



A sampling electromagnetic calorimeter for alpha magnetic spectrometer

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Abstract

We present designs of different three-dimensional (3D) sampling electromagnetic calorimeters for the AMS experiment. The proton rejection power of 3D sampling calorimeters is discussed. A shower shape analysis procedure provides a typical proton suppression factor of $\approx 10^4$ for most of the designs. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

One of the goals of physics in the AMS experiment [1,2] is a search for the dark matter. The dark matter may to a large extent consist of the relic supersymmetric particles such as neutralino (χ) and may constitute the halos of the galaxies. The local density of relic neutralino in the halo can be much higher than the universal average leading to $\chi\chi$ annihilations. These can be detected by detecting stable particles such as $p, \bar{p}, e^-, e^+, \gamma$ resulting from the annihilations [3]. A flux of stable particles produced by the conventional sources and their energy spectra are described by the leaky box model of particle propagation and interaction in space. Neutralino annihilations may manifest themselves as an excess of particles of a given kind

above a level determined by the conventional sources. As an example, Fig. 1 shows an increase of the positron flux due to the heavy neutralino annihilations into heavy leptons and quarks. To measure the positron flux one has to make sure that the positrons are not confused with other particles much more abundant in the cosmic rays (Fig. 2). Protons is the main source of the background of positively charged particles. At energies higher than 10 GeV there are $\sim 10^4$ protons for each positron. To perform a reliable measurement of the positron spectrum one has to suppress protons by a factor $\sim 10^5$. One of the means to perform this job is a sampling electromagnetic calorimeter (EC) [4–6]. An EC is also used to measure the energy of particles which interact electromagnetically (γ, e^-, e^+).

In the following, a calculation of the proton rejection power for several options of the EC proposed for the AMS is presented.

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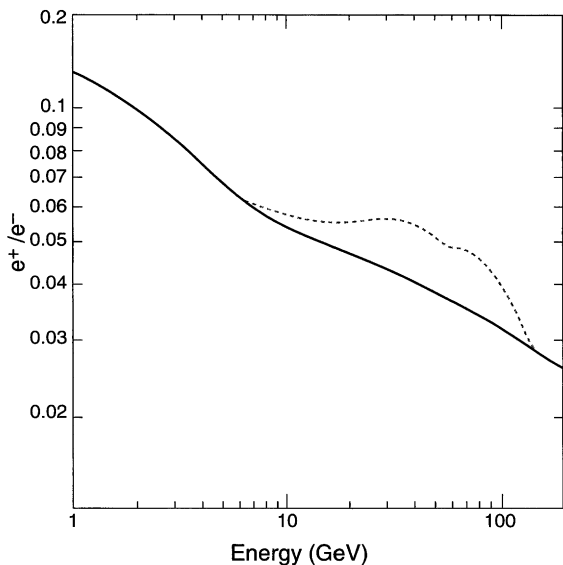


Fig. 1. Calculated positron flux enhancement due to 275 GeV neutralino annihilation into $\tau^+\tau^-$, $b\bar{b}$, $t\bar{t}$ (dotted line). Standard leaky box contribution is given by the solid line.

2. Proton/positron separation with sampling electromagnetic calorimeter (EC)

The accuracy of the electromagnetic energy measurement depends on the calorimeter structure and is given in Table 1.

In addition to the energy-dependent terms the energy resolution of all practical calorimeters have a constant term connected with the rear energy leakage, nonuniformity of calibration of the detector elements etc. In the energy region of interest (up to ~ 100 – 150 GeV) the energy independent constant term is assumed to be 2%.

The separation of protons (hadrons in general) from positrons (electromagnetically interacting particles) is based on the difference of the development of the shower in the absorber material. The longitudinal and lateral division of the EC makes it possible to “visualize” the development of a shower in the calorimeter. A typical shape of an electromagnetic shower is shown in Fig. 3. The longitudinal penetration of the shower changes logarithmically with energy whereas the transversal shape remains almost the same. A hadronic shower is very different from this. Firstly, the thickness of

