Latest Results from AMS (Alpha Magnetic Spectrometer)

SADAKAZU HAINO
INSTITUTE OF PHYSICS, ACADEMIA SINICA

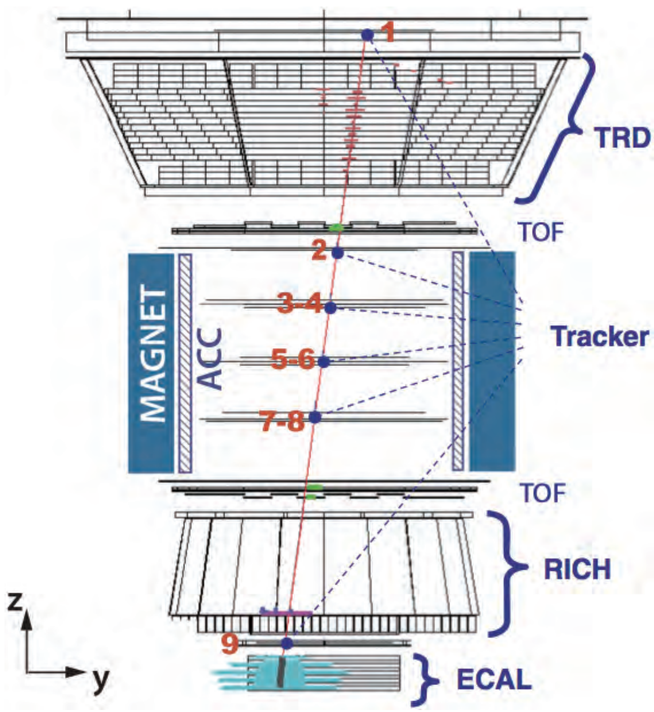

Fig. 1: A 1.03 TeV electron event as measured by AMS on ISS in the bending (y-z) plane [1].

ABSTRACT

The Alpha Magnetic Spectrometer (AMS) is the only major particle physics experiment attached on the International Space Station. In its first four years in orbit, AMS has collected more than 60 billion cosmic ray events up to multi-TeV energies. The AMS collaboration made their first public conference, "AMS Days at CERN" in April of 2015.

In this article, the latest AMS results published and presented so far are summarized, and their implications on the indirect dark matter search are discussed.

THE AMS PROJECT

AMS is a U.S. Department of Energy (DOE) sponsored particle physics experiment under a DOE-NASA implementing arrangement. The project is being carried out by an international collaboration of about fifteen countries from Asia, the America s and Europe. The spokesman and principal investigator (PI) of AMS is Nobel Laureate Academician Samuel C.C Ting of MIT and CERN. The leader of AMS-Taiwan's group, Academician S.C. Lee of Academia Sinica, is one of the deputy PIs.

Fig. 2: AMS installed on the ISS. Photo by NASA.

AMS is a general purpose high-energy particle physics detector. It was installed on the International Space Station (ISS) on May 19, 2011, to conduct a unique long duration mission (up to 20 years) of fundamental physics research in space.

The AMS Detector

The layout of the AMS-02 detector is shown in Fig. 1. It consists of nine planes of the precision silicon tracker, a transition radiation detector (TRD), four planes of time of flight counters (TOF), a permanent magnet, an array of anticoincidence counters (ACC) surrounding the inner tracker, a ring imaging Cherenkov detector (RICH), and an electromagnetic calorimeter (ECAL). The figure also shows an event of a high-energy electron of 1.03 TeV recorded by AMS on ISS [1].

There are three main detectors that allow a significant reduction of the proton background in the identification of the positron and electron samples. They are TRD, ECAL, and the tracker. 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 and the momentum measured with the tracker greatly improves the proton rejection. The proton rejection power of the TRD estimator at 90% electron efficiency measured on orbit is 10^3–10^4. The proton rejection power of the ECAL estimator when combined with the energy-momentum matching requirement reaches 10^4. The performance of both the TRD and ECAL estimators are derived from data taken on the ISS [1-4].

The complete detector was tested at the Super Proton Synchrotron (SPS) at CERN before the launch. In the beam tests, AMS was exposed to secondary beams of positrons and electrons in the momentum range from 10 to 290 GeV/c and the primary 400 GeV/c proton beam. It was also exposed to 10–180 GeV/c charged pions, which produce transition radiation as protons up to 1.2 TeV/c.

