Cosmic Ray Muon Telescope from SiPMs

J.T Hsu, G. Xeinis

May, 2023

Abstract

Muons are elementary particles that are similar to electrons in terms of charge and spin but with a much greater mass. In this project, we attempted to build a functioning muon telescope from scintillators and SiPMs (silicon photomultipliers) by implementing relevant circuit designs. We used the telescope to measure muon rates at 8 different angles. They all closely followed the Poisson distribution with χ^2 ranging from 0.36 to 1.75. The $\cos^2$ angle-rate dependence was also verified with our measurements with χ^2 of 0.21.

1 Introduction

1.1 Muons

Muons are elementary particles that are similar to electrons. Muons have an electric charge of $-1e$ and spins of $1/2$. Due to their larger mass (approximately 207 times the mass of electrons) and their decay mechanism being only mediated by the weak interaction (opposed to the more powerful electromagnetic interaction and strong interaction), they penetrate much deeper in matter and have a much longer mean life time of 2.2μs. These properties allow muons produced by high energy cosmic rays hitting the atmosphere to penetrate through air, reaching ground level and even through underground mines. For this project, we aim to measure and quantify the muons produced from cosmic ray showers in the upper atmosphere that reach ground, into our laboratory in the basement.

1.2 Scintillators and SiPMs

A scintillator is a material that produce photons when hit with radiation or charged particles. For our project, we chose plastic cylindrical scintillators Saint-Gobain BC-408 with 3 inch diameters. SiPMs were used to translate photons emitted by the scintillators into measurable electric signals. Consisting of arrays of avalanche photodiodes, SiPMs can become ideal devices to measure photons as we take advantage of their enlarged depletion region through reverse biasing the device as shown in Figure 1. When a photon hits one of the many PN junctions on the SiPM creating electron/hole pairs, under high reverse bias voltage (about 29.4V) the electron/hole pairs are accelerated in opposite directions, smashing into other atoms and creating additional electron/hole pairs. An avalanche of charge carriers occurs and detectable currents are generated. This process allows us to record the number of muons travelling through our scintillators, functioning as cosmic ray muon detectors.

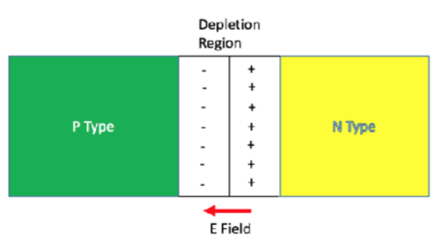


Figure 1: Visualization of a PN junction

1.3 Muon rates at ground and angle dependence

Cosmic ray muon rates at ground have a rate of approximately $1\text{min}^{-1}\text{mm}^{-1}$. From the low probabilistic and discrete nature of the number of muons coming through our detectors, we expect the muon rates per unit time to follow the Poisson distribution. Furthermore, muon rates also follow a well-known angle relation of $\cos^2\theta$, where θ is the angle from zenith. We expect our measurements to display similar behaviors.

2 Methods

2.1 Limiting Cosmic Ray Muon Acceptance

Scintillators produce photons when charged particles pass through, meaning particles coming from all solid angles will produce photons in the scintillator. We are interested in muon rates at different angles to zenith. Therefore, we need two independent detectors, attached as shown in Figure 2, to limit the acceptance angle of muons. Using this approach, only muons passing through both detectors successfully will be contributing to muon rates when measuring the particle's angle dependence properties.

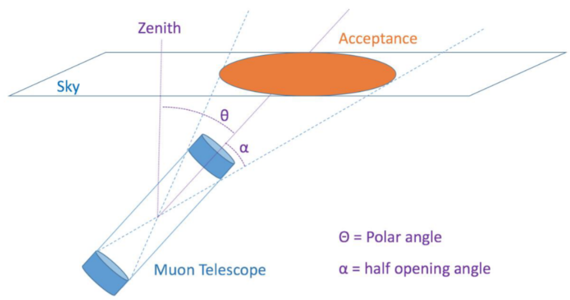


Figure 2: Limiting muon acceptance using two detectors

2.2 Quantifying Detector Signals

As shown in Figure 3, raw signals produced by the scintillator-SiPM pair only have heights of less than 50mV and width of approximately 500ns. They are both too little and too short for data collection devices like Arduino to process. Therefore, the first part of the project would be to design and implement circuits that would both amplify and lengthen the incoming signals. Our circuit design can be roughly divided into three parts: 1. Signal amplification and lengthening 2. Signal digitization and the Schmitt's trigger, and 3. coincidence logic and Arduino data collection.

