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**Identification of positrons and electrons
in the cosmic radiation with the
electromagnetic calorimeter ECAL for
the AMS-02 experiment**

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To my family.

To my friends.

To whom had (erroneously) confidence in me.

Thank you.

Abstract

In May 2011 AMS-02 detector has been successfully installed on the International Space Station (ISS), where it will take data on cosmic radiation from 1 to 1000 GeV for at least 10 years.

Among all scientific objectives of the experiment, one of the most important is the search for Dark Matter (DM), which constitutes $\sim 80\%$ of the Universe matter, but its nature is still unknown. A DM signal can be identified by studying the combined fluxes of positrons, photons, antiprotons and antideutrium. Thanks to its high acceptance and its performances, AMS-02 detector can extend primary cosmic ray physics search to a new energy range with high accuracy.

A key role for these measurements, in particular for the electromagnetic channels, is played by ECAL calorimeter. This subdetector has been developed to measure γ , e^- and e^+ energy with an accuracy of few %. Thanks to its 3D shower reconstruction imaging capabilities, it also has a high separation power between electromagnetic and hadronic showers (*e/p rejection*), essential to eliminate the proton background ($\sim 10^4$) in the positron channel. Finally, it provides the trigger on photons which do not interact in the upper part of the detector (about 72% of the ones in ECAL geometrical acceptance).

In Chapter 1 of this thesis, cosmic ray physics is introduced with details on Big Bang cosmology and on the DM problem. A summary of direct and in particular indirect searches for DM signature is presented.

In Chapter 2 and 3 AMS-02 detector is presented with an overview of each subdetector features and performances. ECAL electromagnetic calorimeter is described in detail.

Chapter 4 describes a flight equalization method, which has been developed and tested on August 2010 Test Beam data, with its application performances on ground and on flight data.

In Chapter 5, the calorimeter capabilities have been used to develop $e^\pm$ identification algorithms, using both ECAL standalone and also tracker momentum measurements. The definition of algorithms, training and testing processes, data-MC comparisons and proton rejection spectrum are described.

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Chapter 1

Cosmic ray Physics

Cosmic ray physics began in the first decades of the twentieth century, when different experiments observed the presence of a very energetic ionising radiation coming from the sky. From the 1930s to the early 1950s, the cosmic radiation provided a natural source of high energy particles, energetic enough to penetrate into the nucleus and produce secondaries. The discovery of positrons, muons, pions and strange particles has been possible in those days thanks to the use of energetic cosmic rays as matter “probe”. By 1950s, accelerator technology allowed to produce energetic particles in the laboratory, becoming the main source used in particle physics studies. Only few decades ago, with the development of new experimental techniques (long duration balloon flights, satellites,...) a new interest on cosmic ray propagation and sources has arisen, in order not only to answer to some fundamental questions on the Universe and Cosmology, but also to test new theories beyond the Standard Model.

1.1 Cosmic ray spectra

The cosmic radiation incident at the top of the atmosphere includes all stable charged particles and nuclei with lifetimes of order 10^6 years or longer. A wide range of energies, ranging from $\sim 10^8$ eV/nucleon to $\sim 10^{20}$ eV/nucleon have been observed, using space experiments to get the best data up to 1000 GeV/nucleon and sub-atmospheric detectors (like balloon experiments or extensive air-shower detectors) to reach the limit of GZK cutoff (10^{20} eV/nucleon) that causes a drop in the flux. The geomagnetic cut-off prevents low energy particles to reach our atmosphere.

It is customary to define “*primary cosmic rays*” the particles accelerated in astrophysical sources, and “*secondary cosmic rays*” the particles produced by the interaction of primaries with interstellar gas. Electrons, protons, helium and stellar nucleosynthesis nuclei (such as carbon, oxygen, iron and so on) are primaries. Nuclei such as lithium, beryllium, and boron (which are not abun-

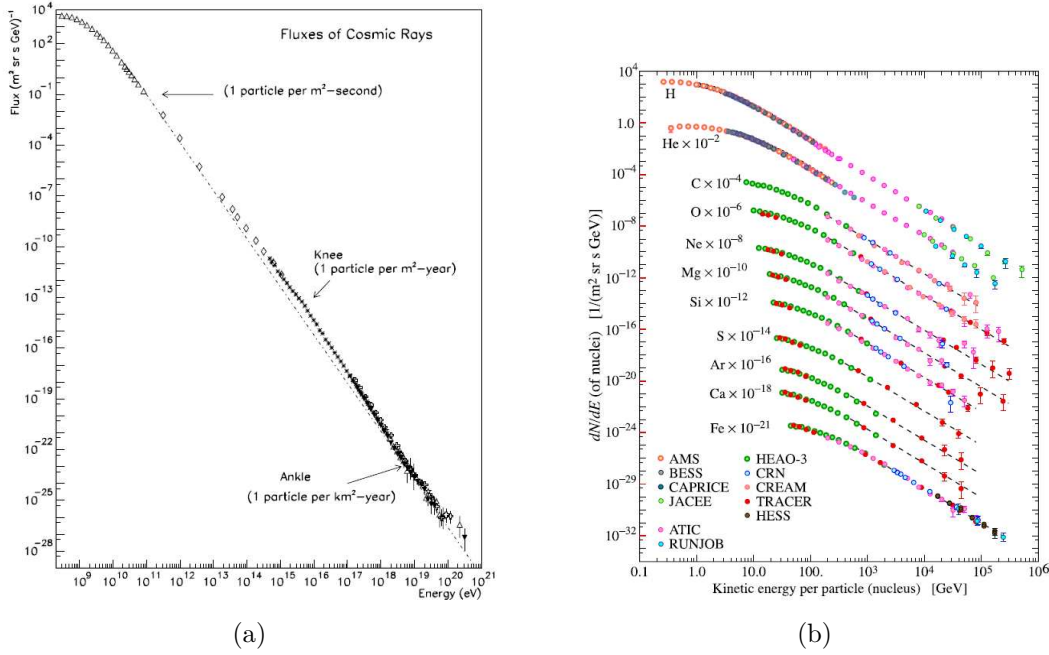


Figure 1.1: a) The all particle spectrum of cosmic rays [1] b) Major nuclei components of the primary cosmic radiation [2]

dant end-products of stellar nucleosynthesis) are secondaries. Antiprotons and positrons are also in large part secondaries, with a possible primary component.

The cosmic radiation is dominated by light nuclei. Roughly it is composed by $\sim 99\%$ protons and nuclei and $\sim 1\%$ electrons. Among the hadrons, $\sim 90\%$ are protons, $\sim 9\%$ are He nuclei and the remaining $\sim 1\%$ are heavier nuclei (see Fig.1.1 for an all nuclei spectrum of cosmic rays). For energies $\lesssim 10$ GeV/nucleon the energy spectra show an attenuation due to *solar modulation*: the effect of solar wind on charged particles which prevents their trajectories to reach Earth.

The primary source of energetic cosmic rays are supernova remnants. Acceleration of charged particles by diffusive strong shocks driven by supernova explosion produces a differential power-law spectrum with spectral index at the source $\alpha_{src} \sim 2$. Diffuse propagation through interstellar medium and magnetohydrodynamic turbulences of the Galaxy steepens the flux to the measured one.

Primary nucleon differential flux is given approximately by [2]:

$$\frac{dN}{dE} \propto E(\text{GeV})^{-\alpha} \frac{\text{nucleons}}{\text{m}^2 \text{ s sr GeV}} \quad (1.1)$$

where E is the energy per nucleon and

$$\alpha = \begin{cases} 2.7 & \text{if } E < 10^{16} \text{ eV} \\ 3.0 & \text{if } 10^{16} \text{ eV} < E < 10^{18} \text{ eV} \end{cases} \quad (1.2)$$

is the differential spectral index of cosmic ray flux. Less abundant species also follow power law spectra with different spectral indexes.

Electrons are primaries: for energies from 10 GeV to 1 TeV the electron spectrum is well described by a power law, like Eq:1.1, with $\alpha_{ele} = 3.0$ and it steepens to $\alpha_{ele} = 3.3$ at higher energies.

Positrons are mostly secondaries. e^- and e^+ differential flux is shown in Fig.1.2. Structures in the absolute flux or in the $e^+/(e^+ + e^-)$ flux ratio could be

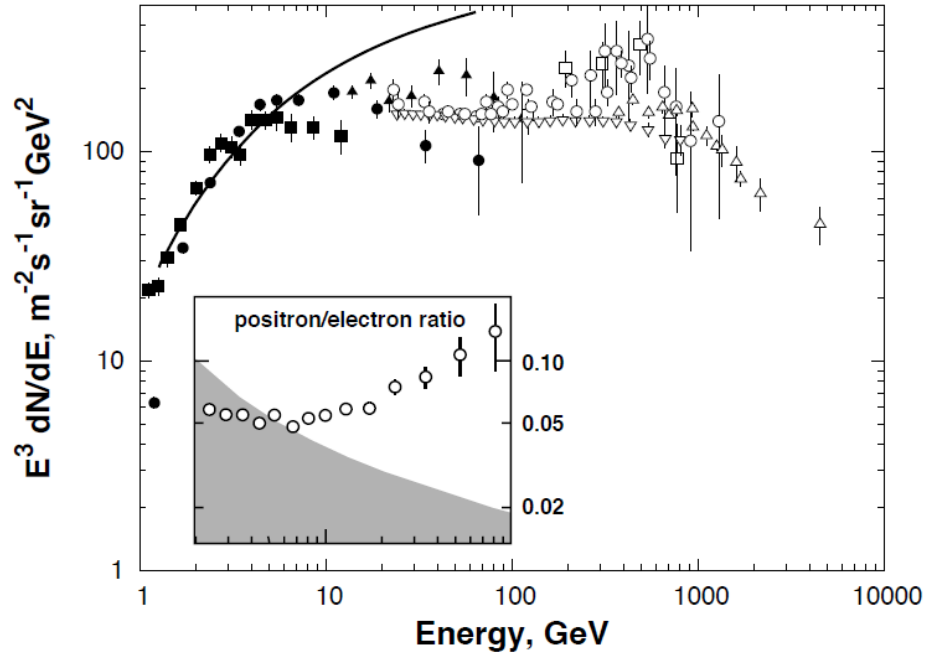


Figure 1.2: Differential spectrum of e^+ plus e^- multiplied by E^3 [2]. The continue line shows the proton spectrum multiplied by 0.01. The inset shows the e^+/e^- ratio measured by PAMELA [5] compared to the expected decrease.

an indirect evidence of an alternative positron primary source.

Among anti-hadrons, only anti-protons have been directly measured. The ratio of $\bar{p}/p$ is $\sim 2 \times 10^{-4}$ above 10 GeV [3], while no antideuteron or antihelium nuclei have been found in the cosmic radiation. The upper limit on the flux of antideuterons around 1 GeV/nucleon is approximately 2×10^{-4} nucleon/ ($\text{m}^2 \text{ s sr GeV}$) [4].

1.2 Big Bang cosmology

Big Bang cosmology is the theory which describes the evolution of the early Universe, starting from a fraction of a second up to now. This theory (which is today validated by different observations like the Universe expansion, the presence

of the cosmic radiation background CMB and the abundance of light elements) is based only on two fundamental principles:

- *Cosmological Principle*: On a large scale ($\gtrsim 10^8$ light years), large enough to include many clusters of galaxies, the Universe is assumed to be homogeneous and isotropic at every point. All positions in the Universe are physically equivalent [6].
- *General Relativity Equivalence Principle*: equivalence of inertial and gravitational mass. For every space-time point in an arbitrary gravitational field it is possible to choose a “locally inertial coordinate system” such that, within a small region of the space-time point, laws of nature can be described by special relativity [6]. The Equivalence principle allows a geometrical description of gravitation, so that the space-time geometry is determined by the distribution of masses.

According to the cosmological principle, it is possible to describe the geometrical space-time properties of the Universe using the Robertson-Walker metrics:

$$ds^2 = dt^2 - a^2(t) \left[\frac{dr^2}{1 - kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2) \right] \quad (1.3)$$

where $a(t)$ is the scale factor which determines the Universe expansion, and k is a parameter which describes the spatial curvature (constant according to homogeneity assumption). Speed of light is set to $c = 1$ from now on.

Together with Eq:1.3, Einstein equations applied to cosmological principle lead to the Friedmann-Lemaître equations, which describe the Universe dynamics:

$$H^2(t) = \frac{\dot{a}^2(t)}{a^2(t)} = \frac{8\pi G}{3}\rho - \frac{k}{a^2(t)} + \frac{\Lambda}{3} \quad (1.4)$$

and

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \quad (1.5)$$

where $G=6.674 \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$ is the Newtonian gravitational constant, p is the isotropic pressure, ρ is the energy density and $H(t)$ is the Hubble constant. The Hubble constant measures the expansion rate of the Universe and it is related to the recession velocities of galaxies via the Hubble law:

$$v = H_0 d = cz \quad (1.6)$$

where v is the galaxy recession velocity with respect to the observer at distance d . Eq:1.6 is valid at small distances d , i.e. at low redshift parameter $z \ll 1$.¹

¹The underscript 0 for cosmological parameters (like H_0 in Eq:1.6) usually refers to the measured value in our epoch: $H_0 \equiv H(t_0)$.

Finally, Λ is the Cosmological Constant, which can give a contribution associated with the vacuum energy in quantum field theory. This term, related to the so-called “Dark Energy”, constitutes today one of the most fundamental field of research in astrophysics and cosmology.

It is common to define several other measurable cosmical parameters. A critical density ρ_c is defined using Eq:1.4 such that $k=0$ when $\Lambda=0$ (a spatially flat Universe without Cosmological Constant):

$$\rho_c = \frac{3H^2}{8\pi G} = 1.05 \times 10^{-5} h^2 \text{ GeV cm}^{-3} \quad (1.7)$$

where the scaled Hubble parameter h is defined as $h \equiv H / (100 \text{ km s}^{-1} \text{ Mpc}^{-1})$. The adimensional cosmological density parameters $\Omega_i = \rho_i / \rho_c$ are defined as the energy density ρ_i relative to the critical density ρ_c for the contributions of matter (Ω_M), radiation (Ω_R), cosmological constant (Ω_Λ) and curvature (Ω_k). Using these definitions, Eq:1.4 becomes:

$$1 = \Omega_k + \Omega_M + \Omega_\Lambda \quad (1.8)$$

where the radiation contribution is set to $\Omega_R \ll 1$ according to CMB temperature observations (more details in next section).

1.2.1 Experimental measurements of cosmological parameters

The most important cosmological parameters measurements are:

- **Hubble constant direct measurement:** Using the period-luminosity relations for Cepheid variable stars, it is possible to obtain the distances of several galaxies. The Hubble Space Telescope Key Project [7] measured the recession velocity for type Ia Supernovae located in nearby galaxies (i.e. $z \ll 1$) and estimated $H_0 = 74 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ using Eq:1.6.
- **CMB spectrum:** The Cosmic Microwave Background is one of the observable relics of the Big Bang. Photons were generated in the early Universe and underwent the last scattering at the recombination time (when H atoms were formed from cosmological plasma, leading to a “transparent” Universe). Today the radiation density is dominated by the energy content in the CMB. Its spectrum today is that of a blackbody. The FIRAS experiment on COBE satellite determined the CMB temperature $T_{CMB} = 2.725 \pm 0.001 \text{ K}$ [8], corresponding to $\Omega_R = 2.47 \times 10^{-5} h^{-2} \ll 1$.
- **Supernovae Ia measurement:** for non-nearby Supernovae Ia stars, Eq:1.6 doesn't hold. In this case, a more complete relation relates distance and redshift:

$$d_L = \frac{1}{H_0} \left(z + \frac{z^2}{2} (1 - q_0) \right) \quad (1.9)$$

where d_L is the luminosity distance and $q_0 = \frac{1}{2}\Omega_M - \Omega_\Lambda$ is the Universe deceleration parameter. Eq:1.9 is well approximated by Eq:1.6 for $z \ll 1$. It is worth to point out that Ω_Λ is the one only contribution to Universe expansion acceleration, and the relative weight between Matter and Cosmological Constant energy contribution defines the sign of Universe acceleration. Using Eq:1.9 and the definition of q_0 for a set of $z > 1$ Supernovae Ia stars, it is possible to determine a confidence interval for q_0 .

Using the described techniques, with other indirect measurements like CMB anisotropies, a confidence region for cosmological parameter values has been defined. Fig:1.3 reports the actual state of research, which constraints the parameters to $\Omega_\Lambda \sim 0.7$, $\Omega_M \sim 0.3$, $\Omega_k \sim 0$; we live in a nearly flat expanding Universe dominated by Matter ($\sim 30\%$) and Cosmological Constant ($\sim 70\%$). The next section shows that “ordinary” matter contributes to a small fraction of Ω_M . The search of the nature of the rest of the Universe matter (*Dark Matter*) is one of the most relevant research field of modern astrophysics and cosmology.

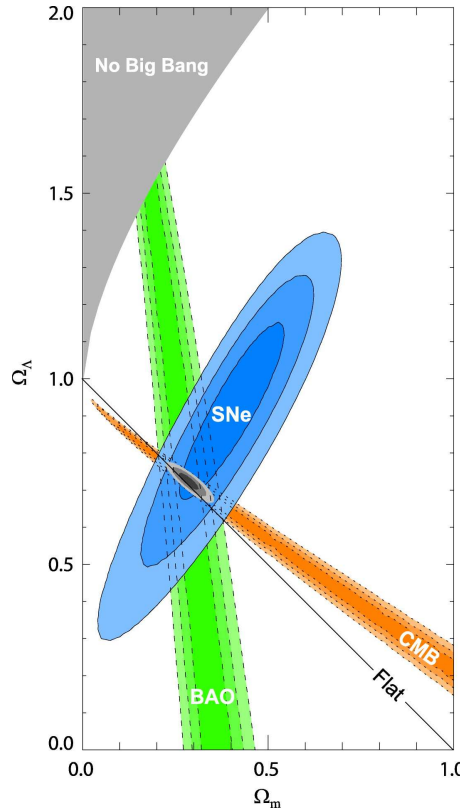


Figure 1.3: Contours at 68.3%, 95.4% and 99.7% in the Ω_Λ and Ω_M plane from the CMB, BOA and SNe Ia set observations [9]

1.3 Dark matter

The first historical evidence of Dark Matter (DM) existence is the measurement of galactic rotation curves: observation of gas clouds in galaxies shows that the rotation velocity tends to a constant as the distance from the galaxy center increases. If the visible matter (i.e. stars) uniquely contributed to the mass of the galaxy, then the rotation velocity outside the luminous disk would decrease proportionally to $1/\sqrt{r}$. Instead, in most galaxies, the rotational velocity tends to a constant for large values of r (see Fig:1.4). This implies the existence of a *dark halo* with $\rho(r) \propto r^{-2}$, or $M(r) \propto r$.

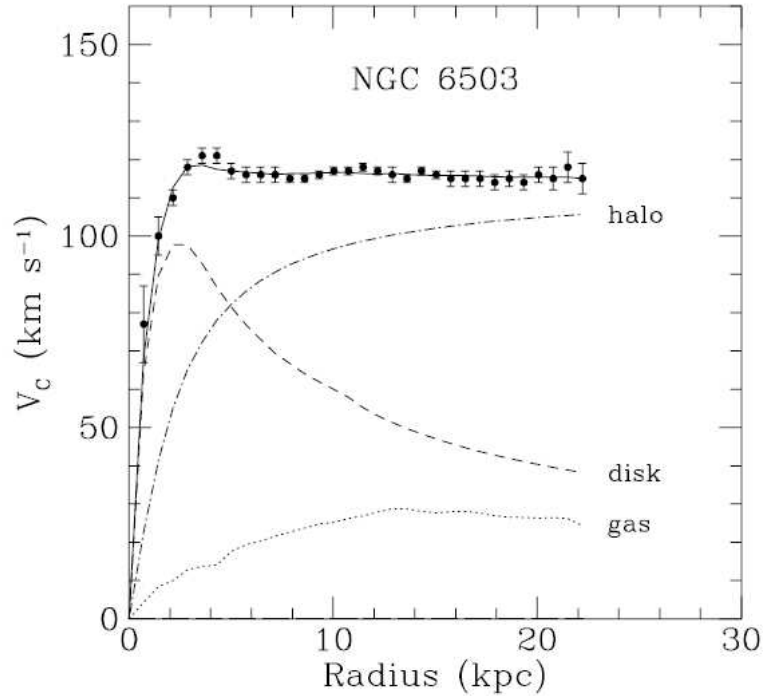


Figure 1.4: Rotation curve of the spiral galaxy NGC 6503. The dashed lines show the rotation curve expected from the disk material (stars) alone, the dot-dashed is the one from the dark matter halo alone [12].

More recently, a strong confirmation of DM existence came from the studies about the Universe barionic matter. The estimation of barionic (i.e. “ordinary”) matter density in the Universe involves different methods, all of which give the same results. The most accurate of this methods is based on the formation of light nuclei during Big Bang nucleosynthesis. The actual observations are consistent with nucleosynthesis hypothesis only if the density of ordinary barions is constricted in a narrow range of values. In particular, the Deuterium to Hydrogen ratio is very sensitive to the baryon density. Recent measurements of D/H ratio,

together with nucleosynthesis predictions, estimate for the barionic matter contribution $\Omega_B \sim 0.03$, which is also in agreement for different nuclei abundances like ^3He , ^4He and ^7Li [10]. This result has been confirmed by other independent observations, like the absorption of light from very distant quasars by intermediate gas and CMB measurements [11]. The cosmic density of (optically) luminous matter is $\Omega_{lum} \sim 0.003 \ll \Omega_B$, so most baryons are optically dark, probably in the form of a diffuse intergalactic medium. The comparison of these results with the measured Matter contribution Ω_M shows that most of the matter in the Universe is not only invisible, but it also has a non-nucleonic nature. This contribution is called *Dark Matter* (non luminous and non absorbing matter), with $\Omega_{DM} \sim 0.25$.

The widely accepted hypothesis is that DM is a *Big Bang Relic*, i.e. a specie of particle observable today, predicted by Big Bang cosmology and bringing informations about the very first epoch of our Universe.

The primordial Universe can be described as a thermodynamic gas in equilibrium, with different species of particles *freezing out* (going out of equilibrium) at different times. When the interaction rate $\Gamma(t)$ of a particular kind of particle with the rest of the environment is well below the Universe rate of expansion:

$$\Gamma(t) \ll H(t) \quad (1.10)$$

then that particular species freezes out and expands without interactions, like a free gas, with a distribution strictly connected with equilibrium. A clear example is CMB, which is the Big Bang relic of photons which underwent the last scattering ~ 100000 years after Big Bang.

Boltzmann equation describes the freezing out of Big Bang relics. The highest relic abundance is obtained by *Cold Relics*, stable particles non-relativistic at freeze out (in opposition to *Hot Relics*, relativistic at freeze out), with an interacting cross section typical of Weak Interactions. These family of particles are usually called WIMP (Weakly Interacting Massive Particles).

Supersymmetric (SUSY) particles are one of the most likely WIMP candidates. Supersymmetry is a fundamental symmetry that relates elementary particles to *superpartners*, whose spin is different by $1/2$. In a theory with unbroken supersymmetry, for every type of boson there exists a corresponding type of fermion with the same mass and internal quantum numbers, and vice-versa. SUSY was firstly introduced to cure the “naturalness problem” of Standard Model Higgs boson at the electroweak scale. In supersymmetric theories, R -parity is conserved: supersymmetric particles have $R = -1$, while ordinary particles have $R = 1$. This symmetry prevents the Lightest Supersymmetric Particle (LSP) to decay. The LSP in the Minimal Supersymmetric Standard Model (MSSM) is the *Neutralino* χ^0 , a fermionic linear superposition of the supersymmetric partners of the photon, the Z boson and the two neutral CP-even Higgs boson. Neutralinos could still be present in the Universe as a *Cold Massive Weak Relic*, and they

could account for the Dark Matter density energy of the Universe if their mass is of the order of TeV. The best direct limit on LSP mass has been established by ALEPH experiment at LEP II: $M_{LSP} > 38$ GeV [13]. The next limit (or evidence) for neutralino from collider experiments will come from LHC experiments.

Dark Matter has played a relevant role in the evolution of the Universe. Immediately after the Big Bang, all matter is relativistic (hot); during the expansion, the Universe cools down until it reaches the temperature at which DM particles decouple from the rest. For SUSY, this happens at the temperature corresponding to 1 TeV. DM, being heavy and non-relativistic, starts to arrange in gravitational structures: the galactic halos. When baryons decouple, they are gravitationally attracted inside DM aggregations to form galaxies. Therefore DM forms the seed of galaxies.

1.3.1 Direct DM searches

As already stated, WIMPs are gravitationally trapped inside galaxies, with a rotational velocity relative to the galactic center similar to that of the stars (~ 220 km/s at the Solar System). Despite they are extremely difficult to be directly detected because of their weak interaction with matter, at these velocities WIMPs can undergo elastic scattering with nuclei. Recoil energies are in the range from 1 KeV to 100 KeV, depending on WIMP mass, with an expected rate of the order of 1 event per day per kg of detector. In order to detect these recoils, detectors must be sensitive to KeV energies. They must also be radio-pure to eliminate natural radioactivity background as much as possible. According to standard WIMP models, Earth is surrounded by an halo of WIMPs, with a distribution of velocities centered at about 200 km/s. Because of the rotation of the Earth around the Sun, it should be possible to observe an annual modulation of the interaction signal. Since the most probable recoil energy of a nucleus is proportional to the incident WIMP velocity, different recoil energy peaks should be observed in June (when the rotation velocity of the Earth sums up to that of the solar system) and December (when the two velocities are opposite). DAMA/LIBRA experiment at Gran Sasso [14] and CoGeNT experiment at Soudan Underground Laboratory [15] measured an annual modulation in their event rate. Elastic scattering of a light WIMP dark matter candidate with mass $m \sim 5 - 10$ GeV is compatible with this signal and also with null results from other experiments [16].

1.3.2 Indirect DM searches: the positron channel

In the standard model of astroparticle propagation, electrons are primaries generated by supernova remnants and, differently from protons, are subject to energy loss processes during their propagation through the interstellar medium (the most relevant are Synchrotron radiation and Inverse Compton). As a consequence

of this, high energy electrons we observe are mainly generated in our galaxy: energy losses prevent extragalactic primary electrons to reach the Earth. Moreover, electron and proton spectra have different shapes. In this context, positrons are secondary cosmic rays originated by the interaction of primaries (mainly protons) with the interstellar medium. In a conventional *Leaky Box* model of cosmic ray propagation, the positrons-to-electrons ratio (or *positron fraction*) is a monotonic function of the particle energy [17]. A deviation from this behavior in favor of positrons may be the hint of an additional source of primary positrons.

Different experiments have measured a deviation of positron fraction ratio from standard expectations.

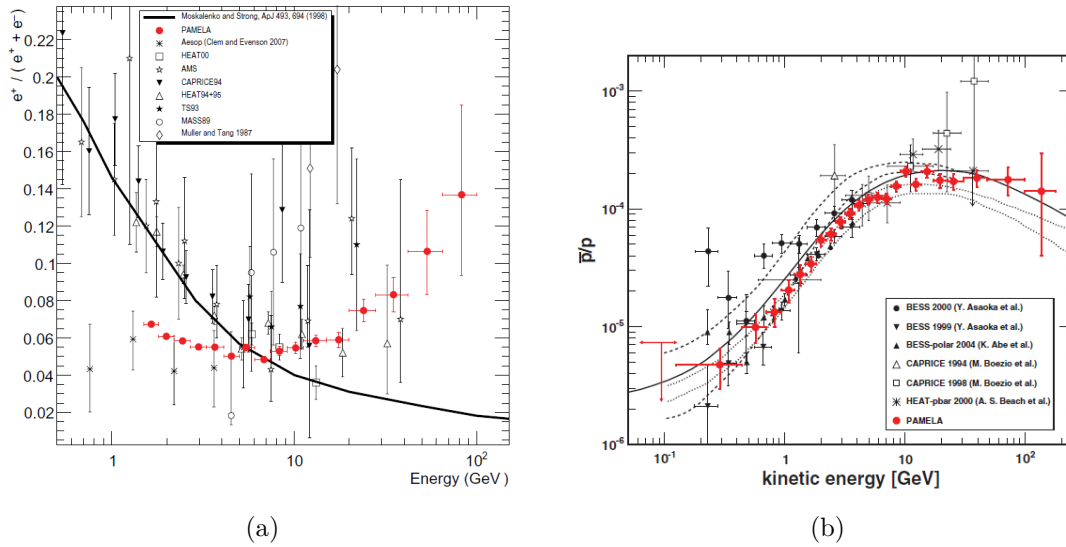


Figure 1.5: a) Positron fraction measured by different experiments (red dots are PAMELA data) [18]. The solid line represents the expectation from a pure secondary production of positrons; b) antiprotons to protons ratio obtained by different experiments (red dots are PAMELA data) with theoretical calculations for several pure secondary $\bar{p}$ production models [3].

The most recent result comes from PAMELA experiment, a satellite experiment launched in 2006 at an altitude ranging from 350 to 600 km. It uses a tracking system and a magnet to recognize the particle charge and discriminate between $e^\pm$ up to an energy ~ 100 GeV. Fig:1.5.a shows the PAMELA positron fraction measurement, compared with previous experiments. While the disagreement in the low energy part of the spectrum is to be ascribed to the time-dependent solar modulation effects on charged particles (the solar modulation cycle is ~ 11 years, correlated with solar activity), the rise above 10 GeV is an evidence of the existence of a primary e^+ source. In order to explain this excess, many solutions have been proposed, from pure astrophysical ones (pulsars or nearby SNR) to DM contributions.

The most problematic issue in order to explain experimental data with the DM hypothesis is the asymmetry between leptonic and hadronic data. As reported in Fig:1.5.b, $\bar{p}/p$ ratio measurement is consistent with a pure secondary production of antiprotons. The hypothesis of a neutralino signature to explain these features requires a very high mass (>10 TeV) and ad-hoc assumptions on the decay channels. Moreover, to explain the positron excess with DM contributions, the average annihilation rate $\langle \sigma v \rangle$ requires a boost factor of the order $\sim 10^3$ with respect to the expected one. Other hypothesis involve an unstable DM particle which decays with a lifetime $\tau \sim 10^{26}$ s [19].

