PROCEEDINGS OF SCIENCE

Understanding the Origin of Cosmic-Ray Electrons

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We present the latest precision measurements of the electron flux based on 57 million electron events collected by the Alpha Magnetic Spectrometer. These results on cosmic-ray electrons in the energy range from 1 GeV to 2 TeV reveal new features that are crucial for providing insights into their origins. Comparing the behavior of the electron spectrum with the spectrum of positrons measured by AMS, we found that at lower energies below few hundred GeV these two spectra have distinctly different magnitudes and energy dependences. This shows that at lower energies these two species of cosmic ray particles have very different origins. At high energies we observe that the source of high energy positrons, which has either particle or astrophysical origin, also manifests itself in the electron spectrum. This is the first indication of the existence of identical charge symmetric source term both in the positron and in the electron spectra and, as a consequence, the existence of new physics.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)065

1. AMS Detector

The AMS Experiment is the most powerful physics detector of charged cosmic rays ever deployed in space. As a magnetic spectrometer, AMS is unique in its exploration of a new and exciting frontier in physics research. Following a 16-year period of construction and testing and a precursor flight on the Space Shuttle in 1998, AMS was installed on the International Space Station, ISS, on 19 May 2011 to conduct a long duration mission of fundamental physics research in space. Its main physics objectives are the understanding of dark matter and complex antimatter in the cosmos, studies of the properties of primary and secondary cosmic rays as well as the search for new, unexpected phenomena. The improvement in accuracy over previous measurements is due to its long exposure time in space, large acceptance, built in redundancy and thorough calibration.

The layout of the AMS detector [1] is shown in Fig. 1 (left). 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 anti-coincidence counters, ACC, surrounding the inner Tracker; a Ring Imaging Čerenkov detector, RICH; and an Electromagnetic Calorimeter, ECAL.

Fig. 1 (right) shows the concept of the AMS upgrade with the 8 m^2 silicon tracker layer on top of the detector, which will be completed by 2025. This will increase of the AMS acceptance by 300%. Results presented in this report correspond to data collected in 2011-2022. Significant improvements in the accuracy and the energy range of the measurements are expected due to almost 3-fold increase of the data statistics due to the AMS upgrade.

