Fitting QPix Reset Distributions with CDFs

3/4/2025
Q-Pix General Meeting
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- Comparing CDF and NumPy methods to muon sample
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Motivation

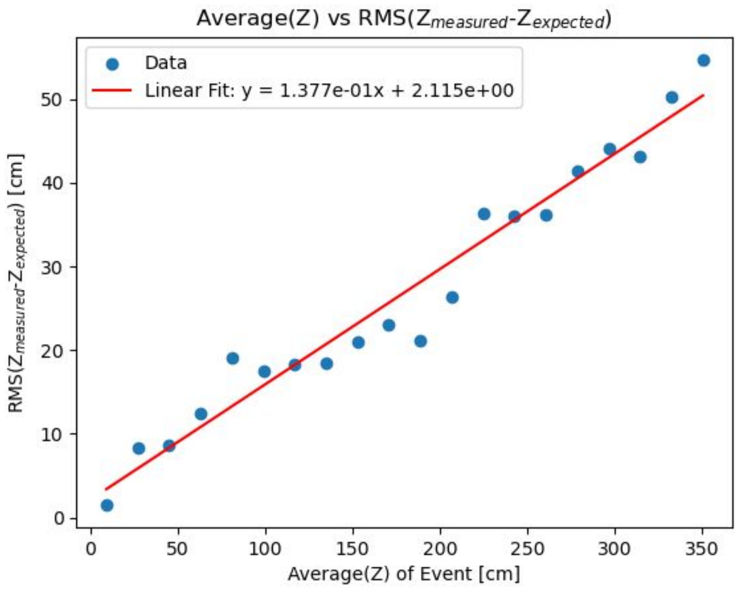
We have previously shown that using the mean and standard deviation of the QPix reset distribution allows us to measure the t_0 of an event as well as Z of particle tracks above a pixel.

- The Z resolution is itself dependent on Z, reaching approximately 50 cm near the top of the standard DUNE APA.

We've also demonstrated that these Z measurements allow us to track the trajectory of muons and calculate their dE/dX.

- In these measurements we assumed that all pixels have resets from a single interaction. This assumption affects both the trajectory and dE/dX measurements.
- Due to the discrete nature of resets we are underestimating the energy deposited in a pixel.

By starting with a more accurate model of electron swarms, we could theoretically improve all of the above aspects. This could lead to more precise tracking and dE/dX measurements, while using even fewer pixels.

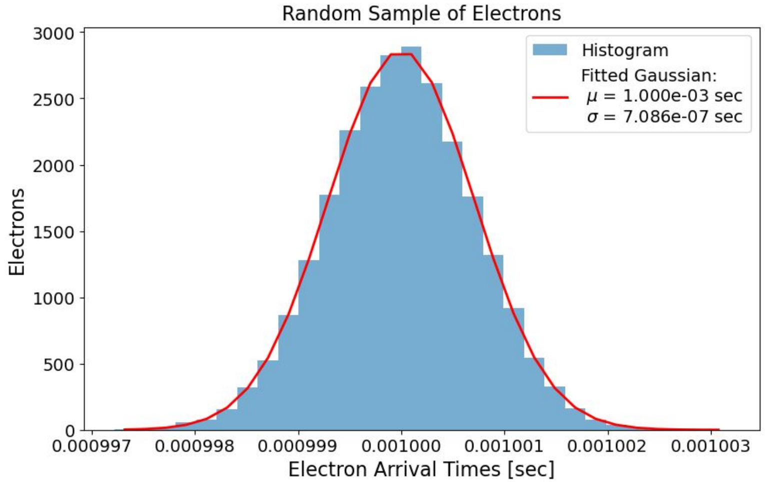


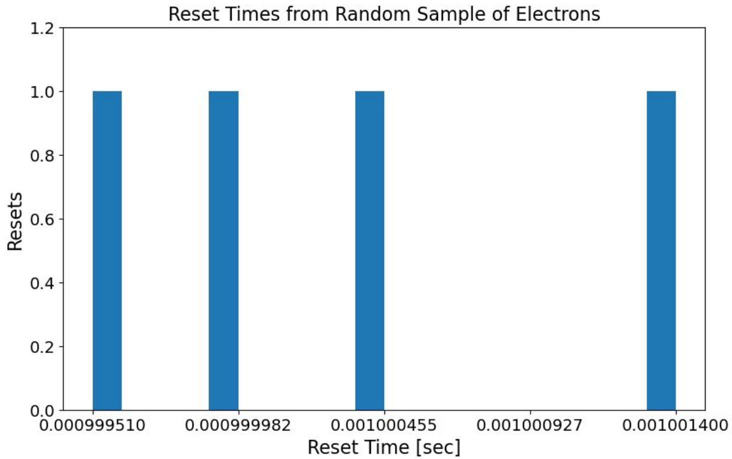
Talk given at QPix General Meeting on May 6, 2024

What should data look like?

In the case where a single interaction (hit) takes place above a pixel, the electron swarm will model a Gaussian distribution due to longitudinal diffusion. Below we have a toy sample of 25,600 electrons (~0.6 MeV) normally distributed around a mean, μ = 1e-3 sec, with the expected standard deviation from longitudinal diffusion, σ = 7.086e-6 sec. This would coincide with Z~165 cm.

In the data, we are not able to fully reproduce the electron swarm due to the trigger threshold of 6250 electrons. We see discrete binnings of the electron swarm through resets. For the toy sample, we would expect ~4.1 resets which would round down to 4 resets.





Using μ and σ to measure t_0 and Z

If we can precisely measure the μ and σ of the electron swarm from the reset distribution, we can then use these values to determine the Z-position and the time (t_0) of the hit that generated the electron swarm. We can do this by relating two functions of Z:

$$Z = v(\mu - t_0)$$

$$Z = \frac{v^3\sigma^2}{2D_L}$$

where v is the electron drift velocity and D_L is the longitudinal diffusion constant. From these, we determine $\sigma_{Expected}$:

$$\sigma_{Expected}(\mu, t_0) = \sqrt{\frac{2D_L \cdot Z}{v^3}} = \sqrt{\frac{2D_L \cdot (\mu - t_0)}{v^2}} = 2.24 \times 10^{-5}\sqrt{(\mu - t_0)}\ \mathrm{sec}$$

In general t_0 is an unknown constant, but for simulations we know that it should be zero (t_0 = 0) for well measured pixels. With the correct t_0, we would expect:

$$\sigma - \sigma_{Expected}(\mu, t_0) = \sigma - 2.24 \times 10^{-5}\sqrt{(\mu - t_0)}\ \mathrm{sec} \rightarrow 0$$

We will call this Δσ(μ, t_0) for simplicity. We can use Δσ(μ, t_0) for well-measured pixels to measure t_0 and Z.

Why μ and σ are not always well-measured - Physics

We list a few Physics Effects (PE) here, but note that this is likely not an exhaustive list.

PE1: Multiple interactions above a pixel

- Multiple interactions above a pixel result in multiple Gaussian distributions for resets. Fitting these to a single Gaussian will yield a larger-than-expected σ due to the overlap as well as a mean value that is the weighted average of the hits.

PE2: The Z of the interactions above a pixel

Transverse diffusion spreads electrons across the XY plane as they drift. The diffusion distance—and the spatial spread on the pixel plane—depends directly on the interaction's Z, as electron drift velocity is constant.

- Diffusion from large Z hits can cause spatially separated interactions to produce overlapping electron swarms, making PE1 even more pronounced.
- Diffusion from large Z hits will cause more pixels to be active, which will reduce the average nResets per pixel and thus reduce the statistical certainty of σ measurements.

PE3: Z momentum of particles

- Particles with Z momentum will create electron swarms with smeared electron arrival times, increasing the σ of the subsequent electron swarms. The hit was not localized to a single point in Z.

In all of these effects, the σ will be over-measured if we use a single Gaussian model. To make a pixel "well-measured" we need to mitigate these effects by using an accurate model of the hit(s) that produced the electron swarm. This is easier said than done…

Why μ and σ are not always well-measured - Detector

We know that higher statistics always helps the resolution of μ and σ, assuming they came from a single hit. The second set of effects are due to limitations from the readout methods which can have an effect on the measurement statistics. These Detector Effects (DE) are caused by the detector electronics and signal readout. We list a few DEs here, but note that this is likely not an exhaustive list.

DE1: Downsampling electrons into resets

- Reset clipping affects the measured σ by causing the electron swarm to abruptly end at the first and last reset. As a result, a standard deviation measurement of the resets can systematically under evaluate the σ of the electron swarm and affect the resolution of the μ.
- The uncertainty in energy deposited arises from the discrete nature of resets, with an intrinsic uncertainty of +1 reset per pixel.

DE2: Reset Threshold

- The number of resets, thus the statistical precision of μ and σ measurements, depends on the reset threshold.
- Reducing the reset threshold will allow us to utilize more statistically significant pixels for measurement, but at the cost of increasing the effects of noise.

DE3: Pixel Size

- Pixel size influences the number of electrons and resets. Electrons diffusing beyond or into pixel boundaries affect total electron counts.
- Larger pixels increase resets but may reduce single-hit purity as well as position resolution.
- Smaller pixels limit ΔZ for particle tracks, reducing arrival time smearing at the cost of lower statistics.

DE4: Clock Speed

- A 1e-8 second clock speed limits the precision of σ measurements at the millimeter scale, where the electron swarm σ ≈ 1e-8 seconds.

This talk is focused on mitigating the PEs and DE1 through improved measurement methodology.

Measurement methods in qpixrec/v2.0.0

A simple way to find μ of the reset distribution would be to calculate the mean of the reset times:

$$\mu = \frac{\sum_i R_i}{N}$$

For σ, we can use the standard deviation of the reset times using the definition of population variance:

$$\sigma = \sqrt{\frac{\sum_i |R_i - \mu|^2}{N}}$$

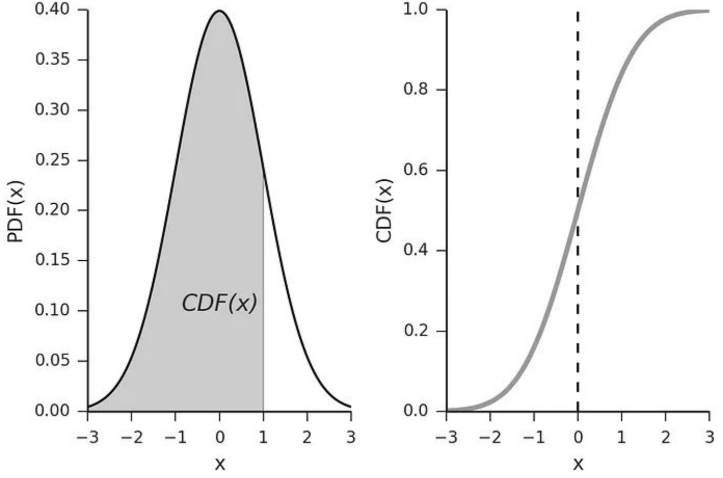
In qpixrec/v2.0.0, μ and σ are measured as described, but this process is biased due to DE1, where the electron swarm abruptly ends at the first and last reset, systematically reducing σ. DE2 also affects the precision of these measurements, particularly for small dE/dx or large Z, where a high reset threshold results in low nResets per pixel.

We also have no way to mitigate the PEs. All pixels are being treated as single-hit, which means we can also be over measuring the σ for some pixels (PE1). Some multi-hit pixels may have a “good” σ for the single-hit hypothesis because DE1 and DE2 are being counterbalanced by PE1. (Example pixel shown on P27)

Using a CDF fit to measure μ and σ

If the electron swarm comes from a single-hit, then it should model a Gaussian distribution, so the accumulation of resets should fit well to a Cumulative Distribution Function (CDF):

$$F\left(x;\ A,\mu,\sigma\right) \ = \ \frac{A}{\sigma\sqrt{(2\pi)}}\int_{-\inf}^{x}\exp\left(\frac{\left(t-\mu\right)^2}{2\sigma^2}\right)dt$$



where μ is the mean and σ is the standard deviation of the corresponding Gaussian distribution. *A* is the number of accumulated resets. We can fit the pixel reset distributions to this function. However, this is a 3 parameter function, so we can only fit pixels with nResets >=3.

This approach gives us greater control over the accumulated charge, helping to mitigate DE1 by eliminating the need to assume an abrupt end to the electron swarm. It will also help us mitigate the PEs. There will be multi-hit pixels that fail to converge to a fit. In turn, we can also use a multi-CDF fit to model multi-hit pixels.

