The First Five years of AMS on the International Space Station

The Alpha Magnetic Spectrometer (AMS) Collaboration announces the fifth anniversary of the AMS Experiment on the International Space Station (ISS) and summarizes its major scientific results to date.

The AMS Experiment (shown in Figure 1) is the most powerful and sensitive physics detector ever deployed in space and is exploring a new and exciting frontier in physics research. As a magnetic spectrometer, AMS is unique in physics research as it studies charged particles and nuclei from original sources in the cosmos before they are annihilated in the Earth's atmosphere. The improvement in accuracy over previous measurements is made possible through its long duration time in space, large acceptance, built in redundant systems and its thorough calibration in the CERN test beam. These features enable AMS to analyze the data to an accuracy of ~1% and thereby requiring new theories to be developed by the physics and astrophysics community.

Figure 1. From its vantage point ~240 miles (400 km) above the Earth, the Alpha Magnetic Spectrometer (AMS) collects data from passing cosmic rays from primordial sources in the universe before they pass through the Earth's atmosphere.

Since its installation on the ISS in May 2011, AMS has collected data from more than 90 billion cosmic rays and has published its major physics results in Physical Review Letters (Appendix I).

A note about cosmic rays: As the products of exploding supernovae, primary cosmic rays can travel for millions of years in the galaxy before reaching AMS. Secondary cosmic rays come from the interaction of primary cosmic rays with the interstellar media. Uniquely positioned on the International Space Station, AMS studies cosmic rays passing through its precision detectors, shown in Appendix II, to define the charge, energy, and momentum of the passing particles in order to obtain an understanding of dark matter, the existence of heavy antimatter, the properties of primary and secondary cosmic rays as well as new, unexpected phenomena. These are among the fundamental issues in modern physics. Appendix III contains a brief summary of AMS for reference.

The scientific results of the past five years include the following:

Elementary Particles in Space

There are hundreds of different kinds of charged elementary particles. Only four of them: electrons, protons, positrons and antiprotons have infinite lifetimes so they can travel through the cosmos forever. Electrons and positrons have much smaller mass than protons and antiprotons so they lose much more energy in the galactic magnetic field due to synchrotron radiation.

Over the past century, there have been many measurements of the electron, positron and proton spectra which had large errors and created many diverse theoretical models. Currently, AMS precision measurements have revealed new and distinct information that has changed our understanding of cosmic rays.

As shown in Figure 2, AMS has observed that with a data set of 16,500,000 electrons and 1,080,000 positrons, the electron flux and positron flux display different behaviors in their magnitude and energy dependence. Before AMS, the spectra of cosmic rays were characterized by a single power law function $\Phi = CE^{\gamma}$ where γ is called the spectral index and E is the energy and that γ was assumed to be constant for the electron and positron spectra. However, AMS has found that the spectral indices are not constant and that the fluxes of electrons and positrons are different both in magnitude and in energy dependence.

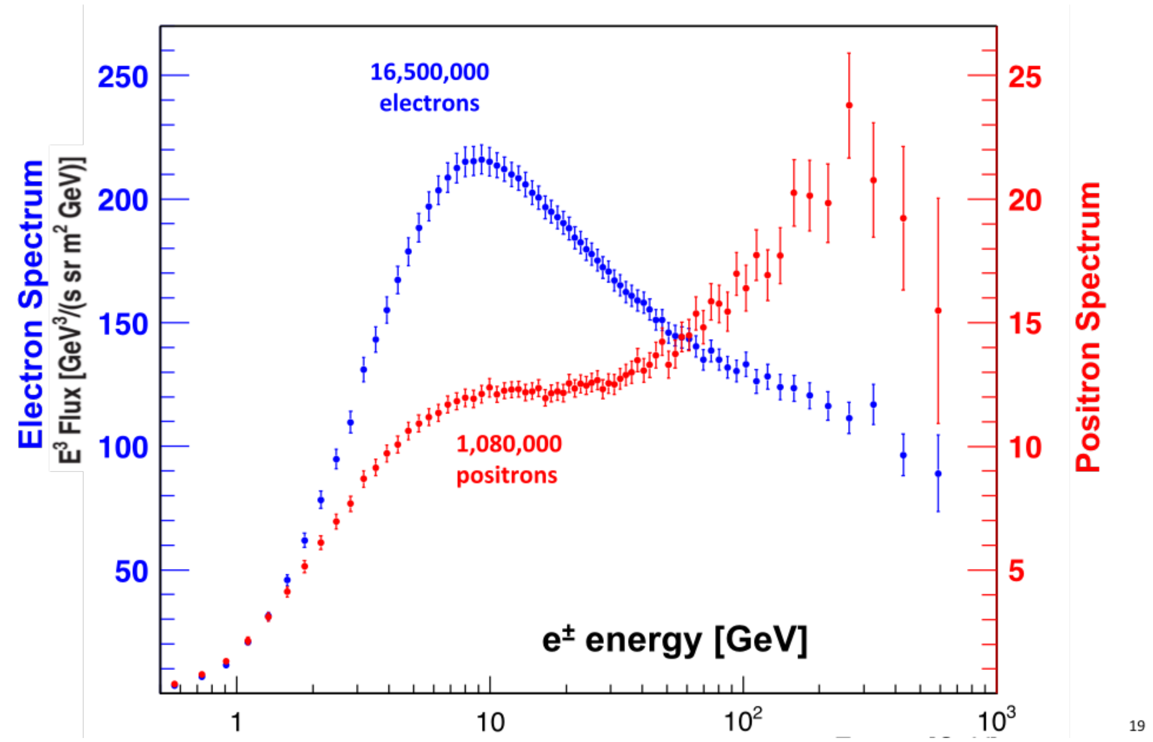


Figure 2. The electron flux and the positron flux are different in their magnitude and energy dependence.

Surprisingly, above 60 GV, positrons, protons and antiprotons display identical rigidity dependence, where rigidity is the momentum per unit charge, but electrons exhibit a totally different energy dependence as shown in Figure 3. The reason that this observation is surprising is that both electrons and positrons lose energy equally when travelling through the galactic magnetic field and at a much higher rate than protons or antiprotons.

