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# Observation of high-energy gamma-rays with the AMS-02 electromagnetic calorimeter

L. Morescalchi(1)(2) on behalf of the AMS-02 ECAL Collaboration

(1) *INFN, Sezione di Pisa - Pisa, Italy*
(2) *Dipartimento di Fisica, Università di Siena - Siena, Italy*

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**Summary.** — The Alpha Magnetic Spectrometer (AMS-02) is a multipurpose astroparticle physics detector installed on the International Space Station (ISS). Since more than 5 years it is measuring with an unprecedented accuracy flux and composition of primary cosmic rays, searching for primordial anti-matter and probing the nature of dark matter. Despite the fact that AMS-02 has been primarily designed as a charged-particle spectrometer, it can also perform precision observations of $\gamma$-rays from a few GeV to beyond one TeV. The key sub-detector used for the photon identification is a lead-scintillating fibers sampling calorimeter (ECAL). Its high granularity allows to reconstruct the direction of the incoming photon with a resolution better than 1 degree. The 3D shower image reconstructed by the calorimeter together with the absence of hits along the reconstructed photon direction allow to reach a very good signal over background ratio. This experimental technique offers the unusual possibility to reconstruct a sky map of the very high-energy photon sources.

## 1. – The AMS-02 detector

The Alpha Magnetic Spectrometer (AMS-02) is an high-energy particle detector that is successfully operating on board of the International Space Station (ISS). Its main components, described in detail in [1], are shown in fig. 1:

- a silicon tracker inside a permanent magnet, to measure the particle momentum and charge;
- a time of flight (ToF) system, to provide the trigger for the charged particles and to measure the particle charge and velocity;
- a transition radiation detector (TRD), to separate hadrons from electrons, to measure the particle charge and to perform a rough tracking of charged particles;

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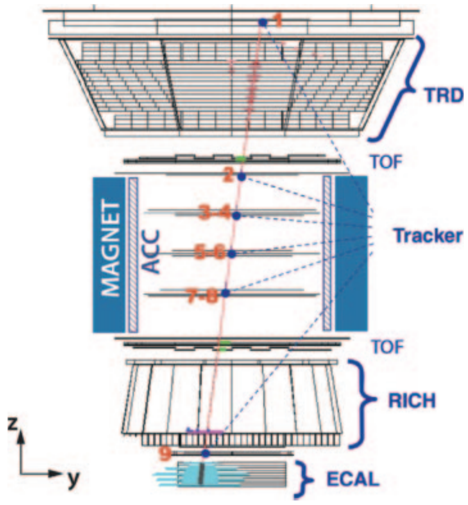


Fig. 1. – AMS-02 detector schematic view, with a 1.03 TeV flight electron event superimposed.

- a ring imaging cherenkov counter (RICH), to measure velocity and charge of particles and nuclei;
- an electromagnetic calorimeter (ECAL), described in details below.

## 2. – The electromagnetic calorimeter

The ECAL [2] is a fine grained lead-scintillating fibers sampling calorimeter consisting of a pancake of 9 superlayers, each made of 11 grooved 1 mm lead foils interleaved with 1 mm diameter scintillating fibers. The resulting composite structure has a relative lead-fiber-glue volume composition of 1:0.57:0.15 and an average density of $6.8 \pm 0.2\,\mathrm{g/cm^3}$. Its total thickness corresponds to $\sim 17 X_0$ or 0.7 $\lambda_I$ for perpendicular incident particles.

