Final Report for DOE Award: DE-SC0010080

Exploring the Cosmic Frontier
Task A: Gold – Direct Detection of Dark Matter
Task B: Matthews – Experimental Particle Astrophysics

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Experimental Particle Astrophysis,Task A

This report summarize the work of Task A2 for the period 2013-2016. The work is for direct detection of dark matter with the single-phase liquid argon experiment MiniCLEAN.

1 MiniCLEAN Experiment

The UNM group consists of Gold (faculty) and Ryan Wang (graduate student). We contributed to the construction of MiniCLEAN by fabricating the acrylic plugs of the optical modules, and by developing, building and delivering the in situ optical calibration system. UNM has also developed the active magnetic compensation system that will mitigate the effect of the Earth's magnetic field on the PMTs, and a magnetic field monitoring system. MiniCLEAN is located underground in SNOLAB located in Sudbury, Canada. Wang has been working underground from February-June of 2015. His effort was crucial to the final construction and commissioning of the detector. A natural LAr run (~ 3 months) is planned for this fall to study backgrounds and a ^{39}Ar spike run (~ 3 months) to measure the ultimate ability of the single-phase technique for ^{39}Ar background discrimination. MiniCLEAN pulse shape discrimination measurements are crucial for any larger LAr experiment. Analysis of calibration and LAr data is the primary thrust of Wang's thesis.

We tested various acrylic samples and selected the type with the best optical properties to serve as shielding blocks in front of the PMTs in the PMT-waveguide cassette assemblies. [1] The blocks were rough-cut at UNM and then precision machined in a local shop. We then sanded, hand-polished, final cut the active surface, and bagged the blocks in dry nitrogen for TPB coating by an outside vendor.

We designed a set of magnetic compensation coils based on magnetic (B) field measurements made at SNOLAB cubehall.[2] We completed the coil design, based on measurement of the earth's B-field before and after installation of MiniCLEAN's water tank. We procured both the power supplies and the remotely controlled switches for emergency turn-off (SNOLAB safety requirement). C-code was written by former postdoc Giuliani [1] to control the remote switches via the MiniCLEAN slow control. To directly measure the compensated field Giuliani designed and prototyped a triaxial magnetic sensor. Five of these devices will be submersed in the water shielding tank. We constructed cases out of PVC piping. Leak tests performed by submerging in colored water. The long 10 wire ribbon cable to power and read out the sensor will be protected from water by inclusion in a flexible plastic tube. The system is controlled via an FPGA micro-controller and readout via a simple DAC with software for extracting the field strength written by undergraduate Mills.

In order to calibrate the PMTs in situ, we developed an LED light injection system. The principle of the calibration method is to use single photons to measure the gain of each of the PMTs. Rather than using an expensive and potentially unreliable cryogenic

[1] Giuliani is now working on PandaX.

fiber feedthrough, the LEDs (6 blue, 6 UV) are mounted inside the LAr and operate at cryogenic temperature. An important concern was the dispersal of light to all 92 PMTs which we ensured by a combination of testing, modification and simulation. For the UV LEDs, we initially proposed coating the ends of the fiber with TPB. However, testing of coated fibers did not show reproducible improvement in the emittance of the beam from the LED. We improved the emittance by increasing the diameter of the fiber. For the blue LEDs we found that adding a lens provided a more uniform light output. Both blue and UV LED-fiber assemblies were tested in our lab for uniformity of light emittance and for operational stability. Simulations showed that all 92 PMTs would receive sufficient blue and UV light. The LEDs are connected into the cryogenic volume by a single coaxial cable. This necessitated the development of a custom electrical pulsing circuit. We designed and prototyped a circuit to provide a very fast ($\sim$ ns) pulser based on a circuit concept introduced by Kaputinsky.[3] Giuliani and Wang invented a method to measure the LED current by this single electrical connection using the reflected signal pulse as a measure of the LED impedance. This was accomplished by a combination of SPICE simulation and prototyping. The pulser trigger is generated and the reflected pulse detected and digitized by a FPGA micro-controller (Digilent Nexys 3) and connected to the 12 pulser circuits via a Digilent "Pmod". The ADC is a separate Digilent Pmod. [2] Wang has done the programming of pulsing sequence in the FPGA which are stored and downloaded from a dedicated PC. This PC also serves to control the pulser voltage power supply. C-code was written by Gold to control the power supply remotely via the slow control. The upload of the Verilog pulsing code to the FPGA is done by a C slow control program written by Giuliani. Gold did analysis of the LED data to measure and track the PMT gains and identified a bad PMT that was replaced prior to final assembly of MiniCLEAN.