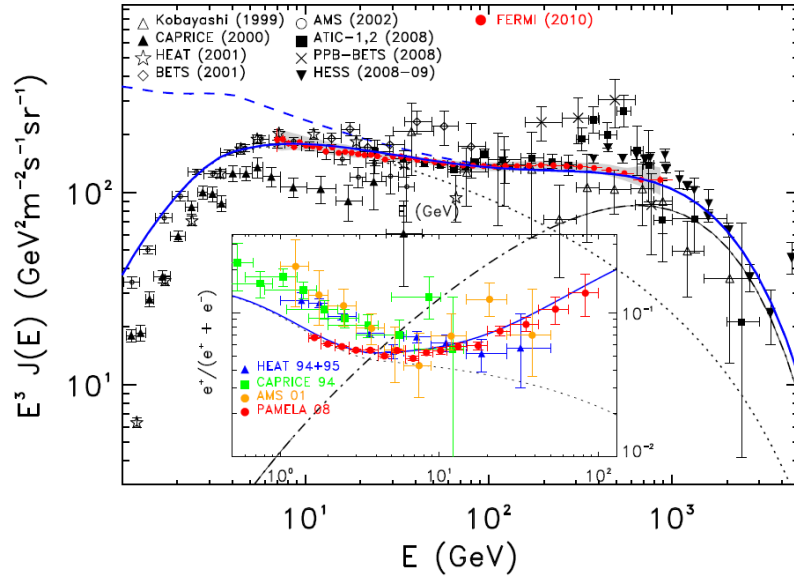


Figure 1.6: The $e^+ + e^-$ spectrum and positron fraction (in the box) for several experiments. The blue solid line represents the total contribution as a sum of standard component (dotted line) and primary pulsar $e^\pm$ component (dot-dashed line), assuming a spectral index 1.5 and energy cut-off 1.2 TeV [20].

Another interpretation of the positron excess is the pulsar hypothesis. Pulsars are isolated, rotating, magnetized neutron stars. The core star is surrounded by a magnetosphere of fully conducting plasma. Electrons accelerated in the magnetosphere of pulsar emit synchrotron gamma rays, which undergo pair production interacting with the high electromagnetic field in this environment. Not all charged particles are tied to the closed magnetic field lines: in a narrow region surrounding the magnetic axis, inside the so-called “light cylinder”, field lines are open, and particles dragged off the poles of the neutron stars can escape. Pulsar positrons that escape nebula contribute to the high energy end of CR positron component, being their spectrum “harder” than the secondary positron

one. Pair production processes in the magnetosphere of pulsars produce therefore high energy positrons which can explain the observed excess.

Positron spectrum from pulsar nebulae exhibits a power-law behavior like Eq:1.1 with a cut-off at high energies. The typical spectral index range is from 1 to 2, while the cut-off energy depends on pulsar age. For a typical medium age pulsar ($T \sim 10\text{-}100$ Myr) the natural range for the cut-off energy is 0.1 - 10 TeV. Because of positron energy losses, only nearby pulsars less than 1 kpc away can give a significant contribution.

Fig:1.6 is an example on how this hypothesis can fit experimental data.

Positron fraction alone is not likely to distinguish between DM and pulsar hypothesis. An helping hint could come from the measurement of a dipole anisotropy in the electron spectrum, which would favor the pulsar explanation. This is not easy to detect, in particular if several pulsars contribute to the positron excess.

New data in the energy interval 100-1000 GeV would be very useful to see whether the positron fraction has a cut off compatible with the pulsar hypothesis or it can be better described by a DM resonance. AMS-02 experiment will explore this range of energies.

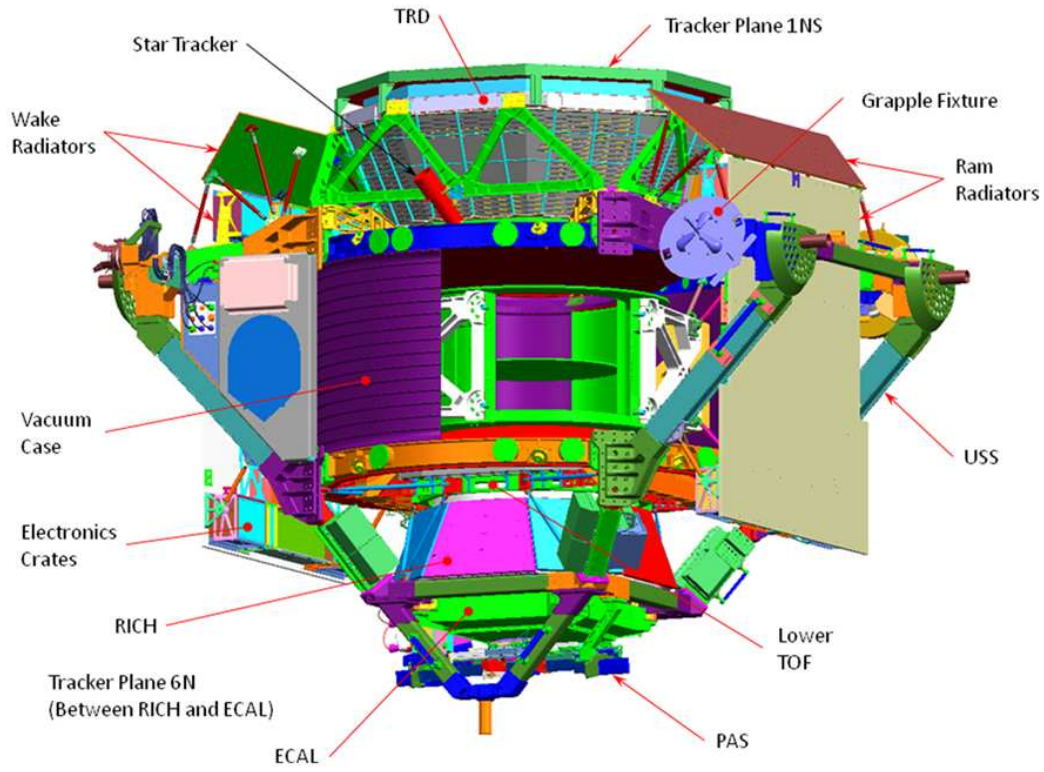
Chapter 2

AMS-02 experiment

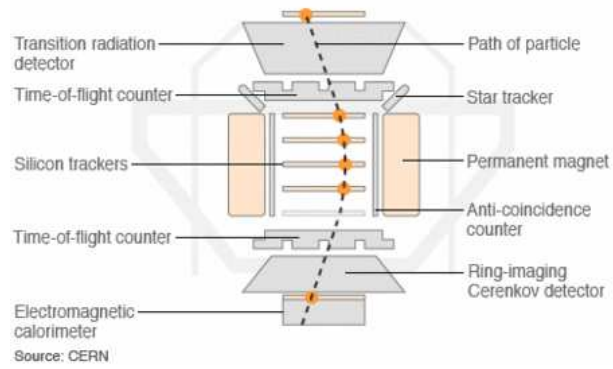
The Alpha Magnetic Spectrometer (AMS-02) is a large acceptance ($0.45 \text{ m}^2\text{sr}$) cosmic ray detector which has been installed on the International Space Station (ISS) in May 2011 during the STS-134 NASA Endeavour Shuttle mission. AMS-02 is an improved version of the AMS-01 space spectrometer, which flew on the Shuttle Discovery (NASA mission STS-91) in June 1998.

AMS-02 has been designed and assembled taking advantages from the experience on high energy particle physics experiments. Its core is composed by a permanent magnet generating a field of about $\sim 0.15\text{T}$ within a cylindrical shaped volume (diameter and height $\simeq 1 \text{ m}$). Seven planes of silicon detectors inside this volume and two planes outside the field volume measure the coordinate of the points used to reconstruct the tracks. The magnetic spectrometer as a whole is able to measure rigidities from fractions of GeVs to few TeVs. At both ends of the magnet two segmented scintillator planes (TOF) are placed. They measure the time of flight of the particle through the planes and provide part of the trigger of the experiment. An anti-coincidence scintillator system (ACC) provides the veto signal in the trigger for side particles. The AMS-02 detector particle identification is completed by other three sub-detectors: a Ring Image Cherenkov (RICH), below the magnet, for the measurement of the particle velocity and charge; the Transition Radiation Detector (TRD), placed on top, for e/p separation and the Electromagnetic Calorimeter (ECAL), at the bottom, for the accurate discrimination between leptons and hadrons and energy measurement. Finally, a star tracker gives the orientation of the detector with respect to the fixed stars with an accuracy of few arc seconds.

The main goal of the AMS-02 experiment is the search for antimatter of primordial origin looking for the presence of anti-nuclei into the cosmic rays flux. The detection of anti-nuclei in cosmic radiation, as a nucleus of anti-He, is a direct proof of the existence of antimatter domains, since the probability of production of anti-He by spallation of primary cosmic rays on the interstellar medium (ISM) is very low. Another relevant goal for AMS-02 concerns the indirect Dark Mat-



(a)

The Alpha Magnetic Spectrometer (AMS-02)

(b)

Figure 2.1: a) AMS-02 apparatus. b): example of particle crossing AMS-02.

ter detection. Thanks to the large acceptance, the long exposure time and the excellent particle identification capabilities, AMS-02 can measure the spectra of the cosmic radiation rare components ($\bar{p}$, e^+ , D , γ) with a great accuracy over a never explored energy range. As already stated in Chap:1, deformation in those spectra could arise from the annihilation of DM particles (for example the neutralino χ^0). The high statistics collected by AMS-02 for all the charged species of the cosmic rays, including chemical species up to Iron and isotopes up to Carbon, will improve the knowledge of the space environment and will help to solve several astrophysics fundamental questions concerning cosmic rays propagation. The AMS-02 detector has also γ -ray astronomy capabilities. γ rays are detectable in two ways: by measurement of a couple of tracks produced in a pair conversion ($\gamma \rightarrow e^+ e^-$) in the material before the Tracker, or by an electromagnetic shower initiated in the electromagnetic calorimeter (in this case ECAL is used as a stand-alone detector).

In this chapter the sub-detectors of the AMS-02 detector are briefly reviewed. A detailed description of ECAL is given in the next chapter.

2.1 AMS-02 apparatus

Requirements for a space-borne high energy physics experiment are extremely challenging. Several constraints are imposed by the transport on the Space Shuttle and by the transfer and the permanence on the ISS, as the strict weight limit of 7 tons, the very low power consumption (≤ 2 kW) and the data rate transfer limited to 6 Mbps.

In addition, the AMS-02 experiment must work properly in space without any external operation for more than ten years and has to withstand vibrations up to 150 dB during shuttle launch and temperature cyclic variations between -30° C and 50° C in vacuum.

Each sub-system and electronics component is produced in prototypes (engineering, qualification and flight models) tested in order to provide the expected physic performances and the mandatory space safety.

2.1.1 Permanent Magnet and Silicon Tracker TRK

AMS-02 permanent magnet is made of 6400 Nd-Fe-B block of sides $5 \times 5 \times 2.5$ cm², arranged in 100 different sections. The magnet has dimensions of a cylinder with ~ 1 m diameter and 1 m height. The bending power of the magnet is $BL^2 = 0.15$ Tm², with a uniform field along the X axis. The geometry minimizes the external field, to avoid mechanical torques and interferences with electronics: the external residual field is below $2 \cdot 10^{-2}$ T.

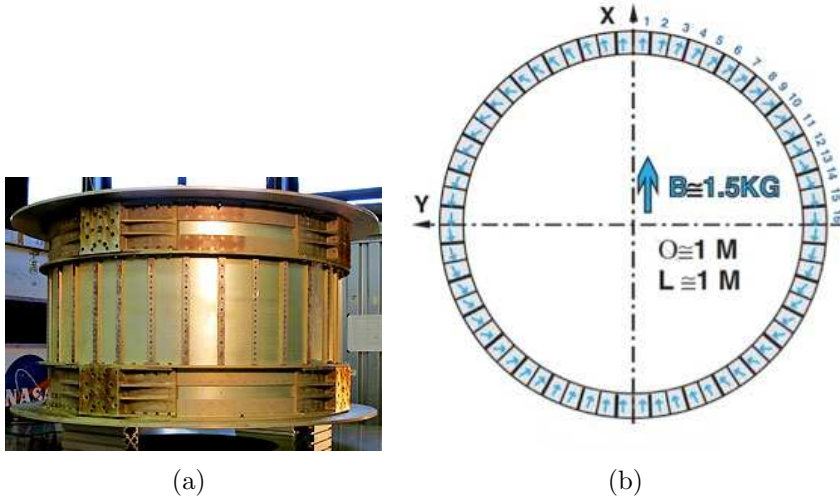


Figure 2.2: Left: AMS-02 permanent magnet. Right: Magnetic field orientation and intensity of the permanent magnet.

Differently from vertex detectors in colliding-beams experiments, used to provide few high precision position measurements near the interaction point, in AMS-02 the tracking information is provided uniquely by the silicon sensors, which implies a large surface area and higher inter-strip capacitances. Each particle trajectory point is determined with an accuracy better than $10 \mu\text{m}$ in the bending direction (Y), and $30 \mu\text{m}$ in the non bending one (X).

Silicon Tracker is composed of $41 \times 72 \times 0.3 \text{ mm}^3$ double-sided silicon micro-strip sensors, for a total detection area of $\sim 6.4 \text{ m}^2$. For readout and biasing, the silicon sensors are grouped together in “ladders” designed to match the cylindrical geometry of the magnet, for a total of 192 read-out units. The ladders are installed in 9 layers. 7 layers are placed inside the magnetic field (Inner tracker). One external layer is placed on top of TRD, and the other one is placed on top of ECAL.

Tracker layers are optically aligned by means of 20 laser beams (*Tracker Alignment System* TAS) and using cosmic rays. The TAS laser diodes, mounted outside of the inner tracker volume, generate straight photon beams that allow to determine the module misplacements with an accuracy better than $5 \mu\text{m}$. The TAS range covers the 7 inner tracker layers.

2.1.2 Transition Radiation Detector TRD

Particles traversing the interface between two different materials have a probability to emit Transition Radiation (TR) X-rays proportional to their Lorentz gamma factor $\gamma = E/m$, where E is the energy and m the rest mass of the particle.



Figure 2.3: Tracker Plane equipped with ladders

The Transition Radiation Detector (TRD) is used to discriminate between electrons, emitting KeV TR X-rays (5 GeV electrons have $\gamma \simeq 10^4$ and 1% probability of TR emission), and protons up to 500 GeV. TRD, placed on top of magnet case, is made up of 328 modules arranged in 20 layers. Layers are oriented parallel and perpendicular to AMS-02 magnetic field axis to provide tracking capability. Each module contains:

- 20 mm thick polypropylene/polyethylene fiber fleece radiators, corresponding to a density of 0.06 g/cm^3 . A large number of interfaces increases the probability of TR X-rays production (up to 50% for 5 GeV electrons);
- 6 mm straw tubes filled with a Xe:CO₂ (80%:20%) gas mixture operating in full-avalanche mode ($\sim 1600\text{V}$).

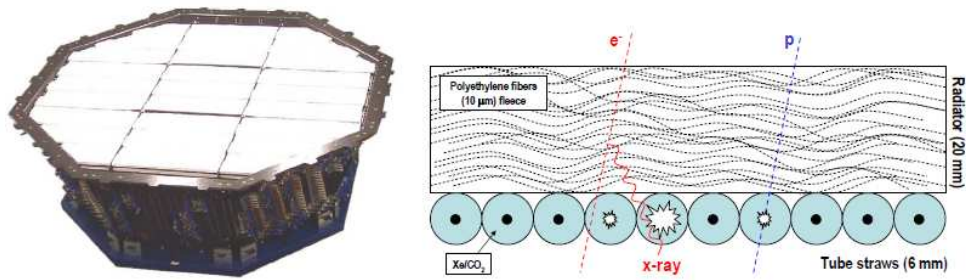


Figure 2.4: Left: a picture of the truncated octagonal pyramid TRD. Right: TR X-rays ($\sim 10\text{KeV}$) produced by electrons in the fleece are efficiently absorbed in the straw tubes, producing a significantly higher signal with respect to MIP ionization ($\sim 1\text{KeV}$) [21]

Inside the TRD, the $\sim 10 \text{ KeV}$ TR X-rays produced by electrons while crossing the fleece interfaces are efficiently absorbed in the straw tubes. Protons, instead,

have a low probability of TR X-rays emission and loose energy only by ionization, producing a lower signal.

Using a likelihood-based selection to combine the measurements in the 20 layers, it is possible to obtain an electron/proton rejection of 10^2 for protons up to 500 GeV, with a 90% electron efficiency.

2.1.3 Time Of Flight system TOF

Charged particle ionization in a scintillating medium causes molecular excitation and dis-excitation processes with the fast emission ($\tau \sim 10^{-8}$ s) of fluorescence light. The photon collection provides a very accurate timing measurements. The AMS-02 Time of Flight system (TOF) is composed by 4 planes of scintillation counters, 2 above and 2 below the magnet, alternatively positioned along the X and Y coordinates. Each counter of the TOF detector is made of a 1cm thick scintillator paddle optically coupled at both ends with two PMTs operating in the fringing field of the magnet without shielding. So PMTs with high capability of working in magnetic fields while keeping good timing characteristics have been chosen for this detector. Straight, tilted and twisted light guides have been designed and built in order to minimize the angle between the direction of the field with respect to the photomultiplier axis for a more accurate response.

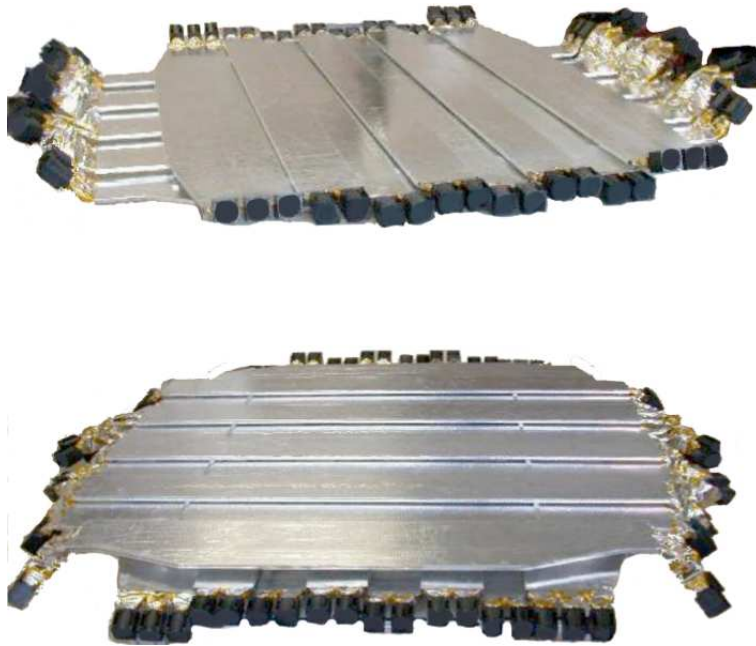


Figure 2.5: TOF planes.

TOF provides not only part of the fast trigger of the experiment, but also a time-of-flight measurement with a resolution of 180 psec sufficient to distinguish upward from downward going particles at a level of at least 10^{-9} . It also pro-

vides a β measurement with a resolution of few % and nuclei absolute charge measurement up to $Z \approx 15$ [22].

2.1.4 Anticoincidence Counter ACC

The Anti-Coincidence Counter (ACC) is composed by 16 paddles arranged on a cylinder surrounding the Tracker. The light coming from the scintillation panels is collected in wavelength shifter fibers of 1 mm diameter and then routed through clear fibers up to the 8 PMTs similar to the TOF ones.

The very high efficiency and a high degree of homogeneity of the scintillating fibers will ensure a reliable and fast ACC veto trigger signal for the high inclination particles, to suppress triggers originating by secondary particles produced by the interaction with the detector support.

ACC veto is used also to reduce the trigger rate during periods of large flux. The measured veto efficiency is better than 10^{-5} , in complete agreement with the design specifications.

2.1.5 Ring Imaging Cherenkov detector RICH

A Cherenkov radiation cone is emitted by a charged particle with velocity β greater than the phase velocity of the electromagnetic field in the material. The properties of the cone depend on the velocity of the charged particle and on the refractive index of the material $n(\omega)$, related to the cone aperture angle θ_C by the relation:

$$\cos(\theta_C) = \frac{1}{\beta n(\omega)} \quad (2.1)$$

The charge of the incoming particle is estimated by measuring the number of produced photons N_γ in a frequency range $d\omega$ for a traversed thickness of material dx :

$$\frac{d^2 N_\gamma}{d\omega dx} = \alpha_{em} Z^2 \sin^2(\theta_C) \quad (2.2)$$

The AMS-02 Ring Imaging Cherenkov detector (RICH) consists of a radiator plane, a conical mirror and a photon detection plane. The detector plane has an empty $64 \times 64 \text{ cm}^2$ area in its center, matching the active area of the electromagnetic calorimeter located below. The radiator consists of an array of 2.7 cm thick aerogel tiles with a refractive index between 1.03–1.05, which surrounds a central $35 \times 35 \text{ cm}^2$ region equipped with 5 mm thick sodium fluoride (NaF) radiator ($n_{NaF} = 1.335$). This combination of radiators optimizes the overall counter acceptance, since the Cherenkov photons radiated by the NaF in large cones will fall within the detection area (see Fig:2.6). Outside the central “hole”, 680 4×4 -multi-anode PMTs are arranged to cover the circular 134 cm diameter surface at the basis of the conical mirror. The radiator and the detection plane are enclosed in the volume of a conical reflecting mirror of height 47 cm. The mirror increases the RICH acceptance reflecting high inclination photons and provide

the necessary photon drift ring expansion, as shown in Fig:2.6. RICH allows to

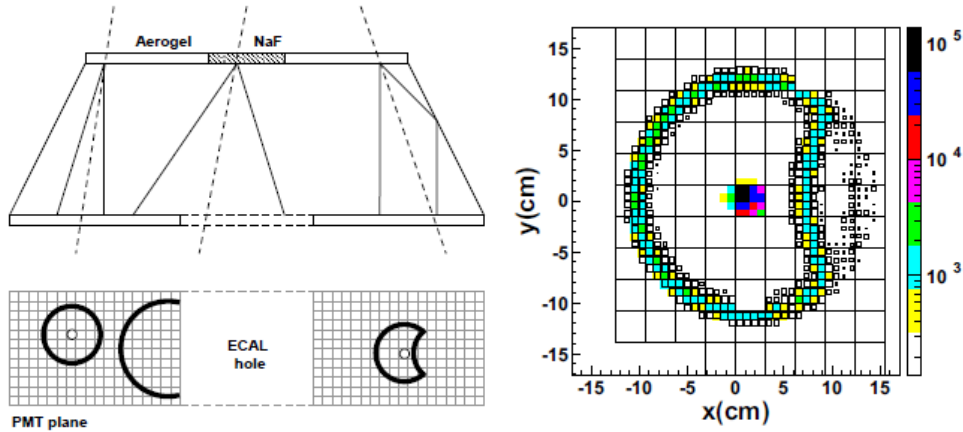


Figure 2.6: Left: RICH techniques to increase reconstruction efficiency. Right: Cherenkov ring for a position fixed beam measured in the 2003 test beam.

measure particle β with a resolution $\sigma_\beta/\beta \sim 0.1\%/Z$. It can also identify nuclei up to Fe ($Z=26$) with a charge confusion not greater than 10%.

2.1.6 Electromagnetic Calorimeter ECAL

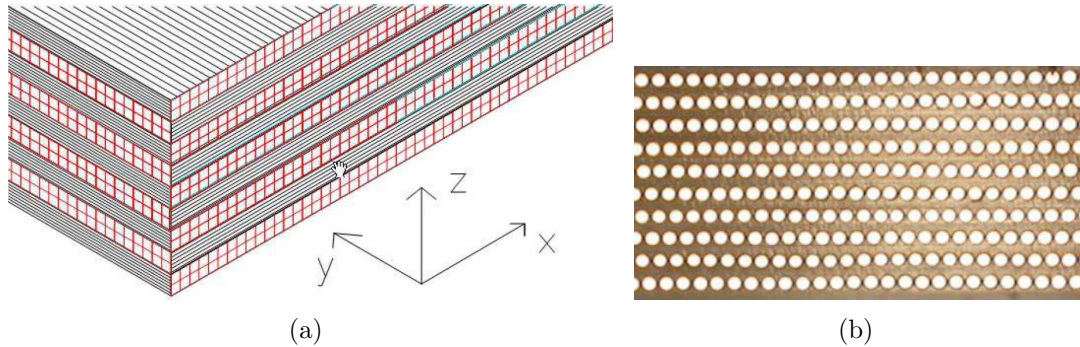


Figure 2.7: Left: ECAL “pancake” geometry. Right: Particular of ECAL superlayer.

The AMS-02 Electromagnetic Calorimeter (ECAL) is a fine grained lead-scintillating fiber sampling calorimeter which allows for an accurate 3D imaging of the longitudinal and lateral shower development. The calorimeter consists of an active volume (“pancake”) composed by 9 Superlayers for a total active area of $685 \times 685 \text{ mm}^2$ and a thickness of 167 mm. The detector imaging capability is obtained by stacking Superlayers with fibers alternatively parallel to the X-axis (5 layers) and Y-axis (4 layers). The pancake has an average density of 6.8 g/cm^3 , for a total weight of 487 kg. Each super-layer is read out by 36 PMTs,

arranged alternately on the two opposite ends. Fibers are read out, on one end only, by four anodes Hamamatsu PMTs; each anode covers an active area of $9 \times 9 \text{ mm}^2$, corresponding to ~ 35 fibers, defined as a “cell” (the minimum detection unit). In total the ECAL is subdivided into 1296 cells (324 PMTs) and this allows for an accurate 3D imaging-sampling of the longitudinal shower profile. The ECAL thickness corresponds to about 17 radiation lengths, including almost all the electromagnetic shower generated by incident electrons or photons. The calorimeter also provides a stand-alone photon trigger capability to AMS-02. The trigger efficiency is 90% at 2 GeV and more than 99% for energies greater than 10 GeV. The ECAL detector will be exhaustively described in the next chapter.

2.1.7 Triggering System

AMS-02 trigger recognizes charged particles passing through the apparatus thanks to the coincidence of fast signal from TOF scintillators. ACC system provides a veto on particles out of AMS-02 field of view. ECAL provides a stand-alone trigger on photons non interacting in the apparatus. *Fast Trigger* FT and *Level1* LVL1 triggers are generated by a logical combination of TOF, ACC and ECAL responses. Possibility of using masks makes the AMS-02 trigger system very flexible. The total LVL1 trigger rate is estimated to vary from 200Hz to 2000Hz, depending on the geomagnetic latitude.

2.2 Charged particle detection

In order to measure the flux of cosmic ray particles, the detector has to be able to measure their charge Ze , velocity v and rigidity R , the latter defined as:

$$R = \frac{pc}{Ze} = \gamma\beta \frac{m_0 c^2}{Ze} \quad (2.3)$$

where p is the relativistic momentum, $\beta = v/c$ is the relativistic velocity, $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor and m_0 is the rest mass. Once Z , v and R are measured, it is possible to infer the particle rest mass using Eq:2.3 and to identify the particle.

The particle velocity β is measured both from TOF and RICH subdetectors. TOF measures the time of flight t of the particle traversing a path $l=L/\cos(\theta)$ between the upper and lower TOF planes, where L is their distance and θ is the trajectory colatitude angle. Given the measure of t , the particle velocity can be inferred by:

$$\beta = \frac{L}{t \cdot \cos(\theta)} \quad (2.4)$$

TOF resolution corresponds to a $\Delta\beta/\beta \approx 0.5\%$, allowing particle velocity to be measured up to $\beta \approx 0.95$. A direct measurement of higher β can be done with RICH detector, using Eq:2.1, allowing a relative precision $\Delta\beta/\beta \approx 0.1\%/Z$ for particles over $\beta_{th} = 1/n$ threshold.

The absolute value of a particle charge Z is obtained by measuring the ionization energy deposit in TOF, TRD and tracker active parts of the detector. According to Bethe-Bloch formula, the average energy lost by a non-electron particle after a path length $d\xi = \rho dx$ through a medium with density ρ , atomic and mass number Z_{med} and A , is:

$$-\frac{dE}{d\xi} = K \frac{Z^2}{\beta^2} \frac{Z_{med}}{A} \left[\frac{1}{2} \ln \frac{2m_e c^2 (\beta\gamma)^2 T_{max}}{\langle I \rangle^2} - \beta^2 - \frac{\delta}{2} \right] \quad (2.5)$$

where $\langle I \rangle$ is the mean ionization energy of the medium, δ is a density correction and T_{max} is the maximum kinetic energy which can be provided to a single electron in a single collision. If the particle β is known, it is possible to infer particle charge Z using 2.5 by measuring the energy deposit in TOF, TRD and tracker layers. Since Cherenkov light depends on Z^2 (see Eq:2.2), also RICH can be used to measure the charge.

Particle rigidity R is measured by the tracker. A particle with charge Z and rigidity R moving in an uniform magnetic field B follows an helix trajectory with radius of curvature

$$\rho = \frac{R}{Bc} \sin(\theta) \quad (2.6)$$

where θ is the pitch angle between particle trajectory and magnetic field. AMS-02 detector magnetic field is not homogeneous and the trajectory is more complicated, but, if the field is known, the reconstruction of the full trajectory (keeping into account energy losses in active regions) can be used to retrieve R . Defining σ_{pos} the spatial resolution of the tracking system in the bending plane, N the number of position samplings and s_B the magnetic field strength along particle path $\int \vec{B} \cdot d\vec{l}$, the relative uncertainty on R can be approximated by:

$$\frac{\Delta R}{R} \approx \frac{R \sigma_{pos}}{s_B \sqrt{N + 4}} \quad (2.7)$$

The *Maximum Detectable Rigidity* MDR is the value of R for which its uncertainty is 100% (i.e. $\Delta R/R = 1$). When the particle rigidity is comparable with the MDR (so the deflection tends to zero), the tracker system provides no information on the charge sign. The tracker resolution is dominated by the signal to noise ratio. The $Z = 1$ particle MDR for the inner tracker is ~ 200 MeV, and can be extended to ~ 2 TeV including the position measurements of both external planes (full span). Energy deposit in silicon strips is proportional to Z^2 , according to Eq:2.5, and full span MDR improves up to 3.8 TeV for $Z > 1$ particles thanks to the higher signal to noise ratio.