2.2.1 Amplification and Lengthening Circuit

Raw signals produced by the SiPM have periods of around 500ns, which is equivalent to a frequency of at least 2MHz. To amplify signals at such high frequency, the LT1807 was our choice of operational amplifier as they have Gain Bandwidth Product of 325MHz. This allows us to implement a gain of 40 as shown in Figure 4. Note that additional circuit components were added for different purposes. The 50Ω resistor to ground immediately after input acts as a terminator. The 100nF Capacitor and $1.6\text{k}\omega$ resistor pair acts as a high pass filter to filter out low frequency background noises below roughly 1000Hz before the amplification circuit.

The amplification circuit ensures thT the pulses are large enough to be processed, but at this point, the pulses were still less than 500ns long, which were too fast for later components including the comparator or logic gates to process. Therefore, signal stretchers were implemented using another LT1807 operational amplifier and two N5148 Shockley diodes.

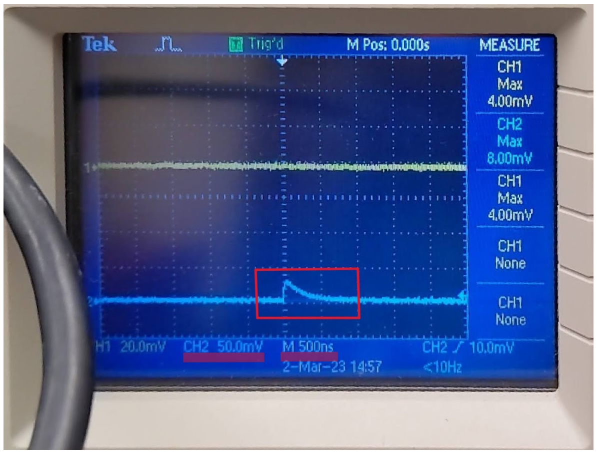


Figure 3: Raw signal registered on the oscilloscope

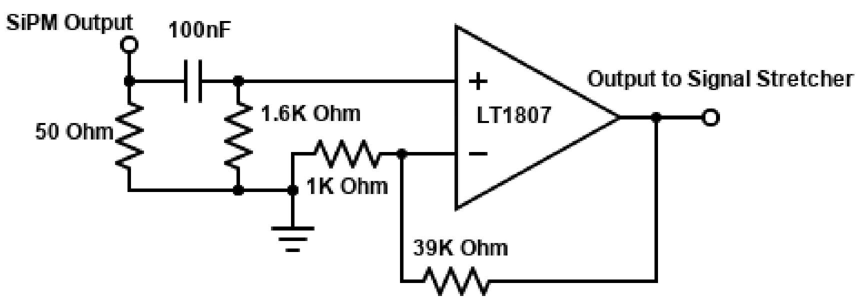


Figure 4: Schematic circuit diagram of raw signal output from SiPM feeding into the amplifying circuit

