Improved Reconstruction Methods with Liquid Argon Detectors using new Q-Pix Technology

Carter Eikenbary
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Outline

Background

- Standard Model of Particle Physics
- Motivating the use of Liquid Argon (LAr) for Particle Detection
- Physics in a Liquid Argon Time Projection Chamber (LArTPC) Detector
- 3D Particle Tracking with Q-Pix Readout Technology

Analysis

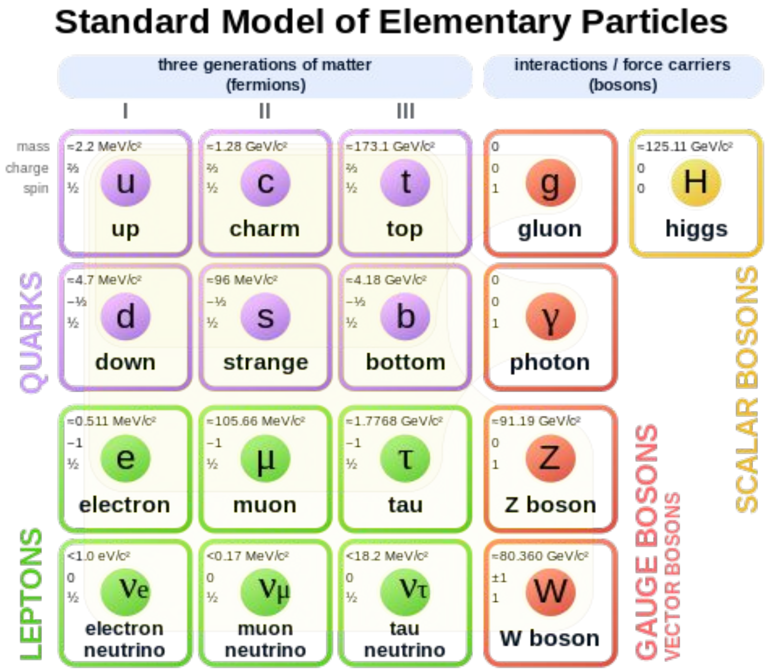
- Simulating a Muon Event with Q-Pix Readout
- An Initial Study of Z Position from Q-Pix Readout
- A More Robust Method to Determine Z
- Testing the New Method on A Simulated Sample

Standard Model of Particle Physics

A catalog of fundamental particles that describes the properties and interactions within the framework of particle physics.

While the standard model has been incredibly successful, there are many things which it doesn't explain.

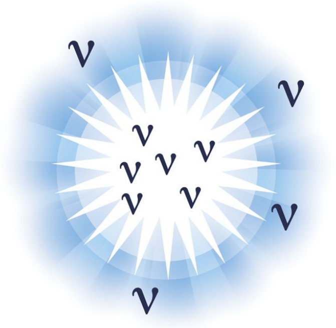
Theoretical studies of particle physics are indeed useful, but for many studies it is valuable or even necessary to have experimental input.



DUNE - A Study of the Neutrino

The Deep Underground Neutrino Experiment (DUNE) is designed to study:

1) the rates of neutrino/antineutrino oscillation with more precision than any other experiment. This could shed light on the matter/antimatter asymmetry in our universe.
2) neutrino signals from supernovae to learn about the formation of black holes and neutron stars.
3) neutrino interactions with new particles beyond the standard model.
4) Many other topics as well…



DUNE will utilize 70,000 tons of liquid argon (LAr) to study the neutrino, the most of any LAr detector to date.

DEEP UNDERGROUND NEUTRINO EXPERIMENT

On the use of LAr for Particle Detection

Direct particle detection requires an interaction to take place.

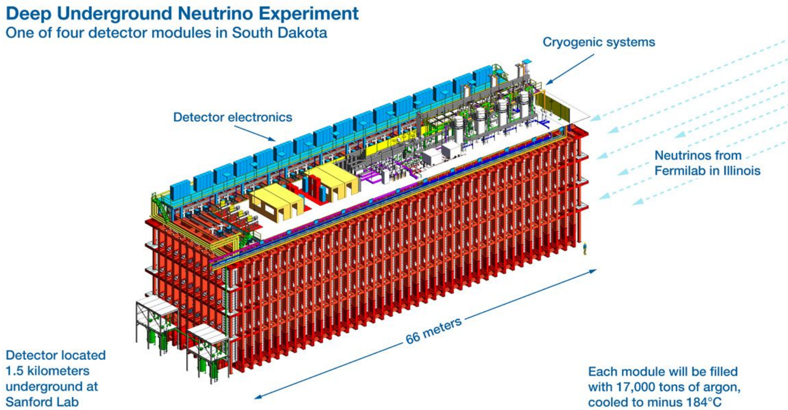
Q.) How can we increase our chances that an interaction happens in a particle detector, especially for particles that rarely interact like the neutrino?

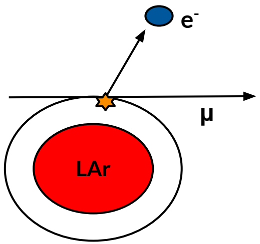
A.) Have a significant quantity of useful target atoms for the particle to interact with.

Liquid Argon (LAr) is an ideal target atom because of its density, availability, and capability to expel electrons through ionization from particle interactions.

When neutrinos interact with Ar atoms, a charged particle, such as a muon, can be produced. These muons will interact frequently with the Ar atoms along its path through the detector.

Next, will be a discussion of these muon interactions and how we will detect them with new readout technology.



