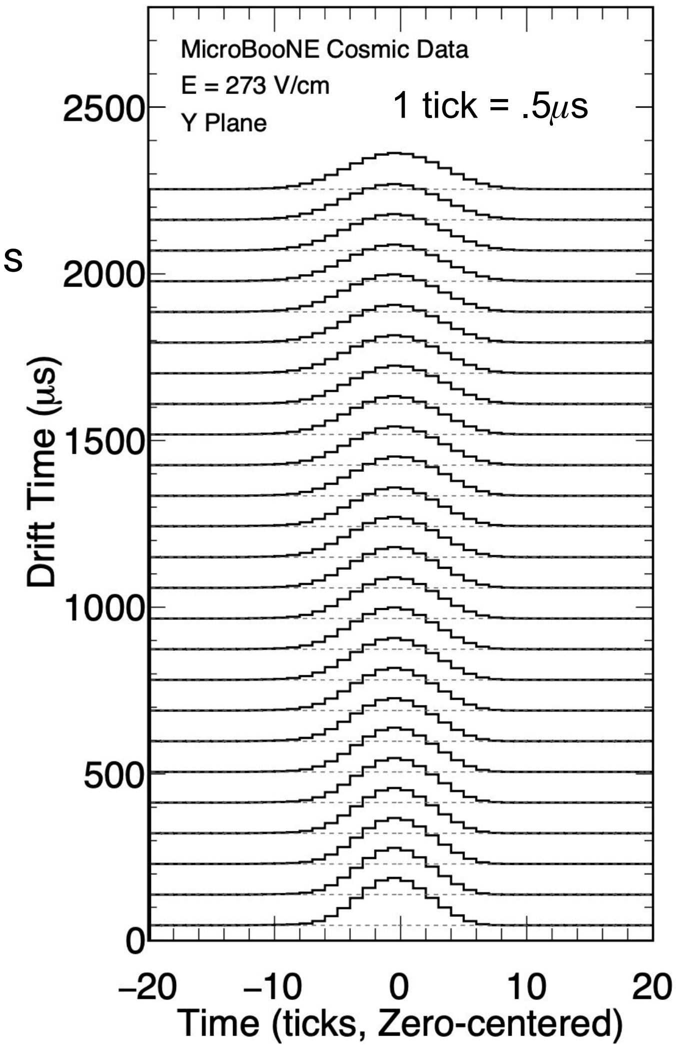
Ionization electron clouds spread out as a function of drift time, reducing SNR. In an electric field, effect can be parametrized by components longitudinal to ($\mathbf{D_L}$), and transverse to ($\mathbf{D_T}$) the field.

The MicroBooNE D_L Measurement

- Measurement made at 273 V/cm using cosmic muons
  - Width of response-deconvolved waveforms increases as a function of drift time, *t*

$$\sigma_t^2(t) \simeq \sigma_t^2(0) + \left(\frac{2D_L}{v_d^2}\right) t$$

where v_d is the drift velocity.



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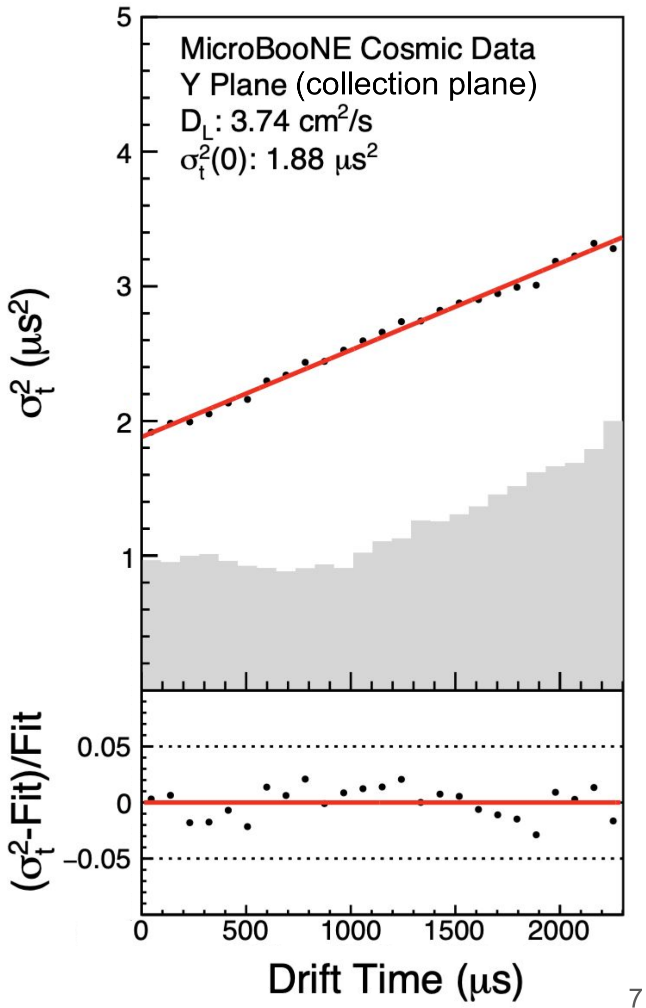
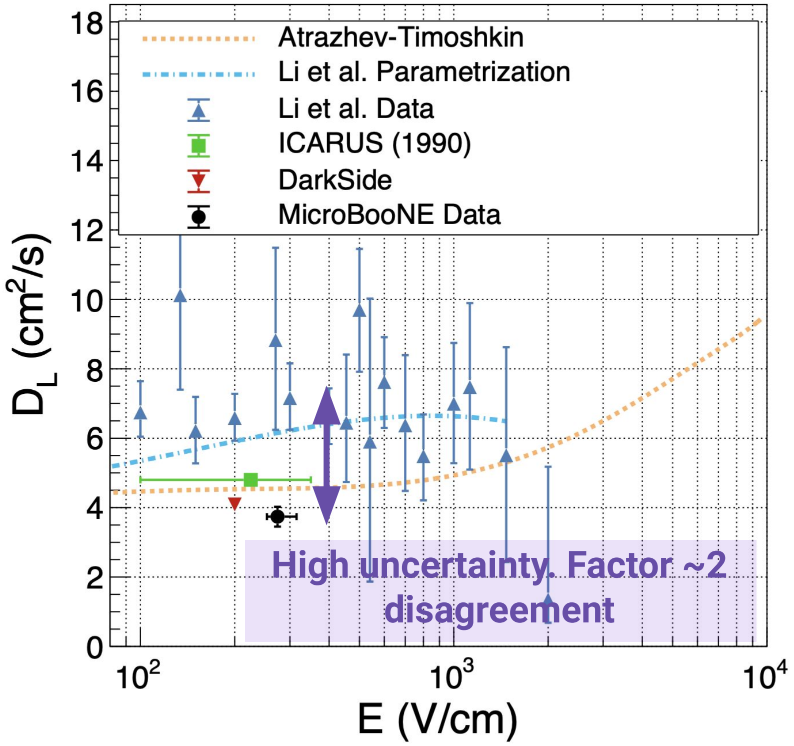
- $D_L = 3.74^{+0.28}_{-0.29}$ cm^2/s.
- Largest systematics
  - Response function (±6%)
  - Drift velocity (+3.9%, -4.1%)
- Published last year **JINST 16 (2021) 09, P09025**



