High-energy Gamma Rays detection
with the AMS-02 electromagnetic calorimeter

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**Abstract**

The AMS-02 experiment, operating on the International Space Station since May 2011, is designed for a 10-20 years long mission, studying the fluxes of different cosmic ray components in the high energy range 1-2000 GeV. Identification of electrons, positrons and photons is provided by the Electromagnetic Calorimeter (ECAL), a fine-grained lead-scintillating fibre sampling calorimeter that provides an excellent reconstruction of the electromagnetic shower energy as well as a precise three-dimensional imaging of the longitudinal and lateral shower development.

Thanks to the 3D shower reconstruction capability, ECAL allows a stand-alone determination of the incoming particle direction, with unprecedented angular resolution. The AMS-02 sub-detectors located above the ECAL provide rejection of charged background. As a result, ECAL is able to identify high energy photons coming from galactic and extragalactic sources. The AMS-02 photon detection strategy will be discussed.
1 \( \gamma \)-rays detection in AMS-02

Detecting high energy \( \gamma \)-rays, one of the less abundant components of cosmic rays, is a primary task of the Alpha Magnetic Spectrometer (AMS-02). This general purpose detector operates continuously on the International Space Station (ISS) since May 2011 and aims to identify and measure the spectra of the cosmic rays components with so far unreached precision in the energy window from 1 GeV to a few TeV \(^1\). The core of the experiment, the spectrometer, consists of a silicon tracker inside a permanent magnet determining the momentum of charged particles, and four planes of time of flight counters (TOF), measuring the particle velocity. The particle charge is redundantly measured by the tracker, the TOF and a ring imaging Cerenkov detector (RICH) below the magnet. A transition radiation detector (TRD), located on top of the detector, and an electromagnetic calorimeter (ECAL) at the bottom, complete the set of sub-detectors that together provide high capability of discriminating the hadronic component of cosmic rays from the electromagnetic one.

![Diagram](attachment:image.png)

Figure 1: a) AMS-02 single photon detection mode. b) Example of background source: \( \pi^0 \) particles generated in interaction of primary protons with the AMS-02 material.

Thanks to the versatile detector configuration, \( \gamma \)-rays can be identified
using two independent and mutually exclusive methods. In *conversion mode* gamma-rays are identified by tracking back the $e^+e^-$ pairs generated in the gamma conversion happened somewhere in the material upstream of the magnet. In *single photon mode*, the photons are directly detected in the ECAL using all the other sub-detectors located above the calorimeter as a veto to suppress charged backgrounds (see figure 1b for an example of background event). Clearly with this second technique the calorimeter has a key role not only measuring the photon energy, but also determining the incoming particle direction, and generating the trigger for the whole experiment.

2 The electromagnetic calorimeter

The sensitive volume of the ECAL consists of a multilayer sandwich of lead foils and scintillating fibers with a square cross section of 648x648 mm$^2$ and a thickness of 166.5 mm corresponding to 17 radiation lengths. The calorimeter is subdivided in nine superlayers, each 18.5 mm thick and made of 11 grooved, 1 mm thick lead foils interleaved with ten layers of 1 mm diameter scintillating fibers. In each superlayer, the fibers run in one direction only. The 3D imaging capability of the detector is obtained by stacking superlayers alternately with fibers parallel to the x and y axes (five and four superlayers, respectively). The fibers are coupled on one end to multi-anode photomultipliers arranged so that the size of the basic light collection area is 9x9 mm$^2$ giving the detector a very high read-out granularity.

The detector commissioning, with the test beam at CERN Super Proton Synchrotron (SPS) and the following in-orbit checks, confirmed that the ECAL completely fulfills the design specifications. In particular, the detector shows a very good energy resolution, below 20% for energies above 50 GeV and a deviation from linearity smaller that 1% in the energy range between 8 and 180 GeV, with the major source of non-linearity being the rear energy leakage, an effect that is easily correctable up to the TeV (see Fig. 2b).

The angular resolution in the reconstruction of the particle incoming direction is measured in two independent ways: using both data from electron beams and electrons collected during the flight, comparing the direction reconstructed by the tracker with the one estimated by ECAL. In both cases the assumption that a shower initiated by an electron is compatible with a shower initiated by a photon in the ECAL has been verified and eventually corrected.
using the Monte Carlo experiment simulation. As pointing accuracy is a fundamental figure of merit in $\gamma$ astrophysics, allowing to discriminate between point sources and diffuse emission, the unique 3D imaging capabilities of the ECAL have been deeply exploited in the development of the algorithms for direction reconstruction. In particular the best results were obtained measuring the position of the shower axis from the fit of the lateral development of the electromagnetic shower. Figure 3a shows the angular resolution defined by the three-dimensional angular opening with respect to the tracker track direction that contains 68% of the events, as a function of energy: it is better than $1^\circ$ above 40 GeV and slightly improves with the inclination of the incoming particle.