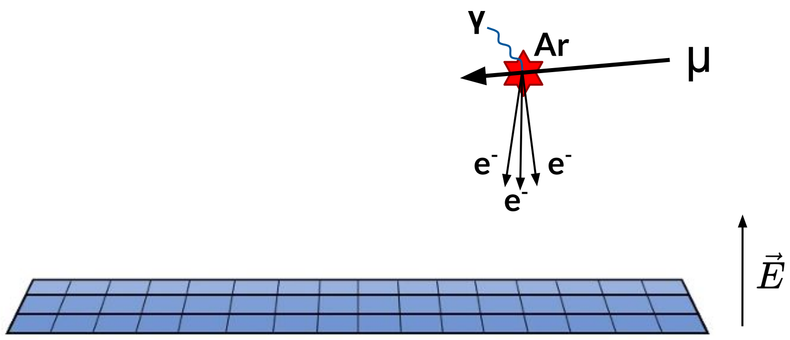


ionization

Liquid Argon Time Projection Chamber

What happens when a charged particle, like a muon, interacts in a Liquid Argon Time Projection Chamber (LArTPC)?

1.) Particle interacts with a target LAr atom which will free electrons in the atom (ionization) and produce light (scintillation).
2.) An electric field will pull the freed electrons towards the detector floor where the amount of charge and when it arrives will be measured.
3.) For some experiments, the scintillation will be detected by photomultiplier tubes (PMTs) which are used to determine when ionization occurs.
However, this is expensive and may not be needed.



We describe next both the new readout technology proposed for DUNE, as well as a new way to use it for 3D tracking.

Q-Pix Overview and Schematic

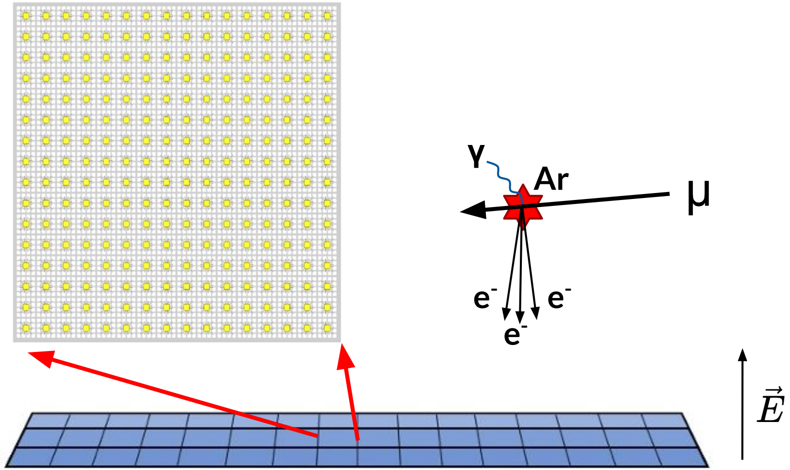
Charge Counting Pixels (Q-Pix) are a novel method for measurements of particle interactions in LArTPCs using pixel-based charge collecting circuits.

Pixels are uniformly distributed in a large 2D grid on the bottom of the LArTPC

- Each pixel comprises a 4x4 mm^2 region of the grid.
- A Charge Integrate-Reset (CIR) block is connected to a 4x4 grid of pixels. (yellow square)

Block will integrate the ionization charge and resets when a desired amount of charge is collected in the circuit, ΔQ = 6250e.

Instead of timestamping the individual charges as they hit the Q-Pix, **the CIR block will timestamp a set of pixel resets**.



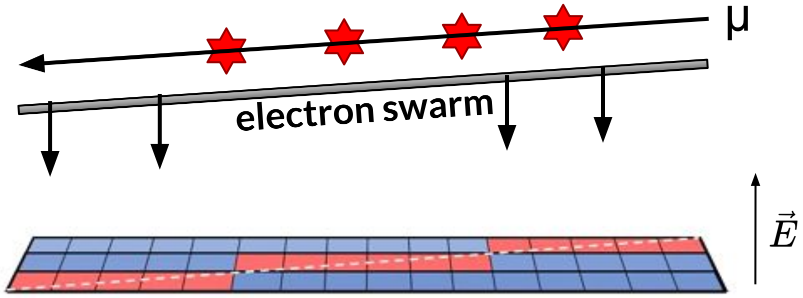
Determining X-Y Trajectory

Muons with large kinetic energies will interact frequently with the LAr atoms along its path. These interactions will cause many electrons to be freed from the Ar atoms.
(These electrons are referred to as the electron “swarm”)

The electric field in the LArTPC will pull the electron swarm towards the Q-Pix plane.

The pixels directly beneath the muon path will be activated by the electron swarm as the charge gets collected by the readout technology.

This gives us direct measurements of the X-Y trajectory to within the width of a single pixel (4mm).



Determining Z Positions

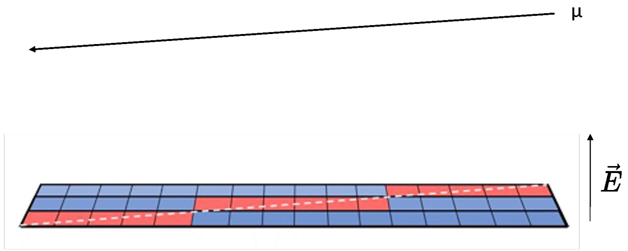
As the electron swarm travels towards the Q-Pix plane, the electrons will have interactions with the Ar which can delay their arrival time on the Q-Pix. As it turns out, these interactions broaden the electron swarm distribution in a systematic way.

Using the known longitudinal diffusion (D_L) and drift velocity (v) for Ar, the RMS of the arrival times is given by:

RMS $= \sqrt{(2D_L * Z/v^3)}$

By measuring the RMS of the electron swarm, we can indirectly measure the Z position to get a 3D measurement of the muon interactions.

