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Lab 2: A Rigorous Empirical Estimate of the Mean Muon Lifetime (MUO)

Shrihan Agarwal[1]

[1] University of California, Berkeley, Department of Astronomy, Berkeley, CA 94720

Abstract

This experiment aims to determine the mean muon lifetime by testing the operation of a muon detector, calibrating its equipment, and performing analysis. Our dataset consists of a 93-hour aggregated muon detection run, and multiple calibration runs to rigorously test the dataset and equipment for possible irregularities. The mean muon lifetime following rigorous estimation was found to be $2.0105 \pm 0.0658\,\mu s$, which did not agree with the true value but rather with the adjusted value accounting for muonic decay in the atom. The Fermi Coupling Constant was also estimated as $G_F = 1.219 \times 10^{-5} \pm 0.019 \times 10^{-5}\,GeV^{-2}$, suffering from the same systematic deviations as the muon lifetime estimate. Further work can be done to reduce uncertainties and systematics by obtaining a larger dataset, analyzing individual decay rates, and testing equipment thoroughly.

1. INTRODUCTION

The muon, also known as the mu lepton, is a subatomic particle that belongs to the lepton family, along with electrons and neutrinos. Leptons are a type of fermion, and cannot be subdivided further into known components. First discovered in 1936 by Carl D. Anderson and Seth Neddermeyer during their cosmic ray studies, the muon became part of the Standard Model of particle physics today. The muon is similar to the electron in many ways, but it is approximately 200 times more massive, and our best estimates today give the muon a lifespan of just approximately 2.196 microseconds.

This is one of the best measured physical constants. Muon particles travel at extremely high speeds subject to relativistic time dilation until they reach the surface of the earth. Muons are unlikely to decay in typical muon detector and only a fraction of the lower energy muons are actually stopped in the scintillator used to detect them. On decay, the scintillator reacts to produce a bust of photons. Therefore, we see two bursts of photons: one when the muon enters the detector and the second when it decays. The time difference between these two photon bursts gives us information about the life-time of a muon.

The muon has been used in a wide range of applications beyond its use in particle physics. One such application is in medical imaging, where muon tomography is being developed as a technique for imaging dense objects such as the human body, with greater resolution and lower radiation dose than traditional X-ray imaging. Muons are capable of going much deeper than X-rays as well, allowing scans of thicker objects than a typical CT scan. In radiography, muons are used to probe the interior of materials and their structure, helping provide information about their composition and integrity. In fact, muon radiography has even been used in art conservation to detect hidden structures and defects in works of art, without damaging the artwork itself.

In this lab, we seek to accomplish explore the muon lifetime. A precise measurement lab, we describe our process in detail, including steps taken to ensure rigor, and methods of calibration of equipment to remove systematic and random uncertainty.

Corresponding author: Shrihan Agarwal
shrihan@berkeley.edu

We briefly describe Background Research Theory on Muons, lifetimes, and typical detector setups in Section 2. We discuss the experimental design for our particular setup in Section 3. The raw data collected and analysis done is described in Section 4. Lastly, the conclusions are presented in Section 6.

2. BACKGROUND RESEARCH AND THEORY

2.1. *Muons*

Muons are unstable leptons which decay in a matter of microseconds, specifically, 2.1969811(22) μs (Particle Data Group, 2016 [(2)]). The formation path for the majority of muons we detect is from the collision of cosmic rays with the upper layers of the Earth's atmosphere. These cosmic rays are usually in the form of protons, and predicted to come from supernovae, pulsars, black holes, AGNs, and more sources. On colliding with molecules in the Earth's atmosphere, they produce a shower of secondary particles, including muons. Once created in the upper atmosphere, they then travel down to the surface of the Earth at large fractions of the speed of light, where they can be detected using our instrument. The number of muons that reach the Earth's surface depends on the energy and intensity of the cosmic rays, as well as the altitude and location of the detector.

Moving rapidly, time dilation allows these muons to reach the Earth's surface notwithstanding their microsecond-length lifetimes. The muons decay into a electron or positron, and a neutrino-antineutrino pair by the following process:

$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

Both these muons have the same lifetime in vacuum. However, if brought close to some nucleus a negative muon may join the atom and decay following a different process:

$$\mu^- + p \to \bar{\nu}_\mu + n$$

This causes a negative bias in our measurements of muon lifetime, since the negative muons have a higher effective decay rate due to the combined effect of these two types of decays. We correct for this effect in a later section.

The muons decay according to a typical decay curve $N = N_0 e^{-\lambda t}$, where λ is the decay constant of the muon. The equation can also be rewritten in terms of the mean muon lifetime τ, as $N = N_0 e^{-\frac{t}{\tau}}$. Here, N is the number of particles that have not yet decayed. We seek to recreate this curve, and fitting it, determine the mean muon lifetime.

2.2. *Muon Lifetime Measurement Principle*

The muon lifetime measurement process is accomplished with the use of a large scintillation tank in 275 LeConte. When the muon encounters the scintillator after travelling from the atmosphere, it causes a burst of photons to appear (scintillations). These photons are detected by a photomultiplier tube (PMT), and they multiply the effect and convert it to an electronic voltage signal. This voltage signal registers to us as a short peak in voltage. Triggering our search on this peak, we search for any muon decay signal, which would similarly produce scintillations, generally of a smaller effect.

These scintillations arise as the mineral oil scintillator rapidly reduces the speed of the muons from their extremely large speeds to the typical RMS velocity of particles in the thermal medium of the scintillator. The sudden change in energy from this reaction and the decay itself excite the scintillator and produce an amplified signal (burst of photons).

The difference between the trigger pulses and the decay pulses, if counted and aggregated, can be used to estimate the muon lifetime. Of course, some time has already elapsed in the time taken for the muon to reach the ground from the upper layers of the atmosphere. We adopt a method that avoids this biasing the result. Since muon decays follow an exponential curve, and we do not receive decays that are not in the detector, we will only end up getting the tail end of the true muon lifetime distribution. Counting up the time differences between the muon entering the detector and the decay, we instead fit the tail end of this distribution to an exponential and determine the half-life - this is constant throughout the curve, and so the half-life, or mean muon lifetime, is successfully calculated.