Each superlayer is read by 36 four anode PMTs for a total of 1296 cells (18 layers $\times$ 72 columns), so to provide a 3D granularity of $9 \times 9\,\mathrm{mm^2}$ in the electromagnetic shower reconstruction. The electromagnetic shower inside ECAL is reconstructed with a simple clustering algorithm that sums the connected cells. After clustering, the shower energy

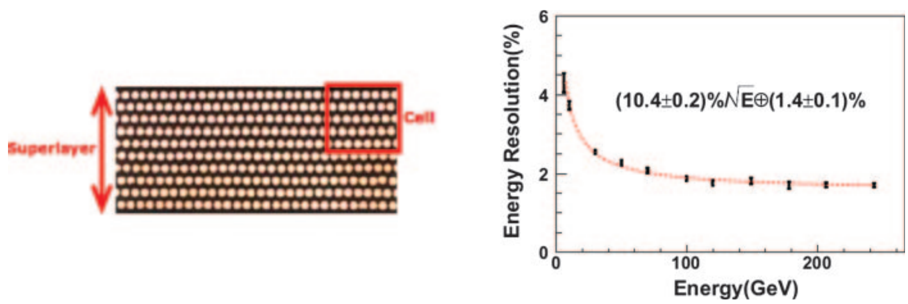


Fig. 2. – Left: section of an ECAL superlayer. Right: ECAL energy resolution at beam test.

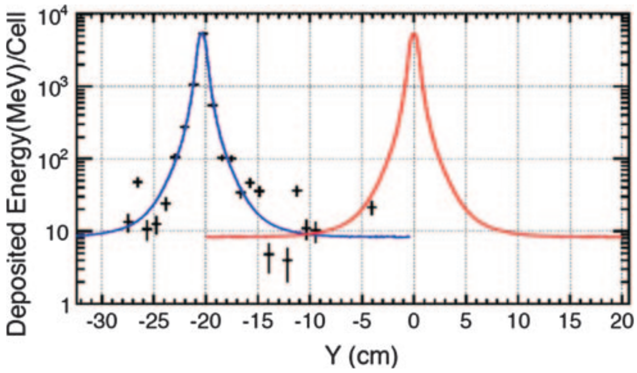


Fig. 3. – Example of the lateral fit method for direction reconstruction: depending on the reconstructed energy and the longitudinal position, the MC shape of the energy deposition in the layer (red), is shifted in position until the $\chi^2$ between data (black points) and MC (blue) is minimal.

is corrected for effects like the attenuation length in fibers, the PMT cathode uniformity, and the lateral and rear leakage. These corrections are described in detail in [3]. The final energy resolution up to 250 GeV is shown in fig. 2.

## 3. – Shower axis reconstruction

The shower direction is reconstructed separately in the $(x,\ z)$ and $(y,\ z)$. Three different methods have been developed to find the shower axis position in each layer.

- Center of gravity (CoG). The shower axis positions are evaluated as follows:

$$x_j^{CoG} = \frac{\sum x_{ij} E_{ij}}{\sum E_{ij}}, \tag{1}$$

  where $x_{ij}$ is the position of the $i$-th cell of the layer $j$ and $E_{ij}$ is its deposited energy.

- Neighbour cells (NC). The ratio of the energy deposited in the adjacent cells to the most energetic one is sensitive to the impact point on the cell. Parametrizing this relation for each layer, it is possible to obtain $x_j$.

- Lateral fit (LF). A detailed GEANT-4 simulation of the shower development is performed to parametrize, layer by layer, the lateral shower shape as a function of the deposited energy. As shown in fig. 3, for each event, the shower shape is compared with the MC shape. The $x_j$ position is obtained by shifting the parametrized shape until the $\chi^2$ is minimal.

These three methods have different resulting resolution on the shower direction, but also different computational cost. Figure 4 shows test beam results with electrons and positrons for CoG, LF and NC. These performances have been confirmed also by flight data taken on the ISS where the electron direction provided by the tracker has been compared with the one reconstructed by ECAL [4].