Before we explore this idea in more detail, we will next turn to simulations of the process.



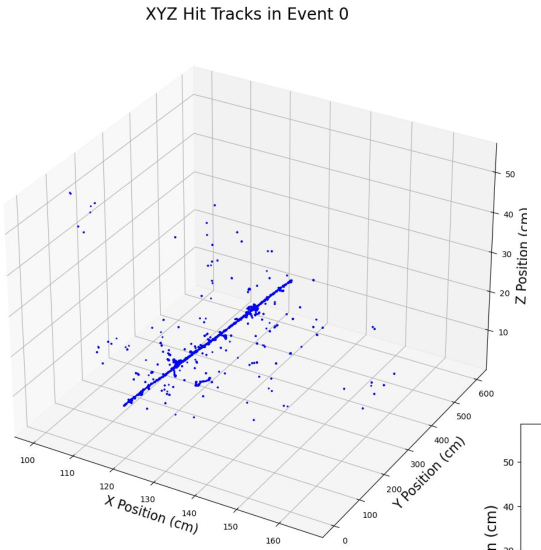
Moving to Simulations: Interactions in the Detector

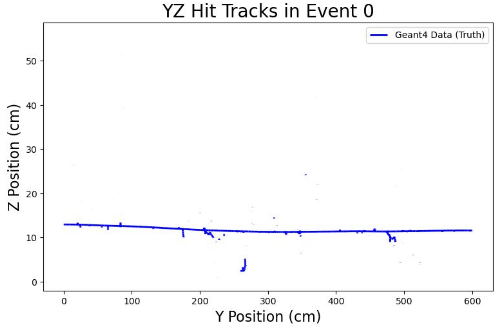
We have developed a standard simulation framework to study the interactions in the DUNE detector using Q-Pix readout.

The figures on the right show a single muon that traverses the detector in 3D (left) and projected into 2D (right).

The blue dots indicate where energy was deposited on an Ar atom. We will refer to those as a “hit”.

Note that there are numerous hits along the trajectory of the muon that indicate it’s primary path. Additionally, there are other nearby groups of hits where photons have emanated from the muon trajectory, traveling a short distance before ionizing Ar atoms which complicate things.





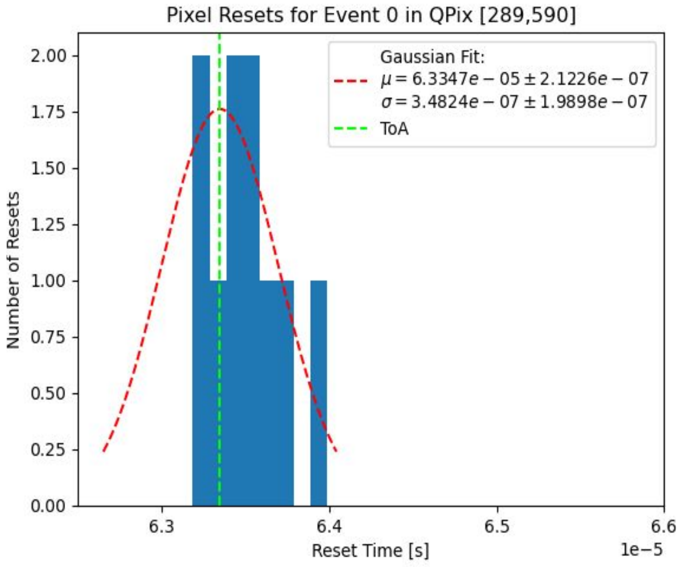
Moving to Simulations: Q-Pix Readout

The same software also simulates the subsequent electron swarms as they travel down to the Q-pix plane, and then simulates the Q-Pix response and readout.

The figure on the right shows the results for a single pixel where we see multiple resets in the histogram.

The Gaussian fit to the data (red dashed line) gives us a mean-time and RMS of the electron swarm.

The RMS will be useful; however, we will see that the mean-time, which we will refer to as the Time-of-Arrival (ToA), is equally crucial for accurately and robustly measuring the entire event.



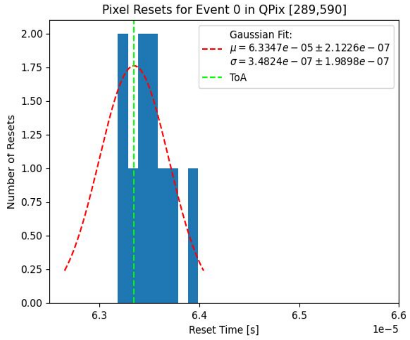
First Estimate of Z Using the RMS

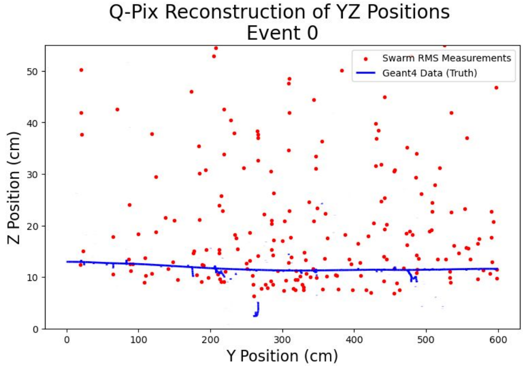
From our simulated data, we found an RMS measurement of the electron swarm for each pixel. (Top plot)

Using the relationship between RMS and Z established earlier, we estimate the Z (shown in red) above each pixel. **Note that many measurements are off the scale, Z>>50cm.** (bottom plot)

As it turns out, many of the Z measurements are poor because there are various reasons why the RMS of a single pixel may get over measured. (Multiple hits in Z)

We need a better way to determine the Z for each pixel. For this, we turn to the ToA measurement of the pixel, which is a more robust measurement if we know when the event occurred.