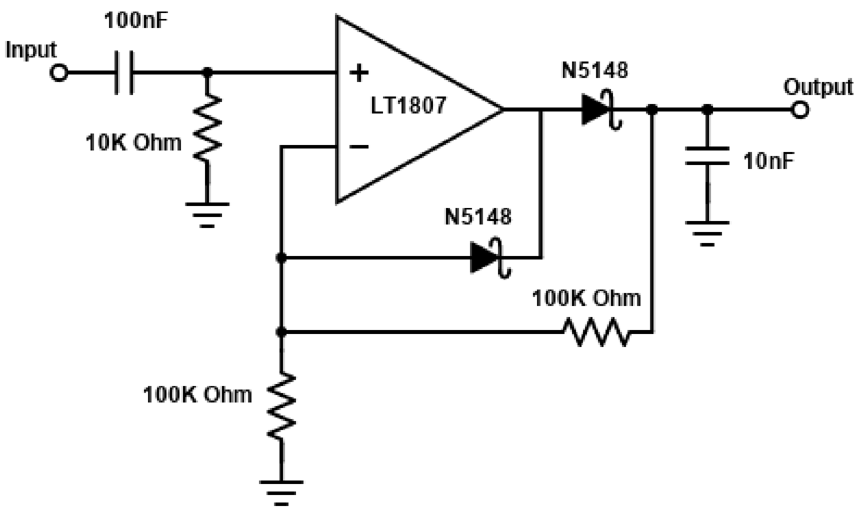


Figure 5: Schematic circuit diagram of the signal stretcher

2.2.2 Comparator and Schmitt's Trigger

The comparator and the Schmitt's trigger were included in our circuit to digitize signal pulses. As shown in Figure 6, the reference voltage is adjustable between 5V and 0V using a 1000ω potentiometer. For this project, we had them set to 0.140V. The comparator circuit also adopts a Schmitt's trigger to implement an hysteresis in reference voltage. This removes false signal counts stemming from the oscillating tails of the raw signal pulses. This design allows us to accurately digitize signal pulses with some acceptance to noises.

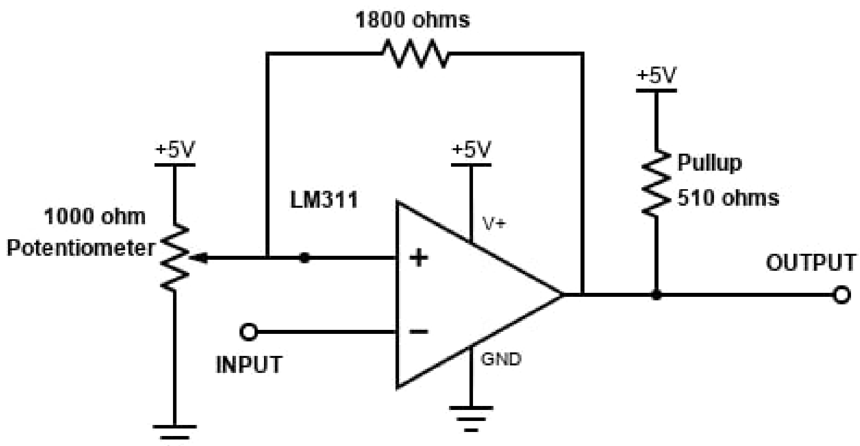


Figure 6: Schematic circuit diagram of the Schmitt Trigger

2.2.3 Coincidence Logic and Arduino Data Collection

At this point of our project, we are able to digitize signals from both detectors, producing LOW voltage when there is a signal and HIGH voltage when there is none. To single out coincidences, the final portion of the circuit needs to respond uniquely to both inputs being LOW only. This is achieved by 3 NAND gate wired as shown in Figure 7. The first NAND gates immediately after each detector essentially act as NOT gates, inverting the voltages so that they are at HIGH when there is a signal. A NAND gate is at LOW only when both inputs are at HIGH. This completes our desired functionality, having LOW outputs only when both detectors receive muons coincidentally. The output then feeds into an Arduino and records the timestamp of each coincidence caused by muons going through both detectors.

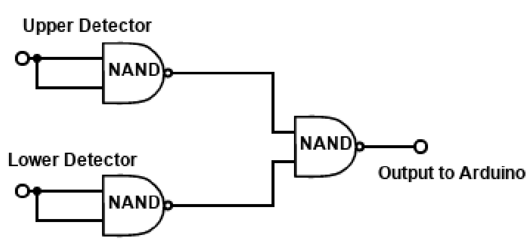


Figure 7: Schematic circuit diagram of the coincidence circuit

2.3 Accidental Coincidence

Our telescope adopts two independent detectors to limit muon acceptance. Using this approach, however, we are prone to receiving some accidental coincidences. This is especially relevant since each signal is stretched before being fed into the coincidence circuit. To take them into account, we used the following formula to quantify these theoretical accidental coincidences.

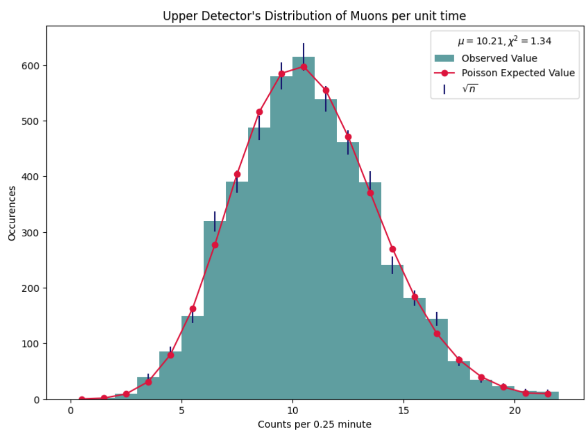
$$R = 2Tr_ar_b$$

R is the accidental coincidence rate, T is the common pulse width of the two detectors (for a conservative estimation, we chose $T = 800$ns, the approximate longer pulsed width of the two detectors), and r_ar_b are the rates of the two detectors respectively. Muon counts at different angles were then adjusted accordingly by subtracting the theoretical accidental coincidences uniformly across all angles.

