Energy measurement in the TeV region with a 'thin' sampling calorimeter

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Abstract

The results of a study related to the measurement of the energy of particles in the TeV region using sampling calorimeter are presented.

Introduction

Calorimeters are widely used for the measurement of particle energy. The energy resolution of calorimeters which fully absorb showers initiated by particles improves with energy. Full absorption of showers of higher energy requires thicker calorimeters. For example, to insure the absorption of electromagnetic showers of 500 GeV at the level of 95 % the calorimeter thickness should be more than 20 radiation lengths, X_0. In homogeneous calorimeters of insufficient thickness the rear leakage leads to distortions of energy measurement both in terms of linearity of response and energy resolution. This is also true for the total signal of sampling calorimeters. However, sampling calorimeters can provide information about spatial development of electromagnetic shower which can be used to determine the energy at a several percent level even when the leakage is as high as 50 %. In the following a method to determine the energy of particles of several TeV energy with a "thin" sampling calorimeter is described. The study is based on the Monte Carlo simulation of showers in the sampling electromagnetic calorimeter of the AMS experiment [1]. The showers are simulated using GEANT 3 code [2].

The calorimeter is made of layers of lead absorber with scintillating fibers of 1 mm diameter embeded into it. The fibers are read out with photomultipliers. Each photomultiplier views 35 fibers of a square cell of 0.9×0.9 cm^2. There are 18 layers in total corresponding to the calorimeter thickness of 17 X_0. The consecutive double layers have orthogonally oriented fibers allowing the detection of shower development in two projections.

Electromagnetic showers

Figure 1 shows the signals produced in the cells of the calorimeter by a 2 TeV electromagnetic shower. The signals from the cells are normalized so that the total signal from the fully absorbed low energy electromagnetic shower corresponds to the particle energy. With this calibration the signal from a minimum ionizing particle (MIP) crossing the cell corresponds to 12.5 MeV of electromagnetic energy deposition.

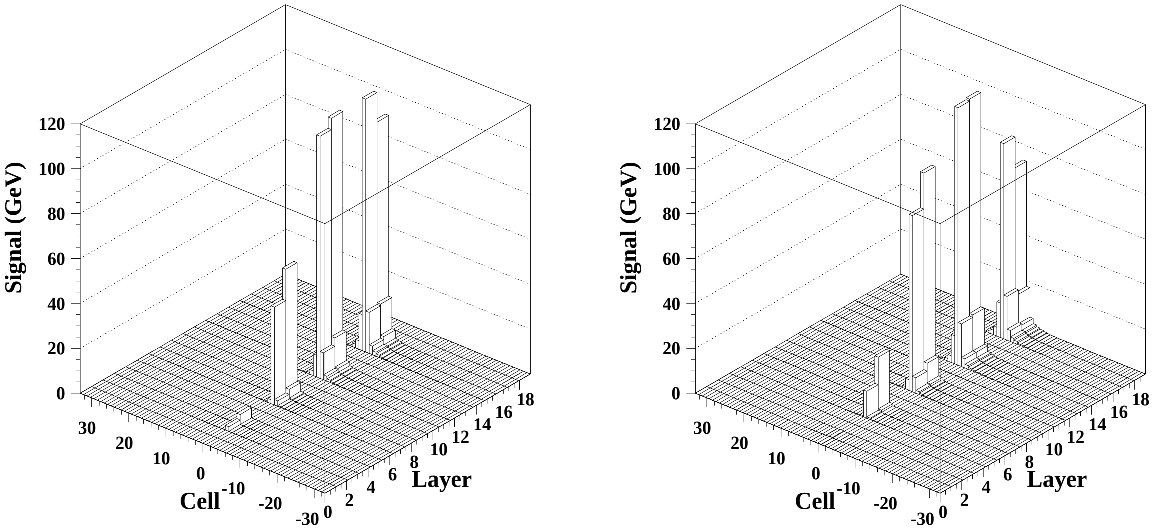

Figure 1: Signals from a 2 TeV positron shower in the cells of two orthogonal projections of the calorimeter.

Figure 2 shows the layer by layer signals from a 2 TeV shower. It is well known [3] that due to relative simplicity of electromagnetic interactions with matter the longitudinal development of each individual electromagnetic shower can be described by a smooth energy dependent function. Therefore, even if the rear leakage from the calorimeter is very big it is possible to determine the full energy of the electromagnetic shower fitting the signals from the layers to a function which describes the longitudinal development of the shower and taking the value of the integral of the function corresponding to full absorption as a measure of the particle energy. The function used in this study is

$$\mathrm{E(X) = E_o[(X + L) * S]^6 e^{-0.67(X+L)*S}},$$

where X is layer number and $\mathrm{E_o}$, L and S parameters.

