Center-Level Portfolio: University of Minnesota

The following table, proposed implementation plans by participating teachers, and when available other examples are intended to provide an overall narrative about how and in what ways program participation has influenced teachers in using QuarkNet content and materials in their classrooms (and in-after class events). The value of these qualitative reviews is to expand on the instructional practices measured quantitatively via Teacher Survey responses to specific sets of questions/self-reported by teachers providing narrative examples of implemented or planned instructional practices in teachers' classrooms and in schools. This evaluation approach is consistent with the use of *authentic assessment* to evaluate performance, "teaching for understanding and application rather than for rote recall" (Darling-Hammond & Snyder, 2000, p. 523).

In keeping with Darling-Hammond, Hyler and Gardner (2017), we do not naively expect a single workshop (or event) to have a measurable impact on teachers' knowledge and subsequent classroom implementation. A characteristic of effective professional development is a program of sustained duration, providing "multiple opportunities for teachers to engage in learning around a single set of concepts or practices; that is rigorous and cumulative" (Darling-Hammond, et al., 2017, p. 15). As such, the table summarizes responses by teachers over the course of several program years and likely several QuarkNet programs and/or events.

These responses come from the Teacher Survey (either the full or update version) where each row represents the responses to open-ended questions from the same teacher over time. Also, each row starts with the original responses to the first time a teacher completes his/her full teacher. If a particular box in the table is blank, it likely means that that teacher did not participate in an event for that program year (or, the center may not have had a major event that year). The table provides the essence of these responses; a given response, as presented, may be a direct quote, a paraphrase, or lightly edited; the intent is to convey the overall idea or its essence from that particular teacher.

Because these are responses to open-ended questions, teachers are free (and encouraged) to provide information that he or she thinks most relevant. Each highlighted response is intentionally anonymous to respect the principles of collecting evaluation data (*Guiding Principles for Evaluators*, American Evaluation Association) and to help encourage teachers to respond frankly to these questions. If a reader is familiar with a given center, it may be possible to "reverse engineer" the identify of a particular teacher. We encourage readers to respect this anonymity. At various times, we may have identified a given teacher by name and/or school; when this happens the written approval of that teacher has been obtained. It is also important to note that the full breath of a response by a given teacher may not be fully articulated in this table. For example, responses related to how QuarkNet may have advanced the knowledge of a given teacher or bolstered a collegial network among participants are likely discussed elsewhere in subsequent evaluation reports.

The table is followed by examples of implementation plans, and at times teacher presentations and student presentations when available. The intent of providing these examples is to deepen the narrative as to what and how teachers have planned (and have used) QuarkNet content and materials in their classrooms and in-after class events (e.g., Physics Club). Examples from Annual Center annual reports may be highlighted as well.

Table
Self-reported Use of Data Activities Portfolio Activities: Based on Responses from the Full Survey and then Responses from the Update Survey in Subsequent Years **University of Minnesota Center**

Center	Program Year (Year of Full Survey)	Subsequent Program Year	Subsequent Program Year	Subsequent Program Year
University of Minnesota	2019	2020	2021	2022
	Penny Histograms, Rolling for Rutherford, That's How We Roll (Dice Histograms) - good hands on ways to show how Histogram data is useful		Rolling with Rutherford	
	Quark Workbench and others. These are valuable resources because I know that have been vetted for accuracy and correct. They also have wonderful directions and teacher notes.	I'm interested in doing a masterclass now that I'm teaching upper-level science courses. I also intend to continue using the lesson examples in the resources that are in QuarkNet. Examples: Quark Workbench Rolling with Rutherford.		I have used a lot of the content of in various ways. Primarily with introducing the basic ideas of particle physics with students and then giving them resources to continue exploration on their own. I also have the resources for activities in various ways to have students collaborate in full blown lessons focused on particle physics. Examples: Quark Workbench, Rolling with Rutherford.
	Quark Work Bench, Mass of US Pennies, Cosmic Rays and the Sun, Cosmic Ray e-Lab	I try to sprinkle in as many activities as I can in my various classes. I also lead the Particle Physics Club at our school. I do plan on adding the Careers in Physics activity this year as well as. Examples: -Step Up: Careers in Physics -Quark Workbench -Rolling with Rutherford.		Quark Workbench, Histograms: The Basics. QuarkNet Changing the Culture, Rolling with Rutherford, Careers in Physics, CMS e-Lab.
	Masses of a Penny QuarkNet Workbench Dice, Histogram, & Probability Calculate the Mass of the Z CMS Masterclass Cosmic Ray e-Lab	Using the e-lab the deal with conservation momentum and vector analysis; along with using the Cosmic Ray detector with students to analyze data and have then choose what they want to explore. Examples: Mass of U.S. Penny, Quark Workbench 2D/3D, Histograms: The Basics, Calculate the Z Mass.		