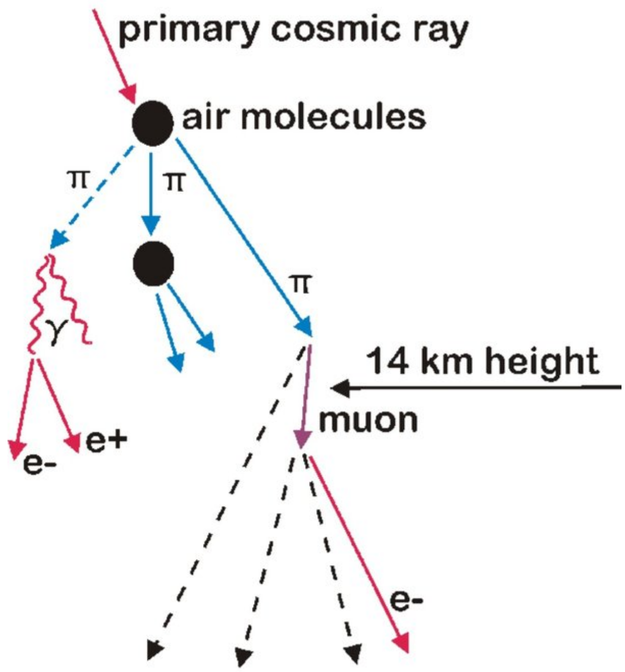


Figure 1: A diagram showing the impact of a cosmic ray hitting the atmosphere and the following decay for a μ^+ .

2.3. *Muon Decay Calculation*

We calculate the number of muons decaying per minute in our scintillation tank in preparation for the lab. We estimate a density of $\rho = 0.8g/cm^3$, use the dimensions of the tank $l = 60\,cm$, $b = 30\,cm$, $h = 240\,cm$ (muons can come from any direction on-sky), and the solid angle on-sky $\Omega = 2\pi/3\,sr$ and the intensity per gram per solid angle of the muon at sea level $I_v = 6 \times 10^{-5}$ from Rossi (1) (where they referred to muons as mesons). Combining these, we find:

$$N = I_v \times \rho \times lbh * (2\pi/3)\,sec^{-1} = 43\,sec^{-1}$$

Therefore, we expect 43, or on the order of 10s of decays per second, even though we expect thousands of muons enter the scintillator per second.

2.4. *Muon Lifetime Measurement Components*

- Scintillator - The detector is composed of a large scintillation tube filled with 125 gallon of mineral oil, contributing density. In this, a scintillating substance is dissolved, making the liquid a scintillator, responsive to fast charged particles.
- Photomultiplier Tubes - The PMTs are extremely precise devices that convert light from single photons into corresponding electrical signal by multiplying the effect in numerous stages.
- Oscilloscope - Though we utilize a LabView program for the final calculation, we use an oscilloscope to visualize the effects of scintillations detected by the photomultiplier tube, namely, to determine the voltage peaks and their heights and widths, as well as an appropriate trigger level.
- Light Probe and Dectector - The laser diode and detector, or the corresponding mirrors, can be moved up and down with the help of knobs or a coarse stepper motors to calibrate the instrument.
- Video Optical Microscope - The video optical microscope probes roughly the same degree of magnification as the AFM, and is hence used in combination with the AFM to help locate features on the surface to be scanned, avoid artifacts or broken portions of the sample, and ensure the laser diode calibrations are done correctly.

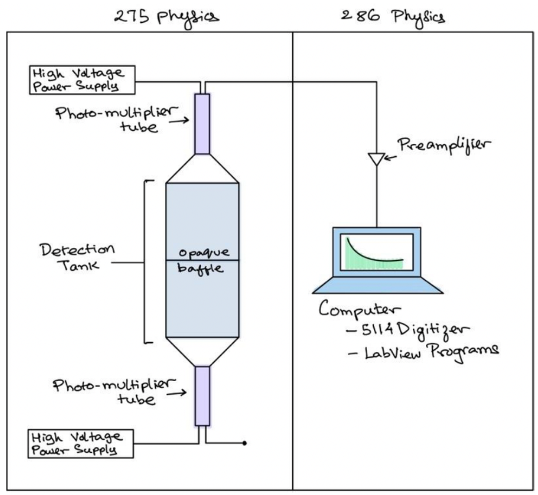


Figure 2: The setup for the muon lifetime experiment. The detection tank is split into two parts named Channel 0 and Channel 1, useful for calibration purposes and removal of false detections. The signal is preamplified before being fed to the lab computer (Credit: Arundhati Ghosal, lab partner).

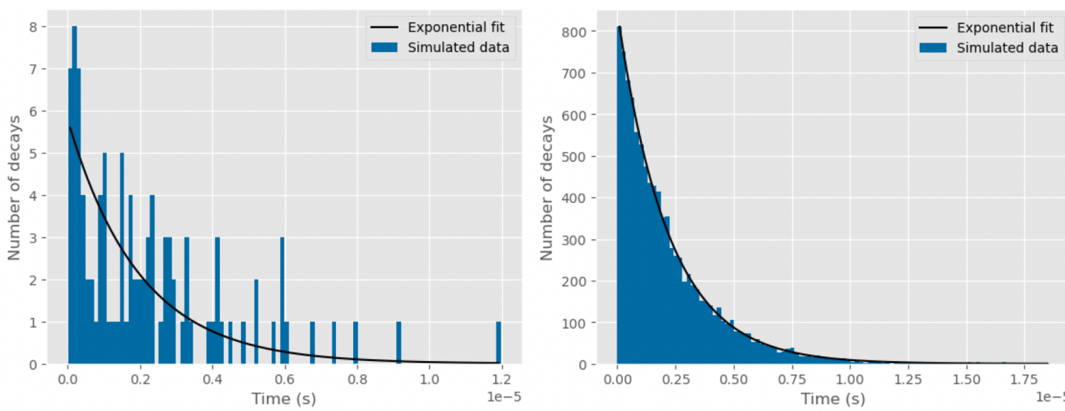


Figure 3: The simulated data is shown for two different values of iterates, n = 100 and n = 10000. We expect the fractional uncertainty to fall as the $\sqrt{N}$, so we find that the estimate becomes significantly more accurate with a greater quantity of iterations. In the left diagram, the mean muon lifetime is 1.978 μs and on the right, it is 2.202 μs.

