PROCEEDINGS OF SCIENCE

Measurement of Cosmic Rays with the AMS-02 Detector on the ISS

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The Alpha Magnetic Spectrometer (AMS-02) is a state of the art particle detector measuring cosmic rays at the International Space Station (ISS) since May 19th 2011. AMS-02 identifies cosmic rays up to iron in an energy range from MeV to TeV. Five physics sub-systems of the detector allow for redundant particle identification with unprecedented precision. With a positron-proton separation power in the order of 10^6 a very high purity of the antiparticle spectra can be obtained. Here, a brief overview of the detector operation and particle identification is given. The measurement of the positron fraction from 0.5 to 350 GeV is presented. The data shows that the positron fraction steadily rises above 10 GeV, whereas the slope of the rise decreases by an order of magnitude towards the highest energies analyzed. The fraction shows no fine structure and the e^+/e^--ratio is consistent with isotropy, therefore an upper limit for the anisotropy is obtained. The measurement clearly indicates that new physics phenomena need to be included to describe the observed positron fraction.

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1. Introduction

AMS-02 is a general purpose high energy particle detector, capable of distinguishing ions up to iron and measuring particle energies from the MeV up to the TeV range. After testing the functionality of the detector in space environment at the ESTEC[1] facilities in Noordwijk, NL, and its physics capabilities with a test beam at the Super-Proton-Synchrotron, CERN[2], AMS-02 was transported to the International Space Station by Space Shuttle Endeavor on the 16th of May, 2011. The detector was installed on the ISS on the 19th of May and started recording cosmic ray events just hours later. In the first 18 months of data taking more than 30 billion events were recorded.

2. The detector

The AMS-02 detector has five main subsystems, which are shown in Fig. 1. Following the designated particle path through the detector these are a transition radiation detector (TRD), a time-of-flight detector (ToF), a silicon Tracker, a ring imaging Cherenkov detector (RICH) and an electromagnetic calorimeter (ECAL). The detector coordinate system has its origin in the center of the magnetic field. The x-axis is parallel to the magnetic field lines, the z-axis is the vertical detector axis, therefore the bending of the track of charged particles inside the magnetic field occurs in the y-z-plane.

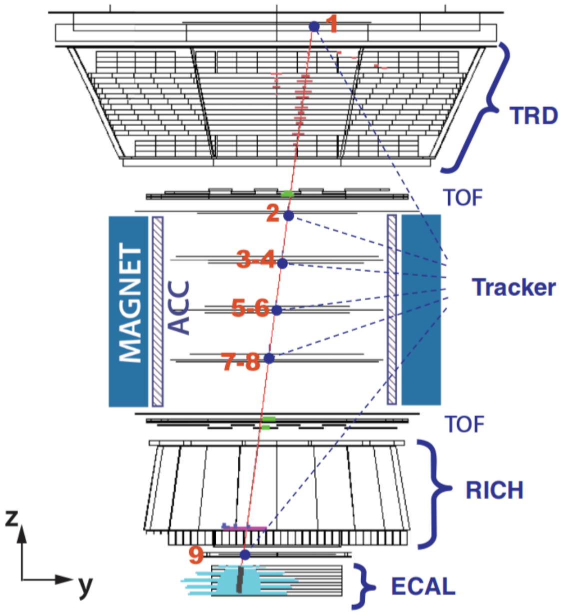

Fig 1: AMS-02 event display of a 1.03 TeV electron showing the detector profile in the y-z-plane. The ToF verifies that the particle traverses the detector from top to bottom and reconstructs the charge of the particle. The electron is identified by the TRD, the shower shape in the ECAL and the matching of reconstructed energy in the ECAL to reconstructed momentum by the Tracker [1].

The TRD [2] is built out of 5248 proportional chambers filled with xenon and carbon-dioxide in a mixture of 90/10. The chambers are arranged in 20 layers with fiber-fleece radiator between each layer. The multiple consecutive measurements allow for a good discrimination between positrons and protons using a likelihood estimator.