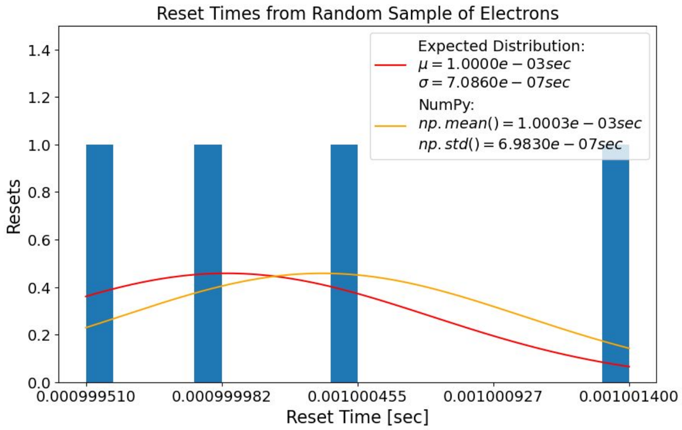
How do methods compare for example swarm?

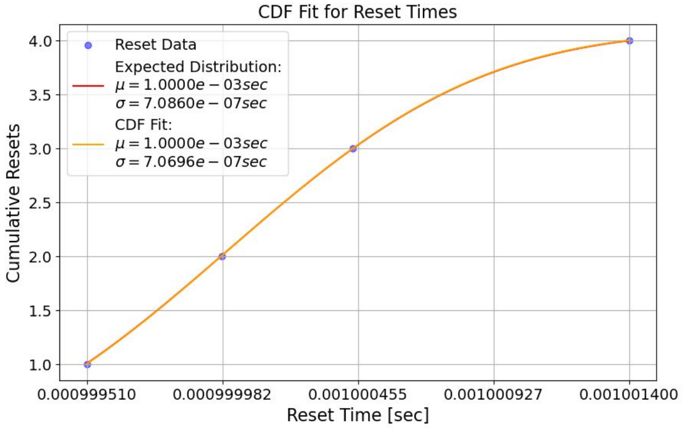
	Actual	NumPy	CDF
Amp (resets)	4.096	4 + 1	4.0983 ± 2.9186e-3
ΔAmp (resets)		-0.096 = -0.014 MeV	2.28e-3 = 0.000336 MeV
μ (sec)	1e-3	1.0003e-3 ± 3.5430e-7	1.0000e-3 ± 9.7886e-10
Δμ (sec)		3.3208e-7	9.5136e-10
σ (sec)	7.08596e-7	(6.9830 ± 0.1334)e-7	(7.0696 ± 0.0151)e-7
Δσ (sec)		-0.10293e-7	-0.0163e-7
Δσ(μ, t0 = 0) (sec)	0	-1.0614e-8	-1.8356e-9

For μ, both the NumPy and CDF method are within uncertainty of the actual μ, though the CDF method has a significantly better statistical precision and accuracy.

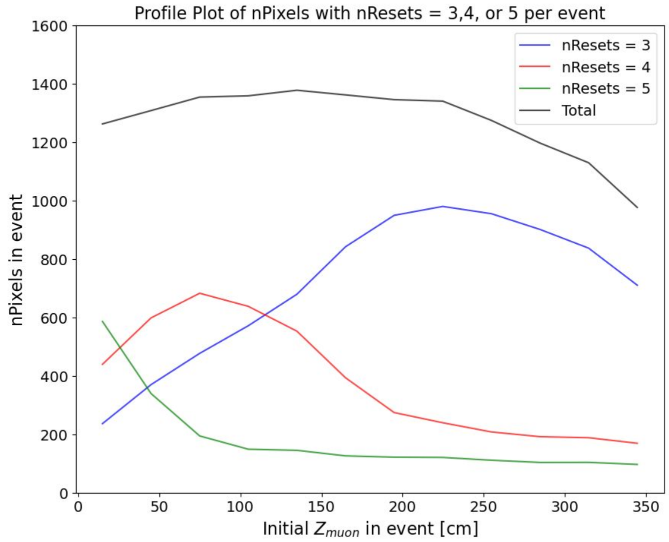
For σ, the NumPy method is within statistical uncertainty of the actual σ, but not the CDF method. However, the statistical accuracy and precision of the CDF method is better than for the NumPy method. It's possible that at this level of precision, PEs and DEs start to dominate so systematic corrections may need to be incorporated in the future.

From here, we will study how well the CDF fitting does with simulations in the DUNE APA.





Muon Events



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

<u>Initial Conditions</u>

- 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.

As we have seen previously, dE/dx of this muon sample follows a Landau curve with a MPV~2.5MeV/cm. For a (4x4)mm pixel this would roughly translate to an energy deposit of ~1MeV over the length of a pixel. With an ionization energy of 23.6eV/electron, this energy deposit would free around ~42,000 electrons and would result in ~6 resets. Considering transverse diffusion (PE2) and the actual XY path of the muon near the pixel, we expect this to be closer to 2-5 resets per pixel (more if low Z and less if high Z).

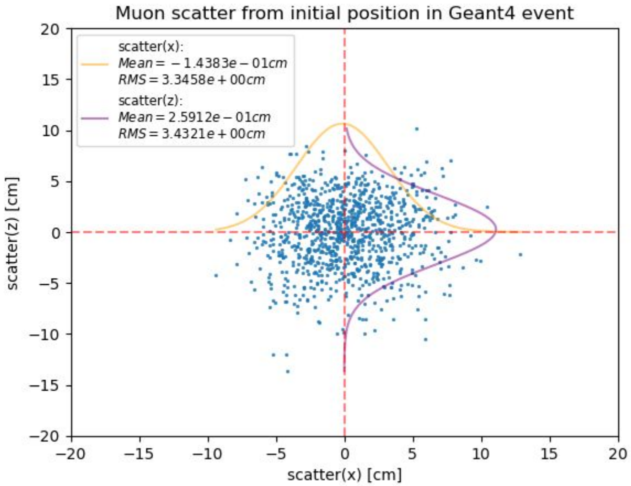
The plot on the right shows the number of pixels with 3, 4, and 5 resets in an event as a function of initial Z of the muon. The prevalence of 3, 4, and 5 reset pixels aligns with PE2, where diffusion causes energy to be spread across more pixels, leading to a decrease in the average nResets per pixel as a function of Z.

For the purpose of our studies, we will assume that 6+ resets correlates to a larger than average dE/dx which is more likely to be from multiple hits. For the following analysis, we are going to only use pixels with nResets = 3, 4 or 5 to keep the purity of single-hit pixels high.

Comparing μ and σ measurements to “truth”

Before we get to the comparisons of μ and σ with "truth”, we note that there are two subtleties that are now important.

1) The resolutions and purities of the 3, 4, and 5 reset samples are different due to different statistical significance, so any results should be taken with a grain of salt.
2) The resolution in Z from the CDF method is so good that the variation in Z position of the muon over the course of its trajectory (scatter) becomes a large effect.
    a) We see that the total scatter distance in X and Z is about 3cm (see plot on the right).



For simplicity, we will show the results where we subtract off the initial Z of the muon, Z_{muon}. However, this means any results we show will be the combination of the resolution as well as the Z variation along the path.

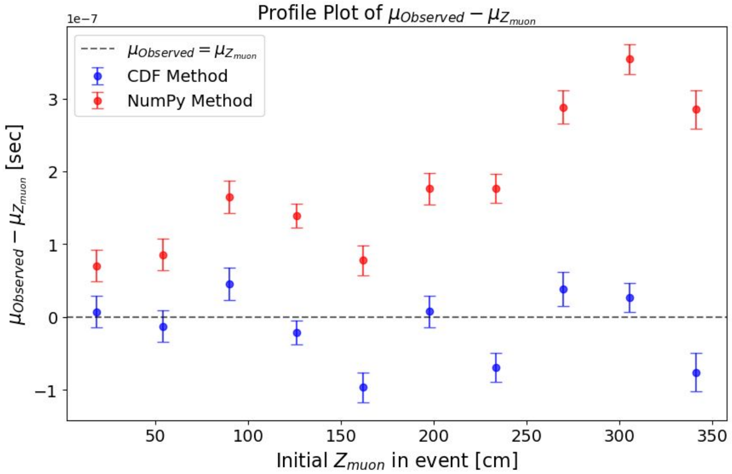
For this reason we will be careful about using the word “resolution”, as our results are really an overestimate of the resolution. We will refer to the combined effect as measurement variation.

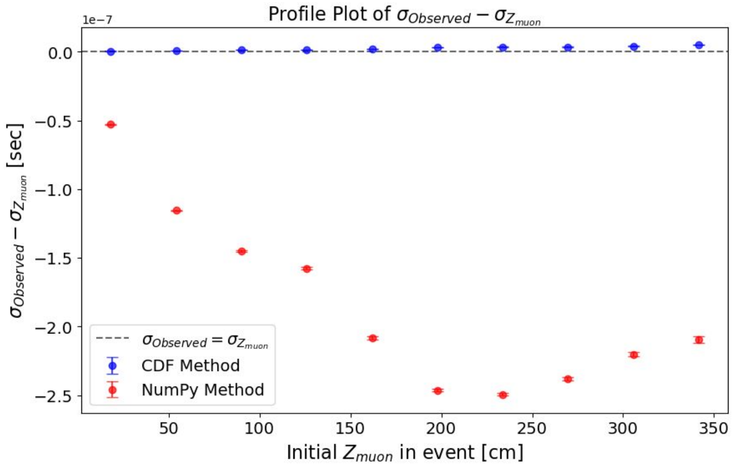
Future studies will address this more properly.

Comparing μ and σ measurement accuracy

Shown below are profile plots of (observed - truth) for μ and σ where we have fit the peak of the bin distribution to a Gaussian. The error bars represent the uncertainty in each bin. We are using the initial Z of the muon to determine μ_{Zmuon} and σ_{Zmuon} so we should take the results with a grain of salt, variations are due to both the resolution and the muon scattering. What matters here is that the CDF method does better than NumPy.

- For the CDF method, the mean of μ is randomly distributed around zero, and doesn't have a noticeable Z dependence. This is not the case for the NumPy method which is consistently above zero and has a clear Z dependence.
- The mean of σ is a big problem for the NumPy method. There seems to be a Z dependence on the mean for both methods but it is difficult to tell the extent of this for the CDF method at the scale used. Regardless, CDF is doing better at measuring σ on average.



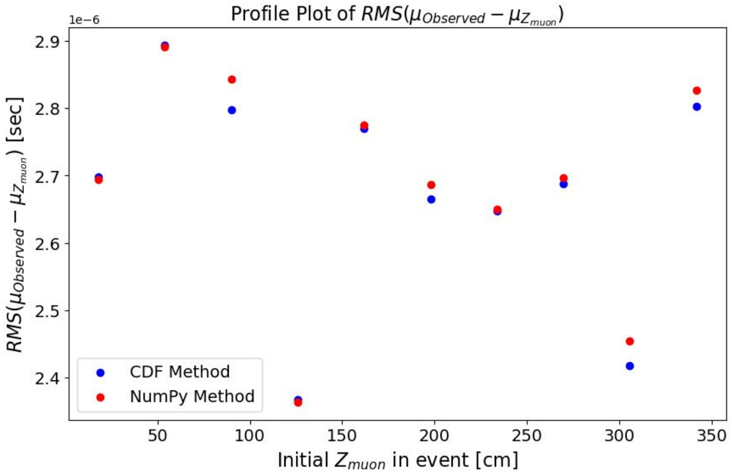


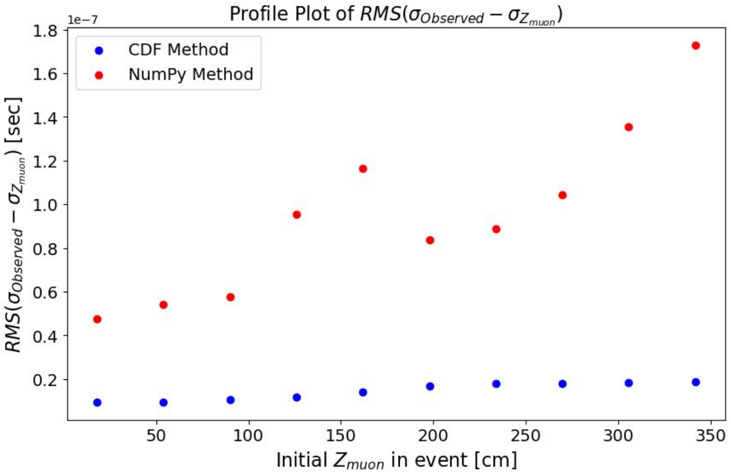
Comparing μ and σ variation

Here we show the RMS for each bin of Initial Z of the muon for μ and σ from the previous page.