The Diffusion Landscape

JINST 16 (2021) 09, P09025 (updated)



- **Li et al.**
  - Test stand measurements, single phase
- **ICARUS**
  - In-situ measurement with cosmic muons, single phase
- **DarkSide**
  - In-situ measurement with Argon-39, dual phase
- **MicroBooNE**
  - In-situ measurement with cosmic muons, single phase

LAr Experiments historically used the prediction from the **Li et al. parametrization**, which was a fit to **their own test-stand data** and to the **ICARUS data**.

Note ***no*** measurements of D_T in this region. Estimated from:

$$\frac{D_L}{D_T} = 1 + \frac{E}{\mu}\frac{\partial \mu}{\partial E}$$

E = Electric field,
μ = Electron mobility

Transverse Diffusion

MicroBooNE publication talks a good deal about transverse diffusion.

As charge drifts, the electron clouds landing on each wire begin to **overlap**, leading to a **bias in the measured diffusion value if tracks at a high angle to the anode plane are let into the sample.**

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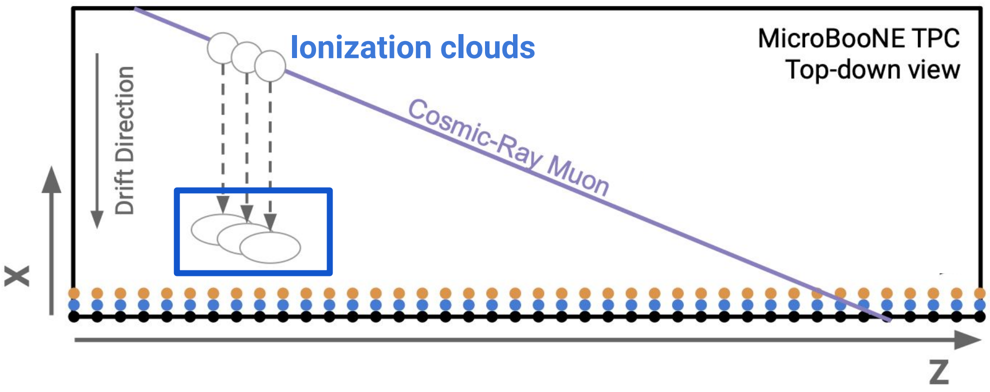

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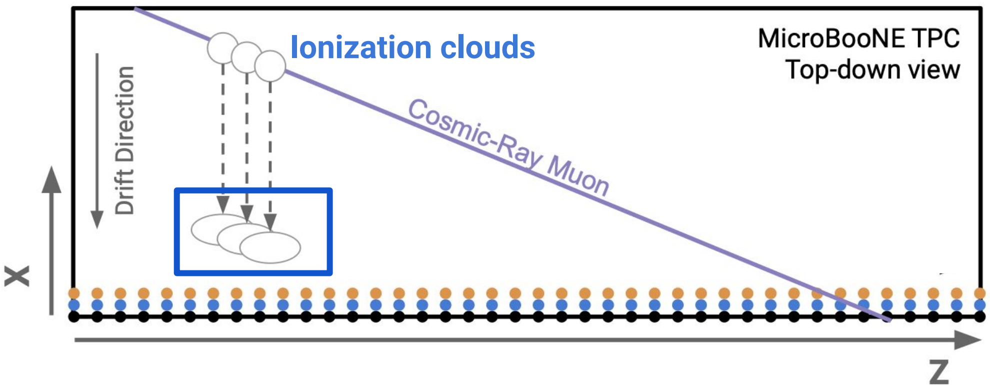


Question

If charge is mixing between detection regions, this should smear dE/dx distributions… how large an effect can this have on calibrations and PID?

Difficult to disentangle this effect in data, so let's look at some simulation.

Some Details on Simulation #1

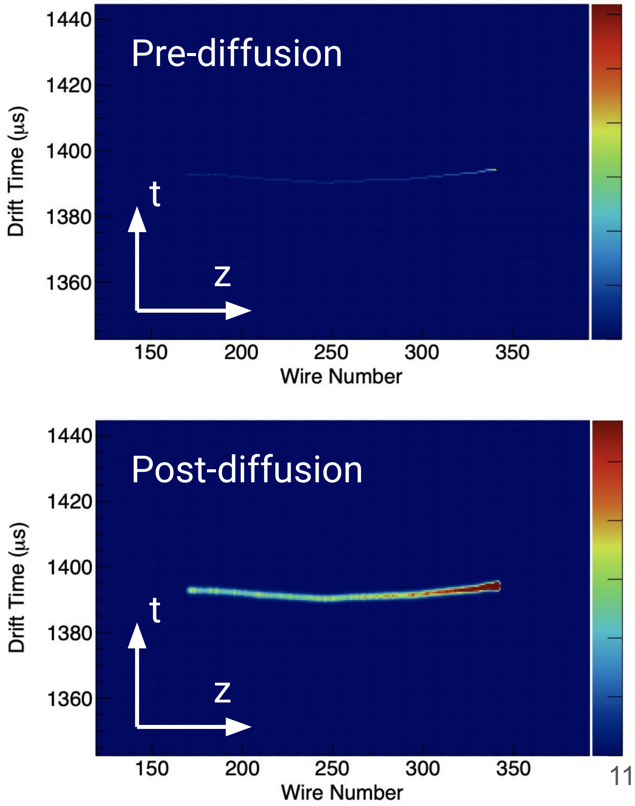
- Use a Geant4 simulation
  - A block of liquid argon is simulated, separated along the Z direction into "detection regions" analogous to a collection plane (**3 mm, 5 mm** spacing used).
  - **Recombination** (Modified box, ArgoNeuT parameters)
    JINST 8 (2013) P08005
  - **No induction planes** or **E-field distortions** for simplicity
  - Apply diffusion to each electron using

$$\sigma_L(\mu s) = \sqrt{\frac{2D_L \cdot t_d}{v_d^2}}, \quad m_L \sim G(0, \sigma_L)$$

$$\sigma_T(mm) = \sqrt{2D_T \cdot t_d}, \quad m_T \sim G(0, \sigma_T)$$

$$t_d^{new} = t_d + m_L,$$
$$y^{new} = y + m_T \cos d,$$
$$z^{new} = z + m_T \sin d.$$

