A LIKELIHOOD SEARCH FOR VERY HIGH-ENERGY GAMMA-RAY BURSTS WITH THE HIGH ALTITUDE WATER CHERENKOV OBSERVATORY

A Dissertation in Physics
by
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Abstract

Gamma-Ray bursts (GRBs) are extremely powerful transient events that occur at cosmological distances. Observations of energy spectra of GRBs can provide information about the intervening space between the burst and Earth as well as about the source itself. GRBs have been observed up to nearly 100 GeV by satellite instruments; however, ground-based detectors are needed to provide enough exposure and statistics to determine the behavior of GRBs at those energies. The High Altitude Water Cherenkov Observatory (HAWC) is a second-generation extensive air shower detector that primarily observes very high-energy (VHE) photons, where VHE is defined as hundreds of GeV to hundreds of TeV. HAWC is built near the peak of Sierra Negra in Mexico at an altitude of 4100 m. The high altitude allows the detector to observe air showers when more information is available for reconstruction. Due to its wide field of view (∼2 sr) and high duty cycle (>90%), the HAWC observatory is sensitive to gamma rays in the sub-TeV to TeV energy range and can constrain the shape and cutoff of high-energy GRB spectra, especially in conjunction with observations from other detectors such as the Fermi LAT satellite. We present a likelihood-based search for VHE emission from the Fermi LAT GRBs that occurred in the field of view of HAWC during the last two years of its construction. Of the five bursts analyzed, no significant detections were observed; upper limits have been placed for each of the bursts. With less than 1/3 of the array active, the HAWC observatory limits for GRB 130702A, which is at a close redshift of $z = 0.145$, reach comparable sensitivity to lower energy instruments and are not limited by the EBL. With the array complete in March 2015, the sensitivity of HAWC is now greatly enhanced compared to the data analyzed in this dissertation. The future for a VHE GRB detection by the HAWC observatory is bright.
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Chapter 1
Gamma-Ray Bursts

1.1 Introduction

Gamma-ray bursts (GRBs) are the most extreme explosive events in the Universe. Massive amounts of energy are expelled in a short time period, producing luminous flashes of light that can even be visible to the naked eye [1]. GRBs typically occur at a rate of a few per day isotropically throughout the universe. Durations range from $10^{-3}\text{s}$ to upward of $10^3\text{s}$, with an approximately bimodal distribution separating short and long bursts at $\sim2\text{s}$. In addition to being uniformly observed in the sky, GRBs are known to originate at cosmological distances, up to Gigaparsecs or $\sim10^{28}\text{cm}$. The peak of their energy spectra occurs in the gamma-ray band between $\sim100\text{keV}$ to $\sim1\text{MeV}$, hence the name Gamma-Ray Burst.

Not only are GRBs brighter than the Sun in the gamma-ray sky, the amount of electromagnetic energy they output is comparable to that of the Sun over $\sim10^{10}\text{years}$ (approximate age of the universe) or from the Milky Way over several years [2]. The massive amount of energy expelled in a burst is related to a gravitational collapse of matter to form a black hole or other compact object. Short GRBs are thought to be the merger of two neutron stars or a neutron star and a black hole [3–6], while long GRBs are most likely related to the core collapse of a massive stellar progenitor [7,8]. A jetted, highly relativistic fireball interacting with itself or the surrounding interstellar matter, forming internal and external shocks in which Fermi acceleration takes place, delivers a plausible explanation for the non-thermal spectrum of GRBs.

After the initial burst of gamma rays, the signal smoothly decays, emitting a
long-lasting “afterglow” at lower frequencies (X-ray to optical). Once the optical afterglow is observed, the redshift for the burst can be determined. Knowledge about the redshift of an object allows us to probe the very distant, early universe.

Observations of energy spectra of GRBs can provide information about the intervening space between the burst and Earth as well as about the source itself. As gamma rays propagate through the interstellar media, they interact with the extragalactic background light (EBL), which can cause attenuation via pair-production. The density of the EBL can consequently be probed with the observation of a high-energy cutoff.

Gamma-ray bursts have been extremely influential in furthering our knowledge about astrophysics and the universe. There has been practically exponential growth in the number of papers about GRBs since the early nineties when the Compton Gamma-Ray Observatory was launched. Section 1.2 highlights our path to relevant astrophysical discoveries, from the first GRBs through discoveries by the satellite instruments of BATSE and Swift and up to the arrival of Fermi. Details about relevant characteristics of high-energy GRBs observed by the Fermi LAT detector are described in Section 1.3. Finally, theoretical models for GRB production are then discussed in Section 1.4 followed by a description of the absorption of gamma rays as they make their way to Earth in Section 1.5.

1.2 GRB Observations

1.2.1 The Early History

GRBs were serendipitously discovered in 1967 by the Vela satellites, spacecrafts carrying omnidirectional gamma-ray detectors flown by the US Department of Defense [9]. The Vela satellites were designed to monitor the upper atmosphere for nuclear explosions that might violate the Nuclear Test Ban Treaty between the US and the Soviet Union. Mysterious flashes of gamma-rays, (luckily) not originating from Earth, were discovered. The following twenty years or so saw little progress in diagnosing the origin of these flashes. Gamma-ray detectors had poor localization while searches at other wavelengths remained unsuccessful.
2704 BATSE Gamma-Ray Bursts

Figure 1.1: Locations of all 2704 BATSE GRBs in galactic coordinates [12]. The color scale is based on fluence, which is the energy flux of the burst integrated over the total duration of the event. Long duration, bright bursts appear in red while short duration, weak bursts appear in purple. Grey is used for bursts for which the fluence cannot be calculated due to incomplete data.

1.2.2 BATSE discoveries

The first breakthroughs in our understanding of GRBs occurred in the 1990’s when the Compton Gamma-Ray Observatory (CGRO) [10] was launched. Onboard CGRO was the Burst and Transient Source Experiment (BATSE) [11], an instrument that operated in the 20 keV-2 MeV range with a 4π sr field-of-view and ∼3-5° angular resolution. BATSE operated from 1991-2000, during which time ∼3000 GRBs were observed isotropically distributed across the sky as shown in Figure 1.1. This discovery indicated that GRBs are not locally distributed in the galaxy; for example if GRBs originated in the galaxy, we would expect to see more bursts toward the center than in the opposite direction since we are not located at the center of our galaxy. As this is not the case, GRBs were thought to originate at cosmological
distances although production in an extended galactic halo was also possible.

The light curves (arrival time distribution of photons) of the BATSE GRB population display a large amount of diversity. Figure 1.2 shows twelve example light curves spanning the wide range seen by BATSE. These light curves range from smooth, fast-rise, and quasi-exponential decays, for example upper right plot in Figure 1.2, to curves with high variability and many peaks, such as the lower right plot in Figure 1.2.

In addition to the significant discovery of the isotropic distribution of GRBs, BATSE also saw that the GRB duration distribution is bimodal, as seen in Figure 1.3. The duration of the GRB, in this case, is described as the time it takes for between
Duration is defined as $T_{90}$, the time it takes the GRB to emit 5% to 95% of the total measured counts. The bimodal shape is clearly evident; the distinction between short and long GRBs occurs at $\sim 2$ s.

5% to 95% of the total number of measured photons to arrive, referred to as $T_{90}$. Two duration classes were designated: short GRBs and long GRBs, separated at $\sim 2$ s, each characterized by specific attributes leading to the hypothesis of different progenitors.

Short and long GRBs have different spectral properties. Figure 1.4 shows the hardness ratio for BATSE bursts. The hardness ratio is that between the fluence, the energy flux of the burst integrated over the total duration of the event, in channel 3 (100 keV-300 keV) in BATSE and the fluence in channel 2 (50 keV-100 keV) in BATSE. Short bursts, on average, have higher hardness ratios than long bursts, due to more high energy events (harder energy spectra). These two distinct populations contribute to the evidence of two different GRB progenitors.

GRB spectra are non-thermal and often can be fit with broken power laws. The typical functional form for GRB energy spectra is that of a “Band” function [17], two power laws continuously joined by an exponential cutoff. The Band function is
Figure 1.4: Hardness ratio as a function of BATSE GRB duration ($T_{90}$)\cite{15,16}. Short GRBs average higher hardness ratios than long ones, supporting the evidence for two distinct types of GRB progenitors.

simply an empirical model with no direct physical motivation. The photon number flux is defined as:

$$N_E(E) = A \begin{cases} 
\left( \frac{E}{100 \text{ keV}} \right)_{\alpha} \exp \left( -\frac{E}{E_0} \right) & : (\alpha - \beta) E_0 \geq E \\
\left( \frac{E - (\alpha - \beta) E_0}{100 \text{ keV}} \right)_{\alpha-\beta} \exp (\beta - \alpha) \left( \frac{E}{100 \text{ keV}} \right)_{\beta} & : (\alpha - \beta) E_0 \leq E 
\end{cases}$$  \hspace{1cm} (1.1)

where $\alpha$ and $\beta$ are the low and high spectral indices respectively, and $E_0$ is the e-folding energy, defined such that the peak energy $E_p$ is equal to $(2 + \alpha)E_0$. The peak energy can clearly be seen in Figure 1.5, an example fit with the Band function to the data for GRB 990123. It is worth noting that the bottom plot on Figure 1.5 shows the Spectral Energy Distribution (SED), $\nu F_\nu$ plot, for GRB 990123. $\nu F_\nu$ plots are standard in multiwavelength astronomy because they give the source power per logarithmic frequency interval and directly show the relative energy output in each frequency band \cite{20}. $\nu F_\nu$ is equivalent to $E^2 N_E$.

Another instrument on CGRO was the Energetic Gamma Ray Experiment
Figure 1.5: Example Band function fit to the photon number flux for GRB 990123 [18,19]. The fit parameters $\alpha$, $\beta$, and $E_p$ are shown. See the text for a complete description of the function and its parameters.

Telescope (EGRET) [21], which operated in the 20 MeV to 30 GeV range. EGRET detected substantial emission above 100 MeV for a few bursts [22–24]. These observations were significant in that they imply diverse temporal and spectral properties at higher energies for GRBs. Of particular interest was GRB 940217 (Figure 1.6) due to the delayed high-energy emission seen up to $\sim$90 minutes after the BATSE trigger. This observation confirmed that despite the low-energy component
Figure 1.6: High-energy gamma-ray photons (red dots) from GRB 940217 as a function of time as seen by EGRET [25]. These showed that >10 GeV emission can last up to ~1 h, even if the low-energy component (black dots) does not.

of the GRB having short duration, the high-energy emission can last much longer.

1.2.3 BeppoSAX and Afterglow Implications

While many GRBs had been detected by BATSE, their precise locations and progenitors were still unknown. It was not until the Italian-Dutch satellite BeppoSAX [26] was launched in 1996 that a definitive piece of evidence concerning the GRB distance question was found. BeppoSAX detected X-ray emission from GRB 970228 with accurate enough localization to allow other ground-based detectors to observe the object. The observed X-ray afterglow of this burst and the subsequent diminished flux after ~3 days is shown in Figure 1.7. Due to the accurate localization, the optical counterpart to the X-ray afterglow was able to be observed, which led to the identification of the host galaxy of the GRB at a redshift of $z = 0.695$ [28]. This conclusively showed that long GRBs are of cosmological origin.

The localization of GRB afterglows with BeppoSAX and its successor the High-Energy Transient Explorer (HETE-2) satellite [29], was typically delayed by hours from the initial gamma-ray detection. A new experiment that could rapidly re-point with extreme accuracy was needed to answer further questions about GRBs.
1.2.4 The Swift Era

Launched in November 2004, the Swift mission [30] is a multiwavelength afterglow satellite consisting of three instruments: the Burst Alert Telescope (BAT) [31], the X-Ray Telescope (XRT) [32], and the UV Optical Telescope (UVOT) [33]. The BAT operates in the 20-150 keV range, detecting bursts at a rate of $\sim 90$ per year. After BAT sees a burst, the satellite autonomously and rapidly slews to the direction of the GRB, which allows the more sensitive XRT and UVOT instruments to study the burst. Swift can re-point in less than 100 s, enabling the detection of short GRB afterglows for the first time. It was for precisely this reason that Swift was designed.

Swift probes the previously unmapped time domain between the bright, chaotic prompt emission and the smooth decaying afterglow of the GRB. Figure 1.8 shows the schematic of Swift’s observed X-ray light curves. The breaks in the afterglow emission help constrain the energetics and models of GRBs.

As of 1 October 2014, Swift has detected 909 GRBs, 285 of which have observed redshifts. Before Swift, only 41 bursts had known redshifts. The GRB redshift distribution is shown in Figure 1.9. Of particular significance are the bursts beyond
Figure 1.8: Schematic of X-ray afterglows as seen by Swift observations, consisting of four power-law segments with a possible flaring component (adapted from [2]). The most common segments are solid blue lines while the dashed red line phases are only in a fraction of the bursts. The power-law spectral indices are shown in the plot. This plot highlights the additional information provided by Swift detections of gamma-ray bursts to the left of the dashed black line.

\[ z = 6 \]. These redshifts date back to a time before the first generation of light sources emitted the light that reionized the intergalactic medium [2].

In light of the significant discoveries made by Swift, it was clear that exploring the higher-energy components of GRBs would be very valuable.

### 1.2.5 Non-detections by IACTs and EAS Detectors

The limited area of satellite-borne instruments becomes a problem when looking for higher energy photons. For this reason, ground-based detectors are needed; two basic types have been developed. Imaging Atmospheric Cherenkov Telescopes (IACTs) are ground based gamma-ray detectors that have the potential to observe GRB emission at TeV energies. Extensive Air Shower (EAS) detectors are also ground based and observe the same energy range with a different technique. The significant GRB (non-)observations from the IACTs H.E.S.S., MAGIC, and VERITAS and
Figure 1.9: Distribution of GRB redshifts through December 2014 (adapted from [34]). The bottom axis is the redshift value of each burst, and the top axis shows the corresponding age of the Universe. Pre-Swift bursts are in red while Swift bursts are in blue. The Swift mission pushed the boundary of known GRB redshifts beyond the end of the “dark ages” when the first generation of light sources reionized the intergalactic medium.

EAS detectors ARGO-YBJ and Milagro are discussed below. The observation methods of each type of detector will be described in Chapter 2.

The High Energy Stereoscopic System (H.E.S.S.) is an array of four 13 m IACTs in the Khomas Highland of Namibia, located at an altitude 1800 m above sea level [35]. H.E.S.S. is sensitive to VHE gamma-rays from hundreds of GeV to tens of TeV. The telescope has a field-of-view (FoV) of $\sim 5^\circ$ with an angular resolution of $\sim 0.1^\circ$ and an energy resolution of $\sim 15\%$. The slewing rate is $\sim 100^\circ$ per minute and can point anywhere in the sky in $\sim 2$ min. From 2003-2007, 22 GRBs occurred in the FoV of H.E.S.S. during instrument up-time with no VHE signal found [36]. H.E.S.S. was able to observe both the prompt and afterglow phases of GRB 060602B because it was coincidentally observing the position prior to the burst. Despite potentially being able to see the prompt emission, no VHE signal was observed [37]. It was, however, an especially soft burst and had no observed redshift. H.E.S.S.
also placed limits on GRB 100621A, an exceptionally bright X-ray burst at a close redshift of \( z \simeq 0.5 \) \cite{38}.

The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) observatory \cite{39,40} consists of two telescopes located on the Canary Island of La Palma. MAGIC-I was completed in 2004 while MAGIC-II became active in 2009. The threshold for gamma-ray detection is around 50 GeV and the slewing time is approximately 40 s. The angular resolution of MAGIC, depending upon the analysis, is \( \sim 0.1^\circ \). From 2005-2006, MAGIC observed nine GRBs and detected no VHE emission \cite{41}. MAGIC placed upper limits on the afterglow emission of GRB 080430 \cite{42}, which was at a redshift of \( z = 0.76 \), as well as on GRB 090102, which occurred farther away (\( \sim z = 1.5 \)). GRB 090102 was observed under favorable circumstances as it was at a low zenith angle in the FoV of MAGIC and the weather was good. Despite these conditions, MAGIC did not see any gamma-ray signal from the burst \cite{43}.

The last IACT, the Very Energetic Radiation Imaging Telescope Array System (VERITAS) \cite{44,45}, has four 12 m detectors and is sensitive to gamma rays from \( \sim 50 \) GeV to \( \sim 100 \) GeV. The telescopes are located at the basecamp of the Fred Lawrence Whipple Observatory in southern Arizona. The FoV of VERITAS is 3.5\(^\circ\), and the angular resolution is 0.1\(^\circ\) (0.14\(^\circ\)) at 1 TeV (200 GeV). At 1 TeV, VERITAS has an energy resolution of 15\%. In 18 months from 2007-2009, VERITAS observed 29 GRBs of which the results for 16 Swift-detected bursts were presented in \cite{46}. Nine of the bursts have measured redshifts. VERITAS did not see VHE emission from any of the GRBs.

Changing ground-based observation techniques, the Astrophysical Radiation Ground-based Observatory at YangBaJing (ARGO-YBJ) experiment contains a single layer of Resistive Plate Counters (RPCs) covering a large area at an altitude of 4300 m a.s.l. \cite{47}. With a large FoV (\( \sim 2 \) sr), the ARGO-YBJ detector operates with a > 90\% duty cycle and observes gamma-rays in the GeV-TeV energy range. From December 2004 to February 2013, 206 GRBs occurred in the FoV of ARGO-YBJ \cite{48}. No significant emission was observed from any of the bursts.

The EAS detector Milagro is a large water-Cherenkov observatory that is sensitive to primary energies of \( \sim 100 \) GeV or higher \cite{49}. Milagro is located at an altitude of 2630 m in the Jemez Mountains of New Mexico. Similar to ARGO-YBJ, Milagro has a FoV of \( \sim 2 \) sr and a duty cycle over 90\%. Seventeen short duration (< 5 s) GRBs as well as 25 GRBs from 2000-2001 were analyzed by Milagro to
search for TeV emission \cite{50,51}. Again, no significant detection of VHE emission was found. Prior to Milagro, however, the prototype detector Miligrito saw evidence for emission above 650 GeV from GRB 970417A, with a post-trials probability of $1.5 \times 10^{-3}$ of being a background fluctuation \cite{52,53}. This observation provides encouragement that VHE emission from GRBs can be found.

1.2.6 The Arrival of Fermi

The Fermi Gamma Ray Space Telescope was placed in orbit in June 2008. The observatory consists of two instruments: the Gamma-ray Burst Monitor (GBM) \cite{54}, whose energy range is 8 keV to 40 MeV, and the Large Area Telescope (LAT) \cite{55}, which operates at energies from 20 MeV to more than 300 GeV. The GBM is comprised of scintillation detectors that have a FoV of $\sim 9.5$ sr. Burst localization is determined from the relative event rates in scintillators with different orientations from the source and is typically accurate to a few degrees. The LAT is a pair-production telescope with a wide FoV (2.4 sr at 1 GeV) and more accurate localizations than the GBM ($\lesssim 1^\circ$). The LAT is able to measure spectra from 20 MeV to more than 50 GeV. The GBM and LAT together measure the spectral parameters of GRBs across seven decades in energy.

The GBM detects $\sim 240$ bursts per year of which about half are in the LAT FoV. Of the GBM-detected burst that occurred in the FoV of the LAT detector, seventy-three GRBs have been observed by LAT from August 2008 through January 2014 \cite{56}. These bursts have provided significant insight into the possible mechanisms for the generation of GRBs, which will be discussed in the next section. Although Fermi covers a wide range in energy, to measure spectra $>50$ GeV, ground-based detectors are needed.

1.3 High-Energy GRB Characteristics

The Fermi LAT Gamma-Ray Burst Catalog \cite{57} summarized current knowledge of the observed high-energy component of GRBs. There are four features that distinguish LAT bursts: (1) high energy release and fluence, (2) delayed emission with respect to the lower energy counterpart detected by GBM, (3) temporally extended emission lasting longer than GBM-detected emission, and (4) a power-law
component in addition to the Band function to fit the energy spectra.

Figure 1.10 shows the fluence $F_\nu$ distribution from 10 keV to 1 MeV for the GBM-detected bursts from the first spectral catalog [58] and LAT-detected bursts through August 2011 [57]. The LAT-detected bursts inhabit, in general, the right-hand side of the fluence distribution, indicating that they are among the brightest seen by the GBM. Additionally, while the ratio of the LAT fluence to the GBM fluence for long GRBs is $\lesssim 20\%$, the fluence ratio for the few short LAT-detected GRBs is $\sim 100\%$.

Recall that GRB duration is typically described by $T_{90} \equiv T_{95} - T_{05}$, where $T_{05}$ and $T_{95}$ are the times it takes the integral number of counts to reach 5% and 95% of the total number respectively. By comparing the onset and duration distributions of the GBM-detected bursts to the LAT-detected ones, we can see the delay in the high-energy emission. The left panel in Figure 1.11 shows that the $>100\text{ MeV}$
Figure 1.11: Comparison of the LAT >100 MeV $T_{\text{95}}$ (left) and $T_{90}$ (right) to those of the GBM-detected bursts in the 50 keV to 300 keV energy band [57]. The four brightest LAT-detected bursts are labeled with square symbols. Short GRBs are plotted in red while long GRBs are shown in blue. The dashed green line is drawn where the LAT and GBM times would be equal. This shows the delay between the lower energy (GBM) emission and that seen by the LAT.

emission systematically starts later than the lower energy GBM emission while the right panel in Figure 1.11 shows that the higher energy bursts have longer durations.

An additional temporal characteristic of LAT-detected GRBs is shown in Figure 1.12, which displays the “late-time decay index” $\alpha_L$ that corresponds to the fit power-law index after the GRB $T_{95}$ such that $F_\nu \propto t^{-\alpha_L}$. This type of behavior is typically seen in the longer wavelength emission during the GRB afterglow phase. As can be seen in Figure 1.12, the late-time decay index is consistent with $\alpha_L = 1$ with the exception of two bursts, which can be attributed to observational bias [57]. This also suggests the afterglow as the common mechanism for this late emission. The peak flux time of the LAT-detected GRBs is shown in Figure 1.13. The constant late-time delay index and peak flux time are taken advantage of during the likelihood analysis described in Section 6.

Finally, all of the bright LAT-detected bursts require an additional power-law component to the standard Band function for joint GBM-LAT spectral fits. For example, the need for an extra power-law can be seen in the fit spectrum of
Figure 1.12: The temporal decay index $\alpha_L$ for LAT-detected bursts [57]. The values cluster around $\alpha_L = 1$, which indicates a common emission mechanism for the extended emission.

Figure 1.13: Time of the peak flux for LAT-detected bursts [57]. Most of the peak fluxes arrive between 1 s and 100 s after the trigger.

GRB 090926B (Figure [1.14] [59]. This aspect of LAT-detected bursts, in particular, is exciting for the potential observation of very high-energy GRB emission in the future.
Figure 1.14: Prompt emission spectra of GRB 090926A [59]. The top panel shows the fit spectra for the entire prompt phase, and the bottom panel shows the fit spectra for different time intervals. An additional power-law is needed in the later time window (purple).

1.4 The GRB Model

As mentioned previously, there are two classes of GRBs: long and short. Long bursts are from the collapse of a massive stellar object [7,8] and are often associated with supernovas. For example, GRB 980425 was associated with SN 1998bw [60–62], and the supernovae signature of SN 2003dh was unambiguously seen in GRB 030329 [63,64]. Short GRBs are thought to be the product of the merger of two neutron stars or a neutron star and a black hole [3,6].

A black hole with several solar masses is likely to be the central compact object for both types of GRBs. The gravitational energy released in the collapse or merger (∼few solar masses) is converted to free energy in a short time scale over a volume of tens of km$^3$. This happens via the accretion of the material/gas onto the black
Figure 1.15: Example radiation mechanisms that affect GRB photons. **Left:** Schematic of synchrotron radiation. An electron spirals around a magnetic field line, the acceleration of which causes it to emit photons. **Right:** Schematic of inverse Compton radiation. A high-energy electron scatters a low-energy photon, transferring energy to it during the interaction.

hole. A large fraction of this energy is radiated in neutrinos and gravitational waves, neither of which have been observed yet. A smaller fraction goes into a high temperature fireball consisting of $\gamma$-rays, $e^\pm$, and baryons (mostly $p$). The GRB photon luminosity from observations and energetics over these timescales is much larger than the luminosity limit at which radiation pressure exceeds self-gravity (the Eddington luminosity $L_E = 4\pi G M m_p c / \sigma T = 1.25 \times 10^{39} (M/M_\odot) \text{ erg s}^{-1}$), thus allowing the fireball to expand.

The fireball expansion is ultra-relativistic. This is known because photons $>100\text{ MeV}$ have been observed from GRBs. The only way these particles could survive without degrading via $\gamma\gamma \rightarrow e^\pm$ to energies lower than $m_e c^2 = 0.511\text{ MeV}$ is if the flow expands with a very high Lorentz factor $\Gamma$. The Lorentz factor is defined as:

$$\Gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \quad (1.2)$$

where $v$ is the velocity of the material and $c$ is the speed of light. If the bulk Lorentz factor is large, the relative angle at which photons collide is less than $\Gamma^{-1}$, which diminishes the pair production threshold allowing the high energy photons to survive.

