A 3-dimensional electromagnetic shower characterization and its application to AMS-02 pointing capability

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Abstract: The electromagnetic calorimeter of the AMS-02 experiment is a 3-dimensional sampling calorimeter, made of lead and scintillating fibers. Taking advantage of the fine granularity of the detector, several methods to characterize the electromagnetic shower development have been established, using the information on the lateral and longitudinal shower shape. The reconstruction of the shower axis impacts the identification of leptons and the rejection of protons as well as the identification of the arrival direction of the incoming particles, that is crucial for photon physics. The shower characterization technique and three methods to reconstruct the shower axis will be described, and their performance shown.

Keywords: cosmic rays, gamma-rays, electromagnetic calorimeter

1 Introduction

The AMS-02 detector is a particle physics detector with large acceptance, operating onboard the International Space Station since May 2011. The main goals of AMS-02 are the search for antimatter and dark matter, and the precise measurements of cosmic rays composition and flux. Moreover, AMS-02 could provide informations on gamma rays in the GeV to TeV range. The detector is composed of several sub-detectors, as it can be seen in figure 1. Silicon tracker [2] planes measure the particle charge and momentum. The transition radiation detector (TRD) [3] is used for lepton/hadron separation. The time of flight (TOF) [4] provides the trigger for charged particles, measures charge and ensures that a particle is downward-going, to reject albedo secondaries. The Ring Imaging Cherenkov detector (RICH) [5] independently measures particles charge and velocity. The electromagnetic calorimeter (ECAL) [6] is used for the measurement of energy as well as for lepton/hadron separation. A permanent magnet provides a magnetic field of about 0.15 T.

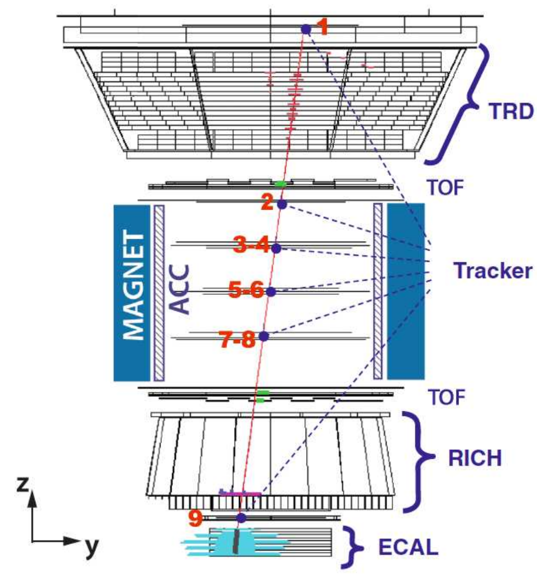

Fig. 1: A 1.03 TeV electron event as measured by the AMS detector on the ISS in the bending (y-z) plane [1]

2 The Electromagnetic Calorimeter of the AMS-02 detector

The AMS-02 ECAL (see [6]) is a lead-scintillating fibers sampling calorimeter, in which particles crossing the active volume produce light collected by photomultiplier tubes (PMTs).
The structure has been designed to have a high granularity (one radiation length in the longitudinal direction, half a Molière radius in the lateral direction) and to maximize the ratio between radiation and interaction lenght. Anodes define ECAL granularity: each anode covers an active area of 9×9 mm^2, corresponding to 35 fibers. The detector allows for 18 longitudinal and 72 lateral samplings, for a total of 1296 readout units, usually referred to as *cells*. A 3 D imaging of the shower development has been achieved by alternating 10 layers with fibers along X axis, and 8

Fig. 2: The honeycomb structure of the electromagnetic calorimeter of the AMS-02 detector

layers with fibers along Y axis. Fibers are read out, on one end only, by four anode Hamamatsu PMTs.

2.1 Detector Performance

The performance of the AMS-02 detector has been tested in 2010 using the primary 400 GeV proton beam of the CERN Super Proton Synchrotron (SPS): proton, electron and positron beams of energies between 8 and 400 GeV have been used. The main purpose of the AMS-02 ECAL is the measurement of energy of electrons, positrons and photons. The energy estimation is performed using the energy deposited in the cells, with corrections for the anode efficiency and the rear leakage, due to limited calorimeter depth. The efficiency is not uniform along the cells, namely it is lower at the cell borders than at their center. The leakage is proportional to the number of particles escaping the ECAL, and it is nearly proportional to the fraction of energy deposited in the last two layers. Once the corrections have been applied, the calorimeter energy resolution can be parametrized as follows[7]:

$$\sigma(E)/E = \frac{10.4 \pm 0.2\%}{\sqrt{E[GeV]}} \oplus (1.4 \pm 0.1)\% \tag{1}$$

The energy linearity has been validated with Test Beam data up to 180 GeV, while for higher energies the Monte Carlo has been used.

