

DISSERTATION

DARK MATTER ANNIHILATION CROSS-SECTION LIMITS OF DWARF SPHEROIDAL
GALAXIES WITH THE HIGH ALTITUDE WATER CHERENKOV (HAWC) GAMMA-RAY
OBSERVATORY AND ON THE DESIGN OF A WATER CHERENKOV DETECTOR PROTOTYPE

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ABSTRACT

DARK MATTER ANNIHILATION CROSS-SECTION LIMITS OF DWARF SPHEROIDAL GALAXIES WITH THE HIGH ALTITUDE WATER CHERENKOV (HAWC) GAMMA-RAY OBSERVATORY AND ON THE DESIGN OF A WATER CHERENKOV DETECTOR PROTOTYPE

I present an indirect search for Dark Matter using the High Altitude Water Cherenkov (HAWC) gamma-ray observatory. There is significant evidence for dark matter within the known Universe, and we can set constraints on the dark matter annihilation cross-section using dark matter rich sources. Dwarf spheroidal galaxies (dSphs) are low luminosity galaxies with little to no gas or dust, or recent star formation. In addition, the total mass of a dwarf spheroidal galaxy, as inferred from gravitational effects observed within the galaxy, is many times more than the luminous mass, making them extremely dark matter rich. For these reasons dSphs are prime targets for indirect dark matter searches with gamma rays. Dark matter annihilation cross-section limits are presented for 14 dSphs within the HAWC field of view, as well as a combined limit with all sources. The limits presented here are for dark matter masses ranging from 0.5 TeV to 1000 TeV. At lower dark matter masses, the HAWC-111 limits are not competitive with other gamma-ray experiments, however it will be shown that HAWC is currently dominating in the higher dark matter mass range.

The HAWC observatory is a water Cherenkov detector and consists of 300 Water Cherenkov Detectors (WCDs). The detector is located at 4100 m above sea level in the Sierra Negra region of Mexico at latitude $18^{\circ}59'41''$ N and longitude $97^{\circ}18'28''$ W. Each WCD is instrumented with three 8 inch photomultiplier tubes (PMTs) and one 10 inch high efficiency PMT, anchored to the bottom of a 5 m deep by 7.3 m diameter steel tank. The tank contains a multilayer hermetic plastic bag, called a bladder, which holds 200,000 L of ultra-purified

water. I will also present the design, deployment, and operation of a WCD prototype for HAWC built at Colorado State University (CSU). The CSU WCD was the only full-size prototype outside of the HAWC site. It was instrumented with 7 HAWC PMTs and scintillator paddles both under and above the volume of water. In addition, the CSU WCD was equipped with the same laser calibration system that is deployed at the HAWC site, as well as the same electronics and data acquisition system. The WCD prototype served as a testbed for the different subsystems of the HAWC observatory. During the three different installations of the prototype, many aspects of the detector design and performance were tested including: tank construction, bladder installation and performance, PMT installation and performance, roof design, water filtration and filling, muon coincidence measurements and calibration system. The experience gained from the CSU prototype was invaluable to the overall design and installation of the HAWC detector.

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TABLE OF CONTENTS

Abstract	ii
Acknowledgements	iv
List of Tables	viii
List of Figures	ix
Chapter 1. Introduction to Dark Matter	1
1.1. Evidence of Dark Matter	1
1.2. Dark Matter Candidates	6
1.3. Dark Matter Annihilation	9
1.4. Dark Matter Detection	11
Chapter 2. High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory	32
2.1. Overview	32
2.2. VAMOS: an Engineering Array	36
2.3. HAWC Expected Performance	37
2.4. HAWC Science	40
Chapter 3. A Water Cherenkov Detector Prototype at Colorado State University	50
3.1. Introduction	50
3.2. Bladder Development and Testing at CSU	51
3.3. Design, Deployment, and Operation of a WCD Prototype	53
3.4. Results from the CSU Prototype	65
Chapter 4. Dark Matter Annihilation Flux	69
4.1. Dwarf Spheroidal Galaxies	69

4.2. Particle Flux from Dark Matter	69
4.3. Dark Matter Density Distributions	72
4.4. Expected Gamma-Ray Flux	75
Chapter 5. Calculations of Limits on the Annihilation Cross-Section	77
5.1. Likelihood Analysis	77
5.2. Calculation of Upper Limits	81
5.3. Stacked Analysis	85
Chapter 6. First Limits with HAWC-111 Data on the Dark Matter Annihilation Cross-Section	87
6.1. HAWC Data	87
6.2. Analysis using HAWC-111 Data	87
Chapter 7. Summary	102
References	104

LIST OF TABLES

4.1	Source parameters for the fourteen dwarf spheroidal galaxies.	74
5.1	Data counts from HAWC-111 data for Segue 1 $M_\chi = 10$ TeV.	81
6.1	Likelihood analysis results for $M_\chi = 10$ TeV $b\bar{b}$ annihilation channel.	89

LIST OF FIGURES

1.1	Energy percentage of the universe.....	1
1.2	Keplerian orbital velocity as a function of radius, and actual observations for M33.	4
1.3	Mean velocities of 21 galaxies as a function of distance from the center of the galaxy.....	5
1.4	Rotation curve for the spiral galaxy NGC6503.....	6
1.5	The bullet cluster.....	7
1.6	Dark matter detection methods.	12
1.7	Dark matter particle annular modulation due to the WIMP wind effect.....	15
1.8	DAMA/LIBRA observed event rate annular modulation.....	15
1.9	Review of limits on the WIMP cross-section for direct detection experiments.	19
1.10	Fermi-LAT 95% confidence level limits on the dark matter decay.....	24
1.11	Fermi-LAT 95% confidence level limits dark matter annihilation.....	25
1.12	HESS 95% confidence level limits on WIMP annihilation.....	26
1.13	VERITAS 95% confidence level limits on the dark matter annihilation cross-section.	28
1.14	Joint MAGIC and Fermi-LAT dark matter results.....	29
1.15	Joint MAGIC and Fermi-LAT dark matter combined study.....	30
2.1	Water Cherenkov Detector (WCD) schematic.....	33
2.2	Photo and schematic of the HAWC site.	34
2.3	Milestones of the HAWC site.....	36
2.4	VAMOS 2012 Forbush decrease.	37

2.5	HAWC differential sensitivity.....	38
2.6	HAWC large scale cosmic-ray anisotropy.....	39
2.7	Schematic of an extensive air shower induced by a gamma ray.	41
2.8	Schematic of the HAWC data acquisition system.	43
2.9	PMT analog and digital signals for a 2 edge event.....	45
2.10	PMT analog and digital signals for a 4 edge event.....	46
2.11	HAWC cosmic-ray and gamma-ray events.	48
2.12	Measured excess for fHit data bins.	49
3.1	Testing bladders from outside companies.	52
3.2	Bladder testing at CSU.	53
3.3	PMT rates in a test bladder.....	54
3.4	PMT rates vs. dark box rates in a test bladder.....	55
3.5	Overhead view of the CSU prototype WCD site.	56
3.6	Scintillator paddles for the CSU WCD prototype.	57
3.7	Physics Tank 1 (PT2) diagram.....	58
3.8	PMT high voltage curve.....	60
3.9	PMT pressure testing at CSU.....	61
3.10	PMT deployment in PT1.....	62
3.11	PT1 deployment and roof structure.	63
3.12	Testing of the PMT wet deployment system.....	64
3.13	Water depth monitoring of the CSU prototype.	67

3.14	Schematic of the HAWC laser calibration system.	68
4.1	Dwarf spheroidal galaxies map.	70
4.2	Dark matter density profiles.	73
6.1	HAWC-111 exclusion curves for $\chi\chi \rightarrow b\bar{b}$	90
6.2	HAWC-111 exclusion curves for $\chi\chi \rightarrow \tau^+\tau^-$	91
6.3	HAWC-111 exclusion curves for $\chi\chi \rightarrow \mu^+\mu^-$	92
6.4	HAWC-111 exclusion curves for $\chi\chi \rightarrow t\bar{t}$	93
6.5	HAWC-111 exclusion curves for $\chi\chi \rightarrow W^+W^-$	94
6.6	HAWC-111 expected combined limit for $\chi\chi \rightarrow b\bar{b}$	95
6.7	HAWC-111 expected combined limit for $\tau^+\tau^-$ and $\mu^+\mu^-$	97
6.8	HAWC-111 expected combined limit for $t\bar{t}$ and W^+W^-	98
6.9	HAWC-111 combined limits for all dark matter annihilation channels.	99
6.10	Gamma-ray flux vs. energy for several dark matter annihilation channels.	100
6.11	Comparison of dark matter annihilation cross-section limits.	101

CHAPTER 1

INTRODUCTION TO DARK MATTER

1.1. EVIDENCE OF DARK MATTER

Dark matter is hypothetical matter that would account for most of the material in the Universe. Studies show that normal baryonic matter accounts for only 4.9% of the total substance in the Universe, while dark matter is theorized to account for 26.8%, and dark energy accounting for the remaining 68.3% [1], as can be seen in figure 1.1.

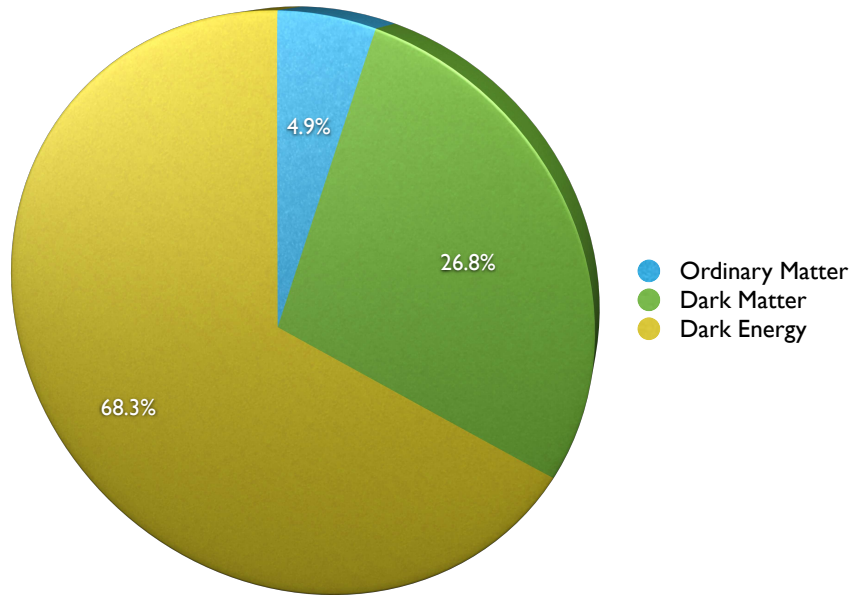


FIGURE 1.1. Energy percentage of the universe. Normal baryonic matter only accounts for approximately 4.9% of the total substance in the universe, leaving the mass percentage dominated by dark matter (26.8%) and dark energy (68.3%) [1].

Dark matter is aptly named as it neither emits nor absorbs any detectable electromagnetic radiation, thus making it difficult to study. While dark matter cannot be directly seen by traditional telescopes, there is ample evidence for the existence of dark matter in other

studies as discussed in [2]. The first evidence for dark matter came in the 1930s when Swiss astronomer Fritz Zwicky was examining the Coma galaxy cluster and used the virial theorem to theorize the existence of some “dark” matter in the cluster.

$$(1.1) \qquad \langle T \rangle = -\frac{1}{2} \langle V \rangle \ .$$

The virial theorem, as seen in equation 1.1, states that for a spherical distribution of objects, the total kinetic energy $\langle T \rangle$ is equal to minus 1/2 times the total gravitational potential energy $\langle V \rangle$ [3]. Thus by finding the kinetic energy of the system, the gravitational potential energy can be found, and the total mass of the system can be inferred. If the determined mass is greater than the mass calculated by observations of luminous matter, then there must be some other non-luminous matter present in the system that interacts gravitationally. By using the virial theorem, Zwicky noticed that the gravitational mass of the cluster was 400 times greater than the observable, or luminous mass. He proposed that there must be another source of non-luminous matter accounting for the observational difference, which he called “dark matter.”

The next contribution to the story of dark matter came decades later when Vera Rubin, an American astronomer, studied the orbital velocities of stars in spiral galaxies. Rubin and her collaborators made detailed measurements of the Doppler shift of objects in galaxies to determine their orbital velocities. What they found was that the orbital velocity did not decrease as predicted if only the luminous mass is accounted for. This meant that there must be more mass in the galaxy that interacted gravitationally with the luminous mass, but was indeed “dark”. In particular, Rubin observed that the galaxies must contain almost 10 times as much dark mass to account for the motion of the luminous mass. This startling discovery

confirmed Zwicky's much earlier claim that there must be a vast amount of dark matter contained in the known Universe. Rubin theorized that there must be an unobservable enormous spherical halo of dark matter surrounding the inner luminous galaxy, comprising most of the galaxy's mass.

By looking at Newton's Law of Universal Gravitation we know that:

$$(1.2) \quad F = \frac{Gm_1m_2}{r^2} = \frac{mv^2}{r} \ ,$$

so then the orbital velocity must decrease as you increase the distance from the center of the galaxy

$$(1.3) \quad v = \sqrt{\frac{Gm}{r}} \ .$$

Thus we would expect to see the orbital velocity fall off as a function of $1/\sqrt{r}$ from the center of a galaxy, as seen in figure 1.2. However, observations of galactic rotation curves of multiple galaxies, as observed by Rubin and others, are not in agreement with the expected $1/\sqrt{r}$ decline. In 1980, Rubin and her collaborators, Kent Ford and Norbert Thonnard, published observations of rotational properties for 21 spiral galaxies, showing that as the distance from the center of the galaxies increased, the rotational velocity stayed constant, or in some cases increased, as seen in figure 1.3.

Many other studies have been done and report similar behaviors for the rotational velocities of galaxies. A study by Begeman, Broeils and Sanders [6] showed similar results for the spiral galaxy NGC6503, as seen in figure 1.4. In addition to showing the observed rotational velocities as a function of the distance from the center of the galaxy, they also show the contributions to the rotational velocity from the luminous disk and gas and from the dark

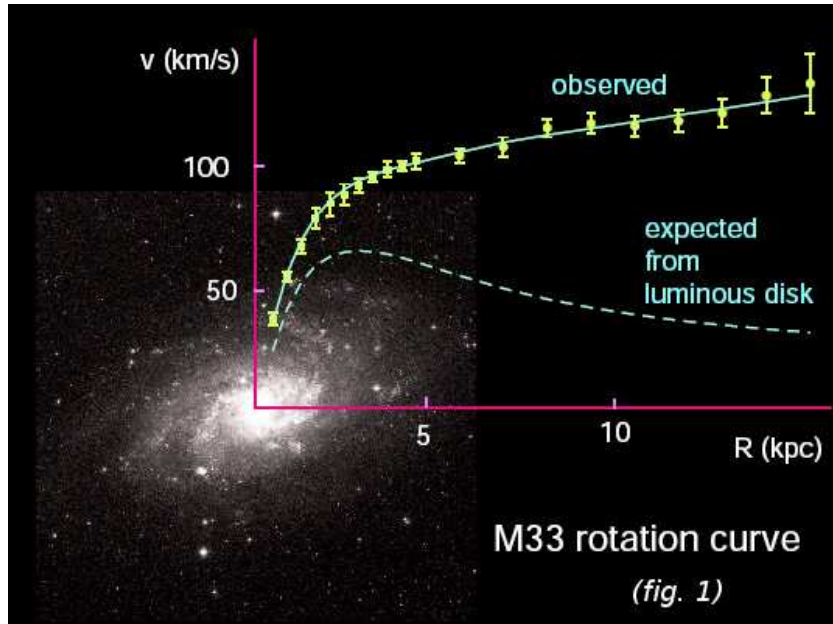


FIGURE 1.2. Orbital velocity as a function of the radius from the center of the galaxy for M33. The expected curve from the luminous mass shows the predicted $1/\sqrt{r}$ relationship as you increase the distance from the center of the galaxy. The observed curve is also shown for M33, showing that the orbital velocity does not decrease as $1/\sqrt{r}$ but instead flattens out. This implies that there is more mass present in the galaxy that interacts gravitationally with the luminous mass but is “dark”. Figure from [4].

halo. These dark matter theories, however, did not hypothesize the exotic dark matter that we theorize today.

Another concrete argument for dark matter came from observations of the bullet cluster, as shown in figure 1.5. The bullet cluster consists of two galaxies which have collided with one another. While the galaxies crossed paths, the stars within the two galaxies passed by each other unscathed, however the gas clouds merging from the galaxies ran together and, due to friction of the gas molecules, slowed down. With the gas clouds slowing down, the galaxies came into clearer view, giving scientists a chance to analyze the mass of the galaxies. They were able to estimate the total mass and gravitational pull in the galaxies without the gas clouds, using gravitational lensing. By looking at how much the light from distance objects beyond the bullet cluster was bent, scientists were able to determine that the cluster

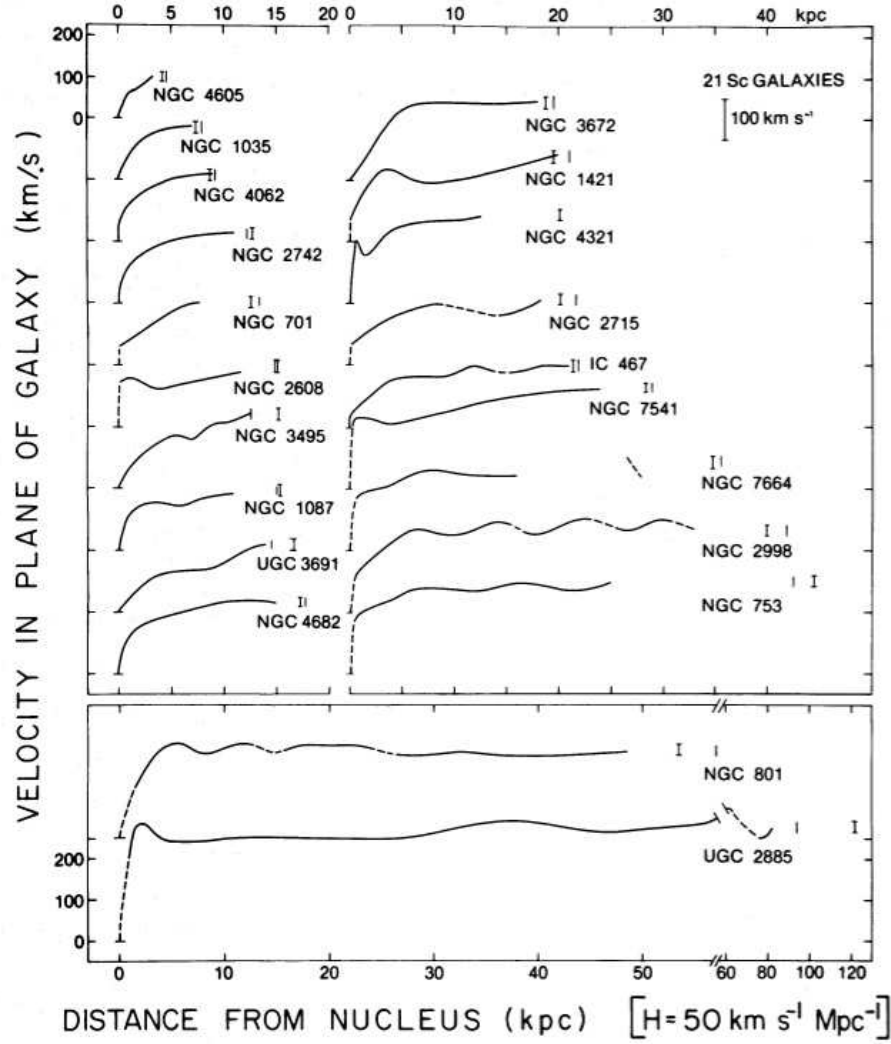
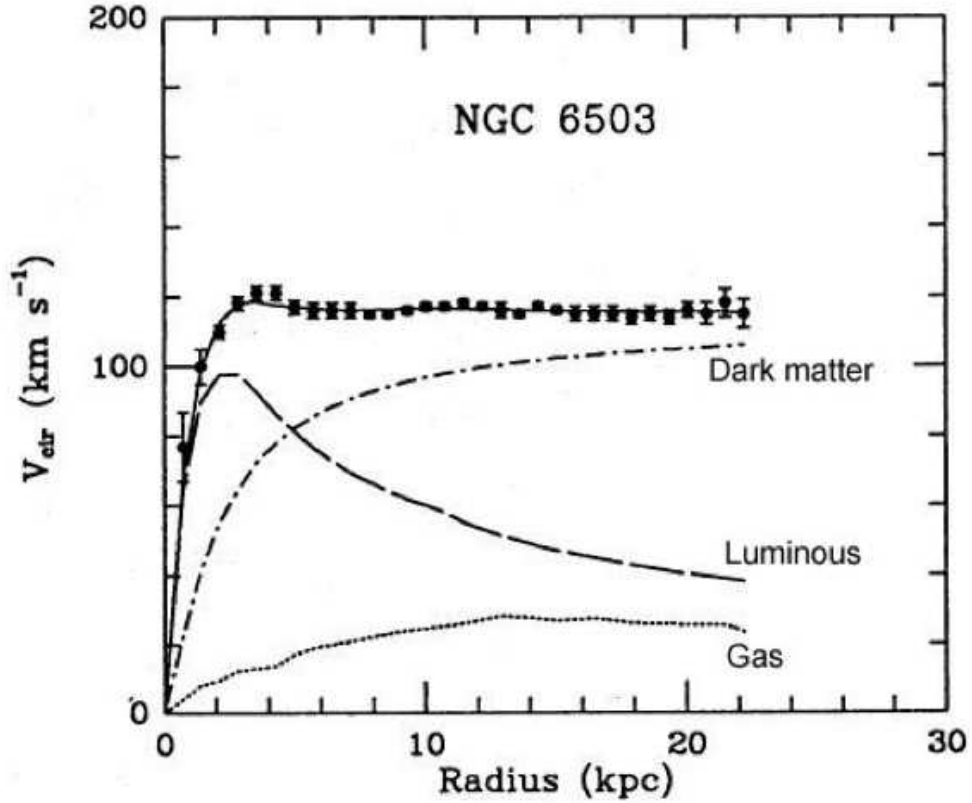


FIGURE 1.3. Orbital velocities of individual stars in galaxies as a function of their distance to the galaxy center, shown for 21 galaxies [5]. As the distance from the center increases the rotational velocity stays relatively constant instead of following the predicted $1/\sqrt{r}$ decline as predicted by the gravitational effects of the luminous mass alone.

bent the light more than it would assuming only luminous mass was present. This meant that there must be significantly more mass present in the cluster than was accounted for by the visible matter [8, 9].

These discoveries paved the way for widespread interest in the study of dark matter, motivating searches for both indirect and direct detection of dark matter particles. While



K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.

FIGURE 1.4. The radial velocity as a function of radius for the spiral galaxy NGC6503 can be seen in the measured data points. The dashed and dotted curves show the contribution of the luminous disk and gas respectively, while the dot-dash curve shows the contribution from the dark halo [7, 6].

the existence of dark matter is well documented, there remain many unanswered questions, particularly the composition of dark matter.

1.2. DARK MATTER CANDIDATES

While the evidence for dark matter is ample, there remains the question of its composition. There are numerous dark matter candidates, most of which fall into two categorizations: baryonic and non-baryonic candidates.

The main baryonic candidates for dark matter are MAssive Compact Halo Objects (MACHOs). MACHOs are astronomical bodies that are theorized to account for the presence

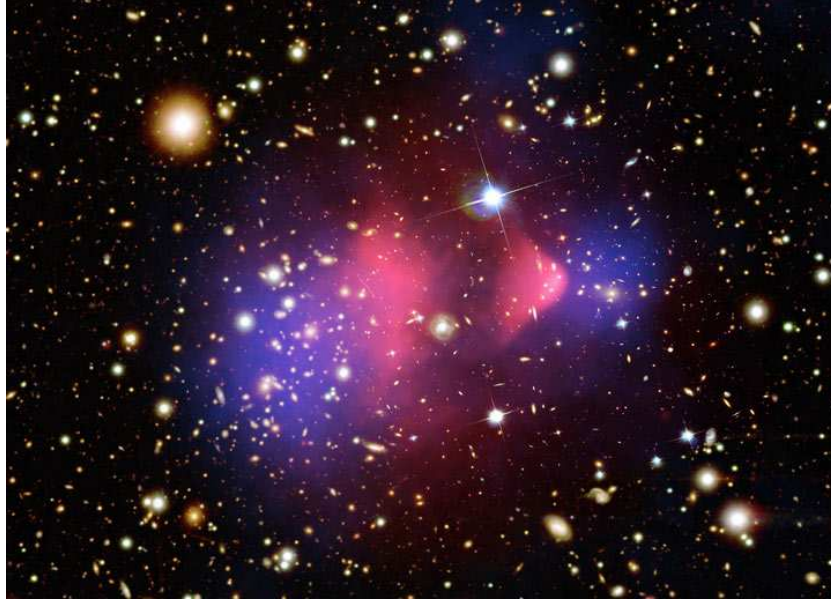


FIGURE 1.5. The bullet cluster as seen by the NASA Chandra X-Ray Observatory. The blue regions show the distribution of the total mass, as determined by gravitational lensing. The red regions show the x-rays emitted from the hot gas clouds that slowed as the two galaxies collided. Since the hot gas slowed during the collision, the mass content of the galaxies (blue regions) allowed scientists to observe the gravitational lensing of distant objects and determine that the galaxies in the Bullet Cluster contained much more mass than was accounted for by the luminous mass. Hence these galaxies must contain a significant amount of dark matter. Photo credit from reference [8].

of dark matter in galactic halos [10]. They are thought to be composed of normal baryonic matter, but emit little to no radiation, nor are they associated with any planetary system: they drift through interstellar space. Since they are non-luminous, MACHOs are very difficult to detect and can only be seen when they pass in front of another light source, bending the light from that source. There have been several experiments searching for gravitational micro-lensing amplification of light due to MACHOs. The MACHO experiment aims to find dark matter in our Galactic halo by monitoring stars in the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). From these observations, the fraction of the halo comprised of MACHOs can be estimated. After several years of observations, the MACHO group estimated that 50% of the halo could be made up of MACHOs. However, Gyuk [11]

showed that the MACHO density is more on the order of $0 - 30\%$ for several different models. Thus there seem to be no instances that account for a model compatible with a 100% MACHO halo [12]. Since the presence of dark matter can not be explained entirely with the MACHO theory, there must be some other candidate contributing to the dark matter halo.

Since the argument for a non-baryonic composition of dark matter was strengthened by gravitational micro-lensing experiments, the search has been on for observing a non-baryonic form of dark matter. There are two categories for non-baryonic candidates of dark matter: “hot” dark matter (HDM) and “cold” dark matter (CDM). A dark matter candidate is considered “hot” if it was moving relativistically in the early stages of galactic formation, whereas CDM was moving non-relativistically at that time.

The leading HDM candidate is the neutrino. Neutrinos would have emerged from the Big Bang with such highly relativistic velocities that they would have smoothed out any fluctuations in matter density at the beginning of the Universe. However, N-body simulations of a purely HDM dominated universe are not consistent with the observed structure [10]. Thus a pure HDM scenario is not likely, and dark matter is most likely cold, or a mixture of hot and cold.

Non-baryonic CDM candidates are theorized elementary particles, mainly axions and Weakly Interacting Massive Particles (WIMPs). Axions are hypothetical particles that arise as the solution to the strong charge parity (CP) problem in quantum chromodynamics (QCD). The strong-CP problem is the question of why QCD does not seem to break CP-symmetry, as seen experimentally, since according to QCD there should be a violation of CP-symmetry for strong interactions [7]. If axions do indeed exist, and have a low mass within a specific range, then they are possible candidates for CDM.

Weakly Interacting Massive Particles (WIMPs) are among the leading hypothetical particle physics candidates for CDM. A WIMP is a dark matter particle (χ) that has fallen out of thermal equilibrium with hot dense plasma during the beginning of the Universe and interacts with known standard model particles via a force similar to the weak force [10]. At the early beginning of the universe WIMPs existed in thermal equilibrium while the temperature of the universe exceeded the mass of the particle (m_χ). WIMP annihilation with its antiparticle ($\bar{\chi}$) into lighter particles l ($\chi\bar{\chi} \rightarrow l\bar{l}$) and vice versa ($l\bar{l} \rightarrow \chi\bar{\chi}$) maintained this equilibrium [10]. When the Universe began to cool, the temperature became less than m_χ , and the equilibrium abundance dropped exponentially until the rate of WIMP annihilation falls below the expansion rate. This is the point known as WIMP “freeze-out”, leaving the Universe with a cosmological abundance of WIMPs [7, 10].

1.3. DARK MATTER ANNIHILATION

If WIMPs are indeed the leading dark matter candidates, the question remains, how do we begin to detect these particles? One way is to look at products of WIMP annihilation. WIMPs are theorized to have a mass in the GeV to TeV range, be electrically neutral and to also be their own anti-particle. Because of this, WIMPs are thought to annihilate into standard model particles like fermions or gauge bosons [13].

$$(1.4) \quad \chi + \chi \rightarrow f + \bar{f}, W^+ + W^-, Z^0 + Z^0, \dots$$

We can begin to look for these annihilation signatures from areas in the universe that are thought to be dominated by dark matter. One of the best solutions is to scan the universe for gamma rays resulting from dark matter annihilation. Gamma rays are electrically neutral and will not interact with magnetic fields before they can be observed on Earth, allowing for

reconstruction of the primary gamma ray back to the point of origin. In this thesis there are five dark matter annihilation channels that are considered (although this does not comprise all of the possible annihilation channels):

$$\begin{aligned}
 &\chi\chi \rightarrow \tau^+\tau^- \\
 &\chi\chi \rightarrow \mu^+\mu^- \\
 (1.5) \quad &\chi\chi \rightarrow W^+W^- \\
 &\chi\chi \rightarrow b\bar{b} \\
 &\chi\chi \rightarrow t\bar{t}
 \end{aligned}$$

The tau lepton (τ^-) has a lifetime of 2.9×10^{-13} s and a mass of 1776.82 MeV/ c^2 . It can decay into a combination of charged pions, neutral pions and tau neutrinos. There are multiple decay channels for τ^- with 6 channels accounting for 90% of the decay possibilities and the remaining 10% accounted for by 25 different decay modes [14]. The 6 main τ^- decay modes are: $\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$, $\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$, $\tau^- \rightarrow \pi^- + \nu_\tau$, $\tau^- \rightarrow \pi^- + \pi^0 + \nu_\tau$, $\tau^- \rightarrow \pi^+ + 2\pi^- + \nu_\tau$ and $\tau^- \rightarrow \pi^- + 2\pi^0 + \nu_\tau$ [14]. From here gamma-ray emission can happen several ways. Mainly the neutral pions (π^0) will decay into two gamma rays ($\pi^0 \rightarrow 2\gamma$), but can also decay into a gamma ray and leptonic components ($\pi^0 \rightarrow \gamma + e^- + e^+$). There can also be final state radiation from products of the τ^- decay. The muon (μ^-) has a lifetime of 2.2×10^{-6} s and a mass of 105 MeV/ c^2 . It decays via the weak interaction: $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$ and $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$, and can again produce gamma rays through final state radiation. The W boson, with a mass of 80.4 GeV/ c^2 , mediates the weak interaction, and can decay into fermion-antifermion pairs. The bottom quark (b) has a mass of 4180 MeV/ c^2 and the top quark (t) has a mass of 173210 MeV/ c^2 . A quark can change from one flavor to another

via the weak interaction by either absorbing or emitting a W boson, and produce gamma rays via final state radiation.