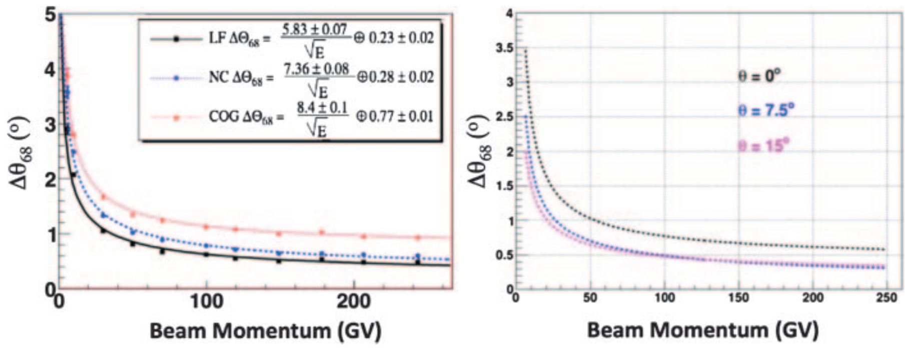


Fig. 4. – Left: angular resolution at the test beam for electrons up to 250 GeV for the three reconstruction methods. Right: interpolation of the test beam angular resolution for different angles of incidence.

## 4. – ECAL standalone trigger

The ECAL is equipped with a standalone trigger system [5] that allows to acquire events that do not fire the charged particles trigger, like $\gamma$-rays. Separately for the $x$ and $y$ sides, the number of PMTs over threshold in the first ECAL layers is used to get a fast trigger decision. Then a fast reconstruction of the incoming particle direction is used to select only showers within the 20 degrees detector axis. Figure 5 shows the measured efficiency for electrons, compared with the Monte Carlo simulation. The ECAL trigger represents $\sim 8\%$ of the total AMS-02 triggers.

## 5. – ECAL capabilities with gamma-rays

The AMS-02 detector can identify and measure $\gamma$-rays by using two independent detection methods: pair conversion and single photon. In the pair conversion method,

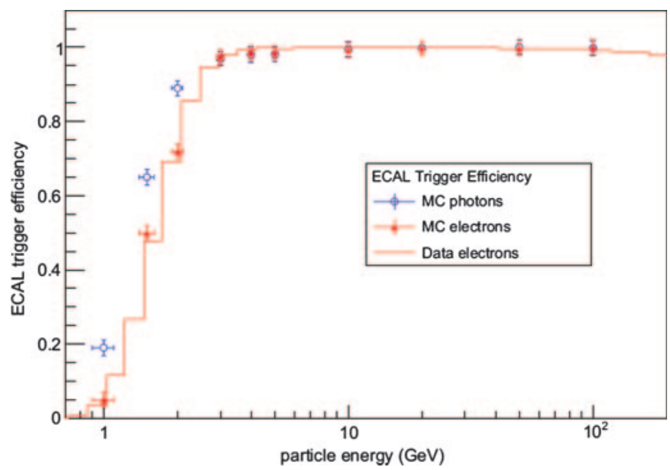


Fig. 5. – The ECAL trigger efficiency measured on flight electron data (red histogram) compared to the MC electrons (red) and photons (blue). The maximum efficiency is reached from 3 GeV.

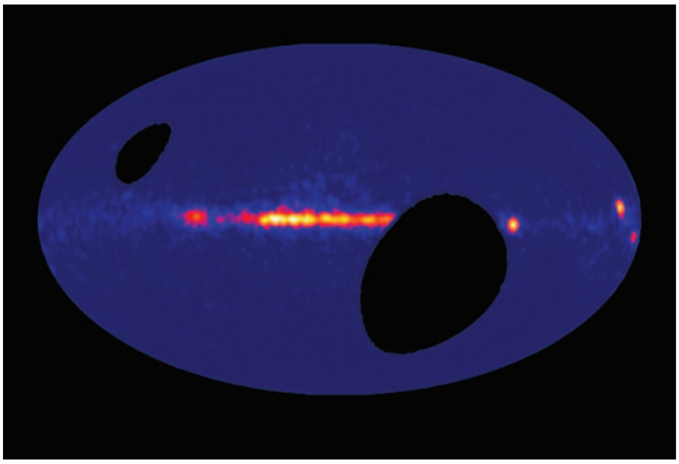

Fig. 6. – The $\gamma$-rays skymap observed by AMS-02 ECAL. Photons of $E > 5\,\text{GeV}$ collected in the first 60 months of data taking are selected.

