Recent results of the AMS-02 experiment on the ISS

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Abstract. The Alpha Magnetic Spectrometer has recently released a first set of precise measurements of cosmic rays detected on the International Space Station in the GeV to TeV energy range. The fluxes of positrons, electrons and protons are presented. Neither of the fluxes is compatible with a single power law. Both the electron flux and the positron flux change their behavior at $\sim 30$ GeV but the fluxes are significantly different in their magnitude and energy dependence. Between 20 and 200 GeV the positron spectral index is significantly harder than the electron spectral index. Above $\sim 200$ GeV the positron fraction no longer exhibits an increase with energy. The proton flux is progressively hardening above rigidity $\sim 100$ GV. The detailed variation with rigidity of the proton flux spectral index is presented.

1. Introduction
The Alpha Magnetic Spectrometer (AMS-02) [1] is a general purpose high-energy particle physics detector operating on the International Space Station (ISS) since 19 May 2011. The goal of the experiment is to carry out precise measurements of cosmic rays in the energy range from $\sim 1$ GeV to $\sim 1$ TeV. Accurate studies of the fluxes of individual components of cosmic rays are achieved thanks to the excellent particle identification and energy resolution of the detector. In particular, the measurement of antimatter in cosmic rays with unprecedented precision may have deep implications in fundamental physics.

First results of the experiment, obtained on $\sim 15\%$ of the expected AMS sample, include the measurement of the positron fraction, that is, the fraction of positron to electron plus positron fluxes [2, 3], as well as the measurement of individual positron and electron fluxes and positron plus electron fluxes [4, 5], and the proton flux [6]. Preliminary results on antiproton to proton ratio and light nuclei fluxes have been also presented [7].

The excess of positrons above $\sim 10$ GeV with respect to the expectations for secondary production is one of the most striking anomalies in cosmic rays and its origin has been widely discussed, including production in standard astrophysical sources [8], dark matter annihilation in the halo of the Galaxy [9] or in the Earth’s vicinity [10]. Other interpretations, such as secondary acceleration in the cosmic ray sources, have been also proposed [11]. Distinctive signatures may include the presence of structures in its energy spectrum, the existence of a high energy cutoff or the detection of some degree of anisotropy in their arrival direction [12]. Only precise measurements of cosmic positrons and electrons in a wide energy range may help to elucidate it.

The discovery potential of the antimatter component in cosmic rays relies on the accurate determination of the astrophysical backgrounds. In particular, a reliable computation of
the secondary contributions to the positron and antiproton fluxes requires a comprehensive description of the cosmic ray sources and their propagation in the galaxy. The aim of AMS is to provide strong experimental constraints on these quantities with the precise measurement of primary cosmic ray fluxes (proton, helium, carbon...), secondary cosmic ray fluxes (lithium, beryllium, boron...) and secondary to primary ratios (e.g., B/C). Specifically, the detailed behavior of the proton flux addressed by AMS must be reproduced by the models intending to describe the galactic cosmic rays in the heliosphere.

In this paper, the results based on the data collected during the first 30 months of AMS operation on the ISS will be reviewed. The electron flux in the energy range from 0.5 to 700 GeV as well as the positron flux from 0.5 to 500 GeV are reported separately. The joint electron and positron flux is measured up to 1 TeV and benefits from reduced systematics. The energy range for the positron fraction extends up to 500 GeV. Finally, the measurement of the proton flux with rigidity 1 GV to 1.8 TV will be presented.

2. The AMS detector

The layout of the AMS detector is shown in Fig. 1. It consists of 9 planes of precision Silicon Tracker; a Transition Radiation Detector, TRD; four planes of Time of Flight counters, TOF; a Magnet; an array of anticoincidence counters, ACC, surrounding the inner Tracker; a Ring Imaging Čerenkov detector, RICH; and an Electromagnetic Calorimeter, ECAL.

![Figure 1. A 369 GeV positron event as measured by the AMS detector on the ISS in the (y-z) plane. Tracker planes 1-9 measure the particle charge and momentum. The TRD identifies the particle as an electron/positron. The TOF measures the charge and ensures that the particle is downward going. The RICH measures the charge and velocity. The ECAL independently identifies the particle as an electron/positron and measures its energy. Electrons and positrons are identified by (i) an electron signal in the TRD, (ii) an electron signal in the ECAL, and (iii) the matching of the ECAL shower energy and the momentum measured with the tracker and magnet.](image)

The tracker accurately determines the trajectory of cosmic rays by multiple measurements of the coordinates with a resolution in each layer of 10 µm in the bending direction. Together, the tracker and the magnet measure the rigidity $R$ of charged cosmic rays. For singly charged particles, the maximum detectable rigidity (MDR) is 2 TV over the 3 m lever arm from the top to the bottom tracker plane.

Each layer of the tracker also provides an independent measurement of the absolute value of the charge $|Z|$ of the cosmic ray. The charge resolution of the layers of the inner tracker together is $\Delta Z \simeq 0.05$ for $|Z| = 1$ particles.

