Final Report for DoE Grant DE-SC-0011689
Studies of Particle Astrophysics at the Cosmic Frontier

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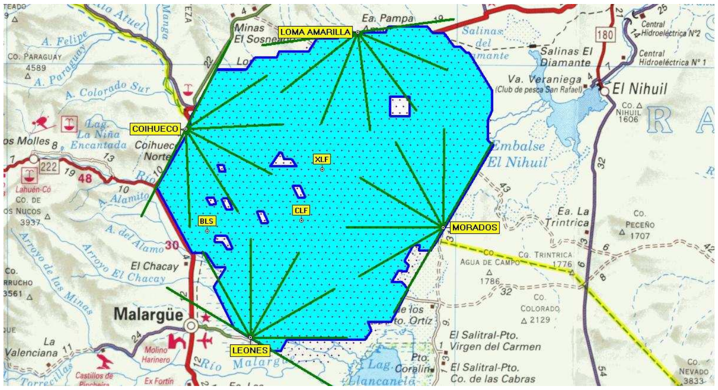

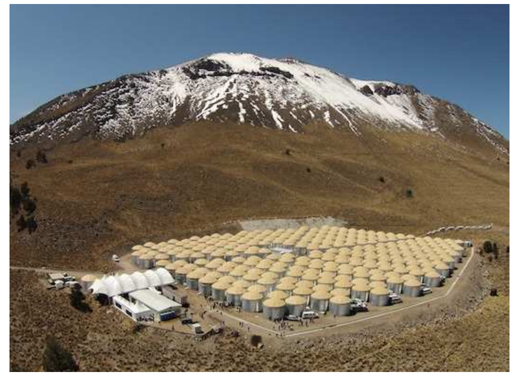

Figure 1: Left - Layout of the Pierre Auger Cosmic Ray Observatory. The dots indicate the positions of 1600 water Cerenkov tanks of the surface detector (SD) spaced 1.5 km apart. The 4 fluorescence detector (FD) sites at Los Leones, Los Morados, Loma Amarilla, and Coihueco are indicated on the border of the array. The points marked CLF and XLF are UV laser installations for atmospheric characterization and FD calibration. The low energy extensions, which are located near Coihueco, and add another 60 tanks, are not indicated. Right - The complete HAWC Observatory with Sierra Negra in the background. (Figure from www.hawc-observatory.org)

Part I

Executive Summary

Our research focuses on the "Cosmic Frontier", one of the three principle thrusts of the DoE Office of Science High Energy Physics research program. The 2013 community summer study "Snowmass on the Mississippi" catalyzed joint work to describe the status and future prospects of this research thrust. Below we include an excerpt from one of the white papers [1] (Nitz is a co-author) which provides a good introduction to the research.

> The origin and nature of the highest energy particles ever observed are fundamental questions whose answers appear to be within our reach in the coming decade. The history of cosmic ray studies has witnessed many discoveries central to the progress of high-energy physics, from the watershed identification of new elementary particles in the early days to the confirmation of long-suspected neutrino oscillations, to measuring cross-sections and accessing particle interactions far above accelerator energies.

In our research we continued this tradition, employing 2 instruments to study high energy physics questions using cosmic rays.

One approach to addressing particle physics questions at the cosmic frontier is to study the very highest energy cosmic rays. This has been the major thrust of our research effort. Below we include another excerpt from the white paper [1] to provide an introduction into this approach of our research.

> Ultra-high energy cosmic rays (UHECRs), now commonly taken to be CRs with energies $> 6 \times 10^{19}$ eV, were first reported just over 50 years ago by John Linsley [2]. These are the only particles with energies exceeding those available at terrestrial accelerators.

