Antiparticle Identification Studies for the PAMELA Satellite Experiment

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AKADEMISK AVHANDLING

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**Abstract**

The PAMELA satellite experiment will soon be launched and during its 3 year mission perform measurements of charged particle fluxes in the cosmic radiation. PAMELA is specifically designed to identify antiprotons and positrons in the vast background of other charged particles. These antiparticle measurements will be performed using: a permanent magnet spectrometer, a scintillator based time of flight system, an electromagnetic imaging calorimeter, a transition radiation detector and a scintillator triggered neutron detector. There is also a scintillator based anticoincidence system to reject spurious triggers from out of acceptance events (developed and built at KTH). These detectors will allow the background in the antiproton and positron measurements to be significantly reduced, and PAMELA will thus be able to perform high precision measurements with unprecedented statistics and over a wide energy range, far surpassing any previous experiment. To determine the antiparticle identification and background rejection capability of the experiment, studies have been performed using simulations and data collected at particle beams. These studies have focused on: the proton rejection in positron measurements (using the calorimeter), contamination by locally produced pions in antiproton measurements and estimations of the expected statistics due to the energy dependence (caused by e.g. the geomagnetic field and the magnetic field in the spectrometer) of the gathering power. This work significantly extends previous studies of the PAMELA performance in antiparticle identification.

**Descriptors:** PAMELA, satellites, astroparticle physics, antiparticles, calorimeters
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Chapter 1

Introduction

Cosmic ray experiments offer an opportunity to study the production and propagation mechanisms of particles within our galaxy. The antiproton and positron components of the cosmic radiation also make it possible to search for new physics beyond the Standard Model, which otherwise may only be possible by means of huge particle detectors at accelerators which are currently under construction or have yet to be built. One such cosmic ray experiment is the PAMELA\(^1\) satellite-borne spectrometer which will be launched during 2005.

1.1 Cosmic Rays

Cosmic rays were discovered in 1912 by Victor Hess, when he was measuring the altitude dependence of the natural background radiation by means of a balloon. The natural background radiation was at the time thought to emanate from the Earth and his results that showed that the radiation increased with altitude were a great surprise. Since then many balloon experiments have been performed, aimed at measuring the cosmic ray energy spectra and composition. At the altitudes reached by these balloon experiments (\(\sim 40\) km), there is however still an overburden of \(\sim 5\) g/cm\(^2\) from the residual atmosphere where particle interactions can occur. This can complicate particle identification. The next step in cosmic ray measurements has therefore been to use satellite-borne experiments. About 1000 cosmic ray particles per square meter hit the Earth’s atmosphere every second and of these about 90\% are protons, 9\% alpha particles and 1\% electrons. There is also a small abundance of heavier nuclei.

1.1.1 Antiprotons and Positrons

Cosmic rays also comprise of antiparticles, i.e. antiprotons and positrons that are produced in the interstellar space by interactions of cosmic rays (e.g. p and He)

\(^1\)Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics.
with the interstellar gas. A detailed knowledge of the energy spectra for antiprotons and positrons is important for understanding the production and propagation characteristics of cosmic rays (since they are thought to be mainly of a secondary origin) and the influence of solar modulation, i.e. the phenomenon caused by the solar wind that prevents some cosmic rays from entering the solar system.

Cosmic ray antiprotons are very difficult to detect because of their very low flux in the presence of approximately $10^4$ times higher background of charged particles. An experiment aimed at detecting antiprotons must be capable of charge identification and separation of antiprotons from the $\sim 10^2$ times higher flux of electrons in the cosmic radiation. This is true also for the positrons where the difficulty also lies in the charge identification and that the positrons have to be well separated from protons. The ratio between protons and positrons is of the order of $10^3$ and a reliable positron identification therefore requires a proton rejection factor greater than $10^4$.

**Production**

The production of antiprotons requires high energies. The production threshold is about 7 GeV (from kinematic constraints) for proton-proton interactions, i.e. $p+p \rightarrow pppp\bar{p}$. Antiprotons can also be created at lower energies in proton-nuclei or nuclei-nuclei interactions, via so-called 'sub-threshold' production [1][2][3]. The observed spectrum indicates that the cosmic ray antiprotons are produced by collisions of cosmic ray nuclei with the interstellar gas and these antiprotons are called interstellar secondary antiprotons. Figure 1.1 [4] shows the calculated contributions to the interstellar antiproton source density spectrum, from various interactions between cosmic ray particles and the interstellar medium.

![Diagram of antiproton spectra](image)

**Figure 1.1:** The interstellar $\bar{p}$ source density spectra resulting from the different interactions between cosmic ray particles and target particles of the interstellar gas [4].
1.1 Cosmic Rays

Energetic cosmic rays that collide with the interstellar medium can interact and produce a large variety of secondary particles, some of which will decay. Electrons and positrons can be produced in these decays (from pions via the decay $\pi^\pm \to \mu^\pm \to e^\pm$). Positrons (together with electrons) can also be produced directly through pair production ($\gamma \to e^+e^-$). Both these kinds of positrons are called interstellar secondary positrons.

The cosmic ray energy spectrum is known to extend from below $10^6$ eV to about $10^{20}$ eV (see figure 1.2). The differential energy spectrum can be described by a power law function, where the spectral index varies depending on the energy region. At low energy the measured spectrum is dominated by solar modulation (see section 1.1.1). At higher energies ($\sim 10^{10} - 10^{15}$ eV) the spectral index is about -2.7, and above $10^{15}$ eV the spectrum steepens and the spectral index falls to -3 (this region is the so-called ‘knee’ of the spectrum). Above $5 \times 10^{18}$ eV the spectrum flattens and the spectral index rises to -2.8 (the so-called ‘ankle’). The acceleration of cosmic rays is believed to take place in the shock fronts of exploding supernovas [5] (i.e. where the envelope meets the interstellar medium), with successive acceleration via the Fermi mechanism. The calculated spectra reasonably well reproduces the measured spectra, but the Fermi acceleration model can however not explain particles with energy greater than $10^{18}$ eV. Active Galactic Nuclei (AGN) are considered as possible candidates to explain the acceleration of particles.

**Figure 1.2**: Cosmic ray energy spectrum.
above $10^{18}$ eV [6].

**Propagation**

If the observed antiprotons and positrons are only or mainly of secondary origin, their energy spectra are valuable tools for judging the validity of propagation models. The measurements of the propagation products (antimatter secondaries) are decoupled from the primary proton and electron spectra.

Determination of the energy spectrum of antiprotons is essential for understanding the propagation of cosmic rays as the interaction mean free path for antiprotons in interstellar space is much larger than the matter traversed by cosmic rays in the galaxy. This is especially important when comparing propagation of light nuclei and antiprotons, since they have different production mechanisms even if they are both produced in collisions between cosmic rays and interstellar matter. The major difference is that antiprotons are primarily produced by cosmic ray protons while light nuclei are produced by spallation and depends strongly on the heavier nuclei, which might have a different model of propagation.

At high energies nucleonic components of the cosmic radiation suffer attenuation only due to collisions with the interstellar gas during their traversal of space. Positrons and electrons suffer in addition severe energy losses when they interact with the interstellar magnetic field and the ambient photons. The additional energy losses are due to synchrotron and inverse Compton processes. In comparison with nucleons and nuclei, the positron and electron component of the cosmic rays give additional information on the physical conditions existing in the region of space where cosmic rays spend most of their time. The energy losses due to inverse Compton scattering with the microwave background radiation limits the lifetime for electrons/positrons and thus the distance they can travel. This implies that the sources must be very close (on a galactic scale) and thus these are the only cosmic ray components for which extragalactic contributions can be excluded.

The propagation of antiprotons and positrons can be approximated by using a transport equation taking into account diffusion and convective particle transport in the Galaxy, energy loss rate, the mean escape time from the Galaxy and sources of particles. Several models have been put forward to solve this equation and descriptions of two of the most frequently used models are described below.

**Diffusive halo model**

The **diffusive halo model** of cosmic ray propagation in the galaxy is based on the assumption that the sources of cosmic rays are uniformly distributed in the galactic disk which is surrounded by a halo. Cosmic rays diffuse through the disk and the halo and escape freely from the boundary of the halo into intergalactic space (see figure 1.3, left). This model is well supported by results from radio astronomy observations of believed cosmic ray sources.
Figure 1.3: Schematic view of the differences between the diffusive halo (left) and leaky box (right) propagation models.

Leaky box model

The leaky box model is a simplified version of the diffusive halo model. In this model the particles are also evenly distributed in the galaxy. The cosmic rays diffuse freely in a confinement volume, which could be either the disk or the halo, and they are reflected at its boundaries (see figure 1.3, right). They have constant probability per unit time of escaping into intergalactic space at each encounter with the boundary, governed by the characteristic escape time from the confinement volume. One important parameter for the leaky box model is the path length which can be described as the average amount of matter that the particle will pass through in their lifetime. The path length can be found by fitting the observed ratios of secondary (e.g. $\pi$) to primary (e.g. p) cosmic ray nuclei.

Cosmic ray clocks

Collisions of primary cosmic ray nuclei with the interstellar medium can cause some of these nuclei to break up into secondary nuclei, some of which are long-lived radioactive isotopes, e.g. $^{10}$Be. These can be used as ‘clocks’ by comparing the observed abundances of these radioactive nuclides with the amount of stable secondary species in the cosmic radiation. In this way one can establish for how long cosmic rays are confined in the galaxy and investigate the density distribution of gas encountered by the particles. By studies of the abundances of electron capture isotopes such as e.g. $^{57}$Co the time between nucleosynthesis and acceleration can be determined.
Solar modulation

Besides the effect of propagation in the Galaxy, the interstellar spectrum of cosmic ray particles is affected by the solar wind. The Sun emits a large flux of particles called the solar wind. This plasma comes out from the Sun’s corona and carries the solar magnetic field at supersonic speeds of about 350 km/h out beyond Pluto (see figure 1.4). This is the origin of the interplanetary magnetic field. This phenomenon will prevent some cosmic rays from entering the solar system and their spectra are consequently modified. This effect varies with the 11 year solar cycle and is known as **solar modulation**. The number of sunspots is an observable parameter used to monitor the solar activity (see figure 1.5), which varies with the same 11 year cycle. The number of sunspots is anticorrelated to the neutron flux on ground (as seen in figure 1.5) since neutrons are created in cosmic ray interactions in the atmosphere. The solar modulation affects the cosmic rays up to energies of tens of GeV, but is only significant at energies below a few GeV. By measuring the cosmic ray spectra over an extended period (by studies of the energy spectra variations), information of the interstellar spectra and the effects on particles of different sign of charge (since the Sun reverses magnetic polarity every 11 years) can be collected.

**Figure 1.4**: The solar wind forming the heliosphere will prevent some of the cosmic rays from entering the solar system.

**Primary antiparticles**

Although the majority of the antiproton measurements are consistent with a pure secondary origin, some of the earlier antiproton measurements [8]-[10] suggested a flux that exceeded model predictions for energies above a few GeV. This was spec-
1.1 Cosmic Rays

Figure 1.5: The number of observed sunspots (top) and the measured atmospheric neutron flux (bottom). The anticorrelation between the number of sunspots and the neutron flux is clearly seen. From [7].

ulated to be due to the existence of exotic sources of antiprotons. These sources include e.g., neutrons evaporated from neutron stars, which after oscillations to antineutrons could decay into antiprotons [11] and evaporation of antiprotons from mini black holes during the last stages of their existence [12, 13, 14]. Possible annihilation of dark matter particles in the galactic halo can give rise to antiprotons with detectable intensity [15, 16, 17], which may dominate the high energy antiproton spectrum depending on the mass of the annihilating particles and the decay channel. A favorite comes from supersymmetric models where the lightest supersymmetric particle, called the neutralino ($\tilde{\chi}^0$), is stable in most supersymmetric models with R-parity conservation. These antiprotons, together with the contributions from possible large regions (galaxy super-cluster scale) of antimatter in the Universe are called primary interstellar antiprotons. This contribution should be possible to decouple from the secondary contribution at higher energies. Therefore, it is necessary to detect and determine the energies of cosmic ray antiprotons up to at least 100 GeV.

The measured positron component is consistent with a pure secondary origin. However a few experiments determined a large positron fraction [18] which lead to speculations about primary sources of positrons as well. Also for positrons one such source is the annihilation of supersymmetric particles [44]. Other sources include e.g., magnetic pair production at pulsars and production of pairs by gamma rays
interacting with optical or ultra violet photons [19]

Current status

All data are consistent with a purely secondary origin for antiprotons and positrons. However, considering that there exists considerable uncertainties in the antiproton production cross sections as well as e.g. path length estimations for the propagation models used, a primary contribution can not be excluded.

Figure 1.6 shows a survey of the current state of the art antiproton measurements together with the results of some theoretical predictions. The two solid curves are predictions of the interstellar secondary antiproton flux based on the standard leaky box propagation model using different path lengths and reflect the uncertainty of these kind of calculations [4]. The dashed curve represents a cal-

![Graph showing antiproton flux vs. kinetic energy](image_url)
Calculation of the secondary antiproton flux derived from a diffusive model [17][27] based on proton data from the CAPRICE94 experiment [26]. The dotted curve is a prediction of the contribution from primary antiproton production by heavy neutralino (964 GeV) annihilation [28], which would be detected as a distortion to the secondary spectrum.

In figure 1.7 the experimental situation for positrons is displayed together with some theoretical predictions. The dashed line is from a calculation based on an older leaky box model assuming a purely secondary origin of positrons [39]. The solid line is also for secondary production but using a diffusive model [40]. The dotted line is a calculation of a primary contribution based on the annihilation of neutralinos with a mass of 336 GeV [44].

The data in figures 1.6 and 1.7 all come (except AMS [30]) from high altitude balloon experiments which are limited in statistics due to a data taking time of 1 -

**Figure 1.7:** The measured positron charge ratio ($e^+/e^- + e^-$) [29] - [38] with theoretical predictions. The dashed curve is a calculation of the secondary positron spectrum based on an older leaky box model [39]. The dotted curve is the calculated contribution of primary positrons from neutralino annihilation assuming a neutralino mass of 336 GeV [44]. The solid curve is based on a diffusive model with only secondary positron production [40]. The grey filled squares are the PAMELA (see chapter 2) expectation after three years of operation based on the solid curve, i.e. a purely secondary spectrum.
2 days. The steepness of the antiproton and positron spectra at higher energies has thus so far limited the measurements to below \( \sim 50 \) GeV. The balloon experiments also have to take into account the interactions occurring in the residual atmosphere (\( \sim 5 \text{ g/cm}^2 \)) above the experiments by estimations derived from simulations, which increase the systematic errors on the data points. These limitations would be removed by taking data over a much longer time period, covering a wider energy range and eliminate the influence of the atmosphere, e.g. on a satellite.

The PAMELA experiment, which will be described briefly in section 1.2 and more in detail in chapter 2, is a satellite-borne experiment for cosmic ray studies and the antiproton (positron) expectation after 3 years is shown in figure 1.6 (1.7). The PAMELA data points include error bars\(^2\) and should be able to resolve both a primary component of antiprotons or positrons in the cosmic rays as well as be used to validate the different propagation models. This is further discussed in chapter 7.

### 1.1.2 The Search for Antimatter

The apparent imbalance of matter and antimatter in the Universe is a great puzzle. According to the Big Bang theory, matter and antimatter should have been present in equal amounts in the first instants of the Universe. The present theories state that if there are any domains of space dominated by antimatter they must be widely separated from matter regions, either in separate clusters or super-clusters of galaxies. This is deduced from the absence of intense gamma radiation which would be expected from antimatter-matter annihilation processes. The electromagnetic radiation emitted by bodies composed of matter and antimatter should according to present knowledge be identical in all respects, and thus antimatter can not be detected by optical or radio astronomy observations. To be able to detect the presence of antimatter, actual antinuclei would have to be found. Finding \( \text{He} \) would indicate the existence of primordial antimatter left over from the Big-bang, while a find of heavier antinuclei (> \( \text{He} \)) that has to be produced through fusion in an ‘anti-star’ would produce convincing evidence for cosmological antimatter on the scale of galaxy clusters [45]. To date, no antinuclei have been found and the antimatter searches have only been able to set upper limits on the anti-helium - helium ratio (see figure 1.8). This picture is also shows the PAMELA expectation after three years.

### 1.2 The PAMELA Experiment

PAMELA is a satellite-borne cosmic ray experiment with the ability to study the charge, mass and energy spectra of the cosmic rays with unprecedented precision and sensitivity. The PAMELA experiment consists of:

- A magnetic spectrometer capable of determining the sign of the electric charge and of measuring the momenta of the particles up to high energies (\( \sim 700 \) GeV/c for protons).

\(^2\)The PAMELA error bars in figures 1.6 & 1.7 only include the statistical error.
Figure 1.8: The ratio of anti-helium - helium [46] in the cosmic radiation as function of rigidity (momentum/charge). So far no experiment has been able to detect any anti-helium nuclei and thus only been able to set upper limits. The 3 year expectation for PAMELA is also shown.

- A ‘velocity’ (Lorentz factor, \( \gamma \)) measuring system based on transition radiation emission, for particle separation.

- An imaging electromagnetic calorimeter that can give measurements of the energy of electrons and particle separation by means of the interaction pattern inside the calorimeter.

- A Time-of-Flight system for albedo rejection, velocity measurements of low energy particles and determination of the absolute value of the particle charge. It also produces the first level trigger.

- An anticoincidence system surrounding the magnetic spectrometer, giving a redundant definition of the acceptance and helping to veto background events (produced by the KTH astroparticle physics group).

- A bottom scintillator counter for TeV electron measurements.
• A neutron detector to help separate electromagnetic and hadronic interactions in the calorimeter.

• A central data acquisition (DAQ) and on-board data handling system.

The experimental acceptance is 20.5 cm$^2$sr and PAMELA stands 130 cm high, is ~45 cm wide, weighs 450 kg and has a total power consumption of 345 W. It will be mounted on a Russian Resurs DK1 Earth-observation satellite and the expected lifetime is estimated to 3 years. The launch will take place during 2005.

1.3 The Author’s Contribution

I first joined the astroparticle physics group at the Royal Institute of Technology as a diploma student in 1998. My work was to study the performance of the CAPRICE98 balloon experiment gas-RICH and perform a small muon charge ratio analysis with flight data [41].

I started my Ph.D. studies in 1999 by developing simulation models for the anticoincidence system aimed at backscattering studies. This work was concentrated on comparisons between simulation and test beam data from the CERN$^3$ SPS and trigger rate simulations of the PAMELA experiment in space. The aim was to estimate and find a method for using the veto capability of the anticoincidence system against the significant background, without losing good events due to self- vetoing from backscattered particles. This work is described in my licenti ate ’half-way’ thesis [42] and later led to a study of a second level trigger for the PAMELA experiment [62]. I have also been involved in the development of the actual anticoincidence scintillators, from crude hand-made prototypes up to the design of the present-day flight model, including qualification tests such as vibration tests of the mechanical structure [43]. The anticoincidence system has been studied, in different stages of completion, at several beam tests both at the CERN PS and SPS, where I have participated and been responsible for writing parts of the monitoring software and off-line analysis software for the data.

Lately my work has been concentrated on studies of the identification capabilities of the PAMELA experiment for antiprotons and positrons. This includes:

• comparisons between simulation and test beam data from the CERN PS and SPS, to determine the rejection factor of the calorimeter for protons and pions in electron measurements (see chapter 4),

• simulation studies of pion contamination in antiproton measurements (see chapter 5) and

• simulation studies of PAMELA’s gathering power and expected statistics (see chapter 6).

$^3$European laboratory for particle physics (Geneva).
1.4 Outline of the Thesis

Chapter 2 gives an overview of the PAMELA experiment and the different detectors. The purpose of chapter 3 is to serve as a lead-in to the three subsequent analysis chapters. In chapter 4 a comparison of test beam data and simulations is performed, aimed at determining the rejection factor and efficiency of the calorimeter for protons and pions in electron measurements. This allows the expected proton contamination in future positron measurements to be determined and ‘validates’ the simulation package used. Chapter 5 describes a simulation study performed to estimate the expected contamination by pions (produced in interactions of cosmic ray protons with the material in and around PAMELA) in antiproton measurements. In chapter 6 simulations are used to study the gathering power, i.e. the relationship between the incident cosmic ray flux and the resulting counting rate, of PAMELA for antiprotons and positrons. These results are used to determine the expected statistical uncertainties on $\bar{p}$ and $e^+$ measurements. The results of chapters 4 to 6 are finally brought together in chapter 7, and the detection of different propagation models from antiproton and positron energy spectra is also discussed.
Chapter 2

The PAMELA Experiment

PAMELA [48, 46] is a satellite-borne experiment for cosmic ray measurements, and in particular to identify antiparticles in the cosmic radiation. Its semi-polar orbit (allowing measurements of low energy particles) will make it possible to perform these measurements over a wide energy range, and the three year lifetime will allow statistics far surpassing any previous balloon or satellite-borne charged cosmic ray experiments to be accumulated. An exploded view of the experiment is shown in figure 2.1 indicating the positions of the various sub-detectors further described in section 2.3.

Figure 2.1: A schematic overview of the PAMELA experiment. The subdetectors indicated in this figure (the $S_4$ detector and neutron detector located below the calorimeter are not shown) are further described in section 2.3.
2.1 Scientific Objectives

The observational objectives of the PAMELA experiment are to measure the spectra of antiprotons, positrons and nuclei over a wide energy range, to study the cosmic ray fluxes over part (3 years) of a solar cycle and to search for primordial antimatter. The PAMELA data will be used to address such issues as the search for primordial antimatter and dark matter and the understanding of the acceleration and propagation of cosmic rays.

The PAMELA experiment will extend the results of balloon-borne experiments over an unexplored range of energies with unprecedented statistics. The observational objectives can be schematically listed as:

- measurement of the antiproton spectrum up to 190 GeV (present limit 50 GeV), where the limit is set by the tracker spatial resolution,

- measurement of the positron spectrum up to 270 GeV (present limit 30 GeV), where the limit is set by the tracker spatial resolution,

- measurements of the spectra for H→C from 100 MeV/n up to 700 GeV/n,

- search for antinuclei with a sensitivity of order $10^{-7}$ in the $\mathrm{He}$/$\mathrm{He}$ ratio (present sensitivity limit $\sim10^{-6}$), where the limit is set by the amount of statistics.

The polar orbit of the satellite enables measurements of the low energy components of the cosmic rays due to the negligible energy cut-off produced by the terrestrial magnetic field in the polar regions. The objectives thus possible are:

- measurements of the antiproton spectrum down to less than 80 MeV,

- measurements of the positron spectrum down to less than 50 MeV,

- continuous monitoring of the solar modulation during 3 years of the solar cycle,

- study of the time and energy distributions of the energetic particles emitted in solar flares and coronal mass ejections. It will also be the first study of positrons emitted in solar flares.