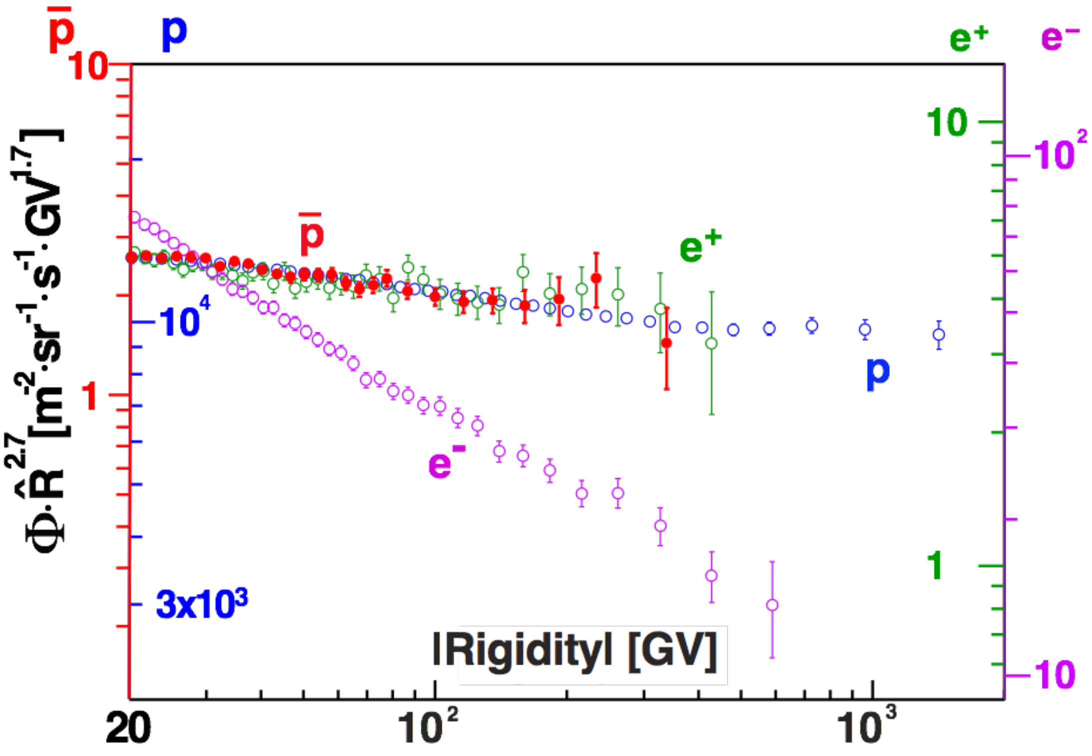


Figure 3. The positron, proton, and antiproton spectra have identical rigidity dependence above 60 GV. The electron spectrum exhibits a totally different behavior, it decreases much more rapidly with increasing rigidity.

Dark Matter and Elementary Particles in Space

There has been much interest over the last few decades in understanding the origin and nature of dark matter. When particles of dark matter collide, they produce energy that transforms into ordinary particles, such as positrons and antiprotons. The excess of positrons and antiprotons can be studied by

- measuring the positron flux,
- measuring the positron fraction, $e^+/(e^+ + e^-)$, or
- measuring the antiproton to proton ratio.

The characteristic signature of dark matter is an increase with energy followed by a sharp drop off at the mass of dark matter as well as an isotropic distribution of the arrival directions of the excess positrons and antiprotons.

Figure 4 shows the current results of the positron flux and Figure 5 shows the current result on the positron fraction. As seen from the figures, after rising from 8 GeV above the rate expected from cosmic ray collisions, the spectrum and fraction exhibit a tendency to sharply drop off at high energies. The positron data is in excellent agreement with the dark matter model predictions with a dark matter mass of ~1 TeV. An alternative speculation for the newly measured positron spectrum and fraction is that this rise and drop off may come from other astrophysical phenomena such as pulsars. By continuing to collect data through the lifetime of the Space Station (2024), AMS will be able to distinguish between these two new sources, as shown in Figure 6.

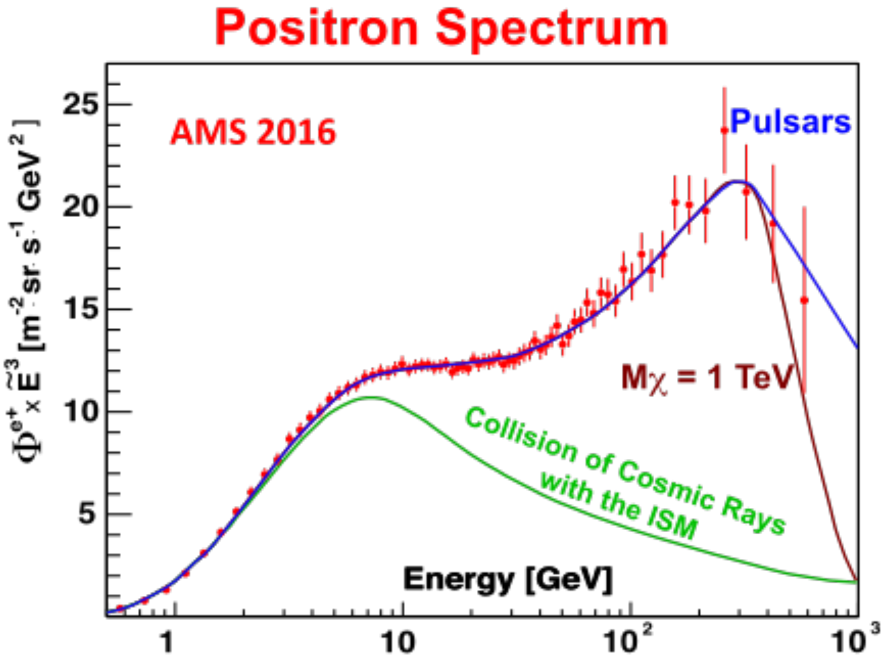


Figure 4. The current AMS positron flux measurement compared with three theoretical models.

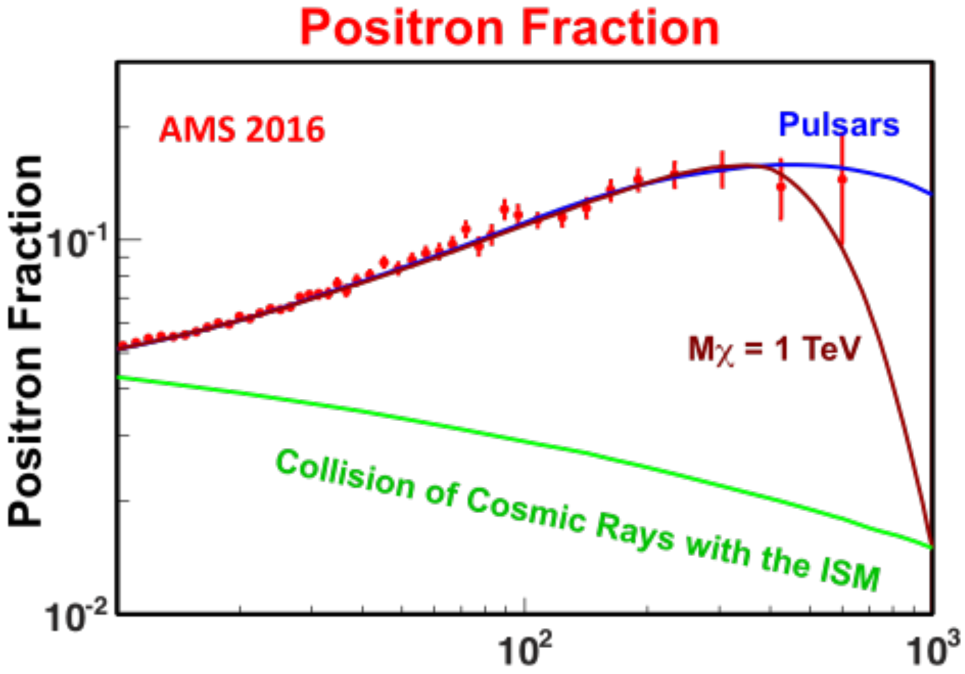


Figure 5. The current AMS positron fraction measurement compared with three theoretical models.

