Upgrading the Deep Underground Neutrino Experiment (DUNE) with Charge Pixel Readout (Q-Pix):

Using Simulations to Determine the Minimum Clock Speed that Does Not Sacrifice Resolution

Dave Elofson
Masters Defense Talk
(March 17, 2021)

Outline

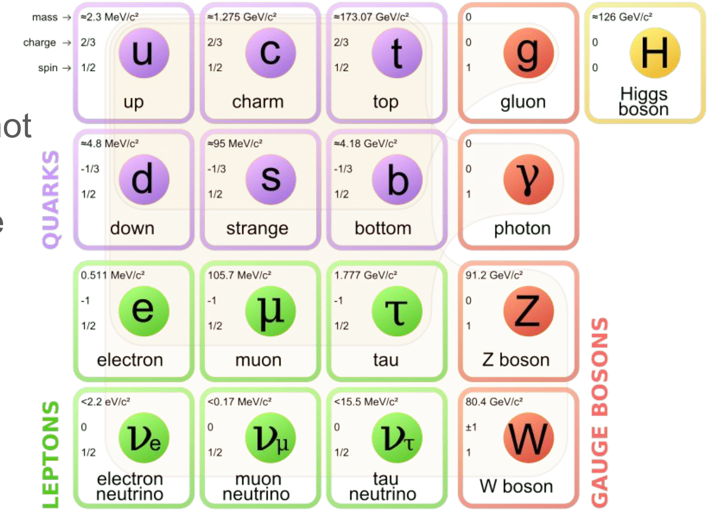
- Motivation
- Deep Underground Neutrino Experiment (DUNE) Current Design
- Detector and Readout Electronics Upgrade Using Charge Pixel (Q-Pix) Technology
- Physics of a Muon Event in a Liquid Argon Detector
- Simulating Q-Pix Response to a Muon Event
- Position Resolution as a function of Clock Speed
- Future Plans
- Conclusion

Standard Model

The standard model of particle physics includes descriptions and behaviors of all known fundamental particles

Trying to study:

- Neutrinos
  - 3 distinct types; able to change between types - this behavior is not covered in the Standard Model or fully understood
  - Small cross section → Interactions with matter are extremely rare

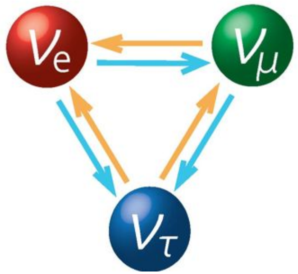


Will use these well understood particles to do so:

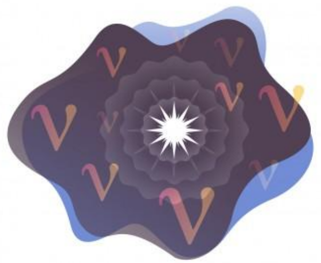
- Photons
  - Particles of light
- Electrons
  - Negatively charged; Common product in neutrino interactions
  - Important part of atoms, can knock free with enough energy
- Muons
  - Heavy electrons; Common products in neutrino interactions

Motivation

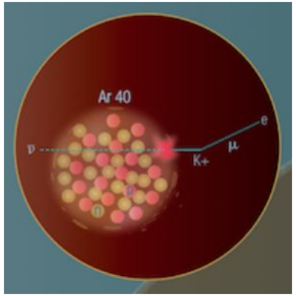
The Deep Underground Neutrino Experiment (DUNE) is an international, state-of-the-art neutrino science and proton decay detector being built to help us address three important issues:



Evidence has been found that neutrinos change types, which is beyond the Standard Model. How does this happen, and what does it suggest about their nature?



A vast majority of a supernova’s energy is carried away in the form of neutrinos. What can we learn about the structure and mechanics of supernovae from the neutrino flux and energy distributions?



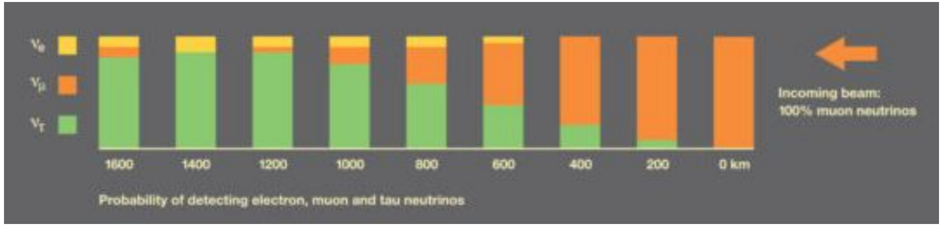
Theories regarding the origin of the universe suggest that proton decay is possible. Can we detect this extremely rare/improbable event and confirm these theories?

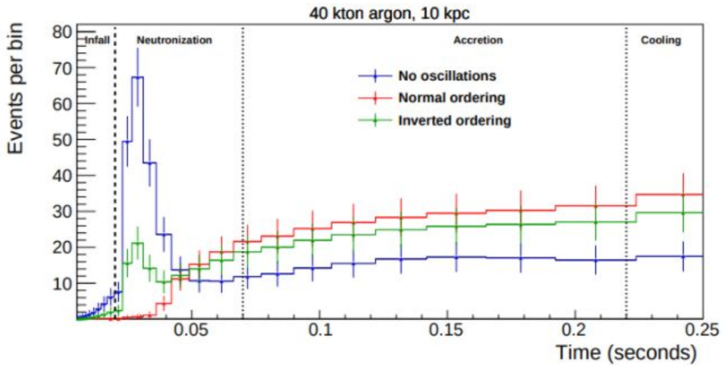
- ➢ Subject for different talks

What DUNE Needs to Be Able to Do

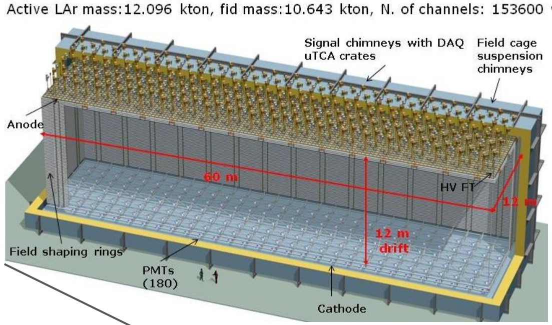
In order to answer these questions, DUNE must be able to:

- Measure how neutrino types and populations change from pure muon neutrinos as a function of distance from a source
- Measure the neutrinos from supernovae with high enough precision to see details
  - Infall, neutronization, accretion and cooling, etc.
- Maximize the opportunity to measure extremely rare events
  - Neutrino interactions occur extremely infrequently



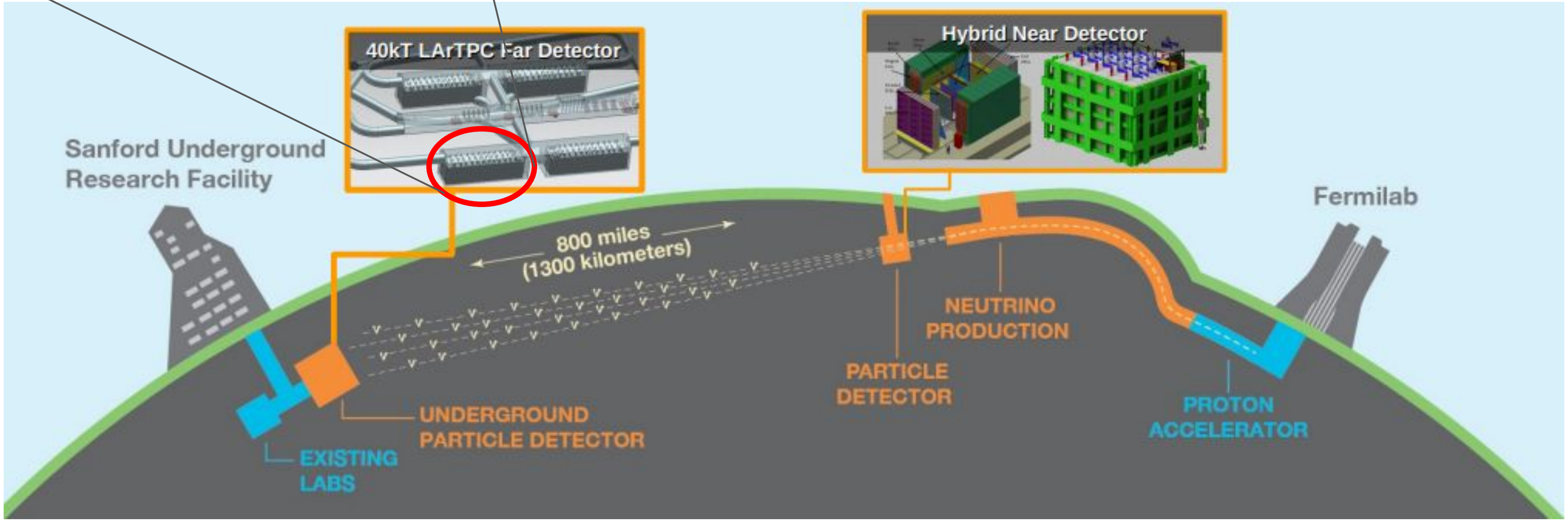


DUNE Designed to Achieve Objectives



DUNE consists of

- Neutrino beam from FermiLab - world's most intense neutrino source
- DUNE Near Detector (DUNE ND) - high resolution detector → Will not be focusing on this
- DUNE Far Detector (DUNE FD) - will be focusing on this for the rest of the talk