- The variation of μ doesn't seem to differ significantly between the CDF and NumPy methods. In both cases, the variation doesn't appear to be Z dependent. This may indicate that the μ variation is dominated by the muon scatter.

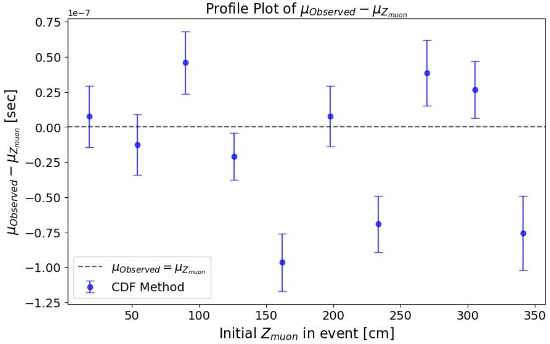
- The variation of σ is also problematic for the NumPy method. There seems to be a Z dependence on the variation for both NumPy and CDF but it is difficult to tell the extent of this for the CDF method at the scale used. The variation is clearly better in the CDF method which shows that most of the variation in the NumPy method is due to the methodology.



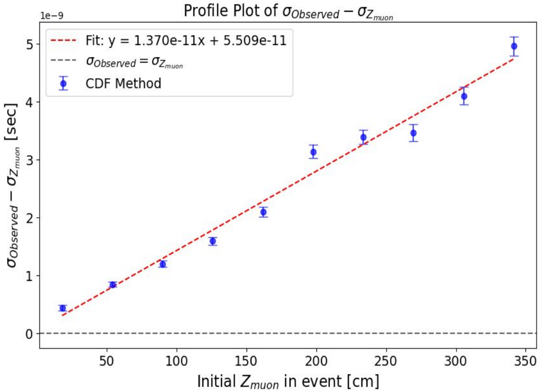


Zooming in on the CDF measurements and variation

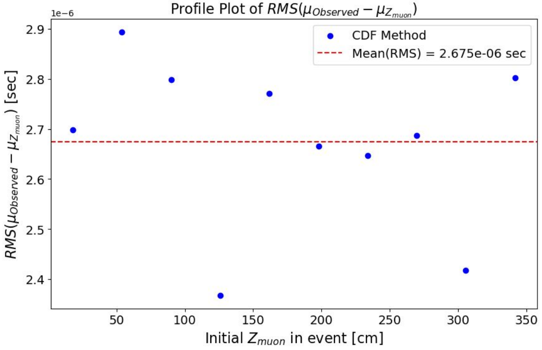
The Mean($\mu_{observed}$ - μ_{muon}) is randomly distributed around zero. Only 3/10 bin measurements are within uncertainty of zero, but there doesn't seem to be any dependence on Z.



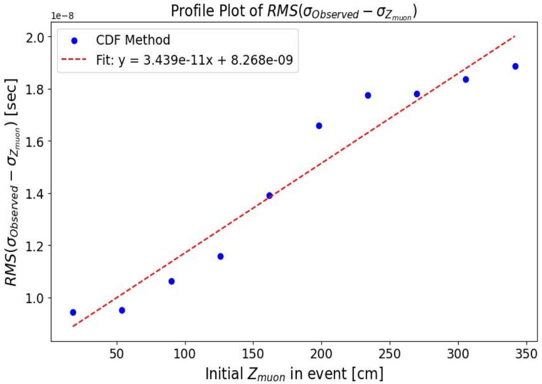
The Mean($\sigma_{observed}$ - σ_{muon}) is greater than zero for all bins. There seems to be a linear dependence on Z (with an asymptote at 5.509e-11sec) which we suspect is due to an increased occurrence of multi-hit pixels (PE1) and (PE2) as a function of Z which would result in an over measurement of σ. We will come back to this in more detail later.



The RMS($\mu_{observed}$ - μ_{muon}) has a mean value of 2.675e-6sec across the bins which corresponds to a Z measurement variation of ~0.44cm which can be compared to the 3cm RMS of true scattering variation in Z. We believe this is an overestimate of the actual μ resoultion.



The RMS($\sigma_{observed}$ - σ_{muon}) also seems to have a linear dependence on Z (with an asymptote at 8.268e-9sec).

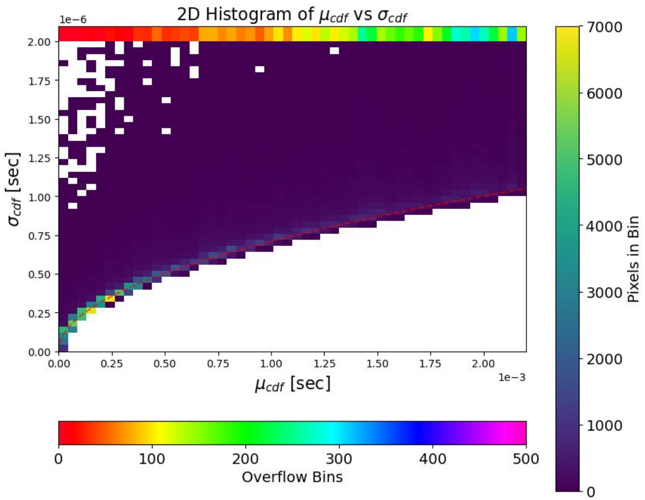


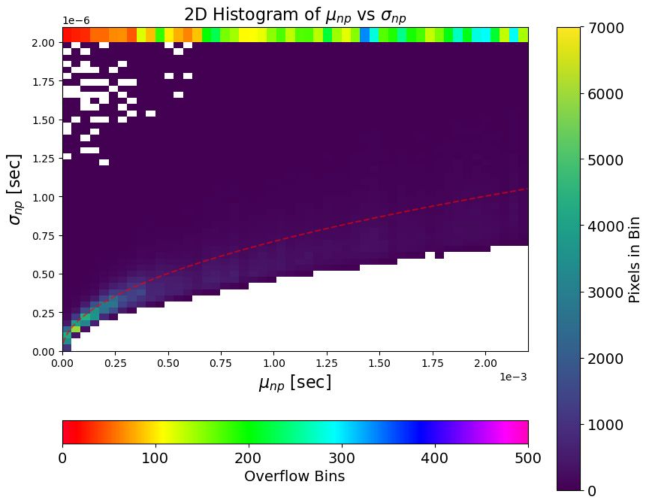
μ vs σ for pixels with 5 resets

Here we compare μ vs σ using CDF and NumPy methods for pixels with nResets = 5. The white background indicates a bin with zero pixels and the red dashed line indicates $\sigma_{Expected}(\mu, t_0 = 0)$. Note that in principle we can mismeasure both μ and σ for the same pixel. We see that:

- There is a large density of pixels at small μ (small Z) as expected from P11.
- The CDF method doesn't under-evaluate σ as often and has much less spread in σ compared to NumPy method.

This indicates that we have significantly reduced the effects of DE1 with the CDF method.



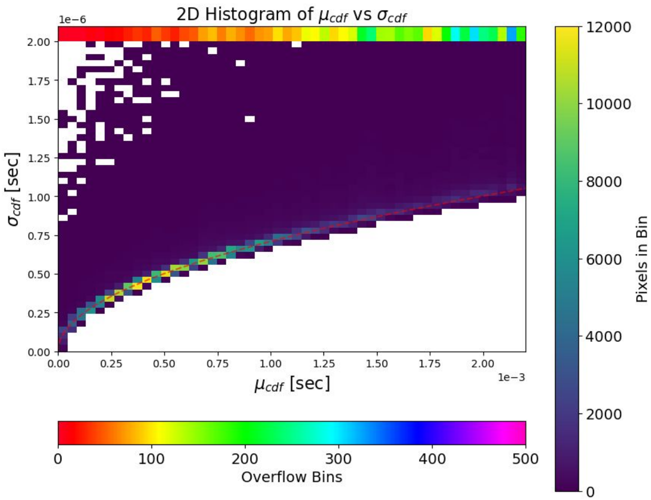


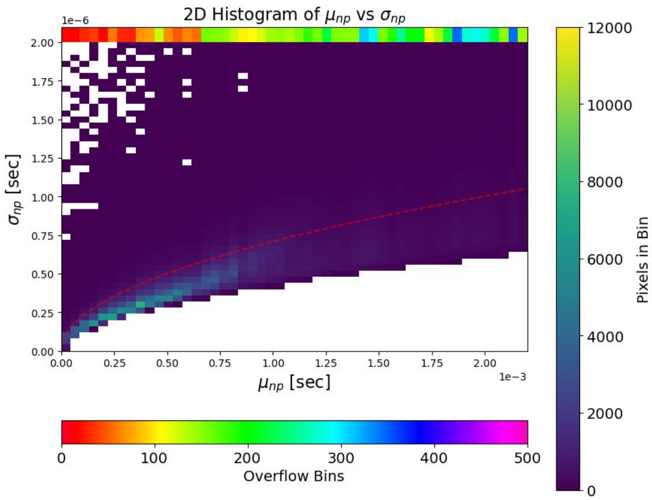
μ vs σ for pixels with 4 resets

We do the same for pixels with nResets = 4. From these plots we can see that

- There is a large density of pixels at midrange μ (midrange Z) as expected from P11.
- The spread of σ has increased from the 5 reset distributions, but much less so in the CDF method.

This is consistent with DE2 as well as PE1 and PE2. **Compared to 5 resets, 4 reset pixels will have a greater statistical uncertainty due to less resets and a larger average Z, thus an increased occurrence of multi-hit pixels due diffusion (PE2).**



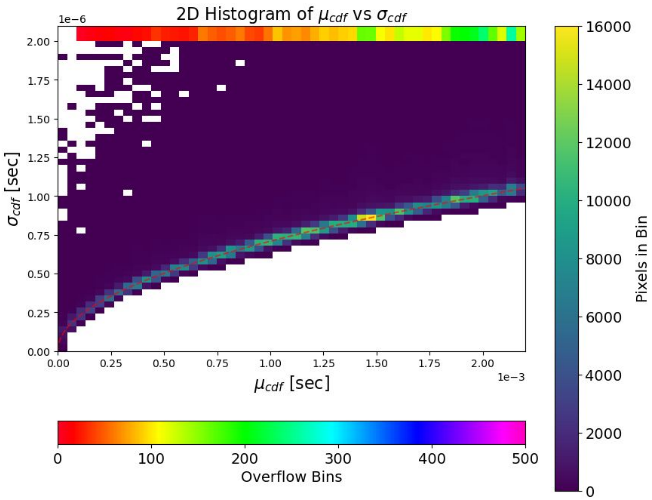


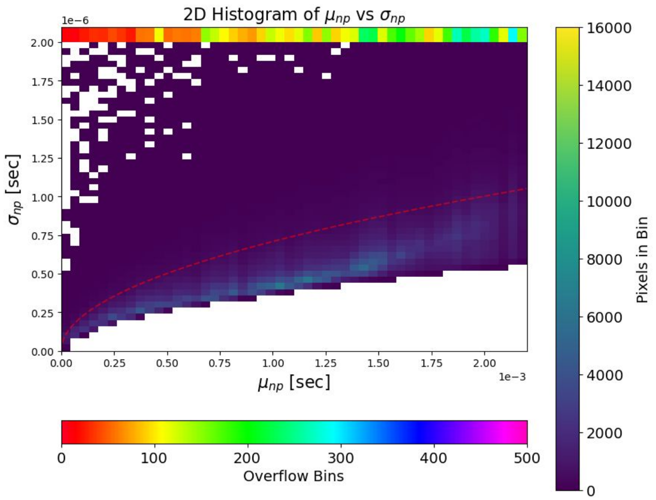
μ vs σ for pixels with 3 resets

We do the same for pixels with nResets = 3. From these plots we can see that

- There is a large density of pixels at large μ (large Z) as expected from P11.
- The spread of σ has increased more from the 4 reset distributions, but much less so in the CDF method.

This is consistent with DE2 as well as PE1 and PE2. **Compared to 4 resets, 3 reset pixels will have an even greater statistical uncertainty due to less resets and an even larger average Z, thus an increased occurrence of multi-hit pixels due diffusion (PE2).**





$\Delta\sigma(\mu, t_0 = 0)$ distributions

We now look at the correlation between μ and σ measurements by looking at $\Delta\sigma(\mu, t_0 = 0)$. With $t_0 = 0$ for simulations, we would expect that $\Delta\sigma(\mu, t_0 = 0) \approx 0$ for pixels where both μ and σ are well-measured.

