PROCEEDINGS OF SCIENCE

Outreach, Investigation, Muons, and the South Atlantic Anomaly

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In May of 2018 and January of 2019, a collaborative group from the University of Notre Dame in the United States and the Pontifical Catholic University of Chile, Masterclass Institutes Collaborating in the Americas IV (MICA IV), travelled south from Santiago, Chile with two overlapping goals. The first was to take cosmic ray data at different latitudes to test for any effect on cosmic ray rate due to the South Atlantic Anomaly, a geomagnetic deflection which extends in the Southern Hemisphere from Southern Africa all the way to Chile. The second goal was to give students and teachers workshop experiences in particle physics, including cosmic ray studies. In May, the collaborators used two QuarkNet cosmic ray detectors in the workshops for both education and as part of the investigation. In January, a return trip focused on taking better data with one of the detectors, while the other took data near-continuously in Santiago. Collaborators in the U.S. and Mexico took additional data to help calibrate the Chilean data. We discuss results of both outreach and investigation.

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1. Introduction

Masterclass Institutes Collaborating in the Americas is a program started in 2014 in response to the first Luksic Foundation Grant solicitation by Notre Dame International at the University of Notre Dame (ND). The purpose of the grant is, in general, to promote collaborative academic work between faculty and staff at ND and Pontificia Universidad Catolica (PUC) in Santiago, Chile. [1] In the specific case of MICA, the award was for collaboration in particle physics outreach and education.

There are two key programs, aside from NDI, that made the MICA proposal possible: QuarkNet and International Masterclasses (IMC). QuarkNet is a program funded by the National Science Foundation through ND and working in collaboration with Fermilab to bring particle physics to high school teachers and students. [2] While MICA was funded by NDI, most of the techniques and intellectual firepower for MICA came from QuarkNet. International Masterclasses is a program sponsored by the International Particle Physics Outreach Group (IPPOG) that organizes particle physics masterclasses at universities and laboratories worldwide for high school students and teachers. QuarkNet is an important participant in the organization of IMC. Teachers bring their students to these masterclasses in which they work together to analyze authentic data from the Large Hadron Collider at CERN—and more recently, other experiments—to be "particle physicists for a day." [3]

In that first year, an ND QuarkNet staff member and two associated teachers traveled from the United States to Chile. The objective was to work with PUC physicists on a workshop for Santiago-area high school physics teachers to bring them up to speed on International Masterclasses in particle physics. PUC and ND participated in IMC later that year with high school teachers and students. In subsequent years, MICA II and III gave the teachers a deeper understanding of particle physics data analysis, began masterclass-related physics workshops at Santiago high schools, and introduced a QuarkNet cosmic ray detector, which the teachers assembled and tested. QuarkNet donated the detector and it remains in Chile today.

MICA IV began in 2018 to venture out of Santiago with both workshops and detectors. A team of four travelled from Santiago south to multiple sites. The team consisted of a QuarkNet staff teacher from ND, an ND particle physics graduate student (since graduated), two physicists from PUC, each participating in about half of the expedition, and a Santiago high school physics teacher. Together they did workshops in five locations. The workshops included masterclass-like analyses of data from the Large Hadron Collider (LHC) at CERN as well as measurements with two cosmic ray detectors: the original left at PUC plus the QuarkNet "traveling detector" brought from the U.S. for the workshops.

The group also responded to information from PUC physicist Ben Koch, prior to the MICA IV proposal, on the South Atlantic Anomaly (SAA), a geomagnetic disturbance which stretches from southern Africa across the Atlantic and all the way to Chile. [4] A worthy second goal was to make cosmic ray measurements at each stop to see if a latitude effect on cosmic ray rate might be found. Such an effect might indicate an influence on incoming muons by the SAA. As a control, then, a parallel pair of high school physics teachers in the ND QuarkNet group travelled south from ND to look for any latitude effect on cosmic ray rates in the Northern Hemisphere.