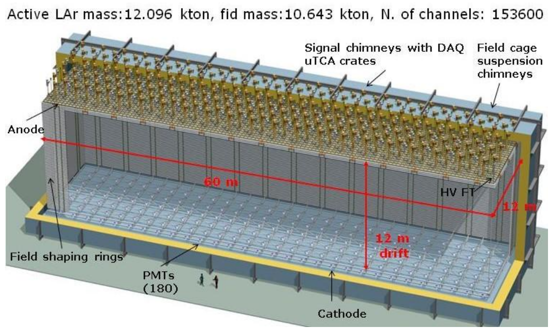
Goals of DUNE Far Detector

Needs to serves two main purposes:

1. Operate as part of the whole experiment (with the neutrino beam and DUNE Near Detector) to compare neutrino type distributions as they travel over a long distance
    a. Needs to be sensitive to high energy neutrino events (on order of 10s of GeV), or the products of their interactions
    b. Needs high precision timing for accurate event reconstruction
2. Operate on its own as a separate detector for supernova and solar neutrinos
    a. Needs to be sensitive to low energy neutrino events (on order of a few MeV), …
    b. Needs to maximize efficiency and useful volume

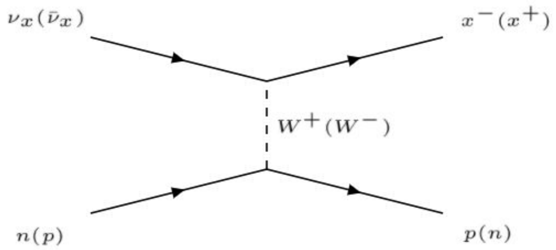
Design Concept of DUNE FD

- FACT: Neutrinos rarely interact with matter
- Maximize the opportunities to see an interaction
  - HUGE detector: 4 Modules, 10 ktons measurable volume in each
  - Liquid argon is denser than water so it will cause more interactions



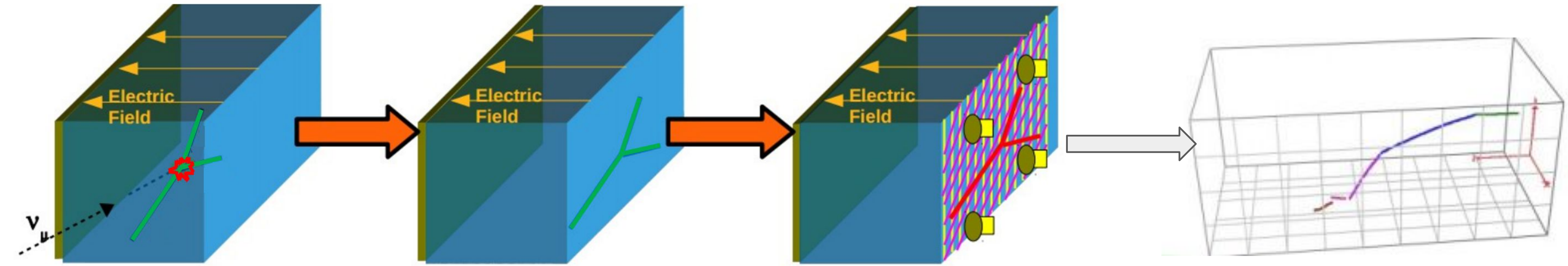
x4

- FACT: When neutrinos DO interact with matter, they usually produce a similarly flavored lepton



- Liquid argon has excellent properties that will let us see the products of these interactions and reconstruct the interaction
  - Ionizes - particles knock free huge numbers of electrons from argon atoms
  - Scintillates - emits light when charged particles pass through

Liquid Argon Time Projection Chamber Concept



Neutrino interaction in LAr produces ionization and scintillation light

Drift the ionization charge in a uniform electric field

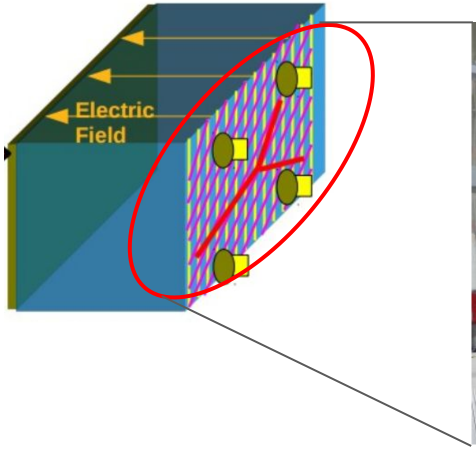
Read out charge and light produced using precision wires and PMT's

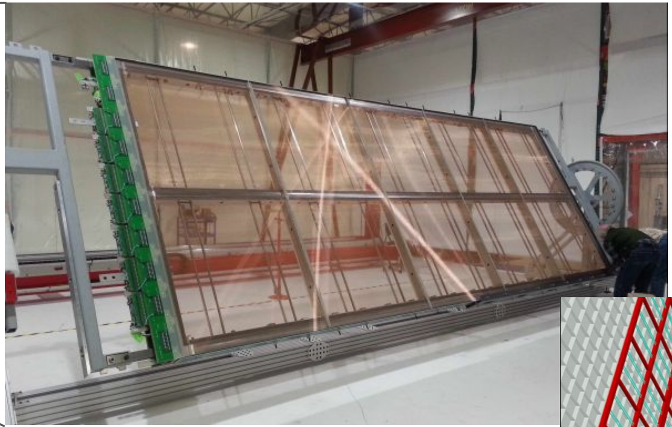
*green lines represent electron swarm from ionization

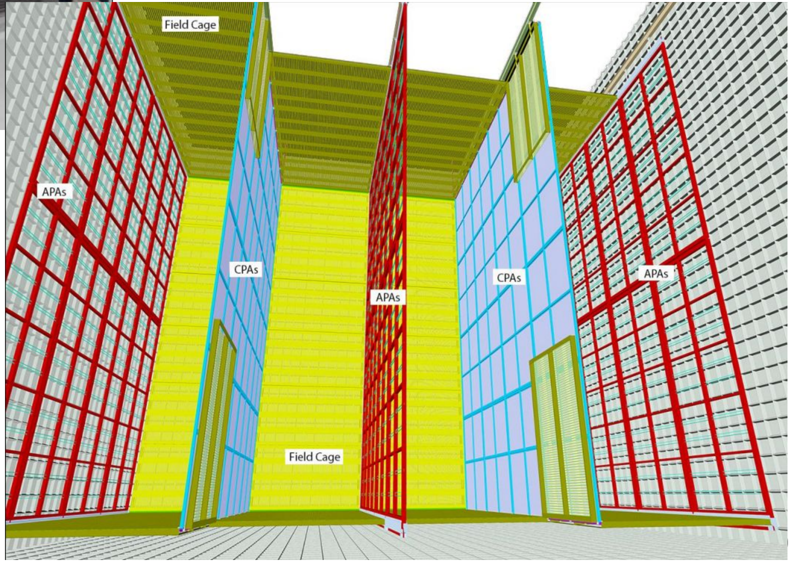
Liquid Argon Time Projection Chamber (LArTPC)

- Liquid argon contained in a detector
- Electric field of 500V/cm pulls charge towards the detector walls
- Wire readout planes will detect charge and report x,y,z information. Photomultiplier tubes will detect scintillation light used in calculating timing
    - Allows us to reproduce events in 3 dimensions with high precision

Current Readout Electronics Construction







Currently using wire plane readout electronics to collect charge

- Every frame holds 10,000 wires
  - Run from one side of the frame to the other
  - Spaced ~4.8mm apart
  - Each holds 0.5lbs of force

3 Different Types of Problems with Current Design

1. Measurement Limitations
    - Wires limit reconstruction abilities in complex topologies
    - Events that run along single wires show up as a blob of charge - Newly arriving charge from later ionization from the same particle will overlap with charge signal as it travels down the wire
2. Risk of Mechanical failures
    - Frames under lots of stress, could deform and cause wires to snap, could short out an entire frame or more
    - Structures built to hold frames require lots of engineering and bulky designs in order to keep frames from deforming and mitigate risk
3. Output Data Size
    - 1,500,000 channels per module, continuously reading out with GPS time precision (~10ns)
    - Produces TBs/sec, most of which is useless or not interesting
    - Limits the sensitivity that can be achieved without drowning in useless data