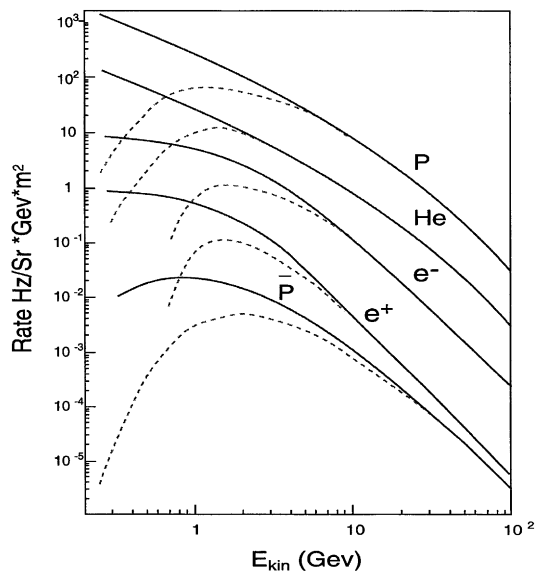


Fig. 2. Interplanetary energy spectra of different cosmic ray particles. The dashed lines illustrate the average spectra for the AMS orbit.

Table 1
Calculated energy resolution for different EC structures

Calorimeter structure	σ_E/E [%] E [GeV]
$22X_0$ BGO	$2.5/\sqrt{E}$
$6X_0$ BGO + $16 \times (1X_0\text{Pb} + 0.5 \text{ cm Scint})$	$9/\sqrt{E}$
$22 \times (1X_0\text{Pb} + 0.5 \text{ cm Scint})$	$16/\sqrt{E}$
$22 \times (1X_0\text{Pb} + 0.06 \text{ cm Silicon})$	$26/\sqrt{E}$

electromagnetic calorimeters considered in this study is only of ≈ 1 nuclear interaction length (λ) and $\approx 35\%$ of all protons pass through the calorimeter without showering. Secondly, a hadronic shower, if it occurs, develops in the absorber differently.

Since in the AMS the particle momentum is measured by a magnetic spectrometer the proton/positron confusion may happen only if in the first interaction with absorber a proton transmits all its energy to a secondary particle which interacts electromagnetically with the matter. Apart from that, to be compatible with a particle interacting electromagnetically the interaction of a proton

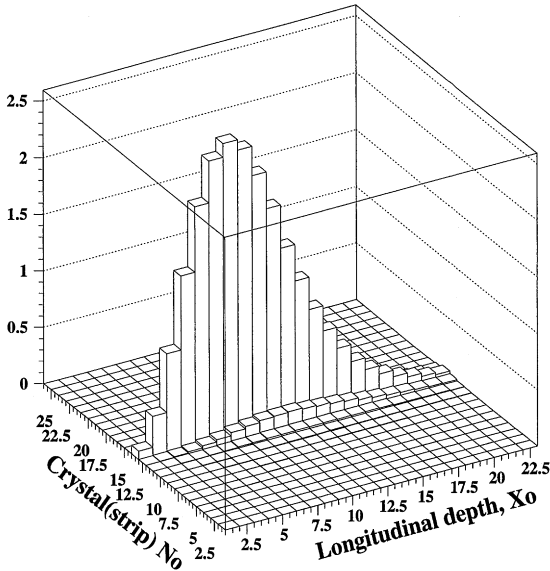


Fig. 3. Electromagnetic shower (30 GeV).

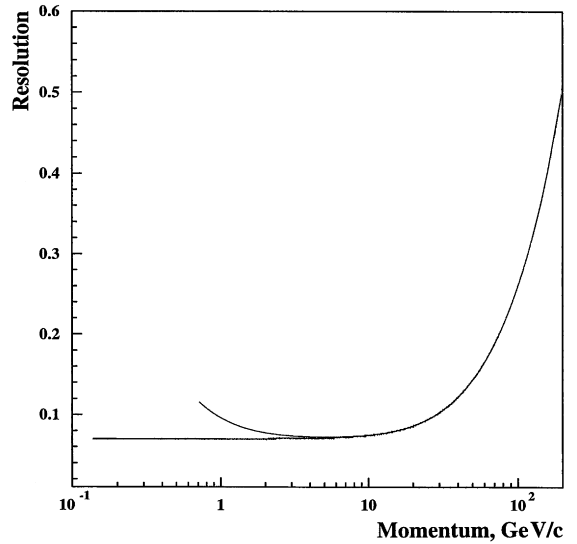


Fig. 4. AMS momentum resolution. The upper curve at small momenta reflects worsening of the resolution for protons due to multiple scattering ($1/\beta$ factor).

faking a positron should occur in the front part of the calorimeter. Thus, in itself the probability for a proton of given energy to produce a shower with the same parameters (amplitude, shape) as a positron of the same energy is extremely small. The confusion may result from an error of the measurement. If, for example, a measured momentum is smaller than the actual momentum of a proton, then the probability of confusion is higher, because of much higher probability of the first proton interaction with an electromagnetically interacting secondary carrying only a part of the initial proton energy. This kind of events can produce a match between the momentum and the energy and shape of the shower and thus to fake positrons.