Using a Pixel's ToA for a Better Z Measurement

Recall, that Q-Pix technology allows us to also measure a pixel's ToA. We can use this to measure the Z of the hit if we know the time between ionization and when the electron swarm reaches a Q-Pix which we call the Time-of-Flight (ToF).

- ToF can be determined from ToA if we know when ionization occurs.
- We refer to the ionization time as t_0.
- We treat t_0 as a constant for the entire event.
  - Time between initial and final ionization is small compared to clock speed.

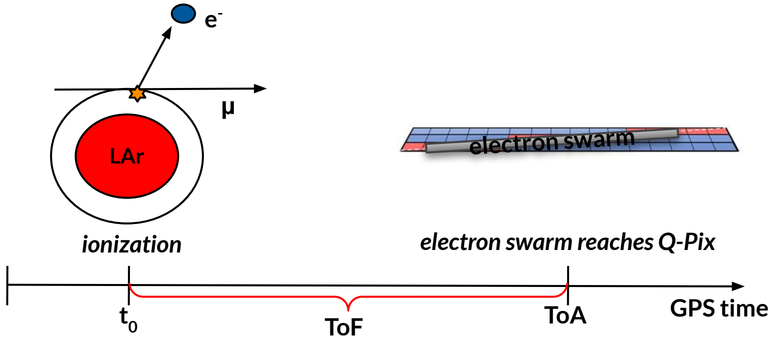
ToF = ToA - t_0

We then determine the Z position with the ToF measurement:

ToF = Z/v

therefore ***Z = v*(ToA - t_0)***

We will now discuss a method for determining t_0, and thus, the Z from the distribution of RMS measurements in the event.



RMS Distribution of a Single Event

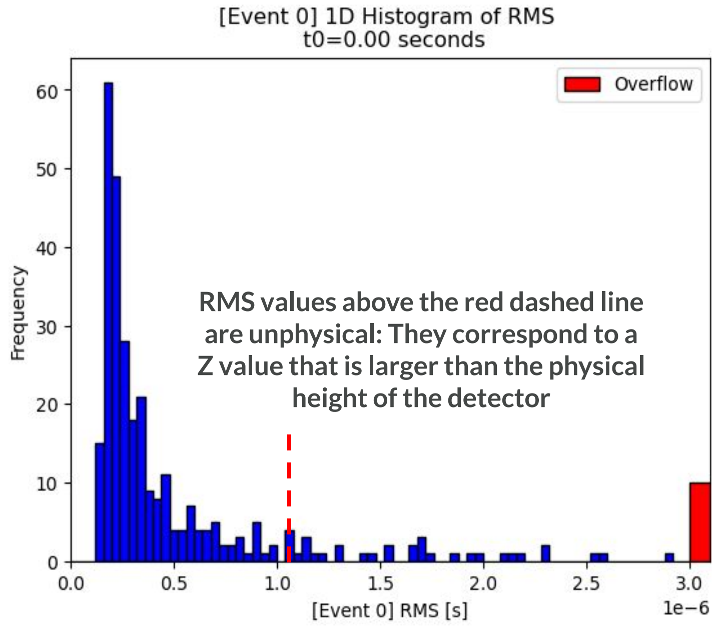
We start by making a distribution of the RMS measurements from the active pixels with **nResets > 5** in the event.

There is some variation in the RMS because the various hits occur at different Z values. These variations are useful.

On the other hand, the high-side of the RMS distribution is not useful for determining Z. (Muon had multiple hits in Z that increased the RMS)

If we only consider the well-measured pixels in the peak region, then we will have a clean sample of RMS values for the event.

With this in mind, we will next determine an $RMS_{Expected}$ value for each pixel and create a $RMS\text{-}RMS_{Expected}$ distribution for this event.



RMS - $RMS_{Expected}$ Distribution of the Event

For each pixel, we determine an $RMS_{Expected}$ value from the pixel's ToA measurement:

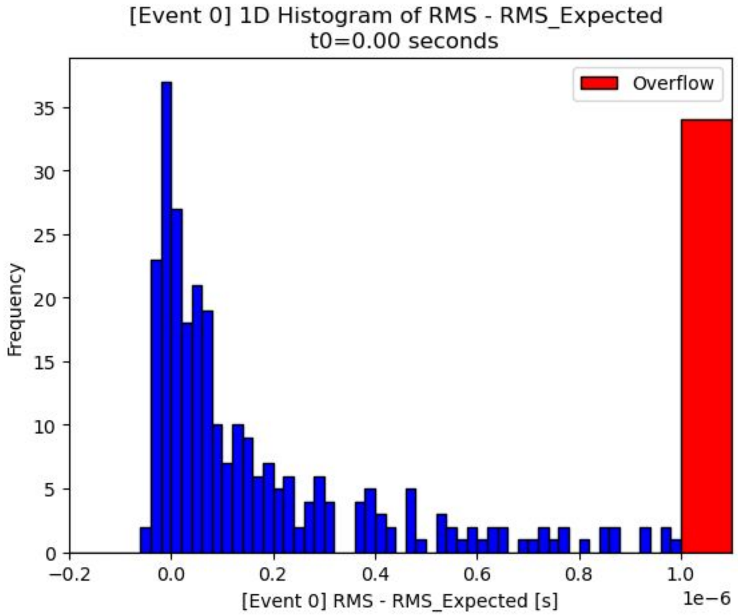
$$RMS_{Expected} = \sqrt{(2D_L * Z/v^3)} = \sqrt{(2D_L * (ToA-t_0)/v^2)} = 2.24 \times 10^{-5}\sqrt{(ToA - t_0)} \text{ seconds}$$

From this, we make a RMS-$RMS_{Expected}$ distribution for the active pixels in the event and make guesses on the t0 variable.