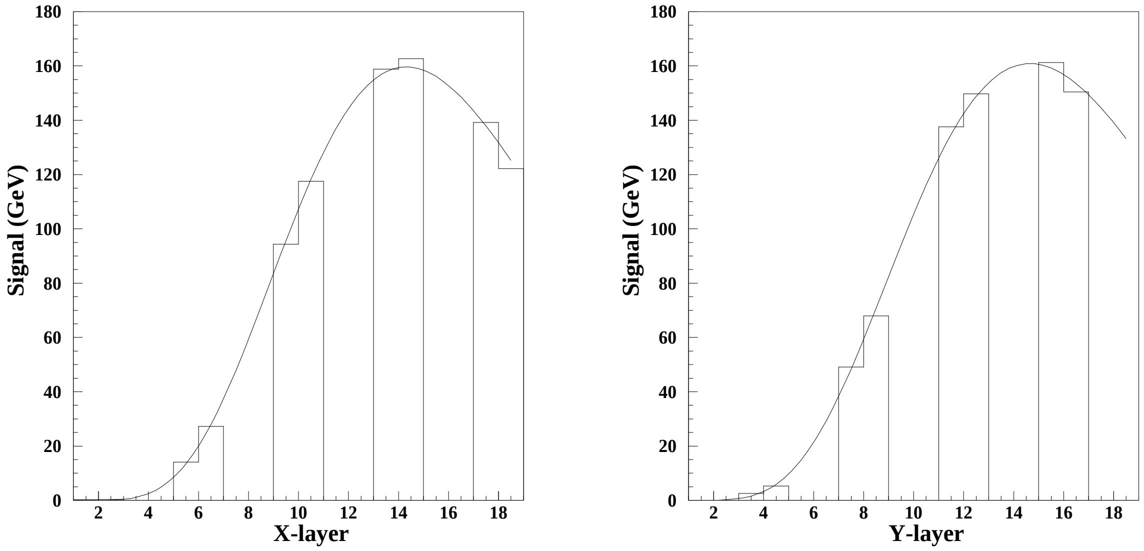

Figure 2: The result of the fit of signals from a 2 TeV positron shower in the layers of the calorimeter.

The extrapolation method of determination of the energy of electromagnetic shower works when the maximum of the shower is inside the calorimeter. Consequently, only the events with maxima of the shower in any layer but the last one are considered. Firstly, the signals are fitted separately in each projection. Secondly, the integrals of functions with parameters obtained in the fit are calculated as if the shower developed through a calorimeter of 40 layers (38 X_o). Finally, in case the result for two projections differ less then 15 %, the average signal is taken as a measure of total shower energy. The efficiency of this procedure goes slightly down but remains above 90 % for electromagnetic showers up to several TeV, while the resulting response is linear and the accuracy of energy measurement stays at the level of 4-5 % (Fig.3). Due to compactness of electromagnetic showers, the maximum signal in the individual cell can be as big as 7 kMIPs/TeV. To avoid nonlinearity of response connected with saturation the detectors and the readout system of the calorimeter is designed correspondingly.

Measurement of high energy hadrons

A sampling calorimeter of the AMS type can be used to measure the energy of hadrons. In a thin calorimeter of the thickness of about 0.6 nuclear interaction length (NIL) a leading hadron as well as most of charged pions produced in the first inelastic interaction with the absorber escape from the back of the calorimeter without second nuclear interaction. On the other hand, neutral pions produced in the same interaction promptly decay into two photons, which in their turn produce e^+e^- pairs in the first electromagnetic interaction.

