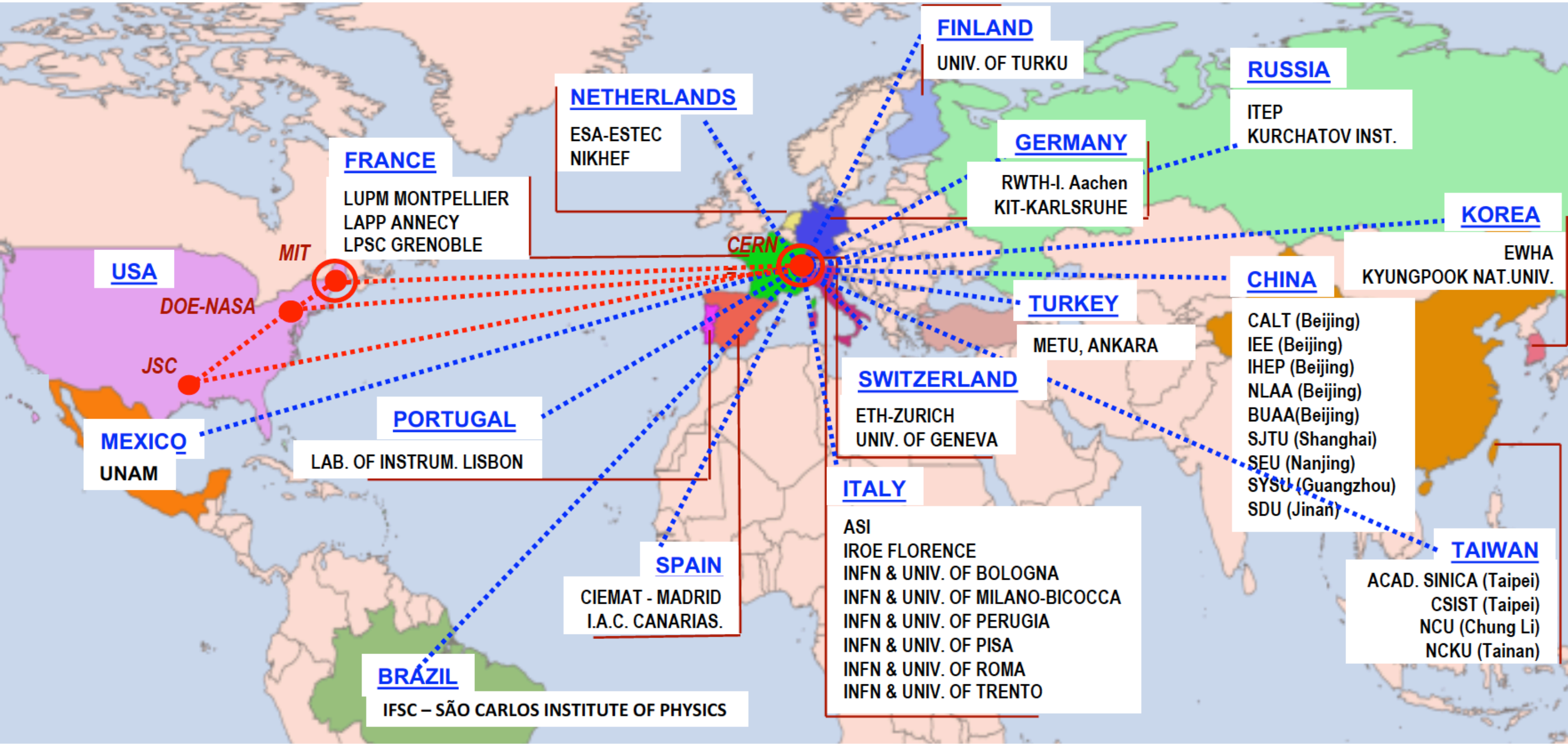
The First Five Years of the Alpha Magnetic Spectrometer on the International Space Station