Table (con't.)
Self-reported Use of Data Activities Portfolio Activities: Based on Responses from the Full Survey and then Responses from the Update Survey in Subsequent Years **University of Minnesota Center**

Center	Program Year (Year of Full Survey)	Subsequent Program Year	Subsequent Program Year	Subsequent Program Year	Subsequent Program Year
University of Minnesota	2019	2020	2021	2022	2023
	Rolling w/Rutherford, Top Quark, Cosmic Ray Experiments of Time of Flight and Lifetime	Introduction content - Use Rolling with Rutherford. Planning to use Careers in Physics and Changing the Culture this coming year as well. End of intro kinematics/constant velocity use Cosmic Rays. Examples: Rolling with Rutherford Top Quark Speed of Cosmic Ray Muons	Rolling with Rutherford for data collection (and achieving an indirect measurement result), Time of Flight cosmic ray experiment for constant velocity, Muon lifetime cosmic ray experiment for relativity. Examples: Rolling with Rutherford, Making Round the Bend, Top Quark.	I use many QuarkNet activities for data analysis. Showing how data can be collected, working with (in spreadsheets and python notebooks) and with outcome results presented. Also, when they tie in to the current topic being covered (time of flight of cosmic ray muons in the constant velocity unit as an example). I try to use QuarkNet activities as I'm able to. Examples: Python notebooks, cosmic ray detector time of flight and muon lifetime experiments, top quark vector analysis, Rolling with Rutherford, Making it Round the Bend.	
	Rolling with Rutherford	Use CMS & Cosmic Ray e-Labs, Masterclass, W2D2, Data Activities Portfolio, and neutrinos extensively in Particle Physics Research Hybrid course. Use these resources to a small degree in AP Physics 1. Examples: Mass of U.S. Pennies, Quark Workbench 2D/3D, QuarkNet: Changing the Culture, Rolling with Rutherford	e-Labs for several activities; to explore conservation laws and standard model; use CMS detectors and CMS data. Examples: Rolling with Rutherford Calculating the Z Mass Cosmic Ray e-Lab.	I use many QuarkNet activities for data analysis. Showing how data can be collected, worked with (in spreadsheets and python notebooks), and with outcome results presented. Also, when they tie in to the current topic being covered (time of flight of cosmic ray muons in the constant velocity unit, as an example), I try to use QuarkNet activities as I'm able to. Examples: Python notebooks, cosmic ray detector time of flight and muon lifetime experiments, top quark vector analysis, rolling with Rutherford, makin' it round the bend.	I use Rolling with Rutherford as a good intro, indirect measurement activity (and also have tacked on some error analysis application to it too). I also have used the Top Quark activity for 2D momentum and by-hand vector analysis. I use the Cosmic Ray time of flight and also Cosmic Ray lifetime activities too, tying them together to apply as an example of relativity. Anytime students get to work with and analyze data is a good day in physics, from my standpoint at least. Many of the data activities portfolios give such an opportunity and also tie in to core intro physics concepts.
	Calculating the mass of the Z boson is probably the most used activity. It is easy to incorporate into the momentum unit. I've also used the quark workbench, rolling with Rutherford, and a few others.	I began by incorporating individual lessons into my regular and advanced physics classes (data activities mainly). I also have had student interest in a "particle physics group." Examples: Quark Workbench Rolling with Rutherford, Making it 'Round the Bend	Preparing an Introduction of Particle Physics based on Data Activities Portfolio activities.	Consistently incorporated QuarkNet materials in my classroom; about 10-12 of the activities from the data activities portfolio with my students. Learned several teaching methods by working with QuarkNet staff: how to create exceptional group work/cooperation; how to engage students and catch their interest. Consistently been bettered through my interactions with QuarkNet staff and other teachers. Examples:	I've used at least half of the activities, maybe 3/4 of them. Mass of the Z Boson is used every year Also: Quark Workbench Making it Round the Bend Masterclasses

				Making it Round the Bend, Quark Workbench, Rolling with Rutherford.	

Table (con't.)
Self-reported Use of Data Activities Portfolio Activities: Based on Responses from the Full Survey and then Responses from the Update Survey in Subsequent Years **University of Minnesota Center**

Center	Program Year (Year of Full Survey)	Subsequent Program Year	Subsequent Program Year	Subsequent Program Year	Subsequent Program Year
University of Minnesota	2019	2020	2021	2022	2023
	Rolling for Rutherford Pennies Dice Histogram. The deeper learning about the topics makes me more confident to teach the concepts in the classroom. The activities are clear and easy to adapt to the level of the students at the current time. The idea that students can analyze REAL data. This makes the concepts so much more real world - even though we are talking about particle physics! Student Interactions. The students are DOING - not just watching. They are communicating with each other and coming up with explanations based on reasoning from data. They are gathering evidence themselves.	Conservation of Momentum, Vector Addition - The Case of the Hidden Neutrino and The Mass of the Top Quark Calculate the Z-Mass. The use of Real Data and 'discovery' is what really engages the students. They like to work with data they can read about with real applications. Examples: Quark Workbench 2D/3D Z-Mass Top Quark Hidden Neutrino. The use of Real Data and 'discovery' is what really engages the students. They like to work with data they can read about with real applications			**In Subsequent Program Year 2024**: I intend to use the Water Waves - Interference Experiment and the Electron Diffraction Experiment during the Waves unit. I intend to use the Millikan Photoelectric Activity and the LED experiment in the Modern Physics unit. Wave Particle Duality is very nicely shown with these activities.