Launch and Operation of AMS

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. The photo of AMS on the ISS is shown in Fig. 2. Once installed on the ISS, AMS was powered up and immediately began collecting data from primary sources in space and the data were transmitted to the AMS Payload Operations Control Center (POCC) located at CERN. Part of the operation is shared by Asia-POCC located at the Chung-Shan Institute of Science and Technology (CSIST) in Taiwan (Fig. 3).

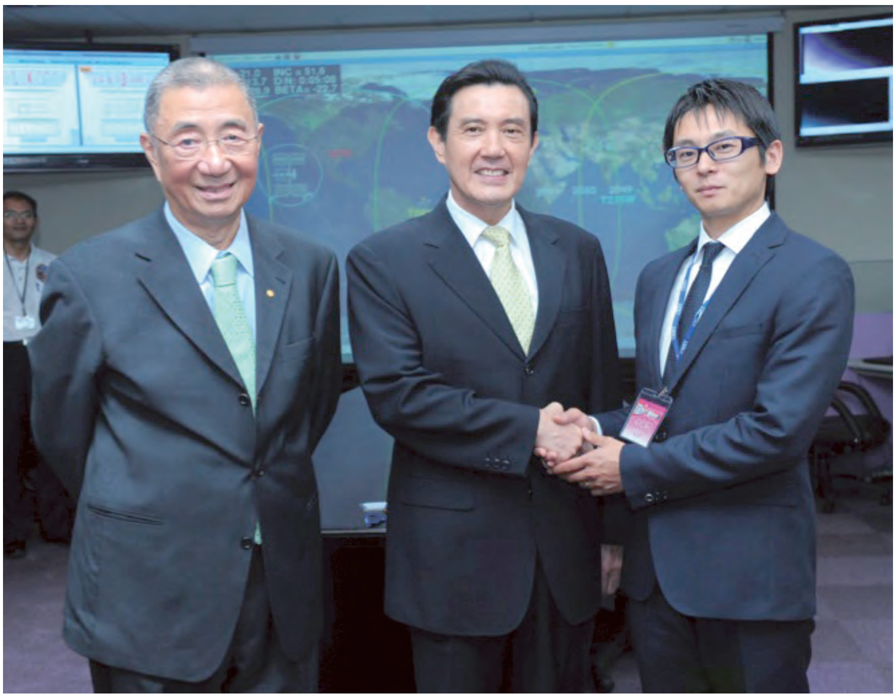

Fig. 3: The July 2012 Inauguration of Asia-POCC at CSIST in Taiwan. From left, Academician S.C.C. Ting, President Y.J. Ma of Taiwan, and the author.

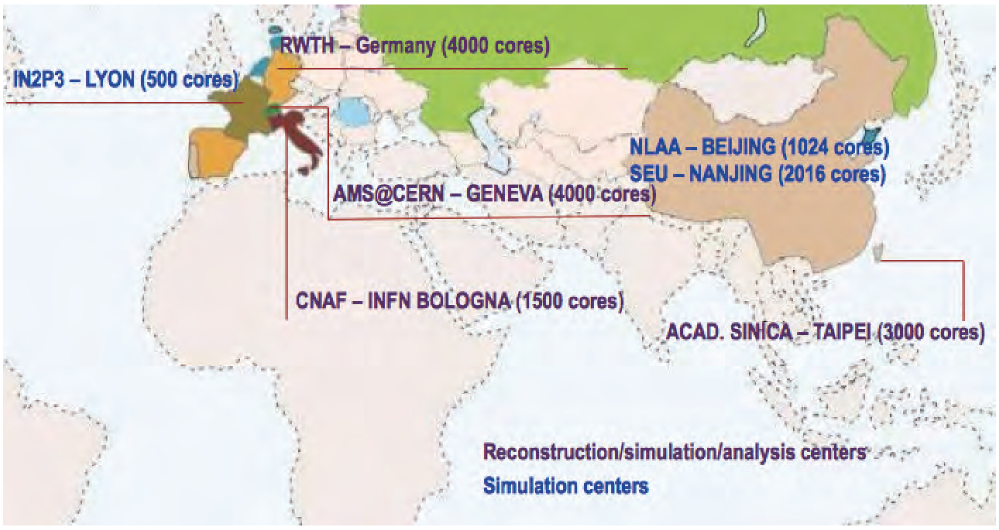

Fig. 4: AMS offline data analysis centers.