2 MiniCLEAN internal documents – Gold

- cl1509008 plan for miniclean analysis Michael Gold 22 Sep 15 MiniCLEAN, Talks
- cl1509007 plan for miniclean analysis Michael Gold 22 Sep 15 MiniCLEAN, Talks
- cl1503004 report on TPB delayed light Michael Gold 24 Mar 15 MiniCLEAN, Technical Reports
- cl1407008 Ar-39 Energy Scale Calibration Study Michael Gold 15 Jul 14 MiniCLEAN, Technical Reports
- cl1407007 board calibration constants study Michael Gold 14 Jul 14 MiniCLEAN, Technical Reports
- cl1406011 wording for poster for CAP 2014 Michael Gold 14 Jun 14 MiniCLEAN, Talks

[2]Due to lack of time and money, the current measurement method was tested but never implimented for MiniCLEAN.

- cl1406005 LED run summary Michael Gold 4 Jun 14 MiniCLEAN, Technical Reports
- cl1404012 Calibration of Test Stand PMT Michael Gold 27 Apr 14 MiniCLEAN, Technical Reports
- cl1306011 draft of optical calibration scheme Michael Gold 12 Jun 13 MiniCLEAN, Technical Reports
- cl1305036 Light calibration update Michael Gold 22 May 13 MiniCLEAN, Technical Reports
- cl1305006 Light calibration update Michael Gold 8 May 13 Meetings, Technical Reports

3 Summary of Works – Jui-Jen (Ryan) Wang

1 In-situ Optical light injection system :

- Hardware :
  - Studies of kapustinsky pulser on Blue and UV LED. (cl1109004 – progress report)
  - LED Injection system talk. (cl1203040 – progress report)
  - Angular distribution results. (cl1209016 – progress report)
  - Fiber with TPB coating. (cl1302013 – progress report)
  - Summary of work done on LED assemblies at SNOLab. (cl1306030 – progress report – Miles Bodmer)
  - LED slow control update. (cl1407003)
- Data analysis :
  - Notes on LED data in argon gas. (cl1403004 – progress report)
  - Calibration of test stand PMT. (cl1404012 – progress report – Michael Gold)
  - Study of PMT gain using LED data. (cl1404013 – progress report)
  - Peak near zero in PMT's charge distribution plot. (cl1405001 – progress report)
  - LED run summary. (cl1406005 – progress report – Michael Gold)
  - PMT gain issue. (cl1408002)
  - Pulse timing study from LED run. (cl1411008 – progress report)
  - Report on TPB delayed light. (cl1503004 – progress report – Michael Gold)
- Presentations :

  - APS slides on optical calibration. (cl1204005 – 2012 APS annual April meeting – 15 minutes talk)
  - LED overviews and studies. (cl1403016 – 2014 collaboration meeting)
  - Quick look at 22Na in vacuum and argon gas. (cl1403020 – 2014 collaboration meeting – Thomas Caldwell)
  - Poster for CAP 2014. (cl1406007 – Canadian Association of Physics annual meeting 2014 – poster section)
  - LED status update. (cl1501007 – 2015 Collaboration meeting)
  - PMT timing analysis. (cl1501015 – 2015 Collaboration meeting)

2 Miscellaneous On-site stuff

- Tagged Na22 source in vacuum. (cl1402013 – progress report – Thomas Caldwell)
- OV MLI pictures. (cl1406012 – progress report – Thomas Caldwell)
- Spill test. (cl1410003 – progress report)
- Route of Cables from IV to OV through cable horns. (cl1410005 – progress report)
- IV move to cube hall. (cl1411003 – progress report – Thomas Caldwell)
- IV hang in OV. (cl1411004 – progress report – Thomas Caldwell)
- Photo album of IV moving and lifting. (cl1411005 – progress report)
- IV cabling picture. (cl1411007 – progress report – Thomas Caldwell)
- Cable horn seal test pictures. (cl1501001 – progress report – Thomas Caldwell)
- IV thermal link issue. (cl1502007 – progress report – Thomas Caldwell)
- Cryocooler spacer installation. (cl1503007 – progress report – Thomas Caldwell)
- Buffer tube assembly. (cl1504004 – progress report – Thomas Caldwell)
- Vertical fill line pictures. (cl1505002 – progress report – Thomas Caldwell)
- Magnetic sensor procedure. (cl1607006 – On-site procedure)

3 Background Study :

- Study of vacuum data. (cl1503003 – progress report)
- Vacuum background study. (cl1507001 – progress report)
- Analysis overview at UNM. (cl1509005 – progress report)
- Cherenkov event cut. (cl1510002 – progress report)
- Summary of vacuum background. (cl1512006 – progress report)
- Alpha simulation update. (cl1607002 – progress report)

4 Ar_{39} Energy Scale :

- Ar39 energy scale fit. (cl1608001 – progress report)

4 References Cited

References

[1] M. Bodmer, N. Phan, M. Gold, D. Loomba, J.A.J. Matthews and K. Rielage, “Measurement of optical attenuation in acrylic light guides for a dark matter detector”, JINST 9 (2014) P02002.