The five annihilation channels used in this analysis were chosen for several reasons. Due to the available phase space, dark matter is expected to annihilate into the heaviest available channel [15], thus we consider the heavy top quark ($t\bar{t}$) and tau lepton ($\tau^+\tau^-$) channels. The $b\bar{b}$ annihilation channel is included since it has been studied by several experiments (Fermi-LAT, MAGIC, etc.) to allow for direct comparison of results. The bosonic W^+W^- channel was chosen since it is the standard boson channel and also widely considered in other experiments. Finally the muon channel ($\mu^+\mu^-$) is included in this analysis since dark matter models which are dominated by annihilation into $\mu^+\mu^-$ may be able to explain measured excesses of local positrons [15].

1.4. DARK MATTER DETECTION

If dark matter is indeed made up WIMPs, then there is an overall cosmological abundance of WIMPs in the universe. Since WIMPs are a leading class of dark matter candidates, there are many experiments currently looking for signatures of them. Dark matter experiments can be divided into three categories: production at colliders, direct detection and indirect detection. Here we explain the theories and technologies behind direct and indirect detection. Direct detection experiments look for an incoming WIMP particle to collide with a standard model particle in a detector, whereas indirect searches look for the incoming standard model products of dark matter annihilation, as seen in figure 1.6.

1.4.1. DIRECT DETECTION. Direct detection experiments work on the assumption that the Universe is filled with an abundance of WIMPs and that many of those WIMPs pass through the Earth. This makes it possible to observe their interactions with matter by

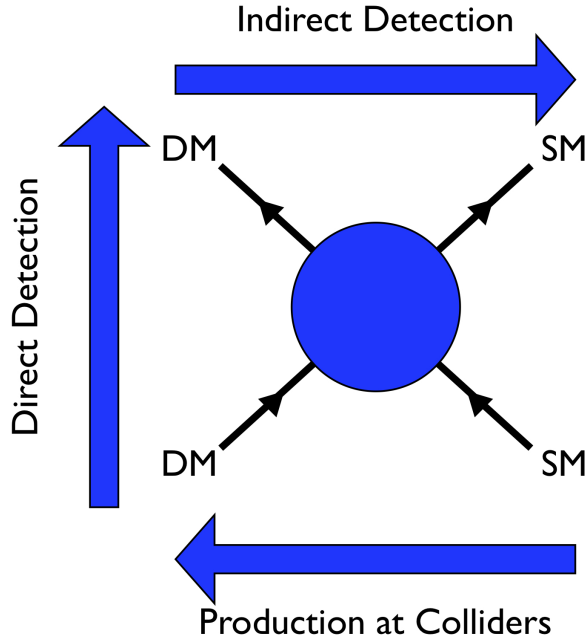


FIGURE 1.6. Schematic for dark matter detection methods, with time flowing in the direction of the large blue arrows. For production at colliders, two standard model particles collide and the by-products are observed. For direct detection, as the figure indicates, a dark matter particle collides with a standard model particle and the recoils are observed. For indirect detection, two dark matter particles annihilate and the standard model products are observed.

observing the recoil energy of nuclei as WIMPs scatter off them. The rate of WIMP detection in direct detection experiments depends on several key factors: the WIMP mass, the local halo density of dark matter, the velocity distribution in the Milky Way and the cross-section on the target nuclei. Thus the rate of events R is given by

$$(1.6) \quad R \propto \sum_i N_i \rho_\chi \langle \sigma_{i\chi} \rangle ,$$

where the index i runs over the number of nuclei species present in the detector, N_i is the number of target nuclei in the detector, ρ_χ is the local WIMP number density, and $\langle \sigma_{i\chi} \rangle$ is the cross-section for the scattering of WIMPS off nuclei in the detector [2]. The recoil energy

spectrum is given by

$$(1.7) \quad \frac{dN}{dE_r} = \frac{\sigma_0 \rho_\chi}{2\mu^2 m_\chi} F^2(q) \int_{v_{min}}^{v_{esc}} \frac{f(v)}{v} dv ,$$

where μ is the WIMP-nucleus reduced mass, $F^2(q)$ is the nuclear form factor (with q being the momentum transfer to the nucleus), σ_0 is the WIMP nucleus interaction cross-section and $f(v)$ is the velocity distribution of WIMPs in the dark matter halo [16]. The integral is evaluated from v_{min} (the minimum WIMP velocity able to generate a recoil of energy E_r) to v_{esc} (the maximum WIMP velocity set by the escape velocity in the halo model).

There are several different technologies utilized for the direct detection of dark matter. Experiments such as DAMA/LIBRA are particle detectors designed to detect dark matter using solid scintillators. DAMA/LIBRA utilizes thallium-activated sodium iodide crystals encased in a low radioactivity enclosure with PMTs to detect particle interactions [17]. DAMA/LIBRA is located at the Laboratori Nazionali del Gran Sasso in Italy, and contains 25 highly radio-pure NAI(Tl) crystals arranged in a 5x5 grid, each coupled to two PMTs. The detector is placed inside a sealed copper box that is flushed with nitrogen, and surrounded with a low-background multi-ton shield to reduce background noise from neutrons and gamma rays inside the detector, as well as 1 m of concrete fully surrounding the shield [18]. DAMA/LIBRA has an event rate of 1 count/kg/keV/day with an energy threshold of 2 keV [17].

The DAMA/LIBRA collaboration claims to see an annual modulation of the dark matter particle flux due to the revolution of the Earth around the Sun. Since the Earth revolves around the Sun, which is moving within the Galaxy traveling towards the constellation Cygnus, the Earth should be crossed by a larger flux of dark matter particles approximately around June 2nd annually [19]. This is due to the fact that in June the velocity of the Earth

around the Sun is added to the velocity of the Sun around the Milky Way galaxy, so the Earth is headed into this “wind” of dark matter WIMPs (if the dark matter halo of the Milky Way is indeed composed of WIMPs). Similarly, we should see a minimal WIMP wind effect during December when when we are traveling with the wind. This is also under the assumption that the dark matter halo of the galaxy does not rotate with the normal matter of the galaxy. A diagram of the WIMP wind effect can be seen in figure 1.7. This annual modulation of dark matter particles should have a well-defined period and phase. DAMA/LIBRA observed a strong annual modulation in their event rate at high statistical significance (9.3σ) for data collected during 7 annual cycles [20]. The results from the DAMA/LIBRA group can be seen in figure 1.8. While this finding seems promising, the result requires a cross-section of interaction between dark matter particles and nucleons of $\sigma \approx 2 \times 10^{-40} \text{ cm}^2$ for a mass $m \approx 10 \text{ GeV}$. These values are excluded by other direct detection experiments, as seen in figure 1.9 [21]. The researchers at DAMA/LIBRA are working to identify other possible sources that might produce the same event rate modulation, but it has been difficult to pinpoint another possible source for the signal modulation.

A possible explanation was thought to lie in combining the event rate modulations due to a seasonal flux from atmospheric muons and neutrinos. The solar neutrino flux at Earth depends on the distance the Earth is from the Sun, a value that varies over the year due to the Earth’s eccentric orbit, therefore the neutrino flux should vary as well. The event rate for muons, originating from the decay of cosmic rays in the atmosphere, also varies with seasonal changes in atmospheric temperature and density, with a minimum occurring in December [23]. This modulation is out of phase with the DAMA/LIBRA data, but only by about 30 days. It was found that the muons and solar neutrinos give no significant contribution to the DAMA/LIBRA modulation [24].

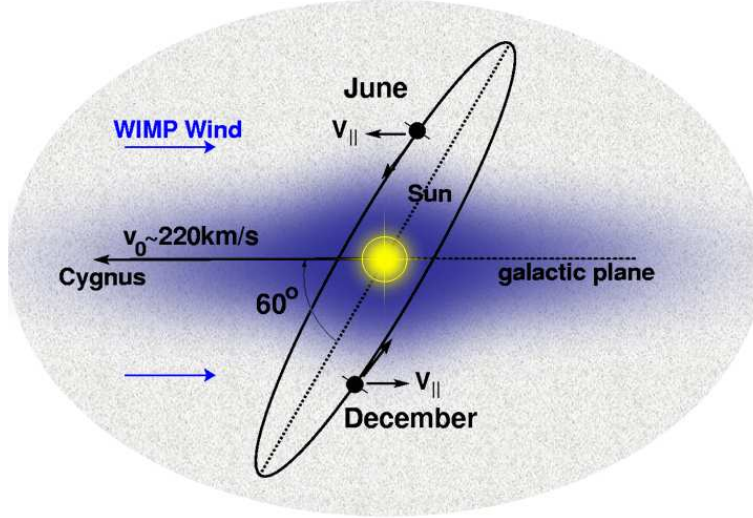


FIGURE 1.7. The annular modulation of the dark matter particle flux due to the WIMP wind. As the Earth travels around the Sun, which travels around the Galaxy, the Earth will experience a greater WIMP flux in the Summer when the Earth is traveling into the WIMP wind, and a smaller flux when the Earth is traveling with the wind. Figure from [22]

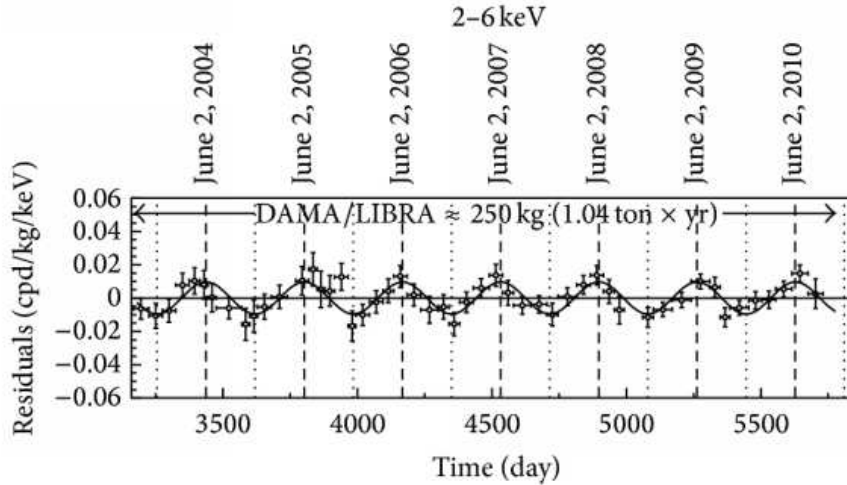


FIGURE 1.8. The DAMA/LIBRA-phase1 experimental rate of events in the 2-6 keV energy range as a function of time, for 7 annual cycles [20]. The annular modulation can be seen, which peaks in June and dips in December, as consistent with a predicted high/low dark matter event rate due to the Earth traveling into/against the WIMP wind respectively. From [20].

Another direct detection experiment is the CoGeNT (Coherent Germanium Neutrino Technology) experiment, which operates in the Soudan Underground Laboratory in Minnesota at a vertical depth of 2341 ft, providing shielding from the cosmic ray background.

CoGeNT uses the ionization signal from a 440 g high-purity Germanium crystal cooled to liquid nitrogen temperatures to detect dark matter interactions [17, 25], by looking for ionization charge from nuclear recoils. Using the ionization charge, constraints can be placed on the mass and dark matter cross-section [25]. Due to the low energy threshold of the detector and ability to reject surface background, CoGeNT can focus on low mass dark matter candidates ($m_\chi \sim 10$ GeV) [26]. The CoGeNT collaboration has seen a time variation in the rate of low energy events with a significance of 2.8σ , a modulation that is consistent with the phase, amplitude and period predicted for the WIMP annular modulation [27]. This result is also consistent with the DAMA/LIBRA experiment, although the result was not reported with nearly the same significance as the statistics were more limited. Results from CoGeNT and DAMA/LIBRA for the spin-independent cross-section can be seen in figure 1.9.

The Cryogenic Dark Matter Search (CDMS) experiment is also located in the Soudan Laboratory in Minnesota. CDMS measures the ionization and phonons produced by particle interactions in their germanium and silicon crystal substrates. The detector is maintained at a very low temperature (on the order of 10 mK) in order to distinguish the deposited energy of the interaction from the thermal energy in the detector [28]. When an incident particle collides with the detector it sets off vibrations (phonons) throughout the crystal lattice, which propagate through the crystal and are absorbed on the surface by aluminum and transfer their energy to Cooper pair electrons. The energy from the phonons breaks the Cooper pairs and gives the energy to their electrons, changing the electrical resistance of the sensors, resulting in an observed pulse [28]. CDMS has found no evidence of an annular modulation in their event rate as seen by CoGeNT and DAMA/LIBRA, and their results exclude or strongly constrain the CoGeNT signal.

Threshold detectors, such as the COUPP (Chicagoland Observatory for Underground Particle Physics) experiment use a bubble chamber for their dark matter searches. The target in COUPP is a superheated liquid (CF_3I) which leads to a local nucleation of a bubble at the interaction site when there is an energy deposition [17]. This pressure increase due to the bubble formation triggers imaging sensors around the detector, allowing for a 3-dimensional reconstruction of the interaction site.

The DRIFT (Directional Recoil Identification From Tracks) experiment is a second generation dark matter directional detector located at the Boulby Laboratory in England, 1100 m beneath ground [29]. The DRIFT detectors are comprised of two negative ion time projection chambers, each with a drift length of 50 cm, housed inside a stainless steel vacuum vessel. These are then encased in a neutron shield of polypropylene pellets. Particle interactions inside the detector ionize target gas molecules, then the free electrons are captured by CS_2 molecules, forming negative ions [29]. The CS_2 ions drift towards the multi-wire proportional counter which then yields the position of the track, the energy of the interaction and the drift time [17]. This is unique in that it allows for a directional and track-length based discrimination of events, allowing for a greater sensitivity in the arrival direction of the incident dark matter particle. This proves particularly useful in detecting effects from the WIMP wind.

The LUX-ZEPLIN (LZ) dark matter experiment is a next generation detector, combining the power of two previous experiments: the Large Underground Xenon (LUX) detector and the ZonEd Proportional scintillation in LIquid Noble gases (ZEPLIN) detector [30]. The LZ experiment will be located 4,850 ft underground at the Sanford Underground Laboratory in the Homestake Mine in South Dakota. It will contain 7 tons of liquid Xenon, where scattering events from dark matter interactions create both a scintillation signal and free

electrons [30]. Electric fields will drift the free electrons into the gas phase where they will produce a secondary scintillation signal. The scintillation signals will be detected by 488 PMTs located both above and below the liquid Xenon volume. The ratio of the first and second scintillation signals will provide discrimination between nuclear recoils and electron recoils, and the time delay between them will give the depth position within the chamber [30]. Since LZ builds on the success of LUX and ZEPLIN, it will have several features to add to the design element. First is the addition of a hermetic liquid organic scintillator outer detector that will surround the central chamber. The outer layer will be capable of rejecting gamma rays and neutrons produced internally which might mimic a WIMP interaction. The combination of the outer detector and the segmented Xenon detector will also form a nearly hermetic detection system for all internal radioactivity [30]. The LZ collaboration projects that a 3 year run of the detector will achieve a sensitivity to WIMP-nucleon spin-independent interactions down to 2×10^{-12} pb for 50 GeV WIMP mass [31].

Direct detection of dark matter is a vast and ever changing field. The above mentioned detectors comprise only a subset of experiments. In order to directly compare experiments it is useful to look at an overview of limits set by each detector on the WIMP-nucleon cross-section, as can be seen in figure 1.9. The spin-independent cross-section limits are shown in the solid lines of figure 1.9 while hints of WIMP signals are shown by the closed contours (as seen by DAMA/LIBRA and CDMS as mentioned previously). The limits shown are upper bound limits, so the cross-section limits exclude everything above them. The dashed lines indicate projections set for future dark matter experiments. Figure 1.9 also shows an approximate band where coherent scattering from solar neutrinos, atmospheric neutrinos and diffuse supernova neutrinos will dominate [21]. While a few experiments have shown

promising signals (such as DAMA/LIBRA), there remain many planned direct detection experiments that could verify and/or expand on dark matter detection.

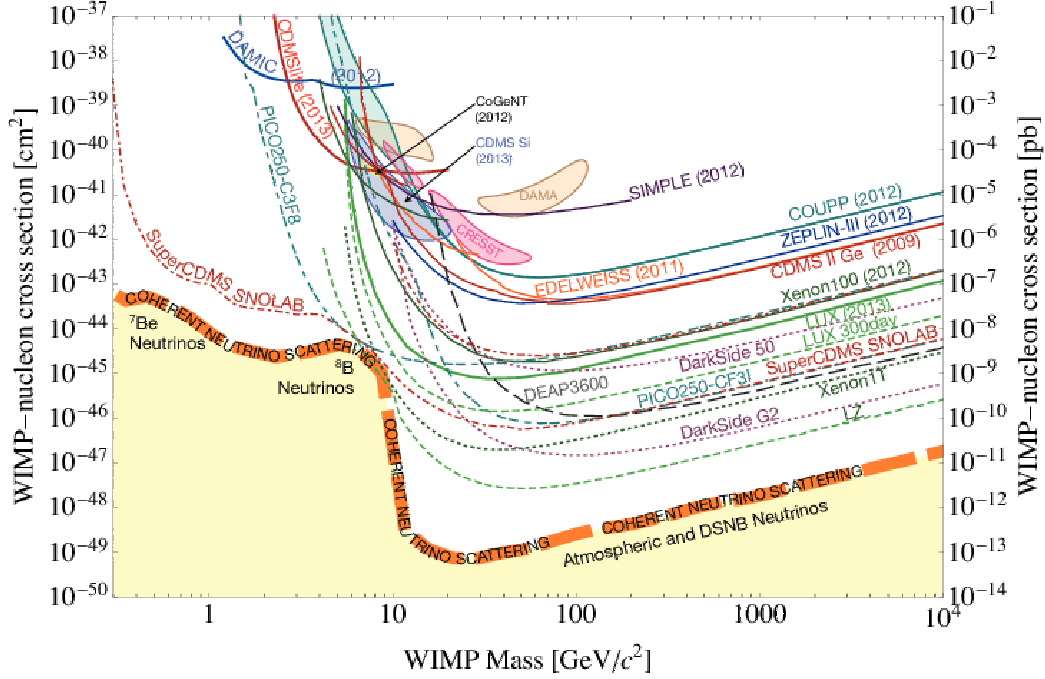


FIGURE 1.9. A review of direct detection experiments, from [21]. The WIMP-nucleon spin-independent cross-section limits are shown by the solid lines, while possible dark matter signals (such as seen by DAMA/LIBRA and CDMS) are shown by the closed contours, and the dashed lines show projections for future experiments. These upper bound limits exclude the cross-sections above these lines.

1.4.2. INDIRECT DETECTION. Direct detection is not the only way to search for dark matter. Indirect detection can be done by observing dark matter annihilation (or decay) products in dark matter dense regions of the universe. The density parameter of the universe Ω is defined as the ratio of the observed density ρ to the critical density ρ_c

$$(1.8) \quad \Omega \equiv \rho / \rho_c .$$

The ratio of the observed density to the critical density determines the overall geometry of the universe [16]. The critical density is the average density of matter required for the universe to halt its expansion and can be expressed as

$$(1.9) \quad \begin{aligned} \rho_c &= \frac{3H_0^2}{8\pi G} \\ &\approx 1.88 \times 10^{-26} h^2 \text{ kg m}^{-3} , \end{aligned}$$

where H_0 is the Hubble constant and h is the dimensionless form of H_0 in units of 100 km/s/Mpc [16]. The density parameter of the universe can tell us the contributions of normal baryonic matter, dark matter and dark energy

$$(1.10) \quad \Omega = \Omega_B + \Omega_D + \Omega_\Lambda .$$

where Ω_B , Ω_D and Ω_Λ are the contributions from normal baryonic matter, dark matter and dark energy respectively. Current observations from the Planck collaboration found that: $\Omega_B = 0.05$, $\Omega_D = 0.265$ and $\Omega_\Lambda = 0.685$ [32]. If dark matter annihilates (or decays) into standard model particles, such as neutrinos, charged leptons or gamma rays, then we will be able to detect these signatures coming from dense regions. Gamma rays and neutrinos are of particular interest to indirect searches as these neutral particles can travel through space undisturbed and their source of origin can be identified.

The dark matter density Ω_D depends on the annihilation cross-section weighted by the average velocity of the particle $\langle \sigma_A v \rangle$. In order for the results to match the abundance measured by the Planck collaboration the dark matter relic density must be equal to $\Omega_D h^2 = 0.1197 \pm 0.0022$ [32]:

$$(1.11) \quad \Omega_D h^2 = 0.11 \frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma_A v \rangle_0} .$$

This means that in order for dark matter to exist today there must have been an annihilation cross-section of $\langle\sigma_A v\rangle_0 \approx 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ at thermal freeze-out [15].

The present flux of these annihilation particles can be calculated by considering the following

$$(1.12) \quad \frac{dF}{dE} = \frac{\langle\sigma_A v\rangle}{8\pi M_\chi^2} \frac{dN_\gamma}{dE} J \ ,$$

where $\langle\sigma_A v\rangle$ is the velocity weighted cross-section, dN_γ/dE is the predicted gamma-ray spectrum for each dark matter annihilation channel, M_χ is the dark matter particle mass and J is the dark matter J-factor [15]. The cross-section is the effective area that quantifies the likelihood of an annihilation, and is velocity-weighted to account for the fact that the two dark matter particles are moving with respect to one another. The velocity-weighted component is the key difference to reporting limits on the dark matter cross-section between direct and indirect experiments. The dark matter J-factor contains all of the astrophysical information about the dark matter source and can be expressed as

$$(1.13) \quad J = \int_{\text{source}} d\Omega \int dx \rho^2(r_{\text{gal}}(\theta, x)) \ .$$

Here J is integrated along the line of sight distance x to the source and over the solid angle of the region of observation. The dark matter mass density ρ can be expressed as a function of the distance to the source $r_{\text{gal}}(\theta, x)$, which can be expressed as

$$(1.14) \quad r_{\text{gal}}(\theta, x) = \sqrt{R^2 - 2xR\cos(\theta) + x^2}$$

where R is the distance to the center of the source and θ is the angle between the line of sight from the detector and the source.

Indirect experiments can be both spaced-based and ground-based. Space-based experiments, such as the Fermi Large Area Telescope (Fermi-LAT) look for lower energy range gamma rays as the products of dark matter annihilation. Since Fermi-LAT is a satellite orbiting Earth, it directly measures gamma-ray intensities with an almost uniform full sky coverage. The primary particle (gamma ray) can be measured by Fermi-LAT in the energy range of 20 MeV to 300 GeV. The instrument is approximately $1.8 \times 1.8 \text{ m}^2$ with 18 tungsten converter layers and 16 dual silicon tracker plates stacked in 16 modular towers. Each module consists of 96 long, narrow CsI scintillators, stacked in 8 layers (alternating in orientation) in order for location and spread of the energy deposition to be determined [33, 34]. When a gamma ray enters the LAT it passes through the anti-coincidence detector and interacts in one of the tungsten sheets, converting the gamma ray into an electron and a positron via pair-production. The tracker then uses the silicon plates to measure the paths of the electron and the positron, which allows the LAT to determine the arrival direction of the incident gamma ray while the calorimeter determines the initial energy. Cosmic-ray particles produce an initial signal in the anti-coincidence detector (unlike a gamma ray), and can thus be rejected as background [35]. Fermi-LAT is sensitive to the products of WIMP annihilation or decay. More than 1800 gamma-ray point sources have been reported in the second source catalog, as well as over 500 sources in the high-energy catalog [33]. Fermi-LAT is also capable of measuring diffuse gamma-ray emission due to its excellent gamma/hadron discrimination.

Fermi-LAT has not published concrete evidence of a dark matter signature, but they have provided some of the most constraining limits on the thermally averaged annihilation cross-section and decay of WIMP dark matter. The Fermi collaboration has published limits on dark matter decay for 25 dwarf spheroidal galaxies that are satellites to the Milky Way.

The 95% confidence level individual lower limits for dark matter decay are shown in figure 1.10 from the eight most constraining dwarf spheroidal galaxies for a selected dark matter annihilation channel: $\chi \rightarrow b\bar{b}$. Figure 1.10 also shows the stacked analysis done by Fermi for several dark matter decay channels. A stacked analysis is done by combining the results for the individual sources in order to get a combined limit that should improve the overall statistics [36]. As can be seen in Figure 1.10 Reticulum II gives rise to the strongest bounds at low masses on the dark matter lifetime: this is due to its proximity and large dark matter J-factor [36]. Other strong dwarf spheroidal galaxies are Draco, Ursa Minor and Ursa Major II. The stacked analysis shown in figure 1.10 shows weaker limits, accounted for by the presence of fainter dwarfs in the analysis.

Fermi has also set limits on the dark matter annihilation cross-section from dwarf spheroidal galaxies. Figure 1.11 shows results from six years of Fermi-LAT data for a combined analysis of 15 dwarf spheroidal galaxies for two selected annihilation channels: $\chi\chi \rightarrow b\bar{b}$ and $\chi\chi \rightarrow \tau^+\tau^-$. The figure also shows the constraints from an older analysis with four years of data for the same 15 dwarf spheroidal galaxies [37].

In addition to Fermi-LAT there are several other experiments doing indirect dark matter searches, including IACTs. IACTs are ground based telescope arrays that are sensitive to the Cherenkov radiation produced during an extensive air shower created by a gamma ray entering the atmosphere. The High Energy Stereoscopic System (HESS) is an IACT that investigates gamma rays in the energy range from 10 GeV to 10 TeV and is located in Namibia near the Gamsberg mountain, 1800 m above sea level. HESS began operation in 2004 with four 12 m telescopes equipped with cameras containing 960 PMTs. These four telescopes were arranged in a square pattern with 120 m side length to provide multiple views of the same air shower. In the second installation phase, HESS added a single telescope in

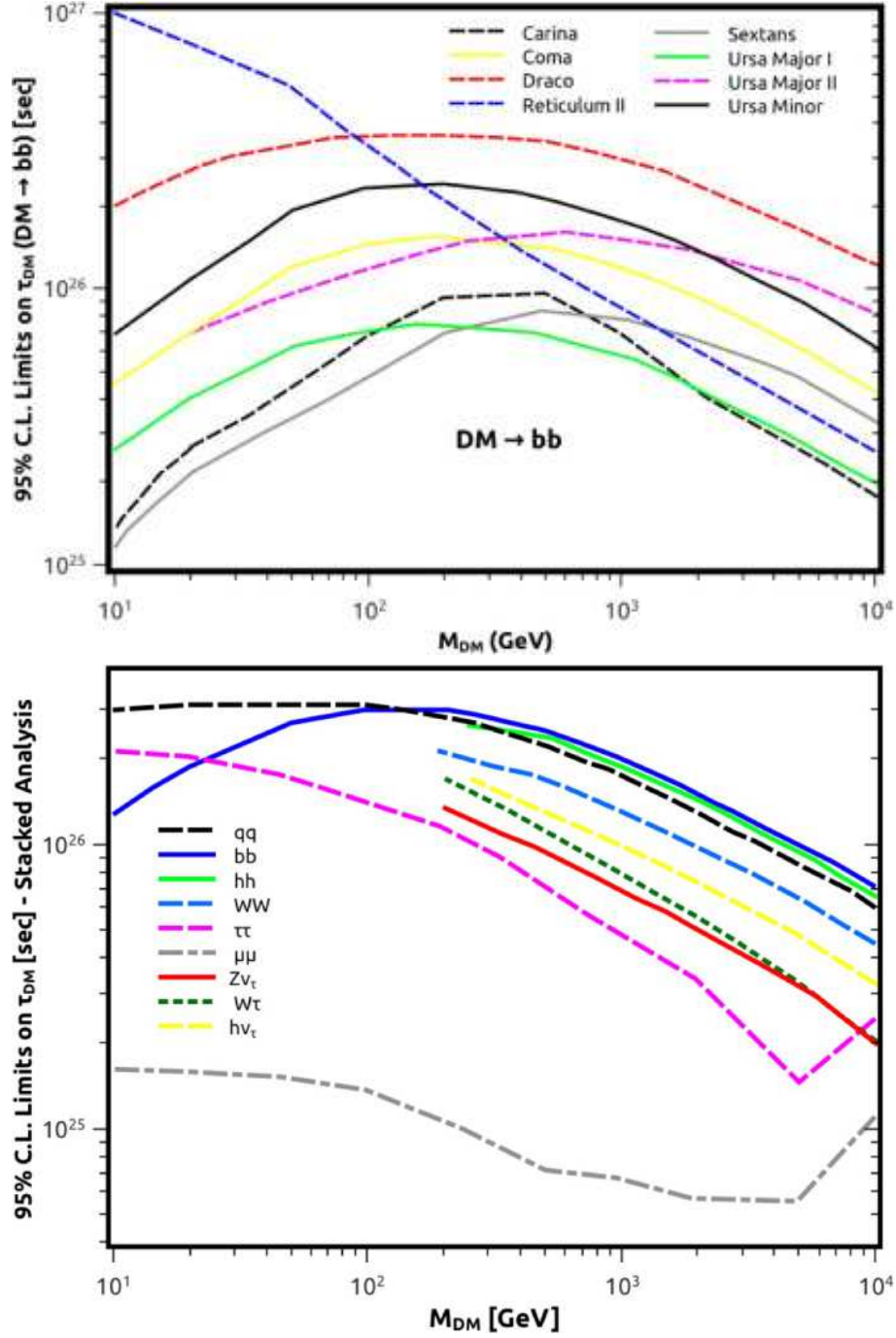


FIGURE 1.10. Lower limits (95% confidence level) on the dark matter decay for several dwarf spheroidal galaxies with Fermi-LAT data. The upper plot shows the eight most constraining dwarf spheroidal galaxies Fermi has observed for a dark matter particle decaying into a $b\bar{b}$ final state. The bottom plot shows the result of a stacked analysis with 20 dwarf spheroidal galaxies for several dark matter decay channels. Figures from [36].