> The Large Hadron Collider (LHC) will reach an equivalent fixed-target energy of 10^{17} eV, whereas UHECRs have been observed with energies in excess of 10^{20} eV. With UHECRs one can conduct particle physics measurements up to two orders of magnitude higher in the lab frame, or one order of magnitude higher in the center-of-mass frame, than the LHC energy reach. As discussed in more detail below, the properties of UHECR air showers appear to be inconsistent with models which are tuned to accelerator measurements; one possible explanation is that new physics intervenes at energies beyond the reach of the LHC. UHECR experiments are the only way to access this energy range and make detailed measurements of air showers in order to address this question. It is worth noting that cosmic ray experiments have already yielded particle physics results at energies far exceeding those accessible to the LHC, one of the latest being a measurement of the p-air cross-section at $\sqrt{s} = 57$ TeV [3], a result which excludes some hadronic models extrapolations beyond LHC energies.

The two largest currently operating UHECR observatories are the Pierre Auger Observatory in the Southern hemisphere, covering an area of 3000 km^2, and the Telescope Array (TA) in the Northern hemisphere, covering about 700 km^2. The observatories sample the cosmic ray air showers at ground level (with 1660 water Cerenkov stations in the Auger surface detector (SD)), and also measure the longitudinal development of air showers on clear moonless nights ($\approx 10\%$ of the events) using atmospheric fluorescence detectors (FDs). The observatories have recently installed low energy extensions, which provide an overlap with the LHC energy regime. The layout of the Auger Observatory is shown in Fig. 1 (*left*). The Auger and TA teams have established joint working groups to discuss experimental methods, compare data analyses and modeling, and perform cross calibrations [4–6].

Another approach is to study high energy gamma rays. The High Altitude Water Cerenkov (HAWC) gamma-ray observatory is located at 4100 m above sea level near Pico de Orizaba in central Mexico. HAWC is the most sensitive, wide field of view, TeV gamma-ray observatory in operation. After 4 years of construction, operation of the full detector began in March 2015. The HAWC detector contains 300 tanks each 7.3 m in diameter and 4.5 m deep containing pure water. Each water tank is instrumented with 4 upward-viewing photomultiplier tubes mounted at their bottom. The water tanks record the energy deposited by and arrival times of the constituent components of impinging extensive air showers (EAS). The tanks are close-packed to optimize the spatial sampling of the shower front. The distribution of deposited energy across the shower is used for $\gamma-$hadron rejection. Showers with large energy deposit away from the core are rejected as being hadron-initiated. The detector operates at full efficiency above 3 TeV. The angular resolution above that energy approaches 0.1°. As the detector operates both day and night, the wide field of view of ~2 sr, allows ~2/3 of the sky to be observed each day. A photo of the completed observatory is shown in Fig. 1 (*right*).

Part II
Accomplishments

1 Introduction

This final report covers the progress during the period May 1, 2014 through March 31, 2016.

The principal investigator was Professor David Nitz. Professor Brian Fick was the Co-PI. PhD students Tolga Yapici and Niraj Dhital were active during the period of the report. Both have now finished and received their degrees (spring/summer 2015). Researcher Johana Chirinos Diaz was part of the group until March 31, 2015, and PhD student Binita Hona participated in the research as well.

The Michigan Technological University (MTU) group plays a strong role in the Auger Collaboration. Professors Nitz and Fick are both founding members of the Auger Collaboration and continue to hold leadership positions within the collaboration. Nitz is Front-End Electronics Sub-task leader, Communications Co-task leader, serves on the Collaboration Board, and has served on several Preliminary Design, Critical Design, and Operational Readiness Reviews for the project. Fick served as co-task leader of the Exotic Search Analysis Task. He chaired the trigger committee and served on several Critical Design Reviews during the early development stage of the experiment. Fick was also a member of the Auger Upgrade Committee which chose the basic design of the proposed Auger Upgrade.

Additionally, since 2011, co-PI Brian Fick has devoted a portion of his research effort to the HAWC experiment. Dave Nitz also contributed to the HAWC experiment during the final 6 months of this reporting period.