- View Signals Software - The View Signals LabView program allowed us to test different thresholds for muon detection, primarily the trigger level for searching for decay, and the count trigger for the decay itself, but also the range to search and pulse delays. We tested that the observed detections and decays agreed with the order of expectations.

- Muon Detection Program - This LabView program was used to aggregate all the data over long periods of time for the various datasets. The parameters determined in View Signals were added to this program and various calibrations steps were also performed. See the following sections.

2.5. *Monte Carlo Computer Simulation of Decay*

We simulated the lifetime distribution of muon decays and generated an exponential distribution to compare against our experimental results. We simulated a uniform random distribution r_i U(0, 1), and applied the transformation $t_i = -\tau_\mu \ln r_i$, where τ_μ is the mean muon lifetime. This means each sample r_i was mapped to an exponential $e^{-\frac{t_i}{\tau}}$, similar to the muon decay distribution where $N_0 = 1$ and there is no background. We fit the data with *scipy.curve_fit*. The results of this generation and fitting are shown in Figure 3.

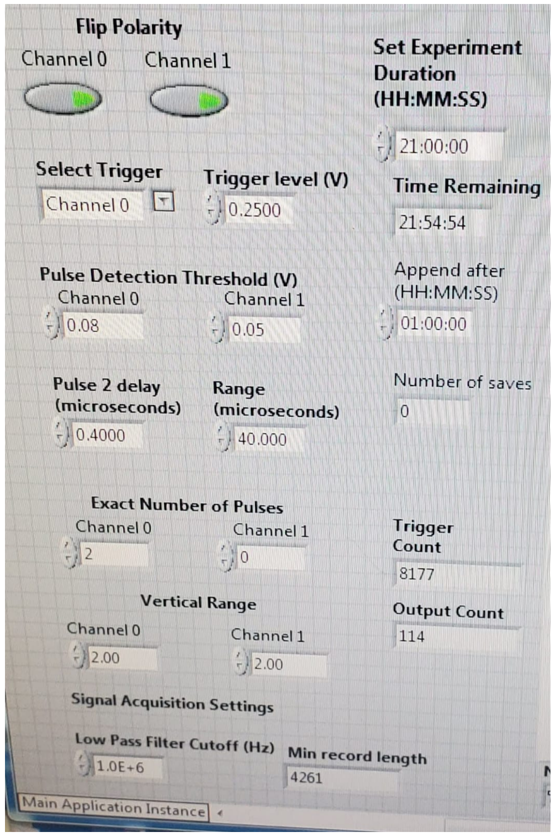


Figure 4: The settings for the Muon Detection Program.

3. EXPERIMENTAL DESIGN

3.1. *Main Experimental Setup*

For the primary experiment, we run the Muon detection program with the below settings. We chose these settings with feedback from the oscilloscope and View Signals programs, and believe they are ideal in order to get large numbers of accurate counts. See 4.

We chose a trigger level of 0.25 V, smaller than the default setting. The higher setting was missing a significant number of trigger events, and setting it to the lower setting did not seem to allow spurious signals to trigger. Additionally, we set the pulse detection threshold at 0.08 V. This was the ideal boundary between clear noise and true muon decays. On adopting these thresholds, the View Signals program produced realistic numbers of counts in accordance with expectations from calculations earlier.

The pulse 2 delay was initially set at 0.4 μs but later increased to 1 μs since the initial trigger pulse had a wider width and different structure than initially expected, reducing the detected counts and increasing mistaken detections. The range was set at 40 μs event though it is extremely unlikely muons last to 40 μs lifetimes. This was primarily to retain background noise for later calibration. The C0 = 2 and C1 = 0, indicating that both decays should be seen in one half of the tube and none should be seen in the other half, ruling out false detections. We left filter cutoffs at the defaults, as these were the values used to test in the View Signals program. In 4, we see a sample where the experiment was started for 22 hours and is 6 minutes in progress. We see 8000 triggers and 114 counts, in line with our expectations of 3 thousand of muon detections for correspondingly, 43 counts of decay. However, this is over the course of 6 minutes. As such, we are seeing 3 times less muons than we expect. We believe these are due to our conservative thresholds, and chose to opt for more accurate data rather than have a larger quantity of data.

The physical experimental setup occurred as follows:

- We take care to safety. The high voltage lines in 275 LeConte were not touched while the PMT was running. We noted a large negative voltage value of -2299V and a current of 2.34 mA. The negative voltage implied we had to flip the polarity in our detection program.
- We observed the green (input), white (output) and black cables passing from 275 to 286. We connected the Channel 0 (top) and Channel 1 (bottom) wires after passing through the preamplifier, to the lab computer.
- We then open the Muon Detection Program, fill in the parameters, time to run, and begin the run. In total, we performed a 22 hour aggregate run, and a 96 hour run over a long weekend. We utilize the 96 hour run in our results in the following sections.

3.2. *Calibration Setup*

Calibration had to be done to correct for systematic uncertainties in our instruments, and data collection processes, as well as to estimate the expected random uncertainty and background noise, increasing the signal to noise ratio.

3.2.1. *Calibration 1: Time Resolution of the Digitizer*

There is a very small difference in time between the entrance of the muons into the detector, and the actual detection of scintillation. This time difference can be estimated by comparing the typical difference in time between the C0 and C1 channels for a through-going muon from directly above.

We set C0 = C1 = 1, and set the trigger to C0 (where it passes first). The trigger and detection thresholds are set at 0.06V, and set the pulse delay to 0.0s. We set the experiment duration to 30 minutes. With this experiment, we hope to generate a histogram of time differences, and judge the uncertainty we need to add in order to account for this. We show this in the following Section 4.