photons interacts in the material of the upper part of the apparatus ($\sim 3X_0$) producing an $e^+e$ pair that is detected by the tracking system. In the single photon method, which is the one presented in this paper, ECAL directly detects the photons which did not convert before. Particles reaching the top of AMS-02 are mainly protons and fully ionized light atomic nuclei, while $\gamma$-rays represent only a very small fraction of the total cosmic rays composition. Fluxes ratio is $\sim 10^{-5}$ with respect to protons and $\sim 10^{-3}$ with respect to electrons. Thanks to the high efficiency and segmentation of the tracker and of the ToF, vetoing on hits in the other subdetector inside a fiducial cone around the reconstructed axis, it is possible to suppress charged background by a factor higher than $\sim 10^4$ without losing significantly efficiency. Some inefficiency on photon events is nonetheless due to the backsplash of the electromagnetic shower in the calorimeter. The core of the photon identification is then based on the analysis of the longitudinal energy deposit and the lateral shape of each shower. The capability of discriminating between electromagnetic and hadronic showers guarantees an additional rejection factor on hadrons larger than $\sim 10^3$, for a total of $\sim 10^7$. On the other hand, the presence of the permanent magnet strongly limits the field of view and the geometrical acceptance of ECAL, making it difficult to perform competitive studies of high-energy sources.

TABLE I. – *Galactic sources identified by ECAL with more than one photon having energy $E >$ 100 GeV. The number of photons, the galactic latitude (l) and longitude (b) measured by ECAL and reported in the Fermi catalogue* [6] *are reported.*

| Source | $n_\gamma$ | $l_{ECAL}$ | $b_{ECAL}$ | $l_{cat}$ | $b_{cat}$ | $\Delta_l$ | $\Delta_b$ |
|---|---|---|---|---|---|---|---|
| Crab | 4 | −175.9 | −5.9 | −175.4 | −5.8 | −0.5 | −0.1 |
| HESS J11825-137 | 3 | 17.3 | 0.8 | 17.6 | −0.4 | −0.3 | 1.2 |
| HESS J1841-055 | 3 | 25.8 | 0.3 | 26.8 | −0.2 | −1.0 | 0.5 |
| Mkn 501 | 2 | 63.5 | 39.0 | 63.6 | 38.8 | −0.1 | 0.2 |
| Mkn 421 | 2 | 180.4 | 64.6 | 179.8 | 65.0 | 0.6 | −0.4 |

The few percent residual background level and the good angular resolution are confirmed from flight data. Figure 6 shows the skymap obtained with photon candidates with $E > 5\,\mathrm{GeV}$: as expected the events are concentrated around the galactic plane and the brightest spots reveal the emissions from Vela, Geminga, Crab and Cygnus. The dark areas correspond to the position of the Earth poles which are not accessible to AMS-02 due to the trajectory of the ISS around the Earth and the limited field of view ($\sim$20 degrees) of ECAL. In table I a few galactic sources of high-energy $\gamma$-rays observed by ECAL are reported and the position measured by *Fermi* LAT is compared with the coordinates determined by ECAL. With the available statistics, results are compatible within half a degree, showing no evidence of a systematic effect in the photons reconstructed direction.

## 6. – Conclusions

Despite the fact that AMS-02 has been primarily designed as a charged-particle spectrometer, it can also perform precision observations of $\gamma$-rays from a few GeV to beyond one TeV. The high granularity of AMS-02 ECAL allows for an efficient identification of high-energy photons and to point back at the sources with an accuracy better than half a degree. Its 17 radiation lengths allow to measure their energies with a few percent resolution up to the TeV scale. With the availability of a sufficiently long data taking, this excellent performance will allow ECAL to measure the high-energy $\gamma$-rays spectra.

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