There are also a number of additional scientific objectives concerning solar physics and the magnetic fields of the Earth [49][50].

After PAMELA's expected three years of operation the expectancies for different types of particles are given in table 2.1. The expectancies for antiprotons and positrons are also shown in figures 1.6 and 1.7 in chapter 1, assuming contributions from neutralino annihilations.
Table 2.1: The PAMELA expectancy after three years.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Number</th>
<th>Energy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>protons</td>
<td>$3 \times 10^8$</td>
<td>80 MeV - 700 GeV</td>
</tr>
<tr>
<td>antiprotons</td>
<td>$&gt;3 \times 10^4$</td>
<td>80 MeV - 190 GeV</td>
</tr>
<tr>
<td>electrons</td>
<td>$6 \times 10^6$</td>
<td>50 MeV - 2 TeV</td>
</tr>
<tr>
<td>positrons</td>
<td>$&gt;3 \times 10^5$</td>
<td>50 MeV - 270 GeV</td>
</tr>
<tr>
<td>He nuclei</td>
<td>$4 \times 10^7$</td>
<td>up to 700 GeV/n</td>
</tr>
<tr>
<td>Be nuclei</td>
<td>$4 \times 10^4$</td>
<td>80 MeV - 700 GeV/n</td>
</tr>
<tr>
<td>C nuclei</td>
<td>$4 \times 10^5$</td>
<td>80 MeV - 700 GeV/n</td>
</tr>
<tr>
<td>antinuclei limit (90% c.l.)</td>
<td>$7 \times 10^{-8}$</td>
<td>80 MeV - 30 GeV/n</td>
</tr>
</tbody>
</table>

2.2 The Resurs Satellite

The satellite that will carry the PAMELA experiment will be the Russian Earth-observing satellite Resurs-DK1. This satellite is mainly designed to collect and transmit data on sea surface status, ice situations, meteorological conditions in the Earth’s polar regions and information for Earth natural resources studies. It will also take high resolution images of the Earth’s surface. The satellite will be continuously oriented toward the Earth in order to perform these observations. The PAMELA experiment will be in a mobile, pressurized container on the side of the satellite. This container will be oriented so that PAMELA faces away from the Earth during data taking and only moved to a downward position during launch and orbital maneuvers. Figure 2.2 shows a schematic drawing of the satellite.

The mass of the satellite is ~10 tonnes, whereas the total mass of the PAMELA container with the experiment installed will be ~750 kg. The average power consumption for the satellite is expected to be 2000 W (PAMELA 380 W) and will be supplied by solar panels and batteries. The orbit is elliptical with a height between 330 and 600 km (see chapter 6) and an inclination of 70.4 degrees. The orbit is semi-polar (i.e. will not pass directly over the poles) and it will traverse both the inner and outer radiation belts when it approaches the polar regions as well as pass through the South Atlantic Anomaly (SAA). In these places the particle flux will increase dramatically due to low energy particles trapped in the Earth’s magnetic field. Figure 2.3 shows the PAMELA trigger rate evaluated over an orbital period. This figure does not include the contribution from the radiation belts.

The carrier rocket will be a SOYUZ TM 2, i.e. the same type that is used for manned missions, and thus reliable. The current launch date is during 2005.

2.3 Detectors

To be able to fulfill the physics goals listed in section 2.1 a set of particle detectors will be used. These detectors will measure the energy and rigidity\(^1\) of the incident particle, determine the sign and absolute value of its charge and deduce the particle

---

\(^1\)The rigidity is defined as $\text{momentum} / \text{charge}$.\)
mass, thus determining the type of particle, i.e. if it is a hadron or a lepton. Figure 2.4 is a schematic overview of the PAMELA experiment and shows the location of the various subdetectors used and that are further described in sections 2.3.1 - 2.3.7 below.

The time-of-flight (ToF) system consists of three groups of scintillators, S1 - S3. It acts as the main trigger by a coincidence of energy deposits in the scintillators. The ToF system will be used to determine the absolute value of the charge of the particle through dE/dx measurements, and for \( \beta \)-selection\(^2\) at low momenta by time-of-flight measurements. The time ordering of the signals from the ToF system will also be used to reject albedo (up-going) particles.

The Transition Radiation Detector (TRD) is used to separate electrons/positrons (leptons) from heavier particles (hadrons), through threshold velocity measurements, and is made up of strawtube detectors interleaved with carbon fibre radiators.

The magnetic spectrometer (‘tracker’) consists of a permanent magnet with silicon microstrip detector planes and is used to measure the rigidity and sign of charge of the incident particles.

The electromagnetic calorimeter consists of silicon strip detectors interleaved

\(^2\) \( \beta = \frac{v}{c} \), where \( v \) is the velocity of the particle and \( c \) is the speed of light.
2.3 Detectors

Figure 2.3: The PAMELA trigger rate evaluated over an orbital period. The dotted curve shows an estimation of the total trigger rate while the solid curve shows the rate of only ‘good’ triggers (i.e. triggers caused by a single charged particle traversing the acceptance of the experiment) for solar maximum and minimum. The large peak to the right is due to the SAA.

with tungsten converter plates and is used to measure the energy of electrons and positrons. It will also be used to distinguish between hadronic, electromagnetic or minimum ionizing particles from the topology of the event in the calorimeter.

The anticoincidence (AC) system consists of plastic scintillator detectors placed on the sides, and as a collar around the top, of the tracker. It is used to help reject out-of-acceptance triggers.

The bottom tail-catcher scintillator S4 is used to sample showers not contained in the calorimeter.

The neutron detector consists of $^3$He filled counters and is used to help separate between hadronic and electromagnetic interactions in the calorimeter.

The subdetectors are read-out when a first level trigger is detected. This is done by a central data acquisition system (IDAQ) which requests information from each of the detectors and the data is then taken care of by the on-board data handling system. Up-linked commands can be used to change the functionality of the data acquisition system. For example, a level 2 trigger could be selected if the daily data volume greatly exceed expectations. Data is stored in an on-board mass memory prior to down-linking to the ground station in Russia. The estimated maximum daily data volume of 20 GB would require a minimum of 2 down-links per day with a transmission rate of 150 Mbit/s.
2.3.1 The Time-of-flight System

The time-of-flight (ToF) system [52] (see figure 2.4) provides flight time information of particles crossing its three layers.

The ToF system consists of three groups of scintillator counters where each group is made up of two layers (see left part of figure 2.5). The first plane (S1) is placed on top of the instrument. The first layer of S1 (S11) is divided into 8 paddles each 330 mm long and 51 mm wide, the second layer (S12) consists of 6 paddles each 408 mm long and 55 mm wide oriented perpendicular to S11. Both layers of S1 are 7 mm thick. The second plane (S2) is located between the TRD and the spectrometer, just above the top anticoincidence counter. The first layer of S2 (S21) is divided into 2 paddles each 150 mm long and 90 mm wide, the second layer (S22) also has 2 paddles (perpendicular to S21) each 180 mm long and 75 mm wide. Each layer of S2 is 5 mm thick. The last plane (S3) is placed between the spectrometer and the calorimeter, just below the magnet. The first layer (S31) is divided into 3 paddles each 180 mm long and 50 mm wide and the second layer (S32) also consists of 3 paddles (perpendicular to S31) each 150 mm long and 60 mm wide. Both layers are 7 mm thick. The paddles are made of plastic scintillator and
Figure 2.5: Left: isometric view of the time of flight system. Right: sample time resolution of a ToF paddle before (top) and after (bottom) time-walk correction (from [52]).

are read out by two Hamamatsu R3900 photomultiplier tubes (PMTs) each, one at each end of the paddle. This gives a total of 48 output channels.

By combining the time of flight information with measurements of the particle trajectory length (using the tracker) through the instrument, the velocity of the particle can be calculated. The accuracy for time-of-flight measurements is demonstrated by the widths of the distributions in the right part of figure 2.5. These two plots show the distributions of the differences (converted to a time) between the impact point reconstructed by the time-of-flight layer and the position derived from an external drift chamber, before (top) and after (bottom) time-walk corrections were applied to the data. The resulting timing resolution allows for a separation between antiprotons (protons) and electrons (positrons) up to about 1.5 GeV. The time of flight information will also be used to discriminate against albedo particles, with a separation of ~60 sigma between up-going and down-going particles. The ToF system also enables charge identification by dE/dx measurements in the
sensitive planes. The dynamic range allows identification from H to C. Finally a coincidence of the fast signal signals coming from the ToF counters will trigger the data acquisition for all the subdetectors.

2.3.2 The Transition Radiation Detector

The transition radiation detector (TRD) [51] will perform particle identification by detecting the transition radiation released by ultra-relativistic charged particles. It will enable hadron-lepton separation and is expected to provide a high detection efficiency for electrons with a hadron contamination of the order of a few percent.

The detector, located at the top of the detector stack (see figure 2.4), has a modular design. It is composed of 9 sensitive planes, each preceded by a radiator layer in which the emission of transition radiation takes place.

The sensitive planes consists of straw tubes of 4 mm diameter and 28 cm length made of 30 μm thick Kapton foil. The straw tubes, filled with an 80:20 mixture of Xe and CO₂, have a central 25 μm tungsten anode wire and operate at 1400 V. The tubes are arranged in two layers of 16 which are glued in a close-packed configuration (see figure 2.6), in order to get a uniform X-ray yield. The straw tubes of each module are kept in place by brass plates that also acts as manifolds for the gas mixture. The radiators are cushions of carbon fibre, whose density of 60 g/l has been considered suitable to optimize the radiation yield based on Monte Carlo simulations and previous experience.

The modules are housed on a special frame to form detection planes. The TRD is composed of 5 planes consisting of 4 modules each, placed above 4 planes with 3 modules each. This gives a total of 32 modules, i.e. 1024 straw tubes.

Relativistic particles crossing boundaries of materials with different dielectric constants will emit transition radiation in the X-ray range, which is then detected by the gas detectors. By measuring this radiation it is possible to separate electrons and positrons from heavier particles. A charge integration technique has been chosen to measure the transition radiation, based on results from particle beam

![Figure 2.6: Artistic view of a 32 straw tube module consisting of two 16 straw tube layers glued in a close-packed configuration. At each end are brass plates keeping the module in place and also acting as manifolds for the gas mixture.](image-url)
tests. At CERN, pion and electron beams have been used to study the detector's separation capability. The results are summarized in figure 2.7 where a 5% \( \pi \) contamination for a 90% electron efficiency is shown using the beam test data. This implies that the TRD can separate electrons from protons with an efficiency of 90% and a contamination of about 5% in the energy range of interest for PAMELA.

The straw tube design also allows a rough tracking in one view, thus making it possible to use the TRD information to reject multiple particle events.

### 2.3.3 The Magnetic Spectrometer

The magnetic spectrometer (‘tracker’) \cite{53}\cite{54} is located in the middle section of the experiment (see figure 2.4). The tracker is capable of determining the sign of the charge and the rigidity of the particles, as well as performing \( \text{d}E/\text{d}x \) measurements in the sensitive planes.

The tracker consists of 5 modules of permanent magnets, made of a Nd-B-Fe alloy, and interleaved by 6 silicon detector planes (see figure 2.8 (left part)).
cavity is 445 mm tall with a cross-section of $161 \times 131$ mm$^2$, giving a geometrical factor of 20.5 cm$^2$sr. The magnetic field is carefully mapped before launch to enable rigidity determination from the measured deflections of the fitted tracks. The mean magnetic field inside the cavity is 0.43 T and has a maximum value in the centre of 0.48 T.

The 6 sensitive planes consists of double-sided silicon detectors, 300 µm thick. Six basic detecting units ($53.3 \times 70$ mm$^2$) form each plane. Each detector is segmented in microstrips on both sides and consists of a high resistivity n-type silicon wafer provided with p$^+$-type strips implanted on the junction side (X view) and n$^+$-type strips on the ohmic side (Y view). On the X view side of the silicon wafer the strip direction is such that it allows determination of the particle position along its bending coordinate and here the implantation pitch is 25 µm and the read-out pitch is 50 µm. A capacitive coupling between two adjacent strips can be taken advantage of to improve the spatial resolution. In the magnetic field direction the strips are 67 µm wide. The total number of electronics channels is 36864.

The measured spatial resolution of the bending view is (3.0±0.1) µm [55] and the right part of figure 2.8 shows how the momentum resolution of the tracker evolves with momentum. The resolution is due to a combination of two effects: multiple scattering and finite measurement resolution and it can be parameterized as:

$$\frac{\Delta p}{p} = \sqrt{a^2 + b^2 \times p^2}$$  (2.1)
where $p$ is the momentum, $a = (3.22 \pm 0.44) \times 10^{-2}$ represents the component due to multiple scattering and $b = (0.845 \pm 0.038) \times 10^{-3} \ (\text{GeV/c})^{-1}$ is the component due to the finite measurement resolution. From this the Maximum Detectable Rigidity (MDR, where the error on the rigidity is 100%) can be calculated to be $(1183 \pm 54) \ \text{GV/c}$, which clearly exceeds the specified value of 740 GeV/c. For cosmic antiparticle flux determination the maximum measurable energy is however not given by the MDR, but by the spillover\(^3\) effect. This effect comes from the wrong determination of the charge sign of the traversing particles, due to the multiple scattering inside the spectrometer combined with the finite spatial resolution of the silicon detectors. The effect decreases with lower energies and by improving the spatial resolution of the tracker. Since antiparticles only are a small fraction of the cosmic rays, the particle spillover gives rise (at high energies) to a non-negligible background. Simulations of the spectrometer has shown that the p, e\(^-\) spillover sets a maximum energy limit of $\sim 200$ GeV for antiprotons and $\sim 300$ GeV for positrons.

The measured track in the spectrometer can also be used to reconstruct the particle trajectories through the whole experiment. This feature can be used to determine the impact positions and directions through other detectors, such as the calorimeter.

### 2.3.4 The Calorimeter

The electromagnetic calorimeter \cite{56} is located close to the bottom of the detector stack, below the tracker and the S3 ToF counters and above the S4 scintillator (see figure 2.4). The calorimeter will be used to measure the energy released by interacting e\(^-\) and e\(^+\) and to reconstruct the spatial development of the shower, allowing separation between electromagnetic showers, hadronic showers and non-interacting particles. As mentioned in chapter 1.1.1 the identification of antiprotons and positrons requires good separation from the backgrounds of electrons and protons, respectively. The calorimeter has been designed to: (i) extract the antiproton signal from the large background generated by the electron flux with an efficiency of more than 90\% and a rejection power better than $10^4$, (ii) identify positrons in the background generated by protons with an efficiency of more than 90\% and a rejection power better than $10^4$.

The calorimeter is a sampling detector made of silicon sensor planes interleaved with plates of tungsten absorber. Each tungsten layer has a thickness of 0.26 cm which corresponds to 0.74 $X_0$ (radiation lengths). Since there are 22 tungsten layers the total depth is 16.3 $X_0$ (about 0.6 nuclear interaction lengths). Each tungsten plane is sandwiched between two layers of silicon sensor planes oriented orthogonally to each other, i.e. the layout of a single detection plane is Si-X/W/Si-Y.

The silicon sensor planes consists of $3 \times 3$ silicon detectors, each with an area of $8 \times 8 \ \text{cm}^2$, giving a total sensitive area of $24 \times 24 \ \text{cm}^2$. The detectors are separated from each other by a $\sim 35 \ \text{mm}$ wide non-sensitive area, called a ‘dead area’. In total $\sim 5\%$ of the total area of a detector plane consists of such dead areas. Each silicon detector is 380 $\mu$m thick and segmented into 32 strips with a pitch of 2.4 mm.

\(^3\)This is further described in chapter 6
Every strip is connected to those belonging to the two detectors of the same row (or column) giving an effective strip length of 24 cm. The number of electronics channels per plane is therefore \(32 \times 3 \times 2 = 192\) and the total number of channels is \(192 \times 22 = 4224\). Two detection planes together form a ‘detection module’ (see left part of figure 2.9). Each module contains one detector plane from each of the 4 ‘views’ (i.e. odd and even numbered X- and Y-planes).

The mechanical structure is based on a modular concept in which the two detection planes forming a detection module are kept together by a frame. All modules are independent and fully extractable: they are inserted like ‘drawers’ into the main mechanical structure and then locked by a cover (see right part of figure 2.9).

![Figure 2.9: Left: schematic figure of one calorimeter module. The module is built up of two detector planes, each consisting of a silicon detector x-view plane, a tungsten converter plate and a silicon detector y-view plane. The calorimeter consists of 11 such modules. Right: Schematic picture of the calorimeter assembly, including the aluminum housing.](image)

The performance of the calorimeter has been extensively investigated with simulations developed from the experimental results of the CAPRICE98 [58] balloon-flight calorimeter [59]. The calorimeter performance has also been investigated using data taken at various test beams. Figure 2.10 (left) shows the number of strips hit in the calorimeter as a function of total detected energy (in mip\(^4\)) for 200 GeV/c test beam electrons and protons. Combining all topological and energetic information available from the calorimeter, a rejection factor better than \(10^4\) for protons and electrons at 95% selection efficiency in positrons and antiproton measurements can be obtained in the energy range of interest for PAMELA [56]. Figure 2.11 shows the spatial development of a hadronic (left) and an electromagnetic (right) shower in the calorimeter, which can be used on an event by event basis for particle selection/rejection. The energy resolution of the calorimeter is constant at 5.5% in the range 20 - 200 GeV (see figure 2.10 (right)).

\(^4\)One mip is defined as the average energy deposited by a minimum ionizing particle.
Figure 2.10: Left: the total number of strips hit versus the total detected energy in the calorimeter for 200 GeV/c $e^-$ and $p$ data taken at the SPS test beam. The good separation between the two particle species is clearly seen. Right: the energy resolution as a function of the incident electron energy [55].

Figure 2.11: The simulated spatial development for two types of showers in the calorimeter. The left(right) figure shows a 10 GeV antiproton(electron) interacting in the calorimeter.

The calorimeter can also be operated in self-trigger mode [56]: this hardware feature allows the stand-alone detection of $e^+$ with an increased acceptance of 470 cm$^2$sr up to an energy of $\sim$2 TeV. An energy resolution of approximately 12% is possible between 200 GeV and 700 GeV. At 1 TeV, the energy resolution climbs
to approximately 16%, due to incomplete shower containment.

2.3.5 The Anticoincidence System

The anticounter (AC) system [60] consists of four lateral detectors (CAS) covering the sides of the tracker and one top detector (CAT) placed above the tracker (see figures 2.4 and 2.12). Each detector is made from 8 mm thick sheets of plastic scintillator read out by multiple compact photomultiplier tubes (CAS: 2, CAT: 8 PMTs). Each anticounter can be tested in-flight using a LED based system.

The anticoincidence system information will be used to help reject the background events produced by out-of-acceptance particles. Through interactions in the mechanical structure of the experiment, these particles can give rise to enough energy being deposited in the ToF system for a (false) trigger to be recorded. The ratio between good and false triggers is 0.3 Hz : 2.8 Hz (7.2 Hz : 17.0 Hz) in equatorial (polar) regions [42]. A problem arises at high energies, since particles backscattered from the calorimeter can enter the anticounters even though the trigger particle passes cleanly through PAMELA’s acceptance - so-called self-veto (this is further described in [42]). This has been studied using simulations and test beam data collected at SPS, and by including calorimeter information the self-veto effect can be substantially reduced. This makes it possible to include the AC system in an on-board second level trigger [62].

The efficiency for detecting minimum ionizing particles has been measured using cosmic ray muons and has been found to exceed 99.9% per detector [61].
2.3.6 The S4 Bottom Scintillator

The S4 bottom scintillator is located just under the calorimeter (see figure 2.4) and has an area of 482 \times 482 \text{mm}^2 and a thickness of 10 mm. The scintillator is read out by six PMTs situated along the two opposite sides of the counter (see figure 2.13).

![Diagram of S4 Bottom Scintillator]

**Figure 2.13:** Schematic layout of the S4 bottom scintillator counter.

The main task of the S4 detector is to detect showers not contained in the calorimeter. When the S4 signal exceeds 10 mips and coincides with the main trigger signal an on-board Neutron Counter is read out. The S4 detector can also be used together with the calorimeter to detect very high energy (>100 GeV) electrons coming from outside the experiment’s main acceptance.

2.3.7 The Neutron Detector

The neutron detector (ND) [63] is located below the S4 scintillator and its purpose is to complement the electron-proton discrimination capabilities of the TRD and the calorimeter. This will be accomplished by exploiting the much larger neutron production due to hadronic showers than to electromagnetic showers in the calorimeter. A combined analysis using the ND and calorimeter will also allow to identify primary electrons at energies up to 10 TeV.

The detector is made of proportional counters, filled with $^3$He, surrounded by a polyethylene moderator enveloped in a thin cadmium layer. The 36 counters are stacked in two planes of 18 counters each, oriented along the Y-axis of the instrument. The size of the neutron detector is 600 \times 550 \times 150 \text{mm}^3.
2.3.8 Particle Identification

To further illustrate the function of the PAMELA experiment subdetectors two types of events will be described, namely an antiproton and a positron event. In figure 2.14 the trajectories for these particles are drawn with an exaggerated deflection in the tracker. For these particle measurements the detectors are used as follows:

![Diagram of particle identification in PAMELA experiment]

**Figure** 2.14: Schematic view of two different types of events, i.e. a hadronic (antiproton) and a leptonic (positron) event. The neutron detector located below $S_4$ is not shown in this figure.

- **ToF**: The detectors are read out when a first level trigger is given by a coincidence of energy deposits in the layers of the ToF system ($S_1 - S_3$). The ToF information for these two events will show that the trigger was caused by down-going particles. The ToF $dE/dx$ measurements will indicate singly charged particles for both the antiproton and the positron.
• **Tracker:** The tracker information will at an early stage be used to reject events with multiple hits, e.g. from interactions or multiple particles. The rigidity and sign of charge of the particles can be determined by fitting a track to the hits in the tracker. The antiproton event will thus be ‘tagged’ as a negative and the positron as a positive particle.

• **Calorimeter:** Studies of the event topology in the calorimeter makes it possible to discriminate between electromagnetic and hadronic interactions and non-interacting particles. The calorimeter data will in the cases displayed here indicate a electron/positron by the electromagnetic shower of the positron and a hadron from the non-interacting signature of this antiproton. The energy of the positron can also be determined with a resolution of \( \sim 5\% \) (see right part of figure 2.10).

