Primary Muon Path Reconstruction and dE/dX

with a short study of CDF Robustness

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Overview of Talk

This talk has two separate goals:

1.) Updated methodology for primary muon track reconstruction and dE/dX measurements from the hits measured by the CDF method.
2.) Study how well we can do with Z measurements with the CDF method when we vary the QPix specifications and particle kinematics/types (robustness).

We have broken this talk into two parts

1.) Primary muon tracking and dE/dX using the new CDF hit reconstruction
    a.) Tracking and dE/dX measurement methods
    b.) How well we do with a sample of events
2.) Robustness of the CDF method results for different QPix specifications and particle kinematics/types
    a.) Goals and Methodology
    b.) Robustness Plots with 1D variations

Introduction to Primary Muon Tracking

1000 muon event sample generated with **qpixg4/v2.0.0** and **qpixrtd/v1.1.0**

Initial Conditions

- Always starts at X=120cm, Y=0cm and Z varies from [0,360]cm.
- Always has 10 GeV of initial momentum in the Y direction.
- No noise or electron/Ar recombination.

High energy muon events such as these are characterized by

1. primary energy deposits made along the muon track through ionization
2. secondary interactions such as delta rays, muon decay, bremsstrahlung, pair production, or photonuclear processes.

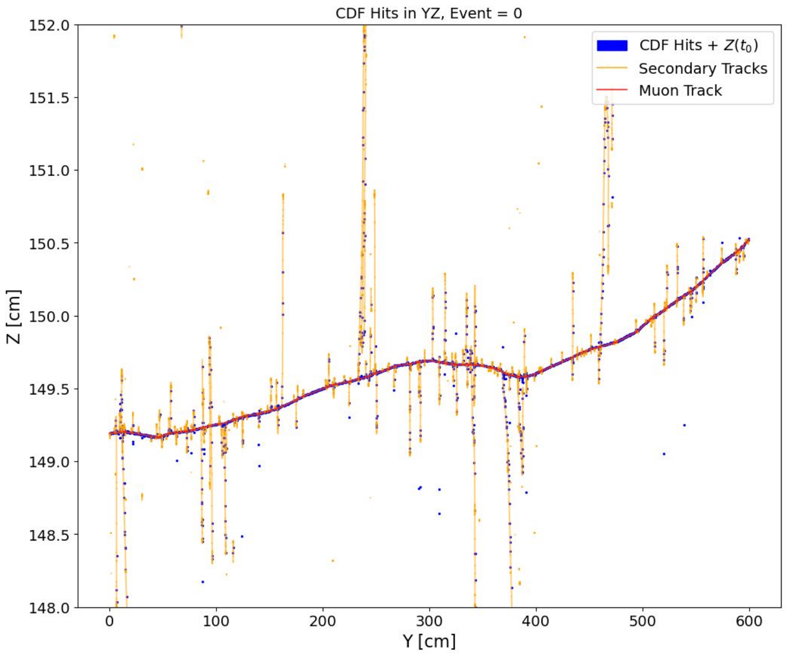
There can be significant variation in muon dE due to these secondary effects. Some events just look like a clean muon trajectory with relatively uniform energy deposits from ionization while others have significant amounts of secondary interactions. A full reconstruction for single muon events would need to be very sophisticated. We start with events that are well described by the primary muon track to see how well we can do with reconstruction.

What do Clean Muon Events Look Like?

On the right, we show an example event where the truth information for both the primary muon (red) and secondary tracks (orange) are overlaid by the single-hit and multi-hit pixel measurements from the CDF method (blue) in 2D (YZ axis).

Most of the secondary tracks have positive y momentum and are significantly shorter than the primary track, but it is difficult to see that due to the different scaling used between the Y and Z axis.

As we can see, the CDF method does a faithful job at reproducing the locations of energy deposits, especially for the primary muon deposits. This event is a good candidate for primary muon tracking, as most of the secondary interactions are delta rays that deposit energy away from the primary track.



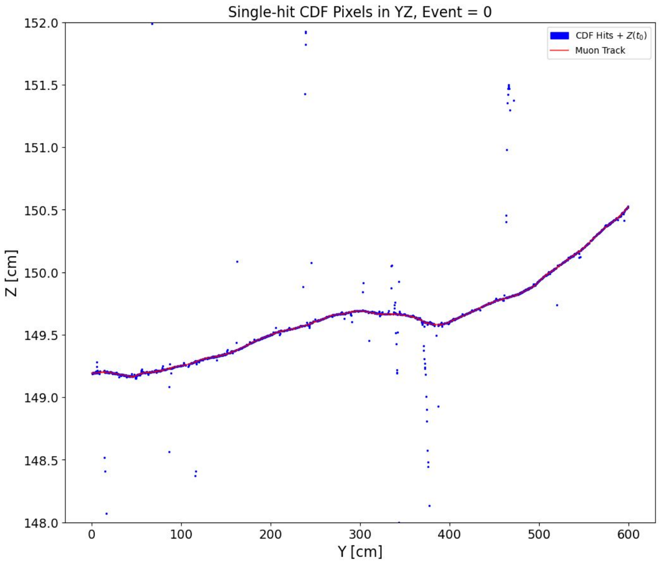
Primary muon tracking procedure

We've already shown a simple muon track fitting procedure in a previous talk, but we would like to make it more sophisticated to fully utilize the CDF method precision.

The tracking procedure we introduce here can be thought of as a set of successive iterations where we start by modeling the trajectory with a straight line and add additional polynomial terms to describe the scattering. At each step, we check all the hits and do a new pruning to see which single-hit pixels should be included.

After we establish a muon track, we will use the nearby hits (single, multi-hit, and unfit pixels) to measure the muon's ionization dE. We will then do a final refit of the muon track with these nearby hits.

Since most of the single-hit pixels are associated with the muon track, we start by only considering the subset of pixels with single hits. This is shown on the right for the example event. We see it does a nice job of cleaning up the event.



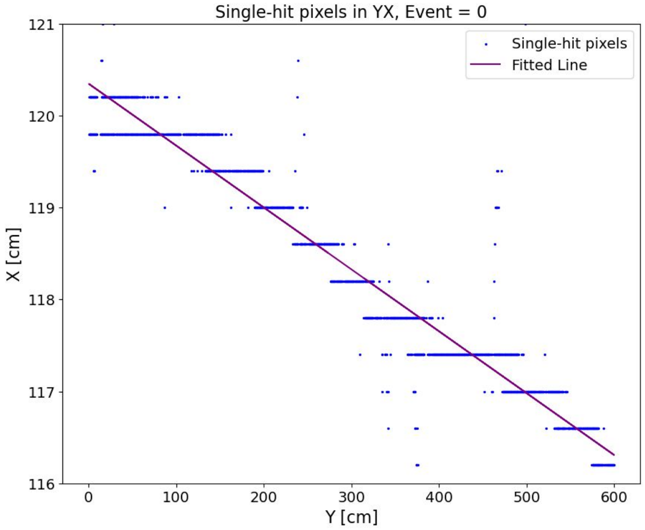
Distance of Closest Approach

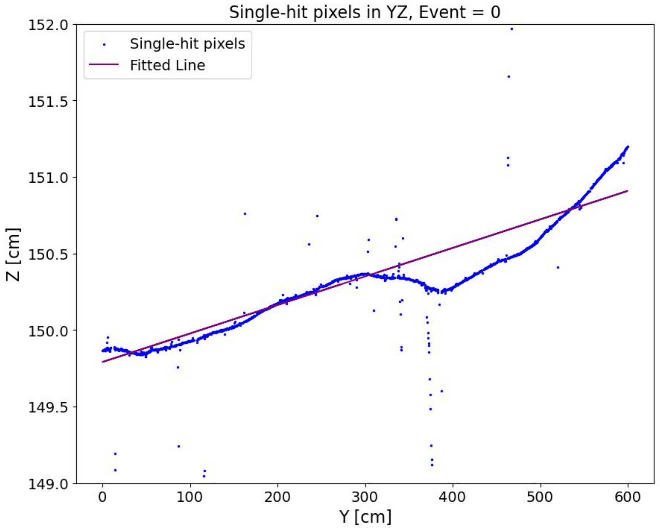
We start with a 1st-degree polynomial fit of the single-hit pixels (shown on the plots for YX and YZ), and minimize based on the distance of closest approach (DOCA) between the fit and each of the single-hit pixels using

$DOCA_x = \sqrt{[(x_{fit}(y)-x_{hit}(y))^2]}$, $DOCA_z = \sqrt{[(z_{fit}(y)-z_{hit}(y))^2]}$

We keep $DOCA_x$ and $DOCA_z$ measurements independent as they have different resolutions.

The X resolution is on the order of a pixel width (4e-1 cm) while the Z resolution is on the order of the clock-speed (1.7e-3 cm at 100 MHz).



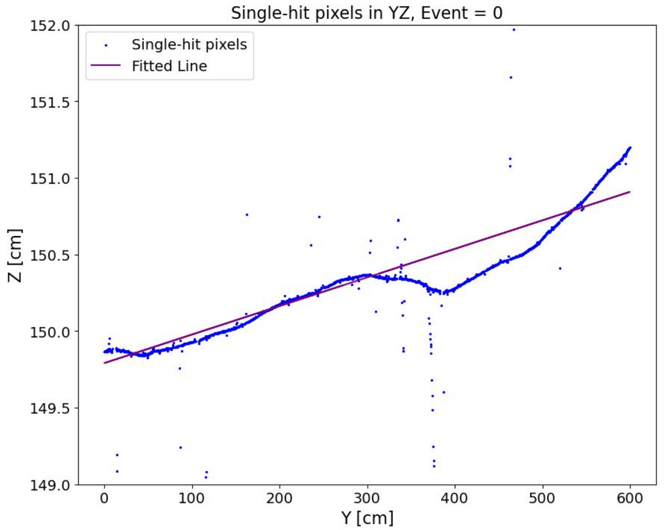


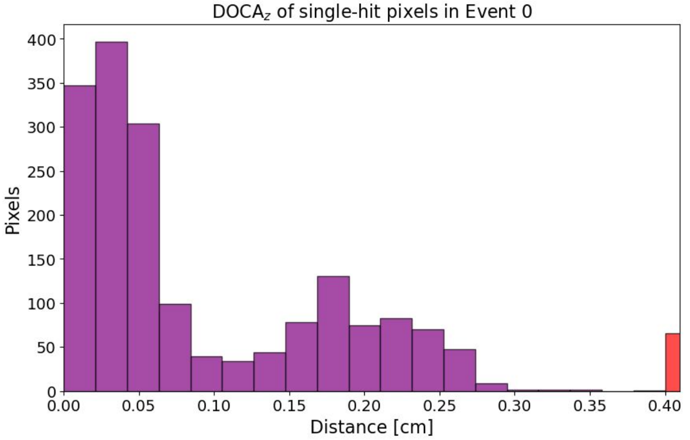
Finding a primary track with DOCA

The $DOCA_z$ measurements are shown in the bottom plot where we can see three different distribution regions of the hits: One where the hits are well associated to the track (small values), ones where the hits would be associated with the track if we had a higher degree polynomial fit (second bump) and those hits which are from secondaries (many, many σ from 0).