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2 Physics Motivation

Correlations between shower observables provide strong constraints on the shower models, which can enable understanding of the hadronic interactions involved in air shower development. Currently, Auger measures several observables, including X_{max}, X^{μ}_{max} (the depth at which muon production is maximum), $\frac{dE}{dX}(X)$ (the full development profile), $\frac{dN_{\mu}}{dX}(X)$ (the full muon production profile) and the number of muons at the ground, for a fraction of the events.

Lower energy observations [7–10], indicate that the composition becomes lighter as energy increases toward $\sim 10^{18.3}$ eV, suggesting that higher energy (presumably extragalactic) cosmic are primarily protons. However the Auger data exhibits a *decreasing* elongation rate (the rate of change with energy of the mean depth-of-shower-maximum, $X_{\max}$) and a *decreasing* spread in $X_{\max}$ with increasing energy above $10^{18.3}$ eV. Interpreted with present shower simulations, this is inconsistent with a proton dominated composition [11, 12]. This is shown in Fig. 2 (*left*).

None of the present hadronic interaction models can satisfactorily reproduce the data. For example, the actual hadronic muon content of UHE air showers measured in hybrid events exceeds the predictions of models tuned to LHC data by a factor $1.3 - 1.6$ [13], even allowing for a mixed composition.

Looking towards the future, it is clear that resolving the fundamental questions of UHECR composition and origins, and investigating particle physics above accelerator energies, will require both

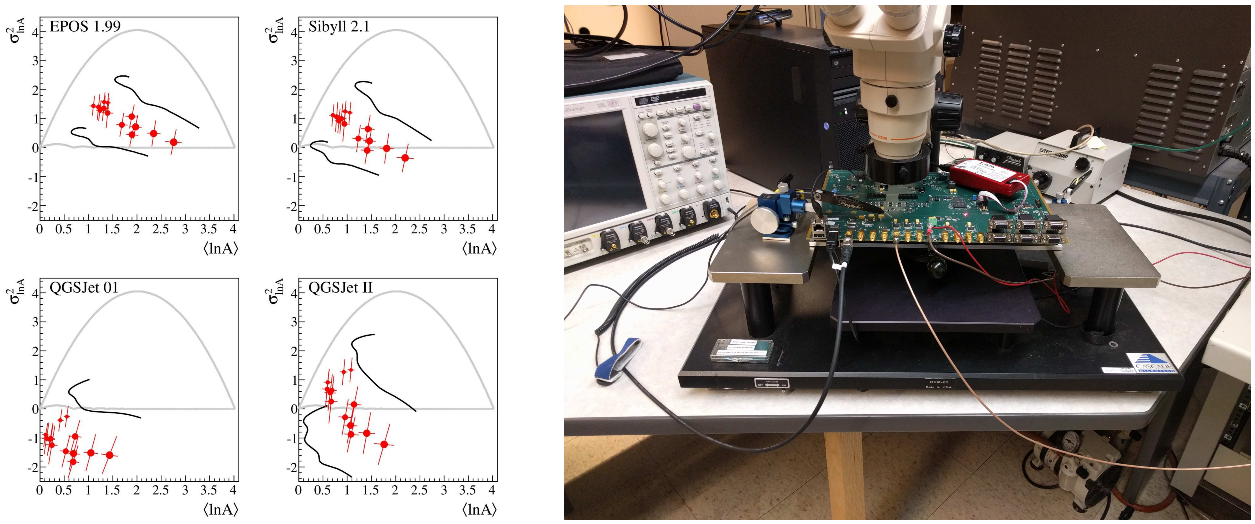

Figure 2: Left - Pierre Auger data in the ($\langle \ln A \rangle$, $\sigma^2 (\ln A)$) plane for different hadronic interaction models. Data points are shown as full circles with statistical errors. The marker sizes increase with the logarithm of the energy. Systematic uncertainties are shown as solid lines. The gray thick line shows the contour of the $\langle \ln A \rangle$ and $\sigma^2 (\ln A)$ values allowed for nuclear compositions. Here $\langle \ln A \rangle$ is the average logarithmic mass of the primaries and $\sigma^2 (\ln A)$ is the variation of the $\ln A$ distribution. Right - An "Upgraded Unified Board" under test at MTU.

enhanced experimental techniques implemented at the existing observatories, as well as a significant increase in exposure to catch the exceedingly rare highest energy events. Pursuing improved ground-based detection techniques and pioneering space-based observation will offer complementary tools to piece together answers to these important but challenging puzzles.

