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Positron identification study with the PAMELA calorimeter

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Abstract: PAMELA is a satellite-borne experiment which is taking data since 2006. It consists of a permanent magnetic spectrometer, an electromagnetic calorimeter, a time-of-flight system, a neutron detector and an anticoincidence system. Positrons are a probe of the local galactic environment, allowing secondary production and propagation models to be tested. Exotic processes such as dark matter particle annihilations may also produce an excess of positrons at high energies. Combining information from different detectors and in particular from the calorimeter, positrons can be identified from the overwhelming proton background. The anomalous positron fraction measured by the PAMELA Collaboration in 2009 [1] covers an energy range up to 100 GeV. A new approach for positron identification is described, based on a combination of shower profile variables in the calorimeter, with the aim of extending the positron fraction analysis up to ~ 300 GeV.

Keywords: Cosmic rays, positrons.

1 Introduction

The PAMELA experiment consists of [2]:

- a time-of-flight system which acts as main trigger and measures the ionisation energy losses dE/dx and time-of-flight of traversing particles
- an anticoincidence system which permits to reject multiple tracks produced above the spectrometer
- a magnetic spectrometer consisting of a 0.43 T permanent magnet and a silicon tracking system which allows the rigidity of charged particles to be measured through their deflection in the magnetic field
- an electromagnetic calorimeter consisting of silicon planes interleaved with plates of tungsten absorbers thus forming a total depth of 16.3 radiation lenghts
- a neutron detector placed below the calorimeter

The PAMELA detector was designed and optimised for the study of the antimatter component in the cosmic radiation, mainly antiprotons and positrons. Combining information from different detectors, positrons can be identified from the significant background due to cosmic ray protons. The proton-to-positron flux ratio in the cosmic radiation is $\sim 10^3$ at 1 GV and increases to $\sim 10^4$ at 100 GV [1]. In particular, the longitudinal and transverse segmentation of the calorimeter permits to discriminate between electromagnetic and hadronic showers induced by leptons and hadrons respectively.

The electromagnetic component of hadronic showers induced by neutral pions could affect the discrimination between positrons and protons. Neutral pions decay into two photons thus inducing an electromagnetic shower which propagates inside the hadronic one. Since the identification of positrons over a large background of protons is one of the main goal of the PAMELA experiment, the electromagnetic contamination of hadronic showers due to π^0 could affect the discrimination between positron and proton events and it becomes extremely important within the context of the positron analysis. In order to investigate the π^0 contamination of hadronic showers, simulations of positron and proton events have been produced and studied. The method followed to evaluate the positron fraction measured by the PAMELA Collaboration [1] starts being less efficient at energies around 100 GeV. This method evaluates the number of electron and positron candidates through a parametric bootstrap analysis with maximum likelihood fitting applied to the calorimeter energy fraction distributions along the track [1]. Around 100 GeV the discrimination of the energy fraction distribution between electromagnetic and hadronic showers starts being less efficient. Thus, in view of extending the positron fraction up to ~ 300 GeV, a new approach for positron identification, based on a combination of shower profile variables in the calorimeter, have been tested on simulations in the energy range $20-100$ GeV.

Shower development in the PAMELA calorimeter and the problem of π^0 contamination of hadronic showers is introduced in section 2. A detail description of PAMELA calorimeter is presented in section 3. The new method for positron identification and the results obtained from simulations are described in section 4.

2 Shower development in the PAMELA calorimeter

Electromagnetic showers are generated by the interaction of electrons, positrons and photons. While electrons and positrons interact via ionisation processes and bremmstrahlung, photons lose energy via photoelectric effect, Compton scattering and pair production. The longitudinal development of an electromagnetic shower is governed by the high energy part of the cascade and scales as the radiation length in the material. The transverse shower profile is characterised by a pronounced central core surrounded by a halo, and usually is described in units of Molière radius ρ_M. About 90 % of the energy of an electromagnetic shower is deposited in a cylinder with radius ρ_M around the shower axis [3]. In the PAMELA calorimeter a radius of $2\rho_M$ around the shower axis corresponds to 8.5 silicon strips [4].

