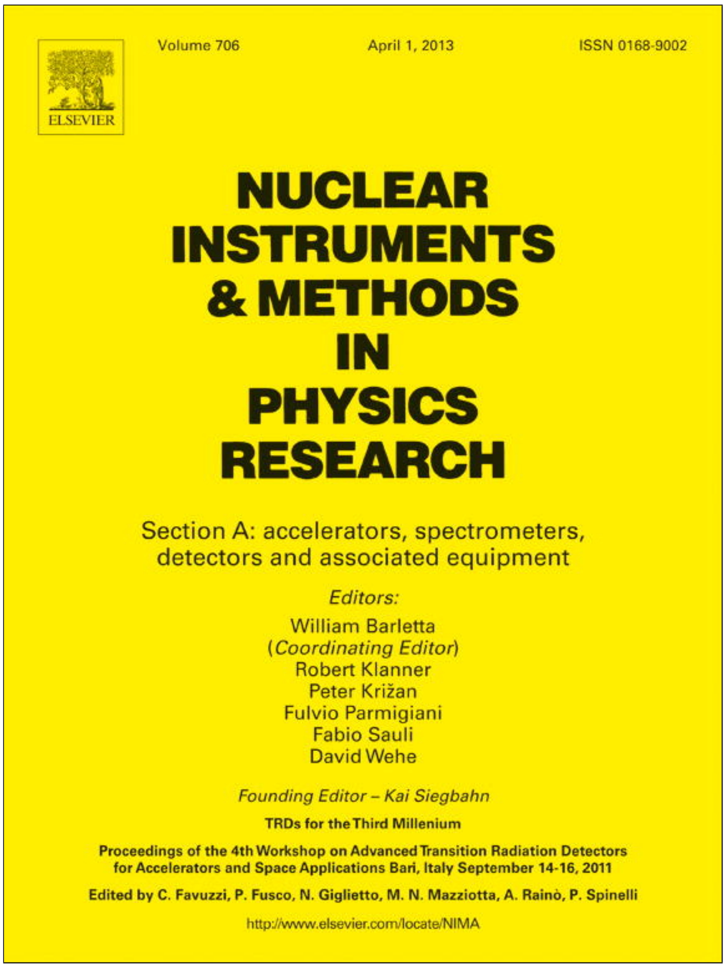

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INSTRUMENTS
& METHODS
IN
PHYSICS
RESEARCH

Section A: accelerators, spectrometers,
detectors and associated equipment

TRDs for the Third Millenium

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The AMS-02 TRD on the international space station

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A R T I C L E   I N F O

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A B S T R A C T

The Alpha Magnetic Spectrometer (AMS-02) is a general purpose high energy particle detector which was successfully deployed on the International Space Station (ISS) on 19 May 2011 to conduct a unique long duration mission of fundamental physics research in space. The main goals of the AMS-02 experiment include antimatter and dark matter search and cosmic ray physics in the energy range from few GeV up to 2 TeV. The indirect search for dark matter candidates requires precise e^+-spectroscopy with a suppression of the dominant proton background by six orders of magnitude. In AMS-02 it will be achieved with a combination of an electromagnetic calorimeter and a transition radiation detector.

1. Introduction

The AMS-02 experiment is a general purpose detector to study primordial cosmic ray particles in the energy range from 0.5 to 2000 GeV. The detector was successfully launched onboard STS-134 mission on 16 May 2011 and deployed on the International Space Station (ISS) on 19 May 2011. AMS-02 is steadily collecting data at a rate of 1.4×10^9 events per month since its activation on the ISS. The technical goals of AMS-02 are to reach a sensitivity of antimatter search of 10^{-10} for the anti-helium to helium ratio, a p/e^+-rejection of 10^6 and to measure the composition and spectra of charged particles with an accuracy of 1%. There is a strong demand for precision measurements of cosmic particles as the recent measurements of the positron to electron fraction ($e^+/(e^+ + e^-)$) by AMS-01, HEAT, PAMELA and Fermi-LAT [1–3] show significant deviations from the expectation for purely secondary production. A possible source of this excess could be dark matter annihilation, a nearby pulsar or a too limited sensitivity and systematic effects of the experiments. AMS-02 with its combination of an electromagnetic calorimeter and a transition radiation detector is expected to provide definitive answers concerning the nature of this deviation.