To that end, we should note that the Auger Collaboration has prepared a design report [14] and proposal for the upgrade of the Auger Observatory. Our group at Michigan Tech has been deeply involved in formulating those plans. The proposal has been reviewed and endorsed by an independent Science Advisory Committee appointed by the Auger Collaboration Finance Board of funding agency representatives. This collaboration wide proposal has subsequently been used as the basis for proposals already submitted to funding agencies in the US and various other countries, as well as those being prepared for submission.

3 Specific Research with the Auger Instrument

3.1 SD Trigger

3.1.1 Historical background

The work during the period of this report builds upon work dating from the beginning of the Auger observatory.

The signals from each of the three 9" PMTs in each Auger SD water Cerenkov detector are recorded at a 40 MHz rate by flash ADCs (FADCs). Programmable logic devices (PLDs) on the front-end board in the surface detector electronics generate the lowest level surface detector triggers using these FADC traces. For the first years of operation, two main triggers were employed: 1) a simple threshold trigger requiring the signal to be above 3.2 vertical equivalent muons (VEM) in at least 2 of the 3 PMTs, and 2) a time-over-threshold (ToT) trigger which requires 13 or more of the 25 ns time bins within a $3\,\mu$s sliding window be above 0.2 VEM in 2 of the 3 PMTs. This latter trigger has proved to be extremely powerful and pure.

In June 2013, the Auger Observatory installed across the entire array two additional SD triggers implemented by Nitz. The additional triggers are variations of the time-over-threshold (ToT) trigger, the mainstay of the Auger Observatory events. The ToT trigger evaluates the number of FADC time bins above a specified threshold within a sliding window [15]. This trigger effectively selects large showers amid the large background of nearby small showers. Indeed, a compact configuration of 3 stations satisfying this trigger is nearly 100% efficient for hadronic showers with zenith angles $< 60^\circ$ above 3×10^{18}eV, with negligible background. However, the efficiency falls off for purely electromagnetic showers such as those expected from photon or neutrino primaries.

The time-over-threshold-deconvolved (ToTd) trigger deconvolves the exponential tail of the diffusely reflected Cerenkov light pulses before applying the ToT condition. This has the effect of reducing the influence of muons in the trigger, since the typical signal from a muon, with fast rise time and $\approx 60\,$ns decay constant, is compressed into one or 2 time bins.

The multiplicity-of-positive-steps trigger (MoPS), on the other hand, counts the number of positive going signal steps in 2 of 3 PMTs within the $3\,\mu$s sliding window. The steps are required to be above a small FADC value (≈ 5 times RMS noise) and below a moderate value ($\approx \frac{1}{2}$ vertical muon step). This reduces the influence of muons in the trigger. Both the ToTd and MoPS triggers also require the integrated signal to be above ≈ 0.5 VEM.

The additional level 1 triggers (operated in parallel with the existing triggers) have improved the performance of the array (with no additional hardware costs) by: 1) lowering the energy threshold of the array (especially important in the infill); 2) reducing the influence of muons in the trigger; 3) reducing the proton/iron composition dependence of the trigger; 4) improving photon and neutrino trigger efficiency; 5) providing more stations in already triggered events; and 6) reducing the dependence of the trigger on details of the falling edges of signals.