William Creus
Academia Sinica (Taiwan)/CERN (Switzerland)
AMS collaboration

Seminar at ICRR
January 10th 2017

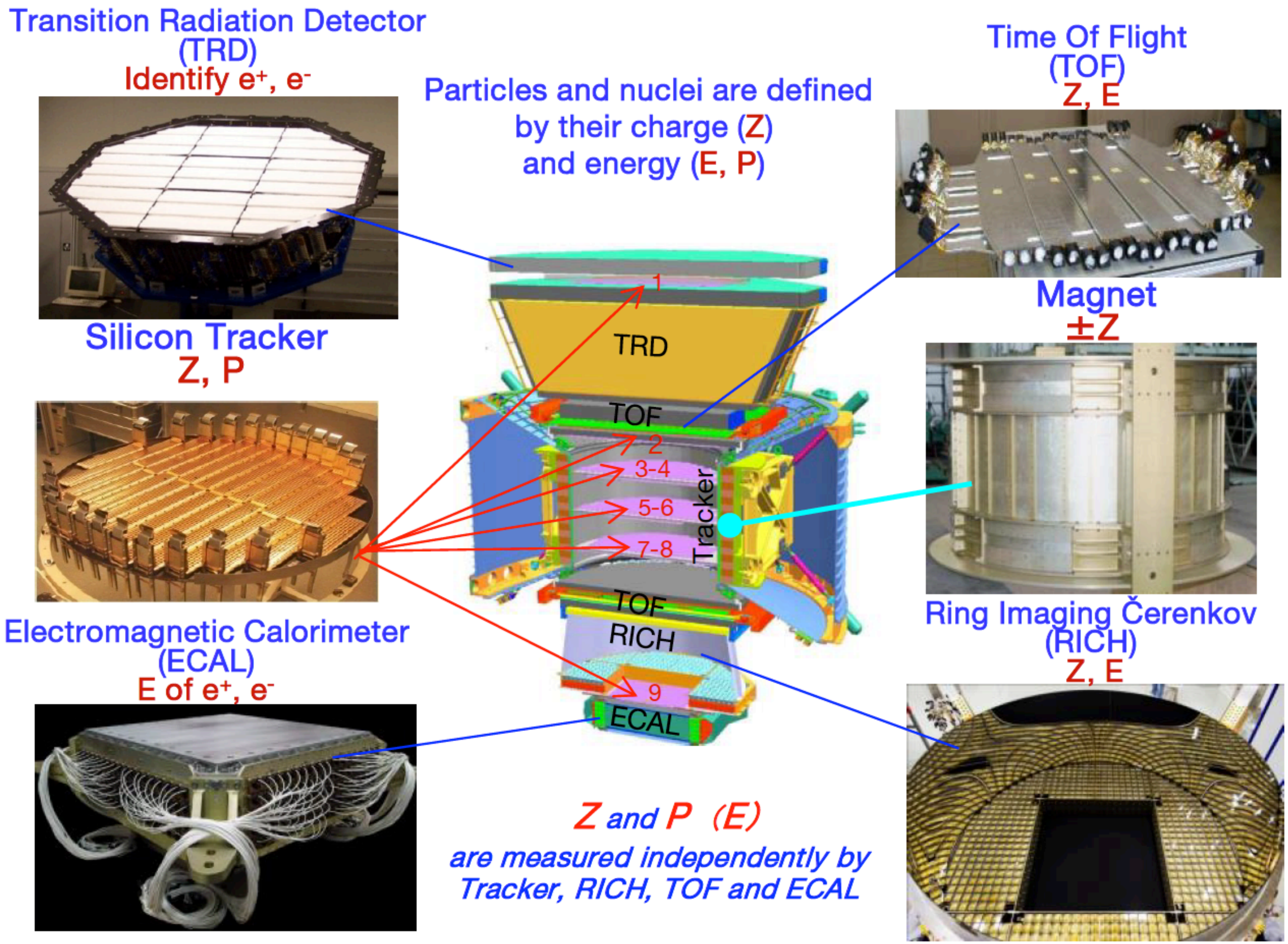
AMS Collaboration



AMS is an international collaboration of 16 countries in 4 continents. Data are received by NASA in Houston, and then relayed to the AMS Payload Operations Control Centre (POCC) at CERN for analysis.

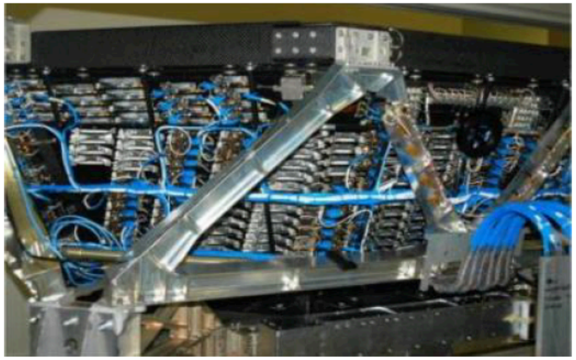
The Alpha Magnetic Spectrometer (AMS)

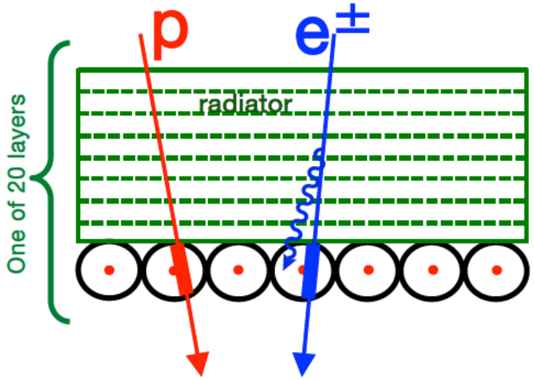
A TeV precision, multipurpose spectrometer



Transition Radiation Detector

20 layers: fleece radiator and proportional tubes





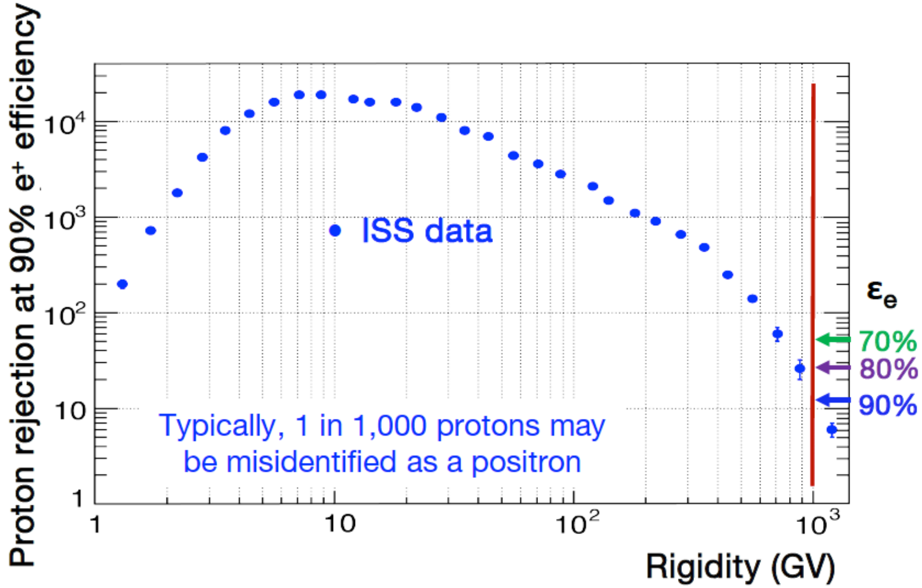
$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$ $P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$