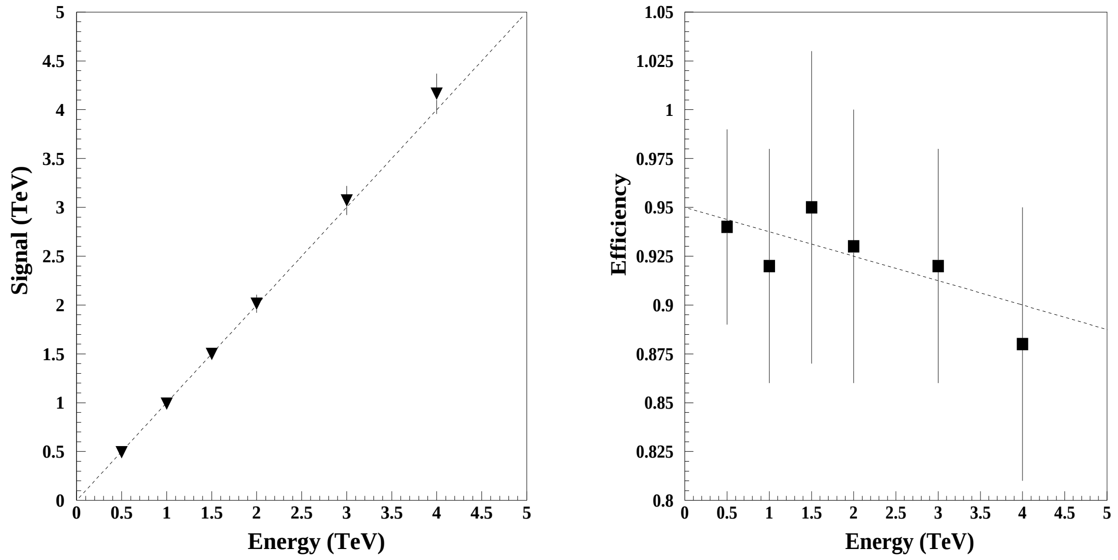

Figure 3: Accuracy and efficiency of electromagnetic shower energy measurement. The error bars in the efficiency picture are of statistical nature.

The particles which emerge from the inelastic interaction have small transverse momenta and their direction is very close to the direction of the initial particle. The average energy of secondary pions is less than 10 % of the energy of the projectile particle. Consequently, the resulting electromagnetic shower from π^0s represents a superposition of several showers each of the energy about 40 less than the energy of initial hadron. Depending on the depth of the point of the first inelastic interaction the compact lower energy electromagnetic showers can be fully or partially contained in the calorimeter.

Figure 4 shows the distribution of the signals initiated by a 4 TeV proton interacting in the front end of the calorimeter. The distribution looks like an ordinary electromagnetic shower. The signals from the "hadronic" part of the shower connected with charged pions and nuclear debris are much smaller and can be visible at the "background" level on the logarithmic scale. For each event the energy of electromagnetic component of the shower resulting from the inelastic interaction of hadron with the calorimeter can be determined with high accuracy. However, fluctuations of the number of pions produced in the inelastic interaction with a nucleus is big. The measurement of charged pion multiplicities in the interactions of protons of 360 GeV/c with Au (A=197) give the negative charged pion multiplicity of 8.9 with dispersion of 5.4 [4]. At all energies the multiplicity distribution can be represented by a universal curve with average number of pions as a unique parameter (KNO scaling) [5]. It is proven experimentally that due to isotopic invariance this applies both to charged [4] and neutral [6] pions. The universal distribution is skewed towards small multiplicity values and has dispersion of about 50 %. Being the same at all energies, the shape of the distribution sets a "best possible accuracy"