Two planes of TOF counters are located above the magnet and two planes are located below it. The average time resolution of each counter for $|Z| = 1$ particles has been measured to be 160 ps and the overall velocity ($\beta = v/c$) resolution to be $\Delta \beta/\beta^2 = 4\%$. This discriminates between upward- and downward-going particles.
Three main detectors provide clean and redundant identification of positrons and electrons with independent suppression of the proton background. These are the TRD (above the magnet), the ECAL (below the magnet) and the tracker. The TRD and the ECAL are separated by the magnet and the tracker. This ensures that most of the secondary particles produced in the TRD and in the upper TOF planes are swept away and do not enter into the ECAL. Events with large angle scattering are also rejected by a quality cut on the measurement of the trajectory using the tracker. The matching of the ECAL energy, \( E \), and the momentum measured with the tracker, \( p \), greatly improves the proton rejection.

To differentiate between \( e^\pm \) and protons in the TRD, signals from the 20 layers of proportional tubes are combined in a TRD estimator formed from the ratio of the log-likelihood probability of the \( e^\pm \) hypothesis to that of the proton hypothesis in each layer. The proton rejection power of the TRD estimator at 90% \( e^\pm \) efficiency measured on orbit is \( 10^3 \) to \( 10^4 \) [3]. To cleanly identify electrons and positrons in the ECAL, an estimator, based on a Boosted Decision Tree algorithm [13] is constructed using the 3D shower shape in the ECAL. The proton rejection power of the ECAL estimator reaches \( 10^4 \) when combined with the energy/momentum matching requirement \( E/p > 0.75 \) [3].

The entire detector has been extensively calibrated in a test beam at CERN with \( e^+ \) and \( e^- \) from 10 to 290 GeV/c, with protons at 180 and 400 GeV/c, and with \( \pi^\pm \) from 10 to 180 GeV/c, which produce transition radiation equivalent to protons up to 1.2 TeV.

Monte Carlo simulated events were produced using a dedicated program developed by the collaboration based on the geant-4.9.6 package [14]. This program simulates electromagnetic and hadronic interactions of particles in the material of AMS and generates detector responses. The digitization of the signals is simulated precisely according to the measured characteristics of the electronics. The simulated events then undergo the same reconstruction as used for the data.

3. Electron and Positron Fluxes

The isotropic fluxes of cosmic ray electrons and positrons in the energy bin \( E \) of width \( \Delta E \) are given by:

\[
\Phi_{e^\pm}(E) = \frac{N_{e^\pm}(E)}{A_{\text{eff}} \cdot \epsilon_{\text{trig}} \cdot T(E) \cdot \Delta E}
\]

(1)

where \( N_{e^-} \) is the number of electrons, \( N_{e^+} \) is the number of positrons, \( A_{\text{eff}} \) is the effective acceptance, \( \epsilon_{\text{trig}} \) is the trigger efficiency, and \( T \) is the exposure time. The effective acceptance is defined as the product between the geometric acceptance of about 550 cm\(^2\) sr, the selection efficiency and the identification efficiency for electrons and positrons. This product is determined by Monte Carlo simulation and includes a minor correction to account for the differences in the efficiencies between data and Monte Carlo simulation. The trigger efficiency is determined from data using unbiased triggers, and it is found to be 100% above 3 GeV. The selection efficiency is determined from the Monte Carlo simulation and found to be a smooth function of energy with a value of \(~70\%) at 100 GeV. The exposure time \( T(E) \) is determined by counting the live time weighted seconds spent at each location for energies above the geomagnetic cutoff, with AMS in nominal data taking conditions and excluding the time spent in the South Atlantic Anomaly. It amounts to \( 1.4 \times 10^7 \)s at 5 GeV, \( 3.4 \times 10^7 \)s at 10 GeV and grows to a constant \( 6.1 \times 10^7 \)s above 30 GeV.

Signals from the 17 radiation length ECAL are scaled to provide the incoming (top of AMS) energy, \( E \), of electrons and positrons. In the beam tests of the AMS detector, the energy resolution has been measured to be \( \sigma(E)/E = \sqrt{(0.104)^2/E + (0.014)^2} \) with \( E \) in GeV. The absolute energy scale is verified by using minimum ionizing particles and the ratio \( E/p \). These results are compared with the test beam values where the beam energy is known to high precision. This comparison limits the uncertainty of the absolute energy scale to 2% in the range covered.
by the beam test results, 10-290 GeV. Below 10 GeV it increases to 5% at 0.5 GeV and above 290 GeV to 4% at 700 GeV. This is treated as an uncertainty of the bin boundaries. The bin widths, $\Delta E$, are chosen to be at least two times the energy resolution to minimize migration effects. The bin-to-bin migration error is $\sim 1\%$ at 1 GeV and decreases to 0.2% above 10 GeV. With increasing energy the bin width is smoothly widened to ensure adequate statistics in each bin. Positrons and electrons produced by the interactions of primary cosmic rays with the atmosphere are rejected by requiring that the minimum energy within the bin exceeds 1.2 times the geomagnetic cutoff for either a positron or an electron at the location where the particle was detected and at any angle within the AMS acceptance.

The identification of the $e^-$ and $e^+$ signal requires rejection of the proton background. Cuts are applied on the $E/p$ matching and the reconstructed depth of the shower maximum. This makes the negatively charged sample, as determined by the rigidity, a sample of pure electrons. A cut on the ECAL estimator is applied to further reduce the proton background in the positive rigidity sample after which the numbers of positrons and protons are comparable at all energies. The identification efficiency, $\epsilon_{id}$, is defined using the Monte Carlo simulation as the efficiency for electrons to pass these three cuts. It is identical for both electrons and positrons.

