QUARKNET

Race & Associates, Ltd.

University of Minnesota
2023-2025

Examples of Student, Staff, and Teacher Work

Over the next several pages, this supplemental document presents examples of implementation plans posted by teachers engaged at this center. This is followed by a presentation given at 2023 AAPT Winter Conference on Neutrino Masterclasses given by Shane Wood. Next is an article authored by a former student who was mentored by a QuarkNet educator. Finally, posters created by teachers during the summer 2025 workshop are presented (authors names are included as posted on the center's website).

August 2026

The following represents implementation ideas and plans for two groups of teachers who participated in the Minnesota QuarkNet Workshop on August 9-10, 2023.

Group One implementation ideas and plans:

1. I will use the new method we used with Rolling with Rutherford. Having students come up with the relationships between the variables - similar to modeling. Also - Discovering how to present “how close is good enough”?
2. Using vector addition and scalar addition with real data - current applications to conservation of momentum and energy
3. Potentially using the quark workbench since it is interactive hands-on. Being able to see the colors, manipulate them, modeling characteristics with color
4. I didn’t realize how much I appreciated the histograms. You’re committed to an answer. It’s a good representation of the statistical values represented in the classroom
5. The zooniverse would be a great extra credit or extension activity
6. It would be good to add coding into some of the classroom activities. Particle physics is a great subject to stress the importance of coding with large data sets.

Group Two implementation ideas and plans: Students in the driver's seat

1. Rolling with Rutherford - nature of science - looking at data - Histogram - how to study the unseen - how we develop models - develop ownership of the procedure and results

2. Card sorting - interactive - they figure out to sort them, https://quarknet.org/data-portfolio/activity/shuffling-particle-deck Build collaboration skills, good at differentiation activity. There is no wrong answer.
https://quarknet.org/data-portfolio/activity/shuffling-particle-deck

3. Exposing students to citizen science, knowing all the chances and opportunities. Zooniverse

- Student a acting demos (2 protons, Z boson, 2 muons)

4. Trying to do some of the coding.

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Neutrino Physics Masterclasses

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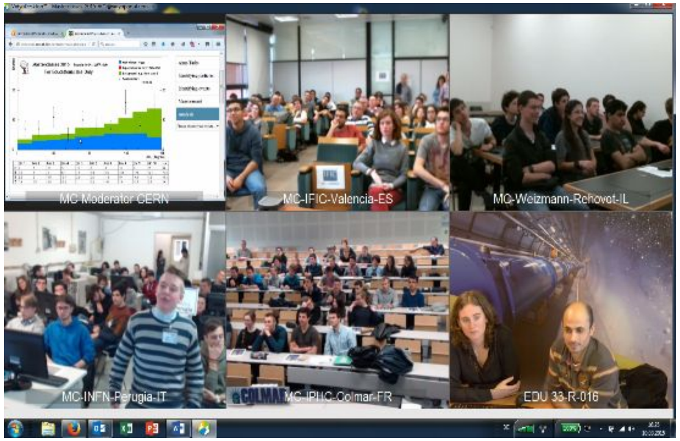
IPPOG NSF U.S. DEPARTMENT OF ENERGY Office of Science Fermilab

What is a Masterclass?

High school students (13k+/year) come to a research lab to be *"scientists for one day"*

- Introduction to particle physics
- Hands-on: data from
  - LHC (ATLAS, CMS, ALICE, LHCb)
  - Neutrino experiments (MINERvA)
  - Belle II
  - Particle Therapy (treatment plan)
- International video conference

  (3-5 groups + CERN / Fermilab / KEK / GSI)



Like a masterclass in the arts…
but in particle physics!

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What is a Masterclass?

Sample agenda…

09:00 Welcome, **Sign-In** & Ice Breaker (Shane will complete **attendance summary**)
09:30 Introductory Talk (Greg)
10:30 Tour 1 Nano Lab/Clean Room
11:30 **Analysis Talk** (Greg & Shane)
12:30 Lunch with a physicist (lunch provided)
13:30 Data Analysis - MINERvA **Student Start Page**: ***http://tiny.cc/mmc-go***
14:30 Tour 2 - Mu2e Lab
15:00 Discussion of results, Q&A
15:45 Break; set up for videoconference
16:00 Video conference (**connect with Zoom**)
16:35 End of day survey (**student survey**, **teacher/mentor survey**)
~16:45 End of day

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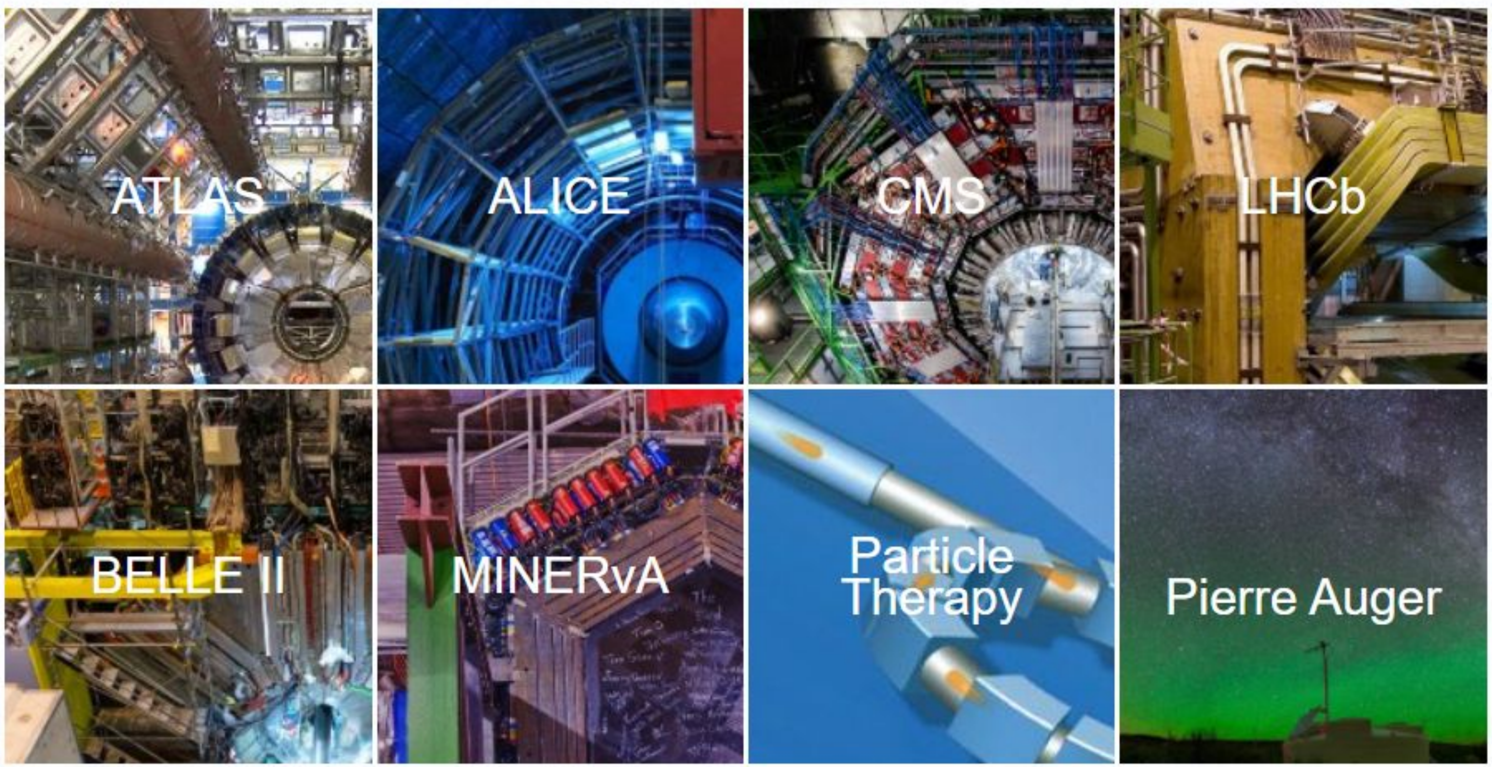
https://physicsmasterclasses.org

International Masterclasses

19th International Masterclasses 2023



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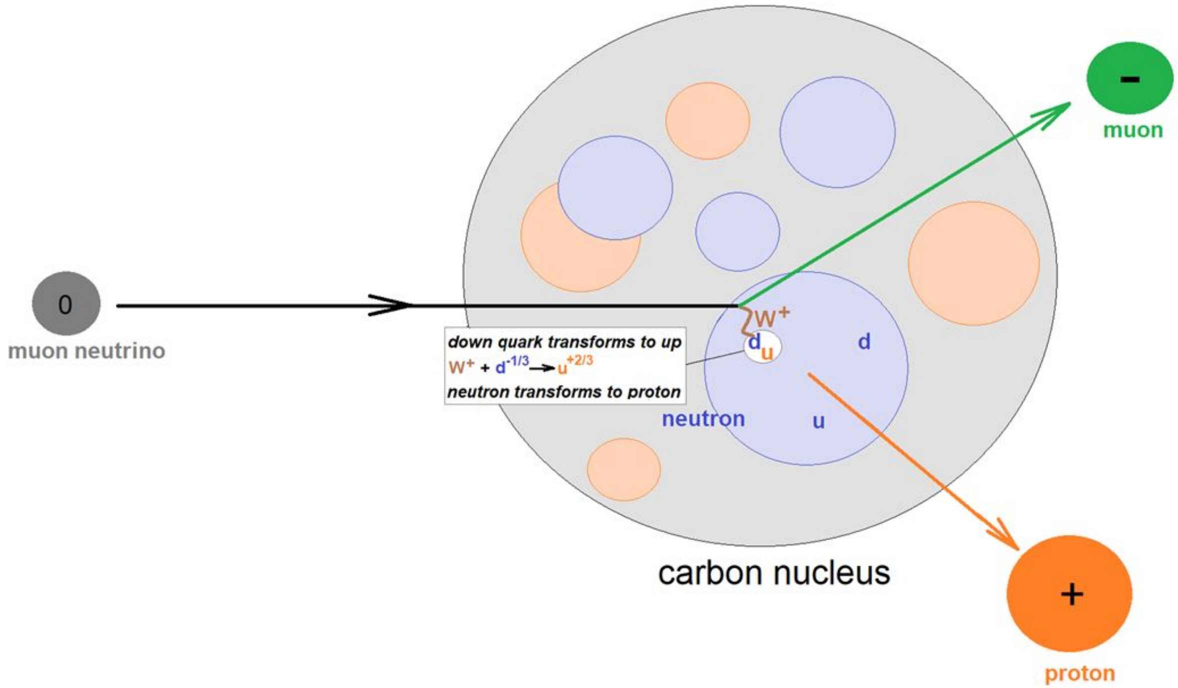
Neutrino-based Masterclasses

