Towards Detecting Lines from Dark Matter Annihilations with GLAST

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Cover illustration: A simulation of the gamma-ray sky as seen by GLAST.
Abstract

Dark matter (DM) constitutes one of the most intriguing but so far unresolved issues in physics. In many extensions of the Standard Model of particle physics, the existence of a stable Weakly Interacting Massive Particle (WIMP) is predicted. The WIMP is an excellent DM particle candidate and one of the most interesting scenarios include an annihilation of two WIMPs into two gamma-rays. If the WIMPs are assumed to be non-relativistic, the resulting photons will both have an energy equal to the mass of the WIMP and will manifest themselves as a monochromatic spectral line in the energy spectrum. This type of signal would represent a “smoking gun” for DM, since no other known astrophysical process should be able to produce it.

When searching for a line, the energy resolution and performance of the calorimeter are key factors. In this thesis, these are investigated using beam test data, taken at CERN in 2006. Four statistical methods that can be used to search for DM spectral lines are, then, studied in terms of their power and coverage. The methods are based on both hypothesis tests and confidence interval calculations. Two peak finding methods are also tested on a simulated data set representing one year of realistic data, obtained with the Large Area Telescope (LAT) on-board the Gamma-ray Large Area Space Telescope (GLAST). The data set is called Service Challenge 2 (SC2) and contains a variety of gamma-ray sources, including different DM components. Finally, an upper limit on $\langle \sigma v \rangle_{\gamma\gamma}$, based on SC2, is calculated.
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BENEATH EXTERNAL NOISE AND CLATTER,
EACH DAY RADIATES ITS TEACHINGS IN SILENCE.

ZEN SAYING
Introduction

Outline of the thesis

This thesis includes two separate analyses with the common denominator being the GLAST mission and its capability of detecting possible signatures of particle dark matter. The first chapters contain theoretical backgrounds relevant to the following analyses. In Chapter 1, the various interactions occurring when particles traverse matter are reviewed. Chapter 2 gives a recapitulation of gamma-ray astronomy, including a historical overview, and Chapter 3 focuses on providing a theoretical background to dark matter. In Chapter 4, the GLAST satellite and its different subdetectors are explained in detail. Chapters 5 and 6 are devoted to the beam tests performed at CERN with a scaled down version of the LAT instrument in GLAST and the analysis of the data taken there, respectively. In dark matter spectral line searches, the energy resolution and performance of the calorimeter are key factors. Therefore, these observables were studied with beam test data and simulated data. Chapter 7, explains the challenges involved in a line search and benchmarks, using the statistical power and coverage, a number of different statistical methods that can be used in such a search. Two methods (Scan Statistics and ProFinder) are, then, tested on a simulated data set, called Service Challenge 2, corresponding to one year of data with GLAST. Finally, in Chapter 8, a discussion and conclusions from the analyses are presented.

Author’s contribution

The beam test efforts were performed by a large number of people within the GLAST LAT collaboration. Before the tests, the author helped in assessing the statistics needed in the planned setups. The author then actively participated in the beam tests at CERN by assisting in the setup and disassembling of the experiments, taking shifts, analysing and validating the quality of the data and Monte Carlo simulation and by presenting the results in shift meetings.

In the following overall analysis of the beam test data, which is at the time of writing still in progress, the author analysed the differences between data and Monte Carlo in terms of direction, position and energy measurements and continuously
presented the results in beam test online meetings. In these studies, most of the
cuts were developed by the author.

In the dark matter analysis, the author was fully responsible for translating the
statistical methods into tools for searching for dark matter lines. The \texttt{ROOT} macros
involved were all written exclusively by the author. The \texttt{DarkSUSY} simulation
package was also adapted by the author to calculate the line-of-sight integral over
a specific region of the sky.

The results from comparing various statistical in terms of their power and cov-
erage, which were presented in a poster and the corresponding proceedings and
described in Section 7.3, were mostly produced by the author.

\section*{Publications}

\begin{itemize}
\end{itemize}
Chapter 1

Particle interactions

This chapter reviews the relevant physical processes involved when particles interact with matter. For a more detailed review including mathematical descriptions, see e.g. [1].

1.1 Muons

In Fig. 1.1, the stopping power for positive muons in copper is shown over nine orders of magnitude in momentum. The plot is divided into different regions, where different effects dominate the interactions taking place.

![Figure 1.1. The average energy loss of positive muons in copper as a function of $\beta\gamma$ and the muon momentum (from [1]).](image)

In the lowest end of the shown range, non-ionising nuclear recoil energy losses dominate the total energy loss for e.g. protons. In the same region, Lindhard
Chapter 1. Particle interactions

and Sharff have described the stopping power as proportional to $\beta = v/c$ [2]. For $0.01 < \beta < 0.05$, i.e. in the second region, no satisfactory theory exists. For protons, however, there are phenomenological fitting formulae developed by Anderson and Ziegler [3].

In the beginning of the third region, the so-called “Barkas effect” yields a stopping power that is somewhat larger for negative particles than for positive particles with the same mass and velocity [4]. Overall, however, the stopping power in the third region is well described by the Bethe-Bloch equation and the particles lose their energy mainly through ionisation and atomic excitation. Due to the muon spectrum at sea level, in which most of the muons have an energy that is around the minimum of the Bethe-Bloch function, muons are often referred to as minimum-ionising particles.

In the last region, radiative energy losses, composed of bremsstrahlung, $e^+e^-$ pair production and photonuclear interactions, take over and become dominating. In the figure, $E_{\mu c}$, represents the critical energy at which ionisation and radiative losses are equal.

1.2 Electrons

As can be seen in Fig. 1.2, which shows the fractional energy loss per radiation length in lead as a function of electron or positron energy, the low energy part is dominated by ionisation although other smaller effects, namely Møller scattering, Bhabha scattering and $e^+$ annihilation, contribute. Above a few tens of MeV, bremsstrahlung is completely dominating in most materials.

![Figure 1.2. The fractional energy loss per radiation length in lead as a function of electron or positron energy (from [1]).](image_url)
In every ionisation event, one or more energetic electrons are knocked out from atoms in matter. If the energy of the ejected electron is much larger than the ionisation potential, they are called delta electrons or $\delta$-rays. Delta electrons with high energies are, however, very rare. For a particle with $\beta \approx 1$, only one collision where the kinetic energy of the delta electron is larger than 1 keV will on average occur along a path of 90 cm in Ar gas [1].

An important process occurring when charged particles traverse a medium is multiple Coulomb scattering. This broadens distributions for direction measurements, because the charged particles are deflected by many small angle scatters. Most of these deflections are Coulomb scatterings, and the distribution of deflections is roughly Gaussian for small angles and with larger tails than a Gaussian for larger angles.

### 1.3 Photons

In Fig. 1.3, the cross-sections of the different processes involved in photon-matter interactions are shown. The cross-sections depend on the material and the figure is an example plot for photons interacting in lead.

![Figure 1.3. The cross-sections of the photoelectric effect, Rayleigh- and Compton scattering, pair production in nuclear and electron fields and photonuclear interactions as a function of photon energy in lead (from [1]).](image)

At low energies, the cross-section for the atomic photoelectric effect, $\sigma_{\text{p.e.}}$, is dominating. In the photoelectric effect, a photon is absorbed by an atom and followed by the emission of an electron. Another process at low energies, which is
Chapter 1. Particle interactions

not as probable as the photoelectric effect is Rayleigh scattering, \( \sigma_{\text{Rayleigh}} \), where a photon is scattered by an atom without ionising or exciting the atom.

In the mid-energy range, Compton scattering, \( \sigma_{\text{Compton}} \), in which photons are scattered by electrons at rest, becomes the dominating process, but photomnuclear interaction such as the Giant Dipole Resonance, \( \sigma_{\text{g.d.r.}} \), where the target nucleus is broken up, also contributes. In the high end of the energy range, pair production in nuclear \( (\kappa_{\text{nuc}}) \) and electron \( (\kappa_{\text{e}}) \) fields is completely dominating.

1.4 Electromagnetic showers

A high-energy electron or photon that interacts with a thick absorber gives rise to a cascade of pair productions from photons and bremsstrahlung photons from the pair produced electrons and positrons. The longitudinal development of the resulting electromagnetic shower, shown in Fig. 1.4, scales as the radiation length in the absorber. When the energies of the electrons and positrons fall below the critical energy, \( E_c \), where the ionisation loss rate is equal to the bremsstrahlung loss rate, additional shower particles are no longer produced and the energy dissipation is, then, provided by ionisation and excitation.

![Figure 1.4](image.png)

Electromagnetic showers are often described by introducing the scale variables \( t = x/X_0 \) and \( y = E/E_c \), in which case the longitudinal distance is measured in units of radiation length, \( X_0 \), and the energy is described in units of the critical energy. One radiation length (which depends on the atomic number \( Z \)) is defined as a characteristic mean distance in which a high-energy electron loses all but \( 1/e \) of its energy through bremsstrahlung and a high-energy photon propagates \( 7/9 \) of the mean free path for pair production. With this notation, the mean longitudinal profile of the energy deposition can be fitted reasonably well with a gamma function, given in Eq. 1.1:
According to EGS4 simulations, the maximum occurs at $t_{\text{max}} = (a - 1)/b = 1.0 \times (\ln y + C_j)$, where $j = e, \gamma$, $a$ and $b$ are free parameters and $C_e = -0.5$ for electron-induced showers and $C_\gamma = +0.5$ for photon-induced showers [1].
Chapter 2

Gamma-ray astronomy

This chapter contains an introduction to gamma-ray astronomy. First, the different mechanisms, in which cosmic gamma-rays can be produced, will be reviewed. This is followed by a description of the astrophysical sources that can emit gamma-rays. Then, a short recap of the main techniques used to observe cosmic gamma-rays is given and finally a historical overview of gamma-ray astronomy is provided.

2.1 Gamma-ray production

Gamma-rays are photons with energies greater than about 100 keV. There are a number of different processes in which astronomical objects can produce them, but the two main categories are either via thermal mechanisms or via non-thermal mechanisms. A thorough review of the different forms of production can be found in [6].

2.1.1 Thermal gamma-rays

A body with a temperature that is different from zero will emit thermal radiation. If the body is a perfect absorber in thermal equilibrium with its environment at temperature $T$, i.e., a black-body, the energy dependent intensity of photons is governed by the Planck formula:

$$I(E_{\text{ph}}) = \frac{2E_{\text{ph}}^3}{(hc)^2} \left[ \frac{1}{e^{\frac{E_{\text{ph}}}{k_B T}} - 1} \right],$$

(2.1)

where $h$ and $k_B$ are the Planck and Boltzmann’s constants, respectively, and $c$ is the speed of light. The average energy of the photons is:
\( \langle E_{\text{thermal}} \rangle \approx 2.3 \times 10^{-10} \left( \frac{T}{K} \right) \text{MeV}, \) \hspace{1cm} (2.2)

In order to get thermal photons at an average energy of 1 GeV, temperatures of about \( 10^{13} \) K are needed. These temperatures only occur in explosive events and in the Big Bang. In addition, that temperature level implies such a large photon density that the mean free path for the photons is less than 1 cm. This leads to self-absorption by pair production. Typical astrophysical gamma-ray sources in the continuum are, therefore, non-thermal in nature.

### 2.1.2 Non-thermal gamma-rays

For gamma-rays that are produced non-thermally, a distinction can be made between gamma-rays from particle-field interactions and gamma-rays from particle-matter interactions. The first category includes the following processes:

- **Synchrotron radiation**, which is created when relativistic charged particles move in a magnetic field. The energy loss rate of an electron moving in a helical path around a magnetic field \( B \) is then given by:

\[
- \left( \frac{dE_e}{dt} \right)_{\text{syn}} = \frac{2}{3} c \left( \frac{e^2}{m_e c^2} \right)^2 B^2 \gamma^2,
\]

where \( e \) is the electron charge, \( m_e \) is the electron mass, \( B_\perp = B \sin \theta \) where \( \theta \) is the pitch angle and \( \gamma = E_e/m_e c^2 \) is the Lorentz factor.

- **Curvature radiation**, which occurs when the magnetic field that the charged particle moves in is non-uniform and the curvature radius, \( R_c \), of the magnetic field line is small. The energy loss is then given by:

\[
- \left( \frac{dE_e}{dt} \right)_{\text{curv}} = \frac{2}{3} c e^2 R_c^{-4} \gamma^4
\]

- **Inverse Compton (IC) interactions**, which refer to the scattering of relativistic electrons on soft photons, where the energy transfer to the photon gives the photon an energy in the gamma-ray region. In the classical limit, the average energy of the emerging photon is \( \langle E_{\text{IC},\gamma} \rangle = (4/3) \langle E_\gamma \rangle \gamma^2 \), where \( \langle E_\gamma \rangle \) is the average energy of the target photon. In the relativistic case, most of the energy of the electron is transferred to the photon and \( E_{\text{IC},\gamma} \approx E_e \).

The second category with particle-matter interactions consists of:

- **Relativistic bremsstrahlung**, which is produced when relativistic electrons are accelerated in the electrostatic field of a nucleus.
2.2. Gamma-ray sources

- **Hadronic gamma-ray emission**, where gamma-rays are produced via the decay of neutral pions, which have a proper life time of $9 \times 10^{-17}$ s. The neutral pions are created through a number of different channels of proton and antiproton interactions.

- **Electron-positron annihilations**, in which gamma-rays are produced through the reaction $e^+ + e^- \rightarrow \gamma + \gamma$. If the electron and the positron are at rest, the photons will have an energy equal to the rest mass of the electron, i.e. 0.511 MeV. If one of the leptons is moving at a high velocity, one of the photons will have a high energy and the other photon will have an energy of about 0.511 MeV.

- **WIMP-WIMP annihilations**. Many extensions of the Standard Model of particle physics predict a stable Weakly Interacting Massive Particle (WIMP), that self-annihilates and produces either gamma-rays directly or indirectly through the decay of the Standard Model particles produced in the annihilation. This possibility has, however, not yet been experimentally verified. The subject of dark matter is covered in more detail in Chapter 3.

### 2.2 Gamma-ray sources

Given the many processes that produce cosmic gamma-rays, the number of sources come in great numbers as well. These include:

- **Circumsolar sources**

  It can be deduced from data taken with the Energetic Gamma-Ray Experiment Telescope (EGRET), described in Section 2.4, that albedo gamma-rays are created in small solar system bodies in the asteroid belt between Mars and Jupiter, the Jovian and Neptunian Trojans and in the Kuiper Belt beyond Neptune through the interaction of cosmic-rays with the solid rock and ice [7]. The diffuse emission from these object has an integrated flux of less than $\approx 6 \times 10^{-6}$ cm$^{-2}$ s$^{-1}$ in the energy range 100–500 MeV. This is about 12 times the gamma-ray flux from the Moon, where the same process occurs.

- **The Sun**

  Although the surface of the Sun was expected to emit gamma-rays in the same way that the Moon does, no significant excess was found in the direction of the Sun with EGRET data. Instead, an upper limit on the flux above 100 MeV was put at $2 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ [8]. A second process that produces gamma-rays in the halo around the Sun is, however, the IC scattering of solar optical photons by GeV-energy cosmic-ray electrons, which produces gamma-rays with energies of 100 MeV and above. The total flux above 100 MeV, determined from EGRET data, was $4.4 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ [9].
Galactic sources
Within the Milky way, there are a number of sources that can emit gamma-rays. The diffuse emission, concentrated in the galactic plane, consists of three components: truly diffuse emission from high energy particle interactions with the interstellar gas and radiation fields, the extragalactic background, whose origin is undetermined so far, and unresolved and faint galactic point sources. Pulsars are rapidly rotating and highly magnetised neutron stars that emit radiation in multiple wavelengths, some even at gamma-ray energies. The gamma-ray pulsars exhibit light-curves with a double-pulse structure, which is different from pulsars at lower energies. They also tend to be younger than other pulsars and have higher magnetic fields. Different models exist as to how the emission is created. Supernova remnants are created when blast waves and reverse waves from supernova explosions propagate in the surrounding medium. The shock waves accelerate particles up to relativistic energies and the resulting extended sources emit synchrotron radiation from radio to X-ray energies. In some cases TeV-energy gamma-ray emission can be observed, but the physical mechanisms causing the emissions are yet to be understood since both hadronic and leptonic interactions can give rise to the observed spectra. Another category is microquasars, which are X-ray binaries with associated jets in which high velocity relativistic shocks are believed to give rise to high energy gamma-rays.