• **TRD:** The TRD allows discrimination between hadrons and leptons and also gives a rough tracking in one view. This tracking can be used for rejection of multiple tracks, e.g. from particles that have interacted in or above the TRD. In the positron case, transmission radiation will be emitted in the TRD tagging the event as a lepton. For the antiproton this signal will be absent, thus indicating a hadron. In the antiproton case no multiple tracks from a pion producing interaction are seen in the TRD, thus indicating a (anti)proton.

• **AC:** The AC system information can be used to help reject the background of out-of-acceptance triggers. In these two cases there will be no veto signal.

• **ND:** The neutron detector will not detect a signal consistent with a hadronic interaction in the calorimeter for either of these events. However, the combined information of the TRD and neutron detector can be used to further diminish the risk of misidentifying the positron as being a hadronic event.

This information about the sign and absolute value of the charge, the hadron-lepton separation and rigidity measurements makes it possible to robustly identify the particles and determine their kinetic energies.

The alignment of the tracker planes will be done by calculating the energy of electrons with the tracker and compare with the calorimeter. The possibility to make redundant measurements with different subdetectors, e.g. energy measurements from calorimeter, rigidity measurements from the tracker and particle separation using the TRD and the calorimeter, enables efficiency determination for the subdetectors using flight data.
Chapter 3

Particle identification and contamination

The purpose of this chapter is to explain the reason for, and give an outline of, the studies presented in chapters 4 to 6.

As described in chapter 1, measurements of the energy spectra of positrons and antiprotons may be used to detect ‘new physics’ such as annihilation of dark matter particles. In chapter 2 it was further described how the PAMELA experiment is capable of distinguishing between charged particles. This should then make it possible to detect new physics in the form of a primary component on top of the expected secondary fluxes of antiprotons and/or positrons. However, antiparticles are much less abundant than protons and electrons and it is therefore important to study the effects of ‘misidentification’, i.e. when a particle is falsely identified as being an antiproton or positron. The contamination from other particle species will produce uncertainties in the measured antiparticle fluxes that, when combined with the statistical errors, will determine if it is possible to separate a signal from the expected background and the uncertainty associated with it.

3.1 Determining uncertainties

The uncertainties on the flux measurements can be classified as either PAMELA dependent, due to contamination and limited statistics, or as model dependent, due to limited knowledge about the secondary production processes. In the following chapters only the PAMELA dependent uncertainties are treated. This is done in three separate studies:

- **Contamination in the positron sample**: The main background when identifying positrons comes from the cosmic ray protons. The design of the PAMELA calorimeter makes it possible to separate electromagnetic and hadronic interactions, but considering that protons are several orders of magnitude more numerous than positrons this places very high demands on the
performance of the detector. The study presented in chapter 4 investigates the rejection capabilities and efficiency of the calorimeter when identifying positrons from a background of hadrons. This is done using test beam data collected at CERN and comparisons with simulations.

- **Contamination in the antiproton sample:** This study focuses on the contamination caused by negatively charged pions. These are produced when cosmic ray particles (in this study protons) interact with the materials surrounding the experiment, such as the pressurized container and the detectors located above the spectrometer. These pion events are in some cases expected to constitute an irreducible background. These types of events are expected to be rare, but considering the low abundance of antiprotons they could introduce large uncertainties on the measurements at low energies. This has to be investigated in detail and is presented in chapter 5.

- **Expected statistics and energy limits:** The size of the statistical errors is dependent on the number of expected events as a function of particle energy. This requires that the energy dependent acceptance for antiprotons and positrons is investigated, that the momentum cut-off caused by the magnetic field of the Earth is taken into account and that the high-energy limit due to misidentified particles of the opposite sign (so-called 'spillover') is determined.

The results of these three studies are brought together in chapter 7. There, it is discussed what signs the PAMELA experiment could be able to detect of neutralino annihilations in a couple of models, and what the expected uncertainty of such a detection would be for these different supersymmetric models.

Each of the studies described above relies on simulations. The same simulation program was used for all the studies and is described further in the next section.

### 3.2 Simulation

The simulations in this thesis have been performed using variations of the PAMELA Collaboration’s official simulation program: GPAMELA [64]. This simulation program is continuously being upgraded and much work is being spent on making the individual detectors as detailed and functional realistic as possible. GPAMELA is based on the GEANT package [65] version 3.21 and uses as default the GHEISHA [66] hadron shower Monte Carlo to simulate the interactions of hadrons with the nuclei of the matter traversed.

The default configuration of GPAMELA is shown in figure 3.1. The only detector not modeled is the neutron counter. Some features in the simulation are less detailed or missing. Many of the mechanical support structures and containers for the individual detectors are either much simplified, both in their geometry and material composition, or not present. These features have however been upgraded or added in studies where they have been needed (see chapter 5.2).
Figure 3.1: The default GPAMELA detector geometry and placement. The detectors described by GPAMELA are: the three ToF counters (S1-3), the transition radiation detector (TRD), the magnetic spectrometer (SPE), the calorimeter (CALO), the top and side anticounters (CAT & CAS) and the bottom scintillator (S4). Also the aluminium pressure vessel (here described by the DOME and the cylindrical CONTAINER) is included.

In each of the studies conducted, the model has been modified by (de)selecting the appropriate detectors and in some cases also changing the placement and geometry of the individual detectors. In GPAMELA the position, direction, particle type and momentum of the generated particles are specified by the user. The generation vertexes are often distributed over a user-defined surface called the 'generation
surface. The size, placement and the vertex distribution of the generation surface has been changed according to the requirements of each individual study. Also the particle types and energy distributions of the generated particles were modified for each study.

Since all the studies described in section 3.1 rely on simulations, the study presented in chapter 4 also has the aim of validating the simulation package by comparing simulated results with results derived from real test beam data.
Chapter 4

Electron-Hadron Separation using the Calorimeter

In chapter 1 it was shown how ‘new’ physics might be detected as distortions to the expected secondary antiproton and positron spectra. The substantial backgrounds of protons (for positrons) and electrons (for antiprotons) however complicates the measurements. The particle identification capability of the PAMELA experiment must therefore be well known in order to get reliable measurements for new physics searches. In this chapter the calorimeter’s ability to separate electrons\(^1\) from hadrons is studied by using test beam data and comparisons with simulations. For cosmic ray positrons the most severe background comes from the main component of the cosmic radiation, i.e. protons. Protons are several orders of magnitude more numerous than positrons, and therefore it is important to have a good separation between the two particle species.

When describing the selection procedure to separate positrons from hadrons it is convenient to introduce some terminology. There are two samples of events: those that one wants to select, \(G\), and those that one wants to reject, \(B\), using a set of conditions (or ‘cuts’), \(C\). The following can then be defined:

- **Efficiency of \(C\)**: the fraction of \(G\) events that are identified as \(G\) events by \(C\).
- **Contamination of \(C\)**: the fraction of \(B\) events that are identified as \(G\) events by \(C\).
- **Rejection factor of \(C\)**: The ratio between the efficiency and contamination of \(C\).

There are several aims to this study:

1. **Rejection/efficiency studies**: to set a lower limit on the calorimeter’s rejection capability and electron selection efficiency. This will be a lower limit

\(^1\)Unless stated otherwise electrons are interchangeable with positrons in the descriptions of interactions in the calorimeter and in the separation from hadrons.
because the test beam set-ups lacked a number of features that will be available in flight, e.g.: 1 a fully functioning tracking system, that can be used to reject multi-particle events and give impact point and direction through the calorimeter with high accuracy, 2 a fully equipped and functioning calorimeter. These are expected to improve the performance substantially.

2. Comparisons between test beam and simulation: can be used to help validate previous simulation studies performed using the ‘complete’ calorimeter configuration in conditions resembling those expected in-orbit, i.e. with a tracking system and with continuous energy spectra of the incident particles. The reliability of the rejection and efficiency derived from those studies can then be estimated more accurately.

3. GPAMELA validation: to better understand the performance and accuracy of the PAMELA experiment simulation package, GPAMELA, which is used in this study and also in the studies presented in the two following chapters. It is therefore important to validate the simulation using test beam data. A complex configuration in which showers can develop and be sampled is a useful test bench to validate simulations.

4.1 Particle Interactions in the Calorimeter

The silicon-tungsten calorimeter has been designed to identify particles through their energy deposits and topological properties of their interactions. Some examples of interactions seen in the calorimeter are shown in figure 4.1. The energy unit ‘mip’ used in this figure and in other parts of the chapter is defined after the most probable deposited energy expected from a minimum ionizing particle. In this section the different interactions in the calorimeter that are useful for particle identification are discussed. Much of the following (especially concerning the electromagnetic and hadronic cascades) is based on a paper by Leroy and Rancoita [67].

4.1.1 Electromagnetic interactions

When a charged particle traverses matter it loses energy by ionizing or exciting the atoms of the medium through inelastic collisions with atomic electrons (so-called ionization or collision losses), as well as through emission of electromagnetic radiation (so-called Bremsstrahlung) due to accelerations in the electric field of a nucleus. The total energy lost, E, per unit length, x, can then be written as:

\[
\left( \frac{dE}{dx} \right)_{\text{tot}} = \left( \frac{dE}{dx} \right)_{\text{ion}} + \left( \frac{dE}{dx} \right)_{\text{rad}}
\]  \hspace{1cm} (4.1)

Ionisation loss

The first term on the right-hand side of equation 4.1 is the ionisation term which is given by the well-known Bethe-Bloch equation. For highly relativistic electrons
4.1 Particle Interactions in the Calorimeter

(i.e. $\beta \approx 1$, where $\beta$ is the velocity in units of the speed of light) can be written as [68]:

$$\frac{dE}{dx} = 2\pi N_A \frac{Z}{A} e^2 m_e c^2 \left( \ln \frac{\pi^2 m_e^2 c^4}{T^2 (1 - \beta^2)^{3/2}} - a \right) \left\{ \frac{MeV}{g \text{ cm}^{-2}} \right\}$$ (4.2)

where $N_A$ is Avogadro’s number, $Z$ and $A$ are the atomic number and mass (in g/mol) of the medium, respectively, $m_e$ and $r_e (= \frac{e^2}{m_e c^2}$, e charge of the electron)

**Figure 4.1:** Examples of particle interactions in the calorimeter. The top left figure shows the hit and energy loss distributions in the calorimeter $y$-view for a 50 GeV/c non-interacting proton from test beam data. The top right figure shows an interacting 50 GeV/c proton from test beam data. The bottom figure shows an electromagnetic shower caused by a 50 GeV/c electron from test beam data. The particles enter the calorimeter at plane 1, strip ~25-30. These plots were produced using only odd planes.
are the mass and classical radius of the electron, respectively, 
1 \text{(} \approx 16 \times Z^{0.9} \text{)} is the
effective ionization potential of the medium and a=2.9 for electrons and 3.6 for
positrons, respectively.

### Radiation loss: Bremsstrahlung

The second term on the right-hand side of equation 4.1 (the radiation loss) is neg-
ligible for particles heavier than electrons and for particle energies below several
hundreds of GeV, since the emission probability varies as the inverse square of the
particle mass. However, for electrons it starts to exceed the collision loss above
a few tens of MeV and dominates the energy loss as the energy increases. The
bremsstrahlung emission depends on the strength of the electric field felt by the
electron and thus on the amount of screening caused by the atomic electrons sur-
rounding the nucleus. For the case of complete screening (and by neglecting the
effect of the electric field of the atomic electrons [68] the average energy loss (per
g cm$^{-2}$ of traversed matter) for electrons due to radiation can be expressed as:

$$
\frac{dE}{dx} = 4\alpha \frac{N_A}{A} Z^2 r_e^2 E [\ln(183 Z^{1/3} + 1/18)]
$$

(4.3)

where \( \alpha \) is the fine structure constant and the other symbols are as defined for
equation 4.2. By comparing the energy loss calculated with this equation to the
energy loss for collisions calculated with equation 4.2, it can be shown that for
high Z materials such as tungsten the energy loss by radiation dominates above
100 MeV for electrons.

A frequently used quantity is the material dependent radiation length, \( X_0 \), which
is defined as the distance over which the electron energy is reduced by a factor \( 1/e \)
due to radiation losses only. It can be expressed as:

$$
\frac{1}{X_0} = 4\alpha \rho \frac{N_A}{A} Z (Z + \zeta) r_e^2 \ln \frac{183}{Z^{1/3}}
$$

(4.4)

where \( \rho \) is the density of the material and \( \zeta \) is a correction taking into account the
contributions of the atomic electrons to the bremsstrahlung process and has values
between 1.2-1.4. The radiation length has a value of 0.35 cm for tungsten.

Another material dependent quantity is the critical energy, \( E_c \), which can be
deefined as the energy where losses by ionization equal those from radiation:

$$
E_c = 2.66 \left( \frac{\rho Z X_0}{A} \right)^{1.11} [MeV]
$$

(4.5)

where \( \rho, Z, A \) and \( X_0 \) are as defined above. This formula gives a value for the
critical energy of 8.1 MeV for tungsten.

### 4.1.2 Electromagnetic showers

The photons produced in the bremsstrahlung process will (neglecting photoelec-
tric effect) materialise as electron-positron pairs (i.e. pair production) or produce
Compton electrons depending on the photon energy. These new electrons can radiate more photons that in turn produce additional electrons in a multiplicative process called a shower. This multiplication will proceed until the energy of the produced secondaries are sufficiently low enough (i.e. \( \leq E_e \)) that collision losses start to dominate over the radiative losses and they dissipate their energy through ionization or excitation of the atoms of the medium.

The bremsstrahlung photons are vital components in the development of a shower and can produce electrons by the following processes:

- **Pair production:** involves the transformation of a photon into an electron-positron pair. This process can only occur in the presence of a third body (usually a nucleus) in order to conserve momentum, and the photon must have an energy of at least 1.022 MeV (i.e. \( 2m_e \)). The pair production process is related by a “crossing symmetry” to bremsstrahlung and also here the screening effect by the atomic electrons play an important role. The mean free path, \( \lambda_{pair} \), of a high-energy photon for pair production can be approximated as:

\[
\lambda_{pair} = \frac{9}{7} \lambda_0
\]  

(4.6)

- **Compton effect:** is the scattering of photons on free electrons. In matter the electrons are bound but if the photon energy is high compared to the binding energy the electron can be considered as free. At high energy the cross section for Compton scattering decreases with increasing photon energy while at low energy (\( E \leq m_e c^2 \)) the cross section for Compton scattering reduces to the classical Thomson scattering cross section, i.e. depending only on the classical radius of the electron.

- **Photoelectric effect:** can be considered to be an interaction between an incident photon and the atom as a whole and involves the absorption of the photon and the subsequent ejection of an electron from the atom. The energy, \( E_e \), of the outgoing electron is then:

\[
E_e = E_\gamma - \Phi
\]  

(4.7)

where \( E_\gamma \) is the photon energy and \( \Phi \) is the binding energy of the electron. The cross section is strongly dependent on the atomic number of the material, and at high energies it is inversely proportional to the photon energy.

The total probability per radiation length for pair production approaches \( 7/9 \) as \( E \rightarrow \infty \) and thus (in high Z materials) photons are mostly absorbed by pair production for energies \( \geq 100 \text{ MeV} \), while at lower energies the dominant effect is Compton scattering and below \( \sim 1 \text{ MeV} \) photon interactions are mostly due to the photoelectric effect.

### 4.1.2.1 Longitudinal development

An electromagnetic shower can be characterized in a simplified manner [69] by assuming that an incident electron of energy \( E_0 \) will, after one radiation length, lose
half its energy to a bremsstrahlung photon. Each photon produced in this manner will after one radiation length convert into an electron-positron pair, each particle acquiring half of the photon’s energy (see figure 4.2). This multiplication will con-

![Diagram](image)

**Figure 4.2**: A simple model of the development of an electromagnetic shower, shown in a silicon-tungsten calorimeter. Solid lines indicate electrons or positrons and wavy lines indicate photons. The width of the shower is exaggerated in this illustration.

...time until the energy of the particles in the shower has reached $E_c$ below which they lose energy due to collision losses only. In this simplified model after $t$ radiation lengths the total number of particles (electrons, positrons and photons) will be $N(t) \approx 2^t$, each with an average energy of $E(t) \approx E_0/N(t)$. This splitting will continue until $E(t) = E_c$ where the total number of particles is at its maximum, $N(t_{max}) = E_0/E_c$, and the maximum depth is given by $t_{max} = \ln(E_0/E_c)/\ln 2$. This is a ‘toy’ description and in reality the development is determined by a statistical process where the number of particles rises exponentially to a broad maximum after which the shower decays slowly. After the maximum the low-energy photons lose their energy by Compton scattering or photoelectric processes while the soft electrons lose their energy mainly through collisions.

A more detailed description of the longitudinal development of an electromagnetic shower has been given by Rossi and Greisen [70]. In this description multiple scattering has been neglected and it is assumed that all particles move in the same direction as the primary particle. The reason for this assumption is that although multiple scattering has a significant effect on the lateral spread of the shower, it does not affect the longitudinal profile since its effect on the total path length is negligible. This theory predicts the number and energy distribution of electrons and photons with an energy significantly larger than 5 MeV. Collisions producing electrons with an energy less than 5 MeV represents the process by which energy is lost from the shower and eventually deposited in matter through ionization and
4.1 Particle Interactions in the Calorimeter

Excitation of atoms. This theory is valid for incoming energies $\gg (mc^2/\alpha Z^{1/3})$ ($\approx 17$ MeV for tungsten) and therefore the radiation and pair production processes can be described assuming full screening while Compton scattering is neglected. In their model ‘approximation B’, collision losses are taken into account but are assumed to be energy independent and equal to the critical energy $E_c$ per radiation length. ‘Approximation B’ gives identical results for all materials if the thicknesses are measured in units of radiation length and energies in units of critical energy. Under ‘approximation B’ the maximum depth is given by:

$$t_{max} = 1.01 \left( \ln \left( \frac{E_0}{E_c} \right) - c \right) \left[ X_0 \right]$$  \hspace{1cm} (4.8)

where $c=1.0$ or $0.5$ for incident electrons or photons, respectively. The location of the centre of gravity of the shower, $t_{cg}$, which is the depth at which half of the incident energy has been deposited by the particles in the shower is given by:

$$t_{cg} = 1.01 \left( \ln \left( \frac{E_0}{E_c} \right) + d \right) \left[ X_0 \right]$$  \hspace{1cm} (4.9)

where $d=0.4$ or $1.2$ for incident electrons or photons, respectively. The number of charged particles at the maximum depth is given by:

$$\Pi_e(t_{max}) = \left( \frac{0.31}{\sqrt{\ln \left( \frac{E_0}{E_c} \right) - e}} \right) \left( \frac{E_0}{E_c} \right)$$  \hspace{1cm} (4.10)

where $e=0.37$ or $0.18$ for incident electrons or photons, respectively. The shower deposits 95% of the incident particle’s energy within a depth of:

$$L(95\%) = t_{max} + 0.08Z + 9.6 \left[ X_0 \right]$$  \hspace{1cm} (4.11)

where $t_{max}$ is given by equation 4.8. These equations are used when constructing some of the variables required for the analysis performed in section 4.3.

4.1.2.2 Lateral development

The lateral spread of the shower depends mainly on the longitudinal depth and less on the energy of the primary electron. At high energies the angular spread is due to the opening angles in bremsstrahlung and pair production, that are of the order of $\theta_{brems, pair} \sim m_e c^2 / E$, where $E$ is the energy of the photon/electron. However, these processes have little effect on the lateral profile and are negligible compared to the multiple scatterings in the absorber. This last effect becomes increasingly important as the energies of the shower particles decrease. This results in two components for the lateral profile: a narrow, strongly collimated central part due to the high-energy particles that are responsible for the deposition of most of the incident energy and a peripheral component (mainly due to the propagation of photons) spreading out as the shower penetrates deeper and low-energy particles.
are created. The lateral profile can be described in a double exponential form that represents the size of the central and peripheral cascade components:

\[ Y(y, t) = a_1(t) e^{-\frac{y}{b_1}} + a_2(t) e^{-\frac{y}{b_2}} \]  

(4.12)

where \( y \) is the distance from the shower axis, \( t \) is the depth in radiation lengths, \( a_1 \), \( a_2 \) are two constants and \( b_1, b_2 \) are the two lateral attenuation lengths representing the central and peripheral cascade components, respectively.

Since it is mainly the low-energy particles that are responsible for the lateral spread of the cascade, the transverse depth is measured in a unit called the Molière radius \( (R_M) \) that depends only on the material and the Coulomb scattering of low-energy particles in the shower. It is defined as the average lateral spread undergone by an electron of energy \( E_e \) traversing one \( X_0 \) of material:

\[ R_M = \left( \frac{E_M}{E_e} \right) X_0 \]  

(4.13)

where \( E_M = \sqrt{\frac{4\pi}{\alpha}} m_e c^2 = 21.2 \text{ MeV} \), and \( E_e \) is the critical energy given by equation 4.5. This formula gives a value of 0.92 cm for tungsten. About 90% of the total deposited energy is deposited inside a cylindrical volume of radius \( R_M \) around the shower axis. The 95% lateral containment for electromagnetic showers is given by:

\[ R(95\%) \approx 2 \, R_M \]  

(4.14)

With \( X_0 = 0.35 \text{ cm} \) for tungsten, \( R(95\%) \) is of the order 1.8 cm (corresponding to a width of 7.5 strips in the silicon detector planes).

The PAMELA calorimeter consists of 44 planes of silicon detectors that are divided into strips and this makes it possible to measure the impact point and angles of incidence of the incident particle by using the energy deposit information in the strips. The position of the impact point is measured by using the centre of gravity of the energies, \( E_i \), deposited in the strips:

\[ \mathcal{X} = \frac{\sum_i x_i E_i}{\sum_i E_i} \]  

(4.15)

where \( x_i \) are the coordinates of each strip hit (a strip is considered hit if it registers 0.7 mip) with respect to the central one, and \( E_i \) is the energy deposited in strip \( i \). By doing this for several planes at different ‘depths’ the direction through the calorimeter can also be determined. The information about the direction and impact point makes it possible to reconstruct the shower axis and thus gives the ‘track’ of the event through the calorimeter. The resolution is however limited \((O(\text{mm}))\) and not comparable to the accuracy achieved if the tracking system is used instead \((O(\mu\text{m}))\).

### 4.1.3 Hadronic showers

Unlike electromagnetic showers no analytical solutions, even following simple approaches, exists for hadronic showers. The hadronic shower results from different
inelastic hadronic interactions and consists of a wide variety of particles and number of nuclear processes, which results in large fluctuations in energy loss and multiplicity between individual showers. In hadronic interactions, about half of the incident energy is carried away by one or more particles (so-called leading particles) and the remaining part is accounted for by the production of secondaries. These secondaries are produced with an average transverse momentum of \( \approx 350-400 \text{ MeV}/c \) [71][72], resulting in a larger lateral spread for a hadronic shower compared to an electromagnetic one. Hadronic interactions with nuclei are similar to interactions with free nucleons except for a multiplicative factor depending on the target nucleus atomic weight \( A \). The multiplicity of the inelastic interaction increases logarithmically with energy (as \( \ln(s) \), where \( \sqrt{s} \) is the centre of mass energy) but with large fluctuations (of the order of 50\%) around this value.