Hadronic interactions take place when hadrons enter a thick material. Strong interactions can arise between the shower particles and the nuclei of the absorbing medium, thus resulting in a more complicated shower development compared to the electromagnetic case. The development of a hadronic cascade is governed by the nuclear interaction length. The hadronic longitudinal development is similar to the profile of electromagnetic showers even though any maximum lies deeper in the calorimeter for a given incident energy. Hadronic cascades are also much broader than electromagnetic ones. The lateral profile is usually composed by a halo, the non-electromagnetic component, and a narrow core, the electromagnetic component generated by neutral pions. Electromagnetic and hadronic shower developments in the PAMELA calorimeter are shown in figure 1.

Thus, hadronic showers generally contain a component that propagate electromagnetically. In the first interaction of protons with nuclei, charged and neutral pions are produced. While charged pions decay or interact hadronically, neutral pions decay into two photons. These photons induce an electromagnetic shower which propagates inside the hadronic one.

3 The PAMELA electromagnetic calorimeter

The PAMELA electromagnetic calorimeter is formed by 44 single-sided silicon sensor planes interleaved with 22 plates of tungsten absorber. Each silicon detector has a sensitive area of (8 × 8) cm^2 and is segmented into 32 read-out strips. The silicon detectors are then arranged in a 3 × 3 matrix thus forming 96 total strips for each plane and a total sensitive area of about (24 × 24) cm^2 [2]. The strips of two consecutive layers are orthogonal and therefore provide two-dimensional spatial information. The total depth of the calorimeter is 16.3 radiation lenghts, corresponding to $\sim$ 0.6 nuclear interaction length. Thus, up to an energy of 1 TeV the maximum of the electromagnetic cascade is well contained [4]. On the contrary, $\sim$ 40 % of hadrons pass through the calorimeter without interacting.

Hadrons and leptons can be discriminated measuring the ionisation energy loss dE/dx providing by the time-of-flight system only for energies $<$ 2 GeV [5]. A powerful way to distinguish between hadron and lepton events at higher energies is to analyse the longitudinal and transverse shower profile inside the calorimeter.

4 A new approach for positron identification

In order to study π^0 contamination of hadronic showers, simulations of hadronic and electromagnetic showers induced by protons and positrons respectively have been produced and initially studied in the energy range $20-100$ GeV. Simulations have been generated using the PAMELA Collaboration's official code, based on GEANT 3.21 code [6], which reproduces the entire PAMELA apparatus. Furthermore, the simulation code was modified in order to artificially boost the number of π^0 produced in hadronic showers and study the consequences for positron identification. The simulated events have been generated with an azimuth angle ϕ = (0, 359)° and, since the track maximum inclination allowed by the PAMELA geometrical factor is 20° [7], with an inclination angle θ = (0, 20)°. The events have been generated with an energy spectrum $\propto$ E $^{-2.7}$ for protons and $\propto$ E $^{-3.0}$ for positrons, in agreement with cosmic ray measurements of proton and electron spectra [8, 9].

The standard positron selection criteria regard event selections in the spectrometer, in the time-of-flight and anticoincidence systems, and in the calorimeter. The silicon layers of the spectrometer have been used to select minimum ionizing singly charged particles, MIP, by requiring the measured dE/dx to be less than twice that expected from a MIP. Constraints on the quality of the fitted track permit to reject particles scattered on the tracker planes or events with multiple tracks. Furthermore, multiple tracks produced in interaction above the spectrometer have been rejected by requiring a single energy deposition in the top time-of-flight scintillator layers. In the same way, no energy deposition have been allowed in the anticoincidence system scintillators which lie above the spectrometer. Moreover, only shower profile variables evaluated in the upper part of the calorimeter, i.e. from plane 1 to plane 20, have been used for positron identification, thus reducing the proton contamination. The probability that an electromagnetic shower will start in the first 3 planes of the calorimeter is $>$ 89 % [10].