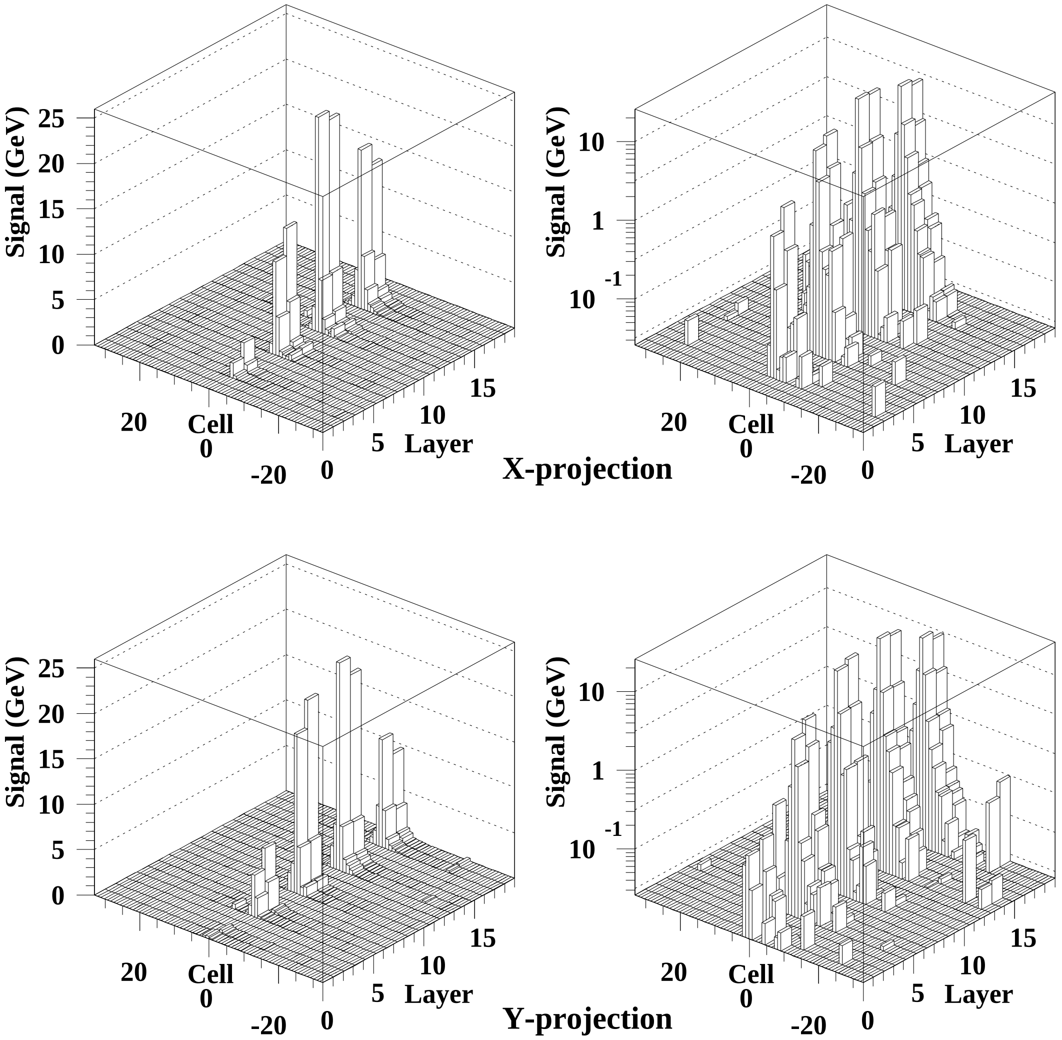

Figure 4: Responce to a 4 TeV proton interacting in the front end of the calorimeter. Left colomn - linear energy scale, reft colomn - logarithmic energy scale.

limit on the energy measurement with a "thin" calorimeter. This limit is reached at high energy when the average multiplicity is high.

The number and the average energy of secondary pions produced in the interactions of high energy nucleons with nuclei increase with energy of the projectile particle. Therefore, measuring the electromagnetic component produced by π^0's one can determine the energy of the incoming particle. However, as it was explained above, the calorimeter responce is determined by fluctuations in the number of secondary π^0s and, consequenly, the accuracy of the measurement is rather poor.