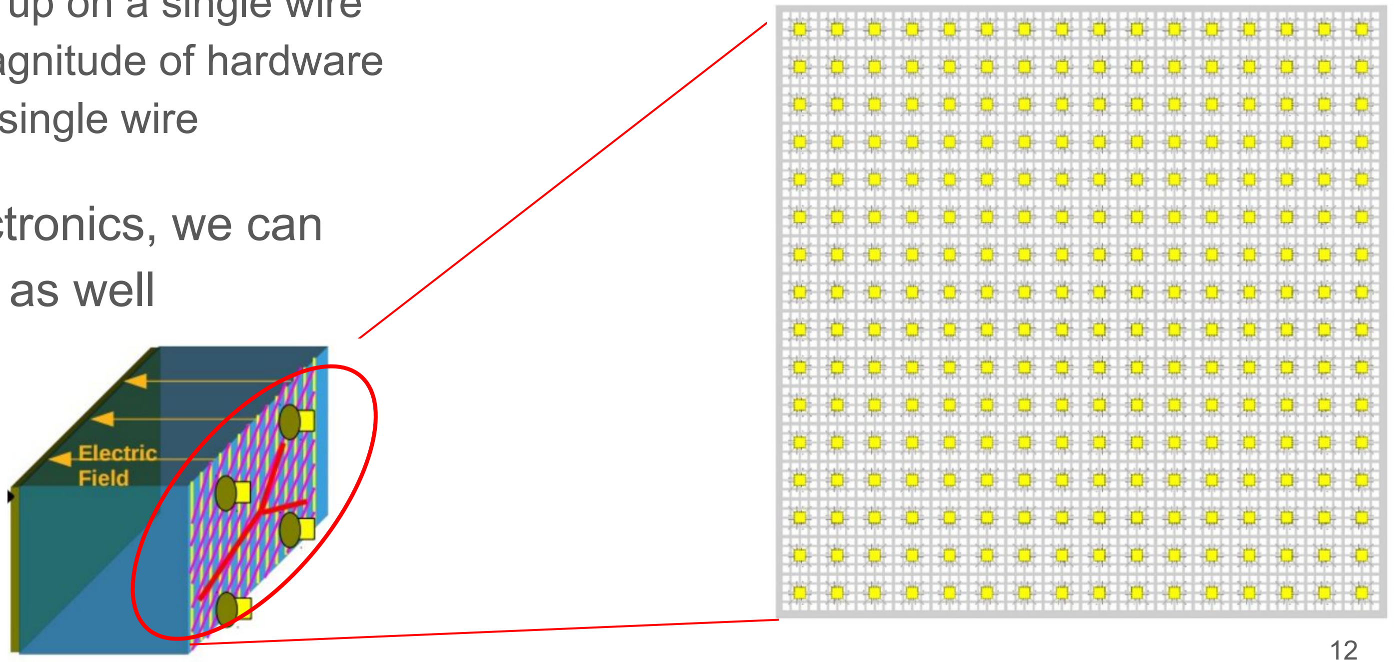
Upgrading to New Charge Pixel Technology

Large grid of charge-collecting pixels (Q-Pix) would replace the wire readout electronics and solve the first two problems

- Reduces charge pile up on a single wire
- Reduces risk and magnitude of hardware failure from that of a single wire

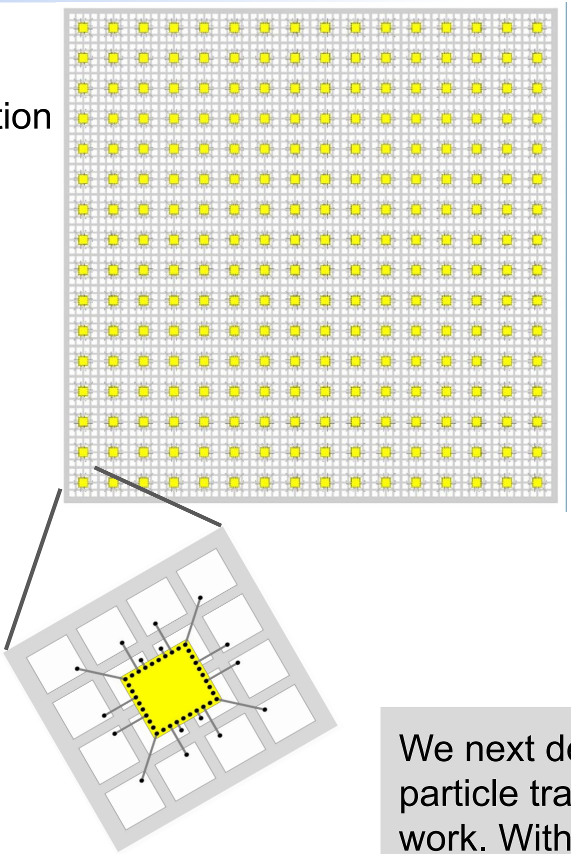
With good readout electronics, we can solve the third problem as well

Large grid of pixels



Two Views of Zooming In

Artist's conception



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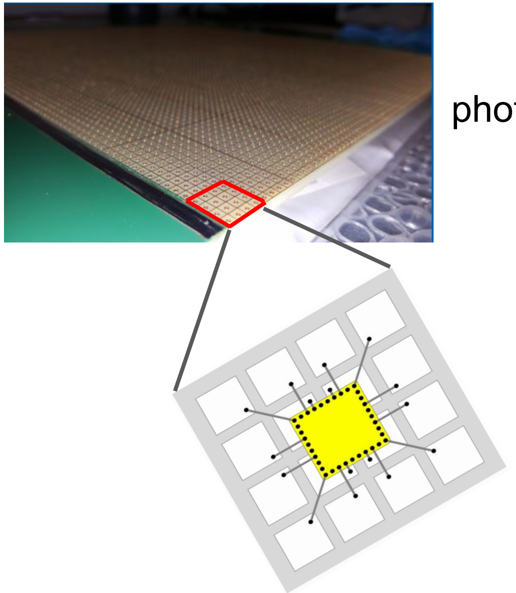


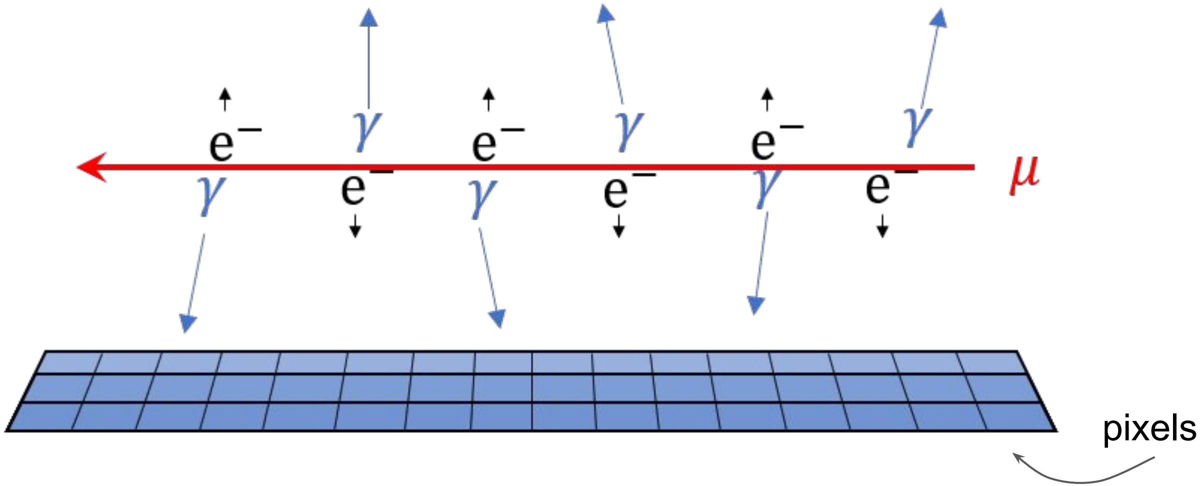
- Each pixel collects charge in a 4x4 mm^2 area
- Each 4x4 grid of pixels (white) has custom Q-Pix readout electronics (yellow)

We next describe how we use this to measure the particle trajectory, and the how the electronics work. With that understanding we can see how we address the last issue: readout size advantage

Following a Muon Event in LArTPC to show how it all works

- Muon neutrino interacts with liquid argon and produces a muon
- Creation of “electron swarm” through ionization
- Drifting of electron swarm in the electric field to the readout electronics
- Electronic response to electron swarm
- Calculation of measured Z position using readout data

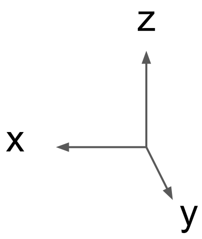
Physics of Muon Traversing Liquid Argon

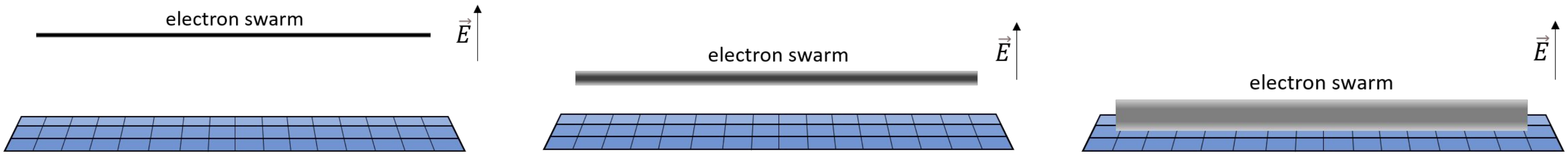


Two types of particles emitted along the trajectory which will be detected

- Electrons: Muon causes ionization, freeing electrons from the liquid argon along its trajectory as it passes
    - Call this the "electron swarm"
- Photons: LAr also scintillates, emitting photons in every direction
    - Photons travel much much quicker in LAr than electrons do
    - Reach the edge of the detector effectively instantaneously (within ns)
    - Will not talk about these further