3.2.2. *Calibration 2: Efficiency of the Digitizer*

It is possible that not all the bins are counted equally efficiently, leading to possible systematic effects. We design an experiment to simulate a uniform distribution of lifetimes, and compare that to the true distribution seen. If there is any linear effect in bin efficiency, we correct for it before presenting our results.

For this experiment, we simulate the counts using through-going muons as the trigger and an external pulse generator which adds predictable pulses every $40\mu s$. We use an adder circuit to combine the simulated and through going muon signals in order to check the uniformity of the detection program.

We set C0 = 2, C2 = 0, trigger level at the typical 0.25V, and the thresholds for the pulse detection at 0.1V. We choose 0.35V as the simulated pulse generator voltage amplitudes resulting in a amplitude of 0.13V after attenuation. The results of this data collection are provided in Section 4.

3.2.3. *Calibration 3: Calibration of the Digitizer Clock*

It is possible that the digitizer's time scale is inaccurate. This would mean that for a time delay $dt = 1\mu s$ we may actually see $1.1\mu s$. This would impact our results significantly. By checking the calibration of the digitizer clock, we can check whether this is an issue, and furthermore, add any variations to uncertainty in our result.

We set the number of pulses as C0 = 2, C1 = 0 for C0 and C0 = 0, C1 = 2 for C1. We also set the channel thresholds to 0.2 V each, range = 40 μs, and pulse 2 delay = 1 us. We took data at 5-μs intervals by generating a signal at that time delay.

We were able to specify the time delay precisely by using two simulated pulses with a n-μs delay in between. We set the pulse widths to 100ns, and their amplitudes to 0.5V such that they were detectable at the 0.2V threshold.

3.2.4. *Calibration 4: Linearity of the Pulse Height Measurement*

We send two pulses into the digitizer from the pulse generator while varying the amplitude, in order to ensure the response of the digitizer to voltage is linear. We set the trigger level to 0.2V, pulse delay to 1 μs, and range = $40\mu s$. From 0.4 to 2.2V in increments of 0.2V, we tested the response. The average of the response ratio is roughly constant, and since it is negligible, we ignored it in future corrections.

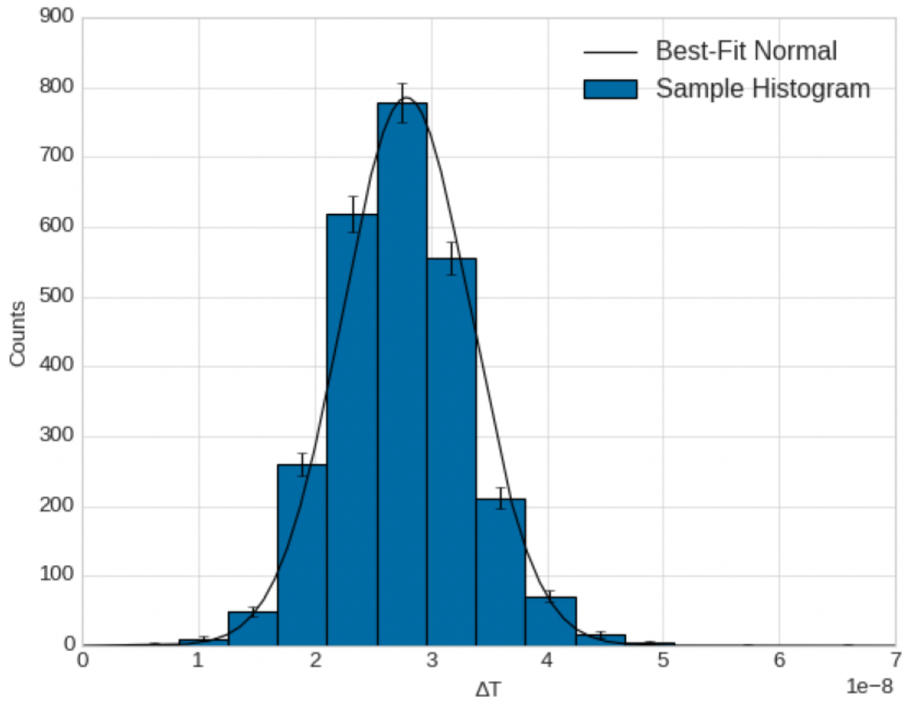


Figure 5: Best fit Normal distribution to the C1 - C0 time differences. There is a systematic shift in the data such that the mean is non-zero, since the through-going muon would typically generate a response in the top PMT before the bottom PMT. We see that the scale on the x-axis is in units of 10 nanoseconds - and both the spread and systematic difference between the PMTs are too small to affect our muon lifetime experiment.

4. RAW DATA AND ANALYSIS

4.1. *Analysis 1: Time Resolution of the Digitizer*

We present the final results of the time resolution estimate below. We generate this distribution by taking time differences between the C0 and C1 detection times in order to get an estimate of the uncertainty due to delay in measurement of the muon decay. The results are binned and graphed in 5, with an uncertainty of $\sqrt{N}$ in the number of counts per bin.

From the graph, we notice that the systematic differences between the top and bottom PMT, or the time it takes to detect a muon decay, are on the order of 40ns at the maximum. Fitting a Gaussian distribution to the sample histogram, we find a $\mu = 27.9ns$ and a $\sigma_1 = 5.52ns$. Though small, we combine the uncertainty σ_1 to our final result for the muon lifetime.

4.2. *Analysis 2: Efficiency of the Digitizer*

Though a small difference, it is evident that the data does not show a uniform response in all bins. We show the distribution of pulse widths and heights for the two channels in 6, which match expectations. We then fit the distribution to a linear fit, and check if there is any evidence of a slope.