We see that:

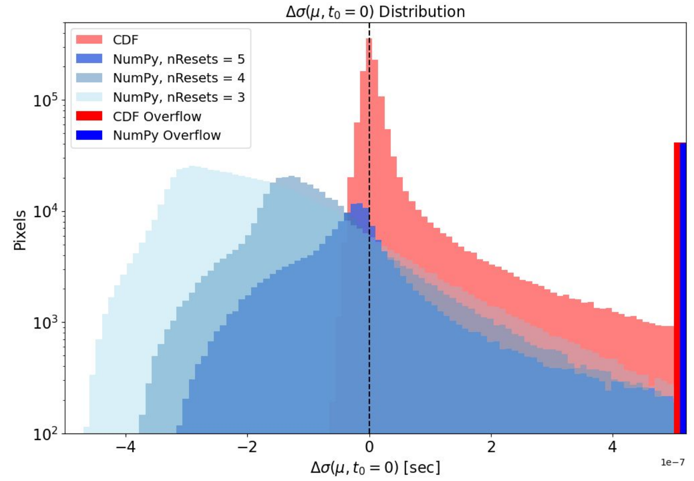
1.) As expected from the systematic biases in the μ and σ results from the NumPy method, the Δσ for NumPy never has a Gaussian component centered at zero.

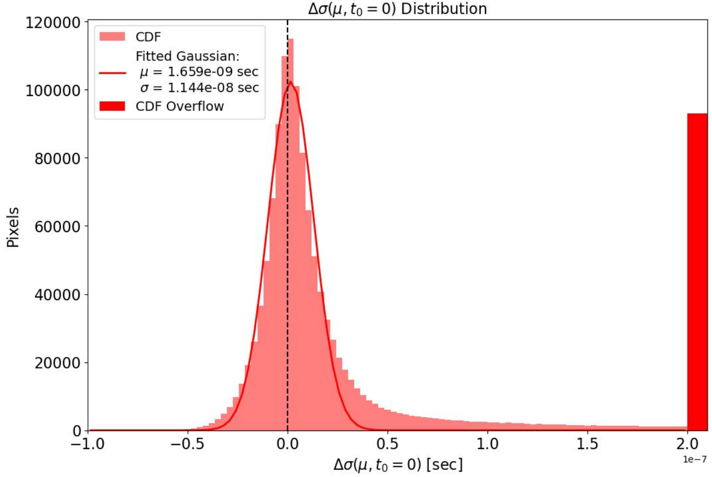
2.) The NumPy method does worse as a function of nResets (DE1 and DE2). This also occurs with the CDF method, however, it is much less prominent (see next page for CDF method as a function of nResets).

3.) Both the CDF and Numpy methods have a long tail towards positive Δσ likely due to multiple hits above the pixel (PE1 and PE2). Multi-hit pixels will still have a systematically large σ if they are fitted to a single CDF. This will need to be handled separately (next talk).

4.) There are fewer CDF entries than NumPy values because some pixels failed to fit to a CDF. This is typically due to multiple hits above the pixel (PE1 and PE2). Most of these unfit pixels have over-measured σ when we used NumPy (pages 26-27).

5.) The measured RMS of the CDF peak is ~1.15e-8 seconds. Recall that the clock speed is 1e-8 seconds.



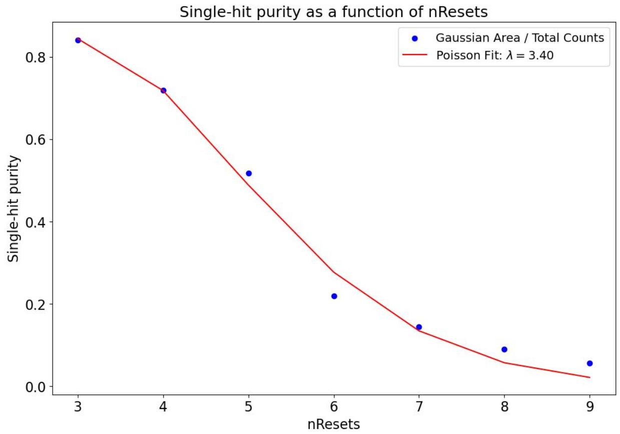


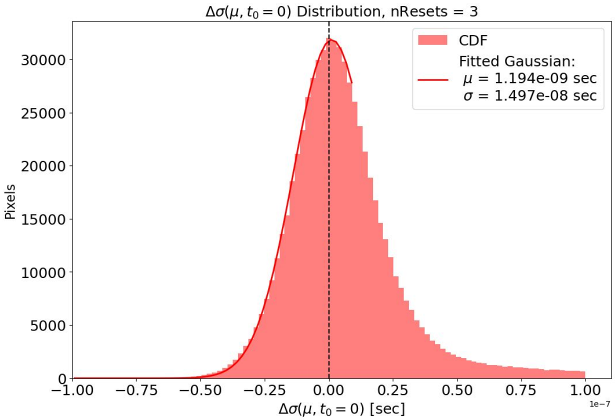
Single-hit purity

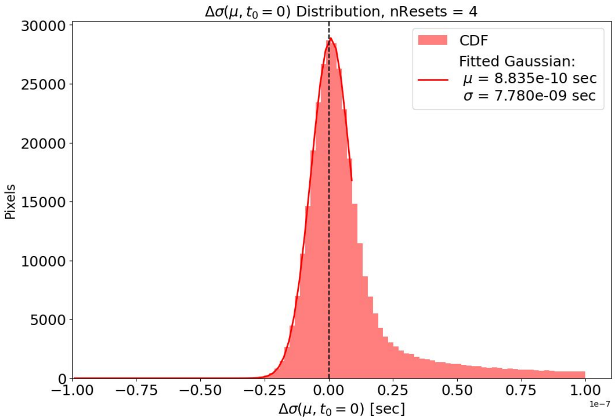
Finally, we examine the Δσ distributions within bins of nResets to assess the single-hit purity as a function of nResets. For each bin, we perform a Gaussian fit and calculate the normalized area under the curve from -∞ to +∞, the fit range was restricted to <1e-8 sec to minimize background interference. This provides an estimate of the single-hit pixels in each nResets bin. The single-hit purity is then determined by dividing the single-hit count by the total number of pixels in the distribution.

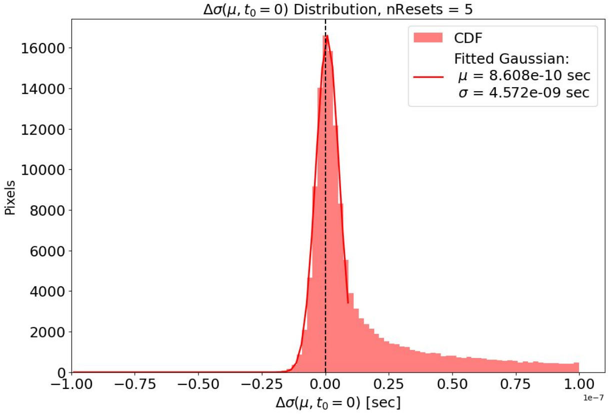
We see that the single-hit purity peaks at pixels with 3 resets. Taking a Poisson fit of the single-hit purity distribution, we see that the most probable value (that most associated with a single-hit) is around λ=3.40 resets. This is consistent with our prediction that all pixels with nResets > 5 have low single-hit purity (we estimate here that it's always less than 25%). The remaining plots (nResets > 5) can be found in the backup slides (P23).

We note that the resolution gets better as a function of nResets (peak narrows). This is expected, as more resets improves the statistics of the CDF fitting. On the other hand, we know there is a correlation between Z and nResets due to the detector effects which we saw from the variation increase as a function of Z. It's hard to disentangle the two effects.









Conclusion

- We have presented a study on ways to deal with multiple pathologies in our measurements, some of which are event-by-event specific, and some are measurement limitations due to electronics choices.

- Using the Cumulative Distribution Function (CDF) of a Gaussian allows us to mitigate the effects of reset clippings (DE1) which causes an under-evaluation of σ. The μ, σ, and amplitude of the Gaussian are free parameters, so we can model an electron swarm beyond the first and last reset. However due to low fitting statistics with 3-5 resets (DE2), there is still statistical uncertainty in the μ and σ measurement.

- We find an asymptotic σ variation of 8.268e-9 seconds which corresponds to a Z measurement variation of ~0.022cm, but rises linearly as a function of Z. The Z measurement variation for σ at the top of the detector is ~0.14cm.

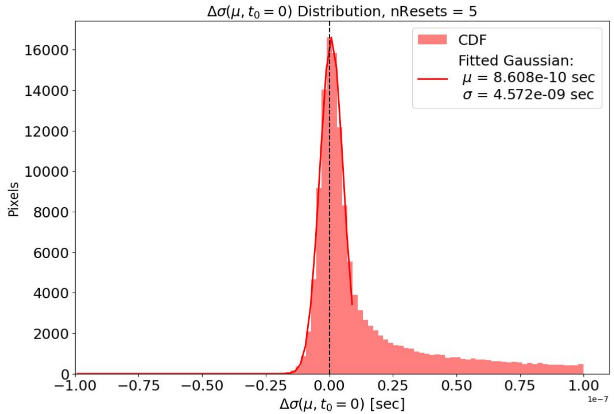
- We find a constant μ variation of 2.675e-6 seconds which corresponds to a Z measurement variation of ~0.44cm. This is likely dominated by the variation of the muon's Z over its path through the detector due to scattering. We've seen that muon scattering for this sample is centered at zero with an RMS of 3cm in the (X,Z) plane at the end of the trajectory.

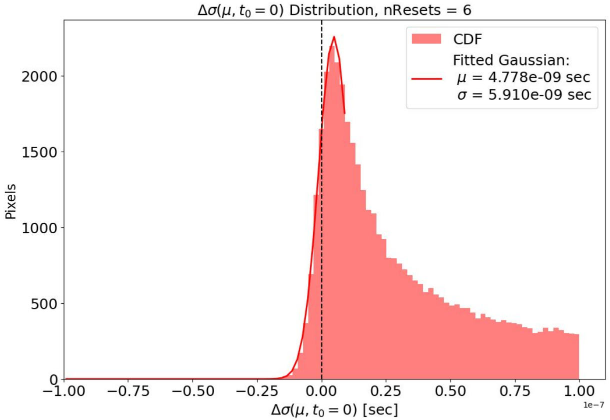
- We find that the $\Delta\sigma(\mu, t_0)$ is well described by a single Gaussian centered at 0 with uncertainty comparable to the clock speed, and a long tail which we suspect is due to multiple energy deposits above the pixel.
    - If we assume that the non-Gaussian tails are from multiple hits above the pixel (probably a good assumption which we will test soon), we see that the purity of single-hit pixels drops significantly as a function of nResets.

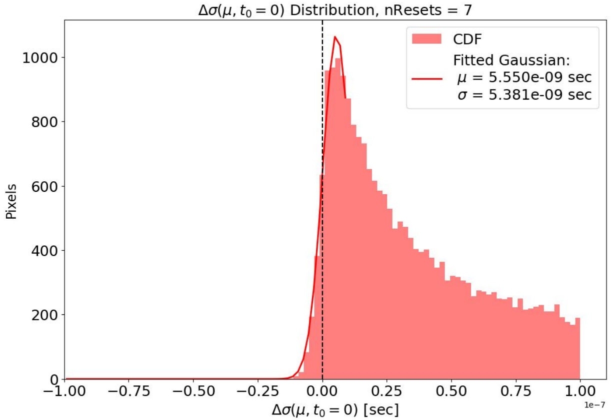
Now that we have shown CDF improves the precision and accuracy of μ and σ measurements (compared to NumPy), what comes next is a study of the event t_0, separating pixel measurements into single and multi-hit categories, and tracking resolutions when we change to the CDF pixel fitting method. We will see that the Z resolution from this method is smaller than the systematic variation in Z as a function of the travel distance, so we will need improved methods to show how well we are doing.