Table (con't.)
Self-reported Use of Data Activities Portfolio Activities: Based on Responses from the Full Survey and then Responses from the Update Survey in Subsequent Years **University of Minnesota**

Center	Program Year (Year of Full Survey)	Subsequent Program Year	Subsequent Program Year	Subsequent Program Year
University of Minnesota	2020	2021	2022	2022
	Rolling with Rutherford, CMS e-Lab. I plan on using the Neutrino oscillation material.			It is always useful to brush on the standard model. I like how we modeled with acting how two protons turn into a Z particle then becomes 2 muons. by having students do this they will make more meaning out of it. Examples: Rolling with Rutherford. NOvA Neutrino data.
	Women in Physics - Career Profiles, and follow up data slides	Using Python notebooks to analyze large data sets and to perform numerical modeling of phenomena. Examples: Dice, Histograms, Probabilities Histograms: The Basics QuarkNet STEP UP: Careers in Physics	Last month I used the Standard Model cards, and the Quark Workbench lessons with my physics class, and I plan to do so even earlier next year. I hope to get rolling on the CRD earlier in the year as well – not sure if we'll run a club, or I'll just get some enterprising students to take care of it during class. Examples: Standard Model Card Sort, Quark Workbench, STEP UP lessons.	
		Using Python notebooks to analyze large data sets and to perform numerical modeling of phenomena. Examples: Dice, Histograms; Histograms: The Basics, QuarkNet STEP UP: Careers in Physics.		
	Program Year (Year of Full Survey)	Subsequent Program Year		Subsequent Program Year
	2022	2023		2024
		Rolling with Rutherford, Quark Workbench, Pennies, etc. Excellent introductions to the topic		I will try to use all of the activities in my end of the year lesson plan
	Program Year (Year of Full Survey)			
	2023			
	Rutherford Roll? Or maybe I'm not thinking of the correct activities you're asking about. Great way to get students involved in 21st Century Science			
	(First Year) The activities seemed useful and interactive			
	Too new (to QuarkNet) I can't wait to use these resources in my classroom!			
	This is my first workshop, still have much to explore with all the resources.			
	(First year) I am looking forward to using the data analysis graphing and coding with my students related to the water quality data they collect around the Twin Cities. New (t)his said I can see how what I have learned will make an excellent impact on what I will do in my classroom next year.			

Note: Each row presents responses from the same individual teacher from a given center. Empty table cells indicate that the teacher did not participate in QuarkNet in that subsequent program year(s). Or, less likely did not complete the Update Survey; or did not answer specific questions about the use of DAP activities in their classrooms.

Over the next several pages, the portfolio will present examples of implementation plans posted by teachers engaged at this center. This is then followed by a presentation given at 2023 AAPT Winter Conference on Neutrino Masterclasses. This is followed by an article authored by a former student who was mentored by Shane Wood during his later high school years.

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.

QuarkNet

Neutrino Physics Masterclasses

Shane Wood
QuarkNet National Staff Teacher
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www.QuarkNet.org

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

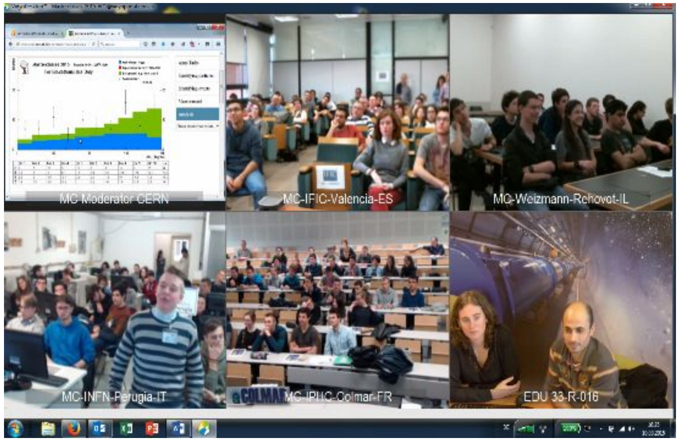
QuarkNet

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!

What is a Masterclass?