Therefore, the proton rejection depends on a combined error of the energy measurement in the calorimeter and an error in the momentum measurement in the tracker. For the purpose of proton/positron separation a calorimeter with high resolution (BGO or BGO + Pb/Scint) has advantage over calorimeters with relatively poor resolution (Pb/Scint or Pb/Silicon) only as long as the error in the measurement of momentum does not dominate the energy measurement error. The AMS momentum resolution for the shuttle flight configuration is shown in Fig. 4.

A combined resolution for the above-mentioned calorimeters and the tracker is given in Table 2 for different electron energies.

3. EC rejection power

One of the possible layouts of the AMS with the EC on the International Space Station (ISS) is presented in Fig. 5.

The following calorimeter structures of $22X_0$ thickness are considered as possible options:

- Full BGO calorimeter;
- Calorimeter with $6X_0$ front part made of BGO crystals of $1X_0$ thickness followed by $16X_0$ of a calorimeter with $1X_0$ Pb absorbers and 0.5 cm thick sampling scintillator counters (see Fig. 6).

The BGO crystals have a thickness of 1.12 cm ($1X_0$) and a 2 cm width. The strips of plastic of the Pb/Scintillator part have a width of 2 cm. The consecutive layers of BGO crystals (or scintillator strips) have an alternating X, Y orientation.

As an example a $22X_0$ thick calorimeter with the face plane surface of $50 \times 50 \text{ cm}^2$ shown in Fig. 6 weighs $\sim 700 \text{ kg}$. A full BGO calorimeter with the

Table 2

Combined resolution of the measurement of the energy and the momentum in the AMS with different EC calorimeters

Electron energy [GeV]	EC structure			
	BGO	BGO + Pb/Scint	Pb/Scint	Pb/Silicon
	Resolution [%]			
2	7.5	9.7	13.5	19.8
4	7.4	8.5	10.8	14.9
10	7.3	7.8	8.9	11.0

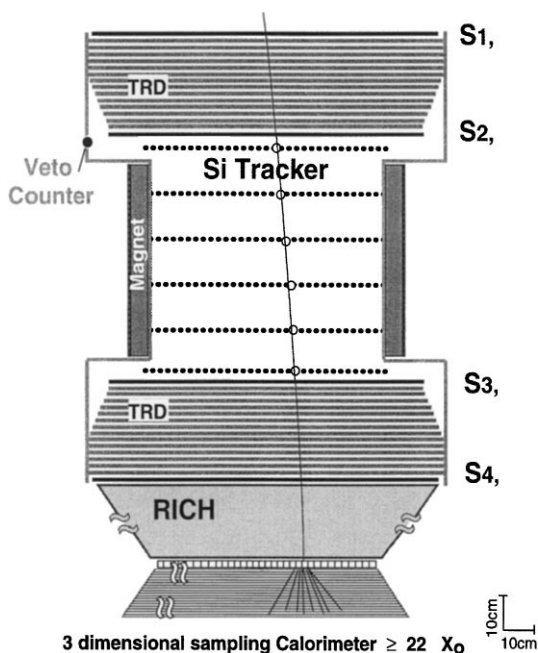


Fig. 5. Layout of AMS on the ISS. S1, S2, S3, S4 – TOF scintillators. TRD – transition radiation detector.

same acceptance and thickness is ~ 80 kg heavier. A geometrical acceptance of this configuration for the positron studies is $\approx 0.2 \text{ m}^2 \text{ sr}$.

In the Monte Carlo simulation the momentum resolution of the AMS detector is assumed as shown in Fig. 4. The particles enter the AMS vertically from the top. The GEANT/GEISHA package is used to simulate the AMS geometry and the particle interactions.