"Top-down view"



Some Details on Simulation #2

Samples used for this analysis have:

- Where not specified, assume wire spacing is 3 mm
- **Using D_L = 6.5 cm^2/s, D_T = 13.0 cm^2/s**
- 500 V/cm, 2 MHz sampling rate
- Closure test: extract input D_L value ✅

"*Worst realistic case*" scenario.
Higher than MicroBooNE, ICARUS, DarkSide

Ionization-only (IO) Samples
- Forward-going particles
- Particles only allowed to ionize, to take out bias from effects like track angle, delta rays

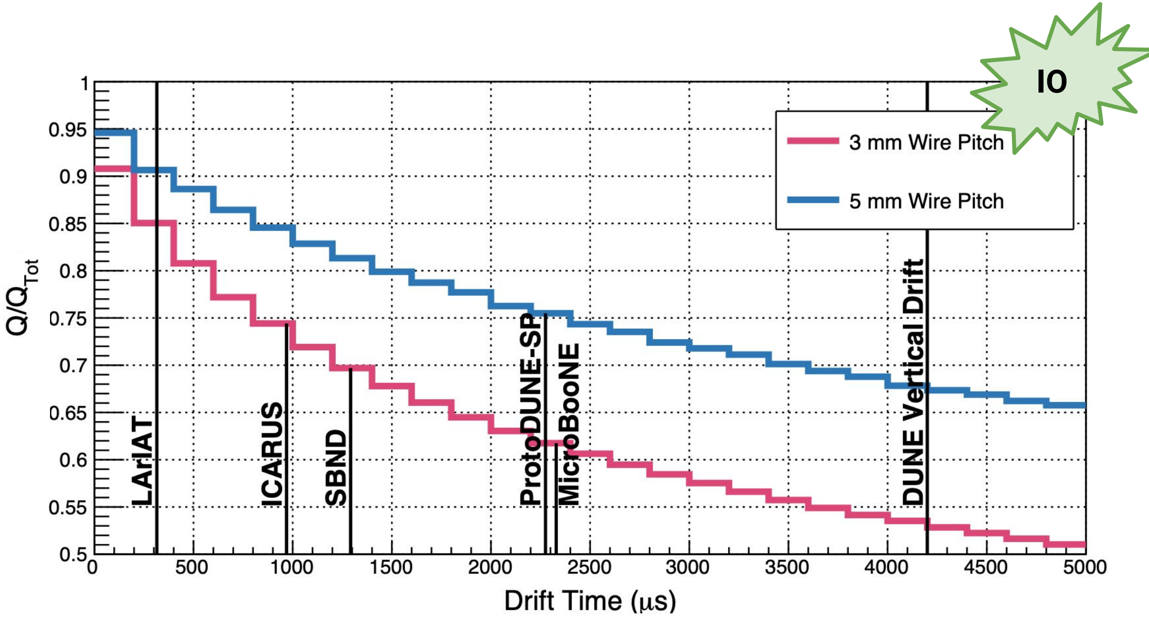
Full-Physics (FP) Samples
- Forward-going particles
- Full QGSP_BERT physics list

First Stop: Charge Efficiency

To try and understand how much charge is really moving around, define charge efficiency, **Q/Q_{Tot}:**

"What fraction of charge expected to arrive on a given wire actually arrives on that wire after diffusion"

This depends only on the drift time of the electrons and the wire pitch.



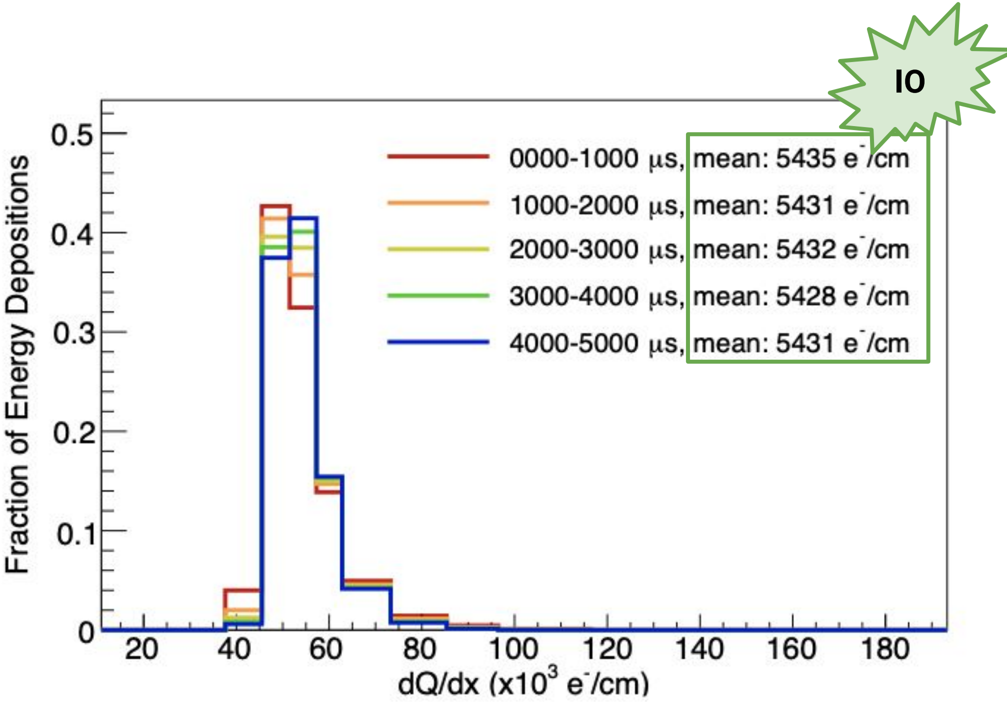
Effect on dQ/dx Distribution

Now, looking at the *dQ/dx* distribution in the presence of diffusion as a function of drift time.