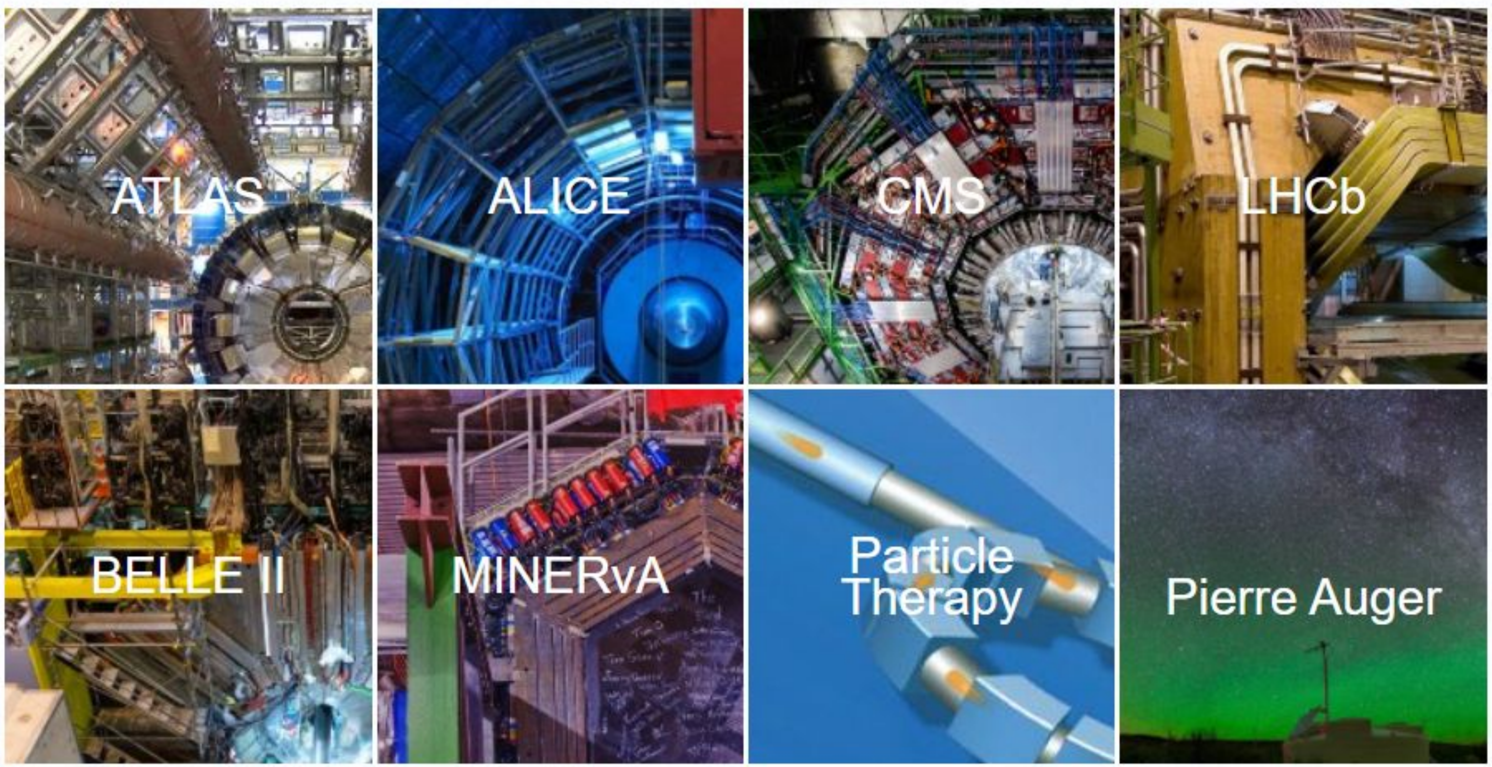
Sample agenda…

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

QuarkNet https://physicsmasterclasses.org

International Masterclasses

19th International Masterclasses 2023

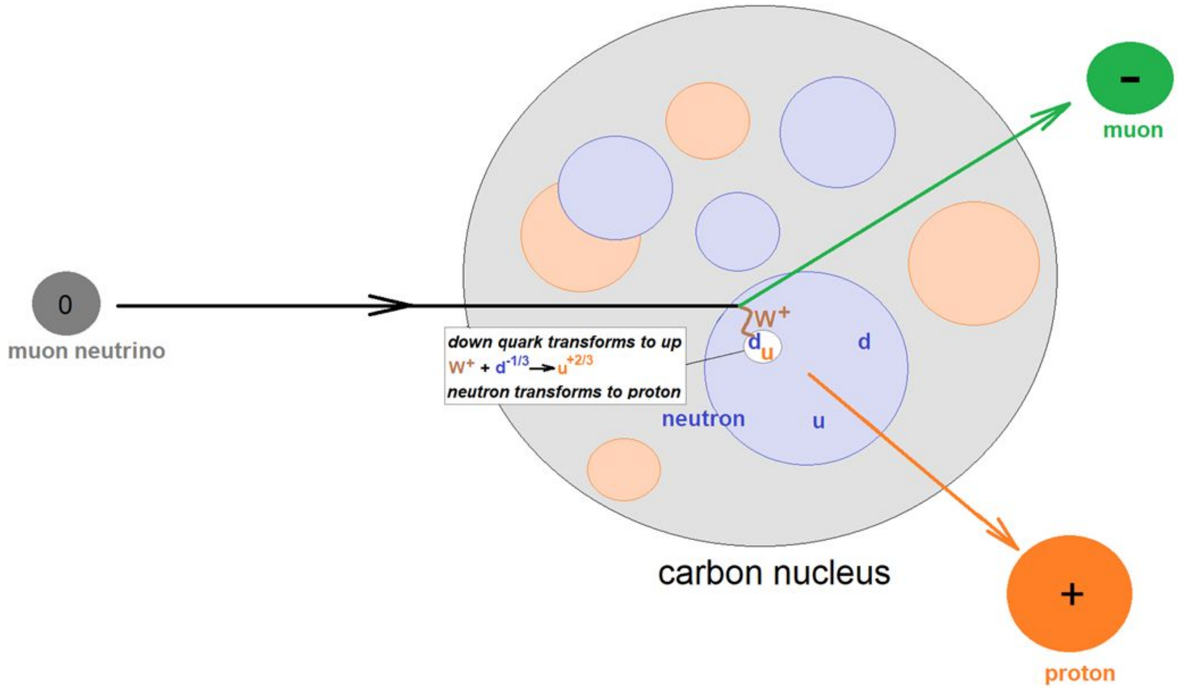


Neutrino-based Masterclasses

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