The small differences between data and simulation are evaluated on negative rigidity samples selected for every cut using information from the detectors unrelated to that cut. The effects of the cut are compared between data and Monte Carlo simulation. The resulting correction is found to be a smooth, slowly falling function of energy. It is -2% at 10 GeV and -6% at 700 GeV relative to $\epsilon_{id}$. In each energy bin, a template fit to the discriminant variables determines the number of electrons, positrons and protons in the sample. The final number of electrons, $N_{e^-}$, and positrons, $N_{e^+}$, is obtained after applying a correction for charge confusion. In total, 9.23 million events are identified as electrons and 0.58 million as positrons.

The systematic error associated with the uncertainty of the TRD template shapes for the signal and the background is due to the finite accuracy of the TRD alignment and calibration as well as to the statistics of the data samples used to construct the templates. This is the leading contribution to the total systematic error above 300 GeV. The amount of charge confusion is well reproduced by the Monte Carlo simulation and a systematic uncertainty takes into account the small differences between data and the Monte Carlo simulation. This uncertainty is only significant for $N_{e^+}$ in the highest energy bin. The systematic error on the effective acceptance is given by the uncertainties on the correction for differences between data and simulation, derived from their comparison for every cut. This includes an overall scaling uncertainty of 2%, which introduces a correlation between energy bins and between the electron and positron fluxes. The acceptance uncertainty is the leading contribution to the systematic error below $\sim 300$ GeV. The total systematic error is taken as the quadratic sum of these three contributions and the minute bin-to-bin migration systematic. As an example, in the energy bin from 59.1 to 63.0 GeV, the statistical error on the positron flux is 4.9% and the total systematic error is 2.9% with 0.8% from the TRD templates, 0.4% from charge confusion, 2.8% from the effective acceptance, and 0.2% from bin-to-bin migration. Large variations of the cuts have been applied to verify the above error assessment. In addition, the time stability of the counting rates of $N_{e\pm}$ has been studied. At high rigidities, all the rates are found to be stable, whereas at low energies, below 10 GeV, variations in time are observed, as expected from solar modulation.

The electron and positron fluxes multiplied by $E^3$ are presented in Fig. 2 together with the most recent measurements [15, 16] for comparison. The figure also shows the detailed behavior for both electrons and positrons below 200 GeV together with previous measurements [15, 16, 17] in this energy range. Below $\sim 10$ GeV, the behavior for both electrons and positrons is affected by solar modulation as seen in the AMS data by variations of the fluxes over the data-taking

1 Charge confusion is defined as the fraction of electrons or positrons reconstructed with a wrong charge sign.
Figure 2. The AMS (a) electron and (b) positron fluxes, multiplied by $E^3$. Statistical and systematic uncertainties of the AMS results have been added in quadrature. Also shown are the most recent measurements from PAMELA [15] and Fermi-LAT [16]. The right hand plots zoom in on the region below 200 GeV and compared with earlier measurements [17].

interval. However, above $\sim 20$ GeV the effects of solar modulation are not significant within the current experimental accuracy. The data show that above $\sim 20$ GeV and up to 200 GeV the electron flux decreases more rapidly with energy than the positron flux, that is, the electron flux is softer than the positron flux. This is not consistent with only the secondary production of positrons [18]. Neither the electron flux nor the positron flux can be described by single power laws ($\propto E^{-\gamma}$) over the entire range. Power law fits over different energy ranges show that $\gamma_{e^+}$ hardens from $2.97 \pm 0.03$ (fit over 15.1-31.8 GeV) to $2.75 \pm 0.05$ (fit over 49.3-198 GeV). Correspondingly, $\gamma_{e^-}$ hardens from $3.28 \pm 0.03$ (fit over 19.0-31.8 GeV) to $3.15 \pm 0.04$ (fit over 83.4-290 GeV) and then levels off. Above $\sim 200$ GeV, $\gamma_{e^+}$ exhibits a tendency to soften with energy.

A dedicated measurement of the sum of electron and positron flux is performed on the same data sample. In this case, the systematics associated to charge confusion cancel. The flux is thus evaluated according to Eq. 1 for the sum of electrons and positrons, in 74 energy bins from 0.5 GeV to 1 TeV. The bin width is chosen to be at least twice the energy resolution, the migration error is $\sim 1\%$ at 1 GeV decreasing to 0.2% above 10 GeV. The absolute energy scale is verified as described above. Events are selected requiring the presence of a downward-going $\beta > 0.83$ particle which has hits in at least 8 of the 20 TRD layers and a single track in the tracker passing through the ECAL. Events with an energy deposition compatible with a minimum ionizing particle in the first $5X_0$ of the ECAL are rejected. Events with $|Z| > 1$ are rejected using $dE/dx$ in the tracker and TRD. Secondary particles of atmospheric origin are rejected with cutoff requirement discussed above.
In each energy bin, TRD classifier templates of the \((e^++e^-)\) signal and the proton background are constructed from the data using pure samples of \(e^-\) and protons. These samples are selected using the ECAL estimator, \(E/p\) matching and the charge sign. The templates are evaluated separately in each bin; however, the signal templates show no dependence on the energy above \(\sim 10\) GeV. Therefore, all the \(e^-\) selected in the range 15.1-83.4 GeV are taken as a unique signal template up to the highest energies. The sum of the signal and background templates is fit to the data by varying their normalizations. This yields the number of signal \((e^++e^-)\) events, the number of background (proton) events, and the statistical errors on these numbers. The other ingredients to the flux measurement are determined analogously to the separate flux measurements discussed above. A total of 10.6 million \((e^++e^-)\) events are identified in the energy range from 0.5 GeV to 1 TeV.

