First 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 on the cosmic rays detected from the International Space Station. The results on the positron fraction in the energy range from 0.5 to 350 GeV and the search for positron anisotropy are summarized. The very accurate data show that the positron fraction is steadily increasing from 10 to ∼250 GeV. The positron fraction spectrum shows no fine structure and the positron to electron ratio shows no observable anisotropy. This is not consistent with only the secondary production of positrons. The parametrization of the positron fraction and the e^+ + e^- flux measurements within the framework of a minimal model provides a complete description of the positron source contribution. The predictions for different scenarios accounting for the positron source component can thus be directly compared to this measurement.

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 ∼1 GeV to ∼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 less than a 10% of the expected AMS sample, include the measurement of the positron fraction, that is, the fraction of positron to electron plus positron fluxes up to 350 GeV [2, 3, 4], as well as preliminary measurements of individual positron and electron fluxes and positron plus electron fluxes [5, 6], proton flux to 1.8 TV [7], helium flux to 3 TV [8] and boron to carbon ratio to 670 GeV/n [9].

The excess of positrons above ∼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 [10], dark matter annihilation in the halo of the Galaxy [11] or in the Earth’s vicinity [12]. Distinctive signatures 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 [13]. Only precise measurements of cosmic positrons in a wide energy range may help to elucidate it.

The description of the measurement of the positron fraction in the energy range from 0.5 to 350 GeV and the systematic search for anisotropies above 16 GeV is presented. The interpretation of the results within the framework of different models will be discussed.
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.

![Diagram of the AMS detector](image)

**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.

There are three main detectors that allow a significant reduction of the proton background in the identification of the positron and electron samples. The TRD, which provides a proton rejection of $10^3$ to $10^4$ at 90% $e^\pm$ efficiency; the Tracker, which determines the trajectory, the absolute value of the charge and its sign, with a maximum detectable rigidity of 2 TV; and the ECAL, which provides a precise measurement of the $e^\pm$ energy and a proton rejection of $10^4$ when combined with the energy-momentum matching requirement $E/p > 0.75$.

The performance of the different subdetectors has been validated on detailed Monte Carlo simulations and test beam data. Moreover, the independent $e/p$ separation capabilities of TRD, Tracker and ECAL allows the selection of clean electron and proton samples on ISS data. Therefore, reference distributions for the TRD estimator, formed from the ratio of the loglikelihood probability of the $e^\pm$ hypothesis to that of the proton hypothesis, are obtained on samples selected using ECAL and Tracker. Likewise, distributions for protons and electrons of the ECAL estimator, based on a Boosted Decision Tree, BDT, algorithm [14] constructed using the 3D shower shape in the ECAL, are obtained on samples selected with the TRD.

3. Measurement of the positron fraction
The reduction of the proton background in the identification of the positron and electron samples is achieved by means of the TRD, the ECAL and the tracker. Events are selected by requiring a track in the TRD and in the tracker, a cluster of hits in the ECAL compatible with and electromagnetic shower with an energy above the geomagnetic cutoff, and a measured velocity $\beta \sim 1$ in the TOF consistent with a downward-going $Z = 1$ particle.

The selection efficiency for positrons and electrons is estimated to be $\sim90\%$ in the acceptance of the ECAL. The selected sample contains $\sim6,800,000$ primary positrons and electrons and $\sim700,000$ protons.

Selected events are grouped into ECAL energy bins. In every energy bin, the 2-dimensional reference spectra for $e^\pm$ and the background are fitted to data in the $(\text{TRD estimator} - \log(E/p))$...
plane by varying the normalizations of the signal and the background. The fit is performed for positive and negative rigidity data samples yielding, respectively, the numbers of positrons and electrons.

Several sources of systematic uncertainty have been estimated. At low energy, the most important contribution comes from the asymmetric acceptance of $e^+$ and $e^-$; at the highest energies, the uncertainty on the charge confusion between electrons and positrons is the dominant effect. The uncertainty on the reference spectra, the influence of the selection cuts and bin-to-bin migration in the energy spectrum are found to be subdominant at all energies. Above $\sim 10$ GeV the measurement of the positron fraction is limited by statistics.

The measured positron fraction is presented in Fig. 2 as a function of the reconstructed energy at the top of the AMS detector. The result is compared with the most recent measurements by PAMELA [15] and Fermi-LAT [16]. The observation that the positron fraction is steadily increasing from 10 to 250 GeV is not consistent with only the secondary production of positrons [17].

