A search algorithm for finding Cosmic-Ray anisotropy with the PAMELA calorimeter

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Abstract. The PAMELA project is the satellite experiment for measurements of the cosmic ray energy spectra in a wide energy range in near-Earth space. The PAMELA apparatus is in orbit from 2006 till today. The calorimeter is the main part of the instrument. It is able to measure energy, to distinguish between hadrons and electrons and to reconstruct the arriving particle direction. Using of special triggers for the calorimeter allows significant increasing of statistics. In consideration of these facts the technique of anisotropy searching in the energy range extending...
higher than 10 GeV has been developed. This technique is based on the calorimeter data and has as content the advanced method of the reconstruction of the secondary particle shower axis in the calorimeter.

1. Introduction

The measurement of the anisotropy of high energy cosmic rays arrival directions is the imperative to study their origin and propagation through Galaxy. The last years the Tibet AS [1] and Milagro [2] collaborations reported about an evidence of the existence of a medium angular scale anisotropy in TeV energy range. The observation of the anisotropies has been recently claimed by the Icecube experiment in the Southern hemisphere [3] and ARGO-YBJ in the Northern hemisphere [4]. While all previous measurements have been executed in the ground based experiments the PAMELA is the satellite-born one.

PAMELA operates on a near-polar orbit since 15th of June 2006. The experiment was designed to measure cosmic ray particle and antiparticle fluxes in a wide energy range. The PAMELA apparatus [5] consists of the following detectors: a magnetic spectrometer with a silicon tracking system (the tracker); a time of flight system (ToF) with three double scintillator planes where each detector layer is segmented in strips, with alternate layer strips are oriented orthogonally to each other; an anticoincidence system; a neutron detector; a bottom shower scintillator detector S4 and a tungsten/silicon sampling electromagnetic calorimeter. The calorimeter is composed of 44 silicon layers interleaved by 22 tungsten plates 0.26 cm thick. Each silicon plane is segmented in 96 strips. 22 planes are used for the X view and 22 for the Y view in order to provide topological information about a shower development inside the calorimeter.

The PAMELA instrument has a magnetic spectrometer allowing precise measurements of the particle rigidity and the charge sign, in the best case up to 1 TeV. In order to provide measurements in the higher energy range the use of the calorimeter is needed. The calorimeter is also equipped with the special-trigger capabilities. A trigger signal is generated when a specific energy value is detected in predetermined planes within the lower half of the calorimeter or just inside the S4 detector. By requiring that triggering particles initiate this energy distribution the geometrical factor becomes 600 cm$^2$sr, i.e. about a factor of 30 larger than the default one defined by the magnetic spectrometer. This allows PAMELA to measure very high-energy particles of cosmic radiation and to increase the statistics significantly.

The incoming particle direction is calculated as a shower axis in the calorimeter.

2. The shower axis reconstruction

2.1. The event preselection

The first step is to select events that have any directions within the calorimeter. The Fig.1a represents the sample of the event without any evident directions inside the calorimeter while the Fig 2 b shows the sample with one.
Fig. 1. The sample of the event (a) without and (b) with an express direction inside the calorimeter in Y view. The black line is the reconstructed trajectory of a particle (the experimental data).

The rejection of events of the first type is based on the facts that in this case the strip with a maximum energy release in a plane is at certain distance from a centre of gravity of energy releases in the same plane. By requiring that within a set of planes of the calorimeter the positions of the maximum and the centre of gravity are approximately the same the amount of events without any directions decrease dramatically.

To reject the low energy particles the threshold for a total deposited in calorimeter energy was installed as 20000 mip. In addition a special cut for the heavy nuclei was applied. It uses the dependence between total energy release and number of hit strips of the calorimeter that for single charged particle is differ from multi charged one.

2.2. The reconstruction algorithm.

The calculation of positions of centres of gravity is done into the metric units of the PAMELA coordinate system – not in strips. The reconstruction algorithm consists of multi-step fitting of the axis equation. The first step is fitting of centers of gravity within the clusters in a set of X and Y planes. The cluster is defined as a set of strips with a signal amplitude - > 0.1 mip. Next 3 steps are a recalculation of the positions of centers of gravity. With the new positions a new iteration of least square linear fit of the trajectory is performed. Such procedure helps to exclude side distorted clusters and determine the better positions of centers of gravity by using only strips from core of the shower.

To define the accuracy of the reconstruction algorithm the results from the calorimeter and tracker data have been compared. The tracker allows to reach the very high accuracy in the measurement of the particle trajectory. Fig. 9 demonstrates the $\Delta X = X_{tr} - X_{calo}$ and $\Delta Y = Y_{calo} - Y_{tr}$ distributions of events, where $X_{calo}$, $Y_{calo}$, $X_{tr}$, $Y_{tr}$ are the coordinates obtained by the calorimeter and the tracker data. These distributions were simulated by GEANT3 [6] and took into account the detector performances.
3. The isotropy map creation

The method of creation the isotropy map is to randomize the reconstructed directions of events. In case the direction distribution of the cosmic ray flux is ideally isotropic, a time-independent intensity should be detected when looking at any given instrument direction. Possible time variation of the intensity would be due only to changes in the operating conditions of the instrument. A set of isotropic simulated events can be built by randomly coupling the times and the directions of real events in local instrument coordinates. The randomization is implemented starting with the position of a given event in the PAMELA frame and exchanging it with the direction of another event, which was selected randomly from the data set with a uniform probability. Starting with this information, the sky direction is reevaluated for the simulated events. The random coupling maintains the exposure and the total number of events [7]. By this construction, the simulated data set preserves exactly the energy and angular (with respect to the PAMELA reference frame) distributions, and also takes into account the detector dead times. The isotropy map is shown on fig.3.

Fig.2 The \(\Delta X = X_{tr} - X_{calo}\) and \(\Delta Y = Y_{calo} - Y_{tr}\) distributions of events. The top: electrons with 1 TeV energy, the bottom: electrons with 300 GeV energy (the simulation data).
Fig.3 The isotropy map. The events are selected in the period 06.2006-09.2009.

4. The Moon shadow

The deficit of cosmic rays in the direction of the Moon is called the Moon shadow effect. The pointing accuracy of the instrument can be determined by observing the position of the Moon shadow. The event map, of size $5^\circ \times 5^\circ$, centered on the Moon location, is filled with the detected events. The significance map is obtained from the experimental events and isotropy map [8]:

$$S(x, y) = \sqrt{2} \left\{ N(x, y) \ln \left[ \frac{\tau + 1}{\tau} \frac{N(x, y)}{N(x, y) + b(x, y)} \right] + b(x, y) \ln \left[ (\tau + 1) \frac{b(x, y)}{N(x, y) + b(x, y)} \right] \right\}^{0.5}$$

With $N(x,y)$ the measured number of events, $b(x,y)$ the number of events expected from the isotropy map and $\tau = 1$ the exposure ratio between measured and simulated sky maps.

Due to unsufficient statistics the moon shadow effect do not exceed the fluctuations level.

This map is used to estimate the statistical significance of the observation. The total number of events in the map observed with data collected in the period 06.2006-09.2011 is about 3000. It is supposed to increase statistics by involving in the analysis the data for all observation period.

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