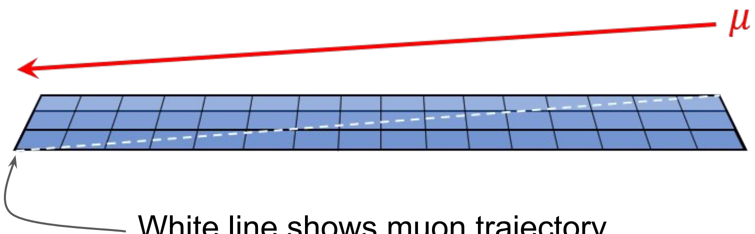
Electron Swarm in Time Projection Chamber



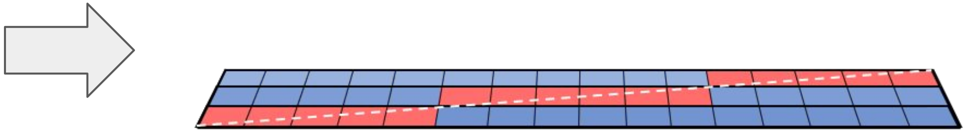


- Swarm moves through the electric field, towards the pixel plane (z direction)
- Electron swarm will be pulled directly towards the pixel wall at an effectively constant velocity by the electric field through the material
- As electrons travel through liquid argon, initial velocities along with later interactions with the liquid argon cause diffusion in a Gaussian pattern at a calculable rate

Determining X and Y



White line shows muon trajectory projected onto pixel wall

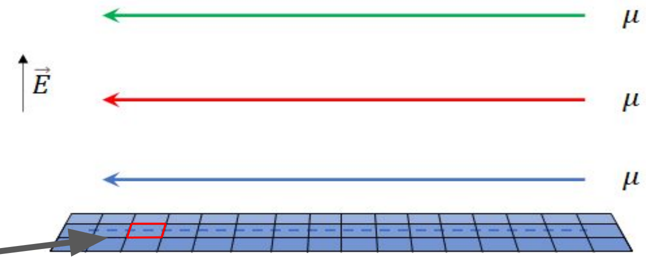


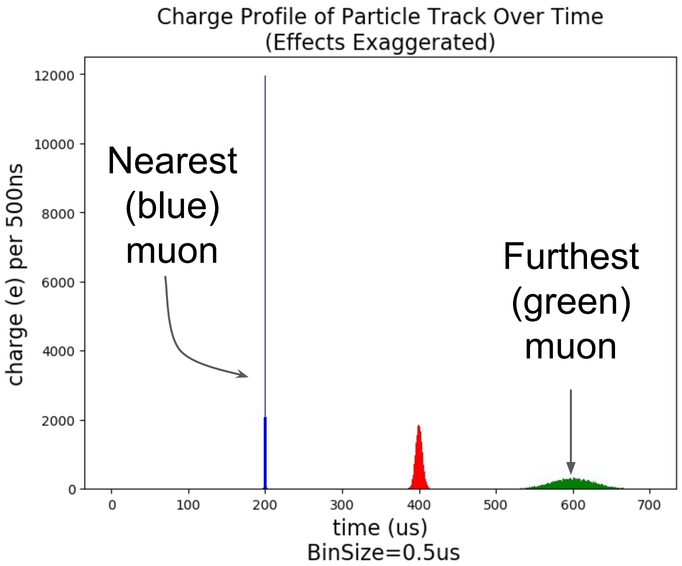
Pixels along original trajectory projection <u>are active</u> → give us the x and y of original trajectory

- Charge is absorbed by pixels directly below (in the -z direction) giving the original x-y trajectory of the initial muon

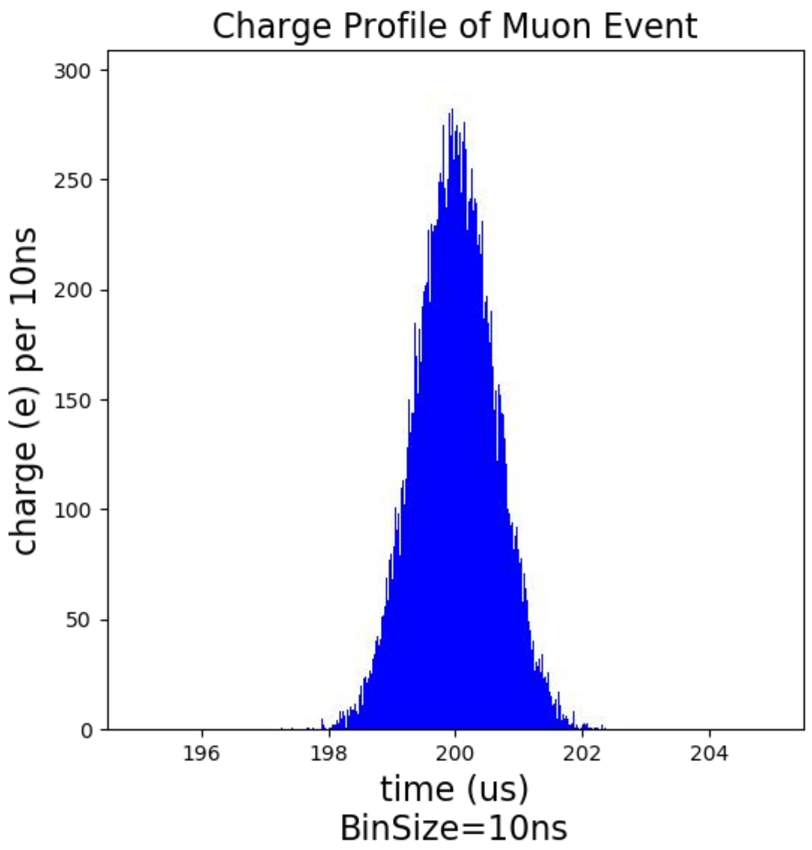
Determining Z

- Focusing on one pixel now in three different cases where lots of charge was emitted at the same X, Y and time
- We know that the electron swarm will:
  - Travel at a constant rate
  - Diffuse at a constant rate
- Differences allow you to measure Z
  - Time of arrival
  - Width of charge profile



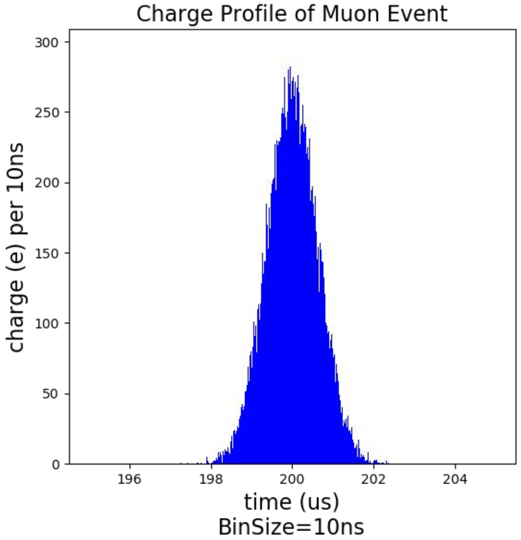


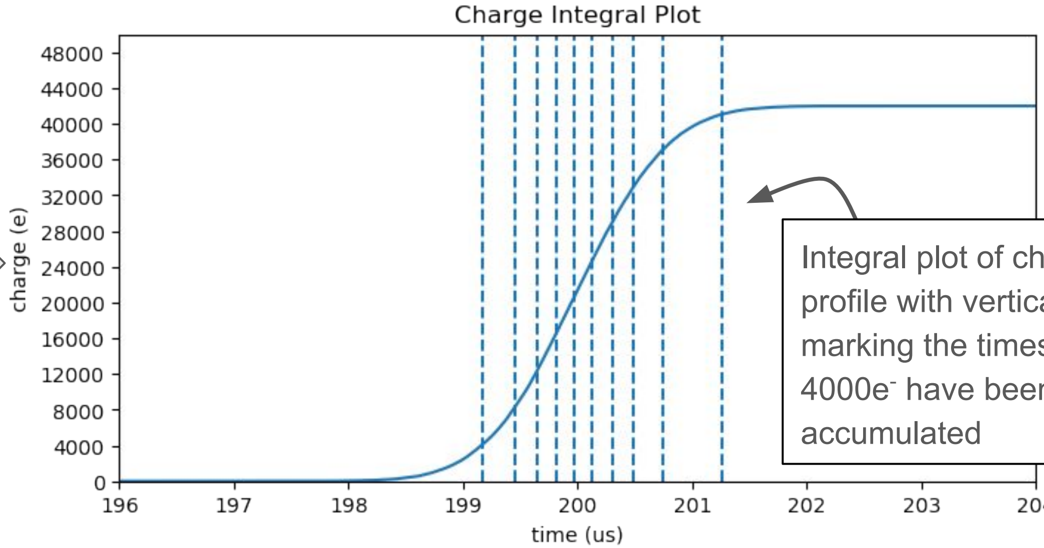
Measuring Z of Original Particle from Electron Swarm



- Current Design: Wire Readout
    1. Measure and record the amount of charge in every bin - will look Gaussian
    2. Can fit to determine the rms and thus drift distance
- New Design: Charge-Integrate-Reset Method
    1. Integrate charge until a certain threshold is reached
    2. Record time, and start over
    3. Use the time between signals to plot 1/dT and determine the fit of the peak
        - Use fit properties to determine rms and drift distance

Charge-Integrate-Reset Method (Ideal)





Integral plot of charge profile with vertical lines marking the times when $4000e^-$ have been accumulated

Example event where ~42,000 charges arrive over a few microseconds.