Chapter 3

Electromagnetic Calorimeter ECAL

AMS-02 Electromagnetic Calorimeter ECAL has been designed to measure $e^\pm$ and γ energy between about 1 GeV and 1 TeV. The main requirements of this detector are a good linearity, a good energy resolution and, most of all, a high rejection power ($\sim 10^4$) against protons. The fine-grained ECAL structure allows to exploit the shower cascade longitudinal and lateral profile in order to discriminate between electromagnetic and hadronic showers. The calorimeter provides also a stand-alone trigger for non-converting γ inside the geometrical acceptance. All these requirements have been achieved by fulfilling power (<100 W) and weight (<640 kg) space experiment constraints.

3.1 Calorimeter design

ECAL is a lead-scintillating fiber sampling calorimeter in which particles crossing the active volume produce light collected by photomultipliers (PMTs) at fiber end.

The structure is developed to increase the X_0/λ ratio (X_0 is the electromagnetic interaction length and λ the nuclear interaction length), and it consists in a lead-fiber-glue volume ratio of 1:0.57:0.15 cm^3 , an average density of $\sim 6.8 \text{ g/cm}^3$ and a radiation length X_0 of about 1 cm.

The active volume is built up by a pile of 9 “superlayers”(SL) consisting of 11 grooved lead foils (1mm thick) interleaved by 1mm plastic scintillating fibers (Fig:3.1). Fibers are glued by means of optical cement. Each superlayer is designed as a square parallelepiped with 68.5 cm side and 1.85 cm height, for a total active dimension of 68.5 x 68.5 x 16.7 cm^3 , corresponding to $\sim 17X_0$ for perpendicular incident particles.

Light collection readout is done by Hamamatsu R-7600-00-M4 multianode photomultipliers, which have been chosen to fit ECAL granularity and to work in magnet fringing field. Each SL is readout on one end only by 36 PMTs, alterna-

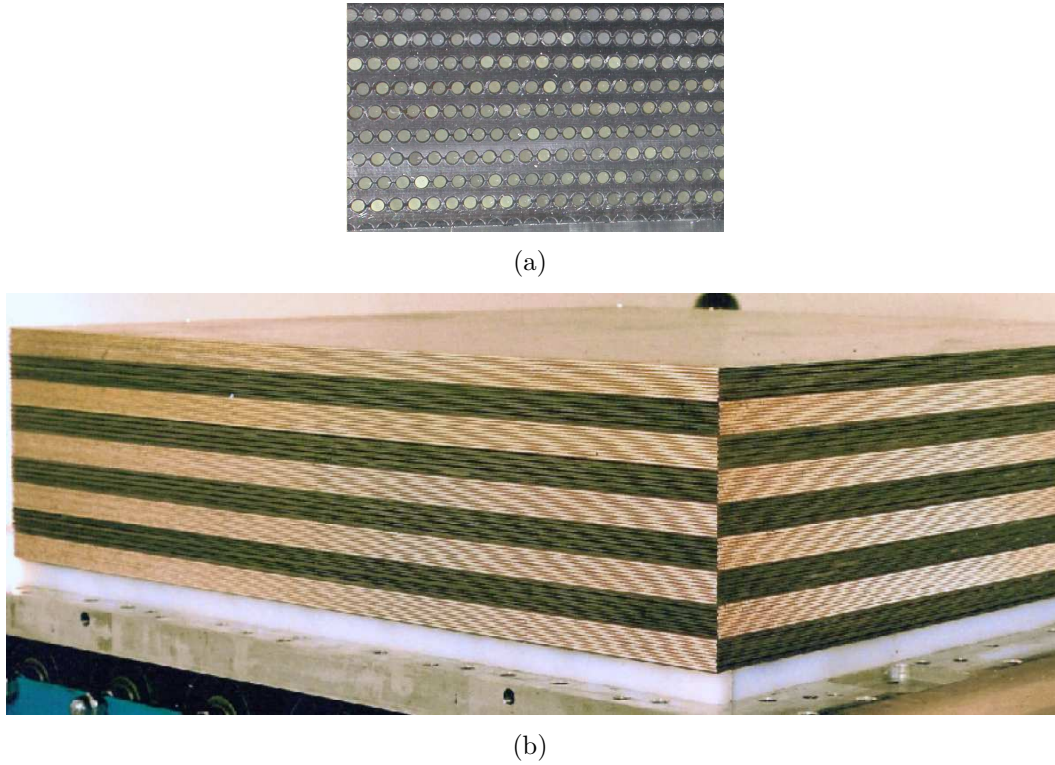


Figure 3.1: a) Particular of ECAL superlayer before milling. b) ECAL active volume.

tively arranged on the two opposite sides to avoid mechanical interference. The coupling to fibers is realized by means of plexiglass light guides, that maximize light collection and reduce cross-talks. Optical contact is enhanced by silicone joints posed on light guides. Finally, PMTs are shielded from magnetic field by a 1 mm thick soft iron square parallelepiped tube, which also acts as mechanical support for the light collection system.

Each PMT accommodates four $8.9 \times 8.9 \text{ mm}^2$ anodes. Anodes define ECAL granularity, for a total of $18 \times 72 = 1296$ readout “cells” (Fig:3.2). 3D imaging of shower development has been achieved by alternating 5 SL with fibers along X axis and 4 SL with fibers along Y axis.

The front-end electronics and digitalization cards are mounted behind the PMT base. In order to obtain the necessary energy resolution on *Minimum Ionizing Particles* (used for detector performance monitoring and equalization) and to measure energies up to 1 TeV using standard 12 bit ADC, digitization is performed at two different gains: *High Gain* for low energy measurements and *Low Gain* for highest ones, with a conversion factor $HG/LG \sim 33$.

Besides the 8 signal from anodes, each PMT last dynode signal is also read-out and its information used both to have a redundant signal in case of anode breakdowns and also to build up ECAL standalone trigger.

PMT High Voltage is provided by a custom programmable HV power supply,

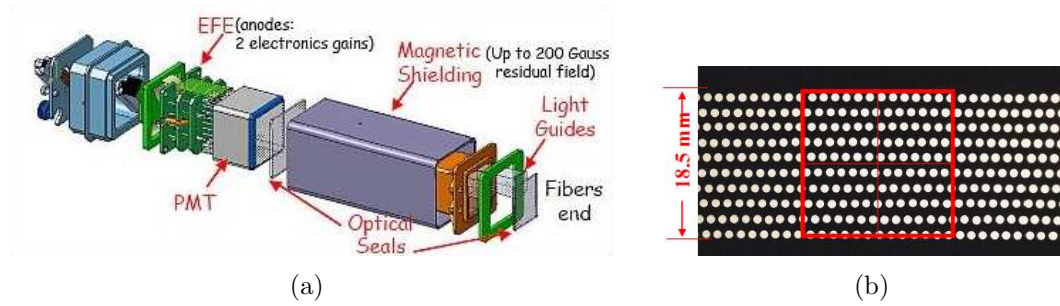


Figure 3.2: a) PMT structure. b) Superlayer fibers readout geometry. PMT anodes (small red boxes) define ECAL granularity.

which sets the average HV PMT value to around 700V, corresponding to a gain factor $\sim 2 \times 10^5$. Only 240 HV channels out of 324 are independent: the others are shared between triggering and non-triggering PMTs (see Sec:3.3). Front-end electronics sends ADC signal to the ECAL Data Reduction board (EDR), where pedestal calculation and zero suppression are performed. Dynode signals are sent to the ECAL Intermediate Board (EIB) that compares them with a programmable threshold to obtain trigger bits. The ECAL TRiGger board (ETRG) produces then the fast and Level1 trigger bits which are sent to the JLV1 AMS-02 trigger board.

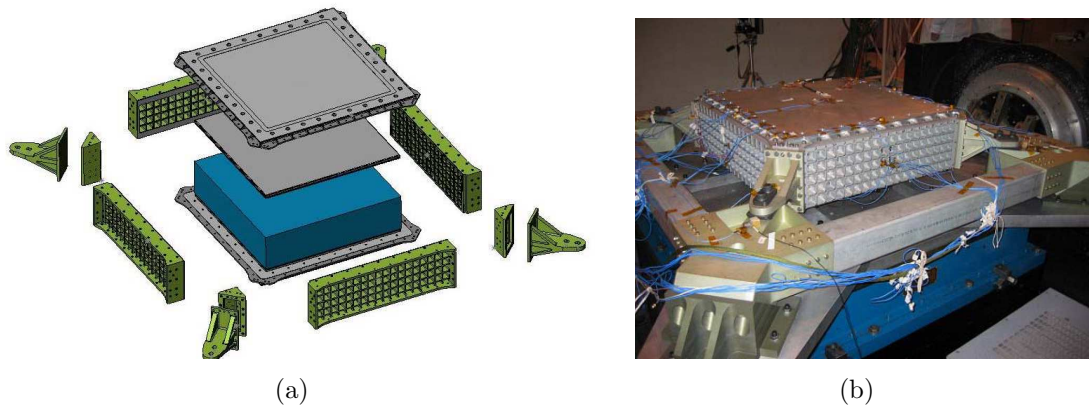


Figure 3.3: a) View of ECAL mechanics. b) Space qualification tests of the detector.

3.2 Detector performances

ECAL has been tested at CERN hadron and electron beams during its development and prototypization. The fully equipped with flight electronics detector has been tested, before its integration with AMS-02, on the H4 CERN beam during July 2007, using protons at energy 100 GeV and electrons with ranging

energy from 6 to 250 GeV.

The first step in the calibration process is to equalize all channels in order to obtain the same response to the same energy deposit. This is a very delicate process, that will affect all the detector calibration. More details are available in Chap:4 .

Energy linearity and resolution can be obtained after correcting for rear leakage, in order to recover the energy not longitudinally deposited in the calorimeter.

The mean longitudinal profile of the energy deposit by an electromagnetic shower is usually described by a gamma distribution [25]:

$$\left\langle \frac{1}{E} \frac{dE(t)}{dt} \right\rangle = \frac{(\beta t)^{\alpha-1} e^{-\beta t}}{\Gamma(\alpha)} \quad (3.1)$$

where $t = x/X_0$ is the shower depth in unit of radiation length, $\beta \sim 0.5$ is the scaling parameter and α the shape parameter. The maximum of the shower can be expressed as following:

$$t_{max} = \frac{\alpha - 1}{\beta} \Rightarrow x_{max} = X_0 \ln(E_0) + \text{const} \quad (3.2)$$

E_0 being particle initial energy.

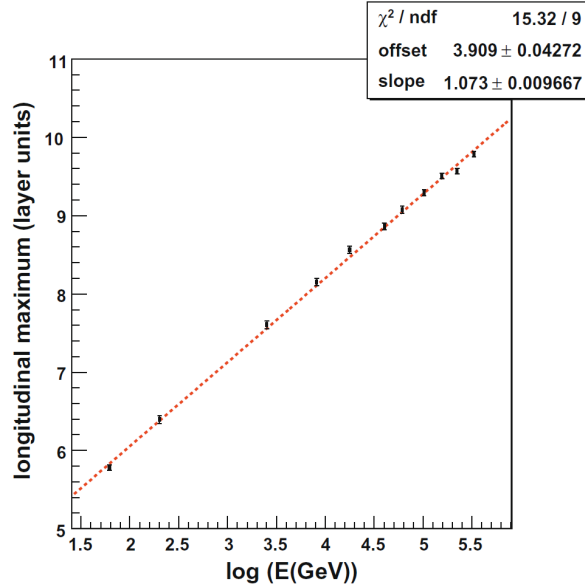


Figure 3.4: Determination of the radiation length in layer units. Each point represents the maximum of each longitudinal profile for electrons at different energies.

Eq:3.2 can be used to evaluate ECAL radiation length. As shown in Fig:3.4, the average longitudinal profile has been fitted for different positron energies using Eq:3.1 and the radiation length measured to be $X_0 = 1.07 \pm 0.01$ layer units,

corresponding to $X_0 \sim 1\text{cm}$ [26]. ECAL total radiation thickness is, therefore, $\sim 16.6X_0$.

Longitudinal leakage is then corrected using the following quadratic function of the last 2 layers deposited energy fraction E_{last}/E_{rec} :

$$\frac{E_{true}}{E_{rec}} = \alpha + \beta \frac{E_{last}}{E_{rec}} + \gamma \left(\frac{E_{last}}{E_{rec}} \right)^2 \quad (3.3)$$

where E_{true} is the true energy, corresponding to the nominal beam energy in a Test Beam environment. An application of rear leakage correction derived in 2007 Test Beam is shown in Fig:3.5.

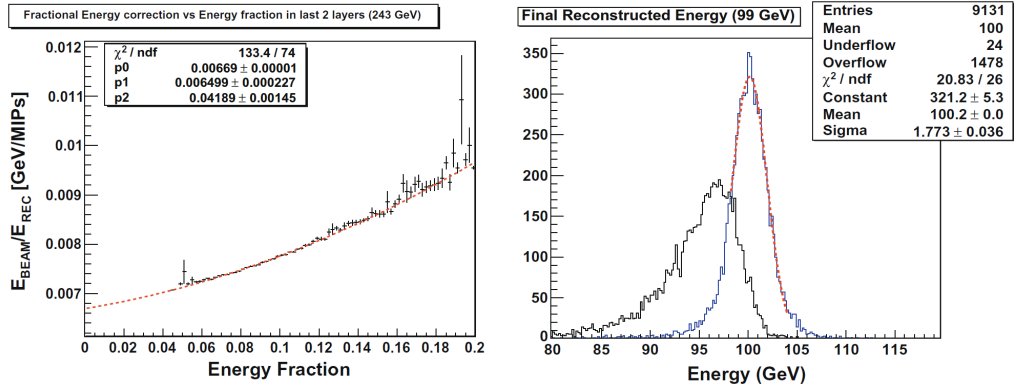


Figure 3.5: Left: energy leakage correction as a function of the last 2 layers deposited energy fraction. Right: The correction recovers the energy tails due to rear leakage.

After longitudinal leakage correction, energy resolution has been measured :

$$\frac{\sigma(E)}{E} = \frac{9.9\%}{\sqrt{E(\text{GeV})}} \oplus 1.5\%$$

for perpendicular particle incidence. Deviation from linearity is less than 1% for energies from 6 to 250 GeV (see Fig:3.6).

Angular resolution is also an important parameter, in particular for gamma ray physics. Using particles impinging perpendicular to the calorimeter, it has been measured to be:

$$\Delta\theta_{68} = \frac{14.5^\circ}{E(\text{GeV})} \oplus \frac{6.3^\circ}{\sqrt{E(\text{GeV})}} \oplus 0.42^\circ$$

where $\Delta\theta_{68}$ is defined as the angular interval containing 68% of reconstructed angles around beam incident angle. The angular resolution improves for higher angles thanks to the higher energy deposit of tilted tracks.

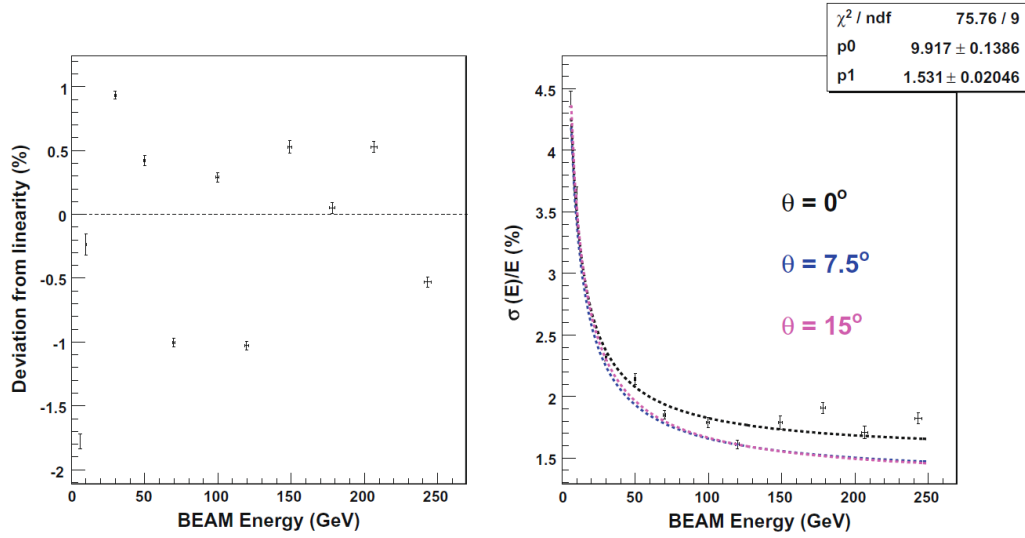


Figure 3.6: Left: Deviation from energy linearity at 0° . Right: Energy resolution for different angles. Resolution improves at higher particle incidence angle because of the larger number of radiation lengths crossed.

3.3 ECAL standalone trigger

AMS-02 calorimeter has a key role in photon identification. γ can be detected in two complementary modes. In the so-called *conversion mode*, they are detected by reconstructing $e^\pm$ pairs from conversion in the material over the inner tracker layers, for an integrated path equivalent to $\sim 20\%$ conversion probability. The tracking system measures the direction of the $e^\pm$ pair; the energy is measured by the tracker itself or by ECAL. This method provides the best determination of the direction of the incoming photon.

About 80% of incident gammas inside ECAL geometrical acceptance do not interact in the upper part of AMS-02 and can be observed only by ECAL, that provides a standalone trigger. ECAL trigger is built up with a granularity of 1 PMT ($1.85 \times 1.85 \text{ cm}^2$): this is a good compromise between a high energy deposit in a single channel (which turns in a better signal to noise ratio) and a good 3D imaging for an angular cut.

ECAL trigger is built up in two steps [23]:

1. *Fast Trigger* is realized by imposing a threshold on each PMT of the most relevant superlayers X2-Y7, as shown in Fig:3.7. Different thresholds are set in each superlayer in order to exploit shower longitudinal development. The default trigger logic requires at least 2 out of 3 superlayers per view with at least 1 PMT over threshold, and the analogical signal is produced in less than 200 ns.
2. in order to discriminate between non-converting photons and charged par-

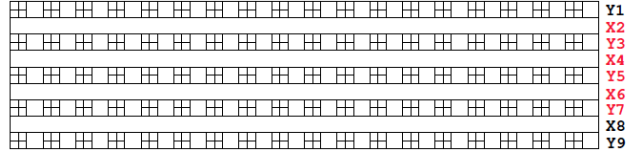


Figure 3.7: In red, ECAL superlayers used for trigger logic.

ticles entering the calorimeter outside its field of view, an angular cut is performed by *Level1 Trigger* to select particles crossing tracker planes, with an incident angle less than 20° (inside ECAL geometrical acceptance). Particle direction is evaluated by taking, for each view, the average position of fired PMTs. *Level1 Trigger* signal is produced by electronics in a time well below $1\mu s$.

The efficiency on photons passing both selection starts from $\sim 20\%$ at 1 GeV and reaches $\sim 99\%$ at 10 GeV, for a total polar orbit rate ~ 115 Hz (approximately 10% of total AMS-02 rate) [24].

Chapter 4

Calorimeter flight equalization

The equalization of the photomultiplier cells allows to obtain a uniform response for the same energy deposit in different cells.

The amplification factor G of a PMT, defined as the ratio between the anode current I_{an} and the photoelectron current I_{pe} , is a function of the feeding HV:

$$G = K \cdot HV^\alpha$$

where K is a constant which depends on dynode configuration and material, and α is a factor proportional to the number of amplification stages.

The response of different PMT anodes to the same energy deposit is not the same, and anodes belonging to the same PMT also have different output spectra. This is due to the different construction features like optical coupling, number of readout fibers, intrinsic fluctuations in gains. In some cases, to save weight and power, the same HV feeds two PMTs. Therefore, a correction per cell is needed in order to equalize ECAL response.

The equalization of the calorimeter is done using *Minimum Ionization Particles* (MIPs). A first effort to equalize the calorimeter has been done during earlier tests, by setting individual HV to get a maximum probable value of energy deposit (MPV) per PMT centered at 15 ADC (after pedestal subtraction). This value is a compromise between a MIP signal well separated from the pedestal and an ADC dynamical range allowing to detect high energy ($\sim$ TeV) particles.

In this chapter, an equalization algorithm using MIPs is exposed and its performances are tested on August 2010 Test Beam data.

The same algorithm is applied on proton flight data to monitor and to identify and correct “bad” channels.

Finally, an application using Helium nuclei is also exposed.

4.1 Minimum Ionization Particles

Equalization of ECAL PMTs has been performed by studying the response to particles that do not generate a shower in the calorimeter, but loose energy

only by ionization (MIPs, see Fig:4.1 for a typical MIP signature in ECAL from August 2010 Test Beam).

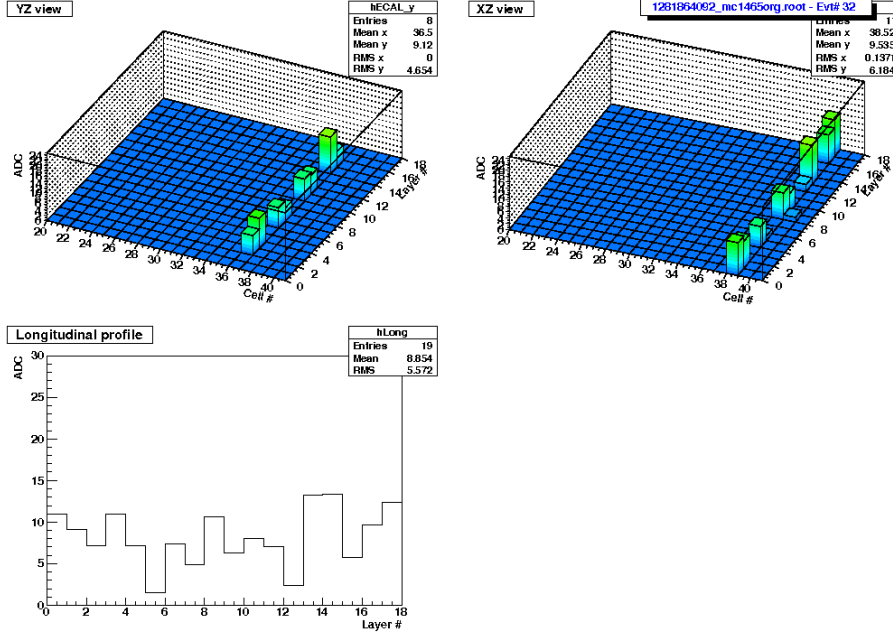


Figure 4.1: A typical MIP signature in ECAL.

Ionization energy loss per unit length $dE/d\xi$ ($d\xi = \rho dx$, ρ is the mean crossed density and dx the travel path in cm) is described by the Bethe-Block formula (see Eq:2.5).

MIPs are a good probe for equalization because their mean energy loss $\langle dE/d\xi \rangle$ is independent from their energy in the relativistic regime. Their energy deposit in a cell does not follow a gaussian distribution, because of the possibility of a high energy transfers in a single collision while traversing a thin material. MIP energy loss distribution is parametrized by a Landau distribution, with a tail for high energies. An approximate analytic description of the Landau distribution is:

$$f(\lambda) = \frac{1}{\pi} \int_0^\infty \exp(-t \ln(t) - u\lambda) \sin(\pi t) dt \quad (4.1)$$

where λ is a linear function of the energy deposit whit a very weak dependence from particle β [27].

In order to take into account statistical fluctuations, like the number of photoelectrons at the first anode, the landau distribution is convolved with a gaussian profile (“langauss” distribution of energy deposit per cell). In a “langauss” distribution, an important parameter used for calibration and equalization is the *Most*

Probable Value (MPV) deposit in the cell. The MPV energy deposit for a proton perpendicular MIP in one ECAL cell is ≈ 7 MeV, corresponding to ≈ 15 ADC.

4.2 Equalization using Test Beam data

The calorimeter has been tested several times in dedicated test beams. The last test beam has taken place in Cern during August 2010, with all AMS-02 detector fully integrated.

The primary beam used during the Test Beam is the *Super Proton Synchrotron* (SPS) 400 GeV proton beam. Negative charge beams and different particle (positrons, electrons, pions...) beams at lower energies are generated by interaction of the primary beam with a 300 mm Be target. These secondary (and tertiary) beams are focused using a dedicated magnet system, which selects particles with a certain momentum and directs them towards the detector.

A mechanical structure allows to rotate and translate AMS-02 detector with respect to the beam line. This enables to have different particle impact points and incident angles as needed.

The standard flight LVL1 trigger has been used to trigger data acquisition. Two scintillators and threshold Cherenkov counters have been mounted on the beam line and their information has been recorded to be used for off-line analysis.

4.2.1 Equalization algorithm

Perpendicular incident particles are available in Test Beam data. Vertical tracks have the same travel path in a cell, and they release in average the same energy deposit.

Perpendicular incident MIPs in a proton beam are easily identified by:

- total deposited energy less then 800 High Gain ADC (HGadc) in ECAL;
- less than 25 fired cells;
- geometrical cut: for each view, the column associated to the average energy deposit is identified and no activity in adjacent cell is required;

The PMT response depends on the impact point along the fiber due to self-absorption of scintillating light. The attenuation factor can be described by the combination of two exponential functions with fast (λ_F) and slow (λ_S) component. The mean attenuation factor is:

$$A(x) = f e^{-\frac{x}{\lambda_F}} + (1 - f) e^{-\frac{x}{\lambda_S}} \quad (4.2)$$

where $\lambda_F=110$ mm, $\lambda_S=2065$ mm and $f=0.115$ is the fast attenuation component fraction (results from 2007 ECAL Test Beam, ref Sec:3.2). Applying Eq:4.2, the

response of each cell has been normalized to the center of the fibers.

A histogram of the energy deposit has been filled per cell, with enough statistics to perform a “languass” fit. The parameters returned by the “languass” fit are:

- *Width*: Landau density width (related to energy deposit fluctuations);
- *MPV*: Most Probable Value of Landau density;
- *Area*: Normalization constant;
- *Gsigma*: Gaussian profile width.

See Fig:4.2 for an example of “languass” fit for a PMT.

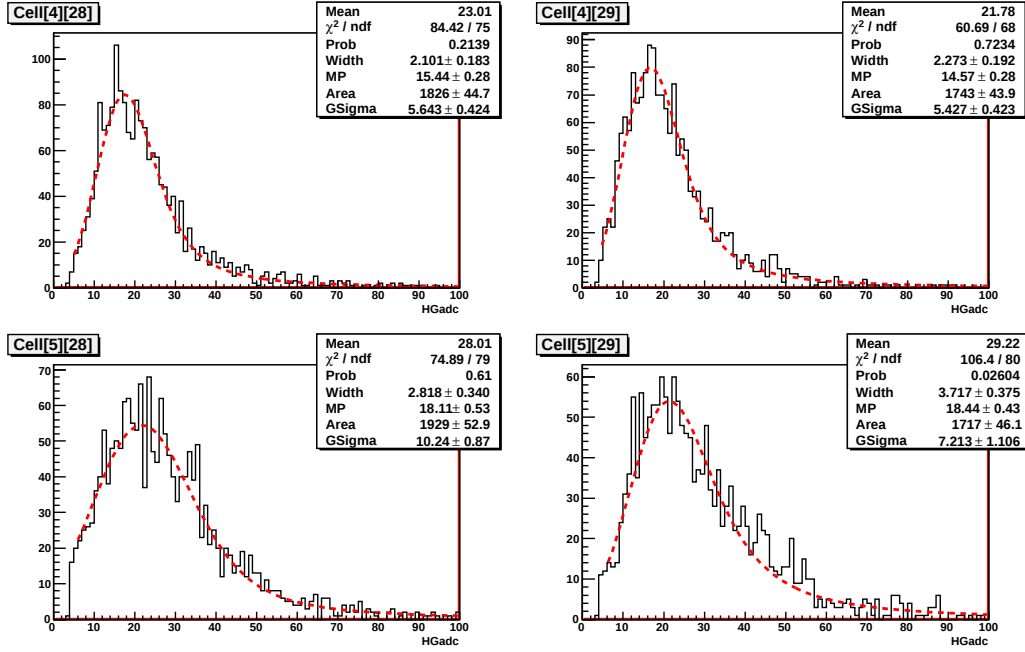


Figure 4.2: “Languass” fit for the 4 anodes of PMT[2][14]. Different MPV values are due to intrinsic fluctuations in anode configuration.

The distribution of MPV per cell and average MPV per PMT are shown in Fig:4.3: the spread is at the level of 17% (dominated by intrinsic PMT fluctuations) and 11%, respectively.

Anode equalization is applied off-line with a correction to the i^{th} cell energy deposit $ADC_{dep,i}$ (after fiber attenuation correction):

$$ADC_{eq,i} = ADC_{dep,i} \times \frac{\langle MPV \rangle}{MPV_i}$$

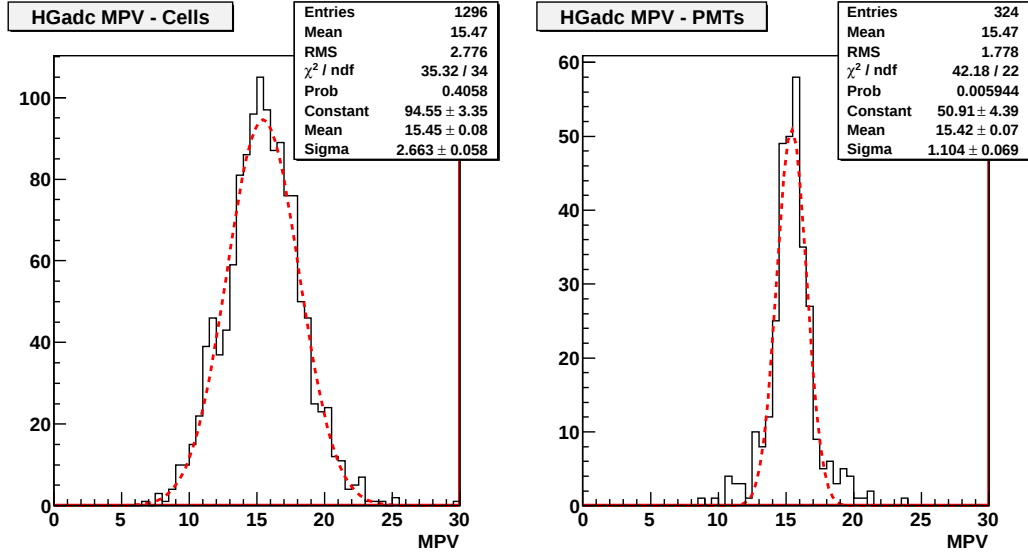


Figure 4.3: MPV distribution per cell (left) and per PMT (right) with gaussian fit superimposed.

where MPV_i is the MPV value returned from the fit of the i^{th} cell and $\langle MPV \rangle$ is the mean MPV value among all the cells.