Fig. 3 shows the result of this analysis. A major experimental advantage of the combined flux analysis compared to the measurement of the individual positron and electron fluxes, particularly at high energies, is that the selection does not depend on the charge sign. Another advantage is that it has a higher overall efficiency. Consequently, this measurement is extended to 1 TeV with less overall uncertainty over the entire energy range. Systematic uncertainties arise from (i) the event selection, (ii) the acceptance, and (iii) bin-to-bin migration and are evaluated as described above. As seen in Fig. 3, the flux cannot be described by a single power law over the entire range. The lowest starting energy of a sliding window that gives consistent spectral indices at the 90% C.L. for any boundary yields a lower limit of 30.2 GeV, above which \(\gamma = 3.170 \pm 0.008 \pm 0.008\) is found, where the first error is the combined statistical and systematic uncertainty and the second error is due to the energy scale uncertainty. It is important to note that a single power law can describe the electron flux above 52.3 GeV and a single power law, with a different spectral index, can describe the positron flux above 27.2 GeV.

Figure 3. The flux of electrons plus positrons measured by AMS multiplied by \(E^3\) versus energy. The AMS error bars are the quadratic sum of the statistical and systematic errors. Also shown are the results from earlier experiments [19].
4. Positron Fraction

When forming the positron fraction $\Phi_{e^+}/(\Phi_{e^+} + \Phi_{e^-})$, the analysis simplifies since systematics corresponding to acceptance and efficiencies cancel to a large extent. It is important to note that in the latest publication [2], systematic errors have decreased with respect to the first AMS result [3], due to the increased statistics in the high energy region. As other uncertainties have decreased, the contribution of the absolute energy scale uncertainty, estimated as described in previous section, becomes noticeable. It results, however, in a negligible contribution to the total systematic error, except below 5GeV, where it dominates.

In each energy bin, the 2-dimensional templates for $e^\pm$ and the background are fit to data in the [TRD estimator-log($E/p$)] plane by varying the normalizations of the signal and the background. This method provides a data-driven control of the dominant systematic uncertainties by combining the redundant and independent TRD, ECAL, and tracker information. The templates are determined from high statistics electron and proton data samples selected using tracker and ECAL information including charge sign, track-shower axis matching, and the ECAL estimator. The purity of each template is verified using Monte Carlo simulation. The fit is performed simultaneously for the positive and negative rigidity data samples in each energy bin yielding the number of positrons, the number of electrons, the number of protons, and the amount of charge confusion.

From the bin-by-bin fits, the sample contains $10.9 \times 10^6$ primary positrons and electrons and $3.50 \times 10^6$ protons. A total of $0.64 \times 10^6$ events are identified as positrons. Several systematic uncertainties have been addressed. In addition to the energy scale, bin-to-bin migration, and a slightly asymmetric acceptance of $e^+$ and $e^-$ below 3 GeV, there are also systematic uncertainties from event selection, charge confusion, and the templates. To evaluate the systematic uncertainty related to event selection, the complete analysis is repeated in every energy bin over 1000 times with different cut values, such that the selection efficiency varies up to 30%. The distribution of the positron fraction resulting from these 1000 analyses contains both statistical and systematic effects. The difference between the width of this distribution from data and from Monte Carlo simulation quantifies this systematic uncertainty.

Two sources of charge confusion dominate. The first source is related to the finite resolution of the tracker and multiple scattering. It is mitigated by the $E/p$ matching and quality cuts of the trajectory measurement including the track $\chi^2$, charge measured in the tracker and charge measured in the TOF. The second source is related to the production of secondary tracks along the path of the primary $e^\pm$ in the tracker. It was studied using control data samples of electron events where the ionization in the lower TOF counters corresponds to at least two traversing particles. Both sources of charge confusion are found to be well reproduced by the Monte Carlo simulation and the respective templates are derived from Monte Carlo samples. The systematic uncertainties due to these two effects are obtained by varying the background normalizations within the statistical limits and comparing the results with the Monte Carlo simulation. They were examined in each energy bin. The proton contamination in the region populated by positrons is small. It is accurately measured using the TRD estimator. The amount of proton contamination has a negligible contribution to the statistical error. The systematic error associated with the uncertainty of the data derived templates arises from their finite statistics. It is measured by varying the shape of the templates within the statistical uncertainties. Its contribution to the overall error is small compared to the statistical uncertainty of data and is included in the total systematic error.

Fig. 4 shows the behavior of the positron fraction at low energies, from 1 to 35 GeV. As seen, below $\sim 8$ GeV the positron fraction decreases rapidly as expected from the diffuse production of positrons [18]. Then the fraction begins to increase steadily with energy. The AMS data provide accurate information on the minimum of the positron fraction. The earlier AMS result [3] in which the increase of the positron fraction was observed together with a decreasing slope above
Figure 4. The positron fraction from 1 to 35 GeV. It shows a rapid decrease from 1 to \( \sim 8 \text{ GeV} \) followed by a steady increase. The AMS data provide accurate information on the minimum of the positron fraction.