The ToF [3] consists of four layers of scintillating ladders, where two layers are located above the magnet case and two layers are below. The ladders of each set of two planes are mounted orthogonally to each other to allow for a three-dimensional spatial measurement.

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[1] ESTEC: European Space Research and Technology Center

[2] CERN: European Center for Nuclear Research

There are nine planes of silicon tracker [4,5] distributed over the detector (see red numbers in Fig. 1). Six of them are located inside the permanent magnet, which has a magnetic field strength of 0.15 T. One layer is located just above the magnet, one is located on top of the TRD (layer 1, Fig.1) and one layer is located between between RICH and ECAL (layer 9, Fig. 1). In total 192 double-sided silicon ladders are distributed over the tracker planes, which measure the particle trajectory with a spatial resolution of 10 μm in the bending direction. The lever arm between the two outermost planes is 3m, which leads to a maximum detectable rigidity of 2.2 TeV for particles with unity charge.

The RICH [6] is built of three main components: a radiator layer, a conical mirror and a photomultiplier (PMT) layer for detecting the produced Cherenkov photons. The area of the detection layer under which the ECAL is located, though, is not covered with PMTs in order to not bias the energy measurement. Therefore a NaF radiator with refractive index n=1.34 is used in the central region and in the outer region aerogel with a refractive index of n=1.04 is used, so that Cherenkov-photons from the entire radiation layer can be detected.

The ECAL [7] is a sampling calorimeter made out of lead and scintillating fibers. It consists of nine superlayers which are stacked alternating in orientation parallel to the y- and x-axis. The thickness of the ECAL provides 17 radiation lengths of detecting medium, which allows for a precise reconstruction of the energy up to the TeV scale for particles initiating an electromagnetic shower. A boosted decision tree (BDT) is used to identify positrons and electrons based on their 3D shower shapes.

While ToF and RICH measure the particle velocity β, the Tracker reconstructs the particle momentum p and the ECAL determines the energy E of electrons, positrons and photons. With its high energy resolution of $\sigma(E)/E=\sqrt{(0.104)^2/E+(0.014)^2}$ (with E in GeV) [1], the ECAL reconstructed energy is the energy variable used for a lepton analysis. The charge of the particle can be reconstructed by all subdetectors, where the best resolution is achieved by Tracker and ToF. The redundancy of the measurement ensures a correct particle identification and allows for reconstruction of particle conversions inside the detector.

3. Operation on the ISS

Mounted on the ISS, AMS-02 is orbiting the Earth at an altitude of about 400 km, with the orbital axis being inclined by 51.6° in respect to the Earth's rotational axis. The detector is mounted on the Space Station with a 12° roll to port side in order to prevent the ISS solar panels from being in the field of view of the detector.

The average trigger rate is 600 Hz with an average event size of 2 kByte. The minimal allocated down-link bandwidth using the ISS communication satellites is 9 Mbit/s during acquisition of signal. The normal operation of the detector is controlled from the AMS-02 Payload Operations Control Center (POCC) located at CERN. Commands regarding data taking are send from there and monitoring of all data and detector systems is also performed in the POCC. This includes health and status data of all sub-systems and the temperatures of the individual components. To ensure that they operate within their nominal limits 1118 temperature sensors and 298 thermostatically controlled heaters have been installed throughout AMS-02.

3.1 Time-dependent alignments

The constantly changing environmental conditions in space represent a challenge for the operation of the detector. While the temperature of the inner Tracker planes is kept stable within 1° C, the TRD and outer Tracker planes support structure experience temperature differences of 10° C during one beta angle[3] cycle, see Fig. 2. These temperature differences result in movements of the structures of up to 1 mm, which makes time-dependent alignments necessary for consistency in tracking quality. The correlation between the movement of the TRD with respect to the inner Tracker and the beta angle can be seen in Fig. 3. The alignment routines use proton data taken on orbit to correct for the movements. For the outer Tracker planes a resolution of 3 μm after alignment is achieved [8], while for the TRD, which has a much worse spatial resolution, still the movements can be corrected with a residual resolution of 20 μm [9].