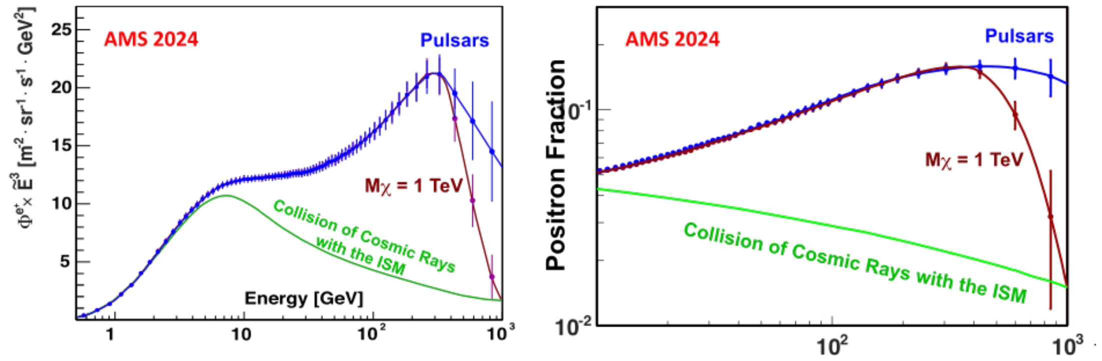
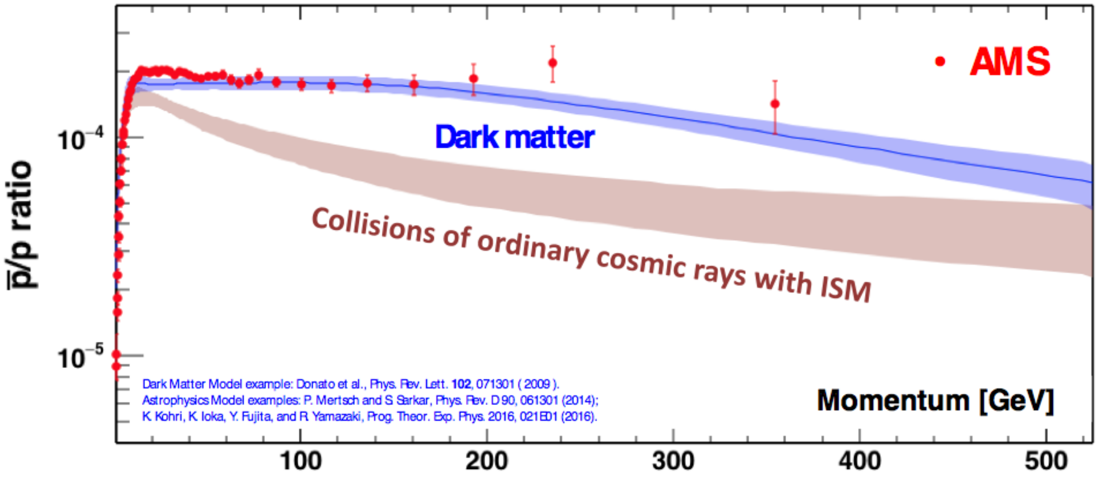


Figure 6. The positron spectrum (left) and fraction (right) measurements expected with AMS by 2024 depending on whether the source of the positron excess is from dark matter annihilations (brown curve) or pulsars (blue curve).

AMS has also studied the antiproton to proton ratio as seen in Figure 7. The excess in antiprotons observed by AMS cannot easily be explained as coming from pulsars but can be explained by dark matter collisions or by other new astrophysics models. Antiprotons are very rare in the cosmos. There is only one antiproton in 10,000 protons therefore a precision experiment requires a background rejection close to 1 in a million. It has taken AMS five years of operations to obtain a clean sample of 349,000 antiprotons. Of these, AMS has identified 2200 antiprotons with energies above 100 billion electron volts. Experimental data on cosmic ray antiprotons are crucial for understanding the origin of antiprotons in the cosmos and for providing insight into new physics phenomena.



Dark Matter Model example: Donato et al., Phys. Rev. Lett. **102**, 071301 (2009).
Astrophysics Model examples: P. Mertsch and S Sarkar, Phys. Rev. D 90, 061301 (2014);
K Kohri, K Ioka, Y. Fujita, and R Yamazaki, Prog. Theor. Exp. Phys. 2016, 021E01 (2016).

Figure 6. The excess of antiprotons observed by AMS cannot come from pulsars. It can be explained by Dark Matter collisions or by other new astrophysics models.

Protons are the most abundant particles in cosmic rays. AMS has measured the proton flux to an accuracy of 1% with 300 million protons and found that the proton flux cannot be described by a single power law, as had been assumed for decades, and that the proton spectral index changes with momentum. In Figure 7 we show the high energy proton spectrum measured by AMS on the ISS compared with the very low energy spectrum measured by the Voyager spacecraft outside the solar system. This comparison provides information on the solar magnetic field.

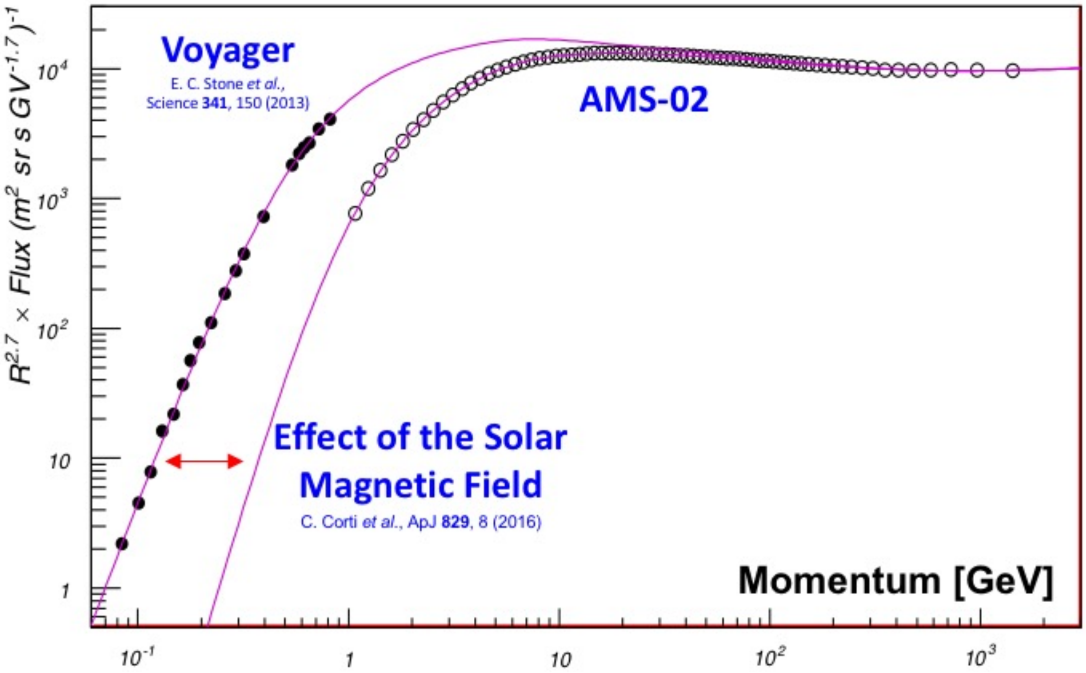


Figure 7. The high energy proton flux measured by AMS compared with the low energy flux measured with the Voyager satellite outside the solar system.