The fireball gains kinetic energy as the particles are relativistically beamed in
Figure 1.16: Schematic of GRB jet outflow [67]. Internal shocks collide to produce prompt MeV emission while external shocks are created when the ejecta collides with the interstellar media. The GRB afterglow is due to the external shock.

The jet. To get the observed non-thermal spectrum of photons, the kinetic energy is converted to electromagnetic radiation via synchrotron radiation and/or inverse Compton (IC) scattering by relativistic electrons in the shocks expected in the optically thin regions of the outflow [68] (see Figure 1.15 for schematics of the particle interactions). When the expanding fireball runs into the external material surrounding the GRB (the circumburst medium), an external shock is created while a reverse shock travels back into the ejecta. Turbulent magnetic fields boosted in the shock interacting with relativistic electrons through Fermi acceleration produce synchrotron emission, resulting in the observed broken power-law spectrum [68,69]. Optical photons are produced by the reverse shock while GeV-TeV photons are produced by inverse Compton emission in the forward shock [70]. Additionally, internal shocks can form when faster parts of the ejecta run into slower portions [71]. Internal shocks are thought to produce the prompt MeV emission while the long-term afterglow is due to the external shocks dissipating from higher energies to lower ones over an extended period of time. Figure 1.16 shows an artist’s interpretation of the fireball model.

While the fireball model is accepted as the general form of GRB emission, there
are many aspects of the model that are still under debate. The internal and external shock model, described above, with electrons being accelerated by magnetic fields in the shocks is the standard leptonic forward shock model. Other models favor hadronic processes as the origin of the GRB emission.

### 1.4.1 Leptonic Models

One model, based on the earliest LAT bursts, argues that the extended GeV emission is due to a radiative, fast cooling forward shock (e.g. [72]). High-energy photons back-scatter toward the source creating $e^\pm$ pairs that allow for quick cooling. The authors also show how this would explain the GeV afterglow emission starting later than the prompt MeV emission. Alternatively, an adiabatic, slow cooling fireball model [73] would also explain the delayed GeV emission. The bolometric afterglow flux decays $\propto t^{-\alpha}$. For the radiative model, $\alpha = 10/7$ while $\alpha = 1$ for the adiabatic case. Due to the extended emission of *Fermi* LAT bursts shown in Figure 1.12, an adiabatic fireball model is currently preferred [57].

There is also debate revolving around the exact type of medium surrounding the burst. There are two typical scenarios: (1) interstellar media with uniform density (ISM) and (2) stellar wind resulting from, for example, a type Ic supernova star (Wind). The density is modeled as $n_0$ (cm$^{-3}$) for the ISM case and $n(r) \propto r^2$ for the Wind scenario.

Recently, GRB 130427A, currently the brightest observed burst at many wavelengths, has challenged the high-energy synchrotron external-shock afterglow emission model that previously explained the high-energy emission seen in the LAT bursts [74]. A record-breaking 95 GeV photon was observed at $T_0 + 244$ s. This photon as well as the other high-energy photons observed cannot be from synchrotron radiation from Fermi acceleration due to their late arrival times. This conclusion holds for either radiative or adiabatic external shocks encountering the ISM or Wind media [74]. However, if the acceleration process is via, for example, magnetic recombination rather than Fermi acceleration, synchrotron radiation could still be the origin of these photons.

If GeV emission is not produced through Fermi-accelerated synchrotron radiation, it could be produced through Compton processes. For example, external-inverse-Compton-scattering of the forward shock electrons interacting with external media
Figure 1.17: Schematic of GRB emission spectrum for a photospheric-internal shock model (adapted from [77]). Peaks in the energy spectrum due to synchrotron emission, synchrotron self-Compton scattering (SSC), photospheric emission, and up-scattering (UP) are shown. Time dependence of the parameters can allow the up-scattered photon peak to overlap the photospheric emission peak.

could also explain the late-time arrival of high-energy photons [75].

Alternatively, the synchrotron photons from the electrons in the internal shock could undergo inverse Compton scattering off the same electrons that produced them. This is called Synchrotron-Self-Compton (SSC) scattering. SSC from the prompt emission is expected to peak at TeV energies. Due to this, SSC is one of the best models for producing the hard power-law component seen at GeV energies in a simple one-emission zone model [76]. However, the time delays between the MeV and GeV emission cause problems for this model. Therefore, more complicated multiple zone models are needed.

In general, multi-zone models are composed of photons with a softer spectra created at an inner source that are then up-scattered by electrons in a region further out [77]. One example of a multiple zone model starts with the soft photons from the GRB jet scattered by the photosphere. These photons peak at the typical GRB MeV
energies but a non-thermal tail extends into the multi-MeV range. The photospheric photons in the tail can up-scatter with the internal shock electrons, creating GeV photons. Numerical simulations show that the time-dependent evolution of these parameters can cause distinct photospheric and up-scattered components or an overlap between them [78]. Figure 1.17 shows an example of the MeV-GeV spectrum for a photospheric-internal shock model of emission from [77]. An alternative multi-zone model proposes the soft photons arise from an expanding cocoon consisting of the dissipation of the jet energy inside the progenitor star and are then up-scattered by the internal shock electrons [79].

1.4.2 Hadronic Models

Hadrons can interact with photons through

\[ p + \gamma \rightarrow \Delta \rightarrow p + \pi^0 \text{ and} \]

\[ p + \gamma \rightarrow \Delta \rightarrow n + \pi^+, \]

which create cascades of particles. If protons are accelerated in the GRB jet, the secondary leptons produce mostly synchrotron or inverse Compton emission, which can be distinguished from that from primary leptons. Figure 1.18 shows an example of a hadronic cascade model for GRB 090510 [80]. The extra power-law feature can be reproduced with reasonable parameter values. Alternatively, if there are strong magnetic fields, a proton synchrotron model could work. The time delay between the MeV and GeV emission can be explained through the proton acceleration and cooling time.

Magnetically dominated models for GRBs also exist and typically fall into two general categories. The first Poynting flux dominated model has baryons in the jet absent or almost negligible [81–83]. The other model allows for baryons in the jet but demands that the load is sub-dominant to the magnetic stresses [84–87].

1.5 Absorption of VHE Emission by the EBL

In the previous section, we described how gamma rays (and other particles) are produced by GRBs. We must now address the propagation of said particles through
Figure 1.18: Photohadronic cascade model of the extra power-law component of GRB 090510 [80]. The black (red) line shows the photon spectra for a stronger (weaker) magnetic field. The blue line shows the model values at the observed photon energy of 3.4 GeV. The fit power-law component is shown as a dashed green line.

The EBL consists of the total emitted light from stars and active galactic nuclei (AGN) over the age of the universe. It is directly linked to the universe’s star formation history. Figure 1.19 shows a schematic of the spectral energy distributions of the backgrounds in the universe. The EBL consists of the cosmic optical background (blue), which is mostly due to direct starlight with a subdominant contribution by AGN, and the cosmic infrared background (red), which mostly consists of reemitted light from dust particles.

Direct observation of the EBL is difficult due to strong foregrounds from our interstellar media as they journey to Earth. The primary means of absorption of VHE gamma rays is through pair production via interactions with the extra-galactic background light (EBL) (see Eq. 1.3).
Figure 1.19: Schematic of the spectral energy distributions of the backgrounds in the universe [88]. From left to right: the cosmic optical background (light from stars), the cosmic infrared background (reemitted light from dust), and the cosmic microwave background.

solar system and the Galaxy. Models are needed to constrain the EBL at multiple redshifts and wavelengths. There are four kinds of phenomenological approaches to creating an overall EBL model, summarized by [89]:

(i) forward evolution beginning with initial cosmological conditions and evolving with time by means of semi-analytic models (SAMs) of galaxy formation;
(ii) backward evolution from current galaxy populations evolved through time;
(iii) evolution of galaxy properties over some range in wavelength;
(iv) direct observation of evolution in galaxy properties over the redshifts that contribute significantly to the EBL.

In this work, we use the Gilmore 2012 fiducial model from [90], which is of type (i) above, to model the absorption of gamma rays. The model is chosen primarily because, while there are still large uncertainties in the EBL beyond $z = 1$, it
models the attenuation for sources at $z > 1$. Figure 1.20 shows the Gilmore model (WMAP5 Fiducial, black line) along with Dominguez 2011 [89], a model of type (iv). Data from direct and indirect detections are also plotted.

### 1.5.1 VHE Gamma Ray Attenuation

Interactions with the EBL cause the universe to be opaque to very high-energy gamma rays. As previously stated, when a very high-energy gamma-ray collides with a photon in the interstellar media, pair production can occur:

$$\gamma_{VHE} + \gamma_{EBL} \rightarrow e^+ + e^- \quad (1.3)$$
The kinematics of photon-photon scattering to electron-positron pairs are well understood. Basically, there must be enough energy in the center-of-mass frame of the two-photon system to produce the pair. This requirement can be written as

$$\sqrt{2E_1E_2(1-\cos\theta)} \geq 2m_e c^2,$$

where $E_1$ and $E_2$ are the photon energies and $\theta$ is the angle of incidence as measured in the cosmological frame. The HAWC observatory is primarily designed to detect gamma rays in the TeV and GeV energy range, corresponding to incident photons in the far-infrared ($\gtrsim 10^{-2}$ eV) to the Lyman limit ($\lesssim 13.6$ eV).

The intrinsic energy spectrum of a source is attenuated as a function of its optical depth:

$$\frac{dN}{dE}_{\text{obs}} = \frac{dN}{dE}_{\text{int}} e^{-\tau(E_{\gamma},z)}$$

where the optical depth $\tau(E, z)$ is dependent on the observed photon energy $E_{\gamma}$ and the redshift $z$. Figure 1.21 shows the attenuation factor as a function of energy for sources at close redshifts. The farther away the source (the larger the redshift), the more high-energy gamma rays are attenuated. For sources at redshifts beyond $z = 1$, photons with energies $\gtrsim 300$ GeV are not able to be observed. An example of the impact of the EBL on the number of events triggering our detector is given in Figure 1.22. The number of events decreases drastically with increasing energy and redshift.

If VHE emission from GRBs is observed and optical instruments catch the redshift of the source, models of star formation history in the high-redshift regime can be constrained. For example, the Fermi LAT collaboration was able to eliminate EBL models due to the high-energy photons from their observed GRBs, especially those from GRB 090902B and GRB 080916C [91]. The HAWC observatory reaches even higher energies than the LAT, which could let us start to probe the long-wavelength peak of Figure 1.20 where the uncertainties are quite large.

### 1.5.2 Very High-Energy GRB Outlook

There are many models for the processes creating the emission from GRBs. While the origin of the lower energy emission is fairly well-known, the high-energy emission mechanisms are still under discussion. Detection of a GRB at TeV energies by
Figure 1.21: Attenuation of gamma rays as a function of gamma-ray energy for sources at $z = 0.03, 0.1, 0.25, 0.5,$ and $1.0$. Of the models shown, we use the 2012 WMAP5 Fiducial model (solid red line). As the source increases in distance from Earth, more high-energy gamma rays are absorbed. Therefore, VHE gamma-ray detectors are more likely to observe closer sources.

the HAWC observatory would help determine the nature of high-energy cutoffs of the hard power-law component, constrain both leptonic and hadronic models, and constrain the EBL.

Additionally, one of the exciting prospects for observation of very high-energy photons from GRBs is the constraints they would allow us to put on Lorentz Invariance Violation (LIV). Special relativity says that the speed of light in a vacuum is independent of energy; however, quantum effects are expected to strongly affect the nature of space-time at the Planck scale ($E_{\text{Planck}} = M_{\text{Planck}}c^2 < 1.22 \times 10^{19} \text{GeV}$). This can be tested by looking for changes in photon speed with energy $[92-98]$. Sharp features in GRB light curves could indicate tiny variations in photon speed (accumulated over the cosmological distance of the burst). Thus, the time delay between MeV photons and GeV photons has consequences for the effective field
Figure 1.22: Example energy distribution of events passing the trigger and cut criteria as a function of the redshift of the source. The simulated GRBs have a power-law spectrum with index $= -2$ and are observed by the full HAWC-300 detector at a zenith angle of $20^\circ$. Events must pass a multiplicity trigger of 50 PMTs and be accurately reconstructed within $1.7^\circ$ of the true source position. The normalization of the plot is arbitrary.

 theory of quantum gravity. For example, the detection of a 31 GeV photon from GRB 090510 less than a second after the onset of emission rules out first-order dependence on $E_\gamma/E_{Planck}$ of any Lorentz invariance violating terms [99]. Detection of VHE photons by the HAWC observatory could help determine the bulk Lorentz factors and test LIV.
Chapter 2
Detecting Cosmic Ray and Gamma-Ray Air Showers

A large background in the search for GRBs with the HAWC observatory are cosmic rays (the remaining background is intrinsic to the detector and discussed in the next chapter.) This chapter discusses those cosmic rays in Section 2.1 and characteristics of both cosmic ray and gamma ray air showers in Section 2.2. In the final section, we discuss detection techniques currently used to observe cosmic ray and gamma-ray air showers.

2.1 Cosmic Rays

In the early 20th century, scientists noticed that isolated, charged electroscope were discharging slowly with time. Initially, they believed this was due to radiation being emitted from the Earth. To test this theory, Victor Hess went on several balloon flights to observe the rate of discharge of electrosopes as the distance from Earth increased. He observed an unexpected increase in the rate, leading to the discovery of extraterrestrial radiation that eventually became known as cosmic rays [100]. In 1936, Hess shared the Nobel Prize for this discovery.

The cosmic rays Hess detected primarily consist of protons, helium, carbon, nitrogen, and other heavy ions up to iron. These particles span over ten decades in energy, as shown in Figure 2.1. Below \( \sim 10^{14} \text{eV} \) the flux of particles is large enough to be directly observed by satellites. Above that, ground-based detectors are needed for indirect detection. The cosmic ray spectrum follows a basic power law, with flux decreasing rapidly with energy. At the “knee” \( \sim 10^{15.5} \text{eV} \), the
spectrum steepens from $E^{-2.7}$ to $E^{-3}$. This may be indicative of the fact that most cosmic accelerators in the galaxy have reached their maximum energy at that point \cite{101}. A second knee, representing a transition to heavier nuclei, was discovered by KASCADE-Grande around $8 \times 10^{16}$ eV \cite{102}. The “ankle” ($\sim 10^{18.5}$ eV) represents a further kink where the spectrum flattens, thought to be the transition from galactic to extragalactic sources \cite{103}.

As previously stated, cosmic rays are primarily composed of protons and other hadronic nuclei. Due to intergalactic magnetic fields, the origin of these charged particles is unknown since the arrival directions are completely scrambled. This leads to a nearly isotropic distribution of cosmic rays at Earth. However, a small anisotropy on the order of $10^{-4}$ at the $10^\circ$ scale is observed at TeV energies \cite{105}–\cite{107}, possibly due to a local magnetic field or a nearby source of cosmic rays.

There is still some debate about the exact acceleration mechanism of cosmic rays, but Fermi acceleration \cite{108} is the widely accepted mechanism. Fermi acceleration is a bottom-up scenario where the cosmic rays begin with low energy and are accelerated by magnetic fields in relativistic shock waves to observed energies. Particles gain energy as they cross back and forth between shocks and interact with the inhomogeneous magnetic fields. First order Fermi acceleration yields the desired nonthermal power law spectrum for cosmic rays:

$$\frac{dN}{dE} \propto E^{-\gamma}$$  \hspace{1cm} (2.1)

where $\gamma$ is typically equal to two. The difference between the power law predicted at the source ($E^{-2}$) and that measured at Earth ($E^{-2.7}$) can be explained by the “leaky-box” model of galactic diffusion \cite{109}. Propagation in that model relies on an energy-dependent escape rate from the galaxy that follows $E^{0.7}$.

The probability of a particle escaping the shock wave must be taken into account when considering the maximum energy to which it can be accelerated. When the particle’s Larmour radius approaches the size of the accelerator, it is very difficult to magnetically contain the cosmic ray in the acceleration region \cite{110}. The Larmour radius is given by

$$r_L \sim 110 \frac{E_{20}}{ZB_{\mu G}} \text{ kpc}$$  \hspace{1cm} (2.2)

where $E_{20} \equiv E/10^{20}$ eV, $Z$ is the atomic number (the cosmic ray has charge
Figure 2.1: Cosmic ray flux as a function of energy as measured by various experiments, from [104] with red arrows added. Below $\sim 10^{14}$ eV the flux of particles is large enough to be directly observed by satellites. Above that, ground-based detectors are needed for indirect detection. The cosmic ray spectrum follows a power law with kinks at the “knee” ($\sim 10^{15.5}$ eV) and the “ankle” ($\sim 10^{18.5}$ eV).
Ze), and $B_{\mu G}$ is the magnetic field in units of $\mu G$. Including the effects of the characteristic velocity $\beta c$ of the magnetic shocks produces the following general condition for the maximum obtainable energy of cosmic rays given specific source characteristics [111]:

$$E_{\text{max}} \sim 2 \beta c Ze B r_L$$

(2.3)

This condition is typically shown as a “Hillas diagram” [111], which was reproduced in [110] and is shown in Figure 2.2. This plot summarizes dimensional arguments for possible origins of cosmic ray acceleration. Very few sources reach $>10^{20}$ eV, and those that do are highly condensed objects with extremely large $B$ or are greatly extended.

### 2.2 Air Shower Physics

After traveling to Earth through the interstellar medium from their sources, cosmic ray and gamma ray primaries interact with nuclei in the atmosphere, producing extensive air showers (EASs). Pierre Auger is usually credited with discovering EASs; he observed a high rate of coincidence of particles between detectors located a few meters apart [112]. He later estimated that the incoming primary particle would have an energy as high as $10^{15}$ eV [113]. Since the discovery of EASs, much has been learned about their production and development in the atmosphere.

If the shower primary is a gamma ray, the first interaction in the atmosphere produces an electron-positron pair. These particles then lose energy by emitting photons as they decelerate via bremsstrahlung due to the magnetic fields of the nuclei in the atmosphere. The photons in turn create electron-positron pairs, and the cycle continues. The left-hand plot in Figure 2.3 shows a schematic of the evolution of a gamma ray-induced air shower. Particle creation continues until the average energy per particle drops below $\sim 80$ MeV. At this point, energy losses to ionization dominate over bremsstrahlung, and the number of particles has reached its maximum; this depth in the atmosphere is known as the shower maximum.

The right-hand plot in Figure 2.3 shows the development of a cosmic ray-induced air shower. After a hadron collides with a nucleus in the atmosphere, it typically creates pions (or kaons) that have large transverse momentum. These particles
Figure 2.2: Hillas diagram of possible particle acceleration sites based on size and magnetic field, from [110]. Assuming $\beta = 1$ in Equation 2.3, the diagonal lines represent lower limits for particle accelerators. Sources below the solid (dashed) red line cannot accelerate protons above $10^{21}$ eV ($10^{20}$ eV), and those below the green line cannot accelerate iron above $10^{20}$ eV.

then decay through the following interactions:

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu (\bar{\nu}_\mu)$$

$$\mu^\pm \rightarrow \bar{\nu}_\mu (\nu_\mu) + e^\pm + \nu_e (\bar{\nu}_e)$$

Muons have a lifetime of $\tau = 2.2 \mu$s but survive to reach the ground due to
Figure 2.3: Schematics of air shower interactions. **Left:** A gamma ray-induced shower. **Right:** A cosmic ray (hadron) induced shower.

... relativistic time dilation. Air shower muons are penetrating particles with large transverse momentum (a large fraction of their momentum is perpendicular to the direction of the primary particle) and are useful in distinguishing cosmic ray-induced air showers from those induced by gamma rays.

The EAS, whether initiated by a gamma ray or a hadron, travels as a nearly flat disc with a diameter of $\sim 100$ m and thickness of $\sim 1-2$ m, widening as the distance from the core increases. The central “core” position of the shower is located along the axis of the initial momentum vector of the primary particle. The curved shower front travels relativistically through the atmosphere, emitting Cherenkov radiation at an angle of $\theta_c = \cos^{-1} (1/\beta n)$, where $n$ is the index of refraction of air and $\beta$ is the ratio of the velocity to the speed of light.

Air shower development is typically described by the radiation length $X_0$, the distance it takes an electron to lose $1/e$ of its energy via bremsstrahlung [114]. This is equal to $7/9$ the mean free path for pair production. A particle interacting at the top of Earth’s atmosphere has approximately 30 radiation lengths worth of material to travel to reach sea level. Path lengths for air shower secondary particles are often scaled by $X_0$ and defined in units of g/cm$^3$ to remove the dependence on the density of the medium. Figure 2.4 shows a simulated air shower with a plot displaying the
atmospheric profile of the number of particles as a function of atmospheric depth (the path length). This distribution is well described by “approximation B” \cite{116}. Approximation B assumes that energy lost due to collisions is constant and so takes only radiation processes and pair production into account in the air shower energy distribution. If we plot the same distribution as in Figure 2.4 for the number of particles as a function of radiation length, we get Figure 2.5. The shower maximum is found at a depth of

$$X_{\text{max}} = X_0 \log \left( \frac{E_\gamma}{E_c} \right)$$  \hspace{1cm} (2.4)

where $X_0$ is the radiation length in air ($\approx 36.6 \text{ g cm}^{-2}$), $E$ is the energy of the
Figure 2.5: Air shower longitudinal development for different primary energies as a function of radiation length in the atmosphere, assuming energy lost due to collisions is constant (approximation B) [117]. The HAWC observatory at an altitude of 4100m covers $\sim 17.4$ radiation lengths and has an intrinsic lower energy threshold for one particle to reach the ground around 30GeV. Sea level is at $\sim 28$ radiation lengths.

primary, and $E_c$ is the critical energy when ionization energy exceeds that of radiation ($\approx 80$ MeV) [114]. Interestingly, after the shower maximum, the slopes of the lines in Figure 2.5 are independent of the primary’s energy. This means that the shower loses $1/1.65$ of its energy for each radiation length traveled: $E/E_\gamma = (1.65)^{-N}$, where $N$ is the number of radiation lengths beyond the shower maximum traversed [117]. The amount of energy reaching the ground is clearly dependent on both the energy of the primary particle and the amount of atmosphere the shower travels through. Of additional importance is the location of the first interaction in the atmosphere. The probability that a particle survives $N$ radiation lengths before interacting is $P(N) = \exp \left( -\frac{9}{7} N \right)$. This turns out to have the largest effect on the energy resolution obtainable by air shower detectors.
The EAS detector observes particles from the air shower that reach the ground while the IACT observes the Cherenkov radiation from the particles in the air shower.

2.3 Ground-Based Air Shower Detectors

As mentioned in Chapter 1.2.5, there are two main types of air shower detectors in the GeV-TeV energy range: Imaging Atmospheric Cherenkov Telescopes (IACTs) and Extensive Air Shower (EAS) detectors. The basic techniques for both types of detection are shown in Figure 2.6 and Figure 2.7 displays examples of each type of instrument.

An IACT is composed of one or more large mirrors with photomultiplier tubes (PMTs) arranged in the focal plane to collect Cherenkov light from EASs. IACTs are able to view the entire longitudinal development of a shower, which provides information needed to determine the energy and arrival direction of the EAS primary. This information gives IACTs excellent background rejection capabilities. Showers initiated by gammas and hadrons can be separated based on the shape of the shower image. The precise angular resolution of IACTs also helps the background rejection process since events that are not near a gamma-ray source can be discarded. These characteristics lead IACTs to have high sensitivity to known TeV sources. In fact, the Whipple Observatory, an IACT, made the first robust detection of TeV gamma rays from the Crab Nebula [120]. The Crab has become a standard candle in gamma-ray astronomy, despite recent observations of flares (e.g. [121]).
(a) VERITAS basecamp and array in Arizona [45]. The four telescopes detect Cherenkov light from air showers.

(b) Inside the Milagro pond [119] in New Mexico. The PMTs collect Cherenkov light emitted by the shower particles as they travel through the water.

Figure 2.7: Example IACT (top) and EAS detector (bottom).

While IACTs are excellent as means of probing source morphology and energy spectra, they are not able to operate all the time due to their optical nature. In addition, they cannot observe the whole sky at a time. IACTs are only able to view \( \lesssim 5\, ^\circ \) of the sky on clear, moonless nights. This greatly limits their capabilities of observing transients and detecting new or extended sources. These observation issues are countered with EAS detectors.

EAS observatories consist of an array of particle detectors spread out over a large area (the size of which depends on the energy scale being probed). Detectors typically have >90% duty cycle and \( \sim 2\,\text{sr FoV} \). The high duty cycle and wide FoV allow EAS observatories to perform unbiased whole-sky searches for localized and extended emissions as well as monitor the sky overhead for transient sources (without needing to move the detector to point at them).
Although IACTs can observe the Cherenkov radiation from the EAS particles passing through the air, EAS arrays cannot. EAS detectors observe Cherenkov radiation from the particles passing through the array faster than the speed of light in that material or collect light emitted by scintillators as the particles interact in the detector material. Figure 2.8 shows a diagram of the air shower as it travels through a detector. PMTs collect the light produced, and the timing of the hits becomes pivotal in reconstructing the direction of the shower. The shower plane can be determined from the hit times, which then can be pointed back to the direction of the origin of the primary of the shower. EAS detectors have worse angular and energy resolution than IACTs and a higher energy threshold (due to the attenuation length of particles being less than that of the Cherenkov light in air). Despite these disadvantages, gamma/hadron discrimination is possible with EAS arrays. Cosmic ray showers have more penetrating hadrons and muons that distinguish them from gamma ray-induced showers. The ability of EAS observatories to detect sources depends on the ability to reject background, the angular resolution, and the energy threshold. The HAWC observatory, discussed in the next chapter, is a second-generation EAS detector.