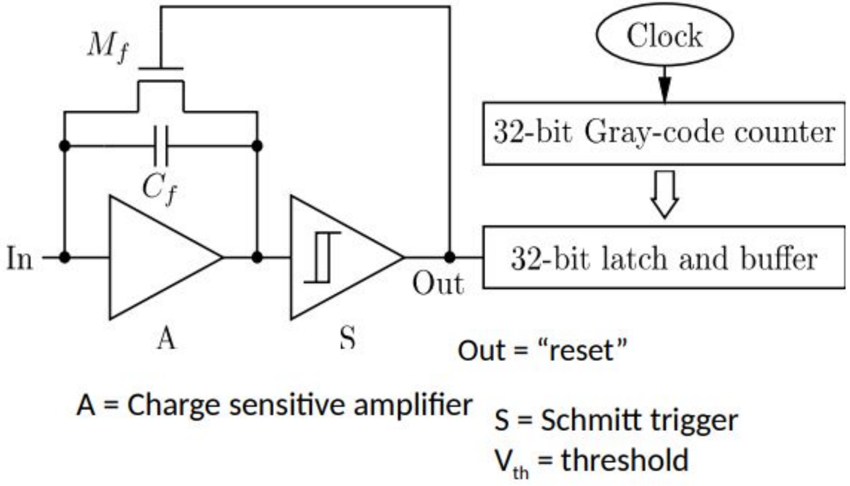
Typically we just bin (here 10ns/bin) to measure the RMS, but we can also use the Charge-Integrate-Reset method where we report the time of arrival of the 4000th charge

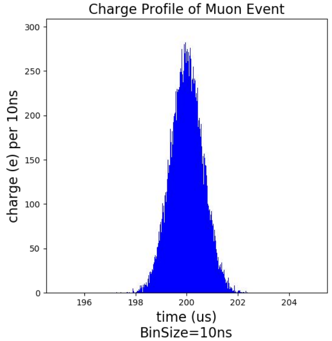
Time of Each dashed line (us)
199.17
199.45
199.65
199.82
199.98
200.14
200.31
200.50
200.76
201.32

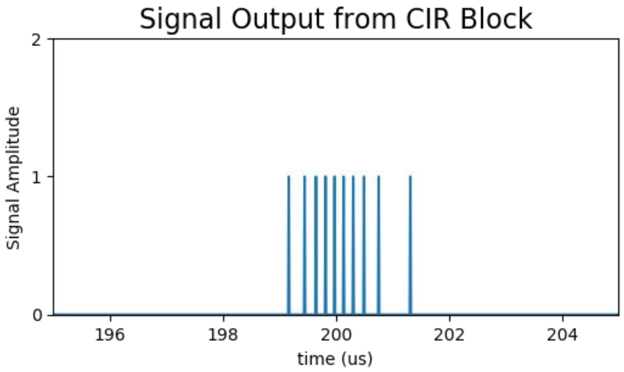
*rounded to nearest 10ns

Charge-Integrate-Reset Block (Experimental)

- Each pixel feeds into a Charge-Integrate-Reset (CIR) block
  - Designed to output a pulse and reset once a specific amount of charge has built up (ΔQ = const)
  - Components can be set to desired values for different responses
    - Accepted design causes CIR block to reset at a threshold of 6000e^-
- Transforms a complex charge profile into a list of reset times



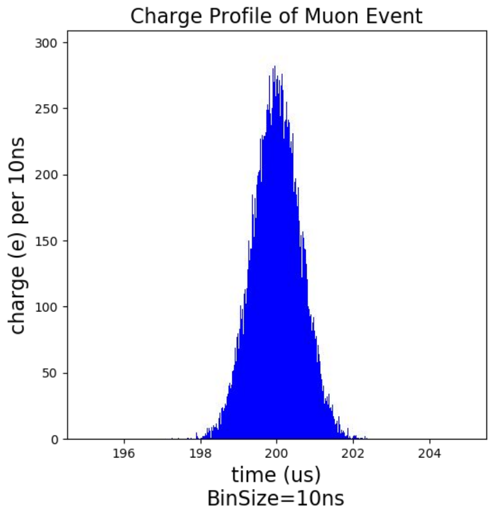




Reset times (us)
199.17
199.45
199.65
199.82
199.98
200.14
200.31
200.50
200.76
201.32

*Clock Speed = 100MHz

Summary: Readout OLD vs NEW Method



(OLD) Wire Readout Method:

- Currently we read out a 32-bit number at ~100MHz continuously
  - Only a few of the 800 bins currently shown are useful
  - Most of the data contains a 0 (mostly useless)
  - Lots of useless data written to disk, and a huge amount of offline processing needs to be done

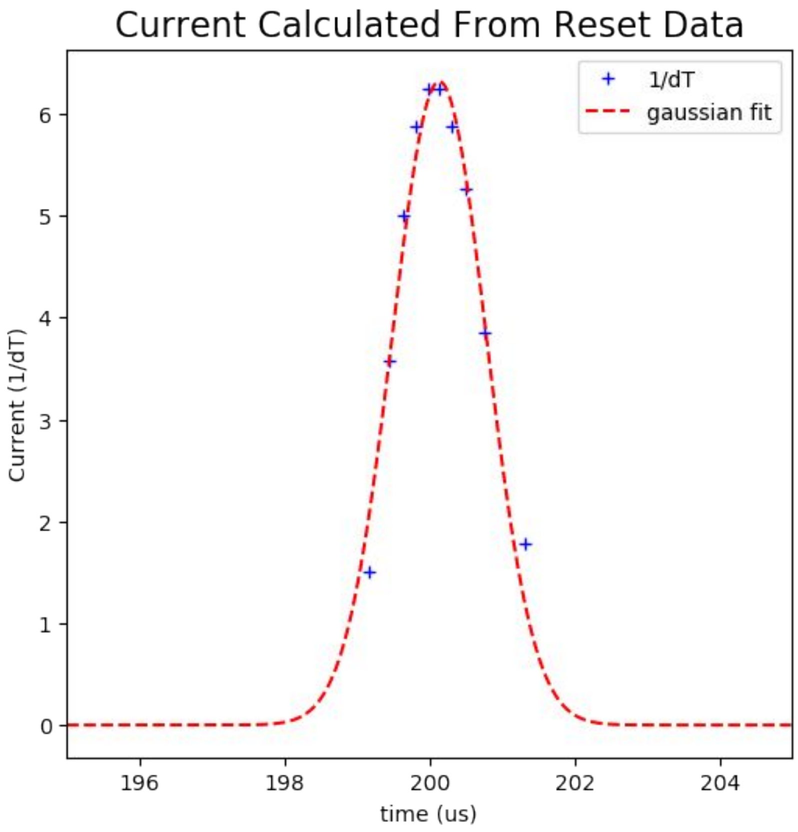
(NEW) CIR Block Method

- Same event, for single pixel, only produces 10 times
- Only reports data if there is data to report (i.e. a reset occurred)
  - Inactive pixels do not report data
  - Active pixels only reset when they have accumulated 4000e^-
- On scale of module, reduces data from TB/sec to MB or GB/sec
- Don't need to filter as aggressively → sensitive to lower energy thresholds

Reset times (us)
199.17
199.45
199.65
199.82
199.98
200.14
200.31
200.50
200.76
201.32

*Clock Speed = 100MHz

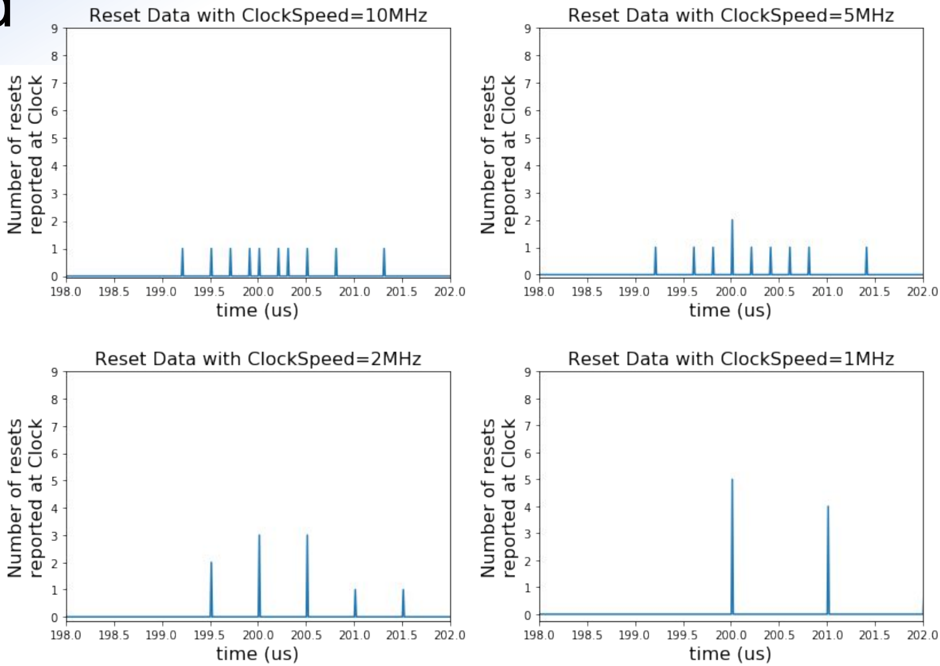
Analyzing Reset Times to measure Z

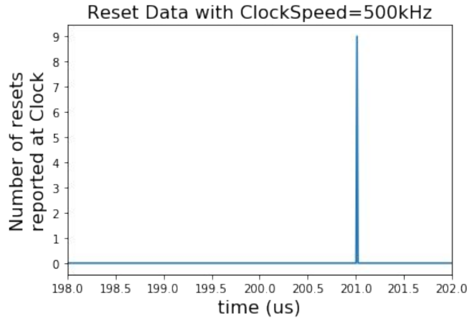


- The dT between resets is time per 4000 units of charge → Plot of 1/dT will be proportional to current
  - Will refer to 1/dT interchangeably with "current"
- Using the rms of the Gaussian fit, we can calculate the drift distance (Z)
  - The better we can fit the data, the more accurate we will be at measuring drift distance.