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

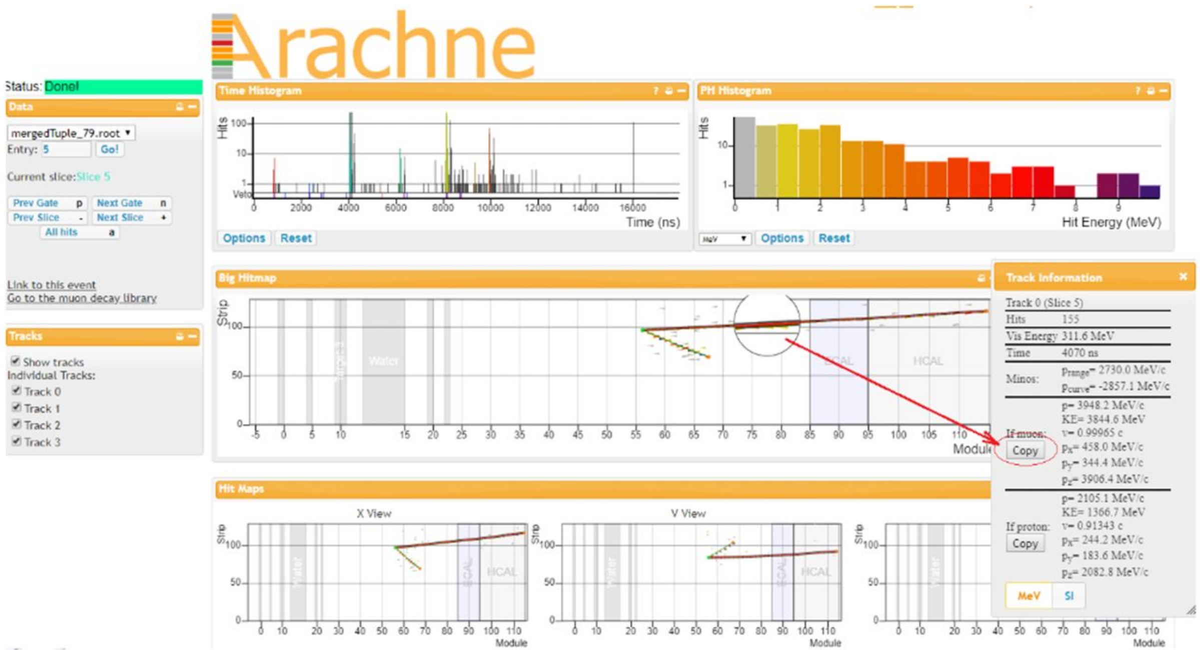
MINERvA Masterclass



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?**

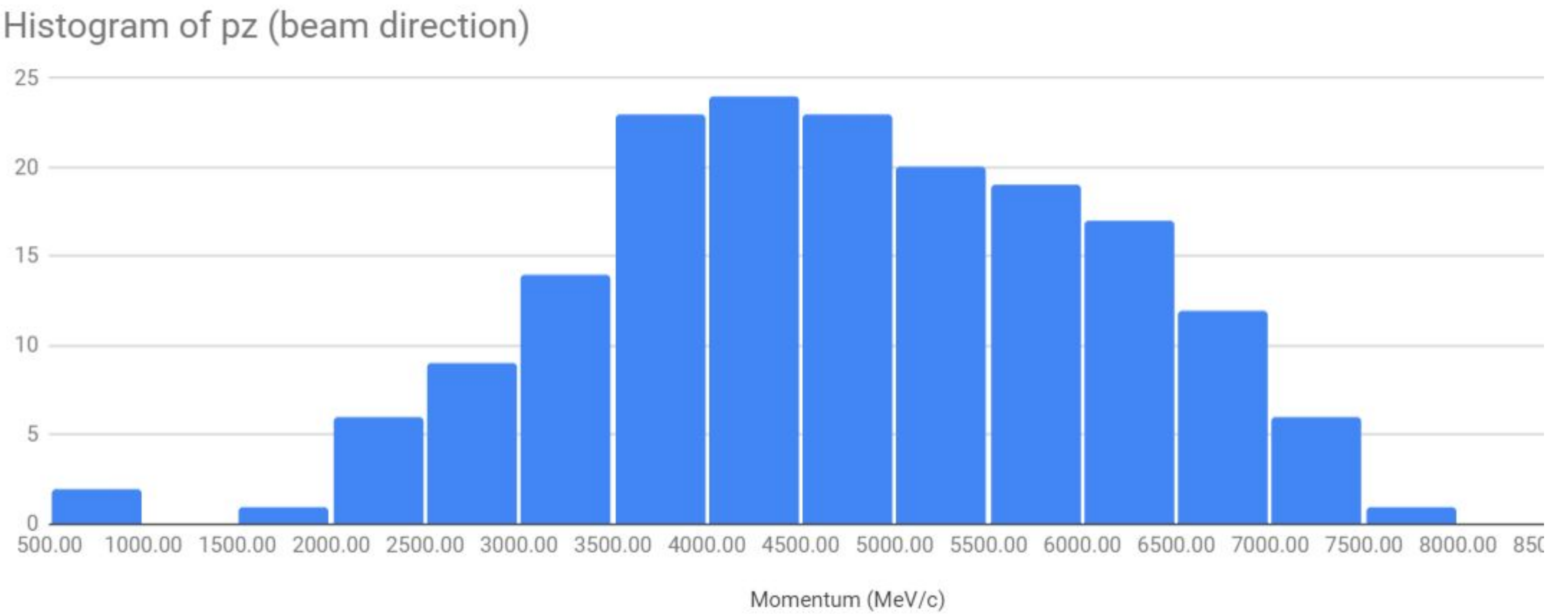
QuarkNet

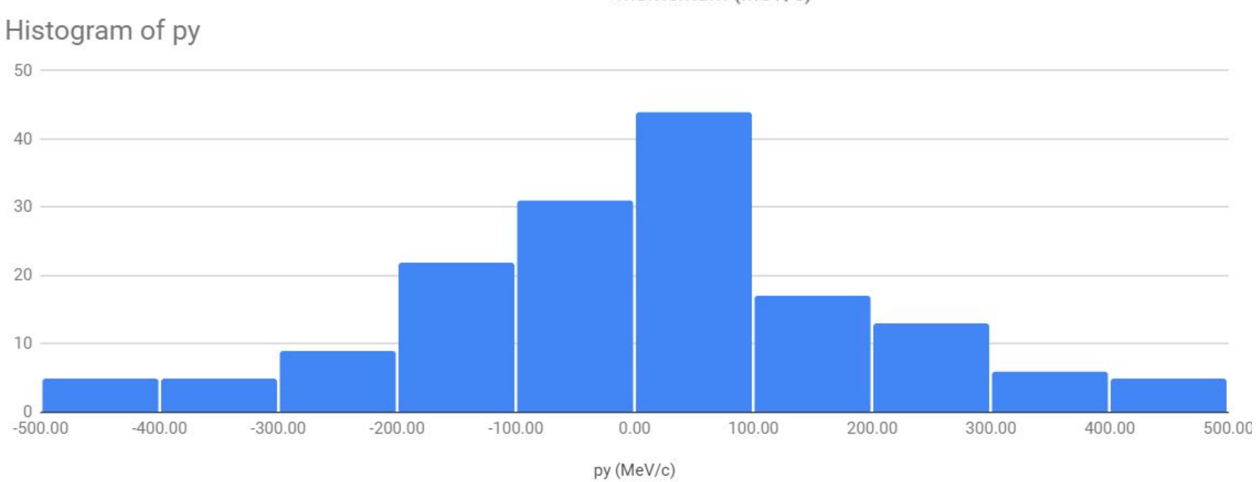
MINERvA Masterclass



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