Figure 2.8: EAS detection technique, from [122]. PMTs collect Cherenkov light as the particles pass through the detector. The hit times are used to reconstruct the shower plane as seen in the lower left.
Chapter 3
The High Altitude Water Cherenkov Observatory

Located at 4100 m a.s.l. in Puebla, Mexico, the High Altitude Water Cherenkov Observatory (HAWC) primarily looks for VHE gamma-rays from extensive air showers. As the successor of Milagro, HAWC builds upon its experience in both the detector design and the hardware and software. Completed in 2015, HAWC consists of an array of 300 water tanks covering an area of about 20,000 m$^2$. Members of the bi-national HAWC Collaboration keep the detector running with a duty cycle >95%. Construction of the HAWC-prototype VAMOS began in 2010, and the complete array was inaugurated in March 2015. One of the advantages of the water tank array design over that of Milagro is that data can be taken throughout construction. Data analyzed in this dissertation were taken during several of the earlier construction phases with less than one third of the array complete. This chapter provides an overview of the construction and design of the detector.

3.1 Detector Location

The HAWC observatory is located on the saddle point between Sierra Negra, a 4600 m volcano, and Pico de Orizaba (Citlaltepetl), the highest peak in Mexico at 5610 m, both of which are inside Parque Nacional Pico de Orizaba, a Mexican national park. The park is on the border between the Mexican states of Puebla and Veracruz. Figure 3.1 shows the Google Earth [123] image of the location as well as a closer view of the HAWC detector. The latitude and longitude of the observatory are N 18°59′48″, W 97°18′34″, and its altitude is 4100 m above sea level. Figure 2.5
Figure 3.1: The Parque National Pico de Orizaba with the HAWC site.

shows that the higher altitude of HAWC allows $\sim 5x$ the number of particles to be observed as its predecessor Milagro. Another advantage to the location of HAWC is that one of the brightest sources in the TeV-sky, the Crab Nebula, transits directly overhead. Additionally, the Galactic center is 45° from zenith in the FoV of HAWC. The instantaneous FoV is $\sim 2$ sr and 2/3 of the sky is visible each day. The FoV of HAWC is shown in Figure 3.2 along with 157 sources from TeVCat.

HAWC is not the only scientific experiment in the area. The Large Millimeter Telescope (LMT) was built on the summit of Sierra Negra and inaugurated in 2006. The infrastructure in place due to the LMT construction was an appeal of the choice of the site for HAWC. In addition to the existing infrastructure, the weather of the site is favorable for the operation and construction of HAWC. The median temperature at Sierra Negra is $4.5^\circ$ C, only going below freezing $\sim 10\%$ of the time in winter. This means that it does not get cold enough to freeze the water in the HAWC tanks. Severe weather does occasionally hit the HAWC site, and earthquakes do occur. Pico de Orizaba is an active volcano, but its last eruption was in 1846. The probability of a minor explosive event is estimated at 0.013 per year. Endurance to high winds and seismic events was incorporated into the design of HAWC.
3.2 Water Tanks and PMTs

As mentioned in the introduction, the complete HAWC array has 300 water tanks with three $8''$ photomultiplier tubes (PMTs) and one $10''$ high quantum efficiency PMT. The PMTs are used to detect the particles that compose an extensive air shower at ground level. Charged particles moving through water in the tanks generate Cherenkov light that is captured by the PMTs. Energetic photons traveling through the water in the tanks will typically Compton scatter, also resulting in Cherenkov light. The Cherenkov light is emitted as a cone with an opening angle of $41^\circ$, shown in the schematic in Figure 3.3 of a particle interacting in a HAWC tank. The two types of HAWC PMTs are pictured in Figure 3.4 with the $10''$ PMT on the left and the $8''$ PMT on the right. The 900 $8''$ Hamamatsu PMTs used in the water tanks are those from Milagro, refurbished for use in HAWC. The
Figure 3.3: Schematic of EAS particle interacting in a HAWC tank. The Cherenkov angle $\theta_c$ is $41^\circ$ in water.

When particle in an air shower pass through the water in the HAWC detectors, they make dim flashes of blue light, a process called Cherenkov Radiation. To record these flashes of light, HAWC scientists use very sensitive detectors called Photomultiplier Tubes (PMTs). These devices are able to record single photons of light striking their surface by an amplification process similar to old vacuum tubes. HAWC consists of 1200 of these sensors with 4 in the bottom of each water tank.

Photomultiplier Tubes

Figure 3.4: HAWC 10" and 8" photomultiplier tubes. Each PMT is attached to a PVC pipe to waterproof the electronics in the tube.

PMTs are placed at the bottom of each tank, upward facing to measure the prompt Cherenkov light. The three 8" PMTs are arranged symmetrically about 1.6 m from the centrally located 10" PMT.

Each tank, made of five curved rings of galvanized steel, is 7.3 m in diameter and 5 m tall. The top is covered by a military-grade opaque canvas roof to protect it from
weather. The 300th HAWC tank is shown behind the local work crew in Figure 3.5. Inside the tank, a dark plastic bladder is filled with \( \sim 200,000 \text{L} \) of purified water to a depth of 4.5 m. The non-reflective bladder is designed to absorb scattered light to reduce noise and the late tail in the PMT timing distribution. There is enough water above the PMTs to cover approximately 10.5 radiation lengths of photons (\( \sim 4 \text{m} \)). The water primarily comes from a well down the mountain in Esperanza although a small fraction from a nearby stream. It takes 10 trips with a 20,000 L truck to fill one tank. The water is filtered and sterilized using a UV light source with a resulting attenuation length between 7-17 m depending on the date when the tank was filled and the source of the water. The transmission length is repeatedly tested using a laser and a 100 cm glass water-filled tube. Approximately 60 million liters of fresh filtered water are used in the HAWC array.
3.3 Electronics and Data Acquisition

Not only are the PMTs from Milagro reused by HAWC, but most of the electronics are as well. HAWC data are collected by two data acquisition systems (DAQs). The main DAQ records individual events created by air showers large enough to simultaneously illuminate a significant fraction of the HAWC array. The secondary DAQ, the scaler system, operates in a PMT pulse counting mode [128], which is sensitive to gamma ray and cosmic ray transient events that produce a sudden increase or decrease in counting rates with respect to those produced by atmospheric showers and noise. The GRB results presented in this dissertation use data from the main DAQ, which is described below.

The electronics for HAWC are stored in the counting house at the center of the HAWC array. Cables from each tank are run through spark gap boxes that lead into the counting house. The spark gaps prevent large surges of voltage from potentially damaging the electronics. After the spark gaps, the cables come up through the floor of the counting house and connect to the back of the electronics racks. Figure 3.6 shows a front-end-board (FEB), time-to-digital converters (TDCs), and one of the electronics racks in the counting house. Each FEB is connected to sixteen PMTs, providing power to the tubes and processing signals from the PMTs. The FEBs then send the signal to the TDCs, which convert the digital pulse into a hit arrival time and charge from the PMT. The technique used for this conversion is known as the Time-Over-Threshold (TOT) method [129].

TOT measures the amplitude of a hit from a PMT by quickly storing charge in a capacitor, which is then discharged slowly via a load resistor. The decay time of the resistor is directly related to the amplitude (charge) of the PMT pulse. The top plot in Figure 3.7 shows an example of this. Two discriminator thresholds are defined to ensure an accurate measurement of the charge from the TOT for a wide range of pulse amplitudes. The bottom plot in Figure 3.7 illustrates how the TDC converts the decaying pulse amplitude into leading and trailing edges, which are recorded by the DAQ with ≈0.5 ns accuracy. Pulses with high charge will have four edges (threshold-crossings) while those that do not have enough charge to cross the high threshold will only have two. Characteristic relationships exist between edge rise times, fall times, low TOT, and high TOT that allow us to distinguish a single large pulse from pairs of small pulses in close coincidence.
Individual events are time stamped with a GPS clock. However, the rise time of the pulse is dependent on the amplitude of the charge. This slewing time is corrected for during calibration. Calibration uses a laser pulse with known time and charge to simulate an event. From this information, actual edge data is converted into times and charges.

In HAWC, the sources of PMT noise are uncorrelated hits from ambient radioactivity in the water and in materials composing PMTs and tanks as well as dark noise from the PMTs. Correlated sources of noise in PMTs, because they cause several PMTs to fire simultaneously, are secondary gamma-rays, electrons and muons from low-energy hadronic cosmic ray showers. Measurements indicate that the total noise hit rate in each PMT is $\sim 10\text{kHz}$.

The main DAQ system runs a simple multiplicity trigger (SMT) to record air shower events. The SMT counts the number of hit PMTs in a specific trigger.
Figure 3.7: Simulation of a PMT pulse as seen by HAWC electronics. The top plot shows the pulse from the PMT quickly charging a capacitor, which then decays with a characteristic time. The rise time of the pulse is amplitude dependent, and therefore the hit time must be corrected for this slewing. Two discriminator levels are set in the FEBs at 1/4 and 5 photoelectrons to separate low-charge and high-charge pulses. The TDC records the time the pulse crosses each threshold and stores the edges seen in the bottom plot. The TOT from the edges is converted into charge of the pulse. Source: S. Benzvi.
Table 3.1: Trigger information for various HAWC construction phases.

<table>
<thead>
<tr>
<th>Date</th>
<th>Construction Phase</th>
<th>SMT</th>
<th>Trigger Time Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early May 2013</td>
<td>HAWC-27</td>
<td>10</td>
<td>150 ns</td>
</tr>
<tr>
<td>Late May 2013</td>
<td>HAWC-48</td>
<td>12</td>
<td>150 ns</td>
</tr>
<tr>
<td>Early July 2013</td>
<td>HAWC-88</td>
<td>15</td>
<td>150 ns</td>
</tr>
<tr>
<td>Late July 2014*</td>
<td>HAWC-78</td>
<td>17</td>
<td>150 ns</td>
</tr>
<tr>
<td>Early August 2014*</td>
<td>HAWC-80</td>
<td>17</td>
<td>150 ns</td>
</tr>
</tbody>
</table>

† The number represents the instrumented, active tanks at the time.

* A lightning incident at the site in mid-July damaged some of the detector so fewer tanks were active at this time.

Figure 3.8: Schematic overview of the HAWC data acquisition and online processing system [130]. Electronics components of the data acquisition system are to the left of the vertical gray line. On the right are the software components of the online processing system. The network switch connecting the readout computers with the reconstruction farm is also shown. Triggering is done in the “Reconstruction Clients.” Different components of the online-processing are allowed to run on different machines.
level; all of the triggering is done in real time with software. This method allows greater flexibility within the trigger and reconstruction algorithms possible with HAWC. Currently, the event rate is reduced to 20 kHz, or a data rate of $\sim 0.02 \text{ GB/s } (2 \text{ TB/day})$ after the trigger is applied to the raw data.

The fast online reconstruction capability means that real time analysis is possible. HAWC will also be able to send quasi-real time alerts (e.g. via the GRB Coordinate Network) that can trigger multi-wavelength campaigns. The means to alert the community is currently in development. Interestingly, the VERITAS IACT is geographically located close to HAWC, and alerts issued by HAWC may be followed by VERITAS as well as other IACTs.
Chapter 4
Event Reconstruction and Data Selection

In Chapter 3 we discussed how air showers trigger the HAWC detector, creating events to be analyzed. Having identified air shower events in data, we now describe, in Section 4.1, the event reconstruction algorithms, including the core fit and the angular fit as well as the gamma/hadron separation parameters. After events are properly reconstructed, we verify no issues from external factors exist in the data used in this analysis by performing checks to ensure data quality, a procedure discussed in Section 4.2.

4.1 Reconstruction Algorithms

The goal of the reconstruction is to take the physical location and timing information from PMTs hit in an air shower event and use it to determine the location and arrival direction of the primary particle. The geometrical reconstruction of the events yields the shower core location on the ground and the relative arrival direction of the primary. Once these are determined, we can separate gamma-ray signal from hadronic background using specific parameters from the reconstruction. For completeness, we describe three background rejection parameters employed in HAWC analyses although only one is used in this dissertation due to discrepancy between the data and Monte Carlo distributions of the specific data set. First, we will discuss the fit parameters and then show how they are used to separate signal events from background ones.
4.1.1 Core Fit Position

The charge information of the hits in an event is used to reconstruct the core position of the air shower. We have two primary core finding algorithms, one of which is used to seed the other, more complicated one. To determine an appropriate seed for the fit, we begin by using a center-of-mass core fitter (COM), shown in Equation 4.1

\[
x_{\text{com}}, y_{\text{com}}, z_{\text{com}} = \frac{\sum x_i Q_i}{\sum Q_i}, \frac{\sum y_i Q_i}{\sum Q_i}, \frac{\sum z_i Q_i}{\sum Q_i}
\]

(4.1)

where \(x, y, z\) are the position of the hit PMT in the detector, \(Q_i\) is the charge of the hit, and the sum is over all hits in an event. This is a simple, fast algorithm that places the core on the HAWC array as a first guess position for the next fitter.

Following the COM core fit, we use a \(\chi^2\) minimization process to fit the lateral distribution of the shower and determine the shower core position. The lateral distribution function describes the density of the charged particles in the air shower as a function of the radius from the axis of the primary particle. Minimizing the fit to this function yields the expected number of photoelectrons \(E_{PE}\). It follows that \(\chi^2\) is defined as

\[
\chi^2 = \sum_{i=1}^{n} \frac{(O_{PE_i} - E_{PE_i})^2}{\sigma^2}
\]

(4.2)

where \(O_{PE_i}\) is the observed number of photoelectrons, \(E_{PE_i}\) is the expected number of photoelectrons from the fit, \(\sigma = \sqrt{E_{PE_i}}\), and \(n\) is the number of hits in the event.

We use a modified Nishimura-Kamata-Greisen (NKG) function \[131,132\] to fit the lateral distribution of the air shower. This function has been found to describe electromagnetic air showers well \[114\]. The NKG function is given by the following:

\[
\rho_{\text{NKG}}(r, s, N) = \frac{N}{2\pi R_{\text{mol}}^2} \frac{\Gamma(4.5 - s)}{\Gamma(s) \Gamma(4.5 - 2s)} \left( \frac{r}{R_{\text{mol}}} \right)^{s-2} \left( 1 + \frac{r}{R_{\text{mol}}} \right)^{s-4.5}
\]

(4.3)

where \(N\) is the amplitude of the fit and \(r\) is the distance from the hit position to the core of the shower. The shower age \(s\) parametrizes the development of the shower such that when \(s = 1\), the number of particles in the plane of the shower reaches its maximum. \(R_{\text{mol}}\) is the Molière radius, which characterizes the spread of low-energy electrons by multiple scattering. More specifically, it is the radius of a cylinder containing roughly 90% of the secondary particles produced in the shower.
\( R_{\text{mol}} \) is given by
\[
R_{\text{mol}} = X_0 \frac{E_s}{E_c \rho}
\] (4.4)

where \( X_0 \) is the radiation length of electrons in air and \( E_s \) is the electron scattering energy. The critical energy \( E_c \) is that at which an electron loses equals amounts of energy per unit radiation length by ionization and Bremsstrahlung. Finally, the air density at the height of the observation is \( \rho \). For HAWC, we use the following values to determine \( R_{\text{mol}} \),
\[
R_{\text{mol}} = \left(37.15 \text{ g/cm}^2\right) \left(21 \text{ MeV}\right) \left(84.4 \text{ MeV}\right) \left(7.4 \times 10^{-4} \text{ g/cm}^3\right) = 124.21 \text{ m}
\] (4.5)

The modification to the NKG function comes in the form of an extra factor of \( R_{\text{mol}}/r \) to change from particle number density to energy density since we measure charge instead of number of particles. The shower age \( s \), the amplitude of the energy density function, and the core position \( r = \sqrt{x^2 + y^2} \) are fit during the \( \chi^2 \) minimization. Thus, we determine the coordinates of the shower core position for the event, which is needed for the angular fit.

An example of the fit core positions for HAWC-49 data is shown in Figure 4.1. One can see that most, but by no means all, of the shower cores are on the array. In Figure 4.2, we demonstrate the accuracy of the NKG core fit as the difference between the true core position from Monte Carlo and the reconstructed core position (\( \text{delCore} \)). The distribution is shown for gamma-ray air shower cores that were reconstructed within 2.77° of the true source position. The simulated GRB is \( \sim 30° \) from zenith with an \( E^{-2.63} \) power-law spectrum and no energy cutoff applied. Of the events shown, \( \sim 35\% \) were reconstructed within 20 m of the actual shower core position.

### 4.1.2 Angular Fit Arrival Direction

Similar to the core fit, the angular fit has two stages: (1) a Gaussian plane fit to the hit times and (2) a likelihood fit using the plane fit result as a seed.

The plane angular fitter performs a least squares fit to a plane defined by the time of each hit in the event.
\[
\chi^2 = \sum_{i=1}^{n} w_i \left(\hat{i}x_i + \hat{j}y_i + \hat{k}z_i + ct_i - ct_0\right)^2
\] (4.6)
Figure 4.1: Reconstructed core positions for HAWC-49 data. The color scale indicates the number of shower events reconstructed at that position in the HAWC array. Most of the events are reconstructed directly on top of the tanks in the array.

Figure 4.2: NKG core fit error, the difference between the reconstructed core and true core position (delCore). The distribution contains gamma-ray events that reconstructed within 2.77° of the true source position. Approximately 35% of the events were reconstructed within 20 m of the actual shower core position. The simulated HAWC-49 GRB is 29° from zenith with an $E^{-2.63}$ spectrum and no EBL absorption applied.
where \( n \) is the number of hits in the event, \((x, y, z)\) is the position of the hit in the timing plane that travels at the speed of light \( c \) during a time \((t - t_0)\), and \( w \) is a weight applied to each hit at each iteration of the fitting algorithm. For example, the fit is refined by iterating over hit charge and time, throwing out hits to isolate the shower plane. The weight contains this information. Sampling and curvature corrections are applied to individual hit times prior to the fit to account for intrinsic detector and air shower characteristics. The sampling effect corrects for the fact that when more PEs are observed in a hit, the first PE is more likely to be observed at an earlier time while the curvature correction accounts for the difference in the actual hit time and the expected hit time based upon the angular location and distance from the shower axis. The shower curvature was discussed in Chapter 2. The plane fit is “Gaussian” because the time residual probability density function (PDF) is modeled in time as such with parameters based on the hit charge and distance from the reconstructed core. This is a quick, analytic fit.

The likelihood angular fit uses the full time residual PDF and all the hits in the event, numerically maximizing

\[
\mathcal{L}(\theta, \phi, t_0) = \prod_{i=1}^{n} P(t_i|\theta, \phi, t_0)
\]  

(4.7)

where \( \theta \) and \( \phi \) are the zenith and azimuth angles respectively. Arrival time distributions are taken from Monte Carlo relative to the propagation plane of the primary photon and binned in a 3D histogram of time residual, radius from the true core, and the logarithm of the charge. The histogram is smoothed along the three axes and forced to be monotonically decreasing along the time axis from the peak arrival time. The likelihood angular fit is more computationally intensive than the plane angular fit but more accurate.

In Figure 4.3, we show the local arrival directions of reconstructed events from the likelihood fit in an equal-area 2-D plot along with plots of the local zenith and azimuth angular distributions in 1-D. The zenith distribution, with a maximum between 20°–30°, is typical given the amount of atmosphere and FoV of the detector. The azimuth distribution reflects the geometry of the array at the time (Figure 4.1). The angular error of the likelihood fit is given in Figure 4.4 for the same burst as described in Figure 4.2. The simulated burst is for the same detector configuration as in Figure 4.1 thus it does not reflect the angular resolution of the full HAWC-300...
Figure 4.3: Left: Reconstructed equal-area local angular distribution for HAWC-49 data. Right: Zenith (top) and azimuth (bottom) angular distributions.

Figure 4.4: Angular fit error, the difference between the reconstructed angular position and true angular position (\(\text{delAngle}\)). More than 50\% of the events were reconstructed within 2.77° of the actual shower angular position for this HAWC-49 GRB. The simulated gamma-ray source has a zenith angle \(\theta_{\text{true}} = 29°\) and \(E^{-2.63}\) spectrum (no EBL absorption is simulated).
detector. For this HAWC-49 burst, more that 50% of the events were reconstructed < 3° from their true direction.

### 4.1.3 Gamma/Hadron Separation Parameters

The HAWC background rejection method is based on three parameters: compactness, core fit reduced $\chi^2$, and angular fit reduced $\chi^2$. Compactness is the ratio of the number of PMTs hit in the event ($n\text{Hit}$) to the charge of the single largest PMT hit at a distance of at least 40 m from the shower core ($C_xPE$). Hadronic air showers are typically characterized by smaller values of $n\text{Hit}/C_xPE$ than gamma-ray-induced showers because of their larger lateral size, lumpiness and the presence of off-axis muons. During reconstruction, additional cuts on the hit selection are applied prior to finding $C_xPE$ to ensure that the hit with the maximum charge beyond 40 m from the core is in the shower plane. The core fit reduced $\chi^2$ and angle fit reduced $\chi^2$ parameters are from the NKG core fitter and the plane angular fitter respectively. For both these parameters, hadrons are more likely to have worse fits, i.e. larger reduced $\chi^2$ values. The core $\chi^2$ cut is the most effective for reducing the background while keeping the greatest number of signal events, further discussed in Chapter 5. Signal and background distributions for these three parameters are also shown in Chapter 5.

Figure 4.5 shows the event display for several HAWC-300 simulated events, gamma-ray showers are shown on the left and proton showers are on the right. The energy of the primary particle increases from top to bottom. The color scale is the time of each hit, i.e. the hits arrive in time from blue to red. The size of the hit circle represents the charge of the hit with larger radii indicating a higher charge. The shower core and angle positions are shown as stars with attached lines for the location and arrival direction respectively. The true position is in green while the reconstructed position is in red. Not only can we see how well the core and angular direction fits work, but we can also see the difference in charge distribution for signal and background showers exploited by the compactness parameter. The black dashed line indicates the exclusion radius 40 m from the reconstructed core position with the bold red circle beyond it showing the PMT with the highest charge used in the compactness calculation. It can clearly be seen that the proton showers have

---

1 A similar cut was used in Milagro 49.
Figure 4.5: HAWC event display. Simulation of gamma-ray (left) and proton (right) air shower events for the HAWC-300 configuration. Shower energy decreases from the top to the bottom. Colors indicate hit times with blue being earlier and red later. The size of the circle shows the amount of charge in the hit. The reconstructed core position (red star) and true core position (green star) are shown with a corresponding line indicating the reconstructed arrival direction (green) and the true arrival direction (red). The dashed black circle is 40 m from the reconstructed core. The bold red circle beyond the dashed black line represents the PMT used in the compactness calculation and is identified by the text in the lower right corner. Proton showers have larger charged hits beyond 40 m due to the shower clumpiness while the gamma-ray shower charge tails off smoothly from the core.
larger, more isolated hits compared to the gamma-ray showers.

4.2 Data Quality Cuts

We ensure that problems with the electronics, weather, etc. do not cause any false discoveries or otherwise affect the analysis by verifying the data quality prior to searching for GRBs. The full analysis described in Chapter 6 is designed to identify GRBs based on the time distribution of their events, not their angular distribution. Keeping this in mind, two separate checks on the data before and after the triggered GRB time window are performed. The overall, full-sky rate is tested for gaps in signal or any wildly obvious problems, for example if half the PMTs stopped receiving signals at once. We also look at the stability of the local angular distribution of events. This is particularly important for the background estimation technique described in Section 6.6. In the following sections, we show example plots for the checks run on the data for GRB 130504C. The rest of the data quality plots for this thesis are given in Appendix A.

4.2.1 Trigger Rate Abnormality Check

To verify the trigger rate around the time of the GRB, we use data ±2 h from the GRB $T_0$ and bin it in one-second intervals. We then determine the symmetric moving-average for 5 s bins such that the rate is

$$MA(i) = \frac{1}{2N} \sum_{j=i-N}^{j=i+N} C(j)$$

where $MA(i)$ is the moving average rate for each bin $i$, $N = 2$ to get 5 s average rates, and $C(j)$ is the number of events (counts) in the one-second time bin. Figure 4.6 shows the one-second time bin rate in blue and the corresponding 5 s average rate in red for GRB 130504C. For reference, the data used during background estimation is shaded in gray, and the data searched during the likelihood analysis is shaded in green. Both of these time windows are discussed in later chapters. We then take the difference between the two curves to get the residuals between the one-second rate and the average rate. We look for deviations from the average rate that are greater than 10% (based upon deviations seen in known poor quality data). If the
Figure 4.6: Data rate relative to the GRB trigger time $T_0$ for GRB 130504C. The one-second rate is shown in blue and the five-second symmetric moving average rate is in red. No gaps or problems are evident. For reference, the data used during background estimation is shaded in gray, and the data searched during the likelihood analysis is shaded in green. Both of these are discussed in later chapters.