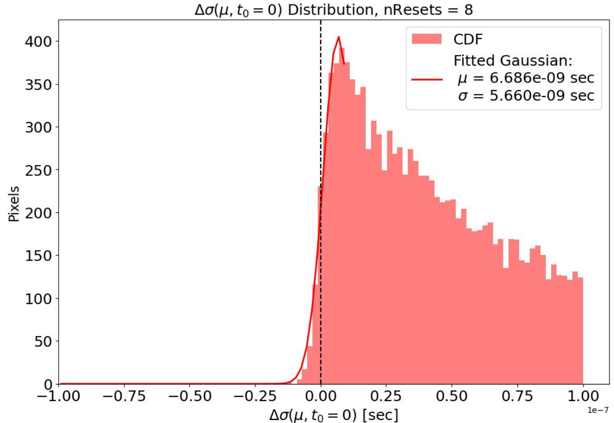
Extra Slides

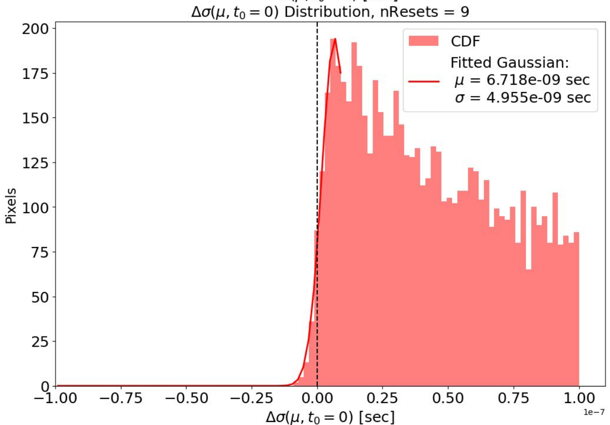
Single-hit purity bins







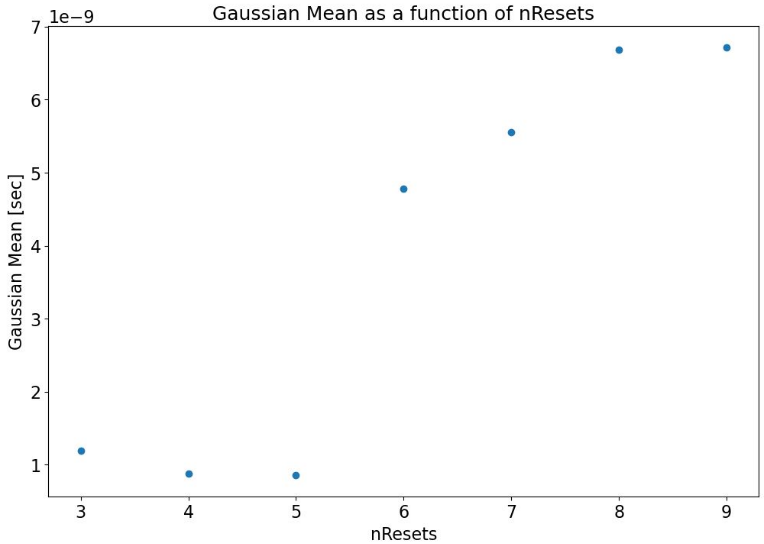


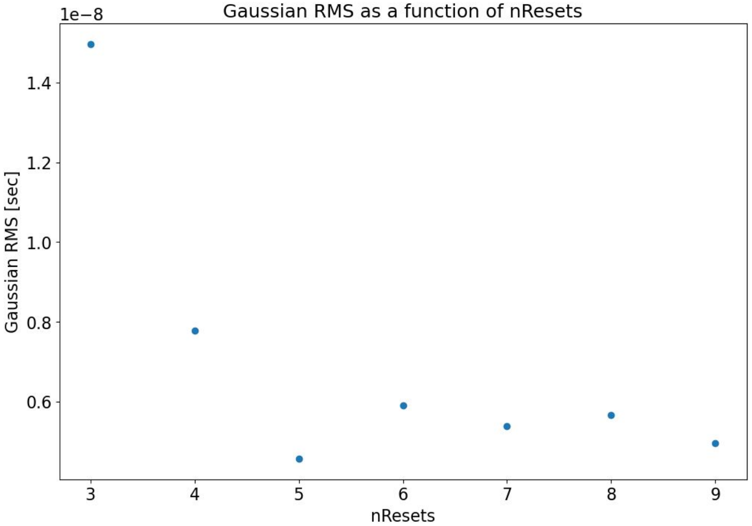


Mean and RMS of Δσ(μ, t0 = 0) in bins of nResets

Here, we show the mean and RMS of the Gaussian fit for each nResets bin of Δσ(μ, t0 = 0).

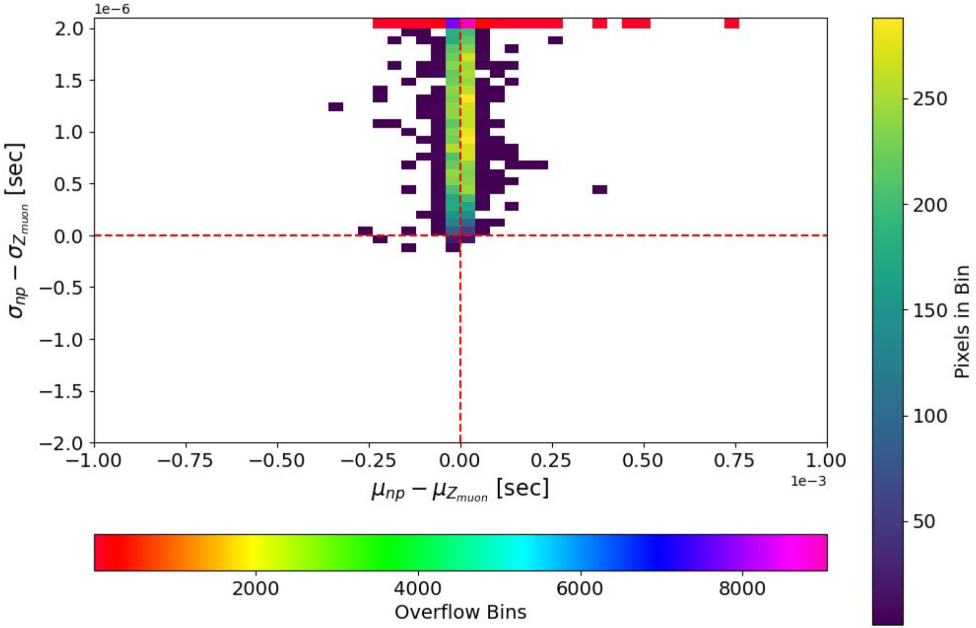
- The mean measurement shows a rapid deterioration when nResets >= 6.
- Additionally, the RMS for the nResets = 3 bin is significantly larger than the other bins, which is likely due to statistical fluctuations. With 3 resets, there are no free parameters in the CDF fit.





The μ and σ measurement for unfit pixels

We plot a 2d histogram of μ_{np} - μ_{Zmuon} vs σ_{np} - σ_{Zmuon} for the pixels where CDF did not find a fit. The μ_{np} is well distributed around the expected value of μ_{Zmuon} but σ_{np} is systematically larger than σ_{Zmuon}. This indicates that σ_{np} is being over measured for these pixels, which is likely a combination of the pixel being multi-hit or the hit had a large ΔZ above the pixel.

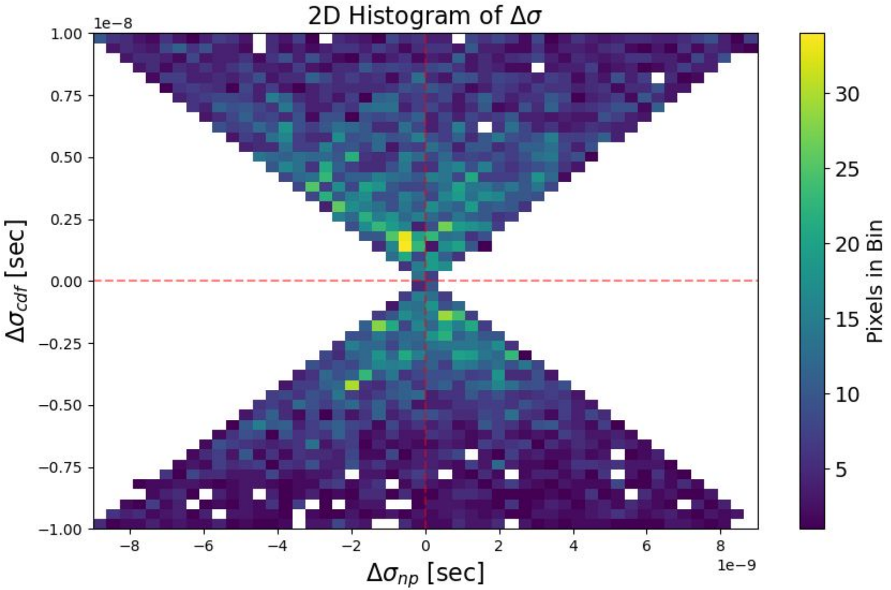


A look at CDF outliers

We look at CDF outliers for pixels that give us good np.std results. To do this we look at pixels where

- **$|\Delta\sigma(\mu, t0=0)_{CDF}| > 1.1*|\Delta\sigma(\mu, t0=0)_{np}|$**
- **$|\Delta\sigma(\mu, t0=0)_{np}| < 1e\text{-}8$ sec**

Only 1.8% of pixels that fit to a CDF fall into this region. But these pixels are where the NumPy method gives us better results and would even provide a reasonable t_0 value. We investigate one of these pixels in more detail on the next page.



Example of CDF outlier when np.std is around $\sigma_{Expected}$

Event Number: 1 Pixel ID: 3455

μ_{np}: 1.0299e-03 sec, σ_{np}: 8.3457e-07 sec

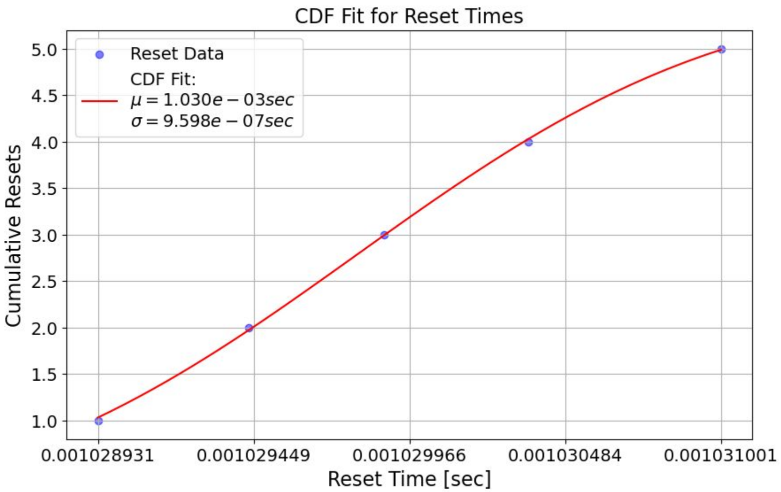
$\Delta\sigma_{np}$(μ, t0= 0): -7.4322e-10 sec

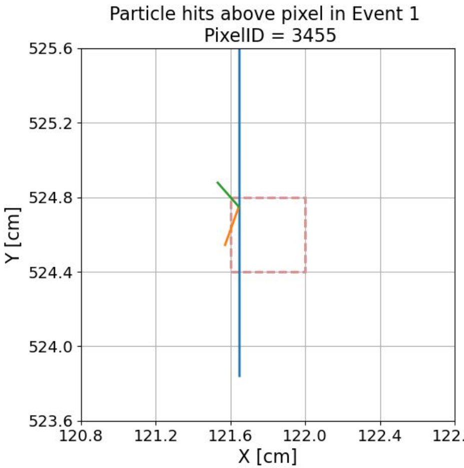
μ_{cdf}: 1.0298e-03 sec, σ_{cdf}: 9.5975e-07 sec

$\Delta\sigma_{cdf}$(μ, t0= 0): 2.4047e-07 sec

This pixel had 3 hits occur above it,
4.2575 MeV deposited over blue line with Avg(Z) = 169.62 cm
0.4545 MeV deposited over green track with Avg(Z) = 169.83 cm
0.3477 MeV deposited over orange track with Avg(Z) = 169.78cm

The energy threshold is 0.1475 MeV per reset which means the distribution of reset times should not model a single Gaussian (all three hits would have significant contribution to the electron swarm). In general, the reset distribution from a multi-hit pixel will have a larger than expected σ due to the different initial Z positions of the electrons (PE1 and PE2). These effects are counteracting on DE1 in such a way that they almost cancel each other out for the NumPy method.