Nuclei in Cosmic Rays

AMS contains seven instruments (shown in Appendix II) with which to independently identify different elementary particles as well as nuclei. Helium, lithium, carbon, oxygen and heavier nuclei up to iron have been studied by AMS. It is believed that helium, carbon and oxygen were produced directly from primary sources in supernova remnants whereas lithium, beryllium and boron are believed to be produced from the collision of primary cosmic rays with the interstellar medium. Primary cosmic rays carry information about their original spectra and propagation, and secondary cosmic rays carry information about the propagation of primary and secondary cosmic rays and the interstellar medium.

Helium is the second most abundant cosmic ray. Helium has been studied over the past century and measurements have been produced but contain large errors. Although lithium is a secondary cosmic ray, its spectrum behaves similarly to protons and helium in that none of the three fluxes can be described by a single power law and they do change their behavior at the same energy as seen in Figure 8.

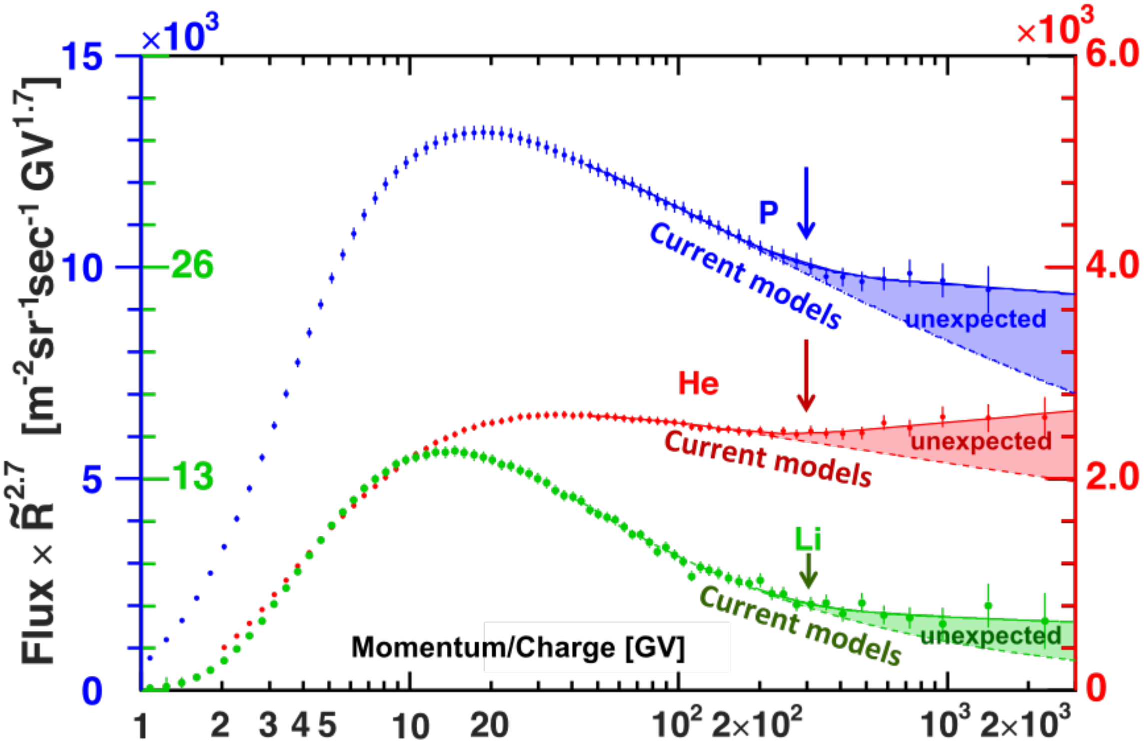


Figure 8. The spectra of protons, helium and lithium do not follow the traditional single power law. They do change their behavior at the same energy.

Since protons, helium, carbon and oxygen are primary cosmic rays and produced at the same sources; thus their flux ratios should be rigidity independent. Figure 9 shows that, from the AMS measurements, for carbon-to-helium and for carbon-to-oxygen these ratios are, indeed, independent of rigidity, i.e., flat, as expected. Unexpectedly, the proton-to-helium flux ratio drops quickly but smoothly with rigidity, as seen in Figure 10.

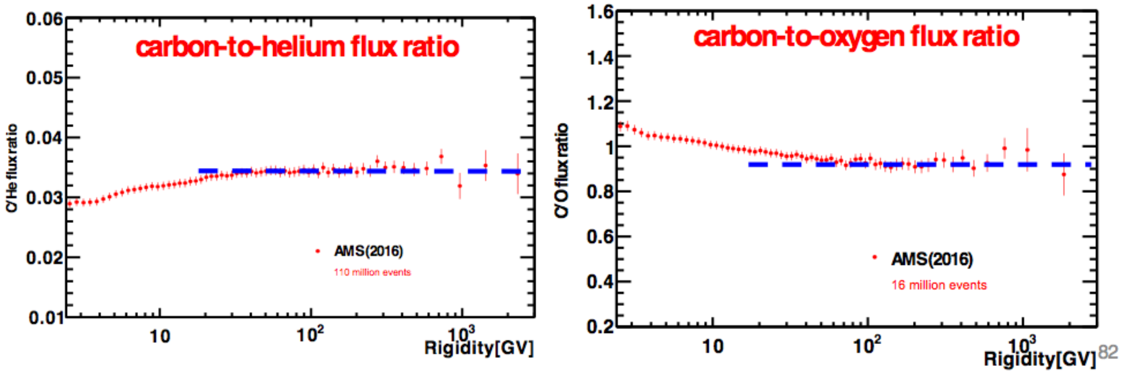


Figure 9. The carbon-to-helium (left) and carbon-to-oxygen (right) flux ratios. Since carbon, helium and oxygen are primary cosmic rays, these ratios, as expected, are rigidity independent as indicated by the dashed horizontal blue lines.