If the difference is greater than 10%, we consider the data suspect and in need of further investigation. The rate residuals for GRB 130504C are shown in Figure 4.7.

We also found one additional rate check necessary to identify problematic data. By looking at the data in 10 ms bins instead of 1 s we can determine if problems with the DAQ software occur. For example, GRB 140723A closely followed a lightning strike to the detector, which briefly damaged the DAQ. During the period of time around GRB 140723A, the clock was jittery and data occasionally received the wrong time stamp. Figure 4.8 shows the instability of the rate that made the GRB unable to be analyzed. For comparison, Figure 4.9 shows a standard distribution (for GRB 140810A). None of the other GRBs in this data set had the same issue as GRB 140723A.
Figure 4.7: Residuals for the rate distributions for GRB 130504C. The percent difference between the blue and red lines in Figure 4.6 is shown. If the difference is greater than 10%, the quality of the data is suspect.

4.2.2 Local Angular Distribution Stability

The local angular distribution stability is checked by creating histograms of the reconstructed zenith and azimuth angles for approximately every two minutes of data. We then perform a $\chi^2$ test [133] to check the deviation between the distributions. If the total number of events in the first and second histograms are $N$ and $M$ respectively, then $N = \sum_{i=1}^{r} n_i$ and $M = \sum_{i=1}^{r} m_i$, where $r$ equals the total number of bins and $n_i$ and $m_i$ are the number of events in bin $i$ in each histogram. $\chi^2$ then equals

$$\chi^2 = \frac{1}{MN} \sum_{i=1}^{r} \frac{(Mn_i - Nm_i)^2}{n_i + m_i} \quad (4.9)$$

We use this $\chi^2$ as a quality parameter to test the stability of the local angular distributions over time. The reduced $\chi^2$ value is required to be below two. Known bad-quality data, e.g. contaminated by laser calibration, yield large values of reduced $\chi^2$. The cut is chosen by inspection of these values. Figure 4.10 shows the
Figure 4.8: Data for GRB 140723A in 10 µs bins (blue) and the 50 µs moving average rate (red). The jitter of the clock is evident in the outliers from the standard rate. This GRB was not able to be analyzed.

Figure 4.9: Data for GRB 140810A in 10 µs bins (blue) and the 50 µs moving average rate (red) for comparison. There is not a wide range in the rate.
angular reduced $\chi^2$ distributions for the zenith and azimuth angles in two-minute intervals for GRB 130504C. All points reside below the quality cut. It is expected that the zenith distribution has a wider spread in $\chi^2$ than azimuth because there is more variation in theta due to the breathing of the atmosphere and the phi distribution is basically flat.

Figure 4.10: Reduced $\chi^2$ for zenith (top) and azimuth (bottom) distributions as a function of time relative to the GRB trigger $T_0$, comparing two-minute intervals of data for GRB 130504C. The stability cut requires $\chi^2/ndf < 2$. Again, the data used for the background estimation is shaded in gray while the data searched during the likelihood analysis is shaded in green.
4.3 Reconstruction Quality Cuts

In addition to checking the rate and angular distribution, we also use standard reconstruction quality cuts. For example, the reconstruction must pass the angular direction fit to be considered well reconstructed. The cut removes 40% of the events for a small detector and less than 15% for some of the larger construction phases. The final quality cut is on the reconstructed zenith angle $\theta$. We found that applying a cut of $\theta < 45^\circ$ made the discrepancy between data and the Monte Carlo simulations smaller. For GRB 130504C, this removes <50% of the total data while for a larger detector it removes $\sim$15-20%.
Chapter 5
Monte Carlo Simulations

Monte Carlo simulations are essential for understanding the HAWC detector and data. It is important to compare data and Monte Carlo, especially with regard to flux measurements from sources. We use the Monte Carlo to convert event counts into gamma-ray flux, and the accuracy of this conversion is determined by the difference between data and Monte Carlo. The more accurate our simulations, the smaller this source of systematic error.

In this chapter we will discuss the particulars of the HAWC Monte Carlo production in Section 5.1, compare data to Monte Carlo in Section 5.2, and show the predicted sensitivity of HAWC to GRBs in Section 5.3.

5.1 Monte Carlo simulation

The first step in the HAWC Monte Carlo chain throws air showers produced with CORSIKA [134] over the detector array. The detector response is then modeled using a Geant4-based simulation package hawcsim [135]. The full 300 tank detector is simulated (see Figure 5.1). To obtain simulation of subsets of HAWC-300, such as HAWC-30, we can mask out PMTs during the reconstruction stage. Each simulated tank contains three 8” PMTs and one central, high quantum-efficiency 10” PMT. The whole array is placed at an altitude of 4100 m. The same event reconstruction procedure used for data is then applied to the simulated events after the addition of noise and application of the trigger to the Monte Carlo. The reconstruction algorithms were described in Section 4.1.
CORSIKA primaries are drawn from the following distribution:

$$\frac{dN}{dE \, dA \, d\Omega} \propto \frac{E^{-2} \cos(\theta) \sin(\theta)}{r}$$  \hspace{1cm} (5.1)$$

where $E$ is the energy of the primary particle, $r$ is the distance from the center of the array, and $\theta$ is the zenith angle. The spatial distribution of showers is peaked at the detector center, decreasing with distance as $1/r$. This ensures that more showers fall on the array than is purely physical. The simulated energy spectrum for all primary particles is proportional to $E^{-2}$ to produce more high-energy events. These nonphysical distributions are compensated for in the re-weighting procedure described in Section 5.1.1. The zenith distribution follows the form $\cos(\theta) \sin(\theta)$,
where the \( \sin(\theta) \) factor describes the larger available phase space for events with higher values of \( \theta \) and the \( \cos(\theta) \) factor reflects the fact that we expect fewer events from higher zenith angles due to the decrease in available detector area.

In addition to gamma-ray induced air showers, multiple nuclear groups are simulated for hadronic showers, including p, He, C, O, Ne, Mg, Si and Fe. As previously stated, in all cases the generated energy spectrum follows a power law \( E^{-2} \). The re-weighting procedure applied afterward scales the particle species’ fluxes to observed experimental energy spectra.

### 5.1.1 Event rate computation

The computation of event rates implies a re-weighting of the simulated events according to a chosen flux model. First, we will discuss the general weighting function for an isotropic source, such as cosmic rays. Then, we show how that procedure is modified for a simulated GRB. The following description draws heavily on J. Pretz’ internal HAWC memo [136].

#### 5.1.1.1 Isotropic Hadronic Weights

Our background hadronic events must be isotropically weighted to their observed energy spectra. We begin by describing the total number of simulated events \( N_{\text{thrown}} \) by

\[
N_{\text{thrown}} = \int \mathcal{T}(E, r) \cos(\theta) \, dA \, d\Omega \, dE,
\]

where \( \mathcal{T}(E, r) \) is proportional to the differential energy and radial parts of the distribution function that we use to throw events (Equation 5.1). To account for the nonphysical nature of the distribution, we must determine the normalization \( \mathcal{T}_0 \) of \( \mathcal{T}(E, r) \):

\[
N_{\text{thrown}} = \mathcal{T}_0 \int_E \int_\Omega \int_A \frac{E^{-2}}{r} \cos(\theta) \\ dA \, d\Omega \, dE
= \mathcal{T}_0 \int_E \int_\Omega \int_0^{2\pi} \int_{R_i}^{R_f} \frac{E^{-2}}{r} \cos(\theta) \, r \\ dr \, d\phi' \, d\Omega \, dE
= \mathcal{T}_0 \frac{2\pi}{2} (R_f - R_i) \int_E \int_0^{2\pi} \int_{\theta_i}^{\theta_f} E^{-2} \cos(\theta) \sin(\theta) d\theta \, d\phi \, dE
= \mathcal{T}_0 \frac{2\pi}{2} (R_f - R_i) 2\pi \left( -\frac{1}{2} \right) (\cos^2(\theta_f) - \cos^2(\theta_i)) \int_{E_i}^{E_f} E^{-2} \, dE
\]
\[
N_{\text{thrown}} = \mathcal{T}_0 \cdot 2\pi (R_f - R_i) \pi \left( \cos^2(\theta_i) - \cos^2(\theta_f) \right) \left( -E_f^{-1} + E_i^{-1} \right)
\]

\[
\mathcal{T}_0 = \frac{N_{\text{thrown}}}{2\pi (R_f - R_i) \cdot \left( \frac{1}{E_i} - \frac{1}{E_f} \right) \cdot \pi \left( \cos^2(\theta_i) - \cos^2(\theta_f) \right)}
\]

It follows then that in our case, the normalized distribution for \( \mathcal{T}(E, r) \) is

\[
\mathcal{T}(E, r) = \frac{N_{\text{thrown}}}{2\pi (R_f - R_i) \cdot \left( \frac{1}{E_i} - \frac{1}{E_f} \right) \cdot \pi \left( \cos^2(\theta_i) - \cos^2(\theta_f) \right) \cdot \frac{E^{-2}}{r}}.
\]

with standard ranges for \( R, E, \) and \( \theta \). HAWC air showers are thrown up to 1000 m from the center of the array and 75° from zenith. The energy range varies for each particle but is approximately 5 GeV/nucleon to 2 PeV/nucleon.

Having accounted for the nonphysical simulation distributions, we now must weight the events to the desired cosmic-ray flux spectra. We can approximate the weighted sum of events as

\[
\sum_{i=0}^{N_{\text{thrown}}} w(E_i, r_i) \approx \int w(E, r) \mathcal{T}(E, r) \cos(\theta) dA d\Omega dE
\]

where \( E_i \) and \( r_i \) are the true energy and thrown core distance of the \( i \)th event in the simulation set and \( w(E, r) \) is the flux weighting function. That is, the sum over weighted simulated events is equal to the integral of some function over \( E, r, \) and \( \theta \). Given an isotropic differential flux \( \Phi_{iso}(E) \), \( dN/dt \) is

\[
\frac{dN}{dt} = \int \Phi_{iso}(E) \cos(\theta) dA d\Omega dE
\]

If we define \( w(E, r) \) as:

\[
w(E, r) = \Phi_{iso}(E)/\mathcal{T}(E, r)
\]

then the event rate can be approximated by a sum over the thrown simulated events:

\[
\frac{dN}{dt} \approx \sum_{i=0}^{N_{\text{thrown}}} w(E_i, r_i)
\]
This gives us a final weight function of the form:

\[ w(E, r) = \frac{2\pi^2}{N_{\text{thrown}}} (R_f - R_i) \left( \frac{1}{E_i} - \frac{1}{E_f} \right) \cdot (\cos^2(\theta_i) - \cos^2(\theta_f)) r E^2 \Phi_{\text{iso}}(E) \]  

(5.8)

For the isotropic cosmic rays, the spectra of hadronic cosmic rays are set according to CREAM measurements \[137\]. For each nuclear group the spectrum is given by a broken (Equation 5.9) or double-broken power law (Equation 5.10):

\[
\Phi_{\text{iso}}(E) = \begin{cases} 
\Phi_0 \left( \frac{E}{E_{\text{norm}}} \right)^{\gamma_1} & : E < E_{B_1} \\
\Phi_0 \left( \frac{E_{B_1}}{E_{\text{norm}}} \right)^{\gamma_1-\gamma_2} \left( \frac{E}{E_{\text{norm}}} \right)^{\gamma_2} & : E \geq E_{B_1}
\end{cases}
\]  

(5.9)

\[
\Phi_{\text{iso}}(E) = \begin{cases} 
\Phi_0 \left( \frac{E}{E_{\text{norm}}} \right)^{\gamma_1} & : E < E_{B_1} \\
\Phi_0 \left( \frac{E_{B_1}}{E_{\text{norm}}} \right)^{\gamma_1-\gamma_2} \left( \frac{E}{E_{\text{norm}}} \right)^{\gamma_2} & : E_{B_1} \leq E < E_{B_2} \\
\Phi_0 \left( \frac{E_{B_2}}{E_{\text{norm}}} \right)^{\gamma_1-\gamma_2} \left( \frac{E}{E_{\text{norm}}} \right)^{\gamma_2-\gamma_3} \left( \frac{E}{E_{\text{norm}}} \right)^{\gamma_3} & : E \geq E_{B_2}
\end{cases}
\]  

(5.10)

where \( \Phi_0 \) is the differential flux at reference energy \( E_{\text{norm}} \), \( \gamma_i \) is the spectral index, and \( E_{B_i} \) is the energy at which the break in the spectrum occurs. The simulated values are listed in Table 5.1.

To get the background rate in a small circular bin on the sky, we need to multiply \( \Phi_{\text{iso}}(E) \) by the bin size:

\[
\Phi(E) = 2\pi \Phi_{\text{iso}}(E) (1 - \cos(\Delta))
\]  

(5.11)

where \( \Delta \) is the bin radius.

5.1.1.2 GRB Point Source Weights

The difference between the isotropic weights described in the previous section and GRB point source weights is that the GRB only emits signal at a specific point \( \theta_B \) in the sky for a specific time \( T_B \). We make a simplifying assumption that the GRB does not transit the sky during the burst, i.e. the entire duration is spent at one zenith angle, \( \theta_B \). However, only a limited number of gamma-ray showers are thrown at a specific zenith angle in the simulation. To improve statistics, we actually use a small band \( (\theta_1 \leq \theta_B \leq \theta_2) \) rather than a delta function at the burst zenith. Therefore, the weight function, which now includes the parameter \( \theta \), is
Table 5.1: The parameters of hadronic cosmic ray spectra used in HAWC simulation (Equations 5.9 and 5.10) and the energy limits for the generation of air showers. The flux normalization $\Phi_0$ is given in GeV$^{-1}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$. The spectra correspond to CREAM measurements [137].

<table>
<thead>
<tr>
<th>Particle type</th>
<th>Spectral index $\gamma_1, \gamma_2, \gamma_3$</th>
<th>$\Phi_0$</th>
<th>$E_{\text{norm}}$ [GeV]</th>
<th>$E_{B_1}, E_{B_2}$ [GeV]</th>
<th>$E_i, E_f$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>-2.82, -2.68</td>
<td>0.32288</td>
<td>50</td>
<td>200</td>
<td>5, $2 \times 10^6$</td>
</tr>
<tr>
<td>He</td>
<td>-2.69, -2.52</td>
<td>2.95135 × 10$^{-2}$</td>
<td>100</td>
<td>550</td>
<td>10, $2 \times 10^6$</td>
</tr>
<tr>
<td>C</td>
<td>-1.93, -2.72, -2.51</td>
<td>3.35 × 10$^{-2}$</td>
<td>36</td>
<td>120, 2.4e3</td>
<td>50, $2 \times 10^6$</td>
</tr>
<tr>
<td>O</td>
<td>-1.93, -2.72, -2.51</td>
<td>2.4 × 10$^{-2}$</td>
<td>48</td>
<td>160, 3.2e3</td>
<td>50, $2 \times 10^6$</td>
</tr>
<tr>
<td>Ne</td>
<td>-1.93, -2.72, -2.51</td>
<td>2.97 × 10$^{-3}$</td>
<td>60</td>
<td>200, 4e3</td>
<td>100, $2 \times 10^6$</td>
</tr>
<tr>
<td>Mg</td>
<td>-1.93, -2.72, -2.51</td>
<td>3.25 × 10$^{-3}$</td>
<td>72</td>
<td>240, 4.8e3</td>
<td>100, $2 \times 10^6$</td>
</tr>
<tr>
<td>Si</td>
<td>-1.93, -2.72, -2.51</td>
<td>2.45 × 10$^{-3}$</td>
<td>84</td>
<td>280, 5.6e3</td>
<td>100, $2 \times 10^6$</td>
</tr>
<tr>
<td>Fe</td>
<td>-1.91, -2.72, -2.51</td>
<td>8.34 × 10$^{-4}$</td>
<td>168</td>
<td>560, 11.2e3</td>
<td>200, $2 \times 10^6$</td>
</tr>
</tbody>
</table>

Defined thus:

$$w(E, r, \theta) = \begin{cases} W(E, r) & \text{if } \theta_1 \leq \theta_B \leq \theta_2 \\ 0 & \text{otherwise} \end{cases}$$  \quad (5.12)$$

We can perform the integral over the solid angle in Equation 5.4 to get

$$\sum_{i=0}^{N_{\text{thrown}}} w(E_i, r_i, \theta_i) \approx \pi \left( \cos^2(\theta_1) - \cos^2(\theta_2) \right) \int W(E, r) T(E, r) \, dA \, dE$$  \quad (5.13)$$

which corresponds to integrating Equation 5.3 over time at a specific angle $\theta_B$:

$$N = T_B \cos(\theta_B) \int \Phi_\gamma(E) \, dA \, dE$$  \quad (5.14)$$

Therefore, $W(E, r)$ is

$$W(E, r) = \frac{1}{\pi} \frac{\Phi_\gamma(E)}{T(E, r) (\cos^2(\theta_1) - \cos^2(\theta_2))}$$  \quad (5.15)$$

Summing over $w(E, r, \theta)$ for all simulated events gives the expected number of GRB signal events from a specific location for a given duration.

The emission of gamma rays $\Phi_\gamma(E)$ is modeled using a power-law spectrum.
Where applicable, the effect of gamma-ray absorption via interaction with the extragalactic background light (EBL) is taken into account. The Gilmore model (Figure 1.21) is used to compute the optical depth $\tau$ as function of gamma-ray energy and redshift $z$. Hence the gamma-ray spectrum at Earth is given by

$$\Phi_\gamma(E) = \Phi_0 \left( \frac{E}{E_{\text{norm}}} \right)^{-\gamma} e^{-\tau(E)}$$

(5.16)

### 5.2 Data/Monte Carlo Comparisons

Now that we can properly reproduce cosmic ray and gamma-ray sources, we can address how to turn actual numbers of observed or fit photons into fluxes from GRBs. We do this through two means: (1) with the comparison of data to background Monte Carlo and (2) checking that data from the Crab, a standard candle in gamma-ray astronomy, reproduces the expected number of gamma-ray events. We will show the data/Monte Carlo comparisons for the GRB 130504C analysis and provide the rest of the comparisons for the analyzed Fermi LAT GRBs in Appendix A. Following that, we briefly discuss data from the Crab and show the comparison with Monte Carlo.

#### 5.2.1 HAWC-27 comparison and systematic error

GRB 130504C occurred during the HAWC-27 construction phase. We simulate the positions of the PMTs active at the time of the burst to get the most accurate representation of the detector. Since HAWC data is dominated by background, we compare the all-sky data prior to the burst to the weighted isotropic cosmic ray simulation. In the following figures, data is shown in blue while hadron Monte Carlo is shown in red. The ratio of data to Monte Carlo is plotted below each reconstruction parameter. The only cuts applied to data and simulation are that the event must have successfully passed the angular fit and have been reconstructed with $\theta < 45^\circ$.

The SMT trigger rate multiplicity is shown in Figure 5.2. The rate is accurately reproduced although at the highest $nHit$ values the distributions are slightly dissimilar due to hit-dropping in the triggering algorithms discussed in Section 3.3. Since the gamma-ray events from GRBs are expected at the low energy range of
Figure 5.2: Comparison of data (blue) and Monte Carlo (red) multiplicity trigger rate distribution for GRB 130504C. The discrepancy at high $n_{Hit}$ is due to hit-dropping in data. Since gamma rays from GRB are anticipated to have low $n_{Hit}$ values due to their low energy, this difference does not change the systematic error significantly. The total rate difference is $<1\%$, which, again, does not contribute significantly to the systematic error.

HAWC, the discrepancy at high $n_{Hit}$ does not cause a large error. The total rate difference for this GRB is $<1\%$.

We also show the zenith angle distribution as another verification of the Monte Carlo in Figure 5.3. The shape of the distribution accurately represents data, thus not contributing to any systematic error based on pointing. Due to uncertainty in calibration at the time of analysis, no gamma/hadron separation was applied for this burst. Comparisons of the background rejection parameters for other bursts are in Appendix A. From these comparisons, we determine that the uncertainty described in the next section dominates the systematic error from the discrepancy between data and Monte Carlo.
Figure 5.3: Comparison of data (blue) and Monte Carlo (red) zenith angle distribution for GRB 130504C. The shape of the distribution is accurately simulated, adding no significant pointing error for this burst.

5.2.2 Comparison with the Crab Nebula

The data/Monte Carlo comparisons described in the previous section examine the accuracy of the background simulation and argue that if cosmic rays are properly reconstructed, then gamma rays ought to be as well. An additional means to verify the HAWC gamma-ray Monte Carlo simulation is to search for gamma rays in the data from a known TeV source, the Crab Nebula. The analysis of the Crab provides a way to directly consider the gamma-ray simulation. An in-depth analysis of the Crab will be the subject of a future HAWC publication. For the purpose of this work, we show the results of the analysis as they pertain to the determination of the systematic error from the accuracy of the Monte Carlo. Figure 5.4 shows the skymap of the Crab, the significance of the signal above the background, for 260 days of data. The detection is above $20\sigma$, which is strong enough to provide good information for Monte Carlo comparisons.

Figure 5.5 displays the comparison between data and Monte Carlo for the
Figure 5.4: Skymap of the Crab Nebula with 260 days of data. Gamma rays from the Crab are seen with high significance above the background. The detection of this “standard candle” in TeV astronomy provides a handle on the systematics due to differences between the data and the gamma-ray simulation.

The standard HAWC binned analysis. The bins are in \( nHit \), which can be thought of as an energy proxy with the low number bins being equivalent to low energies (hundreds of GeV) and, for this data set, the highest bin having a median energy of \( \sim 10 \text{ TeV} \). The red circles represent the number of events seen in a particular energy bin after subtracting the expected number of background events. The expected number of background events is derived from off-source data using a technique called direct integration, which is further explained in Section 6.6. The gray band illustrates the 40% uncertainty in the simulation due to systematic errors with the Monte Carlo. There are two main discrepancies between data and simulation: (1) the angular resolution and (2) the charge scale, e.g. the number of
Figure 5.5: Comparison of data (red circles) and gamma-ray Monte Carlo (gray band) from the Crab Nebula as a function of energy proxy (nHit) bin. The low energy bins contribute to the gamma-ray systematic error for this analysis.

To regain the expected number of photons from the Crab in data, the angular bin, or Point Spread Function (PSF), used for data analysis must be increased by 0.3° in quadrature with the optimal bin given by the Monte Carlo. That is, the Monte Carlo predicts better angular resolution than currently seen in the data. To compensate for this, we hold the angular bin radius in Monte Carlo constant but use a larger angular bin radius in data, i.e. more background, to recover the expected excess on the Crab. This prescription is followed in the GRB analysis of this dissertation. When converting number of signal events to flux, we use the smaller Monte Carlo estimated bin but the larger bin for the data analysis.
In addition to investigating the PSF, the impact of changing the PE scale and number of live/dead PMTs in the Monte Carlo was tested. The effect of different cut values on the excess and background was determined as well. Each individual systematic has a ±20% discrepancy between data and Monte Carlo. Due to probably dependence of the systematics on each other, we could combine the errors in quadrature to get 34% or, to be extremely conservative, combine them linearly and get 60%. A sensible compromise between the two is to quote the data/Monte Carlo discrepancy with the 40% systematic error band seen in Figure 5.5. Using a slightly larger value than the more typical quadrature systematic reflects that this is still early in the lifetime of the HAWC detector and more refined analyses will occur in the future. The background simulation comparison in the previous section supports this error. We use 40% as the systematic error in the number of gamma rays detected due to data/Monte Carlo discrepancy.

5.3 Flux Sensitivity Computation and Optimal Cuts

After simulating accurate cosmic ray background and anticipated GRB signals, we can determine the best cuts to optimize the signal to background ratio and maximize the sensitivity of HAWC to GRBs. The HAWC GRB sensitivity is estimated for two different methods: (1) a single time-bin counting analysis and (2) the likelihood analysis of this dissertation, which is further described in Chapter 6. The single time-bin analysis assumes a top-hat distribution for the GRB signal in a specific time window, counting the total number of events in the window and subtracting the expected number of background events to get the signal. This analysis is used to explore quickly the general trend of the sensitivity of HAWC to GRBs.

Two statistical regimes can be considered: Gaussian and Poisson. Gaussian significance is given by the ratio \( S/\sqrt{B} \), where \( S \) and \( B \) are the number of signal and background events respectively. To determine the flux necessary for a 5\( \sigma \) detection, we compute

\[
\Phi_{5\sigma} = 5 \times \left( \frac{\Phi_0}{N_\gamma/\sqrt{N_b}} \right)
\]

(5.17)

where \( N_\gamma \) is the weighted number of signal events, \( N_b \) is the weighted number of background events, \( \Phi_0 \) is the simulated flux, and \( \Phi_{5\sigma} \) is the desired 5\( \sigma \) flux.
For the Poisson regime, i.e., when dealing with smaller numbers of events, the number of background events remaining after all cuts is used to determine the minimum number of photons detectable at $5\sigma$ significance. The $5\sigma$ level is found using the cumulative Poisson distribution function. The $5\sigma$ discovery potential is defined as the flux level that leads to a 50% probability to detect a $5\sigma$ excess. The discovery potential is first computed in terms of average number of events needed and then converted into flux units using the ratio of the weighted events to their simulated flux. That is,

$$\Phi_{5\sigma} = \frac{N_{5\sigma}}{N_{5\sigma}}$$

where $N_{5\sigma}$ is the number of signal events required for a $5\sigma$ detection and the rest of the variables are the same as in Equation 5.17. It is worth noting that in both statistical regimes $N_{5\sigma}$ is independent of the initially simulated flux.