20 GeV, is consistent with this latest measurement. The increase of the positron fraction has been reported by earlier experiments: TS93 [20], Wizard/CAPRICE [21], HEAT [22], AMS-01 [23], PAMELA [15, 24], and Fermi-LAT [16]. The new result extends the energy range to 500 GeV and is based on a significant increase in the statistics by a factor of 1.7 with respect to the previous AMS measurement.Fig. 5 explores the behavior of the positron fraction at high energies (> 10 GeV) and compares it with earlier measurements. Above \( \sim 200 \text{ GeV} \) the positron fraction is no longer increasing with energy.

To examine the energy dependence of the positron fraction quantitatively in a model independent way, straight line fits were performed over the entire energy range with a sliding energy window, where the width of the window varies with energy to have sufficient sensitivity to the slope. Each window covers about 8 bins, at energies above 200 GeV it covers 3 bins. Above 30 GeV the slope decreases logarithmically with energy and crosses zero at 275 \( \pm 32 \text{ GeV} \).

This confirms the observation from Fig. 5 that above about 200 GeV the positron fraction is no longer increasing with energy. This is the first experimental evidence of the existence of a new behavior of the positron fraction at high energy.

We present a fit to the data of a minimal model, where the \( e^+ \) and \( e^- \) fluxes are parametrized as the sum of their individual diffuse power law spectrum and a common source term with an exponential cutoff parameter, \( E_s \):

\[
\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s} \\
\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}
\]

(with \( E \) in GeV). A fit of this model to the data with their total errors (the quadratic sum of the statistical and systematic errors) in the energy range from 1 to 500 GeV yields a \( \chi^2 / \text{d.f.} = 36.4 / 58 \) and the cutoff parameter \( 1/E_s = 1.84 \pm 0.58 \text{ TeV}^{-1} \), while the other parameters have similar values to those in [3], \( C_{e^+} / C_{e^-} = 0.091 \pm 0.001, C_s / C_{e^-} = 0.0061 \pm 0.0009, \gamma_{e^-} - \gamma_{e^+} = -0.56 \pm 0.03, \) and \( \gamma_{e^-} - \gamma_s = 0.72 \pm 0.04 \). The resulting fit is shown in Fig. 6 as a solid curve together with the 68% C.L. range of the fit parameters. No fine structures are observed in the data. The same model with no exponential cutoff parameter, i.e. with \( 1/E_s \) set to 0, is excluded at the 99.9% C.L.
Figure 5. The positron fraction above 10 GeV, where it begins to increase. The latest AMS measurement extends the energy range to 500 GeV and demonstrates that, above ~200 GeV, the positron fraction is no longer increasing. Measurements from PAMELA [15, 24] (the horizontal blue line is their lower limit), Fermi-LAT [16], and other experiments [20, 21, 22, 23] are also shown.

Figure 6. The positron fraction measured by AMS and the fit of a minimal model (solid curve, see text) and the 68% C.L. range of the fit parameters (shaded). For this fit both the data and the model are integrated over the bin width. The error bars are the quadratic sum of the statistical and systematic uncertainties. Horizontally, the points are placed at the center of each bin.

In [3] we reported that solar modulation had no observable effect on the measured positron fraction and this continues to be the case [2]. An analysis of the arrival directions of positrons and electrons was performed including the additional data. The positron to electron ratio remains consistent with isotropy; the upper limit on the amplitude of a potential dipole anisotropy is \( \delta \leq 0.030 \) at the 95% C.L. for energies above 16 GeV.
5. Proton Flux

The analysis of the primary proton flux [6] is accomplished by selecting events to be downward going and to have a reconstructed track in the inner tracker with $|Z| = 1$. A total of $1.1 \times 10^{10}$ events are selected. In order to have the best resolution at the highest rigidities, further selections are made by requiring the track to pass through the external tracker planes and to satisfy additional track fitting quality criteria such as a $\chi^2/d.f. < 10$ in the bending coordinate. In addition, to select only primary cosmic rays, well above the geomagnetic cutoff, the measured rigidity is required to be greater than 1.2 times the maximum geomagnetic cutoff within the AMS field of view. The small contamination of low energy (below 2 GeV) pions produced in the upper part of the detector is removed by requiring that the mass of the selected particle is larger than $0.5 \text{GeV}/c^2$. These procedures result in a sample of $3.0 \times 10^8$ primary cosmic rays with $Z = +1$.

Since protons are the dominant component of cosmic rays, the selected sample of $3.0 \times 10^8$ events has only small contributions of other particles, mainly deuterons. The deuteron contribution decreases with rigidity; at 1 GV it is less than 2% and at 20 GV it is 0.6% [25]. Deuterons were not removed. The sample also contains protons from nuclei which interact at and above 10 GV. Contamination from $e^+$ and $e^-$ [4] was estimated to be less than 0.1% over the entire rigidity range. The background contributions from nuclei and $e^\pm$, noticeable only below 2 GV, are subtracted from the flux and the uncertainties are accounted for in the systematic errors.

The isotropic proton flux $\Phi_i$ for the $i$th rigidity bin $(R_i, R_i + \Delta R_i)$ is

$$\Phi_i = \frac{N_i}{A_i \epsilon_i T_i \Delta R_i}$$

where $N_i$ is the number of events corrected with the rigidity resolution function (see below), $A_i$ is the effective acceptance, $\epsilon_i$ is the trigger efficiency, and $T_i$ is the collection time.