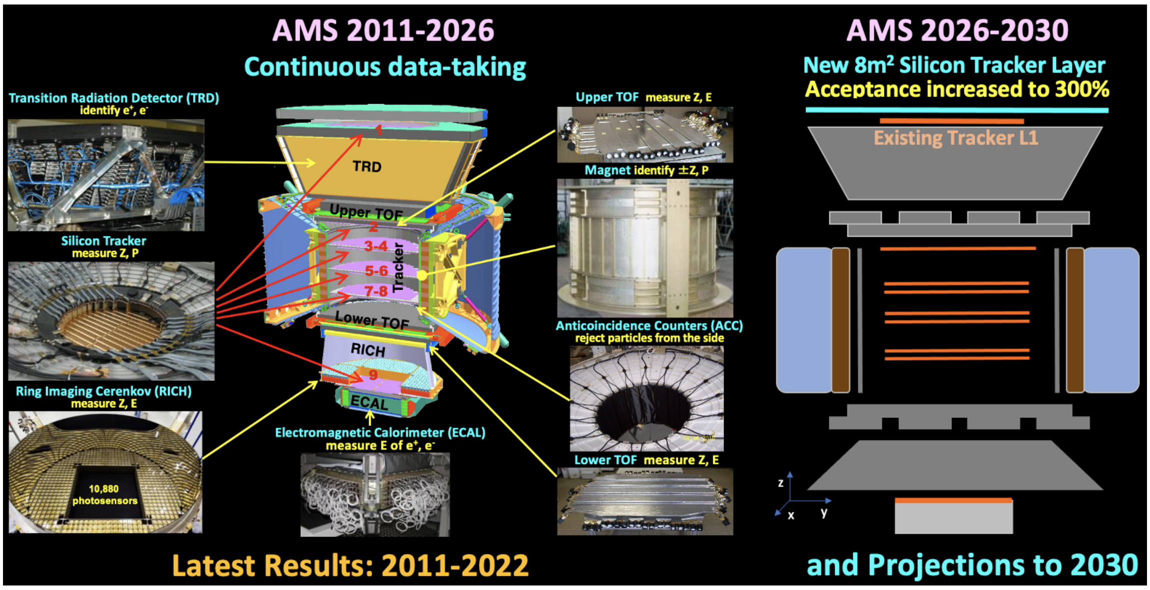

Figure 1: (left) The AMS detector in its initial configuration (2022-2026) and its main elements. The Tracker measure the particle charge, sign and momentum. The TRD identifies electrons and positrons. The TOF and the RICH measure the charge and velocity. The ECAL independently identifies electrons and positron and measures their energy. (right) AMS upgrade configuration (2026-2030) with the 8 m^2 silicon tracker layer installed on top of the detector resulting in the acceptance increase to 300%.

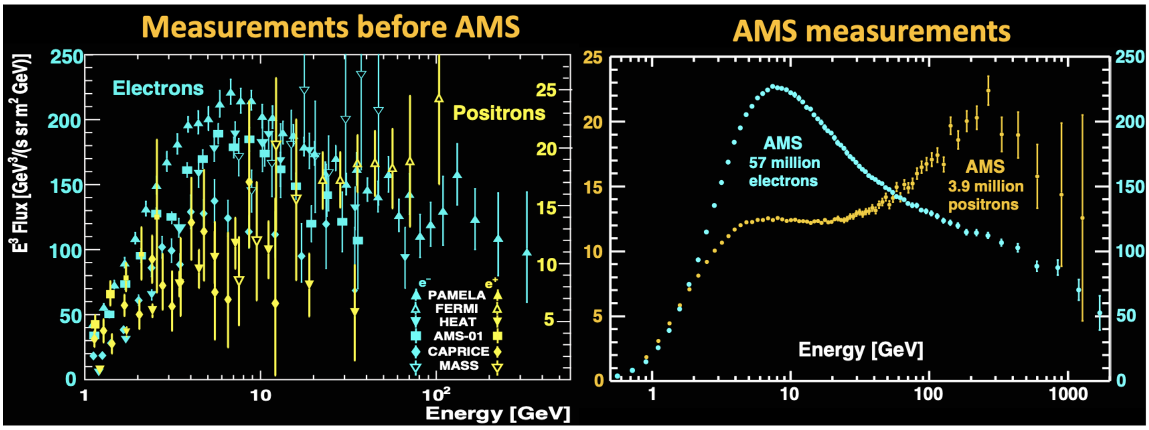

Figure 2: (left) The best measurements of the electron and positron spectra, $E^3\Phi_{e^-}$ and $E^3\Phi_{e^+}$ before AMS. (right) The AMS measurements of the positron and electron spectra extend the energy range to a TeV region.

2. Precision measurements of cosmic ray electrons and positrons

Studies of light cosmic ray antimatter species, such as positrons and antiprotons are crucial for the understanding of new phenomena in the cosmos, since the yield of these particles from cosmic ray collisions with the interstellar medium is small. Our data [2] have generated widespread interest and discussions of the observed excess of high energy positrons. The explanations of these results included three classes of models: production of high energy positrons in the interactions of cosmic ray nuclei with interstellar gas [3], acceleration of positrons to high energies in astrophysical objects [4] such as pulsars, and annihilation of dark matter particles [5, 6].

Over the last fifty years, there have been many measurements of the fluxes in cosmic rays of protons, electrons, positrons, helium, and heavier nuclei. In Figure 2(left), the most recent measurements of the positron and electron fluxes before AMS [7] are presented. As seen, the data have large errors and are not always consistent with each other. AMS performed precise measurements of positron and electron fluxes up to 2 TeV with on 3.4 million of positrons and 57 million electrons collected by AMS from May 2011 to November 2022 (analysis of the first 6.5 years of data is presented in Refs. [8, 9]). These measurements are presented in Figure 2(right). As seen, the new AMS data significantly extend the flux measurements into an uncharted high energy region with much improved precision.