Our method to remove these secondary hits and reconstruct the primary muon track is to:

- Remove the hit with the largest $DOCA_x$ and/or $DOCA_z$ if it is beyond 8σ.
- Refit remaining hits and iterate this process until no hits are removed.
- With the remaining hits, we iterate with a 2nd-degree polynomial until no more hits are removed.
- Continue process until we reach a 12th-degree polynomial.



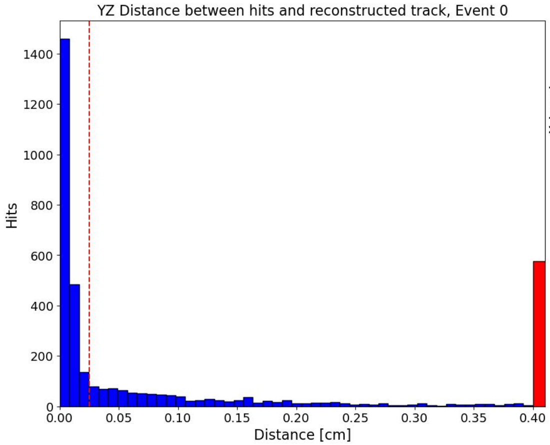


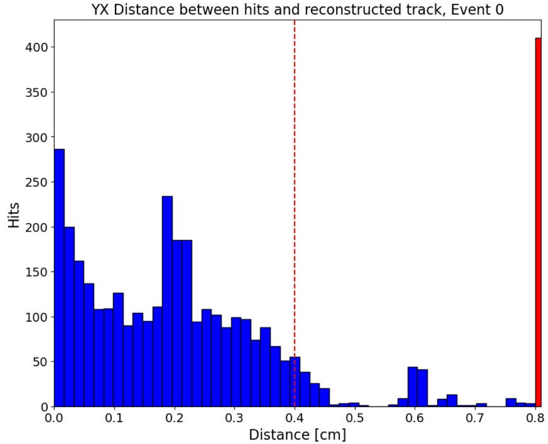
Measuring dE and dX

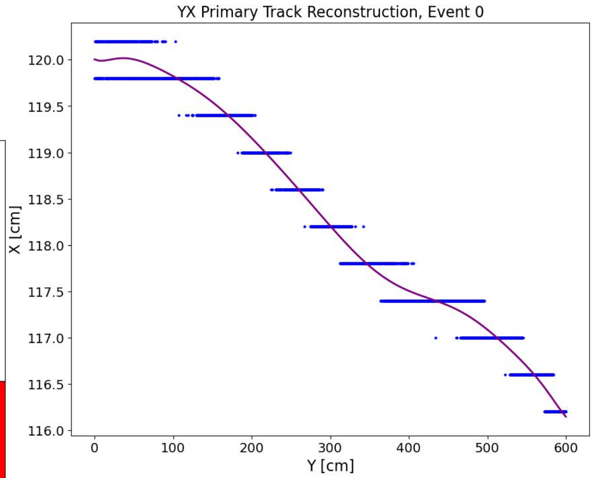
The results after all stages of polynomial fitting are promising, but as a final step, we now consider all hits (single-hit and multi-hit pixels) and unfit resets. Resets from unfit pixels are given an (X,Y,Z) with a constant energy of 0.1475 MeV (MeV/reset for 6250 electrons).

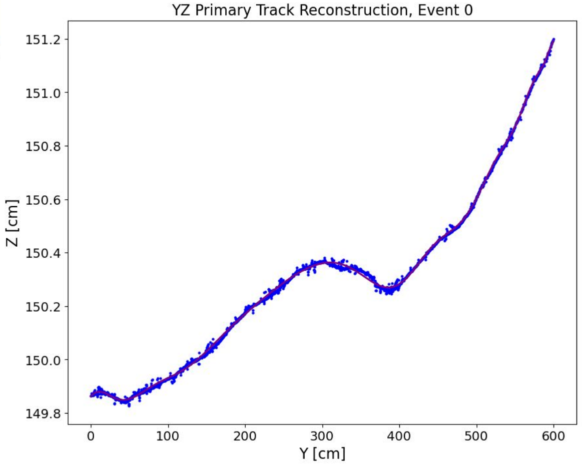
The two left-side plots show a falloff associated with the primary track at a distance of 0.4cm in XY and 0.025cm in YZ.

We make cuts at these distances and use the resulting energy to measure dE of the muon. We also do a final refit (right-side plots) of the remaining hits/resets to measure dX. This process increases the energy measurement when just using the single-hits in the final iteration track by an average of 15%.



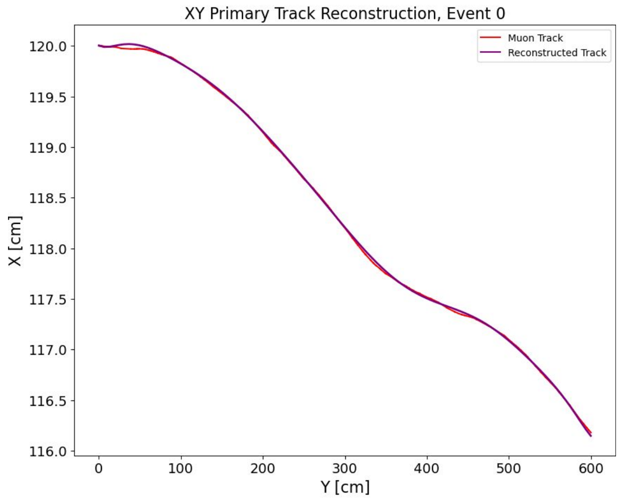






Comparing reconstruction to truth

The top plot shows the XY path and the bottom plots show the YZ path with (left) and without (right) our measured t_0 shift.

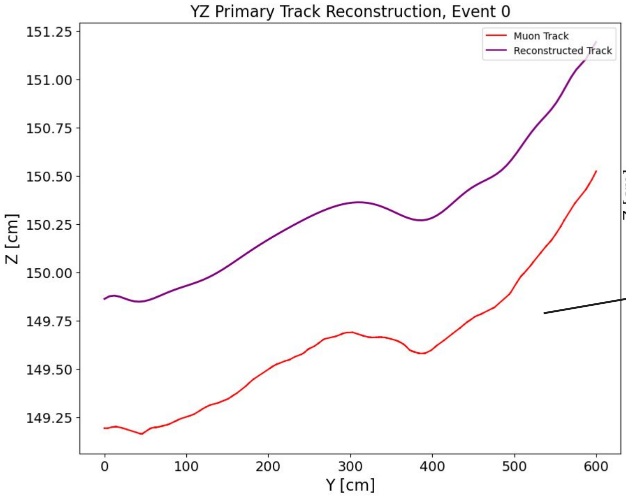


As a reminder, all events are simulated with t_0 = 0, but the resolution of this measurement can be on the order of microseconds which systematically shifts all the Z position measurements together. Note, our hits already have the t_0 shift that remains when using the CDF method,
so to properly compare with truth we have to remove this shift with

$Z(t_0) = v_{drift} * t_0$

where t_0 = -4.09e-6 sec for this event. The expected accuracy at this Z_0 is ~2e-6 sec.

We can only do this correction because we know that t_0 = 0.

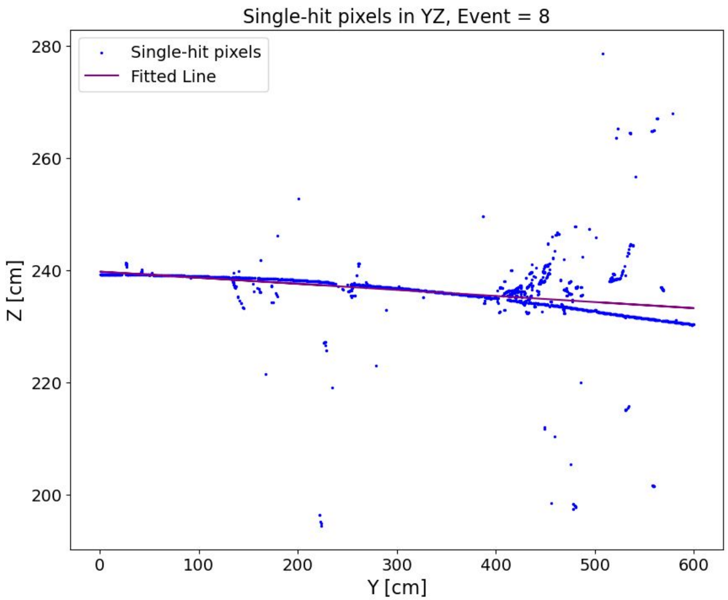


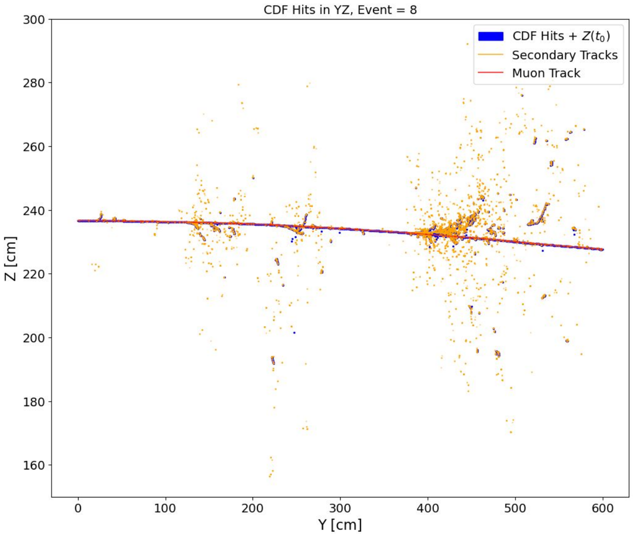
Events we can’t model this way

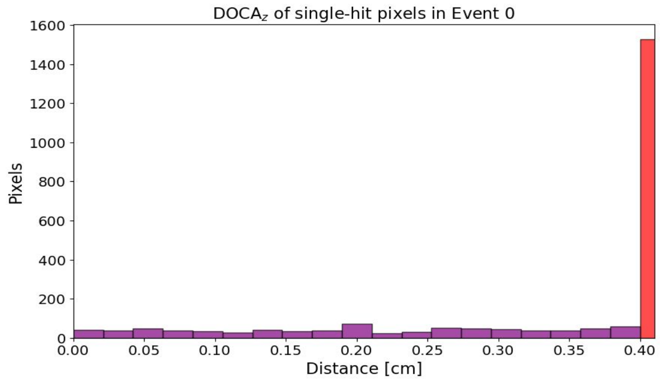
Before we start to assess how well the process works, we reject the subset of events where we were not able to well-model the primary muon track. Event 8 is one such event where there are multiple high energy EM “sneezes” that produce a significant number of single-hit energy deposits (bottom left).

The first pass of our DOCA fitting doesn’t have a clear signal region like we had in the previous event (bottom right) because many single-hit pixels are from the secondary interactions (top plot).

On the next page we outline some cuts that help identify and remove these events.