### 5.3.1 Optimizing the cuts

To maximize the significance of a discovery, it is important to apply optimal cuts on various reconstruction parameters. There are three key parameters to consider: the simple multiplicity trigger level, bin size, and gamma/hadron separation. To choose cuts that produce the greatest the discovery potential, we maximize the following:

$$Q_{\text{Gaus}} = \frac{\epsilon_{\gamma}}{\sqrt{\epsilon_b}}; \quad Q_{\text{Pois}} = \frac{\epsilon_{\gamma}}{n_{5\sigma}^{5\sigma}(\epsilon_b)}$$

where $Q_{\text{Gaus}}$ and $Q_{\text{Pois}}$ represent “Q-values” for the significance analysis in the Gaussian and Poisson regimes respectively, $\epsilon_{\gamma}$ and $\epsilon_b$ are the efficiencies for detecting gammas and hadrons, and $n_{5\sigma}^{5\sigma}(\epsilon_b)$ is the number of gammas needed for 50% chance of a $5\sigma$ detection as a function of the background efficiency.

#### 5.3.1.1 Trigger rate cut

Choosing the trigger rate cut is relatively simple. For each simulated GRB, we plot $Q_{\text{Gaus}}$, the integral rate above the trigger cut for gammas over the square-root of the integral rate above the trigger cut for hadrons. Figure 5.6 shows an example trigger multiplicity $Q_{\text{Gaus}}$ distribution for HAWC-300 GRBs with various redshifts at a zenith angle of $20^\circ$ with an $E^{-2}$ spectrum. A $2.5^\circ$ binsize is assumed, and a quality cut of $\theta < 45^\circ$ is applied. The shaded region indicates the cut required
Figure 5.6: $Q_{\text{Gaus}}$ as a function of event trigger multiplicity for a simulated HAWC-300 GRB at various redshifts. Each line represents the sensitivity to a burst at 20° zenith with index $\gamma = -2$ for different trigger cuts, arbitrarily scaled for easier viewing. A hard $n\text{Hit} \geq 10$ cut is already applied, causing the straight line at low multiplicities. The shaded region indicates the minimum cut for a 15kHz trigger rate, which is close to the maximum rate currently allowed. It means that the optimal trigger cut for any GRB with redshift $z > 0$ will most likely be at trigger level.

for a 15kHz trigger rate for HAWC-300. (15kHz is approximately the maximum allowed rate for HAWC-300 given the current triggering algorithms and computer setup.) For bursts with small redshifts, a higher trigger cut is optimal due to the abundance of high-energy events; however, given the acceptable trigger rate, the redshift of most of the bursts in this analysis, and low number of PMTs due to the construction stage at the time of each observation, an additional trigger cut is most often not applied.

5.3.1.2 Angular resolution cut

The angular distance cut is based on the known position of the GRB. For simulation, the cut is applied to the angle between the simulated and reconstructed direction
of the gamma-ray showers. An example angular error distribution was shown in Figure 4.4. This emulates a cut on the angular distance between the reconstructed shower direction and the position of the source. The maximum angular distance allowed by the cut is also used to compute the rate of background events in the selected area of the sky (see Equation 5.11). Since the number of background events is proportional to the space angle, the optimal cut is given by

\[
\frac{d(N_\gamma/\sqrt{N_b})}{dr} \propto \frac{d(N_\gamma/\sqrt{\pi r^2})}{dr} \propto \frac{d(N_\gamma/r)}{dr},
\]

(5.20)

where \(r\) is the angular distance, and \(N_\gamma\) is the number of events with angular error smaller than \(r\). Notably, the optimal cut, in the case of Gaussian statistics, does not depend on the background and is merely a function of the angular resolution for gamma ray showers. Because the angular resolution depends on energy, the cut has to be optimized for a particular gamma-ray spectrum. Other factors that strongly affect the optimal bin size include the size of the detector, the redshift of the burst, and the location in the FoV of HAWC. As the detector array grows, the optimal bin size decreases due to the increase in the angular resolution with more PMTs. For bursts with high redshift, the lack of high-energy events causes the optimal bin size to increase, and bursts close to zenith will have more events observed by the detector, causing the optimal bin size to decrease. For example, Figure 5.7 displays the normalized Q-values for a simulated HAWC-300 GRB with different energy cutoffs. As the number of high-energy events decreases, the optimal bin size increases.

### 5.3.1.3 Background rejection cut

The hadron rejection method is based on three parameters: the compactness parameter, the core fit reduced \(\chi^2\), and the angular fit reduced \(\chi^2\). Rather than maximize the statistical significance \((N_\gamma/\sqrt{N_b})\) for a particular type of source, we use Poisson statistics for this cut because the number of background events is not large enough for the Gaussian approximation to be valid. The optimal values of all the cuts depend on energy, and therefore on gamma-ray energy spectrum, burst redshift, etc. For all of the plots in this section, the simulated HAWC-49 GRB is 29° from zenith with an \(E^{-2}\) spectrum and a redshift of \(z = 2.488\). The burst duration is 48s. Gamma-ray events are required to be reconstructed within 2.39°
Figure 5.7: $N_\gamma/r$ from Equation 5.20 as a function of bin size (radius $r$) for a simulated HAWC-300 GRB with different energy cutoffs. The optimal bin sizes are marked with dashed lines and the values are given in the legend. As a general trend, bursts with more high-energy events have smaller optimal bin sizes.

of the true source position.

Figures 5.8 and 5.9 show the compactness and $\chi^2$ distributions for gammas (solid red line) and hadrons (dashed blue line). The optimal cut based on the maximum $Q_{\text{Pois}}$ is shown for each parameter by the dashed black line with the arrow indicating the direction of events retained in the analysis. Events to the right of the line are retained for analysis. The core fit $\chi^2$ parameter (5.9a) is the more effective discriminator of the two $\chi^2$ parameters, although both outperform the compactness parameter for maximizing $Q_{\text{Pois}}$.

To determine the final background rejection cuts, we looked at all permutations of the order of optimizing the three cut parameters, from using only individual cuts to all three. Based on the simulated burst parameters and construction stage of the detector, not all cuts are applied. In some cases, for example, $Q_{\text{Pois}}$ is maximized without applying any compactness cut.
Figure 5.8: Compactness parameter distribution for normalized gamma ray-induced (red) and hadron-induced (blue) showers. The simulated HAWC-49 gamma-ray source has a zenith angle $\theta_{\text{true}} = 29^\circ$ and $E^{-2}$ spectrum with a redshift $z = 2.488$. Cuts are applied on the number of hits ($n\text{Hit} > 10$) and the reconstructed zenith angle ($\theta < 45^\circ$). For gamma rays, an angular distance cut is also applied ($\text{delAngle} < 2.39^\circ$). The cut maximizing $Q_{\text{Pois}}$ is shown in black. Events to the right of the cut are kept.

### 5.4 HAWC GRB Sensitivity

To illustrate how the sensitivity of HAWC changes for various source parameters, the next sections explore the sensitivity of HAWC to GRB characteristics using the simple time-bin counting analysis described at the beginning of Section 5.3. We predict the time-integrated flux needed to be seen by HAWC for a significant GRB discovery based on different factors that effect the analysis. The sensitivity for the actual bursts analyzed in this dissertation are calculated correctly for each burst, with redshift, zenith, construction phase, etc. handled in detail. The general trends observed in this section apply to the likelihood-based analysis as well.
Figure 5.9: Distributions for the $\chi^2$ gamma/hadron separation parameters for normalized gamma ray-induced (red) and hadron-induced (blue) showers. The simulated gamma ray source has a zenith angle $\theta_{true} = 20^\circ$ and $E^{-2}$ spectrum with redshift $z = 2.488$. Cuts are applied on the number of hits ($n_{Hit} > 10$) and the reconstructed zenith angle ($\theta < 45^\circ$). For gamma rays, an angular distance cut is also applied ($\text{delAngle} < 2.39^\circ$). The cut maximizing $Q_{Poiss}$ is shown in black. Events to the left of the cut are kept. The core fit $\chi^2$ parameter (5.9a) is the more effective discriminator of the two.

5.4.1 Sensitivity as a function of zenith angle

To determine the triggered sensitivity to bursts at various locations in the sky, a typical GRB is first simulated and then analyzed at different zenith angles. For this case, the simulated GRB has a duration of 10 s, a power-law energy spectrum with spectral index $\gamma = -2$ and resides at a redshift of $z = 0.5$. For the location of the burst, bands $2^\circ$ wide with constant exposure to the source are used, beginning with $\theta = 0^\circ$. Although a GRB will not traverse two degrees in zenith in 10 s, this allows the use of all available Monte Carlo. A quality cut of $\theta < 45^\circ$ is applied prior to cut optimization, which is done for each zenith angle.

We define the sensitivity as the time-integrated differential flux $\left( E^2 \frac{dN}{dE} \right)$ needed for the single time-bin counting analysis to have a 50% chance of a $5\sigma$ detection. Figure 5.10 displays the sensitivity of HAWC-300 to a burst occurring throughout a range of zenith angles for both a higher trigger threshold ($n_{Hit} \geq 66$) and a lower one ($n_{Hit} \geq 30$) for the simple time-bin counting analysis. The average zenith angle in each band is plotted. As can be seen, GRBs that occur at lower zenith angle in the FoV of HAWC are much easier to observe.
Figure 5.10: Sensitivity of the full HAWC detector as a function of zenith angle. The minimum time-integrated differential flux necessary to observe a GRB at $5\sigma$ significance with 50% probability is shown. Results are given for a higher trigger threshold ($n_{\text{Hit}} \geq 66$) and a reduced threshold trigger ($n_{\text{Hit}} \geq 30$) for a range of zenith angles of an astrophysical source. A 10 s GRB with a spectral index of -2 at a redshift of 0.5 is considered. EBL attenuation is modeled following Gilmore et al. [90]. Cuts, other than the trigger and reconstructed zenith angle ($\theta < 45^\circ$), are optimized for each true zenith angle.

5.4.2 Sensitivity as a function of spectral index and maximum observed energy

In addition to knowing the effect of the position of the GRB relative to HAWC, it is also pertinent to be aware of the triggered sensitivity of the HAWC detector to the spectral index of a GRB with known position and duration. To explore this, we begin with a source simulated at $20^\circ$ zenith with a duration of one second. In addition to varying the spectral index, we take into account that some of the high-energy gamma rays will be attenuated by the EBL or suppressed due to an intrinsic source energy cutoff by applying a generic sharp cutoff at specified energies. Due to varying spectral indices, a reference energy is needed to plot $E^2 \frac{dN}{dE}$; 10 GeV
is chosen. Sensitivities are shown in Figure 5.11 for the high trigger threshold \((nHit \geq 66)\) and the low threshold \((nHit \geq 30)\). The time-integrated differential fluxes for several of the brightest *Fermi* LAT bursts are displayed for reference as well. The calculation of these GRB fluxes is addressed in Appendix B.

As expected, sources with harder index and higher energy require fewer events to be detected significantly. If the GRB energy spectrum cut off below 100 GeV, the HAWC observatory would have been able to detect three of the four GRBs at a \(5\sigma\) level (given the lower trigger threshold). Since a 95 GeV photon was observed from GRB 130427A [74], we know that the intrinsic source spectra extends at least that far in at least some cases, which is very promising for a significant HAWC GRB detection.

### 5.4.3 Single time-bin sensitivity vs. Likelihood sensitivity

Finally, we compare the sensitivity of the simple counting analysis to the more advanced likelihood analysis described in the next chapter. The general source sensitivity trends shown in the previous sections apply equally to the likelihood analysis as to the single time-bin one. The main difference between the methods is that the likelihood analysis incorporates a predicted time profile for the burst rather than the top-hat profile intrinsically assumed by the time-bin analysis.

To compare sensitivities, we determine the number of signal events needed for 50% chance of a \(5\sigma\) detection for each technique for specific source time-profiles. The single time-bin analysis is optimal for a top-hat time profile while the likelihood analysis uses a Crystal Ball function (a Gaussian combined with a power-law) as the time profile. The Crystal Ball function and likelihood analysis will be further discussed in the next chapter, but for this comparison, one just needs to know that the likelihood method works best when the true time profile is a Crystal Ball function. We assume a given GRB has most of its events arrive within a 100 s time window after \(T_0\). The counting analysis determines the number of signal event needed for detection based on the background rate in that time window. For the likelihood analysis, we assume the time profiles shown in Figure 5.12: a 100 s flat top-hat distribution, a Crystal Ball distribution with \(T_{90} \approx 73\) s (for a thirty-minute window) with a peak width of \(\sim 5\) s, and a flat 5 s distribution. The results of the comparison are given in Table 5.2.
Figure 5.11: Sensitivity as a function of spectral index and maximum energy. The $5\sigma$ discovery potential for HAWC-300 is shown as a function of spectral index for various values of a sharp high-energy spectral cutoffs for the trigger $n\text{Hit} \geq 66$ (top) and $n\text{Hit} \geq 30$ (bottom). The duration of the burst is fixed to 1 s and the zenith angle of the source is $20^\circ$. Data from several GRBs are inserted for comparison (see Appendix B for references).
Figure 5.12: Simulated time profiles of GRB events. The normalized PDFs are used to compare the single time-bin counting sensitivity to the likelihood sensitivity.

Table 5.2: Sensitivity comparison of simple time-bin counting analysis technique to the likelihood analysis technique. $N_{s5\sigma}$ is the number of signal events necessary for 50% chance of a 5\sigma detection.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>True Time Profile</th>
<th>Signal Width</th>
<th>$N_{s5\sigma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single time-bin counting</td>
<td>N/A</td>
<td>105s (window)</td>
<td>$\approx 283$</td>
</tr>
<tr>
<td>Likelihood</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top-Hat</td>
<td>100s</td>
<td>$\approx 500$</td>
<td></td>
</tr>
<tr>
<td>Top-Hat</td>
<td>5s</td>
<td>$\approx 107$</td>
<td></td>
</tr>
<tr>
<td>Crystal Ball</td>
<td>$\sim 73s \ (T_{90})$</td>
<td>$\approx 141$</td>
<td></td>
</tr>
</tbody>
</table>

Assuming the perfect time window is chosen, the counting analysis needs approximately half as many events as the likelihood analysis if the true time profile is a 100s top-hat distribution, i.e. a wide, flat distribution with no sharp distinguishing characteristics. Given that GRB time profiles are peaked at lower energies (see Figure 1.2), it is quite unlikely that the higher-energy time profile is flat. If, however, the true GRB profile is sharply peaked while still having an $\approx 100s \ T_{90}$, the likelihood method is better by approximately twice the number of events. Half as many events are needed for the GRB to be significantly detected.
using the likelihood technique than the single time-window counting technique, even if the true signal is not a Crystal Ball but rather a narrow top-hat. From this, we can clearly see the advantage of the likelihood analysis method of this thesis over the simple technique previously applied.
Chapter 6
The Search Method

Likelihood methods are standard analysis tools in high-energy particle astrophysics \cite{138,141}. We employ an unbinned likelihood method of detecting GRBs with the HAWC observatory. In contrast to a simple (or even complex) binned time-window counting analysis, this has the advantage of using all available information without reducing the data. External information from other instruments and theoretical models of GRBs, described in Chapter \cite{1} are used to perform a likelihood ratio test to search for GRBs by looking at their light curves.

In Section \ref{sec:6.1} we give a brief introduction to basic likelihood statistics. We then introduce the Crystal Ball function as the generic GRB signal probability distribution function in Section \ref{sec:6.2}. Information about tests of the likelihood framework and modifications to the standard maximum likelihood functions is provided in Section \ref{sec:6.3} with the final likelihood test statistic used in the analysis shown in Section \ref{sec:6.4}. Section \ref{sec:6.5} describes how the multiple seeds for the fit are chosen and how the best fit is determined. The background estimation technique is discussed in Section \ref{sec:6.6}. We discuss the method to obtain significance and discovery potential and account for the systematic error due to the unknown shape of a GRB signal time profile in Section \ref{sec:6.7}. Finally, the identification of flux upper limits derived from the likelihood analysis is discussed in Section \ref{sec:6.8}.
6.1 Maximum Likelihood Method

6.1.1 Hypothesis testing and the likelihood ratio test

Two different hypotheses are tested when searching for a source: $H_0$, the null hypothesis (the data consist of only background cosmic ray and gamma-ray events with no GRB signal present) and $H_1$, the signal hypothesis (the data consist of background events and signal events from a GRB). We use a test statistic $\lambda(data)$ to determine the compatibility of data with either hypothesis. The test statistic is designed to give different values under $H_0$ and $H_1$, allowing us to differentiate between the background-only and background plus signal hypotheses. We define a critical region $w$ in test-statistic space such that there is no more than a given probability $\alpha$ under $H_0$ that the data will yield a result in that region. If data are observed in the critical region $w$, $H_0$ is rejected with the chosen Confidence Level (CL).

If we incorrectly reject $H_0$, this is referred to as a type-1 error. The rate of type-1 errors corresponds to the false-discovery rate. Figure 6.1 shows the false-discovery rate, which can be calculated from the CL of the test as follows:

$$P(\lambda \in w|H_0) = \alpha = 1 - CL$$  \hspace{1cm} (6.1)

If we do not reject $H_0$ but $H_1$ is true, it is called a type-II error. These define the power of the test:

$$P(\lambda \in w|H_1) \equiv \text{power}$$  \hspace{1cm} (6.2)

To maximize the power of the test for a given significance level ($\alpha$), the Neyman-Pearson lemma states that the critical region $w$ should be chosen such that for all data values inside $w$, the ratio

$$\lambda(data) = \frac{P(data|H_1)}{P(data|H_0)}$$  \hspace{1cm} (6.3)

is greater than a given constant, which is determined by the desired $\alpha$. Equation 6.3 is known as the likelihood ratio [142].

To make a significant discovery, the typical CL threshold is chosen to be $5\sigma$ ($3\sigma$), which corresponds to a false-discovery rate of $2.87 \times 10^{-7}$ ($1.35 \times 10^{-3}$) for the
positive tail of a Gaussian distribution. For a given CL, the power depends on the amount of signal present in the data; weaker signals are less likely to be detected. The discovery potential, a figure of merit in this analysis, is the flux (number of signal events) needed to reach a specific power level (usually 50%) at a given CL. This will be further discussed in Section 6.7.

To construct the test statistic for the search, we use the likelihood ratio from Equation 6.3 with maximized likelihood functions, \( \mathcal{L}(H_x) = P(\text{data}|H_x) \), for the numerator and denominator based on probability density functions (PDFs) for the background and signal. Maximum likelihood techniques\[138\] use knowledge of PDFs to estimate parameters of a model. In the case of the GRB search, we use normalized signal and background PDFs to construct a likelihood function to determine if a given set of unbinned data constitutes a signal or merely a fluctuation in the background. When the expected number of events is different from the observed number of events, the likelihood should also be multiplied by a Poisson
term, which allows the total number of events to be a free parameter as well [143]. Therefore the basic likelihood function $\mathcal{L}$ is

$$\mathcal{L}(n_s) = \frac{e^{-N} N_{\text{obs}}^{N_{\text{obs}}}}{N_{\text{obs}}!} \times \prod_{i=1}^{N_{\text{obs}}} \left[ \frac{n_s}{N} S(t_i) + \frac{n_b}{N} B(t_i) \right]$$

(6.4)

where $t_i$ is the time of the event, $S(t_i)$ is the GRB signal PDF, $B(t_i)$ is the background PDF, $N_{\text{obs}}$ is the number of observed events, $n_s$ is the number of fit signal events, $n_b$ is the number of background events, and the total number of expected events $N$ equals $n_s + n_b$. Equation 6.4 is numerically maximized with respect to the number of signal events $n_s$ and other free parameters to determine the best fit value $\hat{n}_s$. Since it does not change the shape of $\mathcal{L}$ at its maximum, the constant factorial term $(N_{\text{obs}}!)$ is often omitted.

The standard test statistic (equivalent to $\lambda$ in Equation 6.3) becomes:

$$D = -2 \log \left[ \frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s)} \right]$$

(6.5)

The factor of $-2$ is a remnant from the possibility of translating the test statistic value to a p-value through Wilks’ theorem [144], which says that, under certain conditions, $-2 \log \lambda$ follows a $\chi^2$ distribution. Wilks’ theorem does not apply in this case as will be further discussed in Section 6.7. We use the cumulative distribution of $D$ from simulated background-only light curves to determine the probability that a measured signal under the null hypothesis is simply a statistical fluctuation of the background. Basically, the larger the $D$-value, the more likely it is that the light curve contains a GRB.

### 6.2 Generic Signal Template: Crystal Ball Function

Now that Equations 6.4 and 6.5 have been introduced, we can discuss specific components that make up the likelihood function. Since no GRBs have been seen at TeV energies thus far, we do not know the expected shape of the GRB light curve time profile; we therefore must make an educated guess as to the shape of the signal PDF $S(t_i)$ to use in $\mathcal{L}$.

Trends in Fermi LAT GRBs were discussed in Section 1.3. Those most important for this choice of PDF for a GRB time profile concern the extended emission. LAT-
detected emission is commonly delayed with respect to the lower energy counterpart detected by GBM. Additionally, a temporally extended phase during which LAT flux decays following a single or broken power law with index close to $F_\nu \propto t^{-1}$ is observed. Finally, joint GBM-LAT spectral fits to all LAT GRBs require an extra power-law component in addition to the standard Band function to fit the bursts.

We take advantage of this knowledge to choose the signal PDF to use for the likelihood search. The generic template used in this likelihood search is a Crystal Ball function [145–147], a Gaussian with a power-law tail:

$$f(t; \alpha, n, \mu, \sigma) = N \cdot \begin{cases} \exp \left( -\frac{(t-\mu)^2}{2\sigma^2} \right) \cdot \left( \frac{n}{|\alpha|} \right)^n \cdot \exp \left( -\frac{|\alpha|^2}{2} \cdot \left( \left( \frac{n}{|\alpha|} - |\alpha| \right) - \frac{t-\mu}{\sigma} \right)^{-n} \right) & \text{for } \frac{t-\mu}{\sigma} \leq -\alpha \\ \frac{n}{|\alpha|} \cdot \exp \left( -\frac{|\alpha|^2}{2} \cdot \left( \left( \frac{n}{|\alpha|} - |\alpha| \right) - \frac{t-\mu}{\sigma} \right)^{-n} \right) & \text{for } \frac{t-\mu}{\sigma} > -\alpha \end{cases}$$

(6.6)

where $\alpha$ is the transition point between the Gaussian and power-law, $n$ is the power-law index, $\mu$ is the Gaussian mean (the peak time), $\sigma$ is the Gaussian width, and $t$ is time. $N$ is the normalization, which is calculated numerically by RooFit. Figure 6.2 shows an example Crystal Ball function. The example time profile has a $T_{90} \approx 600$ s given an approximately thirty-minute time window.

We fix the decay index to $n = 1$, in keeping with the Fermi LAT extended time-decay trend, and fit the Gaussian mean $\mu$, Gaussian width $\sigma$, and transition point $\alpha$. Taking advantage of the peak-time delay with respect to the lower energy GBM light curves, we allow $\mu$ to range from -20 s to 200 s. The remaining parameters $\sigma$ and $\alpha$ range from 0 s to 10 s and -10 to 0 (unitless) respectively. The entire likelihood search window extends from -200 s to 1800 s, chosen to cover the $T_{90}$ durations of the Fermi LAT bursts.

## 6.3 Testing the Likelihood Machinery

The RooFit framework [148] is widely used in experimental particle physics and employs sophisticated techniques to perform maximum likelihood fits.

### 6.3.1 Fit numerical instabilities and effective trial factor

To test the machinery of the likelihood fit, we started with a flat background PDF for $B(t_i)$. Using this, the simplest expectation for a PDF, allowed us to easily check
that the likelihood code performs as expected. We simulated background-only light curves with a rate of 10 Hz during a specific time window. We found that using the standard RooFit minimizer, MINUIT [149], resulted in some numerical instabilities in the fit at the $5 \sigma$ level. Several courses of action were pursued to remove these instabilities.

First, many of the numerical outliers had fit parameters hitting the edge of their allowed range. According to [150], MINUIT has trouble when fit parameters get close to their limits. To discourage the fitter from choosing values near the limits, we apply constraint functions to the fit parameters. Additional information about extended log likelihoods, constraints, and RooFit can be found in [151].

The polynomial piecewise function given in Equation [6.7] is used to constrain the mean $\mu$ and transition point $\alpha$ parameters. The values of these parameters, for a background-only case, should be uniformly distributed throughout the allowed
Figure 6.3: Constraint function from Equation 6.7 used for $\mu$ and $\alpha$. The x-axis represents the allowed range for the parameter values, where the edges are defined such that the values are less likely. The constants $a, b, c$ in Equation 6.7 are chosen such that both the function and its derivative are continuous at the boundaries.