We find a slope of $m = -2.71\,\mu s^{-1}$. In the final data, we shift the bins by the value of the slope at each bin, minus the uniform mean of the sample distribution counts, i.e., $y_{bin} = y_{counts} - (y_{fit} - \bar{y})$

4.3. *Analysis 3: Calibration of the Digitizer Clock*

The raw data results for the digitizer clock calibration are shown in 8. We find that the uncertainty in individual bins for the clock calibration is on the order of nanoseconds for all of the measurements - though small, it is accounted for as σ_3 in our muon lifetime estimation. However, there is a significant shift in the systematics of the calibration, as the results are consistently 0.098us longer than expected. We accomodate its effect by shifting the main data

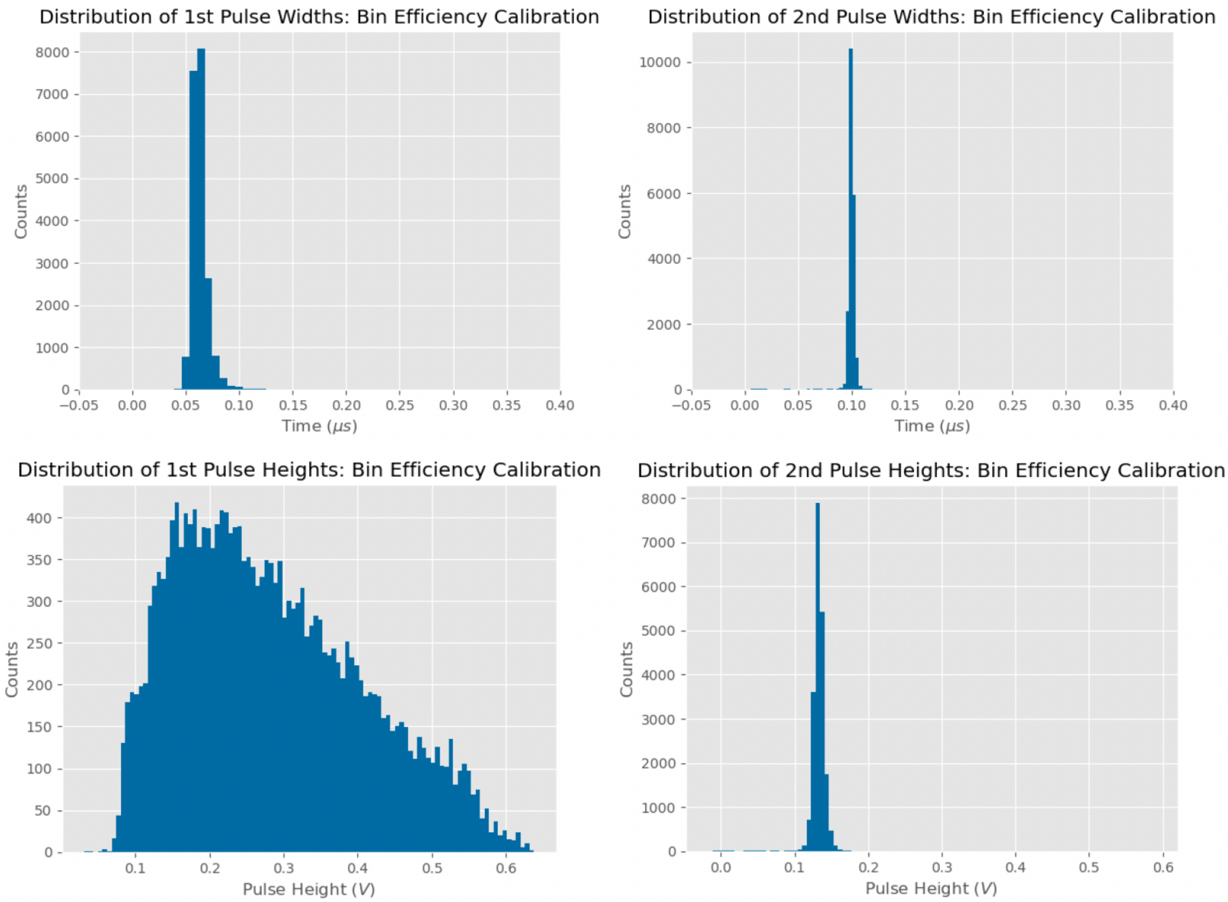


Figure 6: Distribution of first and second Pulse Heights and Widths used for efficiency calibration. The through-going muon, pulse 1, has a uniform width of 0.07 μs, and a spread in height from 0.1 - 0.7 V. The simulated pulse has an expected sharp peak at the expected pulse height and width ($0.1\mu s$).

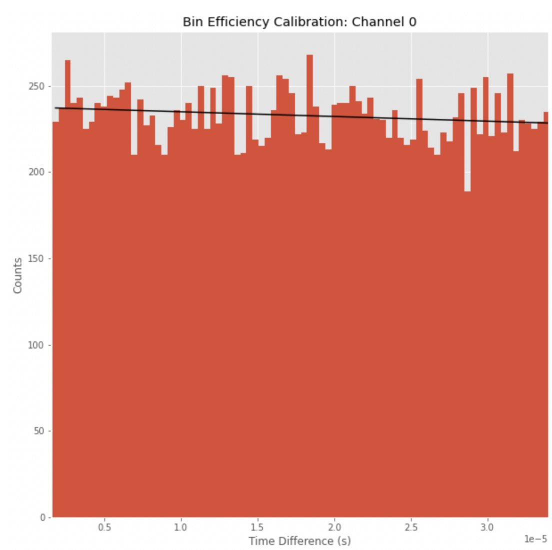
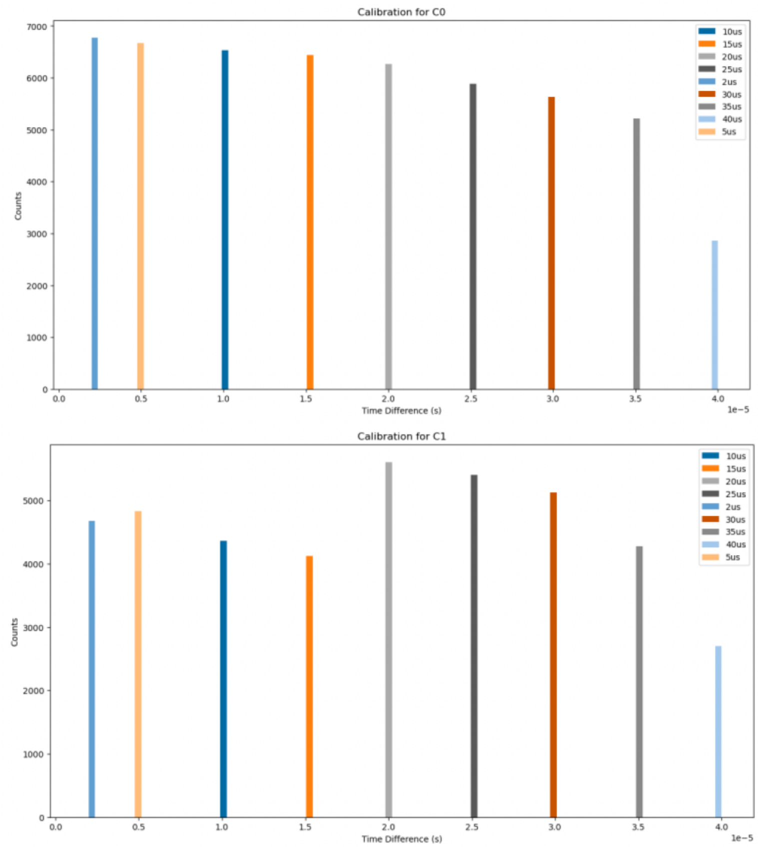