In order to understand better the composition of the electron flux, we need to review the results of the analysis of the positron flux measured by AMS. Its behavior is best described by the simplest model, in which the positron flux is parameterized as the sum of a power law diffuse term and a source term:

$$\Phi_{e^+}(E) = \frac{E^2}{\hat{E}^2}[C_d\,(\hat{E}/E_1)^{\gamma_d} + C_s\,(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)]\,. \quad (1)$$

The fit results are presented in Figure 3(left). The diffuse term describes the low energy part of the flux dominated by the positrons produced in the collisions of ordinary cosmic rays with the interstellar gas [10]. It gradually vanishes with increasing energy. The source term dominates the positron spectrum at high energies leading to the observed excess of the positron flux above

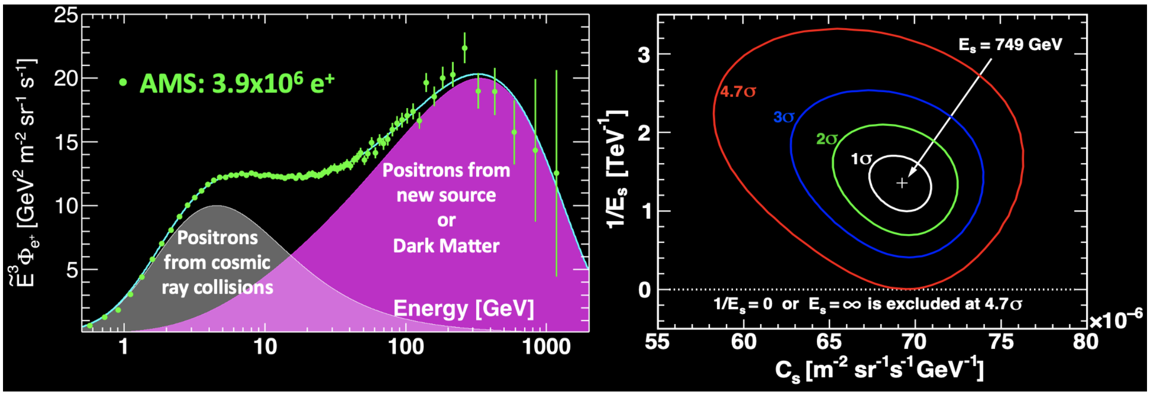

Figure 3: (left) The fit of Eq. (1) (cyan line) to the positron flux in the energy range [0.5 – 1400] GeV. The exponential cutoff of the source term is determined to be 749^{+197}_{-137} GeV from the fit. The AMS data are represented by green points. The source term contribution is represented by the magenta area, and the collision term contribution by the grey area. (right) The projections of the regions of 1σ, 2σ, 3σ, and 4.7σ significance of the $1/\mathrm{E_s}$ measurement onto the plane of parameters $1/\mathrm{E_s} - \mathrm{C_s}$.

~ 20 GeV. The drop-off of the flux above 262 GeV is very well described by the sharp exponential cutoff of the source term with the significance of the finite energy cutoff of 4.7σ.

The characteristic behaviour of the positron spectrum shows that high energies positrons predominantly originate from new sources: either dark matter annihilation [5, 6] or astrophysical sources [4]. As an example, Figure 4 shows the comparison of AMS data (yellow data points) with a dark matter model (magenta line, based on Ref. [5]) with a mass of 1.5 TeV. The study of the rate at which the positron spectrum falls beyond the turning point continues. Figure 4 also shows projected results (cyan data points) for the positron spectrum from AMS through 2030. By then, with the AMS upgrade in 2025, we will have collected 9 million positron events. As seen, by 2030 AMS should be able to measure the positron spectrum accurately to 2 TeV with greatly reduced