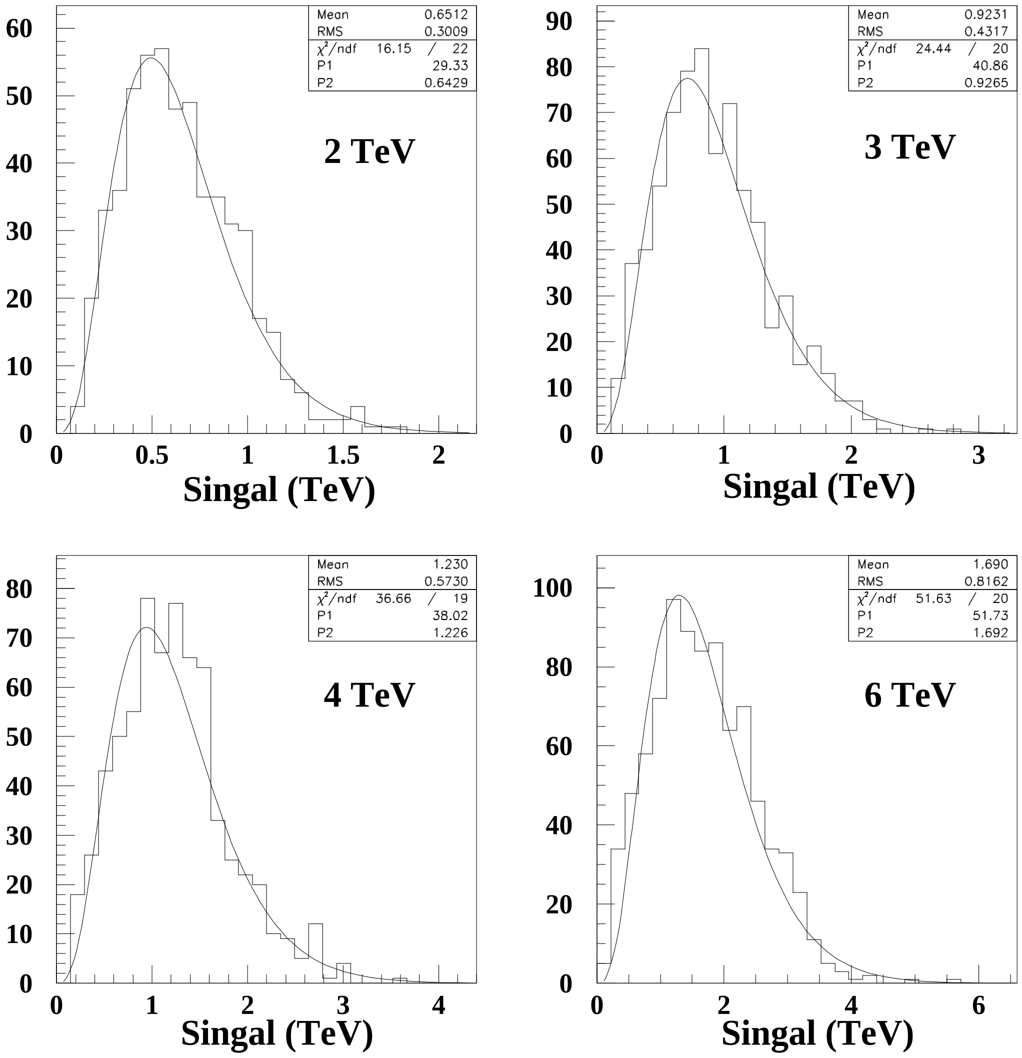

Figure 5: Calorimeter response to high energy protons.

The result of analysis of simulated showers produced by protons of different energies is shown in Fig.5. The mean value of the calculated calorimeter response is a linear function of energy and is equal to about 30 % of the total proton energy (see Fig.6). The error bars correspond to the RMS deviation of the distribution which is is about 50 % at all energies.

The calorimeter response, A, is determined by the probability function:

$$P(A) = N_o(\frac{4.3 * A}{S})^{3.3}exp(-\frac{4.3 * A}{S}),$$

where N_o is a normalization factor and S is a parameter. A numerical factor 4.3 is introduced to adjust the scale of distribution so that parameter S be equal to the mean value of the response distribution. The results of the fit of calorimeter signals to this function are shown in figure 5. Thus, the response function of the calorimeter to protons, which gives a probability, $P(x)$, to get a response $E_r = x * E$ for a proton of energy E can be described by the function

$$P(x) = N_o(14.9 * x)^{3.3}exp(-14.9 * x),$$

with proton energy, E, as a unique parameter. Normalization factor N_o=1.683.