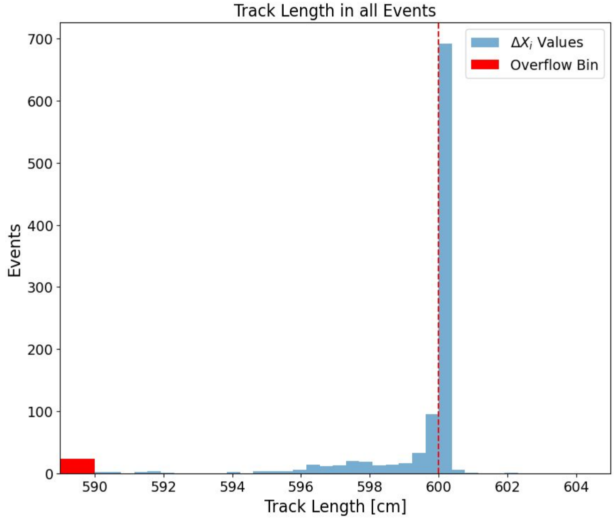
Selecting clean muon events

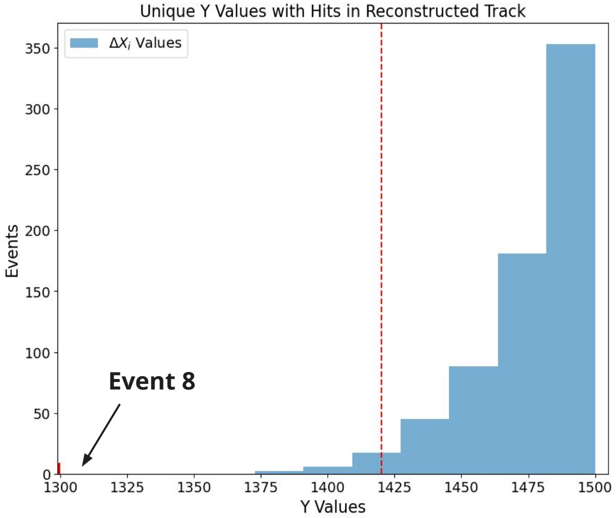
Since we want to study how well the tracking reconstruction works, we select “clean” primary muon tracks from our sample by requiring that

- the final reconstructed track has a length of >=600cm to prevent muon decay backgrounds or premature exit.
- ~94.6% of the possible pixels in y have a hit that is in the muon track (top plot). The detector has a length of 1500 pixels in y (600cm/0.4cm), so 1420/1500 of these values must have a hit in the muon track.

This amounts to 674 clean primary tracks (events) of the total 1000 events. For the clean primary tracks, we will look at reconstructed entry and exit points, scatter, and ionization dE/dX.

In principle, we can develop a more sophisticated method to handle events with large secondary hits, but we will leave that for another time.





With our selection of well-measured tracks we next look to see how well we do with:

- Position reconstruction

- dE/dX measurements

Position resolution, x_0 and x_f

For the clean primary muon tracks we would expect that

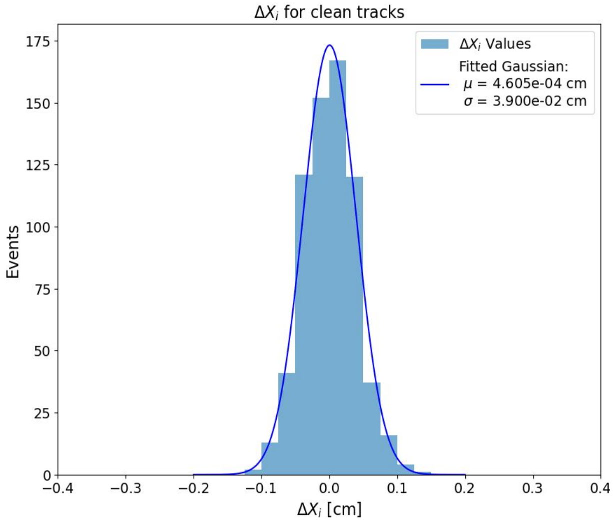
$\Delta x_0 = x_{fit}(y=0cm) - x_{truth}(y=0cm) = 0$, $\Delta x_f = x_{fit}(y=600cm) - x_{truth}(y=600cm) = 0$

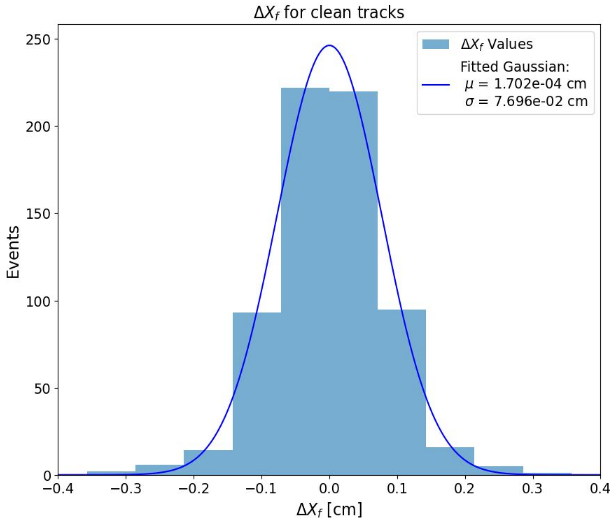
By fitting the Δx_0 and Δx_f distributions to a Gaussian, we find:

$\text{Mean}(\Delta x_0) = 4.61\mu m \pm 15.02\mu m$
$\text{Mean}(\Delta x_f) = 1.70\mu m \pm 29.64\mu m$

The means are consistent with zero within statistical uncertainty.
However, the Δx_f uncertainty is roughly twice as bad as Δx_0.

This is likely due the initial trajectory of the muon. The muon has an initial x momentum of zero and hasn't scattered yet. So it has a relatively simple initial trajectory, which is easier to fit and get correct.





Position resolution, z_0 and z_f

For the clean primary muon tracks we would expect that

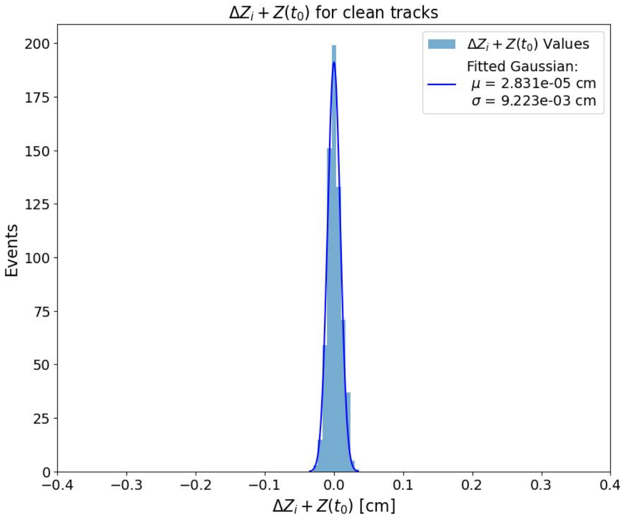
$\Delta z_0 = z_{fit}(y=0cm) - z_{truth}(y=0cm) + Z(t_0) = 0,$
$\Delta z_f = z_{fit}(y=600cm) - z_{truth}(y=600cm) + Z(t_0) = 0$

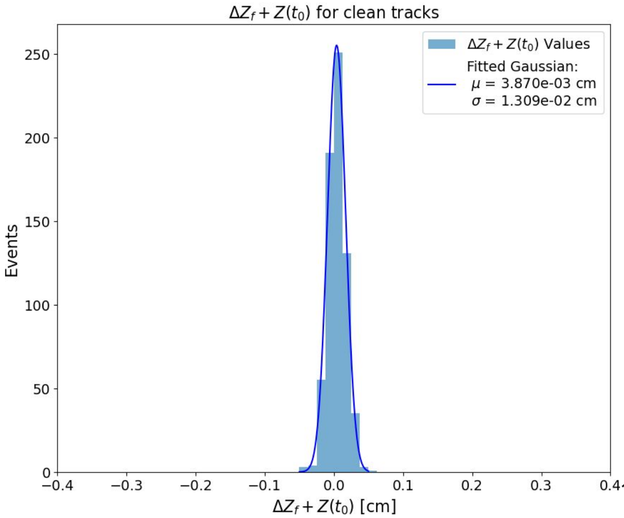
where, as before, $Z(t_0)$ is a factor that removes the t_0 shift. This tells us how precisely we measure z_0 and z_f. To get the z_0 and z_f accuracy, we would keep the t_0 shift. By fitting the Δz_0 and Δz_f distributions to a Gaussian, we find:

$\text{Mean}(\Delta z_0) = 0.28\mu m \pm 3.55\mu m$
$\text{Mean}(\Delta z_f) = 38.70\mu m \pm 5.04\mu m$

As before, the better statistical precision in the z_0 measurement is likely due to the initial trajectory of the muon.

Note that Δz_f is not within statistical error of zero by many orders of magnitude. We explore why that is the case on the next page.





Why is z_f more poorly measured?

With z_f we see that the time it takes the muon to travel to the end of the detector is non-negligible compared to the precision of the CDF hit method. It takes the muon about 20ns to travel through the detector. We will refer to this time as t_f. We can see from the top plot that t_f is not always the same for each event, though the variation is small. It is, however, putting an overall y-dependent bias on the Δz_f distribution.

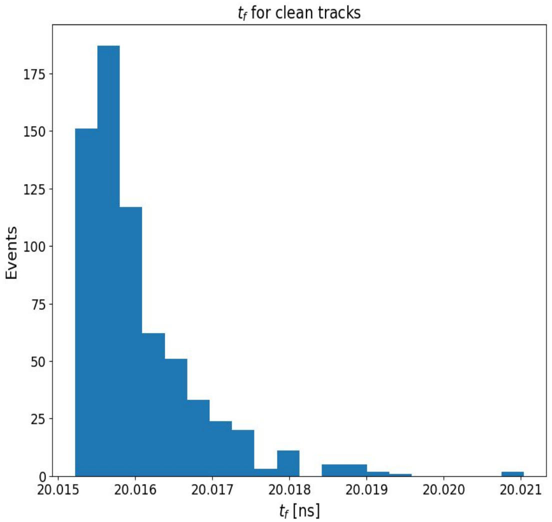
As a simple approximation to see if this is causing the poor measurement, we subtract the t_f from the drift time of the last pixels in the track for each event. This makes the Δz_f more in agreement with zero (bottom plot).

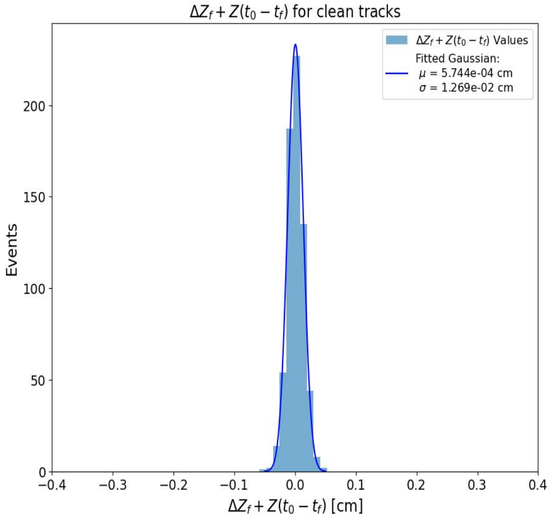
Mean(Δz_f) = 5.74μm ± 4.89μm

Note, this correction could be done because we used truth to determine

1.) the muon direction, thus which pixels were at the end
2.) the time it took the muon to travel through the detector

Without this information, a correction factor could not be determined. Our tracks are slightly deformed because we have been assuming that the muon travel time is negligible. We could further improve z precision if our models accounted for this but again, we will leave this for another time.