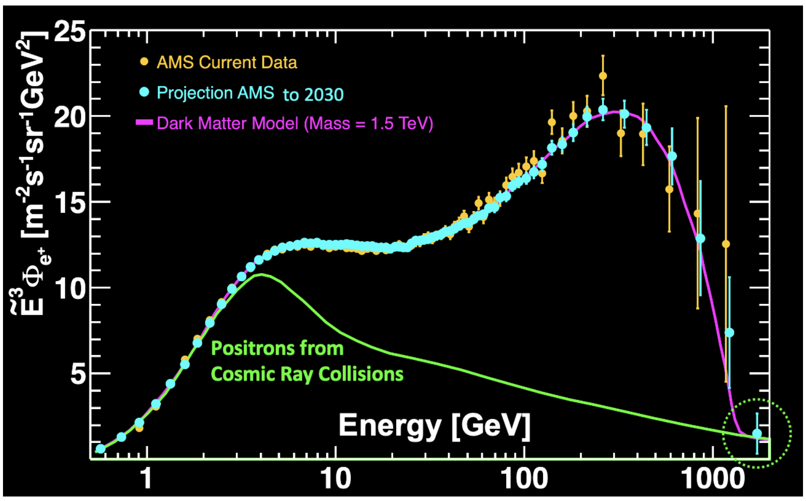

Figure 4: The measured positron spectrum ($E^3\,\Phi_{e^+}$) in comparison with the 1.5 Tev Dark Matter model showing an excellent agreement of the model with the data. .

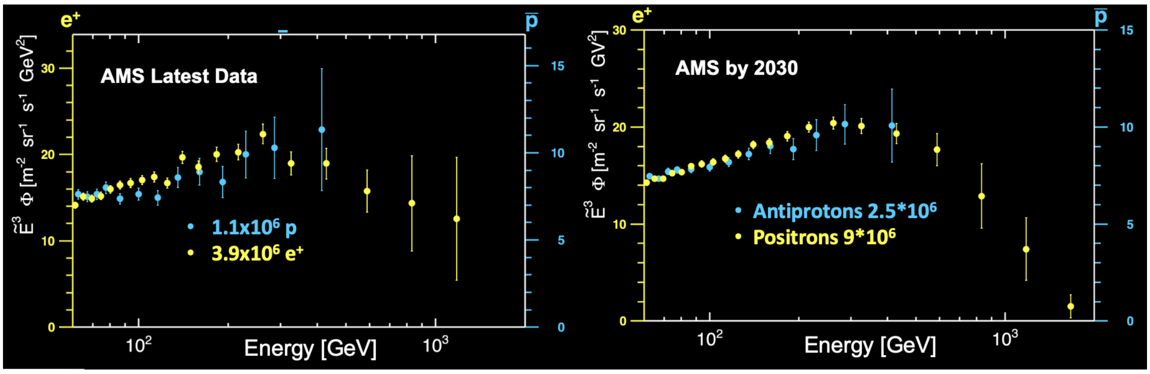

Figure 5: (left) The AMS measured spectra $E^3\,\Phi_{e^+}$ and $E^3\,\Phi_{\bar{p}}$ show strikingly similar behavior above 60 GeV. (right) Comparison of the AMS positron and antiproton spectra projected to 2030. As seen, he much increased accuracy of these measurements will shed more light on the common origin of high energy positrons and antiprotons .

errors. The data point at 1.7 TeV is an important indication that above 1.5 TeV the contribution from dark matter collisions vanishes. This will shed more light on the origin of the positron excess, i.e. help to distinguish the dark matter origin of the excess from other, new astrophysical explanations.

It is important to note that positron and antiproton spectra have strikingly similar behavior at high energies above 60 GeV, as seen in Figure 5(left). This suggests a common source of high energy positrons and antiprotons. Note that antiprotons are not produced by pulsars. The observed identical energy dependence of positrons and antiprotons and the existence of the cutoff in the antiproton energy spectrum is a phenomenon that requires a non-trivial explanation. The continuation of data taking through the lifetime of the ISS will provide an important confirmation of the origin of high energy positrons and antiprotons (see Figure 5(right)).

3. Study of the composition of the electron flux

As seen in Figure 3 the electron and positron spectra have distinctly different magnitudes and energy dependences. The different behaviour of the cosmic-ray electrons and positrons measured by AMS is clear evidence of their different origins.

In our publication, Refs. [9], we found that two distinct power law functions are needed to accurately describe the AMS electron flux. With the increase of data to 57 million electron events, we can now probe new sources of high energy electrons, such as dark matter or new astrophysical objects which both may produce an equal amount of high energy electrons and positrons. We test this hypothesis using the source term from our positron analysis and parametrize electron flux as a sum of two power law components and the positron source term with the exponential energy cutoff:

$$\Phi_{e^-}(E) = \frac{E^2}{\hat{E}^2}[C_a(\hat{E}/E_a)^{\gamma_a} + C_b(\hat{E}/E_b)^{\gamma_b} + C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)]. \qquad (2)$$