3.1.2 More recent work

Trigger work during the period of this report migrated towards the design of triggers for the proposed upgrade of the observatory. Nitz played a key role in this regard in both his role as the Front-End Electronics Sub-task leader, his appointment to lead the firmware development task (work package) for the proposed upgraded surface detector electronics, and as the primary developer of the trigger code (both for the current electronics and the proposed upgraded electronics). During this period, he contributed to the study and selection of the optimal FADC speed for an upgrade, and has been working on the implementation of the level 1 triggers in the upgraded electronics. A prototype of the upgraded electronics is shown in Fig. 2 (*right*). Additionally, he elucidated modifications required of the wireless data communications system in the infill portions of the surface array that would be required along with the Auger Upgrade, and demonstrated that no change to the communications system is required in the standard spacing portion of the array.

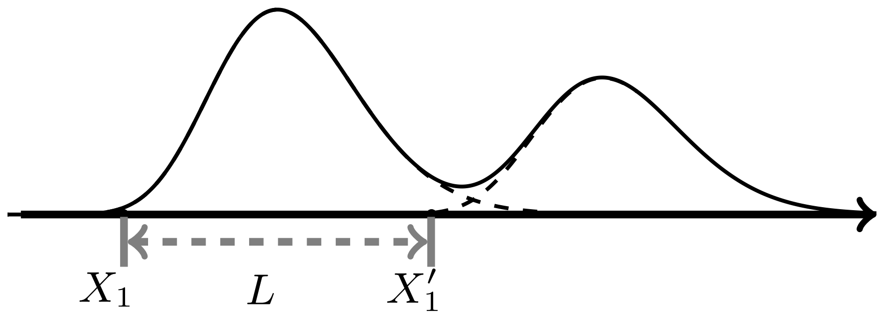

Figure 3: A weakly interacting particle produced at X_1 decays at X_2 and produces its own sub-shower.

3.2 New Particle Physics

The Auger Observatory is capable of investigating extremely high-energy particle collision phenomena. The detector was designed to operate with full efficiency for cosmic ray collisions with air at lab energies above 1×10^{19} eV. The CM-energy available for producing new particles is thus well above $\sqrt{s} = 10$ TeV. The falling cosmic ray spectrum limits the maximum practically observable $\sqrt{s}$ to $\sqrt{s}$ ~100 TeV, however.

Production of such massive particles with lifetimes in the range of picoseconds to a nanosecond are predicted in some extended models of particle interactions. An exotic, weakly-interacting particle produced in this mass range can be detected by the distortions it imparts to the development of its associated EAS. The scenario is as follows: A fraction of E_{CM} goes into the production of a normal EAS. The remaining fraction goes into the creation of the new particle. The particle travels invisibly through the the detector volume until it either decays or re-interacts. In either, case a second EAS superimposed on the first shower is the result (see Fig. 3). Hence, the basic signature for exotic particle production is a double-bump shower development profile (SDP).

In his PhD thesis [16], Niraj Dhital undertook a search for such double-bump showers in data from the Auger SD. The natural instrument to use for this study would have been the Auger Fluorescence Detector as it directly measures the electromagnetic component of the SDP. However, the volume of the FD data set is quite limited by the FD's 10% duty cycle. The SD, on the other hand, operates nearly continuously. The shower development profiles were re-constructed by deconvolving the time traces from the hit SD stations. Candidate double-bump events were distinguished on the basis of the fraction of energy deposited beyond a given atmospheric depth. Background (normal) events and double-bump events were simulated extensively (using CORSIKA [17] and the Auger OffLine framework [18]) to get the expected instrumental responses. Simulations of double-bump showers were performed by superimposing two separate air showers each initiated at a different atmospheric depth. No candidate events were identified above background at the 95% confidence level. Limits on the fraction of UHECR events producing a new particle were calculated and reported at the end of the thesis.