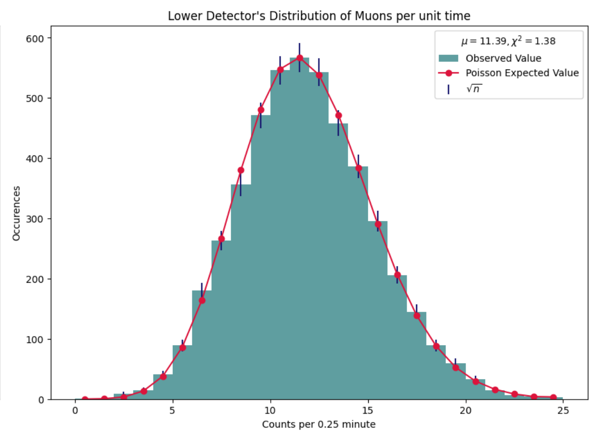
3 Results

3.1 Individual Detector Behaviors

We first tested the behaviors of the two detectors independently.



(a) Top detector



(b) Lower detector

Figure 8: Distribution of muon counts per 15 seconds of each detectors

As shown in Figure 8, the two detectors have mean rates of 10.21 per 15 seconds and 11.39 per 15 seconds respectively. From the discrete, low probabilistic nature of this counting experiment, we expect the distribution per unit time to follow the Poisson distribution. Comparing our observed counts to a scaled Poisson distribution, we get χ^2 values of 1.34 and 1.38. The result showed evidently that our apparatus is capable of collecting results that closely follow theoretical expectations.

3.2 Muon rates at various angles

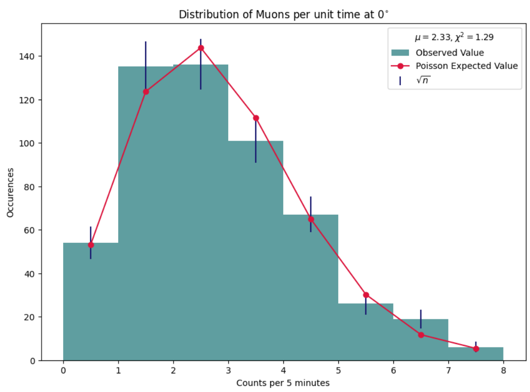
The muon rates at different angle determined through the coincidence logic circuit were also recorded and graphed against the Poisson distribution.

From the results shown in Figure 9, we found a steady decrease in mean rate as angle increases. More importantly, the χ^2 of these measurements were in the range of 0.36 to 1.75 when compared to the Poisson distribution. This shows again that our telescope is able to capture the Poisson nature of the Muons going through our telescope, registering signals.

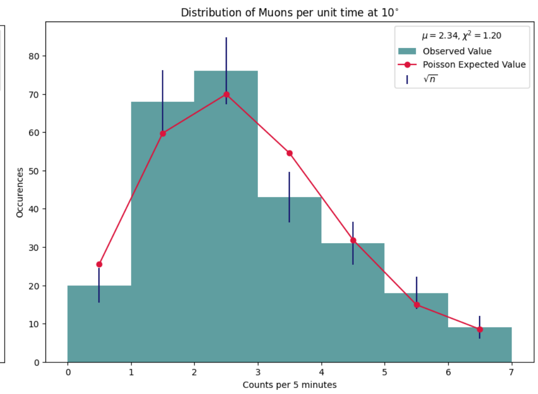
Finally, to test whether our measurements follow the well-known $\cos^2$ relation, we plotted the mean rate at each angle (θ) against the $\cos^2\theta$ distribution.

As shown in Figure 10, our observations overall do follow the $\cos^2$ distribution except for two significant outlying points at $0°$ and $50°$.