The plot on the right shows the RMS-$RMS_{Expected}$ distribution for the active pixels in the event with the assumption that $t_0 = 0$, which is true for our simulated events.

If we have the right t_0, the mean of this distribution should be zero.

Like before, this distribution suffers from over-measurements of the RMS. Thus, we look to describe a method for finding the mean of this distribution from well-measured pixels.



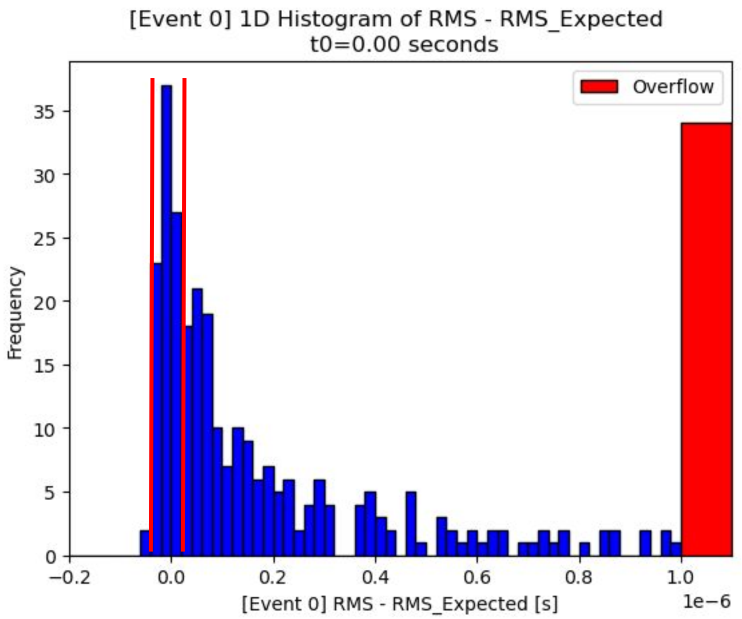
Selecting Well-Measured Pixels

The peak of the RMS-RMS$_{\text{Expected}}$ distribution is composed of well measured pixels.

Find a small region, around the size of the expected resolution, in the RMS-RMS$_{\text{Expected}}$ parameter space with the most pixels and set a selection window centered on this region.
(with some restrictions on the peak not being too far from the lowest RMS measurement to mitigate fluctuations in low statistics events)

For the RMS-RMS$_{\text{Expected}}$ values in the selection window, we take an average $\rightarrow$ Mean(RMS - RMS$_{\text{Expected}}$).

If we selected well-measured pixels, then the Mean(RMS - RMS$_{\text{Expected}}$) will be approximately zero with the correct t_0.



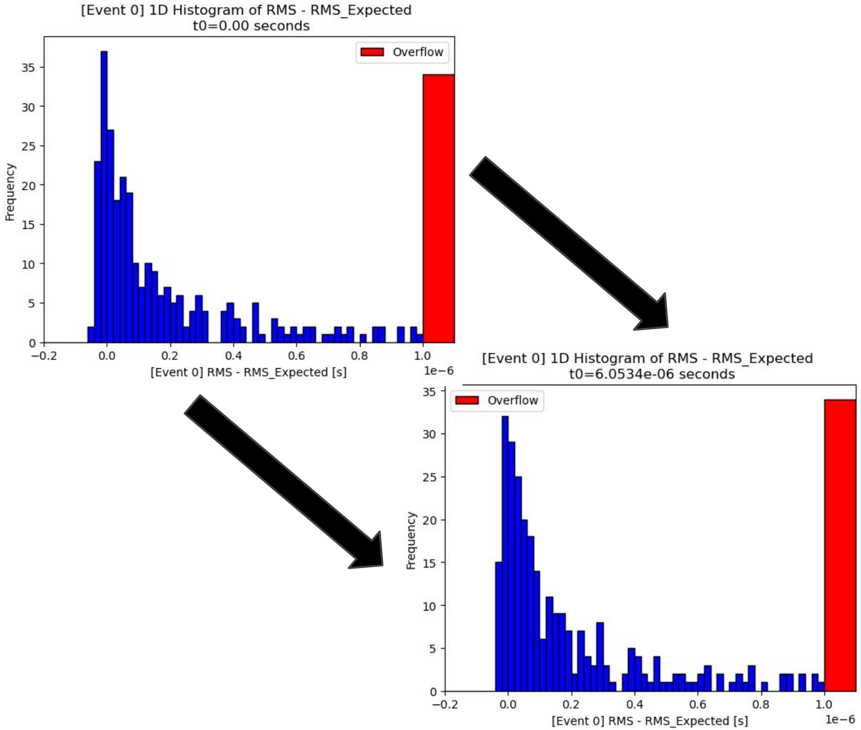
Shifting RMS-RMS$_{Expected}$ Distribution with t_0 Guesses

In principle, there is an optimal t_0 that will get Mean(RMS-RMS$_{Expected}$) as close to zero as possible.

Instead of hand checking t_0 values, we have used a minimization algorithm for the |Mean(RMS-RMS$_{Expected}$)| to determine the optimal t_0.

With the algorithm, we found that t_0 = 6 μsec for this event, which can be compared to our expected t_0 = 0 sec assumption.

NOTE: In real events, we will not have the t_0=0 assumption, so the top plot is artificially good.