In the next section an application of this algorithm for flight equalization using protons is presented.

4.3 Flight equalization

During the launch, AMS-02 mechanical structure has been stressed and vibrations may have influenced PMT optical couplings. Also temperature variations may affect equalization which, therefore, has to be repeated and monitored in flight.

Equalization check is also a monitoring tool for flight operations. “Dead” or noisy channels can be easily identified by looking at the MIP signal. Thanks to the high proton flux in space, the statistics per cell can be collected in few hours, allowing to perform a frequent check of anode equalization.

Differently from Test Beam, in space particles imping on ECAL inside the geometrical acceptance cone of 20° . This implies a correction on the deposited energy as a function of the incidence angle. This is done by requiring that a track fitted by the TRK extrapolates to ECAL and that it is associated to the MIP deposit.

A MIP is selected by:

- total deposited energy less then 800 High Gain ADC (HGadc) in ECAL;

- rejection of multicell clusters: less than 2 adjacent cells hit per layer;
- match between the track extrapolation and the barycenter of energy deposit per layer within 4.5mm (half cell).

The energy deposit in a cell is proportional to the travel path. The track information is used to correct for path-length of inclined tracks. Only the angle in the plane which contains the fiber is relevant for track length correction. The raw ADC deposit ADC_{dep} in one cell is corrected as following:

$$ADC_{corr} = ADC_{dep} \cdot \cos(\theta_{x,y})$$

where $\theta_{x,y}$ is the latitude angle projection on the z-y and z-x plane for X and Y view, respectively.

After this correction, the same algorithm for attenuation length correction and fitting procedure described in Sec:4.2 is applied.

The minimum statistics per cell (at least 700 events/cell) needed to perform a good fit can be collected in ~ 5 hours of data taking. The MPV distribution for an “equalization run” is shown in Fig:4.4.

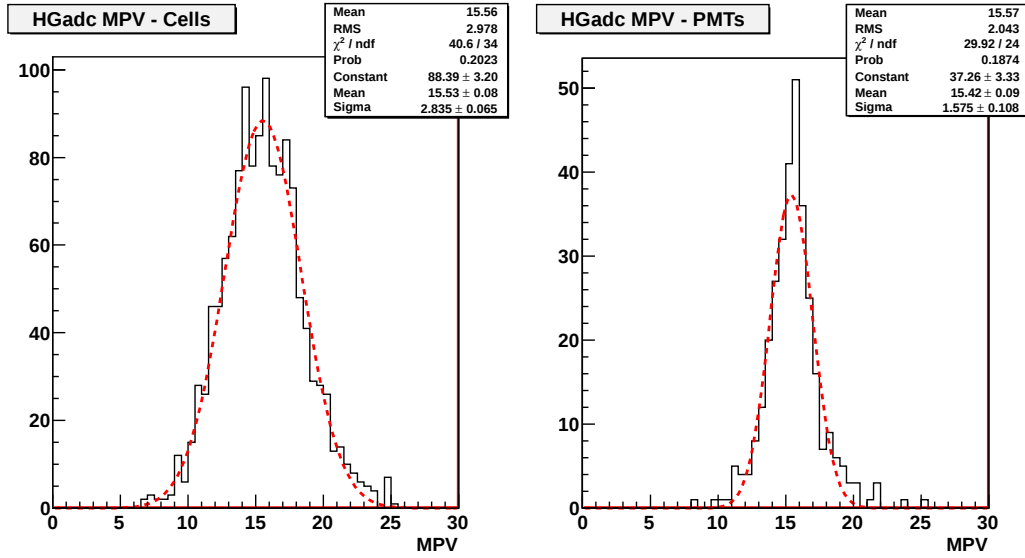


Figure 4.4: MPV distribution per cell (left) and per PMT (right) with gaussian fit superimposed for a flight equalization using protons.

Fig:4.5 shows the comparison between equalization values found at Test Beam and in flight. The spread $\sim 7\%$ is compatible with PMT vibrations at lift-off.

A possible limit of this method is that the peak of the energy deposit can be too close to the pedestal value (~ 4 HGadc), and the fitting procedure can be

unstable. In the cosmic radiation, He nuclei flux is $\sim 5\%$ the proton one, and they can be used for a more stable equalization procedure, as described in the next section.

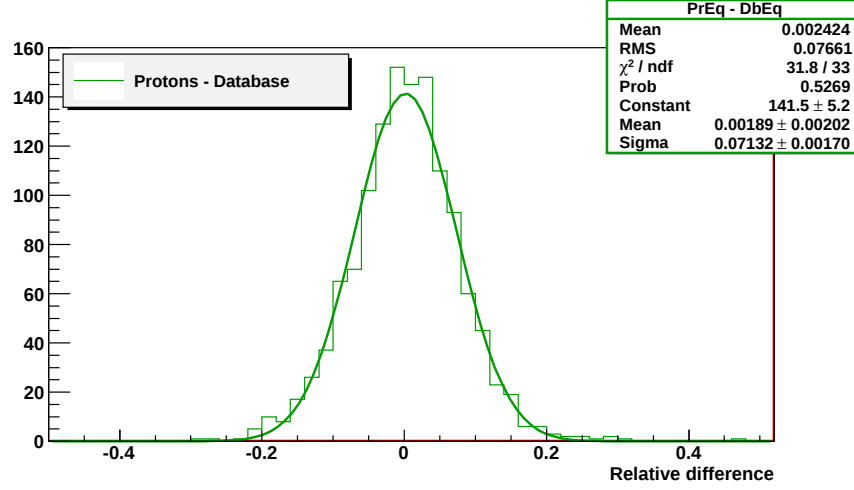


Figure 4.5: Relative difference between equalization parameters found at Test Beam and after a flight equalization run using protons.

4.4 Flight equalization using Helium

He nuclei are the second more abundant hadronic component in the cosmic radiation. Since energy ionization loss (see Eq:2.5) is proportional to the second power of the charge of the particle:

$$-\frac{dE}{d\xi} \propto Z^2$$

He nuclei energy deposit peak is well separated from the pedestal value, so they can be used for a more stable equalization procedure.

In this section a ECAL standalone He MIP identification algorithm and an application of He nuclei for the equalization are described.

4.4.1 Helium MIP identification

He nuclei MIPs can be easily identified using ECAL as a standalone detector. Helium topological MIP signature is similar to the proton one. The difference is in the energy deposit per cell, which is 4 times higher according the Eq:2.5.

A typical ECAL standalone topological selection is applied to select MIPs:

- at least one hit over threshold per layer, for a maximum of total hit < 25 ;
- rejection of multicell clusters.

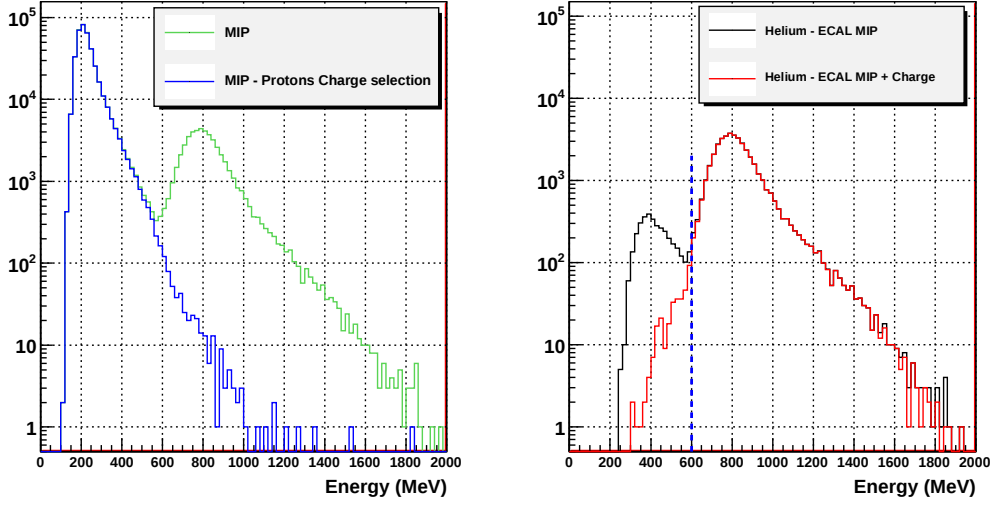


Figure 4.6: Left: ECAL deposited energy distribution after MIP signature topological cut (green). The blue histogram shows the distribution with the selection $Z = 1$ (protons). He and proton energy deposit peak ratio is ~ 4 . Right: Energy cut for He MIP selection (HGadc deposit per cell > 18). The red histogram shows the same distribution with the cut $Z = 2$ (He) and confirms the negligible proton contamination in the He selected sample.

Fig:4.6 (left) shows the distribution of ECAL deposited energy after the MIP signature topological cut. The additional charge measurement using combined informations from other subdetectors is used to tag the proton sample. The Helium and proton energy deposit peak ratio is ~ 4 as expected.

He MIP nuclei can be identified with high efficiency using ECAL standalone by:

- application of the previously described topological selection for ECAL hits with energy deposit > 18 HGadc (which is beyond proton energy deposit MPV in a cell);
- selection on total deposited energy $\gtrsim 600$ MeV.

The ECAL standalone He MIP selection is shown on Fig:4.6 (right): the contamination of protons in the selected sample is negligible.

4.4.2 Equalization using Helium

He MIPs for equalization are identified by applying a selection similar to the one described in Sec:4.3, with a higher cut on the total energy deposit in ECAL and the additional request of reconstructed charge $Z = 2$. Fiber attenuation and track length correction have been applied and the energy deposit distribution per

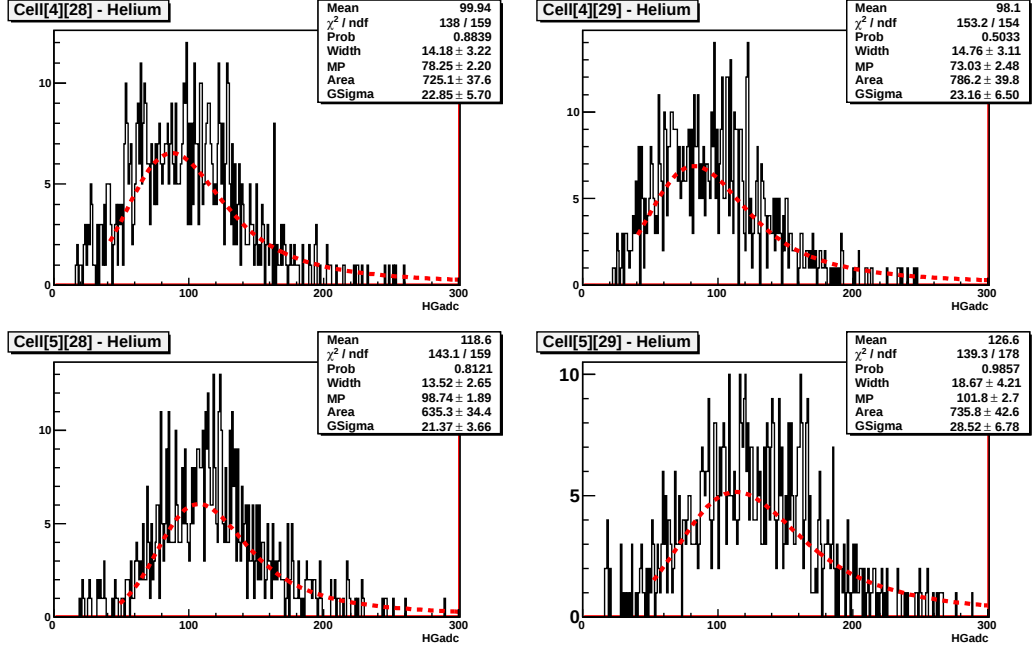


Figure 4.7: “Langauss” fit for the 4 anodes of PMT[2][14] using He.

cell has been fitted using a “langauss” function (see Sec:4.2).

Statistics is collected for a period ~ 1 week, in order to obtain a significant sample to have a good quality fit. An example of fitting result for a PMT is shown in Fig:4.7.

MPV distributions per cell and per PMT are reported in Fig:4.8. The spread is $\sim 17\%$ and $\sim 6\%$, respectively.

As shown in Fig:4.9, the ratio $\langle \mu_{He} \rangle / \langle \mu_p \rangle$ between Helium and proton energy deposit, where μ is the mean value of the fitted “langauss” distribution $L(x)$ per cell:

$$\mu = \frac{\int_0^\infty L(x) x dx}{\int_0^\infty L(x) dx}$$

is ~ 4 , according to Eq:2.5.

A stability check for this Helium equalization procedure is shown in Fig:4.10: the spread in the relative difference of equalization parameters using He nuclei for different time intervals is $\sim 2.5\%$.

The fitting quality using He is improved. Fig:4.11 shows the comparison of “langauss” fit reduced χ^2 for protons and He. The lower mean value of reduced χ^2 proves that the equalization using He MIPs provides a better fit quality.

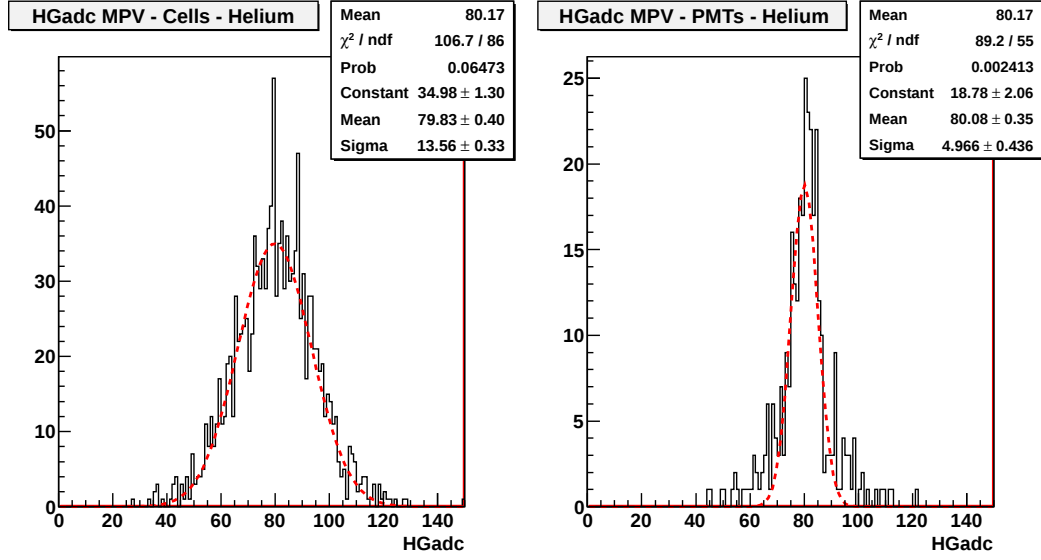


Figure 4.8: MPV distribution per cell (left) and per PMT (right) with gaussian fit superimposed for a flight equalization using He.

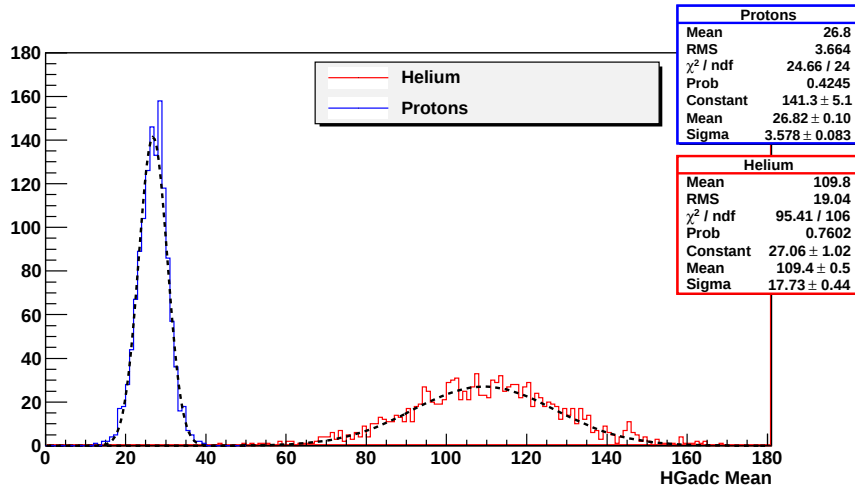


Figure 4.9: Fitted “langauss” mean distribution for equalization using protons (blue) and Helium (red). $\langle \mu_{He} \rangle / \langle \mu_p \rangle \sim 4$, according to Eq:2.5.

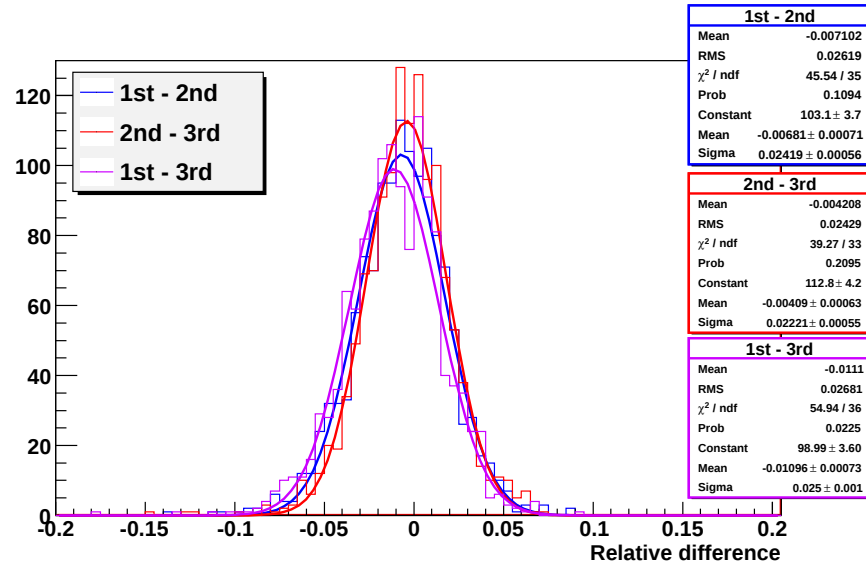


Figure 4.10: Relative difference between equalization parameters calculated using He nuclei for three different periods. Each period corresponds to ~ 1 week of data taking.

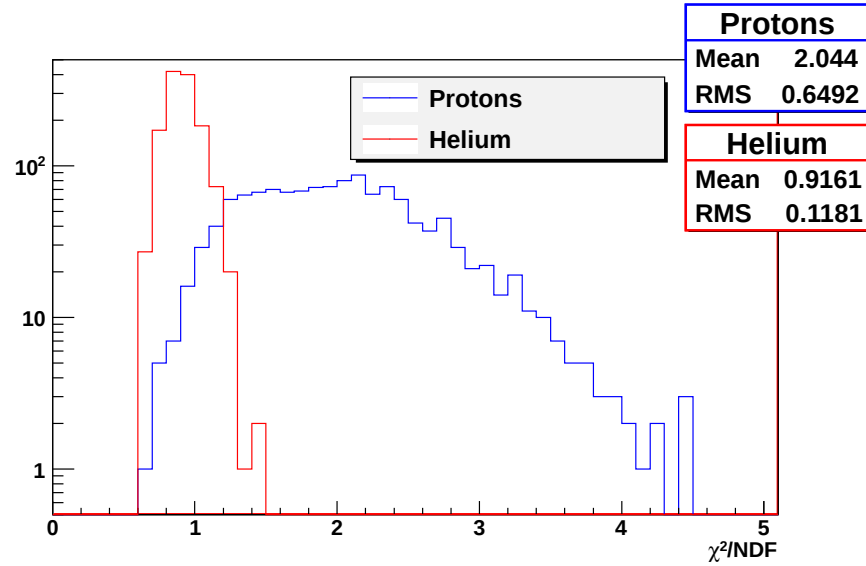


Figure 4.11: Reduced χ^2 distributions of “langauss” fit for proton and He equalization.

A comparison between the equalization values calculated using protons, Helium and found at the Test Beam is shown in Fig:4.12. The relative difference is well below 20%, and the average spread is $\sim 6.5\%$. The algorithms are compatible, and they can be used during flight operations for routine monitoring.

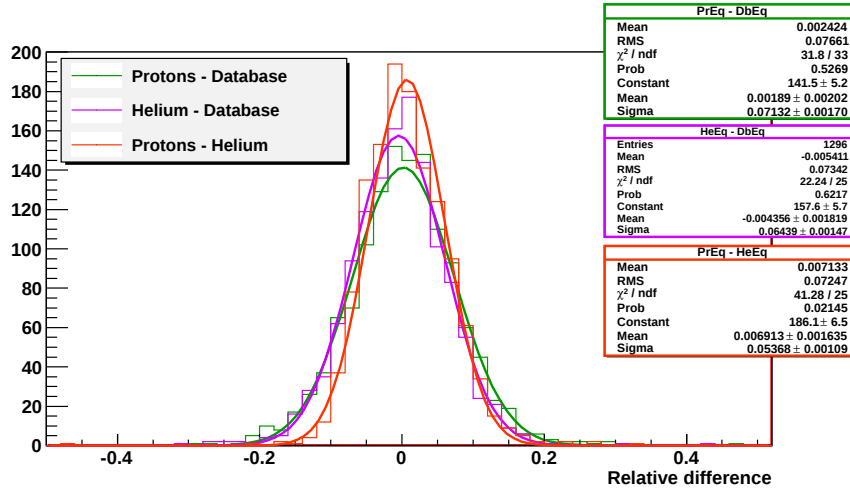


Figure 4.12: Relative difference for equalization parameters found at Test Beam and using proton and helium equalization.

Chapter 5

Positron identification

As already stated in Chap:1, one of the main systematics for the positron spectrum measurement is the proton background subtraction. Due to the different absolute flux, a proton rejection factor of order $\sim 10^5 - 10^6$ is required to keep the systematic error introduced by residual background at the percent level. This goal can be achieved using the combined identification power of ECAL, TRK and TRD. This chapter describes the calorimeter positron identification capabilities.

Positron/electron interactions differ strongly from hadronic ones. Electromagnetic particles impinging on ECAL, or in an absorber in general, initiate an electromagnetic cascade. High energy $e^\pm$ predominantly loose energy in matter by *Bremsstrahlung*, transferring a fraction of their energy to a γ . The typical length scale of traversed matter is represented by the *radiation length* X_0 , defined as the distance after which the particle has lost a fraction $(1 - 1/e)$ of its initial energy. Energy lost by Bremsstrahlung can be parametrized as:

$$\frac{-dE}{d\xi} = \frac{E}{\xi_0} \Rightarrow E(\xi) = E_0 e^{-\frac{\xi}{\xi_0}} \Rightarrow E(x) = E_0 e^{-\frac{x}{X_0}} \quad (5.1)$$

E_0 is the particle initial energy, ρ is the medium density and $\xi = \rho x$ is the density associated to the travel path x . Eq:5.1 holds if the average density $\langle \rho \rangle$ is constant along particle path.

On the other hand, energetic photons ($E \gtrsim \text{MeV}$) interact with matter by *pair production*, leading to the production of a e^+e^- pair with a mean free path $\frac{9}{7}X_0$ (this reflects the similarity of *Bremsstrahlung* and *pair production* mechanisms, according to QED). The combination of these two effects results in the so-called “electromagnetic shower”. An electromagnetic shower develops until its components reach the *critical energy* E_c , defined as the energy at which ionization losses become competitive with Bremsstrahlung ones. Below E_c electrons dissipate their energy by ionization and excitation and photons start to loose energy for Compton scattering or are removed by photoelectric absorption. The particles are absorbed by the material and the shower ends.

The longitudinal development of a shower is usually parametrized by a gamma function (see Eq:3.1). For the lateral energy distribution, different parameterizations are available, starting from a simple superposition of two gaussians, describing the narrow core and the broader background, to more complex descriptions [25]. In any case, the typical scale of the transverse development is the *Molière Radius* $R_M \approx X_0 \cdot 21\text{MeV}/E_c$: a cylinder with radius R_M contains in average 90% of the shower energy. In ECAL, the Molière radius has been measured to be $R_M \approx 2\text{cm}$ [28].

Hadronic interactions in matter are more complicated: protons loose their energy by ionization, but they can also interact with matter nuclei with a mean free path called *nuclear length* λ_N , which is essentially energy independent. Hadronic showering process is a succession of inelastic hadronic interactions. After a nuclear interaction, secondary pions, nucleons and low energetic photons are produced. Part of these secondary products loose their energy by ionization, while others may undergo another nuclear interaction, leading to the production of a hadronic shower. The π^0 component, instead, decays via the channel $\pi^0 \rightarrow \gamma\gamma$, producing an electromagnetic component in the hadronic cascade. Hadronic showers are characterized by a broader lateral and longitudinal distribution with respect to the electromagnetic ones. Moreover, contrary to electromagnetic showers which develop in sub-nanosecond time, the physics of hadronic showers is characterized by different time scales - up to microseconds - for nuclei de-excitation.

To exploit these topological differences between electromagnetic and hadronic induced showers, the AMS-02 ECAL has been built with the aim of maximizing the λ_N/X_0 ratio. The lead-fiber structure has $\lambda_N \approx 26\text{cm}$ and $X_0 \approx 1\text{cm}$, with a thickness of 16.7 cm, corresponding to about 17 X_0 . With this design, $\sim 50\%$ of the protons escape ECAL without nuclear interaction (MIP), while the rest produce a hadronic shower which is partially contained, such that only part of the proton energy is released in ECAL (in average 1/3 - 1/2).

Because of this, the matching between the energy measured by ECAL and the momentum measured by the tracking system is another powerful constraint that can be used in positron identification.

In Fig:5.1 and Fig:5.2, the interactions in ECAL of positrons and protons, from August 2010 Test Beam, are presented.

The irreducible background in the positron channel is due to protons interacting in the first layers of ECAL and transferring a high energy fraction to a π^0 , which decays in a $\gamma\gamma$ pair with a very low angular opening, simulating an electromagnetic shower.

In this chapter, a multivariate method for positron and electron identification using ECAL standalone and other subdetectors is presented. The identification algorithms have been trained using real data (from August 2010 Test Beam) and

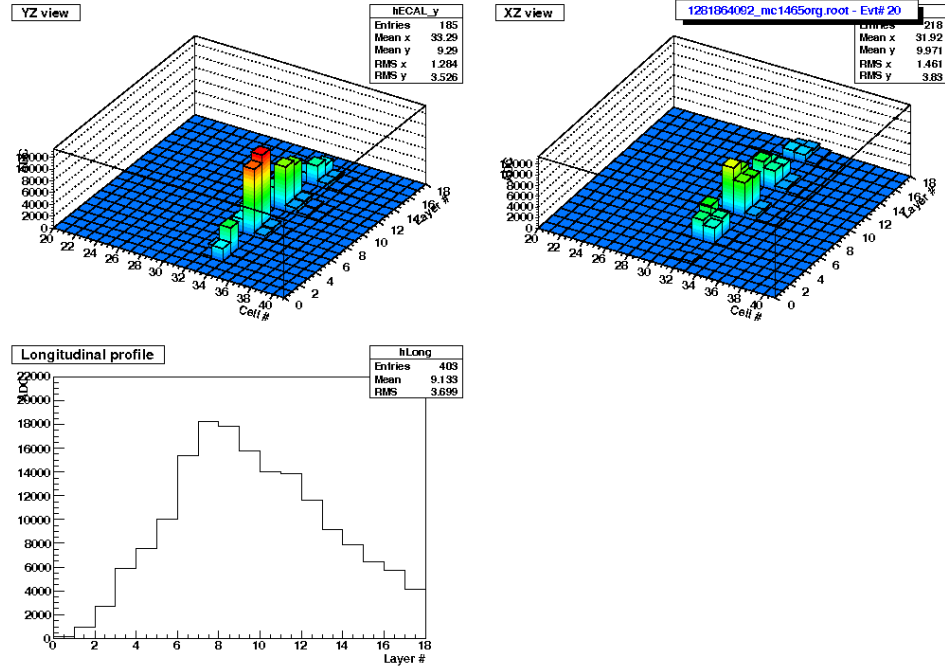


Figure 5.1: A 180 GeV positron interacting in ECAL. Longitudinal profile is almost fully contained in the calorimeter: rear leakage can be easily extrapolated (see Sec:3.2).

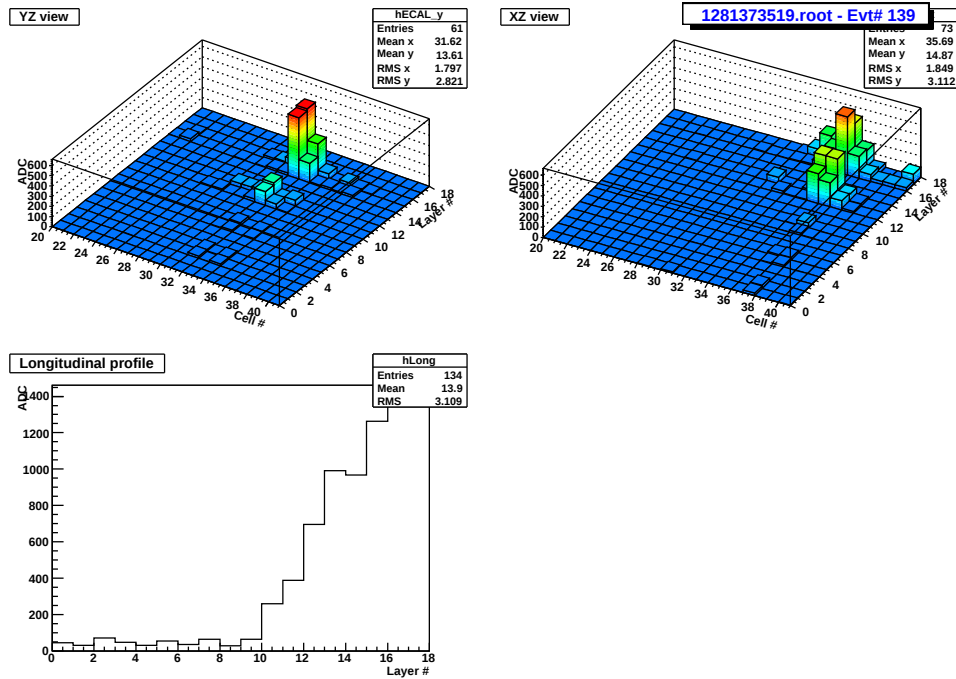


Figure 5.2: A 400 GeV proton interacting in ECAL. Hadronic shower is not contained in the calorimeter.

MonteCarlo.