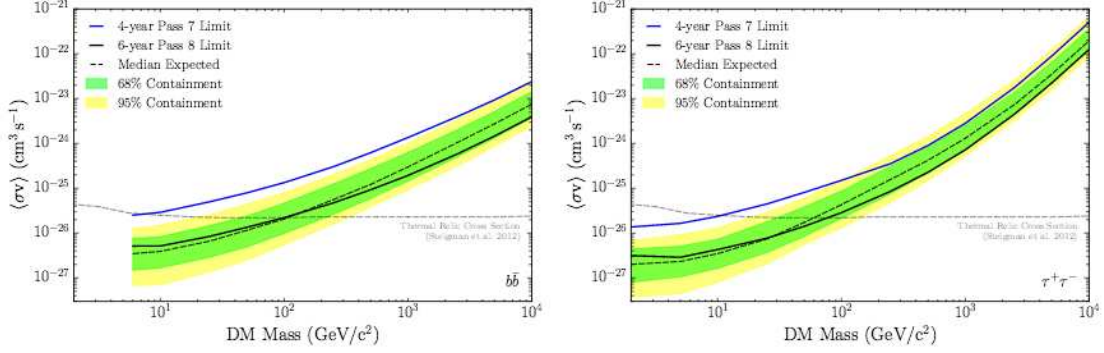


FIGURE 1.11. Constraints on the dark matter annihilation cross-section at 95% confidence level for the $\chi\chi \rightarrow b\bar{b}$ (left) and the $\chi\chi \rightarrow \tau^+\tau^-$ (right) annihilation channel from a combined analysis of 15 dwarf spheroidal galaxies using six years of Fermi-LAT data (solid black line). The figures also show bands for the expected sensitivity. The dashed line shows the median expected sensitivity and the green and yellow bands represent the 68% and 95% containment respectively. The constraint using 4 years of Fermi-LAT data is also shown (blue solid line) from a combined analysis of the same 15 galaxies. Figures from [37].

the center of the array with about a 600 m² mirror area (28 m telescope as compared to the original 12 m telescopes), which greatly increased the overall sensitivity of the array by improving upon the energy coverage and angular resolution [38]. The mirrors of the telescopes focus the Cherenkov light of an air shower event onto the cameras. As a result of HESS being an IACT, it has a very low duty cycle ($\sim 10\%$), since it is limited to operating on clear moonless nights. HESS has observed five dwarf spheroidal galaxies for emission from dark matter annihilation, with more than 140 hours of observation time. HESS found no deviation from background signal, meaning no excess of events, from the five dwarf spheroidal galaxies. The upper limits at 95% confidence level on the WIMP annihilation cross-section are shown in figure 1.12. The upper plot shows the individual limits for the five surveyed dwarf spheroidal galaxies for the W^+W^- and ZZ final states. The dwarf spheroidal Sagittarius is the most constraining galaxy that HESS observed. Figure 1.12 also shows results from a combined analysis for the W^+W^- and ZZ final states. Since Sagittarius is the

most constraining limit, a combined analysis was done both with and without Sagittarius included.

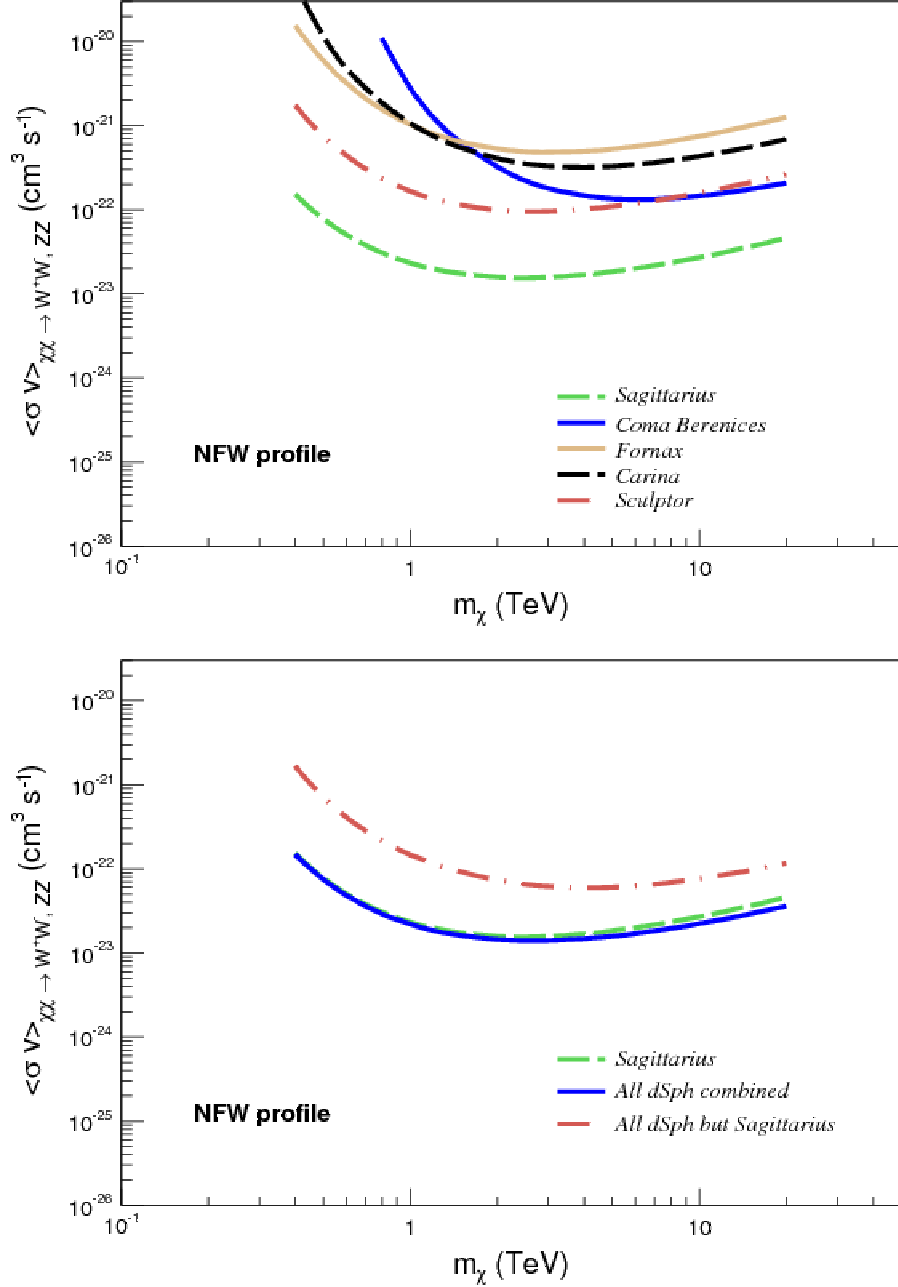


FIGURE 1.12. HESS upper limits (95% confidence level) on the WIMP annihilation cross-section from five dwarf spheroidal galaxies (upper) and a combined analysis (lower). Both plots are for a WIMP annihilation with W^+W^- and ZZ final states. The bottom plot shows a combined analysis both with (solid blue) and without (dashed red) Sagittarius, the most constraining dwarf spheroidal galaxy (individual limit in dashed green) observed with HESS [39].

In addition to HESS, another prominent IACT is the Very Energetic Radiation Imaging Telescope Array System (VERITAS) located at the Fred Lawrence Whipple Observatory in southern Arizona. VERITAS is a gamma-ray detector consisting of an array of four 12 m optical reflectors used to detect gamma rays in the 85 GeV-30 TeV energy range. Each telescope has 350 individual mirrors as well as a 499 pixel camera, with a field of view of 3.5 degrees [40]. VERITAS has a low duty cycle ($\sim 15\%$), an energy resolution of 15-20% and an angular resolution of 0.1 degrees, and it is able to detect the flux of the Crab Nebula (the “standard candle” of gamma-ray physics) at a statistical significance of 5σ for a 25 hr observation window [41]. VERITAS has also observed several dwarf spheroidal galaxies, searching for signals of dark matter annihilation. Figure 1.13 shows the 95% confidence level upper limits on the annihilation cross-section ($\langle\sigma_A v\rangle$) as a function of the dark matter particle mass. Shown are the limits for five dwarf spheroidal galaxies: Draco, Ursa Major, Bootes 1, Willman 1 and Segue 1. Segue 1 is the most constraining dwarf galaxy that VERITAS observed in this analysis [41].

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes is a gamma-ray detector located at the Roque de los Muchachos Observatory, 2200 m above sea level, at the Canary Island of La Palma. It consists of two telescopes, the first of which (MAGIC-I) was built in 2003 with a mirror surface of 236 m², making it the largest Cherenkov telescope in the world at the time. The second telescope (MAGIC-II) was built in 2010, 85 m from MAGIC-I. The MAGIC telescopes are sensitive to gamma rays in the very high energy range of 50 GeV to 50 TeV [42]. Like the previously mentioned gamma-ray detectors, MAGIC has also done studies on the dark matter annihilation cross-section from several dwarf spheroidal galaxies. Most recently, MAGIC published a joint study with the Fermi-LAT collaboration comparing their sensitivities to several dwarf galaxies. Figure 1.14 shows

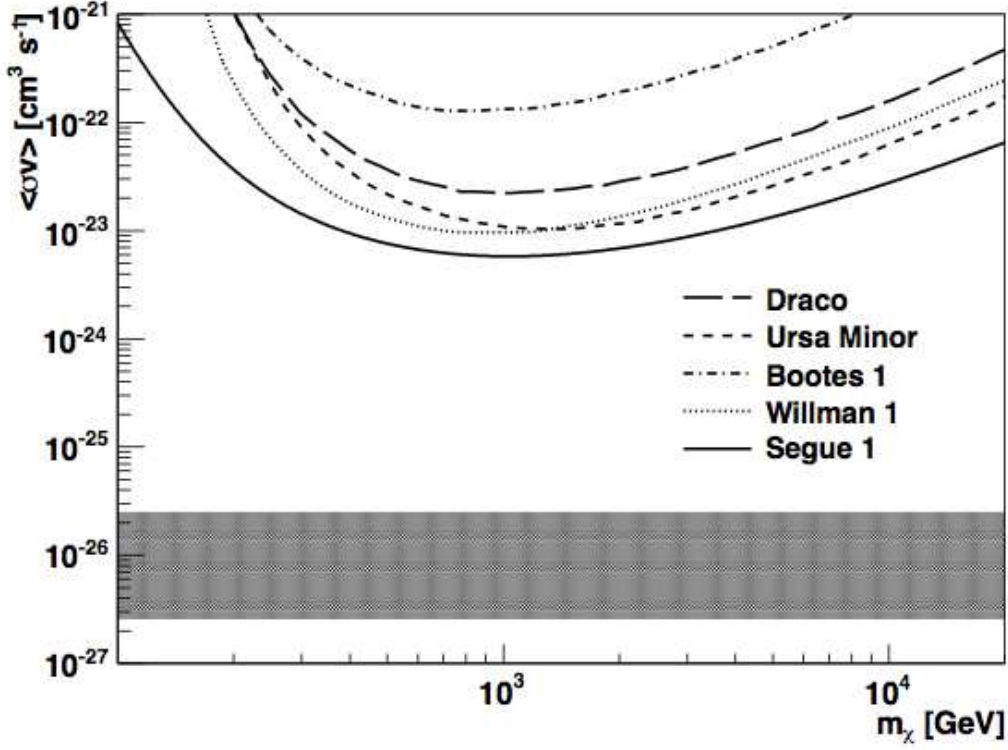


FIGURE 1.13. VERITAS upper limits (95% confidence level) on the dark matter annihilation cross-section for five dwarf spheroidal galaxies. The limits are shown for a composite dark matter annihilation channel ($10\%\tau^+\tau^- + 90\%b\bar{b}$), except for Segue 1 which is a pure W^+W^- channel. The grey band represents a range of generic values for the annihilation cross-section for thermally produced dark matter, [41].

the 95% confidence level upper limits on the thermally averaged annihilation cross-section for dark matter annihilating into four channels: $b\bar{b}$, W^+W^- , $\tau^+\tau^-$ and $\mu^+\mu^-$. Results are shown for a study done by combining Fermi-LAT observations + MAGIC observations for Segue 1, in addition to the individual limits for MAGIC and Fermi-LAT.

Figure 1.15 shows the combined limits for all dwarf spheroidal galaxies from the combined MAGIC and Fermi-LAT study. In both figures 1.14 and 1.15 the combined limits are compared to the median, and the 68% (green band) and 95% (yellow band) containment bands. These estimates were found from the distributions of limits obtained by applying

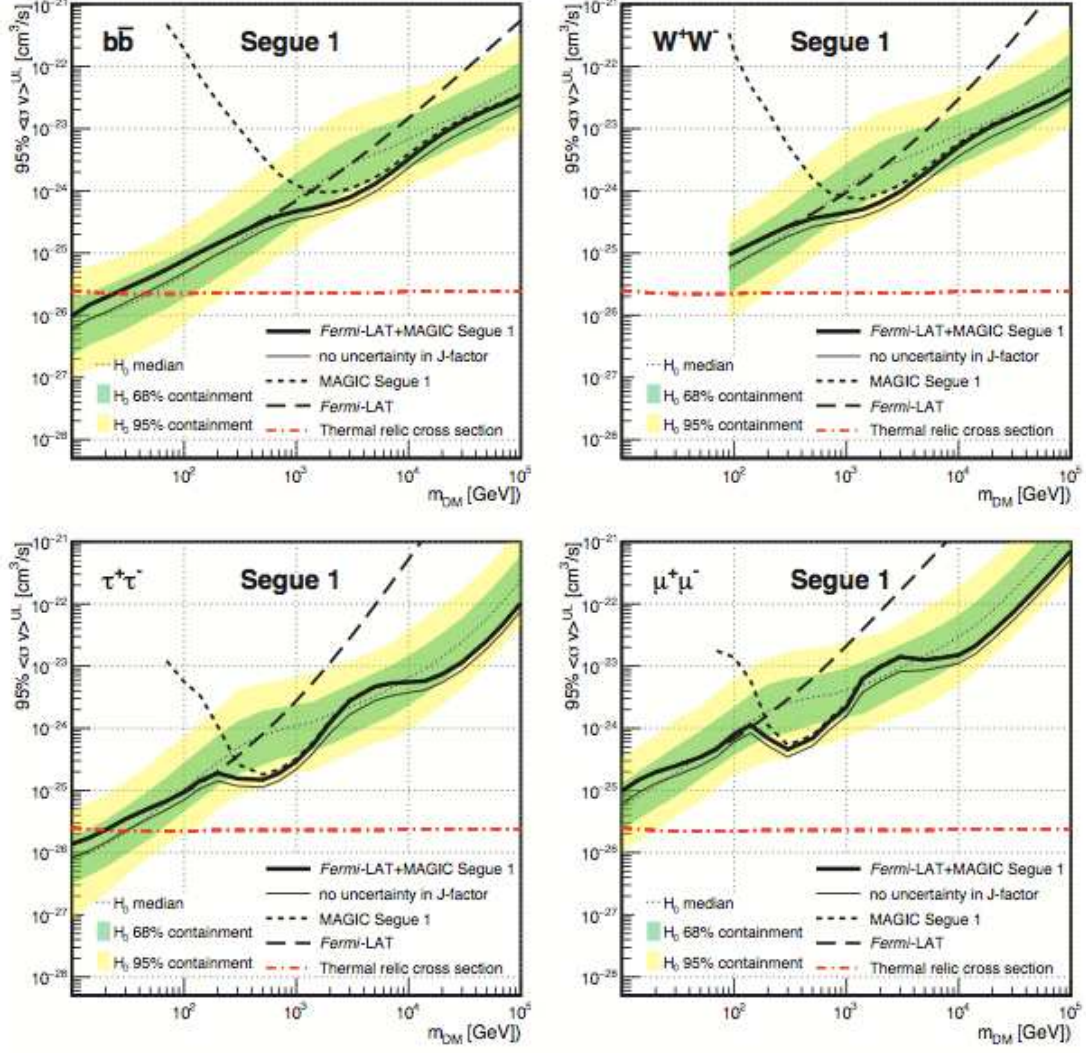


FIGURE 1.14. Upper limits (95% confidence level) on the thermally averaged dark matter annihilation cross-section for a joint analysis between MAGIC and Fermi-LAT. The limits are shown for several dark matter annihilation channels: $b\bar{b}$, W^+W^- , $\tau^+\tau^-$ and $\mu^+\mu^-$. The solid black line shows the limits from a combined Fermi-LAT + the MAGIC analysis for Segue 1, while the dashed lines show the individual Fermi-LAT and MAGIC limits. The green and yellow bands show the 68% and 95% containment bands respectively for the distribution of limits under the simulations where no source exists, [42]. The red dashed line shows the thermal relic annihilation cross-section, $\langle\sigma_{Av}\rangle = 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$, which is the cross-section needed for WIMPs at thermal-freezeout.

the MAGIC+Fermi-LAT analysis to 300 independent simulations where no source is predicted to exist. Each simulation consists of data from Fermi-LAT observations combined with simulations of MAGIC Segue 1 observations [42].

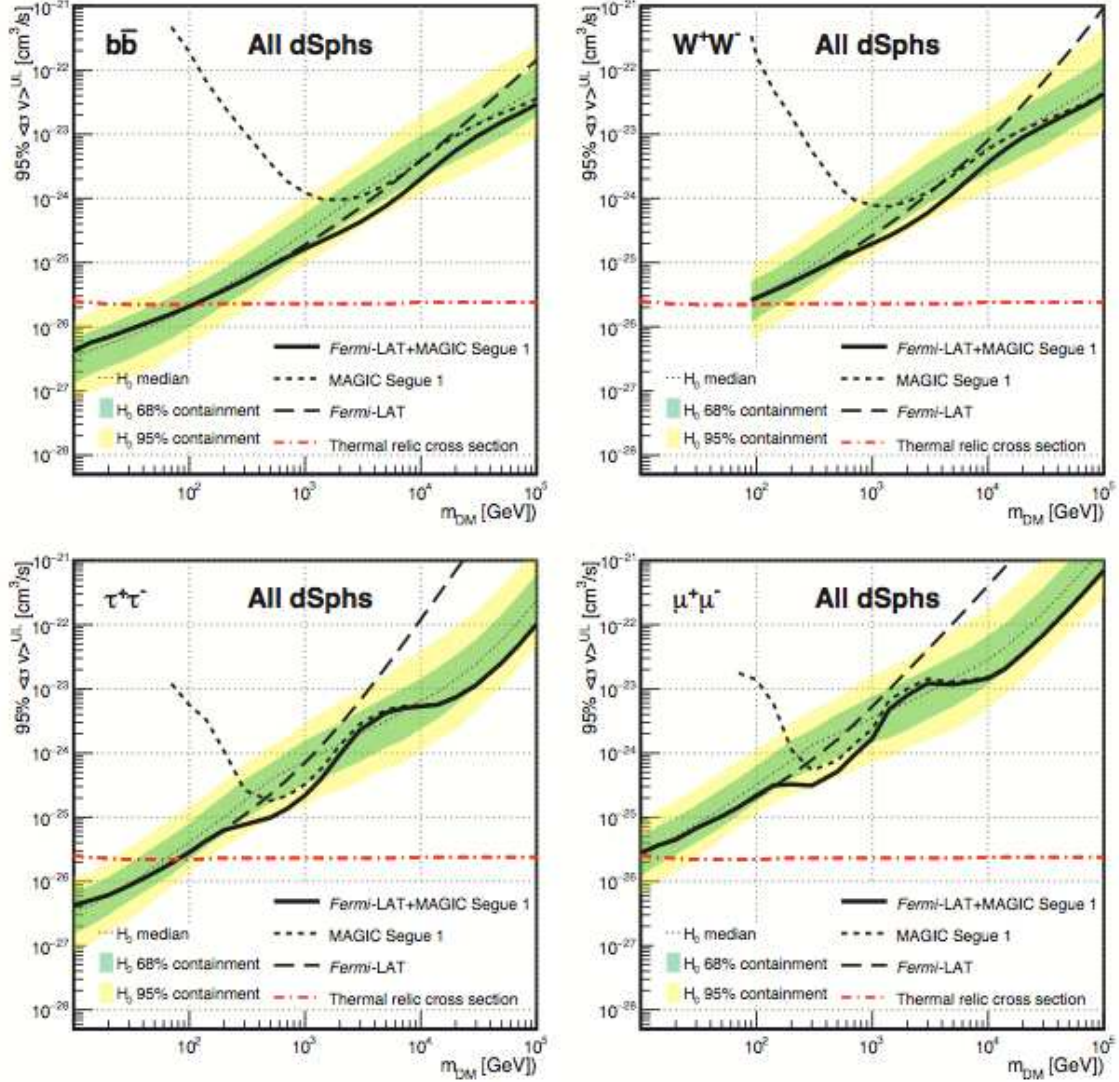


FIGURE 1.15. Upper limits (95% confidence level) on the dark matter annihilation cross-section from a joint MAGIC + Fermi-LAT analysis. The plots are similar to those in Figure 1.14, however here the solid black line is obtained by combining Fermi-LAT observations of 15 dwarf spheroidal galaxies with MAGIC observations of Segue 1, [42].

There are additional gamma ray detectors studying dark matter annihilation and decay, beyond what is mentioned here. In addition to space based observatories and IACTs, indirect detection can also be done via water Cherenkov detection. The water Cherenkov detection technique (as elaborated upon in the following chapters) is used by the High Altitude Water Cherenkov (HAWC) gamma-ray observatory, which is the detector used in this analysis.

While HAWC collaboration members are also setting lower bound limits on dark matter decay, the upper bound limits for dark matter annihilation are considered here and presented in this analysis.

CHAPTER 2

HIGH ALTITUDE WATER CHERENKOV (HAWC)

GAMMA-RAY OBSERVATORY

2.1. OVERVIEW

The High Altitude Water Cherenkov (HAWC) gamma-ray observatory is located at 4100 m above sea level in the Sierra Negra region of Mexico. It surveys the TeV gamma-ray sky, providing a view of the high energy universe. The high altitude location is crucial to studying gamma rays in the TeV energy range, as these particles are undetectable at lower altitudes. HAWC is a second generation water Cherenkov detector that expands on the water Cherenkov air-shower detection technique used by the Milagro experiment [43]. The Milagro observatory was in operation from 2000 to 2008 in the Jemez mountains near Los Alamos, New Mexico. The Milagro water Cherenkov technique directly samples shower particles at the ground level using an optically isolated reservoir. The full HAWC array consists of 300 individual Water Cherenkov Detectors (WCDs). Each WCD consists of a stainless steel tank structure 5 m tall and 7.3 m in diameter, and contains a multilayer hermetic plastic bag (called a bladder), containing 220,000 liters of purified water, as seen in figure 2.1. The WCDs are deployed in a close-packed array, covering an area of approximately 20,000 m². The configuration of the WCDs at the HAWC site can be seen in figure 2.2.

All water to fill the WCDs was hauled by truck to the HAWC site, as there is no fixed plumbing system at the site. Each WCD required eight truckloads of water, so filling the HAWC array drove the rate of deployment. The water filtration system is recycled from the Milagro experiment and is a sub-micron filtration system with a UV filter and a capacity of 760 liters per minute. The site has two “dirty” water tanks that are used to store the water

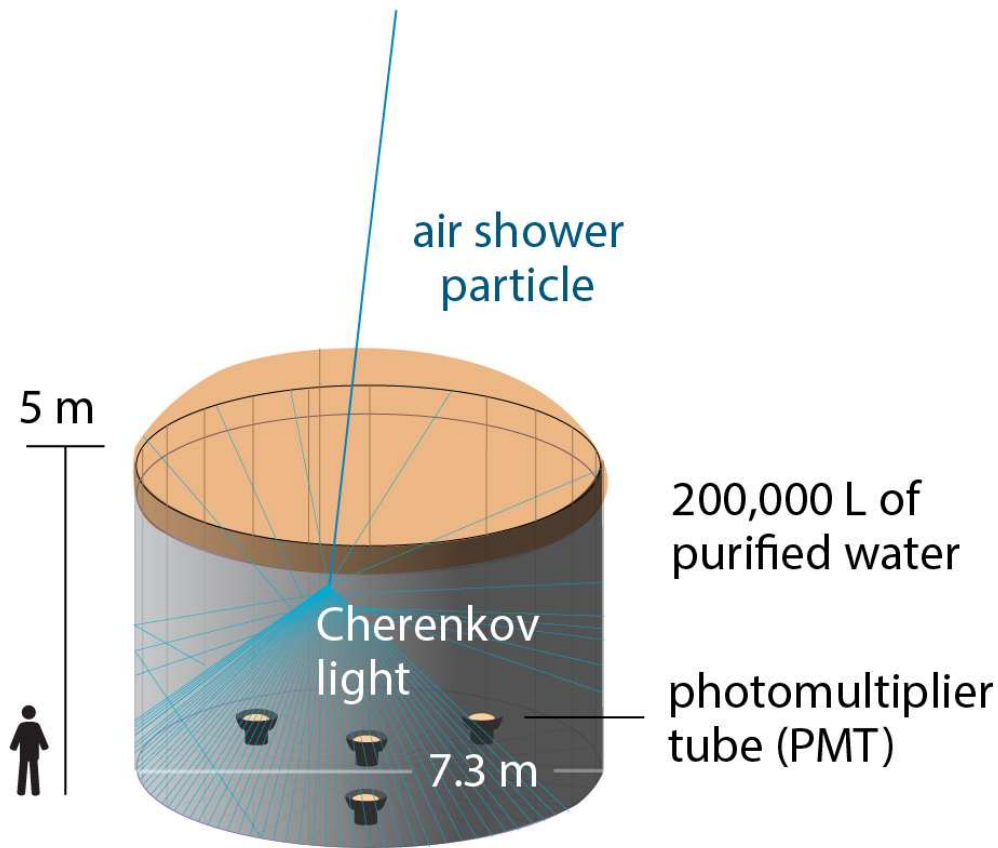


FIGURE 2.1. Schematic of a HAWC WCD. The steel tank is 5 m tall and 7.3 m in diameter, and contains a plastic bladder which holds 200,000 liters of ultra-purified water. The 4 photomultiplier tubes (PMTs) are upward facing and anchored to the bottom of the bladder, which for detection of the Cherenkov light produced by the air shower particle when it enters the tank. Image from D. Fiorino of the HAWC collaboration.

trucked up to the site. The “dirty” water is then piped into the utility house to the water filtration system and stored in four clean water tanks. The “dirty” water and clean water tanks are equipped with custom made liners. From there the now-filtered water is pumped into a WCD.

As mentioned above each WCD contains a custom made multilayer hermetic plastic bladder. The bladders are made out of low density polyethelene (LDPE) and were designed and manufactured at Colorado State University (CSU). Each WCD is equipped with 4

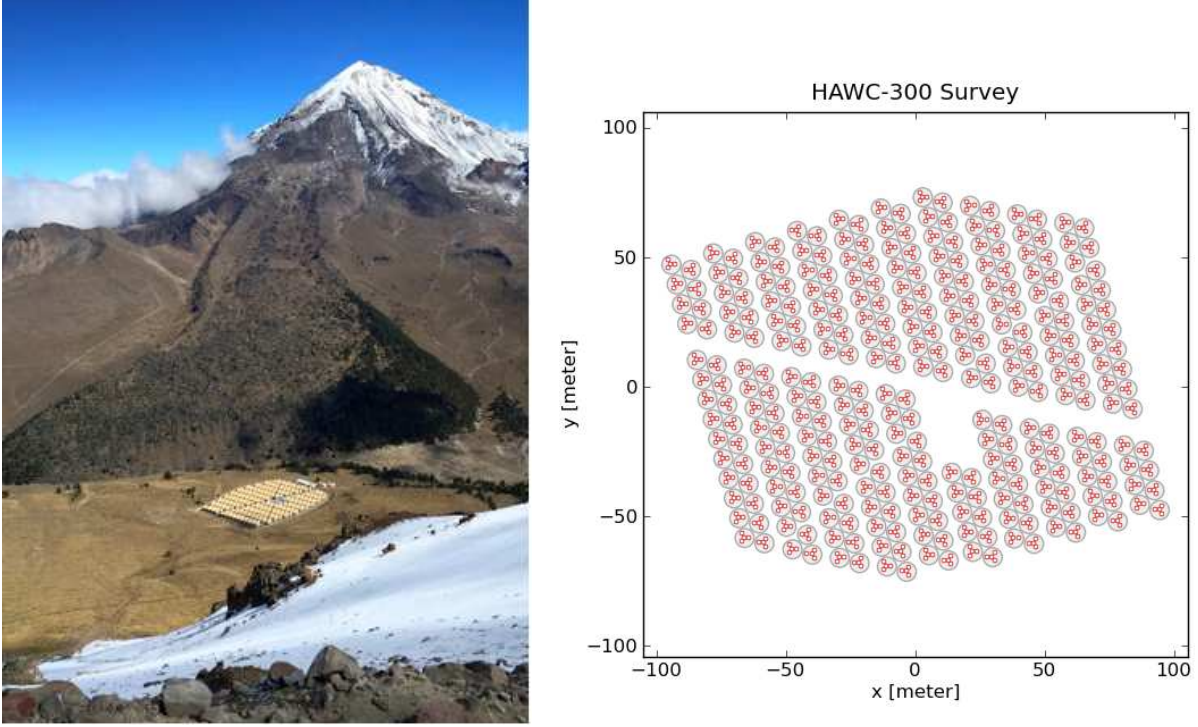


FIGURE 2.2. A photo and schematic of the HAWC site. The left photo was taken from above the HAWC site, with the complete 300 WCD array in view, as well as the volcano Pico de Orizaba in the background (photo taken by J. Goodman of the HAWC collaboration). The right figure shows the surveyed PMT locations (small red circles) inside each WCD (larger black circles). The orientation of the WCDs can be seen, as well as the space allocated for the DAQ counting house in the center of the array.

photomultiplier tubes (PMTs), as can be seen in figure 2.1. Three are 8 inch Hamamatsu R5912 PMTs re-used from Milagro. The 8 inch PMTs are spaced 6 ft from the center and at 120° separation from each other. The fourth and central PMT is a new 10 inch R7081-MOD high-quantum efficiency Hamamatsu PMT. The PMTs are single photon sensitive instruments which makes the water quality, as described previously, essential. The PMTs are used to detect the Cherenkov radiation produced when particles enter the water and travel faster than the speed of light in water. This is described in greater detail in section 2.4. A single RG-59 cable provides high voltage to each PMT and carries the high frequency

signal back to the front-end electronics in the counting house. All PMTs have a reflective cone around the PMT, are upward facing and are anchored to the bottom of the bladder.

While HAWC utilizes the same detection technique as the Milagro experiment, there have been many improvements to the detector design. The Milagro experiment was a large pond, which used two layers of PMTs for gamma/hadron separation. The two layers of PMTs were not optically isolated from one another. The HAWC detector utilizes individual water tanks to optically isolate the PMTs. In addition the HAWC array is larger than Milagro by a factor of 10, at 22,000 m². The increased detector area, as well as the increased altitude (4100 m instead of 2600 m) and optical isolation of the PMTs increases the sensitivity of HAWC to TeV gamma rays by a factor of 15 over that of Milagro [44]. The individual tanks also helped improve on the detector design over the Milagro pond concept. The individual tanks allowed for data collection to start as soon as one WCD was completed. It also helps with maintenance of the detector, as one WCD can be fixed without the whole detector going offline. These changes also help improve the gamma/hadron separation of HAWC. The HAWC detector has the added advantage of being built in stages, which allowed for data collection to start before the 300 WCDs were all deployed. Once a WCD was built and instrumented, it could begin to take data without having to wait on the construction of the remainder of the detector. The first 30 HAWC WCDs yielded a sensitivity comparable to that of the Milagro detector. HAWC had four major milestones during construction: HAWC-30 in August 2012 with 30 operational WCDs, HAWC-111 in August 2013 with 111 operational WCDs, HAWC-250 in November 2014 with 250 WCDs, and the inauguration of the complete HAWC detector (HAWC-300) in March 2015 as can be seen in figure 2.3.