![Figure 2](image1.png) ![Figure 3](image2.png)

**Figure 2.** The positron fraction compared with the most recent measurements from PAMELA [15] and Fermi-LAT [16].

**Figure 3.** The positron fraction measured by AMS fit with the minimal model.

It is convenient to present the results comparing our data with a minimal model, where the $e^+$ and $e^-$ fluxes, $\Phi_{e^+}$ and $\Phi_{e^-}$, are parametrized as the sum of individual diffuse power law spectra and the contribution of a single common source of $e^\pm$:

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

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

where $C_{e^\pm}$ and $C_s$ are the relative contributions from the diffuse and single source spectra. The diffuse spectra are assumed to follow power laws with spectral indices $\gamma_{e^\pm}$ whereas the source spectrum is described as a single power law with spectral index $\gamma_s$ and an exponential cutoff with a characteristic energy $E_s$. With this parametrization the positron fraction depends on 5 parameters. The result of a fit to the data in the energy range 1 to 350 GeV based on the number of events in each bin is shown in Fig. 3 and yields a $\chi^2$ of 28.7 for 57 degrees of freedom $^1$, with a diffuse positron spectrum softer than the diffuse electron spectrum ($\gamma_{e^-} - \gamma_{e^+} = -0.63 \pm 0.03$), a source spectrum harder than the diffuse electron spectrum ($\gamma_{e^-} - \gamma_s = 0.66 \pm 0.05$), a weight for

$^1$ For statistical and systematic errors added in quadrature. A $\chi^2$ value of 37.9 is obtained if only statistical errors are considered.
the diffuse positron flux about $\sim 10\%$ of that of the diffuse electron flux ($C_{e^+}/C_{e^-} = 0.091 \pm 0.001$) and a weight for the common source amounting $\sim 1\%$ of that of the diffuse electron flux ($C_s/C_{e^-} = 0.0078 \pm 0.0012$). Finally, the fit yields $1/E_s = 0.0013 \pm 0.0007 \text{GeV}^{-1}$, corresponding to a cutoff energy of $760^{+1000}_{-280} \text{GeV}$.

The excellent agreement between the data and the model shows that the positron fraction spectrum is consistent with $e^\pm$ fluxes each of which is the sum of its diffuse spectrum and a single common power law source. No fine structures are observed in the data. This study also shows that the slope of the positron fraction as a function of energy decreases by an order of magnitude from 20 to 250GeV.

4. Search for positron anisotropy

The measurement of the positron fraction shows that the positron fraction is not consistent with the sole secondary production of positrons, but requires the inclusion of primary sources, whether from a particle physics or an astrophysical origin. Primary sources of cosmic ray positrons and electrons may induce some degree of anisotropy on the measured positron and electron fluxes.

The study of anisotropies in the positron fraction requires the selection of pure electron and positron samples. This is achieved with the additional requirement of a good energy-momentum matching and explicit cuts on the ECAL and TRD estimators. The overall selection efficiency for positrons and electrons is estimated to be above 80% in the acceptance of the ECAL. The remaining sample contains $\sim 35,000$ primary positrons, $\sim 460,000$ electrons with energies above 16 GeV and a negligible amount of protons.

The arrival directions of electrons and positrons are used to build sky maps in galactic coordinates, ($b, l$), containing the number of observed positrons and electrons. The maps corresponding to electrons and positrons in the energy range from 16 to 350 GeV are displayed in Fig. 4. The spread of the number of events collected on different directions is a consequence of the non uniform sky coverage of the AMS exposure.

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Sky maps showing the arrival directions of selected 16–350 GeV electrons (left) and positrons (right) in galactic coordinates using a Hammer-Aitoff projection. The color code reflects the number of events per bin.

For a given energy range, the positron to electron ratio is computed on each galactic coordinate bin. The consistency of the set of bin-to-bin ratios to a common value is estimated using a $\chi^2$ test. A good agreement is found for all energy ranges. Moreover, no structure is observed on the projections along galactic latitude or longitude.

A general description of the relative fluctuations on the observed positron ratio is obtained by means of a spherical harmonic expansion:
\[
\frac{r_e(b, l) - \langle r_e \rangle}{\langle r_e \rangle} = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\pi/2 - b, l),
\]

where \(r_e(b, l)\) denotes the positron ratio at \((b, l)\), \(\langle r_e \rangle\) is the average ratio over the sky map, \(Y_{\ell m}\) are the real spherical harmonic functions, and \(a_{\ell m}\) are their corresponding amplitudes.