Longer drift times → low-charge and high-charge hits get averaged out → distribution changes

The MPV, median ***shift to higher values.***
The **mean**, notably, does not shift around.

Consequence of central limit theorem.



* I'm not sure that diffusion can be effectively calibrated out, but if someone can convince me offline, I'm all ears! 👂

Calibrations: An Overview

Typically surface-based LArTPCs use cosmic ray muons for calibrations, and it's done in two steps:

Response flattening ("dQ/dx") calibration

Flatten the response using the **median dQ/dx**.

Aims to remove effects of space charge, cross-connected TPC channels, transverse diffusion, longitudinal diffusion*, and electron lifetime*

(From **JINST 15 (2020) 03, P03022**)

Energy scale ("dE/dx") calibration

Sets the energy scale using known dE/dx profile of stopping muons.

Convert dQ/dx → dE/dx, fitting for the calibration constant using the **MPV of dQ/dx**.

The calibration uses the **median** and **MPV** values to avoid bias from presence of delta rays, reconstruction pathologies.

… but given previous slide, we think are likely to be biased. How much?

A Question of Competing Biases

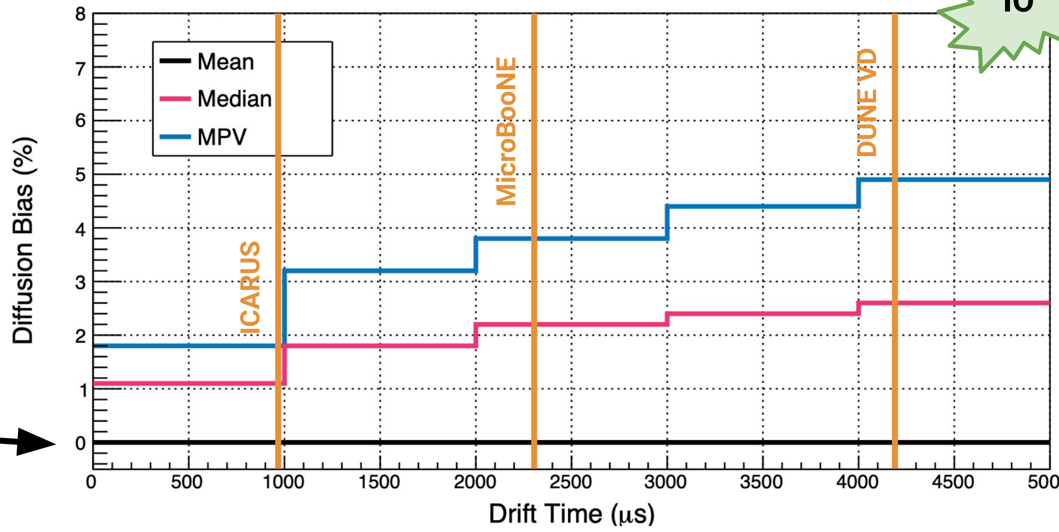
IO

Bias is plotted as a function of drift time for **mean**, **median**, **MPV** of dQ/dx

Shape of bias can be explained by

$$\sigma_T\,(mm) = \sqrt{2D_T \cdot t_d},$$

Note that the **mean** remains completely unbiased across the time range.



Even with very simple simulation, we can show that our calibrations are biased at the few-% level (depending on the true levels of diffusion in data)

But clearly, we have more effects in our data…

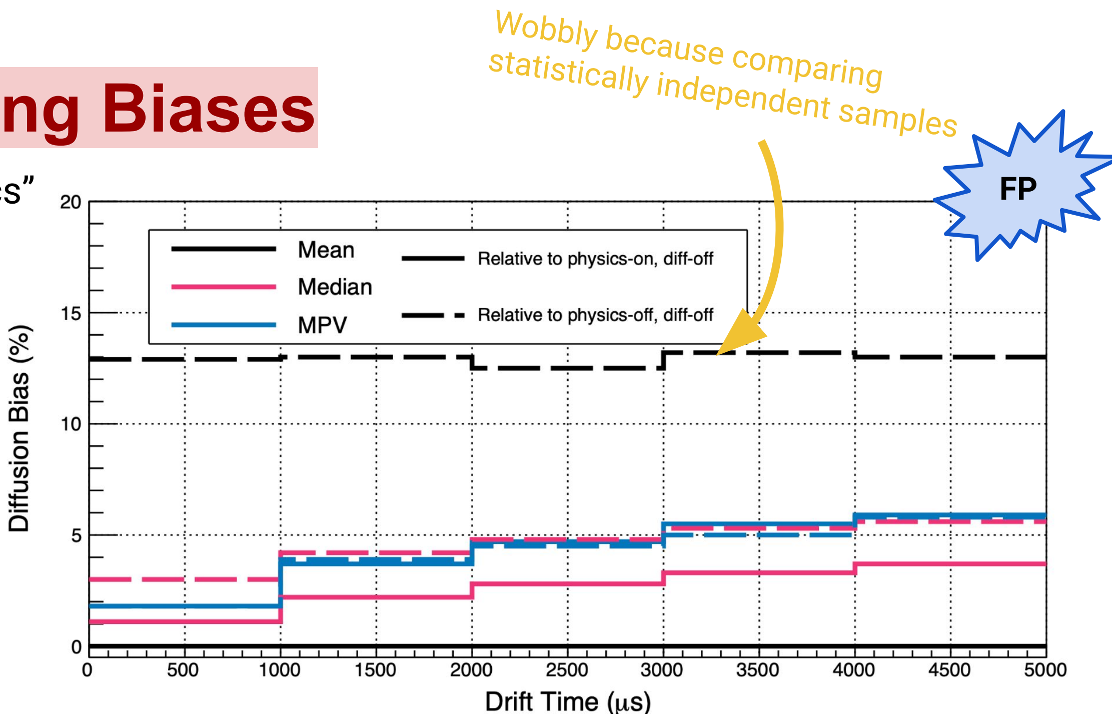
A Question of Competing Biases

We can repeat the study using our "Full-physics" sample.