5.1 Boosted Decision Tree algorithm

Boosted Decision Tree (BDT) algorithm is a multivariate method which has become quite used in HEP experiments in the last years, after its first application in the MiniBooNE experiment at Fermilab [29]. Multivariate methods - BDT, Fisher discriminant or Neural Networks - allow to exploit non-linear correlations among different variables to separate two different populations or classes (commonly referred to as *signal* S and *background* B) in a given sample.

The inputs to multivariate analysis (MVA) algorithms are a *training* sample and a set of discriminating variables. The training sample is a set of events tagged as S or B. This sample is used by the MVA, during the training phase, to learn how to discriminate between the two populations by exploiting the information carried by input variables. At the end of the training phase, the MVA algorithm splits the n -dimensional space of variables with decision boundaries (surfaces in this phase-space) into S and B regions, in a way that maximizes the separation between the two classes.

A potential limit of this technique is the so-called “overtraining”. The classification error rate (S events tagged as B and vice-versa) on the training sample may be very low, but it could be much higher on an independent data sample. This can happen if the decision boundary tends to “conform too closely” to the training data (see Fig:5.3). Therefore, it is important to evaluate the error rate and classification performance on a statistically independent *test* sample.

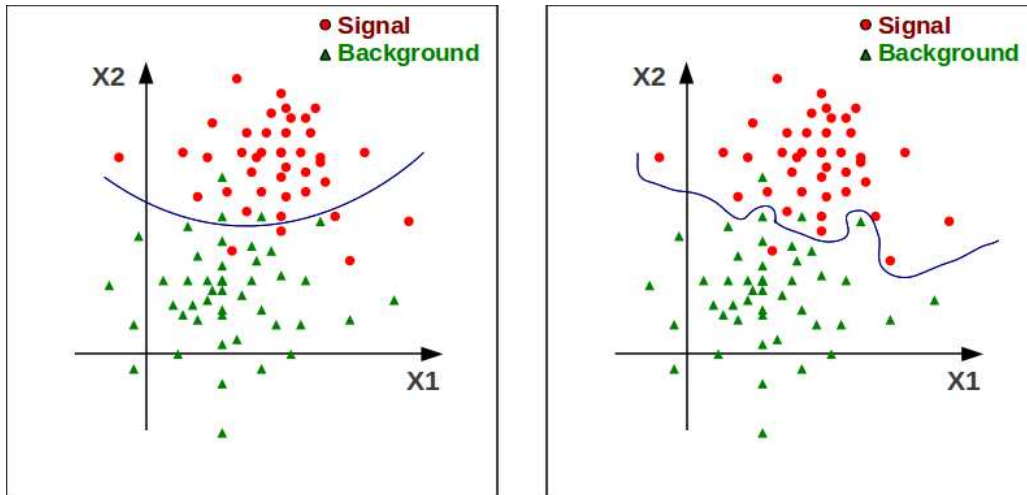


Figure 5.3: Left: 2-dimensional variable space for training signal (red circles) and background (green triangles) with decision boundary (blue line). Right: example of overtraining. The classification has good performances on the training sample, but its discriminating power can become less efficient on an independent test sample.

In the construction of a decision tree, at each step, the variable and the relative cut which allows the best separation between signal and background is selected, and two sub-trees created for events passing / not passing the cut. For each node and each cut, Purity P is defined as

$$P = \frac{\sum_{\text{signal}} w_i}{\sum_{\text{signal}} w_i + \sum_{\text{background}} w_i}$$

where w_i is the weight of the i^{th} event that passed the cut. Different criteria are known to evaluate the S/B separation in a node, without any significant performance disparity. The most popular one, that is used in this work, is the so-called “Gini index”:

$$G = P(1 - P)$$

which is maximum for $P = 0.5$ (fully mixed classes) and minimum for $P = 0$ or 1 (complete separation). The process is iterated for each sub-tree until it reaches a certain condition (for example on the number of events in a node): the sub-tree is then called “leaf”. At this point, the leaf is tagged as “signal” or “background”, depending on the relative fraction of S/B events in it. The phase-space of input variables is therefore divided into hypercubes, each one representing a leaf of the tree.

In Fig:5.4, a graphical example of a tree used in this analysis is shown.

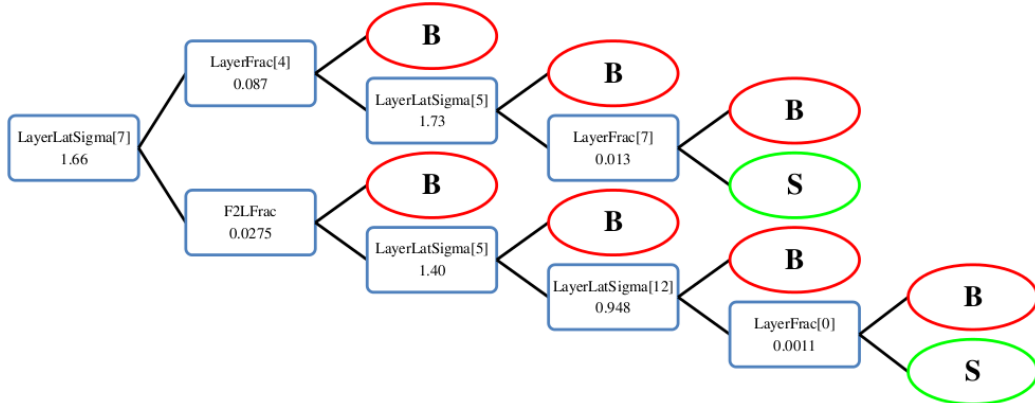


Figure 5.4: Tree #181 from forest *ECALstandalone*, described in Sec:5.3. Blue rectangles represent “branches”, with the associated variable and its relative cut. Circles represent “leaves”, tagged as Signal (green) or Background (red), depending on the fraction of the class of training events that “falls” in.

Following this procedure, a “forest” of trees is built, with each tree exploiting a different set of input variables and cuts. The process of building new trees is optimized by using *Boosting* algorithms. For each iteration, events are re-weighted according to their misclassification rate: in this way, the algorithm “learns” to

take more care about events that have been misclassified in the previous iteration. The forest is completed after a certain number of trees is built, each one with a relative weight based upon the single tree performance.

Finally, the application of BDT algorithm on a test sample results not in a binary classification (S or B), but in a continuous classification parameter, based upon the weighted decision using all the trees in the forest.

5.2 Identification using Test Beam data

August 2010 Test Beam setup has been already introduced in Chap:4. The following datasets have been selected for training/testing BDT algorithm:

- Positrons with energies 180 GeV, 120 GeV, 80 GeV and 20 GeV, impinging on ECAL with several angles and positions;
- Protons at 400 GeV crossing external tracker layers;

For a complete summary on angles and positions, see [30].

5.2.1 Events pre-selection

To study e/p discrimination in ECAL, a clean positron and proton sample among all triggers must be identified. In particular, “positron beams” have a large background from pions, varying with the energy.

Test Beam particles, protons in particular, have momentum that is greater than inner tracker MDR (~ 200 GeV). The full span tracker (layers 1 to 9) has a higher MDR (~ 2 TeV), so in Test Beam energy range both external tracker layers must be fired.

A common pre-selection for positrons and protons has been applied using the following criteria:

- Track geometry and quality cut
 - only one reconstructed track, to avoid overlapping events;
 - good pattern in inner layers: for the definition of good pattern, see Fig:5.5;
 - both external layers associated to the track: this is required to extend the tracker MDR, as described in Sec:2.2;
 - quality cut on half rigidity compatibilities. R_{UP} and R_{LO} are the rigidity values returned using layers respectively from 1 to 8 and from 2 to 9. In the case of bad track quality due to interactions between inner and external tracker layers or inefficiencies in the fitting procedure, these

two half rigidity values mismatch. The variable to cut on for half rigidity comparison has been defined :

$$H_{diff} = \sqrt{(1/R_{UP} - 1/R_{LO})^2 / \sigma_{UL}^2}$$

where σ_{UL} is the relative weight factor. See Fig:5.6 for an example of H_{diff} distribution;

- rigidity > 0 (only positive particles);
- Track Shower Matching
 - A quality cut on the XY distance from shower barycenter (CoG) and the track extrapolation at shower CoG Z coordinate (RCG variable) allows to reject events with wrong or ambiguous matching. Ref Fig:5.7.

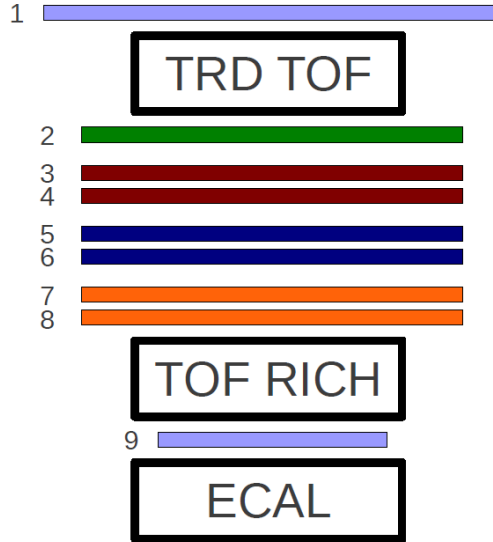


Figure 5.5: Left: Tracker layer numbering scheme. A track is defined to have a “good inner pattern” if it has associated hits in layer 2 and at least in 1 out of 2 layer couple 3-4, 5-6 and 7-8.

Rigidity distribution for proton pre-selected events is displayed in Fig:5.8.

The tracking system does not measure the “Rigidity” p_T/q , but its inverse “Curvature” q/p_T by fitting an helicoidal trajectory in a dipolar magnetic field B. So, while curvature distribution is gaussian, rigidity distribution is not (the inverse of a gaussian is not a gaussian). In Fig:5.8, events reconstructed with negative curvature are “spillover events”, in which the sign of the charge is wrongly assigned. On the contrary, events in the curvature distribution right tail are mapped into the peak close to the zero of the rigidity distribution. Low rigidity events are normally generated by a bad hit pattern assignment. These two populations affect proton rejection because they fulfill the energy/momentum (E/p)

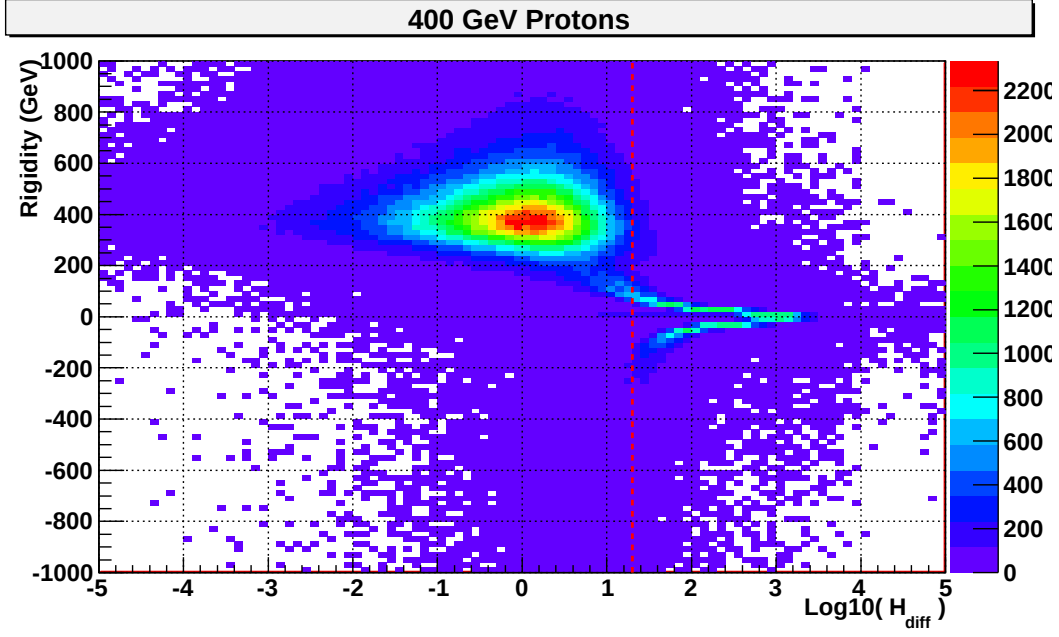


Figure 5.6: H_{diff} distribution for 400 GeV protons. In the plot, the cut applied on H_{diff} , which is the most discriminant variable used to compare half rigidities, is shown.

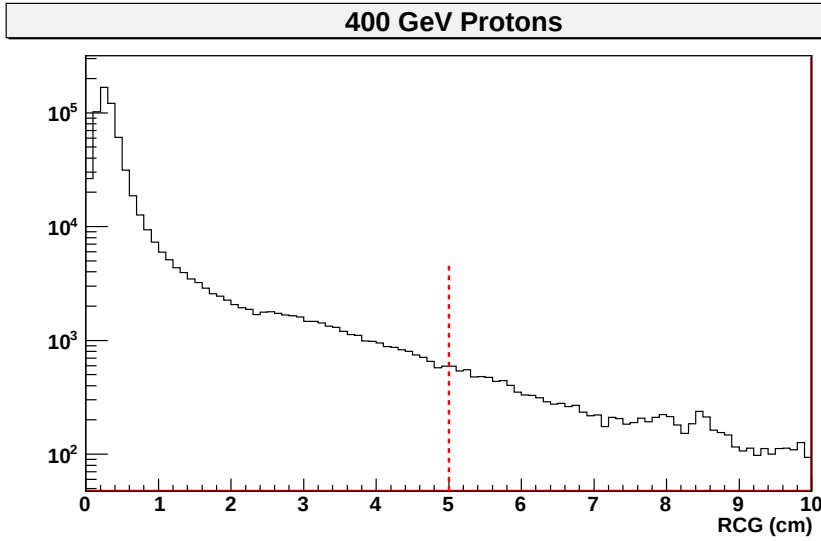


Figure 5.7: RCG distribution for 400 GeV protons with the RCG cut superimposed.

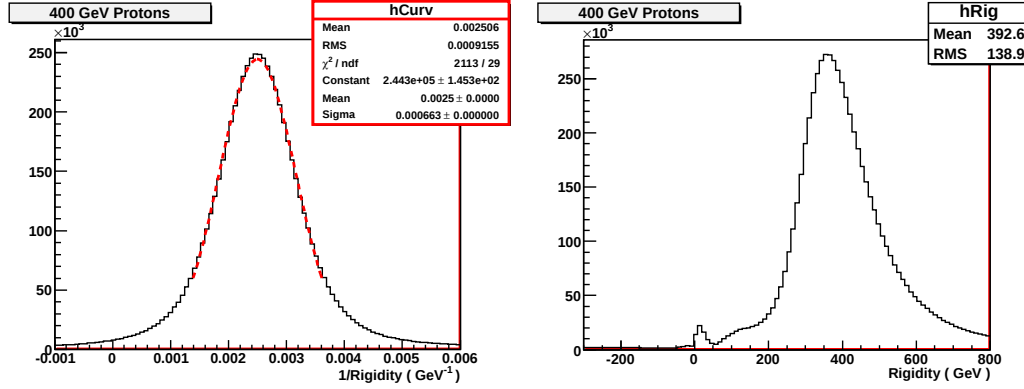


Figure 5.8: Left: 400 GeV proton curvature distribution after pre-selection cuts with gaussian fit superimposed. Right: 400 GeV protons rigidity distribution after pre-selection cuts. High curvature tail maps into low rigidity measured events.

matching criterion. A more refined track quality cut should be applied to limit the bias introduced by these effects.

Positron beams are secondary and tertiary beams with a high contamination of pions. The purest positron sample must be identified and used to train the identification algorithm, because the presence of some non-positron particles in the training sample may introduce a bias in its application. Additional pre-selection cuts are applied to positron beams in order to select the purest sample among pion background:

- external Cherenkov over threshold (see Chap:4 for a description of Test Beam setup);
- 90% efficiency cut on TRD Likelihood;
- shower reconstructed energy compatible in a 4 sigma interval with the mean value centered on nominal beam energy: this cut assures to select positrons with an efficiency $> 99.99\%$, while rejecting hadrons.

Pre-selection efficiencies are listed in Tables 5.1 and 5.2.

Protons which do not interact in ECAL ($\sim 50\%$ of the total) are easily removed by a cut on deposited energy $E < 1\text{GeV}$. In order to train the classifier on a sample which is more similar to the signal, an additional cut $E/p > 0.6$ is applied. Events which fail this selection are easily removed from the background. Fig:5.9 shows the effect of this cut on positrons and protons .

The absolute number of events selected for training/testing BDT are listed in Table 5.3.

5.2.2 Input variables

The use of BDT algorithm for classification purposes allows to use a large set of discriminant variables without introducing any bias or loss of efficiency,

Table 5.1: Event pre-selection common for positron and proton runs.

	Triggers	ExtCh	1Track	InnPatt	ExtPlanes	GoodTr	ShowMatch
400GeV Pro	18483868	18483868	12416187	10935975	7716084	6848127	6739250
		1.000	0.672	0.881	0.706	0.888	0.984
180GeV Pos	7008276	784082	415909	358786	208811	180328	158716
		0.112	0.530	0.863	0.582	0.864	0.880
120GeV Pos	7179407	586368	437792	376414	203225	191962	186347
		0.082	0.747	0.860	0.540	0.945	0.971
80GeV Pos	5702542	282206	210801	180620	98841	93480	89252
		0.049	0.747	0.857	0.547	0.946	0.955
20GeV Pos	2392182	122057	45689	40494	19964	10352	9990
		0.051	0.374	0.886	0.493	0.519	0.965

Table 5.2: Additional pre-selection for positron runs.

	Geom Selection	TRDLikelihood	Energy Match
180GeV Pos	158716	41546	18063
		0.262	0.435
120GeV Pos	186347	21954	2168
		0.118	0.099
80GeV Pos	89252	4966	2184
		0.056	0.440
20GeV Pos	9990	7177	6354
		0.718	0.885

Table 5.3: Events used for training/testing BDT algorithm.

	180GeV Pos	120GeV Pos	80GeV Pos	20GeV Pos
Events	18063	2168	2184	6354

	400GeV Pro (Train)	400GeV Pro (Test)
Events	34042	2820367

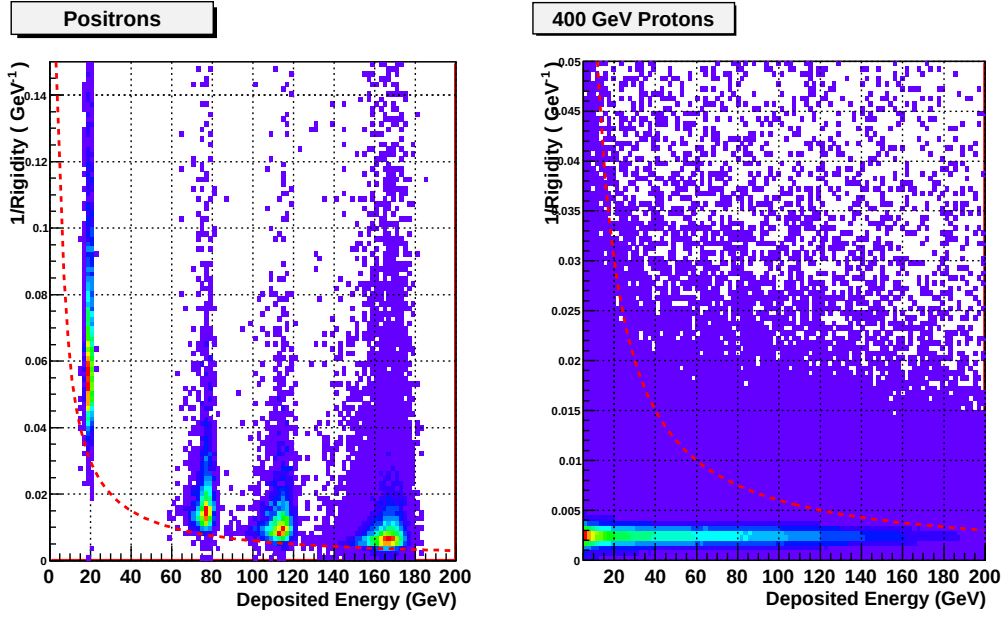


Figure 5.9: E/p match applied on positron (left) and proton (right) samples: the upper right region identifies interacting protons, i.e. protons starting a shower in the first layers.

differently from other multivariate algorithms. Less significant variables are often skipped while choosing the variable to cut on. Sometime, instead, they gain a good statistical significance in a particular tree in the forest and they become useful for classification.

In order to train BDT algorithm to identify and discriminate between hadronic and electromagnetic interactions in ECAL, a set of variables has been chosen to exploit both longitudinal and lateral development of the shower.

- Longitudinal

L2LFrac Last two layers deposited energy fraction

F2LFrac First two layers deposited energy fraction

F2LEnedep First two layers deposited energy (GeV)

LayerCOG Longitudinal development mean (Layer units)

LayerSigma Longitudinal development sigma (Layer units)

Layer Skewness Longitudinal development skewness (Layer units)

Layer Kurtosis Longitudinal development kurtosis (Layer units)

- Lateral

S1S3x S1S3 x view (S1S3 variable is defined as the ratio between the energy deposit in the most energetic cell column and the energy deposit in it and the two most contiguous cells)

S1S3y S1S3 y view

ShowerRadiusEnergy3cm 3cm radius deposited energy fraction

ShowerRadiusEnergy5cm 5cm radius deposited energy fraction

DifoSum $(E_x - E_y) / (E_x + E_y)$, $E_{x,y}$ is the total energy deposit in X,Y view layers

As shown for instance in Fig:5.10 and Fig:5.11, all these variables exhibit dependence on energy. In order not to bias the identification algorithm, each variable has been corrected from this dependence with a renormalization process.

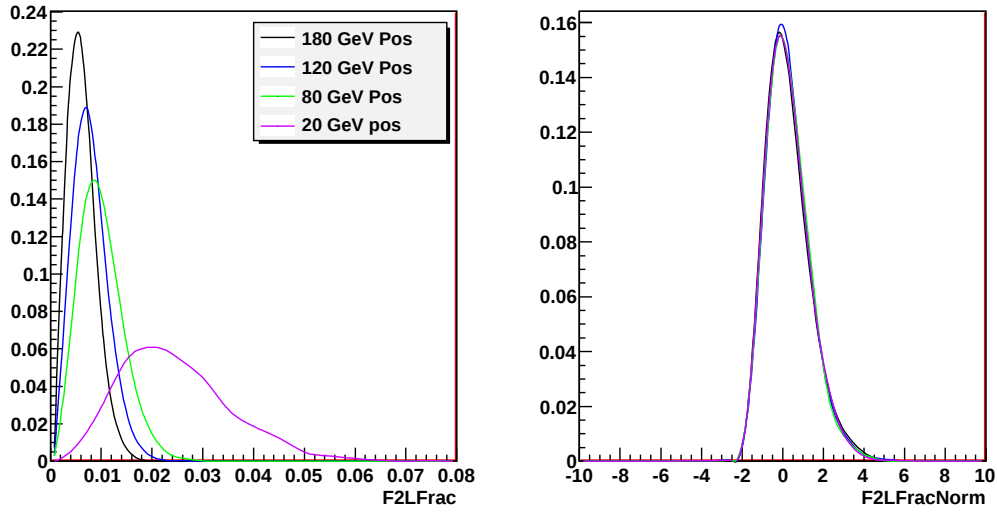


Figure 5.10: $F2LFrac$ variable dependence on positron energy before (left) and after (right) renormalization process.

For each variable $\mathbf{X}$, a gaussian fit of the distribution bulk is performed for the different energies. An example is shown in Fig:5.12.

Then, a new variable $\mathbf{XNorm}$ is defined as:

$$XNorm = \frac{X - \mu_X(E)}{\sigma_X(E)}$$

where $\mu(E)$ and $\sigma(E)$ are the energy parametrization of gaussian mean and sigma for each variable.

An example of this procedure is reported in Fig:5.13 and Fig:5.14.

The renormalization procedure has been applied on positrons and protons for every input variable.

A summary for positron and proton variables distributions is shown in Fig:5.15 and Fig:5.16.

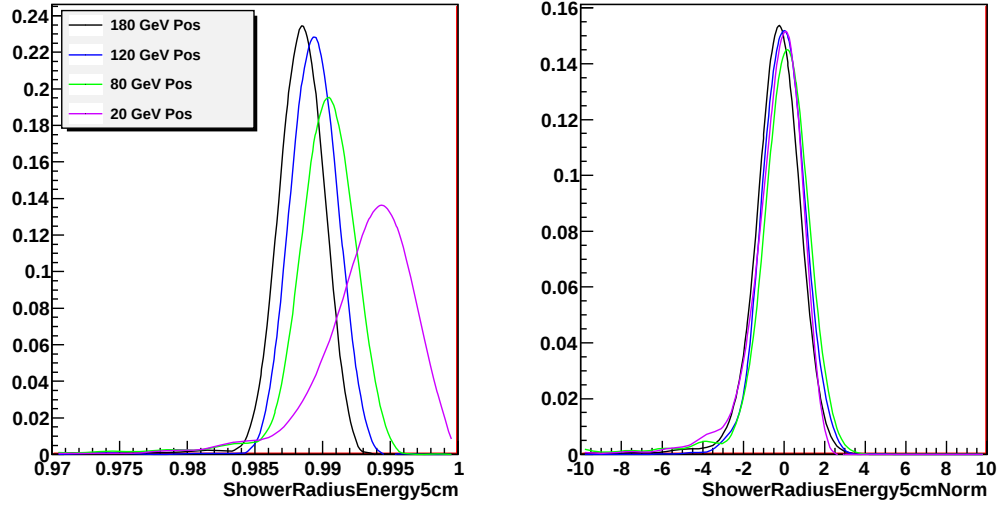


Figure 5.11: *ShowerRadiusEnergy5cm* variable dependence on positron energy before (left) and after (right) renormalization process.

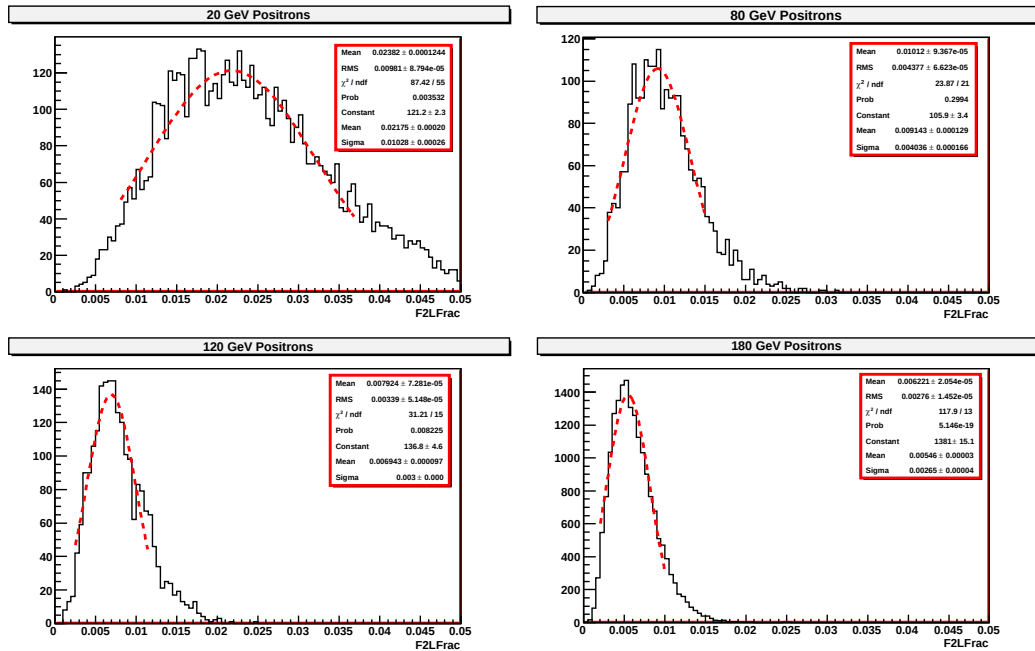
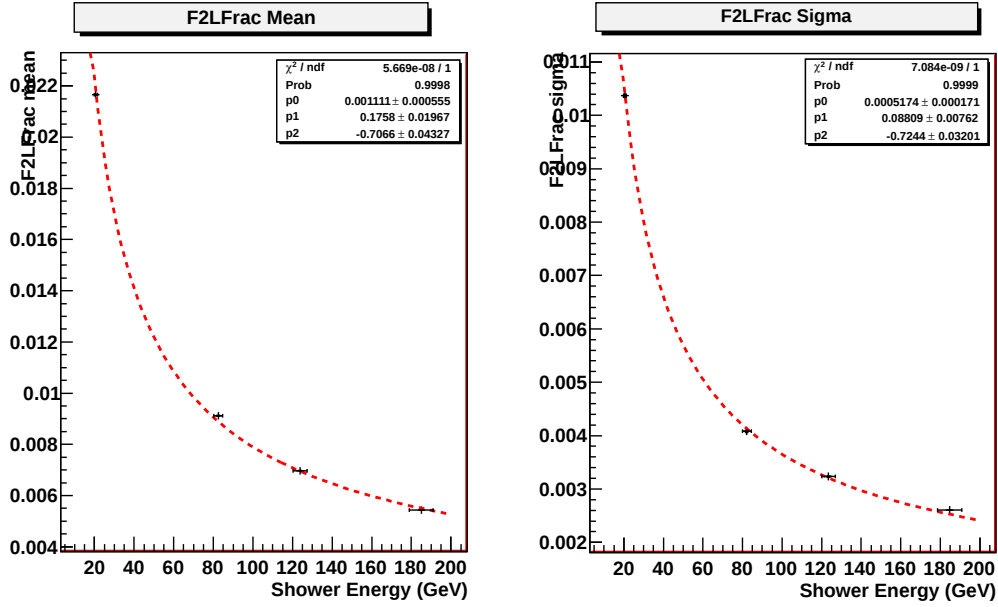
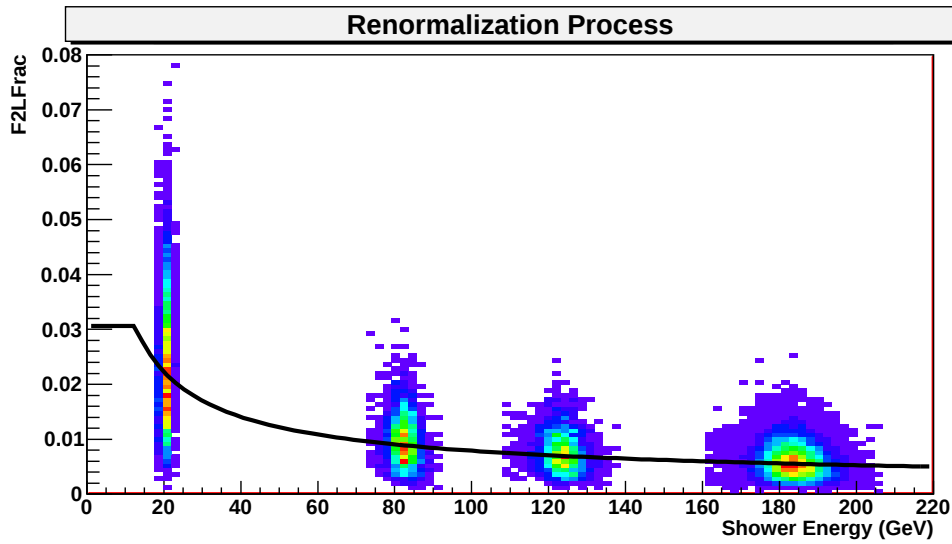


Figure 5.12: Gaussian fits of central distribution for *F2LFrac* variable

Figure 5.13: Analytic fit of $\mu(E)$ and $\sigma(E)$ for $F2LFrac$ variableFigure 5.14: $F2LFrac$ variable with $\mu(E)$ superimposed

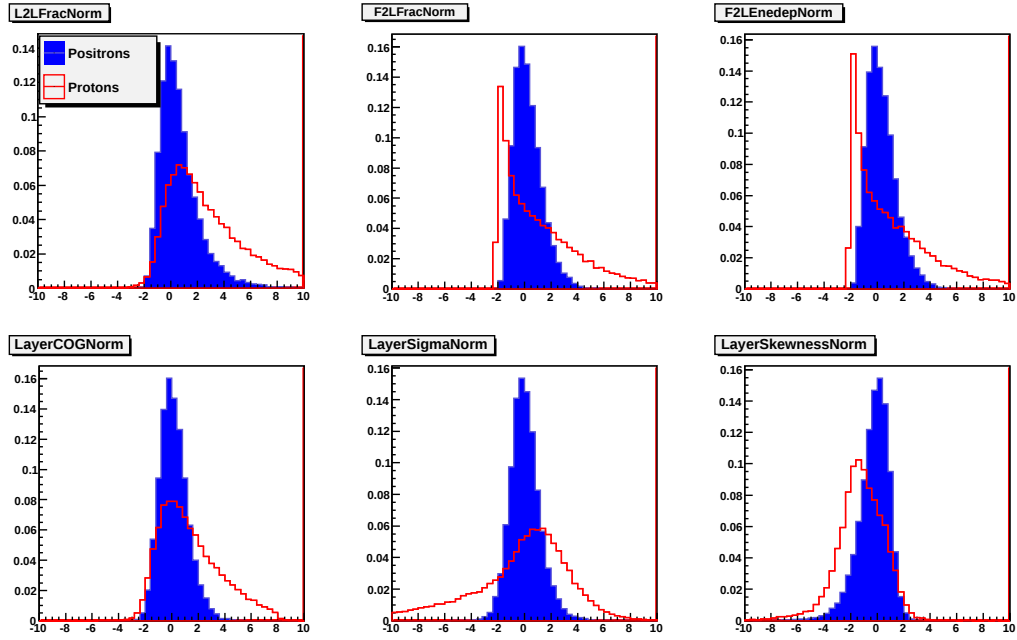


Figure 5.15: Input variables for positrons (signal) in blue and interacting protons (background) in red (1).