Extragalactic sources
As is the case with galactic sources, there are many potential extragalactic sources of gamma-rays. In the Third EGRET Catalogue, there are tens of sources classified as Active Galactic Nuclei (AGNs). The gamma-ray emission is believed to originate in the relativistic jets, associated with the AGNs, but what causes the emission is still under debate. There are also 120 unidentified sources above $|b| > 10^\circ$. The potential nature of these sources include blazars, BL Lacs, starforming galaxies, clusters of galaxies and the diffuse extragalactic background. Another type of objects are Gamma-Ray Bursts (GRBs). They are characterised by a sudden and rapid enhancement of gamma-rays from space. Since the discovery of the first GRB in 1967, several thousand have been detected, isotropically distributed over the sky. The X-ray and radio afterglows from the GRBs have led to the discovery of host galaxies with large redshifts. This places GRBs at cosmological, rather than at galactic, distances.

Dark matter
As mentioned in the previous section, dark matter is a possible source of gamma-rays. The evidence for dark matter is today overwhelming, but its nature remains largely unexplored. The field is, however, highly active and, as explained in Chapter 3, there are a large number of theories for its particle nature and spatial distribution.
2.3 Detection techniques

As explained in Chapter 1, photons interact predominantly through pair-production and the subsequent production of electromagnetic showers above a certain material dependent threshold energy. At these energies, typically above around 10 MeV, two different kinds of detection techniques can be used.

The first technique is based on detecting the primary photon and the shower particles it produces via pair production of photons and bremsstrahlung from charged particles. These detectors are either balloon-based or space-based, since the Earth’s atmosphere absorbs most of the shower. Due to the limited size of the detectors that can be sent up in balloons or satellites, a large fraction of the shower from a high energy photon will leak out of the detector. The longitudinal size of the detector therefore sets a natural maximum energy that can be measured with these instruments. This limit occurs when the maximum of the shower is outside the detector.

The Earth’s atmosphere acts naturally as a gigantic calorimeter and this can be used to detect gamma-rays indirectly in ground-based instruments. The second technique is, therefore, based on looking for the Cherenkov light that is sent out from the charged particles produced in the electromagnetic showers. These so-called Cherenkov telescopes can typically only measure gamma-rays of several tens of GeV and above, since showers from lower energy gamma-rays are absorbed high up in the atmosphere. These energies are, however, much higher than those possible to measure by previous balloon- or space-based detectors. There are currently many ground-based telescopes of this kind looking for gamma-rays. The most successful of these are HESS, MAGIC, VERITAS and CANGAROO-III. The individual designs of these instruments are beyond the scope of this thesis but the interested reader can find an overview in e.g. [10].

2.4 History

This section largely follows the more detailed historical overview given by [6].

Until the early 1960s, detectors were not sufficiently sophisticated to be able to detect gamma-rays from space. The discovery of the gamma-ray was, however, made much earlier by Paul Villard in 1900. Villard saw that gamma-rays were an especially penetrating form of radiation that was unaffected by electric and magnetic fields.

Fourteen years later, in 1914, gamma-rays were after diffraction experiments by Rutherford and Andrade revealed to be a form of light with a much shorter wavelength than X-rays. The first link between gamma-rays and interstellar space was suggested by Millikan and Cameron, who studied cosmic-rays extensively. In 1931, they suggested that cosmic-rays were in fact photons and that they came from interstellar space (rather than from the atmospheres of stars) [11]. Cosmic
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Gamma-ray sources were investigated further also by others, but the idea was then abandoned.

The concept revitalized in the early 1950s, after the discovery of the neutral pion. The earliest contributions came from Feenberg and Primakoff in 1948. In 1952, Hayakawa predicted that when cosmic-rays collide with interstellar matter, gamma-rays should be produced from the decay of neutral pions [12]. The same year, Hutchinson estimated the gamma-ray emission from cosmic Bremsstrahlung. Six years later, in 1958, Morrison estimated the gamma-ray flux from many different astronomical objects [13].

Early gamma-ray detectors suffered from a bad background rejection and were in addition not sensitive enough. The first detector to reliably measure gamma-rays from space was the Explorer-XI satellite, which was launched in 1961. In the Explorer-XI instrument, shown in Fig. 2.1, gamma-rays were converted into electron-positron pairs in a crystal scintillator that consisted of alternating slabs of CsI and NaI. Signals from the scintillator were in coincidence with a Cherenkov detector and were read out if there was no recorded event in the plastic anticoincidence detector. After analysing the recorded data with 127 potential gamma-rays, 22 events remained with a celestial origin whereas the rest were most likely secondary gamma-rays from cosmic-rays interacting in the Earth’s atmosphere [14].

![Figure 2.1. A sketch of the detector on the Explorer XI satellite (from [14]).](image)

The next important detector for gamma-rays to be launched was the Orbiting Solar Observatory (OSO III) in 1967. The gamma-ray instrument on-board consisted of a converter sandwich of CsI crystals and plastic scintillators, a directional
2.4. History

Cherenkov counter and an energy detector with layers of NaI and tungsten, surrounded by an anticoincidence shield of plastic scintillators [15]. The instrument was sensitive to gamma-rays above 50 MeV and recorded 621 events concentrated along the galactic equator [16].

The same year OSO III sent its last data transmission, a series of military satellites called Vela were launched. They were initially constructed to detect nuclear explosions from space but also detected the first transient sources of gamma-rays, later known as GRBs [17]. Vela 5A and 5B, launched in 1969, and Vela 6A and 6B, launched in 1970, recorded 73 bursts altogether with the gamma-ray detectors on-board [18]. The detectors consisted of CsI crystals with a total volume of about 60 cm$^3$ and had an energy range of 150–750 keV.

More GRBs were detected later in the late 1970s and early 1980s by e.g. the Pioneer Venus Orbiter and Venera satellites, which were sent to Venus, and the Prognoz satellites.

In the early 1970s, spark chamber technology spawned, and the first satellite to successfully utilize it was the Small Astronomical Satellite (SAS) II, which was launched in 1972. Spark chambers consist of layers of a high-Z material, e.g. tungsten, in a chamber of gas, usually neon or argon. The choice of material in the plates is important, since the interaction probability is proportional to $Z^2$. In a spark chamber, the plates are alternatingly grounded and at a high voltage and when a particle enters the gas chamber, the gas is ionised and sparks are produced between the plates in the location of the particle trail. The sparks can be recorded and, thus, the direction of the incoming particle can be determined.

The SAS II detector system consisted of 32 modules of wire spark chambers, 16 on either side of four central plastic scintillators. Interleaved between each module were thin tungsten plates, serving as conversion planes for the incoming gamma-rays. The directions of the gamma-rays were measured by the spark chambers and the energy was determined by measuring the Coulomb scattering. At the bottom of the instrument were four directional Cherenkov detectors used for triggering and surrounding the whole instrument was a single-piece plastic scintillator dome, which was used for charge particle discrimination. The different components of the SAS II instrument can be seen in Fig. 2.2.

SAS II recorded approximately 8000 photons with $E > 30$ MeV during roughly seven months before a failure in its power supply ended the data collection. The satellite was revolutionary in the sense that it gave the first detailed view of the gamma-ray sky. These images showed that the flux was concentrated in the galactic plane and the galactic center [19]. SAS II also established that there were objects, other than the Milky Way or the Sun, which emitted gamma-rays, namely pulsars. Intensity peaks, coincident with the Crab and Vela pulsars, were found and an unidentified object, later known as the Geminga pulsar, was discovered.

A few years later, in 1975, the COS-B satellite was launched. The detector system was similar to that of SAS II [20]. The major difference to SAS II was that COS-B was put in a highly eccentric orbit, taking it further out from the background radiation produced by the Earth’s atmosphere. In total, COS-B detected about
200,000 photons during its seven year mission and provided maps of the gamma-ray sky in energy bands ranging from 300 MeV to 5 GeV. A catalogue containing 25 sources was also published, 20 of which were unknown [21].

In 1991, the heaviest scientific instrument ever deployed from a space shuttle, the Compton Gamma-Ray Observatory (CGRO), was put in orbit by NASA. The satellite carried four instruments, the Burst And Transient Source Experiment (BATSE), the Oriented Scintillation Spectrometer Experiment (OSSE), the Imaging Compton Telescope (COMPTEL) and the Energetic Gamma-Ray Experiment Telescope (EGRET).

BATSE consisted of 8 thin scintillation modules placed in each corner of the satellite and was used for detecting transient sources of soft gamma-rays. It recorded in total 2704 GRBs, 1192 solar flares, 1717 magnetospheric events, 185 soft gamma-ray repeaters (objects characterised by large bursts of gamma-rays and X-rays at irregular intervals), and 2003 transient sources. The GRBs were isotropically distributed, which suggested that they are extragalactic in origin.

The OSSE detector had four independent phoswich modules (optically coupled scintillators with dissimilar pulse shapes) consisting of NaI(Tl) and CsI(Na). It was designed to observe nuclear-line emission from low-energy gamma-ray sources in the energy range 0.05–10 MeV. OSSE’s measurements of the galactic center at 511 keV, the energy of photons from electron-positron annihilations, showed that the radiation was concentrated within 10 degrees from the galactic center.

COMPTEL had an energy range of 0.8–30 MeV, given by two detector arrays located 1.5 m from each other, the upper one made of a low-Z liquid scintillator NE213 and the lower one of a high-Z NaI(Tl) scintillator [22]. The whole detector was surrounded by a plastic scintillator dome, used to reject charged particles. The instrument was calibrated using two small plastic scintillator detectors containing weak 60Co sources, located on the sides of the telescope. An incident gamma-ray was Compton-scattered in the upper array and then interacted in the lower array. The energy losses were measured in the two arrays and determined a circle,
which gave the possible directions of the incoming gamma-ray. From COMPTEL measurements, sky maps and a catalogue containing 63 gamma-ray sources, with AGNs, pulsars, galactic black hole candidates, GRBs and supernova remnants, could be produced [23].

EGRET was based on spark chamber technology and had many similarities with SAS II. A diagram, showing the detector system can be seen in Fig. 2.3. The instrument consisted of two modules of wire spark chambers with interspersed conversion material (tantalum foils) for direction determination, interleaved with a time-of-flight system for triggering events from the proper incoming direction [24]. The upper spark chamber module had 28 closely separated wire grids and the lower spark chamber had 8 wire grids more widely separated.

The particle energies were measured with a Total Absorption Spectrometer Crystal (TASC) made from NaI and was located in the bottom. As in most previous gamma-ray telescopes, a single-piece plastic scintillator dome covered most of the instrument and was used to discriminate against charged particles.

The energy range of EGRET was from about 20 MeV to about 30 GeV and in most of this region the energy resolution was 20–25%. The effective area was energy dependent: about 1000 cm$^2$ at 150 MeV, 1500 cm$^2$ in the range 0.5–1 GeV and gradually decreasing for higher energies to about 700 cm$^2$ at 10 GeV for targets near the center of the field-of-view.

EGRET was a very successful mission and spawned many all sky maps as well as detailed studies of different sources. In the final official list of EGRET Sources, the Third EGRET Catalog, 271 excesses with a significance higher than 3$\sigma$ were included [25]. About 70 of the sources included in the list have been identified as AGNs, radio quasars (mostly with a flat-spectrum) and BL-Lacertae, 1 radio galaxy (Centaurus A), the Large Magellanic Cloud (LMC), and 6 gamma-ray pulsars.
The remaining 170 sources are, however, still unidentified. The next generation of gamma-ray satellites, the Gamma-ray Large Area Space Telescope (GLAST), explained in detail in Chapter 4, is, therefore, highly anticipated within the high-energy astrophysics community. A plot of the sources from the Third EGRET Catalog in galactic coordinates can be seen in Fig. 2.4.

![Figure 2.4. Sources from the Third EGRET Catalog, shown in galactic coordinates. The size of the symbol corresponds to the highest intensity seen for the source by EGRET (from [25]).](image)

On April, 2007, the Astro-rivelatore Gamma a Immagini LEggero (AGILE) satellite was launched into orbit [26]. The instrument is quite compact and weighs only about 120 kg, but the components differ in design compared to previous experiments. The satellite carries two instruments, a gamma-ray imager and a hard X-ray imager. At the top is the Super-AGILE hard X-ray detector, which has an angular resolution of 6 arcmin and the energy range 18–60 keV. The system is a so-called coded-mask design with a thin shadowing tungsten mask, 14 cm above a silicon detector plane. The gamma-ray imager covers energies from 30 MeV to 50 GeV and consists on the top of a Silicon Tracker (ST) module, directly below Super-AGILE. The ST has high-resolution silicon microstrip detectors organised in 12 layers at 1.9 cm intervals and with interleaved tungsten conversion planes between the 10 uppermost layers. The ST contains in total 0.8 $X_0$ on-axis and provides the direction of the gamma-rays. Below the ST is a Mini-Calorimeter (MCAL) for energy measurements, which contains 30 CsI(Tl) crystals in 2 layers (corresponding to 1.5 $X_0$). All subdetectors are covered by an anticoincidence (AC) system, where each side is segmented into three plastic scintillators whereas the top has a single plastic scintillator layer.

The AGILE satellite is designed to be complementary to the much larger GLAST satellite. The detector designs are virtually identical but differ in scale. GLAST will, however, in the first phase of the mission perform an all-sky survey, whereas AGILE is focused on fixed pointing observations.
Chapter 3

Dark matter

This chapter provides some general background information to dark matter. It reviews some of the evidence supporting the existence of dark matter, what constraints dark matter particle candidates have and the different approaches that are followed today to detect them. There are many review papers about dark matter available, see e.g. [28] and [29]. This chapter will, therefore, only summarise the subject.

3.1 Evidence

The existence of dark matter (DM) was first suggested by Zwicky in 1933 [30]. Zwicky investigated the radial velocities of eight galaxies in the Coma galaxy cluster and observed an unexpectedly large velocity dispersion. He suggested that the mass of the visible matter was not enough to hold the cluster together and that “dark matter” was required [31].

That luminous objects move faster than what would be expected if the only influence was the gravitational pull of visible matter has since been observed in many different types of objects. These objects include stars, gas clouds, globular clusters and entire galaxies. A typical example, which serves as one of the more compelling and direct evidences for the existence of DM, is the rotational curve of galaxies.

An object that moves in a Keplerian orbit at radius $r$ has a velocity given by $v(r) = \sqrt{GM(r)/r}$, where $M(r)$ is the mass contained within the disk at radius $r$. At larger distances, beyond the optical disc, the rotational velocity should fall as $v(r) \propto 1/\sqrt{r}$. Observations of the 21 cm excitation line from hydrogen, however, show that $v(r)$ is approximately constant. This implies that either there is particle DM in the form of a halo with $M(r) \propto r$ or the gravitational theory needs to be revised.
Since these discoveries were made, many other observations have pointed to the existence of DM, and these include among others the Big Bang Nucleosynthesis (BBN) [32], gravitational lensing [33], the cosmic microwave background [34] and the Sunyaev-Zel’dovich effect [35]. The most visual evidence of DM today, shown in Fig. 3.1, is from the merging galaxy cluster 1E 0657-558 (“Bullet Cluster”), where a clear separation of the mass (determined from gravitational lensing with the HST/ACS) and the X-ray emitting plasma (observed with Chandra) can be seen [36].

![Figure 3.1. A picture of the Bullet cluster, where the mass determined from gravitational lensing (blue) and the X-ray emitting plasma (purple) are clearly separated. Courtesy: X-ray: NASA/CXC/M.Markevitch et al. Optical: NASA/STScI; Magellan/U. Arizona/D. Clowe et al. Lensing Map: NASA/STScI; ESO WFI; Magellan/U. Arizona/D. Clowe et al.](image)

Together, all the observations mentioned above have constrained the fractions of the energy density in the Universe in the form of matter and in the form of a cosmological constant to $\Omega_M \sim 0.3$ and $\Omega_\Lambda \sim 0.7$, respectively, with ordinary baryonic matter only constituting about $\Omega_B \sim 0.05$ [37]. This implies that non-baryonic matter is the dominating form of matter in the Universe.

The favoured model today that is in reasonable agreement with observations is the so-called $\Lambda$CDM model, which features Cold Dark Matter (CDM) in the form of Weakly Interacting Massive Particles (WIMPs) and a contribution from a cosmological constant ($\Lambda$).

### 3.2 Dark matter candidates

There is a large number of DM particle candidates. In order for a particle to be a viable DM candidate, a ten-point test should be passed [38]. A positive answer should, then, be the result of all of the following questions:
3.2. Dark matter candidates

1. Does it match the appropriate relic density?
2. Is it cold?
3. Is it neutral?
4. Is it consistent with the BBN?
5. Does it leave stellar evolution unchanged?
6. Is it compatible with constraints on self-interactions?
7. Is it consistent with direct DM searches?
8. Is it compatible with gamma-ray experiments?
9. Is it compatible with other astrophysical bounds?
10. Can it be probed experimentally?