1. **MINERvA**
   …Has been used for several years

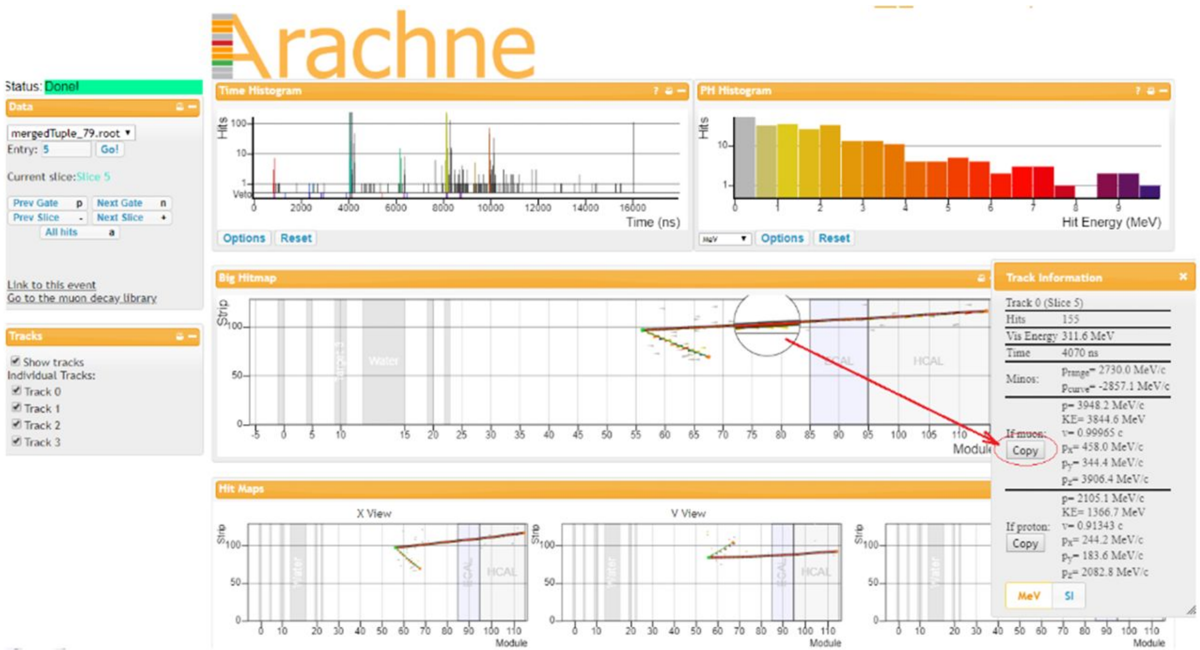
2. **NOvA**
   …Pilot phase → New to IMC

MINERvA Masterclass



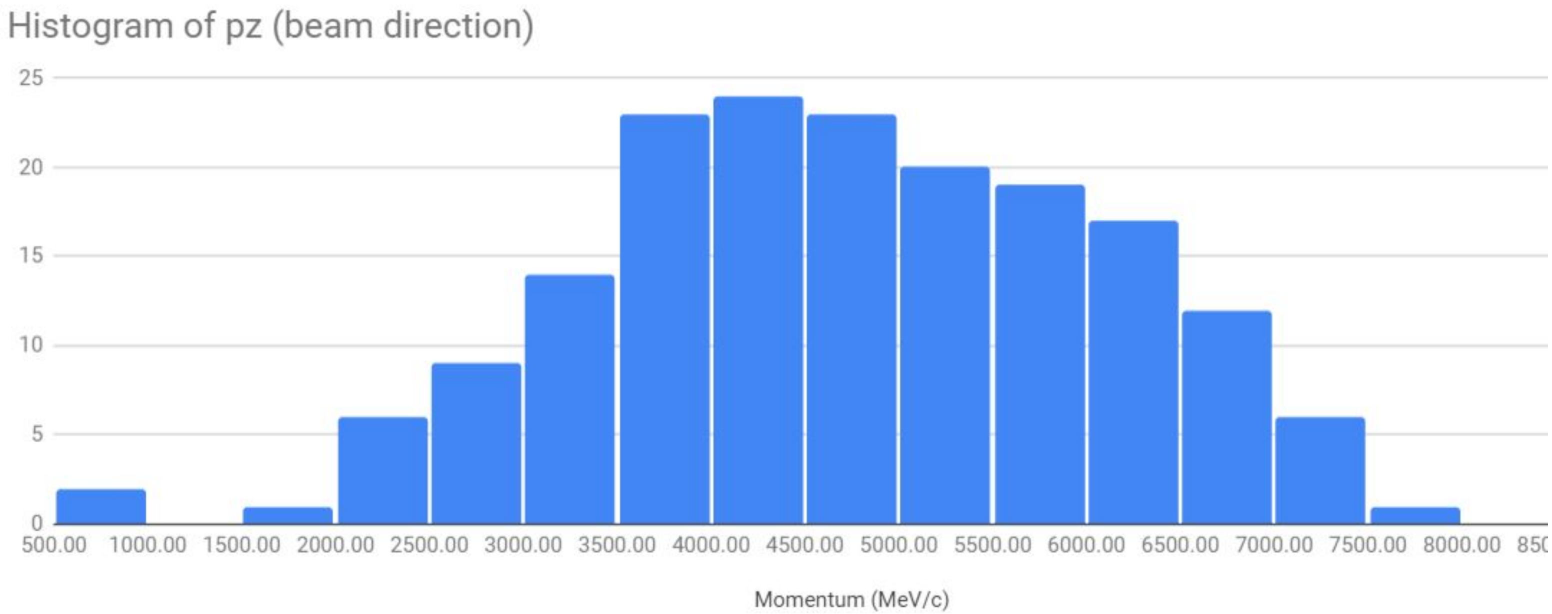
A muon neutrino interacts with a carbon nucleus. The interaction results in a muon and a proton that are ejected from the nucleus. **What happens to the momentum initially carried by the muon neutrino?**

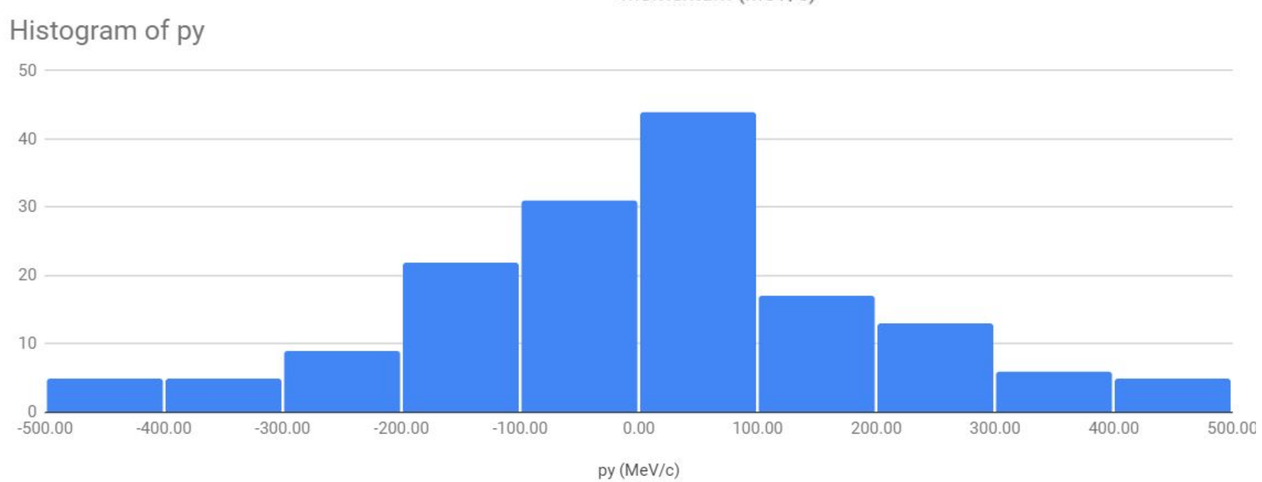
MINERvA Masterclass



A muon neutrino interacts with a carbon nucleus. The interaction results in a muon and a proton that are ejected from the nucleus. **What happens to the momentum initially carried by the muon neutrino?**

MINERvA Masterclass





NOvA Masterclass

New, Focuses on a Result About the Neutrino as a Particle

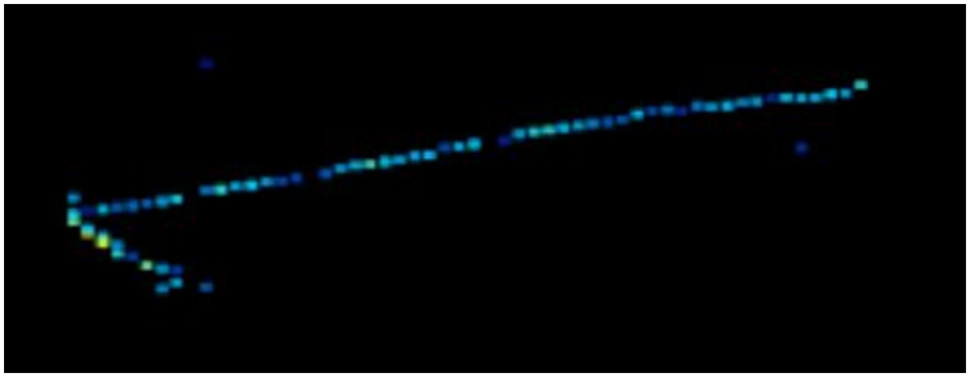
Piloting with Teachers

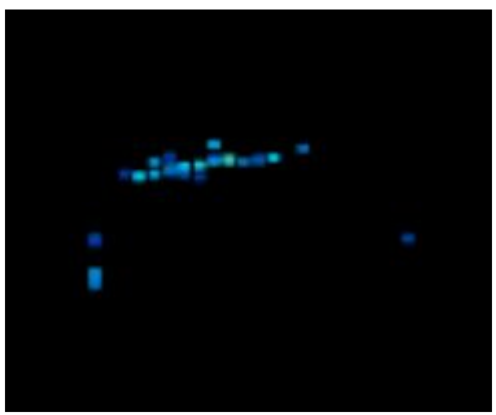
- University of MN Center Teachers
- Neutrino Fellows
- Summer 2022 workshops (4)

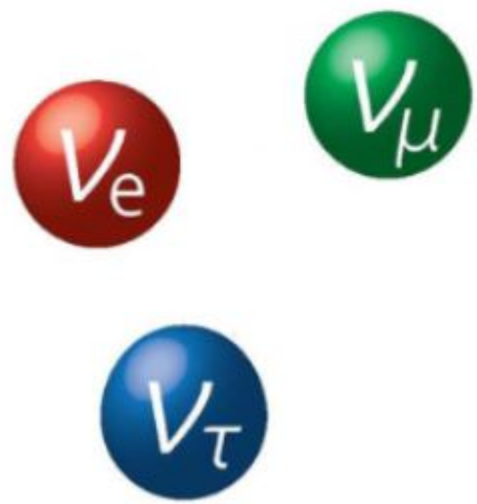
Piloting with Students

- April 23, 2022 at University of MN
- Phase 2 pilot in IMC 2023

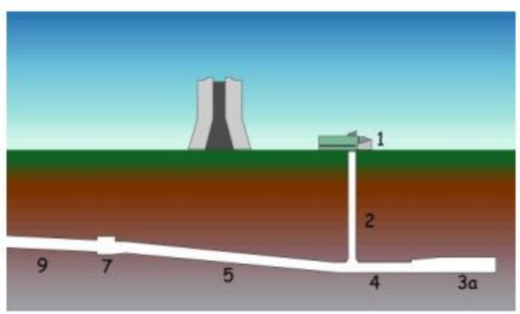
NOvA Masterclass







NOvA Experiment



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NOvA Masterclass

NOvANearAnalysisV2_YourName.ipynb

File Edit View Insert Runtime Tools Help Last edited on Aug 3, 2022

+ Code + Text

Instead, let's see if data analysis tools within this Python document can help us analyze the events r

Importing Data

Now, let's officially turn our analysis to the Near Detector. A set of event data from the Near Detector is available to you. As a starting point, we'll want to import it into this Notebook Document to work with.