For each measured momentum the signals from all BGO crystals (and scintillator strips in the BGO + PB/Scint version) are compared with refer-

ence signals produced by the particles of an electromagnetic shower of the corresponding energy. The reference showers are taken from a bank of presimulated showers of energies between 1.5 and 175 GeV. A deviation from the reference shower shape, D , is calculated using an expression

$$D = \frac{\sum_i ((E_r^i - E_m^i)/(E_r^i + E_m^i))^2 (E_r^i + E_m^i)}{\sum_i (E_r^i + E_m^i)},$$

where E_r^i, E_m^i are reference and measured signals in the i th BGO crystal (scintillator strip).

The comparison of the signals from a proton with the electromagnetic showers provides good proton suppression.

Fig. 7 shows the dependence on the momentum of the probability for a proton of a given momentum to be taken for a positron. The cuts on the measured parameters are chosen to give a 95% efficiency of the positron detection. At an efficiency of 90% the rejection of protons is ≈ 5 times better at energies below 10 GeV and ≈ 3 times better at higher energies.

Both configurations have similar performance above 5 GeV. The rejection quickly deteriorates above 50 GeV.

4. Energy spectrum of fake positrons

In this section, the simulation of the spectrum of fake positrons produced by the cosmic ray protons is presented. The proton spectrum used (Fig. 8) corresponds to the ISS orbit averaged spectrum for the year 2002.

In the calculation of proton/positron separation the information provided by different AMS

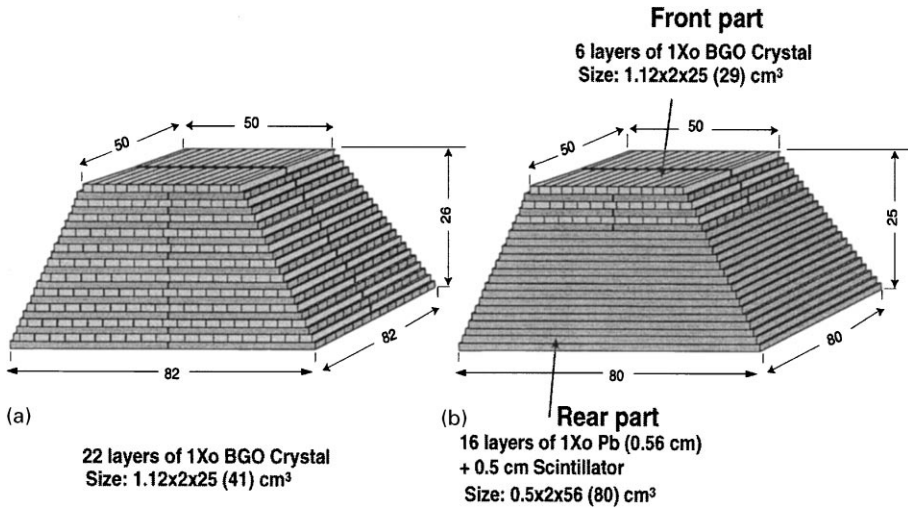


Fig. 6. Sampling electromagnetic calorimeter options. (a) full BGO calorimeter, (b) BGO + Pb/Scintillator calorimeter.

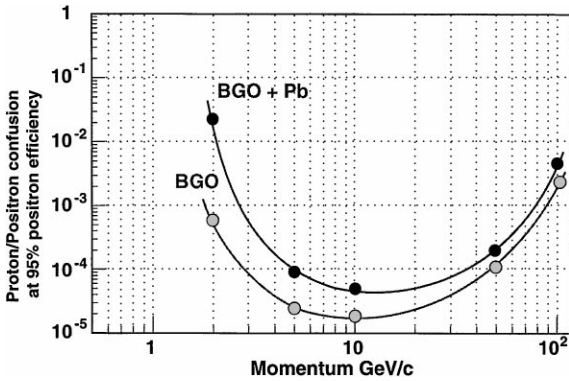


Fig. 7. Probability for protons to be confused with a positron at 95% positron detection efficiency. The grey circles correspond to full BGO calorimeter, the full circles to BGO + Pb/Scint calorimeter.