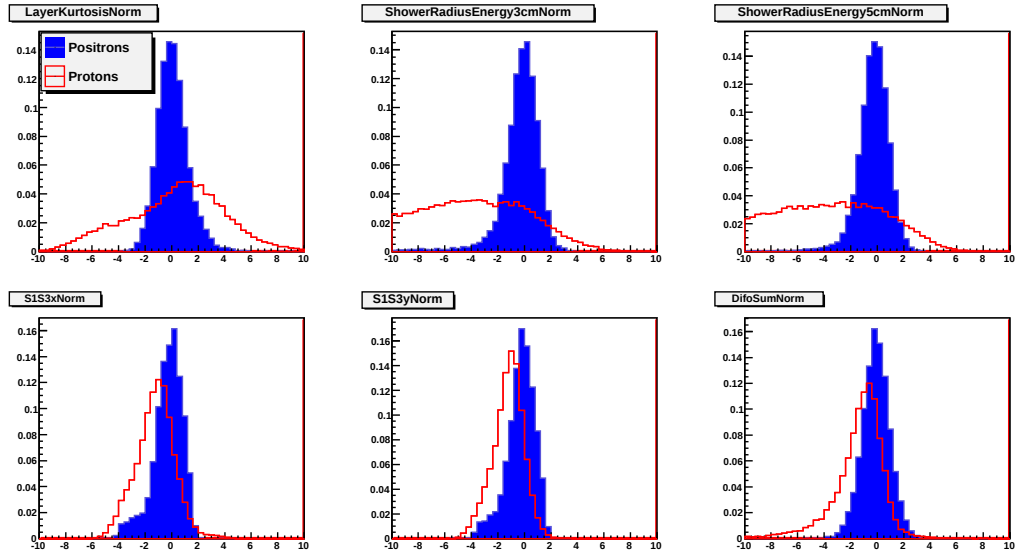


Figure 5.16: Input variables for positrons (signal) in blue and interacting protons (background) in red (2).

5.2.3 Training and testing BDT algorithm

BDT classification training is performed using TMVA [31] libraries provided by ROOT analysis tool [32].

BDT training parameters have been tuned to assure the following classifier features:

- High classification power
- Avoid training data overfitting
- Reasonable computing time for flight data application

All the trees in forest have been boosted and pruned. *Boosting* procedure has been already exposed in Sec 5.1. *Pruning* is a process of cutting back a tree from the bottom up after it has been built to its maximum size. Only statistically insignificant nodes are pruned, in order to reduce overtraining of the tree.

In this work, Boosting and Pruning algorithms are set to default ones (*AdaBoost* algorithm for boosting and *CostComplexity* algorithm for pruning). For a more detailed description, refer to TMVA manual [33].

In order to find a good compromise between computing time (which roughly grows exponentially with the depth of the trees and linearly with the number of trees in the forest) and classification performances, a study has been performed by varying the number of trees in the forest and the maximum depth for each tree.

The trees can be grown for few steps, since the high number of trees in the forest allows to explore all the variable correlations. A range from 2 to 4 maximum depth of the tree has been explored.

A common way to display a classifier performance is the so-called ROC (*Receiver Operating Characteristics*) curve. The ROC curve plots the background suppression = $(1 - \text{efficiency})$ against the signal *efficiency*; the area under the ROC curve is a convenient way to compare different classifier performances. A similar information is also provided by Rejection curves, which plot background rejection $(1/\text{efficiency})$ against signal *efficiency*. A summary for this analysis is reported in Fig:5.17.

A good compromise between computing time and performances has been found by choosing the forest with 200 trees and maximum tree depth set to 4. BDT classifier distribution on a test sample are shown in Fig:5.18.

Input variables energy correction should provide an energy-independent classifier. Distributions of BDT classifier for different positron energies is shown in Fig:5.19, in which a good but not excellent uniformity is evident. Fig:5.20 shows BDT classifier efficiencies as a function of energy for different cuts.

400 GeV protons tend to populate the energy interval $\lesssim 200$ GeV, i.e. half their energy (see Fig:5.21), and they are the main background for 180 GeV

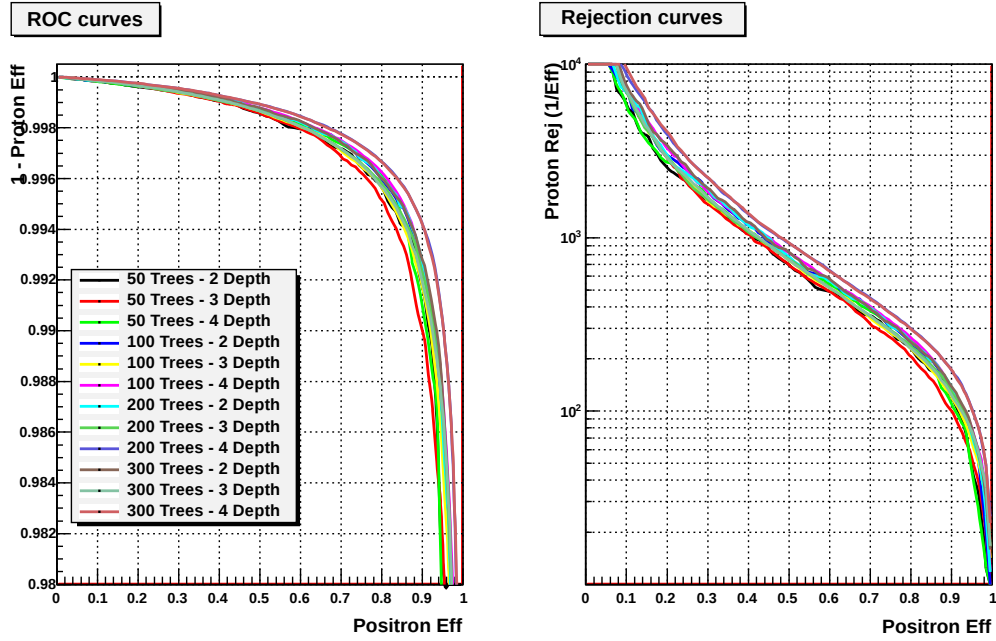


Figure 5.17: Left: ROC curves for different number of trees and tree maximum depths. Right: Rejection curves for different number of trees and tree maximum depths

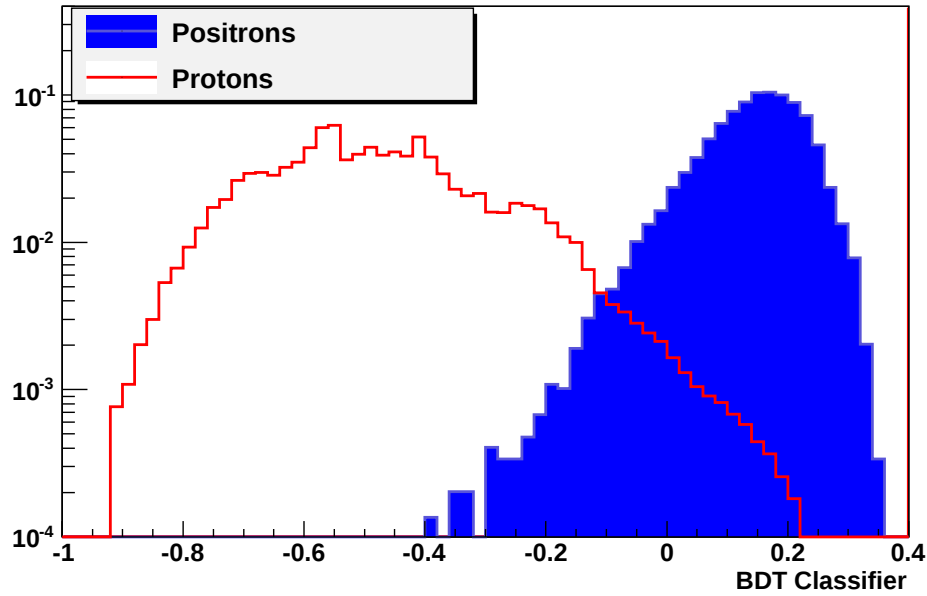


Figure 5.18: BDT classifier distribution for positron (blue) and proton (red) test sample, normalized to unity area. High values correspond to positron-like events, low values to hadron-like events.

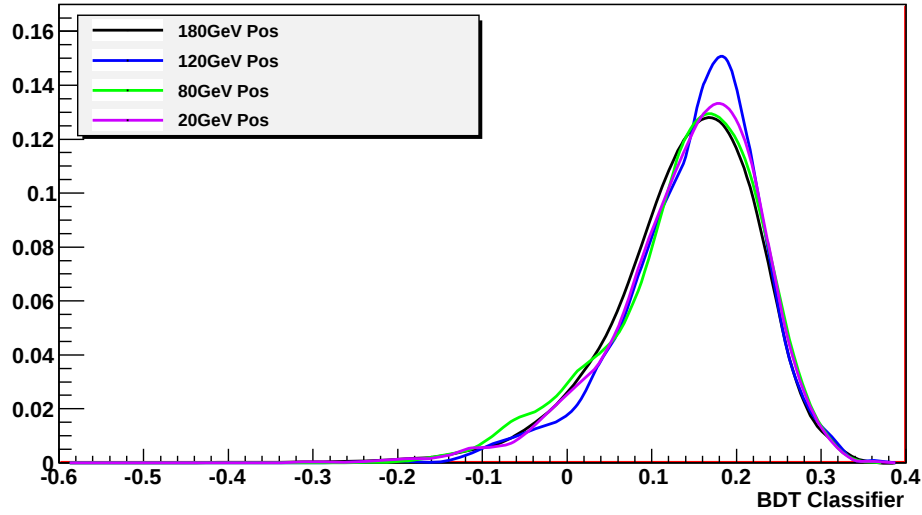


Figure 5.19: BDT classifier distribution for different positron energies, normalized to unity area.

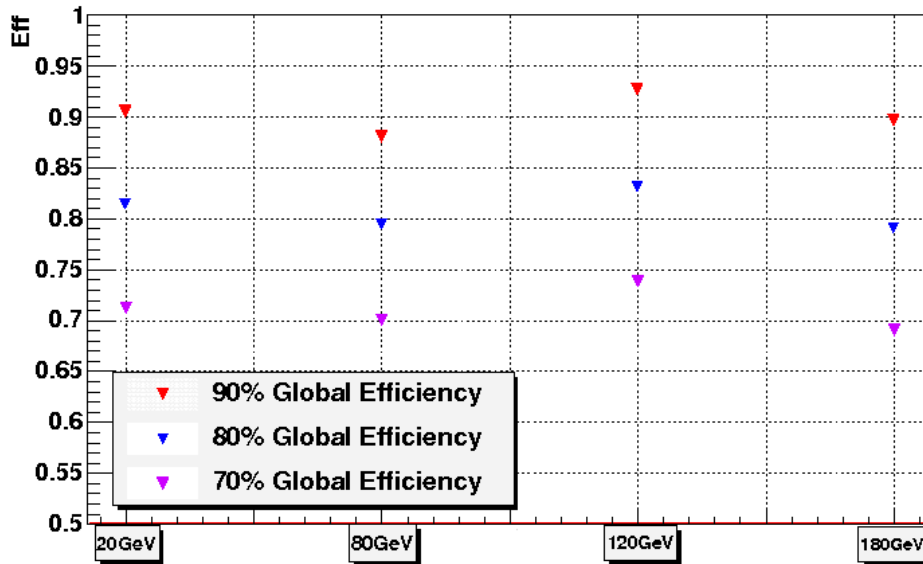


Figure 5.20: BDT classifier efficiency against positron energies for several global efficiencies.

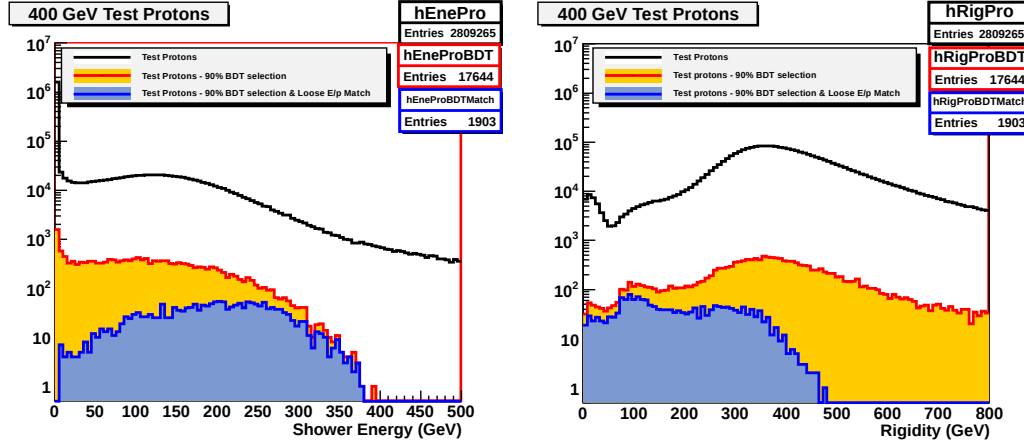


Figure 5.21: Energy (left) and rigidity (right) proton test sample spectrum (black), with BDT selection (red) and Loose E/p match (blue) cuts applied.

positrons.

An additional E/p matching cut is applied on the BDT selected proton sample to increase the total rejection power. The application of a *Loose E/p match* ($E_{\text{nedep}}/\text{Rigidity} > 0.6$) allows to reach a total rejection $\approx 1.5 \times 10^3$ for a signal efficiency $\approx 90\%$. Fig:5.21 shows that most of “low rigidity events” survive this loose E/p match selection. The optimization of the E/p match is done in a more refined BDT algorithm: the *Event* BDT. This algorithm, described in the next section, requires the generation of a continuous MC spectrum.

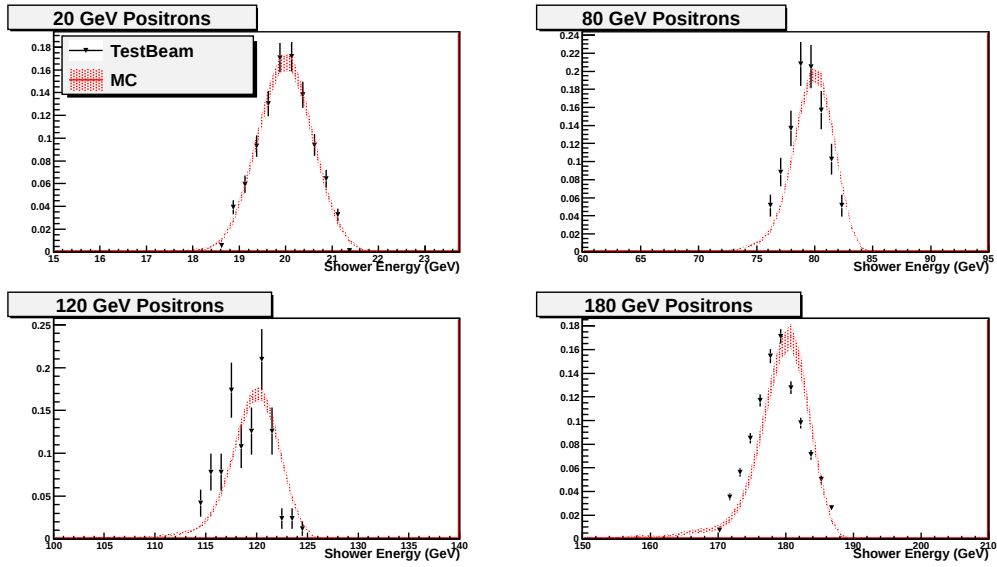
5.2.4 MC comparison

In order to evaluate systematics introduced by background subtraction, a study on a continuous MonteCarlo spectrum is mandatory. For this application it is necessary to check if classifier distributions on simulated samples are compatible with real data.

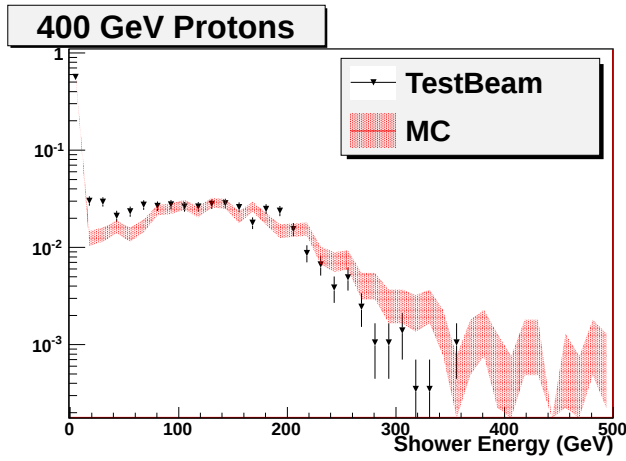
Using geant4 official AMS-02 MonteCarlo software *gbatch*, a set of positron samples reproducing Test Beam conditions (energies, impact positions and angles) has been produced. Classification algorithm has been then applied on these samples and compared with real data distributions.

In Fig:5.22 and 5.23, a comparison for Shower Measured Energy and Classifier variable is shown.

The good matching for the measured energy and for the energy corrected classifier states that the simulation software is able to reproduce electromagnetic and hadronic interactions as needed for this application. MonteCarlo spectrum can be safely used to evaluate residual background systematics introduced by the selection with the classifier.

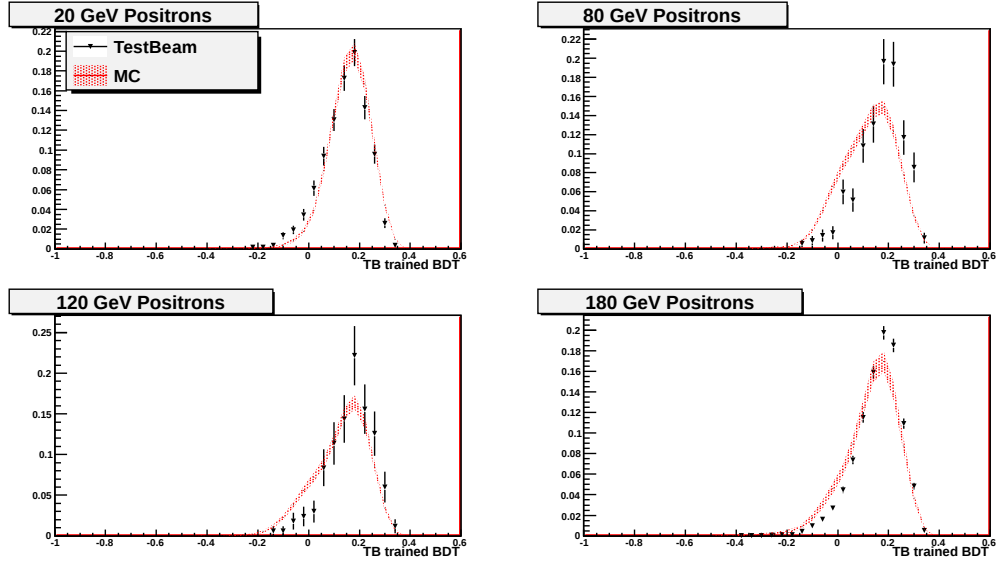


(a)

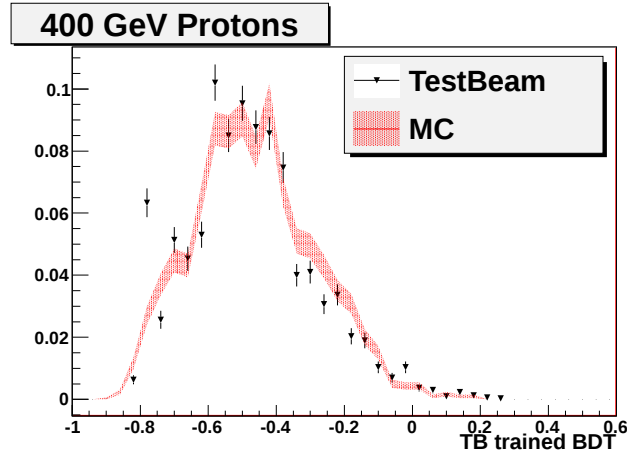


(b)

Figure 5.22: Test Beam and MC Shower Energy distributions for 20, 80, 120 and 180 GeV positrons (up) and 400 GeV protons (down). Red area represents 1 sigma interval for MC data.



(a)



(b)

Figure 5.23: Test Beam and MC *TB trained* BDT distributions for 20, 80, 120 and 180 GeV positrons (up) and 400 GeV protons (down). Red area represents 1 sigma interval for MC data.

5.3 Identification using MonteCarlo

The positron identification algorithm described in Sec:5.2 has been trained and tested on Test Beam data. However, this sample is limited to a few energy points and it requires to correct the energy dependence of input variables to avoid a bias in the identification.

Training the Multivariate Analysis classifier on a continuous MonteCarlo positron and proton spectrum has many advantages:

- it explores a continuous range of energies;
- deposited energy and rigidity, for energy-momentum matching optimization, can be used as discriminating variables without introducing any bias;
- energy dependence correction is no more necessary.

Before applying classification on data, the consistency between MC distributions and real data distributions has been checked.

5.3.1 Input variables

The possibility to introduce different variables allows for the definition of many classification algorithms, each one identified by the set of variables used for discrimination. Three algorithms have been defined:

- *ECALstandaloneBase*: classification algorithm using the same set of variables as the classification described in Sec:5.2, corrected for their energy dependence;
- *ECALstandalone*: classification algorithm using the following set of variables:
 - **L2LFrac** Last two layers deposited energy fraction;
 - **F2LFrac** First two layers deposited energy fraction;
 - **LayerCOG** Longitudinal development mean (Layer units);
 - **LayerSigma** Longitudinal development sigma (Layer units);
 - **Layer Skewness** Longitudinal development skewness (Layer units);
 - **Layer Kurtosis** Longitudinal development kurtosis (Layer units);
 - **DifoSum** $(E_x - E_y) / (E_x + E_y)$, $E_{x,y}$ is the energy deposit in X,Y view layers;
 - **LayerFrac[18]** Deposited energy fraction per layer;
 - **LayerLateralSigma[18]** Deposited energy sigma per layer;
 - **EneDep** Total deposited energy (GeV).

- *Event*: classification algorithm which uses also tracker measurement. This is an extension of the set of variables used for *ECALstandalone* with the inclusion of:
 - **Rigidity** Rigidity measured by the tracker (GeV);
 - **EneRigFrac** Enedep/Rigidity.

With respect to the Test Beam trained algorithm, some integral input variables have been removed from classification algorithm. They are replaced by “per layer” variables, like LayerFrac[18] or LayerLateralSigma[18], which allow for a detailed exploration of shower longitudinal and lateral development.

In order to apply the identification algorithm to the first set of data collected by AMS-02, only the rigidity measurement returned by the Inner tracker has been used. This allows for a gain in statistics of a factor ~ 3 thanks to the higher geometrical acceptance, but it limits the range of energies that can be analyzed (approximately to 200 GeV) due to the MDR of the inner tracker (layers 2 to 8). Data analysis using inner tracker rigidity also has the advantage to be independent from external layer alignment, which are out of TAS range (ref Sec:2.1.1) and need to be aligned using flight data.

5.3.2 Train and test sample

In this section, the following datasets have been used for training and testing:

- Positrons: 10-100 GeV continuous spectrum.
- Protons: 10-200 GeV continuous spectrum.

All events are generated on the top plane of a $3.9 \times 3.9 \times 3.9$ m³ cube centered on AMS-02 with a uniform solid angle distribution and a momentum distribution flat in logarithm ($dN/d\log_{10}(p) = \text{const}$).

Proton maximum energy has been chosen to be at least twice the positron maximum energy, because protons tend to populate measured energy bins $\lesssim$ half their energy.

Training and test samples are selected among all events triggering AMS-02 using the following requests:

- FTC (TOF) Trigger: charge 1 particles in AMS-02 field of view are triggered by the TOF;
- Track geometry and quality cut
 - only one reconstructed track;
 - good pattern in inner layers (see Sec:5.2.1);
 - track quality cut: cut on χ_y^2/NDF , which is the reduced ChiSquare associated to the track fitting in the bending view of the magnetic field (y), more sensitive to the track reconstruction quality.

- Track-shower matching using RCG variable (see Sec:5.2.1);

5.3.3 Training and testing BDT algorithm

Algorithm training is performed using the same machinery exposed in Sec:5.2.3. *Adaboost* and *CostComplexity* algorithms are used for boosting and pruning the “forest”. The number of trees in the forest is set to 200, with a maximum depth set to 6, due to the large number of variables to explore. For all three analyzed algorithms, the classifier distributions, the ROC/Rejection curve, the positron efficiency spectrum and the proton energy spectrum are shown in Fig:5.24, Fig:5.25, Fig:5.26 and Fig:5.27.

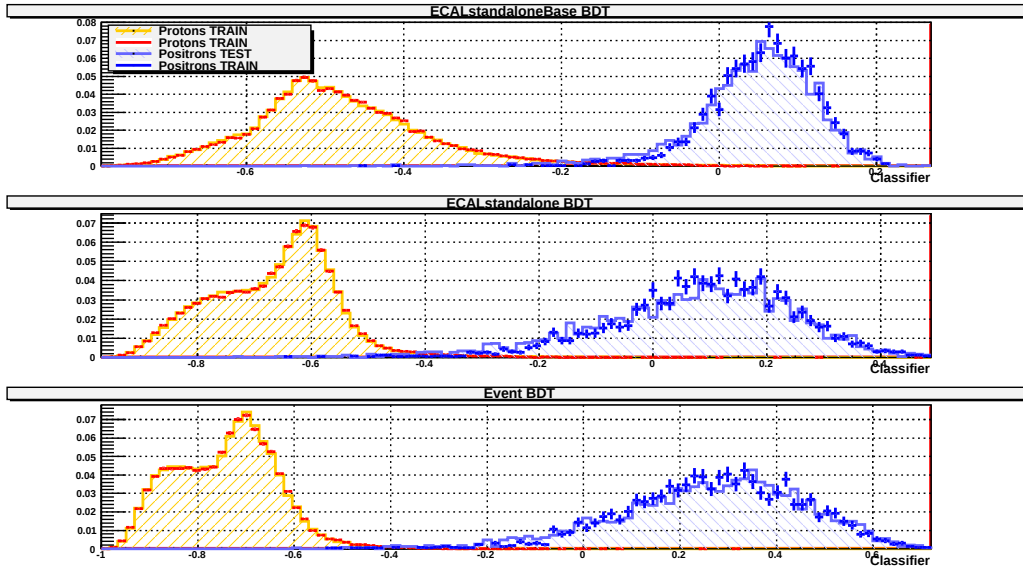


Figure 5.24: Classifier distributions.

The comparison of MC - Test Beam data distributions is shown in Fig:5.28, Fig:5.29 and Fig:5.30.

For protons, all BDT distributions show an overall good matching between Test Beam data and MC. For positrons instead, only *ECALstandaloneBase* MC distributions well describe real data. The data-MC comparison for the two other classifiers is not so good, requiring a more fined tuning of ECAL MonteCarlo simulation and also a wider energy range for classification training in order to apply these classifiers on real data and on higher energies.