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2. Workshops

2.1 General Plan

The workshops took place in May 2019 at eight institutions in Santiago and points south: Orchard College in Curicó, Colegio Seminario Padre Alberto Hurtado and Universidad del Bio-Bio in Chillán, Colegio Maria Auxiladora in Junín de los Andes (Argentina), Colegio Alemán in Villarrica, Liceo Bicentenario in Valdivia, and Colegio Etievan and St. George's College in Satnitago. Most were student workshops; however, the workshop at Universidad del Bio-Bio was for teachers and the workshop at Colegio Maria Auxiliadora was for both students and teachers. The traveling team consisted of team leader Kenneth Cecire (ND QuarkNet staff), Rodolfo Capdevilla (then an ND graduate student, now an incoming postdoctoral researcher at Perimeter Institute and University of Toronto), Daniela Gayoso (a teacher at Colegio Etievan and leader of the PUC teacher group), German Gomez Vargas (PUC postdoctoral researcher) for the first half of the expedition, and Sebastian Olivares (PUC postdoctoral researcher) for the latter half.

Workshops began with an activity with one of the two cosmic ray detectors. The QuarkNet cosmic ray detector consists of four counters (although the detector that traveled from the U.S. had only three) made up of flat scintillators of about 750 cm^2 area each connected to a photomultiplier tube (PMT) with a Cockcroft-Walton base, a voltage control box, a DAQ, and a GPS unit. [5] Students learned about detector operation by observing the effects that moving counters relative to each other would have on the two-fold coincidence rate. They then did a simple experiment in which two counters together would be rotated to test the effect of the zenith angle on the rate. Once this was finished, students moved on to the next part of the workshop while one or two facilitators reset the cosmic ray detectors to take data during the balance of the workshop; this is the data that was applied to searching for a possible latitude effect.

Students then did a series of activities and heard a talk to introduce them to particle physics concepts. They would start with "Particle Cards" designed to familiarize them with the fundamental particles of the Standard Model [6], attend a talk on particle physics, and then do the "Rolling with Rutherford" activity which simulates a particle physics experiment by having the students determine the size of an object by randomly rolling marbles at it and using statistics of the numbers of hits compared to the number of rolls [7]. The capstone activity is an analysis of authentic date from the ATLAS or CMS detector in the LHC at CERN based on analyses done in International Masterclasses. Where teachers were present, they would participate as students do but with a focus on what they might use in the classroom and how they might go about it.

Hora	Actividad
08h30	Saludos y introducciones
08h45	Actividad inicial con el detector de rayos cósmicos
09h15	Actividad: **Cartas de las partículas**
09h30	Introducción al modelo estándar y física de partículas
10h15	Descanso
10h30	Actividad: **Las canicas de Rutherford**
11h15	Introducción al LHC, ATLAS, y actividades de investigación en Chile
12h00	Clase magistral CMS (**animación de CMS**) (**eventos**) (**hoja de calculo**)
13h30	Almuerzo
14h30	Finalizar el análisis de CMS, si es necesario; discusion de resultados y Q&A con físicos
15h30	Descanso
16h00	Discusion de flujo de rayos cósmicos
16h30	Analisis de los datos; subir los datos si es posible

Figure 1. Agenda of workshop in Valdvia.

2.2 Workshop results

The workshops went very well. Students were able to take and analyze data and got good results. Using the cosmic ray detector, they measured how the rate varies with the direction the detector is pointed, with the most cosmic rays coming from the zenith and the fewest from the director of the horizon. In Rolling with Rutherford ("Canicas de Rutherford"), students were able to measure the sizes of targets by rolling marbles at them, just as physicists might measure an atomic nucleus by bombarding it with electrons. Most got results that were a little over the actual target diameter, as was expected due to the non-zero sizes of the marbles themselves. The main event was the masterclass, in which students analyzed data from the Large Hadron collider using event displays to learn about how particles are scattered in the beamline or to find the masses of particles. Students and teachers were very positive about the workshops and asked many good questions.

Figure 2. Student zenith angle cosmic ray results in Chillán (left) and CMS masterclass result from Valdivia (right): In the latter plot, the students found signals to indicate the masses of the J/Psi particle at about 3 GeV, the Upsilon particle at about 10 GeV, and the Z particle at about 91 GeV. The three peaks can be clearly seen in their combined plot.