Effects of Changing Clock Speed

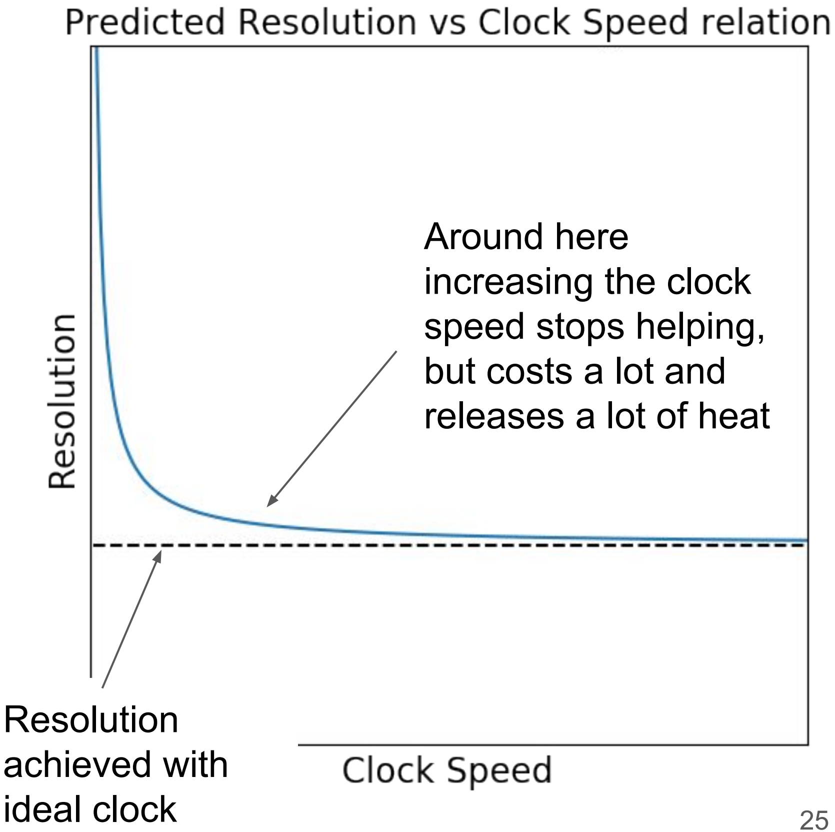
- CIR block is only checked for a reset based on a clock. If it’s been a long time since the last “clock” it can report multiple resets for a single clock (and reports it at the clock time)
    - Said differently, a slow clock means we will accumulate more than one reset (So we need to report the time, and the number of resets)
- A slower clock will take less power but give a much less accurate picture of the original electron swarm → less accurate rms and drift distance. *Need to find a good balance of accuracy and power consumption*





Defining What Is "Good Enough"

- With an infinitely fast clock resets will occur exactly when the 6000th electron reaches the pixel
- Resolution is expected to approach this value asymptotically with increasing clock speed
    - There is an intrinsic resolution to the method that that cannot be exceeded
- About half of DUNE's power/heat budget goes to powering clocks
- *Need to find an minimum clock speed that does not affect resolution so we can save on cost and power*
    - Predicted by D. Nygren (original Q-Pix proposal) to be around 50MHz

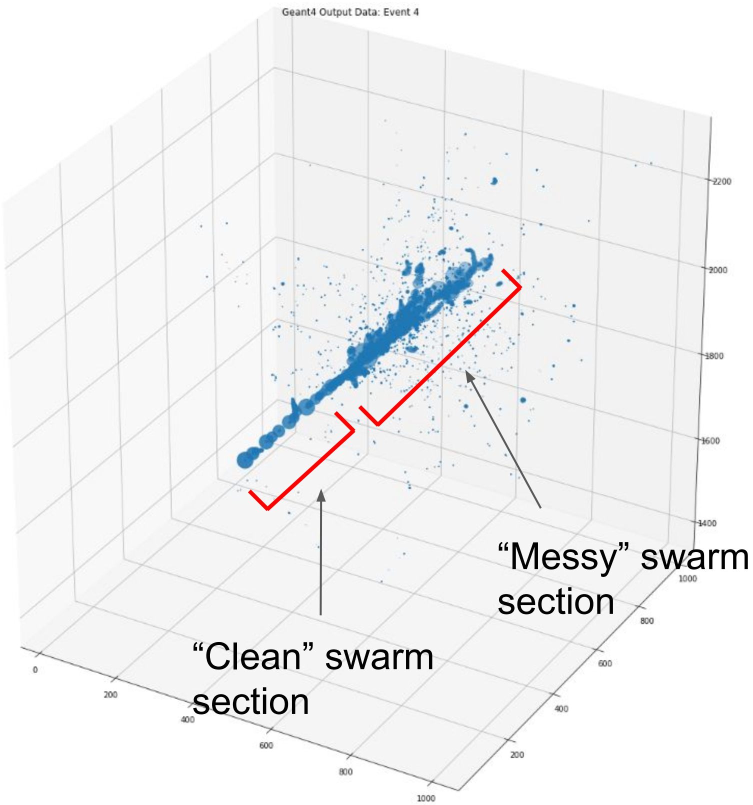


Using Simulations to Determine the Minimum Clock Speed that Does Not Sacrifice Resolution

- Overview of the sample
- Cuts to select for good pixels
- Resolution dependence on Z
- Resolution dependence on clock speed

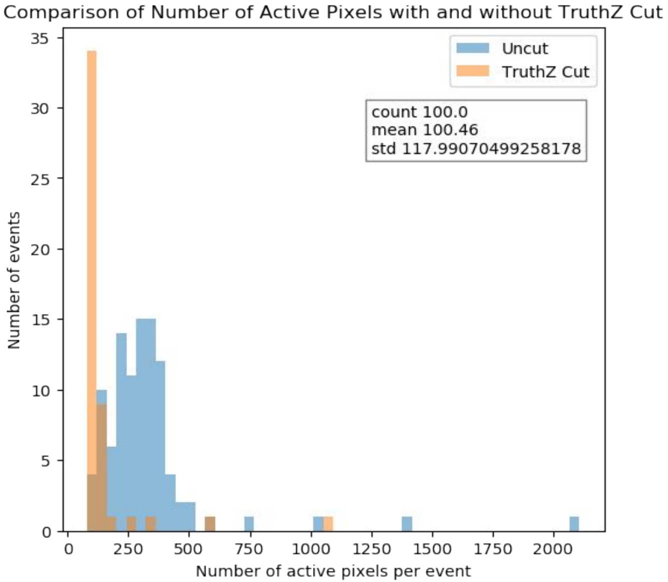
Overview of Simulations

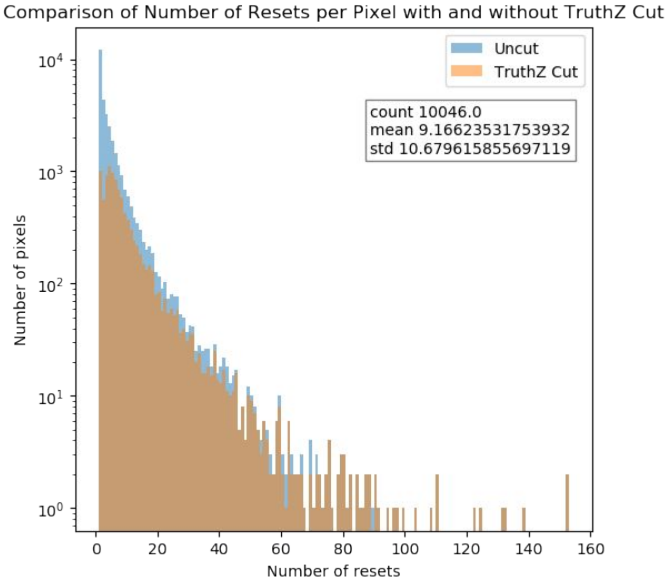
- Run standard simulations to create 100 muon events running parallel to the pixel wall
- LAr produces ~42,000e$^-$/MeV deposited
  - Lots of other particles, like photons which Brem in the detector, included
- Simulation includes drifting and diffusion of all electrons in the electric field
  - Longitudinal Diffusion (already discussed)
  - Transverse Diffusion → slightly changes the X and Y
- Readout data includes arrival time and pixel location of every individual electron after incorporating
  - Have TruthZ of the muon in simulation