[2] M. Bodmer, F. Giuliani, M. Gold, A. Christou and M. Batygov, “Design of an active magnetic field compensation system for MiniCLEAN,”Nucl. Instrum. Meth. A697, 99 (2013).

[3] J. Kapustinsky, *et al., Nucl. Instrum. Meth. A* , **241** *612, 1985.*

A APPENDIX 1: BIOGRAPHICAL SKETCH OF PRINCIPAL INVESTIGATOR

Michael S. Gold

Professor of Physics
Department of Physics and Astronomy
Albuquerque, NM 87131
Email: mgold@unm.edu

Professional Preparation

1986	Ph.D. Physics, University of California, Berkeley
1979	B.A. Physics, Wesleyan University, Middletown, CT *Magna Cum Laude* with High Honors in Physics, The Bertman Prize for Physics, *Phi Beta Kappa*

Appointments

2004–Present	Professor, University of New Mexico
1997–2004	Associate Professor, University of New Mexico
1991–1997	Assistant Professor, University of New Mexico,
1987–1991	Research Associate, Lawrence Berkeley Laboratory

Research Interests

High-energy particle physics; High-energy astrophysics; Dark matter searches; Particle-physics instrumentation; gas detectors; tracking; advanced data analysis techniques

Related Publications

- "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Volume 4 The DUNE Detectors at LBNF"
  R. Acciarri *et al.* [DUNE Collaboration].
  arXiv:1601.02984 [physics.ins-det]
  FERMILAB-DESIGN-2016-04
- "Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) : Volume 2: The Physics Program for DUNE at LBNF"
  R. Acciarri *et al.* [DUNE Collaboration].
  arXiv:1512.06148 [physics.ins-det]
  FERMILAB-DESIGN-2016-02
- "First background-free limit from a directional dark matter experiment: results from a fully fiducialised DRIFT detector"
  J. B. R. Battat *et al.* [DRIFT Collaboration].
  arXiv:1410.7821 [hep-ex]
  DOI:10.1016/j.dark.2015.06.001
  Phys. Dark Univ. **9-10**, 1 (2015)
- "Background Assay and Rejection in DRIFT"
  J. Brack *et al.*.

arXiv:1404.2253 [physics.ins-det]
DOI:10.1016/j.phpro.2014.12.022
Phys. Procedia **61**, 130 (2015)
61C

- "Update on the MiniCLEAN Dark Matter Experiment"
  K. Rielage *et al.* [MINICLEAN Collaboration].
  arXiv:1403.4842 [physics.ins-det]
  DOI:10.1016/j.phpro.2014.12.024
  Phys. Procedia **61**, 144 (2015)
  LA-UR-14-21626
- "Radon backgrounds in the DEAP-1 liquid argon based Dark Matter detector"
  P.-A. Amaudruz *et al.*.
  arXiv:1211.0909 [astro-ph.IM]
  DOI:10.1016/j.astropartphys.2014.09.006
  Astropart. Phys. **62**, 178 (2015)
- M. Akashi-Ronquest, P.-A. Amaudruz, M. Batygov, B. Beltran, M. Bodmer, M. G. Boulay, B. Broerman and B. Buck *et al.*, *"Improving Photoelectron Counting and Particle Identification in Scintillation Detectors with Bayesian Techniques,"* arXiv:1408.1914 [physics.ins-det].
- E. Daw, J. R. Fox, J.-L. Gauvreau, M. Gold, L. J. Harmon, J. M. Landers, E. R. Lee and D. Loomba *et al.*, *"Long-term study of backgrounds in the DRIFT-II directional dark matter experiment,"* JINST **9**, P07021 (2014) [arXiv:1307.5525 [physics.ins-det]].
- J. B. R. Battat, J. Brack, E. Daw, A. Dorofeev, A. C. Ezeribe, J. R. Fox, J.-L. Gauvreau and M. Gold *et al.*, *"Radon in the DRIFT-II directional dark matter TPC: emanation, detection and mitigation,"* arXiv:1407.3938 [physics.ins-det].
- J. Brack, E. Daw, A. Dorofeev, A. Ezeribe, J. L. Gauvreau, M. Gold, J. Harton and R. Lafler *et al.*, *"Background Assay and Rejection in DRIFT,"* arXiv:1404.2253 [physics.ins-det].
- "Measurement of Optical Attenuation in Acrylic Light Guides for a Dark Matter Detector"
  M. Bodmer, N. Phan, M. Gold, D. Loomba, J. A. J. Matthews and K. Rielage.
  arXiv:1310.6454 [physics.ins-det]
  DOI:10.1088/1748-0221/9/02/P02002
  JINST **9**, P02002 (2014)
  LA-UR-13-27947
- "Long-term study of backgrounds in the DRIFT-II directional dark matter experiment"
  E. Daw *et al.*.
  arXiv:1307.5525 [physics.ins-det]
  DOI:10.1088/1748-0221/9/07/P07021
  JINST **9**, P07021 (2014)