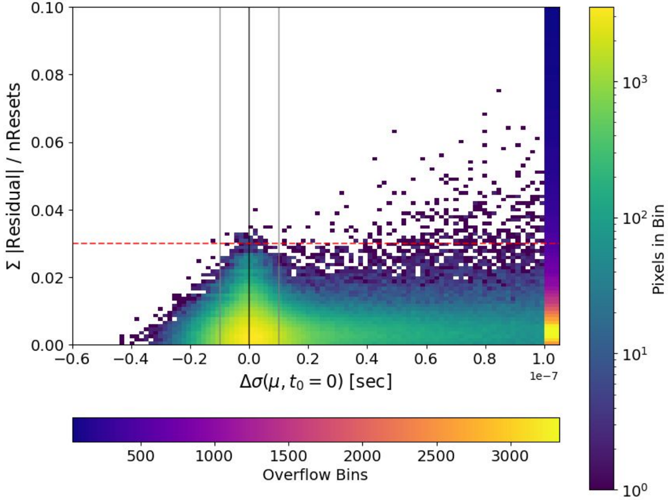


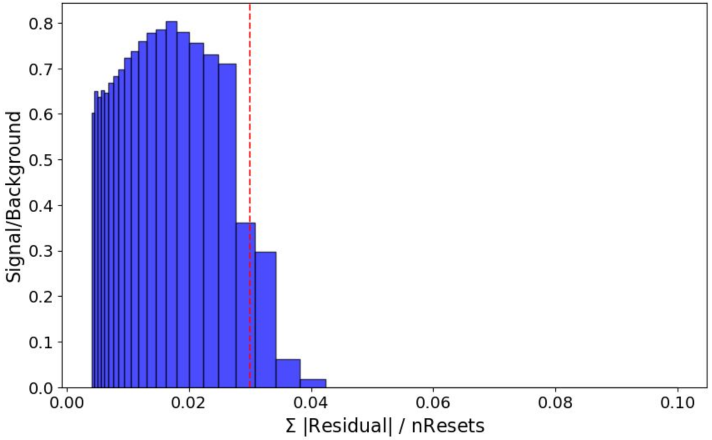
Using Σ|Residual|/nResets to mitigate background

Now we look at Σ|Residual|/nResets as a function of Δσ(μ, t0=0). The left plot shows this for all pixels that fit to the single CDF. The black line indicates where $\Delta\sigma(\mu, t_0=0) = 0$ and the gray lines indicate a signal region of ± 1e-8 sec.

To determine a reasonable place to make a cut, we look at the Signal/Background fraction in bins of Σ|Residual|/nResets. This is equivalent to taking horizontal slices of the left plot and calculating the ratio of pixels within the gray lines to those outside the gray lines for each slice.

The right plot shows a sharp decline in the Signal/Background fraction near Σ|Residual|/nResets=0.03. We set a cut here to reduce the effects that multi-hit pixels will have on t_0 evaluation.





Clock speed effects

Recall that the clock speed is 1e-8 sec. Let's look at a pixel with a hit at Z<1cm.

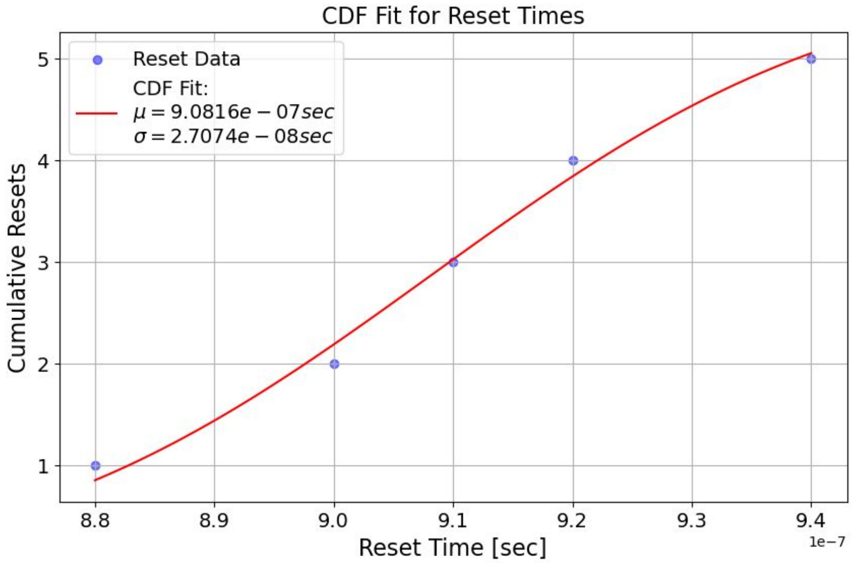
Reset times occur at

8.800000000000e-07
9.000000000000e-07
9.100000000000e-07
9.200000000000e-07
9.400000000000e-07

which roughly translates to a Z of 0.15cm. We can see that the clock speed is only allowing us 1 degree of precision for the reset times in this pixel. This will have a noticeable effect on the measured μ and even more so the σ. We can make a fit with the CDF function, but the residuals are not good,

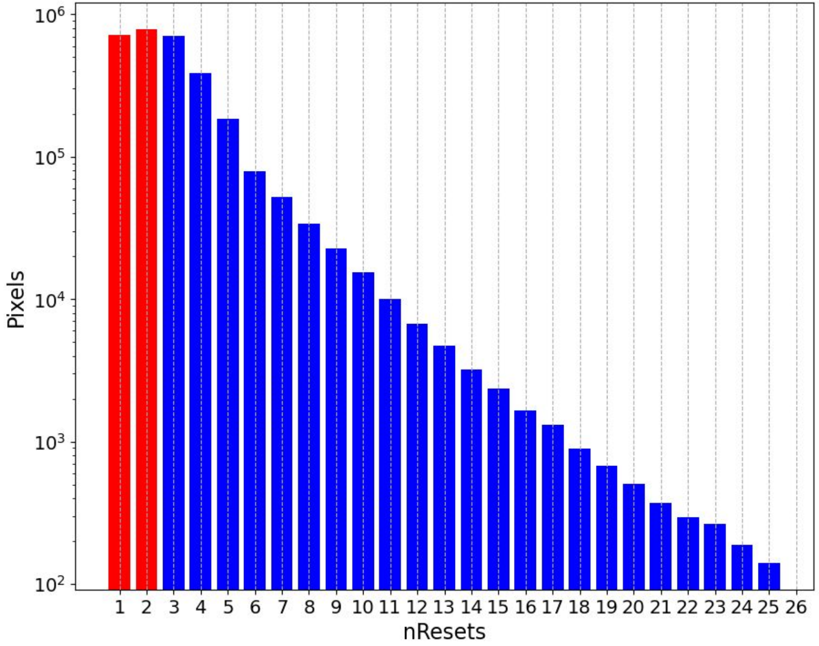
Σ|Residual|/nResets = 0.113

The clockspeed has non-negligible effects on subcentimeter resolution.



QPix electron threshold

The CDF method requires pixels to have at least 3 resets to measure μ and σ. When we have detector noise and electron recombination turned off, we see that nearly 50% of the active pixels had 1 or 2 resets. We could significantly increase the amount of statistics in an event if we reduce the reset threshold, though this comes at the cost of increasing the effects of background interactions.



ΔZ above a pixel

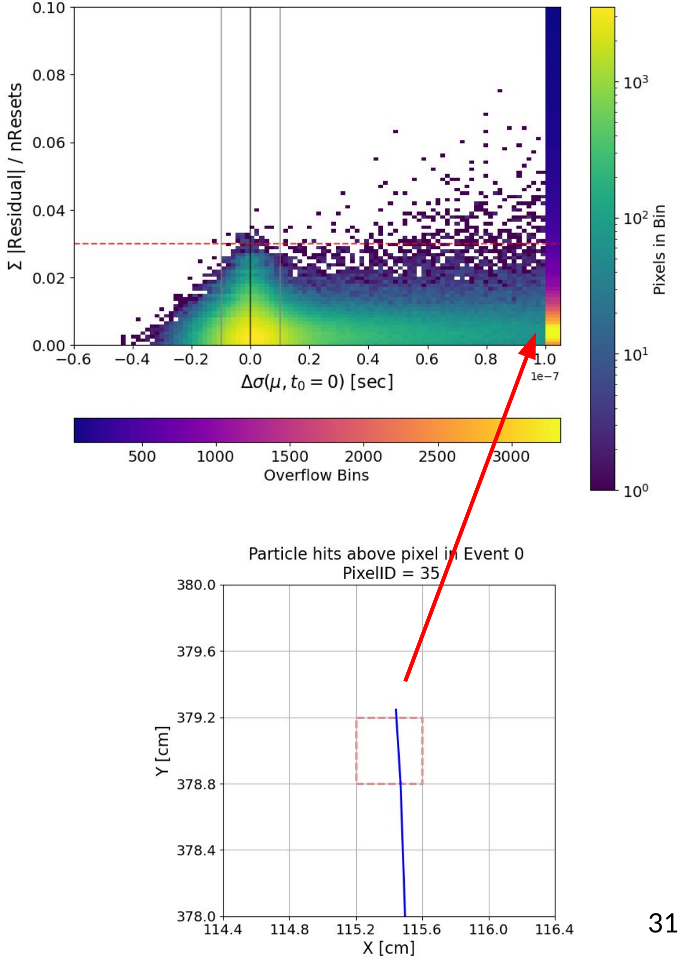
As previously mentioned, well-measured pixels [$\Delta\sigma(\mu, t_0=0) \approx 0$] will come from a single hit in Z.

By "single hit in Z," we mean there was only one particle track above the pixel. However, this alone does not guarantee a well-measured pixel. For that, the particle's Z position must remain relatively consistent along its path over the pixel.

In Event 0, Pixel 35 had a single particle track above it, a high-energy electron. While this might seem like an ideal candidate for $\Delta\sigma(\mu, t_0=0) \approx 0$, the electron's ΔZ above the pixel was around 0.14 cm (corresponding to ~19° angle).

The reason [$\Delta\sigma(\mu, t_0=0) = 0$] does not hold for all single-hit pixels is that particle tracks often vary in Z. Such variations cause the electron swarm to broaden. This means that μ and σ are track angle and pixel size dependent.

- The best results μ and σ will occur when the muon has initial momentum parallel to the detector plane.
- We could reduce the impact of bad track angles if we reduce the size of pixels.
- Assuming the muon does enter the detector parallel to the detector plane, it will have smaller ΔZs than secondary particles. If we use a tracking algorithm to identify pixels associated with the muon track, we can further reduce the $\Delta\sigma(\mu, t_0=0)$ background.



Muon Tracks vs Secondary Tracks

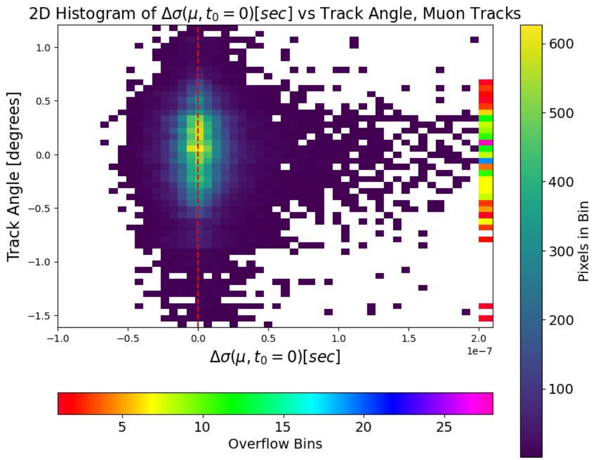
Here we look at pixels with 3-5 resets that had only 1 particle track above it. We measure the angle of the particle track relative to the XY plane (z momentum).

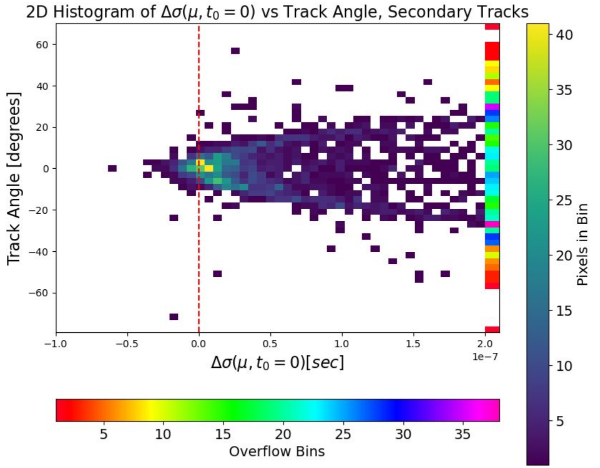
This is a resource intensive mapping between tracks and pixels, so we only ran this for the first 50 events.