The AMS electronics consists of 650 micro- processors and about 300,000 readout channels, most of which were developed and manufactured by the MIT team and in Taiwan. All components and circuits used in the electronics passed rigorous selection and space qualification tests. Onboard data processing reduces the raw data volume by a factor of 1000 without the loss of physics information. The collected data are down linked to the ground at an average rate of 10 Mbit/s. On the ISS, the particle rates in the acceptance vary from 200 Hz near the Equator to about 2000 Hz near Earth's magnetic poles. The data acquisition efficiency is 86% on average, resulting in an average event acquisition rate of about 600 Hz.

Offline Data Analysis

Over the lifetime of the Space Station, AMS is expected to measure hundreds of billions of primary cosmic rays. The main physics objectives of AMS are the search for antimatter, dark matter, and the origin of cosmic rays. The collaboration will also conduct precision measurements of energy spectra of cosmic ray positrons, electrons, antiprotons, protons and nuclei, as well as search for new physics and astrophysics phenomena such as strangelets.

After four years of operations in space, AMS has collected more than 60 billion cosmic ray events. The data is analyzed at the AMS Science Operations Center (SOC) located at CERN as well as collaborating institutes around the world.

As shown in Fig. 4, currently there are three major computing centers in Asia that significantly contribute to the offline data processing. Academia Sinica Grid Center (ASGC) in Taiwan, which is the only Tier 1 center of LHC in Asia, takes part in ISS data processing and Monte Carlo (MC) simulations. Two centers in China at South East University (SEU) and the National Laboratory for Aeronautics and Astronautics (NLAA) take a major part of the MC simulations.

Optimization of all reconstruction algorithms was performed by using the test beam data. Corrections are applied to the data to ensure long-term stability of the absolute scales in the varying on orbit environment. The stability of the electronics response is ensured by calibrations of all channels every half-orbit (up to 46 min). Monte Carlo simulated events are produced by using a dedicated program developed by AMS based on the GEANT4 package. This program simulates electromagnetic and hadronic interactions of particles in the materials of AMS and generates detector responses. The digitization of the signals, including those of the AMS trigger, is simulated precisely according to the measured characteristics of the electronics. The digitized signals then undergo the same reconstruction as used for the data.

Most importantly, several independent analyses are performed on the same data sample by different study groups. Results are published or presented only after these independent results are found to be consistent each

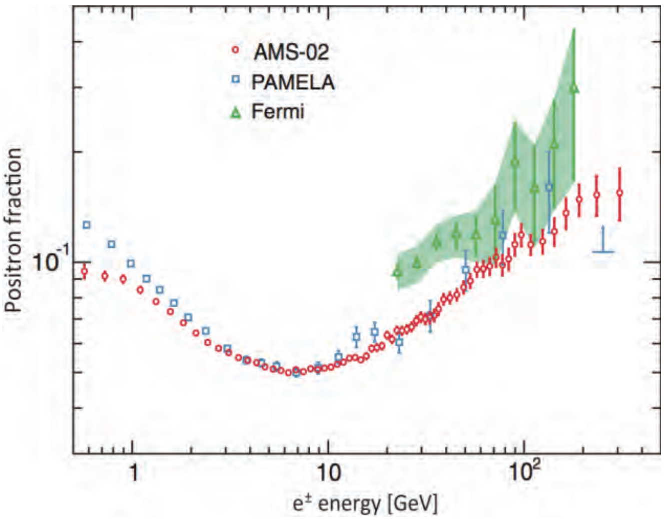

Fig. 5: The first results of AMS on the cosmic-ray positron fraction measurement [1].