- "Design of an active magnetic field compensation system for MiniCLEAN" M. Bodmer, F. Giuliani, M. Gold, A. Christou and M. Batygov. DOI:10.1016/j.nima.2012.09.030 Nucl. Instrum. Meth. A **697**, 99 (2013).
- *"Spin-Dependent Limits from the DRIFT-IId Directional Dark Matter Detector,"* E. Daw, J. R. Fox, J. -L. Gauvreau, C. Ghag, L. J. Harmon, M. Gold, E. Lee and D. Loomba *et al.*, Astropart. Phys. **35**, 397 (2012) arXiv:1010.3027 [astro-ph.CO].

Recent Talks

- *Xenon Doping: Motivation and Plans*, Photon Detector Workshop, Colorado State University, May 17-18, 2016.
- *Searches for Heavy Vector Bosons at CDF* , SUSY09, the 17th International Conference on Supersymmetry and the Unification of Fundamental Interactions, Northeastern University June 2009.
- *DEAP/CLEAN liquid Argon/Neon Detectors for Dark Matter and Neutrinos*, Aspen Center for Particle Physics, Particle/Astronomy, January 25 - February 1, 2009.
- *DEAP/ CLEAN: A Liquid Argon/Neon Detector for Dark Matter and Neutrinos,* 2^{nd} Annual Workshop on the Interconnection Between Particle Physics and Cosmology, Albuquerque, May 2008.
- *Status and Prospects for Drift*, The Hunt for Dark Matter, Fermilab, May 2007.

Synergistic Activities DRIFT directional dark matter experiment.
Collaborators and other Affiliations DRIFT, CDF-II, MiniCLEAN, CAPTAIN
Thesis advisor Professor Gerson Goldhaber (University of California, Berkeley)
Postdocs and students advised:
Dr. Timothy Thomas (currently at University of New Mexico); Dr. Steve Worm (currently at Rutherford Appleton Laboratory), Dr. Volker Drollinger, Dr. John Strologas (University of Ionnia), Dr. Nichelle Bruner, Ph.D. 1999 (currently at ATK-MR) , Dr. Eric Moore, Ph.D. 2001 (currently at DOE), Dr. Dmitri Smirnov, Ph.D. 2005 (currently at BNL), Vladimir Rekovic Ph.D. 2007 (Rutgers University), Johanna Turk, Ph.D. 2008 (National Security Technologies-NSTec), Marcelo Vogel Ph.D 2011, Jui-Jen Wang (current PhD student, miniCLEAN)

Undergraduate student research:

Gary Condon, summer 1992 designed and built driver and receiver boards for high-density cables; data analysis tools; Howard Barnum, summer 1993 MC studies of CP violation in $B \to \psi K$ for CDF II ; Shannon Wells, 1992-1993 silicon detector test stand noise measurements; high-density cable design; Eric Gottlieb, undergraduate: 1994-1995 silicon detector test stand setup and measurements; VxWorks software development for DAQ M. Albanese, summer 1994 characterization of EMF from high-density cable prototypes; Ty DeYoung, summer 1996 silicon detector test stand measurements and studies of noise and grounding ; Joseph Wong, summer 1995 silicon detector test stand noise measurements; development of β-source trigger; setup for silicon detector test beam at KEK (Japanese national laboratory); Ling Yu, summer 1996 study of search for a scalar top; Miles Bodmer, 2010-2013 R&D and design of magnetic field compensation coils for MiniCLEAN; magnetic field mapping underground at SNOLAB, Sudbury, Canada; R&D, design and installation (at SNOLAB) of light injection LEDS for MiniCLEAN; Alex Mills, summer 2014 Assembly and testing of electronics for MiniCLEAN magnetic field compensation coils; LBNE neutrino detector prototype (CAPTAIN) test at LANL.