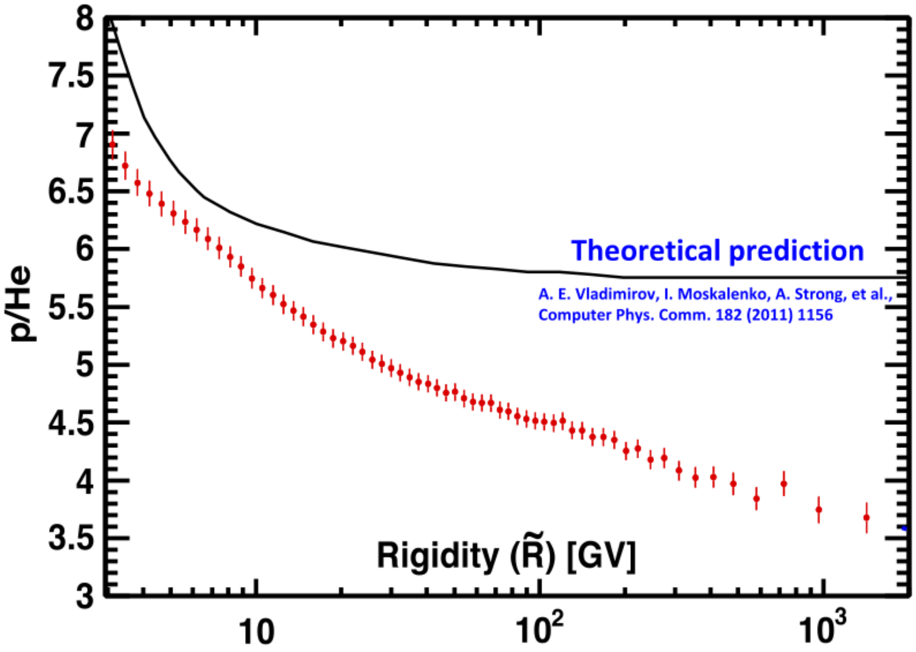


Figure 10. The proton-to-helium flux ratio. Protons and helium are also primary cosmic rays therefore the proton-to-helium flux ratio should also be rigidity independent as indicated by the latest theoretical prediction (black curve). The AMS measurement, red circles, contradicts this theoretical prediction and contradicts the results of other primary cosmic ray ratios shown in Figure 9.

Other secondary cosmic rays being measured by AMS include boron and beryllium. The unstable isotope of beryllium, ^{10}Be, has a half-life of 1.5 million years and decays into boron. The Be/B ratio therefore increases with energy due to time dilation when the Be approaches the speed of light. Hence, the ratio of beryllium to boron provides information on the age of the cosmic rays in the galaxy. From this, AMS has determined that the age of cosmic rays in the galaxy is ~12 million years as shown in Figure 11.

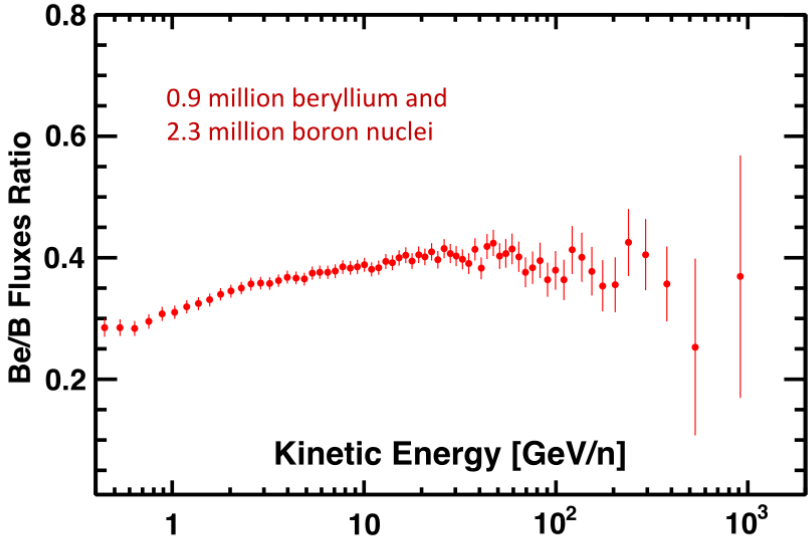


Figure 11. The beryllium-to-boron (Be/B) flux ratio increases with energy due to time dilation of the decaying Be. The measurement yields the age of cosmic rays in the galaxy as ~12 million years.

The flux ratio between secondary cosmic rays (boron) and primary cosmic rays (carbon) provides information on propagation and the average amount of interstellar material (ISM) through which the cosmic rays travel in the galaxy. Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma. Various models of the magnetized plasma predict different behavior of the boron-to-carbon (B/C) flux ratio. Remarkably, as shown in Figure 12, above 65 GeV, the B/C ratio measured by AMS is well described by a single power law B/C= *kR*™ with ™ = -0.333±0.015. This is in agreement with the Kolmogorov turbulence model of magnetized plasma where ™ = -1/3 asymptotically. Of equal importance, the B/C ratio does not show any significant structures in contrast to many cosmic ray models.

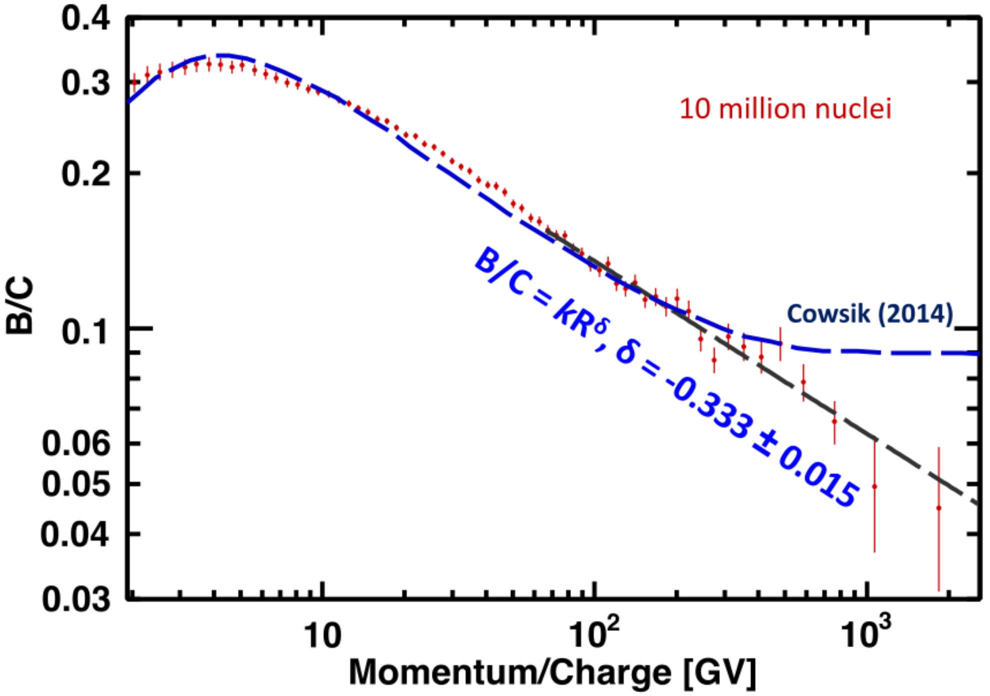


Figure 12. The B/C ratio does not show any significant structures in contrast to many cosmic ray models that require such structures at high rigidities. Remarkably, above 65 GV, the B/C ratio is well described by a single power law B/C = kR^{δ} with $\delta = -0.333 \pm 0.015$. This is in agreement with the Kolmogorov turbulence model of magnetized plasma of $\delta = -1/3$ asymptotically.

The carbon and oxygen fluxes, which are both primary, and the boron, lithium, and beryllium fluxes, which are secondary, have characteristically different rigidity dependences, as shown in Figure 13.