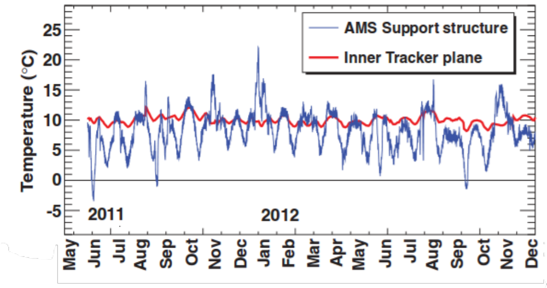

Fig 2: Temperature of the AMS-02 support structure and one Inner Tracker plane during the first 18 months of data taking [1].

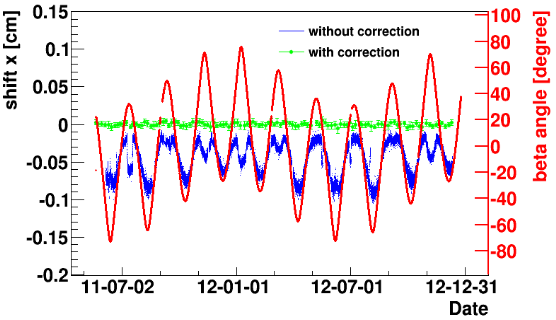

Fig 3: In red the variation of the ISS beta angle is shown, while in blue the shift of one representative TRD module is given. The green points indicate the module alignment after the correction [10].

4. Particle Identification

For the analysis of the positron fraction, the ratio of the number of positrons to the sum of positrons and electrons, only those events are considered which traverse all subdetectors of AMS-02. This reduces the geometrical acceptance of the detector for this measurement to ~ 420 cm^2 sr.

After the geometric acceptance requirements are met, further checks on the quality of the events must be applied to the data, including a check on the tracking and charge reconstruction quality. These checks need to be made carefully so that any inefficiencies cancel out in the calculation of the positron fraction. Finally, only particles identified as having unitary charge by ToF and Tracker are considered in the following.

As the proton flux in cosmic rays dominates over the positron flux by 3 to 4 orders of magnitude, the positron identification is one of the main challenges of this analysis.

For the discrimination of electrons and positrons from protons and antiprotons three discriminating variables are used: a TRD likelihood estimator, an ECAL BDT and the ratio of the reconstructed ECAL energy to the Tracker momentum (E/R). The effect of a cut on the

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[3] The beta angle describes the angle between the solar vector and the ISS orbit plane. This angle varies between ±75° within a 60 day cycle due to the precession of the ISS orbit plane around the earth rotational axis.

ECAL BDT and E/R variable and a combination of both are shown as a function of the TRD likelihood estimator in Fig. 4.

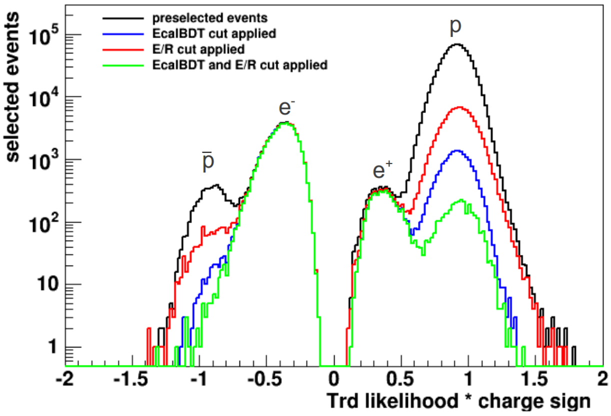

Fig. 4: Reduction of protons and antiprotons in the preselected event sample (black) in the energy bin from 31–38.36 GeV by applying a cut on the ECAL BDT (blue), on E/R (red) and both variables (green) as a function of the TRD likelihood multiplied with the charge sign. The negative and positive x-range shows the effect on the electron and positron sample, respectively [10].