Task B: Experimental Particle Astrophysics

1. Introduction

During the grant period: April 1, 2013 to March 31, 2016 the UNM Task B research focused primarily on indirect searches for dark matter (DM) with the High Altitude Water Cherenkov (HAWC) experiment. In particular HAWC provides an important 1 TeV $\sim$ 1000 TeV high-mass window for indirect searches for DM (*e.g.* WIMP) annihilation or decay. Our group also worked to complete a $\sim$ 15-year program with the Pierre Auger (Auger) experiment related to the highest energy cosmic rays (CRs). Our particular interest was on the extraction of previously unmeasured physics from the Auger fluorescence detector (FD) longitudinal shower profiles. The UNM Task B group supported Professor John Matthews, research associate (research assistant professor) Robert Lauer and graduate student Zhixiang Ren. UNM Professor Michael Gold collaborated on some of our HAWC analyses.

The Task B group has emphasized almost equally: the development of new instrumentation and new physics analyses. Recent instrumentation examples include development of the optical calibration systems for the Auger FDs [1], the development of the optical (laser) calibration system for HAWC [2] and the development of several novel light sources [3, 4, 5] for the critical monitoring of atmospheric aerosols relevant to Auger fluorescence data. Notable previous instrumentation developments are given in Ref. [6]. Recent analysis examples include the development of novel techniques for analyzing the power-law nature of (Auger) cosmic ray spectra [7, 8], for searches for non-isotropy (*clumpiness*) in the arrival directions of cosmic rays [9, 10] and for parametrizing the longitudinal shower profiles [11] for (Auger) FD events. Our HAWC DM physics program is built on our development and implementation of a new, likelihood-based analysis framework [13, 14, 15]. This framework supports HAWC-only data analysis as well as combining HAWC and other gamma-ray (*e.g.* Fermi or VERITAS) data through a new multi-experiment analysis architecture.

The UNM Task B group also had a small program of collaborative detector R&D with UNM Professor Loomba's program on the development of high-precision, directional, DM detectors.

2. Project Description/Progress Report

2.1 Pierre Auger Ultra-high Energy Cosmic Ray Experiment

We have studied Ultra High Energy Cosmic Rays, UHECRs, for almost two decades, witnessing both agreement and disagreement between major experiments. Currently Auger (which views the southern skies) and Telescope Array (TA/HiRes) (which views the northern skies) disagree on the spectrum and the probable composition of the UHECRs.

One measure of CR composition is provided by the average depth, $< X_{max} >$, (and RMS, $X_{max}RMS$) of shower maximum. Auger's composition data, see Fig. 1, suggest two physics scenarios. If the shower Monte Carlo simulations are correct, then the CR composition appears to change from low mass nuclei, proton/helium, for energies $\sim 2 \times 10^{18}$eV, to intermediate/high mass nuclei at the highest CR energies. Alternatively if the primary CRs are predominantly protons (above $\sim 2 \times 10^{18}$eV), then there is a need for the shower Monte Carlos to include new physics [18]. To further stoke controversy Auger provides a unique measurement of the muons in the air showers [19] and Auger measurements disagree with all shower model predictions/simulations!

Auger and TA/HiRes have been working on, and in some cases working together, on these issues. A breakthrough in our understanding is unlikely anytime soon. In contrast our plan has been to focus on two previously unmeasured characteristics of the data: the width, $fwhm$, and shower asymmetry, f, (defined in Fig. 2(Left)) of the extensive air showers [11]. The Gaisser Hillas parametrization is used to reconstruct Auger FD showers, see Fig. 2(Right).

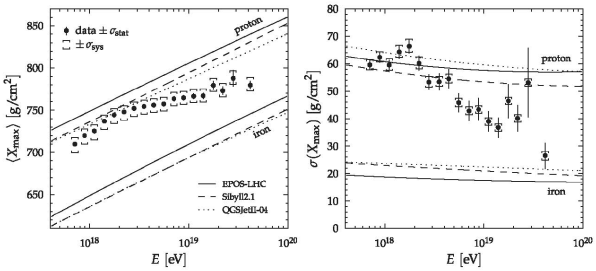
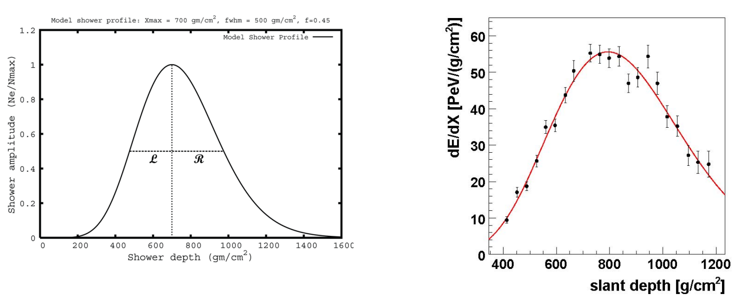


Figure 1: (**Left:**) Auger average depth of shower maximum, $< X_{max} >$. This is now reported to be consistent with TA/HiRes results [17]. Curves show predictions from several different shower simulation models for proton and iron primary CRs. (**Right:**) Corresponding Auger data for $X_{max}RMS$.