Normalized Probabilities

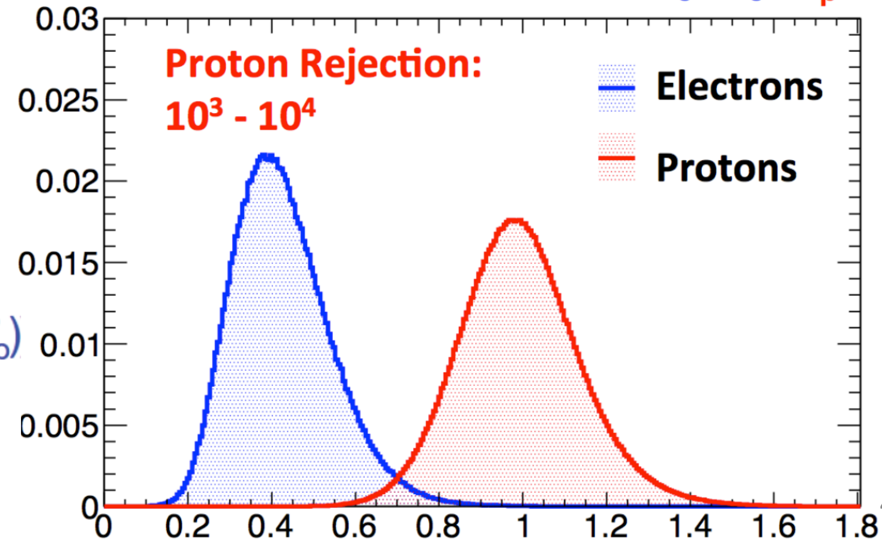
TRD estimator = $-\ln(P_e/(P_e+P_p))$

TRD likelihood = $-\mathrm{Log}_{10}(P_e)$

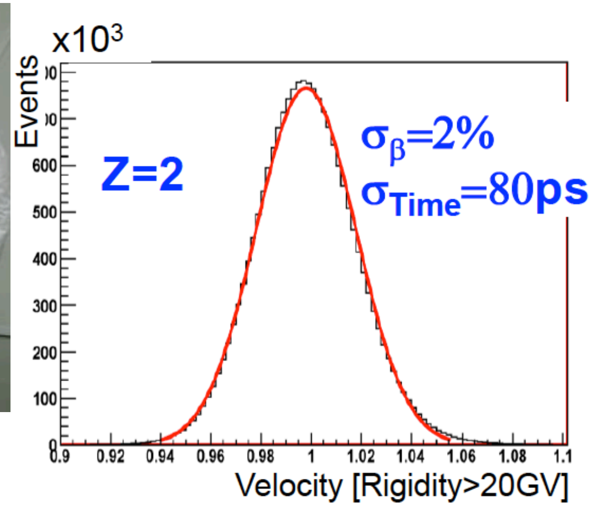
TRD classifier = $-\mathrm{Log}_{10}(P_e)-2$