2. The AMS-02 detector

The AMS-02 detector is a large acceptance particle spectrometer ($0.5\ \mathrm{m}^2\,\mathrm{sr}$). A schematic view of the final layout of the detector is shown in Fig. 1. It consists of a transition radiation detector (TRD), a time-of-flight system (TOF), a permanent magnet (PM), a precision silicon strip tracker, an anti-coincidence counter system (ACC) surrounding the inner tracker, a Ring Image Cherenkov detector (RICH) and a 3D sampling electromagnetic calorimeter (ECAL).

2.1. Permanent magnet and silicon tracker

The AMS-02 detector was constructed to operate on the ISS for 3 years by using a superconducting magnet ($B = 0.8$ T) cooled by liquid helium. The tests at the thermal vacuum chamber of ESTEC showed that the amount of coolant limited its operation to 28 ± 6 months [4]. On 11 March 2010 NASA announced to continue the ISS operation to at least 2020 and most likely 2028. The termination of the shuttle program, the extension of the ISS lifetime and the impossibility of returning or refilling of AMS-02 lead to the decision to replace the superconducting magnet by the AMS-01 permanent magnet with a magnetic field of $B = 0.14$ T [4]. The advantage of using a permanent magnet is to be operational for the duration of the ISS operation. The disadvantage of a lower magnetic field is compensated by the increase of the tracker measuring arm by inserting new single-sided silicon planes on top of the TRD and between RICH and ECAL (Fig. 1). The inner part of the silicon tracker inside the permanent magnet has three double-sided planes. Therefore the silicon strip detector consists of nine layers of in total 192 ladders, containing the silicon sensors, readout electronics and mechanical support. In the bending plane the silicon strip tracker has a single point resolution of 10 μm and 30 μm in the non-bending one. The mechanical stability of the inner silicon tracker is monitored via an infrared

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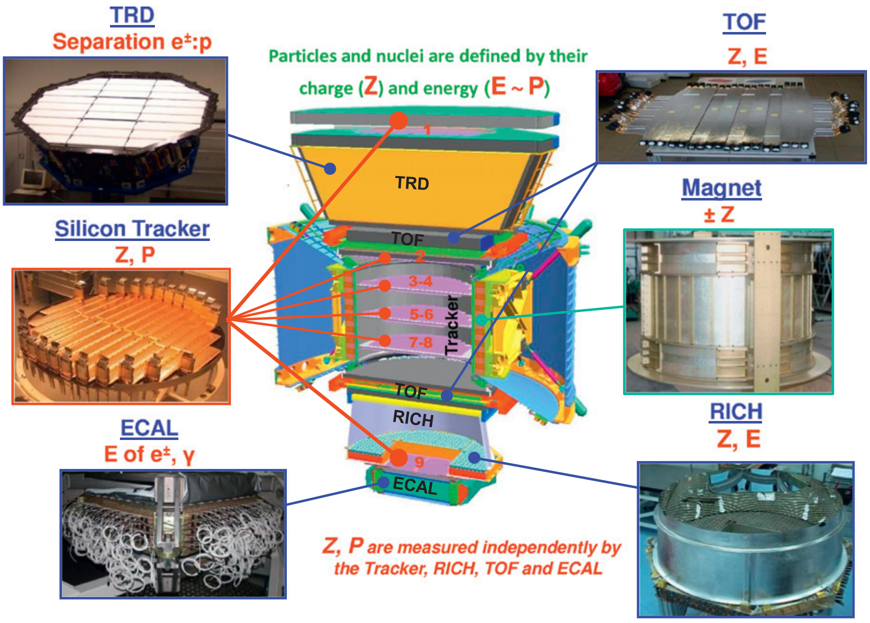

Fig. 1. Schematic view of the final layout of the AMS-02 experiment.

laser system with a position accuracy of better than 5 µm. Together with the bending power of the permanent magnet the spectrometer reaches a maximal detectable rigidity (MDR) of 2.3 GV for protons. The signal amplitude provides a measurement of the particle charge independent of other sub-detectors.