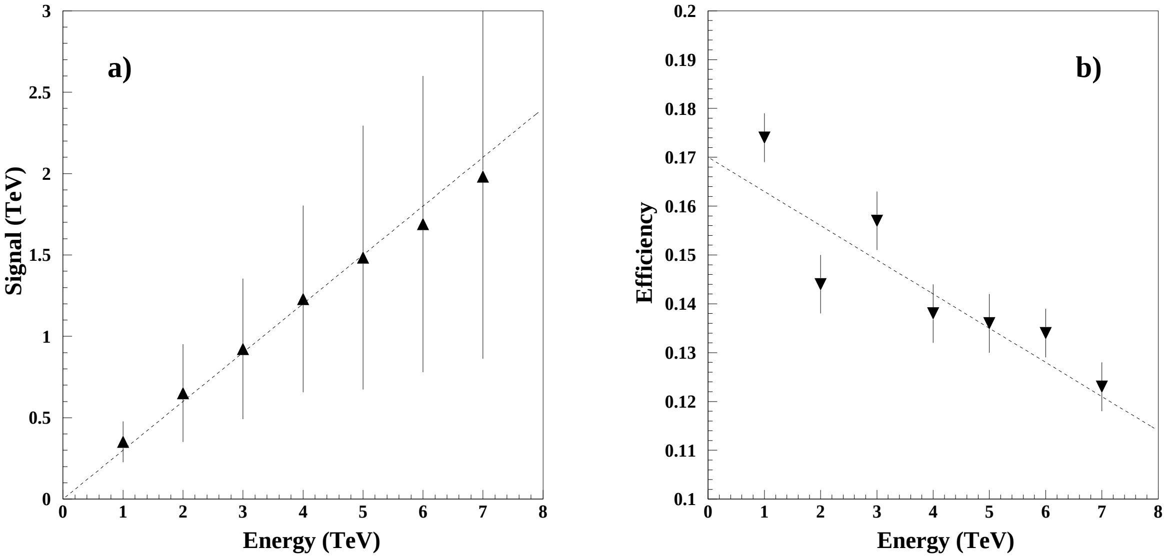

Figure 6: Dependence of the mean calorimeter response, a), and the efficiency, b), on the energy of protons. The error bars in a) are the RMS values of corresponding responce functions. The error bars in b) reflect statistical error. The dashed lines are to guide the eye.

With the above described procedure the energy can be determined only for a part of hadrons which have the point of first hadronic interaction well inside the calorimeter. The depth of the first interaction point for hadrons depends on the nuclear interaction length (NIL) of the absorber. Actually, 55% of hadrons pass through a calorimeter of 0.6 NIL thickness leaving just a trace of one MIP signals. Apart from that, the described above method of measurement of the energy based on the measurement of electromagnetic shower applies only to showers with the maximum inside the calorimeter.

Figure 6 shows the efficiency of the measurement of energy with the "thin" calorimeter as a function of proton energy. A slight decline of efficiency at higher energy is due to the shift in depth of the maximum of the shower with energy.

Spectral index measurement with AMS-02

The energy spectrum of cosmic rays measured at the Earth is known to fall steeply following a power law up to the "knee" at about 3×10^{15} eV [7].

These cosmic rays are believed to be produced in our Galaxy. The power law behaviour is described by a theory, which attributes the energy spectrum to the diffusive shock acceleration in Supernova remnants. Particle acceleration by Supernova remnants expanding supersonically in the surrounding medium together with the effect of diffusion through the Galaxy results in a spectral index of about 2.7, the same for all cosmic ray nuclei. In general, the measurements (Fig.7) are in agreement with this prediction. However, the data on the spectra obtained by direct measurements are, at present, confined to a region below $\sim$ 100 GeV/nucleon. Above that energy the data, mostly obtained in the balloon borne experiments, are scattered and often inconsistent with each other. Measurements with AMS-02 spectrometer using the deflection of particles in the magnetic spectrometer will extend the range of direct measurements up to about 1-2 TeV/n. Calorimeteter extends the measurements up to energies as high as 10 TeV/n. This will make a search for some irregularity in the spectral index possible. A deviation form a unique spectral index in the energy spectrum of any cosmic nuclei would indicate at some unknown phenomena i.e. the presence of some other mechanism of production and acceleration of cosmic rays in our Galaxy [8].

Figure 8a shows different cosmic proton spectra in the rigidity range from 2 to 10 TV/c. The statistics of events corresponds to 3 years of exposure of a 100 % efficient detector with an acceptance of 1 m^2 sr. The solid line histogram gives a spectrum with a unique spectral index of 2.79, as measured by AMS-01 for rigidities below 200 GV/c [16]. This is a "normal" spectrum predicted by the leaky box model. Also shown are the hypothetical spectra with a break in spectral index value at 5 TV/c and the one with an additional peak at 4 TV/c.

In the case of AMS-02 the limiting factor to explore the behaviour of the spectral index is statistics of high rigidity events. Table 1 gives statistics of protons above given rigidity.

For the AMS-02, the statistics in the spectra of fully traced and measured events is much lower than in figure 8a) due to efficiency of calorimeter for proton energy measurement of about 15 % and the value of acceptance of 0.07 m^2 sr. Figure 8b shows the spectra