Many of the good DM candidates are able to produce monochromatic spectral lines via annihilation channels directly into two gamma-rays. If the DM particles ($\chi$) are non-relativistic, the energy of the photons is $E_\gamma = M_\chi$. A spectral line can also be produced if the annihilation of the DM particles creates one photon and some other particle ($X$). The energy of the photon is, then, governed by the mass of the DM particle and the mass of the other particle according to the equation $E_\gamma = M_\chi (1 - M_X^2/4M_\chi^2)$ [37].

An observation of a spectral line would be a “smoking-gun” for DM. However, a halo with a large central concentration or the existence of small-scale structure in the DM halo might be needed in order to see a signal.

The flux from a monochromatic gamma-ray line is given by Eq. 3.1 from [39].

$$\Phi(\psi, \Delta \Omega) = 0.94 \times 10^{-11} \left( \frac{N_\gamma v \sigma_{\gamma\gamma}}{10^{-29} \text{ cm}^3 \text{s}^{-1}} \right) \left( \frac{10 \text{ GeV}}{M_\chi} \right) \langle J(\psi) \rangle_\Delta \Omega \times \Delta \Omega \text{ cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$$

(3.1)

where $N_\gamma = 2$ for $\chi\chi \rightarrow \gamma\gamma$, $M_\chi$ is the DM particle mass, $\Delta \Omega$ is the solid angle and the dimensionless line-of-sight-dependent function $J(\psi)$ is given by:

$$J(\psi) = \frac{1}{8.5 \text{ kpc}} \left( \frac{1}{0.3 \text{ GeV cm}^{-3}} \right)^2 \int_{\text{line-of-sight}} \rho_\chi^2(l) dl(\psi)$$

(3.2)

where 8.5 kpc corresponds the distance from the galactic center to the solar system, 0.3 GeV cm$^{-3}$ is the local DM energy density and $\rho_\chi$ is the DM density. This is averaged over the solid angle according to:

$$\langle J(\psi) \rangle_\Delta \Omega = \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega' J(\psi')$$

(3.3)
3.3 Halo models

The DM distribution on small scales, i.e. on galactic and sub-galactic scales, is still under debate and plays a crucial role for the detection of DM signals. To describe most of the observed rotational curves of galaxies, a phenomenological halo density profile, based on state-of-the-art N-body simulations, is generally used. This smooth and spherically symmetric profile is given by

\[ \rho(r) = \frac{\delta_c \rho_c}{(r/r_s)(1 + (r/r_s)^\alpha)^{(3-\gamma)/\alpha}}, \]

where \( r \) is the angular radius from the galactic center, \( r_s \) is a scale radius and \( \delta_c \) is a characteristic dimensionless density, and \( \rho_c = 3H^2/8\pi G \) is the critical density for closure. There are a number of widely used halo profiles that differ in the values of the \((\alpha,\beta,\gamma)\) parameters. The more popular profiles are the Navarro, Frenk and White (NFW) model with \((1,3,1)\) [40], the Moore model with \((1.5,3,1.5)\) [41] and the Kravtsov model with \((2,3,0.4)\) [42].

3.4 Supersymmetric WIMPs

One of the theories that give a good DM particle candidate is supersymmetry. Supersymmetry is often an integral part of string theory and is an attempt to give a unified description of fermions and bosons and to solve the so-called hierarchy problem, i.e. the enormous difference between the electroweak and Planck energy scales.

In supersymmetry, every particle and gauge field has a superpartner. The gauge fields given by gluons (\( g \)) and the \( W^\pm \) and \( B \) bosons have associated fermionic superpartners called gluinos (\( \tilde{g} \)), winos (\( \tilde{W}^i \)) and binos (\( \tilde{B} \)), respectively, and fermions have associated scalar partners (quarks become squarks and leptons become sleptons). An additional Higgs field is also introduced.

In the simplest models of supersymmetry, there is a multiplicative quantum number called \( R \)-parity, which is conserved. This was originally imposed in order to suppress the rate of proton decay and is defined as

\[ R \equiv (-1)^{3B+L+2s}, \]

where \( B \) is the baryon number, \( L \) is the lepton number and \( s \) is the spin. All Standard Model particles have \( R = 1 \) and all superpartners, or sparticles, have \( R = -1 \). This means that the decay products of sparticles must consist of an odd number of sparticles. A consequence of this is that the Lightest Supersymmetric Particle (LSP) is stable and can only be destroyed through pair annihilation.

The theoretically favoured non-baryonic DM particle candidate and also most widely searched experimentally today is the LSP, which is often assumed to be the neutralino. In the Minimal Supersymmetric Standard Model (MSSM), the neutralino is a mix of the bino, wino and higgsino states. The mix gives the neutralino
four mass eigenstates, $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$, $\tilde{\chi}^0_3$, and $\tilde{\chi}^0_4$, where $\tilde{\chi}^0_1$ is the lightest one, usually denoted by only $\chi$.

In neutralino pair annihilation, the leading channels at low neutralino velocities are annihilations into fermion-antifermion pairs, gauge boson pairs and final states with Higgs bosons. These can eventually through different decay chains produce neutrinos, antimatter and pions that decay into gamma-rays. These gamma-rays could then be observed by GLAST as a continuum spectrum. There also exists a loop-suppressed pair annihilation of neutralinos directly into two gamma-rays, which would produce the spectral line mentioned before.

### 3.5 Detection

There are currently two major ways in which a particle detection of DM is pursued. The first, direct detection, is based on measuring the recoil energy of nuclei when DM particles, generally assumed to be WIMPs, scatter off them. Due to the low energy of the recoils, the experiments must be shielded and placed deep underground to protect the detectors from unwanted background. The best limits so far have been set by the CDMS, Edelweiss and ZEPLIN-I experiments. Only one experiment, DAMA, has claimed detection of an annual modulation caused by the Earth’s movement relative to the WIMP halo [43]. The results are, however, controversial at this point since no other experiment has observed a signal of that kind.

The second detection technique, indirect detection, involves observing DM particles indirectly either through their annihilation products or e.g. by looking for resonances or interactions with missing energy and momentum by using particle accelerators. The first approach is exercised in ground-based air shower telescopes such as CANGAROO-III, HESS, MAGIC and VERITAS, neutrino telescopes such as IceCube in the Antarctic and ANTARES in the Mediterranean, positron and antiproton experiments such as the space-based PAMELA experiment, and finally space-based gamma-ray satellites such as the GLAST experiment. The second approach will be used in the LHC experiment at CERN, where protons will be collided at a center-of-mass energy of about 14 TeV.
Chapter 4

The Gamma-ray Large Area Space Telescope

The next generation in gamma-ray satellites, the Gamma-ray Large Area Space Telescope (GLAST), is an experiment that is highly anticipated by the high-energy astrophysics community. An artist’s conception of the satellite can be seen in Fig. 4.1. The satellite consists of two detector systems, the Large Area Telescope (LAT) and the GLAST Burst Monitor (GBM). This chapter reviews the scientific goals of GLAST and describes the different instruments and subsystems.

![Figure 4.1. An artist’s impression of the GLAST satellite. The box-like structure on the top is the LAT and the yellow detectors on the sides are part of the GBM.](image)

Improvements with respect to EGRET, described in Section 2.4, have been made on many fronts, including the point-spread function, the effective area, the energy range and the field-of-view. This was accomplished partly by increasing the size and partly by using state-of-the-art particle detection technology. Furthermore, none of the subsystems in GLAST rely on consumables. A summary of the differences in performance between GLAST and EGRET can be seen in Table 4.1. For GLAST, the energy dependence of two of the quantities, the effective area and the energy resolution, are shown in Fig. 4.2.

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Chapter 4. The Gamma-ray Large Area Space Telescope

Table 4.1. The performance and specifications of the LAT compared to EGRET. Courtesy: NASA.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>LAT (Minimum spec.)</th>
<th>EGRET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy range</td>
<td>20 MeV – 300 GeV</td>
<td>20 MeV – 30 GeV</td>
</tr>
<tr>
<td>Peak effective area(^1)</td>
<td>&gt;8000 cm(^2)</td>
<td>1500 cm(^2)</td>
</tr>
<tr>
<td>Field-of-view</td>
<td>&gt;2 sr</td>
<td>0.5 sr</td>
</tr>
<tr>
<td>Angular resolution(^2)</td>
<td>&lt;3.5(^\circ) (100 MeV)</td>
<td>5.8(^\circ) (100 MeV)</td>
</tr>
<tr>
<td></td>
<td>&lt;0.15(^\circ) (&gt;10 GeV)</td>
<td></td>
</tr>
<tr>
<td>Energy resolution(^3)</td>
<td>&lt;10%</td>
<td>20–25%</td>
</tr>
<tr>
<td>Dead time per event</td>
<td>&lt;100 (\mu)s</td>
<td>100 ms</td>
</tr>
<tr>
<td>Source location determination(^4)</td>
<td>&lt;0.5(^\prime)</td>
<td>15(^\prime)</td>
</tr>
<tr>
<td>Point source sensitivity(^5)</td>
<td>&lt;6 (\times) (10^{-9}) cm(^{-2}) s(^{-1})</td>
<td>(\sim10^{-7}) cm(^{-2}) s(^{-1})</td>
</tr>
</tbody>
</table>

\(^1\) After background rejection \\
\(^2\) Single photon, 68\% containment, on-axis \\
\(^3\) 1\(\sigma\), on-axis \\
\(^4\) 1\(\sigma\) radius, flux \(10^{-7}\) cm\(^{-2}\) s\(^{-1}\) (>100 MeV), high \(|b|\) \\
\(^5\) >100 MeV, at high \(|b|\), for exposure of one-year all sky survey, photon spectral index -2

Figure 4.2. The energy dependence of the effective area and the energy resolution for the LAT (from [44]).
The satellite orbits the Earth at an altitude of about 560 km, which was chosen to minimise the effect of charged particles that surround the Earth. At that altitude, one orbit will take about 90 minutes. The inclination angle is about 25°, which gives a full sky coverage in only two orbits. The data acquisitions will start and end at the border of the South Atlantic Anomaly (SAA). The reason for this is that the high concentration of charged particles within the SAA could damage the electronics of the instruments. Therefore, the high voltages, powering the satellite and its detectors, must be lowered to a minimum level.

If no part of the SAA is traversed during the orbit, the data acquisition will start and end at the ascending node, i.e. where the orbit crosses the equator. In Fig. 4.3, a visualisation of the orbits can be seen. The presented borders of the SAA and the angle of inclination are not final, since they will be determined more exactly during the first phase of the mission, where calibrations and tunings will take place.

![Figure 4.3. A visualisation of the GLAST orbit. The blue trails represent the orbits of GLAST and the yellow line shows the borders of the SAA. Data acquisition will start and end at the border of the SAA. If no part of the SAA is present in the orbit, the data acquisition will start and end at an ascending node. Note that the angle of inclination and the border of the SAA are not the final ones.](image)

### 4.1 Scientific goals

The scientific goals of GLAST are largely motivated by results from the predecessor EGRET, which measured gamma-rays with energies between around 20 MeV and 30 GeV, and ground-based atmospheric Cherenkov telescope arrays, which measure energies above several tens of GeV. The main scientific goals of GLAST are to:

- **Resolve the gamma-ray sky.** This includes studying the nature of the 170 unidentified EGRET sources, the extragalactic diffuse emission and the origins of the emission from the Milky Way, the nearby galaxies and galaxy clusters.
Chapter 4. The Gamma-ray Large Area Space Telescope

- Understand the particle acceleration mechanisms in celestial sources. A number of sources, where gamma-rays are produced in acceleration processes, exist and these include blazars and AGNs, pulsars, pulsar wind nebulae, supernova remnants and the Sun.

- Study the high-energy processes in GRBs and transients. GRBs, mentioned in Section 2.2, have been studied in many different wavelengths including the X-ray, optical and radio regions. The high-energy behaviour at energies in the LAT energy range remains, however, to be investigated.

- Probe the nature of dark matter. As described in Chapter 3, a stable and weakly interacting particle, with a mass within the LAT energy range, is proposed in many extensions of the Standard Model. Many other alternatives can, however, be investigated with the LAT instrument.

- Investigate the early Universe to $z \geq 6$ using high-energy gamma-rays. The era of galaxy formation can be studied with photons above 10 GeV via the absorption by pair production of accumulated radiation from structure and star formation, also called the extragalactic background light, and of gamma-rays emitted by e.g. blazars.

4.2 Instruments

4.2.1 Large Area Telescope

The LAT, seen in Fig. 4.4, covers the approximate energy range from 20 MeV to more than 300 GeV and was built by an international collaboration consisting of space agencies, physics institutes and universities from France, Italy, Japan, Sweden and the United States.

![Figure 4.4. The Large Area Telescope in cross-section. As shown in the picture, each module has a tracker module and a calorimeter module. The tiles on the sides are part of the anti-coincidence detector shield.](image-url)
The instrument is a pair-conversion telescope, designed to measure the electromagnetic showers of incident gamma-rays over a wide field-of-view while rejecting incident charged particles with an efficiency of 1 to $10^6$. It consists of a 4 x 4 array of 16 identical modules on a low-mass structure. Each of the modules has a gamma-ray converter tracker for determining the direction of the incoming gamma-ray and a calorimeter for measuring its energy. The tracker part of the instrument is surrounded by a segmented anti-coincidence detector. In addition, the whole LAT is shielded by a thermal-blanket micro-meteoroid shield.

The data taking is governed by a programmable trigger that can utilise prompt signals from all the subsystems. The downlink capacity from the LAT to the ground is limited, so when an event triggers the acquisition and all subsystems are read out, the data acquisition hardware reduces the rate of events to about 1 Mbps using on-board event processing.

Tracker

The active detector elements in the directional tracker (TKR) modules are Silicon-Strip Detectors (SSDs). Each TKR module in the LAT has a width of 37.3 cm and a height of 66 cm, where the width was optimised to utilise the longest silicon strips possible while keeping a good noise performance, high efficiency and low power, and the height was a trade-off between having a large enough lever arm between successive events and keeping a low LAT aspect ratio that maximises the field-of-view. For an extensive review of the TKR system, see e.g. [45].

A TKR module consists of a stack of 19 trays, which support the SSDs, the associated readout electronics and tungsten converter foils, where pair production is induced. Only the topmost 16 layer pairs are preceded by a tungsten plane, just above the detector planes. There are 576 SSDs in each TKR module and they are arranged into 18 pairs of x and y planes, where the x and y planes are separated by a gap of 2 mm. In total, each SSD detector plane has 1526 strips with a pitch of 0.228 mm.

The close proximity of the tungsten planes to the active detectors is crucial in order to minimise the effects of multiple scattering of the charged particles in the shower. Multiple scattering can significantly degrade the angular resolution. Therefore, for lower energies, most of the directional information comes from the first two points of the track. At higher energies, however, the effects of multiple scattering are negligible and the angular resolution is limited mainly by the ratio between the strip-pitch and the gap between the silicon detector planes. The total weight of the tungsten in each module is 9 kg and converts about 63% of the gamma-rays at normal incidence above 1 GeV. A sketch of the layer-wise setup and a gamma-ray conversion is shown in Fig. 4.5.

The efficiency and noise performance are in general quite good. For a single plane of silicon, the efficiency to detect a minimum-ionising particle at nearly normal incidence with respect to the active area is >99.4%. The noise occupancy, i.e. the
The probability for a single channel to have a noise hit in a given detector trigger is, after masking of noisy channels (0.06% of the channels), less than $5 \cdot 10^{-7}$.

**Calorimeter**

A GLAST calorimeter (CAL) module consists of 96 CsI(Tl) Detector Elements (CDEs), i.e. 12 CDEs per layer in 8 layers, supported by a carbon composite cell structure. The LAT, therefore, includes a total of 1536 CDEs, which gives the CAL a combined weight of 1376 kg.

The segmentation of the CAL has many advantages and helps e.g. to distinguish between showers produced by gamma-rays and those by charged particles but also helps to constrain the incoming direction of the gamma-ray. In addition it improves the energy measurement by allowing cascade profile fitting to be performed, which compensates somewhat for leakage into gaps and out of the back of the CAL.

The design is hodoscopic, as can be seen in Fig. 4.6, i.e. the crystal directions in odd layers are orthogonal to the crystal directions in even layers. The size of each crystal is $326 \times 26.7 \times 19.9$ mm$^3$, where the widths correspond to roughly one radiation length in CsI(Tl), i.e. 18.6 mm [46]. Two out of the four long side surfaces have been roughened to give a known attenuation with a better uniformity in the light collection along the crystal. To improve light collection and optical isolation, the crystals are individually wrapped with a reflective material called VM 2000.