Another important background comes from charge-confusion of electron events, which occurs due to the finite resolution of the Tracker or can be introduced by non-reconstructed secondary particles near the primary particle track. The charge-confusion contribution can be estimated from data and can also be calculated with Monte Carlo (MC), as both effects causing the charge-confusion are well described in the simulation [1].

Various analyses with different combinations of cuts and template fits in the proton-positron discriminating variables were tested and serve as a cross-check for the published analysis [1]. An analysis applying a cut on ECAL BDT and E/R and for the remaining positron sample performing a template fit in the TRD estimator to determine the residual contamination [10] yields a consistent result with the published analysis. There a cut on the ECAL BDT is applied followed by a two-dimensional fit in the [TRD-estimator vs log(E/R)] - plane [1]. An example of the result of this fit can be seen in Fig. 5. The method allows to determine the contamination from protons and charge-confused electrons from data at the same time, since the TRD likelihood is sensitive to proton contamination while E/R is also sensitive to charge-confusion.

5. Results

Using the first 18 months of AMS-02 data, about 7 million electron and positron events were identified in the energy range from 0.5 – 350 GeV. This measurement extends the energy range of previous measurements by more than a factor two.

Systematic uncertainties contributing to the error of the measurement are the slight difference in acceptance for electrons and positrons and the bin-to-bin migration of events, which only has a weak effect to the low energy bins. Also the impact of the applied selection and the chosen reference spectra for the template fit have been taken into account as well as an uncertainty on the assumed charge-confusion. This uncertainty is given by the difference between the charge-confusion determined from data and from MC. The background subtraction of the residual protons in the positron sample has only a minor effect: since both populations are well separated , as shown in the left plot of Fig. 5, the contamination in the signal region is only around 1% [1].

The result of the analysis, given in Fig. 6, shows that the positron fraction is decreasing up to energies around 8 GeV, as is expected from purely secondary production of positrons in the

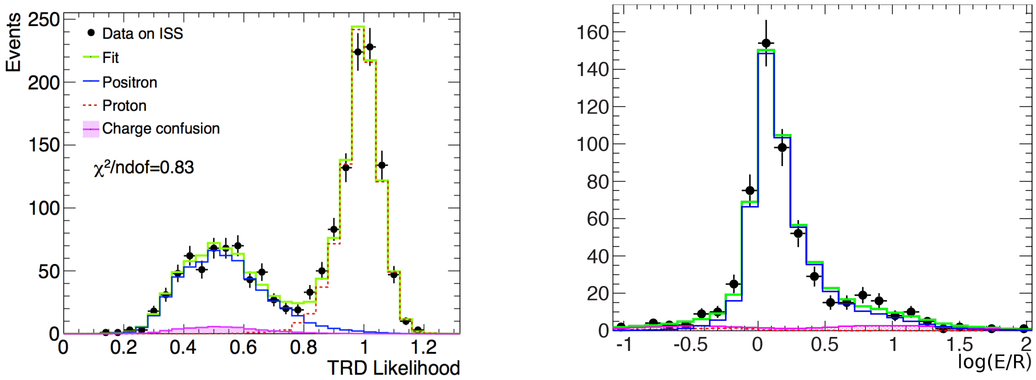

Fig. 5: Result of the fit in the [TRD-estimator vs log(E/R)] – plane of the positive sample of one analyzed energy bin. Left: projection on TRD likelihood estimator, right: projection on log(E/R) [1].

interaction of primary cosmic rays with the interstellar medium. Beyond 10 GeV, though, the fraction is steadily rising up to 250 GeV, while the slope of the rise decreases by an order of magnitude from 20 GeV to 200 GeV, which can be seen from the right plot in Fig. 6. This rise cannot be explained by purely secondary production of positrons, indicating that an additional production mechanism for high energy positrons and electrons is necessary to describe the observed data.