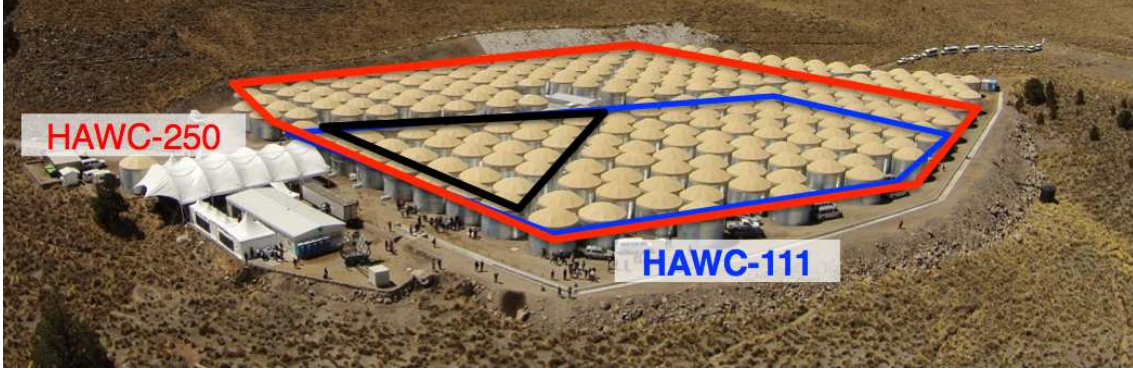


FIGURE 2.3. The different stages of the HAWC detector are shown superimposed on an image taken during the HAWC inauguration. The full HAWC array can be seen as well as the intermediate detector stages of HAWC-30 (black), HAWC-111 (blue) and HAWC-250 (red) [45]. The number in the HAWC label corresponds to the average number of operational WCDs in that particular data set.

2.2. VAMOS: AN ENGINEERING ARRAY

The Verification and Measuring of Observatory Systems (VAMOS) array consisted of 7 WCDs adjacent to the HAWC site. VAMOS served as an engineering array for the HAWC detector, with construction starting in May 2010. It was used to test different tank construction methods, bladder and PMT installation techniques, the water filtration system, electronics installation, and data acquisition (DAQ) methods. The array was completed in July 2011 with 6 fully operational detectors. Data collection continued through the remainder of 2011 and into May 2012, with an average live time of 30%. Through the VAMOS array, the collaboration was able to make numerous changes to the detector design and deployment techniques. As part of my service work to the collaboration I traveled on numerous occasions to deploy the detectors, including the first WCD of the VAMOS array. We implemented many detector design changes developed and tested at CSU (further discussed in Chapter 3). In addition to being a test array for HAWC, VAMOS collected eight months of

data and observed the Forbush decrease of March 2012, as seen in figure 2.4 [46]. A Forbush event describes a decrease in the overall cosmic-ray count following solar mass ejection activity [46].

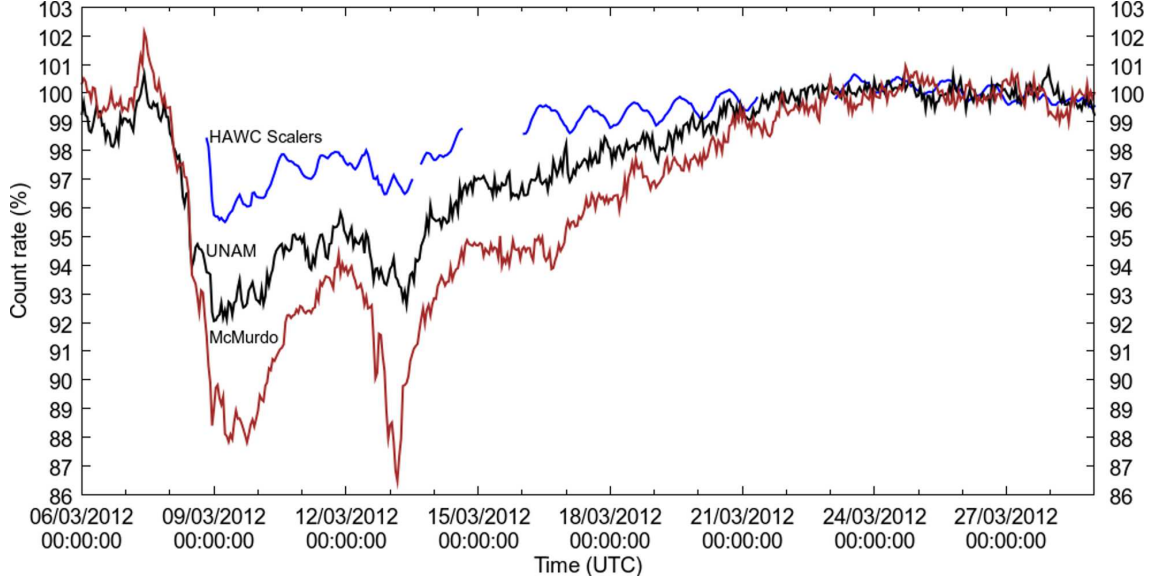


FIGURE 2.4. The scaler rates for the Forbush decrease of 2012 as seen by VAMOS. The count rate is shown for the VAMOS scaler system (blue) as compared to that seen by the neutron monitor of Mexico City at UNAM (black) and the neutron monitor of the McMurdo observatory [46].

2.3. HAWC EXPECTED PERFORMANCE

HAWC is rapidly expanding on the successes of the Milagro experiment. HAWC has an increased sensitivity over Milagro due to the detector's increased elevation, optical isolation of the PMTs and larger footprint, among other factors. The elevation increase allows HAWC to sample particle showers closer to their shower maximum (the point in the air shower where the number of particles reach a maximum before they start to die out). This improved sensitivity allows HAWC to extend the measurement of known sources and also continue to probe the sky for new TeV emitters. HAWC has an unprecedented sensitivity above 10 TeV and will be used to measure gamma-ray spectra of Galactic sources up to 100 TeV [45]. The

location of the HAWC site also allows for simultaneous observation with the Fermi-LAT Gamma-ray Observatory, VERITAS, MAGIC, HESS, etc. The differential sensitivity of the HAWC detector as compared to other instruments can be seen in figure 2.5. In this figure the projected HAWC sensitivity as a function of energy is shown for several stages of the HAWC detector. The differential energy sensitivity is the number of events detected per unit area per unit time, and is dependent on the energy of the event. What is important to note is that five years of data collection with the full HAWC-300 array will make HAWC more sensitive than HESS/VERITAS 50 hr observations at higher energies and will also surpass the Fermi-LAT 5 yr sensitivity.

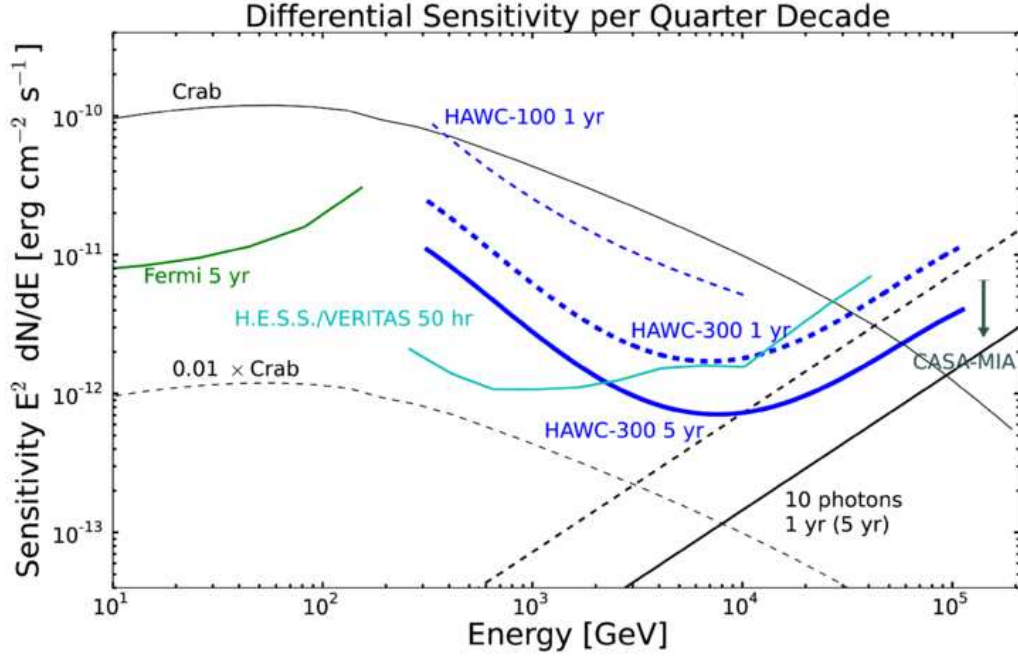


FIGURE 2.5. The differential sensitivity of the HAWC detector as compared to several other gamma-ray experiments. The HAWC-100 1 yr sensitivity calculation is shown compared to the HAWC-300 1 yr and HAWC-300 5 yr sensitivity calculations. The HAWC predicated sensitivity is also compared to those for Fermi-LAT (5 yr) and HESS/VERITAS (50 hr observation window), [43].

Another advantage of the HAWC detector is its continuous observation time, which allows the detector to monitor the sky with a near 100% duty cycle. This is different from other indirect detection gamma-ray experiments, such as IACTs (VERITAS, HESS, MAGIC, etc.), which have low duty cycles due to the fact that they have to operate on clear moonless nights. This enables HAWC to search for bright TeV outbursts from active galaxies, GRBs or galactic transients. HAWC will also search for a number of signatures of new physics including dark matter annihilation (as presented in later chapters), Lorentz Invariance Violation and Primordial Black Hole evaporation. Although HAWC is primarily a gamma-ray detector, our background is dominated by hadronic cosmic rays making HAWC capable of studying cosmic rays in the 100 GeV - 100 TeV range. Hadronic cosmic rays can be used to study solar physics and spatial anisotropies in the cosmic-ray background [45]. HAWC has observed evidence of large-scale cosmic-ray anisotropies as seen in figure 2.6.

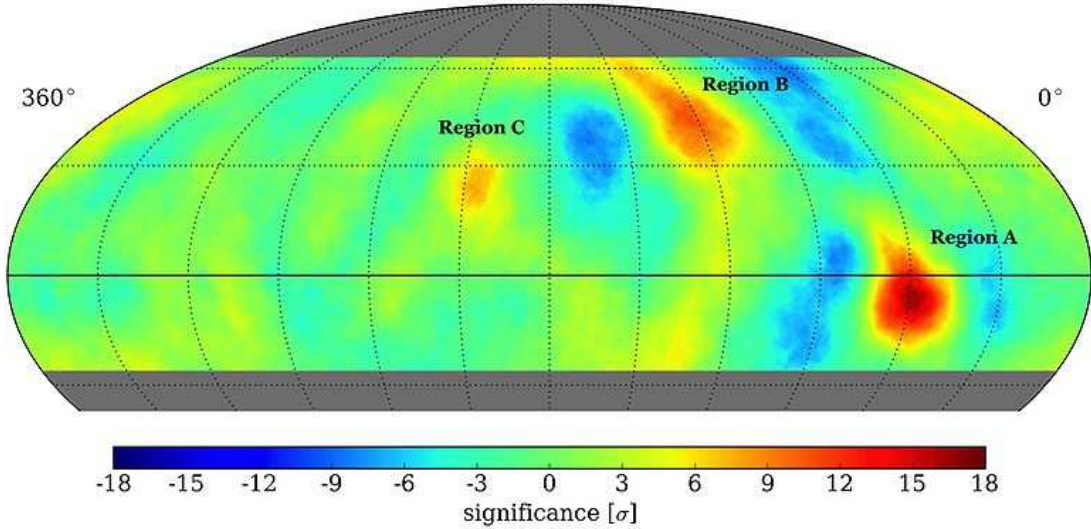


FIGURE 2.6. Observation of large-scale cosmic-ray anisotropy with the HAWC detector. The significance of the cosmic-ray flux is shown for 113 days of HAWC-95/111 in equatorial coordinates, [47].

The figures shown in this section represent a small fraction of the analysis work ongoing in the HAWC collaboration. HAWC has the immense capability of shedding more light on the TeV gamma-ray and cosmic-ray universe, particularly with data collection beginning with the entire HAWC-300 array.

2.4. HAWC SCIENCE

2.4.1. WATER CHERENKOV DETECTION TECHNIQUE. HAWC is a second generation water Cherenkov detector. It uses large tanks of water to detect incoming radiation from the atmosphere. When high-energy gamma rays and cosmic rays enter the Earth’s atmosphere they collide with molecules in the atmosphere, losing their energy via interactions with these molecules. These interactions create particles, which in turn collide with more molecules, producing more particles, etc. This cascade of particle collisions is known as an Extensive Air Shower (EAS). A schematic of a gamma-ray induced EAS can be seen in figure 2.7. This process continues until the energy of the individual particles falls below the threshold for pair production, at which point the interactions lead to the absorption of particles and the cascade of particle interactions lessens. The point at which this occurs is known as shower maximum, meaning the point where there is the maximum number of particles in the shower cascade. Even though the number of particles produced starts to decrease, the footprint of the shower continues to increase as it nears the ground, as the interactions cause the particles to diffuse away from one another.

An EAS can be detected at two stages: during its propagation through the atmosphere, or at the ground level. Imaging Atmospheric Cherenkov Telescopes (IACTs) detect the Cherenkov radiation generated by the cascade of relativistic charged particles in the EAS, as elaborated upon by [49]. Cherenkov radiation is electromagnetic radiation emitted when

Development of gamma-ray air showers

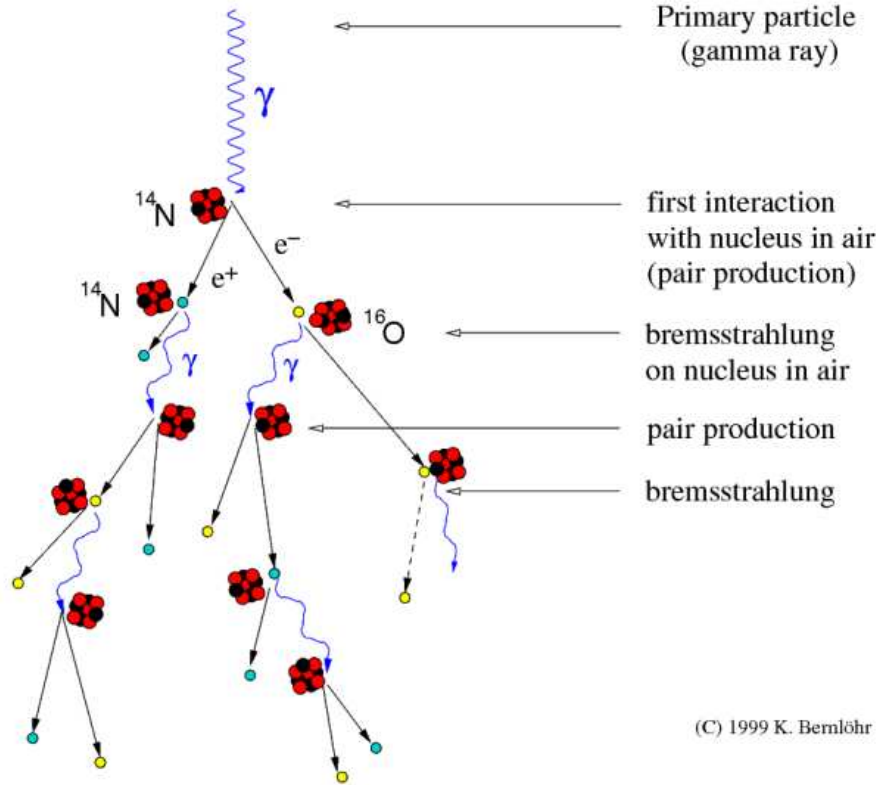


FIGURE 2.7. The above figure shows a schematic of an Extensive Air Shower (EAS) being produced by an incident gamma ray particle, [48].

a charged particle passes through a dielectric medium at a speed greater than the speed of light in that medium. IACTs such as HESS, MAGIC and VERITAS work to detect gamma rays in the GeV to TeV energy range, as elaborated upon in section 1.4.2. They have lower energy thresholds (< 200 GeV) than HAWC, excellent background rejection and good angular resolution. While IACTs have proven effective, they also have disadvantages. They have very low duty cycles on the order of approximately 20%, since they must operate on clear moonless nights, and a small field-of-view ($< 5^\circ$) since they are pointing telescopes (they must slew to their area of observation on the sky).

Air shower arrays detect an EAS on the ground level. They can operate during all weather conditions at any time, giving them a very high duty cycle, and have a much larger field of

view ($> 45^\circ$). They also have higher energy thresholds (> 10 TeV) which lets collaborations push gamma-ray astronomy further into the TeV energy range. While they have the added benefit of detecting gamma rays into the TeV range, they are not sensitive to lower energy gamma rays as observed by IACTs or spaced-based observatories. When the EAS hits ground level, the particles in the shower are detected by the arrays. In the case of HAWC and Milagro, the WCDs detect the EAS particles with photomultiplier tubes anchored to the bottom of the water tank. The EAS particles enter the water in the WCD and produce Cherenkov radiation. Cherenkov radiation is emitted when a particle travels faster than the speed of light in that particular medium. The PMTs are single-photon sensitive and are able to detect this Cherenkov radiation.

2.4.2. HAWC DATA COLLECTION: ELECTRONICS AND DATA ACQUISITION. Once the PMTs are triggered by an EAS, the signal must make its way into the counting house, located in the center of the array. The signals are carried through 175 m of cable from the WCDs to the counting house where they are connected through spark gaps. The spark gaps prevent any large surges in voltage, such as from lightning storms, from damaging the electronics inside the counting house. They do this by grounding out any large surge of voltage that makes its way to the counting house before it reaches the electronics. The PMT cables are then connected to the Front-End-Boards (FEBs), which are recycled from the Milagro experiment. Each FEB is connected to 16 PMTs. The FEBs provide both the high voltage to the PMTs and process the signals returning from the PMTs. The FEBs feed the analog PMT signals into two data acquisition (DAQ) systems: the main DAQ which records individual events by air showers and the scaler system, which counts the signals in each PMT in 10 ms windows [50]. The PMT pulses are shaped and discriminated at two thresholds based on the number of photo-electrons (PEs) produced. The thresholds are $\frac{1}{4}$ PE and 5PE, with the

signals being digitized by CAEN VX1190A multi-hit Time to Digital Converters (TDCs) [51]. A schematic of the HAWC DAQ layout is shown in figure 2.8.

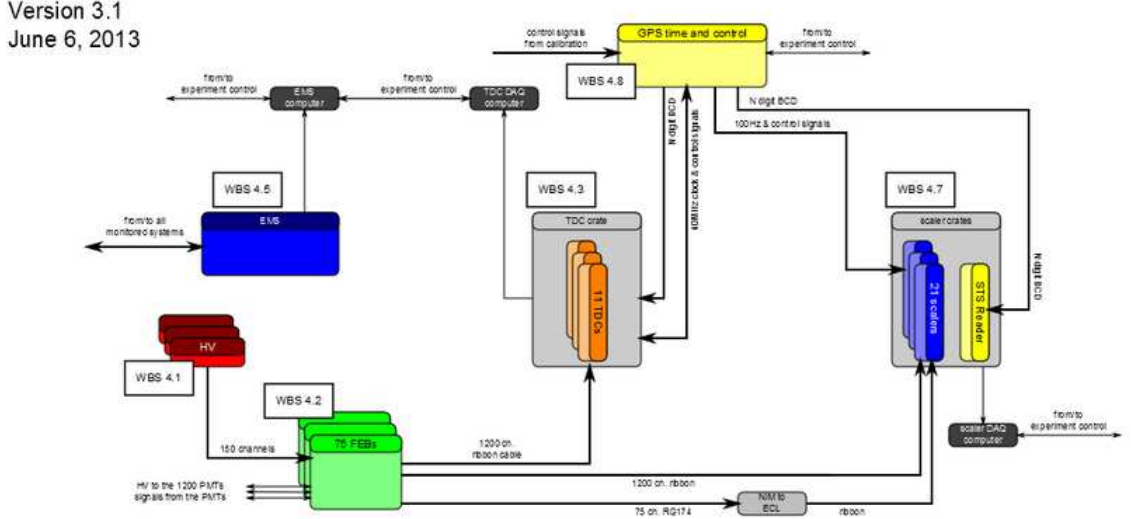


FIGURE 2.8. A schematic of the HAWC data acquisition (DAQ), from [52]. The PMT signals are fed from the WCDs, through RG59 cable, into the front end boards (FEBs) and into the time to digital converter (TDC) where the signals are digitized and shaped.

The TDCs measure the leading and trailing edge of the PMT pulse with the discriminating settings (low and high thresholds), with an accuracy of approximately 0.5 ns, which determines the pulse width, also referred to as the time-over-threshold (TOT). The TOT is a measurement of the charge in a given signal. Pulses with high charge will have four edges, or four places where the signal crosses the thresholds, while pulses with low charge will only have two, meaning they did not have enough charge to make it above the high threshold. Examples of PMT analog and digital signals for a 2 edge and 4 edge event are

shown in figures 2.9 and 2.10 respectively. HAWC records every leading and trailing edge for an event, however the only way to distinguish between a 2 edge or 4 edge event is the timing between pulses. The time for each hit is recorded and time cuts are applied to characterize whether a hit is a 2 edge or 4 edge event. The TOT is used for reconstruction of the shower event and is used to consider corrections to the arrival time of the shower and calibration and energy measurements.

The laser calibration system calibrates the detector by measuring the TOT charge conversion and the response time for each PMT to different laser pulse sizes. Individual events are time stamped with a GPS clock, which is particularly crucial for the measurement of GRBs and other transient sources [54]. After collection by the main DAQ, the events are passed to an online monitoring system for data processing, which is also used to send real-time alerts for interesting time sensitive events. The data collection rate for HAWC is 400 MB/s (since HAWC records every signal in each PMT), dropping to 15-20 MB/s with the application of the software trigger [51]. The trigger requires that at least 15 PMTs have signals above threshold within a sliding time window of 100 ns [47] for the event to be saved. All of the triggering is done in real-time with software, allowing for greater flexibility with the simple multiplicity trigger and the event reconstruction.

2.4.3. EVENT RECONSTRUCTION. Once a WCD has detected a signal from an EAS and the signal has been recorded by the DAQ, the event must be reconstructed. Reconstruction of the air shower event involves several steps. First the air shower core, the dense concentration of the energetic particles directly along the trajectory of the primary particle, is found with a fit to the energy density recorded in the hit PMTs in the array. An accurate core fit is vital to understanding the curvature of the shower front and to finding the best angular fit for the shower. The angular resolution of HAWC is approximated using a 2D Gaussian with

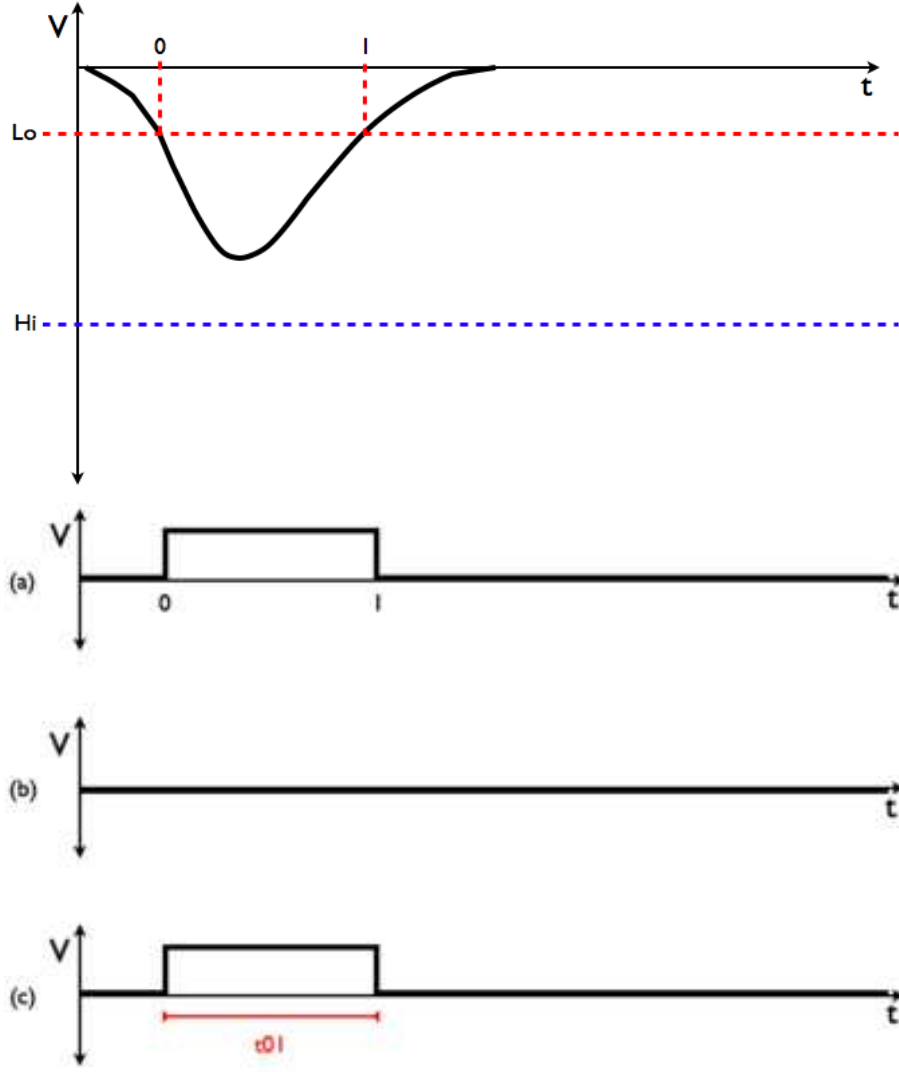


FIGURE 2.9. Illustrated PMT pulse for a 2 edge hit. The top figure shows the analog signal with the high threshold level (HiTOT) in blue and the low threshold (LoTOT) level in red. The pulse did not have enough charge to trigger the high threshold level, so the pulse is considered a 2 edge event as indicated in the bottom figure where: (a) is the LoTOT output, (b) is the HiTOT output and (c) is the summed total of LoTOT and HiTOT. The information from (c) is written to disk at the HAWC site. The figures above are from [53].

a width of $< 0.2^\circ$ for events that trigger most of the tanks in the array, and $1 - 2^\circ$ for events closer to the trigger threshold [51].

Next the direction of the air shower can be determined by looking at the hit times of the PMTs in the array, since particles far from the shower core will have a slightly different

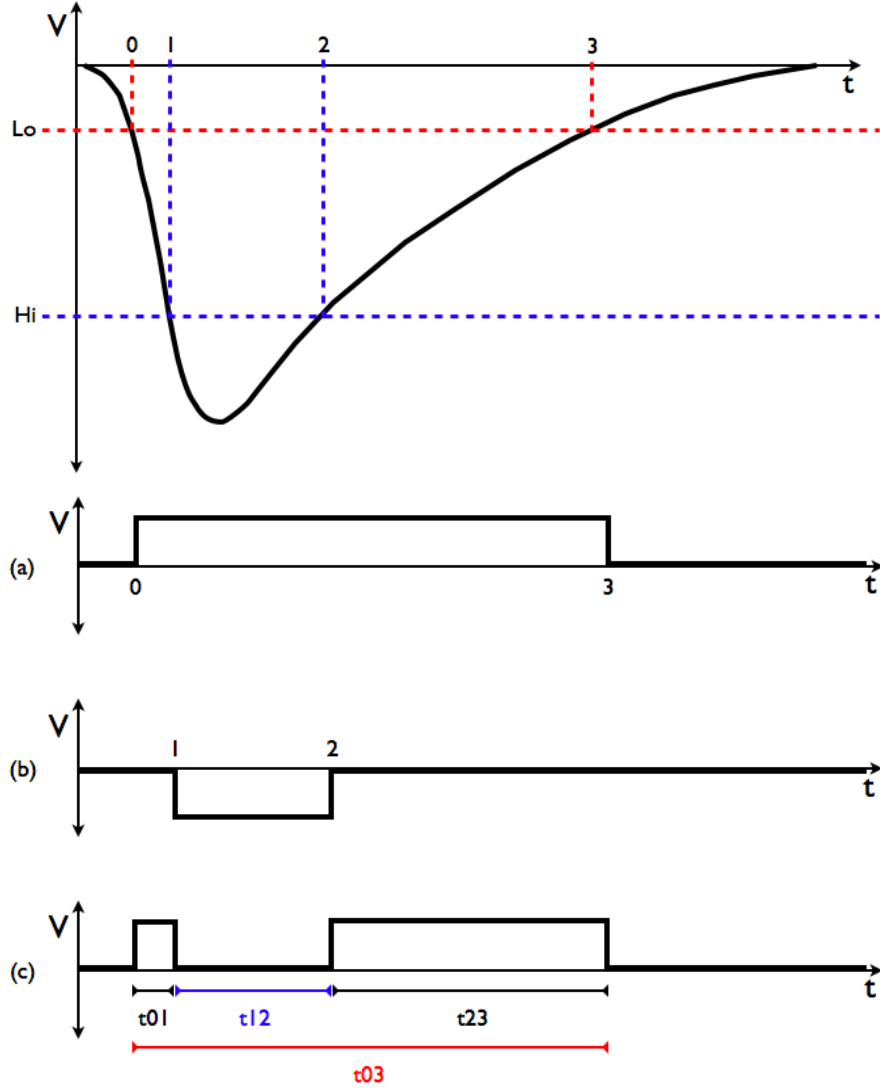


FIGURE 2.10. Illustrated PMT pulse for a 4 edge hit. The top figure shows the analog signal with the high threshold level (HiTOT) in blue and the low threshold level (LoTOT) in red. The pulse had enough charge to trigger the high threshold level, so the pulse is considered a 4 edge event as indicated in the bottom figure where: (a) is the LoTOT output, (b) is the HiTOT output and (c) is the summed total of LoTOT and HiTOT. The information from (c) is written to disk at the HAWC site. The figures above are from [53].

arrival time. This is where slewing corrections for the arrival time are used based on the TOT. The laser calibration system is used to measure the differences in arrival times for PMTs hit with a variety of pulses. By calibrating the PMTs in the array, time delays for certain PMTs can be determined based on their response time to the laser calibration pulses.

These time delays are essential to determine since particles triggering the event in an air shower will strike different PMTs at different times.

Finally the incident particle must be classified as a cosmic ray or a gamma ray [45]. The background for the HAWC detector is cosmic rays, which dominate the number of gamma rays that trigger the detector. Thus it is essential to be able to accurately discriminate between background and signal events. In order to determine if the primary particle was a cosmic ray or gamma ray, the distribution of charge around the shower core is considered. Figure 2.11 shows two events recorded by HAWC, one hadronic cosmic-ray event (left) and one gamma-ray event (right). The core of the shower is seen in the dense region of hard hit PMTs, for both the cosmic and gamma ray events. The hadronic cosmic-ray shower can be differentiated due to the higher number of regions of isolated energy deposition far from the shower core. These isolated energy regions are due to the fact that hadronic cosmic-ray showers produce more muons through interactions in the EAS than gamma-ray showers. These muons are deeply penetrating inside the water tanks and will deposit large energy signals in the PMTs. Thus we expect to see large hits in PMTs (> 30 photoelectrons) deposited far from the shower core. The event reconstruction places a cut on a 40 m radius around the shower core to determine where the majority of energy is deposited [45]. We then consider something called “compactness” of the shower. The compactness parameter is defined as a ratio of the total number of hit PMTs in the event to the largest pulse amplitude that is more than 40 m from the shower core. Gamma-ray induced showers have smaller hits farther from the shower core and will thus have a high compactness parameter, while cosmic-ray showers will have low compactness parameters since they deposit large amounts of energy from the shower core. The reconstruction cuts have a high success rate for constraining

the background events. HAWC can reject anywhere from 75% of the background for near threshold events to $> 99.9\%$ for the largest events triggering close to the entire array, [45].