Measure either bias relative to

FP diffusion-off sample (solid lines).
Find bias from only diffusion

IO diffusion-off sample (dashed lines).
folds in bias from delta rays, other physics. Most fair comparison to data.



- **MPV** bias **is not impacted** by presence of delta rays/other physics,
- **Median** gains a **~2% additional bias** in the presence of delta rays/other physics,
- **Mean** gains a roughly **~13% bias** in presence of delta rays, *but* ~flat across drift time.

Story is complicated by additional (expected!) flat bias, but **overall conclusion is the same.**

Calibration in the Presence of Diffusion

- We can't really escape bias in our calibration
  - Current calibration techniques, using **MPV** and **median** dQ/dx, introduce bias due to D_T.
  - Using the mean introduces bias from the effect of, eg, delta rays, reconstruction pathologies

But not all calibration choices are equally sinful!

- Smaller, drift-time dependent bias?
- Large, ~flat bias?

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One potential option

Flatten response using mean dE/dx

➢ Introduce bias, but flat across drift time

Pin energy scale using MPV

➢ Use only muons close to the anode to minimize bias from diffusion.

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How viable is this?

More investigation using data necessary!

Effects on Particle ID

We investigated the effect of diffusion on PID using a simple χ^2 calculation comparing the simulation with the proton prediction for the last 30 cm of the tracks.

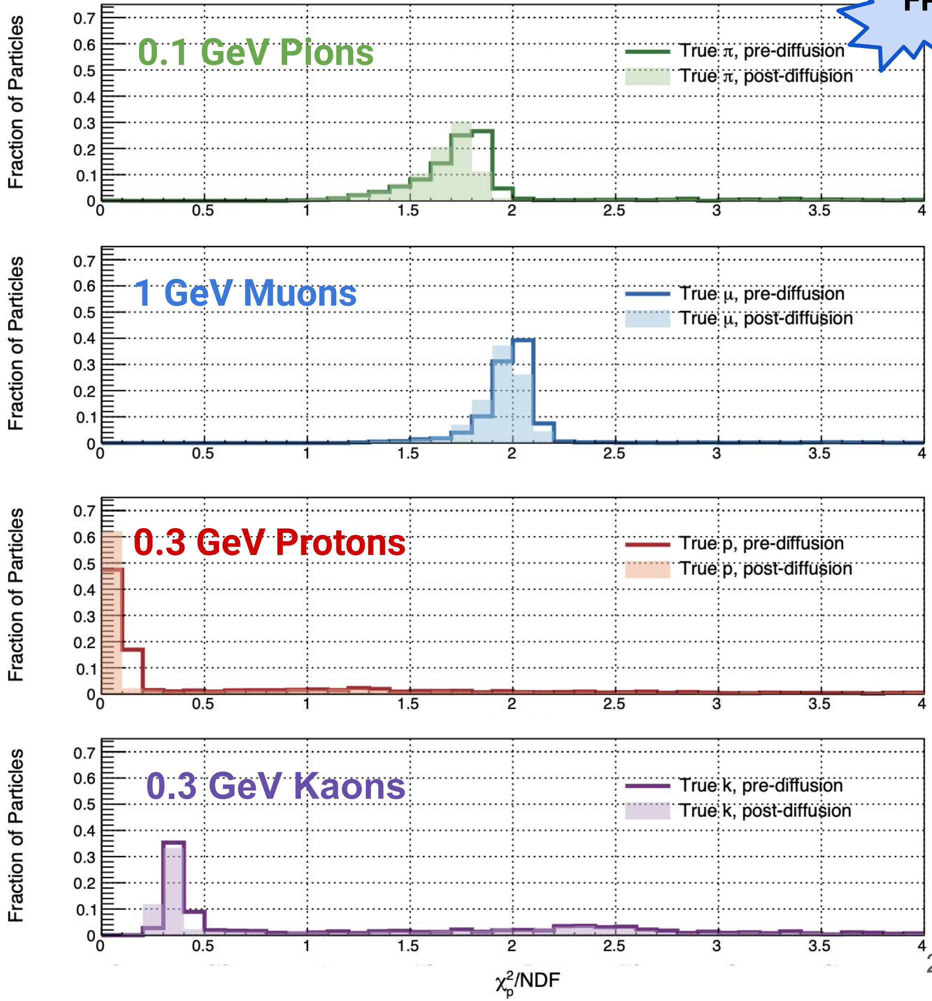
It's **easy**, and it's **ubiquitous**.

The change in distribution is small relative to the separation between muons and **protons**.

But the effect is fairly significant when considering separation between **protons** and **kaons**, or **muons** and **pions**.

A drift-dependent PID might help to improve separation of these populations.