A significant fraction of the secondaries produced comprise of particles (mainly \( \pi^0 \) mesons) that decay via electromagnetic interactions and generate an electromagnetic cascade. This means that there is always an electromagnetic component present in a hadronic cascade. The average fraction, \( f_{\text{em}} \), of incoming hadron energy deposited by electromagnetic cascades can be estimated as

\[
f_{\text{em}} \approx (0.11 - 0.12) \ln(E/\text{GeV})
\]


giving that on average 30\% of the incident energy is released as electromagnetic energy for an incident energy of 10 GeV. The purely hadronic component (i.e. particles depositing their energy by non-electromagnetic processes) deposit their energy via several mechanisms (neglecting the \( \pi^0 \) component):

- by ionization (40-60\%, increasing with decreasing \( A \))
- by generation of neutrons (10-15\%, decreasing with decreasing \( A \))
- by nuclear break-up and recoil of of nuclear fragments including energy carried by neutrinos (30-45\%, decreasing with decreasing \( A \))
- by generation of photons from fission (~3\%)

4.1.3.1 Longitudinal development

The longitudinal development of a hadronic cascade is described in units of (nuclear) interaction length, \( \lambda_A \), which is given by:

\[
\lambda_A = \frac{A}{(N_A \rho \sigma_{\text{nA(inelastic)}})} \text{[cm]}
\]

where \( A \), \( N_A \), \( \rho \) and \( \sigma_{\text{nA(inelastic)}} \) are the atomic weight, the Avogadro number, the density and the inelastic cross-section of the target, respectively. This gives a value of 9.6 cm for the nuclear interaction length of tungsten at high energies.

The hadronic cascade, like the electromagnetic one, develops in the longitudinal direction as long as the produced secondaries have enough energy to continue the multiplication process. The longitudinal profile of the shower rises rapidly in the early phase due to the electromagnetic component, and is then after the maximum dominated by the hadronic component which results in a slow decrease. The shower maximum is reached at:

\[
t_{\text{max}} \approx 0.2 \ln(E/\text{GeV}) + 0.7 \cdot [\lambda_A]
\]
The depth required to contain 95% of the hadronic shower energy can be approximated as:

\[ L(95\%) \approx t_{\text{max}} + 2.5 \lambda_{\text{att}} \quad [\lambda_A] \quad (4.18) \]

where \( \lambda_{\text{att}} \approx \lambda_A (E/\text{GeV})^{0.13} \) is the longitudinal attenuation length.

### 4.1.3.2 Lateral development

The lateral spread is caused by the production of secondaries at large angles. The lateral profile depends on the longitudinal depth and increases almost linearly with it. The overall transverse dependence can be described as consisting of two parts: a main part along the shower axis which decays rapidly, and a large, long peripheral part (mostly consisting of low-energy particles) that survives and carries a large fraction of the energy away from the axis. On average 95% of the shower energy is contained within a cylinder of radius \( \lambda_A \) around the track.

### 4.2 Test Beams

The test beam data used in the analysis in section 4.3.2 were collected at three different occasions at CERN during 2002-2003. At each of the test beams a stand-alone trigger system was used consisting of: two overlapping ‘finger’ scintillators (called T₁ and T₂) and a larger scintillator (called AC) with a circular hole in the middle. T₁ and T₂ were used to form a coincidence, and by letting the hole of the AC cover the overlap of the ‘fingers’ it produced an anticoincidence signal (thus rejecting particles from the halo of the beam coinciding with particles in the beam). The trigger signal is thus defined as: \( (T_1 \cdot T_2 \cdot \overline{AC}) \)

**July 2002**

One test beam took place at the T7 beam line in the PS East Area in July 2002. The T7 beam is produced by sending 24 GeV/c protons extracted from the PS onto a target (the so-called South Target) consisting of e.g. Cu, Al depending on the yield and beam composition required. This results in a secondary beam consisting of hadrons and electrons with momenta in the range 0-10 GeV/c. Figure 4.3 shows the relative momentum distribution of positively charged particle species in the T7 beam. For further information about the beam areas and beam conditions see [73].

At this test beam only the TRD and calorimeter were present. The TRD was a test version consisting of 9 planes of straw tubes interleaved with radiator but with only one straw tube module per plane (only the 8 central tubes were read out), and thus reproduced the full depth but not the lateral dimension. The calorimeter used was the flight version but with 4 (out of 44) of the silicon planes missing. The test beam set-up is shown in figure 4.4.

The test beam area also provided a Cherenkov detector (placed upstream of the set-up) and a lead glass detector (placed downstream of the set-up) for particle identification purposes. The data runs used for this calorimeter analysis were
Figure 4.3: Relative momentum distribution of protons, pions and positrons in the T7-beam [73].

Figure 4.4: The test beam set-up for the July 2002 test beam at the T7 line. Not shown in this figure is the Cherenkov detector placed upstream in the beam line that is used for electron/hadron selection. The lead-glass detector was not used in the calorimeter analysis.
so-called non-classified beams, i.e. a mixture of electrons and hadrons, and the identification/selection of electrons and pions has been performed off-line using the information from the Cherenkov detector and the TRD. The beam composition and the availability of the Cherenkov detector limited the number of useful runs to particles of 3 and 10 GeV/c.

**June 2002 & September 2003**

The other two test beams both took place at the SPS North Area in the H4 and H2 beam lines in June 2002 and September 2003, respectively. The H4 and H2 beams are produced by sending 450 GeV/c protons extracted from the SPS onto a beryllium target called T2. This results in secondary beams consisting of electrons, hadrons and muons of momenta between 10 and 400 GeV/c. The experimental area and beam conditions are further discussed in [74][75].

In the June 2002 test beam the flight versions of the tracking system, the calorimeter and the anticoincidence system were mounted in their flight configuration and placed in the beam (see figure 4.5). The calorimeter was fully equipped with tungsten converters but only 23 planes (out of 44) were read out. Data were collected for electrons of momenta between 50 and 300 GeV/c, and for protons between 200 and 350 GeV/c.

The September 2003 test beam included the flight versions of all detectors mounted in the flight configuration (see figure 4.5) except for the S1 counter and the TRD. The S2 and S3 counters were present but not read out. The calorimeter was fully equipped with tungsten converters but only 33 planes (out of 44) were read

(*) Only present in September 2003

**Figure 4.5:** The test beam set-up for the June 2002 and September 2003 test beams at the H4 and H2 beams. The detectors marked with (*) were not present during the June 2002 test beam, i.e. the S2 and S3 counters, the S4 scintillator and the neutron-counter. The drawing is not to scale.
out. For 4 out of the 6 days of data taking the primary beam was dedicated to LHC experiments to verify electronics and detector designs under realistic LHC operating conditions. This meant that the primary beam from the SPS to the T2 target had a 25 ns bunch structure as shown in figure 4.6. This resulted in a large number

![Diagram of 25 ns bunch structure](image)

**Figure 4.6:** Details of the 25 ns bunch spacing of the primary proton beam for LHC experiments: 48 bunches, each 2.3 ns long and separated by 25 ns, with one bunch train every 23 µs. Each spill is 2.7 s long for a total of 5.6×10⁶ bunches per spill. The radiation safety limits restricts the number of particles that can be sent to the experimental areas, and for the North Area this number is less than one primary proton per bunch. From [76].

of particles per spill for the proton runs compared to normal running conditions, which in turn led to an increased occurrence of multiple particle events, i.e. more than one particle traversing the experiment during one trigger. Data was collected for electrons of momenta between 20 and 180 GeV/c, and for protons between 20 and 150 GeV/c. Due to the many different studies conducted at this test beam, such as the alignment of the tracker and studies of backscattering [76], the number of runs available for the calorimeter study were limited to 40 and 150 GeV/c.

Figure 4.7 shows PAMELA at the September 2003 test beam before being mounted on a support and placed in the beam. On top the CAT detector can be seen with the S2 counter mounted beneath it. Below the CAS detectors the base plate and calorimeter are visible.

### 4.3 Electron-hadron separation

In general the identification of electrons and positrons in the cosmic radiation is complicated by the presence of large backgrounds of other particles such as protons and helium nuclei. Fortunately, since PAMELA is a satellite-borne experiment, there is no background of muons or pions produced in the atmosphere as for balloon-borne experiments, and even though there is a small background of pions produced...
in the payload it does not contribute significantly to the total background (unlike for antiprotons, see chapter 5). The Time-of-Flight system can with very high accuracy select down-going |Z| = 1 particles, and the tracking system provides reliable information on the sign of charge and rigidity (momentum/charge) over a wide range of momenta from about 50 MeV/c up to more than 200 GeV/c (see chapter 2). It thus remains to identify positrons from a background of protons that increases from about 10^3 times the positron component at 1 GeV/c to about 5×10^3 at 10 GeV/c. This means that the PAMELA detectors together have to provide a rejection factor of the order of 10^6-10^8 for protons.

4.3.1 Shower characteristics

As can be seen in sections 4.1.2 and 4.1.3 (see also the examples in figure 4.1) electromagnetic and hadronic showers differ in their spatial development and energy distribution in a way that should be possible to distinguish by the calorimeter. In table 4.1 the main features of the two types of showers in the PAMELA calorimeter are presented. For simplicity, the calorimeter has been assumed to consist of a single block (24.1 × 24.1 × 5.72 cm^3) of tungsten (~16 X_0), i.e. totally neglecting the contribution from the silicon detectors and electronics.

In table 4.1 and in sections 4.1.2 and 4.1.3 it can be seen that the main differences between an electromagnetic and hadronic cascade are:
Table 4.1: Main features of electromagnetic and hadronic showers in the PAMELA calorimeter. The lateral spread is estimated as 2×R(95%) (≈ 4R_M).

<table>
<thead>
<tr>
<th>Feature</th>
<th>Electromagnetic shower</th>
<th>Hadronic shower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation length (X₀)</td>
<td>0.35 cm</td>
<td>-</td>
</tr>
<tr>
<td>Interaction length (λ_A)</td>
<td>-</td>
<td>9.59 cm</td>
</tr>
<tr>
<td>Critical energy (E_c)</td>
<td>8.1 MeV</td>
<td>-</td>
</tr>
<tr>
<td>Molière radius (R_M)</td>
<td>0.91 cm</td>
<td>-</td>
</tr>
<tr>
<td>Depth of shower maximum at 3 GeV/c</td>
<td>≈ 4.9 X₀ = 1.72 cm</td>
<td>≈ 0.92 λ_A ≈ 8.8 cm</td>
</tr>
<tr>
<td>Longitudinal containment (95%) at 3 GeV/c</td>
<td>No containment</td>
<td>No containment</td>
</tr>
<tr>
<td></td>
<td>≈ 7.2 cm needed</td>
<td>≈ 36 cm needed</td>
</tr>
<tr>
<td>Lateral containment (95%)</td>
<td>Full containment</td>
<td>Full containment</td>
</tr>
<tr>
<td></td>
<td>for all particles</td>
<td>for central incidence</td>
</tr>
<tr>
<td>Lateral spread</td>
<td>≈ 3.6 cm</td>
<td>≈ 19 cm</td>
</tr>
</tbody>
</table>

- only for the electromagnetic shower is the shower maximum contained inside the calorimeter for the energy range of interest in PAMELA,
- the lateral distribution of the hadronic shower is much wider,
- the development of the electromagnetic cascade is strongly related to the energy of the primary electron or photon and the electromagnetic shower will with high probability start to develop in the first two to three planes of the calorimeter,
- for electrons there is a linear relationship between the primary particle energy and the deposited energy (up to ~1 TeV for the PAMELA calorimeter). This limit is partly because less of the shower is contained longitudinally as the primary electron energy increases (so-called ‘leakage’).

The characteristics of an electromagnetic shower which can be exploited to separate it from a hadronic shower are:

1. The starting point of the shower.
2. The detectable energy loss.
3. The longitudinal profile.
4. The transverse profile.
5. The topological development of the shower.

4.3.2 Electron selection

As mentioned, the aim of this analysis is to select electrons with as little contamination from protons as possible. This means finding a selection that rejects as large
a part of the hadron samples as possible while retaining an acceptable efficiency for electrons. The analysis is based on the way in which the calorimeter can be used to distinguish the differences between electromagnetic and hadronic showers described in the previous section. This means that the ‘distinctions’ can be grouped into the 5 main categories listed above and described in more detail below. In the description of these categories, examples of some variables used to separate electrons from protons or pions at different energies will be given. The plots shown of these variables and the cuts applied to them are provided to motivate the methods and illustrate the principles. The placement of the individual cuts are the result of all cuts used in the selection, whereas the plots of the variables have been produced without any restrictions applied. The cuts on the variables were all developed using only test beam data, with the exception of the selection used for 10 GeV/c electrons and pions (see section 4.4.3 and table 4.2). In the future flight data analysis the conditions put on the variables will have to be energy dependent.

The analysis performed below is based upon the principles outlined in [77] which presented a similar type of calorimeter used in the CAPRICE94 [78] balloon-borne experiment.

Starting point of the shower

From the value of $X_0$ given in table 4.1 it can be seen that the probability for an electromagnetic shower to start developing in the first three planes is high ($\geq 89\%$). For a hadronic shower the starting point is uniformly distributed through the calorimeter.

A quantity useful to characterize the starting point of the shower is:

$$\sum_{j=1}^{22} \sum_{i=1}^{2} \theta_{ij} \cdot i$$

where $\theta_{ij}=1$ if the $i$-th plane of the $j$-th view has a cluster$^2$ along (less than 4 mm away) the ‘track’ (see section 4.1.2.2) with a deposited energy typical of a proton ($O(\text{mip})$), otherwise $\theta_{ij}=0$. A non-interacting hadron or a hadron interacting after a few planes will result in high values for this variable, up to a maximum of 506 for a straight proton track with hits in all the planes (assuming that the track through the calorimeter has been determined accurately). On the contrary, for an electromagnetic shower developing in the first planes, this variable will have a low value as seen in the left part of figure 4.8.

As stated above, an electromagnetic shower usually starts to develop already in the first 3 planes of the calorimeter while the starting point of the hadronic shower is rather evenly distributed through the calorimeter. This difference has been exploited in the variable shown in the right part of figure 4.8, which is dependent on the energy deposited (number of strips hit) within a cylinder of radius $2 R_M$ around the track in the first 3 planes. The starting point of the shower is therefore used to separate electrons and hadrons.

$^2$ A cluster is here defined as a group of contiguous strips hit
Figure 4.8: Left: Quantity related to the topology and starting point of the shower. The arrow illustrates a cut used to separate electrons from pions of 3 GeV/c momentum from the July 2002 test beam. The same number (~7.5·10^5) of electrons and pions are shown in this plot. Right: Energy deposited in a cylinder of radius ~2 R_M around the track in the first 3 planes for electrons and protons of 40 GeV/c momentum from the September 2003 test beam. Since an electromagnetic shower, unlike a hadronic one, generally starts to develop within the first 3 planes, electrons deposit more energy than hadrons in the first 3 planes. The arrow illustrates where a cut was placed to reject protons. The plot was produced using the full statistics (~10^6 e^- and ~4·10^4 protons) to better illustrate the differences.

The energy loss

Electrons, unlike hadrons, have a ‘well defined’ energy loss distribution that varies in a quasi-linear way with the energy of the incoming electron as long as the leakage due to lack of longitudinal containment does not become too large. This difference between hadronic and electromagnetic showers is frequently used in this analysis and includes variables such as the total energy detected in the calorimeter for an event. As can be seen in the left part of figure 4.9, the distribution for electrons has the Gaussian shape expected from theory. The hadron distribution exhibit a narrow peak arising from non-interacting hadrons on top of a long, nearly flat, distribution due to hadronic interactions. As shown in figure 4.9, these variables can often be used to reject a large part of the hadrons while keeping a high efficiency for electrons. However, due to the decreased longitudinal containment of the electromagnetic showers with increasing incident energy (i.e. ‘leakage’) this variable loses its Gaussian shape as the energy becomes higher and acquires a low energy tail as seen in the right part of figure 4.9^3. This means that even though the separation

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^3 It is worth pointing out that part of the tail is caused by the increased lateral spread of the shower, which increases the effect of the dead areas (see chapter 2.3.4)
Figure 4.9: **Left:** Energy deposited (in mip) in the calorimeter for 3 GeV/c electrons and pions at the July 2002 test beam. The arrow illustrates an example of how this quantity can be used to separate electrons from hadrons, i.e. everything below this value was rejected. The same amount ($\sim 7.5 \cdot 10^3$ events) of electrons and pions have been used in this plot. **Right:** Energy deposited (in mip) in one of the 4 views for 200 GeV/c electrons and protons at the June 2002 test beam. As the incident particle momentum increases the separation between electrons and protons (here is only showed the high energy tail of the proton distribution) becomes more pronounced, however a tail toward lower deposited energies for the electron distribution (arising from the increased 'leakage') can cause a loss in efficiency if a too strict selection is made. The arrow illustrates how this quantity was used to reject protons. This plot was produced using the full statistics ($\sim 10^4$ electrons and $\sim 2.5 \cdot 10^5$ protons) to better illustrate the differences.

becomes more pronounced at higher energies there is a risk of losing a significant number of electrons (thus reducing the efficiency) due to the low-energy tail of the electron energy deposit distribution if a too strict condition is used. The different calorimeter configurations used at the different test beams made it necessary to use variations of this variable depending on the number of planes read out, as illustrated by the right part of figure 4.9 where only one view (out of four) was used.

**Longitudinal profile**

The principal properties of the longitudinal development of an electromagnetic shower are described in section 4.1.2, and have been used when selecting electrons. One such property is that the energy deposit of an electromagnetic shower decreases after the shower maximum and spreads out laterally, unlike for the hadronic showers that deposit their energy either in a more uniform way or have a maximum located
deeper in the calorimeter for the same incident particle energy. One such variable is shown in the top left-hand part of figure 4.10 and shows the differences expected for electrons and hadrons. This variable is based on the fraction of the total energy deposited in the planes of the calorimeter that are located at least 5 planes after the calculated (electromagnetic) shower maximum of the incident particle. As can be seen in the figure, the pions have a much wider distribution where the lower values are due mostly to non-interacting pions and the higher values are due to showers developing deeper into the calorimeter.

As stated above, the multiplicity and energy deposited by an electromagnetic shower decreases after the shower maximum while the hadronic shower maximum is often not contained in the calorimeter. Thus the detected energy distribution is approximately constant for the hadronic shower throughout the calorimeter. The variable shown in the top right part of figure 4.10 is based on the energy deposited inside a cylinder of radius \( \sim 2 R_M \) for the last 4 planes. This variable often has a lower value for electromagnetic showers than hadronic showers for incident particle energies for which the electromagnetic shower maximum is contained in the calorimeter.

Another property of the longitudinal development of an electromagnetic shower that has proved useful in the separation of electrons from hadrons, is the energy loss in the strip with the highest detected energy. This variable is shown in the bottom part of figure 4.10 and is related to the number of electrons at shower maximum (and thus related to the energy of the incident electron). For interacting hadrons the spread of the highest energy loss is much greater than for electrons, and can be of the order of hundreds of m\( \mu \) due to e.g. the breaking of a silicon nucleus whose fragments lose all their energy in one strip.

**Transverse profile**

The division of the calorimeter’s sensitive area into strips makes it possible to exploit differences in the lateral profile for electromagnetic and hadronic interactions. The variables used for this are all dependent on the determination of the impact point and direction through the calorimeter for the incident particle. Under flight conditions this will be provided by the tracking system with high precision, but for these test beams no such information was available and the reconstruction was done by the calorimeter itself, as described in section 4.1.2.2.

The variable shown in the top left-hand part of figure 4.11 describes the energy deposited per strip inside a cylinder with a radius of 8 strips (8 strips\( \approx 2 \text{ cm} \approx 2 R_M \)) around the reconstructed track. For electrons approximately 95% of the total deposited energy is expected to be found within a radius of 2 \( R_M \) around the track. This is not the case for the hadronic showers which are more spread out laterally. The differences between the two types of interactions are clearly seen in both top parts of figure 4.11. They show similar variables but using a smaller radius (\( \sim 1 R_M \)) around the track in the right plot. These types of cuts are, under normal conditions, among the most powerful when it comes to separate hadrons from electrons. Unfortunately, they can not be used to their full advantage in this study since the calorimeter’s less exact track-reconstruction is used (compared to using the spec-
Figure 4.10: **Top left:** Fraction of the total energy ($Q_{TOT}$) deposited after the shower maximum for electrons and pions of 3 GeV/c momentum from the July 2002 test beam. The arrow illustrates a cut used to reject some of the hadronic showers developing further into the calorimeter. The same number ($\sim 7.5 \cdot 10^3$) of electrons and pions were used in this plot. **Top right:** The fraction of the total energy deposited inside a cylinder of radius $\sim 2 R_M$ around the track in the last 4 planes, for electrons and pions ($\sim 7.5 \cdot 10^3$ of each) with a momentum of 3 GeV/c from the July 2002 test beam. The arrow illustrates a cut used to reject pions. **Bottom:** The maximum energy detected in a single strip for electrons and pions with a momentum of 3 GeV/c from the July 2002 test beam. The arrow illustrates a cut used to reject pions. The same number ($\sim 7.5 \cdot 10^3$) of electrons and pions were used in this plot.

trometer). This can result in the reconstructed cylinder not coinciding with the real shower axis, which leads to a low-energy tail. The effect becomes more pronounced
Figure 4.11: These plots show the energy deposited around the track for electrons and hadrons. **Top left:** The energy deposited per strip inside a cylinder of radius \( \sim 2 R_M \) around the track for 300 GeV/c electrons and 350 GeV/c protons from the June 2002 test beam. The arrow illustrates the cut used to select electrons. This plot was produced using the full statistics (\( \sim 10^4 \) electrons and \( \sim 2.5 \times 10^5 \) protons) to better illustrate the differences. **Top right:** Energy deposited in a cylinder around the track with radius \( \sim 1 R_M \) for 200 GeV/c electrons and protons from the June 2002 test beam. This plot was also produced using the full statistics. **Bottom:** The fraction of the total energy not clustered along the track, for electrons and protons of 40 GeV/c momentum from the September 2003 test beam. The same number (\( \sim 9 \times 10^3 \)) of electrons and protons were used in this plot.

as the radius of the cylinder decreases. This can result in a suppressed electron selection efficiency and hadron rejection.