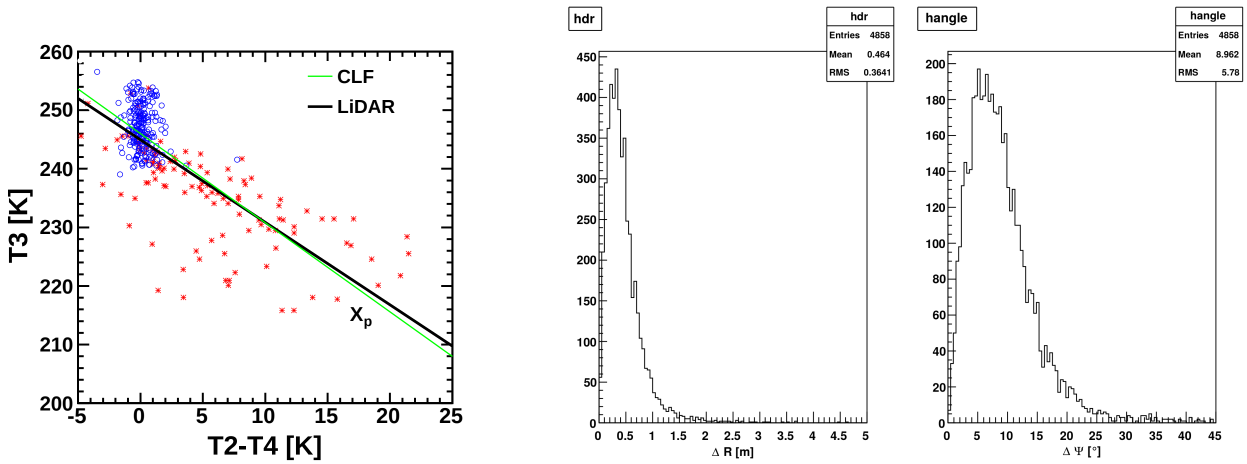

Figure 4: Left - Brightness temperature T3 versus brightness temperature difference T2-T4 of the Coihueco LiDAR satellite pixel in 2007. Open blue circles (red stars) were tagged *clear pixels* (*cloudy pixels*) as determined from the LiDAR study. X_p is the principal axis of the fitted line (black) to the data tagged by the LiDAR. The green line is the fitted line to the data tagged by the CLF in our previous study. Right - Core vector difference (m) and space angle difference (deg) for simulated muons in the HAWC detector reconstructed with using an artificial neural network.

3.3 Composition and Hadronic Interactions

The development of an EAS carries important information regarding the nature of the primary cosmic ray. Of particular importance for the identification of a cosmic ray primary is its mean free path. The distribution of first interaction lengths for a single species set of cosmic ray showers is described by a unique mean free path. In principle, then, one can get at the chemical composition of a set of cosmic ray showers by analyzing their first interaction lengths. What is required is a method of extracting the first interaction length from measured shower development profiles.

In his PhD thesis [19], Tolga Yapici demonstrated that the first interaction length of individual cosmic ray primaries can be found on an event-by-event basis using an artificial neural network (ANN) technique. The ANN was trained on a set of simulated muon production depth distributions (MPDs). It was shown that the technique is essentially independent of the composition and hadronic collision model used to simulate a test set of showers. He further illustrated how the set of first interaction lengths could be used to determine the properties of a two-component composition of cosmic rays.

3.4 A Satellite-Based Cloud Monitoring System

Over the past few years the MTU group (Chirinos) developed a method to monitor cloud coverage over the Observatory using readily available satellite data. A cross check of the method versus LIDAR data is shown in Fig. 4(*left*). The output of this method is, for every night the FD ran, a set of cloud coverage maps which indicate the probability that there was a cloud in any 30 minute interval for each of 360 pixels covering the Observatory. The cloud coverage maps are condensed into a database that is used by the Auger OffLine analysis package. This is documented in a paper

[20] spearheaded by Chirinos. The MTU group (Chirinos) continued to update the cloud probability data through March, 2015.

The cloud data has been extensively used inside the collaboration [21–23]. Unfortunately, since the departure of Chirinos, resources have not been found in the collaboration to continue this work.