Muon scatter across the trajectory

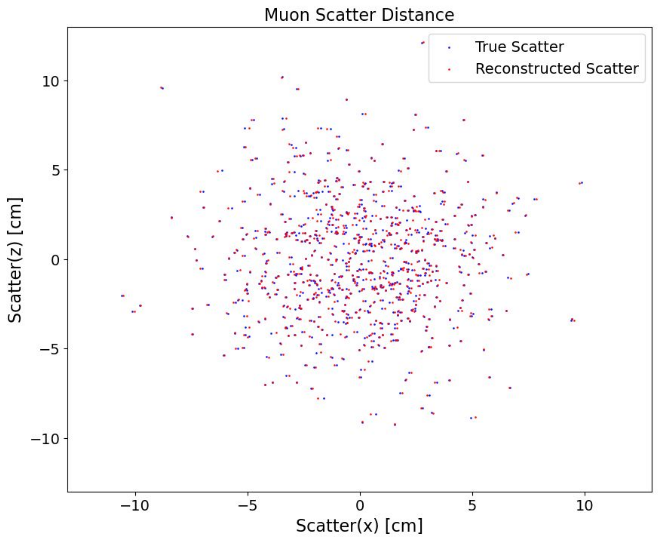
We also check to see that we accurately modeled the scatter of the muon (overall distance between initial and final position). We can see that the reconstructed scatter overlap well with the true scatter. By fitting the scatter distributions to a Gaussian, we see that

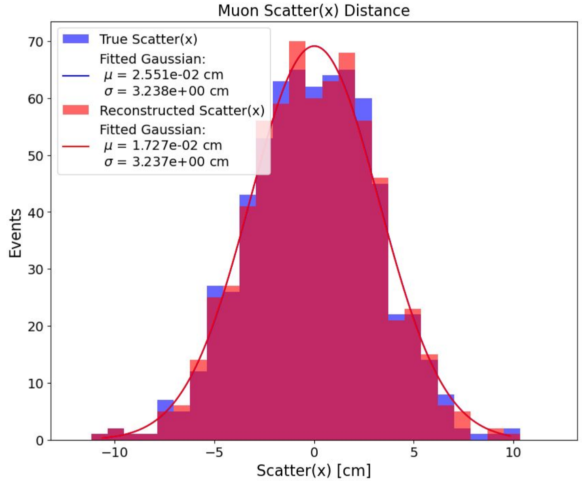
Mean($scatter_{true}$) = (x = 0.25mm ± 1.25mm, z = -1.26mm ± 1.25mm)
Mean($scatter_{rec}$) = (x = 0.17mm ± 1.25mm, z = -1.29mm ± 1.25mm)

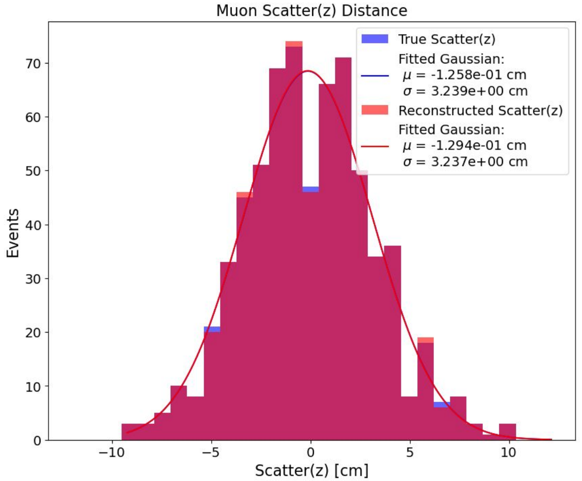
RMS($scatter_{true}$) = (x = 3.24cm, z = 3.24cm)
RMS($scatter_{rec}$) = (x = 3.24cm, z = 3.24cm)

The reconstructed measurements are well within uncertainty of truth.

This isn't too surprising. By definition, the t_0 shift has been subtracted out and the z_f bias we saw is negligible compared to the typical amount of scattering we see (~30μm bias compared to ~mm→cm scattering)







Muon ionization dE/dX

We now transition to describing how well our dE/dX reconstruction does.

The full dE/dX distribution follows a Landau shape with long tails that can be described by the Bethe-Bloch distribution which includes both the primary muon ionization as well as secondary interactions (delta rays, bremsstrahlung, pair production, photonuclear, …).

Since our tracking essentially considers only the ionization processes of the muon track and the hits associated with it (mostly muon ionization), we expect that there will be no long tail on the dE/dX distribution. We are working with 10 GeV muons, so the overall difference in momentum between the start and end of the event is around 1-2GeV (~10-20% of initial).

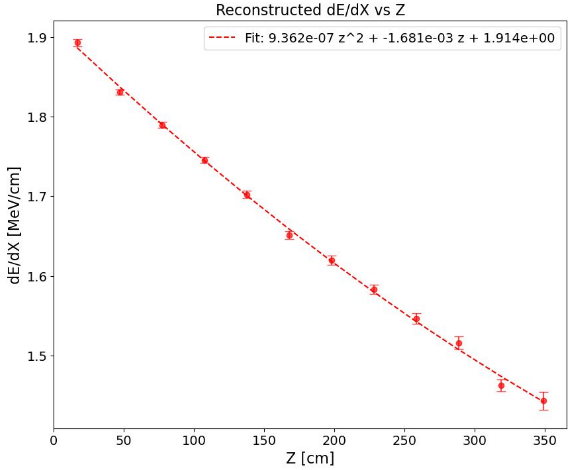
The muon ionization dE/dX distribution should be fairly uniform and on the order of ~2MeV/cm.

Z	A [g/mol]	ρ [g/cm^3]	I [eV]	a	$k = m_s$	x_0	x_1	$\overline{C}$	δ_0
18 (Ar)	39.948 (1)	1.396	188.0	0.19559	3.0000	0.2000	3.0000	5.2146	0.00

T	p [MeV/c]	Ionization	Brems	Pair prod [MeV cm^2/g]	Photonucl	Total	CSDA range [g/cm^2]
10.0 MeV	4.704×10^1	5.687				5.687	9.833×10^{-1}
14.0 MeV	5.616×10^1	4.461				4.461	1.786×10^0
20.0 MeV	6.802×10^1	3.502				3.502	3.321×10^0
30.0 MeV	8.509×10^1	2.731				2.731	6.598×10^0
40.0 MeV	1.003×10^2	2.340				2.340	1.058×10^1
80.0 MeV	1.527×10^2	1.771				1.771	3.084×10^1
100. MeV	1.764×10^2	1.669				1.670	4.250×10^1
140. MeV	2.218×10^2	1.570				1.570	6.732×10^1
200. MeV	2.868×10^2	1.518				1.519	1.063×10^2
266. MeV	3.567×10^2	1.508			0.000	1.508	*Minimum ionization*
300. MeV	3.917×10^2	1.509			0.000	1.510	1.725×10^2
400. MeV	4.945×10^2	1.526	0.000		0.000	1.526	2.385×10^2
800. MeV	8.995×10^2	1.610	0.000		0.000	1.610	4.934×10^2
1.00 GeV	1.101×10^3	1.644	0.000		0.000	1.645	6.163×10^2
1.40 GeV	1.502×10^3	1.699	0.001	0.000	0.001	1.700	8.552×10^2
2.00 GeV	2.103×10^3	1.758	0.001	0.001	0.001	1.761	1.202×10^3
3.00 GeV	3.104×10^3	1.825	0.002	0.001	0.001	1.829	1.758×10^3
4.00 GeV	4.104×10^3	1.870	0.003	0.002	0.002	1.877	2.297×10^3
8.00 GeV	8.105×10^3	1.973	0.007	0.007	0.004	1.991	4.359×10^3
10.0 GeV	1.011×10^4	2.003	0.010	0.010	0.004	2.028	5.354×10^3

Reconstructed dE/dX

Recall that we have measured the dE and dX for the clean muon events. Combining these measurements give us a mean(dE/dX) on a muon-by-muon basis.

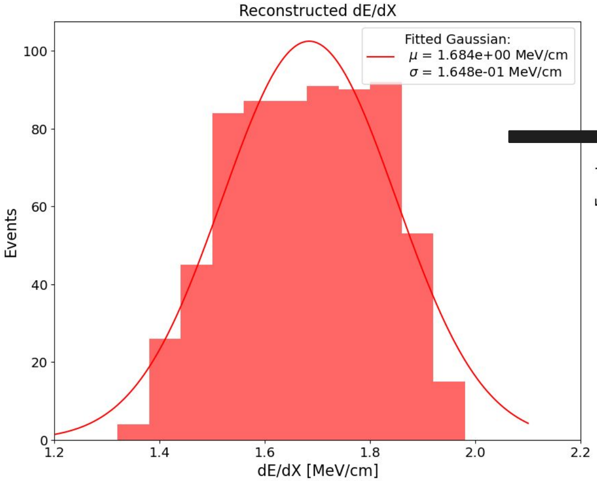


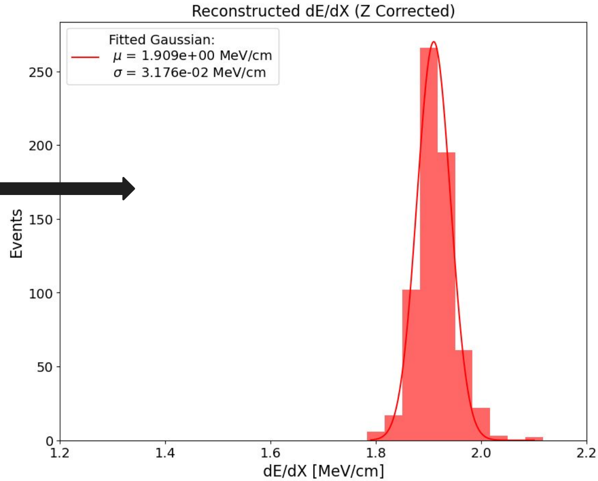
On the bottom left is the reconstructed dE/dX for the clean tracks. We look at this distribution as a function of average Z of the event (top plot) and see that there is a clear quadratic relationship.

We suspect that this is due to longitudinal diffusion, spreading the energy from hits further in (x,y) as a function of Z, such that they are not within our YX limits for the primary muon track.