In order to further investigate the nature of the source of the additional positrons, the anisotropy in the arrival directions of the positron ratio, the ratio of positron flux to electron flux, has been determined for energies from 16 to 350 GeV. The exposure map of AMS-02 can be seen in the left plot of Fig. 7, while the right one shows the positron ratio as a function of galactic coordinates. A spherical harmonic expansion is used to describe the local fluctuations. The coefficients (C_1, C_2...) of the angular power spectrum are found to be consistent with isotropy for all energies. An upper limit on the amplitude of the dipole anisotropy $\delta=3\sqrt{C_1/4\pi}$ is obtained as $\delta\leqslant 0.030$ at 95% confidence level [13].

More data is needed to be able to set a more stringent limit and to extend the measurement to higher energies. As only 8% of the expected final AMS data set have been analyzed so far (assuming the ISS to be operated until 2028) updates of this analysis will follow.

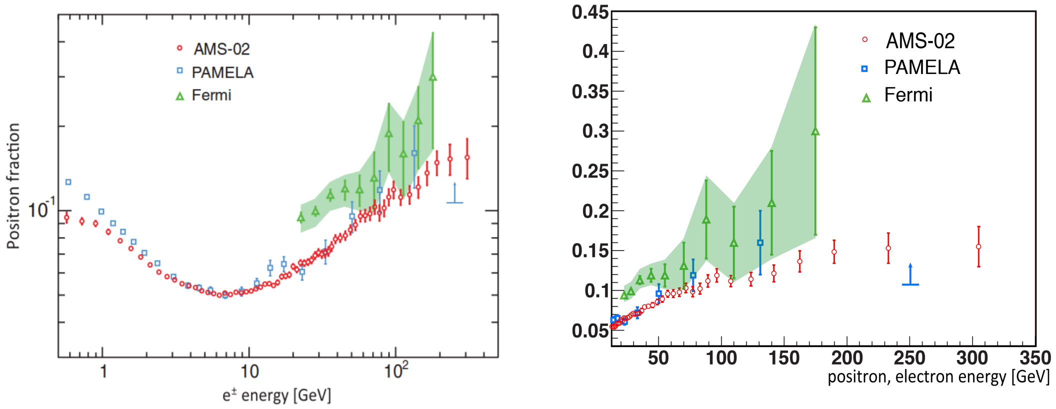

Fig. 6: Result of the positron fraction analysis of the first 18 months of AMS-02 data [1] in comparison to previous experiments [11][12]. Left: double logarithmic scale; right: double linear scale.

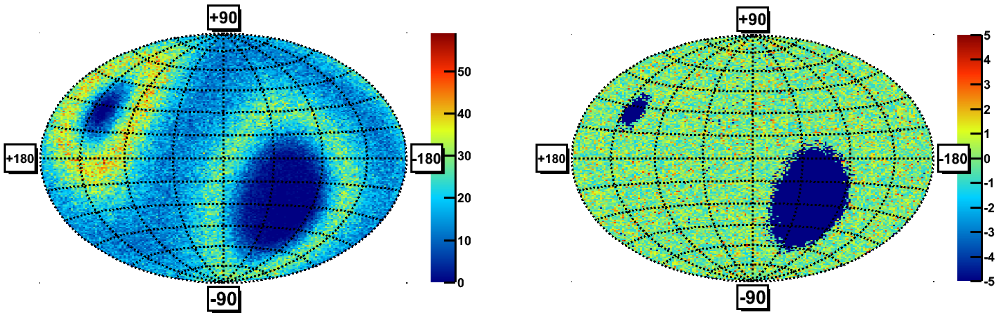

Fig. 7: Left: Exposure map of AMS-02 to cosmic electrons in galactic coordinates. Right: Map of the positron ratio in galactic coordinates. In both figures the gaps in the exposure maps are caused by the inclination of 51.6° of the ISS orbital plane, which means that the full sky cannot be observed [13].

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