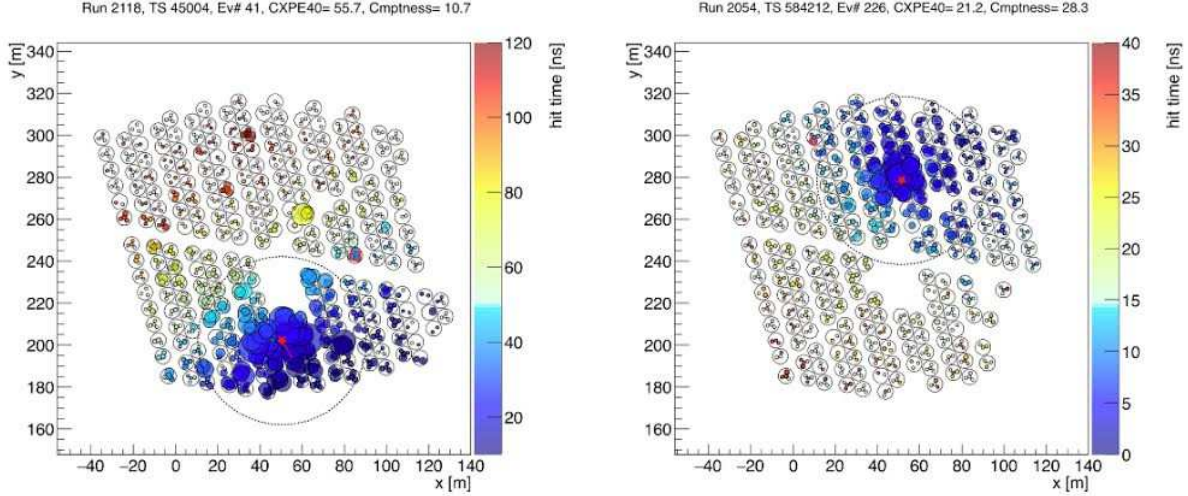


FIGURE 2.11. Two events from the HAWC detector. The figures show the schematic of the full HAWC array with each circle representing a WCD and each smaller point within the circles representing a PMT. The color indicates the time (in ns) at which each PMT was hit during the EAS and the size indicates how hard each PMT was hit (how much Cherenkov light they detected). The event on the left is for a cosmic ray. These events are characterized by large energy depositions far from the shower core (40 m radius around the core as seen by the dotted line) due to the large number of muons in a cosmic-ray induced shower. A gamma-ray event is seen on the right, and does not have many areas of energy deposition far from the shower core. Figure from [45].

The analysis is accomplished by dividing the data into 10 independent bins depending on the total fraction of PMTs hit during the particle shower (“fHit”). The fHit bins are labeled 0-9, ranging from small events near threshold (bin 0) up to large events with nearly every PMT in the array triggered (bin 9). The analysis bins are correlated with the energy of the EAS, but not a direct indicator of the primary particle energy. An example of the measured excess for each fHit (also referred to as “nHit” in the figure) bin for the HAWC-111 detector for the Crab Nebula (the standard “candle” in particle astrophysics) can be seen in figure 2.12, along with the predicted values from a full detector (HAWC-111) simulation.

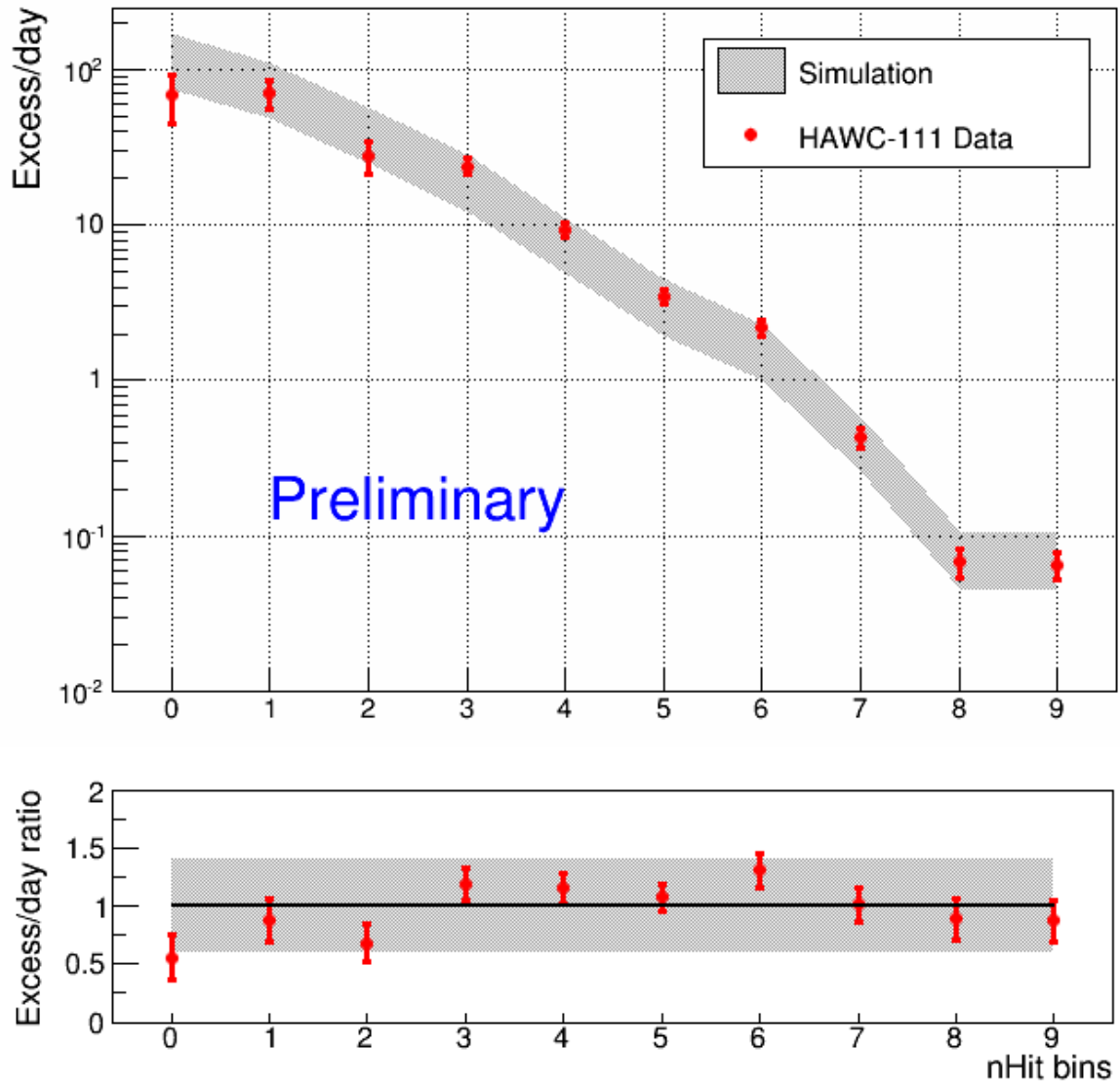


FIGURE 2.12. The measured excess for each fHit bin (referred in the figure as nHit) for the HAWC-111 data set for the Crab Nebula. The predicted values for a full detector simulation are shown in the grey band. A 40% systematic uncertainty is assumed as described in greater detail in Chapter 6. Figures from [51].

CHAPTER 3

A WATER CHERENKOV DETECTOR PROTOTYPE AT COLORADO STATE UNIVERSITY

3.1. INTRODUCTION

Besides the search for dark matter, I was responsible for several hardware projects. I was in charge of the deployment and operation of a WCD prototype. From 2011 to 2014 Colorado State University (CSU) was home to the only full size WCD outside of the HAWC site. This prototype served as a testbed for the design of the HAWC detector. It was located in Fort Collins, CO at an altitude of 1525 m above sea level, compared to the altitude of the HAWC site at 4100 m. The lower altitude and convenient in-town location made it a more effective place to test procedures and deployment techniques before construction began at the HAWC site.

The CSU prototype was first deployed in March 2011. This prototype was equipped with the same electronics as the HAWC site, and had the first laser calibration system installed in a full size detector. The prototype served as a test bed for the various design elements of the observatory. I helped to optimize PMT configuration, detector deployment techniques, laser calibration settings, analysis tools, etc. Prior to the deployment of the full HAWC detector, the collaboration was able to test and modify different components of the detector. The CSU prototype went through three different installations, with each deployment upgrading various components of the WCD and also serving as a testing ground for bladder, PMT, and calibration system deployments. These three installations are described in the following sections.

3.2. BLADDER DEVELOPMENT AND TESTING AT CSU

The first bladders to be tested at CSU were designed and built by two outside companies. I participated in the testing of these bladders with the help of several collaboration members. These bladders were inflated at CSU and tested for light leaks as can be seen in figure 3.1. Each bladder was manufactured out of polyvinyl chloride (PVC) and weighed approximately 500 lbs. Due to the weight of the bladders, they proved extremely difficult to maneuver and the collaboration decided to design and build a custom bladder that was easier to deploy and could accommodate the needs of the detector better. In addition to hosting a WCD, the team at CSU was responsible for designing, building, and testing the bladders that are deployed at the HAWC site. The CSU group operated a custom-built bladder production facility in Fort Collins where the HAWC bladders were designed, built and tested. During the bladder design phase, I devoted much of my time to assisting with the development, manufacturing and testing of the 7 prototype bladders needed at the HAWC site for the VAMOS test array.

The bladders were designed to not only be water tight but also light tight in order to avoid any excess photons inside the tank. The bladders are made out of low density polyethelene (LDPE), which has a high elasticity but which is susceptible to punctures. Any small puncture could leak light into the tank and could potentially leak water once installed. Due to this, each of the early manufactured bladders were inflated and tested for punctures manually and with the aid of a PMT. The bladders were inflated to capacity and were inspected for imperfections or punctures by placing several people inside the inflated bladder and looking for small light leaks. The first testing of the bladders can be seen in figure 3.2. PMTs were first placed in a dark box to determine their dark count rate, which was used in comparison to the rate when inside the bladder. This allowed us to easily locate



FIGURE 3.1. The testing of bladders that were fabricated by outside companies. The two bladders tested weighed approximately 550 lbs each and were extremely difficult to maneuver. Due to this and other factors, including light leaks, the need for a custom bladder facility was decided upon by the collaboration.

small holes and fix them before shipment. A sample test of one of the first bladders is shown in figure 3.3. The rate was taken both before and after light leaks were found and fixed using a small LDPE welder. The rate can be seen to be drastically reduced once the holes were found and patched. In figure 3.4, the PMT rate is shown for the PMT in the test bladder both with and without the overhead lights on, as well as compared to the dark box rate. The rate of the PMT in the patched bladder, with the lights on, is within 10% of the dark box rate.

As bladder development progressed, testing of the bladders with a PMT became unnecessary, since bladders were routinely produced without issues. The bladder production



FIGURE 3.2. Early bladder testing at Colorado State University (CSU). Prior to the bladder production facility, testing took place in the CSU Field House. Shown here are 3 of the first 7 VAMOS bladders. Each bladder was tested for imperfections and light leaks manually and with the aid of a PMT.

facility produced over 300 bladders for the HAWC detector, which included a bladder for every VAMOS and HAWC WCD, water storage tanks, as well as some spares for the site should redeployment become necessary.

3.3. DESIGN, DEPLOYMENT, AND OPERATION OF A WCD PROTOTYPE

In addition to designing and producing a key element of the HAWC detector, CSU was host to the only full size WCD prototype outside of the HAWC site, serving as a major testbed for the development and design of the HAWC detector. The CSU prototype went through three different installations, each time testing new procedures for deployments, WCD features, hardware, software, etc. During each detector lifetime, the bladders were

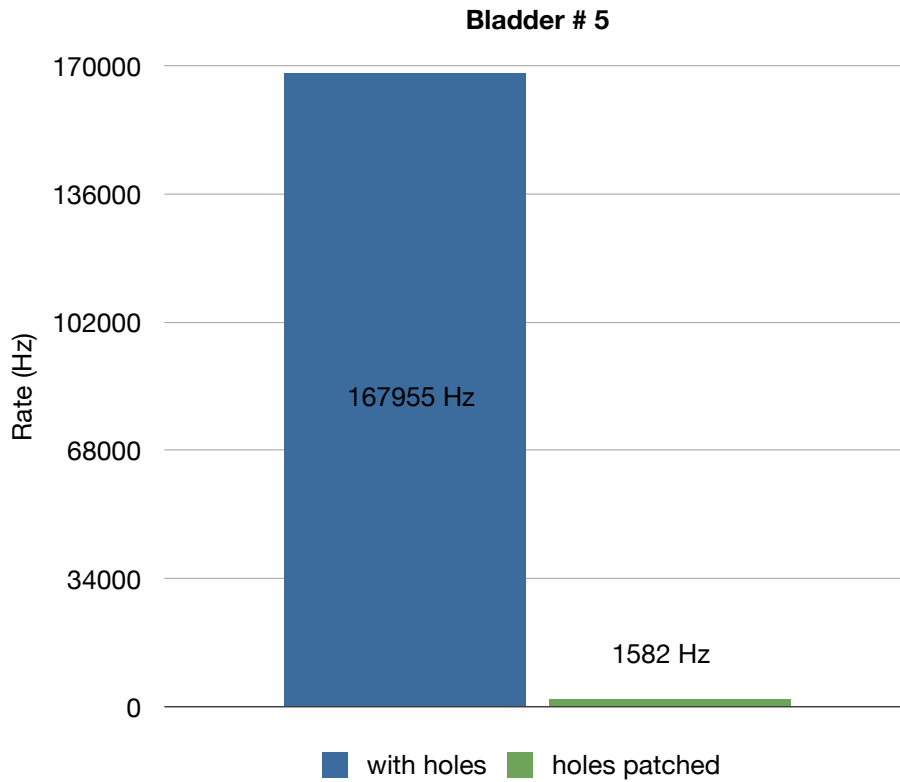


FIGURE 3.3. The PMT rates are shown for a CSU test bladder. The blue histogram shows the PMT rate during initial testing of the bladder when light leaks were found (167955 Hz), while green shows the rate after the leaks were found and patched with a small LDPE welder (1582 Hz). The background “dark” count rate for this PMT was 1431 Hz.

monitored for both water and light tightness, a process which greatly shaped the design and verification of the bladders. The HAWC group at CSU was also responsible for designing key components in the detector installation, including tank construction, access platform development, bladder deployment techniques, PMT deployment techniques, etc. The CSU prototype was a testbed for all of these developments. I oversaw these changes and tests at the CSU tank, and traveled to the HAWC site in Mexico on four separate occasions to help deploy several of the VAMOS detectors (including the first WCD), and several of the initial WCDs at the HAWC site. After these experiences, I wrote the installation procedures for

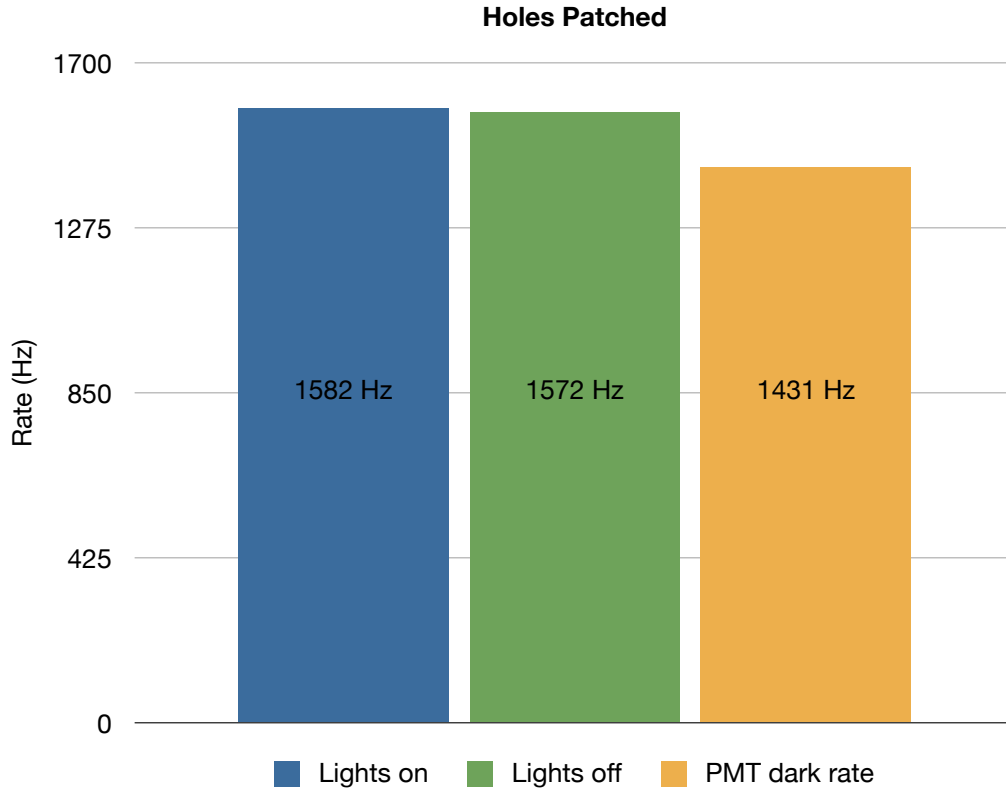


FIGURE 3.4. PMT rates shown for the same test bladder as in figure 3.3. The blue histogram shows the PMT rate for the patched bladder with the overhead gym lights on as compared to the green histogram with the lights off. Both values are within 10% of the dark box PMT rate of 1.43 kHz.

the HAWC bladders, dreamliners (water storage tank liners), wet-deployment of the PMTs, and attachment of the laser calibration system to the central PMT.

3.3.1. CSU WCD PROTOTYPE: PHYSICS TANK 1 (PT1). Construction of the CSU prototype began in May 2010 with preparation of the tank site and building of the steel tank. An overhead view of the tank site can be seen in figure 3.5. The steel tank consists of sheets of corrugated, galvanized steel, standing 5 rings tall with 8 sheets per ring. This makes for a tank height of 5 m and a diameter of 7.3 m. The bottom steel ring is partially buried (1 m deep) in a trench to help with detector stability. The bottom ring was also anchored at four different points to assist with stability, a practice deemed unnecessary at the HAWC site.

At CSU we have experimented with several techniques for tank construction. In addition to our detector, we had a second steel tank which was used as our “engineering” tank. The engineering tank was assembled numerous times and with different construction techniques, until the an effective HAWC procedure was found and optimized.



FIGURE 3.5. An overhead view of the site for the CSU WCD prototype. This Google image was taken during the second installation of the prototype (Physics Tank 2 - PT2). In it you can see PT2 as well as the filling hose connecting from the fire hydrant to the water filtration system and into PT2.

Before the bladder was installed in the CSU Physics tank (PT1), scintillator paddles were buried beneath the tank. Four 6 inch by 6 inch paddles were buried beneath each PMT position, and one larger scintillator paddle (18 inch by 32 inch) was eventually suspended across the width of the tank above the bladder for muon coincidence measurements. The scintillator paddles, as well as their placement can be seen in figure 3.6.

Following the building of the steel tank in May 2010, the first bladder was deployed in March 2011. This delay in deployment was due to the manufacturing and testing of the first custom bladders and coordination with the HAWC collaboration. This deployment was a true collaboration effort, with many collaboration members gathering at CSU to

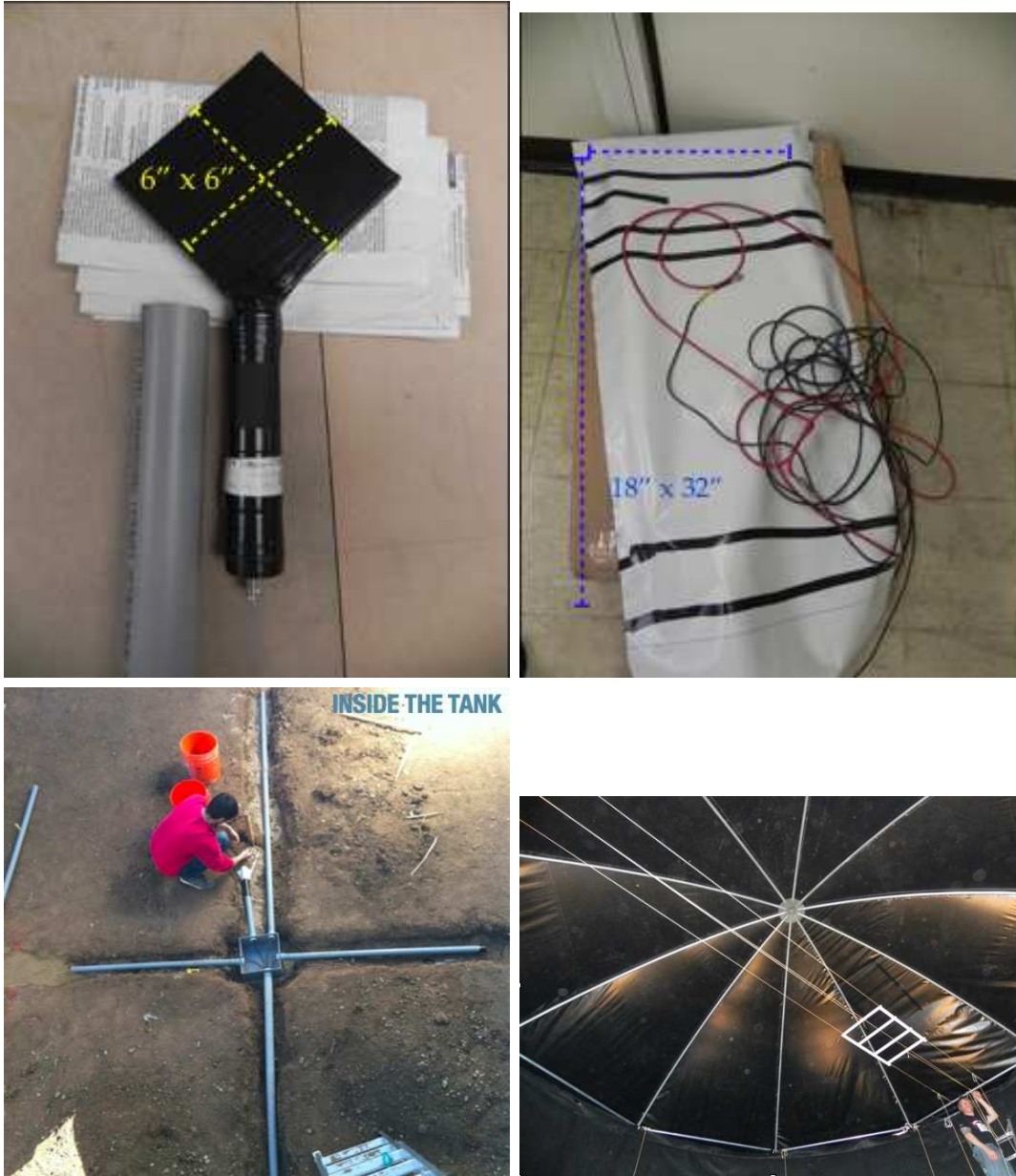


FIGURE 3.6. The above pictures show the scintillator paddles that were present in the CSU WCD prototype. The top left picture shows one of the four scintillator paddles that was buried beneath the prototype WCD underneath the WCD PMT positions, as shown in the lower left picture. The scintillator paddles were covered in bladder material, and the cables were run through PVC conduit to limit moisture near the electrical junctions. The high voltage and signal cables were then trenched out underneath the tank and up into a junction box on the WCD side. The top right picture shows the much larger top muon paddle encased in bladder material. The top scintillator paddle was eventually strung across the top of the bladder underneath the roof (as shown in the lower right picture) on a custom made trolley. The trolley allowed for the scintillator paddle to be moved back and forth across the top to allow for different configurations of muon detection.

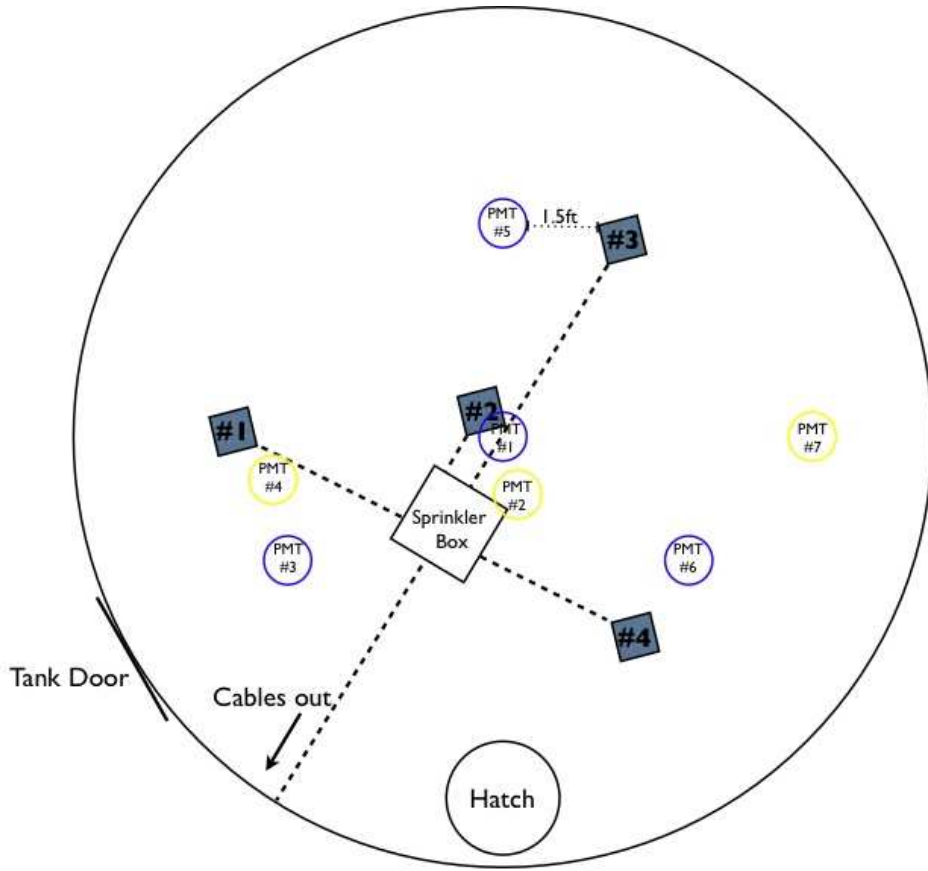


FIGURE 3.7. The placement of the buried scintillator paddles (diamonds) and the seven deployed PMTs (circles) in PT1. PMT 3, 5 and 6 were placed 6 ft from the center at 120° separation from one another. PMT 7 was placed 8 ft from the center, PMT 4 had the baffle (a circular reflective cone) and PMT 5 was the dark PMT (covered in a bucket to limit light detection).

deploy various aspects of the WCD. PT1 received a total of seven PMTs, three more than the standard WCD, in order to determine effective PMT position within the WCDs. The locations of the PMTs, as well as a diagram of the buried scintillator paddles can be seen in figure 3.7. As can be seen in the diagram (figure 3.7) PMT 1 was the central PMT, with PMTs 3, 5 and 6 placed 120° from each other and at a distance of 6 ft from the central PMT, while PMT 7 was placed at a distance of 8 ft. PMT 4 was used to test a baffle from the Milagro experiment. The baffle is a circular reflective white cone placed around the PMT with the purpose of increasing light collection, while also limiting reflections of light from the bottom of the bladder. PMT 2 was located near the central PMT and was shrouded in a

dark cover. This PMT was to aid in muon counting in the prototype, since muons are deeply penetrating into the tank. The shrouded PMT was blind to the volume of water above it in the tank, so it would not see Cherenkov light from other particles interacting in the water, but had 2 inches of space in the dark cover, above the PMT, that was filled with water. Thus any particle that triggered the shrouded PMT would be classified as a muon since the PMT could not see Cherenkov light in the rest of the tank.

The main purpose of PT1 was to test and monitor various components of the detector. Because PT1 was always the test prototype the PMTs were not calibrated at Los Alamos National Laboratory (LANL) before they were installed, like they are at the HAWC site. The PMTs were placed in a dark box at CSU and the rate was monitored as the high voltage was increased. This allowed us to find the high voltage (HV) curve of each uncalibrated PMT and let us find the optimum operating voltage for each. A sample graph of one of the PMTs can be seen in figure 3.8. This changed with later versions of the prototype (PT2 and PT3) and also with the PMTs deployed at the HAWC site in Mexico. Every PMT at HAWC was calibrated at LANL before installation. A description on the PMT calibration can be found in [55]. The PMTs also needed to be checked for water tightness, a very key element, as the PMTs are placed at the bottom of the 5 m tank and experience an additional pressure of roughly 7 psi. Custom water chambers were built at CSU to mimic the pressure experienced by the PMTs at the bottom of the tank. The PMTs were placed in the pressure vessels for roughly 24 hrs, as seen in figure 3.9, and were checked the next day for water leaks by measuring the impedance. I completed this process for every PMT deployment at CSU.

The PMTs in PT1 were deployed before the bladder was filled with water, or what we call a “dry” deployment. After the bladder was installed and inflated in PT1, we descended into the tank via the hatch and set up the PMTs with their weights as can be seen in Figure

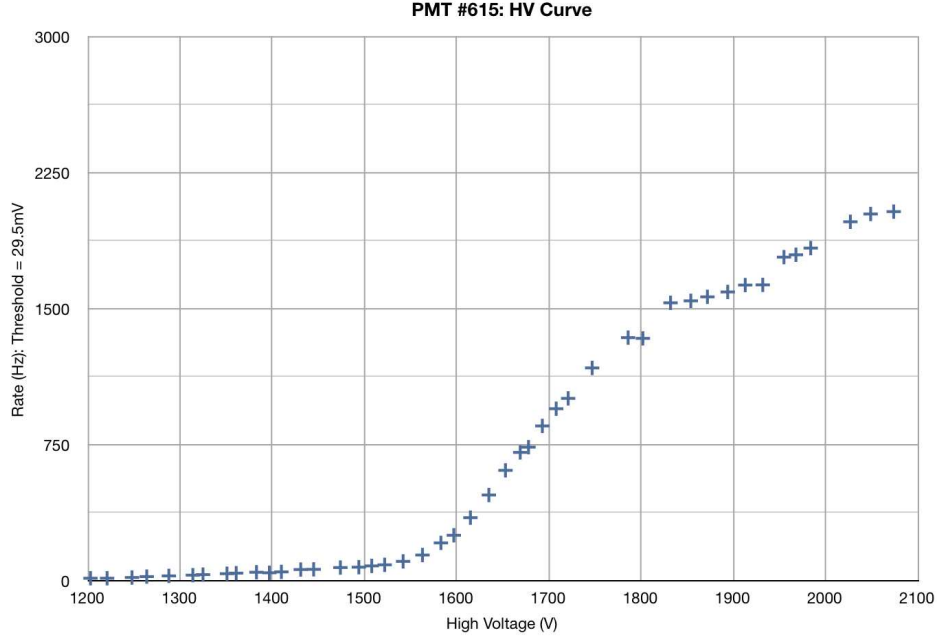


FIGURE 3.8. The PMT high voltage curve for one of the PMTs deployed into the CSU physics tank prototype (PT1). Since the PMTs in PT1 were not calibrated at Los Alamos National Laboratory before deployment, it was necessary to determine the optimum operating voltage for each PMT.

3.10. Initially the weights were built out of PVC pipe and filled with lead shot to keep the PMTs stationary in their positions at the bottom of the tank. Originally the design for the WCDs did not call for a roof, but rather a cover that was draped over the top of the tank to protect the bladder. The top of the bladder can be seen in figure 3.11. The cover had a tendency to collect water in the center during storms, and during one rainstorm it collected so much water in the center that the edges of the tank actually bent in one spot due to the force. Due to this, a roof structure was designed and tested at CSU. The roof structure can be seen in figure 3.11 before it was assembled on PT1. The roof structure was bolted to the top inside of the tank and then a cover was stretched over it to create a dome shaped roof.