Shower simulations suggest that the f-parameter is sensitive to CR composition [11, 22]. However shower shapes differ little over the expected range of f-parameter values [11] and it is unknown whether the f-parameter can be sufficiently well determined by Auger data to provide primary particle discrimination. As a consequence we are particularly mindful of possible analysis biases.

Our group has made significant progress on the data analysis component of the project by successfully modifying the Auger offline reconstruction to now reconstruct shower profiles with the new Gaisser Hillas function, GH(N_{max}, X_{max}, $fwhm$, f), with constraints on $fwhm$ and f; see Ref. [23] for Auger standard reconstruction constraints. Furthermore this new reconstruction has been used to analyze the library of Auger FD showers with *loose* constraints on $fwhm$ and a variety of constraints on the f-parameter.

In parallel we have made some progress with the more complex simulation component of the project. A simplified, *Toy*, shower profile simulation has been written and used to study shower reconstruction issues and biases. The *Toy* simulation suggests that when the shower profile fitting region was not rather symmetric about shower maximum, the reconstructed $fwhm$ depended on the constrained value for the f-parameter, f_{con}. Empirically $fwhm$ depends linearly on the shower length *Before-After* shower maximum. We fit the reconstructed $fwhm$ (*VS Before-After*)



(a) event 1719183, LM, $E = (3.6 \pm 0.2) \times 10^{19}$ eV

Figure 2: (**Left:**) Modified Gaisser Hillas shower profile parameters: $fwhm \equiv \mathcal{L}+\mathcal{R}$ is the shower width at half-maximum and $f \equiv \mathcal{L}/(\mathcal{L}+\mathcal{R})$ characterizes the shower asymmetry (**Right:**) A subset of Auger's FD showers show classic shower profiles with shower maximum, X_{max}, clearly within the field of view (FOV) and with an observed track length $\gtrsim 600 gm/cm^2$ (Monte Carlo simulated events have $fwhm \sim 525 gm/cm^2$). The red curve shows the Gaisser Hillas shower profile *fit*.

to $fwhm_{avg} + fwhm_{slope} \times (Before - After)$. We find that $fwhm_{slope} \approx 0$, *viz* the *bias* goes away, when $f_{con.} =< f >$[1]! Thus by good fortune our *analysis bias* provides a way to estimate the average f-parameter: *viz* evaluate $fwhm_{slope}$ for a range of (tightly constrained) values for the f-parameter, then the $fwhm_{slope} \approx 0$ crossing point of the $fwhm_{slope}$ VS f curve estimates the data's $< f >$-parameter. This is shown in Fig. 3(Left) and (Right) from our $fwhm$, f analysis of QGSJetII shower simulated events and from Auger data respectively.

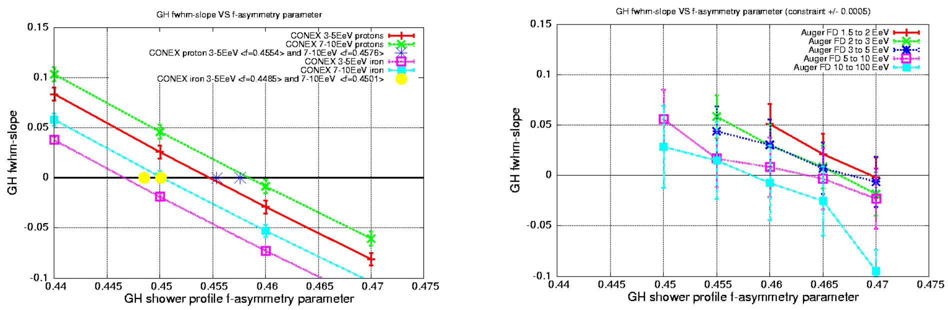


Figure 3: (**Left**:) Plot of $fwhm_{slope}$ VS f_{con} from our $fwhm$, f analysis of QGSJetII simulated proton showers in two energy bins: 3-5 EeV (red) and 7-10 EeV (green) and similarly for iron showers in two energy bins: 3-5 EeV (purple) and 7-10 EeV (turquoise). F.Y.I. 1 EeV = 1×10^{18}eV. The average f-parameter values, $< f >$, for the proton events are shown as the two blue (*stars*) and are characteristically higher than the average f-parameter values for the iron events shown as the two yellow (disks). Empirically the lines of $fwhm_{slope}$ VS f_{con} cross the $fwhm_{slope} = 0$ axis close to the simulated shower events' average f-parameter values. (**Right:**) Plot of $fwhm_{slope}$ VS f_{con} now from Auger FD showers in 5 energy bins: 1.5-2 EeV (red), 2-3 EeV (green), 3-5 EeV (blue), 5-10 EeV (purple) and 10-100 EeV (turquoise).