The proton flux is measured in 72 bins from 1 GV to 1.8 TV with bin widths chosen according to the rigidity resolution. The effective acceptance $A_i$ was calculated using Monte Carlo and then corrected for small differences found between the data and Monte Carlo event selection efficiencies. The trigger efficiency $\epsilon_i$ is measured from data with the unbiased trigger events. The trigger efficiency ranges from 90 to 95%. The 5 to 10% inefficiency is due to secondary $\delta$-rays in the magnetic field entering the ACC. The Monte Carlo agrees with the measured trigger efficiency within 0.5%.

The bin-to-bin migration of events was corrected using a rigidity resolution function obtained from Monte Carlo simulation and verified with the test beam data. Among many unfolding procedures, two are selected. The validity of both were verified by the Monte Carlo simulation. In the first procedure the flux is obtained iteratively [27]. Initially, the flux is evaluated using Eq.(4) without taking the rigidity resolution function into account. Subsequently, at each iteration, the folded acceptance $A'_i$ is calculated for each bin, $A'_i = (1/\Phi_i) \sum_{j} \Phi_j A_{ij} M_{ij}$, where $M_{ij}$ is the migration matrix obtained from the rigidity resolution function. Next, $A'$ is parametrized using a spline function. Finally, the number of events is corrected bin by bin by a factor $A_i/A'_i$ and the flux is reevaluated using Eq.(4). The iteration proceeds until the fluxes between two successive steps agree within 0.1%. The second procedure is based on a forward unfolding technique [28]. A set of spline functions with different node positions is used to parameterize the corrected number of events per bin. The spline functions are folded with the migration matrix $M_{ij}$ and fit to the data. The average of those spline functions compatible with data is used to obtain $N_i$. The small differences between the two procedures ($< 0.5\%$) are accounted as a systematic error. The sensitivity of the results to the binning has been checked by increasing the bin width.
by factors of 2 and 4 as well as reducing the bin width by factors of 2 and 4. The resulting uncertainty is well within the assigned systematic errors.

Extensive studies were made of the systematic errors. The errors include the uncertainties in the trigger efficiency, the acceptance, the background contamination, the geomagnetic cutoff factor, the event selection, the unfolding, the rigidity resolution function, and the absolute rigidity scale. The trigger efficiency error is dominated by the statistics available from the 1% prescaled unbiased event sample. It is negligible (less than 0.1%) below 500 GV and reaches 1.5% at 1.8 TV. The geomagnetic cutoff factor was varied from 1.0 to 1.4 and the resulting proton fluxes showed a systematic uncertainty of 2% at 1 GV and negligible above 2 GV.

The effective acceptance was corrected for small differences between the data and the Monte Carlo samples related to the event reconstruction and selection. Together, the correction was found to be 5% at 1 GV decreasing below 2% above 10 GV, while the corresponding systematic uncertainty is less than 1% above 2 GV.

The detector is mostly made of carbon and aluminum. The corresponding inelastic cross sections of $p + C$ and $p + Al$ are known to within 10% at 1 GV and 4% at 300 GV [29], and 7% at 1.8 TV from model estimations [14]. To estimate the systematic error due to the uncertainty in the inelastic cross sections, dedicated samples of protons were simulated with the $p + C$ and $p + Al$ cross sections varied by ±10%. From the analysis of these samples together with the current knowledge of the cross sections, a systematic error of 1% at 1 GV, 0.6% from 10 to 300 GV, and 0.8% at 1.8 TV was obtained.

The rigidity resolution function was verified with data from both the ISS and the test beam. For this the residuals between the hit coordinates measured in the external tracker layers those obtained from the track fit using the information from only the inner tracker were compared between data and simulation. In order to validate the alignment of the external layers the difference between the rigidity measured using the information from the top and inner planes and from the inner and the bottom plane was compared between data and the simulation. The resulting uncertainty on the MDR was estimated to be 5%. The corresponding unfolding errors were obtained by varying the width of the Gaussian core of the resolution function by 5% and the amplitude of the non-Gaussian tails by ~20% over the entire rigidity range and found to be 0.8% below 200 GV and 3% at 1.8 TV.

There are two contributions to the systematic uncertainty on the rigidity scale. The first is due to residual tracker misalignment. From the 400 GeV/c test beam data it was measured to be less then 1/300 TV$^{-1}$. For the ISS data this error was estimated by comparing the $E/p$ ratio for electron and positron events, where $E$ is the energy measured with the ECAL and $p$ is the momentum measured with the tracker. It was found to be 1/26 TV$^{-1}$, limited by the current high energy positron statistics. The second systematic error on the rigidity scale arises from the magnetic field map measurement and its temperature corrections. This amounts to less than 0.5% for rigidities above 2 GV.

To ensure that the treatment of systematic errors described above is correct, several additional, independent verifications were performed including the check of the stability of the measured flux for different conditions. The variations observed are well within the assigned systematic errors.

Figure 7a shows the proton flux measured by AMS as a function of rigidity with the total errors, the sum in quadrature of statistical and systematic errors. Figure 7b shows the AMS flux as a function of kinetic energy $E_K$ together with the most recent results (i.e., from experiments after the year 2000).