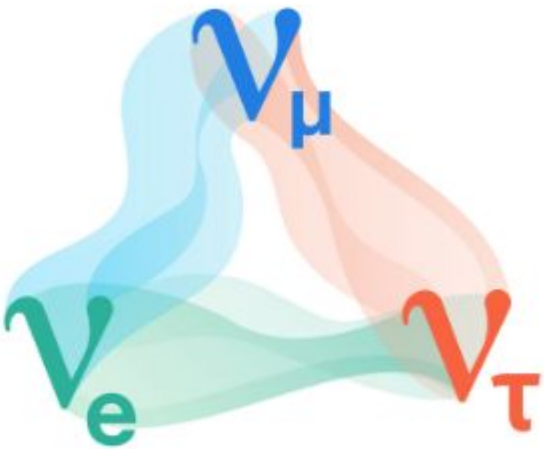
In our notebook, we'll create a "Pandas Data Frame," which is a 2D structure that's able to hold data, and has easy access to many data manipulation and organization tools within the Python environment.

There are many ways to import data. Here we'll use an importing feature that pulls the data in from a "CSV" file that's hosted on a web page (GitHub)

If you need help with this step, a Screen Shot Tutorial can be found here.

```
[ ] # Importing data into a Dataframe from a web based source
    # For this activity, Near NOvA Event Data can be found at this website:  https://github.com/ThePAEngineer/NOvAData
    # The file you'll want to focus on is called:  NOvA-ND-Events.csv
    # Once there, click on the file of interest, then copy the link from the "Raw" button, pasting it in the indicated space below

    dataImported = pd.read_csv('web link here')
```



Students see evidence of neutrino oscillation.

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An Analysis of Muon Flux from Angle Variation of the QuarkNet Cosmic Ray Detector

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(Dated: 27 June 2023)

We present one of the first cosmic ray muon flux-angle variation experiments on the QuarkNet Cosmic Ray Detector (QNCRD). We first describe QNCRD and its calibration. The main focus is then quantifying muon flux decrease as a function of angle from the zenith. The angle of counters of QNCRD were incremented 15° on average every 3.1 days over the range of 0° to 90° for a period of approximately one month. Results showed that as the angle of the detector increased from the zenith, muon flux decreased, which agrees with previous studies. An estimate for the flux based on the model $I(\theta) = I_0 cos(\theta)^n$ had an exponent value of $n = 1.39 \pm 0.01$ for $\theta \leq 75°$, an underestimate of values in other literature. These findings provided a reasonable, although not entirely accurate, estimate for the value of n considering the duration of the study and sensitivity of the instrument. Our results constrain the accuracy of QNCRD and provide a source for future long-term experiments. This study also demonstrates the feasibility of conducting science experiments in high school classrooms, increasing science accessibility.

I. INTRODUCTION

QuarkNet is part of a National Science Foundation funded effort to increase science accessibility across high school classrooms in the United States. This effort also includes training for high school science teachers and students.[1] As part of this network, QuarkNet Detectors are located throughout the world in high school classrooms.[2] These detectors have been used to create and study particle physics experiments in classrooms, which range from the impact of solar eclipses on cosmic ray muon flux[3] to determining average zenith muon flux rate.[4]

Muons are a byproduct of cosmic rays, a stream of particles constantly entering Earth's atmosphere. Cosmic rays are composed of highly energetic particles, mostly consisting of hydrogen and helium nuclei. High-energy cosmic rays originate from neutron stars, while low-energy rays originate from the Sun.[5] The QuarkNet Detector measures[3] muon flux momenta greater than 2 GeV.

When cosmic rays enter Earth's atmosphere, they collide with air molecules, creating a cascading effect known as an air shower.[5] After this collision, pions are produced, some of which decay into muons. Other pions continue into earth's atmosphere and interact with air molecules, creating more air showers.[6] Muons are similar to electrons, with a negative charge and about 200 times as massive than the electron.[7]

These muons can be measured using detectors on earth. As the muons pass through a scintillation counter, they interact with electrons, which release photons. These photons are reflected inside the counter until they reach a detector, where they are transformed into electric signals.

It is currently known that muon flux decreases as the angle of a muon detector increases from the zenith. Previous muon flux studies have used more precise detection methods at various latitudes, longitudes, and altitudes. Shukla and Sankrith[8] describe the theoretical and experimental flux values for a muon detector located at sea level based on the $\cos^2\theta$ model. They also implement their own best-fit model, $I(\theta) = I_0 D(\theta)^{-(n-1)}$, with $n = 3.09 \pm 0.03$. We also implement this model. Schwerdt[9] presents a model based on $I(\theta) = a\cos^2(b\theta + c) + d$. Pethuraj et al.[10] model muonic flux as a function of angle and arrive at an exponential value of $n = 2.00 \pm 0.04$ for their model $I(\theta) = I_0 \cos^n\theta$, located ≈ 160 m above sea level. The cos-squared model is the main comparison of this study, but we also present values for the Schwerdt,[9] Shukla,[8] and Pethuraj et al.[10] models. We find the Schwerdt[9] model provides the best fit for our data compared to the aforementioned models.

While not a flux experiment like the one presented in this paper, Shaffer presents average muon flux rate results using the QuarkNet Detector. Shaffer used QNCRD at an angle of 0° from the zenith to measure muon flux near Topeka, Kansas and found a flux rate of 1200 to 1500 events per meter squared per minute per steradian, values significantly lower than those found in this study. Shaffer's plateau values were different than those used in this study and collected data for several weeks, while this study was one month of data. Shaffer presents a novel solution to measuring steradians using the QuarkNet Detector, a conversion we use in this study. Shaffer's total detector distance between top and bottom counter was 40 cm total, while the maximum spacing for our counters was 13 cm. The coincidence rate used in the plateauing process in this study is approximately equal to the rate used by Shaffer.[4] Coincidence rate is the number of counters needed to qualify muon signals as a detection (see Figure 1).

In Section II, we discuss features of the QuarkNet Detector and provide a description of the calibration process of QNCRD. The experiment is described in Section III. Results from this flux experiment can be found in Section IV, followed by a data analysis in Section V. We follow the analysis with a discussion in Section VI. We conclude with relevant findings and further improvements in Section VII.

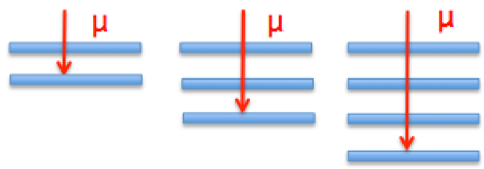

FIG. 1. Illustration of two-, three-, and four-fold coincidence, where the muon is only detected if it passes through all counters in each coincidence configuration.[11]

II. QUARKNET DETECTOR

The detector used in this study is located at Irondale Senior High School, with coordinates $45.0900°N, 93.2072°W$ at an altitude of 276 meters.

QNCRD consists of a data acquisition (DAQ) board, four scintillation counters, Equip software, photomultiplier tubes (PMTs), Global Positioning System (GPS) receiver, a power supply and a power distribution unit (PDU). Each plastic counter has dimensions 25.4 cm x 30.5 cm x 1.27 cm and a "cookie" attached to one corner.[12] This cookie is the interface between the counter and the photomultiplier tube. Each counter is wrapped in reflective shielding to retain any signal from muon interactions. Counters will also be referred to as channels throughout this paper, being labeled as channel 0, channel 1, channel 2, and channel 3.

Each counter has a photomultiplier tube (PMT) that collects electric signals as muons pass through the shielding.[13] The PMTs are SensTech Model P30CW5 photodetector packages.[12] These photodetectors are connected to a power supply[4] and controlled by a PDU, with voltages in the range 0.30 V to 5.0 V.

The data acquisition board is the circuitry necessary for collecting electric signals via the PMTs. This data board also generates the output data to be uploaded to the Equip software.[12] There is a 1.25 ns resolution on the data board, used for separating muon events and unrelated and unwanted ion events.[4]

The GPS antenna is placed outside the school building at all times, while the GPS box is located inside, next to the data acquisition board. The GPS provides the location of the instrument as well as times of the events, which is accurate[4] to 24 ns.

The Equip software records the channels in use, as well as temperature, location, and flux. This also includes the coincidence rate. The software provides an interface to the Cosmic Ray e-Lab, a website where data from QuarkNet Cosmic Ray Detectors across the world are uploaded.[11] Equip was installed and ran on a Windows XP operating system.

A. Plateau process

To ensure reliability of data, performance studies are conducted to measure the time over threshold (ToT) of the PMT to a muon event.[14] The ToT is defined as the amount of time an event is above a predetermined threshold level.[15] Without this process, the flux may be an under- or overestimate of the true value of muons passing through the counters. Such inaccuracies would be due to a high or low voltage value of the PMTs. Voltage values are adjusted through the power supply.

The plateau process involves setting the power supply to 0.3 V, the lowest voltage setting. In order to plateau one counter, another counter has to be used as a reference. Counters 0 and 1 were stacked, channel 0 serving as a reference. The threshold level of the three detectors was set to 300 mV by typing *TL 4 300* into the Equip software. Channel 1 was activated and read a one-fold coincidence. One-fold coincidence means that a muon needs to travel through one detector to be counted as a detection (Figure 1). Waiting for 10 seconds, the voltage was increased until the digital counter on the DAQ board was between 400 to 600 counts. Once the counter was within this range, the voltage was gradually increased until the coincidence counts levelled off.