Electromagnetic showers can also be separated from the hadronic showers by
determining how much of the total deposited energy is in clusters around the track. Electrons will produce many such clusters along the track since they deposit most of their energy within 2–3 cm from the shower axis, while a hadronic shower will have fewer clusters and these will be further away from the shower axis. The difference between hadrons and electrons based on this quantity is illustrated in the bottom part of figure 4.11, which shows the fraction of the total energy not deposited in clusters along the track.

Another example of a variable based on the lateral and longitudinal development of electromagnetic and hadronic showers contain information about the energy deposited outside a cylinder of radius 16 strips ($\approx 4.3 \, R_{\text{MT}}$) around the track in the last 4 planes. The narrow lateral spread of an electromagnetic shower mean that this variable assumes much smaller values for electrons than for hadronic showers due to their larger spread.

**Topological cuts**

These cuts are designed to target the topological differences between hadronic and electromagnetic showers.

The number of secondaries produced in an electromagnetic shower and thus the number of hits produced in the calorimeter are related to the energy of the incident electron. For a hadronic shower in a calorimeter without full containment there is no corresponding simple relation. A simple way to separate electrons from non-interacting hadrons and low-multiplicity hadronic showers is to put a lower limit on the number of strips hit. However for high multiplicity showers a more refined variable is needed to achieve good separation. This can be expressed as:

$$\sum_{j=1}^{2} \sum_{i=1}^{p_{l,\text{max}}} n_{\text{h/d}}(i, j) \cdot i$$

where $n_{\text{h/d}}(i, j)$ is the number of hits in a cylinder of radius 2 $R_{\text{MT}}$ around the track in the i-th plane (where the top plane is number 1 and the sum runs up to plane number $p_{l,\text{max}}$, closest to the calculated electromagnetic shower maximum of the j-th view). This variable exploits the increased multiplication with calorimeter depth of the secondaries of the electromagnetic shower and their collimation along the track. This variable assumes high values for electrons and low values for hadronic showers due to their larger lateral dispersion and limited number of secondaries as can be seen in figure 4.12.

### 4.4 Simulation

As mentioned at the start of this chapter, one aim of this study was to determine how well simulations can predict results that will be achieved with the PAMELA experiment in space. The simulations in this study were performed using GPAMELA (see chapter 3.2).
Figure 4.12: The topological development of the shower. This plots shows the variable of equation 4.20 for electrons and protons with a momentum of 150 and 200 GeV/c respectively (from the June 2002 test beam). This quantity generally assumes lower values for hadrons than for electrons and the arrow illustrates a cut used to reject protons. The same number (~3 \times 10^3) of electrons and protons were used for this plot.

For two of the test beam set-ups (June 2002 and September 2003) GPAMELA was used as released, i.e. in a flight configuration with the exception of the time-of-flight system which was missing in June 2002. For both these test beams the S1 scintillators have been kept in their original position as ‘dead’ material for the trigger finger scintillators. For the July 2002 test beam only the calorimeter, the TRD and S1 were kept in the simulation. The TRD was modified to resemble the test beam version and S1 was moved to match the position of the trigger scintillators at the test beam (in this way the total thickness of the scintillator material becomes less than at the test beam, although only by \sim 0.015 X_0). The calorimeter for each of the 3 simulated test beams was in the configurations described in section 4.2 and was also the only detector read out, the other detectors were only included as ‘material’ in the beam or to provide a magnetic field, in the case of the the tracking system.
4.4.1 Recreating the beam conditions

To make the comparison between test beam and simulated data as accurate as possible, not only the detectors but also the particle ‘beam’ used must be modeled realistically in the simulations.

- **Particles and momentum:** It was assumed that the beam consisted of only the type of particle specified in the logbook for each run. This is a simplification since there is always some contamination present, as discussed further in section 4.4.2, but it was decided that after the preselection the final test beam particle samples could be considered as ‘pure’ (this is further discussed in section 4.5). Another assumption made was that the beam was mono-energetic, i.e. that the momentum-spread was negligible\(^4\).

- **Beam profile and impact point:** The most accurate approach would be to reconstruct the beam profile and the impact position and direction at the front face of the calorimeter using the tracking system. However, even though the tracking system was present at two of the test beams the tracking algorithm is still under development. This means that even if the beam profile can be measured in the tracker it is not possible to use that information to determine the impact point and direction of the beam at the calorimeter surface. It was therefore decided to only use the calorimeter’s reconstruction capabilities for the impact point and direction determination. This was an iterative process where the profile acquired from the test beam calorimeter data was implemented in the simulation, the beam was reconstructed by the calorimeter in the simulation and the result was compared to the experimental beam profile. After the necessary changes had been implemented the process was repeated. This continued until the differences were deemed negligible, and an example is shown in figure 4.13. This process had to be repeated for each test beam simulation and the beam profile was also found to differ for hadrons and electrons. It was also found by comparing the total deposited energy for different simulated beam profiles of electromagnetic showers that it was only necessary to use this level of accuracy when the beam hit close to a dead area. If the beam hit well within the ‘borders’ of one of the silicon detectors the differences for different beam profiles were only of the order of 1%. As soon as the beam was moved closer to one of the dead areas however the differences started to increase and reached levels of the order of 20% when the beam hit in the middle of the dead area between 4 adjacent silicon detectors.

4.4.2 Comparisons of the data sets

There were significant differences between variables reconstructed from test beam and simulated data. When the total deposited energy and the total number of hit strips for electrons were compared between simulated and test beam data a difference of 1-5% was seen for the energy deposit and an even larger discrepancy was

\(^4\)The momentum uncertainty is specified to 0.1% and 1% at the SPS and PS, respectively.
Figure 4.13: Impact point distributions reconstructed using the calorimeter information. The plots show the impact point distributions in x (top) and y (bottom) in millimeters (from the middle of the detector plane) for electrons with a momentum of 3 GeV/c from the July 2002 test beam. This beam profile was modeled using two overlapping Gaussian distributions. The solid line represents test beam data and the dashed line shows the simulated data.

seen for the number of strips hit. These discrepancies are illustrated in figure 4.14 that shows the total deposited energy and number of strips hit for electrons of momentum 200 GeV/c. The following sources have been considered to explain these discrepancies:

1. Misalignment or wrong profile of the simulated beam compared to the test beam. This could mean that the simulated beam is hitting closer to a ‘dead area’ or has the wrong profile, thus making it ‘spill over’ into a dead area. This would result in less strips hit and thus in a lower energy deposit.

This is ruled out by the careful modeling of the impact point and profile described in section 4.4.1 (see figure 4.13). This explanation is also disfavoured since the same magnitude of discrepancy is seen in all of the three different test beams. The lateral energy deposit (energy deposited in a plane as function of strip number) corresponds well between simulated and test beam beam data as shown in figure 4.15 for 200 GeV/c electrons. There are no significant differences close to any of the dead areas.

2. Different amount of material in the simulated beam line compared to the
Figure 4.14: Total energy deposited (left) and number of strips hit (right) for electrons of 200 GeV/c. The solid line represent test beam data and the dashed line shows the simulated data. The dotted line is the simulated data after correction.

test beam. Although the PAMELA detectors have been carefully modeled in the simulation there is a possibility that the effect of additional material that has been ‘neglected’ in the simulation (such as gas in the beam line Cherenkov detectors etc) is not negligible. This could cause either a decrease or increase in the amount of deposited energy. Any (significant) amounts of extra material in the beam could lead to a generation of showers before the calorimeter. This effect would lead to less energy deposited in the calorimeter. Conversely, a ‘premature’ showering might also lead to less leakage at the back end of the calorimeter and therefore a higher deposited energy inside the calorimeter volume. The behaviour displayed in figure 4.16 can be changed by adding approximately 0.25 X₀ of extra material in front of the calorimeter.

This was ruled out because the same effect was seen for all three different test beams and attempts to rectify this effect by introducing extra material in front of the calorimeter were not successful. Although it improved the agreement of the longitudinal profile in the early stages of the shower (up to and around the shower maximum) as well as in the later part of the longitudinal profile, it increased the total energy discrepancy even further.

3. **Corrections to the cross-talk** in the calorimeter preamplifiers and silicon detectors. The calorimeter data are affected by negative cross-talk between strips belonging to the same preamplifier. The resulting effect is to shift the energy zero points toward negative values. The shift depends on the total energy lost registered in the preamplifier and it is the same for all the strips (16) belonging to the preamplifier. A first-order correction was applied to the test beam data to account for this effect. The correction was of the
Figure 4.15: Energy deposit as function of strip number for electrons of 200 GeV/c momentum for planes 3 (top) and 21 (bottom) of the calorimeter’s X-view. The two dead areas are in these plots located between strip number 32-33 and between 64-65. The solid line is from test beam data and the dashed from simulations. This plot is an average made from $\sim 10^4$ events.

order of a few percent. However, for high energy electromagnetic showers this amounted to several mips of negative signals for each strips. Strips with no signal but which were sufficiently noisy were ‘over-compensated’ and exceeded the 0.7 mip threshold. The result was a small increase in the measured total deposited energy and a more significant one in the number of strips hit as seen in figure 4.14. The discrepancies seen in the longitudinal profile (see figure 4.16) can also be explained by this cross-talk correction, since the effects are expected to be most noticeable in regions of high energy losses in the calorimeter, e.g. before and up to the shower maximum.

The discrepancy is therefore attributed to cross-talk and the correction used to compensate it. The relative difference in the total energy deposited in the calorimeter as a function of incident electron energy was investigated and the result is shown in figure 4.17. This shows a systematic difference between the test beam and simulated data. The data points were fitted with a constant function and the value of this function was then used as a correction factor for the simulated data. The real effect is however more complex. This can be seen when the relative total energy difference is studied as a function of depth in the calorimeter (i.e. sampled at different degrees of calorimeter activity),
Figure 4.16: Longitudinal profile (energy deposited per plane) for electrons with 3 GeV/c momentum from the July 2002 test beam (solid line) and from simulated data (dashed line), for the X-view (top) and Y-view (bottom). This plot is an average made from ~6000 events.

see figure 4.18. However, correcting for a constant systematic effect in the whole calorimeter is an acceptable approximation. The result of applying the correction to the simulated 200 GeV/c electron data is shown by the dotted line in figure 4.14.

There were also other differences between data collected at the test beams and simulated data that, although they did not produce clearly discernible discrepancies in the calorimeter variables, could effect the final results obtained for the efficiency and contamination. These differences include contamination by other particle species, occurrence of multiple particle events and problems with simulation of hadronic interactions. The problem with contamination from other particle species is illustrated in figure 4.19. The left plot shows the situation at the July 2002 test beam, where mixed beams of electrons and pions were used, and the right plots shows one of the 150 GeV/c electron runs in the June 2002 test beam, where a hadronic component is present.

The mixed beam at the July 2002 test beam required a preprocessing to select the desired particle species. This was performed using a beam line Cherenkov detector in combination with the PAMELA TRD prototype. At other test beams this was not always possible because there was no other detector able to clean the beam data. This can mean that some of the events surviving the electron selection
Figure 4.17: The relative difference in deposited energy between test beam and simulated data for different momenta of the incident electron. The horizontal line is a first order fit to the points (i.e. $\Delta Q = P1$).

and that are therefore thought to be hadrons are in fact electrons. The result is an overestimation of the contamination. This kind of unwanted contamination has not been added in the simulated data samples. For some runs there are also problems with the occurrence of multiple particle events. The occurrence of these events has been attributed to the following reasons: 1-inefficiencies in the trigger system’s anticoincidence detector that allows particles from the beam halo to pass through in time with the trigger, 2-a very high rate of particles so another particle comes through inside the ‘trigger window’ (e.g. for the 25 ns bunch spacing used at the September 2003 test beam, see section 4.2), 3-particle interactions (by e.g. halo particles) upstream causing showers and thus multiple ‘simultaneous’ triggers. An example of a multiple particle event is shown in figure 4.20 and such events would easily be removed by using the tracking system. However, at the PS test beam no tracker was present and, since the tracking algorithm is still under development, it has not been possible to apply it to the SPS test beam data samples. This effect has also not been included in the simulated data.

The lack of agreement between real experiments and simulation using hadronic shower Monte Carlos (and even between different hadronic shower Monte Carlos) is a ‘well known’ problem and arises because of poor knowledge of cross sections for different processes involved in hadronic interactions. This can e.g. be seen in the results produced by many air-shower simulation studies and particle physics experiments [79]-[86]. These effects are usually most noticeable for high energy, high multiplicity hadronic interactions. This discrepancy can be seen in figure 4.21 that shows the maximum energy deposited in a strip from test beam data and
Figure 4.18: Relative difference in deposited energy between simulated and test beam electrons with a momentum of 3 GeV/c, for the X (top) and Y-view (bottom). The solid line is for uncorrected simulation data while the dashed is for corrected simulation data. The solid horizontal line represents the average value of the deviation from the fit in figure 4.17. The dashed horizontal line is the remaining average discrepancy (for the whole calorimeter) for this particular beam momentum after the correction. All planes, except 18 and 20 in the x-view and 1, 18 and 20 in the y-view, were read out. This plot is an average made from ~6000 events.

simulated data.

4.4.3 Statistics

The data taken at the test beams was divided into different ‘runs’. Each run had a specified momentum, particle type and beam position relative to the PAMELA reference system. In order to perform the analysis/selection described in the previous section, samples of particles had to be formed to study the effect of the selection. The sizes of each of the test beam samples were constrained by the fact that they had to fulfill certain requirements:

- Only particles of the same energy and type could be included in the sample.

- It had to be possible to form a sample with the same requirements as above but of the ‘opposite’ particle type (e.g. protons instead of electrons).
Figure 4.19: Contamination of the beam by unwanted particle species. **Left:** The composition of the mixed beam (with momentum 3 GeV/c) at the July 2002 test beam illustrated using the output of the TRD, which was one of the two detectors used to select the electron and pion samples for the analysis. The dashed line shows the electron component and the dotted line shows the pion component (selected by applying the calorimeter selection). **Right:** The total deposited energy in the calorimeter for what in the June 2002 test beam logbook was defined as an electron run. There is a contamination from hadrons (hatched area) in the electron sample (dashed line). Of the ~5000 events in this file about 40% are hadrons.

- The position of the beam in the PAMELA reference system had to be the same for all runs included in the sample.

These criteria, combined with the fact that in some instances there was substantial contamination from other particle types present, meant that the final statistics for some samples became low (<1·10⁴). The production of the simulated data samples was mainly restricted by processing-time issues and the goal was to at least equal or exceed the statistics in each of the test beam samples. The sizes of the electron, pion and proton samples used in the selection are presented in table 4.2.

4.5 Results and Conclusions

4.5.1 Results

In section 4.3.2 several types of variables along with some examples of criteria for selection of electromagnetic showers have been presented. These variables have then been combined in different ways and with different conditions (see appendix A.2), depending on the test beam and momentum used, and then applied to both the test beam and the cross-talk corrected simulated data. The final results for the selection contamination and efficiency are shown in figure 4.22.
Figure 4.20: A calorimeter view of a 'double' particle event. The two showers are clearly visible in both the X (top) and the Y-view (bottom). The particles enter at the bottom of the plots and travel upward. The sizes of the rectangles are proportional to the energy deposits in each strip. This event was taken from a mixed PS run with a momentum of 3 GeV/c.

In the top part of figure 4.22 the efficiency resulting from the final calorimeter selection is shown as a function of particle momentum. The filled circles represent test beam data and the open squares simulated data. During the analysis, one aim was to keep the electron efficiency at about 90% if possible. As seen in the figure, since the differences between experimental and simulated results are of the order of a few percent, the agreement can be regarded as rather good.

In the bottom part of figure 4.22 the resulting contamination as function of particle momentum is shown for both test beam data (filled circles) as well as for simulated data (open squares). The arrows mark the upper limits achieved when no events survived the selection. The first two data points (at 3 and 10 GeV/c) are for electron/pion separation and thus do not directly apply to the electron/proton study. This is because pions of 3 GeV/c momentum have \( \sim 1 \) GeV more of kinetic energy that can be deposited in the calorimeter, than protons of the same momentum. This should lead to a higher contamination (worse separation) for pions compared to protons. However, they can be used for comparison between simulation and test beam results and thus the open triangle and dashed arrow, which mark the results for simulated protons at 3 and 10 GeV/c respectively, should be representative. The two data points marked by filled stars are for comparisons of 150/200 GeV/c and 300/330 GeV/c (here placed at 175 and 325 GeV/c, respectively) electrons/protons. These points are of interest due to the finite resolution of the tracker and thus the increasing uncertainty on the momentum reconstruc-
Figure 4.21: Energy loss distribution in the silicon strip with maximum detected energy for pions of 3 GeV/c momentum (left) and protons of 200 GeV/c momentum (right). The solid line represents test beam data and the dashed line simulated data. The discrepancy is clearly seen to increase with the momentum of the incident particle.

Table 4.2: The number of events used for each test beam and momentum in the selection. The size of the simulated data samples are on the lines marked with ‘sim →’.

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<th>September 2003</th>
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<td>e−</td>
<td>π−</td>
<td>p</td>
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<tr>
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<td>11661</td>
<td>7634</td>
<td>-</td>
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<td></td>
<td>20000</td>
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<tr>
<td>10 sim →</td>
<td>0</td>
<td>11645</td>
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<td></td>
<td>10000</td>
<td>40000</td>
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<td>40 sim →</td>
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Figure 4.22. **TOP:** Efficiency for electrons of the final calorimeter selection as a function of particle momentum. The filled circles and open squares represent test beam and simulated data respectively. **BOTTOM:** Contamination in the final calorimeter selection as a function of particle momentum. The filled circles and open squares represent test beam and simulated data respectively, the open triangle is for 3 GeV/c simulated protons, the arrows mark upper limits (i.e. no events survived the selection) and the dashed arrow is for simulated protons at 10 GeV/c, and the filled stars are test beam results for comparisons of 150/200 GeV/c and 300/350 GeV/c electrons/protons (placed at 175 and 325 GeV/c, respectively). The open cross shows the result when the Neutron Detector is included (see section 4.5.2).

tion with increasing particle momenta. The points at 40 GeV/c and 150 GeV/c both come from the same test beam, i.e. September 2003. The results are noticeably worse in the agreement between simulated and ‘real’ data, if compared to
e.g., the results from the June 2002 test beam (data points at 150/200, 200 and 300/350 GeV/c). There is no reason to expect the contamination to be higher at 40 GeV/c than it was found to be at 3 and 10 GeV/c (for pions). The explanation for this discrepancy can most likely be found in the beam condition at the September 2003 test beam. As described in section 4.2 the beam had a 25 ns bunch structure resulting in high proton fluxes. This can in some cases result in more than one particle passing through the experiment coincidentally and therefore depositing more energy and having a different topology in the calorimeter than expected from a single interacting proton. This has indeed been discovered when the surviving events have been viewed on an event-by-event basis, using the ‘raw’ tracker data. All such events detectable ‘by eye’ have been removed from the final result but there is still the possibility that some events, where the individual tracks are too close together or one track is not clearly visible due to inefficiencies in the tracker, might have survived this scan. Another explanation can also be the presence of electrons in the proton beams. The fact that the beams are not 100% pure is illustrated in section 4.4.2 and section 4.5.2.

The proton contamination ranges from $\approx 1.4 \times 10^{-4}$ at 3 GeV/c to $\approx 2.2 \times 10^{-6}$ at 200 GeV/c. These contamination values give a rejection factor of $\approx 10^4$. As described in section 4.3 the proton to positron ratio increases from about $10^2$ at 1 GeV/c to about $5 \times 10^2$ at 10 GeV/c. This means that an additional factor of $10^3$-$10^3$ has to be supplied by other detectors, i.e. the TRD and the neutron detector. The TRD is expected to contribute with a factor of about 20 (see chapter 2). The neutron detector has been studied [87] using data from the September 2003 test beam and the results of that study are presented in section 4.5.2.

### 4.5.2 Neutron Detector

The large discrepancies seen between the results achieved with simulations and data from the September 2003 test beam (at 40 and 150 GeV/c) needs to be understood better. The only other detector present capable of distinguishing between electrons and hadrons was the Neutron Detector (ND), which was installed in PAMELA prior to the September 2003 test beam. However, only half of the ND was read out. The following study is from [87].

Figure 4.23 shows the number of neutrons counted by the ND for: a) 40 GeV/c electrons from test beam data; b) 40 GeV/c protons from test beam data (solid line) and simulation (dashed line). The GEANT simulation used does not however reproduce the photo-nuclear absorption and thus no neutrons are produced by electromagnetic showers induced by either incident electrons/positrons or by photons resulting from $\pi^0$ decay. The simulated distributions presented here have been rescaled by the efficiency in detecting neutrons, estimated as the factor that reproduces the experimental distribution of the number of neutrons for protons.

Most of the protons that are non-interacting in the calorimeter do not produce neutrons, so in order to select interacting protons a cut on the number of strips hit in the calorimeter greater than 100 have been used (average expected value at the test beam was about 33). The resulting distributions for the experimental (solid line) and simulated (dashed line) data are shown in the left part of figure 4.24. An
acceptable agreement can be noticed.

The right part of figure 4.24 shows the neutron distribution (solid line) of the 13 proton events surviving the calorimeter positron selection from test beam data at 40 GeV/c. An excess of events with zero neutron counts can be noted. However, this is not the case for the simulation as is shown by the dashed line which indicates the distribution for simulated 40 GeV/c protons selected with the same calorimeter selection. The difference between the two distributions can be explained by assuming that the test beam data were contaminated by positrons. In fact, the experimental distribution can be reconciled with the simulated distribution by assuming a contamination from positrons of about 36%. The result of removing the seven electron events is shown by the open cross in figure 4.22.

From figures 4.23 and 4.24 (right) it can be derived that the Neutron Detector (more precisely half of it) can select electrons/positrons with an experimental efficiency of 0.745 ± 0.012 and an experimental residual contamination of 0.18 ± 0.014 if using the estimated six proton events surviving the calorimeter selection, or a contamination of 0.14 ± 0.01 according to the simulation. The ND will thus be able to contribute to the rejection with at least a factor 5 at 40 GeV/c and the rejection factor will increase with energy.
4.5 Results and Conclusions

**Figure 4.24:** Distribution of the number of neutrons counted by the Neutron Detector. Left: 40 GeV/c protons interacting in the calorimeter for experimental data (solid line) and simulated data (dashed line). Right: 40 GeV/c protons selected as positrons by the calorimeter selection for experimental data (solid line) and simulated data (dashed line). From [87]

### 4.5.3 Conclusions

Considering the contamination of the test beam data and the overall agreement between simulation and test beam results the conclusion is that the simulation results are to be trusted. The absolute values of the contamination will decrease when the tracking system is used in conjunction with the calorimeter. This is mostly due to the more accurate determination of the particle’s impact point and direction through the calorimeter. Therefore these results should be treated as upper limits on the contamination by protons achieved when selecting positrons with the calorimeter in flight.