Figure 7: Left: Fitted slope to the uniformly sampled distribution to judge bin efficiency systematic effects. The variations were corrected for in the final data.

Time (us)	Mean (us)	Channel	Stdev (us)
2	2.098778	C0	0.001842
5	5.098776	C0	0.001843
10	10.098707	C0	0.001871
15	15.098810	C0	0.001829
20	20.098834	C0	0.001818
25	25.098830	C0	0.001820
30	30.098913	C0	0.001779
35	35.098940	C0	0.001766
40	40.000823	C0	0.098928
2	2.098794	C1	0.001836
5	5.098723	C1	0.001865
10	17.617541	C1	19.829021
15	15.098707	C1	0.001871
20	20.098798	C1	0.001834
25	25.098807	C1	0.001830
30	30.098863	C1	0.001804
35	39.161011	C1	4.829175
40	40.002968	C1	0.098834

(a) Time Systematics and Uncertainties



(b) Different Calibration Time Differences

Figure 8: Systematic errors and uncertainties in digitizer clock for Channel 0 and Channel 1. We find a typical shift of 0.098us exists in the digitizer clock. We take this into account by shifting the data accordingly by the mean. The error in a single measurement is low, in the nanosecond regime. The large deviations for some C1 measurements are due to artifacts in the data which were corrected in the right figure. The height of the individual columns in the graph are simply a function of the length of time the data was aggregated for, and does not correspond to any physical effect. We are not interested in counts, but rather the clack calibration.

distribution accordingly. It is unlikely that a horizontal shift would directly impact the measurement of mean muon lifetime however, due to the nature of the exponential distribution.

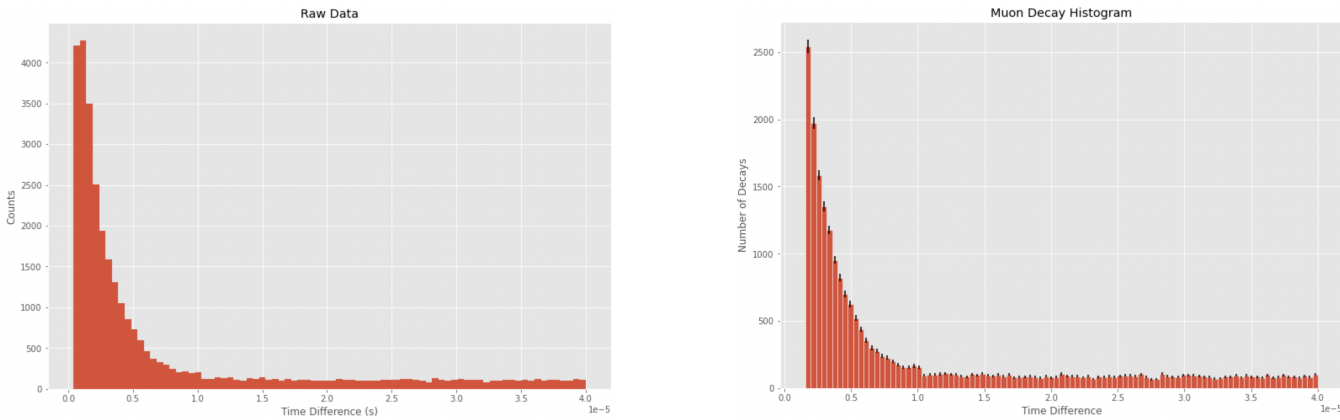
4.4. *Analysis 4: Linearity of the Pulse Height Measurement*

As mentioned in the experimental setup section, we see constant ratios of approximately 2.6 in the digitizer response for both C0 and C1. This indicates the error was negligible and requires no need for further calibration.