FP



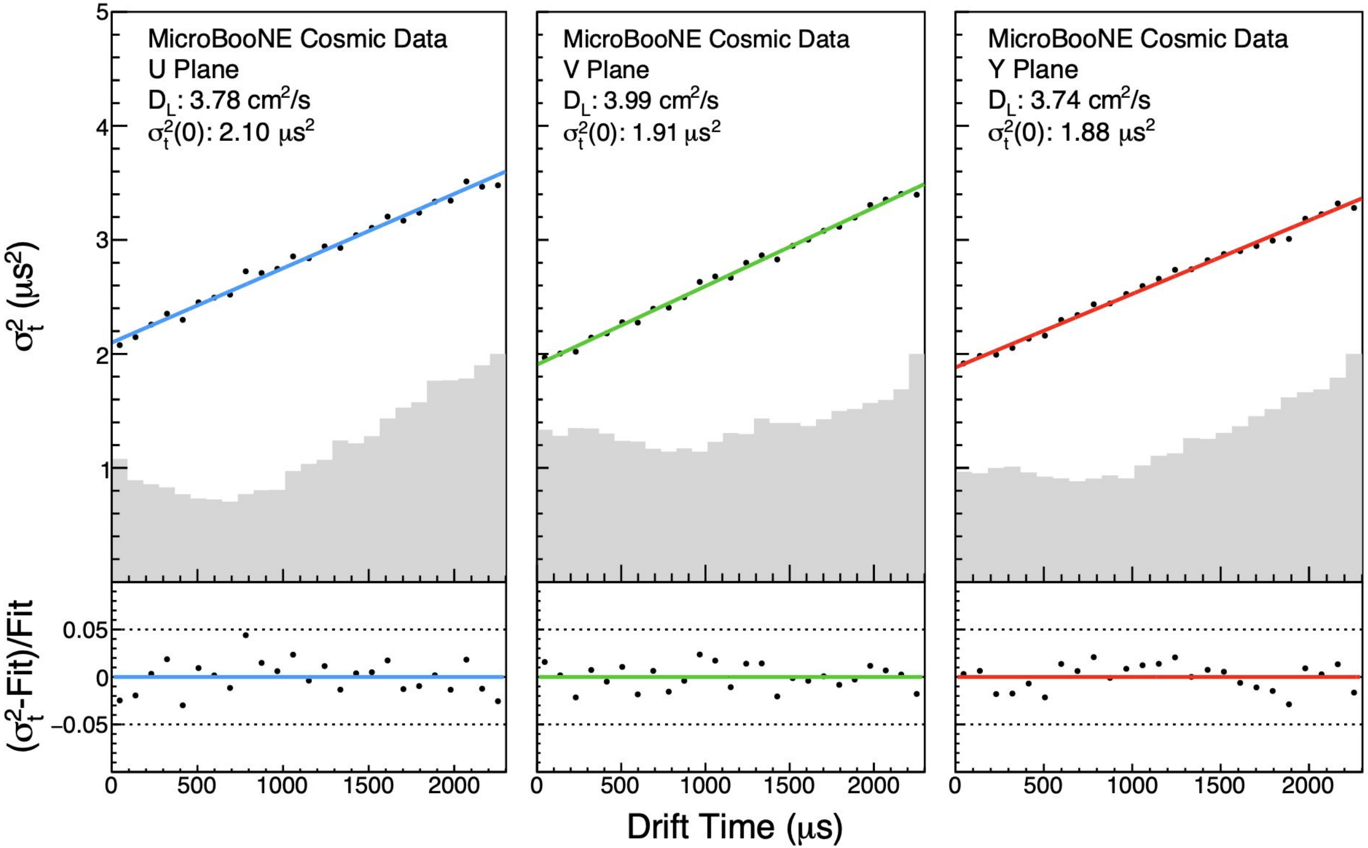
Conclusions

- Transverse diffusion modified dE/dx distributions as a function of drift time
  - This can subtly bias current calibrations!
  - Bias likely at the few-% level for drift times relevant for current and future LArTPCs
    - Broader context: DUNE needs %-level energy resolution for a CP violation measurement! A few-% level effect eats the entire budget (and more)!
  - One way to mitigate this uncertainty, though further study using data is required.
  - PID is relatively unimpeded for particles of very different mass, though potential for improvement for particles of more similar masses.
- There are papers!
  - MicroBooNE D_L Measurement: **JINST 16 (2021) 09, P09025**
  - Effects of Diffusion on Calibrations/PID: **JINST 17 (2022) 07, P07016**
  - Recently, this has also been approached from a different angle, but with similar results (G. Putnam & D. Schmitz) **JINST 17 (2022) 10, P10044**
- **Measurements of transverse diffusion are critical!**

Thanks! Any Questions?

Additional Slides

MicroBooNE Measurement, All Planes



Nucl.Instrum.Meth.A 345 (1994), 230-243

ICARUS Measurement

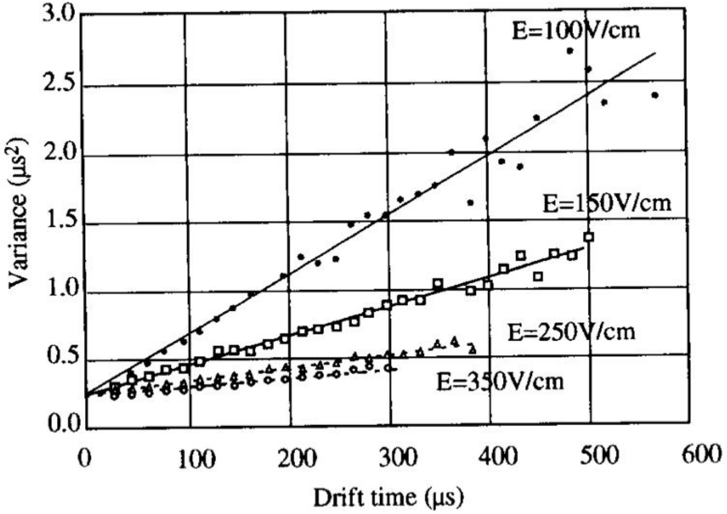


Fig. 15. Pulse rise time squared vs drift time for different fields.

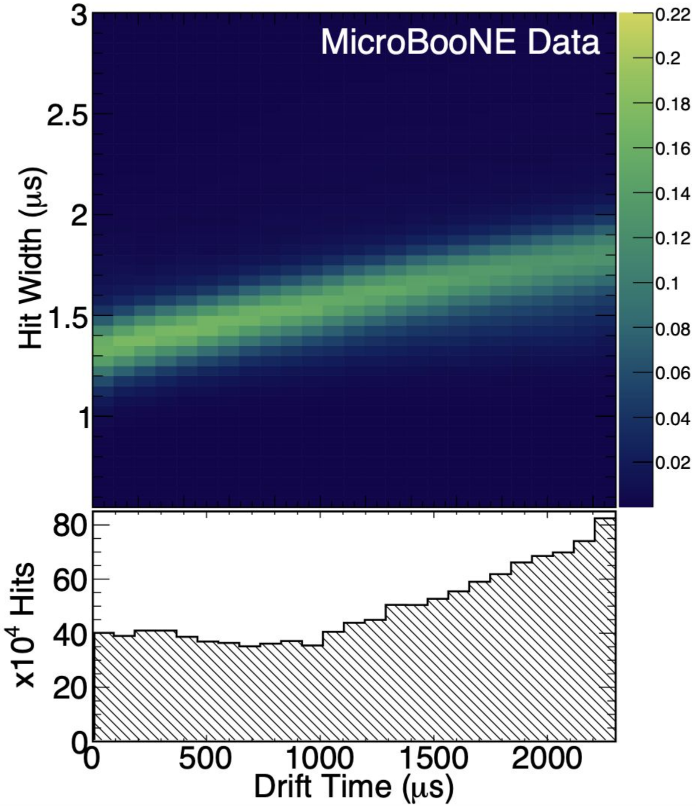
We don’t have a lot of information on the method, but *suspect* that they could have been biased by transverse diffusion. We also don’t have access to the values measured at different fields, and the quoted uncertainty appears to be the uncertainty on the mean.