3. Cosmic Ray Measurements

3.1 Method

The two cosmic ray detectors measured the muon rate at different latitudes and altitudes depending on the workshop location. The goal was to test for a possible latitude effect on cosmic ray rate. Measuring at different altitudes enabled the team to check its cosmic ray rate dependence, helping with systematic uncertainties. ND QuarkNet teachers and graduate students Jeremy Wegner and Jeffrey Chorny did a parallel measurement at different stops between South Bend, Indiana and Huntsville, Alabama. It should be noted that the maximum variation in latitude for each trip—Santiago to Valdivia and South Bend to Huntsville—was about 6 degrees.

One of the disadvantages of the approach was that, taking measurements during workshops in schools, shielding of muons by the building structures might add "burden" as a significant confounding variable. In addition, a longer baseline might help to get more reliable results. Thus, in January 2019 team leader Cecire returned to Chile and traveled with PUC graduate student Leandro Monje to make new cosmic ray measurements. This time, all measurements were made from the roof of the automobile they were using, reducing the non-atmospheric burden to zero. In addition, the two went further south to Puerto Montt, opening the interval in latitude to about 8 degrees.

To make the altitude correction as useful as possible, new altitude data at nearly identical latitudes was taken. This was added to further altitude data taken with Universidad Iberoamericana physicists Salvador Carrillo and Fabiola Vazquez in Mexico City at higher altitudes, albeit at different latitudes, than were available in the region of Chile in which the team traveled.

3.2 A note on uncertainty

The plots below do not have error bars. However, statitistical uncertainties were calculated to be all below ±10%. The lead author suspects this is slightly optimistic, so is is safe to assume ±10% for all plots.

3.3 Altitude result

The combination plot using varying altitudes was made from October 2018 readings in Mexico City and January 2019 readings in Chile. The plot was modeled as an exponential function, as shown below in the plot in Figure 3 using data from Mexico City and Chile.

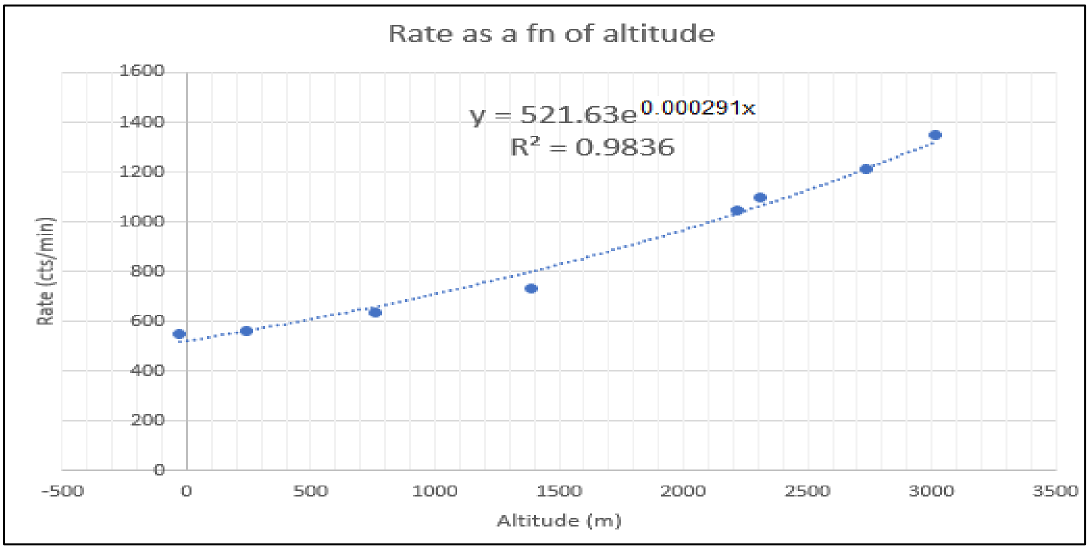

Figure 3. Plot of cosmic ray rate as a function of altitude.

The data fit to an exponential function $r = r_0e^{kh}$, where r is the muon count rate, $r_0 = 521.63$ counts/minute at sea level, h is altitude above sea level in meters, and $k = 0.000291\ m^{-1}$. A fit with only the Chile data gives $k = 0.000203\ m^{-1}$, but application of this alternative fit does not alter results significantly.