We can use this to make a Z corrected dE/dX measurement with the average Z measurement of the track hits (bottom right)

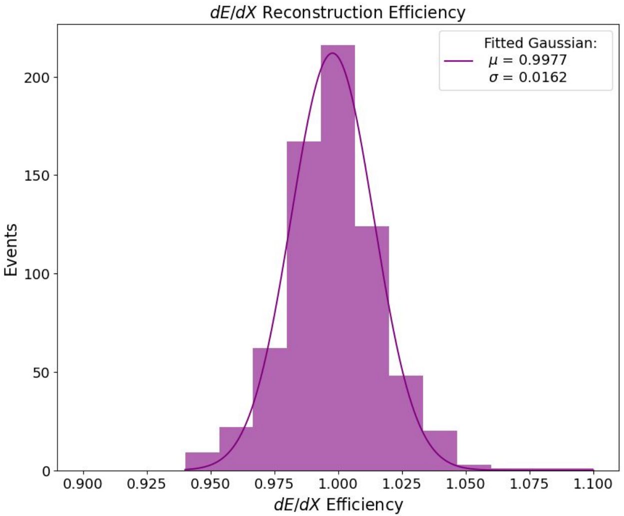
$$dE/dX(z) = dE/dX + 1.681 \times 10^{-3} * z - 9.362 \times 10^{-7} z^2$$





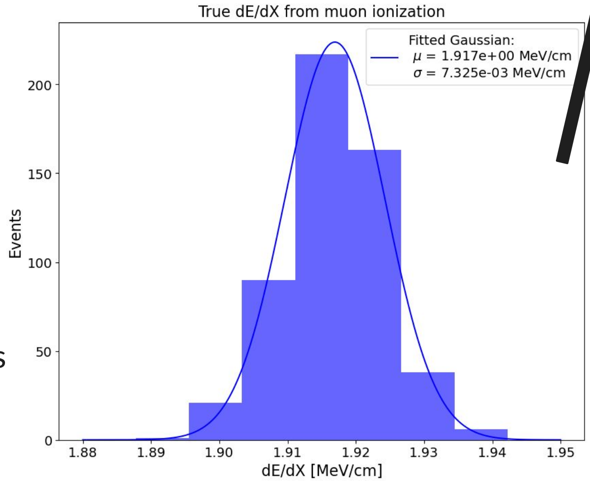
dE/dX reconstruction efficiency

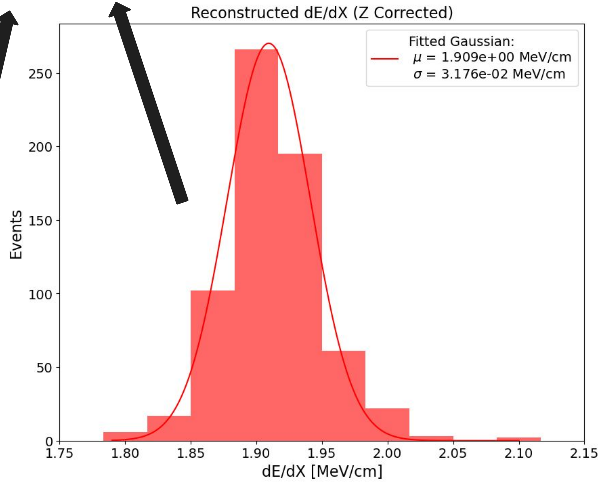
We now compare the corrected dE/dX measurement (bottom right) with the true dE/dX of the muon through ionization process only (bottom left). The true muon dE/dX from minimum ionization is fairly centered on 1.917MeV/cm, which is expected from a suppressed Bethe-Bloch calculation.



The dE/dX efficiency of reconstruction is well centered on 99.77% with an RMS of 1.6% which isn’t within statistical uncertainty of 100%, but this could be due to using a nth-degree polynomial to fit tracks. It’s likely that we are cutting muon ionization or keeping secondary hits due to the model we used.

The high efficiency is due to the correction factor, which has essentially removed the effects of diffusion. We could make a 3σ cut of (1.81 < dE/dX < 2.00)MeV/cm for muon ID.





Tracking conclusions

We have described our updated method for primary muon track reconstruction from hits as measured by the CDF method. For the set of reconstructed tracks that cleanly traverse the full detector, we find that:

- The x_0 and x_f of the reconstructed primary muon track are consistent with truth within the width of a pixel (4mm). The x_0 precision is 390μm and the precision of x_f is 770μm. The z_0 of the reconstructed primary muon track is consistent with truth within a millimeter. The z_0 precision is 92.2μm and the precision of z_f is 131μm. The leading order bias for z_f measurements seem to be the time it takes the muon to reach the end of the detector.

- The reconstructed x and z scattering are well within statistical errors of true scatter.

- Using the hits to do a dE/dX measurement, we find that:
  - The dE/dX drops as a function of Z as expected due to transverse diffusion, but is otherwise Gaussian.
  - An estimate of the energy collection efficiency of muon ionization is 99.77% with a σ of 1.6% which implies that if we knew the energy of the muon, we could make a muon ID cut in the range of 3σ ($1.81 < dE/dX < 2.00$)MeV/cm which is 99% efficient.

Switching topics from muon tracking with the baseline detector, to how well the CDF method does for different detector configurations and how well it does for different particles, energies, and other factors

Robustness of CDF method for different detector designs

We now look at the robustness of the CDF method under varying experimental scenarios. Note, this is NOT about tracking, it's just about the Z position measurement from the CDF method for single-hit pixels. Treat this as an extension of the previous CDF method talks where we try to find conditions that cause the CDF method break down. Here we will vary

1. Different detector configurations
   a. clock-speed
   b. reset-threshold
2. Different event types
   a. initial muon energy
   b. initial muon z
   c. initial muon z momentum
   d. particle type

Our goal here is to survey how well the CDF method performs for different kinds of events and detector configurations relative to benchmark/baseline detector conditions.

Baseline configuration

We will generate a set of 200 events in qpixg4 and qpixrtd with the following baseline configuration and make new samples with 1D variations, i.e. when we study the clock-speed, we will use the default reset threshold, and initial particle conditions. The baseline detector conditions are:

<u>Detector</u>
clock-speed = 100 MHz
reset threshold = 1fC

<u>initial particle conditions</u>
type = muon
Energy = 2 GeV (Note that this is less than we have used previously, so, as we will see, things get a bit worse)
Initial Position = [120cm, 0cm, 180 cm]
p = [0, 1, 0] i.e. pz/py = 0

Accuracy and Precision

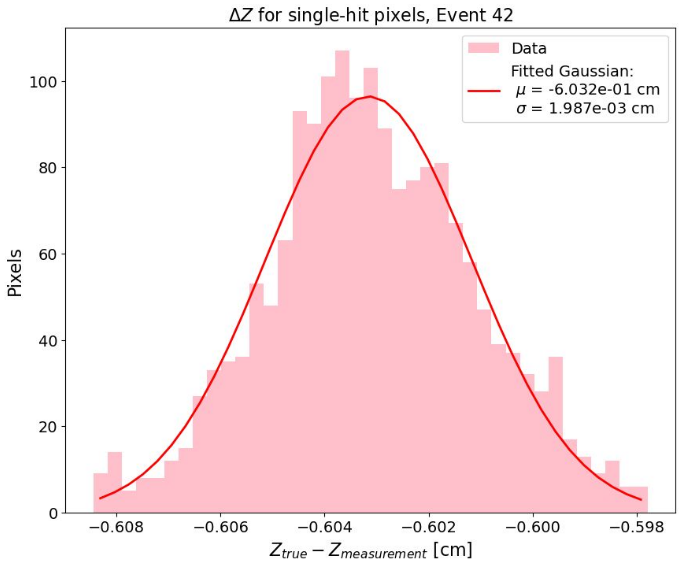
We have previously motivated that the **precision** of well-measured pixels matters more than the overall t_0 shift (**accuracy**) for tracking particle trajectories and vertices. Using the single-hit pixels for Event 0, we find

$$\Delta Z = Z_{true} - Z_{measurement} = Z_{true} - v(\mu_{CDF} - t_0)$$

Here we evaluate ΔZ on a pixel-by-pixel basis using the true particle track energy deposits above each pixel within an expected range of transverse diffusion.

The following plot shows the ΔZ distribution for a typical event where we define the accuracy as $\mu(\Delta Z)$ and precision as $\sigma(\Delta Z)$.

For each sample of different clock-speed or reset threshold, we will have a collection of 200 events each with ~1000 hits to determine the accuracy and precision. To compare measurements between samples, we will use σ(Accuracy) and μ(Precision).



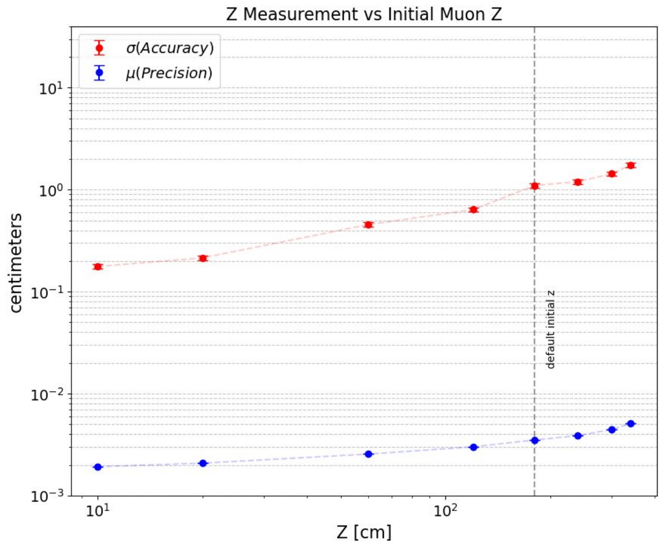
As a function of initial muon Z

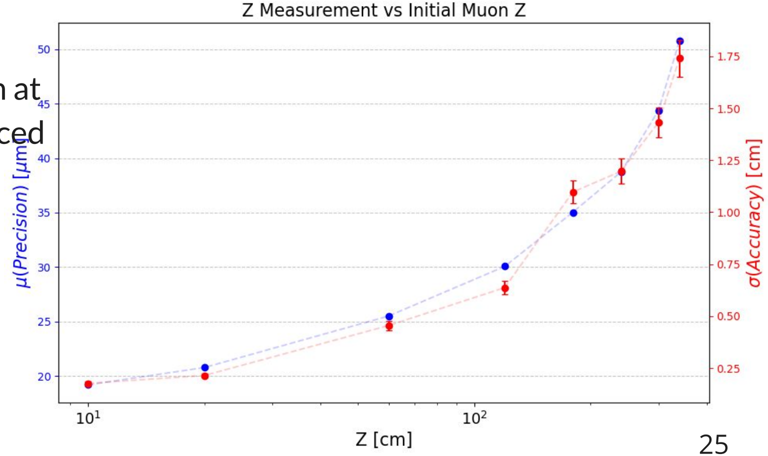
The accuracy and precision of the baseline sample at Z=180cm are 1.097cm and 35.03μm respectively.

As expected, accuracy and precision are Z dependent. As Z increases, longitudinal diffusion makes the arrival time RMS wider and transverse diffusion spreads the electrons across more pixels . Both the number of resets and the RMS of the distribution affect the resolution, and they both rise as a function of Z.

Since the resolution is dependent on the combination of clock resolution and σ of the electron swarm, this suggests that we probably can't gain back resolution at large Z with to a faster clock, but there is an argument to be made about a reduced reset threshold.