Fig.6: Number of citations of the first AMS publication [1] according to the inspire database as a function of time for the first two years.

other. The author of this article is leading data analysis activities of the AMS-Taiwan group, which is stationed at CERN. The AMS-Taiwan group is working closely with Academician Ting and the MIT team mainly on proton, antiproton and nuclei energy spectra. Another group from the Institute of High Energy Physics (IHEP) in China is also working on antiprotons. There are many graduate students from several universities in China who are visiting CERN to take operation shifts at POCC and to study and work on data analysis.

PUBLISHED RESULTS OF AMS

The First Results

In April 2013, almost two years after starting operation on the ISS, the first results were published in Physical Review Letters [1]. The positron fraction, that is, the ratio of the positron flux to the combined flux of positrons and electrons was presented as shown in Fig. 5.

It was selected as a "Viewpoint in Physics" of the American Physical Society (APS) Journals as well as being an Editors' Suggestion. It has been also selected in 2013 APS Physics Highlights, where only a few publications are selected every year. These results generated vast worldwide attention in the community of particle physics and cosmology. Fig. 6 shows the number of citations on the first AMS publication [1] as a function of time for the first two years.

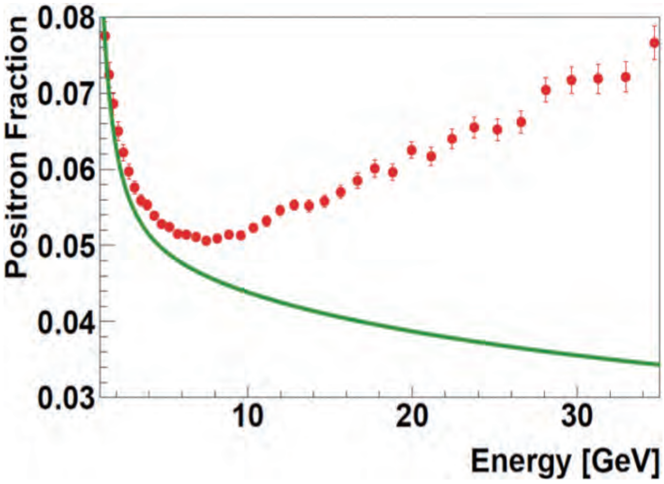

Fig.7: The positron fraction measured by AMS (red circles) compared with the expectation from the collision of ordinary cosmic rays showing that above 8 GeV the positron fraction begins to quickly increase. This increase indicates the existence of new sources of positrons [2].

Positron Fraction

In 2014 AMS has made three important publications on positrons and electrons [2-4]. Among 41 billion primary cosmic ray events, 10 million have been identified as electrons and positrons. AMS has measured the positron fraction in the energy range 0.5 to 500 GeV. We have observed that the energy at which the fraction starts to quickly increase is 8 GeV (Fig. 7), indicating the existence of a new source of positrons.

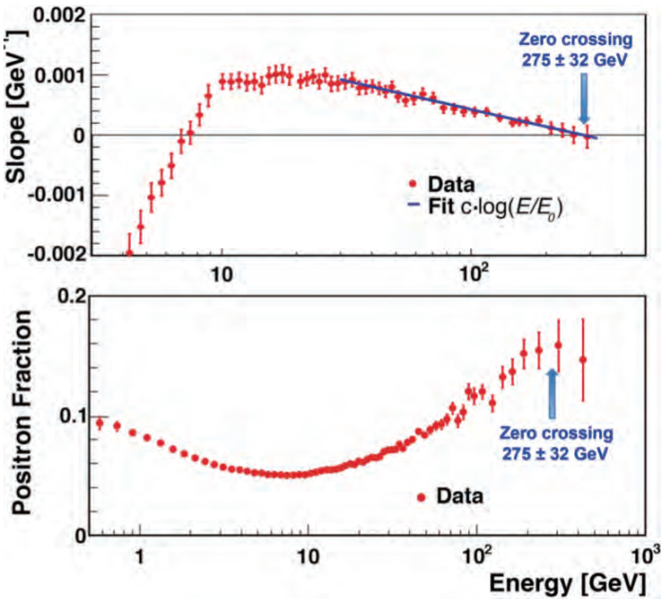

Fig.8: Upper plot shows the slope of positron fraction measured by AMS (red circles) and a straight line fit at the highest energies (blue line). The data show that at 275±32 GeV the slope crosses zero. Lower plot shows the measured positron fraction as a function of energy as well as the location of the maximum [2]. No sharp structures are observed.