2.2. *Time-of-flight system—TOF*

The time-of-flight (TOF) system provides the fast trigger to the experiment, measures the velocity β and the absolute charge Z of charged particles and distinguishes downward from upward (Albedo) going particles. Four planes of scintillators read out by fine-mesh phototubes are assembled into two mechanical structures—the upper TOF on top and the lower TOF below the inner silicon tracker (Fig. 1). The average time resolution of each counter has been measured to be 160 ps and the overall β-resolution of the system has been determined to be 4% for $\beta \approx 1$ particles, according to the design specifications [4].

2.3. *Anti-coincidence counter—ACC*

The inner silicon tracker is surrounded by the anti-coincidence counter (ACC) system [5] to assure clean track reconstruction. The ACC system detects and vetos particles which enter the tracking volume from the side, outside of the main acceptance, in coincidence with a particle going through the TOF system and the inner silicon tracker. The ACC has a modular design consisting of 16 curved scintillator panels (BC-414) each with a thickness of 8 mm and instrumented with wavelength shifting fibers to collect and guide the scintillation light to a connector from where clear fiber cables guide it to fine mesh photomultiplier tubes (Hamamatsu R5946) mounted on the conical flange of the vacuum case.

2.4. *Ring imaging Cherenkov counter—RICH*

The ring imaging Cherenkov (RICH) detector is designed to separate charged isotopes in cosmic rays by measuring velocities of charged particles with a precision of 10^{-3} and allows charge identification of nuclei up to iron. The RICH is located between the lower TOF and the ECAL. The radiator material consists of 92 tiles of silica aerogel (refractive index $n=1.05$) of 2.5 cm thickness surrounding the 16 tiles of sodium fluoride ($n=1.33$) of 0.5 cm thickness in the center region. The emitted photons are detected by 680 4×4-multi-anode photomultiplier tubes in the detection plane. A conical mirror between radiator and detector plane increases the acceptance. The particle velocity β is determined by the measurement of the Cherenkov angle of the cone and the particle charge Z by the intensity of the emitted radiation.

2.5. *Electromagnetic calorimeter—ECAL*

The electromagnetic calorimeter (ECAL) is located at the bottom of AMS-02 below the lower external tracker plane. The ECAL is a sampling device with a 16.7 X_0 (radiation lengths) lead/scintillating fiber structure providing a three-dimensional reconstruction of the shower initialized by primary electrons, positrons or gamma-rays. It separates leptons from hadrons with an e/p-rejection of 10^4 in the energy range from 1 GeV up to 1 TeV. The energy resolution is well parameterized by $\sigma(E)/E=(10.6\pm0.1)\%/\sqrt{E/GeV}\oplus(1.25\pm0.03)\%$

2.6. *Transition radiation detector—TRD*

Besides the enormous increase in acceptance the main difference in electron and positron identification between PAMELA and AMS-02 is the AMS-02 transition radiation detector (TRD). The TRD [6–11] is mounted on top of AMS-02 (Fig. 1).

Transition radiation is produced by highly relativistic charged particles (Lorentz factor $\gamma \geq 500$) passing through the 20 mm thick fleece radiator material with a density of 0.06 g/cm^3 and with 10 µm polypropylene/polyethylene fibers [6]. The TR-photons are detected in proportional mode straw tube modules, filled with a Xe/CO$_2$ (80%/20%) gas mixture at a pressure of 900 mbar. The TRD consists of 20 layers, each with the 20 mm fleece radiator and modules of 16 straw tubes with an inner diameter of 6 mm made out of a double layer kapton–aluminium foil of 72 µm wall thickness. A gold plated 30 µm thick tungsten wire, fixed in polycarbonate endpieces, is used as sense wire. The straw modules are mechanically stabilized by longitudinal and vertical carbon fiber stiffeners. The 20 layers with in total 328 straw tube modules of lengths up to 2 m are arranged in a conical shaped octagon structure (Fig. 2). The top and the bottom four