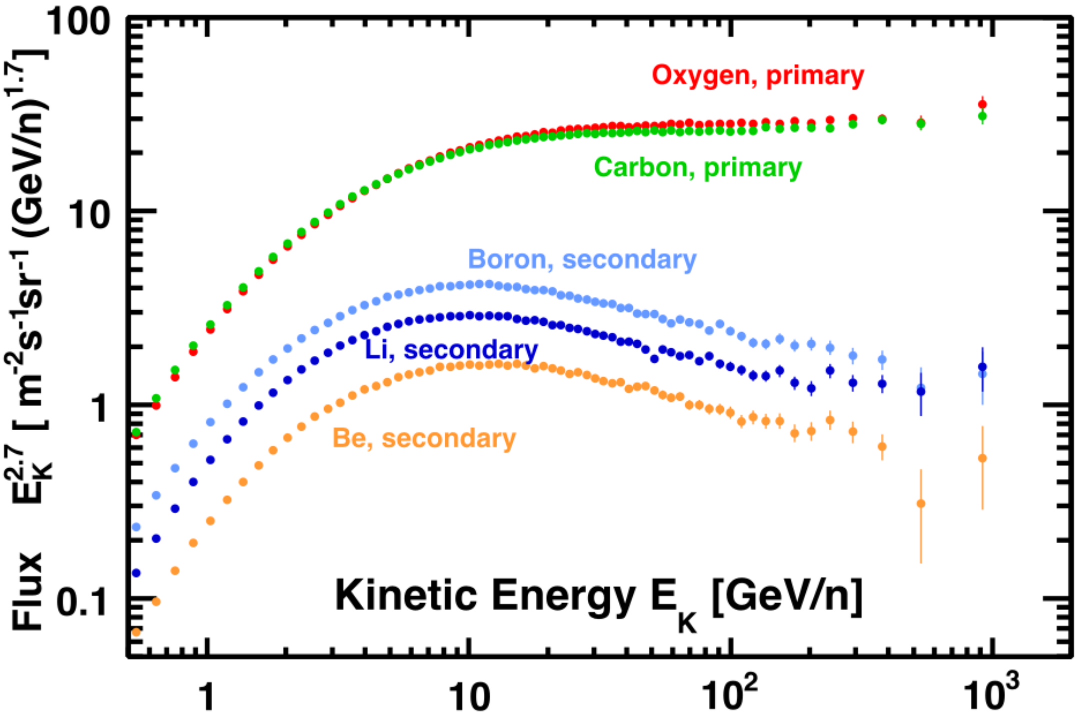


Figure 13. The fluxes of primary (oxygen and carbon) and secondary (boron, lithium, and beryllium) cosmic rays have characteristically different rigidity dependences.

Antimatter in Cosmic Rays

The Big Bang origin of the Universe requires that matter and antimatter be equally abundant at the very hot beginning of the universe. The search for the explanation for the absence of antimatter in a complex form is known as Baryogenesis. Baryogenesis requires both a strong symmetry breaking and a finite proton lifetime. Despite the outstanding experimental efforts over many years, no evidence of strong symmetry breaking nor of proton decay have been found. Therefore, the observation of a single anti-helium event in cosmic rays is of great importance.

In five years, AMS has collected 3.7 billion helium events (charge Z = +2). To date we have observed a few Z = -2 events with mass around ^{3}He. An event is displayed in Figure 14.

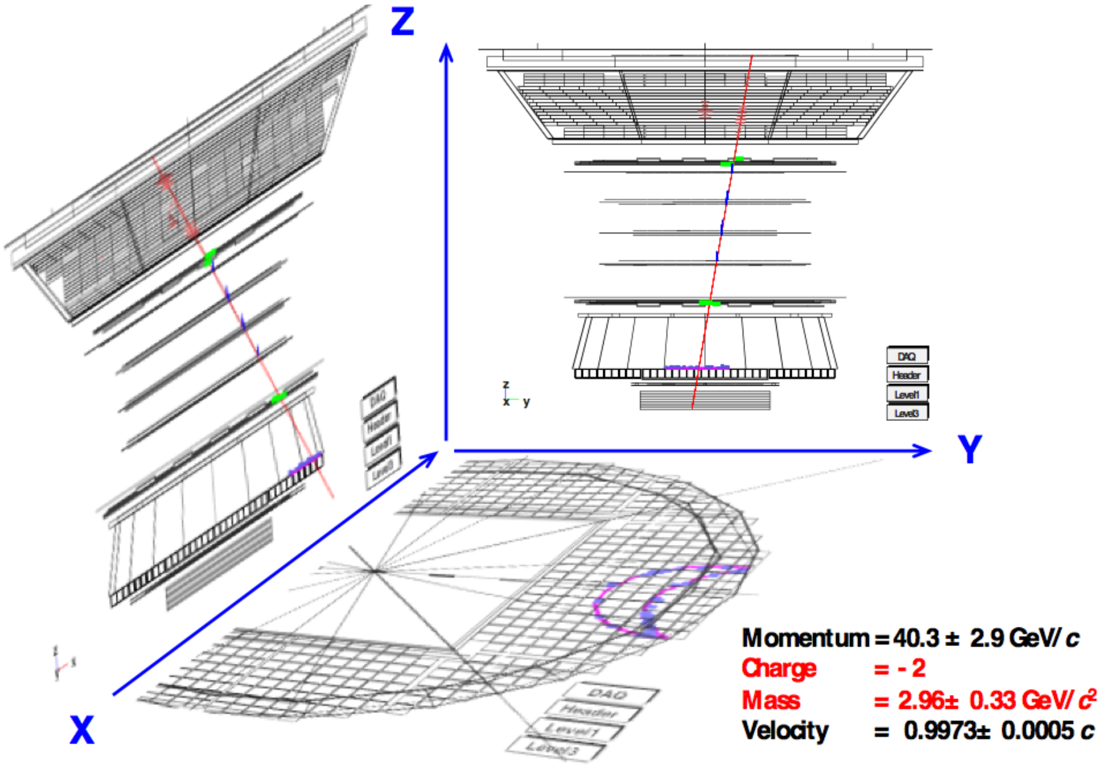


Figure 14. An antihelium candidate.

At a rate of approximately one antihelium candidate per year and a required signal (antihelium candidates) to background (helium) rejection of one in a billion, a detailed understanding of the instrument is required. In the coming years, with more data, one of our main efforts is to ascertain the origin of the Z = -2 events.

Solar Physics

AMS started collecting data during the ascending phase of Solar Cycle 24 and will continue to do so until the next maximum of solar activity, foreseen around 2025. Given its large acceptance and redundant detectors, AMS is the first space-borne experiment to measure the effects of solar activity on all species of galactic cosmic rays above 1 GV with unprecedented accuracy and high time-resolution throughout an entire solar cycle. AMS also makes precision measurements of solar energetic particles accelerated at the sun in their highest energy range (rigidities up to a few GV), which is not covered by other heliophysics spacecraft. Understanding how the particle radiation environment changes with time around Earth due to space weather has become a major concern for governmental agencies, as it is of utmost importance for the safety of the astronauts during current and future space missions as well for the fleet of scientific and commercial satellites, which nowadays plays a fundamental role in society.

Figure 15 upper plot shows the monthly evolution of protons with rigidity around 2 GV over 5 years of time. The proton flux decreases and reaches a minimum in the beginning of 2014, as a result of the increasing solar activity. After the peak of the solar cycle, the flux experiences a recovery as the solar activity decreases towards its minimum, expected around 2020. In addition to the long-term trend, monthly variations related to short-term solar activity, such as solar flares and coronal mass ejections, are evident.