The top plot shows the Δσ(μ, t_0=0) measurement vs track angle for muon tracks. We can see that the angle for the muon tracks are between ±2° and there is a large concentration of pixels near Δσ(μ, t_0=0) = 0.

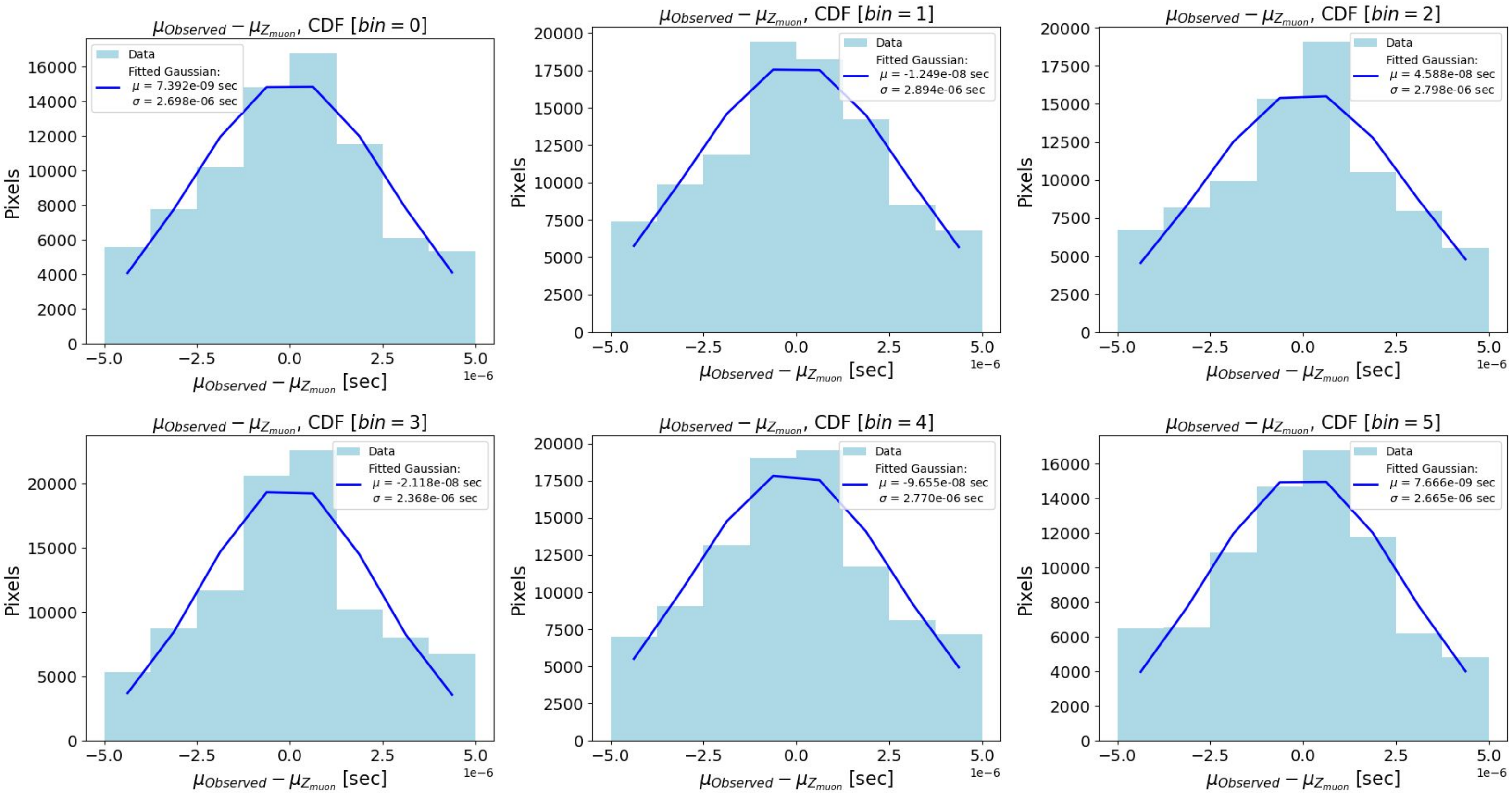
The bottom plot shows the Δσ(μ, t_0=0) measurement vs track angle for secondary tracks. We can see that the angle can deviate significantly from 0° (±60°) and there is a long Δσ (μ, t_0=0) tail.

We can remove background Δσ(μ, t_0=0) measurements (and improve t_0 calculation) if we can match pixels to the muon track before. We have shown that this can be done in a previous talk.





How do the μ reflect truth (CDF Bins)?



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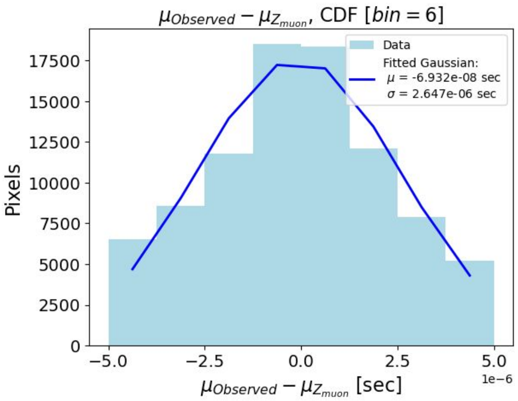
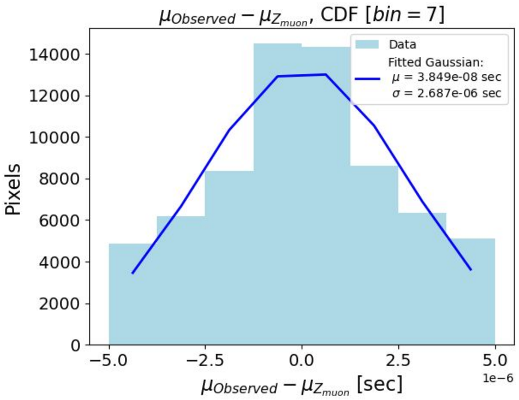
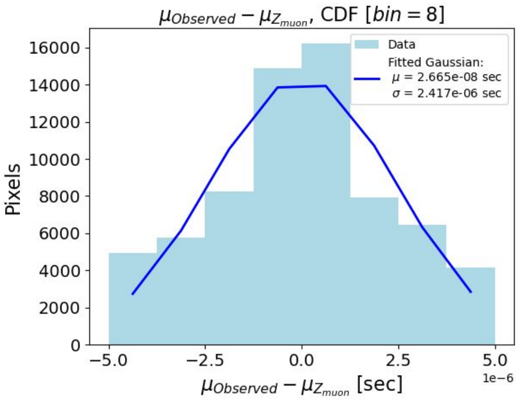
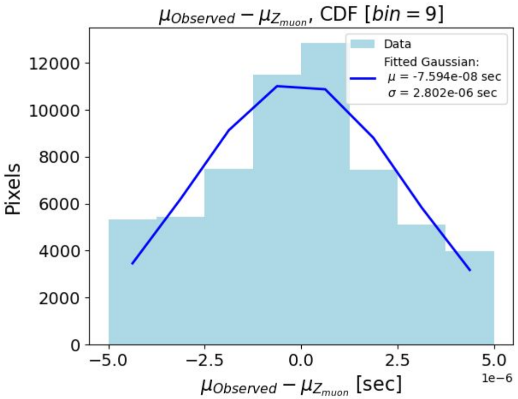
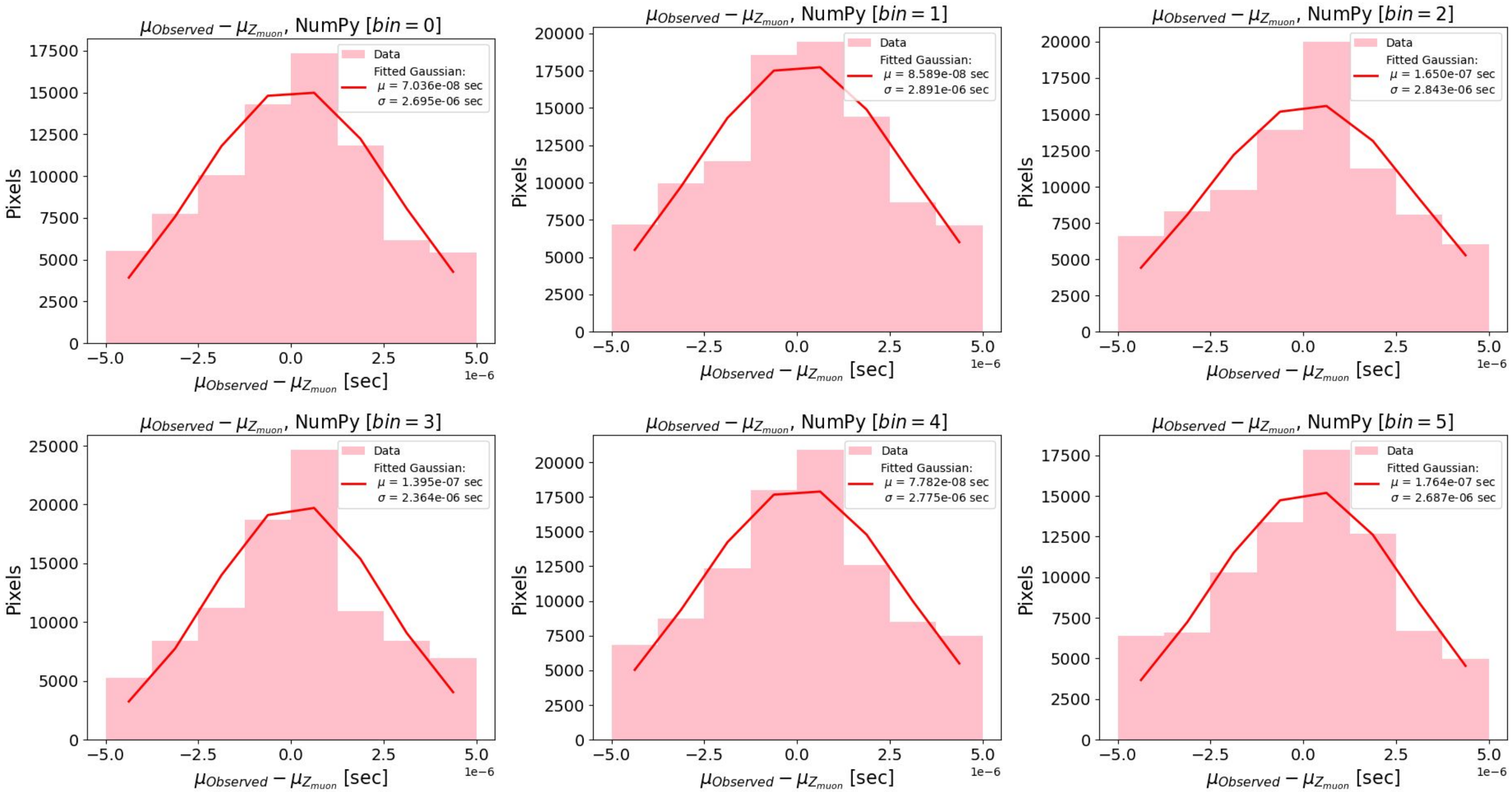




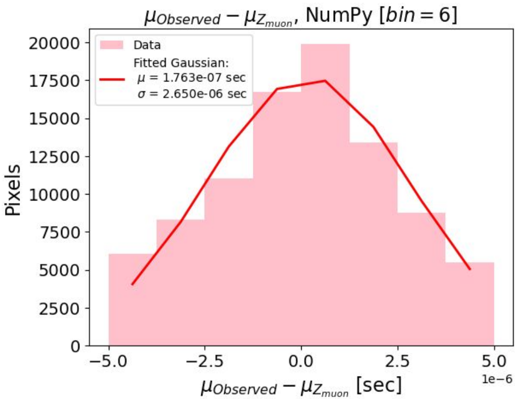


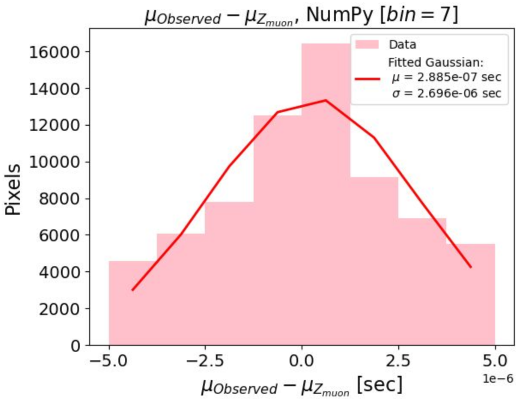


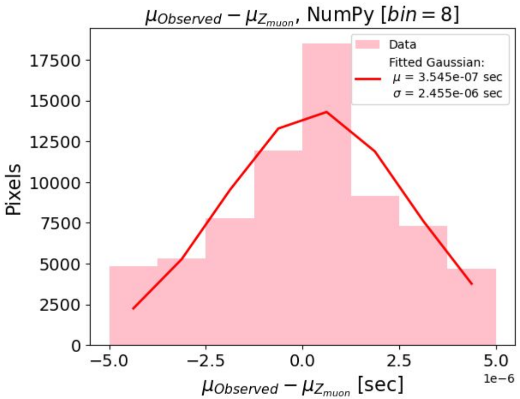
How do the μ reflect truth (NumPy Bins)?