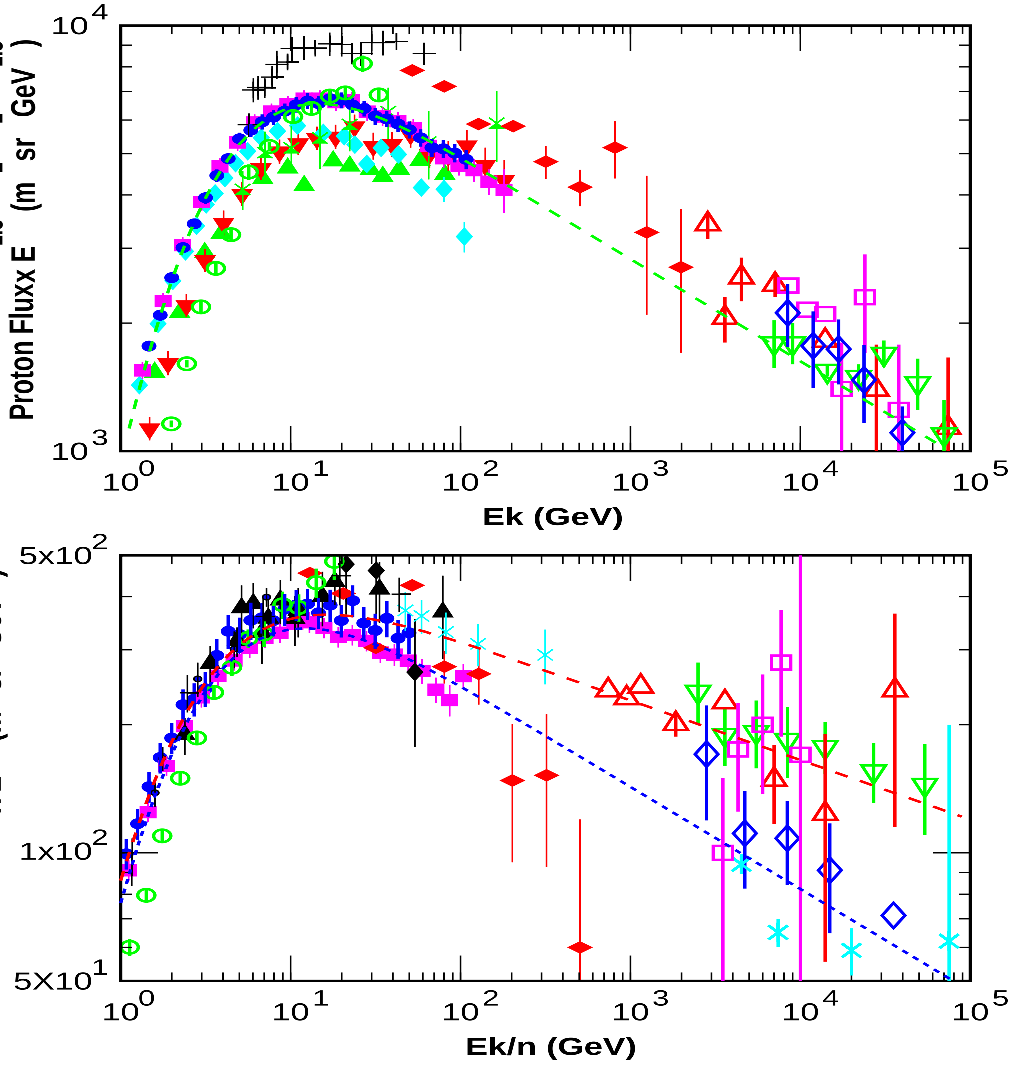

Figure 7: Measured energy spectra of cosmic protons (top) and helium nuclei (bottom). The figure is from [9]. The data are: [10] - crosses; [11] - upward triangles; [12] - open circles; [13] - vertical diamonds; [14] - downward triangles; [15] - circles; [16] - squares; [17] - horizontal diamonds; [18] - downward open triangles; [19] - upward open triangles; [20] - open squares;[21] -open diamonds.

of amplitudes determined using the calorimeter. Although the change in the signal spectra produced by different "abnormalities" does not seem very spectacular, one can clearly see their presence when the measured result is normalized to the amplitude spectrum predicted for protons with rigidity spectrum with the unique spectral index. One can see from Fig.9 that the normalization procedure permits to determine the presence and the position of the anomaly.