These results are comparable to the results obtained by the similar CAPRICE calorimeter [77]. Moreover, the good agreement between simulated and test beam data can validate a previous simulation study done on the full calorimeter in flight-like conditions [56].

The results of the proton contamination (and the effects of including the TRD and ND in the selection) on the positron measurements are further discussed in chapter 7.
Chapter 5

Pion Contamination in Antiproton Measurements

This chapter presents a simulation study aimed at determining the contamination in the antiproton sample caused by particle interactions in the dome covering the PAMELA experiment and also in the upper parts of the experimental payload.

5.1 Introduction

5.1.1 Motivation

As mentioned earlier (see chapters 1 and 3) antiprotons could potentially be used as a tool for detecting new physics such as supersymmetric dark matter. However, besides the large uncertainties present in the estimation of the secondary antiproton production and propagation, the small number of antiprotons expected due to the combined effect of the low antiproton flux and the small experimental aperture make it important to better understand also other sources of uncertainty. One such source is the contamination of the antiproton sample by false antiproton events, i.e. particle events which through interactions are misinterpreted as being real (cosmic ray) antiprotons. The particles that ‘interaction-wise’ most resembles antiprotons are negatively charged pions ($\pi^-$) and muons ($\mu^-$). In balloon-borne experiments there is always a significant background of muons and also a smaller background of pions. The muon background is due to the decay of pions produced in cosmic ray interactions with the atmospheric nuclei above the experiment, while the pion background is due to those pions produced too close to (or in) the experiment to have time to decay. Since PAMELA is a satellite-borne experiment pions can only be produced by particle interactions in the detectors or mechanical structures of PAMELA itself (see figure 5.1), and will therefore not have time to decay to into muons before entering the experiment.
Figure 5.1: Illustrations of possible interactions in/around the PAMELA experiment generating ‘false’ antiproton events. As shown in the left drawing a particle hitting the the top dome with a grazing incidence could produce events impossible to distinguish from real antiproton events. The middle and right drawings illustrate cases where the interaction occur inside the experiment and therefore should be possible to reject, using the information from the different subdetectors.

5.1.2 Description

In this simulation, protons have been directed toward PAMELA at different angles from above and an antiproton selection has been applied aimed at selecting down-going, singly charged negative particles. The remaining selected events (i.e.: falsely identified antiprotons) making up the contamination is then compared to the expected (energy binned) number of secondary antiproton events.

The selection of antiprotons from ‘flight’ data will be made by imposing a set of requirements on the PAMELA subdetectors. To ‘imitate’ a real antiproton (\(\bar{p}\)) event the following conditions must be met:

- enough energy must be deposited coincidentally in the different layers of the Time-of-Flight (ToF) system to trigger the experiment.

- it must be possible to identify a single unambiguous track in the magnetic spectrometer (SPE)

- the (energy) signature in the transition radiation detector (TRD) should not be consistent with an electron

- the (spatial) signature in the TRD must be consistent with a single, non-interacting particle

- the calorimeter (CALO) signal should be either that of a non-interacting particle or show the characteristics of a hadronic interaction

- the time-of-flight behaviour should correspond to a downward moving particle.

These demands naturally limit the number of ways in which the false antiproton events might be produced, since it is unlikely that events where the multiple par-
5.2 Simulation Study

The simulation study was performed using a modified version of the simulation tool GPAMELA. The modifications, particle types and energies are described in the following sections.

5.2.1 The Simulation Model

The model used in the study is shown in figure 5.2, where the simulated PAMELA experiment and its pressurized container, consisting of a dome plus a cylindrical shell of 1 mm thick aluminum, are detailed.

Figure 5.2: The GPAMELA simulation model includes the transition radiation detector (TRD), the Time of Flight system consisting of 3 sets of scintillators: S1, S2 and S3, the magnetic spectrometer (SPE), the calorimeter (CALO), the bottom scintillator S4 and the anticoincidence system: CAT and CAS. Also present are some mechanical structures such as the dome.

Considering the level of complexity achieved once the PAMELA experiment is mounted on the satellite, a number of simplifying assumptions must be made. These simplifications must however be well justified in order not to diminish the
functional or geometrical accuracy and thereby the reliability of the whole study. These simplifications and their justifications are listed below:

- **Removing the satellite.** As seen in section 5.1.2 the ‘fake’ antiproton events most likely to survive an antiproton selection are expected to be down-going, without too much additional activity and thus come from above or interact above the experiment (for example in the dome or above the spectrometer). This makes it possible in a first order approximation to remove the satellite from the simulation model. This is advantageous since the ‘processing time’ is reduced.

- **Modifying the spectrometer.** At the start it was decided to remove the magnetic material of the spectrometer (only keeping the magnetic field and silicon detector planes) in order to save processing time. This was motivated from the fact that real antiproton events will be selected using a demand of clean, unambiguous tracks in the spectrometer, whereas events with particle interactions in the magnet wall are not expected to be ‘clean’. This condition was later changed as it turned out that it introduced uncertainties when using the side anticounters, CAS (see section 5.3.3).

- **Excluding the calorimeter.** A decision made to save processing time but that was later revised, was to exclude the calorimeter since it can only be used to separate pions from antiprotons in the case of annihilations. The reason this decision changed was that use of the anticoincidence (AC) system in the selection requires that possible backscattering from the calorimeter must be taken into account.

In GPAMELA there are few ‘realistic’ support structures present and thus external containers or supports for some of the different subdetectors are missing or are much simplified. For those structures that are outside the acceptance of the experiment this was not considered a problem. However there were also a few additions made aimed at reproducing a more realistic ‘interaction environment’, i.e. additions of materials in or near the acceptance. This included e.g. a titanium-alloy top plate between the TRD and the spectrometer and protective Avion ToF system boxes, complete with foam padding and ‘wrapping’ materials for the scintillators.

### 5.2.2 Particles

Since cosmic rays consist of ~90% protons (see chapter 1) and protons\(^1\) are the main cause of the pion production in the payload this was the only particle species considered in this study. The protons were generated on a square surface (1.5×1.5 m\(^2\)) located just above the aluminum dome covering PAMELA and had a \(\cos^2 \theta\) dependence to simulate an isotropic flux on a flat square. The proton energies were generated according to a spectrum \(J_p(E)\) (see figure 5.3) as a function of kinetic energy.

---

\(^1\)Helium can also be expected to contribute significantly, but have been excluded from this study due to lack of a sufficiently good heavy nuclei Monte Carlo.
energy $E$, which gives the number of particles per square meter, steradian, GeV and second (see [88] and [89]):

$$J_p(E) = A(E + Be^{-cE})^{-d}$$

(A=$12600$ GeV$^{1.7425} / (m^2 \text{ sr s}), B=1.6111$ GeV, $c=0.33884$ GeV$^{-1}$ and $d=2.7425$).

![Graph showing proton spectrum $J_p(E)$](image)

**Figure 5.3**: The proton spectrum $J_p(E)$ expressed in particles per square meter, GeV, steradian and second as a function of kinetic energy (equation 5.1).

The momenta of the generated particles varied between 1 GeV/c and 220 GeV/c which corresponds to kinetic energies between 0.433 GeV and 219 GeV. The lower limit is set considering the threshold for producing pions. The upper bound is a consequence of computing-time and particle abundance issues.

The number of protons ($N_p$) hitting an area corresponding to the generation surface during one day of PAMELA operation in orbit can be calculated using the following formula:

$$N_p = G_p T \int_{E/c_{air}}^{E_{max}} J_p(E) dE$$

where $G_p$ is the geometrical factor ($G_p=\pi \times 1.5 \times 1.5$ m$^2$ sr) of the generation surface, $T$ is the number of seconds in one day and $J_p(E)$ is the proton spectrum shown in equation 5.1. Integrating over the energy range specified above (0.433 → 219 GeV),
for one day was calculated to be $2.2 \times 10^9$. This number was used as a normalization factor when calculating what time will be needed in orbit to equal the total amount of generated protons. This must be known in order to enable a comparison between the remaining events (the contamination) after the selection and the number of antiproton events expected from the same time in orbit. The number $N_p$ is only an estimate since PAMELA’s orbit part of the time passes through areas where the geomagnetic (momentum) cut-off is higher than 1 GeV $/c$, but this is however also true for the expected number of antiprotons. A more detailed study of the relation between the incoming and measured flux is conducted in chapter 6.

In this study a beam of negative muons (5 GeV $/c$ momentum) with cross section $2 \times 2$ cm$^2$ is directed into the experiment (without the done) as a ‘reference’ for minimum ionizing particle (mip) behaviour mainly for the ToF system. This is necessary in order to be able to separate between events where single or multiple particles passes through a single ToF detector. The reference sample is also used to estimate the resulting efficiency for ‘good’ events after cuts have been placed on the various detectors, which is done in order to avoid too strict cuts and thus getting a too low efficiency for ‘true’ antiproton events.

5.2.3 Data

The large number of events needed for this study (due to the size of the generation surface) meant that a rough pre-selection of interesting events had to be performed to reduce the amount of data saved. The pre-selection required events to contain a negatively charged particle (\(\pi^-, \mu^-\) or \(K^-\)) produced above the spectrometer and hitting the bottom ToF (S3) detector. This not only removes the non-interesting and numerous ‘interaction-free’ proton events but it also ensures that there is at least one negative particle traversing the spectrometer that could be misinterpreted as an antiproton.

The data from the simulation runs were the hit coordinates from the different detector elements, the energy deposits registered in them and the particle types producing the hits in the different sub-detectors. No contributions from ‘noise’ in the detectors were added to the data.

As mentioned in section 5.2.1 there exists two sets of data, one without magnetic material and calorimeter and one set with those included. The analysis was performed separately for the two sets of data since there is a difference in the treatment of the conditions on the CAS detectors and the results of the two analysis are only combined after all cuts have been applied to achieve the final result.

5.3 Selections

The goal was to find selection criteria that were not only suitable for detecting antiprotons but that at the same time achieved the lowest possible contamination, i.e. having as few surviving ‘false’ antiproton events as possible. The resulting efficiency for good events must also not be too low since antiprotons have a very low flux. In the following sections the restrictions put on each of the different
detector systems are described in more detail.

5.3.1 Time of Flight $\frac{dE}{dx}$

The primary function of the ToF system is to provide the level 1 trigger signal for the whole PAMELA experiment (see chapter 2). This trigger signal tells the DAQ system when to read out the different subdetectors and requires that sufficient energy has been deposited in each layer of the ToF system. In this study the level 1 trigger signal is given when an event deposits at least one quarter of a mip in each of the ToF layers. Due to ‘statistical’ variations in the energy deposit the energy deposited by a mip particle will vary from the mean value (1.6 MeV/cm). The low energy value chosen for the level 1 trigger is set to ensure that the efficiency for ‘good’ events is close to 100%. In the analysis of the flight data the time ordering of the signals from the ToF system will be used to reject up-going (albedo) particles, but in this study this was not necessary.

![Image]

**Figure 5.4:** The $xy$-distribution of the particle vertexes on the generation surface for events giving a level 1 trigger. The projected PAMELA acceptance occupies an area of $25.7 \times 20.9$ cm$^2$. Even though the vast majority of events are in the center of the generation surface, there are still some vertexes along the outer edges. However, this must be weighed against the processing time that is strongly dependent on the size of the generation surface. The high-energy events are mainly concentrated within the projected acceptance.

Considering that even a low number of misidentified events can cause a substan-
tial contamination, and that such events can originate from outside the acceptance with a large polar angle, the generation surface should be made as large as possible. However, the number of events generated in a certain amount of time scales linearly with the size of the generation surface and the actual size is therefore limited by the processing time. Figure 5.4 shows the distribution of the generation vertexes in the xy-plane for all events causing a level 1 trigger.

In the events where a proton interaction occurs there is the possibility that more than one down-going particle will be produced. If the number of down-going particles hitting the ToF scintillators is greater than one these events may be identified and rejected. For the uppermost layer (S11) the cuts were set by comparing the energy deposit distribution from the reference sample of single minimum ionizing particles with the expected (simulated) distribution from two minimum ionizing particles simultaneously passing through a ToF scintillator (see figure 5.5). The energy ‘window’ thus derived is a compromise between possible contamination from multiple particle events and efficiency for single particle events. The condition is an attempt to reject events where an interaction has taken place in the dome and

![Figure 5.5: Energy deposit distributions (in MeV) in the S11 ToF layer, from single particle (unshaded) and double particle (shaded) events. The arrows mark the cuts chosen to select single particle events. These cuts were selected as the compromise between a low contamination (0.12%) and a reasonable efficiency (94%) that gave the highest efficiency-to-contamination ratio.](image-url)
where all but one of the secondary particles exits the experiment before reaching S2. These events might otherwise be very difficult to reject unless some of the secondaries traverse the TRD volume.

For the lower layers (i.e. S12, S21 and S22, see figures 2.4 & 2.5) that are placed just below another scintillator (or the TRD in case of S21) a different method was used since the production of $\delta$-electrons increases the tail of the deposited energy distributions, resulting in a too low efficiency for the reference sample if the same strict cuts were applied also to those layers. Instead, the tracker was used to select high multiplicity events (see section 5.3.2) among the level 1 trigger events extracted from the proton sample. The resulting energy distributions (see figure 5.6) in the scintillators from these events were then compared with equally sized samples of muons to determine where the cuts should be placed to achieve the best compromise between low contamination and good efficiency. The majority of the events selected by the tracker as being multiple particle events actually interact below S12 and the effect is most clearly seen in S22 (figure 5.6, bottom right). For S3 only a lower limit on the energy deposit was set (i.e. 0.25 mip) due to the possibility of back-scattering from the calorimeter [42].

To further reduce the possibility of multiple particle events it was required that only one scintillator paddle in each of the S1 & S2 ToF layers should register a hit. The resulting efficiency achieved after applying all the ToF cuts to the reference muon sample was 84%.

### 5.3.2 Tracking

The purpose of the magnetic spectrometer is to determine the rigidity (momentum/charge) and sign of charge of traversing particles (see chapter 2). The tracker will also be used to ‘point’ to other detectors, which helps when determining if a particle has traversed the experiment cleanly. The good spatial resolution will make it possible to detect events with more than one track going through the spectrometer. It will also allow to separately reconstruct the tracks for double particle events if the spatial separation of the tracks is sufficiently large.

The cuts placed on the tracking system was in this particular study aimed at removing obvious multiple particle events (see figure 5.7) and events where there appeared to be no real track at all (see figure 5.8). This possibility to actively select double/multiple particle events was used when the cuts on the energy deposits in Time of Flight system was investigated (see section 5.3.1).

The tracking could have been used to reject further events by putting stricter conditions on the particle’s track in the spectrometer. But since the flight tracking algorithm is still under development this more conservative approach was taken. Without the tracking algorithm it is difficult to say how the cuts devised from the simulation output would affect the real efficiency for true antiproton events.

### 5.3.3 Anticoincidence

The intended function of the anticoincidence (AC) system is to reject ‘out-of-acceptance’ events coming from above as well as events where a particle hits the
Figure 5.6: Energy deposit distributions for level 1 triggers (in mip) for single particle events (shaded) from the muon reference sample and multiple particle events (unshaded) from the proton sample. The vertical lines mark the selected cuts for: S11 (top left), S12 (top right), S21 (bottom left) and S22 (bottom right). The distributions for S12-S22 are shown with the S11 cut already applied. A broadening of the tail can be seen as expected when going from S12 to S22 for both the single and the multiple particle distributions.

experiments from the side while another traverses it. This makes the AC system a good tool for rejecting a significant part of the false antiproton events.

As mentioned in section 5.2.3 there were two sets of data produced. In the data set that lacks the magnetic material and the calorimeter an approximation was used to decide which events would give a signal in the side AC detectors (CAS). In the other set the signal from the AC detectors could be used 'directly' with help of a
Figure 5.7: Example of a multiple (double) track event in the spectrometer seen in both the x-view (left) and y-view (right). The points marked with + belong to hits in the ToF system, * to the TRD and o to the spectrometer. The horizontal lines represent the position of the tracker planes and the vertical lines show the inner walls of the magnet cavity.

condition on the calorimeter to account for backscattering, foreseen to be used in a 2nd level trigger [62]).

- CAT: The top anticounter covers the top of the spectrometer outside the acceptance (see chapter 2) and secondaries from interactions occurring above the S2 counter can be registered in this detector. The condition for a good event in this detector is simply no signal above threshold (0.5 mip). The condition put on this detector is in principle the same for the two data sets since it is not sensitive to backscattering in the same way as the CAS detectors [42].

- CAS I: In the first data set the lack of magnetic material makes it necessary to use an approximative method to be able to place cuts on this detector. An estimation is made of the minimum momentum a particle must have in order to reach CAS. Events were rejected when CAS was hit by particles with momenta exceeding this lower limit. The limit was determined by calculating how much energy a particle could lose when passing through the magnetic
Figure 5.8: Example of an event in the spectrometer where there is no real track. The points marked with + belong to the ToF system, * to the TRD and o to the spectrometer. This particular event belong to the data set that lacks the magnetic material and the particle traversing the TRD has interacted with the materials in the side anticounter (CAS) before entering the spectrometer.

material. This was done using the relation:

$$E_{\text{min}} = L \cdot \rho \frac{dE}{dx}$$  (5.3)

by using the longest plausible distance a particle could have to travel through the material (L ~ 50 cm) to reach one of the CAS detectors and assuming that the energy loss ($\frac{dE}{dx} = 1.451$ MeV/(g cm$^{-2}$)) and density ($\rho = 7.87$ g/cm$^3$) is the same as for pure iron. Once this energy was determined it was then converted to particle momentum (assuming the particle to be a pion) and resulted in a limit of ~0.6 GeV/c.

- CAS II: In the case of the second data set the energy deposit in the CAS detectors could have been used directly due to the presence of magnetic material. However, since some ‘good’ events also give rise to signals in the CAS detectors due to backscattering from the calorimeter it was necessary to use the condition from the 2nd level trigger instead. The form of the new AC
5.4 Results

condition is based on the fact that the good events which give rise to a signal in the AC detectors due to backscattering, in general also cause a lot of activity in the calorimeter itself (unlike a ‘true’ AC event). The revised AC signal (i.e. signaling when an event should be rejected) can be expressed as:

\[ AC_{\text{new}} = AC \& \{ \text{CALO} \leq \text{threshold} \} \]  \hspace{1cm} (5.4)

where the calorimeter ‘threshold’ is based on the number of strips hit in each of the four views (even and odd X- and Y-views). This is further described in [62].

5.3.4 TRD

The purpose of the transition radiation detector (see chapter 2) is to discriminate between $e^\pm$ and heavier particles. It can also be used as a simple tracking device in one ‘view’ (the X-view). This particular feature can be useful when trying to reject events where interactions have occurred, especially since the TRD itself occasionally acts as a source of secondary particle production.

The final algorithms for reconstructing tracks and extracting physical parameters from the TRD are still under development and therefore a more conservative approach was taken. In this study the TRD information was only included at the last stages of the analysis, on an event-by-event basis, to reject events where signs of interactions are seen in the TRD. Some examples of this are shown in section 5.4.2.

5.4 Results

With all the cuts described above applied to the $4.4 \times 10^9$ event proton sample, corresponding to 2 days of operation in flight, 352 events survive (see table 5.1) and applying the same cuts to the reference sample the resulting efficiency is 83.4\% (this is further discussed in section 5.6). The fact that the number of events surviving the cuts for both samples are very similar indicate that the simplifying assumptions made, when producing sample A, were valid. The momentum distribution in the spectrometer of the remaining events from the proton sample is shown in figure 5.9.

The surviving events mostly lie under 1 GeV/c. This is because these secondary particles have been produced along with many others and often at large angles from the direction of the original proton (since most of the other secondaries have left the experiment undetected).

As was done in section 5.3.1 (see figure 5.4) the xy-distribution of the original particle generation vertexes are plotted in the left part of figure 5.10 to study the adequacy of the generation surface’s size, although this time with all cuts applied. Even though the majority of the surviving events are concentrated in the centre of the surface there are some events generated further out toward the edges. The right part of figure 5.10 shows the polar angle distribution of the original protons and although a majority of the events shown in the plot have angles larger than $\sim 0.4$ radians there are some events with smaller angles. The conclusion of this is that it would not be safe to either diminish the size of the generation surface or
Table 5.1: Events remaining of the original samples (START) after applying the cuts described in section 5.3. For each cut applied the number of surviving events from sample A and B are given as A/B (without and with magnetic material and calorimeter, respectively). The cuts are: PRE-SEL - the pre-selection that required that a negative particle hits S3, LVL1 - the level 1 trigger condition, NPAD - one paddle hit in each layer of the S1 and S2 counters, dE/dx - restrictions on the energy deposit in the ToF layers, AC - conditions on the AC detectors, SPE - using the tracker information to remove double tracks and non-tracks.

<table>
<thead>
<tr>
<th>CUTS</th>
<th>Number of events (A / B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>START</td>
<td>2.2 x 10^6 / 2.2 x 10^6</td>
</tr>
<tr>
<td>PRE-SEL</td>
<td>106087 / 40903</td>
</tr>
<tr>
<td>LVL1</td>
<td>17244 / 14262</td>
</tr>
<tr>
<td>NPAD</td>
<td>5539 / 4061</td>
</tr>
<tr>
<td>dE/dx</td>
<td>959 / 690</td>
</tr>
<tr>
<td>AC</td>
<td>213 / 214</td>
</tr>
<tr>
<td>SPE</td>
<td>352 (170 / 182)</td>
</tr>
</tbody>
</table>

put restrictions on the polar angle in order to reduce the processing time when generating more statistics.