With more resets, we may be able to reduce the number of falsely classified single-hit pixels (resolve multi-hit pixels better), and thus improve single-hit purity with a goodness-of-fit test. But going from 1fC to 0.5fC would only give us a statistical benefit of sqrt(2), which might not make a difference. We will make this more quantitative soon.



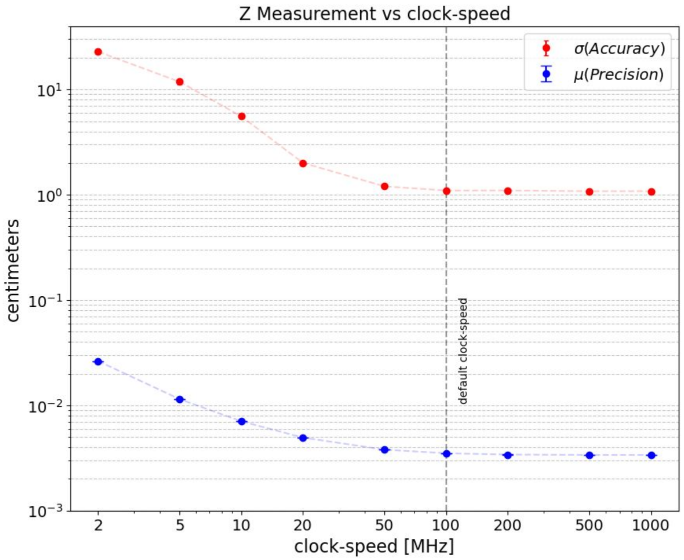


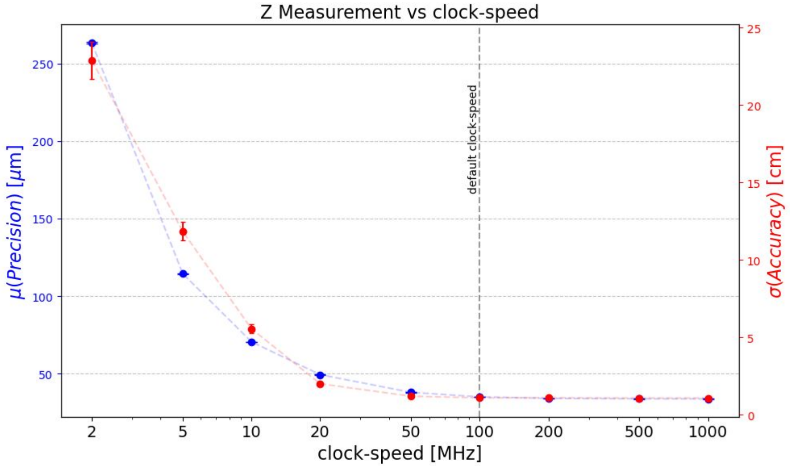
As a function of clock-speed, Z=180cm

As expected, a slower clock speed makes accuracy and precision worse, but there also isn't really a benefit in making the clock-speed faster than 100MHz at Z=180cm.

The inflection point occurs when the clock-speed is slower than 50 MHz. Our current clock-speed of 100MHz seems to be at a sweet spot for drift heights of Z=180cm.

We should, however, be careful here as the electron drift time will be on the same order of magnitude as the clock-speed when we get to centimeter drift.





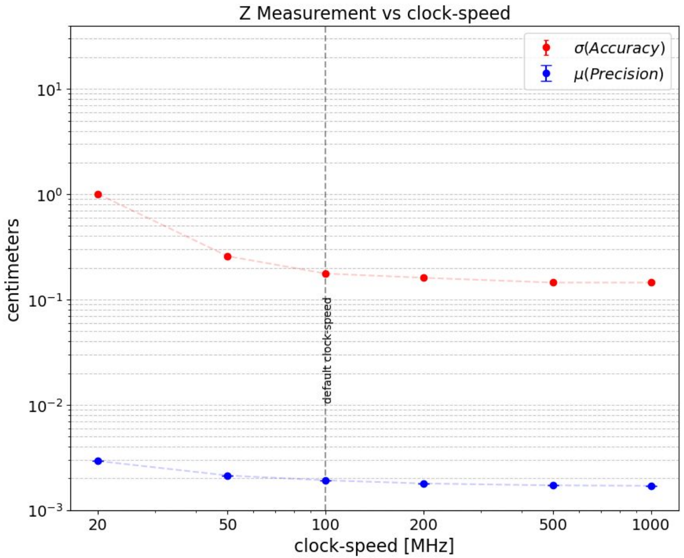
As a function of clock-speed, Z=10cm

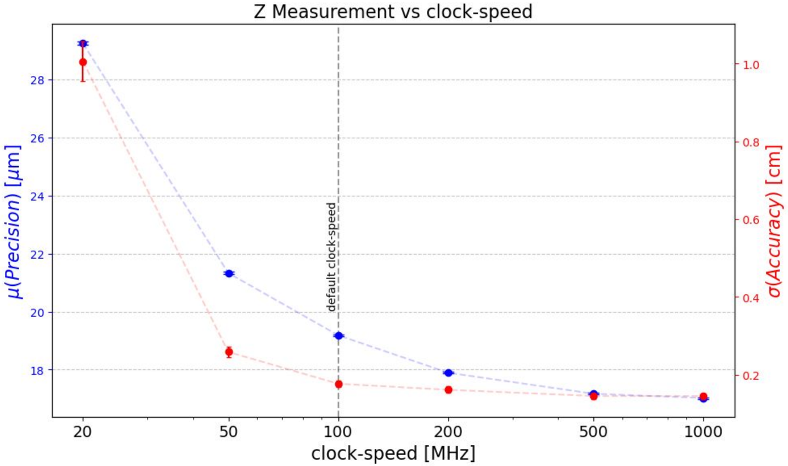
While the previous page showed our baseline clock-speed is good at Z=180cm, we check how the inflection points change for a much smaller Z.

When we place the muon at Z=10cm, the accuracy and precision at the nominal clock-speed at 100MHz are 0.176cm and 19.18µm respectively.

The inflection point moves from about 100MHz to around 200MHz and improvements start to level off at 500MHz. We might be limited by our baseline clock-speed if the drift distance is less than 10cm, such as in the UTA/H teststand.

Bottom line: Our current clock-speed is a fine choice for a large range of Z. Making it much lower will make things much worse quickly, and there is no significant gain (~10% at Z=10cm) when we make it much faster.





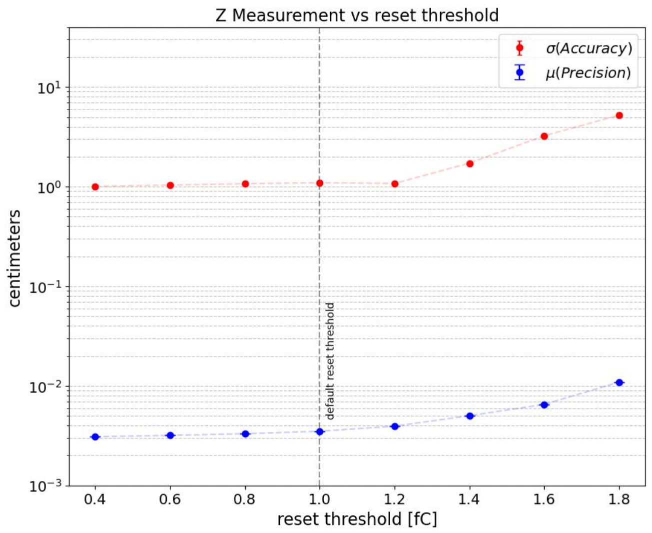
As a function of reset threshold, Z=180cm

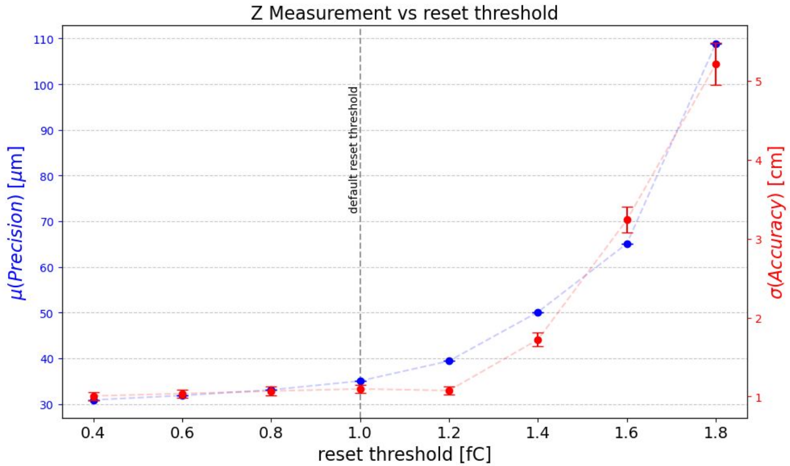
As expected, a larger reset threshold makes accuracy and precision worse because we are reducing the the number of resets in the single-hit pixels.

There is a marginal boost in precision when we reduce the reset threshold to 0.4-0.8fC, but no noticeable boost in accuracy.

Recall that we have been using 3-5 reset pixels to find t_0. These limits have been adjusted for each sample to maintain similar single-hit purity between the samples.

Bottom line: Our choice of reset threshold seems to be fine. Making it larger could quickly make things much worse, and making it much lower doesn't look like it will help much, but could introduce other issues (including sensitivity to noise). There might be value to investigating how the reset threshold affects the muon track reconstruction, dE/dX measurements and other particle type events before making a final decision.





We next move to seeing how well the baseline detector configuration is expected to work with different kinds of events

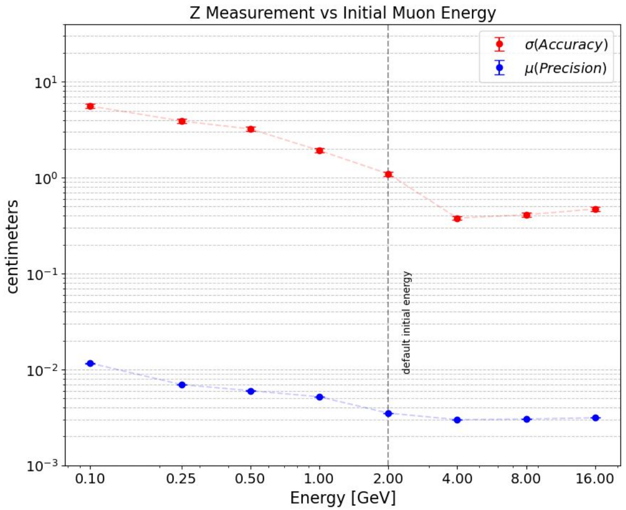
As a function of initial muon energy

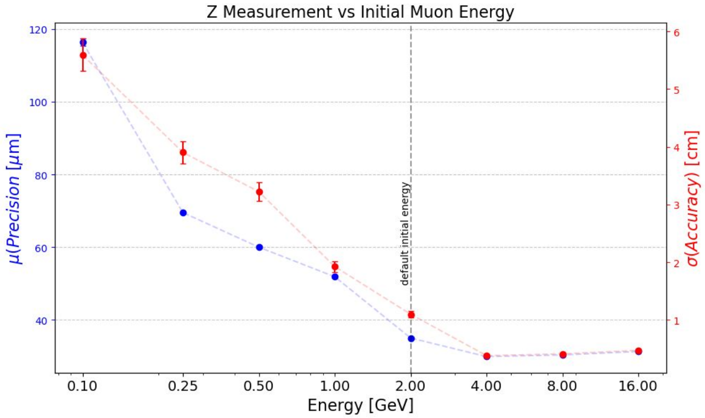
Since interactions with the muon are energy dependent, we expect variation in the accuracy and precision with different dominant effects at different energies.