The scintillation light from the crystals are collected at each end of each crystal using two silicon PIN photodiodes, which have a spectral response that is matched
4.2. Instruments

Figure 4.6. A picture showing the hodoscopic design of a GLAST calorimeter module.

to the scintillation spectrum from CsI(Tl). The diodes are of different size to be able to cover the large energy range of GLAST. The larger diode has an active area of 1.5 cm$^2$, which is a factor of 6 larger than the active area of the smaller diode (0.25 cm$^2$). The larger diode is designed to measure smaller energy deposits, from 2 MeV to 1.6 GeV, whereas the smaller diode handles larger energy deposits, from 15 MeV to 100 GeV.

Anti-Coincidence Detector

The anti-coincidence detector (ACD) on the LAT consists of 89 Tile Detector Assemblies (TDAs) made of plastic scintillator material. The layout is sketched in Fig. 4.7.

The scintillator tiles are 10 mm thick, except for the central row on top of the LAT, which is 12 mm, and range in size from 15 × 32 cm$^2$ to 32 × 32 cm$^2$ depending on the location of the TDA. An example of an unwrapped tile is shown in Fig. 4.8. These tiles lie outside of the primary field-of-view of the LAT, where no events will be accepted as gamma-rays. Each tile is, furthermore, wrapped with two layers of high reflectance white Tetratec followed by two layers of light-tight black Tedlar.

Each TDA is connected to 1 mm in diameter wavelength shifting (WLS) fibers, which transmit the scintillation light to PMTs, which are located on the sides of the LAT, below the TDAs. For redundancy, each tile is read out by two PMTs.

The tiles are overlapping in one dimension, as shown in Fig. 4.9, to minimise the open areas. The remaining gaps in the other direction, typically 2–3 mm, are unavoidable due to the wrapping material and since the tiles must be allowed to thermally expand and vibrate during launch. To detect entering charged particles, the gaps are instead covered with flexible scintillating fiber ribbons.

The so-called “crown” tiles, i.e. the top most rows of tiles on the four sides of the LAT, also seen in Fig. 4.7, are extended above the tiles on the top of the LAT. The reason for this is to minimise the irreducible background caused by protons that hit
the Micro-Meteoroid Shield (MMS) at a shallow angle, which produce gamma-rays that enter the detector. According to simulations, the contamination from this type of events would without the crown tiles be significantly higher.

The MMS surrounds the whole ACD, to shield it from micro-meteoroids and space debris, and consists of four layers of Nextel ceramic fabric separated by four layers of 6 mm thick Solimide low-density foam, which is backed by 68 layers of Kevlar fabric. According to calculations there is a 95% probability of allowing no more than 1 penetration of the MMS in 5 years.

The ACD has a segmented design for mainly two reasons. Firstly, it is utilised to avoid events with backsplash from being vetoed. Backsplash is a process, where
4.2. Instruments

Figure 4.9. A sketch of the overlapping anti-coincidence detector tiles on top of the LAT (a) and in cross-section (b) (from [47]).

charged particles, produced in the electromagnetic showers from gamma-rays in the field-of-view, propagate the detector in the opposite direction of the incident gamma-rays and hit the ACD tiles. A simulation showing the chain of events can be seen in Fig. 4.10. In experiments, such as EGRET, this process caused a significant decrease in effective area and additional dead time due to the single piece design of the anti-coincidence shield. The effects of backsplash have been thoroughly investigated and taken into consideration when designing the ACD.

Figure 4.10. A simulation of backsplash in the LAT to the anti-coincidence detector (from [47]).

The second reason for having a segmented design is for usage in the background rejection, further discussed below.

A substantial difference between EGRET and the LAT is the lack of a directional trigger system, i.e. time-of-flight detectors. Instead, the trigger on the LAT requires coinciding signals in three consecutive tracker XY layer pairs or an energy deposition in the calorimeter that exceeds a certain chosen threshold. The particles can, thus, come from any direction, which results in a very high first-level trigger rate that
can be up to 10 kHz. The triggers are mostly caused by charged particles, which as mentioned before outnumber the gamma-rays by six orders of magnitude.

To reduce the huge amount of data caused by these triggers down to the downlink capacity to the ground, most of the charged particle induced triggers must be rejected already in space, using the on-board filter. The responsibility of identifying the charged particles for rejection lies mainly on the ACD.

The science requirements for the LAT state that the residual background should be no more than 10% of the diffuse gamma-ray background intensity. To meet this goal, protons must be suppressed by a factor of about $10^6$ and electrons by a factor of about $10^4$ [47].

The CAL and TKR can be used to suppress protons by at least a factor of $10^3$, by using event patterns in the TKR and shower shapes in the CAL. The remaining factor of $10^3$ must be provided by the ACD.

For electrons, the required rejection is tightest for lower energies due to the steep decrease with energy of the electron spectrum. The TKR can be used to suppress electrons by a factor of 10, by identifying tracks that point to inefficient regions of the ACD. The remaining suppression of 0.9997 for the ACD is done in several different ways.

Firstly, the tracks, as measured by the TKR, that point back to “shadowing” ACD tiles that recorded a signal are vetoed. Secondly, the information from the TKR and CAL in combination with the ACD are compared, to reject events that have a high probability of being charged particles. This reduces the amount of data to the capacity of the downlink to the ground. Transmitting a very small fraction of charged particle events to the ground is useful for calibration purposes. Therefore, the efficiency of the ACD to reject charged particles must at this point only be $\geq 0.99$. Finally, the required efficiency of 0.9997 for the ACD to detect singly charged particles is accomplished via data analysis off-line on the ground and includes e.g. pulse height analysis.

The ultimate background rejection that meets the science requirements for the LAT is, then, achieved via further data analysis on the ground.

For a more thorough review of the ACD design and specifications, see [47].

4.2.2 GLAST Burst Monitor

The GLAST Burst Monitor (GBM) is a set of burst detectors located on the sides of the GLAST satellite, as can be seen in Fig. 4.1. As opposed to the LAT, which has a field-of-view of about 2 sr, the GBM has an almost complete coverage of the sky.

The LAT is, by itself, fully capable of detecting GRBs with a precision of about 10 arcmin, and is expected to detect between 50 and 100 GRBs per year. One of the most important features in the energy spectra of GRBs is a break, where the spectrum changes from one power-law to another. This break is located between 100 and 500 keV, which is well below the lower energy threshold at 20 MeV of the
4.3 Event reconstruction

LAT. To simultaneously measure low and high energy contributions from the GRBs would, therefore, highly increase the scientific return.

The GBM includes 12 thin NaI(Tl)-plates, sensitive in the energy range between around 10 keV and 1 MeV, and 2 BGO detectors covering the energy range from 150 keV to 30 MeV. The BGO detectors, therefore, provide an overlap in energy with the LAT instrument and are mounted on opposite sides of the LAT to provide observations of almost the whole unocculted sky. The NaI(Tl) detectors are arranged to give a large field-of-view of >8 sr. There are 6 NaI(Tl) detectors in the equatorial plane, 4 at a 45° angle and 2 at a 20° angle (on opposite sides). The location of a burst is given by the relative count rates of the different NaI(Tl) detectors. A sketch of the detectors in the GBM can be seen in Fig. 4.11.

![Sketch of detectors](image)

**Figure 4.11.** A sketch of the NaI(Tl) detectors (top) and the BGO detectors (bottom) in the GLAST Burst Monitor (from [48]).

The GBM has three main tasks: to provide a GBM burst alert to be transmitted to the ground, the location of the burst and finally the low-energy energy spectrum and light curve of the burst.

4.3 Event reconstruction

In the TKR, the event reconstruction is based on a Kalman filter, which is an iterative fitting method. First, the strips that were hit are converted into positions. If two adjacent strips have been hit, they are merged to form a single hit cluster. In the second step, candidate tracks are formed based on the reconstructed clusters and individual track energies aid in the track recognition. Then, the three-dimensional position and direction are determined and their errors are estimated. Finally, the fitted tracks are used to determine the vertex, where the pair-production took place. The iteration occurs when the tracks are used to get an improved energy estimate after which the tracks can be refit and a new vertex position can be found.

In the CAL, the energy is determined by first applying pedestals and gains to the raw digitized signals from each crystal. The energy is then the sum of all depositions above a certain threshold in all crystals. The longitudinal position in each crystal, where the energy deposition took place, is calculated from the known relation between this position and the energy measured in the two crystal ends. If
Chapter 4. The Gamma-ray Large Area Space Telescope

the light attenuation in the crystal is strictly exponential, this relation takes the mathematical form of Eq. 4.1,

\[ x = K \cdot \tanh^{-1} A \]  (4.1)

where \( A = (\text{Left} - \text{Right})/(\text{Left} + \text{Right}) \) is the so-called light asymmetry, \text{Left} and \text{Right} are the measured energies in the two crystal ends, respectively, \( x \) is the longitudinal position of impact in the crystal and \( K \) is a constant factor.

With the calculated array of energy depositions and positions for each crystal in the CAL, the direction can be determined via energy moments analysis for each shower. This procedure is similar to a moments of inertia analysis, in which a moments ellipsoid is calculated. The principal axis of this ellipsoid provides the incoming direction of the particle and the center of the ellipsoid determines the center of gravity for the shower.

The raw energy given by the CAL is never the same as the initial photon energy, since energy is always lost in internal gaps between CAL modules and between crystals and via leakages out of the back and the sides of the instrument. Therefore, different energy correction algorithms have been developed to compensate for these effects and to correct the energy to correspond to the incoming photon energy. There are currently three such algorithms:

- **The parametric method** combines energy measurements from both the TKR and the CAL. At 100 MeV, about 50% of the total energy deposition is deposited in the TKR. The fraction decreases rapidly with energy and is only about 5% at 1 GeV. Energy estimations in the TKR can be done in many ways. There is, e.g. a correlation between the number of SSD hits near or on the track and the particle energy, due to the large amount of multiple Coulomb scattering at lower energies. The opening angle for pair produced \( e^+e^- \) is also an energy estimator. The parametric method provides a starting point for the re-fitting of the track in the TKR and the energy is re-evaluated using the two other methods below. The corrected energies from the parametric method are stored in a variable called \text{EvtEnergyCorr} and is included in one of the ROOT N-tuples used for analysing detector information.

- **The likelihood method** makes use of the correlation between the number of hits in the TKR, the energy deposited in the last layer of the CAL and the total raw energy deposited in the CAL. It has been optimised for various classes of Monte Carlo events, such as gamma conversions occurring in the thin or thick tungsten layers in the TKR. The corrected energy using the likelihood method is stored in a variable called \text{CalLkHdEnergy}.

- **The profile fitting method** looks at the layer-by-layer energy deposition and fits the longitudinal shower development. The method works best when the shower maximum is contained within the CAL. The corrected energy using the likelihood method is stored in a variable called \text{CalCfpEnergy}. 

Chapter 5

Calibration Unit beam test

In 2006, a major beam test campaign was performed at CERN by the GLAST LAT collaboration. This chapter gives an introduction to the beam tests, including the motivations to having them and the experimental setups.

5.1 Introduction

In the GLAST LAT collaboration, the LAT instrument has been modelled with a Monte Carlo simulation package based on Geant4 [49]. Many properties of the LAT, like the instrument response function, which includes the effective area and the point-spread function, the background rejection and some of the energy reconstruction algorithms, have been determined with this model. The accuracy of this model is, therefore, crucial, which means that beam tests that measure the actual response of the instrument in a controlled environment are of great importance.

In the beam tests, the physical processes in Geant4, including e.g. multiple scattering and shower development, and the detector modelling, including the electronics, were tested. Geant4 only determines the energy loss in a given volume. Therefore, the electronics have to be modelled independently and many quantities derived from calibration procedures or from specifications have to be used.

The LAT was not tested in a beam test due to the risks involved. Therefore, the instrument could only be calibrated on ground using cosmic muons. Since the muon energies are much lower than the upper end of the LAT energy range, the calibration had to be tested also at high energies. This was also one of the motivations to do a beam test.

The large energy range and field-of-view of the LAT yield a very large total phase space that can be studied with a beam test and a continuous scan of the whole phase space is not feasible. The goals of the validation can, however, be met with a sampling of the phase space. In the performed beam tests, the sampling meant tilting the detector with respect to the beam axis to different angles. The
Chapter 5. Calibration Unit beam test

tilted runs are useful when estimating the effects of gaps, inherent between towers and between calorimeter crystals, and the accuracy of the geometry describing them.

Two tests were performed at CERN and one at GSI. The latter facility provided testing of heavy ion responses but will not be reviewed here in this thesis. The beam tests at CERN were performed at the Proton Synchrotron (PS) facility, starting in July 2006, and in the Super Proton Synchrotron (SPS) facility during September 2006. The PS facility provided photons via tagging (explained in Section 5.3), electrons, protons and pions at energies 0.5–10 GeV, whereas the SPS facility only provided electrons, protons and pions at 10–282 GeV.

5.2 Calibration Unit

As mentioned above, using the LAT itself in a beam test was not feasible. For this reason, the decision was made to build a new instrument using flight spare modules and flight-like read-out electronics. This detector was named the Calibration Unit (CU) and is shown in Fig. 5.1.

![Figure 5.1. A photo of the GLAST LAT Calibration Unit on top of a positioning table.](image)

Two full towers, with a TKR module and a CAL module, and an additional CAL module were placed in a 1 × 4 support structure of aluminium. The detector modules were enclosed in a protecting nitrogen-flushed, 2 mm thick aluminium Inner Shipping Container (ISC). Five flight-like ACD tiles were also included outside the ISC, since the ACD is an integral part of the LAT. The tiles were included also to be able to study backsplash, a significant issue in the EGRET experiment, where shower particles hit the ACD tiles and give rise to a rejection of primary photons.
The tiles were placed outside the ISC in order to be able to change tile configurations quickly during the beam tests.

The CU was placed on a positioning table, capable of moving the CU along two horizontal axes (x and y) and rotating the CU around the vertical axis ($\theta$). The positioning table can also be seen in the figure. The black plates, seen in the middle of the figure, contain the ACD tiles.

### 5.3 PS facility test

A beam of photons was not directly available at CERN. Therefore, one was created in the T9 beam line at PS by deflecting electrons from an electron beam using a magnet, thereby leaving mostly bremsstrahlung photons created in the detectors upstream. This so-called photon tagger was a two-arm spectrometer and the detectors included are sketched in Fig. 5.2. A photograph of the test site is shown in Fig. 5.3.

![A sketch of the experimental setup at PS, showing the locations of the Cherenkov detectors (C1 and C2), the plastic scintillators (S0, S1, S2, S4 and Sh) and the Silicon-Strip Detectors (SSD1–SSD4) relative to the magnet, the beam dump and the CU. The electrons are deflected with the magnet which leaves a beam of bremsstrahlung photons created in the detectors upstream.](image)

The first arm had two gas threshold Cherenkov-counters (C1 and C2) that were used for particle identification, five plastic scintillators (S0, S1, S2, S4 and Sh) that were used for monitoring, triggering and vetoing and silicon-strip detector (SSD) hodoscopes, SSD1 and SSD2, used for particle track measurements. S0 ($15 \times 40 \times 1 \text{ cm}^3$) provided monitoring of the total number of particles in the beam and Sh ($15 \times 40 \times 1 \text{ cm}^3$), with a hole of 2.4 cm in diameter, was used to reject particles in the “halo” of the beam. Both S1 and S2 had a small cross-section and a thickness of 2 mm. They were used to select a small area of the beam.

After the first arm, a dipole magnet with a maximum bending power given by 50 cm x 1 T, deflected the electrons into the second arm of the spectrometer. In the second arm, two additional SSD hodoscopes, SSD3 and SSD4, measured the deflected electron direction. The final scintillator, Sf’ ($10 \times 10 \times 1 \text{ cm}^3$), defined the acceptance of the spectrometer and was used for triggering.
The bended track provided the energy of the deflected electron and by difference with the energy of the beam, the energy of the photon going into the CU could be determined. In Fig. 5.4 from [50], the energy distributions measured by the CU and the tagger with 2.5 GeV electrons is shown. The dotted line represents the photon energies measured by the CU, the dashed line shows the deflected electron energies measured by the tagger and the solid line is the sum of the two. As can be seen in the figure, the sum is peaked around the beam energy.

To recover from lost beam time due to accelerator issues, a second set of photon data was also collected by using a different configuration. In this setup, the CU operated as a stand-alone detector and the tagger information was neglected. The accepted photons, then, constituted the full bremsstrahlung spectrum and a faster
read-out rate could be achieved. The direction of the photons were assumed to coincide with the beam direction given by the detectors before the magnet.