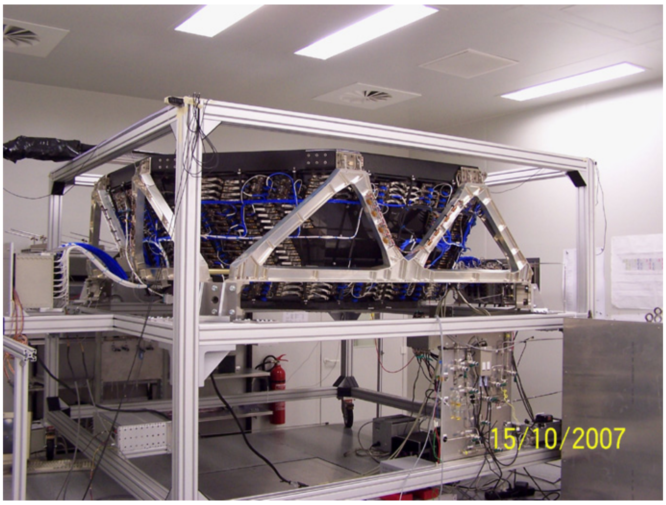

Fig. 2. The AMS-02 TRD after completion of the construction in a clean room at RWTH Aachen.

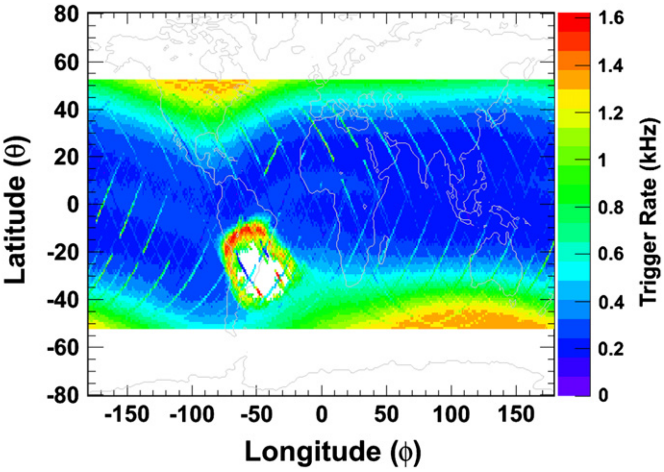

Fig. 3. The AMS-02 detector trigger rate depending on the ISS orbit.

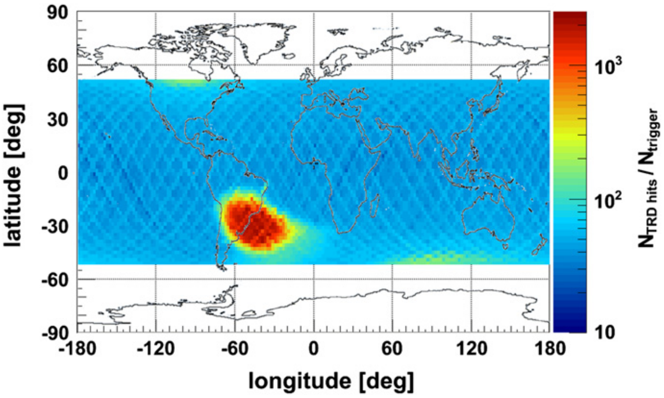

Fig. 4. The number of hits in the AMS-02 TRD straw tubes in relation to the number of triggers depending on the ISS orbit.

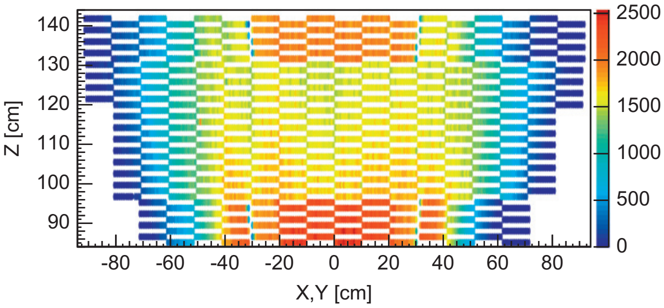

Fig. 5. Occupancy of AMS-02 TRD straw tube modules in side view.

layers are oriented parallel to the AMS-2 magnetic field while the middle 12 layers run perpendicular to provide 3D tracking.