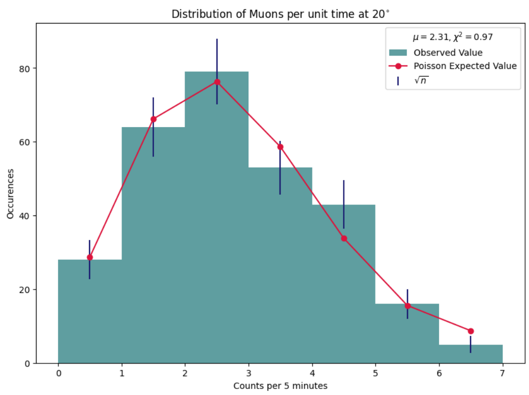
In addition to comparing our observations to the expected $\cos^2$ distribution, we also ran a simple best fit program to determine the specific powers of cosine distribution that would minimize deviation



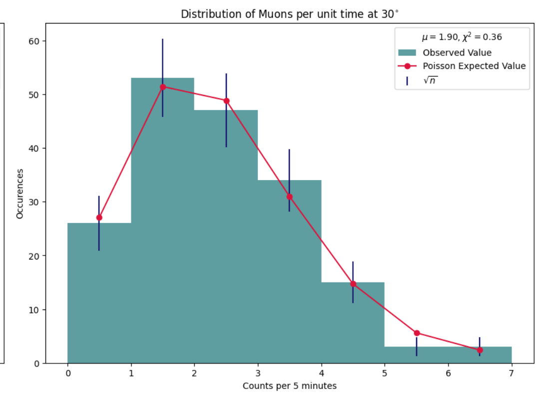
(a) 0°



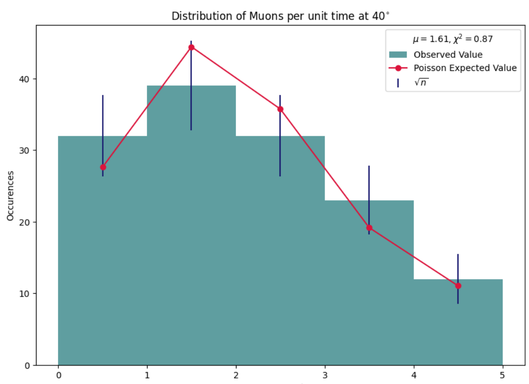
(b) 10°



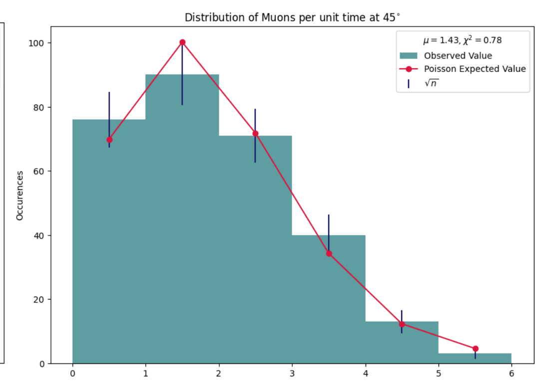
(c) 20°



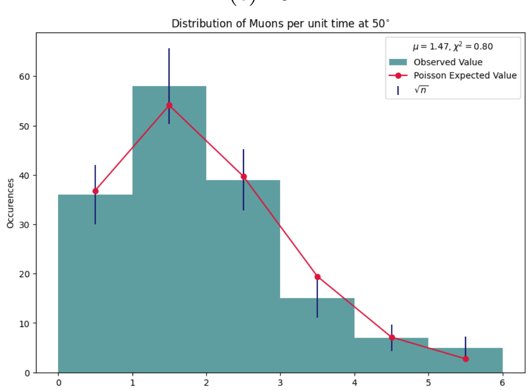
(d) 30°



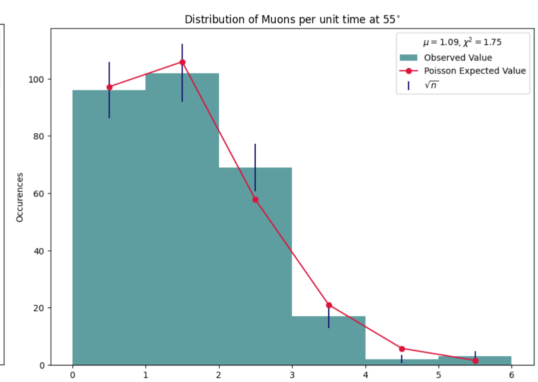
(e) 40°



(f) 45°



(g) 50°



(h) 55°

Figure 9: Distribution of muon counts per hour at different angles to zenith

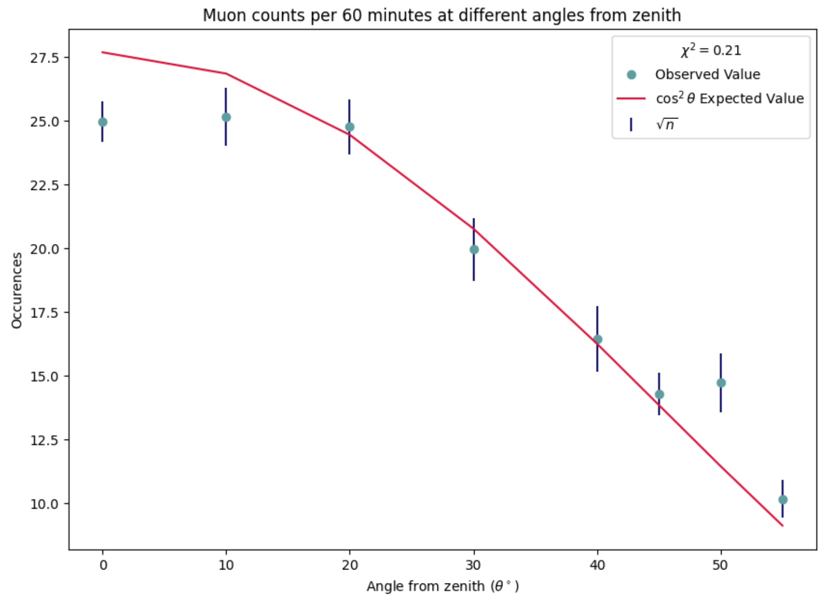


Figure 10: Mean muon rate at different angles compared to the $\cos^2\theta$ distribution.

from observation. As shown in 11, the $\cos^{1.5}$ distribution best fitted out observation by the definition of producing the minimum χ^2.

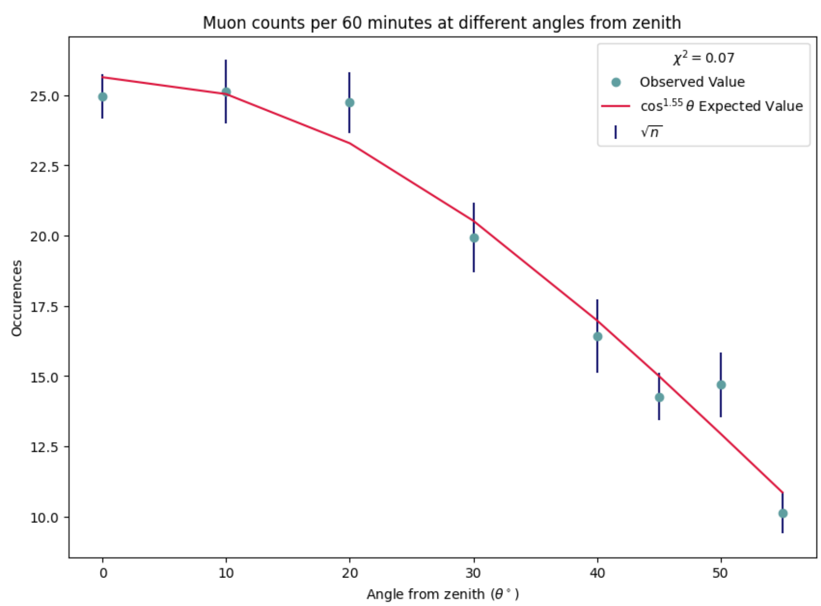


Figure 11: Mean muon rate at different angles compared to the best fit $\cos^{1.5}\theta$ distribution.

4 Discussion

Throughout the build of the project, we struggled to implement circuits with enough efficiency so that our two detectors could act as a cosmic-ray muon telescope. Through try and error, we were able to include additional circuit components like by-pass capacitors and signal terminators that improved our signals. A novel addition we included into our project was a high pass filter before the initial amplifying circuit. Before including the filter, we saw many of our signals failing to be amplified by the circuit, but saw no problem when fed with a function generator. We suspected that it was the background noises that hindered the op-amp's functionality, and after trying both the high-pass and low-pass filters, we saw the high-pass filter to have a significant positive effect on the efficacy of our amplifying circuit. Another high-pass filter was installed between the amplifying circuit and the stretching circuit for the same reasons.