We obtain the longitudinal diffusion coefficient from the analysis of the rise time (R_T) of the signal of the collection wires. The square of the latter is the sum of a constant term ($R^2_{T_0}$) and of a term proportional to the square of the spread (σ^2) of the signal due to diffusion. Also, if t is the drift time and ν the drift velocity, we have $\sigma^2 = 2Dt/\nu^2$. In conclusion a linear fit of R^2_T (or equivalently σ^2) versus drift time gives directly the longitudinal diffusion coefficient D. We took data at drift field intensities of 350, 250, 150 and 100 V/cm. For each sample we fitted the signal rise shape with the convolution of a step function and of a gaussian. The fitted values of the variance of the Gaussian are shown in Fig. 15. Linear fits to the data give, at the different fields, values that are equal inside the errors. Taking their average we obtain $D = 4.8 \pm 0.2$ cm^2/s.

At the relatively low field intensities of our data, the electrons are expected to be thermal; in this case the Einstein relation $qD/\mu = kT$ should hold. With the mobility value that we have measured, $\mu = 480$ cm^2 V^{-1} s^{-1}, we then expect $D = 3.8$ cm^2/s. A further contribution to the diffusion is known to come from the Coulomb repulsion amongst the electrons. Calculating their contribution with the approximated method of ref. [8] we find a value of about 2 cm^2/s, that should be added (linearly not quadratically). We can conclude that our measured value agrees with the expectations.

Level of Data/Simulation Disagreement

JINST 16 (2021) 09, P09025



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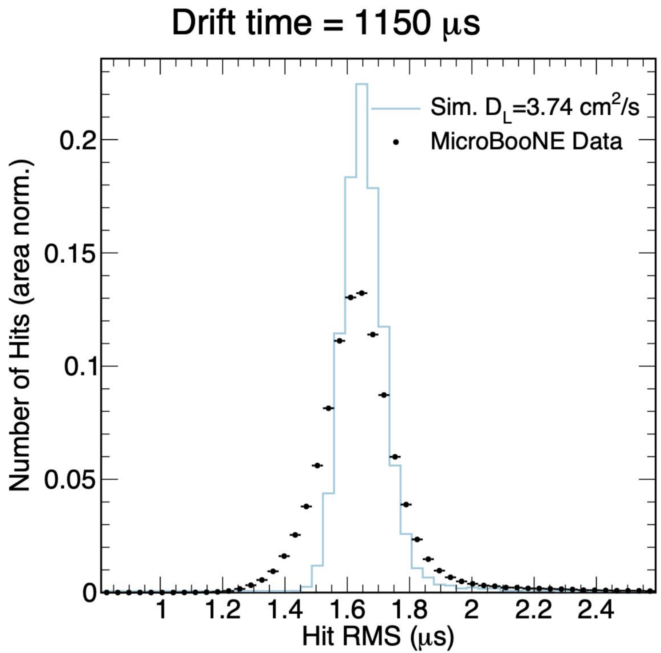
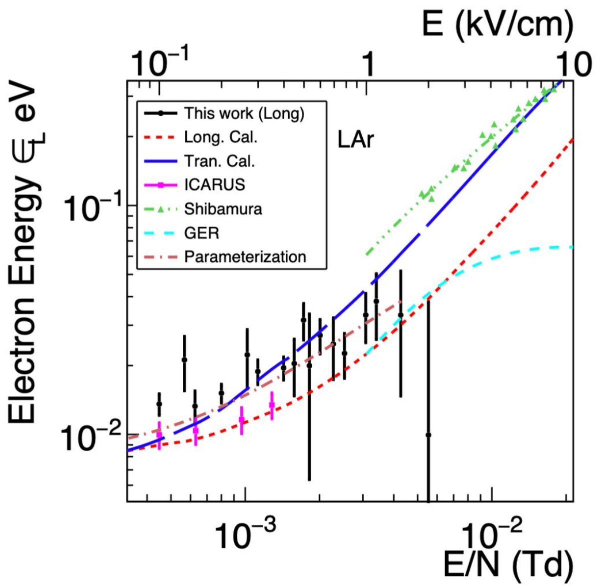


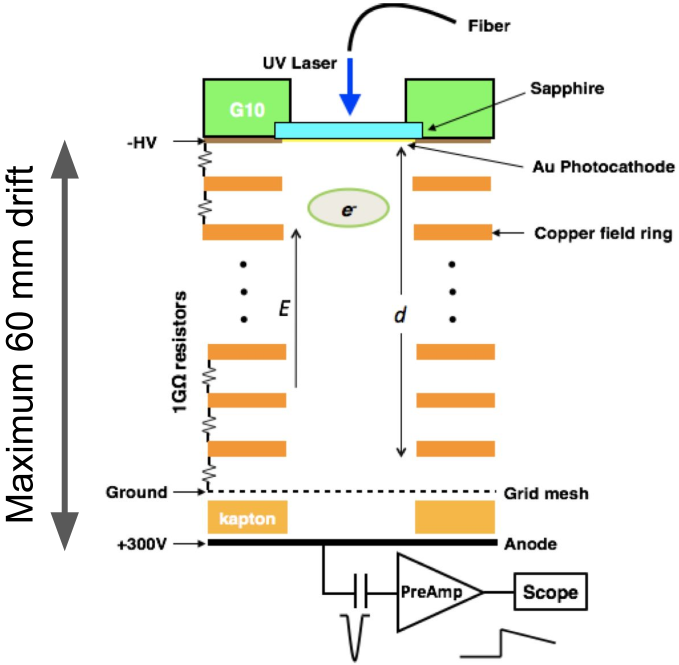
Nucl.Instrum.Meth.A 816 (2016), 160-170

The BNL Measurements

$$D_L = \frac{\mu(E)\epsilon_L}{e},$$

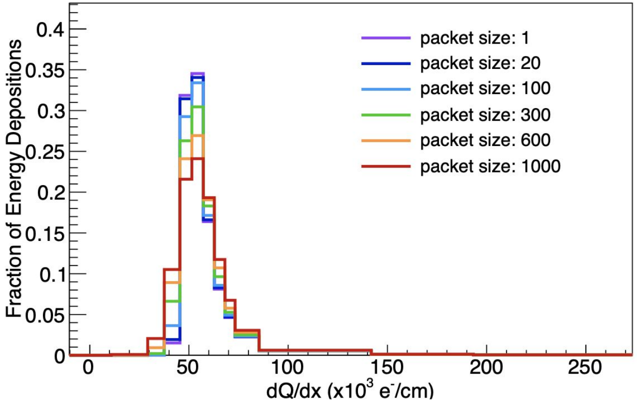
With μ(E) being the electron mobility as a function of the E-field.