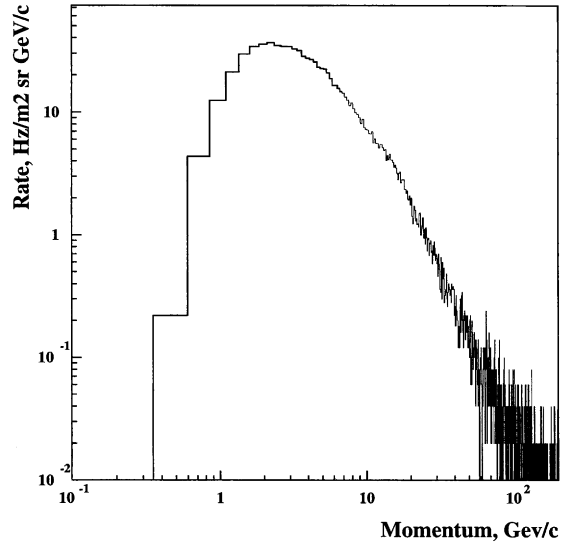


Fig. 8. Proton spectrum used in the calculations.

detectors is taken into account. The AMS TOF system is very efficient for the separation of protons from positrons (or electrons from antiprotons) up to ≈ 2 GeV/c. Fig. 9 shows the dependence of the proton suppression by the TOF system on the momentum. The time of flight is assumed to be measured by the TOF scintillators with 100 ps accuracy.

In the following, all distributions presented are obtained for the BGO calorimeter option. The cor-

responding distributions for the BGO + Pb/Scint option are similar to those presented.

Positron selection is based on the following criteria:

1. The TOF compatible with $\beta = 1$ within ± 300 ps ($\pm 3\sigma_{TOF}$).

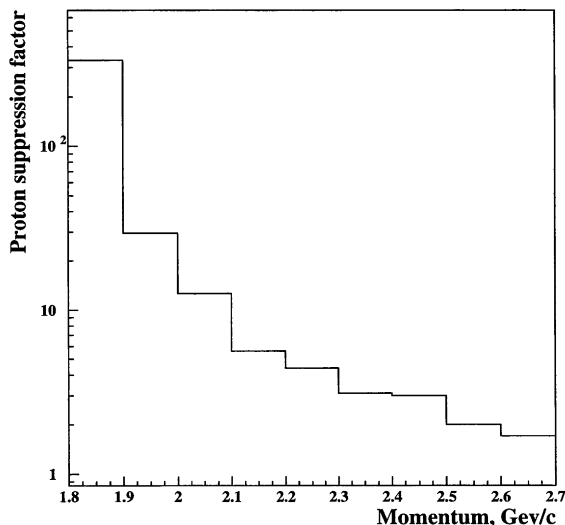


Fig. 9. Proton suppression by the TOF system. Compatibility with $\beta = 1$ within ± 300 ps ($\pm 3\sigma_{\text{TOF}}$) is required.

2. The ratio of the energy measured in the calorimeter over the momentum determined with the tracker is equal to 1 within $\pm 2\sigma$, where $\sigma = \sqrt{\sigma_{\text{tracker}}^2 + \sigma_{\text{EC}}^2}$.
3. The shape of the shower in the calorimeter is compatible with an electromagnetic shower.

Figs. 10 and 11 show the distributions of various parameters measured by the calorimeter for positrons and protons as a function of measured momentum. As mentioned above, the TOF measurement provides efficient separation up to 2 GeV/c using the cut (1): $\text{TOF} = 4.3 \pm 0.3$ ns.

The cut (2) on the energy/momentum ratio further suppresses proton background at all energies. Fig. 12 shows the energy distribution of fake positrons after cuts 1 and 2 are applied to the proton sample. (This would be the case for a BGO calorimeter with a vertical orientation of crystals, i.e. without longitudinal segmentation.) The suppression of protons is not satisfactory. The number of real positrons collected in the same period of time as this many fake positrons is expected to be 25 times less for an energy region of 0–10 GeV and 80 times less at the energies higher than 10 GeV.

Fig. 13 shows the energy distribution of fake positrons after a cut on the shape parameter, D (see