This process was repeated for counters 2 and 3, channel 0 serving as the reference channel.[16] Results for channel 3 are shown in Figure 2. After this plateau process, data were collected over the next two weeks for eight hours each day. This data was collected to ensure the counters were calibrated correctly. The counters were stacked 1, 0, 2, 3, from bottom to top, with a 0 degree angle from the horizon. Three-fold coincidence was used for counters 0, 2, and 3, as counter 1 was determined inoperable due to improper wrapping of the reflective shielding in that counter.

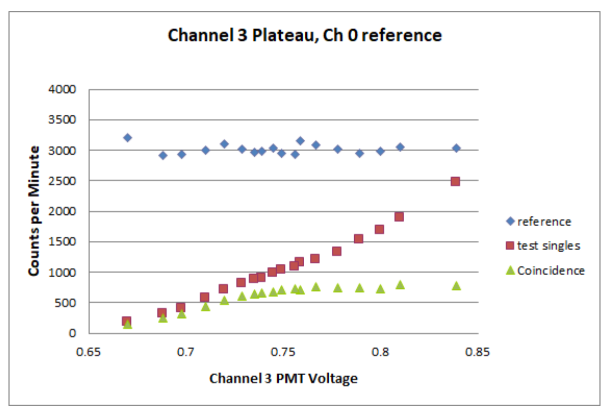

FIG. 2. Plateauing coincidence rate in channel 3 is indicated by the green triangles. The coincidence of channel 3 plateaued within a specific voltage range. This plateauing is from the second round of calibration.

During the initial plateau process, results from counter 2 started to cause concern. The channel rate was displaying a peak pattern at the same time of day. This prompted a recalibration of QNCRD as the preliminary voltage was set too low. The plateau process was therefore repeated, with new data collected over two weeks. The voltages after the second plateau process are shown in Table I, which were used for the remainder of this study. The voltage values were estimated from the plateau graphs where the coincidence values were just beginning to plateau (Figure 2).

TABLE I. Voltage values determined from plateau process. See Figure 2 for the voltage estimate in counter 3.

Counter	Voltage (V)
3	0.770
2	0.800
0	0.709

III. EXPERIMENT

Data was collected almost every day between the end of October 2019 to the beginning of December 2019. The initial angle of the detectors was 0 degrees from the horizon (i.e., parallel to the horizon). The detector angle was incremented by 15 degrees approximately every 3.1 days, with the study ending with the panel surfaces perpendicular to the horizon, defined to be 90 degrees. Data was uploaded from the QuarkNet Detector to the Cosmic Ray e-Lab website, where raw flux data was extracted.

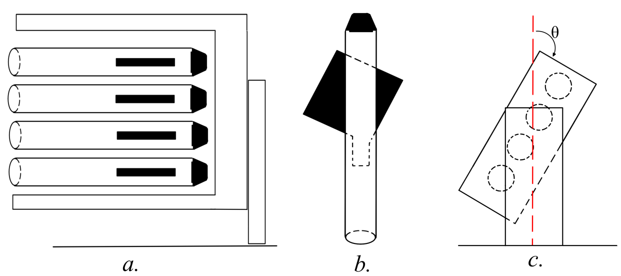

FIG. 3. Schematic of the detector configuration is highlighted in Figure 3*a*. Starting from the top, the counters are labeled Counter 3, Counter 2, Counter 0, and Counter 1. The individual counters are shown in Figure 3*b* and are represented as black rectangles. Figure 3*c* represents how the QuarkNet Detector angle was varied throughout the duration of this experiment. Note that only the top three counters were used in this study, as the fourth detector was deemed inoperable. Diagrams are not to scale.

TABLE II. Relative vertical spacing of counters used in this study, with negative values being measured below the origin set at the GPS box.

Counter	Vertical Spacing (m)
3	-1.5
2	-1.565
0	-1.63

The QuarkNet Cosmic Ray Muon Detector was set up using three counters (see Figure 3) and three-fold coincidence. The configuration of the counters remained stacked 1, 0, 2, 3, from bottom to top. The relative vertical spacing measured from the QNCRD GPS box is provided in Table II and illustrated in Figure 3.

IV. FLUX RESULTS

The flux data were collected at 15° increments for a minimum of 1.5 days using the voltage values in Table I. The detector's final angle ended at 90° (a vertical orientation relative to the horizon). Data were not collected on Wednesdays because computers in the school were automatically turned off, preventing any data collection during this time period.

Since the QuarkNet Detector does not have the capability of measuring flux per steradian, we use Equation 1 as described by Shaffer to convert our data to make its analysis easier:[4]

$$\tan\theta = \frac{w}{d} \quad (1)$$

where w is the width of the detector and d is the total distance between the top and bottom channel. Utilizing the fact that the angular measurement of 32.77 degrees from the normal equals one steradian, the width of the QuarkNet Detector counter being 0.26 m, and the distance between the top and bottom counter of the detector being 0.13 m (see Table II), we found the needed adjustment of data to be:[17]

$$\arctan\left(\frac{w}{d}\right)\cdot\frac{1sr}{32.77^\circ} = \arctan\left(\frac{0.26m}{0.13m}\right)\cdot\frac{1sr}{32.77^\circ} = 1.936sr$$

We now converted flux results from the Cosmic Ray e-Lab into units of $events/m^2/min/sr$. A combination of all the muon flux measurements at increasing detector angles is shown in Figure 4. This experiment continues to verify the general trend that muon flux decreases as the angle of the detector increases from the zenith.

While collecting data, we found discrepancies in data at 30° and 75°. We attributed this to an improper alignment of the counters and a computer malfunction. We resolved these issues by conducting the experiment again over 1.5 days for each affected angle.

V. ANALYSIS

A statistical analysis was performed on the flux data, which included removing outliers and then comparing data to the $\cos^2\theta$ function, as this is widely believed to be the most accurate description of muonic flux as a function of angle.[8,10,4,18,19] We also fitted flux data to models given by Shukla and Sankrith,[9] Schwerdt,[8] and Pethuraj et al.[10] We find Schwerdt's[9] model best represents the data presented in this paper, which is supported by a reduced chi-squared test with a value of $\chi^2{}_\nu = 0.467$.

We first cut outliers in the flux data, using the 25th and 75th percentile values. These outliers were based on the interquartile range of the data. Any values lying below the 25th percentile minus 1.5 times the interquartile range were cut and

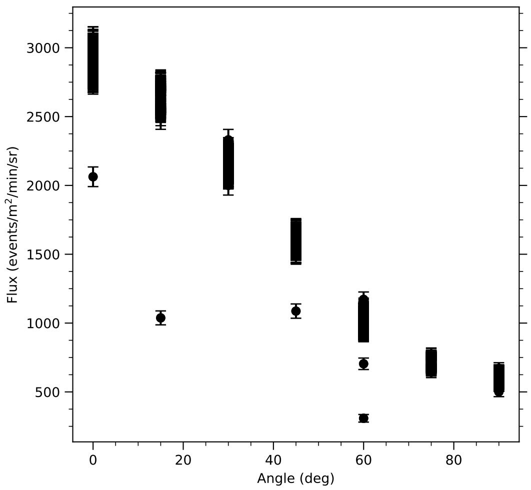

FIG. 4. Decrease of flux starting at 0° ending at 90°. These results are from channel 0 for detector 6709.

values above the 75th percentile plus 1.5 times the interquartile range were cut. This removes the 5 outliers as seen in Figure 4.

Due to construction occurring during measurements, it is possible that electrical interference may have affected the results causing the outliers in our data. Another cause of outliers could have been the relative age of the detector, and according to Bae and Chatzidakis, detections of high zenith angles ($\theta > 60°$) saw high levels of uncertainty.[20] However, we find outliers for $\theta < 60°$.

Once we cleaned the data of outliers, we were able to generate a comparison based on the $cos^2(\theta)$ model. Converting the flux in units of steradians also helps validate our findings, as the data can now be easily compared to other flux studies. This comparison is seen in Figure 5.

Grieder and Pethuraj et al. state that the intensity of muons follows the empirical model:[21,10]

$$I(\theta) = I_0 \cos^n \theta \quad (2)$$

where I_0 is the vertical intensity and θ is the angle from the zenith. However, this equation is used to approximate intensities[21] only for $\theta \leq 75°$. Using the curve_fit function from the scipy.optimize package and the experimentally determined Pethuraj et al.[10] model, we fit our data for $\theta \leq 75°$. We calculated an exponential value of $n = 1.39 \pm 0.00657$, with $r^2 = 0.973$.

We also try modeling to the Shukla and Sankrith function, given by:[8]

$$I(\theta) = I_0 D(\theta)^{-(n-1)} \quad (3)$$

with

$$D(\theta) = \sqrt{\left(\frac{R^2}{d^2}\cos^2\theta + 2\frac{R}{d} + 1\right)} - \frac{R}{d}\cos\theta \quad (4)$$

where Shukla and Sankrith[8] fit the ratio $R/d = 174.0$. Using this model, we find $n = 2.41 \pm 0.00645$ with $r^2 = 0.974$.

Finally, we compare to the Schwerdt model:[9]

$$I(\theta) = a\cos^2(b\theta + c) + d \quad (5)$$

with a representing a vertical stretch, b a horizontal stretch, c a horizontal stretch, and d a vertical shift. This model is more mathematical in nature, representing the most general form of the cos-squared function.[9] We find this model best represents the data, especially towards increasing values of θ and has $r^2 = 0.997$. This function is approximated by

$$I(\theta) = 2241.21\cos^2(1.047\theta + 0.0678) + 665.13 \quad (6)$$

There are several differing values for n, all looking at flux data with $\theta \leq 75°$. Grieder[21] states that the average value of $n = 1.85 \pm 0.10$. Useche and Avila[22] state the experimental value for $n = 1.96 \pm 0.22$. Other results[18,22] have estimated the value of n to be $n = 1.95 \pm 0.08$ and $n = 2.11 \pm 0.03$. See Figure 5 for a comparison of models mentioned in this paper with flux data collected in this study. See also Table III for a comparison of exponential values from other studies.

Authors	Mag. Lat. (°N)	Alt. (m)	n value
Crookes and Rastin	53	40	2.16 ± 0.01
Greisen	54	259	2.1
Judge and Nash	53	0	1.96 ± 0.22
Karmakar et al	16	122	2.2
S.Pal	10.61	0	2.15 ± 0.01
S. Pethuraj et al.	1.44	160	2.00 ± 0.04
This study	45	276	1.39 ± 0.01

TABLE III. Comparison of muon flux data to previous studies.[10] Note that 0 m altitude corresponds to sea level.

We also perform a chi-squared test on the four models discussed in this study. We find that the reduced chi-squared χ^2_ν value for the Schwerdt[9] model best represents the data, which is also supported by a coefficient of determination of $r^2 = 0.997$. Figure 5 displays how well this model follows the data. We summarize our statistical results in Table IV.