The other particle types (electrons, positrons, protons and pions) were collected using different configurations. The trigger settings of each particle type are summarised in Table 5.1 from [50].

Table 5.1. The different configurations used for the different particle types in the PS beam test. The trigger is composed of the logical AND of the detectors involved and a bar over the detector corresponds to the logical NOT; the last column refers to what gas was used in the Cherenkov detectors and what particles were tagged by the counter in order to get the particle of interest.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy (GeV)</th>
<th>Trigger</th>
<th>Magnet</th>
<th>Cherenkov</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{\text{tag}}$</td>
<td>$\approx0.05$–$1.5$</td>
<td>$C1\ C2\ S1\ S2\ Sh\ S4$</td>
<td>ON</td>
<td>CO$_2$, tag $e^-$</td>
</tr>
<tr>
<td>$\gamma_{fb}$</td>
<td>0–2.5</td>
<td>$C1\ C2\ S1\ S2\ \overline{Sh}$</td>
<td>ON</td>
<td>CO$_2$, tag $e^-$</td>
</tr>
<tr>
<td>$e^-$</td>
<td>1, 5</td>
<td>$C1\ C2\ S1\ S2\ \overline{Sh}\ S3$</td>
<td>OFF</td>
<td>CO$_2$, tag $e^-$</td>
</tr>
<tr>
<td>$e^+$</td>
<td>1</td>
<td>$C1\ C2\ S1\ S2\ \overline{Sh}\ S5$</td>
<td>ON</td>
<td>CO$_2$, tag $e^+$</td>
</tr>
<tr>
<td>$p$</td>
<td>6, 10</td>
<td>$S1\ S2\ \overline{C1}\ C2\ \overline{Sh}$</td>
<td>OFF</td>
<td>CO$_2$, tag $K$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>5</td>
<td>$S1\ S2\ \overline{C1}\ C2\ Sh\ S3$</td>
<td>OFF</td>
<td>CO$_2$, tag $\mu^-$</td>
</tr>
</tbody>
</table>

One important topic is the study of the different sources of background that the LAT will encounter in orbit. The following areas have, therefore, also been studied with the CERN beam test data.

- **Albedo gamma-rays.** These are gamma-rays produced when cosmic rays interact with the atmosphere of the Earth and enter the LAT from the side and the back. Some of these can mimic a gamma-ray with normal incidence.

- **Hadronic interactions.** Protons can interact with the instrument or with the spacecraft, generating a hadronic cascade that can mimic an electromagnetic shower in the CAL. To help reject most of these events, the LAT background rejection uses many reconstructed variables such as the transverse size of the shower and the distance between the first hit in the tracker and the ACD.

- **Charged particles interacting in the Micro-Meteoroid Shield (MMS).** If charged particles enter the instrument, the ACD can be used to reject most of them. However, if the charged particle interacts with the MMS, photons can be produced within the LAT field-of-view. For this study, an extra scintillator, $S5$, in front of a small MMS was used. The positrons, used for the study, were clean from bremsstrahlung photons since the magnet was used to deflect only the positrons into the CU.

The analysis shown in the next chapter was performed on a subset of the total amount of data collected and the focus has been put on photons and electrons, since these are most relevant for the dark matter line search described in Chapter 7.
5.4 SPS facility test

At the H4 beam line in the SPS beam test, secondary beams of electrons, positrons, pions and protons in the energy range 10–300 GeV were available from a primary beam of protons at 450 GeV, but also tertiary clean beams of electrons, pions and protons could be used.

The external detectors and the experimental setup were similar to those in the PS beam test and are shown in Fig. 5.5 and Fig. 5.6. The $S_1$, $S_2$ and $S_h$ scintillators composed the external trigger and two helium gas threshold Cherenkov-counters were used for particle identification. The $S_h$ scintillator consisted in this case of four 15 $\times$ 40 cm$^2$ tiles (denoted $Sv1$–$Sv4$ in the figure), which were arranged to form a 4 cm square hole in the middle. The remaining scintillator, $S0$, had the same purpose as in the PS beam test.

The various trigger settings for the different particle types are shown in Table 5.2. As can be seen in the table, the Cherenkov counters were empty for the electron and pion runs, since the tertiary beams mentioned above were used.

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**Figure 5.5.** A sketch of the experimental setup at SPS, showing the locations of the Cherenkov detectors ($C1$ and $C2$) and the plastic scintillators ($S0$, $S1$, $S2$, $Sv1$, $Sv2$, $Sv3$ and $Sv4$) relative to the CU.

**Figure 5.6.** A photo of the experimental setup at SPS. The CU is located between the two beam pipes.
Table 5.2. The different configurations used for the different particle types in the SPS beam test. The trigger is composed of the logical AND of the detectors involved and a bar over the detector corresponds to the logical NOT. The last column refers to what gas was used in the Cherenkov detectors and what particles were tagged by the counter in order to get the particle of interest.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Energy (GeV)</th>
<th>Trigger</th>
<th>Magnet</th>
<th>Cherenkov</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$</td>
<td>10–282</td>
<td>$S_1 S_2 S_h$</td>
<td>OFF</td>
<td>empty</td>
</tr>
<tr>
<td>$p$</td>
<td>20, 100</td>
<td>$S_1 S_2 \bar{C}_1 \bar{C}_2 S_h$</td>
<td>OFF</td>
<td>He, tag $\pi$</td>
</tr>
<tr>
<td>$\pi^-$</td>
<td>20</td>
<td>$S_1 S_2 S_h$</td>
<td>OFF</td>
<td>empty</td>
</tr>
</tbody>
</table>
Chapter 6

Beam test analysis

During the beam test campaign at CERN during 2006, a large amount of data was collected. This chapter contains the analysis of a sample of that data chosen for this thesis because of its relevance to dark matter searches. It will start with a presentation of the general approach of the analysis and what cuts have been made in order to get as clean a sample as possible. Then, the studies of the three different observables position, direction and energy are shown.

6.1 Analysis approach

The focus of the analysis presented in this thesis was put on the photon data collected at the PS beam test, since the LAT instrument is dedicated to measuring this type of particle, and the electron data collected at both the PS and the SPS beam tests. As mentioned in the previous chapter, these particles are most relevant for the search of a dark matter line from WIMP annihilations, which is described in Chapter 7. The correct modelling of protons and pions is important for the background rejection but irrelevant for the dark matter studies in this thesis.

In the SPS beam test, where higher energies could be achieved, no photon data was collected. The energy resolution at the high end of the LAT energy range, where searches for dark matter annihilation lines are theorised to be more successful, was therefore determined with electron data. Since both photons and electrons produce electromagnetic showers, the results should be comparable.

The primary question investigated here is the following. Does the Geant4-based simulation package developed for the LAT reflect reality? Any differences that might exist in a comparison between real data and a simulated counterpart can, in principle, only have their origin in the following four categories:

- Calibration
- Geometry
Chapter 6. Beam test analysis

- Software
- Physics

The first category is a problem with the real detector. If the subdetectors have been incorrectly calibrated in terms of their various thresholds and calibration constants, the effects would primarily present themselves in variables connected to energy measurements. However, to the calibration category can also be included e.g. timing and trigger settings.

The next category points to differences in material and precise geometry. In reality, imperfections are bound to exist in the form of cracks, misalignments and impure materials both in the CU, the external detectors and in the beam line.

The last two categories are issues in the simulation package. Software errors can in many cases produce effects that can be mistaken as an issue belonging to the other categories and the physics, implemented in Geant4, can in some cases be simplified and may not account for all subprocesses occurring in reality.

All these issues affect the comparison between real data and simulated data. Disentangling them and determining which of the aforementioned categories each difference belongs to is complicated and can in some cases prove to be impossible. The results obtained can, however, be used to tune the Monte Carlo (MC) simulation to better correspond to what is observed.

Any unresolved differences should be taken into account as systematic uncertainties in future physics analyses based on LAT data. It should be stressed, however, that translating differences between data and MC, that are observed for the CU, to the LAT is non-trivial. Even though the main subdetectors in the CU are flight spares and, thus, identical to the subdetectors in the LAT, many properties still differ. This includes e.g. the flight-like read-out electronics used and the geometry and composition of the material surrounding the detector towers.

The analysis described in this thesis focuses on identifying differences and, where possible, finding reasons for them. Comparisons between data and MC can be done in multiple ways. One way is to calculate containment radii for the distributions and compare them. Another approach is to calculate the statistical moments. The most important moments are the mean value and the RMS. Correlations between different variables can also be investigated, in order to determine the origin of any discrepancy. All these approaches have been exercised in this analysis.

What has been done within the beam test working group spans over all the four categories listed above. The calibration has been improved by including non-linearities in the crystals and corrections for the effects of cross-talk between adjacent crystals and diodes. Using dedicated calibration runs, the parameters determining the asymmetry curve in each CAL crystal and pedestal values have been calculated. New digitisation algorithms have been developed for the tracker. Comparisons have also been made between Geant3, Geant4, EGS5 [51] and Mars15 [52] to track down differences in physics and the material within the detector and in the beam line has been thoroughly investigated. The analysis of the beam test data in
6.2 Creating a clean sample

The measured data consists not only of the particles that are of interest. Various sources of contamination and other effects are also included, which in turn diminish the quality of the data sample. The most important of these effects are:

- Cosmic ray contamination
- Beam contamination
- Noise
- Pile-up
- Gaps

In the MC simulation, the detector is in a background free environment, with no interference from the effects mentioned above unless they are intentionally put there. A first step in the analysis procedure must, therefore, be to create as clean a data sample as possible.

Cosmic rays, consisting mostly of muons at ground level, affect the measurements in two different ways. Either they coincide with a particle from the beam or they interact alone in the detector.

In the first case, the muon can create a track that leads into a neighbouring TKR or CAL module. An example of how this could affect the analysis is if a significant enough energy deposition is made by the muon in another CAL. This will distort the reconstructed direction of the beam particle by the CAL. This scenario can be avoided by cutting on the location of the energy centroid calculated in the CAL, i.e. by requiring the centroid to be in the right tower.

For the second case, one of the dedicate muon runs, taken at various points during the beam tests, can be looked at. As explained in Section 1.1, muons are minimum ionising particles and interact according to the Bethe-Bloch formula. Most muons will, therefore, on average deposit a similar amount of energy in the CAL, thus, forming a peak in the energy spectrum. If an appropriate cut is made in the total energy deposited in the CAL, most of the muons can be rejected. The threshold should, however, not be too high, since then a major portion of the correct events can be rejected as well.

In Fig. 6.1, the energy spectrum for a muon run is shown. For this distribution, the 95% quantile can be calculated. Doing this for the particular muon run gave
a threshold placed at about 267 MeV. This cut was used in all analyses except in the energy resolution studies, where the threshold was, instead, set at 1000 MeV.

![Energy spectrum of muons](image)

**Figure 6.1.** The energy spectrum of muons.

A second cut, designed to remove coincident muons as well as contamination in the beam, is to reject energies larger than the beam energy. The energy of e.g. a bremsstrahlung photon cannot be higher than the energy of the electron that gave rise to it.

Events caused by noise can be a contributing factor and should be rejected so that distributions of interest are not affected. The TKR is, however, already a low noise instrument and in the CAL, various thresholds were set to reject crystal read-outs with an energy deposition below the threshold. For this reason, no cut was included purely for the purpose of avoiding noise.

If the rate of particles in the beam is high enough, comparable to the dead time of the instrument, the resulting pulses measured by the instrument can pile up and give a false reading. To avoid this, a cut can be made on the time between consecutive events. In this case, motivated by the characteristics of the electronics, only events with a time between events that was larger than 0.5 ns were accepted.

A large contribution to differences between data and MC can come from geometrical effects in the form of gaps between towers and between CAL crystals. This means that the fraction of events that go into gaps can be different between data and MC, because the beam spots are not exactly the same. This can have a large impact on the end result.

To avoid as many geometrical effects as possible, the following cuts can be made. The first cut rejects any events, whose first hit in the TKR is outside a given perimeter around the beam spot. The position of the energy centroid is also
required to be in the correct tower and not close to any of the tower edges. Another
cut designed to have the same effect makes sure that the reconstructed track is not
close to gaps between towers or between CAL crystals. These cuts also avoid
scenarios where particles deposit energy close to or directly into the crystal diodes.
In these cases, the relation between position and light yield becomes unreliable and
the measured energy in the diodes can have large fluctuations. To further avoid
these effects, all studies have been performed on data runs with a incoming particle
inclination of 0° relative to the z-axis of the CU.
To be able to compare the direction and position as measured by the TKR and
CAL, a track in the TKR is required. Therefore, a cut was included on the total
number of potential tracks in the TKR. The requirement was that there should be
at least one.
A final cut was made on the reconstructed directions in the CAL. The direction
distributions should be monotonically decreasing from the beam spot. A small
fraction of events, however, had a reconstructed direction in the CAL that was
about 90° away from the reconstructed TKR direction. These events are clear
cases of failed reconstructions and the fraction of events with failed reconstructions
can be different from run to run. Therefore, only events with an angle less than the
angle where the monotonically decreasing distribution turns into a monotonically
increasing distribution were accepted.

6.3 Position reconstruction in the CAL

When studying the CAL in terms of its position and direction reconstructions,
the TKR can be used as a reference. Quantifying how well data and MC agree
for position measurements in the CAL was done as follows. An extrapolation of
the track as measured by the TKR module was made from the location of first
hit to the top of the CAL at -47.8 mm along the z-axis by using the directional
information reconstructed from the TKR. The same was done for the CAL, but
the extrapolation was, then, done from the measured energy centroid (the center
of "gravity" for the reconstructed energy ellipsoid) and up to the top of the CAL
using the directional information reconstructed for the CAL.
The equations used to extrapolate the tracks are given in Eq. 6.1 and Eq. 6.2
\[
S_{\text{ext.TKR}[X/Y]} = Tkr1[X/Y]0 + \frac{(-47.8 - Tkr1Z0)}{Tkr1ZDir \cdot Tkr1[X/Y]Dir}
\]
\[
S_{\text{ext.CAL}[X/Y]} = Cal[X/Y]Ecntr + \frac{(-47.8 - CalZEcntr)}{CalZDir \cdot Cal[X/Y]Dir}
\]
where \(Tkr1[X/Y/Z]0\) is the x-, y- and z-coordinate for the first hit in the TKR
and for the best track out of all potential track permutations in the TKR. The
two variables, \(Tkr1[X/Y/Z]Dir\) and \(Cal[X/Y/Z]Dir\), are the so-called directional
cosines, i.e. the cosines of the angles relative to the three coordinate axes and
Cal\[x/y/z\]Ecntr is the x-, y- and z-coordinate of the energy centroid in the CAL for each event.

Once the extrapolated positions were measured at the same point, in this case at the top of the CAL, the difference between the extrapolated positions from the TKR and the CAL (the difference between the two equations above) could be taken. The resulting distributions should be centered at zero and this was confirmed by observations. The 68% quantile was then taken on the absolute value of the distributions. The results both in the x- and the y-direction for bremsstrahlung photons from electrons at 2.5 GeV, tagged photons from electrons at 2.5 GeV and electrons at 5 GeV, are shown in Table 6.1. The relative difference in per cent between the quantiles of the distributions from data and MC can be found in Table 6.2 and the distributions from which the quantiles are calculated, normalised by the number of counts, can be seen in in Fig. 6.2– 6.4.

### Table 6.1.
The 68% containment of the absolute value of the difference between the extrapolated TKR position and the extrapolated CAL position for the different types of particles studied. The value calculated for Monte Carlo is denoted by MC.

<table>
<thead>
<tr>
<th>Particle</th>
<th>(X_{68%}(mm))</th>
<th>(X_{MC,68%}(mm))</th>
<th>(Y_{68%}(mm))</th>
<th>(Y_{MC,68%}(mm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma_{fb})</td>
<td>12.0 ± 0.2</td>
<td>10.6 ± 0.2</td>
<td>11.6 ± 0.2</td>
<td>10.2 ± 0.1</td>
</tr>
<tr>
<td>(\gamma_{tag})</td>
<td>12.9 ± 0.2</td>
<td>10.5 ± 0.1</td>
<td>12.3 ± 0.2</td>
<td>10.6 ± 0.1</td>
</tr>
<tr>
<td>(e^-)</td>
<td>4.7 ± 0.1</td>
<td>4.2 ± 0.1</td>
<td>5.2 ± 0.1</td>
<td>4.3 ± 0.1</td>
</tr>
</tbody>
</table>

### Table 6.2.
The relative differences in position reconstruction between data and Monte Carlo for the different particle types studied.