In the early trials of our experiment, we were getting rates of approximately 10 counts per hour at 0° to zenith, the angle producing the best rate. If we were to collect data for the telescope at 45°, which according to the $\cos^2$ distribution would be a rate of 5 counts per hour, we would need at least 24 hours of data before the error ($\sqrt{n}$) goes below 10% of the total count. This rate was not ideal considering the number of different angles we wish to collect data from. Therefore, we adopted a better operational amplifier with higher Gain Bandwidth Product (GBP.) Opposed to our original op-amps LT-6201 with GBP of 165MHz, the new op-amps LT-1807 has GBP of 325MHz. This allowed the amplification circuit to process smaller and shorter signals, thus improving the telescope's overall efficiency by two factors.

While initially analyzing our telescope's effectiveness in replicating cosmic ray muon's $\cos^2$ distribution, we did not take accidental coincidences into account and plotted the results as it is.

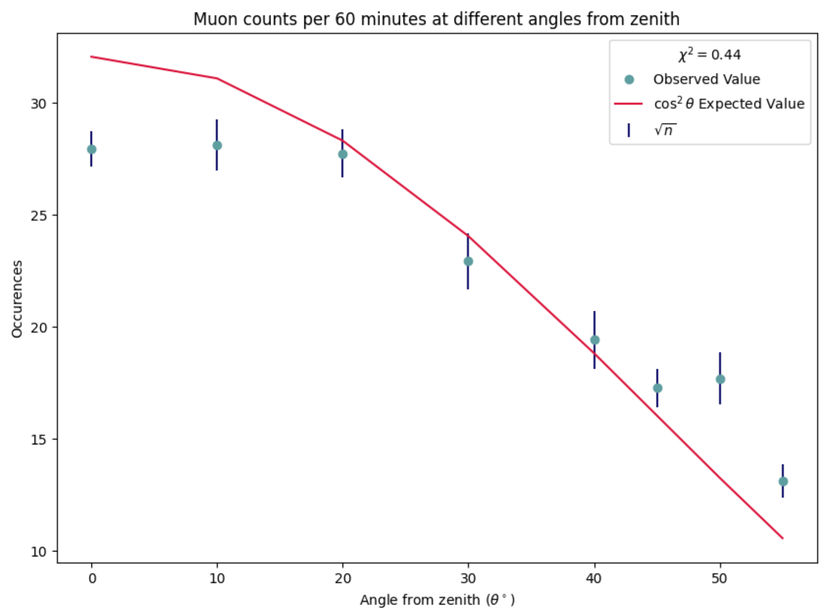


Figure 12: Mean muon rate at different angles compared to the $\cos^2\theta$ distribution without taking accidental coincidence into consideration.

As shown in Figure 12, our measurements, without processing accidental coincidences, fits worse to the $\cos^2$ distribution compared to Figure 10 , with χ^2 values of 0.44 and 0.21 respectively. This shows that while the probabilities of two separate muons hitting two detectors within a window of 800ns are low, they still contribute, evidently, to producing results closer to the theoretical $\cos^2$ distribution.

In both cases, with or without counting accidental coincidences, we measured rates that were significantly lower than the $\cos^2$ distribution at 0° and 10°. This is a phenomenon that we could not explain, but our initial guess was that the building where our laboratory is located might have obstructed some cosmic ray muons from coming through our telescope. We believe this reason is highly probable considering that our laboratory is located in the basement, underneath a 3 story building. An interesting measurement to make would be to repeat the experiments outdoors without significant obstructions. Unfortunately, time was not on our sides and we did not have the time to make such measurements.

5 Conclusions

Using scintillators, SiPMs, and relevant circuit designs, we successfully created a muon telescope that is capable of detecting muons from cosmic ray showers. Each detector behaved as the theory predicts, and the telescope produced results that closely followed the $\cos^2$ angle dependence relation between detector angles and muon rates. The telescope measured lower rates than expected at low angles, but we believe it was due to the location at which our experiments were made. In the future, if possible, we plan to repeat the experiment at an location without significant obstruction to cosmic ray muons, perhaps preforming the experiment outside.

References

[1] Brett Fadem *Muon Telescope Rate vs. Angle Experiment Instructions*

[2] *Counting statistics of random events: A tutorial*, available at `http://courses.washington.edu/phys433/muon_counting/statistics_tutorial.pdf`.