As shown on the right, there is a distinct minimum around 4GeV, a gradual rise in the accuracy and precision at higher energies, and a sharp rise at lower energies. This is likely to do with the Bethe-Bloch curve:

1.) At lower energies, dE/dX increases rapidly. Most of these muons don't reach the end of the detector, so we have a lower number of pixels being reset and Michel electron background.
2.) At higher energies, the number of secondary interactions goes up and they become more energetic on average.
3.) At 3-4GeV, the muon is mostly doing minimum ionization.

It's not clear that changing the detector configurations would improve this result. The variation in accuracy and precision we see here seems to be due to the types of interactions, not *how* they were measured. This suggests that most benefit would come from more sophisticated reconstruction methods.

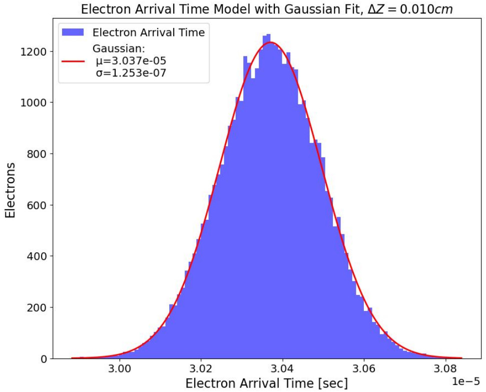


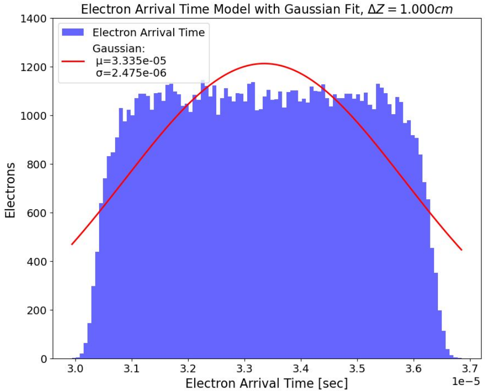


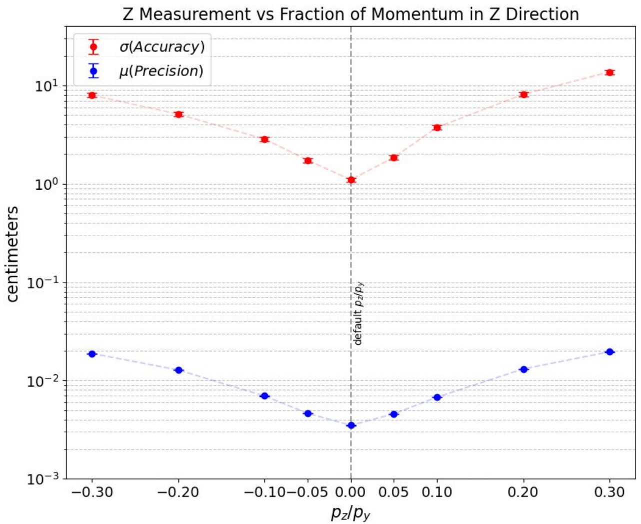
As a function of initial muon p_z

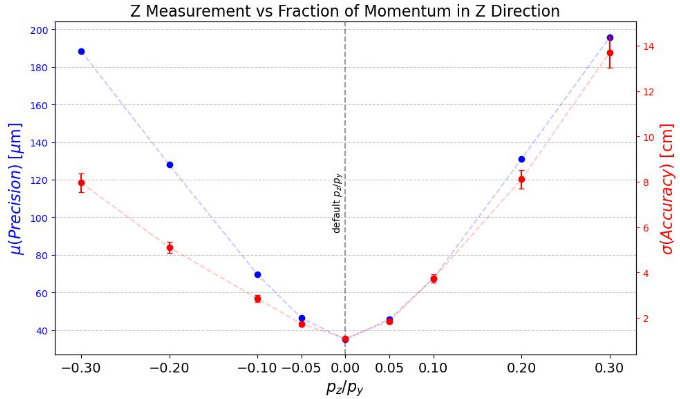
The accuracy and precision measurements of the current CDF reconstruction method do worse when the muon has Z momentum, as shown on the right plots. This is because, in this case, the Z of interactions above a pixel are no longer well localized to a single point. Instead, the arrival time of the electron swarm gets smeared, as shown on the left plots, which the CDF model does not account for. See page 36 for more details.

The variations due to Z are biased with the direction of p_z, so we don't expect the p_z effects to be symmetric. We could probably do better with a more sophisticated CDF model in the future. This will be an important effect for downward going muons in the teststand.



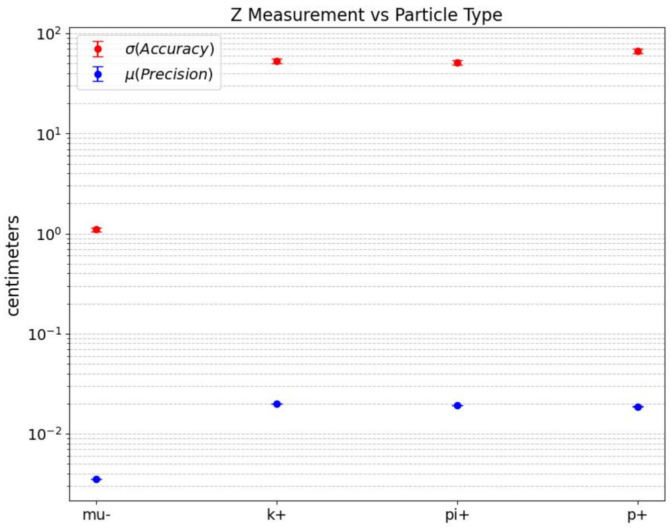






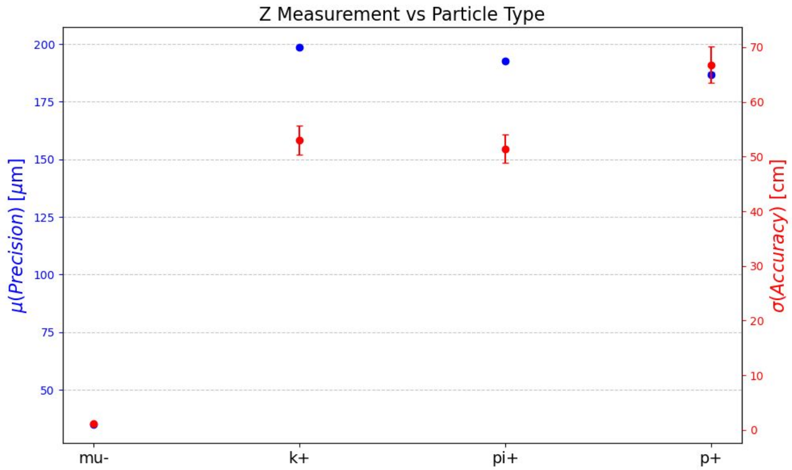
As a function of particle type

The CDF method can find t_0 for 2GeV k^+, pi^+, and proton events, but the accuracy and precision measurements are not good “out of the box” because of the larger energy deposit above each pixel. The results shown on the right are for the case where we have the baseline detector configuration at Z=180cm.



The pixels we are using to find t_0 (3-5 resets for single-hits) is only a good assumption for muon ionization. To do better, we should study the k+, pi+, and proton processes in more detail.

As it turns out, there are well-measured single-hit pixels beyond 10 resets in the k+, pi+, and proton events, so we should start there for a more general CDF methodology. More on this on page 37.



Robustness Conclusion

We have studied the accuracy and precision of Z position reconstruction using the current CDF method, and compared the results for a number of different variations to the default detector configuration for a 2GeV muon at Z=180cm.

For the default detector design, the CDF method is robust for a wide range of muon events with varying Z_i, E_i, $p_{i,z}$. In general, we don't see significant gains for the muon events when we make the clock-speed faster or the reset-threshold smaller, but we do see a rapid fall off when the clock-speed is slower or the reset-threshold is larger. Since the worst variations come from particle types, kinematics, and interactions, it's not clear changing the detector is the right way to go.

Should we think about changing things?

Default detector design:

- For drift heights smaller than 10cm, there appears to be value in having a faster clock as the drift time σ would be on the order of 1e-8 sec. We could see ~10% improvement around Z=10cm, and even more at lower Z.
- The current reset threshold seems to work well for a wide range of muon events, but there may be benefit in investigating how it affects other particle types. The statistical gains when we reduce the threshold seem to be marginal.

CDF methodology:

- A more sophisticated CDF model is needed when there is Z momentum.
- A number of assumptions in the current CDF method are not well suited for the dE/dX of other particle types.

Conclusions

The primary muon tracking and dE/dX methodology described here is a first step to utilize and quantify the measurement precision achievable with the CDF method. For muon events with small Z momentum that don't have significant secondary activity, we find that:

- The precision of the x_0 and x_f measurements are consistent with truth with a resolution dominated by the width of a pixel at the beginning and our ability to model scattering at the end. The x_0 precision is 390μm and the precision of x_f is 770μm.
- The z_0 measurement is consistent with truth with a precision of 92.2μm. The precision of z_f is 131μm, but is inconsistent with truth. This inconsistency is dominated by the time it takes the muon to traverse the detector. The z_f measurement was much closer to agreement with truth when we accounted for this.
- The measured muon ionization dE/dX was a significant fraction (99.77%) of the true muon ionization dE/dX with a relatively tight σ that could be used for muon ID. A 3σ cut would be $(1.81 < dE/dX < 2.00)$MeV/cm.

More sophisticated tracking methods will be needed for quality reconstruction of muon trajectories with lots of secondary activity or large p_z.

The accuracy and precision of z-position reconstruction using the CDF method with the baseline sample (2GeV muon, Z=180cm, p_z=0) are 1.097cm and 35.03μm respectively. The CDF method is quite robust overall, with noticeable declines in performance occurring where we would anticipate them such as for large value of the Z momentum or non-muon interactions. Our studies suggest,

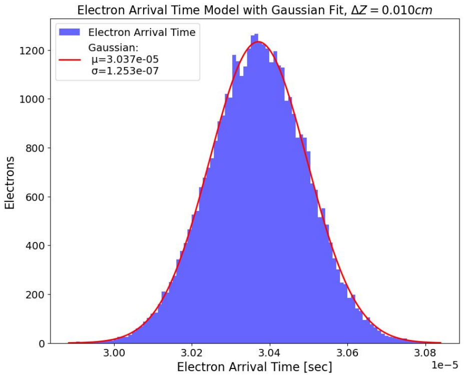
1. There doesn't appear to be big improvements to be had from changing the detector, but it wouldn't be hard to make it much worse.
2. There is significant room for improvement on the interpretation of the detector output for a wider range of event topologies with better, more generalized, algorithms and models.