Model	Equation	χ^2_ν	r^2
Pethuraj et al.	$I_0 \cos^n \theta$	5.70	0.973
Shukla	$I_0 D(\theta)^{-(n-1)}$	5.35	0.974
Schwerdt	$a\cos^2(b\theta + c) + d$	0.467	0.997
cos-squared	$I_0 \cos^2 \theta$	22.7	0.916

TABLE IV. Summary of statistical tests performed on the four models presented in this study for $\theta \leq 75°$.

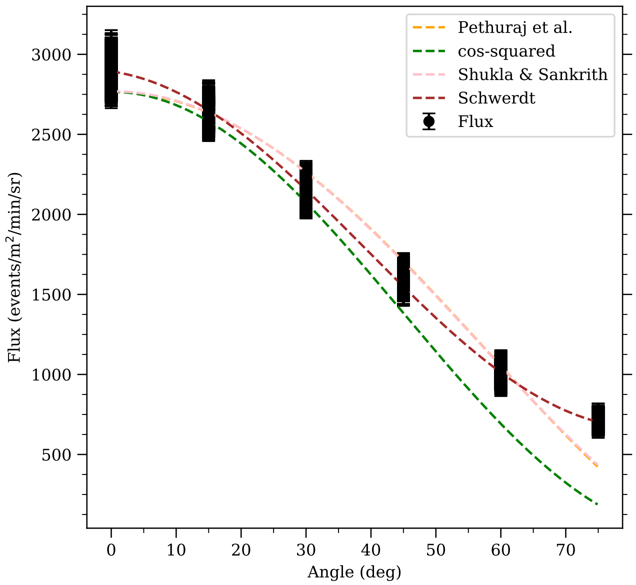

FIG. 5. Comparison of muon flux models as a function of angle with data collected in this study. Note that we only fit for $\theta \leq 75°$. Observe how well the Schwerdt[9] model agrees with the data. The Shukla and Sankrith[8] model and Pethuraj et al.[10] model agree so well they overlap.

VI. DISCUSSION

In general, we saw the flux decrease as the angle increased, which agrees with measurements made by Schwerdt[9] and Useche and Avila.[22] The reason for this flux decrease is that as the angle increases, the cosmic ray muons are not able to penetrate the counters at extreme angles. The majority of muons are "raining" down on the channels at 0°; the intensity of muons entering at 90° would be significantly less.

The improved model to estimate the cosmic ray muon flux for all detection conditions is especially significant for high zenith angles ($\theta > 60°$) because the cosine-squared model is limited in use for low zenith angles due to large uncertainties and assumes a flat earth model.[20,23]

While the reduced chi-squared test favored the Schwerdt model, a value of $\chi^2_\nu \approx 1$ suggests the model and measurements follow error variance. For the Schwerdt model, we found the reduced chi-squared to be slightly less than 1, which may suggest an improper error fit for this model.[9]

Our results highlight a significant underestimate of previous flux studies, with most agreeing with $n = 2$ for the exponential value. However, given the duration of this study, as well as the equipment used, this presents a precise, although not entirely accurate, flux study. Indeed, if the duration of the study were longer, more flux data could be obtained, presenting more values to use in best fit models. Additionally, only three counters were in full operation. Using a fourth counter would change the flux data being collected, since cosmic ray muons would now have to traverse four counters in order to be classified as a detection (Figure 1). However, this would add an additional distance of approximately 10 cm to the top and bottom detector distance, which may change the flux data. In this case, it would be expected for the cosmic ray muon flux to decrease since a fourth counter would raise the requirement of being considered a measurement. The location of the detector may also explain why we found flux values to be below the expected value of $n = 2$. Construction was ongoing throughout the school day (8:35 AM CST to 3:15 PM CST). Any electrical interference may have affected these results. Our results in general suggest an under performance of the QuarkNet Detector.

VII. CONCLUSION

We conducted a short-term cosmic ray muon flux experiment to test the cos-squared model using the QuarkNet Cosmic Ray Detector and found the muon flux to decrease as the detector angle from the zenith increased. This agrees with previous experiments that varied the angle of cosmic ray detectors. For relatively low angles ($\theta < 45°$), our results roughly correspond to the $\cos^2\theta$ model, with several areas for improvement. We did find discrepancies in flux data at 30° and 75°, which we attributed to experimental issues. Resolving such issues would most likely improve our current flux model. We also found the Schwerdt[9] model to best represent the data, especially for data at high angles. The vertical shift in this model accurately accounts for muon flux at larger detector angles, whereas the simple cos-squared model would yield a null flux result.

Our findings are important for several reasons. Most notably, this is one of the first type of experiments performed on the QuarkNet Cosmic Ray Muon Detector to analyze the relation between muon flux and angle. This paper serves as a baseline for future studies that can improve upon our current value of $n = 1.39$ for QNCRD. These results also present an accurate representation of other flux experiments as detailed here, legitimizing the QuarkNet Detector as a tool for scientific research and study.

While our study was short compared to previous studies, and involved equipment with much less sensitivity than other detectors, these results are important for improving the accuracy of the detector. High schoolers, as well as particle physicists, may use this paper to guide their own studies similar to this.

This experiment not only provides a constraint on the accuracy of detecting muonic flux at varying angles for QNCRD, but also provides a framework for future long-term studies to be implemented resembling this experiment description. We have several suggestions that could improve the accuracy of this detector. More data should be collected over a longer period of time for several reasons. Ensuring that there is no seasonal, diurnal, or other temporal variations could not have been completely verified with this short of study. Collecting over a longer period of time would increase the data set, improving flux collection at various angles. We suggest collecting data over at least six months.

Using a fourth counter should improve the results. Having a four-fold coincidence would greatly increase the accuracy of the data and may bring the flux results down for high angles.

The effect of latitude on cosmic ray muon flux can be better studied with this detector. Given that QNCRD is located across the globe, this paper shows that a worldwide study may be performed to better understand how flux changes with latitude.[2] A similar study may be performed to study variations in altitude.

ACKNOWLEDGMENTS

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RCV would like to thank Shane Wood for taking the time to meet with him after school and directing this study, as well as providing comments for this paper. From his class, RCV learned the fundamentals of cosmic rays, but with his guidance, he has been able to explore the subatomic world in much more depth. RCV would also like to thank Dr. Mary Sande and Logan Doroff for allowing this study to take place in their high school classroom. Finally, RCV would like to thank Rodney Venterea for supporting his scientific endeavors and providing feedback for this paper.

DATA AVAILABILITY

The data used in this study are publicly available here: `https://github.com/ricco-hub/cosmic_rays/tree/master/Angles`.

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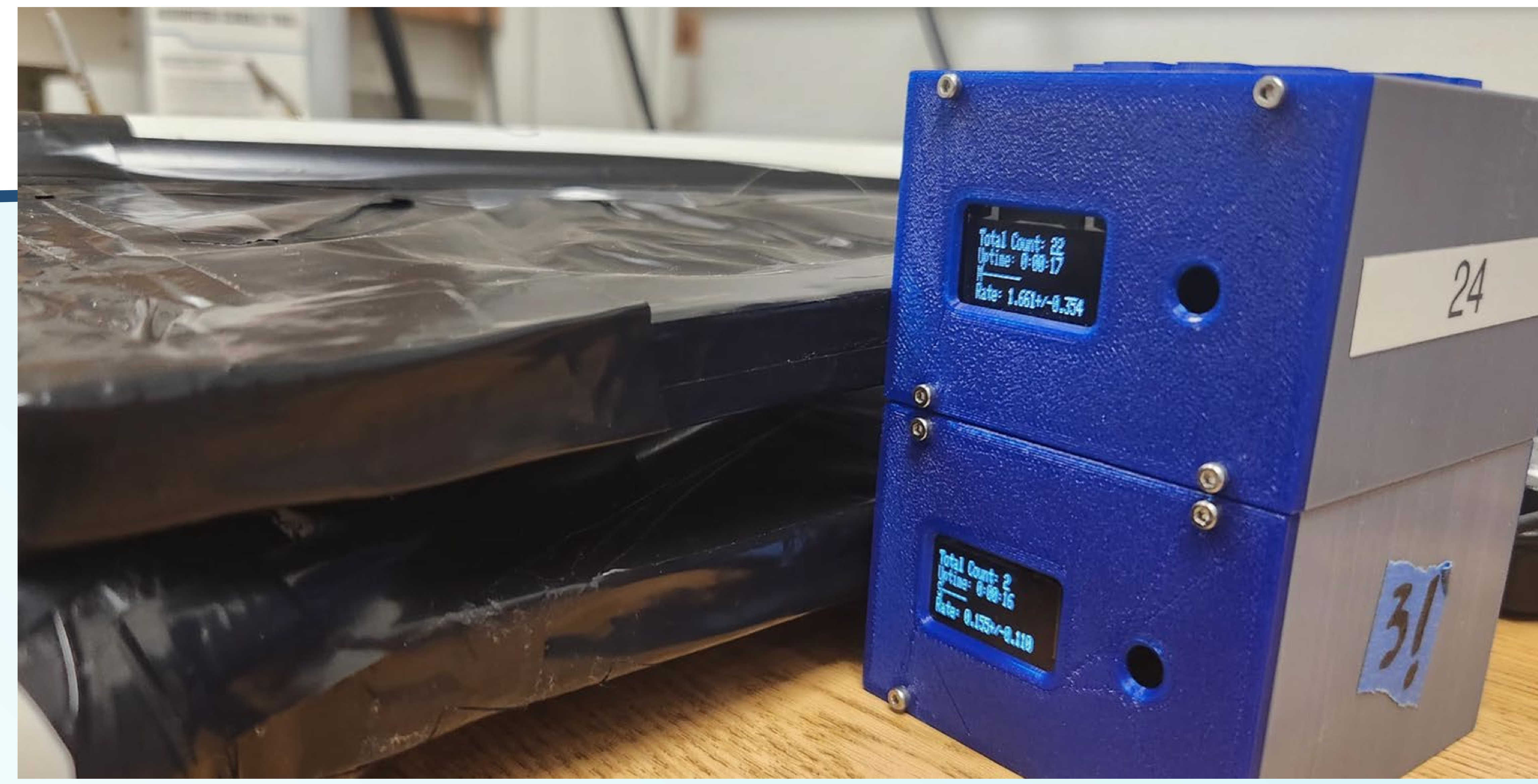
Muon Detection Rate Comparison - CRMD vs Cosmic Watch Acceptance Matters

Joe Bollinger - Prior Lake High School

Randy Hedlund - South High School Minneapolis

Mike Plucinski - Providence Academy



Introduction

Greetings! The cosmic watch provides a portable, user friendly option for detecting cosmic ray muons in the classroom, but how does it compare to Fermilab's larger Quarknet

Both utilize plastic scintillator sheets and detect light from charged particles, such as muons, within them. Their area sizes are different, though and also, when setup in 2 fold coincidence, they have different angles of acceptance unless their vertical spacing is adjusted.