4.5. *Main Muon Lifetime Experiment Analysis*

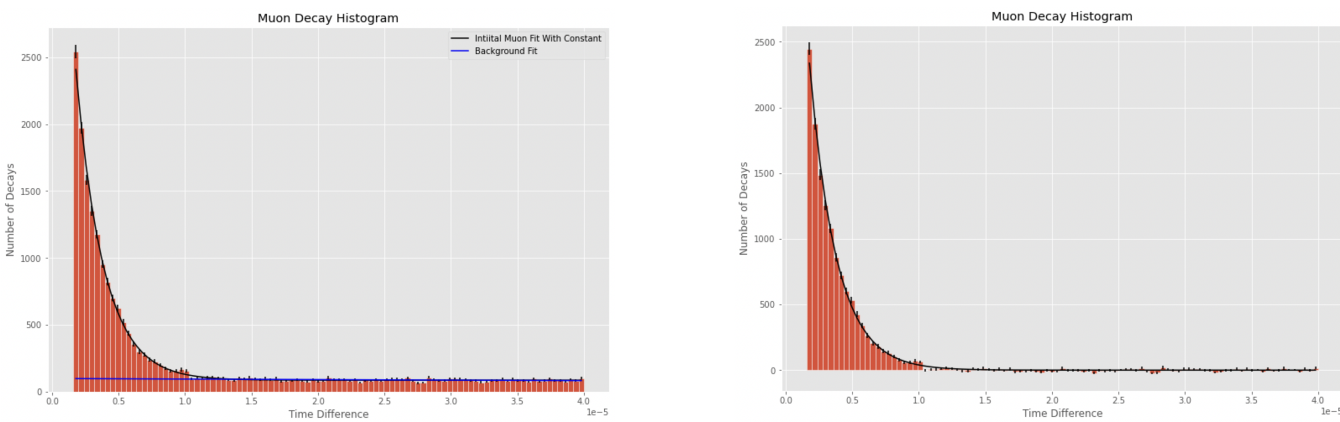
The raw data for the muon lifetime experiment was calulated as described in Section 3.2. Run for 93 hours over 4 days, we get the following raw data distribution seen in 9a. On taking out counts at the beginning of the distribution (abnormally high), and correcting on pulse height and width, specifically selecting channel widths below $0.2\mu s$ and trigger pulse heights of 0.1V, we get a cleaned distribution. The cleaned distribution is also shown in Figure 9b.

The cleaned data is then background subtracted. This is accomplished by fitting the background data ($dt > 1.2\mu s$) to a linear fit. The background linear fit by $np.polyfit$ and a preliminary $ae^{-bx} + c$ fit performed by $scipy.curve\_fit$ are shown in Figure 10, along with the result following background subtraction. The result of this preliminary fit produces a mean muon lifetime $\tau_\mu = 2.013\,\mu s$, calculated as the absolute value of the inverse of b.



(a) Raw Data (b) Cleaned Data

Figure 9: 93 hour muon lifetime data (a) before cuts and (b) following cuts. Note the x and y-axes limits change in both cases. The cleaned histogram must undergo further preprocessing before the data can be fit to it.



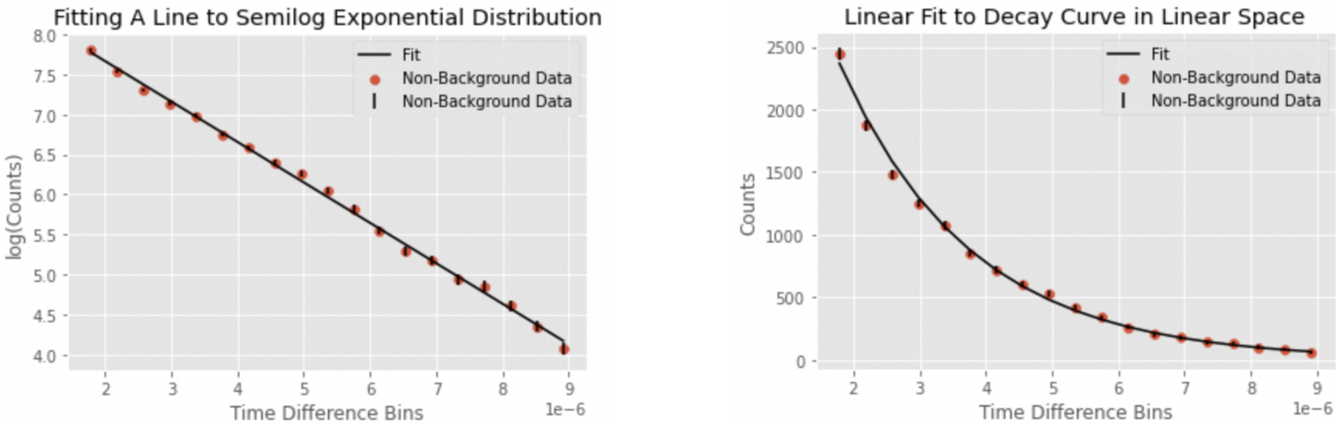
(a) Before Background Subtraction (b) After Background Subtraction

Figure 10: The figures describe the background subtraction applied. (a) The fit to the $dt > 1.2\mu s$ background is shown, as well as a preliminary *scipy.curve_fit* model that takes a constant background into account. (b) The same sample distribution with background removed, and an identical *scipy.curve_fit* model.

To this dataset, the calibration shifts and corrections are applied. Primarily, we apply the correction to the data from the digitizer clock calibration, where we see all the measurements are systematically shifted by $0.098\ \mu s$ and we also apply a shift correction from the delay in time from the muon decay to detection, i.e. the first calibration: Time Resolution of the Digitizer. Both these shifts constitute small but non-negligible effects in the final fit results.

The correction from the digitizer efficiency makes small yet significant changes to the distribution, effectively reducing the decay rate by making the exponential curve more gradual, and therefore increasing the mean muon lifetime. Lastly, no changes were made with regards to the pulse height calibration, as they did not have any effect on the results.

The quality and uncertainty of the curve fit may be best estimated with a linear fitting procedure. To do this, we convert the background subtracted counts into logspace, and find that $\log N = \log N_0 - \frac{t}{\tau}$. This can be rewritten as a linear fit procedure y $= at + b$, and can be used to find b, the constant of interest, and hence $\tau = -\frac{1}{b}$ in a similar fashion. The uncertainties in the data are scaled accordingly. We take out datapoints from the background subtracted region to get the linear fit shown in Figure 11 in both linear and logarithmic count-space.



(a) Logarithmic (b) Linear

Figure 11: The figures describe the best-fit line to the sample distribution. (a) The fit to the $dt > 1.2\mu s$ background is shown, as well as a preliminary *scipy.curve_fit* model that takes a constant background into account. (b) The same sample distribution with background removed, and an identical *scipy.curve_fit* model.