3.5 Data checks

The AMIGA low energy extension to Auger aims to enhance the composition sensitivity of Auger at the lower energy end of the cosmic ray spectrum. Chirinos performed an analysis of data from the AMIGA unitary cell to verify the quality of the data.

The AMIGA unitary cell consists of an Engineering Array of buried muon detectors deployed as a hexagon of six 30 m^2 modules plus one at the center. Two of the muon counters are paired with a nearby twin. At the time of these checks only one set of twins was fully deployed. Because the separation between twin detectors is small in comparison to the dimensions of a shower at the ground, the responses of the detectors can be compared without significant corrections for the shower lateral distribution.

Using AMIGA data from 2013, we compared the number of muons recorded in a 30 m^2 muon detector with its nearby twin. In addition, studies of the 5 m^2 versus 10 m^2 modules were performed. As a result of these studies we were able to document a number of performance issues with the counters, which helped lead to the discovery that some "discriminator" thresholds had not been properly set.

4 Specific Research with the HAWC Instrument

4.1 Muon Calibration Studies

The intent of this study was to determine the feasibility of obtaining an absolute amplitude calibration of the PMTs in a tank using the emission from single muons as a standard candle. The HAWC fiber calibration system is already an excellent way to get the relative time and amplitude calibration. But, the muon calibration would allow us to assign the photo-electron scale based on the Cerenkov photon distribution from an actual relativistic particle traversing the detector. The amount of light hitting the PMTs depends heavily on the trajectory of the muon. In our study we concentrated on finding the geometry of the muon tracks. To find the geometry we trained an artificial neural network (ANN) on a large set of 5,000 simulated single muon events with randomized trajectories. Input to the ANN were the hit times and amplitudes of the 4 PMTs as well as the true muon path. We tested the resulting ANN model against an additional 5,000 simulated muon events. The performance is shown in Fig. 4 (*right*), where we plot histograms of the space-angle difference (between true and reconstructed quantities) and core vector differences. The reconstruction accuracy is better than anticipated, but whether it is sufficient to do reasonable calibrations must be determined by future studies.

4.2 Lightning Protection Grid

Brian Fick, who designed and built the CASA lightning protection system, was consulted on a potential lightning protection system for HAWC. To mitigate the effects of a direct strike on the instrument and to suppress the effects of distant lightning strikes on the small signals in the DAQ system it was decided to build a high-frequency Faraday cage to surround the entire HAWC experiment. Upper and lower wire planes were created by connecting the tops and bottoms of each HAWC tank to those of its neighbors.

4.3 Outriggers

An outrigger array (a sparse array of water Cerenkov detectors surrounding the closely packed main HAWC array) will increase HAWC's aperture, extend the energy range, improve the energy resolution, and improve the angular resolution, and improve the $\gamma -$ hadron separation. This, in turn, improves the limits HAWC can set on new particle phenomena, including Dark Matter [24], Q-balls [25], Lorentz Invariance Violation [26], primordial black holes [27], and Axions [28].

Los Alamos National Lab provided internal funding for hardware for the outrigger array sufficient to equip several hundred outrigger detectors. During the last 6 months of this reporting period Nitz began development of HV pick-off electronics for the outrigger array. Ph.D. student Binita Hona assisted Nitz in this endeaver. That work was passed on to the University of Wisconsin HAWC group at the end of the period reported here.

5 Products

5.1 Ph.D Students

During the period reported here, 2 graduate students received their Ph.D from Michigan Tech.

Tolga Yapici developed a method to determine the interaction length of cosmic ray primaries in the atmosphere using an atrifical neural network technique. This work is documented in his Ph.D thesis "A Method for Determining the Mass Composition of Ultra-High-Energy Cosmic-Rays by Predicting the Depth of First Interaction of Individual Extensive Air Showers".

Niraj Dhital performed a seach for the production of long lived weakly-interacting massive particles produced in cosmic ray air shower collisions. This work is documented in his Ph.D thesis "Search for Long-Lived Weakly Interacting Particles Using the Pierre Auger Observatory".