A power law with a constant spectral index $\gamma$, $\Phi = CR^\gamma$, where $R$ is in GV and $C$ is a normalization factor, does not fit the flux in Fig. 7a at the 99.9% C.L. for $R > 45$ GV. Applying solar modulation in the force field approximation [34] also does not fit the data at the 99.9% C.L. for $R > 45$ GV. Therefore, the flux is fitted with a modified spectral index [35].
\[ \Phi = C \left( \frac{R}{45 \text{ GV}} \right) \gamma \left[ 1 + \left( \frac{R}{R_0} \right)^{\Delta \gamma/s} \right]^s \]  

(5)

where \( s \) quantifies the smoothness of the transition of the spectral index from \( \gamma \) for rigidities below the characteristic transition rigidity \( R_0 \) to \( \gamma + \Delta \gamma \) for rigidities above \( R_0 \). Fitting over the range 45 GV to 1.8 TV yields a \( \chi^2/d.f. = 25/26 \) with

**Figure 7.** a) The AMS proton flux multiplied by \( R^{2.7} \) and total error as a function of rigidity. b) The flux as a function of kinetic energy \( E_K \) as multiplied by \( E_K^{2.7} \) compared with recent measurements [30, 31, 32, 33].
Figure 8. a) The AMS proton flux multiplied by $R^{2.7}$ as a function of rigidity $R$. The solid curve indicates the fit of Eq. 5 to the data. For illustration, the dashed curve uses the same fit values but with $\Delta \gamma$ set to zero. b) The dependence of the proton flux spectral index $\gamma$ on rigidity $R$.

$$C = 0.4544 \pm 0.0004(\text{fit})^{+0.0037}_{-0.0047}(\text{sys})^{+0.0027}_{-0.0025}(\text{sol}) \text{ m}^{-2}\text{sr}^{-1}\text{sec}^{-1}\text{GV}^{-1},$$

$$\gamma = -2.849 \pm 0.002(\text{fit})^{+0.004}_{-0.003}(\text{sys})^{+0.004}_{-0.003}(\text{sol}),$$

$$\Delta \gamma = 0.133^{+0.032}_{-0.021}(\text{fit})^{+0.046}_{-0.030}(\text{sys}) \pm 0.005(\text{sol}),$$

$$s = 0.024^{+0.020}_{-0.013}(\text{fit})^{+0.027}_{-0.016}(\text{sys})^{+0.006}_{-0.004}(\text{sol}),$$

$$R_0 = 336^{+68}_{-14}(\text{fit})^{+66}_{-20}(\text{sys}) \pm 1(\text{sol}) \text{ GV}.$$

The first error quoted (fit) takes into account the statistical and uncorrelated systematic errors. The second (sys) is the error from the remaining systematic errors, namely from the rigidity resolution function and unfolding, and from the absolute rigidity scale, with their bin-to-bin correlations accounted for using the migration matrix $M_{ij}$. The third (sol) is the uncertainty due to the variation of the solar potential $\phi = 0.50$ to 0.62 GV [36]. The fit confirms that above 45 GV the flux is incompatible with a single spectral index at the 99.9% C.L. The fit is shown in Fig. 8a. For illustration, the fit results with $\Delta \gamma$ set to zero are also shown in Fig. 8a.
To obtain the detailed variation of $\gamma$ with rigidity in a model independent way, the spectral index is calculated from

$$\gamma = \frac{d[\log(\Phi)]}{d[\log(R)]}$$

over independent rigidity intervals above $\sim 8 \text{ GV}$, with a variable width to have sufficient sensitivity to determine $\gamma$. The results are presented in Fig. 8b. As seen in Fig. 8b, the spectral index varies with rigidity. In particular, the spectral index is progressively harder with rigidity above $\sim 100 \text{ GV}$.

6. Summary and Outlook

The AMS experiment has operated successfully for the first 4 years of its mission in space. AMS is expected to continue collecting data for at least 10 more years on the ISS.

The precise measurements of cosmic ray positron, electron and proton fluxes obtained on the data sample corresponding to the first 30 months have been reviewed. The accurate measurements in the GeV to TeV energy range have already provided new insights on the origin and propagation of the galactic cosmic rays. In particular, the excess of positrons with respect to the expectations of propagation models has been characterized in detail. On top of that, neither of the measured fluxes is found to be compatible with a single power law.

Preliminary results on antiprotons and light nuclei [7] show again new features which challenge the currently accepted models for the origin and propagation of cosmic rays. For instance, the tantalizing excess observed in the antiproton to proton ratio may point towards an exotic antiproton component.

The nature of the features in the cosmic ray positron and antiproton spectra observed by AMS will become evident with more statistics. Furthermore, the uncertainties on the predictions of the astrophysical backgrounds for these channels will decrease when the new AMS measurements of light elements become available.