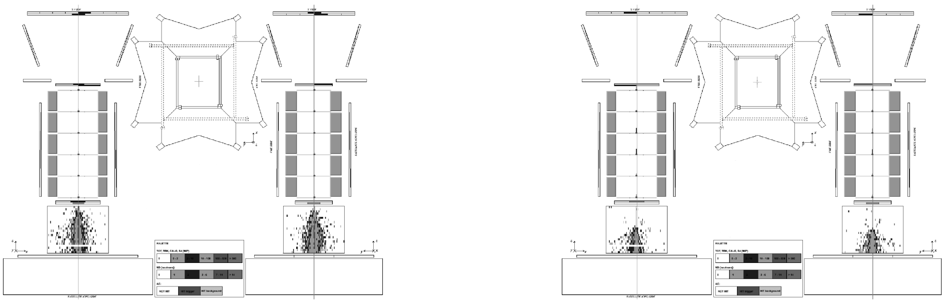

Figure 1: Electromagnetic (*left*) and hadronic (*right*) shower development in the PAMELA calorimeter: showers are initiated by a 100 GeV positron and a 100 GeV proton respectively, and are obtained by GEANT3 simulations. On the left and on the right of each figure the x-view (bending) and the y-view (non-bending) of the apparatus are shown respectively; a view of the events from above are depicted too. The vertical line corresponds to the z-axis. The scale in grey indicates the detected energy in each calorimeter strip [11].

In order to find efficient shower topological selections in the calorimeter, shower profile variables distributions for simulated proton and positron events have been studied in a detailed way. In particular, the main goal was to test the possibility of discriminating between positrons and protons (in the case where the number of π^0 has been artificially boosted) in an efficient way and to find out what are the shower profile variables which permit the most efficient selection.

The procedure consists of:

1. choose shower profile variables for which distributions as function of the rigidity, as reconstructed by the spectrometer, are well separated between positron and proton simulated events, like shown in figure 2
2. construct the variable χ^2 using different shower profile variables combinations tuned on simulated positrons in the energy range $20-100$ GeV
3. find the variable combination which selects positrons in the most efficient way with the lowest proton contamination

The variable χ^2 is constructed as:

$$\chi^2 = \sum_{i=1}^{n} \chi^2_{variable[i]} = \sum_{i=1}^{n} \frac{(variable[i] - \overline{variable[i]})^2}{\sigma^2_{variable[i]}} \tag{1}$$

where *n* is the number of the shower profile variables considered. Shower profile variables depend on the rigidity, and the values of a variable in each rigidity bin is well approximated by a gaussian distribution (see figure 3) with a certain mean and standard deviation. Iterating this procedure for each rigidity bin a distribution of mean and standard deviation as function of the rigidity is obtained for each variable ($\overline{variable[i]}$ and $\sigma_{variable[i]}$). The distributions of $\overline{variable[i]}$ and $\sigma_{variable[i]}$ have been fitted mostly with linear or exponential functions [11].

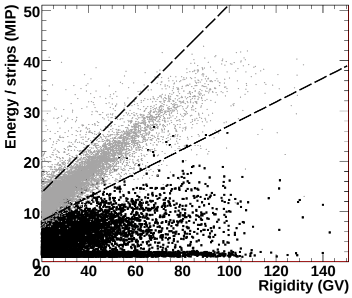

Figure 2: Ratio between the energy deposited in a cylinder of radius eight silicon strips around the shower axis and the number of strips hit in the same cylinder, as function of reconstructed rigidity, for simulated positrons (grey) and protons (black) in the energy range $20-100$ GeV. The dashed line shows the selection $\overline{variable} \pm 3 \cdot \sigma_{variable}$ which has been tuned on the simulated positron sample.

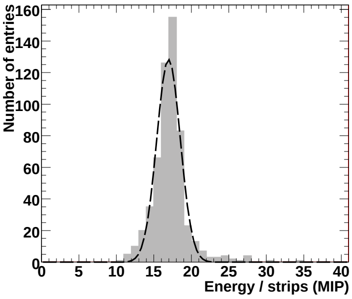

Figure 3: Ratio between the energy deposited in a cylinder of radius eight silicon strips around the shower axis and the number of strips hit in the same cylinder, in the rigidity bin $37-38$ GV, for simulated positrons in the energy range $20-100$ GeV (full grey). The values are well approximated by a gaussian distribution (dashed black line).