The TRD gas volume of 230 l is divided into 10 separable gas groups, nine contain four and one contain five gas circuits connected in parallel and each of the 41 gas circuits consists of eight straw modules connected in series. The circulating TRD gas system supplies the Xe/CO_2 gas mixture from two storage vessels holding 48 kg of Xenon and 5 kg of CO_2. An analog pulse height readout is used to distinguish efficiently wire signals due to pure ionization losses (protons) from signals containing both dE/dX and absorbed TR-photons (positrons, electrons). The digitization of the signals from the 5248 straw tubes is done with 82 front-end-boards. Each board serves four TRD straw modules and is attached directly to the octagon support structure. The boards are equipped with 12-bit ADCs covering a dynamic range of 60 mips at a gas gain of 3000. The data reduction and low/high voltage supply units are situated in separate crates next to the TRD. In total the front-end-readout consumes 20 W of electrical power. The TRD is fully covered in a multi-layer-insulation (MLI) foil to keep the spatial orbit temperature gradient low.

3. AMS-02 data taking on ISS

AMS-02 was installed on the International Space Station on 19 May 2011 and since that date the detector is collecting data at an average rate of 10 Mbps. The experiment is orbiting the earth at an altitude of about 350 km. The cosmic particle rate is correlated to orbital position, the geodetic longitude and latitude. Therefore particle rates over one ISS orbit vary between 200 Hz near the equator to about 2000 Hz near the Earth magnetic poles. In the South Atlantic Anomaly the particle rate is so high that the data acquisition live time is zero (Fig. 3) so that no events can be triggered. The data acquisition efficiency is on average 85% resulting in an average event acquisition rate of 700 Hz. Over five billion events have been collected during the first 4 months of operation in space. Over its lifetime of ≈ 20 years AMS-02 will collect 300 billion triggers which will provide unprecedented sensitivity to search for new phenomena.

3.1. AMS-02 TRD performance

The amount of hits per triggered event inside the 20-layer TRD is shown in Fig. 4. Due to the higher cosmic particle flux at the polar regions and in the SAA the amount of hits increase drastically compared to the equator regions.

The occupancy of the TRD straw tubes for clean single track events is shown in Figs. 5 and 6. Due to the geometrical acceptance of AMS-02, the straw modules in the central part of the detector show a higher occupancy than the ones at the sides. The influence of the bulkheads which support mechanically the straw modules is visible in the top view.

A fast calibration of the TRD is needed to account and correct for environmental influences on the gas gain of the proportional mode straw tubes. The gas gain depends on the gas parameters like pressure and temperature, the CO_2-fraction of the gas mixture and the applied high voltage.

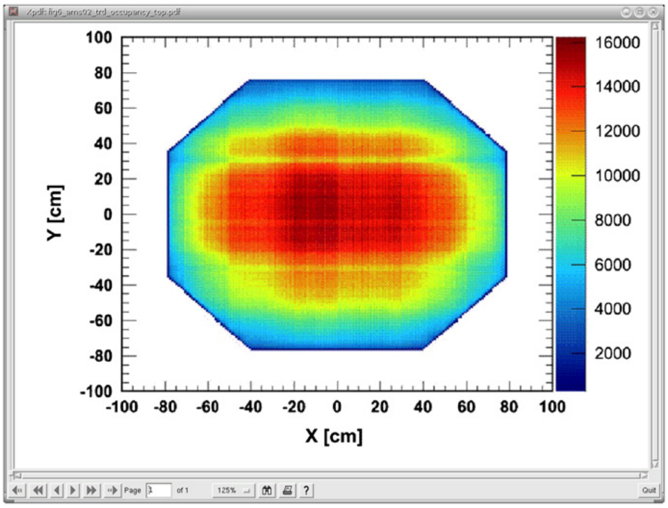

Fig. 6. Occupancy of AMS-02 TRD straw tube modules in top view.

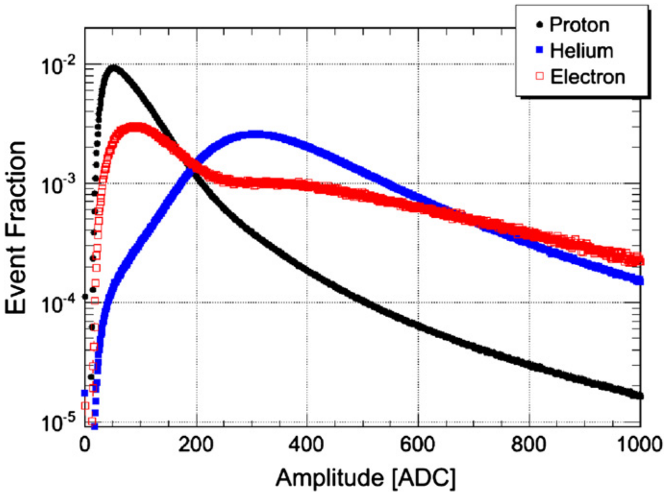

Fig. 7. Single straw tube energy deposition spectra for proton, electron and helium events on clean single tracks.