References

[1] A. Kounine, Int. J. Mod. Phys. E 21 (2012) 123005.
[2] L. Accardo et al., Phys. Rev. Lett. 113 (2014) 121101.
[3] M. Aguilar et al., Phys. Rev. Lett. 110 (2013) 141102.
[4] M. Aguilar et al., Phys. Rev. Lett. 113 (2014) 121102.
[5] M. Aguilar et al., Phys. Rev. Lett. 113 (2014) 221102.
[6] M. Aguilar et al., Phys. Rev. Lett. 114 (2015) 171103.
[7] The AMS Collaboration, presentations in AMS DAYS AT CERN - The Future of Cosmic Ray Physics and Latest Results, CERN, 15-17 April 2015. https://indico.cern.ch/event/381134
[8] A. K. Harding and R. Ramaty, Proc. 20th ICRC, Moscow, USSR (1987); D. Hooper, P. Blasi and P. Serpico, J. Cosmol. Astropart. Phys. 01 (2009) 25; D. Grasso et al., Astropart. Phys. 32 (2009) 140; S. Profumo, Cent. Eur. J. Phys. 10 (2011) 1-31.
[9] J. Silk and M. Srednicki, Phys. Rev. Lett. 53 (1984) 624; J. R. Ellis et al., Phys. Lett. B 214 (1988) 403; M. Cirelli et al., Nucl. Phys. B 813 (2009) 1.
[10] P. Schuster et al., Phys. Rev. D 82 (2010) 115012.
[11] P. Mertsch and S. Sarkar, Phys. Rev. D 90 (2014) 061301.
[12] S. Profumo, J. Cosmol. Astropart. Phys. 02 (2015) 1502; I. Cernuda, Astropart. Phys. 34 (2010) 59.
[13] B. Roe et al., Nucl. Instrum. Meth. A 543 (2005) 577.
[14] J. Allison et al., IEEE Trans. Nucl. Sci. 53 (2006) 270; S. Agostinelli et al., Nucl. Instrum. Methods Phys. Res., Sect. A 506 (2003) 250.
[15] O. Adriani et al., Phys. Rev. Lett. 111 (2013) 081102; O. Adriani et al., Phys. Rev. Lett. 106 (2011) 201101.
[16] M. Ackermann et al., Phys. Rev. Lett. 108 (2012) 011103.
[17] C. Grimani et al., Astron. Astrophys. 392 (2002) 287; M. Boezio et al., Astrophys. J. 532 (2000) 653; M. Aguilar et al., Phys. Lett. B 484 (2000) 10; M. A. DuVernois et al., Astrophys. J. 559 (2001) 296.
[18] P.D. Serpico, Astropart. Phys. 39-40 (2012) 2; T. Delahaye et al., Astron. Astrophys. 501 (2009) 821; I.V. Moskalenko and A.W. Strong, Astrophys. J. 493 (1998) 694.
[19] S. Torii et al., Astrophys. J. 559 (2001) 973; M. A. DuVernois et al., Astrophys. J. 559 (2001) 296; J. Chang et al., Nature 456 (2008) 362; K. Yoshida et al., Adv. in Space Res. 42 (2008) 1670; F. Aharonian et
al., Phys. Rev. Lett. 101 (2008) 261104; F. Aharonian et al., Astron. Astrophys. 508 (2009) 561; M. Ackermann et al., Phys. Rev. D 82 (2010) 092004.

[20] R. Golden et al., Astrophys. J. 457 (1996) L103.

[21] M. Boezio et al., Adv. Sp. Res. 27-4 (2001) 669.

[22] J.J. Beatty et al., Phys. Rev. Lett. 93 (2004) 241102; M.A. DuVernois et al., Astrophys. J. 559 (2001) 296.

[23] M. Aguilar et al., Phys. Lett. B 646 (2007) 145.

[24] O. Adriani et al., Astropart. Phys. 34 (2010) 1; O. Adriani et al., Nature 458 (2009) 607.

[25] E. Vannuccini, in Proceedings of the 28th International Cosmic Ray Conference, Tsukuba (2003) 1801. M. Aguilar et al., Phys. Rep. 366/6 (2002) 331.

[26] The AMS Collaboration, Measurement of the Flux of Helium Nuclei in Primary Cosmic Rays with the Alpha Magnetic Spectrometer on the International Space Station, (to be published); the AMS Collaboration, Measurement of the Flux of Light Nuclei in Primary Cosmic Rays with the Alpha Magnetic Spectrometer on the International Space Station, (to be published).

[27] G. D’Agostini, Nucl. Instrum. Meth. A 362 487 (1995); V. Blobel, DESY-84-118 (1984); A. Kondor, Nucl. Instrum. Meth. 216 (1983) 177.

[28] J. Albert et al., Nucl. Instrum. Meth. A 583 (2007) 494.

[29] N. Abgrall et al., Phys. Rev. C 84 (2011) 034604; J.R. Letaw, R. Silberberg, C.H. Tsao, Astrophys. J. Supp. 51 (1983) 271; A.S. Carroll et al., Phys. Lett. B 80 (1979) 319; S.P. Denisov et al., Nucl. Phys. B 61 (1973) 62; G. Bellettini et al., Nucl. Phys. 79 (1966) 609; T. Bowen et al., Il Nuovo Cimento 9 (1958) 908.

[30] A.D. Panov et al., Bull. Russian Acad. Sci. 73 (2009) 564.

[31] O. Adriani et al., Astrophys. J. 765 (2013) 91; O. Adriani et al., Science 332 (2011) 69.

[32] K. Abe et al., Phys. Rev. Lett. 108 (2012) 051102; Y. Shikaze et al., Astropart. Phys. 28 (2007) 154; S. Haino et al., Phys. Lett. B 594 (2004) 35; T. Sanuki et al., Astrophys. J. 545 (2000) 1135.

[33] Y.S. Yoon et al., Astrophys. J. 728 (2011) 122.

[34] L.J. Gleeson, W.I. Axford, Astrophys. J. 154 (1968) 1101.

[35] K. Beuermann et al., Astron. Astrophys. 352 (1999) L26.

[36] I.G. Usoskin, G.A. Bazilevskaya, G.A. Kovaltsov, J. Geophys. Res. 116 (2011) A02104; K.G. McCracken, J. Beer, J. Geophys. Res. 112 (2007) A10101; I.G. Usoskin, K. Alanko-Huotari, G.A. Kovaltsov, K. Mursula, J. Geophys. Res. 110 (2005) A12108.