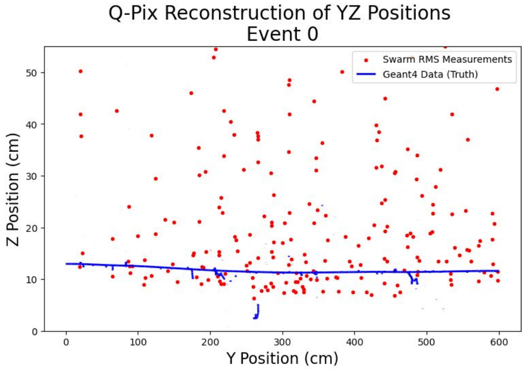


Reconstructing the 3D Positions

With a high quality measurement of t0, we can use the ToA to determine the Z position above a pixel.

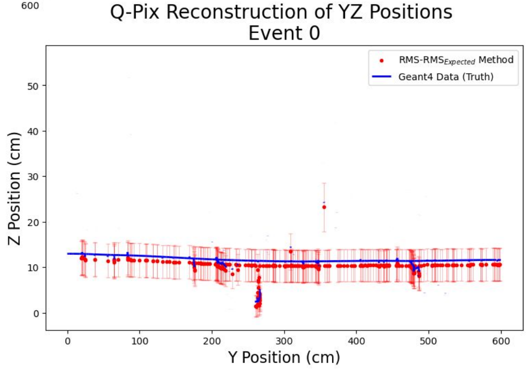
Combining with the X and Y measurements from the pixel's coordinates, we have a full 3D reconstruction of interactions for the event.

The improvement in our measurement for the muon event goes from the result on the left to the result on the bottom right.



RMS Only Method

Using t_0 Method

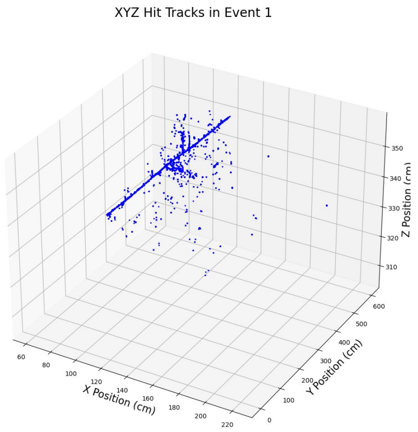


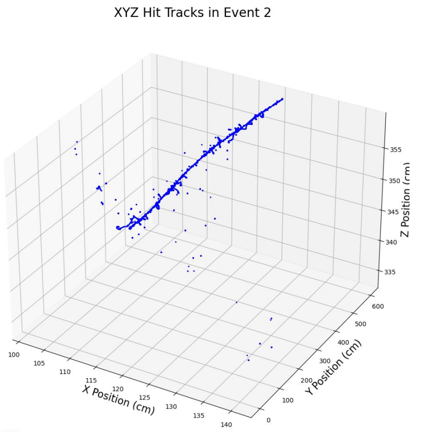
Expanding Beyond a Single Event

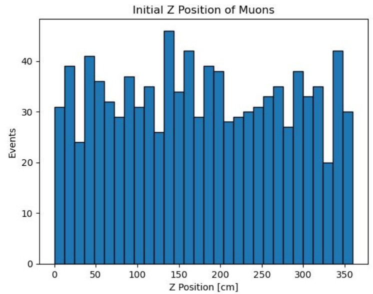
How will the RMS-RMS$_{Expected}$ algorithm perform on a large simulated sample of muon events where the muons have a random initial Z position?

To study this, we simulated 1000 muon events in the DUNE detector with Geant4.

- All muons enter DUNE detector at [120,0, z] cm (z can vary from 0-360cm)
- muon has 10 GeV of kinetic energy with momentum in y
- No noise or electron/Ar recombination



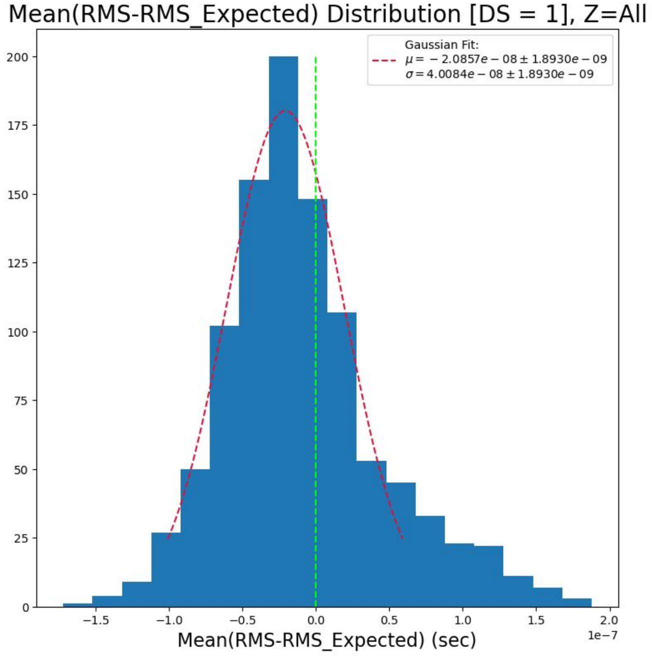


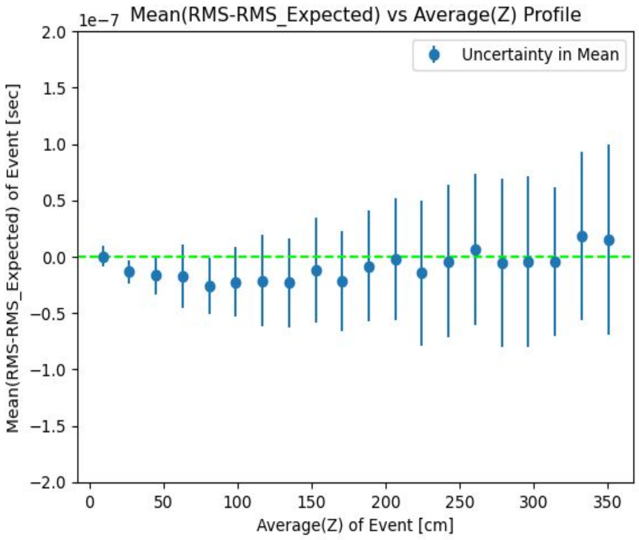


How Well We Expect the Algorithm to Perform

For simulated events we know that t0=0, so by simply considering the difference between our measured distribution and expectations we get a sense of how well we will do.