The function is as follows:

$$C(x) = \begin{cases} 
 a + bx + cx^2 & \text{for } x < x_{\text{min}} \text{ or } x > x_{\text{max}} \\
 1 & \text{otherwise} 
\end{cases} \quad (6.7)$$

where $x = \mu$ or $\alpha$ and $a, b, c$ are chosen such that both the function and its derivative are continuous at the boundaries. Figure 6.3 shows how this function penalizes the parameter boundaries.

For the width $\sigma$ constraint, in addition to the boundary condition penalization, another effect must be taken into account. If the position and duration of a peak are unknown, multiple fits are being used to test a single hypothesis. This is known as the look-elsewhere effect \footnote{138} and results in the need to take into account the effective trial factor. The effective trial factor describes the number of independent ways to choose the peak within the time window for the fit. The peak time is dependent on the burst duration, which is directly related to $\sigma$. A larger
trial factor is needed for bursts with shorter duration (smaller $\sigma$) since there are more possibilities to fit a narrow peak within the fixed time window. The likelihood method does not account for this and favors shorter duration bursts.

To compensate, we use the constraint described in J. Braun et al. [140]. Basically, we marginalize the likelihood with respect to the burst time using a uniform Bayesian prior that results in a dependence on $\sigma$ relative to the search time window. The necessary constraint function becomes

$$C_\sigma(\sigma) = \frac{1}{T_{\text{max}} - T_{\text{min}}} \times \begin{cases} a + b\sigma + c\sigma^2 & \text{for } \sigma < \sigma_{\text{min}} \text{ or } \sigma > \sigma_{\text{max}} \\ \sigma & \text{otherwise} \end{cases}$$

(6.8)

where $T_{\text{min}}$ and $T_{\text{max}}$ are the limits of the likelihood time window and, again, $a$, $b$, and $c$ are chosen such that both the function and its derivative are continuous at the boundaries. Figure 6.4 shows how the constraint function takes the effective

![Figure 6.4: $\sigma$-constraint function from Equation 6.8. The linear dependence on the width of the peak reflects the effective trial factor due to the fit of the peak time and duration. The boundary penalization is done through polynomial functions at the edge of the allowed parameter range. The constants $a, b, c$ in Equation 6.8 are chosen such that both the function and its derivative are continuous at the boundaries.](image)
Figure 6.5: Fit peak width $\sigma$ for background-only light curves without the constraint function applied (red) and with the constraint (blue). The initial seed of the fit is at $\sigma = 5$. Applying the constraint effectively flattens the distribution, as it should to account for trials.

The result of adding the constraint term to the likelihood trial factor into account. The result of adding the constraint term to the likelihood is shown is Figure 6.5. The distribution of the fit peak width parameter for background-only light curves both with and without the constraint applied is given (a seed of $\sigma_{seed} = 5$ is used for all fits). Narrow peaks become less likely; effectively flattening the $\sigma$-distribution.

Finally, $\mu, \sigma, \text{and } \alpha$ are not the only parameters fit. The number of signal events $n_s$ and number of background events $n_b$ are key results from the fit. The decision to fit the background as well as the signal is discussed in Section 6.5.1. The background fit never hits the boundaries of the parameter’s range. Since we are looking for excesses from GRB signals, the range for $n_s$ was initially only allowed positive values. However, the same numerical instabilities seen when the Crystal Ball function parameters hit the edge of their given range was seen for $n_s$, especially when fitting background-only light curves. The true $n_s$ equals zero in that case, hitting the lower bound and causing problems. To compensate, we allow $n_s$ to be negative and keep only positive fits during the fit selection procedure discussed in Section 6.5.3
Table 6.1: Table of the likelihood $\mathcal{L}$ fit parameters with their ranges. The constraint range describes when the penalty factor for each $C$ in Equation 6.9 begins.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit Range</th>
<th>Constraint Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t$</td>
<td>$[-200 \text{ s}, 1800 \text{ s}]$</td>
<td>-</td>
</tr>
<tr>
<td>$n_s$</td>
<td>$[-1000, 1000]$</td>
<td>-</td>
</tr>
<tr>
<td>$n_b$</td>
<td>$[0, 10^6]$</td>
<td>-</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$[-20 \text{ s}, 200 \text{ s}]$</td>
<td>$[0 \text{ s}, 199 \text{ s}]$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>$[0 \text{ s}, 10 \text{ s}]$</td>
<td>$[0.01 \text{ s}, 9.99 \text{ s}]$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>$[-10, 0]$</td>
<td>$[-9.99, -0.99]$</td>
</tr>
</tbody>
</table>

### 6.4 The GRB Test-Statistic

Putting together everything from Section 6.3, the test statistic for this analysis becomes:

$$D = -2 \log \left[ \frac{1}{C(\hat{\sigma})} \times \frac{1}{C(\hat{\alpha})} \times \frac{1}{C(\hat{\mu})} \times \frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\hat{n}_s, \hat{\mu}, \hat{\sigma}, \hat{\alpha}, \hat{n}_b)} \right] \quad (6.9)$$

This measures the likelihood that this analysis detects a GRB signal, with larger $D$'s yielding higher probabilities that a GRB was observed. Table 6.1 shows the final parameter ranges for the likelihood GRB analysis.

### 6.5 Seeding the Fit

Once confident that the machinery of the likelihood fit performs as expected, we examined the effect of the parameter seeds on the goodness of fit. First, we considered the seed for $n_s$ and found that the initial value of $n_s$ has very little to no effect on the results. If a signal with a peak is present in the data, the starting value does not matter, the fitter can recover it. A seed of $n_s = 5$ was chosen for all fits. Although a simple seed is chosen for $n_s$, the other parameters’ seeds bear further examination. The next two sections describe tests run on the benefit of fitting $n_b$ with a given initial seed and the importance of the initial parameters of $\mu$, $\sigma$, and $\alpha$. 

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6.5.1 Fitting the number of background events

There is some uncertainty in the total number of events expected (which is why the likelihood is extended). The background estimation procedure direct integration is described in Section 6.6. This procedure not only provides the PDF $B(t_i)$ but yields an estimate of the number of background events $n_b$ in the time window. We investigated the change in sensitivity when allowing $n_b$ to be fit in addition to the other Crystal Ball parameters.

To do this, we simulated background-only light curves with the total number of background events drawn from a Poisson with three different mean values: (1) $n_b$, (2) $n_b + \sqrt{n_b}$, and (3) $n_b + 5\sqrt{n_b}$. The first value is given by the background estimation technique. The second value is chosen to take into account statistical errors in the background estimation. The final value reflects the case that the background estimation is significantly off.

All three types of light curves are fit with only 4-parameters ($n_s, \mu, \sigma, \alpha$) to find the $D$-value needed for a 3σ detection. The method to determine significance of the detection is described in Section 6.7. This tests how well the 4-parameter fit performs with an incorrect fixed number of background events $n_b$. Figure 6.6 shows the cumulative distribution of the test statistic $D$ for the 4-parameter fits. The 3σ discovery potential value occurs when the dashed line crosses the distribution. As the actual number of background events gets further from the fixed $n_b$ value, the test statistic required for a 3σ discovery became significantly larger.

Following the 4-parameter fits, we run the analysis on the same light curves with 5 parameters fit, i.e. we allowed $n_b$ to vary as well. The results are shown in blue and yellow in Figure 6.6. There is no significant difference in the necessary test statistic for a 3σ GRB discovery between a 4-parameter fit with accurate fixed $n_b$ and a 5-parameter fit. When the number of estimated background events is significantly different than the actual number, the 5-parameter fit is almost as sensitive as that when the number of estimated background events is the actual number. This indicates that fitting the background as well is not detrimental to the sensitivity of the analysis.

To confirm that the sensitivity was not significantly hurt by allowing $n_b$ be fit, we also tested the 5-parameter fit for fake GRBs thrown on top of the background-only light curves. Figure 6.7 shows the distribution of the test statistic $D$ for light curves
Figure 6.6: Cumulative distribution of test statistic $D$ for fixed $n_b$ (4-parameter) and fit $n_b$ (5-parameter) background-only light curves with different number of background events. When the background estimate is significantly different from the actual number of events (green line), the test statistic $D$-value needed for a $3\sigma$ discovery (dashed line) is greatly increased, causing the test to be much less sensitive. When $n_b$ is allowed to float (blue and yellow lines), there is very little change in $D_{3\sigma}$. Thus, if the initial background estimate is inaccurate, we should fit $n_b$.

with fake GRBs and different numbers of background events. Since there is not much difference in the curves, we can conclude that the sensitivity does not pay a large penalty by adding $n_b$ as a parameter of the likelihood fit.

Therefore, we seed the number of background events with the estimate from the direct integration technique and allow that parameter to be fit as well during the analysis.

### 6.5.2 Choosing seeds for the Crystal Ball parameters

Moving on to choosing the seeds for the signal shape parameters $\sigma$ and $\alpha$, the entire allowed parameter space for each parameter was scanned to test the effect of the width seed $\sigma_{\text{seed}}$ and transition point seed $\alpha_{\text{seed}}$. The global maximum test statistic was found by seeds in a limited parameter space. $\sigma$ and $\alpha$ are not highly dependent upon $\sigma_{\text{seed}}$ and $\alpha_{\text{seed}}$. Therefore, we chose two values for the seeds of each that
allowed the fit to recover the maximum $D$ for one or more of the combinations of $\sigma_{\text{seed}}$ and $\alpha_{\text{seed}}$.

In contrast to $\sigma_{\text{seed}}$ and $\alpha_{\text{seed}}$, the peak time seed $\mu_{\text{seed}}$ is very important. If $\mu_{\text{seed}}$ is not close to the correct value, the fitter has a hard time escaping that region. We therefore employ a more sophisticated algorithm to determine the seed for the Gaussian mean and test several other fixed values. We use a symmetric moving average to find the peak time in the likelihood fit window, described by

$$ MA(i) = \frac{1}{2N} \sum_{j=i-N}^{j=i+N} C(j) $$

(6.10)

where $C(j)$ is equal to the number of events (counts) in a one-second time bin. We chose to average over 5 s bins. An example of the moving average algorithm for a specific light curve is shown in Figure 6.8. The maximum average count time is the first seed for the fit.
Figure 6.8: Example GRB light curve with the moving average seed algorithm in red. The maximum of the red line becomes the peak time seed $\mu_{\text{seed}}$.

Figure 6.9 shows the fit results given the initial moving average seed. The true value of $\mu$ is at 1. The red bin shows that $\approx 80\%$ of the 100 light curves have a moving average seed close to the true value. The line of bins rising to the right support the previous statement that the fitter has difficulty moving from the initial peak time seed. To recover the other 20% of light curves, we run additional fits with different seeds to better cover the parameter space. After testing the peak time seed every 10 s, we found that the moving average seed supplemented by the seeds $\mu_{\text{seed}} = T_0$ and $\mu_{\text{seed}} = T_0 \pm 10$ allowed the fit to find the correct peak time for the light curves. Table 6.2 show a summary of the seeds for each of the fit parameters.

6.5.3 Determining the “best” fit to a light curve with multiple seeds

For each light curve, both for data and simulation, we run a total of 16 fits. The question then becomes which of the results should be chosen as the final result. There are several factors in addition to the test statistic used to make this decision.
Figure 6.9: Fit mean $\mu$ as a function of the mean seed $\mu_{\text{seed}}$ for fake GRB light curves with $\mu_{\text{true}} = 1$ s. The moving average algorithm finds a good seed for all but 17 out of the 100 light curves. We add three additional seeds close to the trigger time to recover these events.

Ideally, we could just keep the fit with the largest test statistic; however, quality cuts to ensure the accuracy of the fit are needed first before we can pick the best fit. As mentioned in Section 6.3, the number of signal events $n_s$ is allowed to be negative to avoid numerical instabilities. Therefore we first remove any fit with $n_s < 0$ and, to avoid fit values hitting the upper bounds, we cut on $n_s < 999$. The error on the fit number of events is also returned for each fit. We use this as an additional quality cut. Fits with $n_s_{\text{err}} < 1$ and $n_s_{\text{err}} > n_s$ are removed. Finally, we demand that the best fit of those remaining after quality cuts have the largest $D$ with the smallest ratio of $n_s_{\text{err}}/n_s$.

### 6.6 Background Probability Density Function

Rather than using the flat PDF from testing for $B(t_i)$, we determine the background probability density function from data for each individual GRB. We use a modified
Table 6.2: Table of the likelihood $\mathcal{L}$ fit parameters with their seeds. $n_{b\text{est}}$ is from the background estimation technique described in Section 6.6. For the peak time $\mu$, $MA$ refers to the moving average peak time from the maximum of Equation 6.10 while $T_0$ is the trigger time of the burst from the external trigger. A total of 16 fits are done for each light curve, covering the entire parameter space scanned by the seeds.

<table>
<thead>
<tr>
<th>Fit Parameter</th>
<th>Seed(s)</th>
<th>Initial Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_s$</td>
<td>5</td>
<td>$\sqrt{5}$</td>
</tr>
<tr>
<td>$n_b$</td>
<td>$n_{b\text{est}}$</td>
<td>$\sqrt{n_{b\text{est}}}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$MA, T_0, T_0 \pm 10$</td>
<td>10</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.2, 4.2</td>
<td>0.01</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>-4, -2</td>
<td>0.01</td>
</tr>
</tbody>
</table>

method of direct integration $^{49,152}$ to estimate the background events in the source bin from the data.

Direct integration takes advantage of the stability of the local arrival directions of events and the all-sky event rate to estimate the background for a specific region in the sky. Changes in the detector and atmosphere are taken into account. Figure 6.10 shows an example of the background computation for a specific declination band. The total background rate is a function of sidereal time $\tau$, declination $\delta$, and local hour angle $h$. The all-sky event rate $R(\tau)$ (top panel) and local angular dependence $\varepsilon(h,\delta)$ (middle panel) are taken as independent. Despite the overall event rate potentially changing often, the local angular distribution of events is nearly constant. Events from a 2 h integration duration period before the GRB trigger time in a specific right-ascension $\alpha$ and declination $\delta$ band form the local angular distribution of events $\varepsilon(h,\delta)$. This is a normalized probability density function that represents the efficiency of the detector. The background estimate for a source is the convolution of the efficiency map with the all-sky rate:

$$B(\alpha,\delta) = \int \varepsilon(h,\delta) \cdot R(\alpha - h) dh$$  \hspace{1cm} (6.11)

Thus, $B(\alpha,\delta)$ gives a background estimate from data prior to the GRB at the GRB location (bottom panel).

To determine the background PDF $B(t_i)$, we take the value of the estimated
background at the GRB right-ascension and declination every second. Direct integration is done for each second in the likelihood time window with the efficiency map from 2h prior. This gives a histogram of the expected background counts as a function of time in one second bins. RooFit then transforms the histogram into a properly normalized probability density function (interpolating by an order of 2 between bins), which we use as $B(t_i)$. Note that the shape of the PDF is held
constant but the normalization \( n_b \) is allowed to float. Figure 6.11 shows HAWC data with the corresponding background estimated PDF.

![Figure 6.11: Example HAWC light curve data with \( B(t_i) \) in blue, derived using direct integration.](image)

### 6.7 Evaluating Significance and Discovery Potential

To determine the significance of the result, we generate many light curves drawn from the background PDF \( B(t_i) \) to test the null hypothesis, i.e. how often background mimics signal. We cannot assume the cumulative distribution of the likelihood ratio test statistic approaches a chi-square distribution as per Wilks’ theorem due to the constraint functions that change the distribution. Figure 6.12 shows the cumulative distribution of \( D \) for these background-only light curves from \( B(t_i) \) for GRB 130504C. Note, the test statistic distribution is shifted left from zero due to the constraint functions. This plot shows how often we can expect a false discovery for a given test statistic value. For example, to make a 4\( \sigma \) discovery, we would need \( D_{\text{data}} \geq 7.85 \).

We then simulate a Crystal Ball function on top of the background with

\[ D \text{ (data)} \geq 7.85 \]
Figure 6.12: Cumulative distribution of test statistic $D$ for background-only light curves drawn from the background PDF $B(t_i)$. The blue lines represent the probabilities for a specific discovery potential. The red line is the exponential fit to the curve used to determine $D_{5\sigma}$.

parameters such that the shape and duration are similar to those described by GCN Circulars [154] for that burst. For example for GRB 130504C, we use the Crystal Ball function shown in the top panel of Figure 6.15. The true number of signal events is drawn from a Poisson function with a given mean flux. Example fits are shown in Figures 6.13-6.14 for various numbers of mean signal events.

After simulating the GRB with many mean flux values, we obtain the distribution of the test statistic for each and determine how often $D_{3\sigma}$, $D_{4\sigma}$, and $D_{5\sigma}$ occur, which yields the discovery potential. The discovery potential for GRB 130504C is shown in Figure 6.15 for the given time profile shape. We would only need $\sim 141$ signal events in the whole 2000s time window for 50% chance of a 5$\sigma$ detection.

### 6.7.1 Sensitivity to unknown time profiles

Since we do not know the exact shape of the expected time distribution of GRB emission at high energy, we test the robustness of the fit to multiple signal PDFs
Figure 6.13: Example fit to fake GRB with mean flux of 170 signal events. Simulated events are shown in black with the purple squares showing the fake GRB signal contribution. The fit background PDF $B(t_i)$ is shown in blue with the combined signal plus background PDF fit in red. The fit parameters (with the exception of $n_b$) are given followed by the difference between the true numbers of signal and background events and the fit numbers. The number of events in the peak $N_{\text{peak}}$ is defined as the time between $\mu_{\text{true}} \pm \sigma_{\text{true}}$. The GRB would have been detected with $> 5\sigma$ significance since $D > D_{5\sigma}$.

to determine how dependent the search algorithm is upon an accurate GRB model. There are two areas of dependence that we explore: the functional form of the true profile and the true peak width.

Figure 6.16a shows the four shape profiles tested for GRB 130504C. For the Gaussian function, we choose the same $\sigma$ as that of the Crystal Ball function ($\sigma = 2\, \text{s}$). For the Bifurcated Gaussian and the Landau functions, the parameters are such that the peak width is close to that of the Crystal Ball function. We display the discovery potential for a test statistic $D = -10$, which corresponds to a p-value of $\sim 90\%$ for this burst, in the lower plot in Figure 6.16. The percent spread in the range of the mean flux needed for 50% chance of seeing that $D$-value yields the systematic error due to GRB functional model dependence. For the case shown, the one-sided systematic error is -15%. This functional shape systematic is
Figure 6.14: Example fits to fake GRB with low significance of detection. The plot characteristics are the same as described in Figure 6.13. The GRB would not have been detected with $>3\sigma$ significance in either case since $D < D_{3\sigma}$.
(a) Assumed GRB time profile, a Crystal Ball with $T_{90} \approx 300$.

(b) Discovery potential for different sensitivity levels.

Figure 6.15: Discovery potential for GRB 130504C assuming a Crystal Ball time profile with peak width $\approx 15$ s and $T_{90} \approx 300$ s (top). The Poisson mean number of signal events needed for 50% chance of a $3\sigma$, $4\sigma$, and $5\sigma$ detection are $\sim 97$, $\sim 116$, and $\sim 141$ respectively (bottom).
fairly insignificant compared to that from the data/Monte Carlo discrepancy (and much smaller than the peak width uncertainty).

To ensure that this spread is constant independent of the $D$-value used to define the discovery potential, we looked at the range of 50% discovery potentials for different test statistics. The top plot in Figure 6.17 shows discovery potential for $3 - 5 \sigma$ significant detections for a Crystal Ball, a Gaussian, and a Landau. The ratio of the mean flux needed for the 50% chance of a specific significance detection is displayed in the bottom plot. If the lines in this plot are flat, the percent spread is independent of the test statistic chosen. As they are, we can therefore define the range of the systematic error for any observed test statistic.

After considering the dependence on the functional form of the GRB time profile, we then investigate the effect of the peak width. The power-law index restriction to -1 constrains the tail of the profile. The Crystal Ball parameter with the greatest influence on $T_{95}$ is the Gaussian-power law transition point $\alpha$. To maintain a constant $T_{90}$ for the burst, this parameter is held as close to constant as possible. The Gaussian width $\sigma$ has the largest effect on the rise time of the peak, corresponding to $T_{05}$. By inspection of light curves in the Fermi LAT burst catalog, we chose two values to test for a “narrow” peak (0.2 s) and a “wide” peak (5 s). The final upper limits for the bursts will only be valid for this range of rise times. Figure 6.18 shows the effect of different parameters on the sensitivity of the fit. The value of $\sigma$ affects the discovery potential, but the value of $\alpha$ does not. We conclude that testing a range of $\sigma$’s is important but not a range of $\alpha$’s.

The choice of peak widths and resulting discovery potential are displayed in Figure 6.19. Since the “standard” peak width is chosen close to the middle of the $\sigma$-range, in this case, the relationship to the wide and narrow peaks is similar. The systematic errors are $+36%/-40%$. This is the largest systematic error due to the model dependence of the unknown GRB time profile. To determine the final time profile shape systematic error, the values from the functional form dependence and the peak width dependence are combined in quadrature.

### 6.8 Evaluating Flux Limits

We determine GRB flux limits based on the frequentist technique of Feldman-Cousins [155]. Since the observable test statistic $D$ is not discrete, we cannot use
(a) Assumed GRB time profiles with different functional forms.

Figure 6.16: Functional shape discovery potential for GRB 130504C assuming the above time profiles. The range in 50% flux values (dashed vertical lines) yields the percent systematic error due to the unknown functional form of the true GRB profile. The lower limit from the Gaussian is 15% while the Crystal Ball itself is the upper limit in this case.

(b) Discovery potential for different functional shapes of the GRB time profile.
Figure 6.17: Comparison of discovery potential for different significances for three functional forms of the time profile. The top plot shows the mean number of signal events needed for 50% chance of a significant detection (dashed vertical lines). The percent difference in the values for the Gaussian and Landau are compared to those of the Crystal Ball in the bottom plot. The flat lines indicate the independence of the range from the test statistic value chosen for the discovery potential.

The first step to determine the confidence band is to generate light curves drawn from a Poisson with mean flux \( n_s \) to obtain \( P(D|n_s) \). The light curves are drawn from the standard time profile used in the systematic tests. For each \( D \), we find \( P(D|n_{s_{\text{best}}}) \), where \( n_{s_{\text{best}}} \) is the flux value at which \( P(D|n_s) \) is maximized. We then
Figure 6.18: Discovery potential sensitivity to Crystal Ball time profile parameters. The value of the transition point parameter $\alpha$ on the number of events needed for 50% chance of a detection is negligible. The Gaussian width parameter $\sigma$ does effect the sensitivity. When considering the peak width model dependence, a range of $\sigma$’s must be taken into account.

Construct the band using the ratio:

$$R = \frac{P(D|n_s)}{P(D|n_{\text{best}})}.$$  \hspace{1cm} (6.12)

Values of $D$ are added to each horizontal $n_s$ band in the order of maximum $R$ until 90% of the events are contained. An example 90% confidence interval band for GRB 130504C can be seen in Figure 6.20.

The result of the likelihood analysis produces a best fit test statistic $D_{\text{obs}}$. To determine the limits for this $D$, we draw a vertical line through the confidence interval in Figure 6.20. The intersections of the line with the band are the 90% limits. In our case, only the upper bounds are constrained for all bursts. Lots of statistics are needed to construct each Feldman-Cousins confidence level band. For each Poisson mean flux, we draw 10,000 light curves. Due to limited CPUs, we do not simulate additional curves or at every flux value in the band. This results in a statistical error on the flux upper limit value. By looking at how the band changes based on different test-statistic binning, we determine a range for the upper limit.
(a) Assumed GRB time profiles with different peak widths.

(b) Discovery potential for different peak widths of the GRB time profile.

Figure 6.19: Peak width discovery potential for GRB 130504C assuming the above time profiles. The range in 50% flux values (dashed vertical lines) yields the percent systematic error due to the unknown peak width of the true GRB profile. The upper limit from the wide peak ($\sigma=5$ s) is 36% of the Crystal Ball flux while the lower limit from the narrow peak ($\sigma=0.2$ s) is 40%.
Figure 6.20: Feldman-Cousins confidence level band for GRB 130504C. The black dashed line is drawn at the value of the observed test statistic $D_{\text{obs}}$. By looking at the flux value that corresponds to the crossing point, we determine the upper limit on the number of signal events for this GRB.

Figure 6.21 shows a closer look at where $D_{\text{obs}}$ crosses the confidence level band. The black dashed line shows the upper limit value with the band representing the statistical error range. This source of error is completely insignificant with respect to those due to the unknown time profile and data/MC discrepancy.
Figure 6.21: Confidence Level band statistical error. A zoomed in look at the crossing point from Figure 6.20 to determine the statistical error due to the construction of the band. For all bursts, the statistical error due to the confidence level band construction is negligible.
Chapter 7
Results and Conclusion

7.1 Introduction

Having described the data quality checks, data/Monte Carlo comparisons, and analysis method in Chapters 4-6 respectively, we now discuss the results of the search for GRBs with the HAWC observatory. Seven Fermi LAT GRBs occurred in the FoV of HAWC while the detector was taking data from May 2013 – December 2014. While over 130 GRBs from various instruments were in the FoV, we chose these because high-energy photons were seen by the LAT detector and are thus more likely to have VHE gamma rays from the GRB, which can be observed by the HAWC detector. Unfortunately, the main DAQ was not taking data when GRB 130907A occurred due to problems with the Uninterrupted Power Supply (UPS). Additionally, GRB 140723A occurred closely following a lightning strike to the detector from which the DAQ was still recovering. Data from this burst are shown in Appendix A.