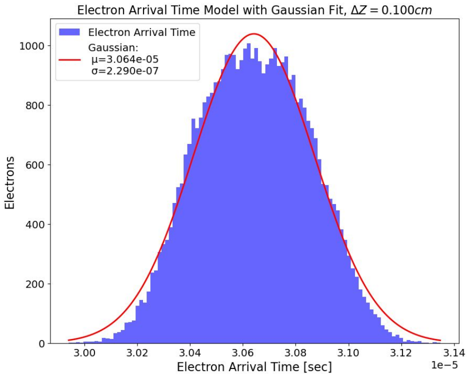
Extra Slides

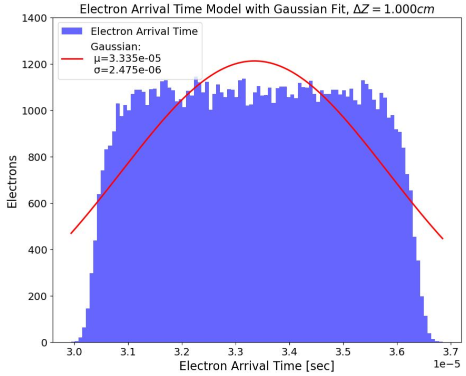
Simple Muon Event Model with p_z

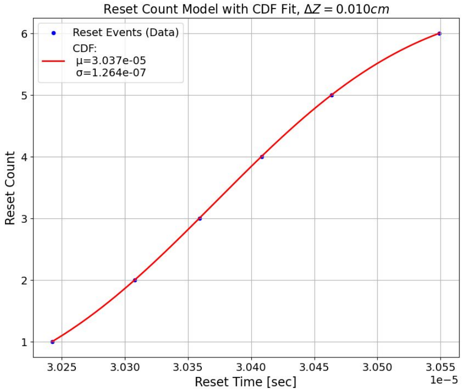
Assume the muon travels 0.4 cm across a pixel. We look at the electron arrival times when the muon also has a known ΔZ. All muons start at Z = 5 cm. Based on total pathlength, sqrt($0.4^2 + \Delta Z^2$), and a constant 2MeV/cm for muons, we uniformly place electrons along the muon track. We calculate the number of electrons using the ionization energy constant 23.6 eV per electron.

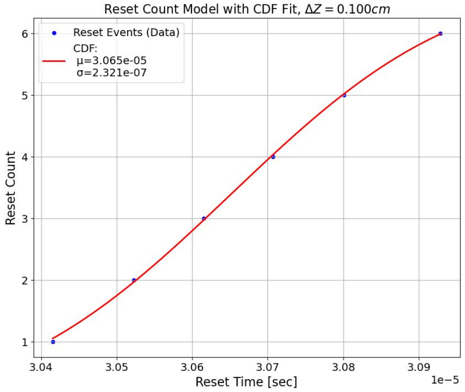
Using the known electron drift velocity, we determine the electron drift arrival time. We allow for longitudinal diffusion, which means electrons can arrive before or after the calculated electron drift arrival time. We also allow for transverse diffusion, so electrons near the edge of the pixel may not be counted (drifted to another pixel). We show the electron arrival time and reset count models for various ΔZ.

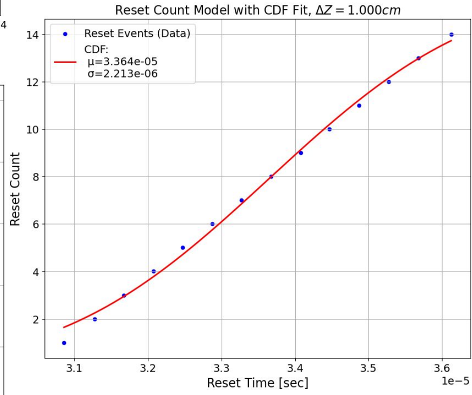












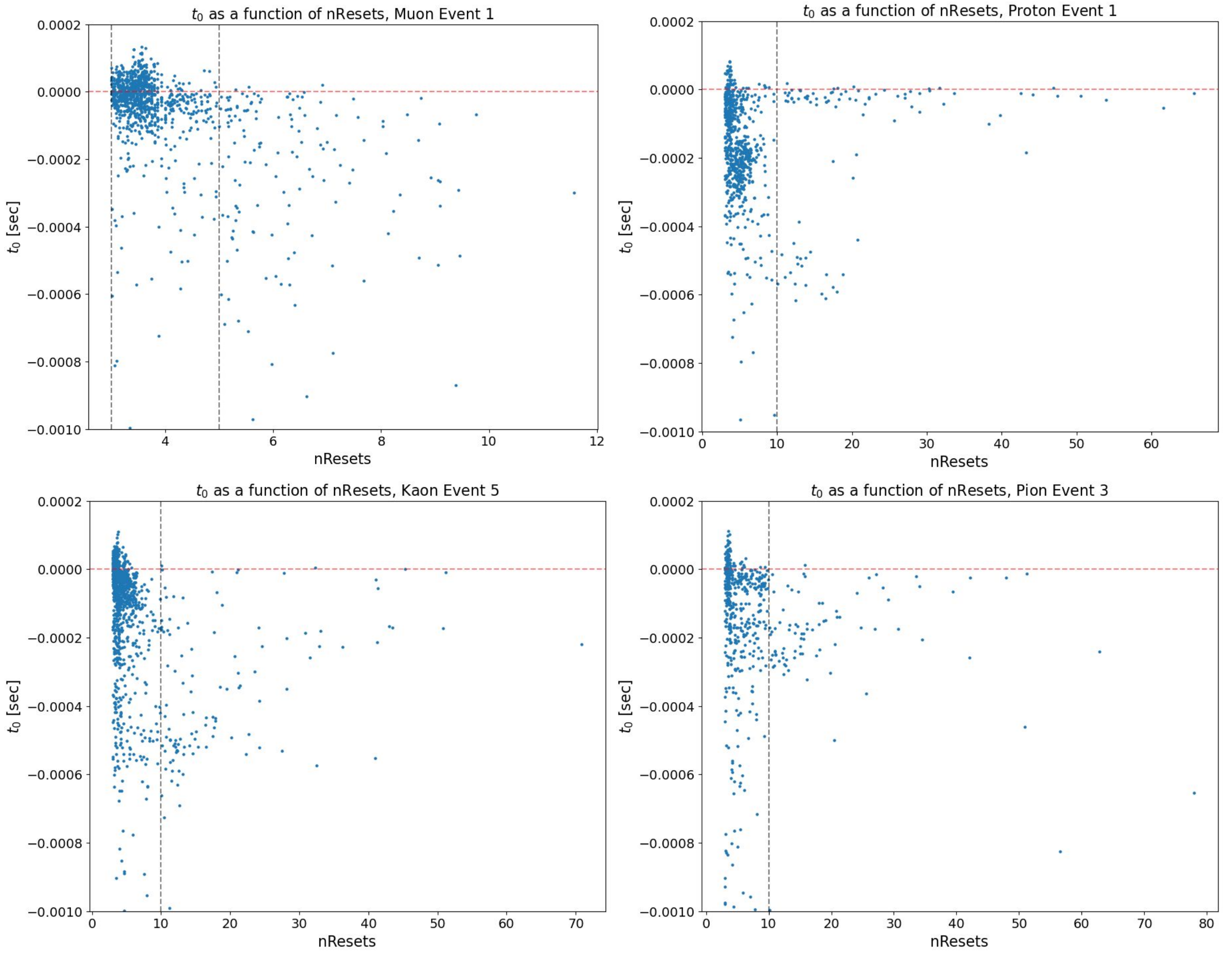
Particle type t_0

The k^+, pi^+, and proton events look very differently from the muon events.

As we have previously seen, muons have high single-hit purity for pixels up to 5 resets. We can see that beyond ~8 resets the t_0 values as measured by a muon event pixel are systematically less than 0.

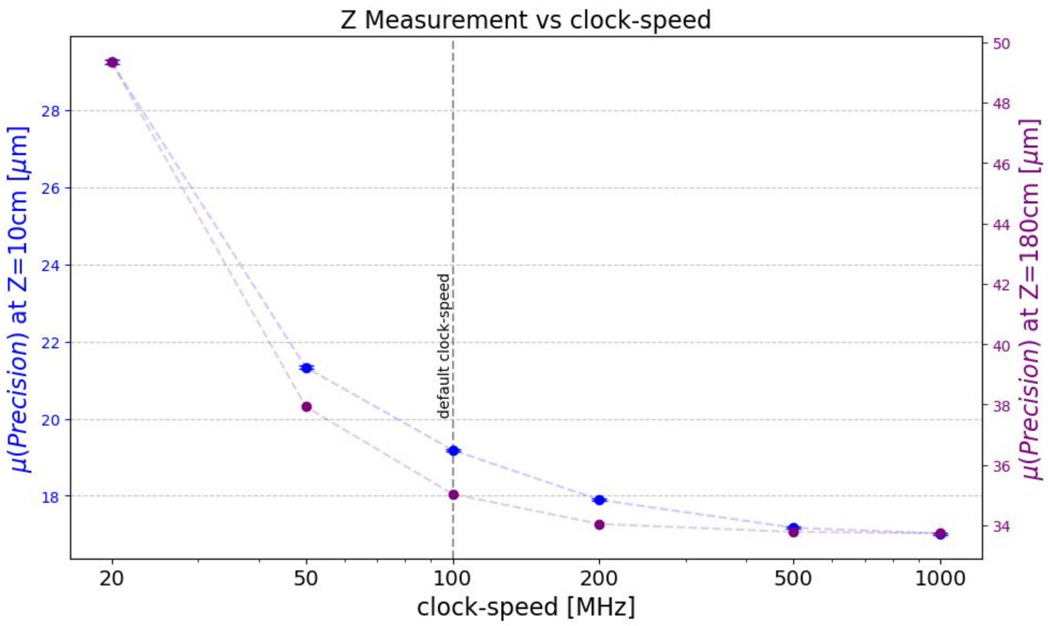
This is not the case for the other particle types, where there are still single-hit candidates beyond +10 resets.

The dE/dX of these other particle types varies considerably compared to the muon, and are not well localized to a small region of nReset parameter space.



Relative d(precision)/d(clock)

When we put the precision measurements of the clock-speed at Z=180cm and Z=10cm on the same relative scale, we see that the relative rate of change of the precision as a function of the clock speed is larger at 180cm. The turnoff point is reached slower at Z=10cm, around 500MHz, as opposed to 200MHz at Z=180cm.



Can we determine direction from t_0 measurements?

Here we check to see whether t_0 measurements closer to the start of the event, y<200cm, are smaller than the t_0 measurements closer to the end of the event, y>400cm. In principle, the t_0 measurements at the end of the event should be larger than the t_0 measurements at the start of the event so their difference,$\Delta t_0 = t_{0,\, y<200} - t_{0,\, y>400}$ should be negative.

What we found is that their difference is

Mean(Δt_0) = -74.82 ns ± 269.86 ns

which means that this method doesn't really do any better than random guessing. If we could improve the t_0 resolution, we could, theoretically, see the difference and use it to determine the direction.