4.1 Positron selection efficiency and proton contamination

As already described, many combinations of different shower profile variables have been used in order to obtain the best positron selection efficiency with the smallest proton contamination. The proton-to-positron flux ratio is $\sim 10^3$ at 1 GV and increases at $\sim 10^4$ at 100 GV [1]. Thus, the proton contamination should be lower than $\sim 10^{-5}$. The best combination was found using the following six variables in the construction of χ^2 (eq. 1):

- the shower particle multiplicity, measured as the number of hit strips in each plane and in both x- and y-view; the final value is obtained summing over all the calorimeter planes up to the plane closest to the calculated electromagnetic shower maximum
- the fraction of the calorimeter energy inside a cylinder of radius 0.3 ρ_M centred on the shower axis
- the energy deposited in a cylinder of radius two strips around the shower axis and only in the first four planes of the calorimeter
- the number of strips hit in a cylinder of radius eight strips around the shower axis
- the ratio between the energy deposited in a cylinder of radius eight strips around the shower axis and the number of strips hit in the same cylinder
- the average energy deposited in each silicon strip

The χ^2 is constructed using six variables. Thus, if the six variables are totally independent the probability for a χ^2 distribution to be ≤ 6 for 6 degrees of freedom is ~ 60 %. The result obtained shows that $\chi^2 < 6$ selects 55.4 % of the simulated positron events (see table 1).

The selections applied to simulated positrons have been then applied to simulated protons in order to study the contamination, i.e. how many protons pass the positrons cuts. The results obtained are the following:

- no proton events are selected as positrons up to high values of χ^2 (> 13)
- the number of proton events selected as positrons in the case when all the charged pions are converted into π^0 is of order of $\sim 10^{-5}$ for $\chi^2 < 5$.

Results of positron selection efficiency and corresponding proton contamination for different cuts on χ^2 are summarized in table 1 [11].

χ^2	e$^+$ efficiency	proton contamination
< 3	0.328 ± 0.006	$(0.49\,^{+\,1.84}_{-\,0.46}) \cdot 10^{-4}$
< 4	0.423 ± 0.007	$(0.49\,^{+\,1.84}_{-\,0.46}) \cdot 10^{-4}$
< 5	0.497 ± 0.008	$(0.66\,^{+\,1.42}_{-\,0.54}) \cdot 10^{-4}$
< 6	0.554 ± 0.008	$(1.19\,^{+\,1.53}_{-\,0.77}) \cdot 10^{-4}$
< 7	0.600 ± 0.009	$(3.50 \pm 1.67) \cdot 10^{-4}$
< 8	0.634 ± 0.009	$(5.68 \pm 2.05) \cdot 10^{-4}$

Table 1: Positron selection efficiency and corresponding proton contamination for different cuts on χ^2. The analysis was performed using simulated proton events in the energy range 20−100 GeV and artificially boosting the number of π^0. All the errors have been evaluated at 90 % confidence level [11].

5 Conclusions and outlook

The method followed to evaluate the positron fraction measured by the PAMELA Collaboration [1] starts being less efficient at energies around 100 GeV. In view of extending the positron fraction up to ~ 300 GeV, a new approach based on selections placed on shower profile variables in the calorimeter was studied and tested on simulations in the energy range 20−100 GeV. The method consists on evaluating the variable χ^2 (eq. 1) using a combination of shower profile variables. This new approach permits to obtain a positron selection efficiency of ~ 0.50 with a corresponding proton contamination of order of 10^{-5} in the case where the number of π^0 has been artificially boosted. This simulated sample has been used in order to study how the π^0 contamination affects the positron identification. Some results of this analysis are summarized in table 1. It has been proved that this method is efficient in discriminating between positrons and protons and it will be studied at higher energies, up to ~ 300 GeV.

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