<table>
<thead>
<tr>
<th>Particle</th>
<th>(\Delta X_{68%}/X_{68%}(%))</th>
<th>(\Delta Y_{68%}/Y_{68%}(%))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\gamma_{fb})</td>
<td>11.8 ± 0.3</td>
<td>12.0 ± 0.3</td>
</tr>
<tr>
<td>(\gamma_{tag})</td>
<td>18.8 ± 0.4</td>
<td>14.0 ± 0.3</td>
</tr>
<tr>
<td>(e^-)</td>
<td>12.1 ± 0.2</td>
<td>16.9 ± 0.2</td>
</tr>
</tbody>
</table>

### 6.3.1 Asymmetry curves

As described in Section 4.3, the light asymmetry, i.e. the relation between the energy deposition and its longitudinal position in each crystal of the CAL, is an integral part of the CAL calibration procedure. An illustration and a validation of this asymmetry can be done with the proper data set.

During the beam tests, a set of runs were taken, where the impact point of the beam was stepwise changed along two crystals facing in perpendicular directions in the center of the CAL. A schematic of the set of runs can be seen in Fig. 6.5. This particular set of runs can be used to inspect the asymmetry properties of the CAL.
6.3. Position reconstruction in the CAL

Figure 6.2. The distribution of positional difference between the TKR and CAL position, extrapolated to the top of the CAL, in the $x$ (top) and $y$-direction (bottom) for bremsstrahlung photons from electrons at 2.5 GeV. The solid line is data and the dashed line is Monte Carlo.
Figure 6.3. Same as in Fig. 6.2 but for tagged photons from electrons at 2.5 GeV.
Figure 6.4. Same as in Fig. 6.2 but for electrons at 5 GeV.
Chapter 6. Beam test analysis

crystals. Full coverage in the form of a 12 x 12 array of impact points would have been ideal but due to limitations in beam time, a solution with limited coverage was used instead.

![Figure 6.5. Schematic showing the placement of the beam in the calibration runs.](image)

The analysis procedure was as follows. In order for calibration to be successful, the crystals that have been hit by the trajectory and shower of each incoming particle must be known. Multiple tracks can cause multiple hit points in the same crystal, which makes calibration more difficult. Another issue occurs if the track reconstruction is bad. Then, an extrapolated track might not point to the real point of impact. Therefore, only events with one single track in the TKR and a $\chi^2$ value of the track that was between 1 and 2 were selected for analysis. For muons, no shower is produced, and, therefore, no cut on the $\chi^2$ value was needed.

The crystal that was hit is deduced by extrapolating the track from the TKR down to the CAL crystal of interest and selecting only events that lie within the crystal boundaries.

In the left plot of Fig 6.6, the asymmetry has been plotted as a function of the TKR position, extrapolated to the level where the crystal of interest is located. For the calibration runs described above, electrons at 5 GeV and 0° incoming angle were used. In this case, for crystals in the 2nd layer from the top, which is the first layer that has crystals in the same direction as the beam scanning direction, the beam deposited most energy in the 7th crystal.

The right plot of Fig 6.6 shows the same thing as the left plot, but the axes have been binned into 12 bins of equal width. In each bin, the mean asymmetry was calculated. The bin size was chosen to correspond to approximately the width of a crystal. The points were fitted, for simplicity, with a quadratic function, since its precision will suffice for the study shown below. In the first and the last bin, the position measurement relation fails. For this reason they were not included in the fit.

For comparison, the same log was studied with muon data, which is also used for other calibration purposes on ground. The corresponding plots can be seen in Fig. 6.7.

Using the fit parameters, the difference between the position derived from the asymmetry and the position calculated from an extrapolation of the track in the TKR can be determined. From the resulting plot for both electrons and muons,
6.3. Position reconstruction in the CAL

Figure 6.6. The light asymmetry as a function of the extrapolated tracker position in one calorimeter crystal (layer 2, crystal 7) for electrons at 5 GeV and 0° angle. The left plot illustrates the spread in light asymmetry and the right plot shows the mean light asymmetry in each bin fitted with a quadratic function.

shown in Fig. 6.8, the 68% containment, centered at zero position error, can be calculated.

Figure 6.7. The light asymmetry as a function of the extrapolated tracker position in one calorimeter crystal (layer 2, crystal 7) for muons. The left plot illustrates the spread in light asymmetry and the right plot shows the mean light asymmetry in each bin fitted with a quadratic function.

The design requirements of the CAL crystals state that the position precision should be at least 30 mm. In Fig. 6.8, the position error in one CAL crystal is shown for both electrons at 5 GeV and muons. The plots show the difference between the extrapolated TKR position into the log and the position deduced from the asymmetry, which is based on the fits in Fig. 6.6 and Fig. 6.7. For electrons, the 68% containment, centered at zero, of the position error in one CAL crystal was 4.3±0.2 mm. For muons, the equivalent value was 13.1±0.4 mm. The design requirements are, therefore, met.

The larger spread for muons comes from the fact that many muons traverse the crystal at an angle and deposit energy in a larger segment than what a pencil beam of electrons do, where the incoming particle directions are mostly approximately
perpendicular to the crystal log. The asymmetry properties are, therefore, distorted somewhat.

![Figure 6.8](image)

**Figure 6.8.** The difference between the extrapolated tracker position and the position of hit deduced from the light asymmetry in one calorimeter crystal (layer 2, crystal 7) for electrons at 5 GeV (left) and muons (right).

### 6.4 Direction reconstruction in the CAL

Directional variables in LAT data, as explained before, are output in the form of directional cosines. This means that the cosine of the angles between the incoming particle direction vector and the three different axis are calculated. A distribution on which a 68% containment calculation can be performed, similar to the ones for the position reconstruction, can be obtained by using the following formula.

$$\theta = \pi - \arccos(Tkr1XDir \cdot CalXDir + Tkr1YDir \cdot CalYDir + Tkr1ZDir \cdot CalZDir)$$ (6.3)

where $\pi$ comes from the fact that the coordinate systems in the TKR and in the CAL are defined differently. In the TKR a right-handed coordinate system is used with the positive z-direction pointing in the direction of the beam. In the CAL, a left-handed coordinate system is used with the negative z-axis pointing in the direction of the beam. To get the proper angle between the two direction vectors, the one from the TKR and the one from the CAL, a translation of 180° must be done. The expression inside the parenthesis is the scalar product between the two vectors. Since the vectors are normalised, the multiplication of the lengths of the two vectors is one.

The same three particle types, studied in terms of the position reconstruction, were also studied here. Fig. 6.9-6.11 show the resulting distributions. The cuts explained in Section 6.2 have been used and the distributions are again normalised by the total number of counts. The 68% quantiles and the differences between data and MC are given in Table 6.3.
6.4. Direction reconstruction in the CAL

Figure 6.9. The space angle distribution for bremsstrahlung photons from electrons at 2.5 GeV. The solid line is data and the dashed line is Monte Carlo.

Figure 6.10. Same as Fig. 6.9 but for tagged photons from electrons at 2.5 GeV.

Figure 6.11. Same as Fig. 6.9 but for electrons at 5 GeV.
Table 6.3. The 68% containment of the difference between the TKR direction and the CAL direction for bremsstrahlung photons from electrons at 2.5 GeV, tagged photons from electrons at 2.5 GeV and electrons at 5 GeV and the difference between data and Monte Carlo.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Ψ_{68%} (°)</th>
<th>Ψ_{MC,68%} (°)</th>
<th>ΔΨ_{68%}/Ψ_{68%} (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ_{fb}</td>
<td>11.5 ± 0.1</td>
<td>9.9 ± 0.1</td>
<td>13.6 ± 0.2</td>
</tr>
<tr>
<td>γ_{tag}</td>
<td>12.0 ± 0.1</td>
<td>9.8 ± 0.1</td>
<td>18.4 ± 0.3</td>
</tr>
<tr>
<td>e⁻</td>
<td>3.9 ± 0.03</td>
<td>3.0 ± 0.02</td>
<td>22.1 ± 0.2</td>
</tr>
</tbody>
</table>

6.5 Energy reconstruction in the CAL

Many aspects of energy reconstruction can be studied with the collected data. For this thesis, raw energy distributions, shower profiles in the longitudinal direction and energy resolutions were studied.

6.5.1 Raw energy distributions

There are several variables in the data that are related to energy measurements. Among these are the layer-wise raw energies measured in the CAL. There is also a variable called CalEnergyRaw, which contains the sum of all energy depositions in all crystals and is further investigated in terms of the energy resolution in Section 6.5.3. The layer-by-layer approach offers a more in-depth look than simply looking at the total energy. Here the figures-of-merit are the statistical moments, or more specifically the mean value and the RMS.

In Fig. 6.12, the difference between data and MC in terms of the statistical moments, in all the eight layers of the CAL, are plotted. The plots, as before, correspond to bremsstrahlung photons from 2.5 GeV electrons, tagged photons from electrons at 2.5 GeV and electrons at 5 GeV, respectively. The difference is less than 10% in all layers for photons and less than 16% for electrons. The trend is similar in all the three plots, namely that the agreement is better the higher the layer number is.

6.5.2 Longitudinal profile

In Fig. 6.13, the sum of all longitudinal shower profiles is visualised. In the plots, the energy deposition is shown as a function of the eight layers in the CAL.

The figure shows that the two photon data have an almost identical shape, with a shower maximum located mostly in the second layer of the CAL. The shower maximum for electrons, on the other hand, is most common in the middle layers of the CAL, in layers 4 and 5. The difference in shower maxima between the photon runs and the electrons run can be explained by the fact that the beam energy is a factor of two larger in the electron run. Since the shower maximum changes...
6.5. Energy reconstruction in the CAL

Figure 6.12. The difference between data and MC in terms of the mean value (solid line) and the RMS (dashed line) in the energy depositions in the eight CAL layers for bremsstrahlung photons from electrons at 2.5 GeV (top), tagged photons from electrons at 2.5 GeV (middle) and electrons at 5 GeV (bottom).
Figure 6.13. The energy deposition as a function of the calorimeter layer for bremsstrahlung photons from electrons at 2.5 GeV (top), tagged photons from electrons at 2.5 GeV (middle) and electrons at 5 GeV (bottom). At each layer there are two columns. The left column is data and the right column is Monte Carlo, respectively.
logarithmically with the incoming energy, the maximum for higher energy particles occur later in the CAL.

6.5.3 Energy resolution

The photon tagger was only available in the PS beam line. Therefore, electromagnetic properties at higher energies must by studied with electron data from the SPS beam line. The behaviour in the high end of the LAT energy range should be studied since the masses of many dark matter particle candidates are predicted to be located there. A key factor in these searches is the energy resolution. The larger the energy resolution, the more photons from sources other than dark matter are included in a bin matched to the energy resolution. This will decrease the significance of a spectral line from dark matter and will, consequently, make a line search more difficult.

In Fig. 6.14–6.20, the energy distributions for data and MC are shown for electrons at the energies 5, 10, 20, 50, 99, 196 and 282 GeV. The distributions that are included consist of the measured raw energy in the CAL (CalEnergyRaw), the three available algorithms for energy reconstruction (CalCfpEnergy, CalLkHdEnergy and EvtEnergyCorr), and just for comparison for MC, the MC truth (McEnergy). CalCfpEnergy represents the energy estimated with the profile fitting method, CalLkHdEnergy contains the energy estimated with the likelihood method and EvtEnergyCorr is the energy estimated with the parametric method. The three energy reconstruction algorithms are further described in Section 4.3.

In LAT data, the best of the three energy algorithms is chosen event-by-event and stored in CTBBestEnergy. This variable is not meant to be used with the CU, since it is part of a complicated algorithm that bases the choice on classification tree analyses. How the choice is made depends also on what version of the software that processes the data, since developments and improvements are made continuously. For these reasons, CTBBestEnergy was not included in these plots.

The energy resolutions were calculated by first fitting the tip of each energy distribution with a Gaussian function. Since the distributions are not symmetrical in shape, the Gaussian fitting interval was not extended to the whole spectrum but restricted to the tip of the peak. The fit provided an estimate for the value at which the most probable energy was located. From that point, the events were calculated symmetrically in both directions around the most probable energy, until 68% of the total number of events were accounted for. The resulting energy interval divided by two is the equivalent of a Gaussian standard deviation and yields the relative energy resolution when divided by the most probable energy.

In Fig. 6.21 and Fig. 6.22, the resulting energy resolutions as a function of the energy are shown for data and MC, respectively. Fig. 6.23 shows the relative difference between the two. As can be seen in Fig. 6.20, CalLkHdEnergy has a sharp cut off at 300 GeV. The reason is that the method has only been extended to this energy. Since CalLkHdEnergy does not function well at the highest energy at 282 GeV, the value of the energy resolution was left out at this energy.
Figure 6.14. The energy distributions for electrons at 5 GeV for data (top) and Monte Carlo (bottom) are shown. They consist of the measured raw energy (CalEnergyRaw), the three algorithms for energy reconstruction (CalCfpEnergy, CalLkHdEnergy and EvtEnergyCorr), and for Monte Carlo, the Monte Carlo truth (McEnergy).
Figure 6.15. Same as Fig. 6.14 but for 10 GeV.
Figure 6.16. Same as Fig. 6.14 but for 20 GeV.
6.5. Energy reconstruction in the CAL

Figure 6.17. Same as Fig. 6.14 but for 50 GeV.
Figure 6.18. Same as Fig. 6.14 but for 99 GeV.
Figure 6.19. Same as Fig. 6.14 but for 196 GeV.
Figure 6.20. Same as Fig. 6.14 but for 282 GeV.
Figure 6.21. The energy resolutions for data, determined from the different energy distributions at the energies 5, 10, 20, 50, 99, 196 and 282 GeV.

Figure 6.22. The energy resolutions for MC, determined from the different energy distributions at the energies 5, 10, 20, 50, 99, 196 and 282 GeV.
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Figure 6.23. The difference in energy resolution between data and MC, determined from the different energy distributions at the energies 5, 10, 20, 50, 99, 196 and 282 GeV.

In Fig. 6.24, the relative difference in the fitted peak position between data and MC is shown. As can be seen in the figure, the peak position in data is larger at all measured energies but the trend is relatively flat.

Figure 6.24. The difference in the energy of the peak between data and MC, determined from the different energy distributions at the energies 5, 10, 20, 50, 99, 196 and 282 GeV.
Chapter 7

Dark matter line search

This chapter focuses on an analysis towards finding a dark matter (DM) spectral line in GLAST LAT data. It contains a discussion on where a signal can be looked for and a description of some of the statistical methods that can be used in the search. Two methods were investigated in more detail, Scan Statistics and ProFinder, and applied to a simulated data set called Service Challenge 2.

7.1 Initial discussions

7.1.1 Region-of-interest selection

The gamma-ray sky has never been measured at the high end of the LAT energy range. This means that the gamma-ray emissions, which serve as a background to a spectral line from DM annihilations, are largely unknown. Therefore, an optimisation as to where to look for the DM line is required. The optimal window that gives the highest signal-to-noise ratio depends on the distribution of DM in the Universe and on the distribution of gamma-rays from all other sources. For more discussions on the subject, see e.g. [53] and [54].

For the analysis presented in this thesis, the region-of-interest has been taken from [53]. In the paper, a DM distribution with inherent substructure for a “Milky Way-like” galaxy was produced using N-body simulations, given a flat ΛCDM Universe with assumed parameters. Within the Milky Way, the dominating background will come from the galactic diffuse emission. Motivated by the results from the N-body simulations and accounting for an extragalactic background, an angular window given by a broken annulus around the galactic center with a radius from 25° to 35° but excluding the region within 10° from the galactic plane was used in the paper to determine 3σ detection limits with GLAST. In this region, the diffuse emission was assumed to be zero. This assumption may not, however, reflect real conditions.
The chosen region, which focuses more on the galactic halo than the galactic center, is not necessarily the best place to be looking in for a DM annihilation line with GLAST data. The galactic center has large photon statistics but is affected by source confusion and diffuse photon background. Alternative locations, which may prove to give a better signal-to-noise ratio include DM satellites, where the photon background is lower and source identification is better. The extragalactic background may also prove to be a better location. Therefore, an optimisation must eventually be done on the data.

As described in Section 3.3, the distribution of DM in galaxies can be modelled with different halo models. For the analysis presented here, the NFW profile was used.

### 7.1.2 Data selection

A search for a DM line could be improved significantly by improving the energy resolution of the LAT through a new energy reconstruction algorithm that is better than the ones already in place. The utilisation of such an algorithm would, by definition, decrease the smearing of the line signal over a larger energy range and would, consequently, improve the measured significance of the signal. The development of a new energy reconstruction algorithm is beyond the scope of this thesis, but should be considered in the future in order to maximise the chances of finding a DM line signal.