At given location, then, the uncorrected rate at that location r_{loc} is to the corrected rate r_{corr} as r from the plot is to r_0, or $r_{loc}/r_{corr} = r/r_0$ and therefore $r_{corr} = r_0r_{loc}/r$. But since $r = r_0e^{kh}$, we can write $r_{corr} = r_{loc}e^{-kh}$ or $r_{corr} = (522\ cts/min)e^{-(0.00291/m)h}$ where h is the still the altitude. This equation was applied to data taken from the two detectors in May 2018 and from the QuarkNet traveling detector in January 2019.

3.4 Latitude result

The plots that follow each have both uncorrected data and altitude corrected data.

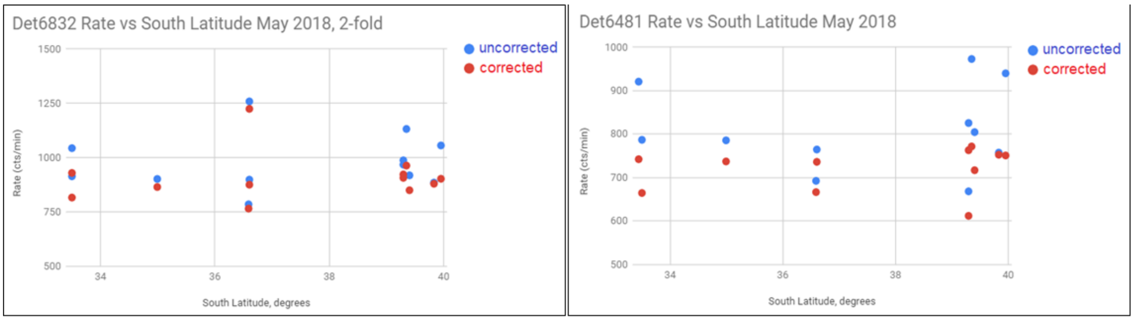

Figure 4. Data from PUC detector (6832 and and QuarkNet detector (6481) running at two-fold coincidence.

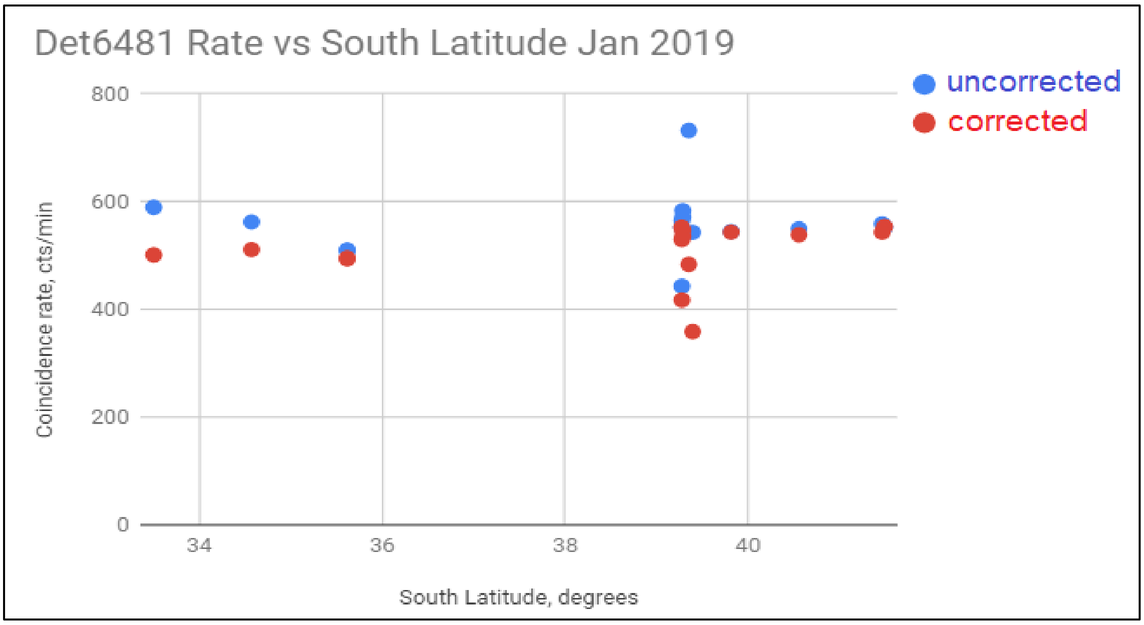

Figure 5. Data from detector 6481 taken January 2019. This coincidence level is set to three-fold.