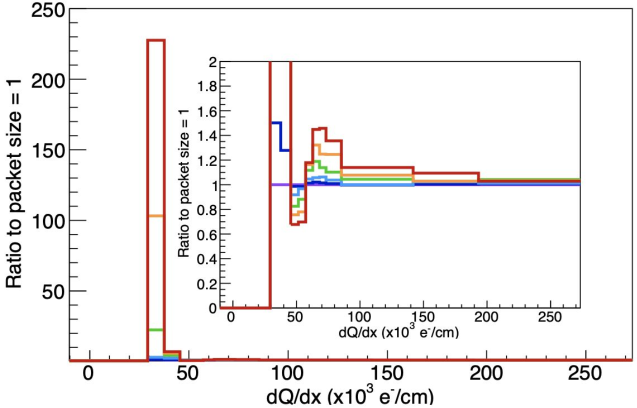




- Very detailed paper, thorough theoretical overview.
- Longitudinal diffusion measured in a test stand makes it a valuable result from an alternative source.
- We've not been able to pin down uB/ICARUS/DarkSide data doesn't agree with the BNL measurements.

An Aside on Simulating Diffusion





One might consider applying diffusion to packets of electrons in order to speed up simulation.

We looked into how this might impact the dQ/dx distribution in the absence of diffusion and found that it’s a pretty significant effect.

For this work, we took the computational hit and simulate diffusion on every ionization electron.

Effect on dQ/dx Distribution

Think of the detected charge as being a combination of charge in nearby detection regions after diffusion.

Detection regions

pre-diffusion

dr. 1	dr.. 2	dr. 3	dr. 4	dr. 5	
6000e	10000e	7400e	7500e	6000e	Mean: 7380e Median: 7400e

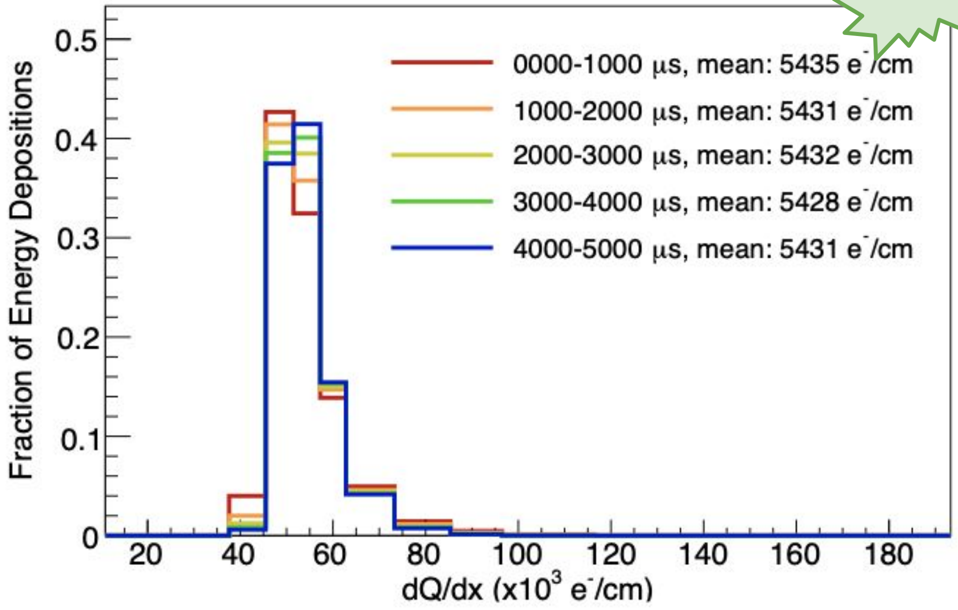
Assume each detection region loses 25% electrons each way

post-diffusion

7000e	8350e	8075e	7100e	6375e	Mean: 7380e Median: 7100

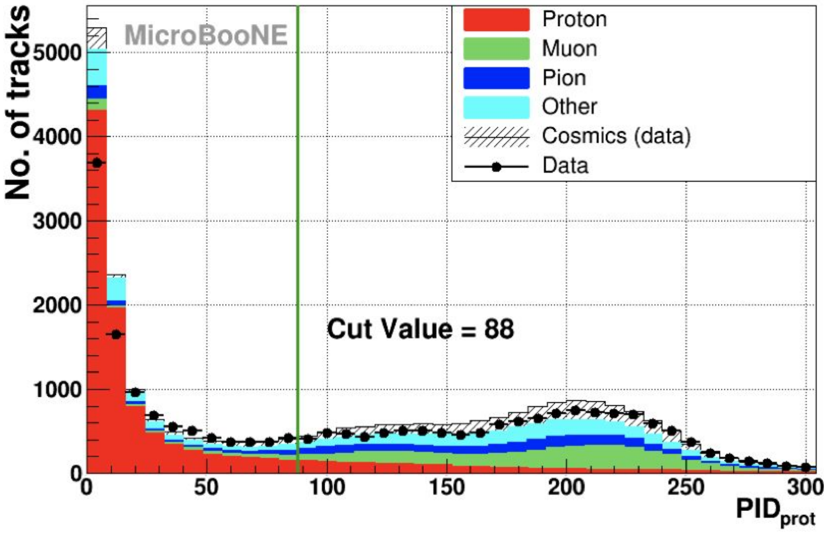
For example, reg. 2 = (0.25*6000)+(0.5*10000)+(0.25*7400) = 8350

IO



Effect on Particle ID

Phys.Rev.D 102 (2020) 11, 112013



Reminder that **data** is far messier than this simulation, for example this PID, from the MicroBooNE CCNp0π paper, which is constructed in a similar way to our χ^2 metric.

A drift-time dependent particle ID could improve particle ID algorithms!

- Particularly true with for separating particles with similar masses, ie muons/pions which have typically proven challenging to separate in LArTPCs.
- Even true for muons/protons, where other detector effects may smear the distributions together already.