- Mean of the distribution is within 1σ of 0.
- Tail feature seen here is mostly due to resolution effects at large Z.
- Small systematic variations as a function of Z.

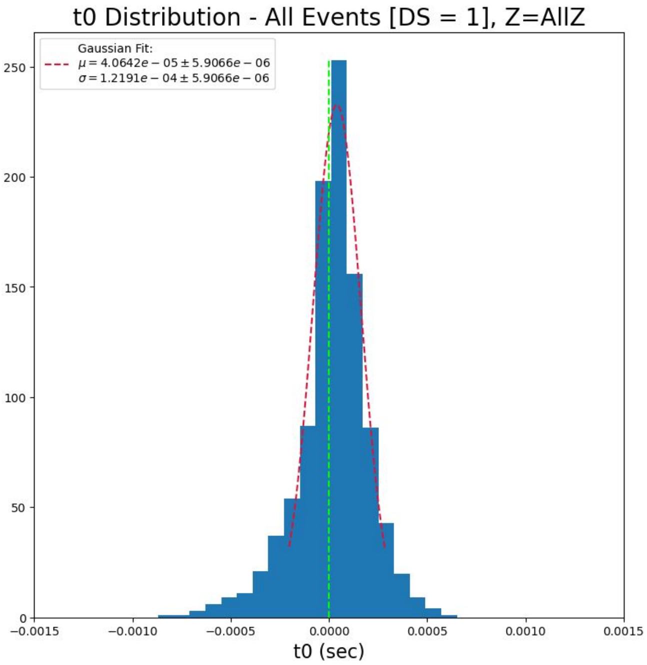


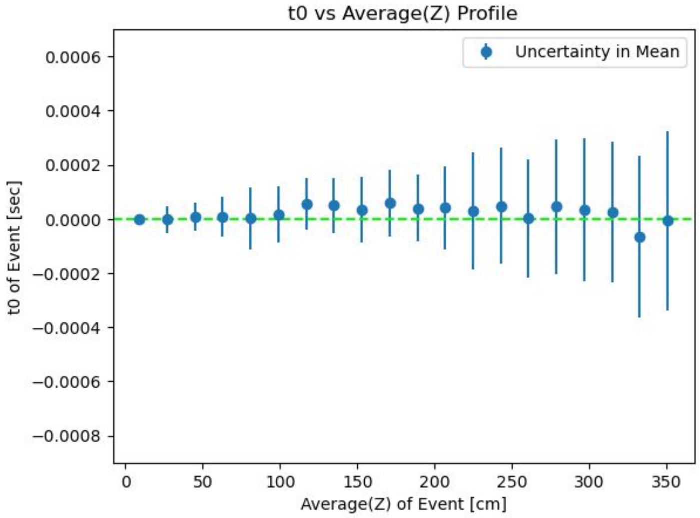


Determining t_0 for the Full Data Sample

With the minimization algorithm, we can determine the t_0 for each event. For our sample we see that:

- The mean of the distribution is within 1σ of 0.
- There is some low-side asymmetry.
- The method is robust for all values of Z for the detector.