It can be argued that a slightly larger fraction of charged particles can be accepted if the gain is a better energy resolution, which increases the chance of seeing a DM line signal. Another approach is, therefore, to modify the current selection of gamma-rays in LAT data. This implies, more specifically, a relaxation of the cuts used in rejecting charged particles if the energy resolution is improved. This optimisation can be performed in a number of ways but is not included in this thesis due to time constraints. It may, however, be necessary for future analyses.

### 7.2 Statistical methods

There are a large number of statistical methods that can be used to search for spectral lines. For this thesis, a subset of these have been studied in more detail.

A toy model, where $S \sim \text{Pois}(s + b)$ and $B \sim \text{Pois}(\tau b)$, is considered for all the methods below. The capitalised letters $S$ and $B$ denote random variables and the lower case letters $s$ and $b$ correspond to the signal and background parameters respectively. If the background estimate is taken from a sideband measurement, $\tau$ is the ratio between the size of the background region and the size of the signal region. In the toy model used below, $\tau = 1$.

The two random processes above yield two hypotheses, $M_0$ and $M_1$, with Poisson likelihoods given by:
7.2. Statistical methods

\[ M_0 : \mathcal{L}(b|n_S, n_B) = \frac{n_S e^{-b}}{n_S!} \cdot \frac{b^{n_B} e^{-b}}{n_B!} \quad (7.1) \]

\[ M_1 : \mathcal{L}(s, b|n_S, n_B) = \frac{(s+b)^{n_S} e^{-(s+b)}}{n_S!} \cdot \frac{b^{n_B} e^{-b}}{n_B!} \quad (7.2) \]

where \( n_S \) and \( n_B \) are realisations, or observed values, of the random variables \( S \) and \( B \), respectively.

7.2.1 Coverage and power

Coverage is a concept defined for confidence intervals (CIs). It means that a fraction \((1 - \alpha)\) of an infinite set of CIs obtained from an infinite number of identical experiments should contain the true value of the parameter to be estimated. In other words:

\[ P(s \in [s_1, s_2]) = 1 - \alpha \quad (7.3) \]

where \( s_1 \) and \( s_2 \) are the lower and upper limit of the CI. A method with this property satisfied is said to have nominal coverage. If instead, \( P(s \in [s_1, s_2]) < 1 - \alpha \), the intervals “undercover” for that \( s \). Significant undercoverage for any \( s \) is a serious flaw [56]. For \( P(s \in [s_1, s_2]) > 1 - \alpha \), the intervals are said to “overcover” for that \( s \). The intervals that overcover for some \( s \) and undercover for no \( s \) are “conservative”.

Overcoverage is not as big of a problem as undercoverage but leads to a loss of power, described below. In the context of hypothesis testing, \( \alpha \) is called the type I error and corresponds to the probability that the null hypothesis gets rejected even though it is true.

Power is a concept defined for hypothesis tests. The power of a test is the probability that the null hypothesis is rejected when the alternative hypothesis is true. In other words, power = \( 1 - \beta \), where \( \beta \) is the probability of a type II error, i.e. the probability to accept the null hypothesis when the alternative hypothesis is true. When using CIs for hypothesis testing, power is the fraction of cases where \( s = 0 \) is not contained in the interval given that \( s > 0 \) is true. If the null hypothesis is the alternative hypothesis, power reduces to \( \alpha \).

7.2.2 Bayes factor method

In Bayesian theory, a test statistic (TS) can be defined by taking the ratio of the posterior probability distributions, in this case called Bayes factors, for the two hypotheses given by Eq. 7.4 and Eq. 7.5,
\[ B_{\text{fact, } M_0} = \int b^{n_S + n_B} e^{-2b} P(b) \, db \]  
\[ B_{\text{fact, } M_1} = \int \int (s + b)^{n_S} b^{n_B} e^{-(s+2b)} P(s) P(b) \, ds \, db \]  
if the priors \( P(s) \) and \( P(b) \) are specified. The priors can e.g. be uniform distributions or Gaussian distributions centered on the most likely values of the true parameters. The ratio of the two Bayes factors measures the probability that a signal is present independent of the amplitude of the signal and the background, since both \( s \) and \( b \) have been integrated out. Confidence intervals (CIs) are then dealt with by integrals of the ratio of the posterior over the corresponding intervals.

### 7.2.3 \( \chi^2 \) method

For the comparison in Section 7.3, a non-standard \( \chi^2 \) method was used. In this method, the TS is given by:

\[ TS_{\chi^2} = \left( \frac{n_S - n_{null}}{\sqrt{n_{null}}} \right)^2 = \frac{(n_S - n_{null})^2}{n_{null}}, \]  

where \( n_{null} \) is the expected number of counts when the null hypothesis is true. The TS can be used to calculate the coverage and power, respectively, by requiring that the TS in each experiment is greater that the quantile of a \( \chi^2 \) distribution that corresponds to the confidence level.

### 7.2.4 Feldman & Cousins

A popular frequentist technique to calculate CIs in recent years is the technique suggested by Feldman & Cousins [56]. The method consists of constructing an acceptance region for each possible hypothesis (in the way as proposed by Neyman [57]) and fixing the limits of the region by including experimental outcomes according to rank which is given by the likelihood ratio:

\[ \lambda_{FC}(s|n_S) = \frac{L(s, b|n_S)}{L(s_{\text{best}}, b|n_S)} \]

where \( s_{\text{best}} \) is the signal parameter most compatible with \( n_S \). In this method, it is assumed that the background (also called nuisance parameter) is perfectly known.

### 7.2.5 Profile likelihood

The maximum likelihood estimates \((\hat{s}, \hat{b}) = (n_S - n_B/\tau, n_B/\tau)\) to the likelihood function in Eq. 7.2 can be found by maximising the function over both \( s \) and \( b \).

A standard result in statistics is that \(-2 \log \mathcal{L}\) behaves approximately like a \( \chi^2 \) distribution with \( k \) degrees of freedom (in this case \( k = 1 \)). An uncertainty
7.4. Peak finding methods

in the background estimate can be treated by maximising the log likelihood over the background estimate with fixed $s$, in which case the likelihood function (“profile likelihood”) can be expressed in terms of the signal estimate only [58]. The maximisation is done by requiring:

$$\frac{\partial}{\partial b} \log L(s, b| n_S, n_B) = \frac{n_S}{s+b} + \frac{n_B}{b} - (1 + \tau) = 0.$$  \hspace{1cm} (7.8)

which yields the Profile Likelihood ratio:

$$\lambda_{PL}(s) = \frac{L(s, \hat{b}(s)| n_S, n_B)}{L(\hat{s}, \hat{b}| n_S, n_B)}.$$  \hspace{1cm} (7.9)

7.3 Statistical properties

A comparison between different statistical methods can be done with the toy model described in Section 7.2. The most basic approach is to divide the energy spectrum of the data into a signal region (where signal and background are supposed to be present) and a background region (where only background is supposed to be present) from which the contribution from the background to the signal region counts is estimated [55]. These two regions correspond to $S$ and $B$, defined in Section 7.2.

The question of presence of signal (detection) and calculation of CIs are in general different topics in mathematical statistics (see e.g. [59]). The Bayes factor method and the frequentist $\chi^2$ method described above represent hypothesis tests whereas the frequentist methods Feldman & Cousins and profile likelihood are CI calculation methods. As demonstrated by ProFinder (described in Section 7.4.1), however, also CIs can be used for claiming detection by requiring that $s = 0$ is not included in the calculated CI.

The two figures-of-merit, coverage and power, were benchmarked for the methods above, using a set of 1024 toy Monte Carlo experiments. Fig. 7.1 shows a comparison of the coverage for the different methods as a function of the signal parameter. For the $\chi^2$ method and the Bayes factor method, the null hypothesis was $s = s_0$. This also means that for the $\chi^2$ method, $n_{null} = s + b \approx s + n_B$ in Eq. 7.6 in Section 7.2.3.

The power for the different methods as a function of the signal parameter is shown in Fig. 7.2. For the $\chi^2$ method and Bayes factor method, the null hypothesis was $s = 0$. This corresponds, for the $\chi^2$ method, to $n_{null} = b \approx n_B$ in Eq. 7.6 in Section 7.2.3.

7.4 Peak finding methods

Two methods were developed to search for spectral lines in an energy spectrum, ProFinder and Scan Statistics.
7.4.1 ProFinder

The Profile likelihood peak Finder (ProFinder) presents a novel way of using profile likelihood CIs as a means of finding signal peaks in a background distribution. Profile likelihood is implemented as a class, Trolke, in the ROOT software package.

First, the spectrum in the interesting energy range is divided into a certain number of bins of equal width and, then, the profile likelihood CI is calculated in each bin. The background estimate needed for the calculation is obtained by fitting the spectrum with a background model. If there is a narrow line signal in the spectrum, the fitting should not be significantly affected, unless the peak is very
strong. A signal detection at a chosen confidence level occurs when the lower limit in any of the calculated CIs for the spectrum is greater than zero.

If a potential peak is located in the middle of two bins, the signal strength will be divided between the two bins and the significance of the peak will decrease. To avoid this, two bin sets can be used that are shifted by one half of a bin width. The bin width itself must be optimised so that two requirements are met. The bin width can not be less than the energy resolution of the instrument at any given energy and it can not be so large that the sensitivity for a line is compromised at energies with large amounts of background photons.

Fig. 7.3 demonstrates the principle of ProFinder with an example plot, which includes a power-law background spectrum and a spectral line at 260 GeV. For presentational purposes, the number of counts in the simulated line is large compared to the observed background at the location of the peak. In the figure, the $5\sigma$ CI has been calculated in each bin using ProFinder. The departure from zero of the lower limit at 260 GeV signifies a detection that is $\geq 5\sigma$.

![Figure 7.3. A demonstration of the detection principle of ProFinder. The dashed line corresponds to the upper limit in each bin from Profile Likelihood confidence intervals and the solid line to the lower limit in each bin. When the lower limit is greater than zero, a signal with a significance greater than or equal to the chosen significance has been detected.](image)

### 7.4.2 Scan Statistics

Scan Statistics (SS) is a statistical method that can be used to detect a bump or excess in a uniform spectrum. The method works as a powerful and unbiased alternative to the traditionally used techniques involving $\chi^2$ and Kolmogorov distributions. SS has better power than both $\chi^2$ and KS, as can be seen in Fig. 7.4, where $s = 20$ and $b = 100$ [60]. This motivates further studies to apply SS to GLAST LAT data.
In SS, the TS is given by the largest number of counts found in any subinterval of $[A, B]$ of length $w(x)$. The variable bin width, $w(x)$, is used in the case of a non-uniform spectrum under the null hypothesis, which holds for the analysis presented in this thesis, but reduces to a constant, $w$, if the spectrum under the null hypothesis is uniform. In mathematical form, the TS is:

$$TS_{SS}(w(x)) = \max_{A \leq x \leq B-w} \{Y_x(w(x))\}, \quad (7.10)$$

where $Y_x$ is the number of counts in the $x$:th bin.

SS differs significantly from standard methods in signal searching that are based on likelihood ratios. In a likelihood ratio approach, the data set is often fitted with two different models, one with background only (null hypothesis) and the other with background plus signal (alternative hypothesis). The TS is, then, compared to a null distribution (often assumed to be a $\chi^2$), which yields the significance of the signal.

For each non-uniform background model, the null distribution in SS is created ad hoc. The advantage is that the constructed null distribution is directly comparable to the TS taken from data and the result depends only on the uncertainty in the background model and the accuracy of the variable binning.

Before applying SS to an actual data set, albeit a simulation, its capabilities in terms of its power, i.e. the probability to reject the alternative hypothesis when it is true, should be tested. This can be done with toy Monte Carlo experiments.
For the test, an energy range from 50 GeV to 350 GeV was chosen, since this is the theoretically more interesting range for DM line searches with GLAST. The energy range was divided into 15 bins of variable width that have the same expected number of counts under the null hypothesis.

Into each experiment, 1518 random events with a standard deviation of $\sqrt{1518}$ were generated from a power-law with an index of $\approx2.5$. A total of $10^7$ pseudo-experiments were generated with this setup, and the TS given by SS was extracted in each experiment. An example experiment, from which the highest number of counts was extracted, and the resulting null distribution after repeated experiments can be seen in Fig. 7.5.

![Figure 7.5. An example experiment (top) and the null distribution, from repeated experiments (bottom), for Scan Statistics.](image)

To get a measure of the power, 1000 experiments with the same background model but also an included signal were generated at each end of the energy range, i.e. in the first and the last bin. This choice both gives a sensitive enough estimate
of the power for the study and gives an indication of whether or not the power is constant over the energy range. The signal strength was set to give an average reference significance of $4\sigma$, calculated as the ratio between the number of signal events, $n_{\text{signal}}$, and the square root of the number of background events, $\sqrt{n_{\text{bkg}}}$. For each experiment, the TS was extracted and the power at 99% confidence level was, then, given by the probability of finding the correct bin multiplied by the probability that the significance of the correct bin exceeded the 99% quantile of the null distribution.

The results from the test can be seen in Table 7.1 and in Fig. 7.6. As can be seen in the table, the significance from SS is lower than the reference significance at both ends of the energy range. This is explained by the fact that for SS the line is searched for in several bins and not just one, as is assumed when calculating the reference significance. The resulting trial factor reduces the significance of the detection and is taken into account in SS via the production of the null distribution.

### Table 7.1. Results from testing the bin dependence of the performance of Scan Statistics (SS) with 1000 experiments. The 1st column denotes the bin where the signal was included, the 2nd column in how many experiments SS found the correct bin, the 3rd column the average of the calculated significances from SS and the 5th and final column the corresponding average of the calculated reference significances from $n_{\text{signal}}/\sqrt{n_{\text{bkg}}}$.

<table>
<thead>
<tr>
<th>Bin</th>
<th>$n_{\text{correct bin}}$</th>
<th>$&lt;SS_{\text{sign}}&gt;$</th>
<th>$&lt;\text{Ref}_{\text{sign}}&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>950</td>
<td>$\approx$96.9%</td>
<td>$\approx$99.9%</td>
</tr>
<tr>
<td>15</td>
<td>953</td>
<td>$\approx$97.1%</td>
<td>$\approx$99.9%</td>
</tr>
</tbody>
</table>

### 7.5 Application on Service Challenge 2 data set

This thesis does not include analysis of real LAT data, since GLAST at the time of developing the analysis had not been launched yet. The basis for the studies included is, therefore, simulated data. The data set that was used is called Service Challenge 2 (SC2). The simulation is based on a parametrisation of the LAT instrument response function that is implemented in the GLAST observation simulator gtobssim, developed by the GLAST LAT collaboration. The simulator is part of a larger software package called Science Tools, which is partially based on the NASA tool FTOOLS.

SC2 corresponds to one year of normal data taking with 54 occasions of 5 hour pointed observations and the remaining time in sky survey mode. A counts map, with all the photons in the vicinity of the galactic center, can be seen in Fig. 7.7. A long list of gamma-ray sources are simulated and four different DM components were included:
Figure 7.6. The power, \((1 - \beta)\), at 99\% confidence level (top) and the number of experiments in which the correct signal bin was found out of 1000 experiments (bottom), both as a function of the signal parameter \(s\). The background model was a power-law with \(b = 1518\) and 15 bins with variable widths, matching the power-law, were used.

- **Galactic center**: continuum and 2 lines within 1° radius.
- **Halo**: continuum and 2 lines from 1° radius from the galactic center and extending to full sky.
- **Extragalactic**: continuum and 1 line isotropically distributed over the sky.
- **Satellites**: continuum only.

Additional information about the different components can be found in Table 7.2.

As a search region, the broken annulus around the galactic center, described and discussed in Section 7.1.1, was selected. This included the sky at a radius from 25°
Table 7.2. The different dark matter components included in the SC2 data set. Fluxes are given in units of $10^{-20} \text{m}^{-2} \text{s}^{-1}$.