FIGURE 3.9. Testing the PMTs deployed in the CSU prototype WCD for water tightness. The PMTs were placed in a small water tank (as seen in the photos) and the pressure was increased with an air compressor until it reached about 7 psi (the pressure at the bottom of the WCD). The PMTs were left for 24 hrs and then the impedance was checked to determine if water had leaked into the PMT base during that time.

The roof proved more effective than the cover, but it went through several modifications before final deployment at the HAWC site. The final roof designed was purchased from the same manufacturer who provided the steel tank structure (Corgal Water Tanks).

3.3.2. CSU WCD PROTOTYPE: PHYSICS TANK 2 (PT2). PT1 was successfully monitored and operated until February 2012, when it was upgraded to PT2. The detector was taken apart and redeployed with all of the changes deemed necessary over the previous year. First we rebuilt the steel structure. We replaced the top “half” tank ring with a full ring to slightly increase the height of the tank, as decided by the collaboration. This also allowed us to install and test a second generation roof structure for the detectors. Rebuilding the steel structure not only allowed us to install the new roof, but it also allowed us to install and test a working platform that was designed at CSU. The next generation bladder was then installed, which used a new wet-deployment system for the PMTs. The first generation of bladders required the PMTs to be dry-deployed (as had been in PT1), before the detector



FIGURE 3.10. The PMT deployment for PT1. The deployment was “dry”, meaning that the PMTs were deployed in the installed bladder prior to filling the bladder with water. The PVC weights can be seen for the PMTs, as well as the shrouded PMT. The dry deployment technique proved inefficient and was later changed to a “wet” deployment system which was designed and tested at CSU.

was filled with water. In the new design the bladder was installed, filled with water, and the PMTs were attached to a Kevlar string. The string runs down to a PMT mount, welded to the bottom of the bladder, allowing the PMT to hook in place. This also allowed the PMTs to all be pre-surveyed for exact PMT location. The survey for PMT placement was done at the HAWC site before the tanks were built. Stakes were placed in each position and when the bladders were installed, the PMT mounts hook underneath to a cap placed on the stakes.



FIGURE 3.11. The above figures show PT1 during deployment. The top left picture shows the full WCD, while the top right picture shows the top of the filled bladder. Originally the WCD had a cover that was placed over the top of the bladder and tied down, however during rain storms water collected in the center of the cover and exerted enough force on the edges of the tank to bend them in on one side. Because of this issue, the need for a roof was realized and the first roof design was deployed at CSU, as can be seen in the bottom picture.

The prototype at CSU was the first detector to test the wet-deployment system, as can be seen in figure 3.12. Since CSU was a testbed for HAWC, our prototype varied slightly from the HAWC WCDs. We had 7 PMTs in PT2: 4 in the HAWC positions, 1 shrouded (dark) PMT near the center, and 2 extra PMTs. The 4 HAWC position PMTs were wet-deployed while the extra PMTs were dry-deployed before the bladder was filled with water.



FIGURE 3.12. Testing of the PMT wet deployment system that was developed at CSU. The PMTs were installed after the bladder was filled with water. The PMTs were attached to a loop of Kevlar string (top right) that allowed the PMTs to be pulled to the bottom of the tank and click into the PMT mounts (top left) that were welded to the bottom of the bladder (bottom left). This also allowed the PMTs to be removed in the event they needed maintenance and re-deployed in the same position. The testing was done in a smaller tank we had at CSU, while the bottom right picture shows the wet deployment of the PMTs into PT2.

In September 2012 we implemented several upgrades to the prototype. We replaced the central 8 inch PMT with a new high efficiency 10 inch PMT. This PMT was installed using the wet deployment system, along with the laser calibration system, allowing CSU to be the first to calibrate a 10 inch PMT. We also installed a scintillator paddle above the volume of water, as seen in figure 3.6, allowing us to start performing muon coincidence measurements. We deployed temperature sensors in the volume of water to monitor the temperature gradient. In the winter, the top layer of water in the detectors is known to

freeze, so it is important to understand the temperature swings and how this affects the components inside the detector, and the PMT rates.

3.3.3. CSU WCD PROTOTYPE: PHYSICS TANK 3 (PT3). In February 2013 the detector underwent another series of upgrades. A new bladder was installed with 7 PMT mounts instead of the typical 4 normally in a HAWC bladder. This allowed all 7 PMTs to be installed using the wet-deployment system. The shrouded PMT was again deployed next to the center PMT, but this time the temperature probes were installed attached to this PMT. This allowed the temperature probes to monitor the temperature gradient near the center of the tank, instead of near the edge as it had been doing in the previous installation. The prototype also received an upgrade to its electronics in September 2013. The data acquisition system (DAQ) was upgraded to a single board computer (SBC) instead of the older PCI bridge. The new component to the DAQ made the electronics at CSU identical to those at the HAWC site.

3.4. RESULTS FROM THE CSU PROTOTYPE

The CSU prototype has proved invaluable to the development of the HAWC array. Since March 2011, we have tested and optimized many aspects of the detector and the electronics. The prototype had the first CSU manufactured bladder deployed, so we were responsible for evaluating the bladder design, functionality and long term performance. We monitored the water level in the detector daily to check the status of the bladder. This played a key role in the initial phase of bladder development. Because of monitoring at CSU, we learned that the hatch on the bladder needed to be redesigned, with more support. The first bladder at CSU lost water gradually as the hatch sunk and leaked water through the cable feed-throughs. Water depth monitoring also helped us verify manufacturing techniques of the

bladders. Figure 3.13 shows how the water depth was monitored over the lifetime of the CSU WCD. Diagrams are shown for both PT1 and PT2. As can be seen in the top graph of figure 3.13, we had an average loss of water of about 0.8 cm per week. This water loss prompted the re-filling of the tank in September 2011. From monitoring the water loss in PT1 we learned of a few necessary design changes for the next generation of bladders. The water depth monitoring for PT2 can be seen in the lower graph of figure 3.13. PT2 had a more precise depth sensor installed that was capable of taking and recording measurements every second. With the changes to the bladder, modified hatch, etc., the water depth stayed consistent for PT2. While there are moderate fluctuations in the depth readings, they are within the ± 2 cm error of the depth sensor.

CSU was also unique in the fact that we had the first operational calibration system in a full size detector, and the only full calibration system outside of the HAWC site. The calibration system is composed of a green laser (532 nm wavelength) that fires light pulses at a given frequency through an optical fiber [56]. The laser light is run through a splitter, which splits the light into two paths. One path goes directly to a radiometer that reads the amount of energy in each pulse. The second path runs through a system of filter wheels, which attenuates the light before arriving to the tank, and runs through a second radiometer [56], as can be seen in figure 3.14. The light is spread into the tank by a diffuser, which is fixed to and floats at a known distance above the central PMT. At CSU, we tested the filter wheel settings, several different light diffusers, the calibration software, the DAQ and calibration interface, etc. Preliminary studies were done to ensure that the calibration system functioned properly prior to being deployed at the HAWC site.

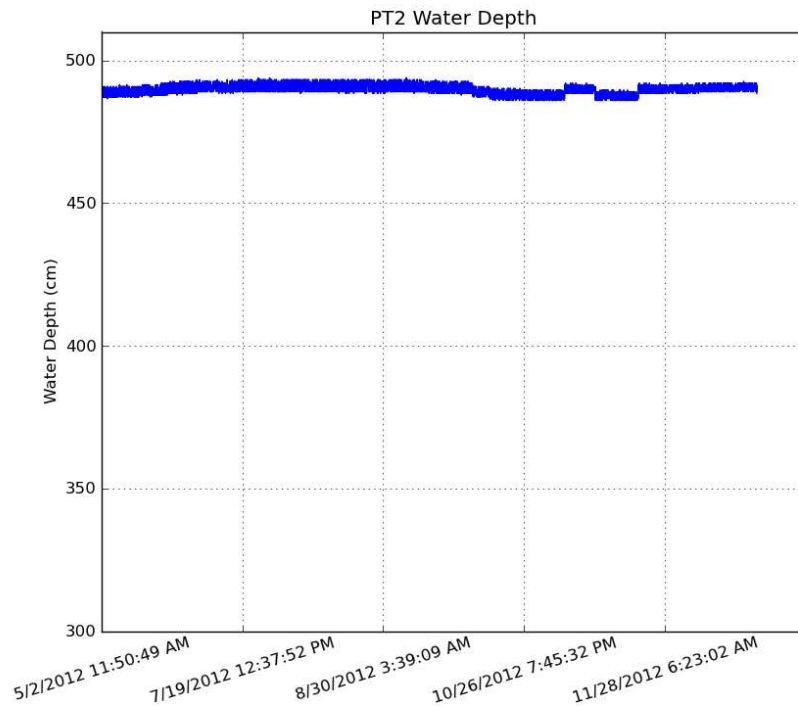
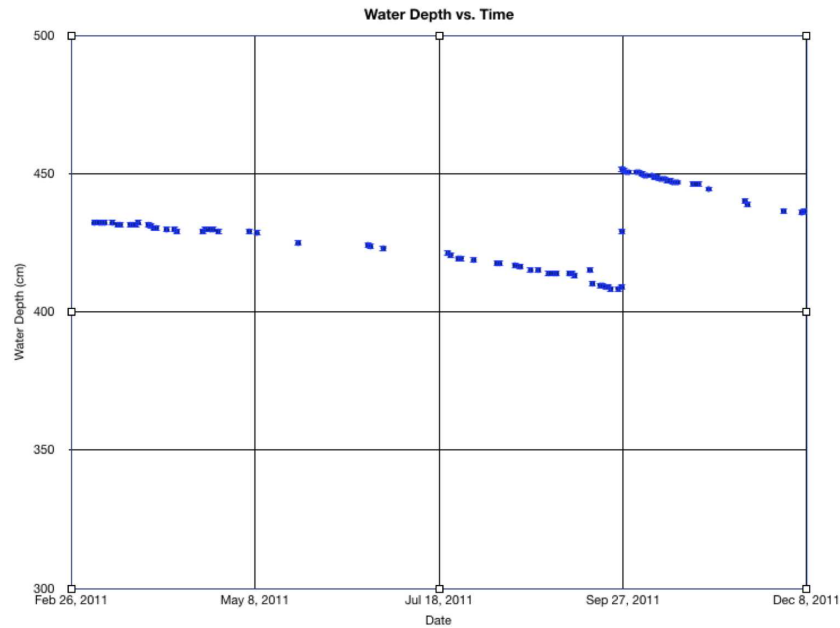


FIGURE 3.13. Two examples of the water monitoring for PT1 (above) and PT2 (below). As seen in the graph for PT1, from March 2011 to September 2011, we had an average water loss rate of about 0.8 cm per week. As can be seen in the graph for PT2, which hosted a second generation bladder, the water depth remained consistent. We also had a more precise depth sensor, and the slight depth fluctuations are consistent within error of the instrument.

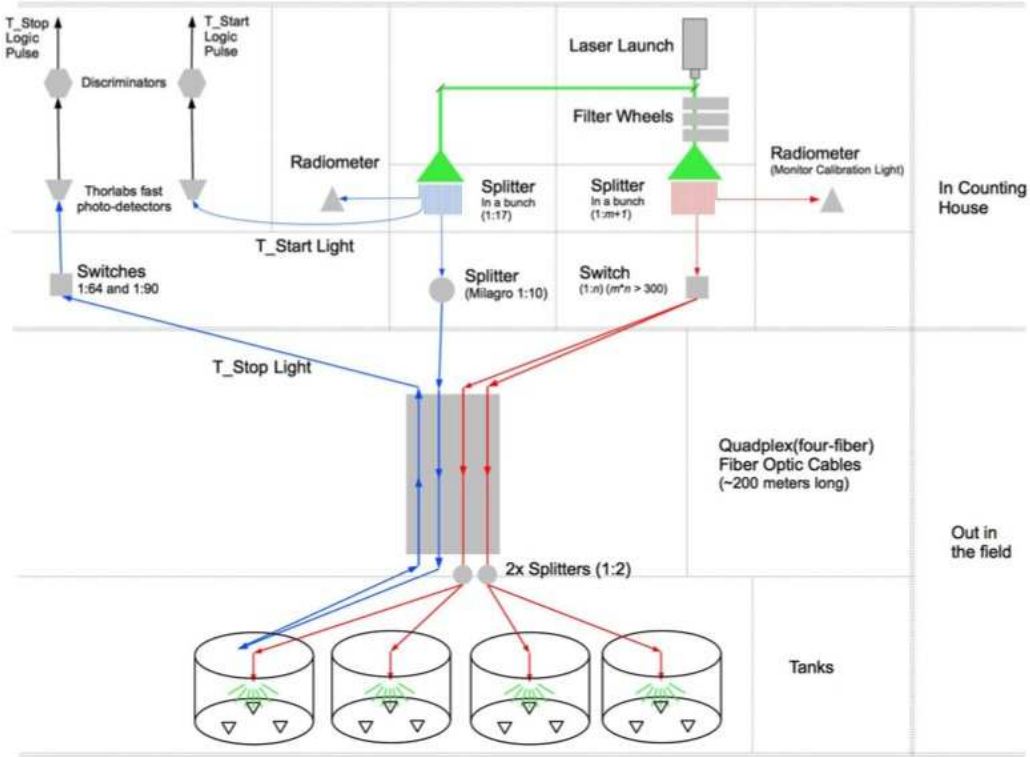


FIGURE 3.14. A schematic of the laser calibration system, from [56]. The calibration system setup was the same at CSU as it is at the HAWC site. The green laser (532 nm) was attached to the central PMT and attached to a float so that it stayed at a known distance inside the tank. The laser light was run through a splitter and fed into two different paths: the radiometer and the filter wheels. The radiometer reads the amount of energy in each laser pulse, while the filters wheels attenuate the light before arriving to the tank [56]. The light is then spread into the tank through a diffuser. The time it takes for the light to reach the tank and return is also measured for calibration purposes.

CHAPTER 4

DARK MATTER ANNIHILATION FLUX

4.1. DWARF SPHEROIDAL GALAXIES

While there are many promising places in the universe to look for signatures of dark matter, dwarf spheroidal galaxies (dSphs) are among the best candidates for a dark matter search. They are theorized to be extremely dark matter rich, as the gravitational effects indicate more mass present than the luminous material can account for. The dwarf spheroidal galaxies considered in this analysis are companion galaxies to the Milky Way, in what is known as our Local Group. They are very low luminosity galaxies, with low diffuse Galactic gamma-ray foregrounds and little to no astrophysical gamma-ray production [36]. Due to these reasons, and their high dark matter content it is useful to set constraints on the dark matter annihilation cross-section from dSphs.

Figure 4.1 shows the dwarf spheroidal galaxies as observed with HAWC. While there are numerous dSphs near the Milky Way, a total of fourteen are considered in this analysis: Bootes I, Canes Venatici I, Canes Venatici II, Coma Berenices, Draco, Hercules, Leo I, Leo II, Leo IV, Segue 1, Sextans, Ursa Major I, Ursa Major II and Ursa Minor. These dSphs were chosen for their favorable declination angle for the HAWC observatory. Values for the distance from Earth and position in the sky of each of the chosen dwarf spheroidal galaxies can be seen in table 4.1.

4.2. PARTICLE FLUX FROM DARK MATTER

4.2.1. DARK MATTER ANNIHILATION FLUX. In order to predict the expected gamma-ray flux from dark matter annihilation, we need to know some information about the source. We also must make some assumptions about the initial and final state radiation from the

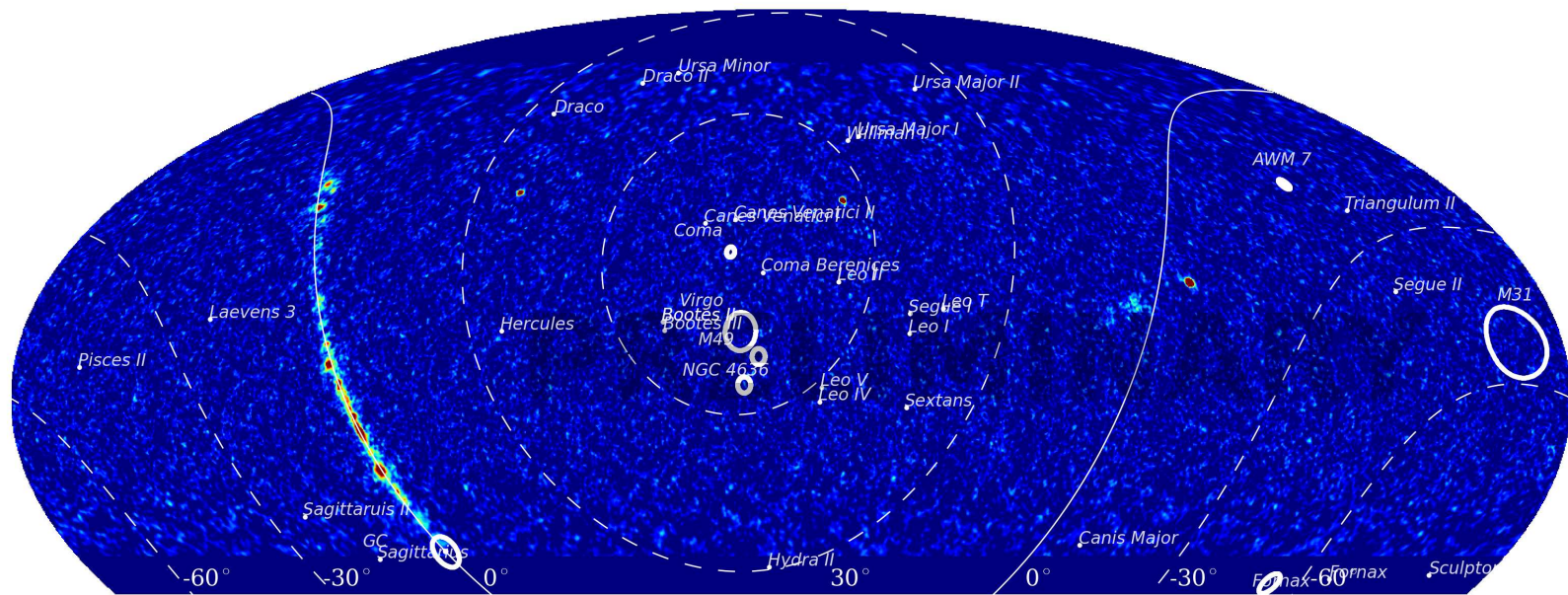


FIGURE 4.1. Sky map of the dwarf spheroidal galaxies as observed by HAWC and mapped onto the HAWC coordinate frame. The figure shows the locations of several dwarf spheroidal galaxies within the HAWC field of view, fourteen of which are considered in this analysis. Figure by Tolga Yapici of the HAWC collaboration.

dark matter annihilation. The differential gamma-ray flux dF/dE_A integrated over solid angle of the source can be expressed as

$$(4.1) \quad \frac{dF}{dE_A} = \frac{\langle \sigma_A v \rangle}{8\pi M_\chi^2} \frac{dN_\gamma}{dE} J ,$$

where $\langle \sigma_A v \rangle$ is the velocity weighted annihilation cross-section and is the target variable in this analysis for setting our limits. dN_γ/dE is the expected gamma-ray spectrum per dark matter annihilation (from simulation) and M_χ is the dark matter mass [15]. The factor of 2 in the above equation (dividing by 8π instead of 4π) comes from the fact that there are two dark matter particles annihilating, so we divide by two in order to not double count the number of expected photons from that particular annihilation. We define the dark matter J -factor J as the dark matter mass density ρ squared integrated along the line of sight of the source x , and integrated over the solid angle of the observation region as

$$(4.2) \quad J = \int_{\text{source}} d\Omega \int dx \rho^2(r_{gal}(\theta, x)) .$$

The dark matter density ρ is squared again because we are considering two dark matter particles annihilating. The distance from the source is given by

$$(4.3) \quad r_{gal}(\theta, x) = \sqrt{R^2 - 2xR \cos(\theta) + x^2} ,$$

where R is the distance to the center of the source and θ is the angle between the source and the line of sight.

4.2.2. ALTERNATE MEASURES OF DARK MATTER WITH GAMMA RAYS. While the analysis presented here sets upper bound constraints on the dark matter annihilation cross-section, it is important to note that lower bound constraints can also be placed on dark

matter decay. Lower limits have been set by other HAWC collaboration members on dark matter decay [15], but are not shown here.

Another way to probe dark matter is via its decay. The gamma-ray flux from dark matter decay is similar to the dark matter annihilation gamma-ray flux as described earlier in equation 4.1. The decay flux dF/dE_D depends on the dark matter lifetime, τ_χ , instead of the annihilation cross-section, the gamma-ray spectrum for each dark matter decay mode, as well as on a single power of the dark matter density ρ (since there is only one dark matter particle decaying) as seen in equation 4.4 [57]

$$(4.4) \quad \frac{dF}{dE_D} = \frac{1}{4\pi\tau_\chi M_\chi} \frac{dN_\gamma}{dE} \int_{\text{source}} d\Omega \int dx \rho(r_{gal}(\theta, x)) \ .$$

4.3. DARK MATTER DENSITY DISTRIBUTIONS

Density profiles describe how the density ρ of a spherical system varies with distance r from its center. In this analysis there are two dark matter density profiles that are used: the Navarro-Frenk-White (NFW) profile and the Einasto profile. The NFW profile, proposed by Julio Navarro, Carlos Frenk and Simon White [58, 59], is the simplest model consistent with N-body simulations. The NFW density profile is

$$(4.5) \quad \rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2} \ ,$$

where ρ_s is the scale density and r_s is the scale radius of the galaxy. The Einasto profile, proposed by Jaan Einasto, [60] is

$$(4.6) \quad \rho_{\text{Einasto}}(r) = \rho_s \exp \left[-\frac{2}{\alpha} \left(\left(\frac{r}{r_s} \right)^\alpha - 1 \right) \right] \ ,$$

where again ρ_s is the scale density, r_s is the scale radius of the galaxy and α controls the degree of curvature of the profile.

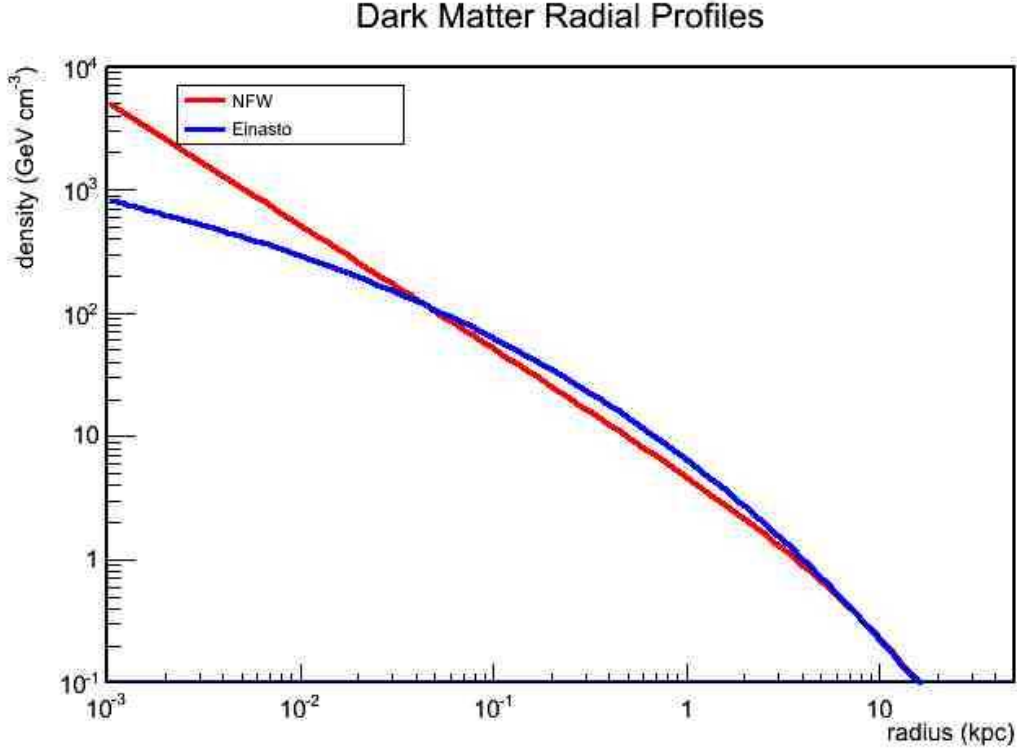


FIGURE 4.2. Einasto and NFW dark matter density profiles. The dark matter density in GeV cm^{-3} is shown as a function of the radius of the galaxy in kpc. In this particular analysis Segue 1 uses an Einasto profile while the rest of the dwarf spheroidal galaxies are modeled with an NFW profile. Figure courtesy of J.P. Harding of the HAWC collaboration.

Depending on the chosen density profile model, we can substitute $\rho(r)$ into equation 4.2 to calculate J for a particular source. We use the Einasto model with $\alpha = 0.303$ for Segue 1 [15], while we use the NFW model for the remaining dwarf spheroidal galaxies. Segue 1 is traditionally modeled with an Einasto profile, so an Einasto profile is considered here so there can be direct comparison between HAWC and limits set by other gamma-ray experiments. The two different density profiles can be seen in figure 4.2. The figure shows the dark matter density in GeV cm^{-3} as a function of the radial position in kpc. As can be seen, the Einasto model is a more conservative estimate of the dark matter density profile

TABLE 4.1. Astrophysical parameters for the fourteen dwarf spheroidal galaxies within the HAWC field of view and their references. The source, right ascension (RA), declination (Dec), scale density ρ_s in GeV/cm^3 , scale radius r_s in kpc, distance to the source R in kpc, and the dark matter J-factor J in $\text{GeV}^2\text{cm}^{-5}\text{sr}$ are all listed above. The significance σ is also shown for each source as detected by the HAWC observatory. The significances listed are for $M_\chi = 10$ TeV and the $\chi\chi \rightarrow b\bar{b}$ annihilation channel. We use an Einasto dark matter density profile with $\alpha = 0.303$ for Segue 1, and a NFW profile for the remaining sources.

Source	RA	Dec	ρ_s (GeV/cm^3)	r_s (kpc)	R (kpc)	J ($\text{GeV}^2\text{cm}^{-5}\text{sr}$)	σ $M_\chi = 10\text{TeV } b\bar{b}$	Ref.
Bootes 1	210.05	14.49	8.12	0.27	66	3.8×10^{18}	-0.04	[61, 62]
Canes Venatici I	202.04	33.57	0.79	0.55	218	2.9×10^{16}	0.91	[61, 63]
Canes Venatici II	194.29	34.32	4.77	0.13	160	2.5×10^{16}	0.34	[61, 63]
Coma Berenices	186.74	23.90	9.76	0.16	44	2.6×10^{18}	0.88	[15, 61]
Draco	260.05	57.07	0.98	2.1	76	2.0×10^{19}	0.30	[15, 61]
Hercules	247.72	12.75	0.80	0.32	132	1.6×10^{16}	-1.67	[61, 63]
Leo I	152.11	12.29	16.20	0.28	254	1.2×10^{18}	0.13	[61, 64]
Leo II	168.34	22.13	162.01	0.06	233	1.2×10^{18}	-0.02	[61, 64]
Leo IV	173.21	-0.53	1.99	0.15	154	7.3×10^{15}	0.51	[61, 63]
Segue 1	151.75	16.06	4.18	0.15	23	1.8×10^{19}	-0.33	[15, 61]
Sextans	153.28	-1.59	3.38	0.37	86	1.0×10^{18}	-1.55	[61, 62]
Ursa Major I	158.72	51.94	2.39	0.31	97	2.3×10^{17}	-0.37	[61, 63]
Ursa Major II	132.77	63.11	13.79	0.17	32	1.1×10^{19}	0.10	[61, 62]
Ursa Minor	227.24	67.24	3.89	0.65	76	9.6×10^{18}	0.26	[61, 62]

than the NFW model due to its lower dark matter density estimation at lower radii. The source parameter values for the fourteen dwarf spheroidal galaxies presented in this analysis are listed in table 4.1. The parameters can be seen for each of the 14 dSphs considered in this analysis including the location of the source, dark matter density, scale radius, distance to the source, dark matter J factor and the source significance as detected by the HAWC observatory.

4.4. EXPECTED GAMMA-RAY FLUX

The Pythia program [65] is used to generate high-energy physics events and to model the interactions between the incoming particles and the outgoing particles. This makes the program ideal for simulating interactions between two dark matter particles and monitoring the number of gamma rays we expect to see as a result of dark matter annihilation. Pythia 6.4 [65] was used in this analysis to calculate the expected photon spectrum for a particular WIMP dark matter mass and annihilation channel. The photon radiation of charged particles was simulated, as well as the decay of particles such as the π^0 [15, 57]. For each annihilation channel and each dark matter mass, the average number of photons in each energy bin per annihilation event was calculated. This differential flux, dN_γ/dE , was used to determine the total dark matter annihilation flux for a particular source, dark matter mass and dark matter annihilation channel. The dark matter annihilation channels considered in this analysis are: $\chi\chi \rightarrow b\bar{b}$, $\chi\chi \rightarrow \tau^+\tau^-$, $\chi\chi \rightarrow \mu^+\mu^-$, $\chi\chi \rightarrow t\bar{t}$ and $\chi\chi \rightarrow W^+W^-$. These are not the only possible dark matter annihilation channels, but were included in this analysis for the reasons discussed in section 1.3. We consider the heavy top quark ($t\bar{t}$) and tau lepton ($\tau^+\tau^-$) channels due to available phase space. The remaining channels were considered in order to

directly compare results from the HAWC detector to those from other indirect detection experiments, such as Fermi-LAT and MAGIC, as they are widely considered.

CHAPTER 5

CALCULATIONS OF LIMITS ON THE ANNIHILATION CROSS-SECTION

5.1. LIKELIHOOD ANALYSIS

5.1.1. **WILKS'S THEOREM.** In order to analyze a particular region of the sky, we perform a likelihood ratio test. In our case, we have two unknown parameters: 1) the expected number of source photons $\langle N_S \rangle$, and 2) the expected number of background photons $\langle N_B \rangle$. The likelihood ratio test is a ratio of the likelihoods of two different hypotheses: 1) Null hypothesis - no extra source exists and all observed photons are due to background ($\langle N_S \rangle = 0$), and 2) Alternative hypothesis - a source exists. We use Wilks's Theorem [66, 67] to calculate the probability we have seen a gamma-ray source in the sky.

Wilks's Theorem - Define observed data $X = (x_1, x_2, \dots, x_N)$, unknown parameters $\Theta = (E, T) = (\epsilon_1, \epsilon_2, \dots, \epsilon_r, \tau_1, \tau_2, \dots, \tau_S)$, and statistical hypotheses:

Null hypothesis: $E = E_0 = (\epsilon_{10}, \epsilon_{20}, \dots, \epsilon_{r0})$,

Alternative hypothesis: $E \neq E_0$,

define the maximum likelihood ratio

$$(5.1) \quad \lambda = \frac{L(X|E_0, \hat{T}_c)}{L(X|\hat{E}, \hat{T})} = \frac{P_r(X|E_0, \hat{T}_c)}{P_r(X|\hat{E}, \hat{T})} ,$$

where $L(X|\Theta')$ is the likelihood function of N observed values X given parameters $\Theta = \Theta'$, that is, the probability of experimental results X given $\Theta = \Theta'$; $\hat{E}$ and $\hat{T}$ are the maximum likelihood estimates of parameters E and T ; $\hat{T}_c$ are the conditional maximum likelihood estimates given $E = E_0$. If the null hypothesis $E = E_0$ is true, variable $-2 \ln \lambda$

will asymptotically follow a χ^2 distribution with r degrees of freedom, while $N \rightarrow \infty$, as denoted by

$$(5.2) \quad -2 \ln \lambda \sim \chi^2(r) \ .$$

In our case, the observed data $X = (N_{\text{on}}, N_{\text{off}})$ (where N_{on} is the total observed signal and N_{off} is the signal from background), estimated unknown parameters $\Theta = (\langle N_S \rangle, \langle N_B \rangle)$, and

Null hypothesis: $\langle N_S \rangle = 0$,

Alternative hypothesis: $\langle N_S \rangle \neq 0$.