Designing the ECAL stand-alone trigger 4), major efforts were spent to recover the efficiency down to the lowest possible energy while containing the acquisition rate and the power consumption. In particular the system has been designed to be almost 100% efficient on high energy deposits (above 10 GeV) and as highly efficient as possible at low energies; to produce a trigger rate below 100 Hz; to have low sensitivity to external conditions (temperature, solar activity ...) and high robustness, assuring good performances even in case of a broken PMTs (hot or dead) or of global gain fluctuations; to require a power consumption below 15 Watt and components weight below 5 kg. The basic idea to fulfill all these requirements is to build up a trigger with a granularity of 1 PMT (18x18 mm$^2$). The signals of the last dynode of the PMT's of
the 6 central superlayers are sent as input to a set of comparators and the outputs combined to produce the first decision level of the trigger, i.e. the “fast trigger”: usually for each view (x and y) at least 2 (out of 3) superlayers must have at least one photomultiplier above threshold. These thresholds, one for each superlayer, have been optimized using the AMS-02 Monte Carlo to obtain more than 90% efficiency on 2 GeV photons, enhancing the rejection of hadronic background with a longitudinal profile resembling the electromagnetic shower one. If the fast trigger request is satisfied, the incoming particle direction is roughly evaluated by taking, for each view, the average position of the fired PMTs: the angular distance of the barycenters of the 2 most distant superlayers is requested to be inside 20° in order to produce the final trigger decision, the “level 1” trigger. This reduces the trigger rate rejecting background particles entering the calorimeter from outside the ECAL field of view.

Data taking operations in space demonstrated that the ECAL stand alone trigger, thanks to its flexible configuration and reliable design, can easily accommodate the required performances. The transfer function of the comparators has been reconstructed from flight data showing the correct behavior with an effective applied threshold within a few percent with respect to the design value; only few channels got lost after the launch. To evaluate the trigger efficiency
we first use a highly pure electron sample triggered by the TOF and passing inside the detector field of view; then the results have been used to tune the Monte Carlo simulation and to finally estimate the efficiency on photons. This resulted to be completely in agreement with the expectations, being about 80% at 2 GeV and reaching 99% at 10 GeV (see figure 3b). For an average polar orbit the trigger rate is contained in about 120 Hz (approximately 10% of total AMS-02 rate).

3 Photon identification

The first step of the photon identification strategy consists in an event pre-selection requiring the presence of one shower in the ECAL, a reconstructed incoming direction inside the upper TOF plane active area, very low activity in the sub-detectors upstream the calorimeter. Among the remaining candidates the main background source consists of protons and electrons reaching ECAL from the lateral and the rear sides, generating a shower whose axis is wrongly reconstructed: to clearly identify the \( \gamma \)-rays a very high rejection power (of the order of \( 10^6 \)) is required. This is obtained using boosted decision tree (BDT) methods combining the variables describing the 3D electromagnetic shower shape in ECAL with the variables measuring the activity in other AMS sub-detectors, like the energy deposit in the 4 TOF layers, the time difference between the TOF hits closest to shower axis in the four TOF layers, the number of TRD tracks and the minimum TRD track distance from shower axis. Two BDT’s classifiers, one to reject electrons and one for protons, were trained separately using both data and Monte Carlo simulations: the photon candidates are finally selected applying tight cuts on both the two estimators as shown in figure 4a.

Figure 4b shows the level of background rejection reached applying the full selection algorithm; even considering the feeble flux out of the galactic plane the expected contamination above 30 GeV is lower than 10%: it’s possible to look at the high energy gamma sky and search for high energy sources. For the single photon mode detection the corresponding AMS-02 effective area (defined as the surface integral of the detection efficiency as a function of energy and incoming direction) is shown in figure 4c as a function of \( \cos \theta \), where \( \theta \) is the particle inclination angle, and \( \log_{10}(E/\text{GeV}) \).
Figure 4: a) BDT classifiers applied to photons. Two BDTs trained on electrons and protons are combined in a unique classifier, the “BDT radius” which defines the circular sector of good candidates. b) The background rate applying the selection procedure. Since the geomagnetic cut-off is not considered, the background is overestimated below 10 GeV. c) The differential effective area as a function of $\cos \theta$ and $\log_{10}(E/\text{GeV})$.

4 Conclusion

The AMS-02 electromagnetic calorimeter is an imaging calorimeter operating in space since May 2011. The high granularity guarantees excellent performances for both lepton/hadron separation and pointing. These characteristics, along with the robust and fully configurable standalone trigger, allow the ECAL to directly detect $\gamma$ particles. By means of accurate discriminant analysis techniques, the level of background can be sufficiently contained, as confirmed by the sky map (see figure 5) obtained with photon candidates applying the correction for the detector exposure. In the map, the galactic plane, as well as the brightest gamma-rays sources like Vela, Geminga, Crab and Cygnus, are clearly visible. In the future, thanks to the very long data taking time foreseen for AMS-02, more results are expected in particular in the investigation of structures in the photon spectrum, where the very good calorimeter energy resolution will play a key role.
Figure 5: Gamma all-sky map for energy above 5 GeV in $2^\circ \times 2^\circ$ pixels in galactic coordinates. The map is obtained for a period of 24 month of data taking, correcting for the exposure of the instrument (the two empty ovals correspond to regions out of the AMS field of view).

References