To account for solar modulation effects, the force-field approximation is used, with the energy of particles in the interstellar space $\hat{E} = E + \phi e^-$ and the effective modulation potential ϕe^-. The two power law components a and b are characterized by normalization factors C_a, C_b and spectral

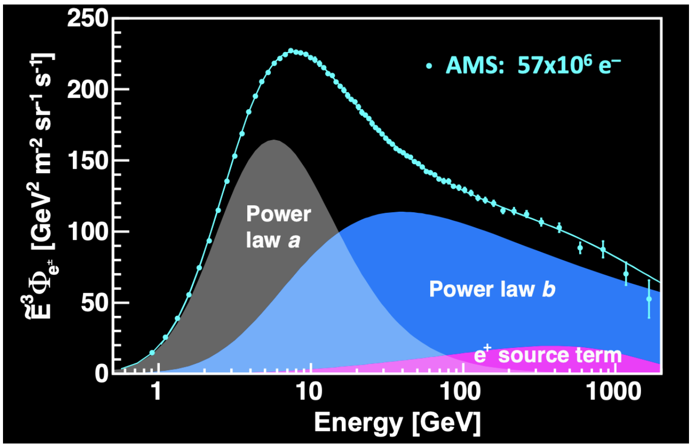

Figure 6: The fit of Eq. 2 to the electron flux data. The two power law components a and b are represented by the gray and blue areas respectively. They are characterized by normalization factors C_a, C_b and spectral indices γ_a, γ_b, respectively. The new source contribution is represented by the magenta area.

indices γ_a, γ_b, respectively. All the source term parameters C_s, γ_s, E_s are taken from the fit to positron data (Figure 3(left)), i.e. assuming the existence of identical charge symmetric source term both in the positron and in the electron spectra.

The fit to the data is presented in Figure 6. The two power law components a and b are represented by the gray and blue areas respectively and the positron source term by the magenta area. Performing the fit to data with and without the positron source term we determined its significance to be 2.6σ (or 99% CL) at present. This is the first indication of the existence of identical charge symmetric source term both in the positron and in the electron spectra and, as a consequence, the existence of new physics. With the AMS upgrade in 2025, we will determine the significance of the charge symmetric source term to 4σ (see Figure 7).

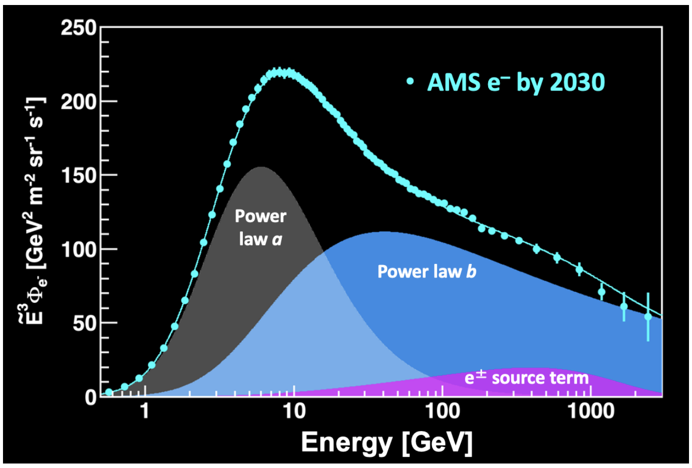

Figure 7: The AMS measurement of the electron spectrum extrapolated to 2030. By then we will not only increase the accuracy of the measurement, but also extend the energy range to 3 TeV to establish the significance of the charge symmetric source term at 4σ C.L.

4. Anisotropy of cosmic ray electrons and positrons

Astrophysical point sources like pulsars will imprint a higher anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo. If the excess of positrons has a dark matter origin, it is expected to be isotropic. The maps of arrival directions in galactic coordinates for positrons and electrons are presented in Figures 8 and reffig:anisotropy, respectively. The dipole anisotropy is given by $\delta = 3(C_1/4\pi)^{1/2}$, where C_1 is the dipole moment. Limits on the amplitude of a dipole anisotropy δ in any axis in galactic coordinates in the energy range above 16 GeV were found to be $\delta < 0.019$ for positrons and $\delta < 0.005$ for electrons at the 95% C.L. Over its lifetime, AMS will reach a dipole anisotropy sensitivity for positrons of $\delta \simeq 0.005 \pm 0.002$, which is sufficient to exclude pulsar origin of positrons [11] at the 95% C.L.