In this case only one parameter, $\langle N_S \rangle$, is involved in the null hypothesis; thus $r = 1$. So according to Wilks's theorem, if the null hypothesis is true and both $N_{(\text{on})}$ and N_{off} are not too few, $-2 \ln \lambda$ will follow a χ^2 distribution with 1 degree of freedom [66]

$$(5.3) \quad -2 \ln \lambda \sim \chi^2 \ .$$

According to Li and Ma [67], if σ is a standard normal variable, then σ^2 will follow a χ^2 distribution with 1 degree of freedom

$$(5.4) \quad \sigma^2 \sim \chi^2(1) \ .$$

So we can see that if the null hypothesis is true, $\langle N_S \rangle = 0$, then the variable $(-2 \ln \lambda)^{1/2}$ will be equivalent to the absolute value of a standard normal variable. Thus

$$(5.5) \quad \sigma^2 = -2 \ln \lambda \ .$$

5.1.2. LIKELIHOOD RATIO TEST. To estimate the significance of a source, we calculate the likelihood ratio λ . We know that a discrete random variable X is said to have a Poisson distribution with parameter $\mu > 0$, if, for $k = 0, 1, 2, \dots$, the probability distribution function of X is given by

$$(5.6) \quad Pr(X = k) = L(\mu|x) = \frac{\mu^k e^{-\mu}}{k!} .$$

where $L(\mu|x)$ is the likelihood function of μ , given the outcome x of X . We can now define the likelihood of the null hypothesis (L_0) and the alternative hypothesis (L). Each of the two competing hypotheses are fitted to the data and the log likelihood recorded. The ratio of the two likelihoods, given by λ from above, is then

$$(5.7) \quad \lambda = \frac{L_0}{L} ,$$

where L_0 is the null likelihood that no source is present and L is the alternative likelihood that a source exists. Then by Wilks's theorem as stated previously

$$(5.8) \quad \sigma^2 = -2 \ln \left(\frac{L_0}{L} \right) .$$

Let us call the significance σ^2 the likelihood Test Statistic (TS) [67], then

$$(5.9) \quad TS = -2 \ln \left(\frac{L_0}{L} \right) .$$

Using our definitions for the null and alternative likelihoods, we know that

$$(5.10) \quad \begin{aligned} L_0 &= \frac{\mu_0^k e^{-\mu_0}}{k!} \\ L &= \frac{\mu^k e^{-\mu}}{k!} . \end{aligned}$$

Then our test statistic will yield

$$\begin{aligned}
 TS &= 2 \ln L - 2 \ln L_0 \\
 (5.11) \quad &= 2 \ln \left(\frac{\mu^k e^{-\mu}}{k!} \right) - 2 \ln \left(\frac{\mu_0^k e^{-\mu_0}}{k!} \right) .
 \end{aligned}$$

We can define our values for the null and alternative hypotheses. For the alternative hypothesis, μ is the number of expected counts in each bin ($\mu = E + B$ where E is the expected number of signal counts and B is the number of background counts), and k is the number of total events in each bin from data (what we refer to as N). For the null hypothesis, we make similar definitions, where μ_0 is the number of expected counts in each bin for the null hypothesis B , and k is, again, the number of total events in each bin from data N . Substituting these definitions for the null and alternative hypotheses into equation 5.11 we get

$$(5.12) \quad TS = \sum_{bins} [2N \ln(E + B) - 2(E + B) - 2 \ln(N!) - 2N \ln(B) + 2B + 2 \ln(N!)] .$$

With some simplification, equation 5.12 reduces to:

$$(5.13) \quad TS = \sum_{bins} \left[2N \ln \left(1 + \frac{E}{B} \right) - 2E \right] .$$

Some typical values for N , B and E are shown in table 5.1 for each fHit data bin for the HAWC-111 data set considered in this analysis. The values shown are for a $M_\chi = 10$ TeV and for the Segue 1 dSph. The observed signal is the total number of counts either above or below the background count estimate ($N - B$). Segue 1 actually shows an under-fluctuation of events for several fHit data bins. The background count estimate B is also listed for each fHit data bin. Lastly, the expected number of counts E from simulation are shown

for three dark matter annihilation channels: $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- . This shows that the expected number of signal counts from a source is definitely dependent on the dark matter annihilation channel considered.

TABLE 5.1. Data counts from observed signal and the expected number of counts for a $M_\chi = 10$ TeV and Segue 1. The values are listed for each of the 0-9 fHit data bins for HAWC-111 data. The observed signal column shows the number of signal counts either above or below background (Segue 1 shows some under-fluctuation in several data bins) and the background shows the observed background counts for HAWC-111 for each data bin. The expected counts from simulation are also shown for three dark matter annihilation channels: $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- .

fHit bin	Observed Signal	Background	$b\bar{b}$	Expected $\tau^+\tau^-$	W^+W^-
0	1126	3.18×10^7	239	278	226
1	3056	1.12×10^7	171	238	168
2	-809	2.47×10^6	84	145	88
3	-694	4.67×10^5	35	84	40
4	-31	4.55×10^5	16	54	20
5	-68	7.01×10^3	4.7	26	6.7
6	25	1.42×10^3	0.76	8.3	1.3
7	6	95.99	0.13	2.1	0.023
8	3	11.04	0.01	0.19	0.01
9	4	15.88	0	0.08	0

5.2. CALCULATION OF UPPER LIMITS

Now that we have a way to estimate the significance of a source using the likelihood ratio test and Wilks's theorem, we can begin to set an upper bound constraint on the dark matter annihilation cross-section for a source. In Wilks's theorem we made the assumption that we had both the null hypothesis, which assumes no source exists, and the alternative hypothesis, which assumes a source exists. For the definition of our significance to hold true, $\sigma^2 = 2 \ln(L/L_0)$, we assumed the null model was indeed true. So to find the significance of our source we must find the TS as defined in equation 5.13.

For the purposes of our dark matter searches, the assumption that the null hypothesis is true is a good approximation, as we actually see little to no gamma-ray signal coming from the direction of the dwarf spheroidal galaxies. But in the event there is a positive detection from a source, that is we do see an excess of gamma rays from a source, we need to account for it in our test statistic and our likelihood analysis. To do this, we introduce the parameter TS_{max} , which is the actual significance squared (σ^2) of the source.

$$(5.14) \quad TS_{\text{max}} = \sum_{\text{bins}} \left[2N \ln \left(1 + \frac{\beta E_{\text{ref}}}{B} \right) - 2\beta E_{\text{ref}} \right] .$$

In equation 5.14, N is the total number of counts from data, B is the background count estimate from data and E_{ref} is the expected number of counts in each bin for the reference annihilation cross-section $\langle \sigma_A v \rangle_{\text{ref}}$. The scale factor β is used to determine the maximum number of gamma-ray counts we expect to see from a given source. We scale the number of expected counts E_{ref} by β until the actual significance of the source is reached. TS_{max} will be equal to zero in the event there is no gamma-ray signal from a source, and greater than zero in the event there is a significant gamma-ray signal from a source. Since there is no significant gamma-ray detection observed with HAWC on these sources, $TS_{\text{max}} \approx 0$. In a few of the dwarf spheroidal galaxies we observe, such as Segue 1, there is an under-fluctuation of events below background forcing β to be negative, and so we set it to zero. Thus, by not considering the under-fluctuations of a source, we are placing a more conservative estimate on the dark matter annihilation cross-section limits. This will be addressed in further studies with HAWC, but is beyond the scope of this thesis.

The reference annihilation cross-section used in this analysis is $\langle \sigma_A v \rangle_{\text{ref}} = 1.0 \times 10^{-22} \text{cm}^3 \text{s}^{-1}$. This reference annihilation cross-section was chosen as an appropriate starting point for the

limit calculations, but is arbitrary. The reference annihilation cross-section is used to determine the dark matter annihilation flux from a particular source for a specific dark matter mass and annihilation channel

$$(5.15) \quad \frac{dF}{dE_A} = \frac{\langle \sigma_A v \rangle_{\text{ref}}}{8\pi M_\chi^2} \frac{dN_\gamma}{dE} J \ .$$

By choosing an appropriate starting point for $\langle \sigma_A v \rangle_{\text{ref}}$ the scale factors β and ξ (as introduced in equation 5.17) that we use to scale the number of expected counts E_{ref} will be of an appropriate magnitude.

In order to calculate an upper limit on the dark matter annihilation cross-section, we need to set the level for which we are confident in our limit. Since we are looking for a one-sided fluctuation in our limit, the confidence intervals presented here are one-sided. In this analysis the limits presented are calculated to be 2σ , meaning that HAWC will be sensitive to a particular annihilation cross-section at the 97.7% one-sided confidence level interval. The one-sided confidence level interval arises from the fact that we are looking for a one-sided fluctuation from zero events above background. This means that we also need to define a new parameter, $TS_{97.7}$, which is the test statistic given our 97.7% confidence level. Since we have already found TS_{max} we can now consider

$$(5.16) \quad \Delta TS = TS_{\text{max}} - TS_{97.7} \ ,$$

where ΔTS is now the difference between TS_{max} (which equals zero, except in the case of a significant positive detection), and $TS_{97.7}$. In order to have a 97.7% confidence level in our annihilation cross-section limit, which corresponds to a significance of 2σ , we need to

consider the case where $\Delta TS = TS_{\text{max}} - TS_{97.7} = 4$ and find the appropriate value of $TS_{97.7}$ that satisfies this condition.

In order to calculate $TS_{97.7}$ and impose the condition that $\Delta TS = 4$, we need to scale our expected number of counts from a source by some scale factor ξ . This allows us to calculate the number of expected signal counts we would need in order to be sensitive to a 2σ excess of gamma rays being emitted from a potential dark matter source. Thus we need to find ξ such that

$$(5.17) \quad 4 = TS_{\text{max}} - \sum_{\text{bins}} \left[2N \ln \left(1 + \frac{\xi E_{\text{ref}}}{B} \right) - 2\xi E_{\text{ref}} \right] ,$$

where N is the total number of counts from data, B is the background count estimate from data and E_{ref} is the expected number of counts in each bin for the reference annihilation cross-section $\langle \sigma_A v \rangle_{\text{ref}}$. Once ξ is found that satisfies the condition in equation 5.17 we can set our limit on the annihilation cross-section. In order to find our $TS_{97.7}$, we had to scale our expected gamma-ray signal from our source by ξ . We can then scale our reference annihilation cross-section $\langle \sigma_A v \rangle_{\text{ref}}$ that was used to calculate the dark matter annihilation flux dF/dE_A , for a given dark matter mass M_χ and annihilation channel, by the same parameter ξ . Thus our 2σ one-sided confidence-level upper limit on the dark matter annihilation cross-section becomes

$$(5.18) \quad \langle \sigma_A v \rangle_{97.7\%} = \xi \times \langle \sigma_A v \rangle_{\text{ref}} .$$

5.3. STACKED ANALYSIS

The stacked analysis, or combined analysis, is a simultaneous study of all dwarf spheroidal galaxies. Since the statistics are low for each individual dSph, a combined analysis would increase the overall statistics and should produce a better constraint on the dark matter annihilation cross-section. The same likelihood analysis procedure is followed as described in the previous section. First we must find $TS_{\max}$ for the combined analysis with all dSphs. Thus we must find a new scale factor β such that $TS_{\max}$ is the maximum possible value, just as was done before in equation 5.14

$$(5.19) \quad TS_{\max} = \sum_{\text{bins}} \sum_i^{\text{dSph}} \left[2N_i \ln \left(1 + \frac{\beta E_{i,\text{ref}}}{B_i} \right) - 2\beta E_{i,\text{ref}} \right] ,$$

where now in addition to summing over all fHit data bins, we are summing over all dSphs as well. As in the single dSph limit case, $TS_{\max}$ is zero in the event there is no significant gamma-ray signal above the observable background.

We continue to follow the same Likelihood ratio procedure as described in the previous section, however, now equation 5.17 becomes

$$(5.20) \quad 4 = TS_{\max} - \sum_{\text{bins}} \sum_i^{\text{dSph}} \left[2N_i \ln \left(1 + \frac{\xi E_{i,\text{ref}}}{B_i} \right) - 2\xi E_{i,\text{ref}} \right] ,$$

where each parameter per each data fHit bin is summed over all dwarf spheroidal galaxies ($i \rightarrow \text{dSph}$). N is the total number of events in each bin from data summed over all the dSphs, B is the total number of background counts from each dSph and E_{ref} is the total expected number of counts in each bin for the reference annihilation cross-section ($\langle \sigma_A v \rangle_{\text{ref}}$) for all the dSphs. The same procedure is then followed, we find ξ by imposing the condition in equation 5.20, such that the difference between $TS_{\max}$ and $TS_{97.7}$ is equal to 4 for the

combined analysis. There is only one scale parameter ξ for each combined limit, meaning the total summed expected counts from each dSph are scaled by a single parameter ξ . Once ξ is found, we can then scale our reference annihilation cross-section in order to set our constraint for the combined analysis of the dSphs, as seen in equation 5.21. Again the reference annihilation cross-section $\langle\sigma_A v\rangle_{\text{ref}} = 1.0 \times 10^{-22} \text{ cm}^3 \text{ s}^{-1}$, and was arbitrarily chosen.

$$(5.21) \quad \langle\sigma_A v\rangle_{97.7\%,\text{Combined}} = \xi \times \langle\sigma_A v\rangle_{\text{ref}} \text{ .}$$

CHAPTER 6

FIRST LIMITS WITH HAWC-111 DATA ON THE DARK MATTER ANNIHILATION CROSS-SECTION

6.1. HAWC DATA

The data used in this analysis were taken before completion of the HAWC detector. The data presented here were taken when there was a roughly a third of the total 300 WCDs in operation. We refer to this as the HAWC-111 data set. The HAWC-111 data used here were collected from August 2, 2013 to March 5, 2015, comprising a total of 180 full sidereal days of data. During this data collection period the number of active WCDs grew from 106 to 133.

6.2. ANALYSIS USING HAWC-111 DATA

Presented in this analysis are individual and combined limits from fourteen dwarf spheroidal galaxies within the HAWC field of view for the HAWC-111 data set. The limits were calculated by treating the dSphs as point sources, not extended sources. Through detailed simulation of the HAWC gamma-ray sensitivity and backgrounds, the significance of the gamma-ray flux for a range of dark matter masses, 0.5 TeV - 1000 TeV, and five dark matter annihilation channels has been found. Following the likelihood method described in Chapter 5, the projected source significance is used to determine the exclusion curves on the dark matter annihilation cross-section, $\langle\sigma_{Av}\rangle$, for the individual dSphs. A combined (stacked) analysis was also completed by combining the statistics for all fourteen dSphs in order to increase the sensitivity of the analysis.

The reference annihilation cross-section (as seen in equation 5.18) used was $\langle\sigma_{Av}\rangle_{\text{ref}} = 1.0 \times 10^{-22} \text{cm}^3 \text{s}^{-1}$. This reference annihilation cross-section was chosen as an appropriate starting point for the limit calculations, as it was near where we expected the HAWC constraint to be. In order for the dark matter density distribution to exist as it is today, WIMPs needed an annihilation cross-section of approximately $\langle\sigma_{Av}\rangle_0 = 3.0 \times 10^{-26} \text{cm}^3 \text{s}^{-1}$ at thermal freeze-out [15]. Thus the closer the limit on the annihilation cross-section is to $\langle\sigma_{Av}\rangle_0$, the more constraining the limit is for HAWC. The scale factors ξ from the Likelihood analysis were found and multiplied by the reference annihilation cross-section to determine the upper limits for the dSphs, as explained in Chapter 5. For reference, the scale factors for a 10 TeV dark matter mass annihilating into the $b\bar{b}$ channel can be seen in table 6.1. The values shown in the table list the fourteen dSphs in the HAWC field of view considered in this analysis, as well as their scale factors ξ for the single limit case, and the corresponding upper bound limit on the annihilation cross-section. The scale factor ξ for the combined limit resulting from a stacked analysis of all dSphs is also shown in table 6.1.

The 97.7% one-sided confidence level upper limits for dark matter annihilating with a 100% branching ratio into the $b\bar{b}$ channel are shown in figure 6.1. The figure shows the annihilation cross-section in $\text{cm}^3 \text{s}^{-1}$ as a function of the dark matter mass in GeV for the fourteen individual sources. The upper bound limits can also be thought of as exclusion curves, meaning that everything above the limit line is excluded by this analysis. As seen in figure 6.1, Segue 1 is the most constraining dwarf, particularly at low dark matter masses. This arises from several factors: the high dark matter J factor of Segue 1 due to its proximity to the Milky Way, and its ideal declination angle for HAWC. At higher dark matter masses ($M_\chi > 10 \text{ TeV}$) Draco becomes the most constraining limit for HAWC. Draco dominates in the higher dark matter mass range due to its declination angle to HAWC. Draco has a

TABLE 6.1. Results from the likelihood analysis of fourteen dSphs for the $b\bar{b}$ dark matter annihilation channel as well as the combined $b\bar{b}$ analysis. Results are shown for the 10 TeV dark matter mass to provide scope for the scale factor values (ξ) from the likelihood analysis and equation 5.18. The reference annihilation cross-section from equation 5.18 is $\langle\sigma_A v\rangle_{\text{ref}} = 1.0 \times 10^{-22} \text{cm}^3 \text{s}^{-1}$. The source, dark matter mass, likelihood scale factor ξ , and the upper limits on the dark matter annihilation cross section are listed.

Source	Dark Matter Mass (TeV)	Likelihood Scale Factor ξ	Upper Limit ($\text{cm}^3 \text{s}^{-1}$)
Bootes I	10	58.0	5.80×10^{-21}
Canes Venatici I	10	1.47×10^4	1.47×10^{-18}
Canes Venatici II	10	1.31×10^4	1.31×10^{-18}
Coma Berenices	10	130	1.30×10^{-20}
Draco	10	69.2	6.92×10^{-21}
Hercules	10	2.33×10^3	2.33×10^{-19}
Leo I	10	235	2.35×10^{-20}
Leo II	10	183	1.83×10^{-20}
Leo IV	10	6.00×10^4	6.00×10^{-18}
Segue 1	10	10.7	1.07×10^{-21}
Sextans	10	79.1	7.91×10^{-21}
Ursa Major I	10	2.62×10^3	2.62×10^{-21}
Ursa Major II	10	853	8.53×10^{-20}
Ursa Minor	10	804	8.04×10^{-20}
Combined	10	11.3	1.13×10^{-21}

comparable J factor to Segue 1 ($2.0 \times 10^{19} \text{GeV}^2 \text{cm}^{-5} \text{sr}$ as compared to Segue 1 at $1.8 \times 10^{19} \text{GeV}^2 \text{cm}^{-5} \text{sr}$) so we would expect Segue 1 and Draco to have comparable annihilation cross-section limits. However Draco is at a much higher declination than Segue 1 (57.07° compared to Segue 1 at 16.06°), and thus gamma rays seen at this declination will travel through more atmosphere before they trigger the detector. Because of this the lower dark matter masses for Draco will not produce gamma rays with enough energy to trigger the detector but the higher dark matter masses will. Figure 6.1 also shows the combined limit resulting from a stacked analysis of all fourteen dSphs. The combined limit is dominated by the most significant dwarfs (Segue 1 or Draco) depending on the dark matter mass. The addition of the remaining twelve dSphs does not greatly improve the statistics for the

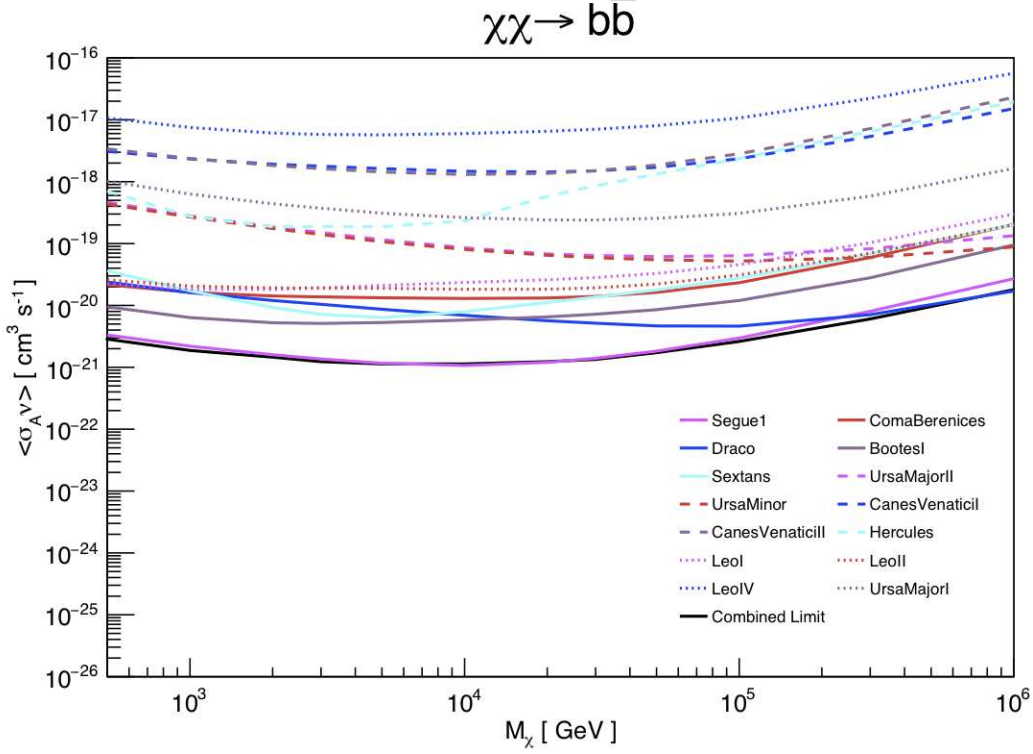


FIGURE 6.1. Upper bound limits on the dark matter annihilation cross-section for fourteen dwarf spheroidal galaxies within the HAWC field of view for the $b\bar{b}$ annihilation channel. The individual limits are shown from the likelihood analysis for all fourteen dSphs with the colored dashed and solid lines. The solid black line shows the combined limit using all dSphs resulting from a stacked analysis.

combined limits. The combined limit uses one scale factor ξ per dark matter mass and dark matter annihilation channel, as seen in table 6.1.

Figure 6.2 also shows the upper bound limits on the dark matter annihilation cross-section as a function of dark matter mass, but for dark matter annihilating with a 100% branching ratio into the $\tau^+\tau^-$ channel. Again Segue 1 proves to be the most constraining dSph at lower dark matter masses, while Draco dominates at higher dark matter masses for the same reasons as explained previously. Figures 6.3, 6.4 and 6.5 show the results for the dark matter annihilation channels $\mu^+\mu^-$, $t\bar{t}$ and W^+W^- respectively. The same trends appear across these dark matter annihilation channels, with Segue 1 being the most constraining

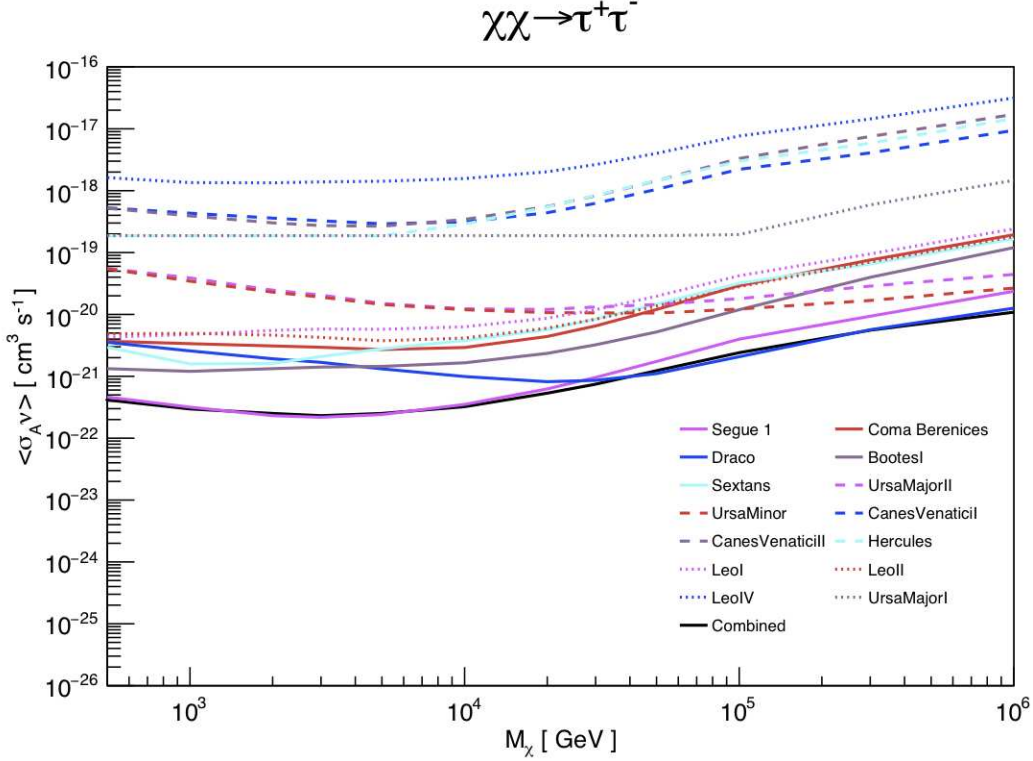


FIGURE 6.2. Upper bound limits on the dark matter annihilation cross-section for fourteen dwarf spheroidal galaxies within the HAWC field of view for the $\tau^+\tau^-$ dark matter annihilation channel. The colored solid and dashed lines show the individual limits while the solid black line shows the combined limit from a stacked analysis.

dSph at lower dark matter masses (up to 30 TeV for the $t\bar{t}$ annihilation channel) and Draco dominating at higher dark matter masses.

In addition to the limits presented from HAWC data, the expected combined limits on the annihilation cross-section for the HAWC detector were calculated. The expected limits assume that there was no observed signal above background (or a zero-sigma significance). This shows what HAWC would expect to see from a dSph since we do not expect to see any counts above background. This was done on the combined limit as a check on the analysis to ensure that we were reasonably within error of the expected value. Figures 6.6, 6.7 and 6.8 show the individual limits for the five most significant dSphs in the HAWC field of view for the annihilation channels $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, $t\bar{t}$ and W^+W^- . The individual limits are the

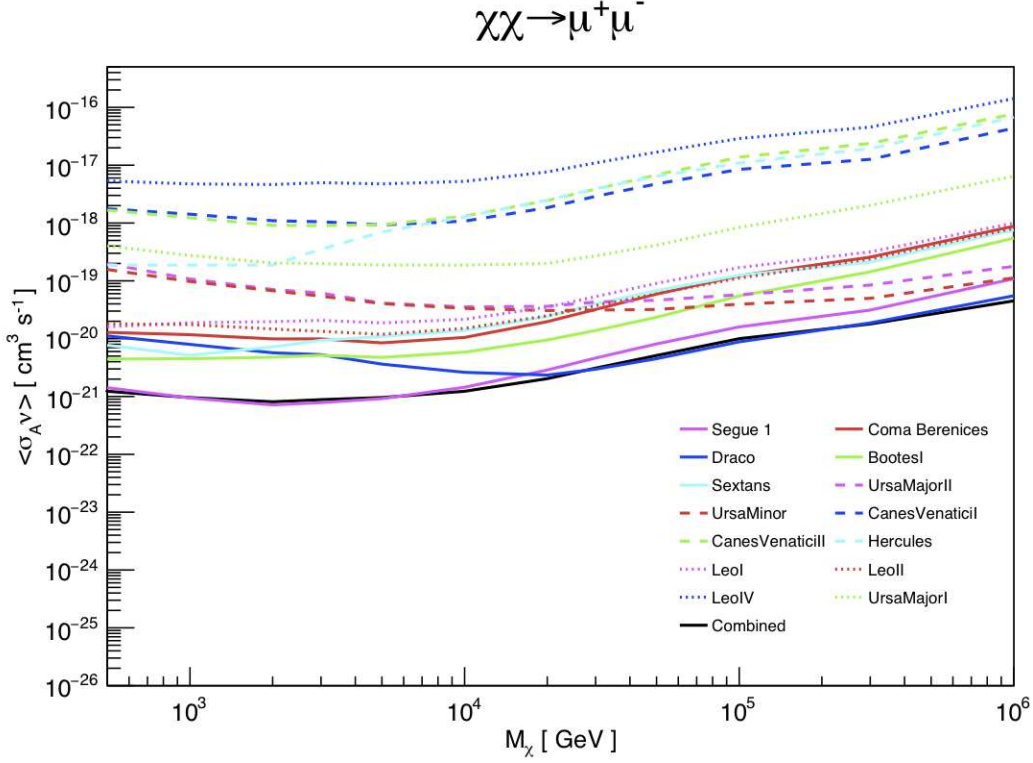


FIGURE 6.3. Upper bound limits on the dark matter annihilation cross-section for fourteen dwarf spheroidal galaxies within the HAWC field of view for the $\mu^+\mu^-$ dark matter annihilation channel. The colored solid and dashed lines show the individual limits while the solid black line shows the combined limit from a stacked analysis.

same as those presented previously, but are shown only for the five most significant dSphs: Segue 1, Draco, Sextans, Coma Berenices and Bootes I. The figures also show the combined limit for each annihilation channel from the stacked analysis with all fourteen dSphs, as well as the expected combined limits for each annihilation channel. The expected combined limit lies in the middle of the hatched grey area in figures 6.6, 6.7 and 6.8, with a $\pm 40\%$ systematic uncertainty. These figures allow for a more clear view of the most significant individual limits, the combined limit and the expected combined limit with the systematic uncertainty.