5.4 Proton rejection

Proton rejection spectrum and e/p rejection depend on particle fluxes, because protons of all higher energies contribute to the background in a particular energy

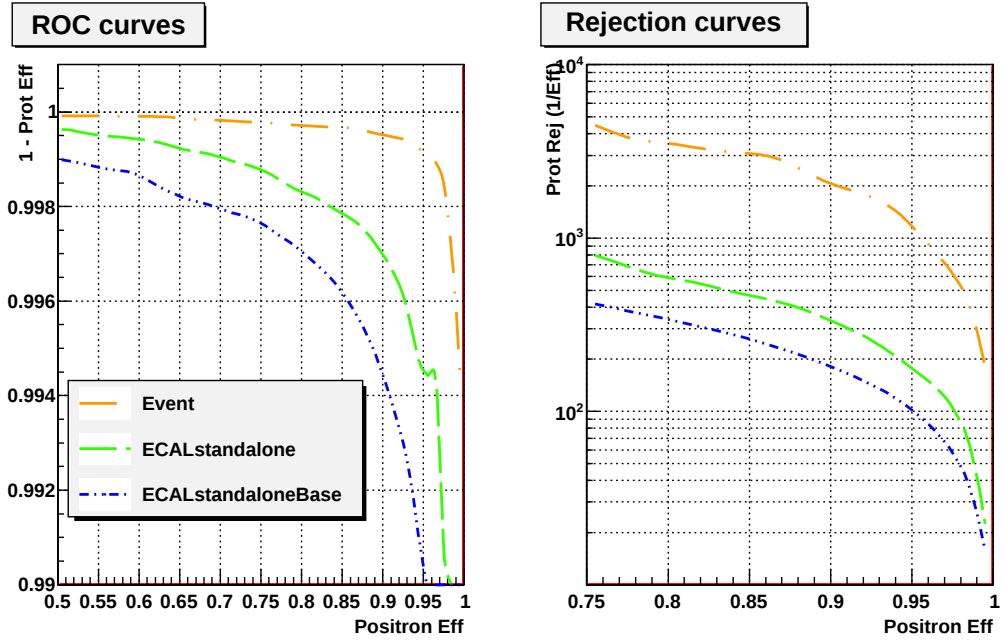


Figure 5.25: Rejection curves.

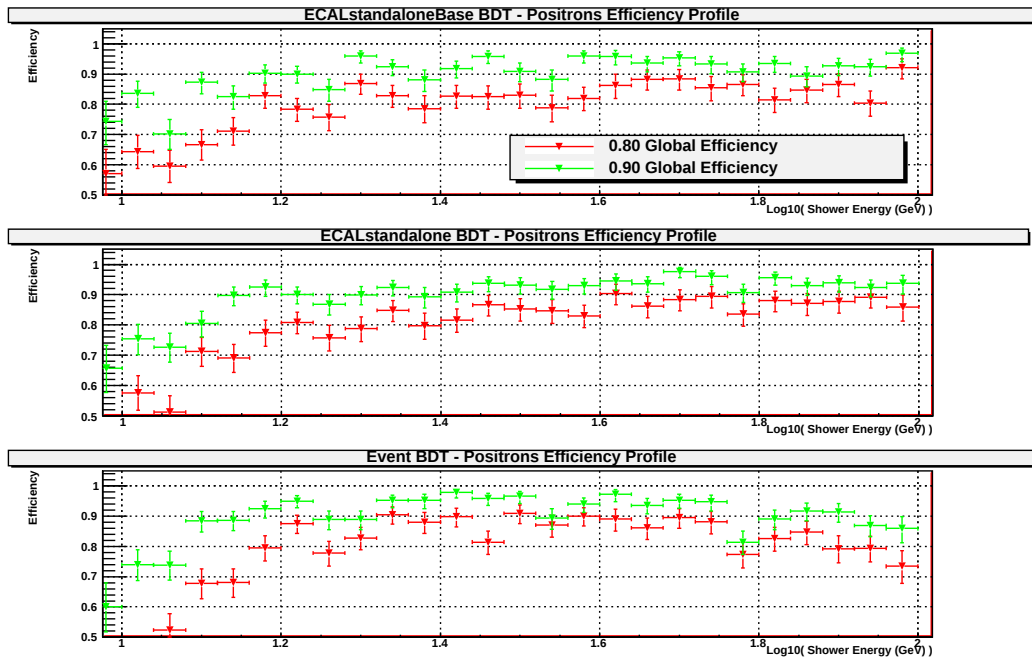


Figure 5.26: Positron efficiency profile.

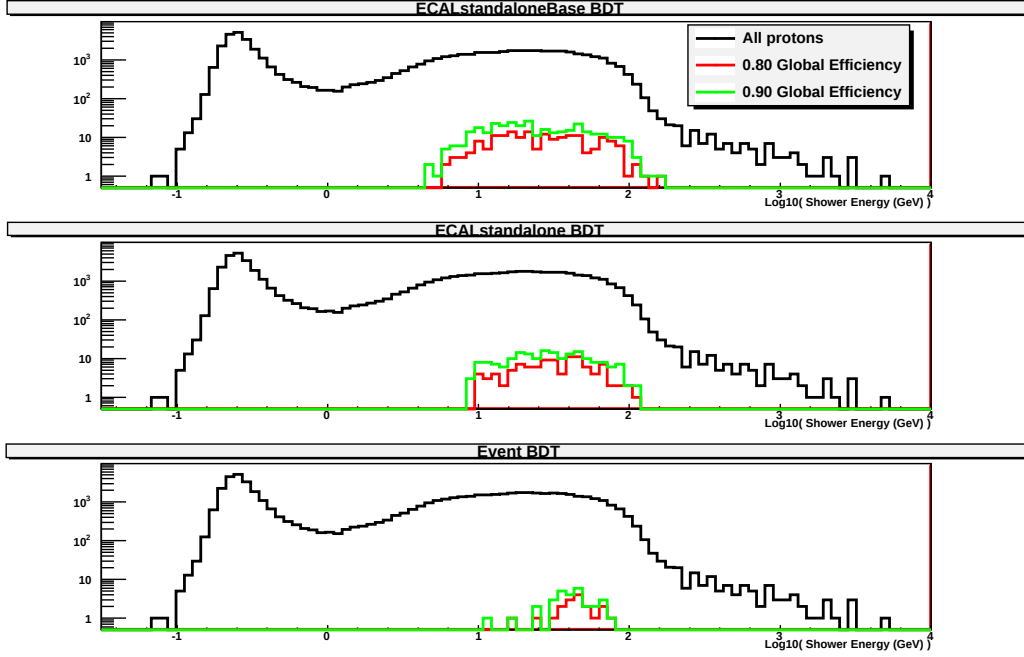


Figure 5.27: Proton energy spectrum.

interval. In order to evaluate the rejection spectra, it is necessary to know the incoming flux at the top of AMS-02.

In this section, MonteCarlo simulations are used to evaluate AMS-02 positron and proton expected spectra and then to calculate e/p rejection against energy for the identification algorithms presented in Sec:5.2 and Sec:5.3.

5.4.1 AMS-02 expected spectra

The rate of entries of a particular particle per energy bin can be expressed as:

$$\frac{dN(E_{meas})}{dt} = \sum_{E_{true}} J(E_{true}) \cdot A(E_{true}) \cdot P(E_{meas}|E_{true}) \cdot \varepsilon(E_{meas}, E_{true}) \cdot \Delta E_{meas} \quad (5.2)$$

where E_{true} is the proper particle energy defined in the simulation, E_{meas} is the energy measurement of ECAL, $J(E_{true})$ is the absolute flux at the top of AMS-02 expressed in $\text{GeV}^{-1} \text{s}^{-1} \text{m}^{-2} \text{sr}^{-1}$, $A(E_{true})$ is the geometrical acceptance of the detector expressed in $\text{m}^2 \text{sr}$, $P(E_{meas}|E_{true})$ defines the smearing due to energy measurement (in particular for protons), $\varepsilon(E_{meas}, E_{true})$ is the tagging efficiency (which in principle depends both on the particle true energy and on its measured value) and ΔE_{meas} is the width of the energy bin. The sum is intended to loop over all true energy bins.

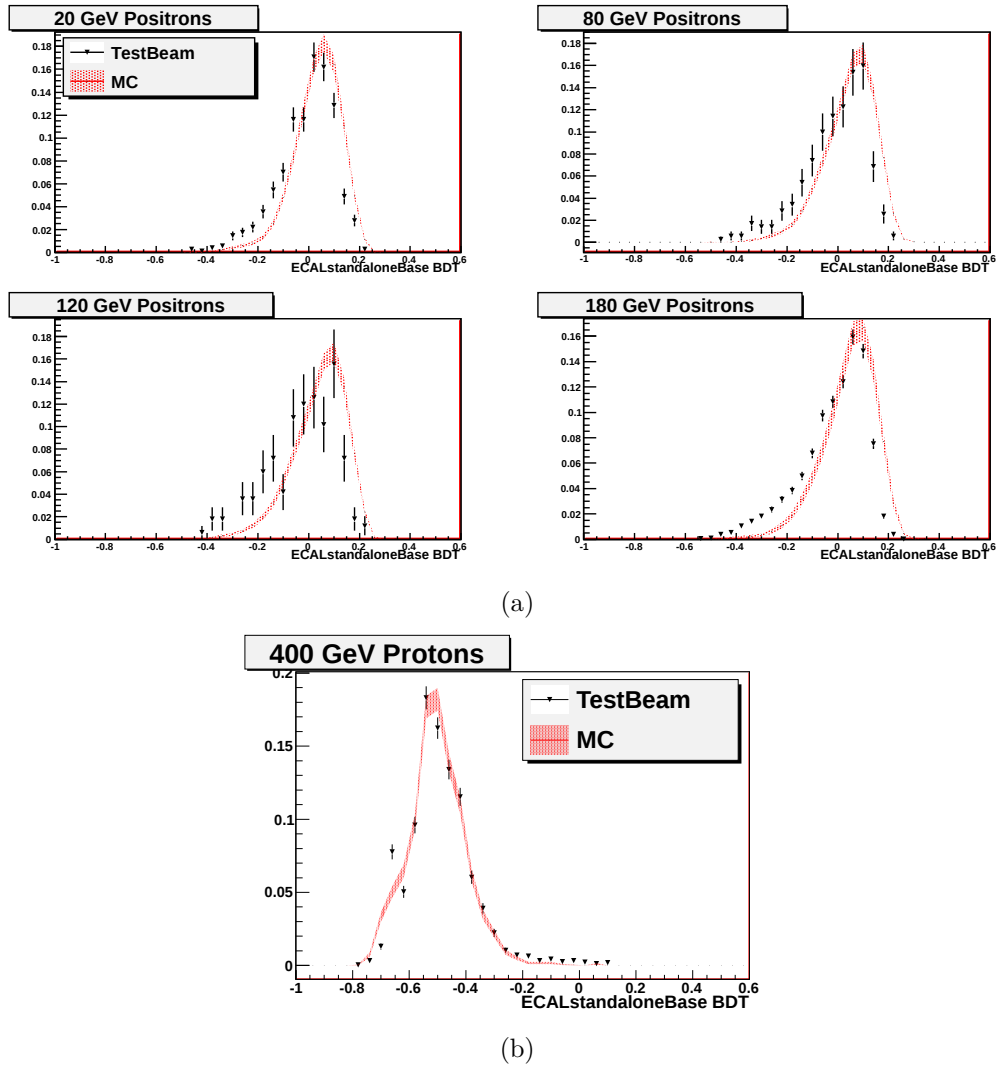


Figure 5.28: Test Beam and MC $ECALstandaloneBase$ distributions for 20, 80, 120 and 180 GeV positrons (up) and 400 GeV protons (down). Red area represents 1 sigma interval for MC data.

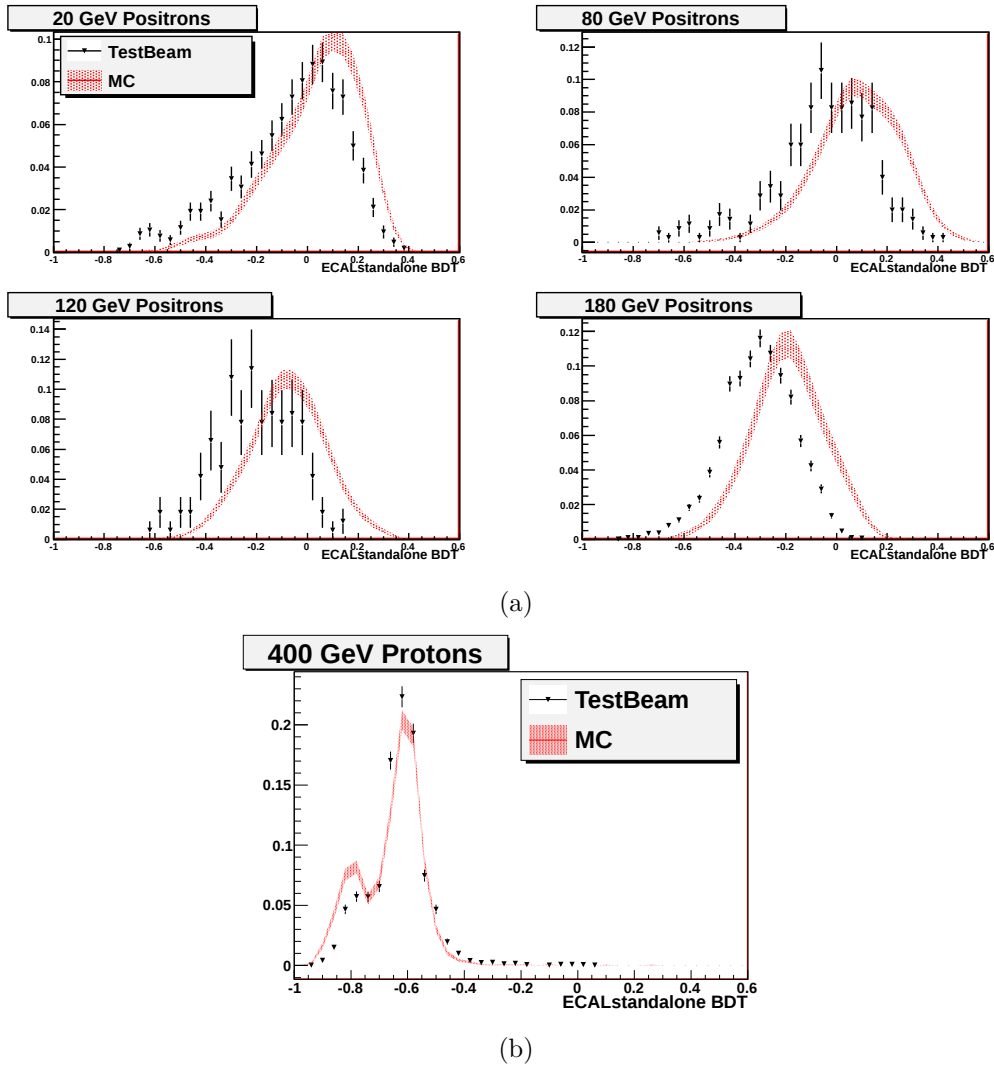


Figure 5.29: Test Beam and MC $ECAL_{standalone}$ distributions for 20, 80, 120 and 180 GeV positrons (up) and 400 GeV protons (down). Red area represents 1 sigma interval for MC data.

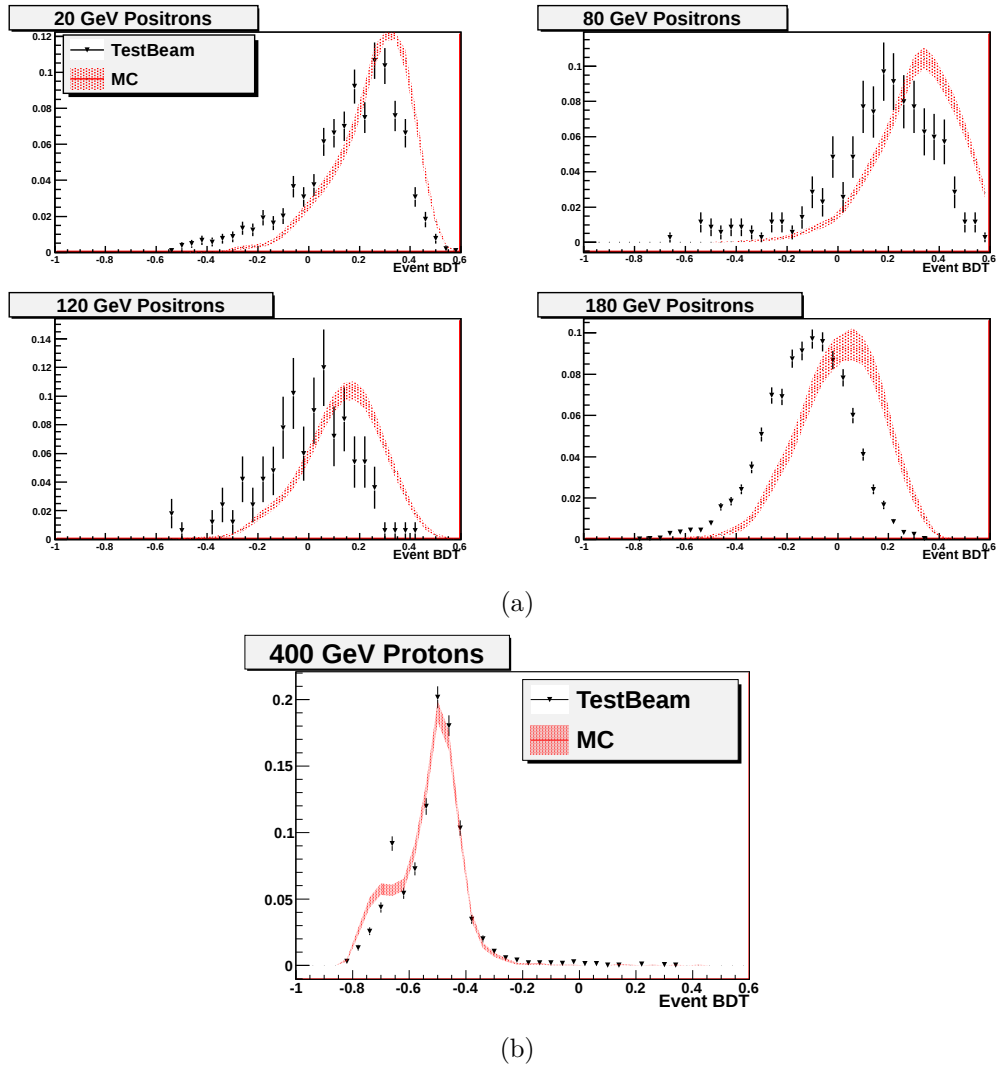


Figure 5.30: Test Beam and MC *Event* distributions for 20, 80, 120 and 180 GeV positrons (up) and 400 GeV protons (down). Red area represents 1 sigma interval for MC data.

In order to apply Eq:5.2 and to compute AMS-02 expected positron and proton rates, all these factors must be evaluated from MC simulations. The MC sample used for this analysis is composed by:

- 10 - 300 GeV positrons. The higher energy spectrum (>100 GeV) is used only for acceptance calculation: BDT algorithms trained on a 10-100 GeV positron sample are not optimized to be efficient on these energies;
- 10 - 200 GeV protons.

This energy range includes the one explored by current experiments and will be the first one to be explored by AMS-02.

The absolute flux for protons at the top of the payload has been measured by several experiments, and an analytical description is available [2]:

$$J_p(E) \approx 10^4 \cdot (E/\text{GeV})^{-2.7} \text{GeV}^{-1} \text{s}^{-1} \text{m}^{-2} \text{sr}^{-1} \quad (5.3)$$

For positrons and electrons, a numerical model for $J_{e^\pm}(E)$ that well fits PAMELA data and FERMI positron and electron spectrum has been used [34]. Spectra are derived using DRAGON simulation package [35], assuming a typical “Kraichnan” diffusion model with diffusion coefficient $\delta = 0.5$. Fig:5.31 shows the absolute flux spectra assumed in this analysis.

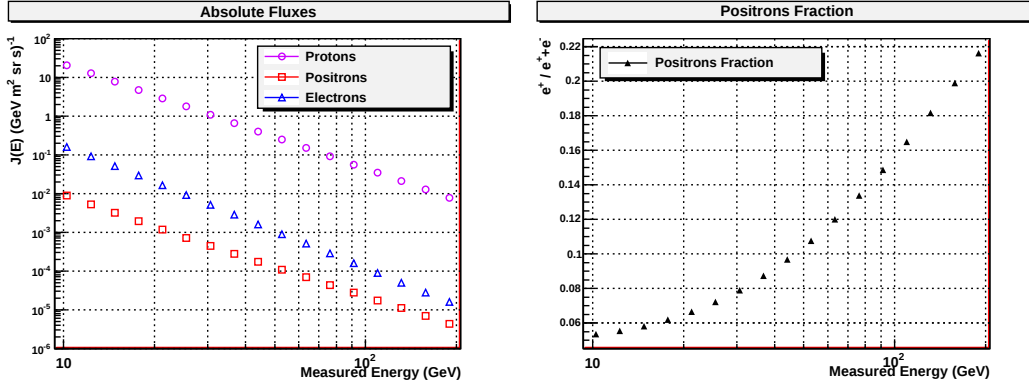


Figure 5.31: Left: Representation of proton, electron and positron differential fluxes assumed in the following analysis. Right: Positron fraction derived using previously presented numerical model.

The acceptance calculation has been performed using MC. The acceptance factor $A(E)$ contains not only the geometrical factor, but also the selection efficiencies necessary to perform analysis on a triggered event. So it can be factorized $A(E) = G(E) \cdot \xi(E)$, $G(E)$ being the pure geometrical acceptance (expressed in $\text{m}^2 \text{sr}$) and $\xi(E)$ the pre-selection efficiency on all the sample.

As already discussed in Sec:5.3.2, MC sample has been generated isotropically in the top plane of a “standard AMS” cube $3.9 \times 3.9 \times 3.9 \text{ m}^3$ centered in AMS, so all the calculations have been normalized to this acceptance.

The geometrical acceptance of a surface A, defined as the ratio between measurable events and incident flux, can be calculated using:

$$\int_A \int_{4\pi} d\vec{\Omega} \cdot d\vec{S} \quad (5.4)$$

where the angle integral is done over all 4π sr solid angle. The geometrical acceptance of a 2D surface is $2\pi A$ for a 4π isotropic flux. The standard AMS-02 top plane acceptance is calculated to be $G=95.52 \text{ m}^2 \text{ sr}$ (divided by a factor of 2 if only downgoing particles are considered).

In this analysis, a particle is defined to be inside the geometrical acceptance of the detector if it fires the TOF fast trigger (FTC) and hits at least 10 out of 18 ECAL planes. Then, the same pre-selection on track quality and shower matching introduced in Sec:5.3.2 has been applied. Efficiencies and total acceptances for positrons are shown in Fig:5.32 and Fig:5.33.

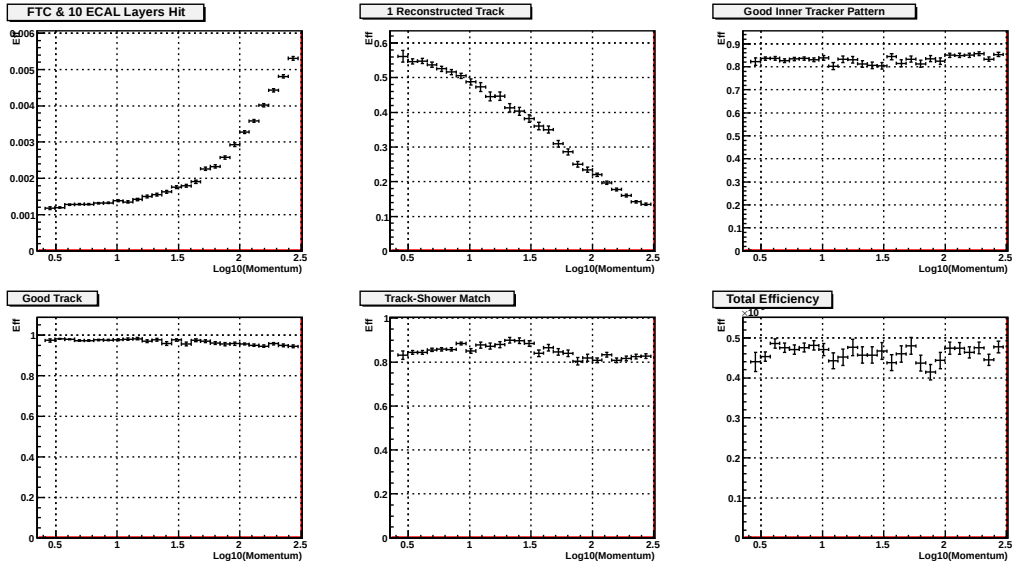


Figure 5.32: Geometrical and pre-selection efficiencies for positron MC sample.

Protons of a given E_{true} energy populate the E_{meas} energy intervals $E_{meas} \lesssim \frac{1}{2}E_{true}$, as shown in Fig:5.34. The background of protons in a particular E_{meas} energy bin is therefore due to the spectrum above E_{meas} . To take into account all the proton energy spectrum for background evaluation, the smearing factor $P(E_{meas}|E_{true})$ and the efficiency factor $\varepsilon(E_{meas}, E_{true})$ in Eq:5.2 have been combined in an unique factor $\beta_i(E_{true}, E_{meas})$, where the index i indicates the classifier algorithm applied for identification. A convenient representation of the

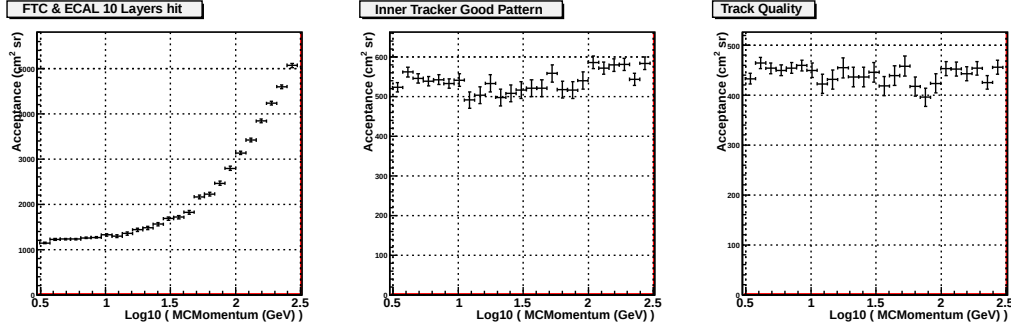


Figure 5.33: Geometrical Acceptance for positron MC sample. The first plot on the left represents the pure geometrical acceptance, while the most right plot represents the global geometrical and pre-selection acceptance.

$\beta_i(E_{true}, E_{meas})$ factor is a 2D “smearing” matrix, in which for each true energy value, the fraction of events populating a given measured energy value is plotted. Bins are normalized such that $\sum_{E_{meas}} \beta_i[E_{true}][E_{meas}] = \varepsilon(E_{true})$, where the sum is intended to loop over all measured energy bins.

In Fig:5.35 an example of β matrix for *ECALstandalone* is displayed.

Eq:5.2 can be rewritten as follows:

$$\frac{dN(E_{meas})}{dt} = \sum_{E_{true}} J(E_{true}) \cdot A(E_{true}) \cdot \beta[E_{meas}][E_{true}] \cdot \Delta E_{meas} \quad (5.5)$$

and applied to estimate AMS-02 expected spectra rate.

5.4.2 e/p rejection

A rejection factor of $\sim 10^6$ is necessary to make the residual proton background in the positron signal negligible. AMS-02 experiment can use ECAL, TRD and Tracker subdetectors to reach the desired rejection factor. Among all the subdetectors, ECAL is certainly the most important for this purpose. Positron identification algorithms, presented in Sec:5.2 (*TB trained*) and 5.3 (*ECALstandalone* and *Event*), can be used to evaluate ECAL and ECAL+Tracker *e/p rejection*. The results on AMS-02 expected fluxes in Sec:5.4.1 can be extended and applied in this context. Eq:5.3 has been applied to parametrize proton flux at the top of AMS-02 and numerical models exposed in Sec:5.4.1 have been used to parametrize positron fluxes: the expected event rate energy spectra are shown in Fig:5.36.

Expected spectra are used to calculate *proton rejection*, defined as the inverse of the fraction of protons in the detector acceptance tagged as positrons per energy bin, and *e/p rejection*, defined as the ratio $\varepsilon_{e^+}(E)/\varepsilon_p(E)$, where $\varepsilon(E)$ is the BDT classifier efficiency on positrons and protons for a given energy. In this procedure, the statistics of MC protons (corresponding to approximately 2 months of AMS-02 operations) used to evaluate $\varepsilon_p(E)$ is extremely low after the

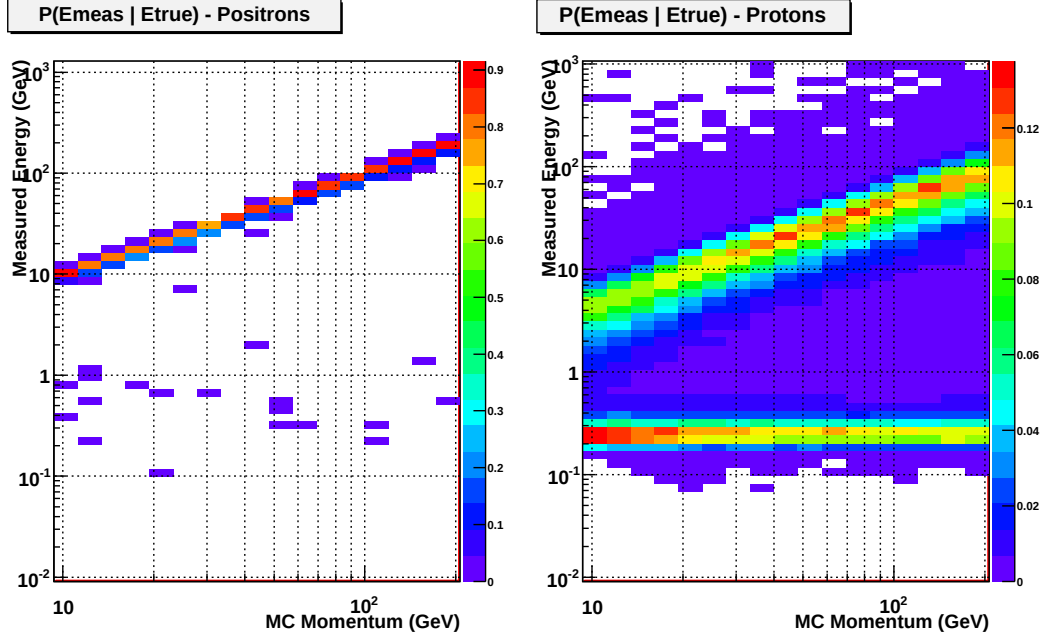


Figure 5.34: $P(E_{meas}|E_{true})$ for positron (left) and proton (right) MC sample. While positrons tend to populate the matrix diagonal (i.e. $E_{meas} \simeq E_{true}$, as expected from an electromagnetic calorimeter), for protons the most populated regions are the MIP band (on the bottom) and the $E_{meas} \lesssim \frac{1}{2}E_{true}$ band, according to the fact that interacting protons usually tend to lose a fraction of their energy in the form of an electromagnetic deposit.