Fig. 8 shows that the exact rate at which the positron fraction increases with energy has now been accurately determined and the fraction shows no observable sharp structures. The energy at which the positron fraction ceases to increase (corresponding to the turning point energy at which the positron fraction reaches its maximum) has been measured to be 275 $\pm$ 32 GeV as shown in Fig. 8 (upper plot). This is the first experimental observation of the positron fraction maximum after half a century of cosmic rays experiments. The excess of the positron fraction is isotropic within 3%, strongly suggesting the energetic positrons may not be coming from a preferred direction in space.

Positron and Electron Flux

We have also published the precise measurements of the electron flux and the positron flux [3,4]. These measurements show that the behavior of electrons and positrons are significantly different from each other both in their magnitude and energy dependence. Fig. 9 (upper plot) shows the electron and positron fluxes multiplied by the energy cubed (E^3, for the purpose of presentation). The positron flux first increases (0.5 to 10 GeV), then levels out (10 to 30 GeV), and then increases again (30 to 200 GeV). Above 200 GeV, it has a tendency to decrease. This is totally different from the scaled electron flux.

The behavior of the flux as a function of energy is described by the spectral index and the flux was expected to be proportional to energy E to the power of the spectral index. The result shows that neither flux can be described with a constant spectral index; see Fig. 9 (lower plot). In particular, between 20 and 200 GeV, the rate of change of the positron flux is surprisingly higher than the rate for electrons. This is important proof that the excess seen in the positron fraction is due to a relative excess of high energy positrons, as expected from dark matter collisions, and not the loss of high energy electrons.

Dedicated measurements of electrons plus positrons up to 1 TeV with reduced statistical and systematic errors were also made and published [4]. Over the last 50 years, there have been many experiments that measured the

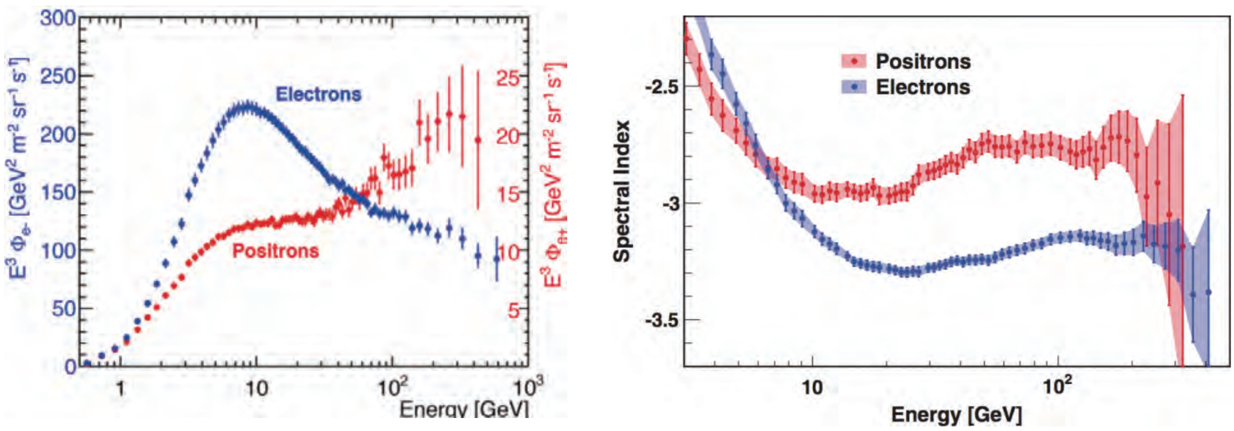

Fig.9: The left plot highlights the difference between the electron flux (blue dots, left scale) and the positron flux (red dots, right scale). The right plot shows the spectral indices of the electron flux and of the positron flux as functions of energy.