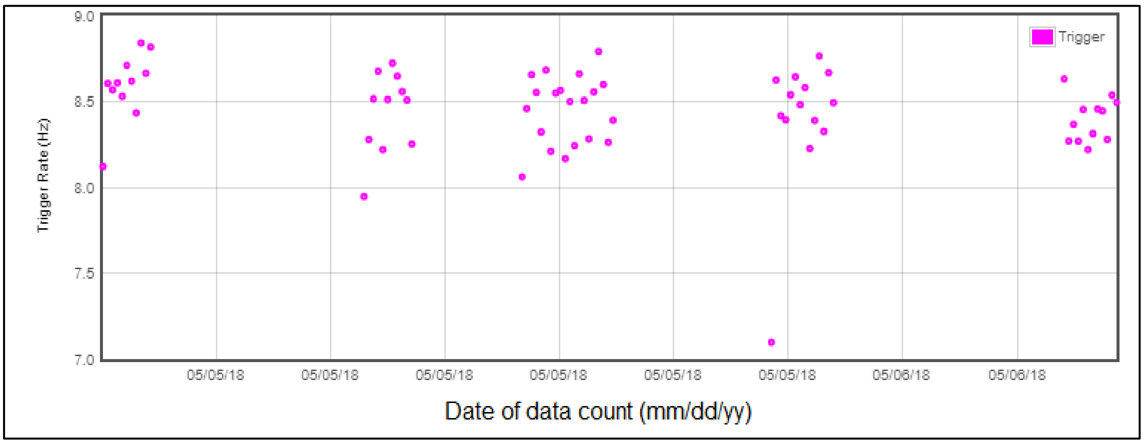

Figure 6. Trigger rate in Hz multiplied by 60 gives muon count rate in cts/min. The plot shows five different rate measurements taken between South Bend and Huntsville with detector 6401 The plot for detector 6130 in nearly identical. Both plots are from the QjuarkNet Cosmic Ray e-Lab [8].

None of the plots show variations in count rate due to a change in latitude that are more significant than random variation. The corrected data in Figure 5, taken with the QuarkNet traveling detector at three-fold coincidence in January 2019, shows a particularly flat repsonse aside from some excessive variations at about 39.2 degrees south latitude.

4. Conclusions

It was not possible to find make a clear correlation of the cosmic ray rate with the South Atlantic Anomaly with our data. As it stands now, we cannot conclude that such a correlation exists. Because the data was taken in short intervals (on the order of hours), we may not have amassed sufficient statistics. In addition, in any one interval there were variations in rate due to either ambient conditions, natural fluctuations, or the detector.

However, we do see a curious dip in the January 2019 results at latitude 39.2 degrees south (figure 5). These data were taken in the vicinity of the Villarrica volcano and could be the result of local systematics or indicate a fault in altitude correction. Future, more precise measurements in the same vicinity, at the same latitude but at different locations, would be helpful, along with further validation of the altitude correction.

As components of educational outreach, the use of the detectors and the study itself were a net positive. The detector engendered real interest among students and teachers alike. There is no good substitute for instrumentation that enables workshop participants to make hands-on measurements of elementary particles. It not only makes particle and cosmic ray physics real to the students and teachers, but the equipment itself is inherently interesting. There was added value in workshop participants knowing that the measurements were also part of a larger investigation, which gives them a connection to research.

In the future, the team, with some changes, will travel to the north of Chile to make further measurements and see if the null result continues. We invite others to make similar studies.

References

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[5] QuarkNet, *Cosmic Ray e-Lab Development – Introduction to the QuarkNet cosmic ray detector*, http://i2u2-dev.crc.nd.edu/elab/cosmic/teacher/detector.jsp.

[6] QuarkNet, *Shuffling the Particle Deck*, https://quarknet.org/data-portfolio/activity/shuffling-particle-deck.

[7] QuarkNet, *Rolling with Rutherford*, https://quarknet.org/data-portfolio/activity/rolling-rutherford.

[8] QuarkNet, *Cosmic Ray e-Lab*, https://www.i2u2.org/elab/cosmic.

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