3 Shower axis reconstruction methods

An accurate shower axis reconstruction is important for both lepton/hadron separation and gamma ray physics. The identification of electromagnetic-like showers based on a detailed description of the shower shape, takes advantage of the method for the shower maximum determination. An accurate reconstruction of the shower axis implies good knowledge of the particles arrival direction, that is crucial for photon physics.
Combining the energy deposited in each cell, the shower direction is determined separately in the (x,z) and (y,z) view, and then is combined by fitting the axis position in each layer. Three methods have been developed for the reconstruction of the direction of the electromagnetic showers, namely:

- the *Center of Gravity*, evaluated by taking into account the energy deposition in all the cells belonging to the shower, as follows:

$$x_{COG}(y_{COG}) = \frac{\sum_i x_i(y_i)E_i}{\sum_i E_i} \tag{2}$$

  where $x_i(y_i)$ is the position of the i-th cell belonging to the shower, and E_i is the energy deposited on the i-th cell

- the *Neighbouring Cells* method uses, for each layer, the ratio of the energy deposited in the neighbouring cells to the most energetic one, as function of the impact point on the cell.

- the *Lateral Fit* method, in which the electron shower shape is parametrized as a function of energy, using a GEANT4 simulation.

Given a sample of electrons, selected according to the TRD, the tracker and the time of flight, the performance of the different algorithm have been tested on the data collected by the AMS-02 detector in space, as well as on Test Beam data. In the *Neighbouring Cells* method, the ratio of the energy deposited in the neighbouring cells to the most energetic one decreases as a function of the impact point on the cell, as it can be seen in figure 3. This relation can be parametrized as follows :

$$log(EdepL/EdepR) = A + Bx_i(y_i) \tag{3}$$

where $EdepL/EdepR$ indicates the energy deposited ratio, $x_i(y_i)$ indicates the impact position on the cell, as given by the tracker. The coefficients A and B are obtained from the fit and they have been parametrized as function of energy. Once the coefficients A and B are obtained, the position

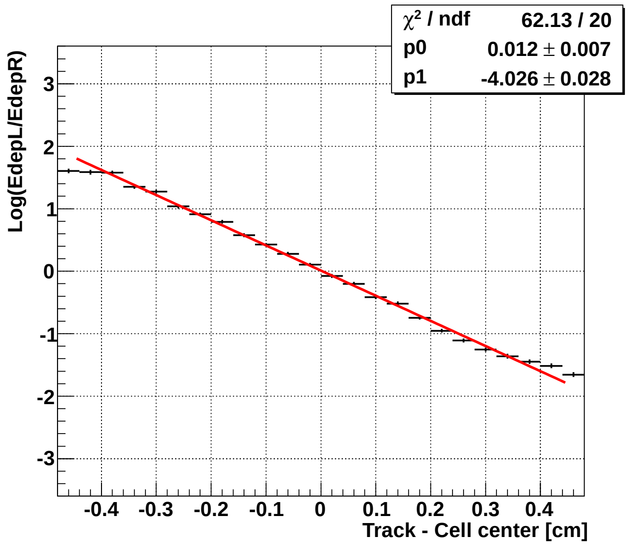

Fig. 3: The ratio of the energy deposited in the adjacent cells of the most energetic one, $EdepL/EdepR$, as a function of the impact position on the cells (with respect to the cell center), for one layer of the AMS-02 ECAL. This relation holds for all the layers of the calorimeter, and it is the core information of the *Neighbouring Cells* method. Events in this plot are electrons selected according to the TRD, the tracker and the TOF, their energy being between 30 and 40 GeV.

measurement on each layer is combined to fit the axis direction. The position measurement has been compared to the measurement provided by the AMS-02 silicon tracker, that is known to have a precision of about 10μm [8] [2]. The distribution of the residuals is shown in figure 4, for a given layer. The distribution of the residuals with respect to the tracker position can be well fitted to a gaussian: the width of the residuals is shown as a function of the depth in the calorimeter in figure 5 (full squares). This quantity is used as a weight in the fit, to get the axis position.
The *Lateral Fit* method makes use of a detailed simulation of the shower development in the detector, based on GEANT4. Its basic principle is shown in figure 6. The shower profile is studied by comparing, on an event by event basis, the simulated shape to the one obtained in the data, and the best shower position is the one that minimizes a χ^2, based on the information on the position and

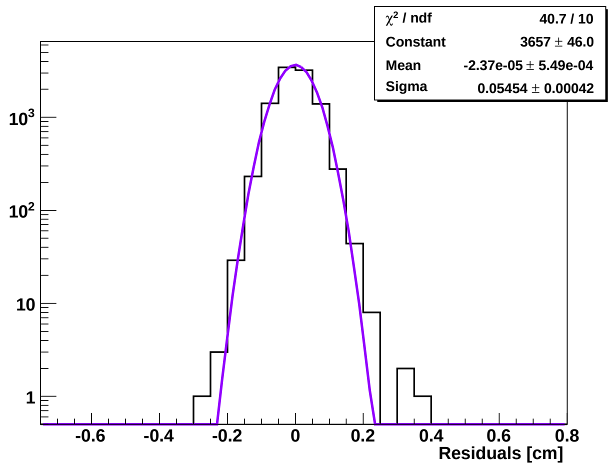

Fig. 4: Position measurement difference, i.e. residuals, between the *Neighbouring Cells* method and the tracker, for 100 GeV Test Beam electrons, for a given layer of the calorimeter.