With regards to the uncertainties during the fit, the uncertainty is estimated from a combination of the uncertainty $\propto \sqrt{N}$, σ_{bin} and combined with the clock digitizer uncertainty σ_3. Fitting this x-y uncertainty, we find the true fitting uncertainty σfit, expressed in the variance of the covariance matrix output by *scipy.curve_fit*. This is combined with the time resolution uncertainty σ_1 in quadrature to obtain the final mean muon lifetime.

From the linear fit $\log N = mt + b$, we find a slope of $m = -5.04 \times 10^6\ s^{-1}$, and a constant $b = 8.67$, which corresponds to a muon lifetime $\tau_\mu = 1.982\mu s$. After applying the shifts and uncertainty calculations, we find that our estimate for the final mean muon lifetime after all calibration steps is $2.0105 \pm 0.0658\,\mu s$. This is not in agreement with the true mean muon lifetime of $2.1969811(22)\,\mu s$ (Particle Data Group, 2016 [(2)]). We discuss the possible causes for this disagreement in the following section.

5. DISCUSSION

We mentioned in Section 2 that the mean muon lifetime estimate will be hindered due to the muonic atom decay of the μ^- muon. We can approximate the effective decay constant as $\lambda_{eff} \approx \frac{\lambda_+ + \lambda_-}{2}$, where the minus and plus muons decay with different rates. Additionally, we know that the $\lambda_- = \lambda_{\text{combined}} = \lambda_+ + \lambda_{\text{captured}}$, and that $\lambda_{\text{captured}}$ is approximately $\frac{1}{26\mu s}$. This means that the expected measured value of the muon lifetime is lesser, rather $\tau_{\mu,\text{eff}} = \frac{2}{\lambda_+ + \lambda_-} = \frac{2}{0.949}\,\mu s = 2.107\,\mu s$, an underestimate of the true value. Of course, this assumes λ_{eff} can merely be approximated using the average of the positive and negative muon's separate decay constants, but it gives results that explain our underestimated measured result to a better degree. See Figure 12.

To improve our results to reach agreement, we may attempt to do a more complex fitting routine where we fit for the negative and positive muon decays separately, and combine them. However, it is likely that this will suffer from degeneracies, and require a very high-quality experimental dataset. This can be achieved by running for longer periods of time, performing more careful cuts on height and width of detection, and improving the experimental setup to capture a larger quantity of muons.

The Fermi Coupling Constant can be similarly calculated from the mean muon lifetime. Since the constant is inversely proportional to the square root of the mean muon lifetime, the Fermi constant is calculated simply as $G_F = 1.219 \times 10^{-5} \pm 0.019 \times 10^{-5}\,GeV^{-2}$.

6. CONCLUSION AND FURTHER WORK

In this experiment, we tested the operation of a muon detector, calibrated its equipment, ran a long time-baseline experiment, and performed analysis in order to determine the value of the mean muon lifetime. After time resolution

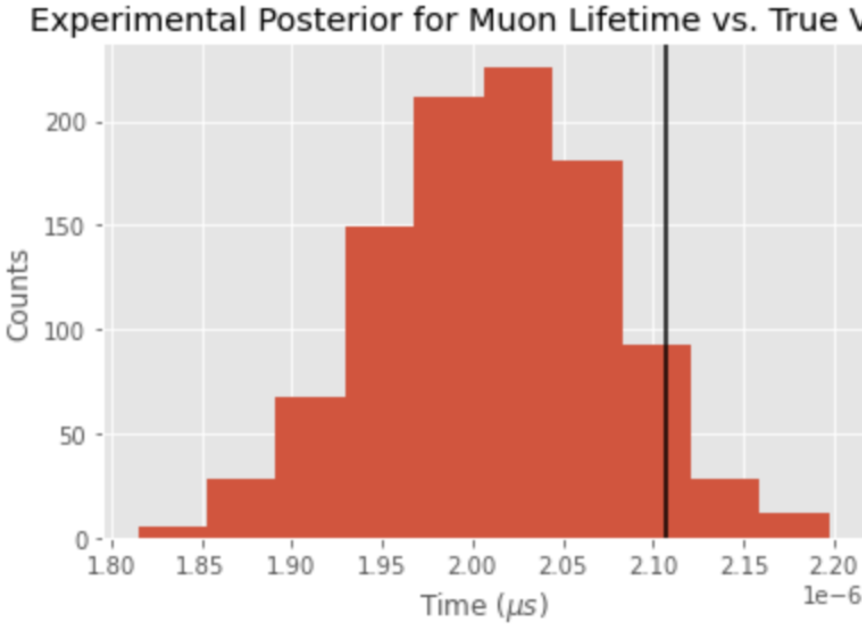


Figure 12: The experiment agrees with the expected effective muon lifetime at a $2-\sigma$ level. The red is the assumed posterior distribution of mean muon lifetime values and the black line is the expected value after considering muonic decay.

calibration, clock digitizer calibration, and bin efficiency calibrations, we determined that the mean muon lifetime was $2.0105 \pm 0.0658\,\mu s$. This was not in agreement with the true value, $2.1969811(22)\,\mu s$, but rather in agreement with the adjusted value of $2.107\,\mu s$ accounting for muonic decay in the atom. We also calculated the Fermi Coupling Constant as $G_F = 1.219 \times 10^{-5} \pm 0.019 \times 10^{-5}\,GeV^{-2}$ from the muon lifetime estimate. Though an overestimate, it suffers from the same systematic deviations as the muon lifetime estimate.

Further work can be done to reduce the uncertainty and systematics. First, a larger dataset can be obtained by studying a longer timescale. The current experiment was limited to first-order effects, and likely does not contain sufficient information to distinguish betwen the muonic atom decay rates and the typical decay rates. With a high-quality dataset, further analysis into the individual decay rates can be done with a more complex fitting program, and determine more accurate posteriors using a Monte Carlo fitting process. Equipment can also be tested thoroughly for systematics, and types of peaks seen in the voltage can be analyzed further to obtain a cleaner dataset.

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