The cosmic ray composition is dominated by protons (~ 89%). Therefore protons as clean single track events are ideal to calibrate the detector on a short time basis. For the calibration of the TRD, protons are identified using the information of the inner tracker and the TOF-system about the charge of the particle. In addition a matching of the inner tracker track and the TRD track is required.

The most probable (MoP)-value of the proton spectra (Fig. 7) can be used to intercalibrate the 5248 single straw tubes of the TRD and to monitor the time depending proton energy deposition including environmental influences on the gas gain of the straw tubes. Fig. 8 shows the over all straw tubes averaged MoP-values of the proton energy deposition as a function of time. The TRD gas losses are due to diffusion of CO_2 and microscopic leaks in the gas system which lead to a rise of the gas gain and for this reason of the most probable energy deposition. Due to the gas losses, gas refills from the supply vessels via the circulating system into the TRD straw modules are necessary and lead to a decrease of the MoP-values. The same effects can be observed due to high voltage adjustments to keep the detector signal in a certain ADC-range.

For the analysis of the TRD performance concerning the proton rejection the calibration of the other subdetectors need to be done to preselected events for different particles like leptons, protons and helium nuclei. A clean event topology and well reconstructed subdetector track events are required and in addition a matching between ECAL showers and tracker tracks is performed. The charge of the particle is determined using the information of the TOF and tracker system, for leptons an associated electromagnetic shower in the ECAL is required. The single straw tube spectra for protons, electrons and helium is shown in Fig. 7. The proton spectrum follows a landau-like distribution for the energy deposition. Due to the particle charge dependency of ionization energy depositions the helium spectrum is shifted to higher ADC-values and follows a more gaussian-like distribution. Besides the ionization distribution the detection of TR-photons in the electron spectrum is clearly visible.

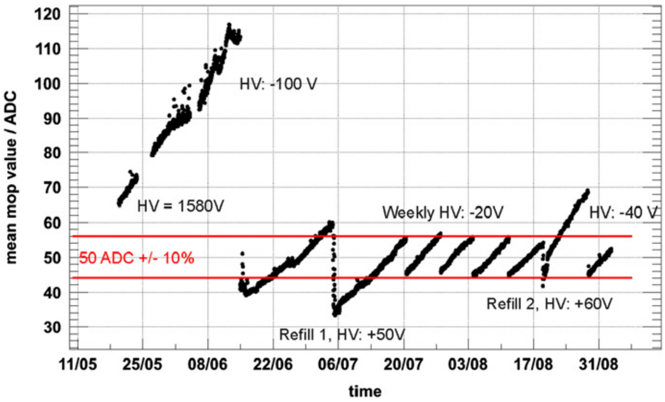

Fig. 8. Time evolution of the average MoP-value of the proton energy deposition.

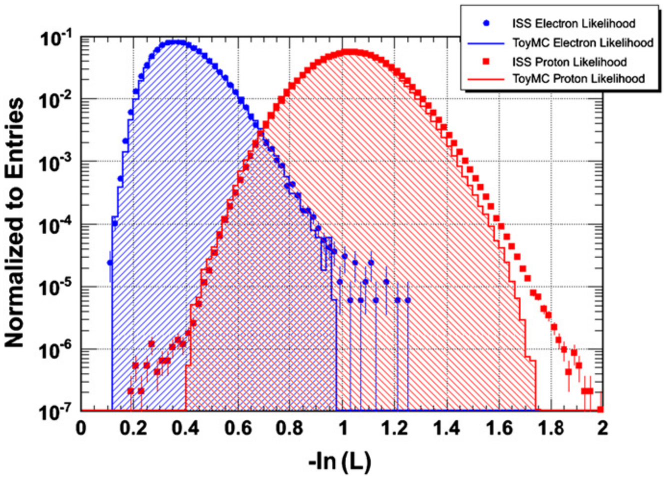

Fig. 9. Probability density functions (PDFs) for electrons and protons for the time period since installation on ISS till the end of August 2011.