Comparison of flux rates is made to determine the effect of scintillator area, as well as angle of acceptance.

Materials & Setup

A Quarknet Cosmic Ray Muon Detector with 2 scintillator counters as well as 2 Cosmic Watch Detectors. Both setup in 2 fold coincidence. The Quarknet detector was plateau to observe a count frequency of approximately 28 Hz.

Initial data collection was made with the counters each placed as close as possible to each other, as seen in the top center image.

- Quarknet Detector vertical separation: 3.2 cm
- Cosmic Watch vertical separation: 5.2 cm

To produce the same angle of acceptance as the Cosmic Watch detectors (approx 50 degrees), the Quarknet Detector counters were separated to a vertical distance of 29 cm

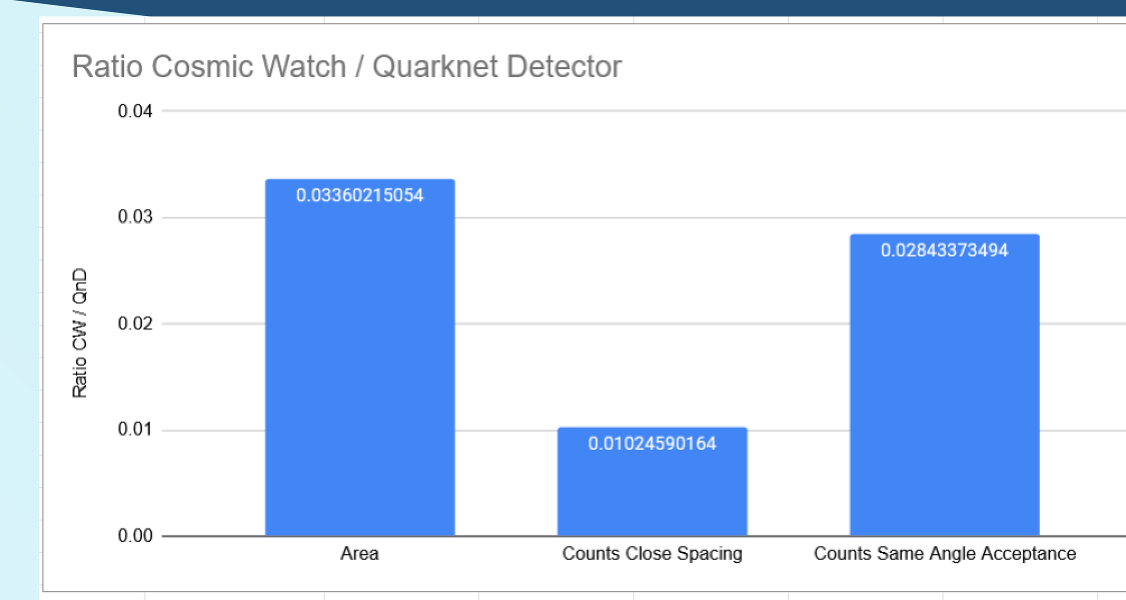
Coincident counts for each detector type was measured and compared for 5 minute periods.

Results

Size of Large detector	Size of small detector	Expected ratio of Muons
744 cm^2	25 cm^2	30:1

Spacing	CRMD Counts	Cosmic Watch Counts	Ratio	Average
CRMD - 3.2 cm CW - 5.2 cm	2795	28	100:1	
CRMD - 3.2 cm CW - 5.2 cm	2834	36	79:1	
CRMD - 3.2 cm CW - 5.2 cm	2723	28	97:1	
CRMD - 3.2 cm CW - 5.2 cm	2872	23	125:1	**100:1**
CRMD - 54 cm CW - 5.2 cm	522	35	15:1	**15:1**
CRMD - 29.2 cm CW - 5.2 cm	1058	19	56:1	
CRMD - 29.2 cm CW - 5.2 cm	1009	31	33:1	
CRMD - 29.2 cm CW - 5.2 cm	990	30	33:1	
CRMD - 29.2 cm CW - 5.2 cm	1093	38	29:1	**38:1**

Results



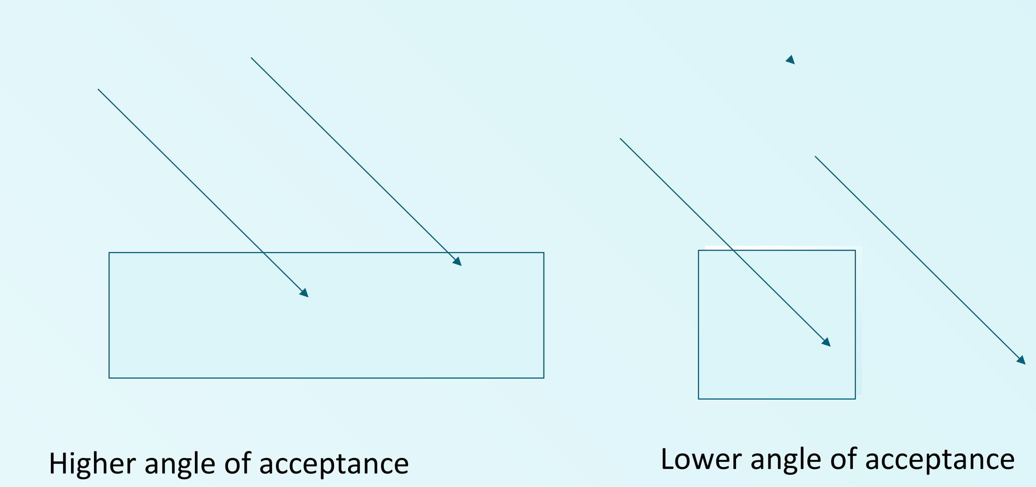
Error of Counts for Same Angle Acceptance Ratio is +/- 0.0089

Conclusion

In conclusion Acceptance matters.

If the detectors were working with the same efficiency the cosmic ray muon detector (CRMD) should be 30 times greater than the cosmic watch (CW) due to size alone. Differences in muon counts could be due to differences in scintillators, difference in angle of acceptance or other factors. When we moved the larger detector to match the angle of acceptance of the smaller cosmic watch our muon detection rate (38;1) was closer to our expected size ratio (30:1).

Further studies could be done in determining idea acceptance ratios.

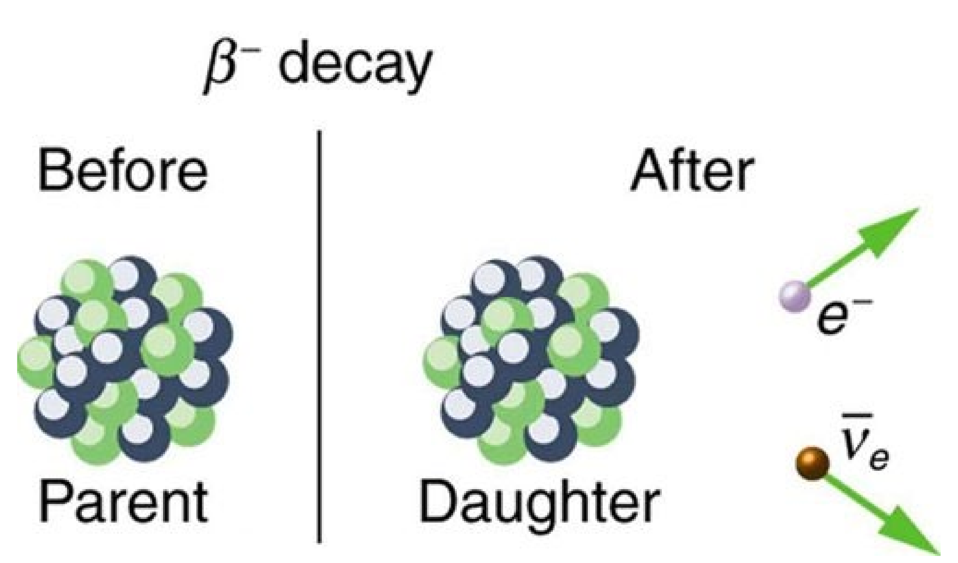


Beta Decay Detection vs Distance

Karina Houle and Michael Hamann
QuarkNet Ninjas

Abstract

The Cosmic Watches are a simple and portable means to detect the high energy particles that are all around us. They utilize a solid scintillator that emits a photon when interacting with a beta particle. Potassium-40 is a naturally occurring isotope of potassium that undergoes beta-decay. This isotope makes up about 0.012% of natural potassium so any potassium chloride purchased will be a weak beta emitter. We were able to see the exponential decay of the detectable events as the distance between the source and the detector increases.

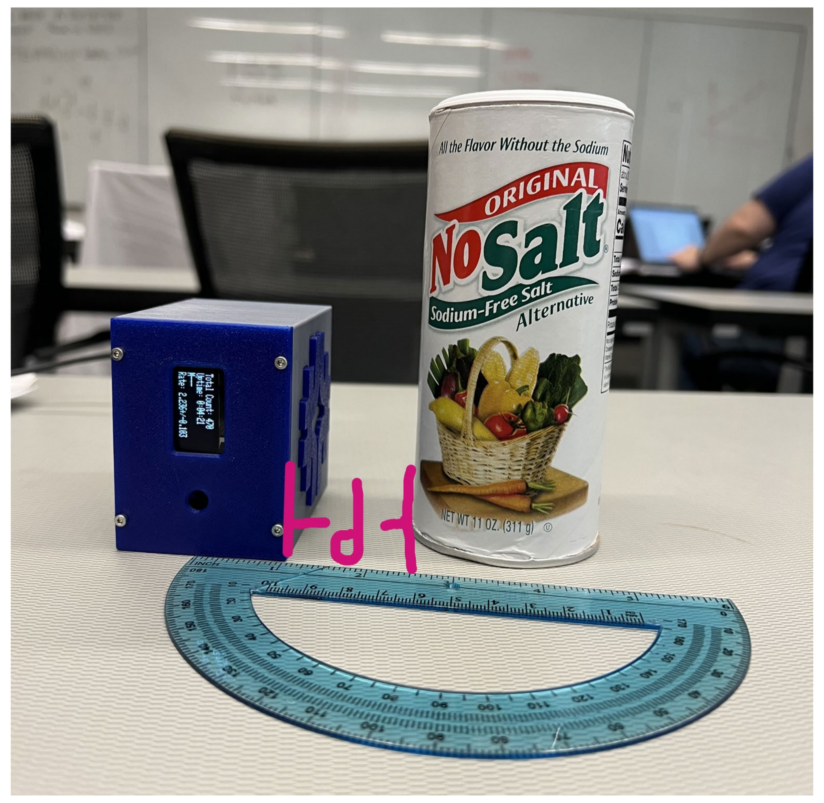


Introduction

We want to investigate the relationship between the Cosmic Watch detector and the KCl beta source effects the detection of the beta particles.