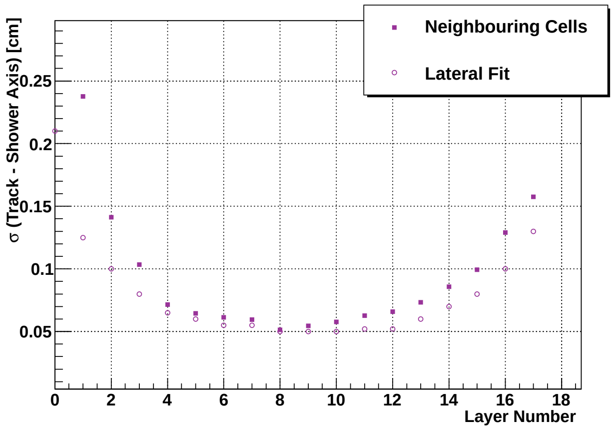

Fig. 5: Gaussian sigma of the residuals of the position measurement for the *Neighbouring Cells* compared to the *Lateral Fit* method, as a function of the layer number, for 100 GeV Test Beam electrons.

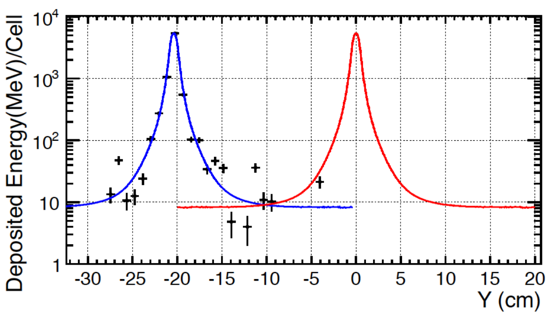

Fig. 6: Deposited energy as a function of the position on a given layer of the ECAL, illustrating the principle of the Lateral Fit method. The red curve indicates the standard shower profile from the simulation, the black dots indicate the energy deposition in data and the blue curve indicates the lateral shape function that is the result of the fit.

the energy deposited in each cell. The precision on position measurement obtained with this method is shown in figure 5 (empty circles) as a function of the depth in the calorimeter, for a fixed energy. The performance are compatible to the ones of the *Neighbouring Cells* method.

3.1 Angular Resolution

The AMS-02 ECAL can detect high energy photons coming from both Galactic and extra-Galactic sources, provided that an electromagnetic shower is detected and no, or limited, activity is reported on sub-detectors located above the calorimeter. The precision of the photon direction measurement has been estimated using electrons detected in flight, identified using the TRD, the tracker and the time of flight, under the hypothesis that both photons and electrons will initiate an electromagnetic shower in the calorimeter. The angular resolution is defined by the three-dimensional angular opening with respect to the tracker track direction that contains 68% of the events, and it is shown in figure 7, as a function of energy. Above few tens of GeV, the *Neighbouring Cells* and the *Lateral Fit* method show compatible performance, namely an angular resolution of 0.6 degrees, that is about a factor of two better than the *Center of Gravity*.

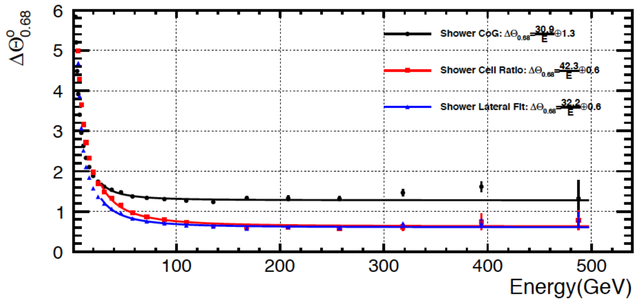

Fig. 7: Angular resolution of the electromagnetic calorimeter of the AMS-02 detector, as a function of energy, for the three methods described in the text

4 Conclusions

The electromagnetic calorimeter of the AMS-02 detector is an imaging calorimeter operating in space since May 2011. The high granularity of the detector implies good performances for both lepton/hadron separation and position measurement. The precision in the position measurement is an important tool for the reconstruction of the shower direction, that impacts both lepton/hadron separation and photon physics. For this purpose, three methods have been developed within the AMS-02 collaboration, namely *Center of Gravity*, *Neighbouring Cells* and *Lateral Fit*. The three methods have been decribed and their performance in terms of position measurement and pointing accuracy, relevant for gamma ray astronomy, have been shown. A angular resolution of about half a degree at energies higher than 50 GeV can be achieved using *Neighbouring Cells* or *Lateral Fit* methods.

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