The energy depositions on track are used to identify particles crossing the TRD by comparing the observed signature to expected particle signatures, the probability density functions (PDFs, Fig. 9) using a maximum likelihood method. For the proton PDFs the tube-energy spectra are averaged over the 20-layers whereas the electron PDFs are defined layer-wise because the amount of absorbed TR-photons depends on the detector depth. This algorithm selects electrons with 90% efficiency and rejects protons well above 10^3 in the momentum range of 3 GV up to 100 GV as shown in Figs. 10 and 11. The TRD performs better in space than expected by rejection studies in beam tests on ground (Fig. 11).

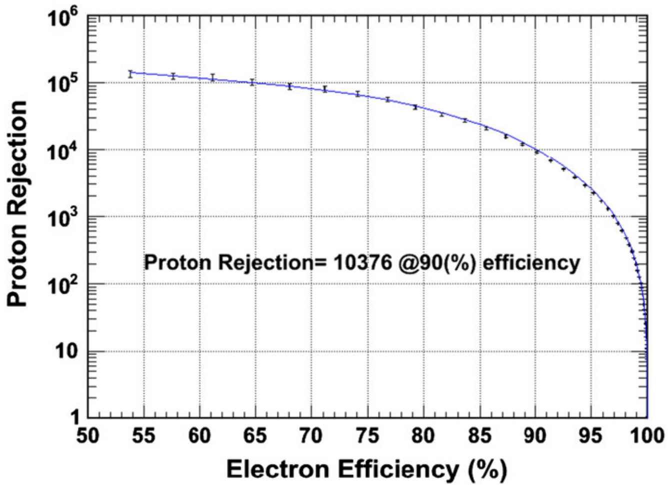

Fig. 10. Proton rejection as a function of electron efficiency for particle rigidities between 3 and 100 GV determined from clean single track events with a maximum likelihood algorithm for the time period since installation on ISS till the end of August 2011.

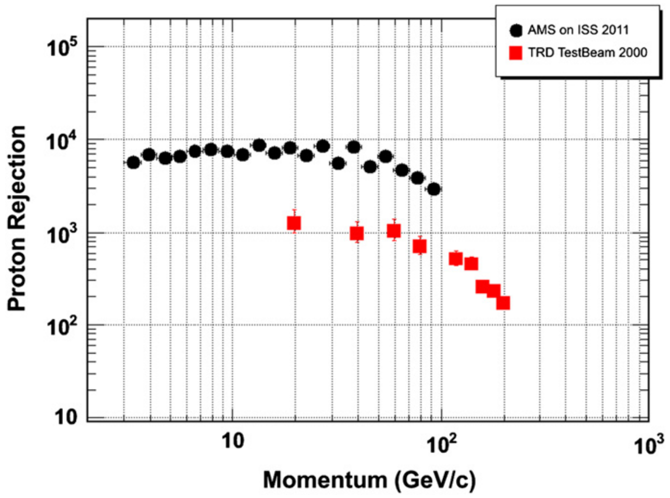

Fig. 11. Proton rejection for 90% electron efficiency in dependence of particle rigidity determined from clean single track events with a maximum likelihood algorithm compared to on-ground measured beam test results.

4. Conclusion

AMS-02 is a general purpose particle detector capable of identifying and measuring simultaneously all cosmic ray particle species: photons, electrons, protons and nuclei as well as all corresponding anti-particles. This feature becomes very important for distinguishing signals from new phenomena and background processes. It is also important to extend the energy range of the measurements to a 1 TeV range in order to assess any changes in the behaviour of the positron fraction at high rigidities up to 1 TeV. The combination of the ECAL and the TRD allows to reject protons from positrons by 10^6. The TRD delivers a proton rejection well above 10^3 up to 100 GeV. AMS-02 will collect data over 18 years of the ISS lifespan which provides unprecedented statistical significance of AMS-02 data sample. All AMS-02 subsystems are fully operational with the performance expected from ground measurements. Variations of ambient conditions are studied and will be accounted for with proper calibrations and alignments. Therefore intensive calibration work for all detector systems is going on now in order to maximize the accuracy of the measurements.

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