Methodology

A sample of Potassium Chloride (KCl) was placed directly next to a Cosmic Watch. The distance was measured from the end of the Cosmic Watch to the Potassium Chloride source as noted in Figure 1. The Cosmic Watch was reset so as to gather data only for a given time period of five minutes. The number of events counted for that time period was recorded.



Conclusion

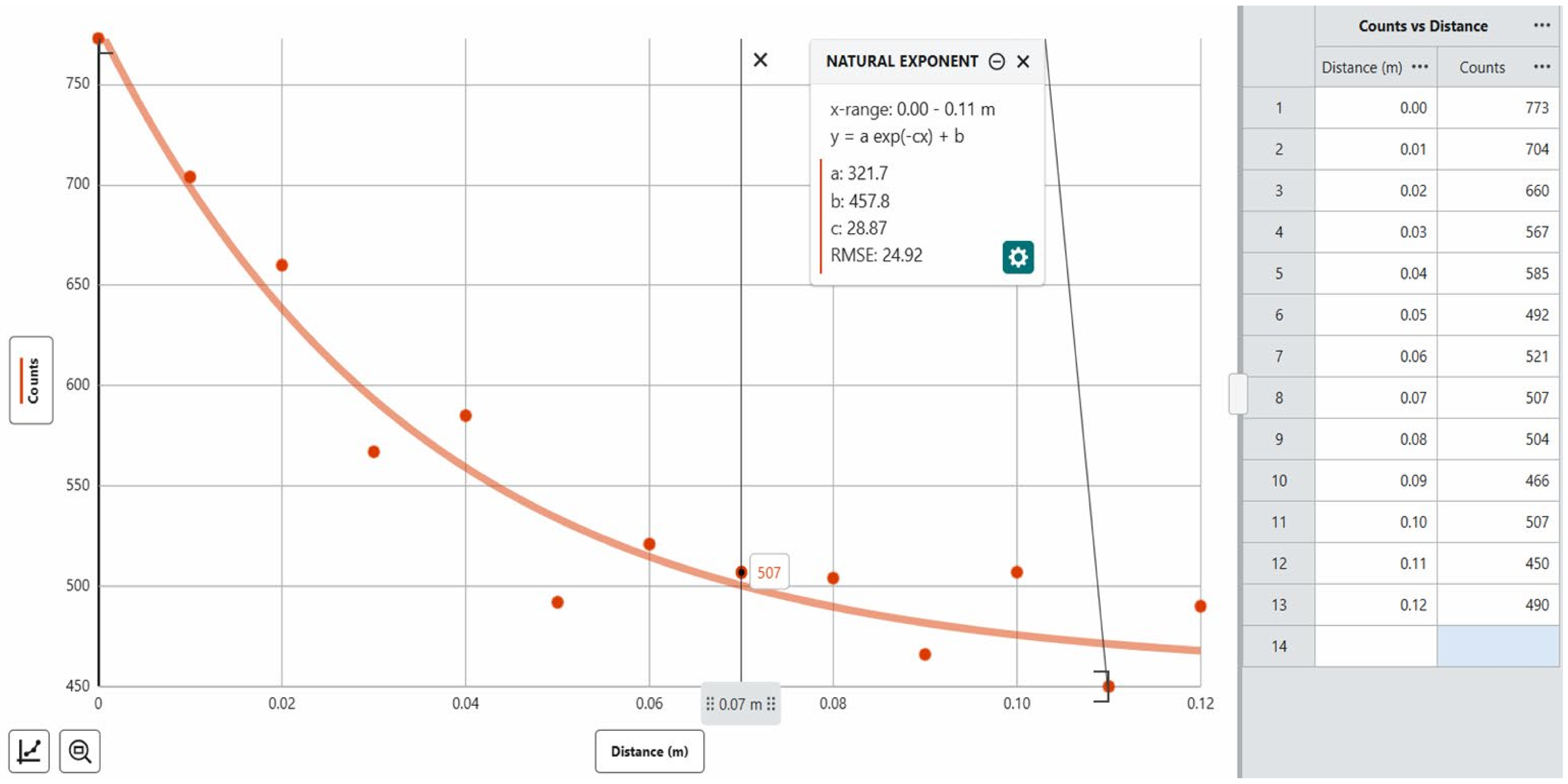
As the beta source increases it's distance from the detector the number of decay particles detected decreases. The data suggests the background amount of particles detected from outside sources is 458 per 300 seconds of time.

A future investigation would included two Cosmic Watches in sequence. This would eliminate the background noise. Thus, we would suspect that data to have a similar results yet with a b value of 0. We conclude that this is a valid experiment that students could conduct in a reasonable period of time to learn about numerous physics topics including beta decay, exponential decay, and other topics related to particle physics.

Results

We found that the number of detections vs the distance between the detector and the beta source followed a predictable exponential decay that can be described as the following:

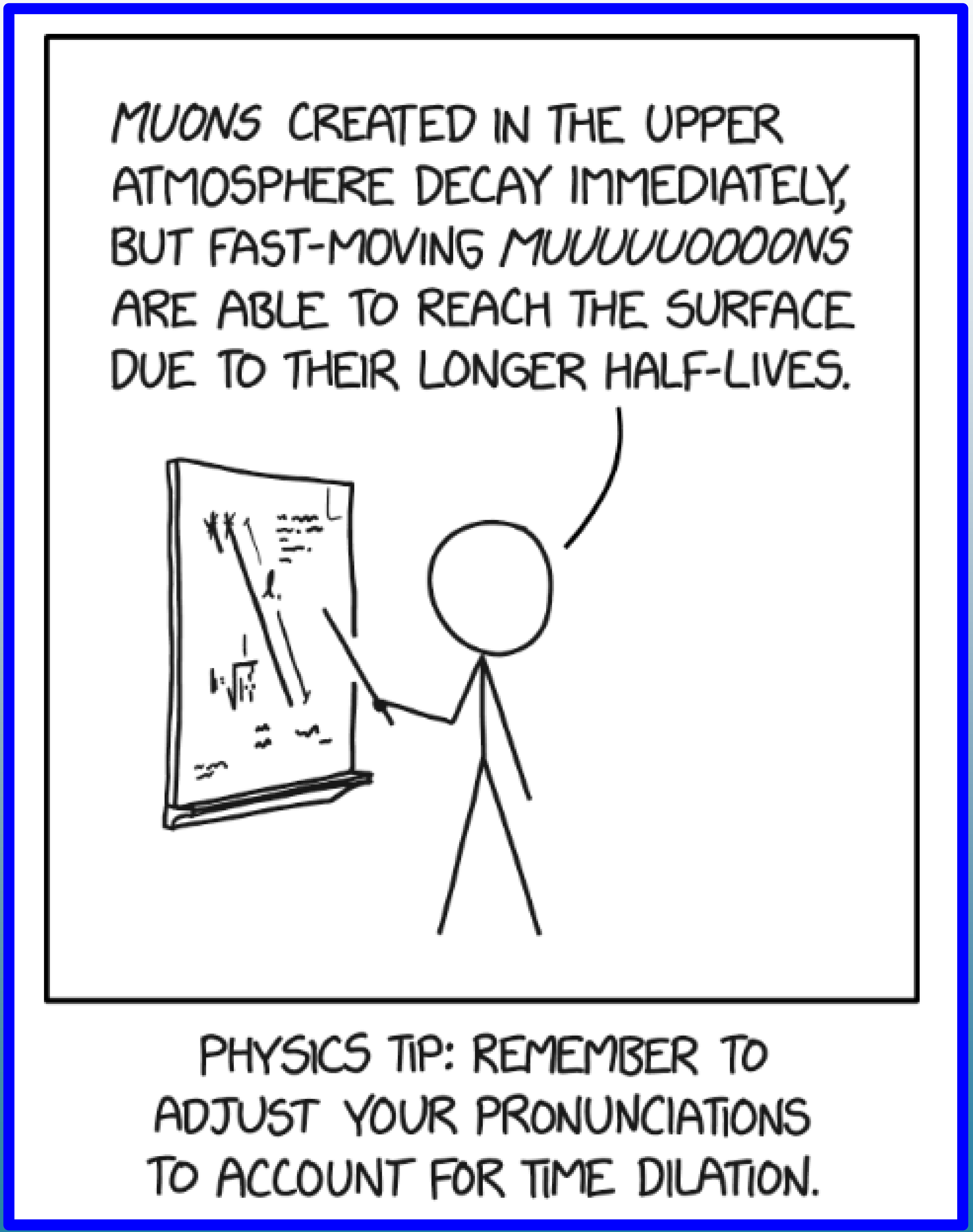
$$\#\,Counts = 321.7e^{-28.87*Distance} + 457.8$$



The number of counts appears to be diminishing by a smaller and smaller amount as distance between the detector and the source decrease. This suggests that the number of counts will never reach zero and this means that there is a base number of counts due to background events that are independent of the KCl beta source. Based on our data, we predict that the background events will settle around 458 counts as the beta source reaches greater distances.

The effects of detector separation on coincident counts for vertically oriented Main and Secondary Cosmic Watch detectors

Matt Washenberger Mounds View HS,
Jon Huber Burnsville HS



The effects of detector separation on coincident counts for vertically oriented Main and Secondary Cosmic Watch detectors