Simulated muon event in LAr, showing energy deposited via ionization along trajectory

Pixel Readout Results for Full Sample

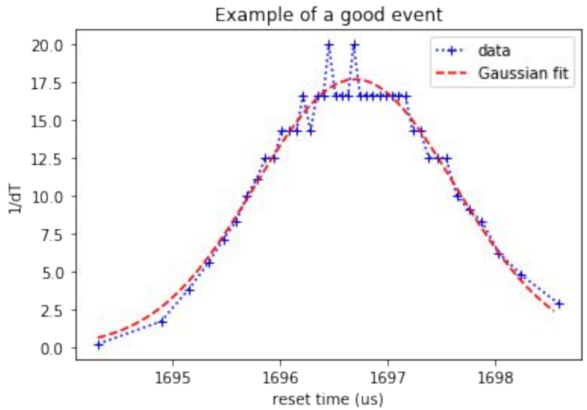




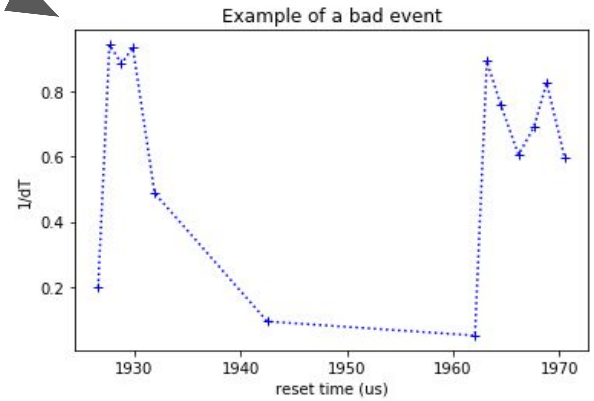
- On average 300 pixels have a reset per event, but typically each pixel only has a single reset per event (blue)
- To simplify the analysis, we only consider pixels where the original electron was directly above the pixel in Z (gives us TruthZ for comparisons)
  - Number of pixels for use in our study goes down, but the number of resets per pixel (per event) goes up and allows for a measurement (orange)

Selecting Pixels with a “Clean Swarm” Measurement

- Pixels corresponding to a clean swarm have a time distribution which will be Gaussian
  - Will lead to a good measure of RMS and drift distance



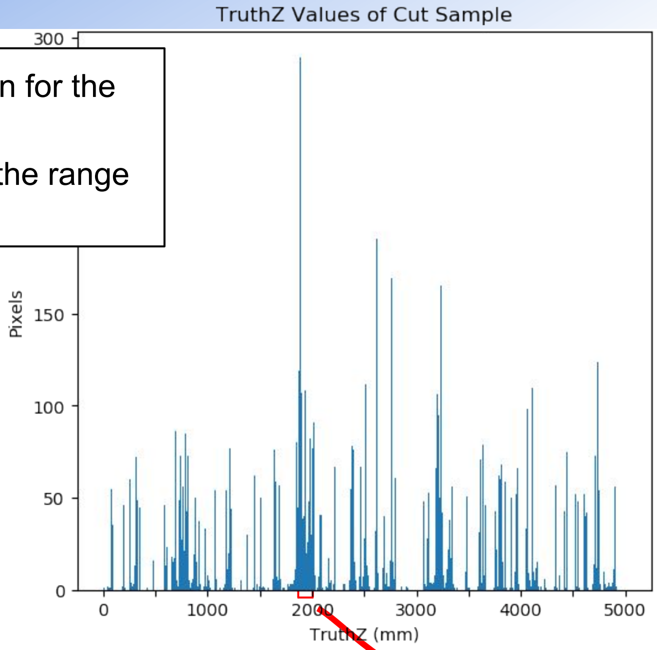
- Pixels corresponding to a messy swarm are not Gaussian or have multiple peaks
  - Gaussian fit returns inaccurate RMS measurements or huge chi squareds
  - Potentially caused by
    - Multiple energy depositions with the same x-y
    - “Crossover” where electron swarms overlap due to transverse diffusion
    - Buildup of $6000e^{-}$ from noise or stray e^{-}

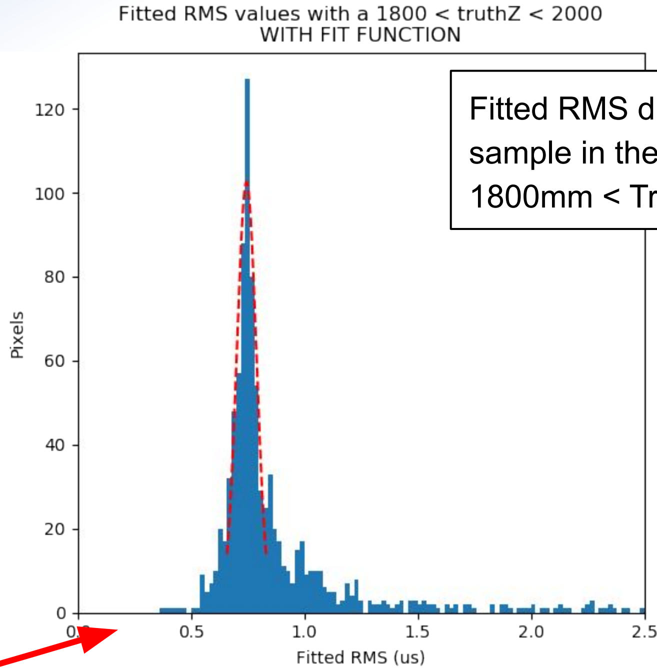


- Filter out pixels with nResets ≤ 3 to ensure we select well-measured events

Select Events Based on TruthZ After Selecting Good Events

TruthZ distribution for the sample
Select events in the range 1900±100mm



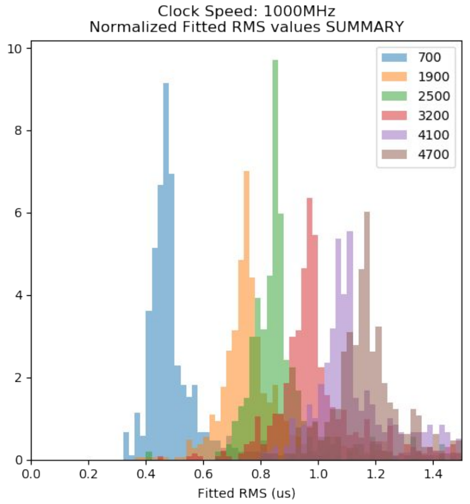


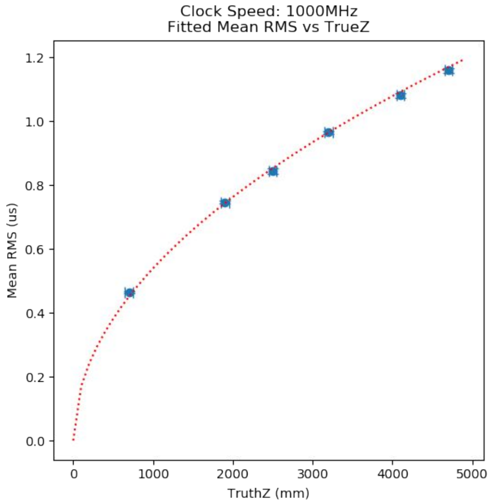
Fitted RMS distribution for the sample in the range 1800mm < TruthZ < 2000mm

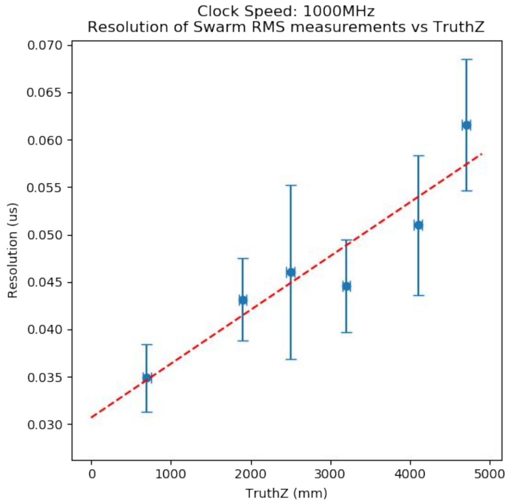
Only consider events in the peak (±2σ) - tails are likely from messy swarms

Mean from fit (see red) is used to calculate drift distance (Z) and rms is the resolution