Our (very preliminary) results, Fig. 3(Right), are compatible with $0.455 \lesssim f \lesssim 0.470$ for the Auger data above 1.5 EeV which is most compatible with a proton primary CR composition: *cf* Fig. 3(Left). However in detail, and for the restricted energy interval 1.5 to 10 EeV, the Auger data are consistent with $0.460 \lesssim f \lesssim 0.470$ which is curiously inconsistent (*i.e.* greater than) QGSJetII predictions for all nuclei! The analysis is also consistent with a trend to decreasing values for f-parameter with increasing CR energy[2]. Curiously a trend of decreasing f-parameter with increasing energy above ~ 2 EeV is reminiscent of the possible change from low mass nuclei, proton/helium, for CR energies $\sim 2EeV$ to intermediate/high mass nuclei at the highest CR energies observed in the X_{max} data.

2.2 HAWC TeV gamma-ray experiment

The High Altitude Water Cherenkov (HAWC) experiment [24] is a next-generation, water Cherenkov based detector of TeV gamma-rays with construction recently completed in spring 2015. HAWC builds on the previous Milargo [25] experiment with notable upgrades: to decrease the shower energy threshold by moving to a higher site (4100m), to improve the identification of gamma-ray showers by segmenting the water Cherenkov detector (WCD) into ~ 300 individual (7.3m diameter by 4.5m tall) WCD tanks, and by increasing the sensitive area of the array. Each

[1] $< f >$ is the average value of the f-parameter of the simulated shower events.

[2] Note that energy dependent trends may result from the strong shower energy:average distance correlation in the data!

WCD includes 4 photo-multiplier tubes: three 8" (salvaged from the Milargo detector) and one, new, high efficiency 10" PMT. The direction of gamma-ray showers is reconstructed from the times of the triggered PMTs in an event. The shower energy and gamma:hadron separation are determined from the PMT signals in *number of photo-electrons*, n_{PE}. The gamma:hadron separation results from an important detail of extensive air showers: the primary particle *type* can be distinguished by the pattern of shower energy deposition on the HAWC array as gamma-rays are *smooth* and CRs are *clumpy*; see Fig. 4.

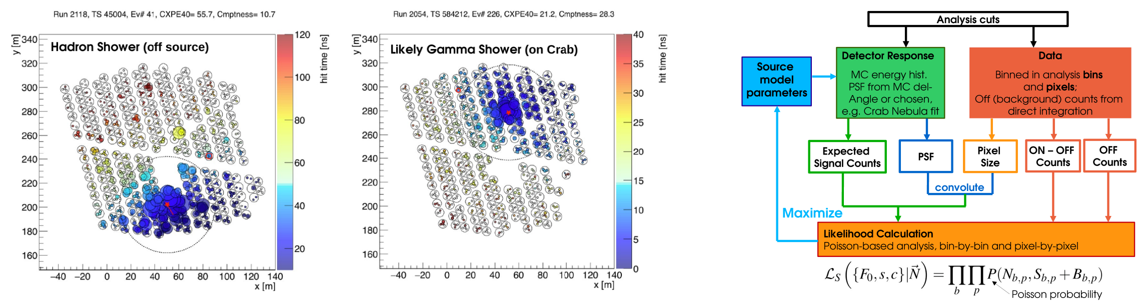


Figure 4: (**Left:**) HAWC event display of typical CR shower. The reconstructed shower *core* is shown by the dotted circle with central red (dot). Characteristic of CR events, large PMT signals, shown by *large colored circles* (radius $\propto n_{PE}$), are distributed across the array. (**Middle:**) Likely TeV gamma-ray shower, from the Crab pulsar, showing few (no) large PMT signals (*large colored circles*) outside the shower core region (dotted circle: 40m radius). (**Right:**) Simplified outline of the LiFF analysis framework: the main HAWC analysis tool to compare and fit gamma-ray source models to sky maps of reconstructed HAWC data.

HAWC benefits from its *southern* location at 19-degrees north latitude. As a consequence, it surveys approximately 2/3 of the sky each day with an instantaneous view of ~ 2 steradians that is constrained by an increasing energy threshold for air showers far from local zenith. While this makes HAWC an ideal telescope for monitoring variable sources (*e.g.* flaring AGNs, GRBs, ...), it allows HAWC to do a program of indirect searches for DM annihilation and/or decay [16] limited only by the possible candidate sources (*e.g.* dwarf spheroidal galaxies, to spiral galaxies, to galaxy clusters, to DM clumps ...) within the HAWC field of view. That said, HAWCs sensitivity depends most critically on event angular resolution (sensitive to HAWC's timing uncertainties) and on event gamma:hadron separation (sensitive to HAWC's PMT calibration).