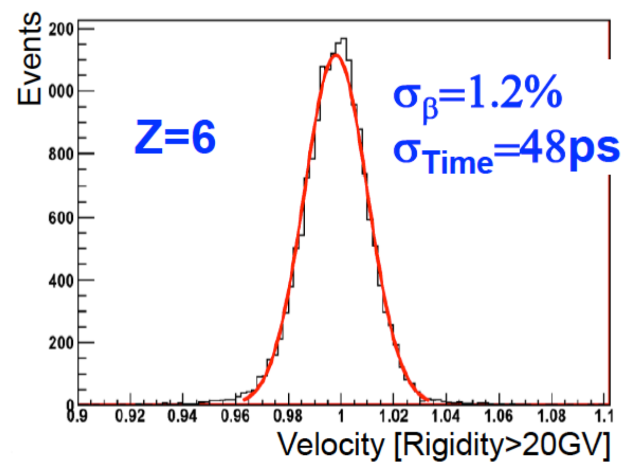


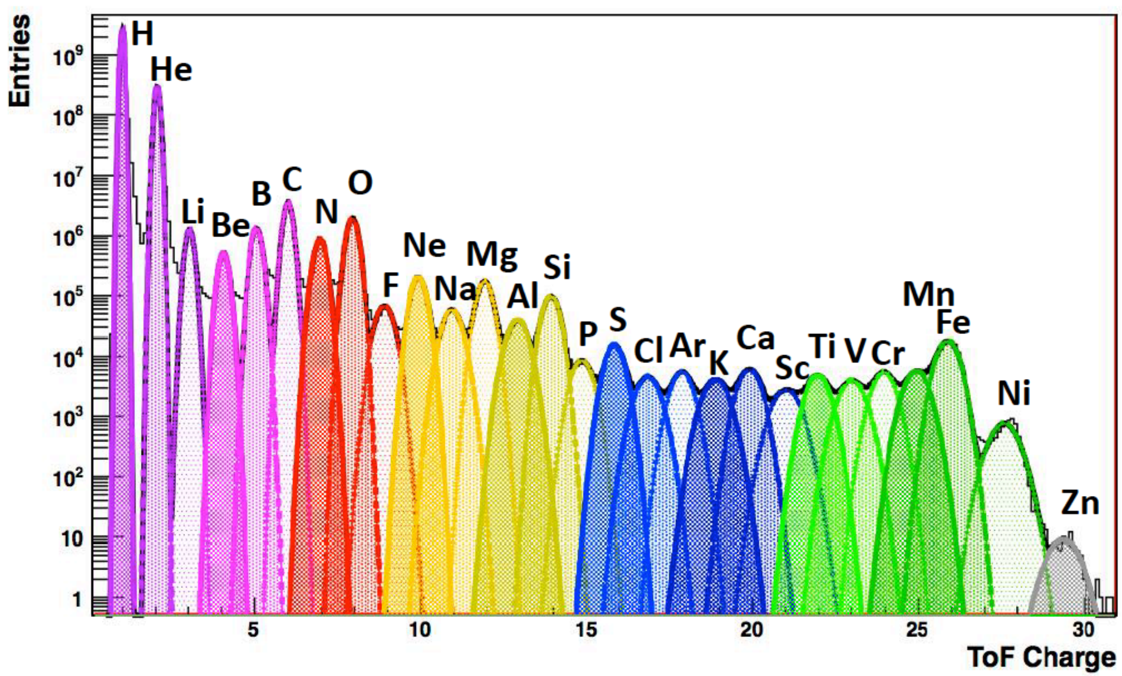
TRD estimator = $-\ln(P_e/(P_e+P_p))$



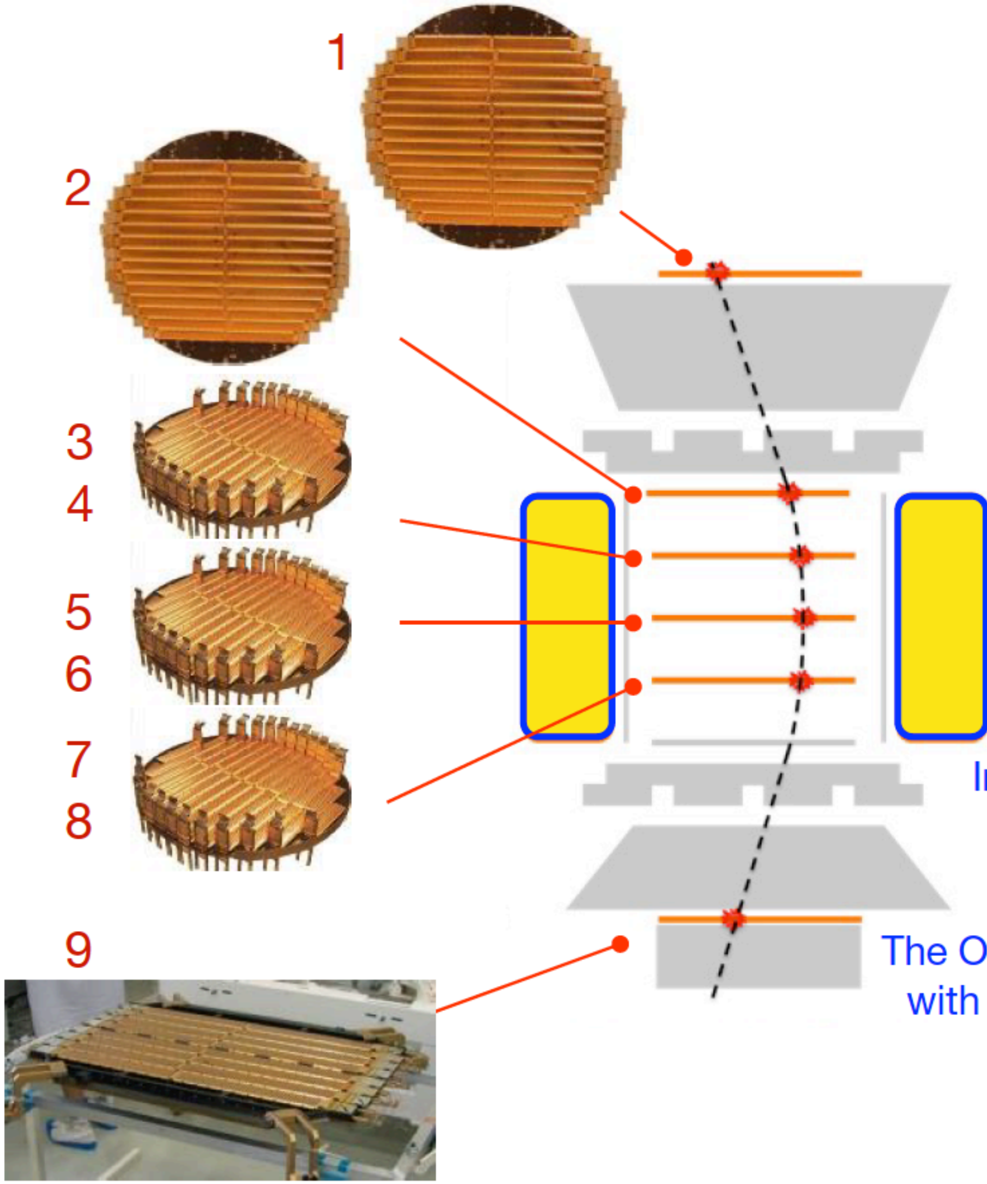
Time of Flight System



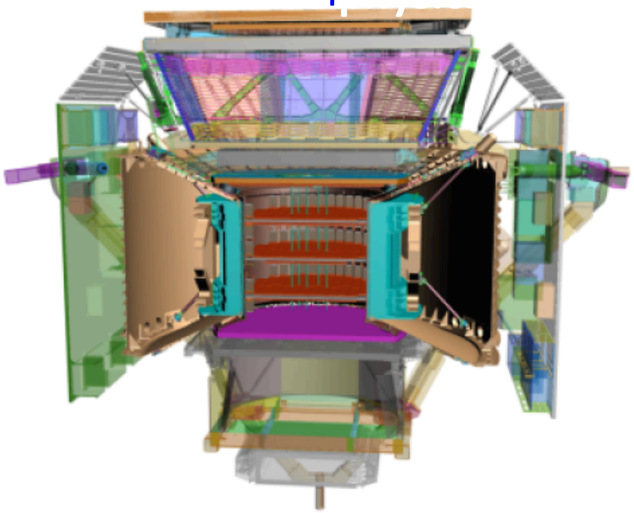




Tracker



9 planes, 200.000 channels
The coordinate resolution is 10 µm

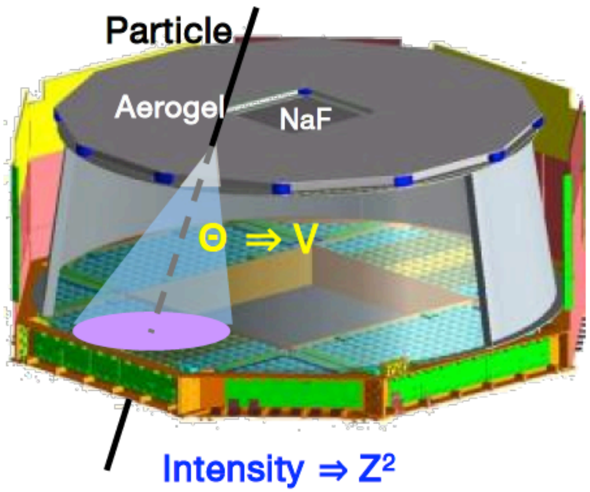


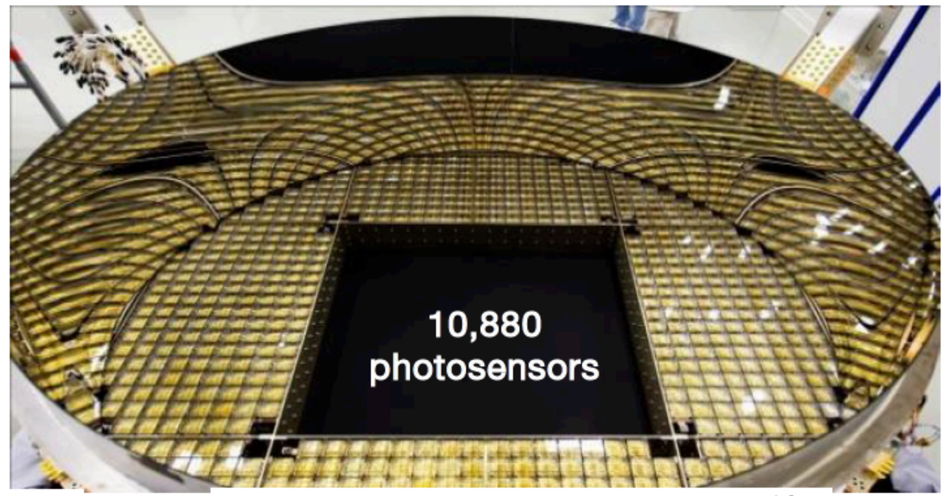
Inner tracker alignment stability monitored with IR Lasers.