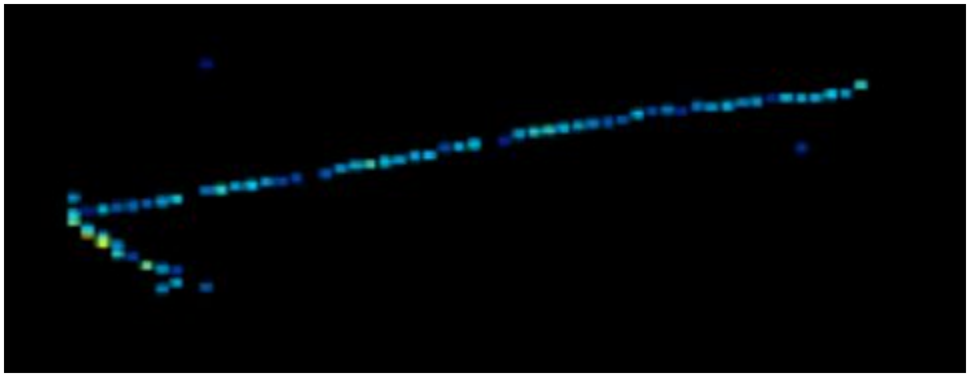
Piloting with Teachers

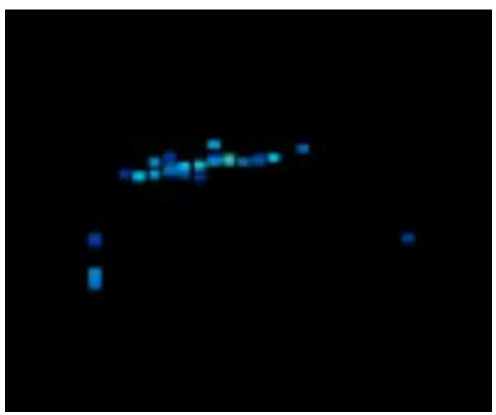
- University of MN Center Teachers
- Neutrino Fellows
- Summer 2022 workshops (4)

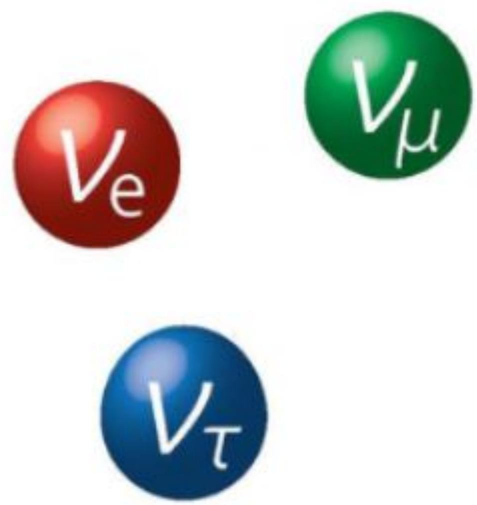
Piloting with Students

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