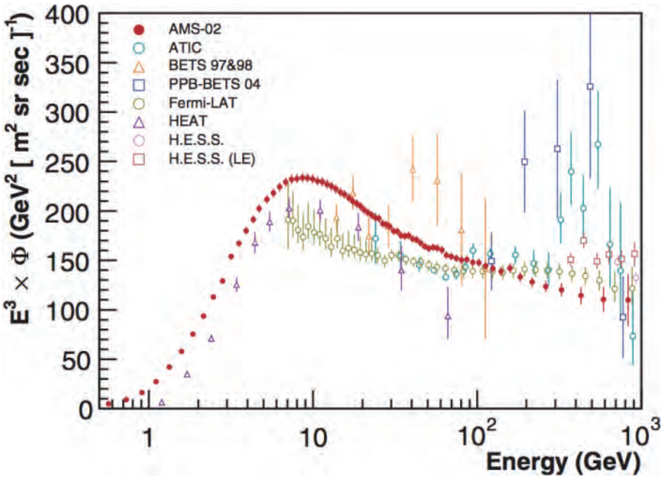

Fig.10: The flux of electrons plus positrons measured by AMS and compared with the results from earlier experiments [4].

combined flux of electrons plus positrons in cosmic rays with non-magnetic detectors in space and on the ground. These measurements have yielded interesting results and few of them indicated the possible existence of a structure at 300-800 GeV. After collecting 41 billon cosmic ray events, AMS has been able to provide a measurement of the flux of electrons plus positrons, shown in Fig. 10. The combined flux is smooth and reveals new and distinct information. Most interesting is the observation that, at high energies and over a wide energy range, the combined flux can be described by a single, constant spectral index.

THE NEW RESULTS OF AMS

AMS Days at CERN

In April 15-17, 2015, the AMS collaboration held a three-day meeting, "AMS Days at CERN". It was an occasion that brought together many of the world's leading theoretical physicists and principal investigators of some of the major experiments exploring the field of cosmic ray physics.

The main objective of this scientific exchange was to understand the interrelation between AMS results and those of other major cosmic rays experiments and current theories. The latest results (published and to be published) from AMS were also presented.

To distinguish if the observed new phenomena in positrons are from dark matter, measurements are underway by AMS to determine the rate at which the positron fraction falls beyond its maximum, as well as the measurement of the antiproton to proton ratio. The antiproton to proton ratio stays constant from 20 GeV to 450 GeV kinetic energy. This behavior cannot be explained by secondary production of antiprotons from ordinary cosmic ray collisions. Nor can the excess of antiprotons be easily explained from pulsar origin.

Proton Flux

In addition, a thorough understanding of the process involved in the collision of ordinary cosmic rays is a requirement in understanding the AMS results mentioned above. The AMS Collaboration also reported on the most recent results on the precision studies of nuclei spectra (such as protons, helium and lithium) up to multi-TeV energies. The latest data on the precision measurement of proton flux in cosmic rays from 1 GV to 1.8 TV rigidity (momentum/ charge) will appear shortly in Physical Review Letters [5]. These results are based on 300 million proton events. AMS has found that the proton flux is characteristically different from all the