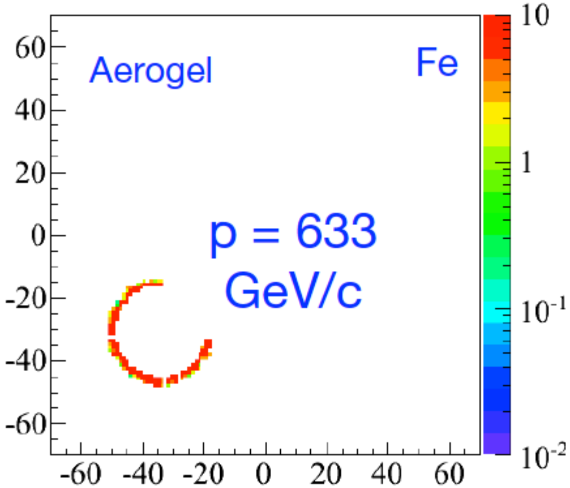
The Outer Tracker is continuously aligned with cosmic rays in a 2 minute window

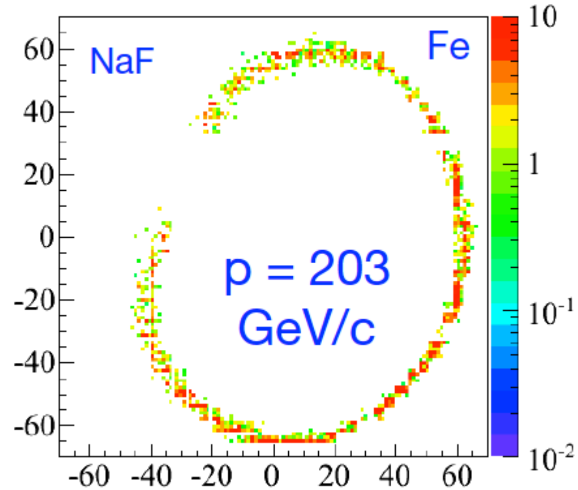
Ring Imaging Cherenkov

Measurement of Nuclear Charge (Z^2) and its Velocity to 1/1000



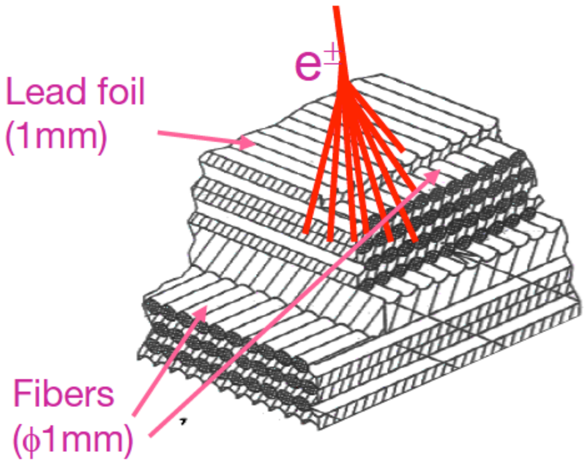


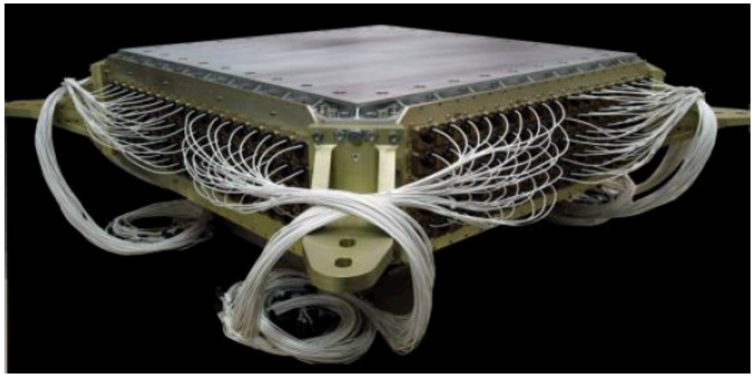


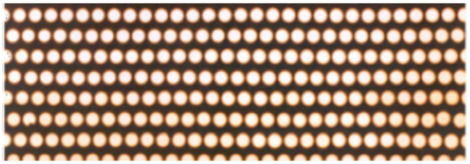


Electromagnetic Calorimeter

A precision, 17 X_0, TeV, 3-D measurement
of the directions and energies of electrons and positrons