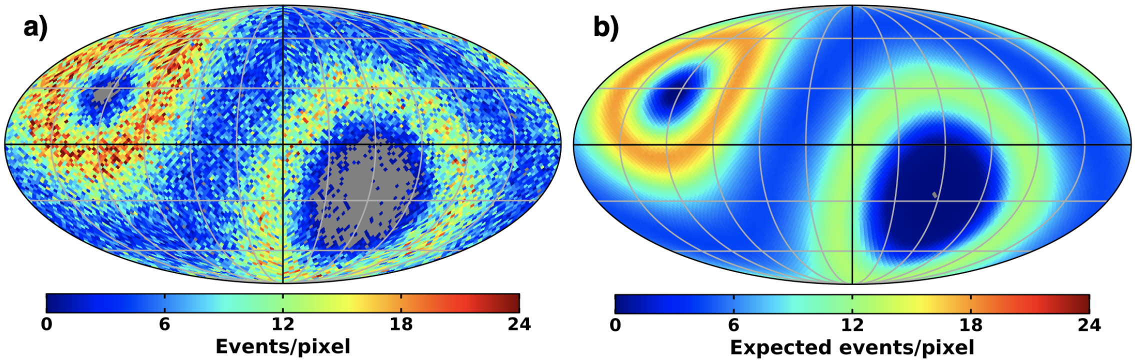

Figure 8: (left) Map of the incoming positron directions in galactic coordinates observed by AMS on the ISS. (right) Expected map of the incoming positron directions in galactic coordinates assuming an isotropic positron flux.

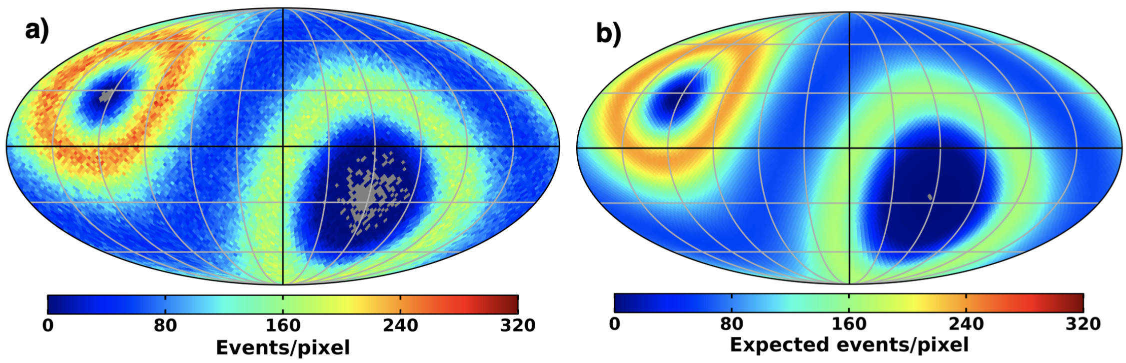

Figure 9: (left) Map of the incoming electron directions in galactic coordinates observed by AMS on the ISS. (right) Expected map of the incoming electron directions in galactic coordinates assuming an isotropic electron flux.

5. Conclusions

In twelve years on the ISS, AMS has recorded more than 220 billion cosmic ray events. The latest AMS measurements of the cosmic ray positrons, electrons, antiprotons, protons and nuclei provide precise and unexpected information on the production, acceleration and propagation of cosmic rays. We have observed that the source of high energy positrons, which has either particle or astrophysical origin, also manifests itself in the electron spectrum. This is the first indication of the existence of identical charge symmetric source term both in the positron and in the electron spectra and, as a consequence, the existence of new physics.

As a magnetic spectrometer studying cosmic rays, AMS is unique in its precision and energy reach. For the foreseeable future this is the only magnetic spectrometer in space to perform precision measurements and to explore the unknown with high expectations for exciting discoveries. The accuracy and characteristics of the AMS data, simultaneously from many different types of cosmic rays require the development of a comprehensive model of cosmic rays.

6. Acknowlwdgement

This work is supported by the US DOE grant DE-SC0011848.

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