For optimal shower reconstruction, especially event angular pointing resolution, the systematic timing uncertainty of the PMT/electronic channels in HAWC needs to be $\lesssim$1ns. While this goal has been exceeded in laboratory conditions[26] the challenge was to meet this goal over the ~ 150m $\times \sim 150$m, *mountain top* site for HAWC. UNM, in collaboration with Los Alamos National Laboratory (LANL), Michigan Technological University (MTU) and Pennsylvania State University (PSU) are responsible for the laser calibration system to calibrate the ~ 300 WCDs (~ 1200 PMTs) in HAWC to this precision. During the design and prototyping phase of the calibration system UNM lead the project. Following the calibration system installation and commissioning at the HAWC site and with routine operation of the calibration system, MTU, PSU and UNM now share the major calibration responsibilities.

Since first HAWC data in 2012, Robert Lauer has lead the software effort establishing the database of calibration results, checking the validity of the results, and applying these calibrations to air shower data analysis. With the growth of the HAWC array to 1200 PMTs the identification of bad channels, *i.e.* PMTs with calibration parameters, or responses, well outside the norm, needed to be automated. To this end, Zhixiang Ren developed and implemented software that fits the shape of the (calibrated) PMT charge distributions to quantify how well the PMT rates and shapes match expectations. Ren's program, which fills the *good PMT* data base, is now part of the automated reconstruction of HAWC data, and has also led to the identification and repair of various hardware issues inside the PMT optical modules, and in the front-end electronics, and thus helped reduce the fraction of channels excluded from data taking to about 1%.

The capability of performing a deep survey of TeV photons over 2/3 of the sky makes HAWC an exceptional instrument to search for fundamental constituents of our Universe, in particular DM (assuming DM annihilation or decay to photons). The UNM Task B group's primary contribution to this goal is to continue our leadership of the flexible high-level analysis framework that allows us to evaluate and compare different hypotheses for gamma-ray observations with HAWC data. It is *high-level* in the sense that the input data are maps of air shower event directions and simulations of the HAWC response, produced by existing and well-established HAWC software. In the framework, these data are analyzed in the context of a model for gamma-ray emission chosen for each particular analysis. The physics model is convoluted with the HAWC detector response to gamma-ray air showers, calculated from simulations and reference sources. The likelihood formulation compares data and model for each analysis bin and sky location and yields the significance of an observation. It also provides the methods to fit parameters of the model, *e.g.* flux values or spectral parameters, via the maximum likelihood approach.

The first implementation of this software framework, written by Patrick Younk (LANL) and Lauer, was in summer of 2014 and is called **Li**kelihood **F**itting **F**ramework (LiFF) [13]. A simplified schematic of the framework structure is shown in Fig. 4(Right). As Younk now has only a fraction of his time on HAWC, Lauer is the sole leader/coordinator of LiFF development. The LiFF code is already part of the general HAWC software architecture and is being used in several ongoing high-profile analyses including: DM searches based on dwarf spheroidal galaxies [29], light curve studies [15], and the galactic plane analysis [30]. In practice, LiFF has become the main multi-purpose high-level analysis code in HAWC.

Our improvement of the LiFF analysis framework has been done in parallel with the development of specific DM search applications using LiFF. The first example was the search for gamma-rays from dwarf spheroidal galaxies [29]. These are effectively point-sources for HAWC. For (more) extended source regions we have moved from analytic descriptions of DM halo profile models to pixelated maps of the expected gamma-ray fluxes. Michael Gold has implemented code to populate DM annihilation maps, for *e.g.* the Virgo galaxy cluster, using the HEALPix [31] parametrization of sky coordinates. This example has been used to test the improved model interface of LiFF which allows a HEALPix map of gamma-ray fluxes as input. In this approach, we generated a library of halo model maps and compare likelihood results when analyzing data.

The development of the LiFF software has happened in parallel with work on the **M**ulti-**M**ission **M**aximum **L**ikelihood (3ML) framework [14] (led by Giacomo Vianello, Stanford U.), designed for extended-energy analyses of astrophysical models with observations from several experiments. This code has been developed in close collaboration with work on the HAWC-internal LiFF code to ensure compatibility. A test of this code with a simultaneous fit of HAWC and Fermi-LAT data is ongoing. Eventually, a joint DM analyses of these and other experiments (e.g. VERITAS) will profit from combining data directly through the 3ML framework.

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