We therefore analyze the remaining five bursts. Table 7.1 shows the triggered GRB information from several source instruments for the GRBs used by this analysis.

It is worth mentioning that the nearby super-luminous burst GRB 130427A happened just prior to the start of this data set. Fermi LAT observed a 95 GeV photon from the burst, whose emission extended in gamma rays over 20 hours \[74\]. Due to construction at the site, the main DAQ was down during this time. The scaler DAQ, however, was able to set upper limits on the burst extension to TeV energies. Unfortunately, the zenith angle of the burst was at 57° and setting, which prohibited the analysis from setting stringent upper limits. For more information on this burst and the HAWC analysis, see [156].
In this chapter, we tabulate information about the Monte Carlo simulations used to convert numbers of events to fluxes in Table 7.2, the optimized cuts used in the analysis of each burst in Table 7.3, the default time profile models in Table 7.4 and results from the likelihood analysis in Table 7.5. The GRB positions and times are taken from Table 7.1. The default models are chosen from Fermi LAT, GBM, and Konus-Wind GCN circulars. There is not very much information about the high-energy time profile contained in LAT circulars (nothing beyond the arrival time of the highest energy photon, extended emission time, and sometimes LAT Low Energy (LLE) multipeak width duration). The range of rise times covered in the time profile systematic error is more important than the default model’s rise time. To support the results given in Table 7.5, we provide plots specific to each GRB and finally show the time-integrated differential flux upper limit along with spectra from other detectors for each burst. Information on an individual GRB’s data quality and Monte Carlo comparisons is given in Appendix A while the assumptions made for each external instrument’s energy spectrum are clarified in Appendix B.

### 7.2 Fermi LAT burst analysis

#### 7.2.1 GRB 130504C

There is no known redshift for GRB 130504C, but the Fermi LAT detector observed emission $>100$ MeV lasting out to 1000 s with a $\sim5$ GeV photon arriving at $T_0+250$ s [157]. GRB 130504C occurred in May 2013 during the HAWC-27 construction phase at a zenith angle of $\sim30^\circ$. The large bin size in Table 7.3 reflects the small number of PMTs available for reconstruction as well as the uncertainty in the accuracy of the simulations of the data recorded at that time. For HAWC-27, there is not enough data to significantly reconstruct the Crab to more accurately determine the point spread function (PSF) of the detector at that time, as described in Section 5.2.2. For this reason, in this case, the Monte Carlo bin size and the data bin size are the same while other bursts use the information from the Crab PSF for the choice of bin size. Additionally, unlike those of the other GRBs, the analysis of GRB 130504C does not use any gamma/hadron separation cuts due to the small array.
Table 7.1: External GRB Alert Information for GRBs seen by Fermi LAT in the FoV of HAWC during up-time.

<table>
<thead>
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<th>Name</th>
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<th>Date</th>
<th>Time (UTC)</th>
<th>RA (J2000)</th>
<th>Dec (J2000)</th>
<th>Source</th>
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<tbody>
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<td>2013-05-04</td>
<td>23:28:57.0</td>
<td>91.63°</td>
<td>3.83°</td>
<td>Swift-XRT</td>
</tr>
<tr>
<td>130518A</td>
<td>130518580</td>
<td>2013-05-18</td>
<td>13:54:37.0</td>
<td>355.67°</td>
<td>47.48°</td>
<td>Swift-BAT</td>
</tr>
<tr>
<td>130702A</td>
<td>130702004</td>
<td>2013-07-02</td>
<td>0:5:23.0</td>
<td>217.31°</td>
<td>15.77°</td>
<td>iPTF</td>
</tr>
<tr>
<td>140729A</td>
<td>140729026</td>
<td>2014-07-29</td>
<td>00:36:53.7</td>
<td>195.95°</td>
<td>15.35°</td>
<td>Fermi-LAT</td>
</tr>
<tr>
<td>140810A</td>
<td>140810782</td>
<td>2014-08-10</td>
<td>18:46:10.09</td>
<td>119.04°</td>
<td>27.55°</td>
<td>Fermi-LAT</td>
</tr>
</tbody>
</table>

Table 7.2: Simulated burst information used to determine optimal cuts and convert number of events to flux.

<table>
<thead>
<tr>
<th>Name</th>
<th>Construction Phase</th>
<th>Duration</th>
<th>$\theta_{GRB}$ ($\theta_{MC}$)</th>
<th>Redshift/ Cutoff Energy$^\dagger$</th>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>130504C</td>
<td>HAWC-27</td>
<td>105 s</td>
<td>29.69° (29°)</td>
<td>100 GeV</td>
<td>-2</td>
</tr>
<tr>
<td>130518A</td>
<td>HAWC-48</td>
<td>100 s</td>
<td>29.30° (29°)</td>
<td>$z = 2.488$</td>
<td>-2</td>
</tr>
<tr>
<td>130702A</td>
<td>HAWC-88</td>
<td>59 s</td>
<td>31.85° (31.5°)$^\ast$</td>
<td>$z = 0.145$</td>
<td>-2</td>
</tr>
<tr>
<td>140729A</td>
<td>HAWC-78</td>
<td>78 s</td>
<td>21.69° (21.5°)$^\ast$</td>
<td>100 GeV</td>
<td>-2</td>
</tr>
<tr>
<td>140810A</td>
<td>HAWC-80</td>
<td>100 s</td>
<td>23.70° (24°)</td>
<td>100 GeV</td>
<td>-2</td>
</tr>
</tbody>
</table>

$^\dagger$ Duration is only relevant for choosing the optimal cuts, not for the conversion to flux.

$^\ast$ Optimized using the average from GRBs simulated at 29° and 34° (GRB 130702A) and 19° and 24° (GRB 140729A).

Table 7.3: Optimal cuts for each GRB analysis. Optimized using data distributions for the background.

<table>
<thead>
<tr>
<th>Name</th>
<th>Trigger Cut</th>
<th>MC bin size</th>
<th>Data bin size</th>
<th>$\chi^2$ core</th>
<th>$\Delta Q_{Pois}$ with gh cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>130504C</td>
<td>10</td>
<td>4°</td>
<td>4°</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>130518A</td>
<td>12</td>
<td>2.47°</td>
<td>2.49°</td>
<td>11.6</td>
<td>+6%</td>
</tr>
<tr>
<td>130702A</td>
<td>15</td>
<td>1.85°</td>
<td>1.87°</td>
<td>18.8</td>
<td>+21%</td>
</tr>
<tr>
<td>140729A</td>
<td>17</td>
<td>2.00°</td>
<td>2.02°</td>
<td>15.2</td>
<td>+12%</td>
</tr>
<tr>
<td>140810A</td>
<td>17</td>
<td>2.12°</td>
<td>2.14°</td>
<td>14.4</td>
<td>+10%</td>
</tr>
</tbody>
</table>
Table 7.4: Upper limit default time profile parameters. $T_{90}$ and $T_{05}$ are calculated for the time window $[-200s, 1800s]$.

<table>
<thead>
<tr>
<th>Name</th>
<th>$T_{90}$</th>
<th>$T_{05}$</th>
<th>Crystal Ball</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$\mu$</td>
<td>$\sigma$</td>
<td>$\alpha$</td>
<td>$n$</td>
</tr>
<tr>
<td>130504C</td>
<td>205s</td>
<td>27.67s</td>
<td>30.78s</td>
<td>2.0s</td>
<td>-2.00</td>
<td>1</td>
</tr>
<tr>
<td>130518A</td>
<td>100s</td>
<td>5.23s</td>
<td>10s</td>
<td>3.0s</td>
<td>-2.15</td>
<td>1</td>
</tr>
<tr>
<td>130702A</td>
<td>59s</td>
<td>0.73s</td>
<td>2s</td>
<td>0.8s</td>
<td>-2.20</td>
<td>1</td>
</tr>
<tr>
<td>140729A</td>
<td>78s</td>
<td>3.93s</td>
<td>10s</td>
<td>3.8s</td>
<td>-2.20</td>
<td>1</td>
</tr>
<tr>
<td>140810A</td>
<td>100s</td>
<td>1.50s</td>
<td>5s</td>
<td>2.2s</td>
<td>-2.20</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.5: Likelihood analysis results.

<table>
<thead>
<tr>
<th>Name</th>
<th>$D_{obs}$</th>
<th>$n_s$</th>
<th>$n_s$ Statistical Error</th>
<th>$n_s$ Systematic Error</th>
<th>Total Error</th>
<th>$\Phi_{max}$ [erg/cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Time Profile</td>
<td></td>
<td>31.6-100 GeV 100-316 GeV</td>
</tr>
<tr>
<td>130504C</td>
<td>-14.65</td>
<td>84</td>
<td>±1.7</td>
<td>+30</td>
<td>+45</td>
<td>1.3$^{+0.68}<em>{-0.75}$ $\times 10^{-4}$ 3.0$^{+1.6}</em>{-1.8}$ $\times 10^{-5}$</td>
</tr>
<tr>
<td>130518A</td>
<td>-9.59</td>
<td>64</td>
<td>±0.56</td>
<td>+12</td>
<td>+28</td>
<td>1.1$^{+0.48}<em>{-0.78}$ $\times 10^{-4}$ 1.8$^{+0.81}</em>{-1.3}$ $\times 10^{-5}$</td>
</tr>
<tr>
<td>130702A</td>
<td>-14.81</td>
<td>26</td>
<td>±0.68</td>
<td>+21</td>
<td>+24</td>
<td>4.0$^{+3.7}<em>{-2.0}$ $\times 10^{-5}$ 6.3$^{+5.9}</em>{-3.2}$ $\times 10^{-6}$</td>
</tr>
<tr>
<td>140729A</td>
<td>-17.04</td>
<td>33</td>
<td>±1.1</td>
<td>+3</td>
<td>+14</td>
<td>2.4$^{+0.98}<em>{-1.7}$ $\times 10^{-5}$ 3.4$^{+1.4}</em>{-2.5}$ $\times 10^{-6}$</td>
</tr>
<tr>
<td>140810A</td>
<td>-14.56</td>
<td>40</td>
<td>±1.9</td>
<td>+15</td>
<td>+22</td>
<td>4.0$^{+2.2}<em>{-2.3}$ $\times 10^{-5}$ 5.1$^{+2.8}</em>{-2.9}$ $\times 10^{-6}$</td>
</tr>
</tbody>
</table>
Figure 7.1: Data from GRB 130504C with likelihood best fit. The full PDF is shown in red with the background component highlighted in blue. The resulting test statistic from the fit is $D_{\text{obs}} = -14.65$, which is not significant given the null likelihood light curve results.

After finding the background PDF using direct integration, we compute the test statistic needed for a significant detection and then fit the data. The best fit is shown in Figure 7.1 with a resulting test statistic of $D_{\text{obs}} = -14.65$. Since this value is not greater than that needed for a significant detection, we move on to determine the upper limit for this burst. First, a reference Crystal Ball time profile is chosen. This is shown in Figure 7.2a and determined from information in the GCN circulars [157–159] and trends from the Fermi LAT catalog. We then create the confidence interval band seen in Figure 7.2b to determine the upper limit on the number of events from GRB 130504C. The 90% CL limit is $84 \pm 1.7$ events.

Next we determine the systematic error due to the unknown time profile. The time profiles tested and subsequent discovery potentials are shown in Figures 7.3 and 7.4 for different functional forms and peak widths respectively. These errors are combined in quadrature to produce the time profile error in Table 7.5, and the total error is produced by combining all sources of error in quadrature. The final upper limit becomes $84^{+45}_{-50}$. Figure 7.5 shows this limit converted to time-integrated...
Figure 7.2: Confidence Level band for GRB 130504C with $D_{\text{obs}}$ (black dashed line) and statistical error (red band). The upper limit on the mean flux $n_s$ from the GRB is $84 \pm 1.7$ events, given the model shown in the top plot.
(a) GRB 130504C assumed time profiles with different functional shapes.

(b) Discovery potential for different functional forms of the GRB 130504C time profile.

Figure 7.3: Functional shape discovery potential for GRB 130504C assuming the above time profiles. The range in 50% flux values (dashed vertical lines) yields the percent systematic error due to the unknown peak width of the true GRB profile. The lower limit from the Gaussian is 15% while the Crystal Ball itself is the upper limit in this case.
(a) GRB 130504C assumed time profiles with different peak widths.

(b) Discovery potential for different peak widths of the GRB 130504C time profile.

Figure 7.4: Peak width discovery potential for GRB 130504C assuming the above time profiles. The range in 50% flux values (dashed vertical lines) yields the percent systematic error due to the unknown peak width of the true GRB profile. The upper limit from the wide peak ($\sigma=5\,\text{s}$) is 36% of the Crystal Ball flux while the lower limit from the narrow peak ($\sigma=0.2\,\text{s}$) is 40%.
Figure 7.5: Time-integrated differential flux 90% CL upper limits for GRB 130504C. Two energy bands are defined from 31.6 to 100 GeV and 100 to 316 GeV with an $E^2$ spectrum assumed in each band. The light gray band represents the total error on the flux while the darker band shows part of the error related to the GRB time profile model dependence. Reference spectra from Fermi GBM (red) [158], Konus-Wind (blue) [159], and Fermi LAT (magenta) [160] are shown as well.

differential flux units. The GRB is assumed to have an $E^{-2}$ energy spectrum with all of the 84 allowed signal events contained in each individual energy band. The total error is shown through the light gray band in Figure 7.5 while the time profile portion of the total error is specified by the darker band. Energy spectra from [158] and [159] are shown for reference. The HAWC limits for GRB 130504C do not strongly constrain this burst.

7.2.2 GRB 130518A

GRB 130518A occurred in May 2013 as well but during a later construction phase with more tanks, HAWC-48. Fortunately, optical instruments were able to capture a redshift for the burst. Unfortunately, it is quite far away at $z = 2.488$ [161,162] so much of the VHE emission is attenuated by the EBL. The Fermi LAT instrument
observed emission lasting approximately 100 s [163].

As GRB 1305018A is at approximately the same zenith angle as GRB 130504C, the impact of the larger array is immediately evident in the smaller optimal bin size in Table 7.3. Additionally, we are now able to apply a gamma/hadron separation cut. Due to some discrepancy between the compactness and angular fit $\chi^2$ distributions for background Monte Carlo and data, we do not cut on these parameters, although they should be useful in future analyses. Only the core fit $\chi^2$ cut is employed to separate hadrons from gammas at this time.

The best fit to the data for GRB 130518A is shown in Figure 7.6 with a resulting test statistic of $D_{obs} = -9.59$. Although this value is higher than that for GRB 130504C, it is still not greater than that needed for a significant detection; upper limits must be found. The reference Crystal Ball time profile is shown in Figure 7.7a and the confidence interval band is displayed in Figure 7.7b. The 90% CL upper limit for GRB 130518A is 64 ± 0.56 events.

The systematic error due to the unknown time profile for this burst is found next. The time profiles tested and corresponding discovery potentials are shown
Figure 7.7: Confidence Level band for GRB 130518A with $D_{\text{obs}}$ (black dashed line) and statistical error (red band). The upper limit on the mean flux $n_s$ from the GRB is $64 \pm 0.56$ events, given the model shown in the top plot.
Figure 7.8: Functional shape discovery potential for GRB 130518A assuming the above time profiles. The upper limit from the Landau is 3% of the Crystal Ball flux while the lower limit from the Gaussian is 10%.
(a) GRB 130518A assumed time profiles with different peak widths.

(b) Discovery potential for different peak widths of the GRB 130518A time profile.

Figure 7.9: Peak width discovery potential for GRB 130518A assuming the above time profiles. The upper limit from the wide peak ($\sigma=5$ s) is 19% of the Crystal Ball flux while the lower limit from the narrow peak ($\sigma=0.2$ s) is 57%.
Figure 7.10: Time-integrated differential flux 90% CL upper limits for GRB 130518A. The same energy band conventions are used as in Figure 7.5. For the HAWC-48 limits, an $E^2$ energy spectrum. The large redshift of the burst, $z = 2.488$, causes the absorption of the VHE emission from interactions with the EBL. Reference spectra from Fermi GBM (red) [164] and Konus-Wind (blue) [165] are shown as well with the corresponding absorption by the EBL. The observed spectrum from Konus-Wind must be modified to be consistent with the HAWC limits.

in Figures 7.8 and 7.9 for different functional forms and peak widths respectively. We combine these errors with the 40% from the data/MC discrepancy to yield the final upper limit: $64^{+28}_{-45}$. Figure 7.10 shows this limit. An $E^2$ power-law spectrum is assumed in each of the energy bands. Attenuation from the EBL for a source at $z = 2.488$ is shown assuming spectra from [164] and [165]. The upper limits for this burst verify that the Konus-Wind spectrum cannot extend unmodified $>100$ GeV.

7.2.3 GRB 130702A

GRB 130702A is an extremely close burst with a redshift of $z = 0.145$ [166][167] and is associated with Supernova SN 2013dx [168][170]. The Fermi LAT satellite observed a 1.5 GeV photon 260 s after the GBM trigger and more than five photons
Figure 7.11: Data from GRB 130702A with likelihood best fit. The resulting test statistic from the fit is $D_{\text{obs}} = -14.81$, which is not significant given the null likelihood light curve results.

above 100 MeV in 2200 s [171]. This is the most exciting GRB analyzed in this dissertation.

The burst happened during July 2013 when the HAWC array had 88 instrumented tanks. With the most active PMTs, the bin size for GRB 130702A is the smallest of the analysis since reconstruction becomes more accurate with the addition of PMTs. Similarly, with the larger array size the gamma/hadron separation power becomes greater as seen in the final column of Table 7.3.

Figure 7.6 displays the best fit from the likelihood analysis to the data for GRB 130702A. The observed test statistic from this fit is $D_{\text{obs}} = -14.81$. While this do not provide a significant detection of the GRB, the upper limit on the number of photons does help constrain the source characteristics. The Crystal Ball time profile used to determine the limit is shown in Figure 7.7a and the confidence interval band is displayed in Figure 7.7b. The 90% CL upper limit for GRB 130702A is 26 ± 0.68 events.

Systematic errors from the unknown GRB time profile are determined from the distributions shown in Figures 7.13a and 7.14a. The range on the error is taken
(a) Assumed Crystal Ball time profile for GRB 130702A.

(b) Confidence Level band for GRB 130702A.

Figure 7.12: Confidence Level band for GRB 130702A with $D_{\text{obs}}$ (black dashed line) and the statistical error (red band). The upper limit on the mean flux $n_s$ from the GRB is $26 \pm 0.68$ events, given the model shown in the top plot.
(a) GRB 130702A assumed time profiles with different functional shapes.

(b) Discovery potential for different functional forms of the GRB 130702A time profile.

Figure 7.13: Functional shape discovery potential for GRB 130702A assuming the above time profiles. The upper limit from the Landau is 6% of the Crystal Ball flux while the lower limit from the Gaussian is 11%.
(a) GRB 130702A assumed time profiles with different peak widths.

(b) Discovery potential for different peak widths of the GRB 130702A time profile.

Figure 7.14: Peak width discovery potential for GRB 130702A assuming the above time profiles. The upper limit from the wide peak ($\sigma=5\,\text{s}$) is 83% of the Crystal Ball flux while the lower limit from the narrow peak ($\sigma=0.2\,\text{s}$) is 27%.
Figure 7.15: Time-integrated differential flux 90% CL upper limits for GRB 130702A. The same energy band conventions are used as in Figure 7.5. The burst’s redshift is $z = 0.145$. *Fermi* GBM (red) and Konus-Wind (blue) did not observe cutoffs the energy spectrum of the burst [172,173]. Assuming the given EBL model (green), the HAWC upper limits show that the source spectra does not extend with the spectral index observed by the GBM.

from the corresponding discovery potentials in Figures 7.13 and 7.14. Combining these errors with that from the difference between data and Monte Carlo yields a 90% CL upper limit of $26^{+24}_{-13}$ for GRB 130702A. The upper limits for our two energy bands are shown in Figure 7.15. Neither the *Fermi* GBM nor Konus-Wind satellites observed a cutoff in energy for the burst [172,173]. Extending the power laws to HAWC energies and applying EBL attenuation for a source at $z = 0.145$, we can determine that the intrinsic source spectra cannot follow the GBM power law given the assumptions of this analysis. These limits could potentially be of use in modeling the VHE emission from GRB 130702A, whether it be SSC, Inverse Compton or another mechanism of radiation.
Figure 7.16: Data from GRB 140729A with likelihood best fit. The resulting test statistic from the fit is $D_{\text{obs}} = -17.04$, which is not significant given the null likelihood light curve results.

7.2.4 GRB 140729A

GRB 140729A occurred over a year later during July 2014. Unfortunately this happened after a lightning incident damaged a large fraction of the HAWC array. For this reason, only 78 tanks were instrumented and working at the time, fewer than were active for GRB 130702A. As the sensitivity of HAWC greatly increases with additional PMTs, this was quite unfortunate. The zenith angle of the burst is the most favorable of the five GRBs analyzed here, being at $\sim 20^\circ$. No redshift was observed for GRB 140729A. The Fermi LAT satellite observed more than 100 photons above 100 MeV and 13 photons above 1 GeV [174]. A 1.3 GeV photon arrived 44 s after the GBM trigger.

Figure 7.16 displays the best fit from the likelihood analysis to the data for GRB 140729A. The observed test statistic from this fit is $D_{\text{obs}} = -17.04$, not significant. Figure 7.17b shows the reference Crystal Ball function used to determine the upper limits for this burst with the corresponding Feldman-Cousins confidence interval band. The 90% CL upper limit for GRB 140729A is $33 \pm 1.1$ events.
Figure 7.17: Confidence Level band for GRB 140729A with $D_{\text{obs}}$ (black dashed line) and the statistical error (red band). The upper limit on the mean flux $n_s$ from the GRB is $33 \pm 1.10$ events, given the model shown in the top plot.
(a) GRB 140729A assumed time profiles with different functional shapes.

(b) Discovery potential for different functional forms of the GRB 140729A time profile.

Figure 7.18: Functional shape discovery potential for GRB 140729A assuming the above time profiles. The upper limit from the Landau is 6% of the Crystal Ball flux while the lower limit from the Gaussian is 11%.
(a) GRB 140729A assumed time profiles with different peak widths.

(b) Discovery potential for different peak widths of the GRB 140729A time profile.

Figure 7.19: Peak width discovery potential for GRB 140729A assuming the above time profiles. The upper limit from the wide peak ($\sigma=5$ s) is 10% of the Crystal Ball flux while the lower limit from the narrow peak ($\sigma=0.2$ s) is 60%.
Figure 7.20: Time-integrated differential flux 90% CL upper limits for GRB 140729A. The same energy band conventions are used as in Figure 7.5. Reference spectra from Fermi GBM (red) [175] and Konus-Wind (blue) [176] are shown as well.

Following the same procedure, systematic errors from the unknown GRB time profile are determined from the range in the discovery potentials from the distributions shown in Figures 7.18 and 7.19. These errors, combined with those from data/MC, yield the total error for the limit. The final 90% CL upper limit for GRB 140729A is $33^{+14}_{-24}$ events. The converted time-integrated differential flux is shown for the standard energy bands in Figure 7.20. The spectra from Fermi GBM and Konus-Wind detectors, the limits by HAWC do not strongly constrain the burst or EBL characteristics.

### 7.2.5 GRB 140810A

Shortly after GRB 140729A, GRB 140810A, the last Fermi LAT burst in this dataset, occurred in August 2014. A couple more tanks in the array were active again although the whole detector had not returned to its pre-lightning size. The
Figure 7.21: Data from GRB 140810A with likelihood best fit. The resulting test statistic from the fit is $D_{\text{obs}} = -14.56$, which is not significant given the null likelihood light curve results.

The zenith angle of the burst is $\sim 24^\circ$, and, unfortunately, no redshift was observed for GRB 140810A. More than 20 photons above 100 MeV and 3 photons above 1 GeV were observed by the LAT [177]. The highest-energy photon, 16 GeV, was detected 1500 s after the GBM $T_0$.

The best fit to the data from the likelihood analysis for GRB 140810A is shown in Figure 7.21. The observed test statistic from this fit is not significant, $D_{\text{obs}} = -14.56$. Figure 7.22b shows the reference Crystal Ball function used to determine the upper limits for this burst with the corresponding Feldman-Cousins confidence interval band. The 90\% CL upper limit for GRB 140810A is $40 \pm 1.9$ events.

The range in the systematic errors due to the unknown GRB time profile are shown in Figures 7.23 and 7.24 for different functional forms and peak widths of the time profile. Combining these errors with those from data/MC yield the total error for the limit. The final 90\% CL upper limit for GRB 140810A is $40^{+22}_{-23}$ events.

The converted time-integrated differential flux is shown for the standard energy bands in Figure 7.25. The spectra from [178] and [179] are shown for reference. Due
(a) Assumed Crystal Ball time profile for GRB 140810A.