5.4.1 Time-of-Flight

The time of flight (ToF) system makes it possible to separate pions from antiprotons at low momenta. The timing information from the ToF system can be used to measure the flight time of the particles traversing the experiment (see chapter 2). The flight time \( t \) (in ps) can be expressed as a function of particle mass and momentum (NB, \( c=1 \)) as:

\[
    t = \frac{3333}{p} \cdot \sqrt{p^2 + m^2} \cdot L
\]

where \( m \) is the particle mass in GeV, \( p \) is the momentum in GeV and \( L \) is the flight path in meter. This function is plotted for (anti)protons (\( m_p=0.9383 \) GeV) and pions (\( m_{\pi^\pm}=0.1396 \) GeV) with \( L=0.81 \) m in the left plot of figure 5.11. This shows that the ToF system can be used for particle identification/separation at low momenta. The momentum below which the ToF system is able to distinguish between pions and antiprotons is derived by using the Time-of-Flight difference \( \Delta t \):

\[
    \Delta t = t_p - t_{\pi} = \frac{3333}{p} \cdot \left( \sqrt{p^2 + m_p^2} - \sqrt{p^2 + m_{\pi^\pm}^2} \right) \cdot L
\]

and assuming that it corresponds to at least 4-5 times the ToF system time resolution, which has been set to \( \sim 1.50 \) ps to be conservative, as shown in the right plot of figure 5.11. This gives a momentum ‘threshold’ of \( p_{T,\text{ToF}}=1.16-1.30 \) GeV/c which is marked with arrows in figure 5.9. As can be seen this momentum cut rejects all but a few events (13-8) from the sample in figure 5.9.
Figure 5.9: Momentum distribution in the tracker of the surviving 352 events after all cuts have been applied. The arrows mark the momentum threshold for (anti)proton-pion separation calculated in section 5.4.1.

5.4.2 Remaining events

The 13 events remaining after the ToF momentum cut has been taken into account are categorized in table 5.2 after being inspected on an event-by-event basis in the spectrometer and TRD. Events that show clear signs of interactions or multiple particles in the TRD tracking ($\times$) view have been marked in the TRD column. Events that would be rejected by a track reconstruction algorithm, i.e. tracks pointing into the magnet wall or events that are not consistent with a single particle traversing the spectrometer, have been marked in the TRK column. Figures 5.12 and 5.13 show examples of events that have been marked with a ‘$\gamma$’ in the TRK and TRD categories, respectively. Both these events belong to sample ‘A’, which is why there is no calorimeter information included in the figures. Figure 5.12 displays an event with a spectrometer momentum of 1.22 GeV/$c$. This is in-between the two ToF cut levels and might therefore be possible to reject using the flight time information. The importance of being able to identify tracks within the TRD volume is also clear since there is a ‘multiple particle’ signature x-view (‘tracking’ view) in that detector. The track also points into the magnet wall and would therefore most likely be rejected by a track reconstruction algorithm. With all
Figure 5.10: Left: The x-y-distribution of the generation vertexes of the original protons for the 352 particles that survived all the cuts. Although they are mostly concentrated toward the middle there are some further out. The rectangle shows the PAMELA acceptance projected onto the 1.5×1.5 m² generation surface. Right: The polar angle distribution for the same events as in the left plot. The shaded events are those that survived the time-of-flight cuts described in section 5.4.1.

Figure 5.11: Left: Flight time (in ns) for (anti)protons and pions. Also shown are the 2σ and 3σ limits derived by setting σ equal to the ToF system resolution (~150 ps). Right: Flight time difference (in ns) for (anti)protons and pions. Also shown are the momentum thresholds corresponding to a 4-5σ separation.
Table 5.2: The remaining events after the (5σ) ToF momentum threshold has been taken into account. The events are labeled according to their momenta and are marked with a ‘√’ in the TRK (spectrometer signature) and TRD (TRD signature/energy deposit) categories if they can be rejected by those detectors. Events below a momentum of 1.3 GeV/c also have an increased probability to be rejected due to the time-of-flight information. In the column labeled: SAMPLE it is indicated if the events derive from sample A or B (see table 5.1). The events which are deemed difficult to reject have been shaded. However, the event marked with * have an increased probability to be rejected due to a hit in the AC system.

<table>
<thead>
<tr>
<th>Momentum GeV/c</th>
<th>TRK</th>
<th>TRD</th>
<th>SAMPLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.22</td>
<td>√</td>
<td>√</td>
<td>A</td>
</tr>
<tr>
<td>1.23</td>
<td>-</td>
<td>√</td>
<td>A</td>
</tr>
<tr>
<td>1.27</td>
<td>-</td>
<td>√</td>
<td>B</td>
</tr>
<tr>
<td>1.29</td>
<td>-</td>
<td>√</td>
<td>A</td>
</tr>
<tr>
<td>1.30</td>
<td>-</td>
<td>-</td>
<td>B</td>
</tr>
<tr>
<td>1.33</td>
<td>√</td>
<td>-</td>
<td>B</td>
</tr>
<tr>
<td>1.39</td>
<td>√</td>
<td>-</td>
<td>A</td>
</tr>
<tr>
<td>1.58</td>
<td>-</td>
<td>√</td>
<td>B</td>
</tr>
<tr>
<td>1.82</td>
<td>√</td>
<td>√</td>
<td>B</td>
</tr>
<tr>
<td>2.11</td>
<td>√</td>
<td>√</td>
<td>A</td>
</tr>
<tr>
<td>3.31</td>
<td>√</td>
<td>-</td>
<td>B</td>
</tr>
<tr>
<td>3.44 *</td>
<td>-</td>
<td>-</td>
<td>A *</td>
</tr>
<tr>
<td>3.79</td>
<td>-</td>
<td>-</td>
<td>B</td>
</tr>
</tbody>
</table>

these factors combined the event is therefore considered as having a high probability of being possible to reject. The event shown in figure 5.13 has a spectrometer momentum of 1.29 GeV/c. This event is between the two ToF cut levels and might therefore be possible to reject. The multiple particle signature in the TRD x-view is very pronounced and this allows to reject the event with this detector in the selection.

Figures 5.14-5.16 display the events that are shaded in table 5.2 and that are considered as definitely not possible to reject (with the exception of the event marked with (*), see below and figure 5.15). The first of these events has a spectrometer momentum of 1.30 GeV/c and is shown in figure 5.14. It has too high momentum to be distinguished from an antiproton by the ToF timing information and is compatible with a singly charged track in all detectors. In figure 5.15 the event (from sample ‘A’) has a spectrometer momentum of 3.44 GeV/c (considering the 5 lower hits). Due to the lack of a fitting routine it is difficult to assess whether this event would be reconstructed as pointing into the wall of the magnet cavity and thus rejected, or if the top hit in the spectrometer would be taken into account and the track thus reconstructed with a lower momentum due to its larger bending. The CAS detector registers a hit of a negative pion with momentum 0.59 GeV/c
at a z position of ~64 cm (i.e. level with the second tracker plane). Considering the short distance the pion would have to travel through the magnetic material (0.6 GeV/c was calculated for a distance of ~50 cm) to reach the impact point with the CAS detector it is very probable that this particle would traverse the magnetic material and therefore be rejected. By also combining all the other available information (i.e. the track in the spectrometer, the positions of the hits in the ToF system as well as the track in the TRD pointing into the magnet) the probability is increased that this event would be rejected, which is why it is marked with a * in table 5.2. The last event in table 5.2 is shown in figure 5.16 and has a spectrometer momentum of 3.79 GeV/c. The event looks very ‘clean’ with a substantial hadronic shower in the calorimeter and is impossible to distinguish from a real antiproton event.

5.5 Conclusion

Since the aim of the study was to estimate the contamination in the antiproton sample, the number of expected antiprotons in 2 days (2\times N_p) must be calculated. This number was estimated in the same way as the expected number of protons (N_p) but using the acceptance of PAMELA and a spectrum of secondary antiprotons [90]. Calculating for the whole PAMELA energy range (80 MeV-190 GeV),
5.5 Conclusion

Figure 5.13: View of an event with a spectrometer momentum of 1.29 GeV/c. There is a clear multi-particle signature in the TRD x-view. From sample ‘A’.

and assuming that the efficiency achieved for the muon reference sample also applies to antiprotons, gives a total expectancy of \(\sim 52.1\) antiprotons in two days. Of these 0.76 are expected below the ToF momentum threshold of 1.16 GeV/c, which corresponds to a kinetic energy of 0.55 GeV for antiprotons.

The final contamination is dictated by the two surviving events shown in figures 5.14 and 5.16, corresponding to antiproton kinetic energies of 0.67 GeV and 2.97 GeV, respectively. The events were placed in two connecting kinetic energy bins: 0.55-2.65 GeV and 2.65-5 GeV. The sizes of the bins were chosen so that they contained the same number of expected antiprotons. The resulting contamination is: \((7.8^{+18.6}_{-6.5})\)% in each bin. Since there were no events with higher momenta produced that survived all the selection criteria, there is no possibility to make a quantitative estimate of the contribution from the pion contamination above a kinetic energy of 5 GeV. However, a qualitative estimation can be made:

1. high momenta of the produced pions requires higher momenta of the original protons,
2. higher proton momenta lead to increased number of high-energy pions produced,
3. the higher the energy of the produced pions the more collimated they are along the direction of motion of the original proton,
4. this increases the probability that more than one particle from the interaction traverse the experiment and therefore also the probability that the event will
Figure 5.14: View of a π⁻ event with a spectrometer momentum of 1.30 GeV/c. The event belongs to the data sample ‘B’ that includes the calorimeter and the hits belonging to that detector are marked with ‘x’. This event is not possible to distinguish from an antiproton event by any means.

be rejected by the antiproton selection.

This can be expected to decrease the probability of misidentifying a pion as an antiproton event, with increasing pion momentum. If also the effects of the energy dependence of the proton flux is included, the probability decreases even further. However, to be able to draw any definite conclusions about the expected contamination at higher energies, more statistics is needed. The effects of the pion contamination on the antiproton measurements are further discussed in chapter 7.

5.6 Outlook

The following points could be used to extend this study in the future:

- The statistics should be improved since more generated events will diminish the statistical errors and possibly also allow to estimate the contamination at higher energies. The statistics in this study was limited by the amount of processing time, which corresponded to ~5 months of continuous running on various Linux PC clusters.

- A realistic track fitting routine is needed in order to get a more accurate picture of the rejection capacity of the spectrometer and overall efficiency.
5.6 Outlook

Figure 5.15: The hits marked on the 5 lower planes belong to a negative pion with a momentum of 3.44 GeV/c. Not shown here is a 0.59 GeV/c negative pion hitting a CAS detector (the one located just to the right of the spectrometer in the x-view) on level with the second tracker plane from the top (z~64 cm). From sample ‘A’.

This will also make it possible to loosen the cuts on the ToF dE/dx by instead putting restrictions on the track in the spectrometer, and/or use the reconstructed momentum to decide the expected energy deposit in the ToF counters. This will increase the efficiency for ‘good’ antiproton events compared to the more conservative value of the efficiency used here.

- Events such as the ones shown in figures 5.12 & 5.15 illustrate the valuable role which the TRD can play in rejecting interacting protons. The tracking capability of the TRD needs to be understood more clearly. This might serve to increase the overall efficiency for ‘good’ events in a similar way as for the spectrometer.

- The simulation should also be extended to include particles hitting the TRD from the side and possibly also at a later stage the effects of including the satellite and contributions from albedo particles.
Figure 5.16: View of a $\pi^-$ event with a spectrometer momentum of 3.79 GeV/c. Except for the extra hit in the top TRK detector plane there are no indications of any interactions signaling a false antiproton event. From sample ‘B’.
Chapter 6

Gathering Power and Expected Statistics

Besides the uncertainties caused by contamination (as described in the two previous chapters), the statistical error also contributes to the overall uncertainty when reconstructing the energy spectra for antiprotons and positrons. The aim of this chapter is to make a detailed study of the expected number of antiprotons and positrons during the PAMELA mission, thus making it possible to estimate the statistical uncertainty of the final results.

Before proceeding it is convenient to introduce some definitions generic to this chapter:

- The **geometrical factor** is determined only by the geometry of the experiment. In PAMELA this is determined by the dimension of the magnetic cavity. The geometrical factor for PAMELA is 20.5 cm$^2$sr (see section 6.2).

- The **acceptance** also takes into account the loss of low-energy charged particles caused by the magnetic field of the spectrometer and the loss of positrons and antiprotons due to interactions in the material above the spectrometer.

- The **gathering power** is the factor of proportionality relating the final counting rate to the incident (interplanetary) flux of particles. It is dependent both on the acceptance of the experiment and the effects of the geomagnetic field.

The number of detected particles is limited by several factors (some of which must be determined by simulations, such as the acceptance) which will be further investigated in this chapter:

1. The magnetic field of the Earth sets a lower limit on the momentum of charged particles and effects the total number of low-energy particles reaching the experiment.

2. The geometry of the spectrometer sets an upper limit to the value of the geometrical factor, while the materials above the spectrometer and the mag-
getic field inside the spectrometer introduces an energy dependence to the acceptance.

3. The spatial resolution of the spectrometer sets an upper limit to the energies which can be measured.

The first point ‘modifies’ the flux of particles reaching the experiment and together with the two last points determine the total gathering power of the whole experiment. These factors are each described in more detail in the following sections.

6.1 Geomagnetic cut-off and orbit

The magnetic field of the Earth can be approximated as a dipole field [91] with the axis displaced about 11 degrees with respect to the axis of rotation. Low-energy particles are prevented from reaching the Earth due to the deflection caused by the geomagnetic field. The Earth’s magnetic field is distorted by the magnetic field frozen into the solar wind (see top part of figure 6.1) and a region is created around the Earth called the magnetosphere. Due to the interaction with the solar wind, the magnetic field of the Earth is compressed in the direction of the Sun at a distance of \(~11 \text{R}_E\) (where \text{R}_E\ is the radius of the Earth), while it is stretched out in the opposite direction where the magnetosphere extends up to \(~60 \text{R}_E\) in the magnetotail. Two regions where the effects of the magnetic field drops to zero, called the polar cusps, are present above the poles and provide places of entry for low energy particles. The intensity of the solar wind is governed by the 11 year solar cycle and modulates the flux of interstellar cosmic ray particles reaching the Earth. This solar modulation is insignificant for particles with rigidities in excess of 10 GV per nucleon [92] and the variation in the cosmic ray flux between solar maximum and minimum is of the order 20% [93].

The magnetic field of the Earth not only deflects but also traps some low-energy particles (those from outside and also those created in the atmosphere) that are reflected back and forth between magnetic mirror points as they gyrate along the field lines. This effect is the origin of the radiation belts.

As mentioned above, the magnetic field of the Earth deflects the low-energy particles and thus acts as a spectrometer where the particles are selected based on their rigidity. The momentum (and thus also the rigidity for \(\mathbf{p}\) and \(e^+\)) needed for a vertically incident particle to reach the Earth depends on the magnetic latitude \(\lambda\) (see lower part of figure 6.1) and this can be written as [91]:

\[
p \geq 14.9 Z \cos^4 \lambda \ [GeVc^{-1}].
\] (6.1)

This takes into account that the cut-off is higher near the equator where the field lines are perpendicular to the motion of the particle, than at the poles where the effect of the magnetic field vanishes.

The geomagnetic field sets a lower limit on the energies needed for antiprotons and positrons to be able to reach the experiment. It also limits the number of low-energy particles ‘available’ since part of the time is spent in regions with a higher
6.1 Geomagnetic cut-off and orbit

![Diagram of Earth's magnetic field and related terms]

**Figure 6.1:** Top: A schematic diagram of the Earth's magnetic field. The field is distorted by the solar wind and the resulting magnetosphere extends much further in the direction facing away from the Sun than toward the Sun. Bottom: The definition of magnetic latitude $\lambda$ relative to the magnetic north pole.

cut-off. Furthermore, for a satellite experiment orbiting the Earth, the geomagnetic cut-off is not constant along the orbit and the minimum value is determined by the inclination of the orbit. For this study an average PAMELA orbit lasting ~1.5 h was used (see figure 6.2), where coordinates for the geographic latitude and longitude were produced [95] (in 16 second intervals) by the Satellite Tool Kit.
Figure 6.2: An illustration of an (arbitrary) average orbit projected on a map of the world [94]. The black squares mark the coordinates at different times between 0 and 5648 seconds (i.e. the time taken for one orbit). The orbit has an inclination of 70.4° and an altitude varying between 350 to 600 km (in the northern hemisphere).

The geographical coordinates were subsequently converted into geomagnetic coordinates [97] and the momentum cut-off calculated for each point. The cut-off as function of time is shown in the left part of figure 6.3 and varies between 133 MeV/c and 14.9 GeV/c. To be able to calculate the number of antiprotons and positrons with a particular momentum expected over a period of time, the fraction of the total time spent at geomagnetic locations with a cut-off lower than a certain value (as shown in the right part of figure 6.3) must be calculated.

In this study a number of simplifications have been made:

- The altitude dependence of the geomagnetic cut-off (decreasing the cut-off by ~20% at an altitude of 600 km w.r.t. sea level) has been disregarded.

- The azimuthal direction dependence of the cut-off (the so-called east-west effect) that causes the cut-off to vary between a minimum of ~10 GeV/c and a maximum of ~60 GeV/c at the (magnetic) equator, resulting in more positive (negative) particles arriving from the west (east), has not been taken into account.

- The anomalies caused by the 400 km offset between the axis of the magnetic dipole and the centre of the Earth, such as the South Atlantic Anomaly (SAA) where the flux of low-energy particles is very high, and where ~20% of the PAMELA orbits pass through, have not been included.
Figure 6.3: Left: The geomagnetic cut-off as a function of time in an orbit. The inclination of the orbit results in more time spent in the 'polar' regions than in the equatorial regions. Right: The fraction of the total time that is spent at geomagnetic locations with a geomagnetic cut-off lower than a certain value, e.g. \(~52\%\) of the total time will be spent in locations with a cut-off lower than 5 GeV/c.

- The traversals of the inner and outer radiation belts, in the polar regions, where the flux of low-energy (trapped) particles is high have been neglected.

6.2 The geometrical factor

The geometric constraints of a particle telescope can be described by the geometrical factor \(G_F\). If a telescope consists of two thin, arbitrarily shaped detectors with areas \(S_1\) and \(S_2\) placed on parallel planes a distance \(L\) apart (as shown in figure 6.4), \(G_F\) can be expressed as [98]:

\[
G_F = \int_{\Omega} d\Omega \int_{S_2} dS_2 \cos \theta \quad [cm^2 sr]
\]  

(6.2)

where \(d\Omega\) is the solid angle under which a surface element \(dS_1\) on \(S_1\) is seen from a surface element \(dS_2\) on \(S_2\) and \(\theta\) is the angle with respect to the normal of the surfaces to the solid angle element \(d\Omega\). This is a very general formula but it can be calculated analytically for simple geometries. In the case of PAMELA, where the geometrical factor is determined by the two rectangular openings of the magnetic cavity, it has been calculated to 20.5 cm\(^2\)sr.

The geometrical factor can be viewed as an upper limit of the actual acceptance, reached only by high-energy particles. One reason for this is the presence of the magnetic field in the spectrometer which sets a lower limit on the momentum a particle must have to be able to traverse the spectrometer and trigger the experiment. Particles having a too low momentum will 'bend out' and hit the inside of
the magnet. The effect decreases with increasing momentum as can be seen in figure 6.5 which shows the generation vertexes for simulated positrons of momentum 0.2 GeV/c (left) and 5 GeV/c (right) that were generated above the dome, reached the S3 scintillator and produced a level 1 trigger. The outer rectangle marks the boundary of the S1 counter and the inner rectangle shows the size of the magnet cavity. Another reason why the actual acceptance is expected to be lower than the geometrical factor for energies below a few GeV is the presence of materials in the path of the particles, e.g. the dome and the ToF scintillators, with which the incident particles can interact. This is especially significant at low energies for antiprotons due to the increasing annihilation cross section.

These effects on the gathering power have been determined through simulations as described in the following section.

6.3 Calculating the acceptance

The simulation study was conducted using GPAMELA in the configuration shown in figure 6.6 and included all detectors except the calorimeter and neutron detector. Positrons and antiprotons were generated on a square surface (80x80 cm²) just above the dome, with momenta ranging from 60 MeV/c to 20 GeV/c for positrons and from 400 MeV/c to 30 GeV/c for antiprotons. Particles of lower momenta were generated for each species but no particles survived the selection. The upper limits were set to where the particle losses due to the magnetic field were no longer significant (see figure 6.7). The selection used in this study required that:

- the S3 scintillator must be hit by the particle created on the generation surface,
Figure 6.5: Vertex distributions for positron events of two different momenta that survived the selection (i.e. reaching S3 and giving a level 1 trigger). The plots were produced using the same number of generated positrons with a momentum of 0.2 GeV/c and 5 GeV/c in the left and right plot, respectively. The ‘shift’ seen between the two plots is due to the effects of the magnetic field on the particles in the spectrometer, which is more pronounced in the low-energy (left) plot. The outer rectangle show the size of the S1 detector while the inner rectangle show the size of the magnetic cavity.

- the particle had passed within the boundaries of the S1 and S2 scintillators and through the top opening of the magnetic cavity,
- the particle had deposited at least 0.25 mip in each of the ToF layers,
- it had been contained, and had not interacted, within the spectrometer volume.

At each momentum $10^6$ particles were generated and the acceptance $\Gamma_F$ for each momentum was calculated according to [98]:

$$\Gamma_F = \frac{n_{\text{surv}}}{n_{\text{gen}}} \pi A_s \text{ [cm}^2 \text{ sr]}$$

(6.3)

where $n_{\text{surv}}$ is the number of events surviving the selection, $n_{\text{gen}}$ is the total number of generated events and $\pi A_s$ is acceptence of the generation surface (with area $A_s$).

The resulting acceptance as function of incident kinetic energy is shown in figure 6.7 for positrons (open circles) and antiprotons (filled squares). As can be seen in this figure the low-energy limit for positrons is not set by the acceptance but rather by the geomagnetic cut-off at 133 MeV/c that corresponds to a kinetic energy of 132 MeV for positrons. For antiprotons on the other hand the geomagnetic cut-off corresponds to a kinetic energy of 9 MeV and the lower limit is therefore set by
the acceptance at ~ 80 MeV kinetic energy (which corresponds to a momentum of ~400 MeV/c). At higher incident particle energies the acceptance assumes a value close to the geometrical factor, i.e. 20.5 cm²sr. This study includes not only the effects of the geomagnetic field, but also the energy dependence of the acceptance, when determining the total gathering power.

In the selection of positrons, no account has been taken of the fact that a surviving positron might have been shifted into a lower energy bin due to the emission of a bremsstrahlung photon. This will distort an incoming spectrum and will have to be accounted for in the analysis.

6.4 High-energy limit

At higher energies the limits for detecting antiprotons and positrons are set by the spatial resolution of the spectrometer. The spectrometer measures a quantity called the deflection $\eta$ which is defined as the inverse of the rigidity and the finite precision leads to a distortion of the measured spectrum at higher energies. If the incoming spectrum would be a $\delta$-function around a specific deflection then the resulting output from the spectrometer would be a Gaussian shaped distribution centered around that value. The width of the distribution is determined by the maximum detectable rigidity of the spectrometer (MDR: the rigidity where the relative error on the rigidity is 100%) as $\Delta \eta = 1/\text{MDR}$. The MDR is in turn determined by the
Figure 6.7: The acceptance of the PAMELA telescope for positrons (open circles) and antiprotons (filled squares) as a function of kinetic energy. This plot not only includes the effect of the geometrical factor but also the effects of the magnetic field in the spectrometer and the interactions (e.g. annihilations) with the materials in the path of the particles. At higher energies the acceptance of both particle species level out at a value of 20.5 cm² sr.