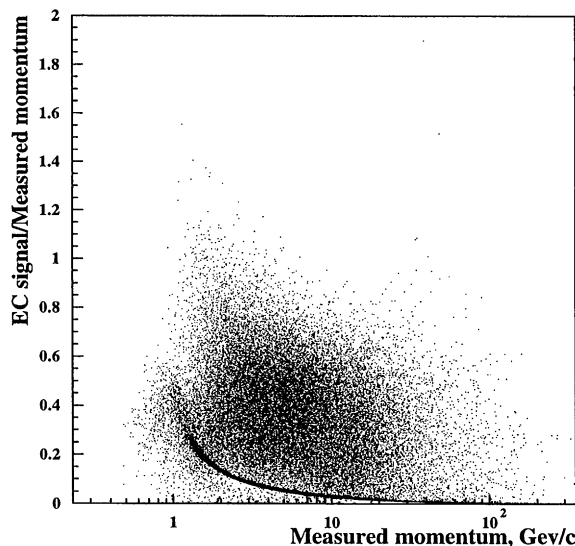
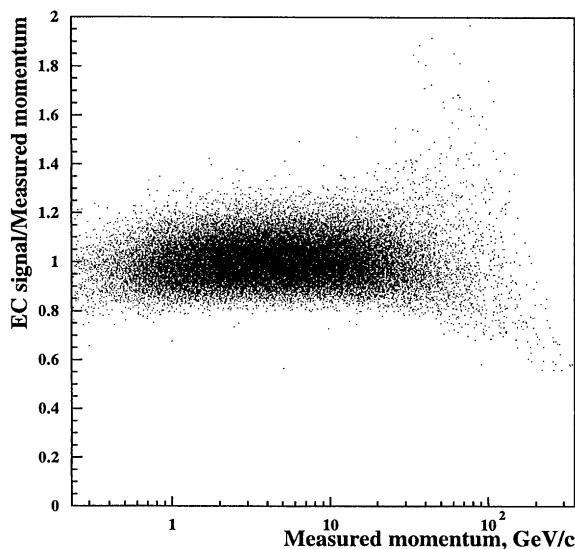


Fig. 10. The energy/momentum ratio for positrons (top) and protons (bottom).

Fig. 11). Table 3 gives the statistics of fake (background) positrons arising from 500 000 protons detected in the AMS with the sampling calorimeter.

The efficiency of positron detection after the selection using the cuts on the TOF, the energy/momentum ratio and the shower shape parameter is presented in Fig. 14. One can see from Table 3 that at the energies higher than 30–50 GeV the rejection

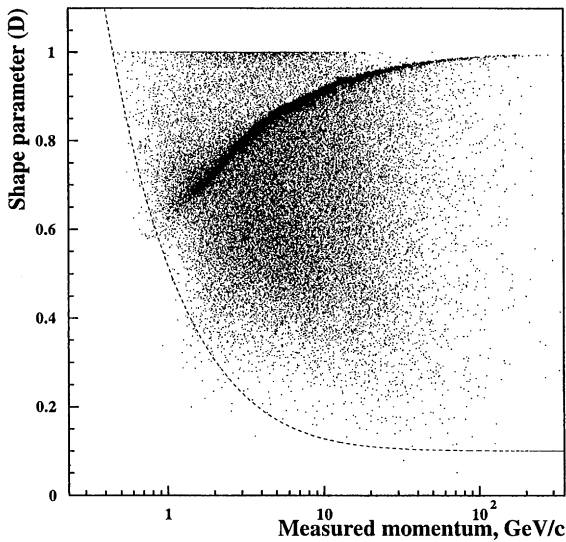
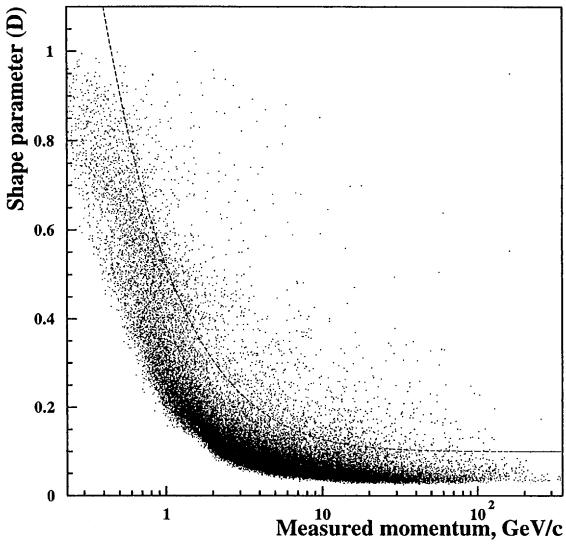


Fig. 11. Shower shape parameter D (defined in the text) for positrons (top) and protons (bottom). The dotted lines correspond to the selection cut.