In order to directly compare the combined limits on the annihilation cross-section for each individual dark matter channel, the results are shown together in figure 6.9. The most

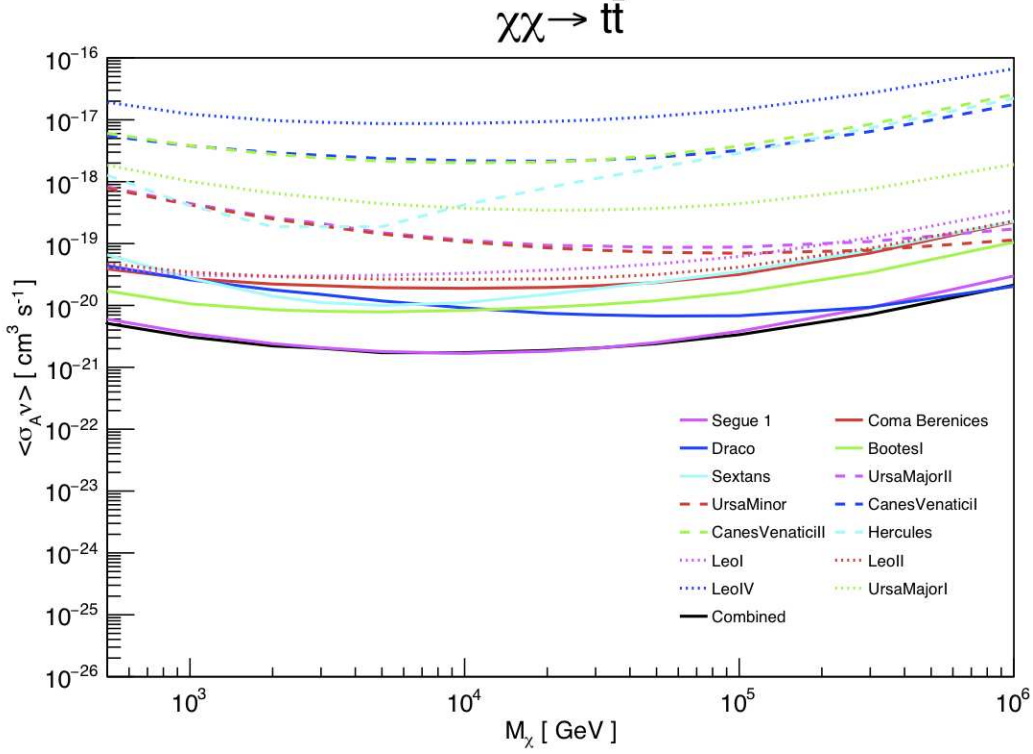


FIGURE 6.4. Upper bound limits on the dark matter annihilation cross-section for fourteen dwarf spheroidal galaxies within the HAWC field of view for the $\tau^+\tau^-$ dark matter annihilation channel. The colored solid and dashed lines show the individual limits while the solid black line shows the combined limit from a stacked analysis.

constraining limit comes from the $\tau^+\tau^-$ annihilation channel for all dark matter masses considered here. The $\tau^+\tau^-$ channel is the most constraining due to the fact that it produces a gamma-ray flux closer to the peak energy sensitivity of HAWC, as can be seen in figure 6.10. This figure shows the gamma-ray flux as a function of the energy in GeV for three dark matter annihilation channels: $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- . The gamma-ray flux peaks at an energy of ≈ 0.3 TeV for the $b\bar{b}$ and W^+W^- channels and peaks higher at around ≈ 3 TeV for the $\tau^+\tau^-$ channel. The $\tau^+\tau^-$ channel peaks at an energy range closer to the peak sensitivity of HAWC (in the few TeV range). This happens mainly because we expect to see more gamma-ray production from the $\tau^+\tau^-$ annihilation channel due to the tau lepton decay into neutral pions (π^0) and then decay into gamma rays ($\pi^0 \rightarrow 2\gamma$).

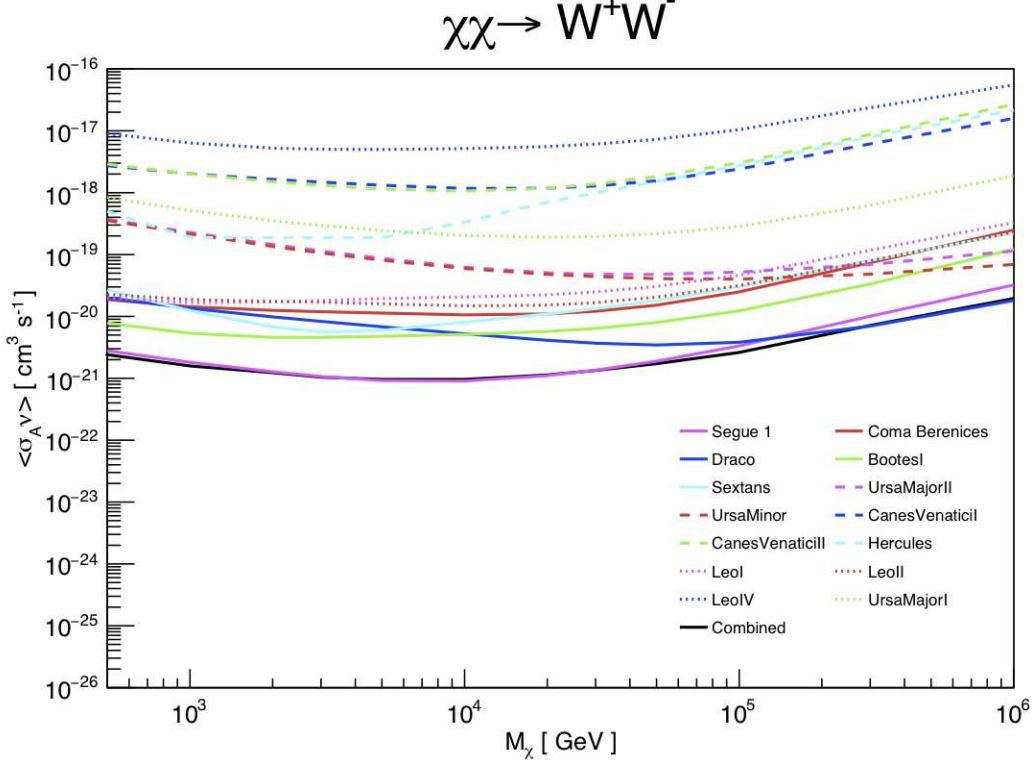


FIGURE 6.5. Upper bound limits on the dark matter annihilation cross-section for fourteen dwarf spheroidal galaxies within the HAWC field of view for the $W+W-$ dark matter annihilation channel. The colored solid and dashed lines show the individual limits while the solid black line shows the combined limit from a stacked analysis.

6.2.1. DATA UNCERTAINTIES. The systematic uncertainties in the HAWC-111 data set arise from a number of sources within the detector. One source is the uncertainty associated from taking data at different stages of the detector, and thus having a changing number of active PMTs in the data sets. Since HAWC was operational during its construction, there are data uncertainties due to the changing number of online WCDs and PMTs. The data set referred to in this analysis is the HAWC-111 data set and it comprises data taken from August 2013 to March 2015. During this time the detector grew in size from 106 to 133 operational WCDs, thereby increasing the total number of active PMTs. Due to this, the effects of an increasing number of PMTs were studied using a set of simulations. Different simulations were run assuming a different number of PMTs and the change in the detector

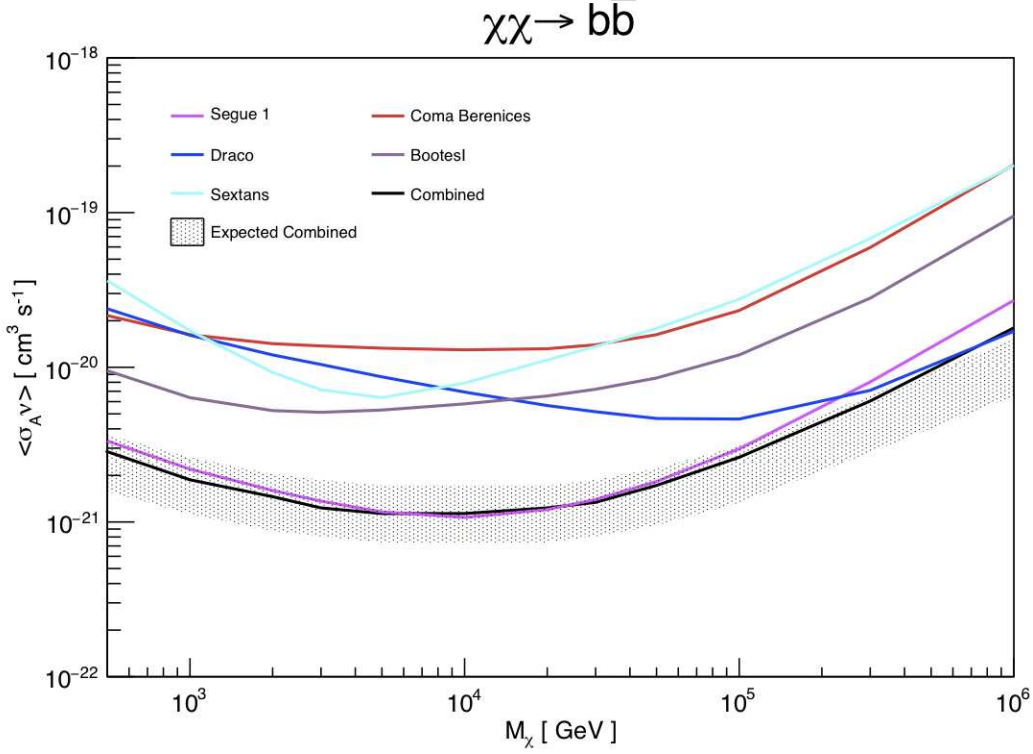


FIGURE 6.6. Upper bound limits on the dark matter annihilation cross-section for the five most significant dSphs within the HAWC field of view for the $b\bar{b}$ annihilation channel. The individual limits are shown with the colored dashed and solid lines and the solid black line shows the combined limit using all fourteen dSphs resulting from a stacked analysis. The dashed region shows the expected combined limit from HAWC simulations and its uncertainty. The expected limit lies in the middle of the dashed region with a $\pm 40\%$ systematic uncertainty region.

response was determined [68]. The discrepancy on the signal passing rates between the different simulations was found to be less than 20% [68]. Another uncertainty comes from the measured number of photo-electrons (PEs) based on how well we simulate the detector, since muon studies have shown there is a discrepancy between the simulated PMT charge and the charge from actual data. By scaling the simulations to match the data and comparing signal passing rates, the effect is also less than 20% [68]. There is also an uncertainty associated with the angular resolution of HAWC. A circular angular bin is used to get the number of events, a parameter that was chosen to maximize the significance on the Crab

Nebula. HAWC collaborators found that with measuring our angular resolution from data using a Gaussian point spread function, there is a $\pm 20\%$ variance around the optimal angular bin, translating into a $15 - 20\%$ uncertainty in the fraction of signal contained in the circular angular bin [68]. With these listed effects taken into consideration, and by adding these sources of error in quadrature, it was found that there is an overall systematic uncertainty on the HAWC-111 data set on the order of roughly 40% [68]. For the analysis presented here, the uncertainties on the expected dark matter annihilation limits were quoted at $\pm 40\%$ to account for the systematic errors found for the HAWC-111 data set by [68].

6.2.2. COMPARISON OF HAWC UPPER LIMITS TO MAGIC AND FERMI-LAT. The results were also compared to two other gamma-ray experiments, as seen in figure 6.11. The figure shows the upper bound limits on the dark matter annihilation cross-section as a function of dark matter masses in TeV. The limits in this figure are shown for Segue 1, since it proved to be the most constraining dSph for HAWC at the time of this analysis. The result for the individual HAWC-111 180 day Segue 1 limit is shown, as well as the HAWC Segue 1 5 year predicted limit as compared to the Segue 1 limits for Fermi-LAT and MAGIC (158 hr observation time). The HAWC Segue 1 predicted 5 year limit comes from the limits calculated with the HAWC Monte Carlo simulations and the detector response. As can be seen in the figure, Fermi-LAT and MAGIC have more constraining limits than HAWC at lower dark matter masses (in the GeV range). However, HAWC dominates in the higher TeV (and into the PeV) dark matter mass range, due to its higher energy sensitivity. So while other experiments rule at lower dark matter masses, HAWC has both the potential to improve its lower mass constraints with more time and data collection and more importantly, it sets the most constraining bounds for dark matter masses greater than 10 TeV.

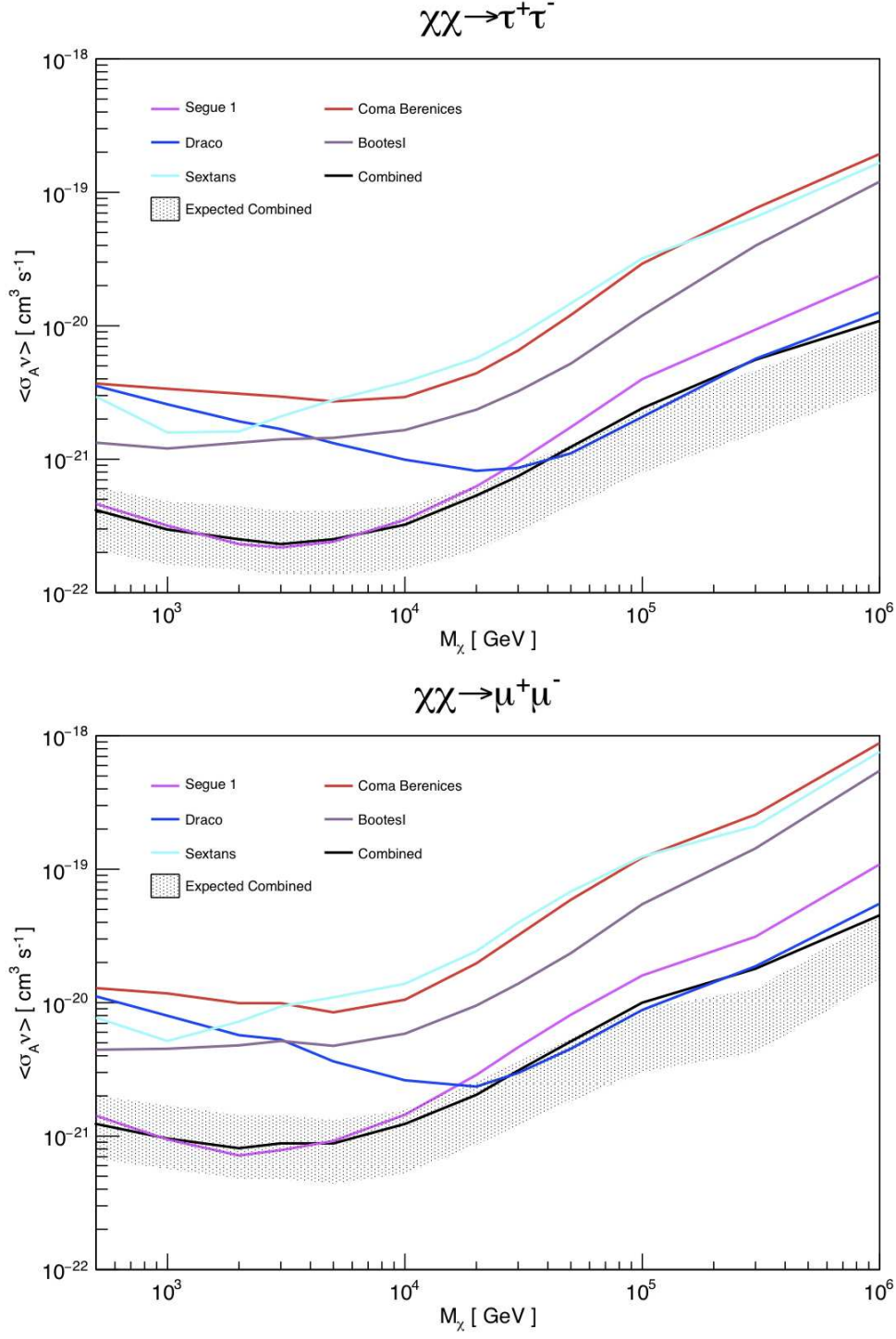


FIGURE 6.7. Upper bound limits on the dark matter annihilation cross-section for the five most significant dSphs within the HAWC field of view for the $\tau^+\tau^-$ and $\mu^+\mu^-$ annihilation channels, plus the combined limit from all fourteen dSphs and the expected combined limit region with $\pm 40\%$ systematic uncertainty region.

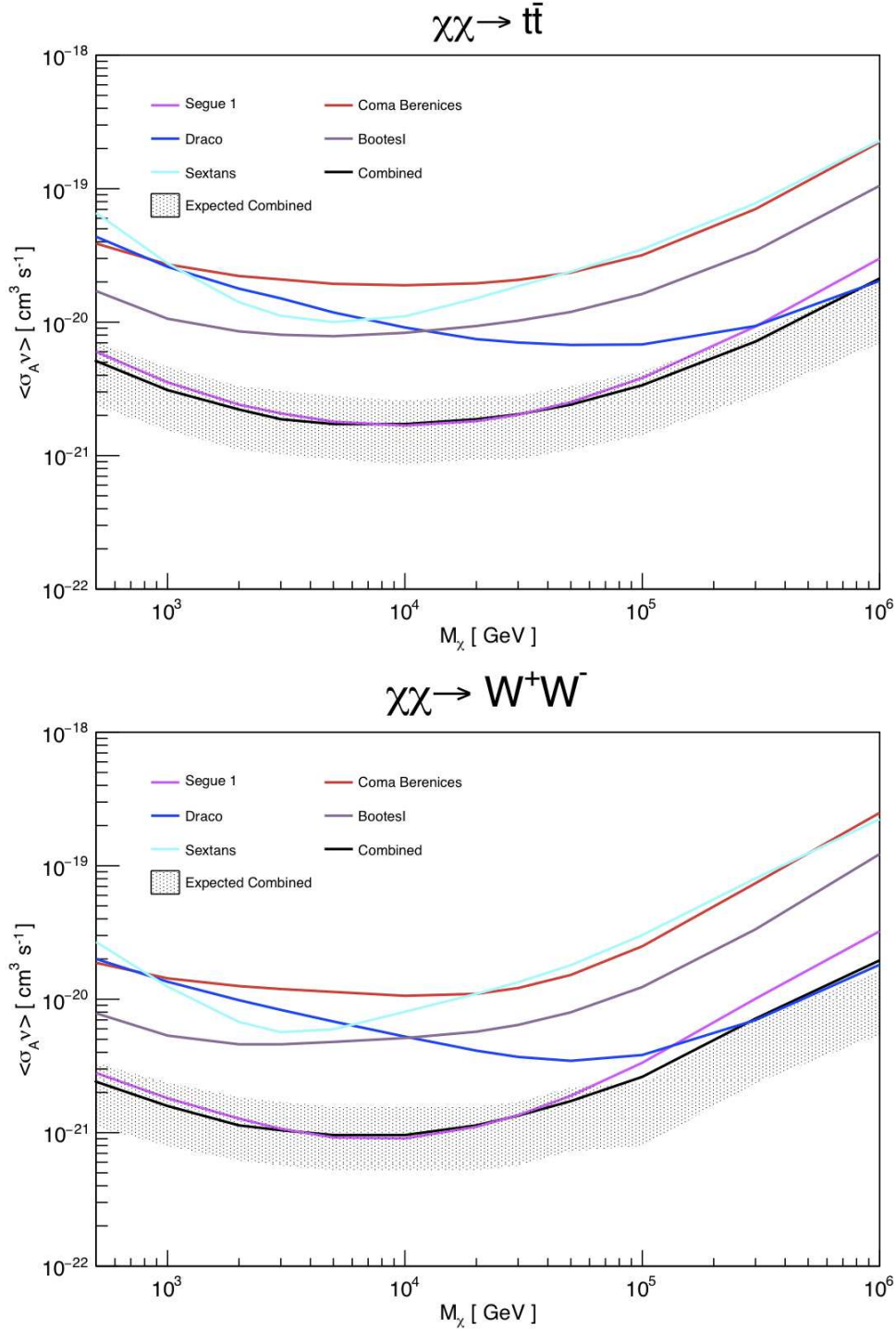


FIGURE 6.8. Upper bound limits on the dark matter annihilation cross-section for the five most significant dSphs within the HAWC field of view for the $t\bar{t}$ and W^+W^- annihilation channels, plus the combined limit from all fourteen dSphs and the expected combined limit region with $\pm 40\%$ systematic uncertainty region.

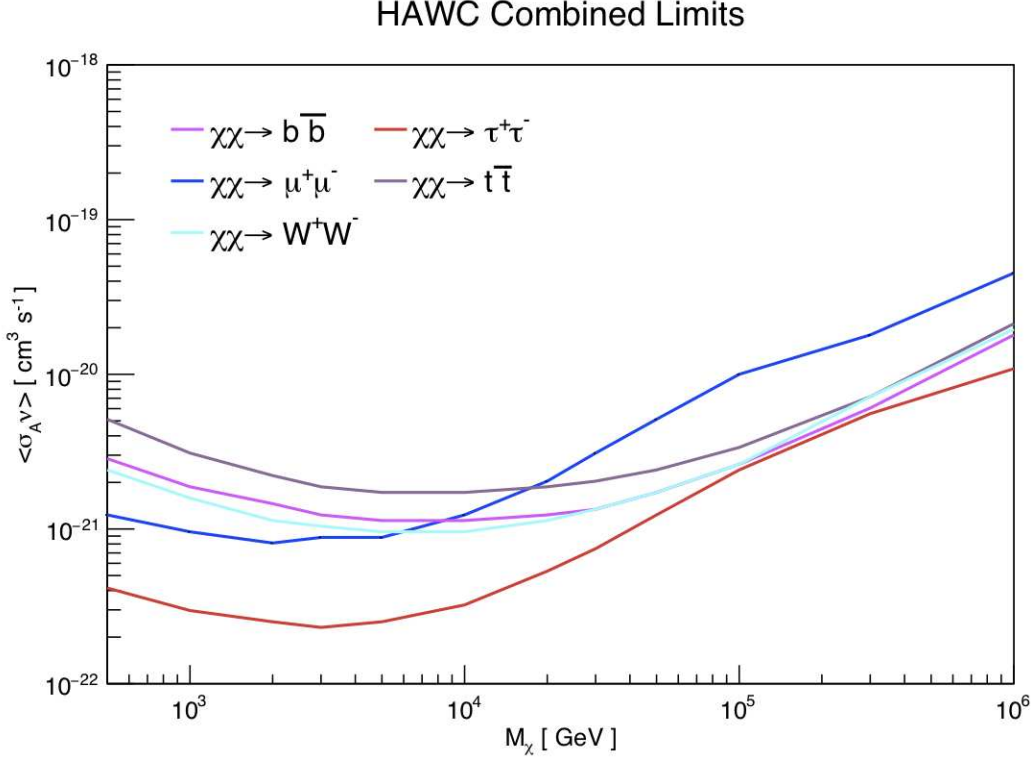


FIGURE 6.9. The upper limits on the dark matter annihilation cross-section for the five dark matter annihilation channels considered in this analysis. The limits shown are the combined limits resulting from the stacked analysis. The $\tau^+\tau^-$ annihilation channel produces the most constraining combined limit due to the fact that gamma-ray flux from this channel peaks at an energy closer to the HAWC peak energy sensitivity. We also expect to see a higher number of gamma rays from the $\tau^+\tau^-$ due to the creation of neutral pions.

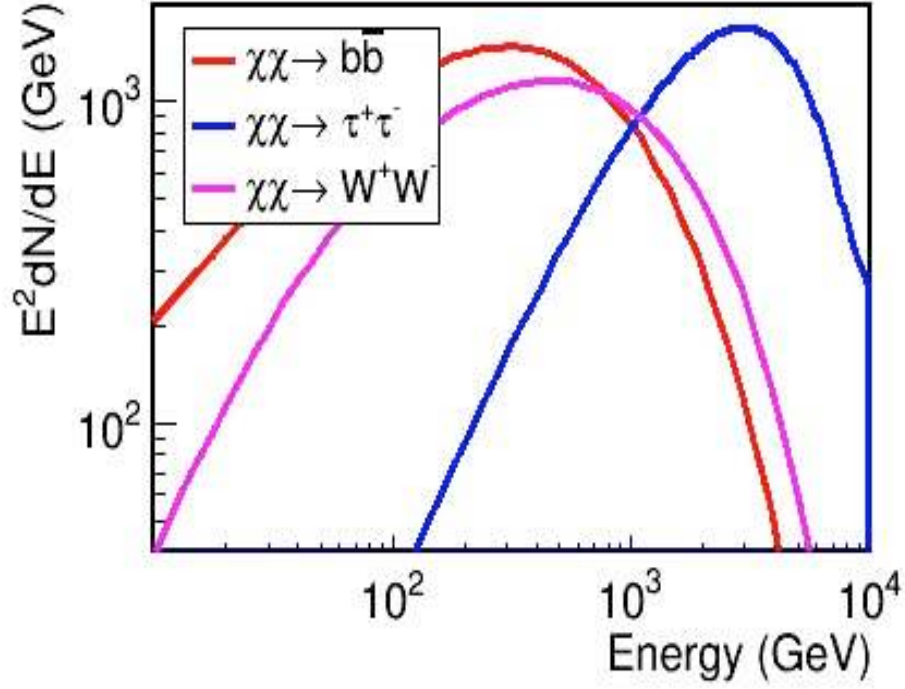


FIGURE 6.10. The gamma ray flux as a function of the energy in GeV for three dark matter annihilation channels: $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- . The gamma ray flux peaks at an energy of ≈ 0.3 TeV for the $b\bar{b}$ and W^+W^- channels and peaks higher at around ≈ 3 TeV for the $\tau^+\tau^-$ channel. This explains why the $\tau^+\tau^-$ channel is the most constraining of the annihilation cross-section limits, as it peaks closer to the HAWC sensitivity energy range. Figure courtesy of J.P. Harding of the HAWC collaboration.

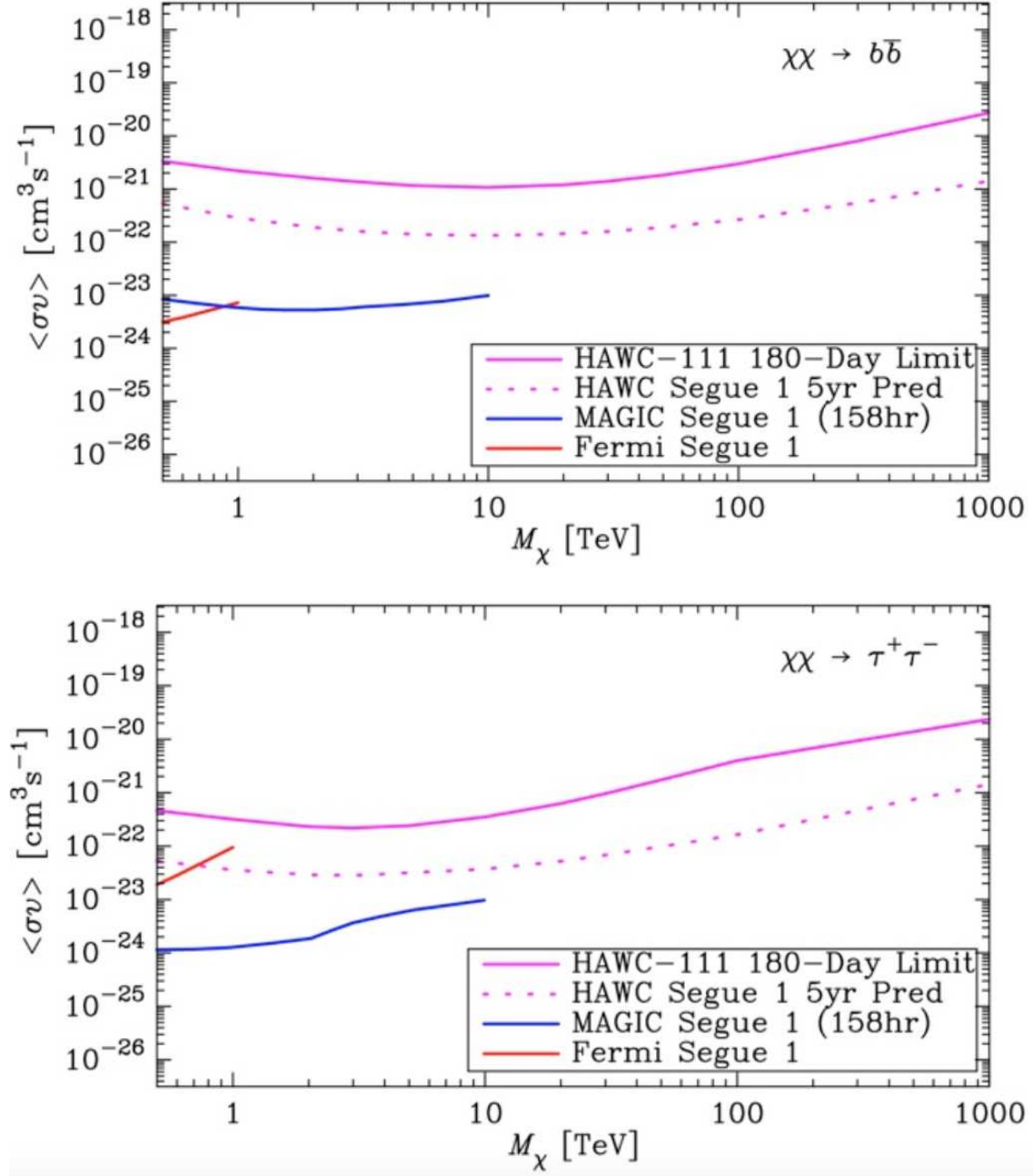


FIGURE 6.11. Comparison of the dark matter annihilation cross-section limits of HAWC to MAGIC and Fermi for the $b\bar{b}$ (top) and $\tau^+\tau^-$ (bottom) annihilation channels for the most constraining dSph for HAWC: Segue 1. The HAWC-111 180-day limit from data is shown by the pink solid line, while the HAWC 5 year expected limit is shown in the pink dashed line. The Segue 1 limits for 158 hr observation time for MAGIC (solid blue) and Fermi (solid red) are shown for comparison. Figures courtesy of J.P. Harding of the HAWC collaboration.

CHAPTER 7

SUMMARY

This thesis presented both my hardware and analysis contributions to the HAWC gamma-ray observatory. The CSU WCD prototype was the only full size detector outside of the HAWC site and served as a testbed for the design and construction of HAWC. The CSU prototype tested construction techniques, the bladder design and performance, the HAWC instrumentation and DAQ, and the HAWC calibration system. It provided invaluable information for the deployment of the VAMOS array and HAWC.

This analysis also presented limits on the dark matter annihilation cross-section using data collected from the HAWC detector. These are the first limits using the HAWC-111 data set. Individual limits were shown for fourteen dwarf spheroidal galaxies within the HAWC field of view using a likelihood ratio analysis method for five dark matter annihilation channels and a range of dark matter masses. Combined limits from a stacked analysis of all dwarf spheroidal galaxies were also shown. The combined analysis was done to increase the statistics and improve the overall sensitivity of the detector. However, since Segue 1 has proven to be the most constraining dSph at lower dark matter masses (0.5 TeV - 10 TeV) and Draco dominates at higher dark matter masses (>10 TeV) the combined limit is dominated by these two dSphs. The annihilation cross-section limits for both Segue 1 and Draco lie around $\langle\sigma_A v\rangle \approx 10^{-21}\text{cm}^3\text{s}^{-1}$. The HAWC-111 Segue 1 limits were also compared to two other gamma-ray experiments, Fermi-LAT and MAGIC. While the Segue 1 limits for HAWC-111 180-day data set are not as constraining as those set by Fermi-LAT or MAGIC at low dark matter masses, it demonstrates that the full HAWC detector has the potential to be competitive in the future as more data is collected. It was also shown that HAWC completely

dominates over Fermi-LAT and MAGIC at higher dark matter masses (greater than 10 TeV) and has the most constraining limits in the TeV and PeV dark matter mass range.

Since this analysis presented data from the HAWC-111 partial array, dark matter annihilation limits for dSphs will be an ongoing analysis as more data are available from the full HAWC array. Limits are expected to improve by an order of magnitude by using data from the full HAWC array (as seen in figure 6.11 for the HAWC 5 year predicted Segue 1 limit). Further analysis by the collaboration will also include modeling the dwarf spheroidal galaxies as extended sources, instead of treating them as point sources as presented here.

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