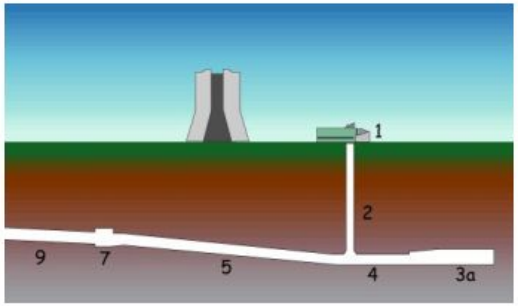
NOvA Masterclass







NOvA Experiment



QuarkNet

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.

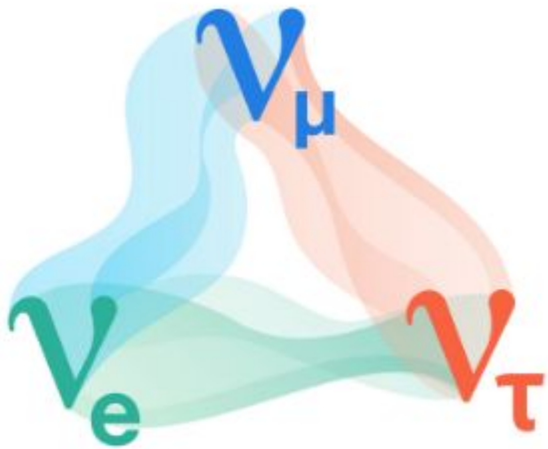
There are many ways to import data. Here we'll use an importing feature that pulls the data in from a "CSV" file that's hosted on a web page (GitHub)