5.2 Recent Refereed Publications

The publications listed below are all "full author list" Auger Collaboration papers, and as such involve support from multiple countries and funding agencies.

1. "Azimuthal asymmetry in the risetime of the Surface Detector signals of the Pierre Auger Observatory", Pierre Auger Collaboration, Phys. Rev. **D93**, 072006 (2016).
2. "Nanosecond-level time synchronization of autonomous radio detector stations for extensive air showers", Pierre Auger Collaboration, JINST **11**, 01018 (2016).
3. "Prototype muon detectors for the AMIGA component of the Pierre Auger Observatory" , Pierre Auger Collaboration, JINST **11**, 02012 (2016).
4. "Search for correlations between the arrival directions of IceCube neutrino events and ultrahigh-energy cosmic rays detected by the Pierre Auger Observatory and the Telescope Array", Pierre Auger Collaboration, JCAP, **1601**, 037 (2016).
5. "Improved limit to the diffuse flux of ultrahigh energy neutrinos from the Pierre Auger Observatory", Pierre Auger Collaboration, Phys. Rev. **D91**, 092008 (2015).

6. “Large scale distribution of ultra high energy cosmic rays detected at the Pierre Auger Observatory with zenith angles up to 80 degrees", Pierre Auger Collaboration, ApJ **802**, 111 (2015).
7. "Measurement of the cosmic ray spectrum above 4×10^{18}eV using inclined events detected with the Pierre Auger Observatory", Pierre Auger Collaboration, JCAP **1508**, 049 (2015).
8. "Muons in air showers at the Pierre Auger Observatory: Mean number in highly inclined events", Pierre Auger Collaboration, Phys. Rev. **D91**, 032003 (2015).
9. "Search for patterns by combining cosmic-ray energy and arrival directions at the Pierre Auger Observatory", Pierre Auger Collaboration, Eur. Phys. J. **C75**, 269 (2015).
10. "Searches for Anisotropies in the Arrival Directions of the Highest Energy Cosmic Rays Detected by the Pierre Auger Observatory", Pierre Auger Collaboration, ApJ **804**, 15 (2015).
11. "The Pierre Auger Cosmic Ray Observatory", Pierre Auger Collaboration, Nucl. Instrum. Meth. **A798**, 172 (2015).
12. "Depth of Maximum of Air-Shower Profiles at the Auger Observatory: Measurements at Energies above $10^{17.8}$eV", Pierre Auger Collaboration, Phys. Rev. **D90**, 122005 (2014).
13. "Depths of Maximum of Air-Shower Profiles at the Pierre Auger Observatory: Composition Implications", Pierre Auger Collaboration, Phys Rev. **D90**, 122006 (2014).
14. "Probing the radio emission from cosmic-ray-induced air showers by polarization measurements", Pierre Auger Collaboration, Phys. Rev. **D89**, 052002 (2014).
15. “Searches for Large-Scale Anisotropy in the Arrival Directions of Cosmic Rays above 10^{19}eV at the Pierre Auger Observatory and the Telescope Array”, Pierre Auger and Telescope Array Collaborations, ApJ **794**, 172 (2014).
16. “A search for point sources of EeV photons”, Pierre Auger Collaboration, ApJ, **789,** 160 (2014).
17. “Muons in air showers at the Auger Pierre Auger Observatory: measurement of atmospheric production depth”, Pierre Auger Collaboration, Phys. Rev. **D90,** 012012 (2014).
18. “Origin of atmospheric aerosols at the Pierre Auger Observatory using studies of air mass trajectories in South America”, Pierre Auger Collaboration, Atmospheric Research **149,** 120 (2014).
19. “A Targeted Search for Point Sources of EeV Neutrons”, Pierre Auger Collaboration, ApJ **789**, L34 (2014).
20. “Reconstruction of inclined air showers detected with the Pierre Auger Observatory”, Pierre Auger Collaboration, JCAP **08,** 019 (2014).

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