Figure 15 lower plot shows the proton-to-helium (red), proton-to-electron (magenta) and proton-to-positron (green) normalized ratios at about 2 GV. Positive and negative particles show a different behavior depending on the phase of the solar cycle related to the change of the solar magnetic field polarity. This intriguing result has never been observed before in such detail and will require improvements to current theoretical models to be understood.

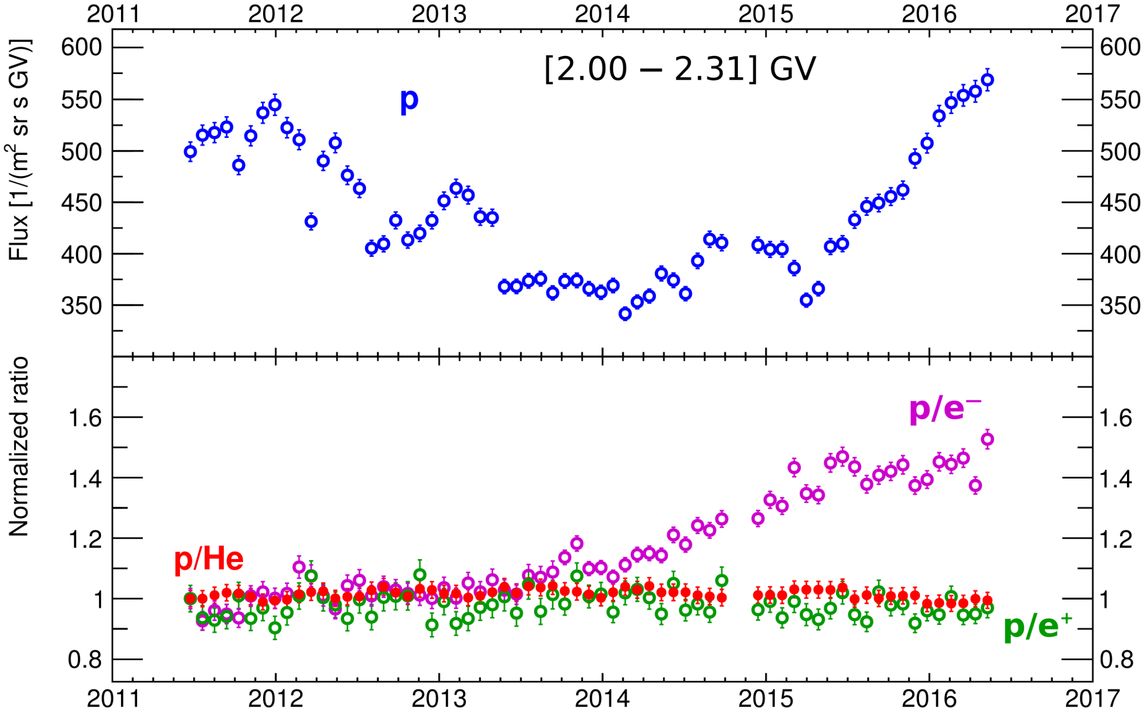


Figure 15. Upper plot: monthly proton flux at about 2 GV over 5 years of time. Lower plot: proton-to-helium (red), proton-to-electron (magenta) and proton-to-positron (green) normalized ratios at about 2 GV over 5 years of time.

In five years, AMS on the ISS has recorded more than 90 billion cosmic ray events. The latest AMS measurements of the positron spectrum and positron fraction, the antiproton/proton ratio, the behavior of the fluxes of electrons, positrons, protons, helium and other nuclei provide precise and unexpected information on the production, acceleration and propagation of cosmic rays. The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays require the development of a comprehensive model. In the coming years, with more data, one of our main efforts is to ascertain the origin of the $Z = -2$ events.

Most importantly, AMS will continue to collect and analyze data for the lifetime of the Space Station. As the results to date have demonstrated, whenever a precision instrument such as AMS is used to explore the unknown, new and exciting discoveries can be expected.

Appendix I

Major AMS Publications in Physical Review Letters

“First Result from the Alpha Magnetic Spectrometer on the International Space Station : Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV”, M. Aguilar et al., Phys. Rev. Lett. **110**, 141102 (2013) (Selected as Editors’ Suggestion).

“High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-500 GeV with the Alpha Magnetic Spectrometer on the International Space Station”, L. Accardo et al., Phys. Rev. Lett. **113**, 121101 (2014) (Selected as Editors’ Suggestion)

“Electron and Positron Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station”, M. Aguilar et al., Phys. Rev. Lett. **113**, 121102 (2014) (Selected as Editors’ Suggestion).

“Precision Measurement of the ($e^+ + e^-$) Flux in Primary Cosmic Rays from 0.5 GeV to 1 TeV with the Alpha Magnetic Spectrometer on the International Space Station”, M. Aguilar et al., Phys. Rev. Lett. **113**, 221102 (2014).

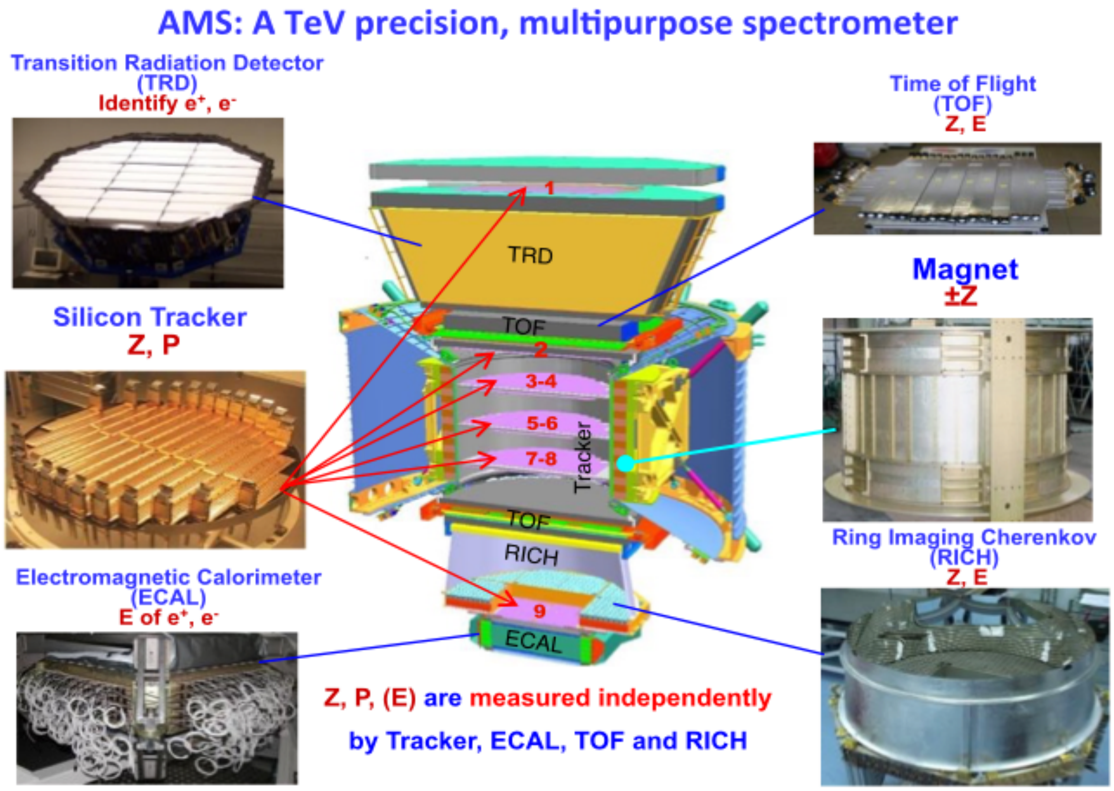
“Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station”, M. Aguilar et al., Phys. Rev. Lett. **114**, 171103 (2015) (Selected as Editors’ Suggestion).

“Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station”, M. Aguilar et al., Phys. Rev. Lett., **115**, 211101 (2015) (Selected as Editors’ Suggestion)

“Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station”, M. Aguilar et al., Phys. Rev. Lett., **117**, 091013 (2016).

“Precision Measurement of the Boron to Carbon Flux Ratio in Cosmic Rays from 1.9 GV to 2.6 TV with the Alpha Magnetic Spectrometer on the International Space Station”, M. Aguilar et al., Phys. Rev. Lett., **117**, 231102 (2016) (Selected as Editors’ Suggestion).

Appendix II



AMS: A TeV precision, multipurpose spectrometer

Z, P, (E) are measured independently by Tracker, ECAL, TOF and RICH

Appendix III

Background of AMS

AMS is a U.S. Department of Energy and NASA sponsored international collaboration made up of 15 countries from Europe, Asia and the Americas (Brazil, China, Finland, France, Germany, Italy, Korea, Mexico, Portugal, Russia, Spain, Switzerland, Taiwan, Turkey, and the United States). AMS institutes are listed below. AMS is supported by the national high energy institutes INFN, IN2P3, CIEMAT, U.S. DOE, Academia Sinica, NCSIST, the Swiss National Science Foundation and by the space agencies ASI, CAST, CDTI, CNES, DLR, ESA and NASA. The AMS detector components were integrated at CERN, Geneva by the collaborating groups along with CERN engineers and space qualification tests were conducted at the ESA's ESTEC facility in the Netherlands. Extensive calibration of the AMS detector with different particle beams at different energies was carried out at CERN. These test results provide key reference points for detector verification in space.

The Principal Investigator of AMS is Prof. Samuel Ting of MIT and CERN. Deputy PIs include M. Capell and A. Kounine of MIT/USA, J. Berdugo of CIEMAT/Spain, B. Bertucci of INFN-University of Perugia/Italy, S.C. Lee of Academia Sinica/Taiwan and S. Schael of RWTH-Aachen/Germany. AMS operates on the International Space Station under a DOE-NASA Implementing Arrangement. The Collaboration works closely with the NASA AMS Project Office from Johnson Space Center as it has throughout the entire process. AMS was launched by NASA to the ISS as the primary payload onboard the final mission of space shuttle Endeavour (STS-134) on May 16, 2011. Once installed on the ISS, AMS was powered up and immediately began collecting data from primary sources in space and these were transmitted to the AMS Payload Operations Control Center (POCC). The POCC is located at CERN, Geneva, Switzerland and an Asia POCC is located in Taiwan.

After five years of operation, AMS has collected more than 90 billion cosmic ray events. The data is analyzed at the AMS Science Operations Center (SOC) located at CERN as well as at AMS universities around the world. Over the lifetime of the Space Station, AMS is expected to measure hundreds of billions of primary cosmic rays. Among the physics objectives of AMS is the search for antimatter, dark matter, and the origin of cosmic rays. Over the first five years on the ISS, the AMS Collaboration has conducted precision measurements of cosmic rays to study elementary particles and nuclei.

It is important to note that, in the search for an understanding of dark matter, there are three distinct approaches:

1. Production experiments, such as those being carried at the LHC with the ATLAS and CMS experiments, use particle collisions to produce dark matter particles and detect their decay products. This is similar to experiments at the Brookhaven, Fermilab, CERN-SPS and CERN-LHC which led to the discovery of CP violation, the J particle, Z and W bosons, the b and t quarks, and the Higgs boson.
2. Scattering experiments utilize the fact that dark matter can penetrate deep underground and that it can be detected by recoil nuclei from the scattering of dark matter with pure liquid or solid targets. This is similar to electron-proton scattering experiments performed at SLAC leading to the discovery of partons and the electro-weak effects.
3. Annihilation experiments for dark matter are done in space and are based on the fact that dark matter collisions can produce excesses of positrons and anti-protons. These are the main goals of AMS. On the ground, annihilation experiments are done in electron-positron colliders (SPEAR, DORIS, PETRA, LEP, PEP-II, KEK-B) leading to the discovery of the psi particle, the heavy electron (tau) and gluons, precision measurements of CP violation effects and the properties of Z and W bosons.

The scattering experiments, the production experiments, and the annihilation experiments each produce unique physics discoveries. The absence of a dark matter signal from one of these three ways does not exclude its discovery by the other two.

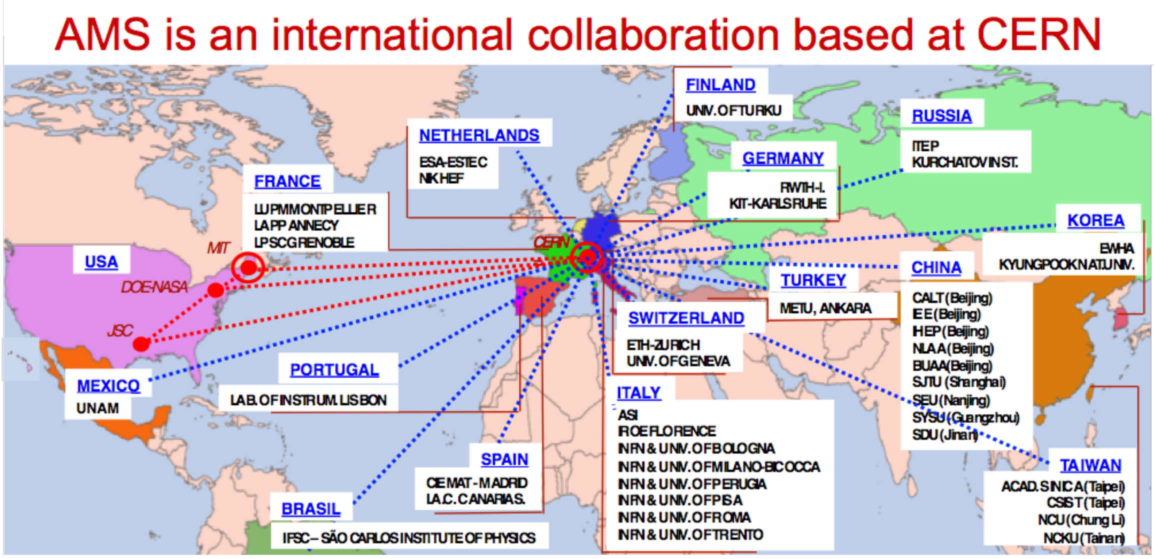


Figure 1. The AMS international collaboration.

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