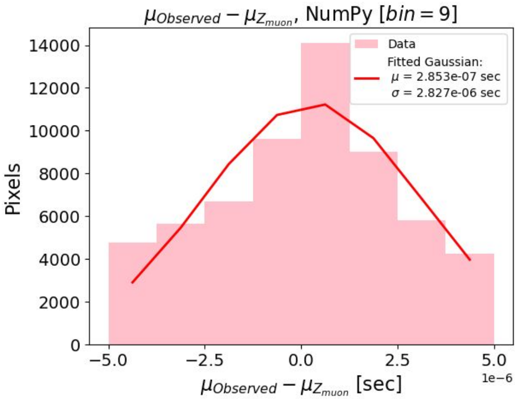


How do the μ reflect truth (NumPy Bins)?

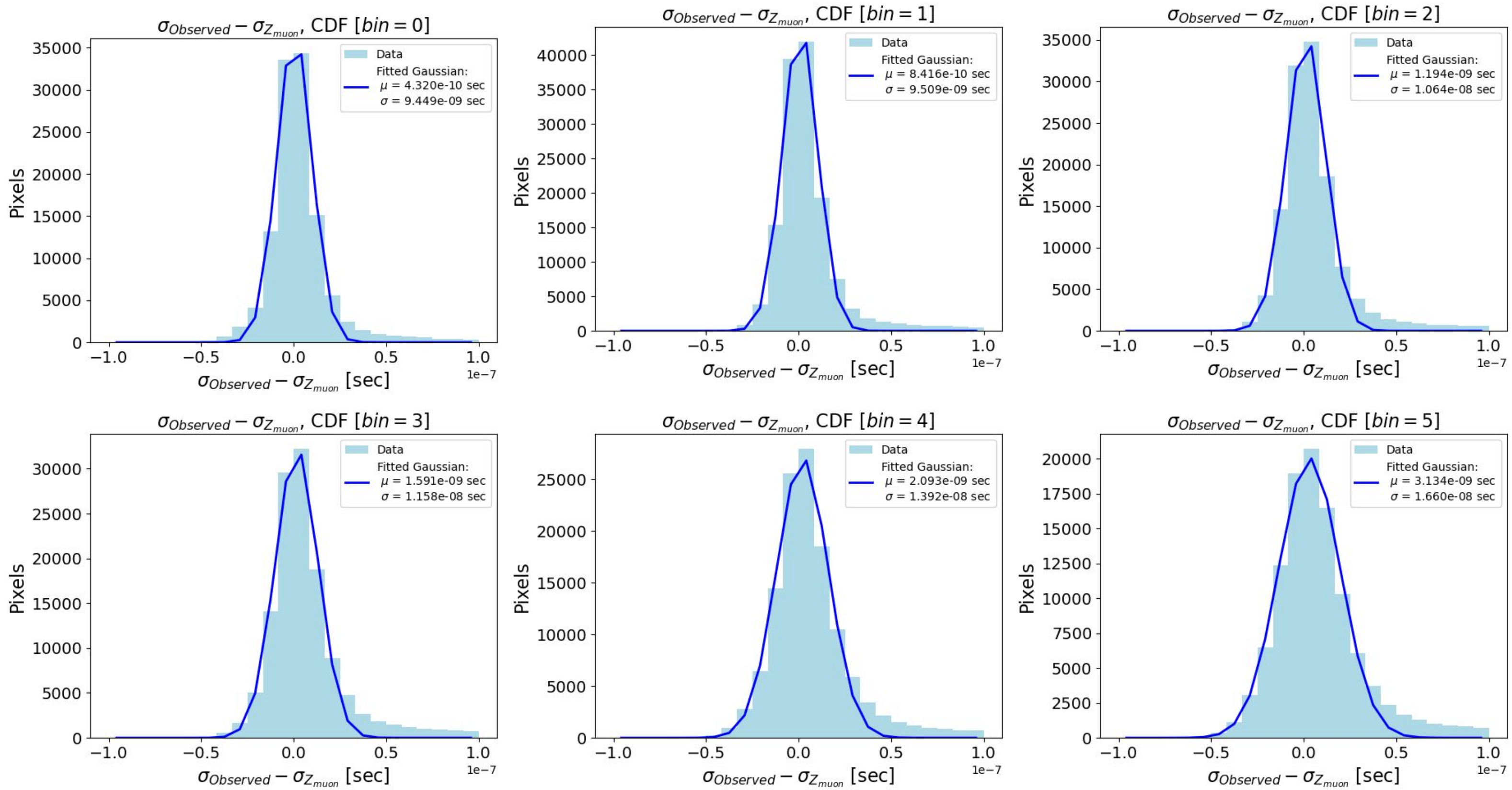




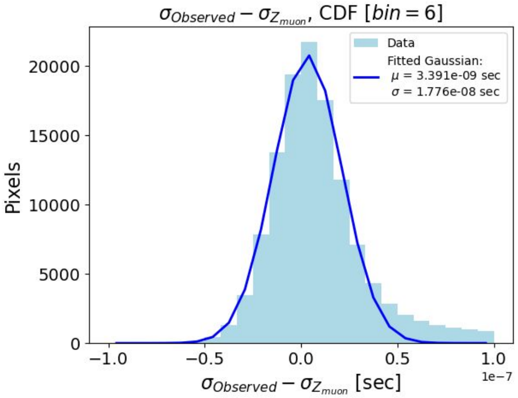


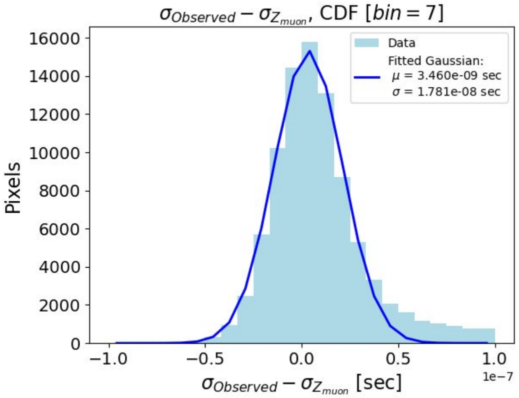


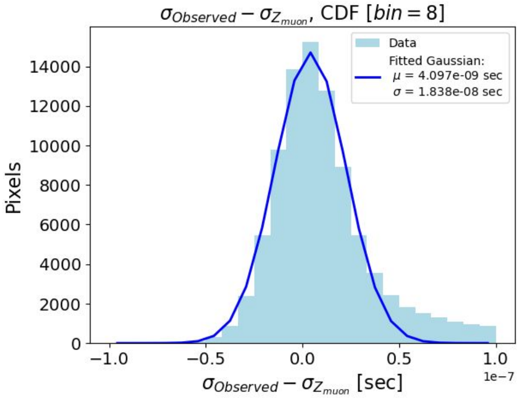
How do the σ reflect truth (CDF Bins)?

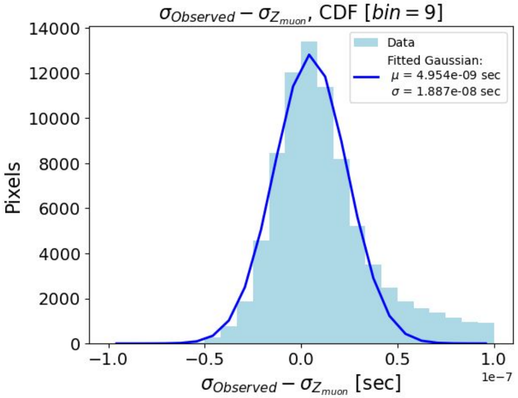


How do the σ reflect truth (CDF Bins)?

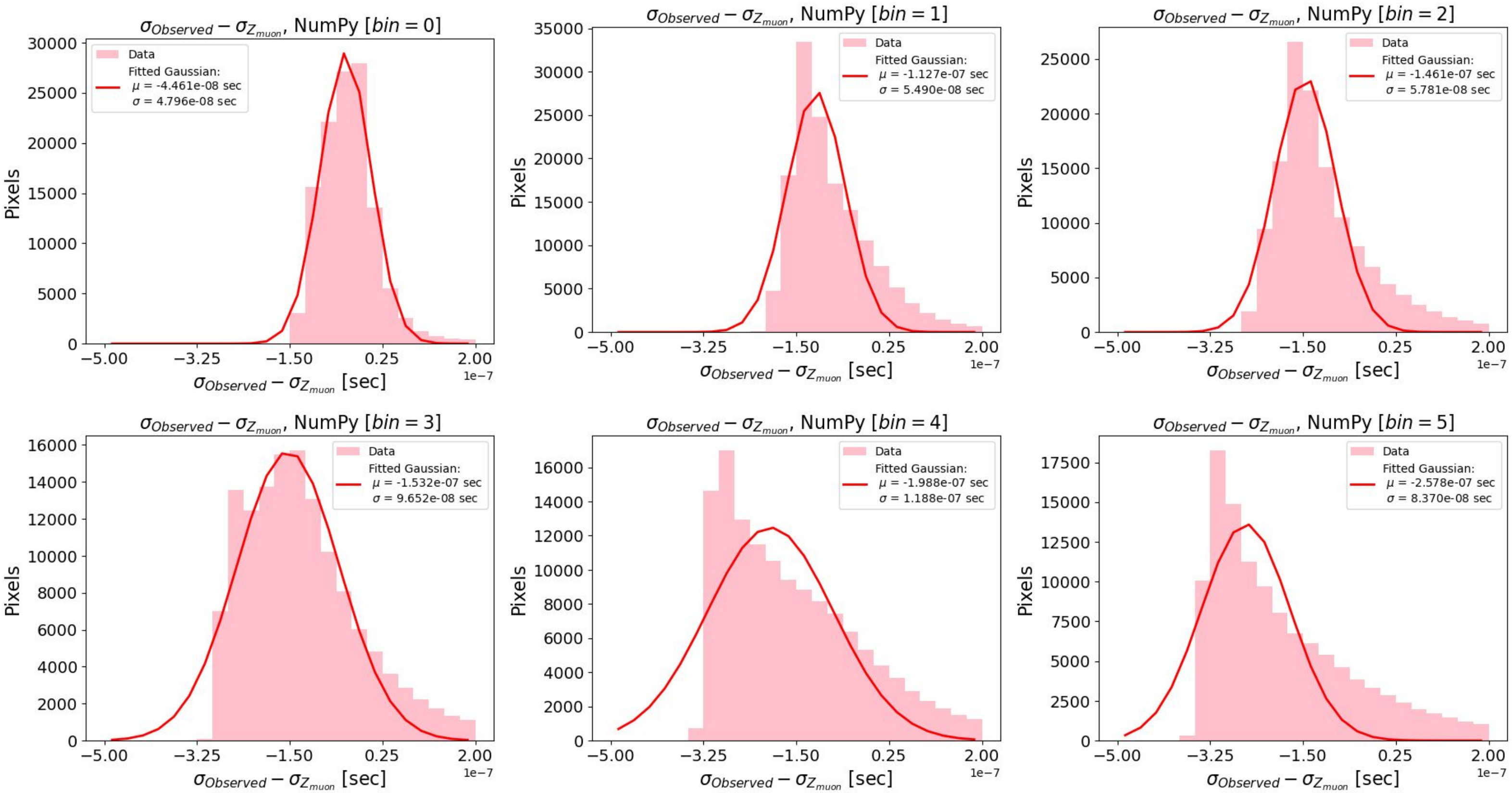








How do the σ reflect truth (NumPy Bins)?



How do the σ reflect truth (NumPy Bins)?