Checking the TruthZ Dependence of the RMS

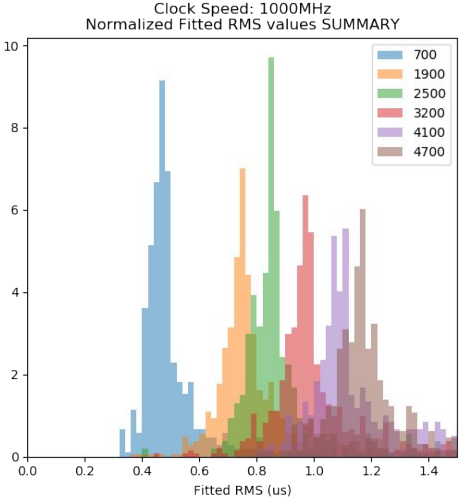


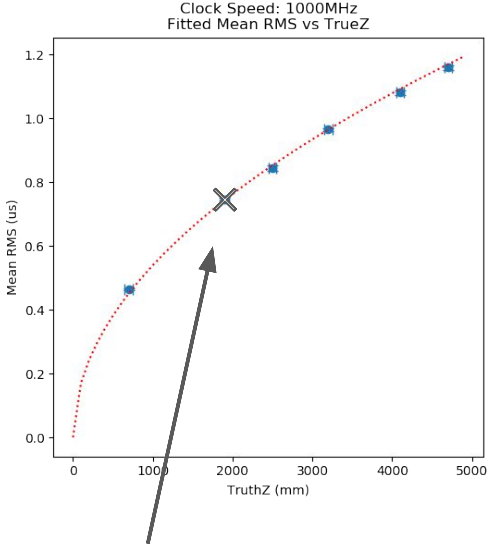


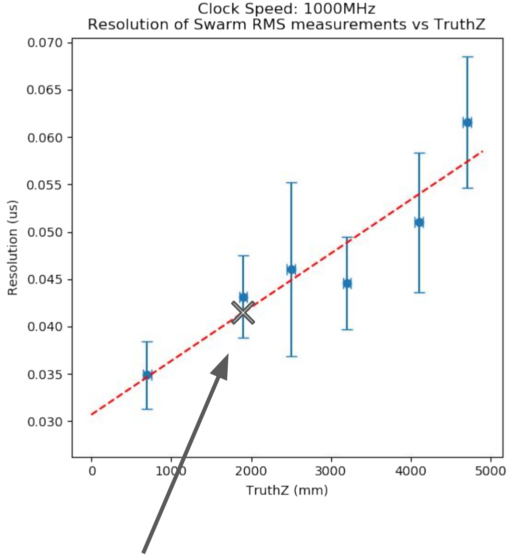


- Look at smaller ranges of TruthZ spanning the entire sample
- Gaussian fits of the RMS distributions in a restricted range yield expected square root relation
- Resolution is dependent on TruthZ

Checking the TruthZ Dependence of the RMS







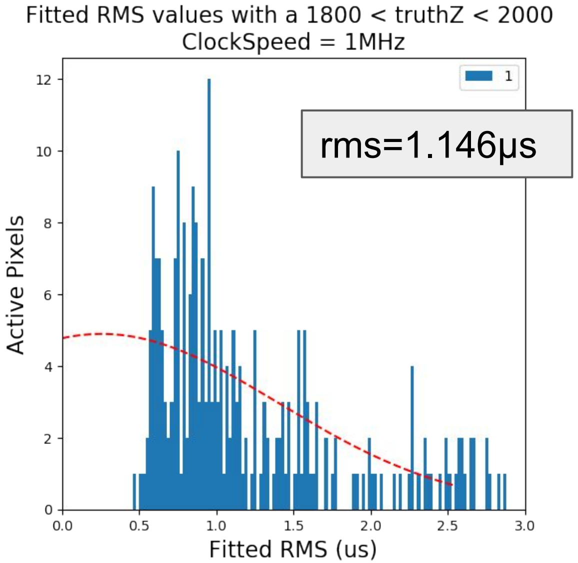
Ballpark uncertainty in Z at 1900 mm:

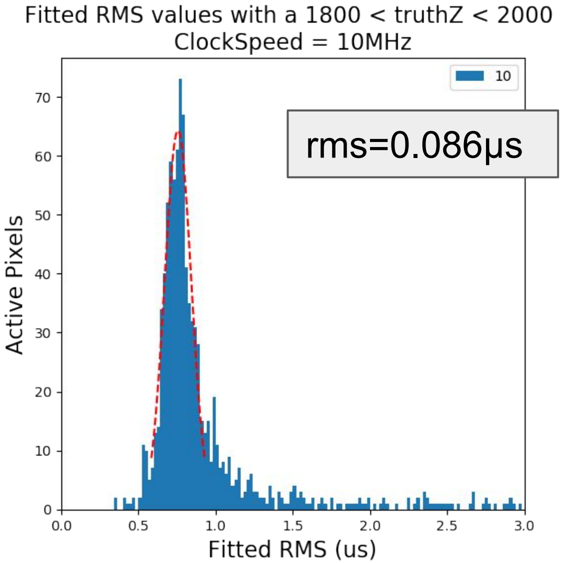
- We see a mean RMS of our measurement of about 0.75 and a resolution of about 0.04. Call this about 5.3% of RMS. Since Z prediction goes as RMS^2, we get about a 10.6% uncertainty in Z which is about 200 mm

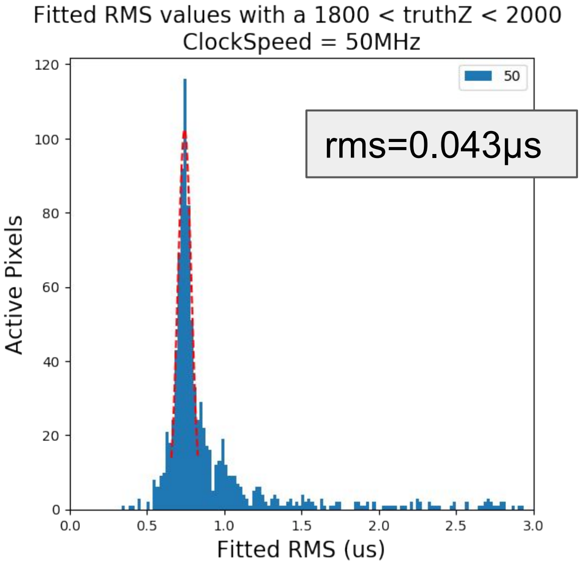
Resolution behavior as a function of Clock Speed

Focus only on TruthZ = 1900mm and look at distribution for different clock speeds.

- Distributions corresponding to the slowest clock speeds are impossible to fit well so we will not consider them further
- Faster clock speeds tend to have a lower rms (resolution) and will asymptotically approach an intrinsic resolution

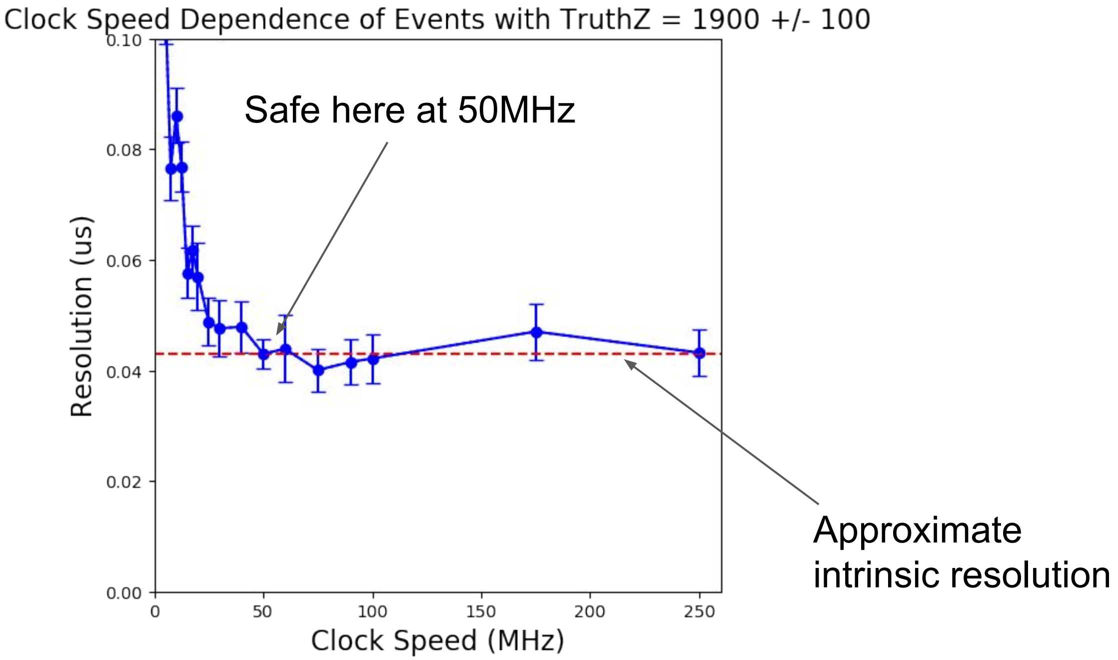






Z Measurement Resolution as a Function of Clock Speed

Resolution reaches intrinsic level at a clock speed of about 50MHz as expected, although there is still some variation around that point. We suspect more statistics and more sophisticated analysis would smooth this out. (in progress)



Future Steps

My next steps:

- Create larger samples
- More robust measurement techniques to separate between well-measured swarms and charge collection
- Combine individual pixel measurements to get a time-of-arrival measurement and reconstruct particle path for the full event

Q-Pix Project:

- Refine simulations and examine more scenarios to confirm that Q-Pix can at least match the performance of the current wire readout electronics
- Determine DUNE's sensitivity to supernova neutrino spectra and how much Q-Pix will help, especially at low energies

Conclusions

- DUNE is capable of answering multiple outstanding questions we have about the standard model and physics beyond the standard model as well as supernova events if they occur
- Q-Pix technology will be an improvement to the current wire readout electronics used in DUNE FD through disambiguation, protection against failures, and a decrease in readout data
- Our studies have shown that we can save energy without losing resolution by limiting the Q-Pix clock speed to 50MHz
- Looking forward to Q-Pix's inclusion in DUNE, and the science we can do with it