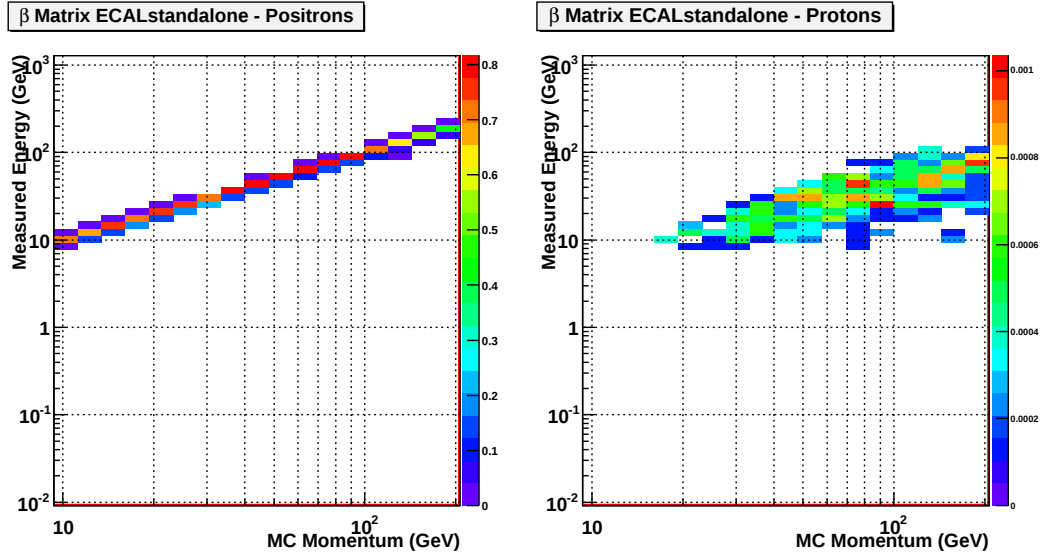


Figure 5.35: β Matrix *ECALstandalone* for positron (left) and proton (right) MC sample.

selection (see Fig:5.27), so the confidence interval estimation for the binomial ratio $\varepsilon_p(E)$ has been evaluated using the *Clopper-Pearson* coverage interval [36], which is more accurate than the standard one when the estimated probability p tends to 0 or 1.

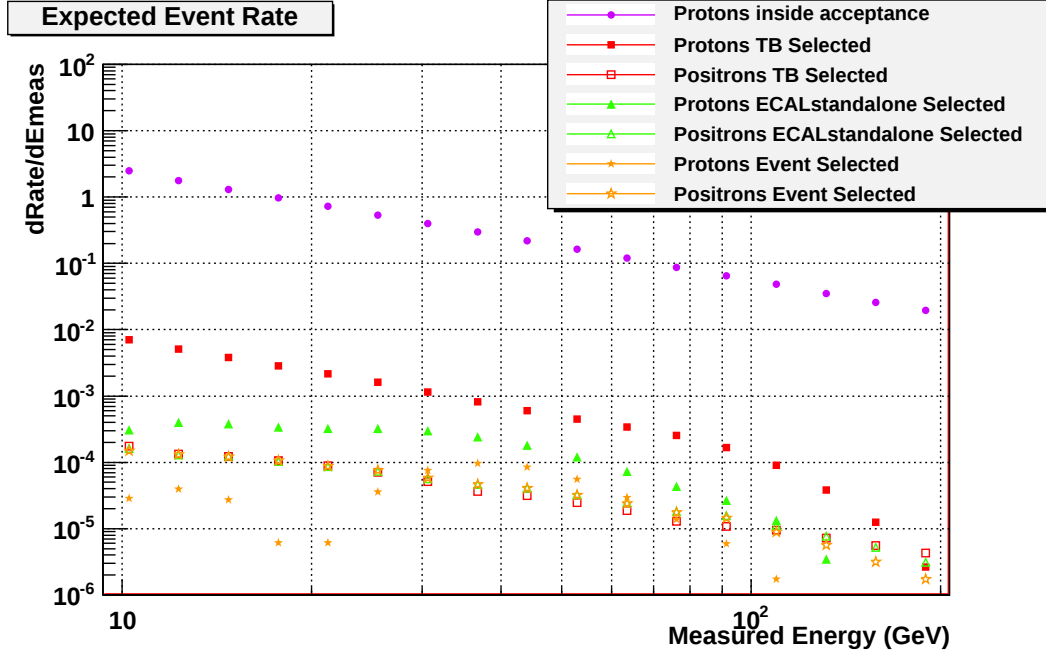


Figure 5.36: Expected event rate in AMS-02 for protons (full symbols) and positrons (empty symbols) using different classifier selection. Violet circles represent the rate of protons inside AMS-02 and ECAL acceptance. Squares, triangles and stars represent positron and proton expected rate after the selection using *TB trained*, *ECALstandalone* and *Event* BDT respectively, with a 90% efficiency on positrons.

Proton rejection and *e/p rejection* spectra are shown in Fig:5.37. The statistical confidence level uncertainty is dominated by the low proton statistics used to estimate $\varepsilon_p(E)$. *ECALstandalone* and *Event* classifiers have been trained over a maximum positron energy of 100 GeV, so only the range up to this energy is relevant. *TB trained* classifier corrects variables for the energy dependence, so all the energy range that will be explored by AMS-02 during the first period of operations (up to 200 GeV) is shown.

As expected, ECAL can be used as a standalone detector to discriminate positrons against protons with a rejection better than 10³. Including also tracker measurement, the *E/p* comparison allows to gain a factor ~ 10 in the rejection, depending on the particle measured energy.

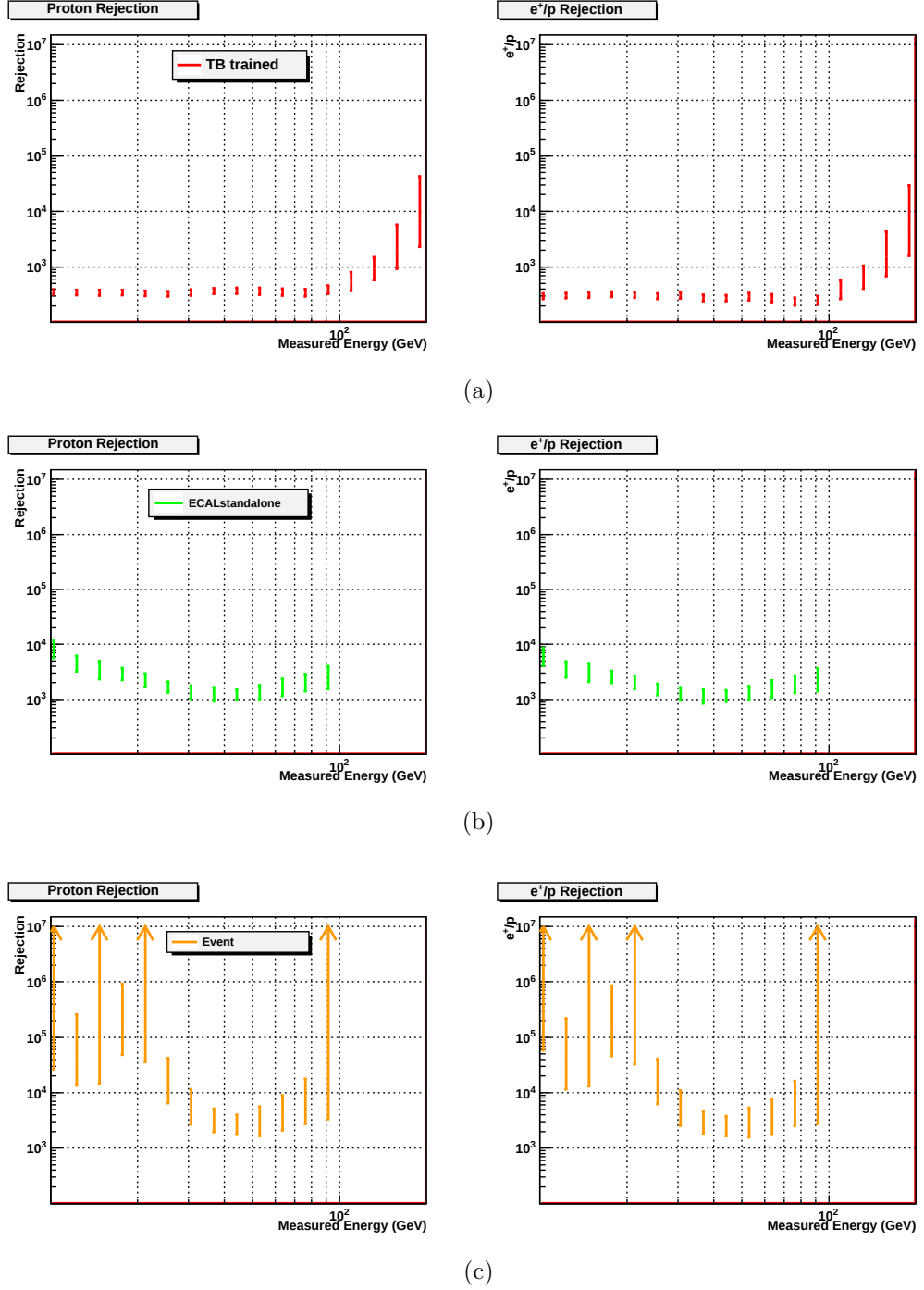


Figure 5.37: *Proton rejection* (left) and *e/p rejection* (right) for *TBtrained* (a), *ECALstandalone* (b) and *Event* (c) BDT classifiers. Error bars represent the 1σ confidence level interval for these values. The uncertainty on this measurement is dominated by the low proton statistics used to calculate the efficiency confidence levels.

5.5 Applications

The algorithms described in Sec:5.2 and Sec:5.3 have been applied to the first flight data in order to cross-check their performances. In this section, a dataset corresponding to ~ 1 week of AMS-02 data taking has been analyzed.

For this check, only the negative charged events have been used, since their signal to background ratio is better than for the positive channel and their absolute flux is also higher. The natural background for electrons are antiprotons, whose flux is ≈ 100 times weaker than the electron one. Proton flux is orders of magnitude more intense, and protons with a negative reconstructed charge (“spillover” protons), which are a fraction of the total flux, are an additional background for the negative channel. For positrons, instead, protons are the natural background. The ratio of $\sim 10^4$ between background and signal in the positive channel is too high to use it for this cross-check.

Negative charged events are pre-selected in the energy range 10-100 GeV, using similar cuts as described in Sec:5.3.2 for the quality of the track (“good inner pattern”, cut on χ_y^2/NDF , match between the track and the ECAL shower).

On this pre-selected sample, which consists of electrons and of their background ($\bar{p}$ and “spillover” p), electrons can be selected independently from ECAL classifier using TRD and tracker. TRD can identify electrons using a likelihood-based selection. Tracker measurement can be used to identify electrons by matching the energy deposit in ECAL (E) with the rigidity measurement of the tracker (p).

Fig:5.38 shows TRD Likelihood and E/p against ECAL classifier distributions. For both the distributions, the two populations of electrons and hadrons are well separated. The ECAL classifier correctly identifies positrons and rejects the hadron background. Fig:5.39 shows the distribution of electrons in this sample, selected using a 90% efficiency cut on *TB trained* classifier.

A comparison for all the trained algorithms between electron flight data, positron Test Beam data and positron MonteCarlo data is shown in Fig:5.40. For *TB trained* classifier, which has been developed using Test Beam data and with input variables corrected by their energy dependence, all the electron flight spectrum has been used. The other classifiers have been trained on a 10-100 GeV MC positron sample, and input variables have a dependence on the deposited energy. Test Beam data in this energy range are available only for 20 GeV and 80 GeV. The comparison is possible only for the 20 GeV energy range, because flight data statistics at 80 GeV is poor.

The overall comparison between flight electron and Test Beam positron distribution is acceptable. This also confirms that the distributions of ECAL classifiers are in good approximation charge independent, as expected. For *TB trained* and *ECALstandaloneBase* (which also uses the energy independent definition of input

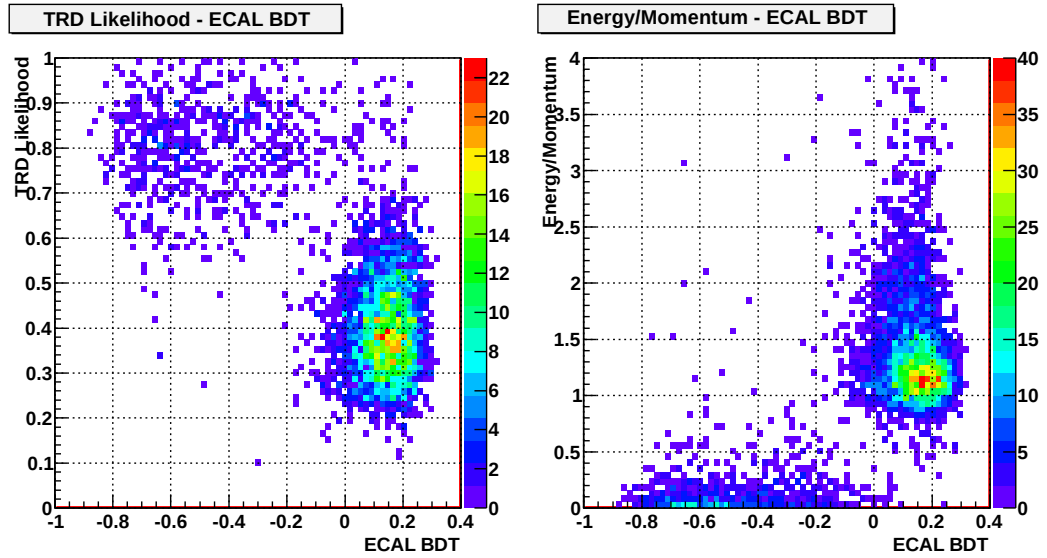


Figure 5.38: TRD Likelihood (left) and E/p (right) against ECAL *TB trained* classifier applied on negative charge flight data. The two populations of electrons and hadrons ($\bar{p}$ and “spillover” p) are well separated.

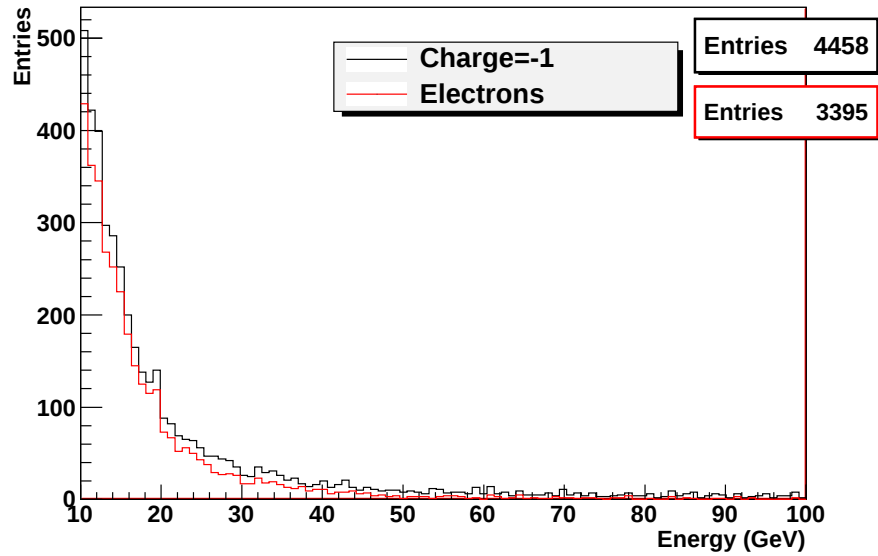


Figure 5.39: Negative charge events distribution (black) and electron distribution (red) for flight data. Electrons are selected using a 90% efficiency cut on *TB trained* classifier.

variables) the matching quality between real data and MonteCarlo data is good. For the other algorithms the application on real data exhibits a shift in the distributions, and the comparison is not good. This confirms the necessity, already exposed in Sec:5.3.2 for the Test Beam - MC comparison of the same algorithms, of a refined MonteCarlo tuning.

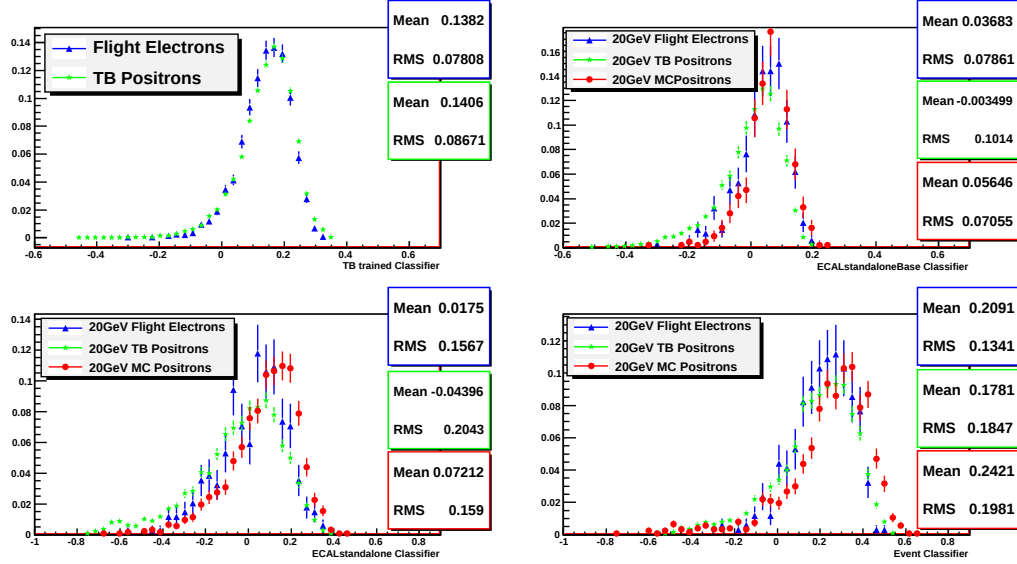


Figure 5.40: Comparison between *TB trained*, *ECALstandaloneBase*, *ECALstandalone* and *Event* classifiers for flight electrons (blue triangles), Test Beam positrons (green stars) and MonteCarlo positrons (red circles).

5.5.1 Positron fraction expected spectrum

Although the data-MC comparison has still to be refined, ECAL selection can be applied to the expected $e^\pm$ spectra to evaluate AMS-02 performances for the positron fraction measurement.

One of the main systematics in the positron fraction measurement is the subtraction of the residual proton contamination in the positive sample (positrons).

The number of $e^\pm$ measured events N^{obs} has a contribution of hadronic contamination, protons in the positron channel and antiprotons and “spillover” protons in the electron channel:

$$N_{e^+}^{obs} = \varepsilon_{e^+} N_{e^+}^{true} + \varepsilon_p N_p^{true}$$

$$N_{e^-}^{obs} = \varepsilon_{e^-} N_{e^-}^{true} + \varepsilon_{\bar{p},p} N_{\bar{p},p}^{true}$$

where N^{true} is the absolute flux, ε_i is the selection efficiency for the particle i and $N_{\bar{p},p}$ is the total hadronic contribution of antiprotons and “spillover” protons to the electron channel. The contribution of “spillover” antiprotons to the positron background is negligible with respect to the proton one.

Flight electron - Test Beam positron comparison in Sec:5.5 shows that the selection efficiency for ECAL classifier is at a good level charge independent ($\varepsilon_{e^+} \simeq \varepsilon_{e^-}$), and the positron fraction can be expressed as:

$$\frac{N_{e^+}^{true}}{N_{e^-}^{true} + N_{e^+}^{true}} = \frac{N_{e^+}^{obs} - \varepsilon_p N_p^{true}}{N_{e^-}^{obs} + N_{e^+}^{obs} - \varepsilon_{\bar{p},p}(N_p^{true} + N_{\bar{p}}^{true})}$$

Assuming a good knowledge of absolute fluxes and efficiencies, the main residual systematic is due to the background subtraction. The results in Sec:5.5 show that the ECAL classifier correctly identifies $e^\pm$ and the error introduced by the background subtraction is small if compared to the statistical fluctuations on the signal event number, at least in the first period of data taking. The uncertainty in the positron fraction measurement is dominated by statistical fluctuations for the first period of AMS-02 operations.

Fig:5.41 and Fig:5.42 show expected $e^\pm$ and fraction spectrum during the first data taking periods. For this first period, only the inner tracker can be used for rigidity measurements, because the external layers (which are out of the TAS range) must be aligned using flight data. So only the energy range below the inner tracker MDR (~ 200 GeV) can be explored at the beginning of AMS-02 operations. In 2 months of data taking, after the commissioning period, AMS-02 will collect the needed statistics to improve over current results.

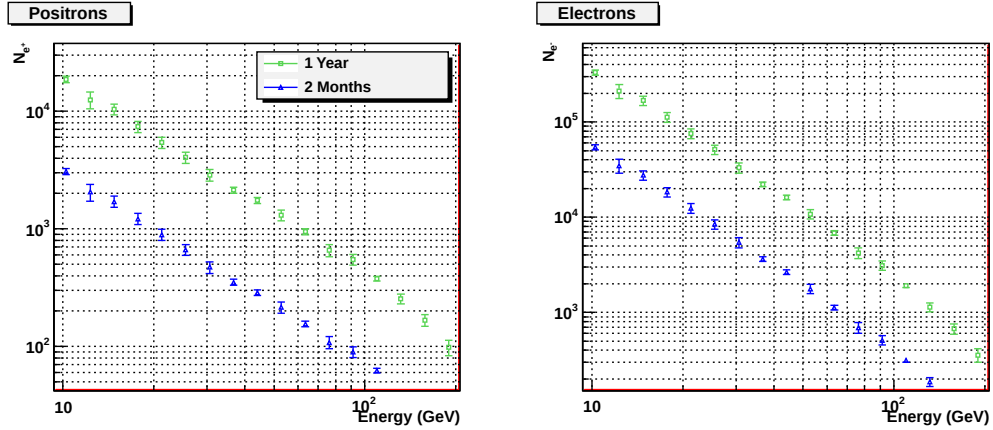


Figure 5.41: Expected positron (left) and electron (right) measured number of events after for 2 months and 1 year of data taking time. Fluxes at the top of the payload $J(E)$ are derived using numerical models (see Sec:5.4.1).

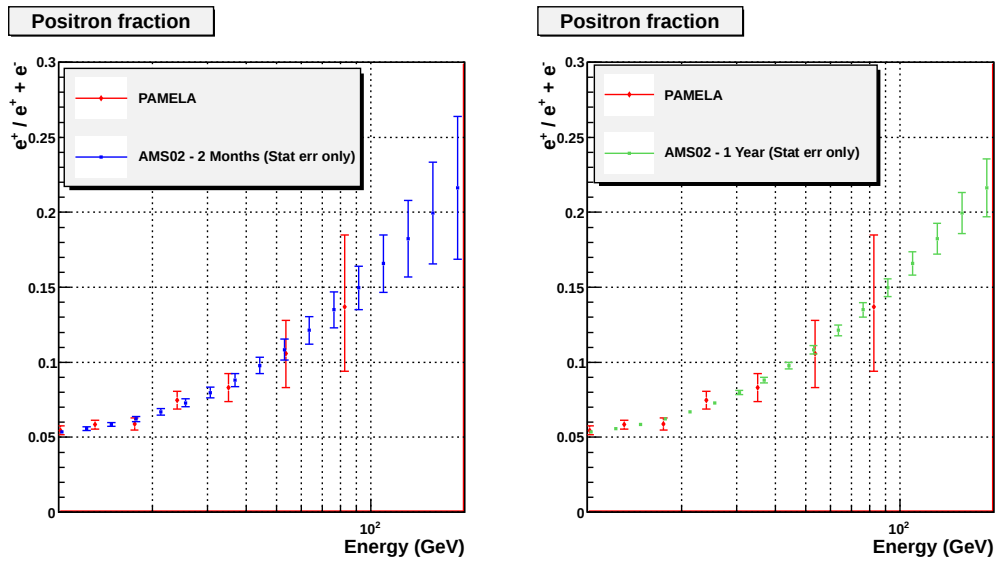


Figure 5.42: AMS-02 expected positron fraction after 2 months (blue) and 1 year (green). Only statistical errors reported. Red data represent PAMELA fraction measurement [5].

Conclusions

The performances of ECAL electromagnetic calorimeter have been evaluated on the basis of 2007 Test Beam data. The calorimeter satisfies all the requirements to perform high precision measurements of $e^\pm$ spectra up to 1 TeV. The equalization of ECAL cells and the correction for rear leakage applied on deposited energy enables to obtain an energy resolution $\sigma(E)/E = 9.9\% / \sqrt{E(\text{GeV})} \oplus 1.5\%$ with deviation from linearity less than 1%.

ECAL also has a standalone γ ray measurement capability, and provides the trigger for non converting photons inside AMS-02 field of view with an efficiency better than 99% for energies > 10 GeV.

A ECAL cell equalization algorithm has been developed and tested using 2010 Test Beam protons. The same algorithm has been tested on the first flight protons. Its performances have been confirmed and equalization values have been found compatible with Test Beam analysis.

He nuclei MIP identification algorithm has been described. The statistics collected in ~ 1 week provide a stable equalization process.

ECAL 3D imaging capabilities have been investigated in order to develop a e^+/p discrimination tool for energies up to 100 GeV, which is the interval currently investigated by other experiments. MC data have been used to evaluate e^+ and p expected spectra in AMS-02 acceptance. This is essential to measure ECAL proton rejection capabilities by taking into account the background contribution of all energies in the spectrum.

A *Boosted Decision Tree* multivariate analysis algorithm has been developed and tested using 2010 Test Beam positron and proton data.

The use of MC continuous spectrum allows to use more powerful identification algorithms. *ECALstandalone*, adding the layer energy deposit information, increases e/p rejection to more than 10^3 . The optimization of energy-momentum matching in the *Event* classifier adds a factor ~ 10 to the rejection.

All algorithms have been applied on MC, Test Beam and on the first electron flight data. The classifier trained on Test Beam can be safely applied on cosmic data. The comparison for MC trained algorithms shows the necessity of a finer tuning of the simulation software in order to apply these classifiers to flight data.

The application of ECAL selection to AMS-02 expected $e^\pm$ number of events

shows that AMS-02 will collect the necessary statistics to improve over current positron fraction results in about 2 months of operations.

Bibliography

- [1] S.P.Swordy, *Space Science Reviews*, **99**:85-94 (2001)
- [2] K.Nakamura et al, (Particle Data Group), *J. Phys. G* **37** (2010)
- [3] O.Adriani et al, *Phys. Rev. Lett.*, **105**:121101 (2010)
- [4] H.Fuke et al, *Phys. Rev. Lett.*, **95**:081101 (2005)
- [5] O.Adriani et al, *arXiv:0810.4995 [astro-ph]* (2008)
- [6] S.Weinberg, *Gravitation and Cosmology:Principles and applications of the general theory of relativity* (1972)
- [7] A.G.Riess et al, *Astrophys. J.*, **699**:539-563 (2009)
- [8] J.C.Mather et al, *Astrophys. J.*, **512**:511-520 (1999)
- [9] M.Kowalski et al, *Astrophys. J.*, **686**:749-778 (2008)
- [10] D.N.Schramm, N.S.Turner, *Rev. Mod. Phys.*, **70**:303-318 (1998)
- [11] N.Jarosik et al, *Astrophys. J. Supp.*, **192**:14 (2011)
- [12] A.H.Broeils et al, *Mon. Not. R. Astr. Soc.*, **249**:523 (1991)
- [13] L.Serin et al, *arXiv:0010049 [hep-ex]* (2000)
- [14] R.Bernabei et al, *arXiv:1002.1028v1 [astrp-ph.GA]* (2010)
- [15] C.E.Aalseth et al, *arXiv:1106.0650v2 [astro-ph.CO]* (2011)
- [16] A.Liam Fitzpatrick et al, *arxiv:1003.0014v2 [hep-ph]* (2010)
- [17] M.S.Longair, *High Energy Astrophysics* (1994)
- [18] M.Boezio et al, *New J. Phys.*, **11**:105023 (2009)
- [19] C.Weniger, *arXiv:0910.5625v1 [hep-ph]* (2009)
- [20] G.Di Bernardo et al, *arXiv:1101.1830v1 [astro-ph.HE]* (2011)

- [21] T.Kirn et al, *Nucl. Instr. and Meth. A*, **535**:165–170 (2004)
- [22] V.Bindi et al, *Nucl. Instr. and Meth. A*, **623**:968–981 (2010)
- [23] F.Pilo, *Diffuse Gama Ray emission detection with the AMS-02 electromagnetic calorimeter*, **AMS note** (2005)
- [24] S.Di Falco et al, *Studies on a stand-alone ECAL trigger*, **AMS note** (2003)
- [25] G.Grindhammer and S.Peters, *arXiv:0001020v1 [hep-ex]* (2000)
- [26] S.Di Falco, *Adv. Space Res.*, **45**:112-122 (2010)
- [27] W.L.Leo, *Techniques for Nuclear and Particle Physics Experiments* (1994)
- [28] F.Cadoux et al, *Nuc. Phys. Proc. Suppl.*, **113**:159-165 (2002)
- [29] Hai-Jun Yang et al, *Nucl. Instr. and Meth. A*, **555**:370-385 (2005)
- [30] http://ams.cern.ch/AMS/vitali/ams02_bt_2010_aug_11.pdf
- [31] <http://tmva.sourceforge.net>
- [32] <http://root.cern.ch>
- [33] <http://tmva.sourceforge.net/docu/TMVAUsersGuide.pdf>
- [34] G.Di Bernardo et al, *arXiv:1010.0174v2 [astro-ph.HE]* (2010)
- [35] <http://www.desy.de/~maccione/DRAGON>
- [36] L.D.Brown et al, *Statist. Sci.*, **16**:101-133 (2001)