Spatial resolution and magnetic field strength of the spectrometer.

At higher rigidities the incoming spectrum follows a power law in rigidity described by:

\[
\frac{dN}{dR} \propto R^{-\alpha} \tag{6.4}
\]

as is shown in the left part of figure 6.8, and since the deflection is defined as the inverse of the rigidity the ‘deflection spectrum’ follows (right part of figure 6.8):

\[
\frac{dN}{d\eta} \propto \eta^{a-2} \tag{6.5}
\]

Figure 6.9 shows how the spectrometer deflection resolution distorts the measured spectrum (grey line with black dots) from its original shape (black line). The relative error on the deflection measurement increases with decreasing deflection and thus increases the likelihood that high-energy particles might be assigned the wrong bending direction and therefore the wrong sign of charge, so-called ‘spillover’. This means that a number of protons and electrons will be given the wrong curvature and thus be identified as antiprotons and positrons, respectively. Since protons are \(10^4\) to \(10^5\) times as abundant as antiprotons this will set an upper limit on the antiproton measurements. The same principle holds also for the positrons and the
Figure 6.8: Left: At high rigidities the incoming particle spectra follows a power law. Right: The same particle spectra (as in the left plot) as a function of the deflection (the deflection is inversely proportional to the rigidity).

Figure 6.9: The error on the deflection $\Delta \eta$ causes some of the high-energy (low deflection) particles to be reconstructed with the wrong bending and they thus ‘spill over’ into the sample having the opposite sign-of-charge.

measured MDR of 1183 GeV/c (see chapter 2) thus sets an upper rigidity limit for antiprotons of 190 GeV/c and for positrons of 270 GeV/c.
6.5 Results

By using the results from the previous sections the number of expected particles \( N_i \) \((i=\pi, e^+\)) collected during a time \( T \) in the energy-interval \( E_1 \) to \( E_1+\delta E \) can be expressed as:

\[
N_i(E) = \int_0^T dt \int_{E_1}^{E_1+\delta E} \Gamma_{F,i}(E) F_{F,i}(E) J_i(E) dE \tag{6.6}
\]

where \( T \) is expressed in seconds, \( E \) is expressed in GeV, \( \Gamma_{F,i}(E) \) is the energy dependent acceptance determined in section 6.3 (see figure 6.7) and expressed in units of \( \text{m}^2\text{sr} \), \( F_{F,i}(E) \) is the fraction of the total time spent in locations with a lower geomagnetic cut-off than \( E \) as described in section 6.1 (see right part of figure 6.3), transformed into a function of kinetic energy for each particle species, and \( J_i(E) \) is the flux expressed in particles/(\( \text{m}^2\text{sr s GeV} \)). These numbers are plotted for different kinetic energies in figure 6.10 for antiprotons (top) and positrons (bottom) for one year of PAMELA operation, where the fluxes of positrons and antiprotons \( (J_i(E)) \) are for the cases of purely secondary production [40][17].

The number of expected particles in each energy interval (bin) is used to calculate the statistical errors expected in the corresponding bin of the measured flux as is shown in figure 6.11 for antiprotons (top) and positrons (bottom) assuming three years of PAMELA operation. The dashed line in the top part of figure 6.11 is a calculation of the secondary antiproton spectrum assuming a diffuse halo propagation model [17][27]. The solid curve in the bottom plot is from a calculation of the secondary positron spectrum based on a diffusive model with only secondary production and no re-acceleration [40].

The expected statistical errors calculated in this chapter, together with the uncertainties caused by the contaminations that were investigated in chapters 4 and 5, will be used to estimate the total errors on the measured fluxes of antiprotons and positrons in chapter 7.
Figure 6.10: The number of expected antiprotons (top) and positrons (bottom) as a function of kinetic energy after one year of data taking. The horizontal error bars show the width of each energy interval (bin) used in the calculation. The ‘features’ seen in these plots (e.g. the ‘flattening’ around 1-2 GeV for positrons) are due to the binning.
Figure 6.11: The expected antiproton spectrum (top) and positron charge ratio: \(e^+/(e^+ + e^-)\) (bottom). Top: The dashed line is a calculation of the secondary antiproton spectrum in a diffuse halo model [17][27]. Bottom: The solid curve is based on a calculation of the secondary positron spectrum based on a diffusive model with only secondary production and no re-acceleration [40]. The filled squares and error bars mark the expectation after three years of operation.
Chapter 7

Results and Conclusions

The uncertainties on the measurements of antiproton and positron energy spectra which have been considered in this thesis are the capability to reject the background from other particle species, i.e., contamination, and the accumulated statistics. The rejection studies of the pion contamination for antiprotons, and the proton contamination when identifying positrons with the calorimeter, have been presented in chapters 4 and 5, respectively. The expected statistical uncertainties were investigated and presented in chapter 6. The aim of this chapter is to combine these results to illustrate the antiparticle identification capability of the PAMELA experiment. In section 7.4 the PAMELA 3 year expectancies for the antiproton and positron energy spectra are revisited, in light of these new results.

7.1 Positron analysis

The main background for the positron analysis, after selecting singly charged down-going particles, will be cosmic ray protons and locally produced pions. This background of singly charged hadrons can be rejected by the different detector systems:

- The ToF system will make it possible to separate positrons from protons (pions) up to ~1.3 GeV/c (~0.2 GeV/c).
- The calorimeter will provide a rejection factor of $10^4$-$10^6$ for protons (and at least $10^9$ for pions) up to the spillover limit.
- The TRD will provide an additional rejection factor of ~20 for hadrons above 2 GeV/c.
- The ND will contribute to the rejection with at least a factor 5 at 40 GeV/c and this factor will increase with energy.

Figure 7.1 shows the ratio between the expected number of protons selected as positrons, and positrons correctly identified by the PAMELA calorimeter as a function of kinetic energy. These numbers have been obtained using the proton
Figure 7.1: The proton contamination in the positron sample as a function of kinetic energy. The dashed line shows the expected remaining contamination from protons after the calorimeter positron selection, based on the calorimeter test beam results. The dotted line (from 40 GeV) shows the case when the calorimeter is used together with the ND, assuming a constant value of the ND rejection. The dash-dotted line shows the situation for the joint calorimeter and TRD selection. The solid line (from 40 GeV) is the expected result of using all three detectors in the selection, i.e. calorimeter, ND and TRD.

spectrum from [99] and the positron spectrum from [40]. The dashed line indicates the result of the positron selection made solely with the calorimeter. This ratio is based on the test beam results presented in chapter 4 and is therefore expected to be worse than in flight (i.e. when the calorimeter is used in conjunction with a tracking system and in a complete flight version). The steep rise of the dashed curve is due to the results from the September 2003 test beam (at 40 GeV and 150 GeV/c momentum, see chapter 4.5) and contradicts the expected behaviour, i.e. that the rejection should increase with momentum, and also results from previous simulation studies [56]. This is most likely a consequence of the beam quality, as described in chapter 4.5. The behaviour seen between 3 GeV and 10 GeV is due to the combined effect of dividing the fluxes and the calorimeter selection. The rejection factors used at 3 GeV and 10 GeV are based on the results from the July 2002 test beam for pions. The result for protons is expected to be better as is
shown below 3 GeV where results from the similar CAPRICE94 calorimeter [77] have been used. The TRD will provide an additional rejection factor of at least 20 as is shown by the dash-dotted line which includes both the TRD and calorimeter. For this line it has been assumed that the TRD will only provide rejection from 2 GeV/c and also that the ToF system will reject all protons with a momentum below 1.3 GeV/c. As described in chapter 4.5.2 the ND will be able to provide a rejection of at least 5 at 40 GeV/c, and this is expected to increase with energy. The dotted line shows the combined effect of using the calorimeter and ND selections, assuming (conservatively) a constant ND rejection factor of 5 from 40 GeV/c for the ND. The solid line shows the expected remaining contamination after applying selections with all three detectors, i.e. the calorimeter, TRD and ND.

The contamination from locally produced pions is potentially a problem since the ToF can not efficiently separate pions and electrons above 0.2 GeV/c. However, the number of locally produced pions is expected to be significantly less than the number of cosmic ray positrons and thus even a rejection of $10^2$-$10^3$ against pions from the calorimeter is sufficient to reduce the contamination to a fraction of a percent. Adding also the rejection factor from the TRD will make the remaining pion contamination negligible.

## 7.2 Antiproton analysis

The two main backgrounds for antiproton measurements will be cosmic ray electrons and locally produced pions ($\pi^-$). The identification of antiprotons will be performed by selecting electrons with the highest possible efficiency and rejecting them. All surviving events are then defined as antiprotons. This will also lead to negative pions being identified as antiprotons, unless they have a momentum below ${\sim}1.2$ GeV/c where they can be rejected by the ToF system. However, this misidentification is only possible if they appear as singly charged particles in the detectors. As shown in chapter 5 the majority of these pion events results in large energy losses in the ToF system, multiple tracks in the tracking system (and/or TRD) or hits in the anticounter system and can therefore be rejected. The resulting contamination due to negative pions (which have only been determined up to ${\sim}6$ GeV/c) is expected to be less than 10\% (see chapter 5.5) and is shown by the dash-dotted line in figure 7.2.

The electron rejection will be performed using four detectors:

- The **ToF** system will be able to reduce the electron contamination to a negligible amount below 1.2 GeV/c.
- The **TRD** will be able to reject electrons above 2 GeV/c.
- The **calorimeter** will be able to identify electrons in the whole energy range of interest.
- The **ND** is expected to be efficient above several GeV.

The calorimeter rejection has been studied with simulations (as detailed in [56]) and the dashed line in figure 7.2 shows the ratio of the remaining number of electrons
Figure 7.2: The expected contamination from electrons and pions in the antiproton sample selected by the PAMELA detectors, as a function of momentum. The dashed line shows the ratio between the expected number of electron selected as antiprotons, and antiprotons correctly identified by the PAMELA calorimeter (from [56]), as a function of momentum. The dotted line shows the remaining contamination after also applying the rejection factor of the TRD. The dash-dotted line is the resulting pion contamination in the antiproton flux after the antiproton selection from chapter 5 and the solid line shows the total expected contamination from pions and electrons.

after the calorimeter antiproton selection, and the number of correctly identified antiprotons after the same selection. These numbers have been obtained using the electron flux from [31][32] and an antiproton spectrum from [17]. The dotted line shows the remaining electron contamination after also applying the TRD rejection (from 2 GeV/c). The solid line is the total expected contamination after applying the calorimeter and TRD rejection for electrons and with the pion rejection from chapter 5. The discontinuity in the solid line is due to the fact that the pion contamination could only be determined up to ~6 GeV/c.
7.3 Results

The solid squares in figure 7.3 show the expected positron charge ratio for only secondary production (top) and with a primary contribution (bottom). The error bars in each bin include the statistical errors based on the results of the study presented in chapter 6 and the errors caused by the remaining proton contamination, using the calorimeter and TRD (dash-dotted line in figure 7.1). The rejection factor of the ND was not included since more work is needed to complete the study of this instrument. Although the rejection factor will increase with energy, it is not known at present what the rejection will be at lower energies. The solid and dashed lines are based on a diffusive model with only secondary positron production [40], with and without re-acceleration respectively. The dot-dashed line is a calculation of the secondary positron spectrum based on an older leaky box model [39] and the dotted line is the calculated contribution of primary positrons from neutralino annihilation [44]. The TRD should also be able to provide some rejection down to 1 GeV/c but this must be studied further with test beam data to determine the rejection factor and efficiency. As seen in this figure it should be possible to distinguish between these propagation models as well as detect the signature from this specific primary contribution.

Figure 7.4 shows the expected antiproton flux for only secondary production (top) and with contribution from neutralino annihilations (bottom). The error bars in each bin include the statistical errors based on the results of the study presented in chapter 6 and the errors caused by the pion and electron contamination (solid line in figure 7.2) up to ~6 GeV, and the electron contamination using the calorimeter and TRD rejection above that energy. The solid line in figure 7.4 is a calculation of the secondary antiproton spectrum using the CAPRICE94 proton data [26] in a diffuse halo model [17][27] and the dashed lines are predictions for the secondary antiproton flux based on the leaky box model with differing path lengths [4]. The dotted line is a prediction of primary antiproton production by neutralino annihilation [28]. As seen in the figure it should be possible to use the PAMELA antiproton measurements to e.g. determine the path length in some propagation models and to detect signatures of neutralino annihilations at higher energies for this particular model.

7.4 Conclusion

This study has included not only a determination of the expected contamination in antiproton and positron measurements but also the energy dependence of the gathering power, thus making it possible to get a more coherent picture of the expected uncertainties. This work thus significantly extends previous studies of the PAMELA performance in antiparticle identification.

The proton contamination for positrons is largely based on the calorimeter test beam results which are expected to be worse than the performance in flight because the data points (at 40 GeV/c and 150 GeV/c) from the September 2003 test beam were not completely reliable due to abnormally high beam fluxes and
positron contamination (as described in chapter 4.2 and shown by the ND analysis at 40 GeV/c in chapter 4.5.2), the calorimeter was never read out in the flight configuration and that the calorimeter will have its maximum performance when used in conjunction with the tracking system information. The ‘real’ situation is thus expected to be better and in better agreement with the simulated results in chapter 4 and in [56].

In conclusion it has been found that the PAMELA experiment will be able to perform high precision measurements, i.e. with a low contamination and high statistics, over a large range of energies. However, to get a more complete understanding the following should be considered in future studies:

- the 150 GeV/c test beam data need to be further investigated (e.g. with the ND);
- the CAPRICE98 data [100] can be used to check the calorimeter proton rejection capability above 10 GeV/c;
- the ND performance has to be studied at lower energies and the process of neutron production by photons has to be included in the simulation;
- all test beam data should be reanalysed when the spectrometer track fitting algorithm is available;
- the performance of the ToF system has to be more fully investigated with ground data;
- an extended version the simulation study presented in chapter 5 has to be performed, with higher statistics and accounting also for the complete PAMELA structure and satellite presence;
- the separation for other propagation and neutralino models should also be studied.

7.5 Outlook

At the time of writing this thesis the PAMELA experiment is going through the final stages of integration in Rome and will soon be shipped to Russia, for installment on board the host satellite and the subsequent launch into space. The launch will take place during 2005 and PAMELA will during its mission be able to conduct many highly interesting and important cosmic ray particle measurements, in a wider energy range than any previous experiment and with unprecedented statistics. Figure 7.5 shows PAMELA, during the current stage of integration (2004-10-01), in the clean-room at INFN, Tor Vergata, in Rome.
Figure 7.3: **Top:** the expected positron charge ratios for only secondary production for PAMELA (filled squares). The solid and dashed curves are based on a diffusive model with only secondary positron production [40], with and without re-acceleration respectively. The dot-dashed curve is a calculation of the secondary positron spectrum based on an older leaky box model [39]. The error bars have been calculated assuming three years of PAMELA data taking, using the proton contamination expected after a calorimeter + TRD selection (see figure 7.1). **Bottom:** the dotted curve is the calculated contribution of primary positrons from neutralino annihilation, assuming a neutralino mass of 336 GeV [44]. The PAMELA expectancy (filled squares) in this plot follow the sum of the solid and dotted lines, i.e. secondary production with a primary contribution from neutralino annihilations.
Figure 7.4: **Top:** the expected antiproton spectra for only secondary production for PAMELA (filled squares). The solid curve is a calculation of the secondary antiproton spectrum using the CAPRICE94 proton data [26] in a diffuse halo model [17][27]. The error bars have been calculated assuming three years of PAMELA data taking, using the pion contamination expected after the antiproton selection described in chapter 5 and an electron contamination after calorimeter and TRD selections (see figure 7.2). The dashed curves are predictions for the secondary antiproton flux based on the leaky box model with differing path lengths [4].

**Bottom:** the dotted curve is a prediction of primary antiproton production by neutralino annihilation, assuming a mass of 964 GeV [28]. The PAMELA expectancy (filled squares) in this plot follow the sum of the solid and dotted lines, i.e. secondary production with a primary contribution from neutralino annihilations and with contributions from neutralino annihilations.
Figure 7.5: A photograph, taken 2004-10-01, of PAMELA in the clean-room during integration at Tor Vergata in Rome.
Appendix A

Test Beam Information

A.1 Summary of test beams

In table A.1 a list of PAMELA test beams is given. The test beams conducted in June 2002, July 2002 and September 2003 are described in chapter 4. The test beams in July 2000 and October 2001 are further described in [42].

Table A.1: PAMELA beam tests. The detectors listed are the calorimeter (CALO), tracker (TRK), transition radiation detector (TRD), ToF (S2-S3), the anticoincidence system (AC), S4 and neutron detector (ND). A star (*) indicates the flight model of the detector was used. A tick (√) in the ‘Author present’ column indicates a test beam at which the author of this thesis has participated.

<table>
<thead>
<tr>
<th>Date, beam</th>
<th>Detectors present</th>
<th>Author present</th>
</tr>
</thead>
<tbody>
<tr>
<td>May 2000, PS</td>
<td>CALO, TRK, TRD, AC</td>
<td>√</td>
</tr>
<tr>
<td>July 2000, SPS</td>
<td>CALO, TRK, TRD, AC, S4</td>
<td>√</td>
</tr>
<tr>
<td>October 2001, SPS</td>
<td>CALO, AC</td>
<td>√</td>
</tr>
<tr>
<td>June 2002, SPS</td>
<td>TRK*, CALO*, AC*</td>
<td></td>
</tr>
<tr>
<td>July 2002, PS</td>
<td>TRD, CALO*</td>
<td></td>
</tr>
<tr>
<td>September 2003, SPS</td>
<td>TRK*, CALO*, S2-S3* (no read-out), AC*, S4*, ND*</td>
<td>√</td>
</tr>
</tbody>
</table>
A.2 Test beam selections

The study presented in chapter 4 uses variables constructed from the calorimeter information. In tables A.2-A.8 selections based on these variables are detailed for each test beam and energy used. The selections ‘cuts’ have been performed on the following variables:

- **QTOT** - the total measured energy (in mip) in the calorimeter.
- **NSTRIP** - the total number of strips hit.
- **QTOT1** - as QTOT, but only for one view.
- **QLow** - as QTOT, but below the calculated electromagnetic shower maximum.
- **QMAX** - the maximum energy detected in a strip.
- **Q(N)CYL** - the measured energy deposited (number of strips hit) in a cylinder of radius 8 strips around the shower axis.
- **Q(N)PRE** - as Q(N)CYL, but only for the first three planes.
- **QLAST** - as QCYL, but only for the last four planes.
- **Q(N)TR** - as Q(N)CYL, but with a radius of 4 strips.
- **QLAST1** - as QLAST, but with a radius of 1 strip.
- **Q(N)PRESH** - as Q(N)CYL, but with radius 2 strips and only in the first four planes.
- **QTRACK** - the energy deposited in the strip closest to the track and the neighbouring strip on each side.
- **QTRACKXX(Y)** - measured energy in clusters along the track in the x(y)-view.
- **NINT** - $\sum_{j=1}^{2} \sum_{i=1}^{22} \theta_{ij} \cdot i$, where $\theta_{ij} = 1$ if the i-th plane of the j-th view has a cluster along (less than 4 nm away) the track with a deposited energy typical of a proton ($O(mip)$), otherwise $\theta_{ij} = 0$.
- **N(Q)CORE** - $\sum_{j=1}^{2} \sum_{i=1}^{P_{max}} n_{hit}(i, j) \cdot \cdot i$, where $n_{hit}(i, j)$ is the number of hits in a cylinder of radius $2 R_M$ around the track in the i-th plane (where the top plane is number 1 and the sum runs up to plane number $P_{max}$, closest to the calculated electromagnetic shower maximum of the j-th view). QCORE is similar but uses the measured energy instead of the number of strips hit.
- **QOUT** - measured energy outside a cylinder of radius 16 strips in the last four planes.
Table A.2: Electron selection at 3 GeV/c. From the July 2002 test beam. The number marked with (*) is after removal of double showers.

<table>
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<td>qtot&gt;600</td>
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<td>10668</td>
<td>18350</td>
<td>7 (3*)</td>
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Table A.3: Electron selection at 10 GeV/c. From the July 2002 test beam.

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<td>58</td>
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<td>noore&gt;1300</td>
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<td>qtrackx,y&gt;1000</td>
<td>-</td>
<td>8939</td>
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Table A.4: Electron selection at 200 GeV/c. From the June 2002 test beam.

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<td>(\text{q}_{\text{track}}) &gt;35</td>
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<td>qtot1&gt;11000</td>
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<td>9040</td>
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Table A.5: Electron selection at 150 GeV/c (protons at 200 GeV/c). From the June 2002 test beam.

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<td>ncore &gt; 2400</td>
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<td>$\text{qtot}_{1} \geq 1000$</td>
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<td>$\frac{\text{trig}}{p_{\text{tot}}}$ &lt; 0.009</td>
<td>2933</td>
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Table A.6: Electron selection at 300 GeV/c (protons at 350 GeV/c). From the June 2002 test beam.

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<td>$\frac{p_{\text{trig}}}{p_{\text{tot}}}$ &gt; 80</td>
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<td>$\frac{p_{\text{trig}}}{p_{\text{tot}}}$ &gt; 0.81</td>
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<td>ntr &gt; 175</td>
<td>10579</td>
<td>9696</td>
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<td>qtot &gt; 15500</td>
<td>10532</td>
<td>9568</td>
<td>26</td>
<td>20</td>
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<td>$\frac{\text{trig}}{p_{\text{tot}}}$ &lt; 0.009</td>
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<td>npresh &gt; 8</td>
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<td>9497</td>
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Table A.7: Electron selection at 40 GeV/c. From the September 2003 test beam. The number marked with (*) is after removal of double tracks. The number marked with (**) is after the Neutron Detector selection (described in chapter 4.5.2).

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<td>8227</td>
<td>13012</td>
<td>17 (13*/6**)</td>
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Table A.8: Electron selection at 150 GeV/c. From the September 2003 test beam.

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</table>
Appendix B

Acknowledgments

I would like to start with thanking Professor Per Carlson for welcoming me into the Experimental Particle Physics group all those years ago, and thereby giving me the opportunity of doing this very interesting and exciting work. I would also like to thank Docent Ton Francke for introducing me to PAMELA and helping me getting started with simulations.

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[43, 47, 60, 61, 62]
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