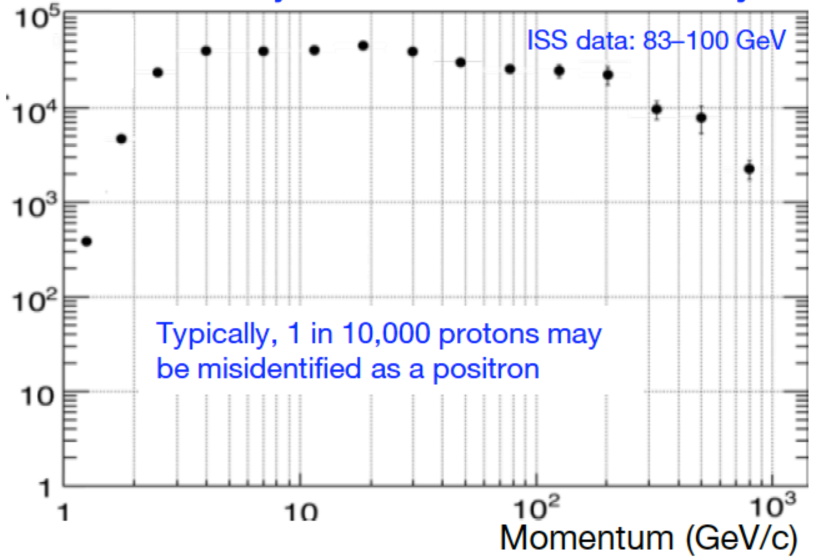




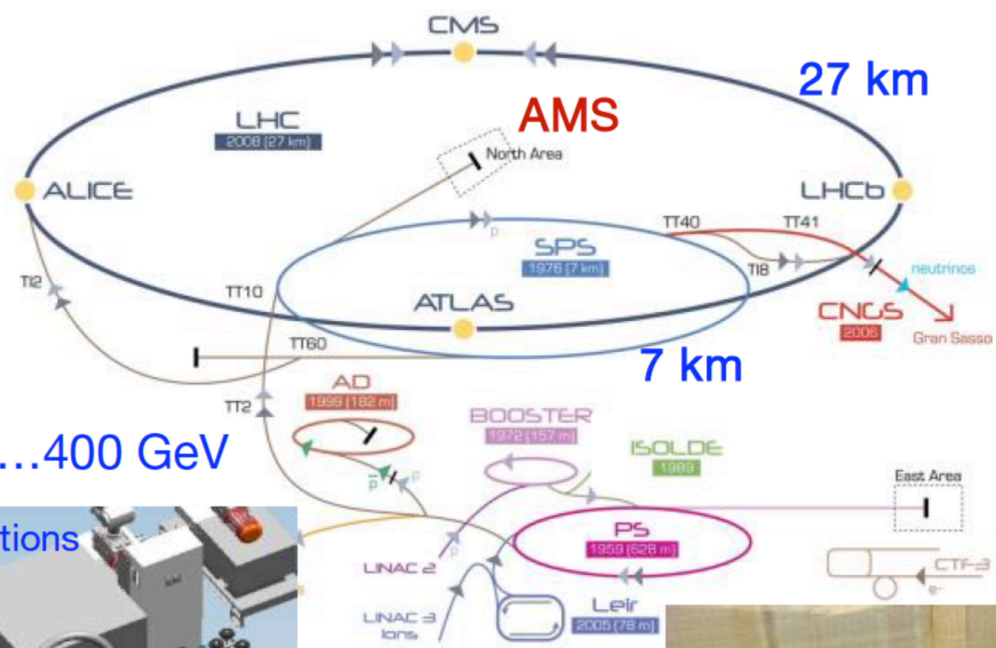


50,000 fibers, ϕ = 1 mm
distributed uniformly
inside 600 kg of lead

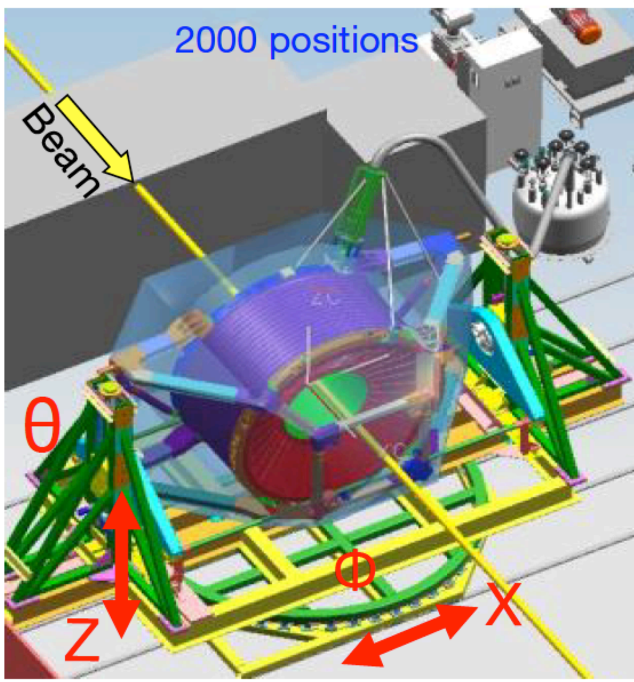
Proton rejection at 90% e^+ efficiency

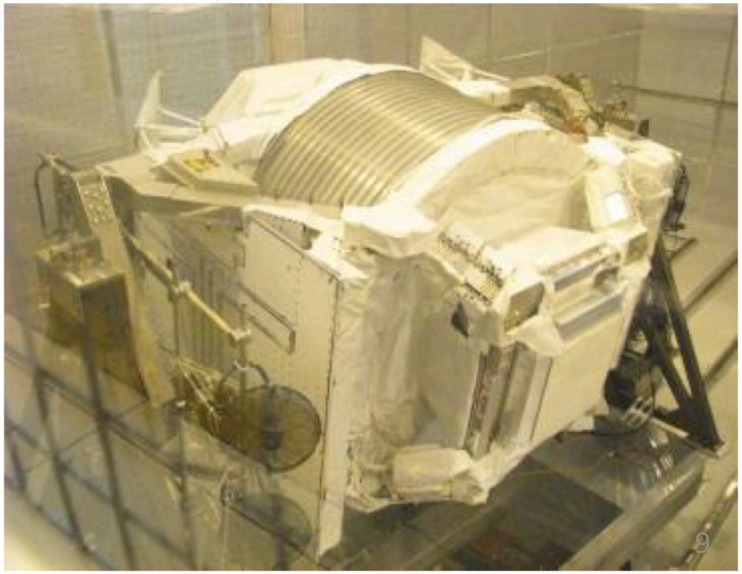


Beam Tests at CERN



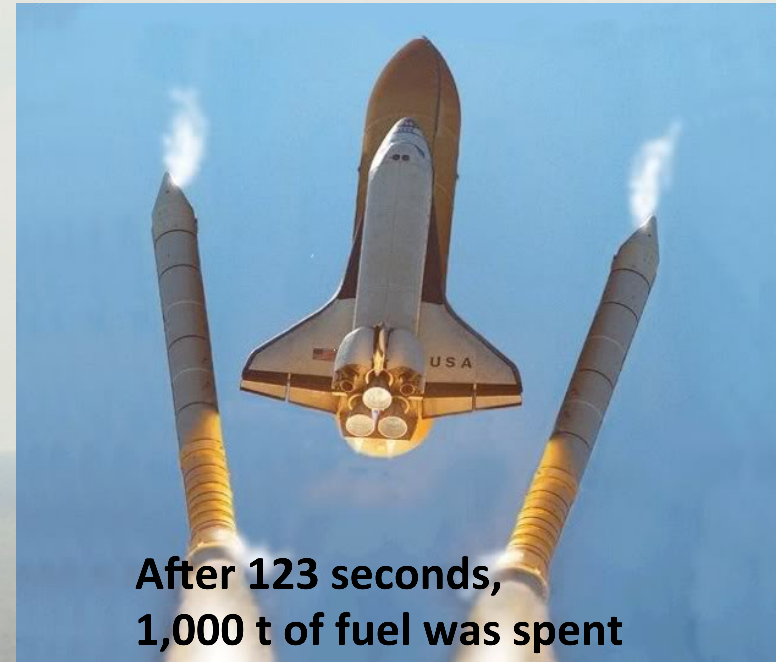
p, e^+, e^-, π 20…400 GeV





Launch of AMS-02

- May/16/2011
- Last Endeavour flight
- Total weight 2008 t
- AMS 7.5 t