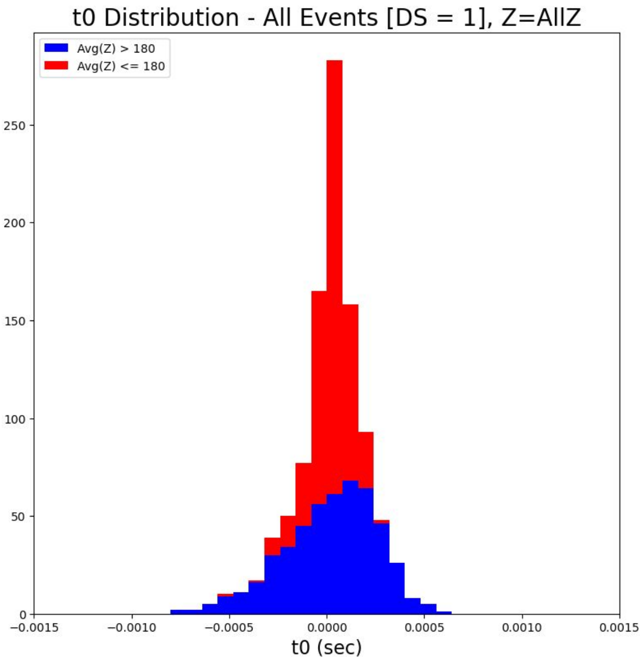


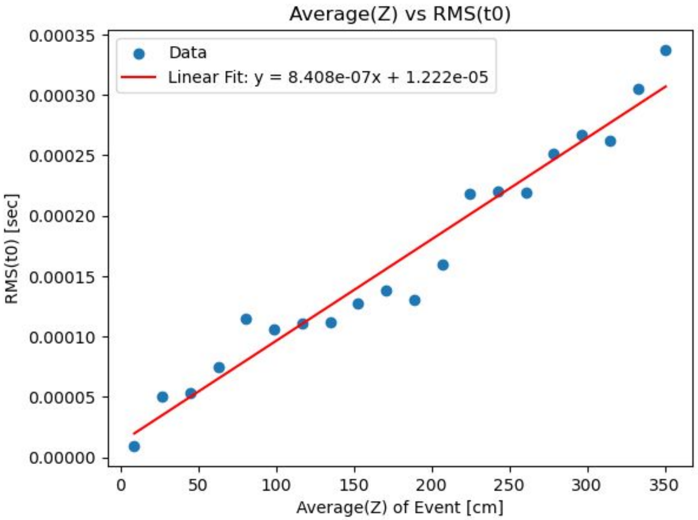


Accuracy of the t_0 Measurement as a Function of Z

Next we would like to determine the accuracy of the t_0 measurement as a function of Z. We see that:

- The distribution tails are from the largest Z events as expected.
- The resolution of the t_0 measurement asymptotes to 12 μsec at Z=0 and is 163 μsec at Z=180cm.



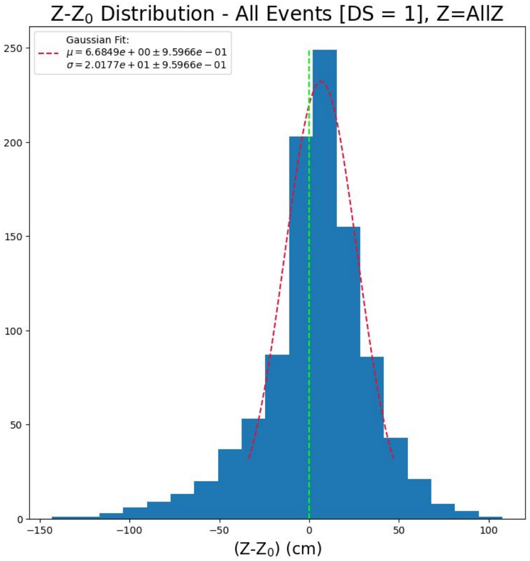


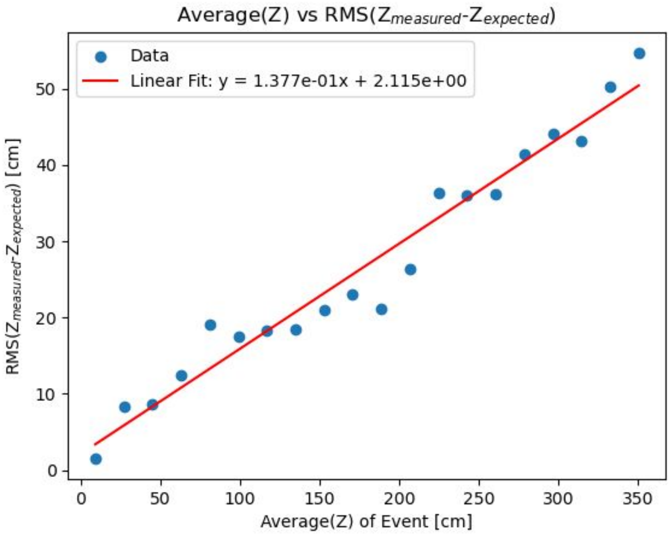
Resolution of the Z Measurement

The resolution of the t_0 measurement can be converted to the resolution in the Z with the electron drift velocity, v.

$RMS(Z_{measured} - Z_{expected}) = v*RMS(t_0)$

Resolution as a function of Z asymptotes to 2 cm at Z=0cm and is 27 cm at Z=180cm.





Next Steps

The new method seems to be working very well. Of course there is always room for improvement.

For example, in its current state, the new method to determine event t_0 and Z above each pixel exhibits

- some systematic variation in Z
- worse resolution at large Z

Both of these could be addressed with subsequent work on

1. nReset and selection window limits
2. Adding weights to RMS values based on the pixel's nReset value
3. corrections to the $RMS_{Expected}$ function

Further studies on resolution effects due to real electronics and detectors can also help make this method more realistic.

Conclusion

- We have described the new Q-pix technology for LArTPC detectors to study neutrino interactions.
- Our new method of using the full set of pixel information from the event to determine a t_0 allows us to get from 2D to reliable 3D tracking in LArTPC detectors.

- Using fully simulated events we estimate that the $\mathbf{t_0}$ and Z resolution for this new method rises linearly as a function of Z.
  - t_0 resolution asymptotes to 12 μsec at Z=0 cm and is 163 μsec at Z=180 cm (midpoint of APA)
  - Z resolution asymptotes to 2 cm at Z=0 cm and is 27 cm at Z=180 cm

- The ability to have 3D tracking with Q-Pix provides exciting new capabilities which may enable detectors like the DUNE experiment to expand their sensitivity for neutrino studies.

Using the Mean(RMS-RMS$_{\text{Expected}}$) to Find the Event t_0

Mean(RMS - RMS$_{Expected}$) = Mean(RMS) - 2.24 x 10^{-5}√(ToA - t_0) seconds ≈ 0

For any given event, start with the assumption that Mean(RMS - RMSExpected) should be zero.
(we expect the measured Mean(RMS) to be the same as RMS$_{\text{Expected}}$)

Introduce a variable t_0 shift so that we can minimize |Mean(RMS - RMSExpected)|.

In practice, finding the t_0 shift that results in a minimized |Mean(RMS - RMSExpected)| is a non-trivial process, so we implement a Nelder-Mead minimization method for non-linear optimization.