<table>
<thead>
<tr>
<th>Source name</th>
<th>L</th>
<th>B</th>
<th>Flux$^a$</th>
<th>Flux$^b$</th>
<th>Flux$^c$</th>
<th>DM model</th>
</tr>
</thead>
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<tr>
<td>Lcc2_GC_cont</td>
<td>0</td>
<td>0</td>
<td>508</td>
<td>451.02</td>
<td>179.81</td>
<td>LCC2$^1$</td>
</tr>
<tr>
<td>Lcc2_GC_gg</td>
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<td></td>
<td>0.188</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Lcc2_GC_gz</td>
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<td>0.503</td>
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<tr>
<td>Lcc2_halo_cont</td>
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<td>0</td>
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<td>7812.90</td>
<td>3114.81</td>
<td>LCC2</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Lcc2_halo_gz</td>
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<td></td>
<td>8.71</td>
<td></td>
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<td></td>
<td>4170</td>
<td>3032.73</td>
<td>796.09</td>
<td>GM 1$^2$</td>
</tr>
<tr>
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<td></td>
<td>3.67</td>
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<td>Lcc2_clump45</td>
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<td>5.49</td>
<td>1.94</td>
<td></td>
<td>LCC2</td>
</tr>
</tbody>
</table>

$^a >10$ MeV

$^b >100$ MeV

$^c >1$ GeV

1 LCC2 model (from [61]): WIMP mass = 107.9 GeV, $<\sigma v> = 1.64 \times 10^{-26}$ cm$^3$ s$^{-1}$, branching fraction for $\gamma\gamma$ line is $3.7 \times 10^{-4}$ and for $\gamma Z$ line $9.9 \times 10^{-4}$.

2 Generic model 1: WIMP mass = 100 GeV, $<\sigma v> = 3 \times 10^{-26}$ cm$^3$ s$^{-1}$, branching fraction for $\gamma\gamma$ line is $10^{-3}$.

3 Generic model 2: WIMP mass = 100 GeV, $<\sigma v> = 2.3 \times 10^{-26}$ cm$^3$ s$^{-1}$.
7.5. Application on Service Challenge 2 data set

Figure 7.7. A counts map (in galactic coordinates) of the area around the galactic center in the Service Challenge 2 data set.

to 35°, but excluded the region within 10° from the galactic plane. The assumption that the diffuse emission is zero in this region is, however, not true for SC2.

The final result of any line search can have two obvious outcomes. Either there is a line signal above a chosen threshold significance or there is not. The way in which the result is generally presented differ in the two cases. In the former case the 68% CI is often calculated around the maximum likelihood estimate and in the latter case the 90%, 95% or 99% upper limit is often given.

For this study, the two methods presented in Section 7.4 were chosen, namely ProFinder and Scan Statistics. In a sense, the two methods are complementary. ProFinder can find several peaks simultaneously whereas Scan Statistics can determine an exact significance (limited by the number of entries in the null distribution).

In its current implementation, Scan Statistics cannot be used for upper limit calculations and, therefore, only the results from a peak search are presented. Fig. 7.8 shows the resulting spectrum when using a variable binning based on a power-law fit of the SC2 data in the broken annulus. The largest number of counts was found in bin 14, but with a significance from the null distribution of only about 1σ.

For ProFinder, the energy spectrum from 30 GeV to 350 GeV for the broken annulus was divided into 16 bins. A second bin set, with a relative shift of 10 GeV compared to the first bin set, was also defined. When using ProFinder on the SC2 data set, there was no 5σ detection. The 5σ CI limits on the number of signal events can be seen in Fig. 7.9. The conversion of this into an upper limit flux, using the exposure of the broken annulus region, is described in the next section.
Chapter 7. Dark matter line search

Figure 7.8. The resulting histogram from the Service Challenge 2 data set, when using bins of variable size based on a power-law fit of the energy spectrum. The largest number of counts is found in bin 14 but only corresponds to $\approx 1\sigma$ when comparing to the null distribution.

Figure 7.9. ProFinder $5\sigma$ confidence interval limits calculated on the Service Challenge 2 data set. The lower limit is never greater than zero, which means that a line with a significance of $5\sigma$ or greater could not be found.

Neither Scan Statistics nor ProFinder is able to detect a DM signal in the SC2 data set. This, however, does not necessarily mean that the methods themselves are bad. It should be noted that none of the DM models included in SC2 are expected to be within the sensitivity of GLAST [62].
7.5. Application on Service Challenge 2 data set

7.5.1 Exposure

The exposure over the sky is almost but not completely uniform, due to the complex movement of the GLAST satellite with respect to the sky. The movements include the orbital inclination of the satellite with respect to the Earth’s equator and the rotational inclination of the Earth with respect to the solar system plane.

In analyses of the data sets, the non-uniform and energy dependent exposure must be taken into account. In this case, the simplest approach is to calculate the average exposure in the region-of-interest. For the SC2 data set, the exposure can be calculated with Science Tools. In Fig. 7.10, an average exposure over a specific energy range for the full sky is shown. The broken annulus is marked with a dotted line.

![Figure 7.10](image)

**Figure 7.10.** The full sky exposure in the Service Challenge 2 data set in units of cm$^2$ s and in galactic coordinates. The dotted line corresponds to the broken annulus chosen for the analysis.

The energy dependence of the exposure is illustrated in Fig. 7.11. The average value of the exposure shown in the figure is about $2.1 \times 10^{10}$ cm$^2$ s.

7.5.2 Upper limits

To calculate the upper limit on the gamma-ray line flux per steradian, the solid angle occupied by the broken annulus must be calculated. This can be determined by using the relation between the area of the broken annulus and area of the full sky, $C_{\text{fraction}}$. The upper limit on the flux per steradian is, then, given by:

$$\Phi(E) = \frac{n_s(E)}{D_{\text{exp}}(E)[\text{cm}^2\text{s}]} \frac{C_{\text{fraction}}}{4\pi}$$

(7.11)

where $n_s(E)$ is the upper limit on the number of signal counts for each energy bin, $D_{\text{exp}}(E)$ is the energy dependent exposure and $4\pi$ is the full sky solid angle. The
resulting upper limit on the flux at 95% confidence level is shown in Fig. 7.12. It should be noted that the trial factor pertaining to a search in multiple bins has not been taken into account in the calculations of the upper limit.

The flux from a monochromatic gamma-ray line is given by Eq. 3.1 in Section 3.4. From this equation, the velocity averaged cross-section can be deduced. Using the upper limit on the flux along with the exposure from the previous section, the velocity averaged cross-section, $<\sigma v>_{\gamma\gamma}$, can be plotted against the WIMP-mass, $M_\chi$. 

**Figure 7.11.** The energy dependence of the broken annulus exposure in the Service Challenge 2 data set.

**Figure 7.12.** The profile likelihood 95% upper limit on the flux from dark matter particle annihilations into $\gamma\gamma$ in the Service Challenge 2 data set.
The line-of-sight (LoS) integral, i.e. $J(\psi)$ in Eq. 3.2, can be calculated with DarkSUSY, a publicly available advanced numerical package for DM calculations [39]. As mentioned before, a NFW halo model is assumed. For a given halo model, the LoS integral is a function of only the solid angle, $\psi$, which spans from the galactic center to the angular radius of choice. In other words, it is symmetric around the galactic center. Calculating the average of all LoS integrals in the broken annulus, thus, poses a problem, since the region is not completely symmetric around the galactic center due to the exclusion of the galactic plane.

This can be solved by binning the full annulus, defined by the inner and outer radius alone, into bins of equal area and defining measuring points in the center of gravity of each bin. The average value of all LoS integrals over the annulus, with the exclusion of the galactic plane taken into account, can then be calculated. The visual representation of the aforementioned grid can be seen in Fig. 7.13. The average value of all LoS integrals over the grid was $\approx 6.7$.

The final result can be seen in Fig. 7.14. The figure shows the 95% upper limit on the velocity averaged cross-section of the $\chi \chi \rightarrow \gamma \gamma$ process, $< \sigma v >_{\gamma \gamma}$, as a function of the WIMP mass, $M_{\text{WIMP}}$.

The cross-section limits can significantly improve if the DM density is concentrated and increased via DM substructures or steeper DM halo profiles. An example of this is shown in Fig. 7.15, where the cross-section upper limit obtained with ProFinder for SC2 have been boosted by a factor of $10^3$ and overlaid on a plot by J. Edsjö at Stockholm University that shows the allowed regions in SUSY parameter space for two specific SUSY models: MSSM, which was mentioned in Section 3.4 and minimal supergravity (mSUGRA), which is a constrained version of the MSSM. Experimental bounds from accelerators and the WMAP have been
Figure 7.14. The profile likelihood 95\% upper limit on the velocity averaged cross-section for dark matter particle annihilations into $\gamma\gamma$ as a function of the WIMP mass, calculated from the Service Challenge 2 data set.

taken into account in the figure, but not results from direct detection experiments. The dashed line shows the boosted upper limit. The calculated limit excludes all models above the dashed line.

Figure 7.15. The profile likelihood 95\% upper limit from Fig. 7.14, boosted by a factor of $10^3$ (dashed line). The shaded areas represent allowed regions in SUSY parameter space for two specific SUSY models, MSSM and mSUGRA.
Chapter 8

Discussion and conclusions

8.1 Beam test analysis

For the figures-of-merit for position reconstruction in the CAL, namely the 68% containment of the distributions with the difference between the extrapolated tracks from the TKR and CAL, respectively, to the top of CAL, the values for data are larger by 11.8–18.8% for both electrons and the two types of photons (bremsstrahlung photons and tagged photons). The difference is also clearly seen in the corresponding distributions, where the distributions for data are less peaked than for MC.

When looking at the position reconstruction in the individual CAL crystals, the observed 68% containments of the position error in one of the CAL crystal were 4.3 ± 0.2 mm for 5 GeV electrons and 13.1 ± 0.4 mm for muons, which is well below the design requirement of 30 mm. As explained before, the large difference between electrons and muons can be explained by the difference in incoming angle. Since the muons are not bundled in a pencil beam, like the electrons, they deposit energy in a larger segment of the crystals. This makes position determination more difficult and, therefore, the distribution more spread out.

The same tendency, seen for position reconstruction in the CAL, holds for direction reconstruction in the CAL. For the 68% containment of the distribution of space angles between the TKR direction and the CAL direction, the values for data are again larger by 13.6–22.1%. In this case, the difference is largest for electrons, which is also evident from the corresponding figures.

When looking at the individual direction variables in both the TKR and the CAL, not shown in this thesis, it can be seen that most of the runs exhibit a large bias in the CAL direction variables compared to the beam direction and compared to MC, whereas TKR direction variables are approximately coinciding. For the runs used for energy resolution studies, the runs from SPS manifest a bias that is often, but not always, negative in the x-direction and positive in the y-direction. This
could point to a misalignment of the CAL with respect to the TKR, but since other runs, such as the 5 GeV electron run from the PS, demonstrated unbiased direction distributions, a misalignment is unlikely. The individual direction variables for the CAL also showed that the distributions for data are in general broader. Both these effects contribute to the large difference between data and MC for position and direction reconstructions but further studies are needed in order to determine what is causing the effects.

The figures for the layer-wise energy deposition in the CAL shows that the mean value for data is greater than for MC by less than 10% in all layers for photons. For electrons the difference is largest in the 1st layer where the value for data is almost 16% greater than for MC. The trend for all particle types is that the agreement is better the higher the layer number is until a turning point occurs in the 5th layer for tagged photons and in the 6th layer for bremsstrahlung photons and electrons. For these runs, the minimum difference in the mean value is less than 1%.

The most recent simulations made within the beam test working group, where extra material in the form of lead has been put in front of the TKR, have shown that the large differences in the first layers of the CAL decrease, thereby flattening the curve. The exact nature of this extra material that might exists in the beam line or detector but is missing in the simulation is still, however, unclear.

The figures showing the energy resolutions in data and MC have similar trends for data and MC for both the raw energy and two of the three energy reconstruction algorithms. Only \texttt{CalLkdEnergy} demonstrates large differences. This method is in fact the least maintained out of the three algorithms. Furthermore, it is only extended to 300 GeV and divides the energy range up into bins, which may give rise to bin-edge effects. These factors may explain the strange behaviour at higher energies. Overall, however, with the exception of \texttt{CalLkdEnergy}, the differences between data and MC in terms of the energy resolution are relatively small and stay below 10% over most of the tested energy range.

Generally speaking, the energy resolution should be worse at higher energies due to the increasing leakage. As seen in the figure, showing the difference in peak position between data and MC, the peak position is consistently about 10% greater for data than for MC. This may partially explain the differences in energy resolution between data and MC.

In absolute terms, both data and MC energy resolutions are consistent with the LAT science requirements, which state that the energy resolution must be $<10\%$ for 100 MeV – 10 GeV and $<20\%$ for 10–300 GeV for on-axis photons, especially those from the corrected energies. The reader is reminded that a plot of the energy dependence of the LAT energy resolution, determined from simulation, was shown in Fig. 4.2 in Chapter 4.

Shortly before this thesis was ready, an error in the Geant4 code was discovered by the beam test working group. The error was an incorrect implementation of the so-called Landau-Pomeranchuk-Migdal (LPM) effect, which governs the energy dependent suppression of bremsstrahlung in charged particle interactions. The impact of this error should be more significant for higher energies.
8.2. Dark matter line search

While waiting for a better implementation by the Geant4 team, the LPM effect was turned off in Monte Carlo. The reprocessing of the runs with a correct implementation of the LPM effect were not finished in time for this thesis, so the conclusions must be drawn from the results in this thesis. A correctly described LPM effect is, however, expected to alter many of the distributions studied in this thesis and give a better agreement between data and MC, but by how much is unclear.

It should be stressed that the beam test analysis in the working group is still an ongoing effort and that the results shown here are preliminary. At this time, beam line effects that do not apply to the LAT cannot be ruled out as the source of the differences seen between data and MC distributions. The differences are potentially caused by a combination of geometrical effects, physics and calibration.

Fortunately, there are ways to confirm the simulation package with on-orbit data. Pulsars can e.g. be used to test the point-spread function. Furthermore, the calibration procedure of e.g. the CAL differs between the beam test and the satellite. Although muons were used to calibrate the satellite on ground, the calibration is renewed in space using heavy ion cosmic rays. The differences seen in the energy studies may, therefore, not apply for the LAT. Thus, it remains to be seen if the differences must be taken into account as systematic uncertainties in the upcoming analyses.

It is clear that further efforts are needed in order to rule out beam line effects. The beam test campaign has, however, already been useful for understanding the detector and has uncovered many instrumental effects and software errors that would have, otherwise, been hard to detect.

8.2 Dark matter line search

In this thesis, different statistical methods have been benchmarked in terms of their coverage and power. The tested methods were a Bayesian method with Bayes factors, Feldman & Cousins, profile likelihood and a non-standard $\chi^2$.

In designing a hypothesis test or a method for confidence interval calculation, the first requirement is on the probability for a false detection (i.e. how often the true signal parameter is not contained in the intervals). From the results, it can be seen that only the profile likelihood has the nominal coverage (nominal rate of type I error). It is followed by the Feldman & Cousins method, which ignores the uncertainties in the background estimate, and the Bayes factor method. The $\chi^2$ method, undercovers by as much as 10%, probably due to the fact that it also ignores uncertainties in the background estimate and that it should become less reliable for low statistics.

Allowing more false detections should intuitively imply larger power. The profile likelihood has the worst power and the $\chi^2$ method has the largest power. However, one needs to keep in mind that using the $\chi^2$ method, a detection nominally on 99% confidence level only corresponds to between 90 and 96% actual confidence level.
Comparing power for methods which do not have the same coverage does not make much sense. The choice of method should be a two step process. Firstly, the *de facto* coverage (or false detection rate) should be calculated. Secondly, the method with the largest power should be chosen from the ones with similar coverage.

Two statistical methods have also been developed to search for line signals in a given data set. The methods were tested on a one-year full sky simulation called Service Challenge 2, but no lines were found at the 5σ level. The flux of dark matter implemented in the simulation was, however, not within the GLAST sensitivity and a significant line signal would most likely not have been detected by any statistical method.

Both Scan Statistics and ProFinder are flexible and can handle many possible scenarios. They should, however, perform worse than methods which also include information about the shape of the line. In the studies presented here, the bin width has been defined to include most of the simulated line. Any information about the line shape was, therefore, neglected. How great the influence of the line shape is on the significance of a detection can only be determined by comparing with a method that takes it into account. Such methods are used by members of the GLAST LAT collaboration, but a comparison between all these methods has not been performed so far.

Both methods are also expected to perform worse if the measured background cannot be easily parametrised. For Scan Statistics, this would introduce a difficulty in constructing a set of variable bin widths that gives a uniform spectrum. For ProFinder, the difficulty would instead be to perform a good fit from which the background estimates can be drawn. The methods are also both binned, which inevitably leads to a loss of information. An unbinned method should give better results and should, therefore, be developed for comparison in the future.
Acknowledgements

My deepest gratitude goes to both my supervisors, Jan Conrad and Staffan Carius, for giving me the opportunity to work on such an interesting and rewarding experiment as GLAST. An extra thanks goes to Jan Conrad, whose skilled guidance kept me in the master plan and on the right path. Without his help, this work would have been significantly more impossible.

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