Table 3

Number of fake and real positrons corresponding to 500 000 protons. All cuts applied

Energy range, GeV	Fake positrons	Real positrons	Signal/Background
0–5	30	240	8
5–20	3	36	12
20–50	6	3.5	0.6
50–200	9	< 1	< 0.11

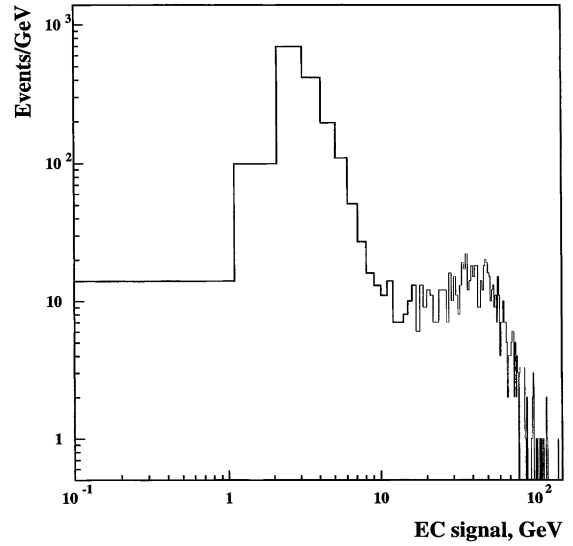


Fig. 12. EC signal of fake positrons in case the shape parameter rejection is not applied.

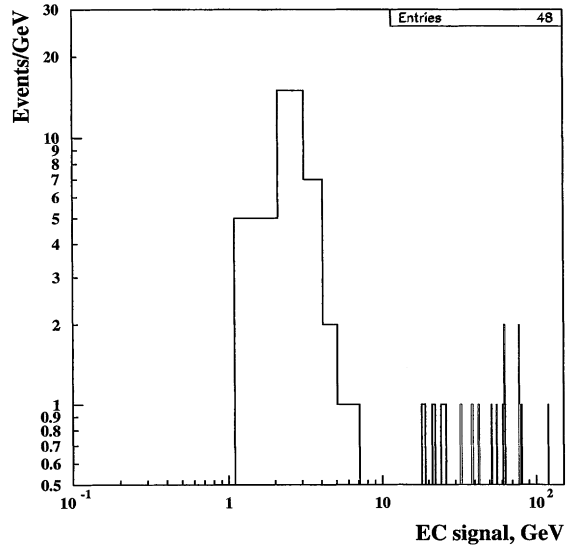


Fig. 13. EC signal of fake positrons. 500 000 protons generated. Cuts 1,2 and 3 applied.

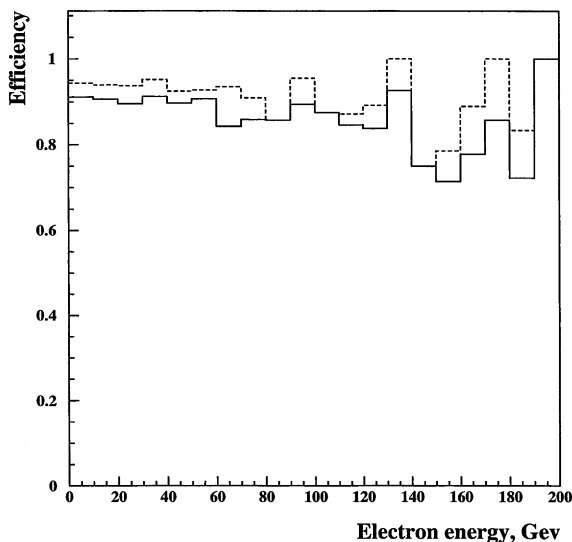


Fig. 14. Efficiency of positron detection. Dashed line - with cuts 1 and 2 on the positron sample. Solid line - with cuts 1,2 and 3 (see text) applied.

of protons becomes insufficient. The possible increase of the AMS magnetic field by a factor of 5 to 10 will give an order of magnitude improvement of the signal/background ratio. This together with the installation of a TRD detector (see Fig. 5) will ensure clean e^+/p separation at high energy.

5. Conclusion

A sampling electromagnetic calorimeter added to the AMS detector helps to suppress proton background in the positron sample (or electron background in the antiproton sample) keeping positron detection efficiency at 85–90%.

The rejection through the shower shape analysis depends on both the momentum resolution of the tracker and the energy resolution of the EM calorimeter. The discussed 3D AMS sampling calorimeters can provide a proton background suppression of $\approx 10^4$ up to ≈ 50 GeV.

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