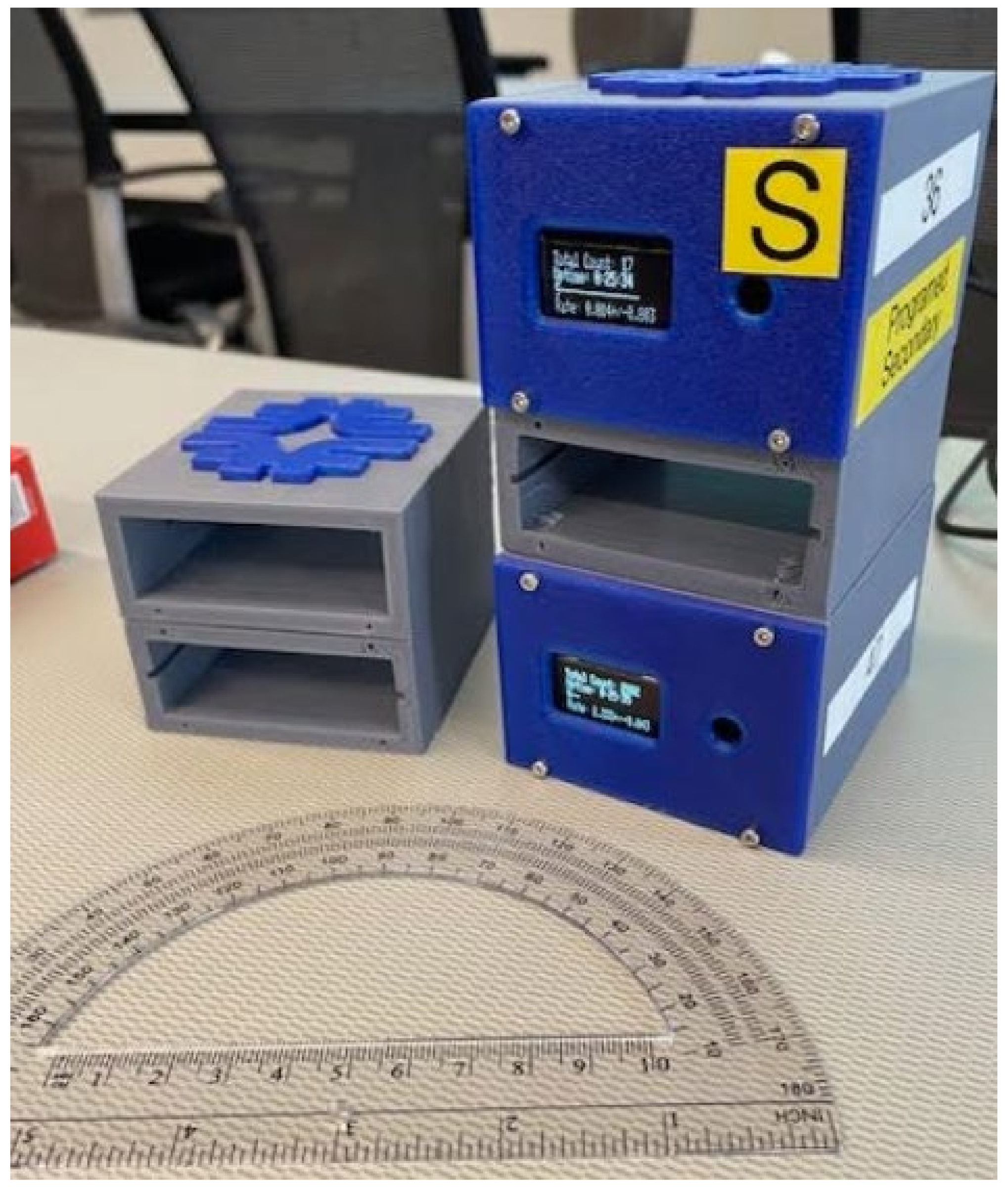
Matt Washenberger Mounds View HS,
Jon Huber Burnsville HS

Abstract

This research explores the relationship between counter (Cosmic Stopwatch) separation distance and the rate of coincident counts in a Cosmic Watch detector system. Using a two-counter scintillation setup connected via a coincidence circuit, we measured the number of simultaneous particle detections—coincident counts—at varying distances between the counters. The primary aim was to investigate how spatial separation affects the detection of cosmic ray muons, which typically travel in near-straight trajectories.

Experimental Equipment Setup

2 - Cosmic Stopwatches
3 - Cosmic Stopwatch Spacers
1 - Centimeter measuring device



Theory

The coincidence count rate is influenced by several factors, one of which is the separation distance between the counters. When the counters are aligned vertically and closely spaced, a greater number of muons can pass through both detectors, resulting in a higher coincidence rate. As the distance between the detectors increases, the geometric acceptance (or solid angle subtended) of the system decreases. Fewer muons have the appropriate trajectory to pass through both detectors, leading to a reduced coincidence rate.

Methodology

Collecting the data for this lab involved placing one Cosmic Stopwatch (the secondary stopwatch) directly on top of the primary Cosmic stopwatch. We reset the clocks by unplugging and plugging in the Master stopwatch. We allowed the setup to run for 15 minutes. We then recorded the counts displayed on the secondary clock since the primary clock displayed total counts and the second displayed only coincident counts. After recording the data we added a spacer between the main and secondary clocks and repeated the data collection as described above.

Results

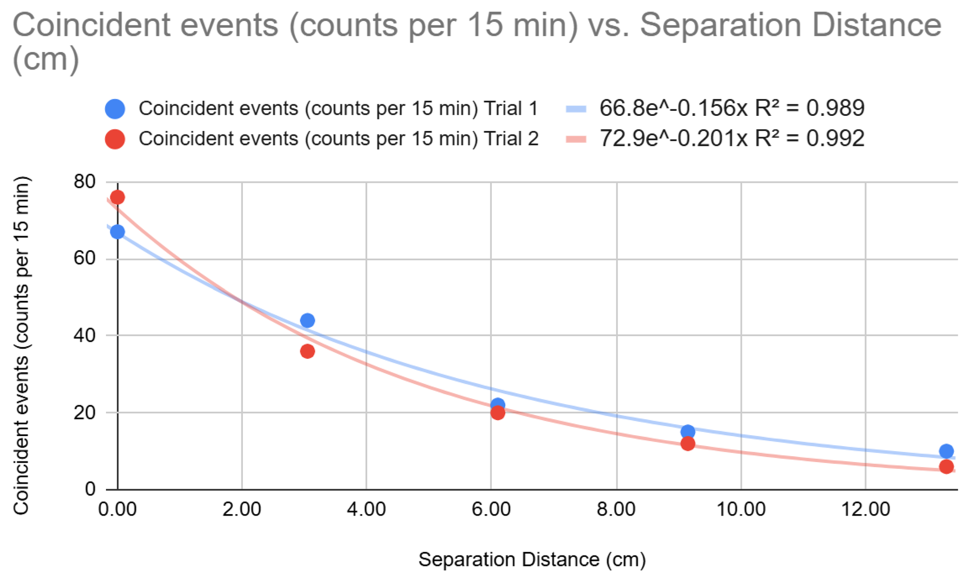


Figure : Coincidence as a function of counter separation with initial separation set at zero.

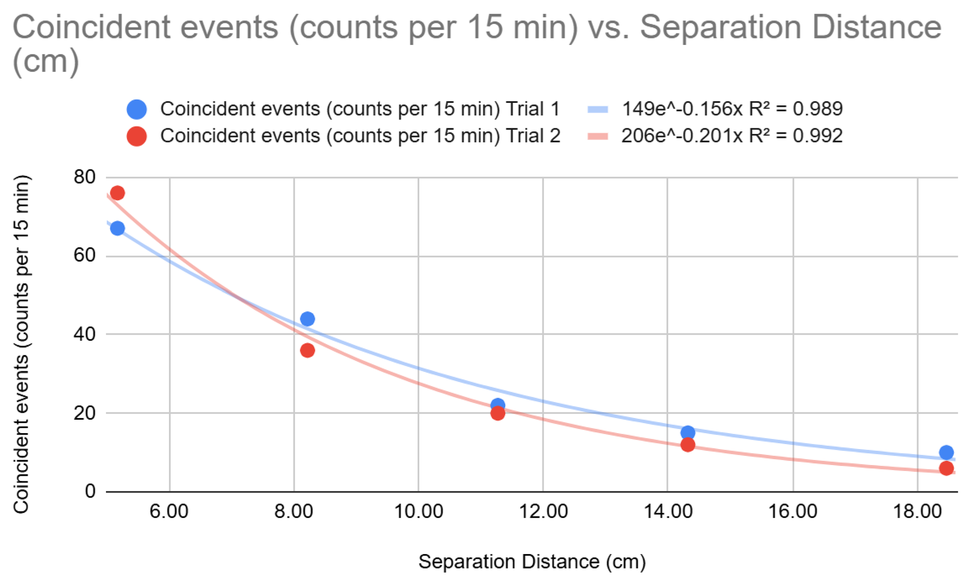


Figure : Coincidence as a function of counter separation with initial separation set at height of counter. (assumed distance between scintillators)

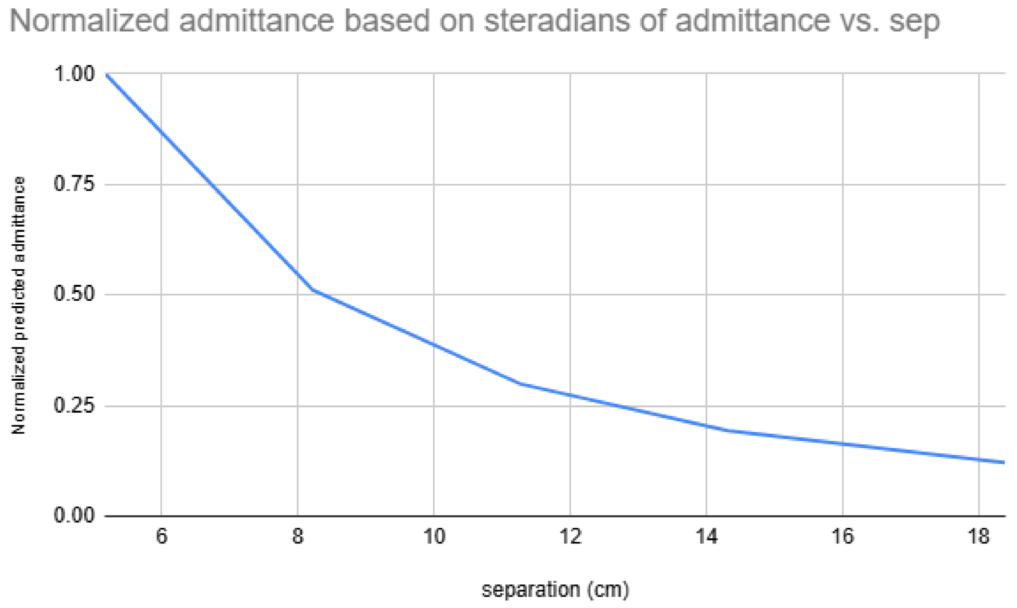


Figure :Prediction of admittance (Normalized) based on Steradians assuming conic geometry.

Conclusion

Our results show a clear inverse relationship between counter separation and coincident count rate, consistent with the expectation that fewer muons simultaneously traverse both detectors as the distance increases. The findings support the hypothesis that coincident count rate decreases approximately exponentially with increasing separation, primarily due to the angular spread of incident muons and geometrical alignment constraints.

Recommendations

- This experiment underscores the importance of detector geometry in cosmic ray studies and offers a foundation for optimizing future detector array configurations.
- In order to better see the trends it would be beneficial to have more, thinner stopwatch separators. The data set could be more complete such that the confidence in the shape of the trends would be more confidently indicated.
- We chose to use 15 minute time intervals due to time constraints for this research. We proposed to use different amount of data collection times in order to discover if there is an "optimal" amount of data collection time.

Acknowledgements

We thank Nate Unterman and Shane Woods for the opportunity to conduct this investigation as part of the summer 2025 UMN QuarkNet workshop, the University of Minnesota School of Physics and Astronomy for the use of PAN facilities, and QuarkNet for the ongoing support of our work in educating our students..

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