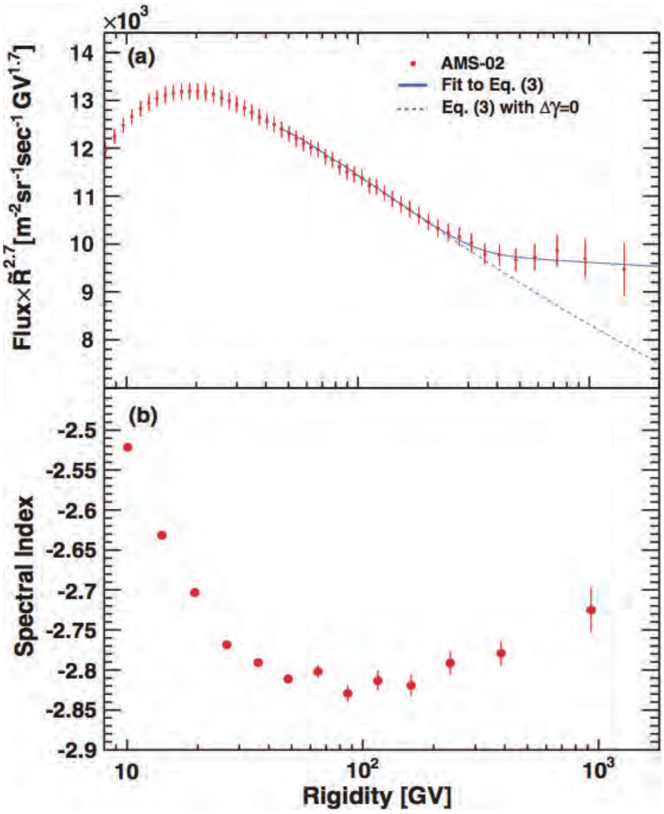

Fig.11: a) The AMS proton flux multiplied by $R^{2.7}$ as a function of rigidity R. The solid curve indicates the fit of Eq. (1) to the data. For illustration, the dashed curve uses the same fit values but with Δγ set to zero. b) The dependence of the proton flux spectral index γ obtained from Eq. (2) on rigidity R.

existing experimental results. As seen in Fig. 11a, the AMS result shows the measured flux changes its behavior at ~300 GV rigidity. We therefore fit the flux with a modified spectral index;

$$\Phi = C\left(\frac{R}{45\ \text{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s} \qquad (1)$$

where s quantifies the smoothness of the transition of the spectral index from γ 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 χ^2/d.f. = 25/26 with
$\gamma = -2.849 \pm 0.002(\text{fit})^{+0.004}_{-0.003}(\text{sys})$,
$\Delta\gamma = 0.133^{+0.032}_{-0.021}(\text{fit})^{+0.046}_{-0.030}(\text{sys})$,
$s = 0.024^{+0.020}_{-0.013}(\text{fit})^{+0.027}_{-0.016}(\text{sys})$, and
$R_0 = 336^{+68}_{-44}(\text{fit})^{+66}_{-28}(\text{sys})$ 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.

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. 11a. For illustration, the fit results with $\Delta\gamma$ set to zero are also shown in Fig. 11a.

To obtain the detailed variation of γ with rigidity in a model independent way, the spectral index is calculated from

$$\gamma = d\,[\log(\Phi)]\,/\,d\,[\log(R)] \qquad (2)$$

over independent rigidity intervals above 8.5GV with a variable width to have sufficient sensitivity to determine γ. The results are presented in Fig. 11b. As seen, the spectral index varies with rigidity. In particular, the spectral index is progressively harder with rigidity above 100GV.

Most surprisingly, AMS has also found, based on 50 million events, that the helium flux exhibits nearly identical and equally unexpected behavior as the proton flux. AMS is currently studying the behavior of other nuclei in order to understand the origin of this unexpected change. These unexpected new observations provide important information on the understanding of cosmic ray production and propagation. The latest AMS measurements of the positron fraction, the antiproton/proton ratio, the behavior of the fluxes of electrons, positrons, protons, helium, and other nuclei provide precise and unexpected information.

The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays, require a comprehensive model to ascertain if their origin is from dark matter, astrophysical sources, acceleration mechanisms or a combination of sources.

Acknowledgement: The author acknowledges the support of Academia Sinica and the Ministry of Science and Technology (MOST) in Taiwan under Grant No. 103-2682-M-008-002.

References

[1] M. Aguilar et al., [AMS Collaboration], Phys. Rev. Lett. 110 (2013) 141102.
[2] L. Accardo et al., [AMS Collaboration], Phys. Rev. Lett. 113 (2014) 121101.
[3] M. Aguilar et al., [AMS Collaboration], Phys. Rev. Lett. 113 (2014) 121102.
[4] M. Aguilar et al., [AMS Collaboration], Phys. Rev. Lett. 113 (2014) 221102.
[5] M. Aguilar et al., [AMS Collaboration], Phys. Rev. Lett. 114 (2014) 171103.

Sadakazu Haino is an associate research fellow at the Institute of Physics, Academia Sinica in Taiwan. After receiving a PhD at the University of Tokyo in 2004, he worked at the High Energy Accelerator Research Organization (KEK) in Japan, Istituto Nazionale di Fisica Nucleare (INFN) in Italy, and National Central University in Taiwan before joining Academia Sinica in 2014. His research field is experimental particle physics and astrophysics. He is now coordinating data analysis activities of the AMS-Taiwan group, which is stationed at the Organisation Européenne pour la Recherche Nucléaire (CERN) in France and Switzerland.