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')
```

NOvA Masterclass



Students see evidence of neutrino oscillation.

Shane Wood

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www.QuarkNet.org

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

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(Electronic mail: rcv38@cornell.edu)

(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.

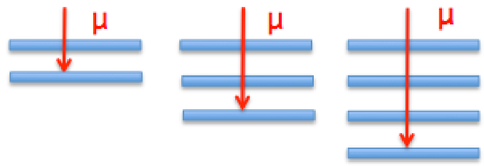

FIG. 1. Illustration of two-, three-, and four-fold coincidence, where the muon is only detected if it passes through all counters in each coincidence configuration.[11]

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.

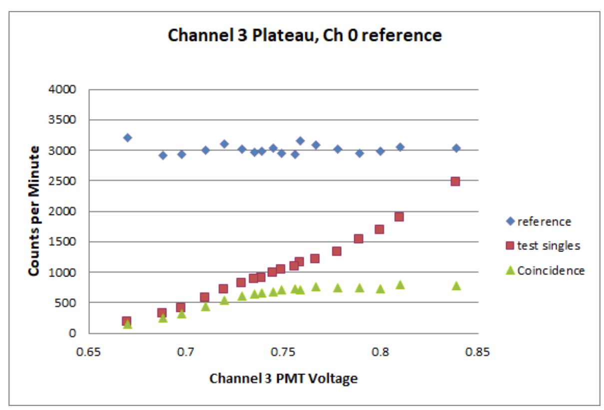

FIG. 2. Plateauing coincidence rate in channel 3 is indicated by the green triangles. The coincidence of channel 3 plateaued within a specific voltage range. This plateauing is from the second round of calibration.

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.

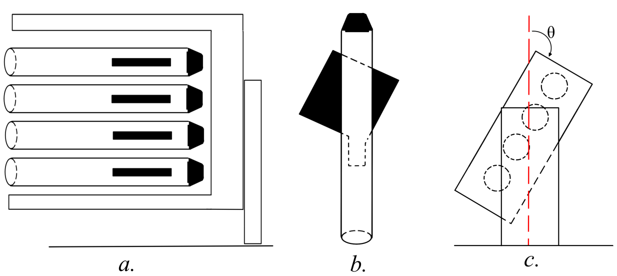

FIG. 3. Schematic of the detector configuration is highlighted in Figure 3*a*. Starting from the top, the counters are labeled Counter 3, Counter 2, Counter 0, and Counter 1. The individual counters are shown in Figure 3*b* and are represented as black rectangles. Figure 3*c* represents how the QuarkNet 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]

$$\tan\theta = \frac{w}{d} \tag{1}$$

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

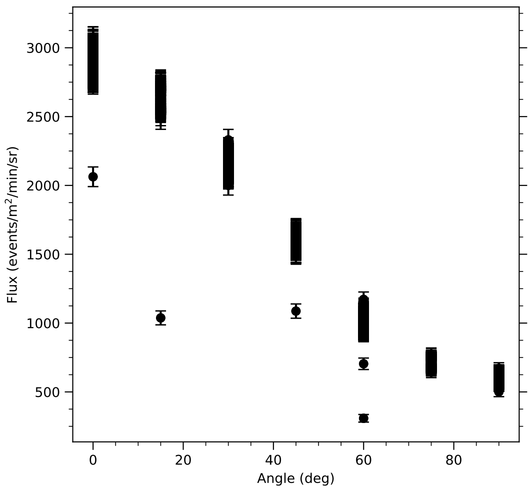

FIG. 4. Decrease of flux starting at 0° ending at 90°. These results are from channel 0 for detector 6709.

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]

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

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]

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

with

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

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]

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

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

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

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 $\theta \leq 75°$.

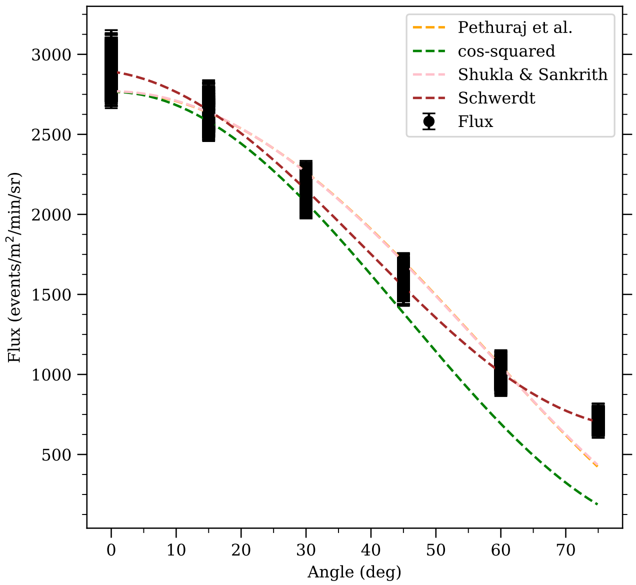

FIG. 5. Comparison of muon flux models as a function of angle with data collected in this study. Note that we only fit for $\theta \leq 75°$. Observe how well the Schwerdt[9] model agrees with the data. The Shukla and Sankrith[8] model and Pethuraj et al.[10] model agree so well they overlap.

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.

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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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