The amplitudes of spherical harmonic contributions at fixed angular scale, \(\ell\), are fit to the data independently for dipole (\(\ell = 1\)), quadrupole (\(\ell = 2\)) and octopole (\(\ell = 3\)) contributions with a \(\chi^2\) minimization. No significant \(a_{\ell m}\) is found at any angular scale (\(\ell = 1, 2, 3\)) and energy range. As an example, in Fig. 5 the results corresponding to a dipole contribution perpendicular to the galactic plane, \(a_{10}\), are displayed together with the 1, 2 and 3\(\sigma\) contours as a function of the minimum energy. Similar sensitivity is obtained on the amplitudes of the other spherical harmonic contributions.

![Figure 5](image)

**Figure 5.** Amplitudes \(a_{10}\) obtained from fits of a dipole contribution to the data on different energy ranges. The dashed lines correspond to the 1, 2 and 3\(\sigma\) contours.

![Figure 6](image)

**Figure 6.** AMS upper limits on the dipole anisotropy parameter \(\delta\) at the 95\% confidence level on different energy ranges.

The intensity of the fluctuations on the studied angular scales is quantified with the coefficients of the angular power spectrum defined as \(C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^2\). The values of the coefficients \(C_1\), \(C_2\) and \(C_3\) obtained from the fits are consistent with the expectations from pure statistical fluctuations on all energy ranges.

The anisotropy induced by primary sources is expected to follow a dipole pattern with the maximum pointing towards the source and the minimum to the opposite direction. It is then customary to define the dipole anisotropy parameter, \(\delta\), as the relative difference between maximum and minimum amplitudes. Therefore, \(\delta\) can be derived from the coefficient \(C_1\) with the expression \(\delta = 3\sqrt{C_1/4\pi}\).

Since, for all energy ranges, the coefficients of the multipole expansion are consistent with the expectations from isotropy, limits on the coefficients of the angular power spectrum, \(C_\ell\), can be obtained. In particular, limits on the dipole anisotropy parameter \(\delta\) are derived for any axis in galactic coordinates. The upper limits at the 95\% confidence level for the 5 cumulative energy ranges are shown in Fig 6. The limit obtained for the energy range from 16 to 350 GeV is \(\delta < 0.030\).

The stability of the results is verified by repeating the analysis on sky maps constructed with different binning and by changing the requirement on the minimum number of electrons per bin in a wide range. In all cases, negligible differences are found.
The effect of a possible anisotropy in the electron flux is investigated by repeating the analysis on the positron to proton ratio. In addition, the influence of geomagnetic effects can be estimated on this ratio with the use of the directions obtained after backtracing in the geomagnetic field to the border of the Earth’s magnetosphere \(^2\)[18]. The sensitivity to a dipole anisotropy using the positron to proton ratio is found to be compatible with that obtained on the positron to electron analysis and similar sensitivity to a dipole anisotropy is found after backtracing.

Dark matter annihilation or decay in the Sun vicinity [12] could generate a relative positron excess towards the Sun direction. This effect is enhanced on the appropriate reference system. A similar analysis is performed using sky maps built in geocentric solar ecliptic coordinates, where the Earth-Sun axis defines its primary direction and its equatorial plane lies on the ecliptic. No significant deviation from isotropy is found and similar limits on a dipole anisotropy as those obtained in the analysis on galactic coordinates are derived. A complementary approach based on the methods for extended source evaluation in \(\gamma\)-ray astronomy [19] has been applied to the search for a local excess towards the Sun. No significant excess is found.

5. Discussion
Within the framework of the minimal model described in Sec. 3, AMS measurements of the positron fraction and the \(e^+ + e^-\) flux [6] provide a complete description of the source component. The predictions of the different scenarios accounting for the positron excess can thus be directly validated.

For each particular scenario, the predictions for the positron source component and its distribution across the Galaxy can be computed. The propagation of the cosmic positrons from their sources to the heliosphere requires solving the transport equation which accounts for the diffusion, convection and energy losses. An analytical solution of the propagation equation for the primary sources can be obtained using the Green functions formalism as described in [21], where the two main processes, diffusion and energy losses, are considered.

Two different potential sources of high energy positrons have been investigated: Dark matter (DM) annihilation in the halo of the Galaxy and positron production in standard astrophysical objects. Dark matter (DM) annihilation or decay can produce a large amount of positrons and electrons, hence, it constitutes a very attractive candidate to explain the reported excesses. However, conventional WIMP annihilation rates with canonical thermally averaged cross sections \(\langle \sigma v \rangle = 3 \times 10^{-26}\) cm\(^3\)/s are too small to account for the observations. Moreover, the absence of an excess in antiprotons indicates that the annihilation through hadronic channels must be strongly suppressed.