(b) Confidence Level band for GRB 140810A.

Figure 7.22: Confidence Level band for GRB 140810A with $D_{\text{obs}}$ (black dashed line) and the statistical error (red band). The upper limit on the mean flux $n_s$ from the GRB is $40 \pm 1.9$ events, given the model shown in the top plot.
(a) GRB 140810A assumed time profiles with different functional shapes.

(b) Discovery potential for different functional forms of the GRB 140810A time profile.

Figure 7.23: Functional shape discovery potential for GRB 140810A assuming the above time profiles. The upper limit from the Bifurcated Gaussian is 1% of the Crystal Ball flux while the lower limit from the Gaussian is 9%.
(a) GRB 140810A assumed time profiles with different peak widths.

(b) Discovery potential for different peak widths of the GRB 140810A time profile.

Figure 7.24: Peak width discovery potential for GRB 140810A assuming the above time profiles. The upper limit from the wide peak ($\sigma=5\,\text{s}$) is 36% of the Crystal Ball flux while the lower limit from the narrow peak ($\sigma=0.2\,\text{s}$) is 41%.
Figure 7.25: Time-integrated differential flux 90% CL upper limits for GRB 140810A. The same energy band conventions are used as in Figure 7.5. Reference spectra from Fermi GBM (red) [178] and Konus-Wind (blue) [179] are shown as well.

to the cutoffs in energy observed by the Fermi GBM and Konus-Wind detectors, the limits by HAWC do not strongly constrain the burst or EBL characteristics.
7.3 Outlook for VHE GRB observations with HAWC

Although no GRBs were significantly detected in this dissertation, the outlook for a VHE GRB observation by the HAWC observatory remains strong. The likelihood analysis technique demonstrated in this work substantially increases the sensitivity of HAWC to GRBs. Upper limits on VHE emission for five Fermi LAT-observed bursts were set. The upper limit for GRB 130702 is particularly interesting since no high energy cutoff was observed by the lower energy satellite instruments, and the redshift is known. With less than 1/3 of the array active, the HAWC observatory limits for GRB 130702A, which is not a particularly bright GRB, reach comparable sensitivity to lower energy instruments and are not limited by the EBL.

There are several avenues forward to improve this analysis. First, simply increasing the number of GRBs in the search will increase the probability of a detection. There is no need to restrict the analysis to only Fermi LAT GRBs. Many GRBs from Swift and the GBM, for example, also occur in the FoV of HAWC and should be considered. Second, expand the likelihood method to look not just in time but in space as well. Not all GRBs are well localized, especially those seen only by the GBM, so fitting the position as well as the time profile could help the sensitivity of the analysis. Third, expand the range of time profiles tested. This would help cover more of the parameter space and thus help the limits constrain more situations. Fourth, the analysis could be split into energy bins similar to those described in Section 5.2.2 for the Crab analysis. If there is strong high energy emission from a GRB, a weighted analysis could enhance the significance from the high energy component, although not as many energy bins would be necessary as in the Crab study. Finally, a specific low energy trigger could help as well. Lowering the SMT trigger threshold by even one PMT increases the sensitivity of HAWC drastically so a more advanced triggering method could easily lower the energy threshold. For example, using multiple time windows with different SMT thresholds could allow smaller showers to trigger the detector without overwhelming the DAQ.

There are also general improvements over time that will help HAWC analyses. For example, as more data is taken and analyzed, the Monte Carlo can become more accurate. Improvements in the simulation help limit the systematic error in the flux normalization due to data/Monte Carlo discrepancy. With more confidence in the simulation, we may also be able to use the other gamma/hadron separation
parameters described in Chapter 4.1.3 rather than only the core fit \( \chi^2 \) cut employed here. The calibration of the detector also becomes more accurate with more data and a more stable configuration. Understanding the charge discrepancy as well as ensuring quality time residuals is important for future HAWC analyses. Additionally, the reconstruction algorithms themselves can also be improved. The core fitter, for instance, has already undergone numerous incarnations despite the detector not even being fully built. A combined core and angular fit could potentially increase the accuracy of the reconstruction. New gamma/hadron separation parameters are under investigation as well. In particular, a method using the mean spatial spread of the mean charge in a selection of hits shows promise at low energies.

While the likelihood analysis is performed offline for externally triggered bursts, other GRB analyses do not have those restrictions. Two analyses are currently run online in real-time at the site. One analysis blindly searches the sky for GRBs, looking for an excess in counts in time and space without an external trigger, while the other looks in specific time windows for externally triggered GRBs. These are designed to be able to provide external alerts to the community as well as receive and act upon alerts sent to HAWC. The blind real-time analysis can detect previously unknown GRBs, which is especially relevant for the more difficult to catch short GRBs.

With the full detector now complete, Figure 7.26, the sensitivity of HAWC has greatly increased. The larger data set and near-continuous duty cycle will make HAWC the most sensitive full sky ground-based TeV detector with a bright future for VHE GRB discovery.

Figure 7.26: HAWC-300 array on February 25, 2015. With the detector complete, future GRB discoveries await!
Appendix A
Data Quality Checks and Data/Monte Carlo Comparisons

This appendix contains the detailed background information described in Chapters 4 and 5 needed for the likelihood GRB analysis. For consistency, we show plots for every GRB, even those already displayed in the previously mentioned chapters. Reconstruction quality cuts on the status of the angular fit result and event flags are always applied. Additionally, we require $\theta < 45^\circ$ as another quality cut.

A.1 GRB 130504C

GRB 130504C occurred during the HAWC-27 construction phase. We first review the data quality plots shown in Section 4.2 and then show the data/Monte Carlo comparisons that support the systematic error for the flux conversion factor in Section 5.2. Figure A.1a shows the one-second time bin rate in blue and the corresponding 5 s average rate in red for GRB 130504C. The rate is $\sim 5.25$ kHz with no obvious problems. The rate residuals, deviations from the average rate, for GRB 130504C are shown in Figure A.1b. There are no differences greater than 10%. Figure A.2 shows the angular chi-square distributions for the zenith and azimuth angles in two-minute intervals for GRB 130504C. None of the values come close to the quality cut.

We simulate the positions of the PMTs active at the time of the burst to get the most accurate representation of the detector. In the following figures, data is shown in blue while hadron Monte Carlo is shown in red. The SMT trigger rate multiplicity is shown in Figure A.3. The rate is accurately reproduced, although at
Figure A.1: Rate data quality check for GRB 130504C. *Top:* Rate relative to the GRB trigger time $T_0$ for GRB 130504C with the one-second rate in blue and the five-second symmetric moving average rate in red. *Bottom:* Rate residuals, the percent difference between the blue and red lines in Figure A.1a. No gaps or problems are evident in the data, and no large residuals exist. This burst passes the rate data quality check.
the highest $nHit$ values the distributions are slightly dissimilar due to hit-dropping in the DAQ, which has since been rectified. Since the gamma-ray events from GRBs are expected at the low energy range of the HAWC detector, the discrepancy at high $nHit$ does not cause a large error. The total rate difference for this GRB is $<1\%$. The zenith angle distribution is shown in Figure A.4. The shape of the distribution accurately represents data, thus not contributing to any systematic error based on pointing. Due to uncertainty in calibration at the time of analysis, no gamma/hadron separation was applied for this burst. We no large error from the background data/MC comparison for this dataset, we use the 40% uncertainty from the Crab analysis described in Section 5.2.2 as the systematic error.
Figure A.3: Comparison of data (blue) and Monte Carlo (red) multiplicity trigger rate distribution for GRB 130504C. The total rate difference is <1%, which does not contribute significantly to the systematic error.

Figure A.4: Zenith angle distribution comparison for GRB 130504C. The shape of the distribution is accurately simulated, adding no significant pointing error for this burst.
A.2 GRB 130518A

Figure A.5a shows the one-second time bin rate in blue and the corresponding 5s average rate in red for GRB 130518A. At \( \sim 4000 \) s after the burst, the detector rate jumps from \( \sim 7.4 \text{kHz} \) to \( \sim 7.5 \text{kHz} \). There is no information in the logbook regarding any changes taking place at the site during this period; the cause remains unclear. Regardless, the background estimation technique uses data prior to the burst and any signal beyond 1800 s is outside the likelihood time window so the jump does not affect the analysis. (Also, direct integration takes care of rate discrepancies.) The rate residuals for GRB 130518A are shown in Figure A.5b. There are no differences greater than 10%. However, there are two outliers from the distribution, one of which falls inside the likelihood time window around 1500 s. Figure A.6 shows the angular chi-square distributions for the zenith and azimuth angles in two-minute intervals for GRB 130518A. None of the values come close to the quality cut.

To get the most accurate representation of the detector, we again simulate the positions of the PMTs active at the time of the burst. The trigger cut and gamma/hadron separation cut from Table 7.3 are applied in the following two distributions. The SMT trigger rate multiplicity is shown in Figure A.7. The discrepancy at high \( nHit \) is due to the same issue as for the GRB 130504C comparison: hit dropping. Again, since the gamma-ray events from GRBs are expected at the low energy range of HAWC, the discrepancy at high \( nHit \) does not cause a large error. The total rate difference for this GRB is \( \approx 5\% \). The zenith angle distribution is shown in Figure A.8. The shape of the distribution accurately represents data, except at the zenith angles beyond \( \sim 40^\circ \).

Distributions of the gamma/hadron separation parameters described in Sections 4.1.3 and 5.3.1.3 are shown in Figures A.9, A.10, and A.11 (without the core fit \( \chi^2 \) cut from Table 7.3 applied). Although the shape of the compactness distribution is similar, we do not use this cut due to the PE scale uncertainty in the Monte Carlo. The compactness parameter is strongly dependent upon large charge signals being accurate. Figure A.10 shows the angular fit \( \chi^2 \) parameter. The large discrepancy between the shape of the data and Monte Carlo for this distribution indicates that it is not a reliable parameter at this time. The only background rejection parameter employed in this dissertation is shown in Figure A.11. For the remaining bursts, we only show the core fit \( \chi^2 \) distribution.
Figure A.5: Rate data quality check for GRB 130518A. The plots follow the same description as in Figure A.1. No rate issues occur prior to or inside the likelihood analysis time window (<1800s), and no residuals are greater than 10%.

(a) Rate distribution for GRB 130518A quality check.

(b) Residuals for the rate distributions for GRB 130518A.
Figure A.6: Reduced chi-square for zenith (top) and azimuth (bottom) distributions for GRB 130518A. The plots follow the same description as in Figure A.2. No values are above the quality cut.
Figure A.7: Comparison of data (blue) and Monte Carlo (red) multiplicity trigger rate distribution for GRB 130518A.

Figure A.8: Comparison of data (blue) and Monte Carlo (red) zenith angle distribution for GRB 130518A.
Figure A.9: Compactness distribution for GRB 130518A. Charge uncertainty in the simulation makes this parameter unreliable. It is not used in this analysis.

Figure A.10: Angular fit reduced $\chi^2$ distribution for GRB 1301518A. This parameter is not used for background rejection due to the shape discrepancy between the data and Monte Carlo.
Figure A.11: Core fit reduced $\chi^2$ distribution for GRB 130518A. This is the only background rejection parameter used in the analysis. The optimal cut is at 11.6, which increases $Q_{\text{Pois}}$ by 6%. The cut removes $\sim$23% of the gammas from the burst simulated in Table 7.2 and $\sim$50% of background (data).
A.3 GRB 130702A

Figure A.12a shows the one-second time bin rate and the corresponding 5 s average rate for GRB 130702A. The gap in the rate from $\sim$3425 s to $\sim$3225 s is the transition between runs. This gap does not effect the background estimation. The rate residuals for GRB 130702A are shown in Figure A.12b. The differences greater than 10% (not shown) and the excess at zero are due to the gap. The outlier at $\sim$7% is due to this as well. Figure A.13 shows the angular chi-square distributions for the zenith and azimuth angles in two-minute intervals for GRB 130702A. None of the values come close to the quality cut.

Monte Carlo simulation for this burst has the same PMTs active as in data. The SMT trigger rate multiplicity is shown in Figure A.14 with the trigger cut and background rejection cut from Table 7.3 applied. Hit dropping is still present at high $nHit$. The total rate difference for this GRB is $\approx 7\%$. The zenith angle distribution is shown in Figure A.15. Figure A.16 displays the core fit $\chi^2$ distribution for GRB 130702A. The optimal cut is at 18.8.

A.4 GRB 140723A

GRB 140723A is the Fermi LAT burst mentioned in Section 7.1, the GRB that closely followed a lightning strike to the detector, which briefly damaged the DAQ. During the period of time around GRB 140723A, the clock was jittery and data occasionally received the wrong time stamp. Binning the data every 10 ms shows this. The bad data from GRB 140723A is shown in Figure A.17 followed by data from GRB 140810A in Figure A.18 with the same binning for comparison. The instability of the rate for GRB 140729A made this GRB too difficult to analyze.
Figure A.12: Rate data quality check for GRB 130702A. The plots follow the same description as in Figure A.1. The rate gap represents the transition between data runs. The differences greater than 10% in the bottom plot (not shown) and excess at zero are due to the gap and do not affect the analysis.
Figure A.13: Reduced chi-square for zenith (top) and azimuth (bottom) distributions for GRB 130702A. The plots follow the same description as in Figure A.2. None of the values come close to the quality cut.
Figure A.14: Comparison of data (blue) and Monte Carlo (red) multiplicity trigger rate distribution for GRB 130702A.

Figure A.15: Comparison of data (blue) and Monte Carlo (red) zenith angle distribution for GRB 130702A.
Figure A.16: Core fit reduced $\chi^2$ distribution for GRB 130702A. This is the only background rejection parameter used in the analysis. The optimal cut is at 18.8, which increases $Q_{Pois}$ by 21%. The cut removes $\sim 10\%$ of the gammas from the burst simulated in Table 7.2 and $\sim 45\%$ of background (data).
Figure A.17: Data for GRB 140723A in 10 µs bins (blue) and the 50 µs moving average rate (red). The jitter of the clock is evident in the outliers from the standard rate. This GRB was not able to be analyzed.

Figure A.18: Data for GRB 140810A in 10 µs bins (blue) and the 50 µs moving average rate (red) for comparison. There is not a wide range in the rate.
A.5 GRB 140729A

The one-second time bin rate and the corresponding 5 s average rate are displayed for GRB 140729A in Figure A.19a. There are no gaps in the data, but prior to -6000 s, the detector rate jumps to \(\sim 7.7\) kHz before settling back to \(\sim 7.5\) kHz. The cause of the rate jump is unclear as the run appears to be standard in the logbook. As previously stated, the background estimation technique takes care of rate discrepancies such as this so despite the unknown cause, since it is outside the GRB analysis window, the data are okay. The rate residuals for GRB 140729A are shown in Figure A.19b. There are no differences greater than 10%. Figure A.20 shows the angular chi-square distributions for the zenith and azimuth angles in two-minute intervals for GRB 140729A. None of the values come close to the quality cut.

The SMT trigger rate multiplicity is shown in Figure A.21. The trigger cut and background rejection cut from Table 7.3 is applied, and hit dropping is evident. The total rate difference for this GRB is \(\approx 13\%\). The zenith angle distribution is shown in Figure A.22. Figure A.23 displays the core fit \(\chi^2\) distribution for GRB 140729A. The optimal cut is at 15.2.

A.6 GRB 140810A

Figure A.24a shows the one-second time bin rate and the corresponding 5 s average rate for GRB 140810A. There are no obvious problems with the rate. The rate residuals for GRB 140810A are shown in Figure A.24b with no differences greater than 10%. Figure A.25 shows the angular chi-square distributions for the zenith and azimuth angles in two-minute intervals for GRB 140810A. The zenith distribution fails the \(\chi^2/ndf < 2\) stability cut around 2000 s. While this could indicate an issue with the data, we do not consider this point problematic for several reasons. First, the data is outside of the likelihood analysis time window and thus does not by necessity indicate a problem with the analyzed data. Next, the outlier may just be a remnant of binning effects since it falls below the stability cut when the \(\theta < 45^\circ\) cut is removed or when we use 5 min bins instead of two. Finally, the stability problem occurs after the GRB, while the key stability region is before (and during) the analysis time window for the direct integration background estimate. We therefore
Figure A.19: Rate data quality check for GRB 140729A. The plots follow the same description as in Figure A.1. The jump in the rate at the beginning of the time window does not affect the background estimation, and no residuals are greater than 10%.
do not consider the data quality an issue for this burst.

The SMT trigger rate multiplicity is shown in Figure A.26 with the trigger cut and background rejection cut from Table 7.3 applied. The total rate difference for this GRB is $\approx 14\%$. The zenith angle distribution is shown in Figure A.27. Figure A.28 displays the core fit $\chi^2$ distribution for GRB 140810A. The optimal cut is at 14.4.
Figure A.21: Comparison of data (blue) and Monte Carlo (red) multiplicity trigger rate distribution for GRB 140729A.

Figure A.22: Comparison of data (blue) and Monte Carlo (red) zenith angle distribution for GRB 140729A.
Figure A.23: Core fit reduced $\chi^2$ distribution for GRB 140729A. This is the only background rejection parameter used in the analysis. The optimal cut is at 15.2, which increases $Q_{Pois}$ by 12%. The cut removes $\sim22\%$ of the gammas from the burst simulated in Table 7.2 and $\sim51\%$ of background (data).
Figure A.24: Rate data quality check for GRB 140810A. The plots follow the same description as in Figure A.1. No gaps or problems are evident, and no residuals are greater than 10%.
Figure A.25: Reduced chi-square for zenith (top) and azimuth (bottom) distributions for GRB 140810A. Although one point is higher than $\chi^2/\text{ndf} = 2$, it is outside the analysis time window, disappears with different binning, and is not used during the direct integration background estimation; therefore, this does not indicate that the data should be thrown out.
Figure A.26: Comparison of data (blue) and Monte Carlo (red) multiplicity trigger rate distribution for GRB 140810A.

Figure A.27: Comparison of data (blue) and Monte Carlo (red) zenith angle distribution for GRB 140810A.
Figure A.28: Core fit reduced $\chi^2$ distribution for GRB 140810A. This is the only background rejection parameter used in the analysis. The optimal cut is at 14.4, which increases $Q_{Pois}$ by 10%. The cut removes $\sim25\%$ of the gammas from the burst simulated in Table 7.2 and $\sim53\%$ of background (data).
Appendix B
Reference GRB Spectra

When calculating the sensitivity of HAWC to GRBs, it is useful to reference historical GRBs for comparison. In some of the figures in Chapters 5 and 7, we show points for time-integrated GRB flux or measured spectra at lower energies. In this appendix, we show the derivation of these values from published numbers, GCN circulars, etc.

B.1 Historical GRBs

We show sensitivity as time-integrated differential flux $E^2 \frac{dN}{dE}$ in ergs cm$^{-2}$ at 10 GeV. To make real GRB comparisons, we must make sure that the correct parameters and units are plotted. Energy fluence is defined as

$$F = \int_{E_{\text{min}}}^{E_{\text{max}}} E \frac{dN}{dE} dE.$$  \hspace{1cm} (B.1)

where the units of $F$ are energy (ergs) per unit area (cm$^2$). If we consider the power-law component of a given GRB flux,

$$F = \int_{E_{\text{min}}}^{E_{\text{max}}} E A_{PL} \left( \frac{E}{E_{\text{ref}}} \right) ^\gamma dE$$  \hspace{1cm} (B.2)

where $A_{PL}$ is the constant time-integrated differential flux at the reference energy $E_{\text{ref}}$. Solving for $A_{PL},$

$$F = \frac{A_{PL}}{E_{\text{ref}}^\gamma} \int_{E_{\text{min}}}^{E_{\text{max}}} E^{\gamma+1} dE$$  \hspace{1cm} (B.3)
\[
A_{PL} = \frac{A_{PL}}{2 + \gamma} \left( E_{\text{max}}^{\gamma} \left( \frac{E_{\text{max}}}{E_{\text{ref}}} \right) - E_{\text{min}}^{\gamma} \left( \frac{E_{\text{min}}}{E_{\text{ref}}} \right) \right)
\]

To get the time-integrated differential flux \( E^2 \frac{dN}{dE} \) in ergs cm\(^{-2}\) at 10 GeV, we find

\[
E^2 \frac{dN}{dE} = (10 \text{ GeV})^2 A_{PL} \left( \frac{10 \text{ GeV}}{E_{\text{ref}}} \right)^\gamma
\]

while making sure to use consistent energy units throughout the calculation.

The *Fermi* LAT catalog [57] gives values for the fluence of the extra power-law component of burst spectra in the GBM \( T_{90} \) window in Table 11. We use these values to derived the time-integrated differential flux in Table B.1 for several of the most remarkable GRBs yet observed. For GRB 130427A, we use the flux from the extra power-law component in time interval c given in the supplementary materials of [74]. This is the interval during which the extra component becomes statistically significant.

**B.2 Analyzed GRB Spectra**

We use information provided by GCN circular to draw the time-integrated differential spectra on the upper limit results plots in Chapter 7. In Table B.2, we show each burst’s fluence with the best fit values for the spectra from the *Fermi* GBM and Konus-Wind satellites. The *Fermi* LAT spectra for GRB 130504C was received through private communication and is not quoted here.
Table B.1: Parameter values for reference GRBs

<table>
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<tr>
<th>GRB</th>
<th>Fluence $F_{10\text{keV}-10\text{GeV}}$ $(10^{-7}\text{erg/cm}^2)$</th>
<th>Power-Law Index $\gamma$</th>
<th>$E_{\text{ref}}$ (GeV)</th>
<th>$A_{PL}$ $(10^{-4}\text{GeV}^{-1}\text{cm}^{-2})$</th>
<th>$(E^2 dN/dE)^b$ $(10^{-7}\text{erg/cm}^2)$</th>
</tr>
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<tbody>
<tr>
<td>080916C</td>
<td>$181_{+114}^{+102}$</td>
<td>$-2.01_{-0.13}^{+0.07}$</td>
<td>1</td>
<td>7.80</td>
<td>12.2</td>
</tr>
<tr>
<td>090510</td>
<td>$84_{+19}^{-17}$</td>
<td>$-1.61_{+0.03}^{-0.04}$</td>
<td>1</td>
<td>8.37</td>
<td>32.9</td>
</tr>
<tr>
<td>090902B</td>
<td>$985_{+58}^{-56}$</td>
<td>$-1.94_{+0.01}^{-0.01}$</td>
<td>1</td>
<td>57.0</td>
<td>104.9</td>
</tr>
<tr>
<td>130427A</td>
<td>$-1.66 \pm 0.13$</td>
<td>1e-4</td>
<td></td>
<td>90.3</td>
<td>72.5</td>
</tr>
</tbody>
</table>

$^a$GRB 130427A numbers from [74] while the others are from [57]

$^b$Time-integrated differential flux at 10 GeV

Table B.2: Parameter values for observed GRBs.

<table>
<thead>
<tr>
<th>GRB</th>
<th>Fluence $[10^{-6}\text{erg/cm}^2]$</th>
<th>$\Delta E$ [keV]</th>
<th>$\Delta T$ [s]</th>
<th>Band/Power Law$^\dagger$</th>
<th>Instrument</th>
</tr>
</thead>
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<tr>
<td>130504C</td>
<td>134 10-1000 188 637 1.23 2.28</td>
<td>GBM</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>200 20-10000 105 452 1.32 2.15</td>
<td>Konus-Wind</td>
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<tr>
<td>130518A</td>
<td>93.0 10-1000 50 396 -0.86 -2.27</td>
<td>GBM</td>
<td></td>
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<tr>
<td></td>
<td>150 20-10000 20 370 -0.92 -1.97</td>
<td>Konus-Wind</td>
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<td></td>
</tr>
<tr>
<td>130702A</td>
<td>6.3 10-1000 16 -1.65 -</td>
<td>GBM</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>6.70 20-1200 21 -1.87 -</td>
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<tr>
<td>140729A</td>
<td>17.0 10-1000 78 866 -0.9 -</td>
<td>GBM</td>
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<tr>
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</table>

$^\dagger$ Spectrum is either a standard GRB Band function parameters or a power law with exponential cutoff at $E_p$. 

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*GCN Circular 16680*.

“Konus-Wind observation of GRB 140810A,” *GCN Circular 16679*. 
Vita
Kathryne Sparks Woodle

Selected Publications

Upper Limits from the partial HAWC detector on the VHE emission from GRBs observed with the *Fermi* LAT
HAWC Collaboration: A. U. Abeysekara et al.
in preparation 2015.

On the Sensitivity of the HAWC Observatory to Gamma-Ray Bursts
HAWC Collaboration: A. U. Abeysekara et al.

Education

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Ph.D. in particle astrophysics focusing on detecting gamma-ray bursts
August 2015

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Masters of Education in Physics, August 2015

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Bachelor of Arts in Physics with honors, May 2007

Awards

Woman Physicist of the Month American Physical Society Committee on the Status of Women in Physics, July 2014

Graduate Student Service Award Pennsylvania State University, 2014

Achieving Women Award Commission for Women, Penn State University, 2014

Duncan Fellowship Pennsylvania State University, 2011-2013

Downsbrough Fellowship Pennsylvania State University, 2011

Climate and Diversity Award Eberly College of Science, Penn State, 2009

H. George Apostle Prize Physics Department, Grinnell College, 2007