Operation and Data link

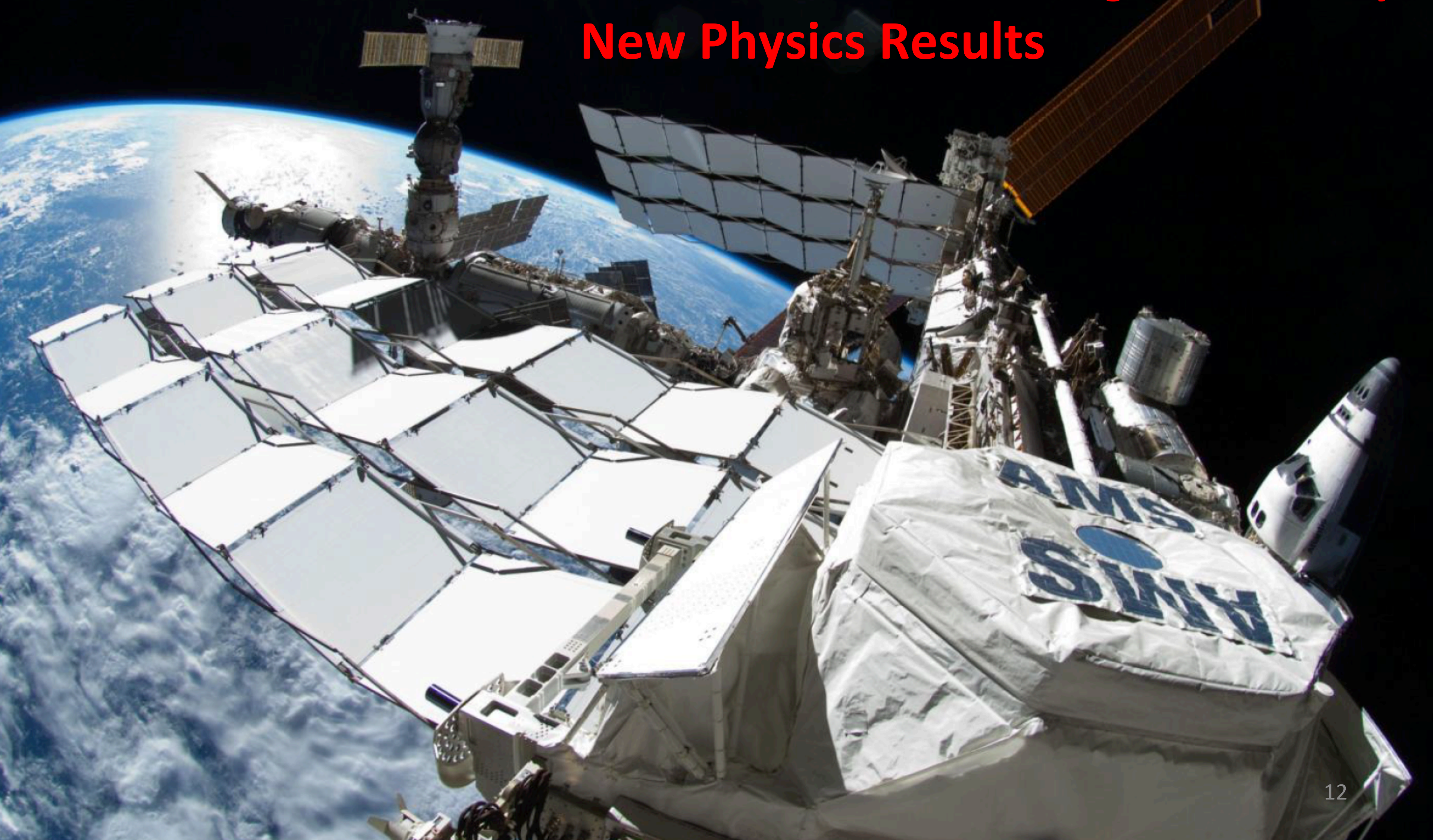
Ku-Band (down):
Events <10Mbit/s>

S-Band (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

AMS in Space

Installed in ISS on 19/May/2011
Starting taking data only 4 hours later

In five years of operation on the ISS
AMS has collected more than 90 billions charged cosmic rays
New Physics Results



Elementary particles in Space

There are hundreds of different kinds of charged elementary particles.