A scan in the \(M_{DM} - \langle \sigma v \rangle\) parameter space for a model-independent dark matter scenario, where DM particles annihilate into \(\mu \bar{\mu}\) or \(\tau \bar{\tau}\) final states, has been carried out. The mass distribution in the Galaxy halo is taken from the results obtained on recent N-body simulations [22, 23]. The resulting fluxes have been used to perform joint fits to the AMS positron fraction and \(e^+ + e^-\) flux data for energies above 30 GeV, where solar modulation can be safely neglected. AMS data can be reproduced with thermally averaged annihilation cross sections \(\sim 10^{-23}\) cm\(^3\)/s for \(\sim\) TeV DM mass candidates [20].

Standard astrophysical sources, such as SNR and pulsars, can also contribute to the observed positron excess. A pulsar model has been used to illustrate this scenario. The contribution from all gamma ray pulsars in the ATNF pulsar catalog \(^3\) to the positron flux has been fit to the AMS data. The contribution from individual sources is gauged by their conversion efficiency, \(\eta_{e^\pm}\), of the total spin-down power into \(e^\pm\). The pulsars that contribute most to the positron flux are Geminga and Monogem, due to their distance and age. For them, best fits are obtained with

\(^2\)http://www.geomagsphere.org/

\(^3\)http://www.atnf.csiro.au/research/pulsar/psrcat
\[ \eta_\pm \sim 16\% \] and \( \eta_{e^\pm} \sim 4\% \) respectively with a negligible contribution from other pulsars [20].

The positron sources from these two scenarios are compared to the minimal model fit to AMS data in Fig. 7. A good agreement is found for both the pulsar and DM origin in the energy range of the AMS measurement where the minimal model uncertainty is small. Nevertheless small differences are apparent in regions where the minimal model presents large uncertainties. At low energies, a systematic undershoot in the physics models is observed, that could be an indication of either an incomplete description of the diffusion setup, solar modulation effects, or could even point out the presence of additional sources such as distant objects contributing to the low energy range. At very high energies near the source cutoff energy, the DM and pulsar models underestimate the source contribution to the total flux, which could reflect the presence of unaccounted young pulsars in a pulsar scenario, or a larger DM mass in a dark matter scenario.

![Figure 7](image1.png)

**Figure 7.** AMS \( e^+ + e^- \) flux measurement [6], together with the positron source contribution within the minimal model described in the text (green line and blue shaded areas). Best fits for a DM model (blue line) and a pulsar model (red line) with Geminga (red dashed line) and Monogem (blue dashed line) contributions are also displayed.

![Figure 8](image2.png)

**Figure 8.** AMS upper limits on the dipole anisotropy parameter \( \delta \) at the 95% confidence level on different energy ranges. The predictions from the best fit DM (brown line) and pulsar models (blue line and gray shaded area) are also shown.

Given that for both production mechanisms the sources are distributed in the Galaxy with some spatial structure, small anisotropies should be present in the arrival directions. A residual dipole anisotropy in the source positron flux for both pulsar and dark matter models can be computed after their diffusion in the Galaxy [24], and the degree of anisotropy in the positron to electron ratio can be estimated taking into account the isotropic background for both positrons and electrons.

The expected dipole anisotropy for the different production mechanisms is shown in Fig. 8 together with the upper limits derived in Sec. 4. Experimental limits are well above theoretical expectations and therefore both models are compatible with the observations [20].
6. Summary and outlook

The precise measurements of cosmic ray positrons and electrons performed by AMS on the ISS indicate a steady increase in the positron fraction from 10 to 250 GeV with no spectral structure and no observable anisotropy. This observation is not consistent with the sole secondary production of positrons and requires the inclusion of primary sources, whether from a particle physics or an astrophysical origin.

Models reflecting these two possible scenarios have been tuned to reproduce the positron source flux derived from the AMS positron fraction and the e^+ + e^- flux measurements. A DM inspired model with enhanced leptonic decays is able to reproduce the positron source term at the expense of a boost in the thermally averaged cross section. On the other hand, a pulsar model which incorporates the contribution from most relevant individual sources is also compatible with the AMS data, provided that their conversion efficiency of spin-down power into e^± is \( \sim 10\% \). Both scenarios predict a degree of dipole anisotropy on the positron to electron ratio compatible with the AMS limits.

In spite of its unprecedented precision, the uncertainty on the AMS measurement of the positron fraction and its anisotropy is dominated by the limited statistics. Current results have been obtained on less than 10% of the expected sample as AMS will continue collecting data for more than 10 years. This will allow clarifying the high energy behavior while extending the energy range towards 1 TeV as well as improving its sensitivity to a dipole anisotropy to 1%.

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