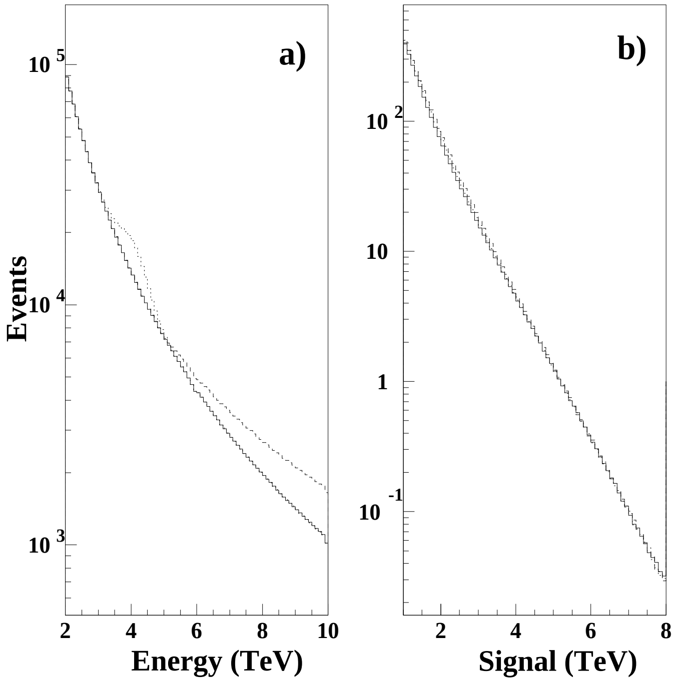

Figure 8: a) Energy spectra of protons. Solid line - ”normal” (leaky box), dash-dotted line - ”normal” plus a peak at 4 TeV, dotted line - a ”knee” : spectral index changes from 2.79 to 2.1 at 5 TeV. b) Spectra of signals measured in 3 years of exposure of AMS-02.

Conclusion

The present study demonstrates the possibility to measure the energy of high energy hadrons with a ”thin” calorimeter. In connection with AMS-02 it is shown that the

Rigidity threshold (TV)	Proton rate $Hz/m^2 \cdot strad$	Statistics in 3 years for 1.0 $m^2 \cdot strad$ detector
1.0	$3.63 \cdot 10^{-2}$	$3.3 \cdot 10^6$
2.0	$1.05 \cdot 10^{-2}$	$1.0 \cdot 10^6$
10.0	$5.89 \cdot 10^{-4}$	$5.7 \cdot 10^4$
100.0	$9.56 \cdot 10^{-6}$	$9.0 \cdot 10^2$
1000.0	$1.55 \cdot 10^{-7}$	15.0

Table 1: High rigidity proton statistics in case of unique spectral index of 2.79.

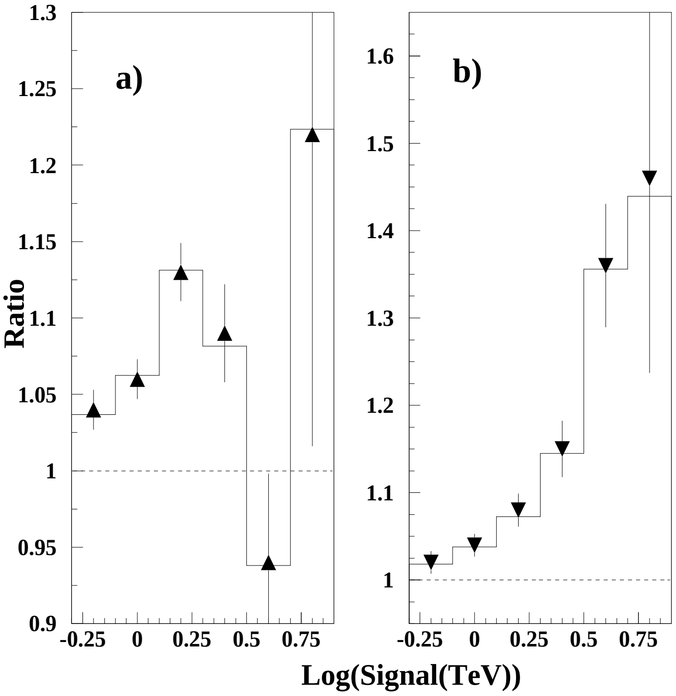

Figure 9: Ratio of the number of events of the given amplitude measured in case of a) the peak at 5 TeV and b) change of spectral index at 4 TeV to those expected from the leaky box prediction. The error bars correspond to statistics for 3 year exposure with acceptance of 0.07 $\mathrm{m}^2 \cdot$ strad and reconstruction efficiency of 15 %.

electromagnetic calorimeter can extend the range of cosmic hadron spectra measurements up to several TV/c making the detection of eventual anomalies in the cosmic particle spectral indexes possible.

The reliability of the results obtained is closely linked to the knowledge of the resolution function, which depends on the pion multiplicity fluctuations. Consequently, the simulation program should properly describe the known deviations from KNO scaling at very high energies [22].

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