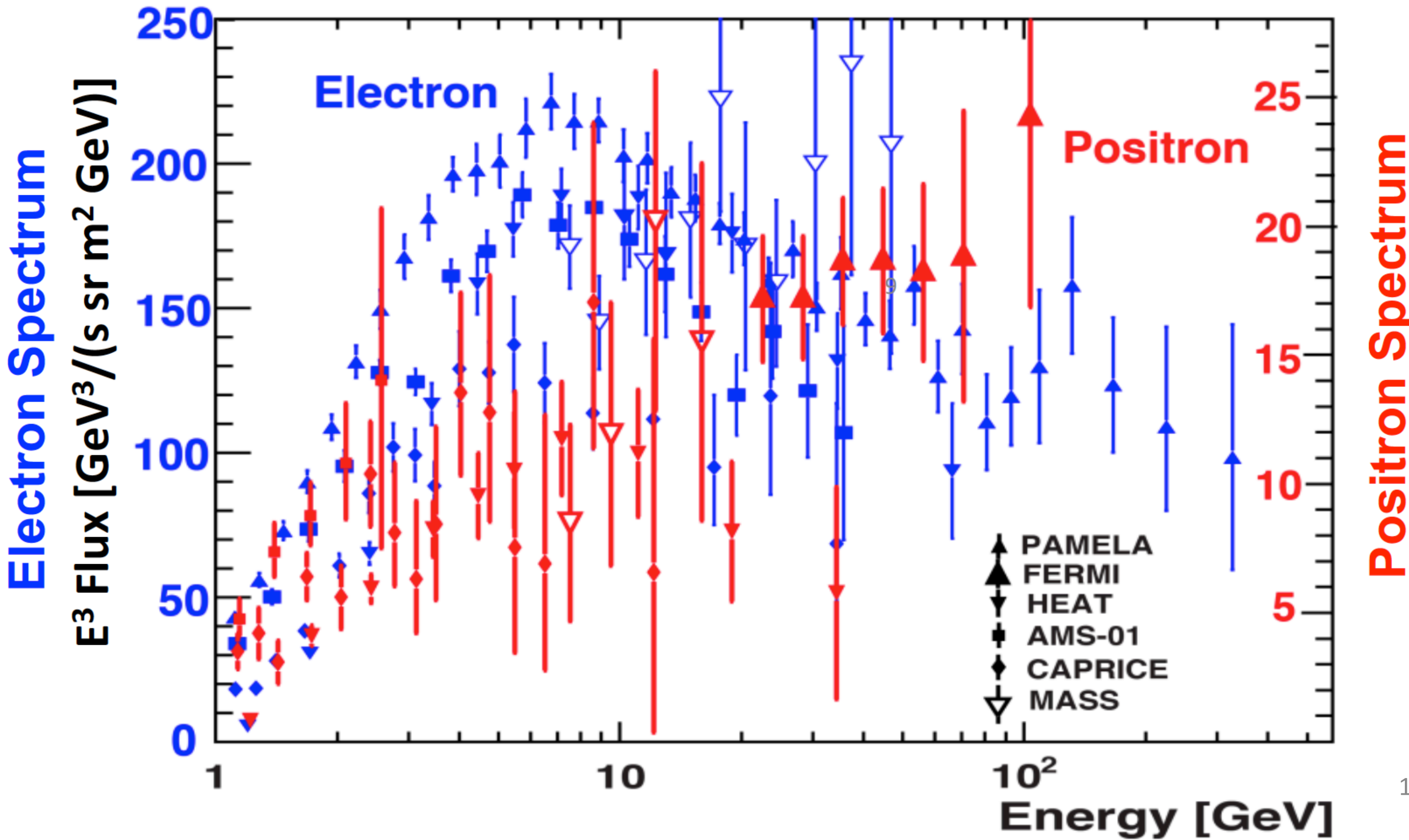
Only four of them, electrons, protons, positrons, and antiprotons, have infinite lifetime, so they travel in the Galaxy.

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.

AMS

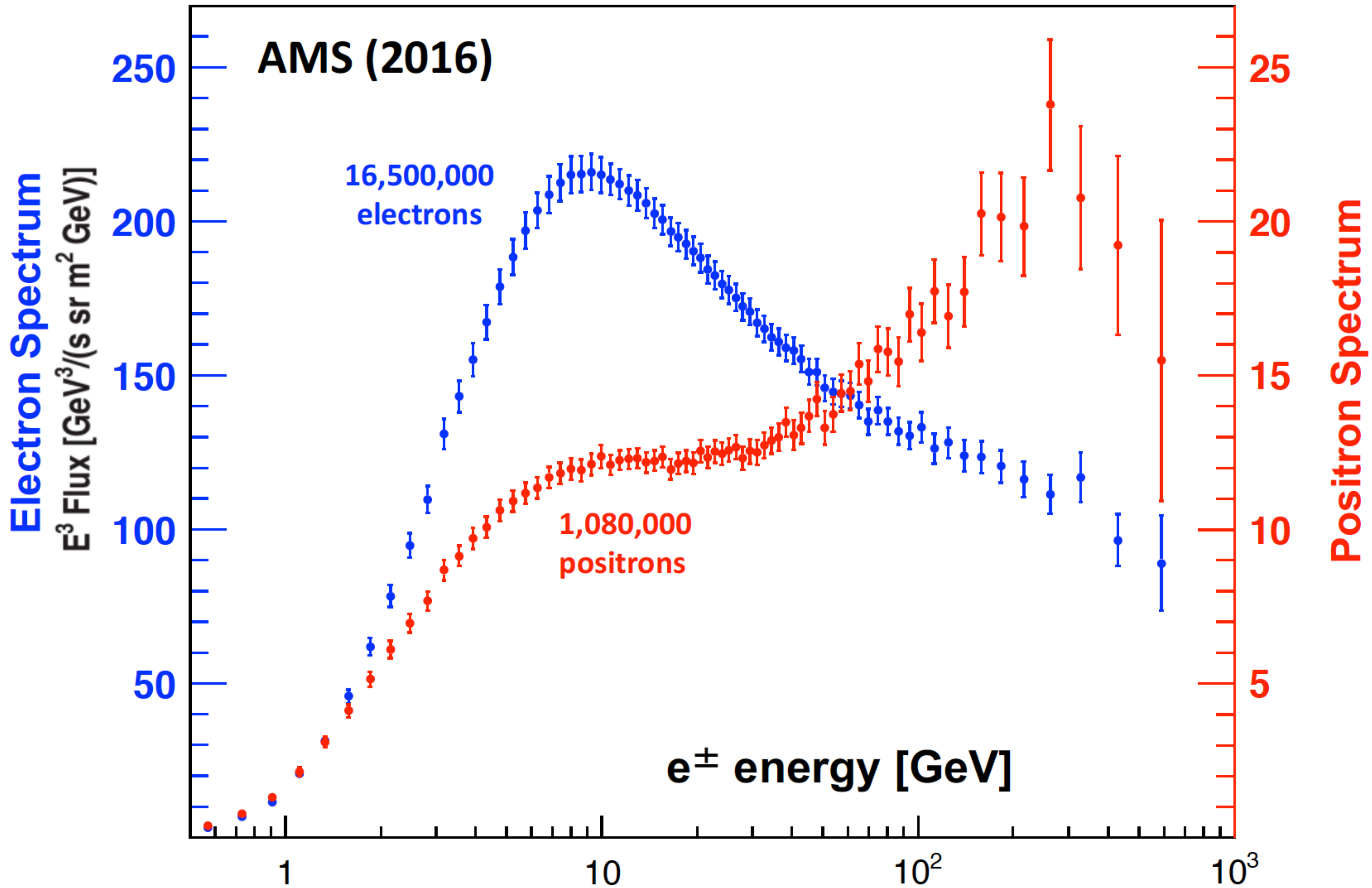
Before AMS : Electron and Positron spectra

- ➢ **Large errors and inconsistent**
- ➢ **Create many theoretical speculations**



Physics Results 1: The Electron and Positron fluxes

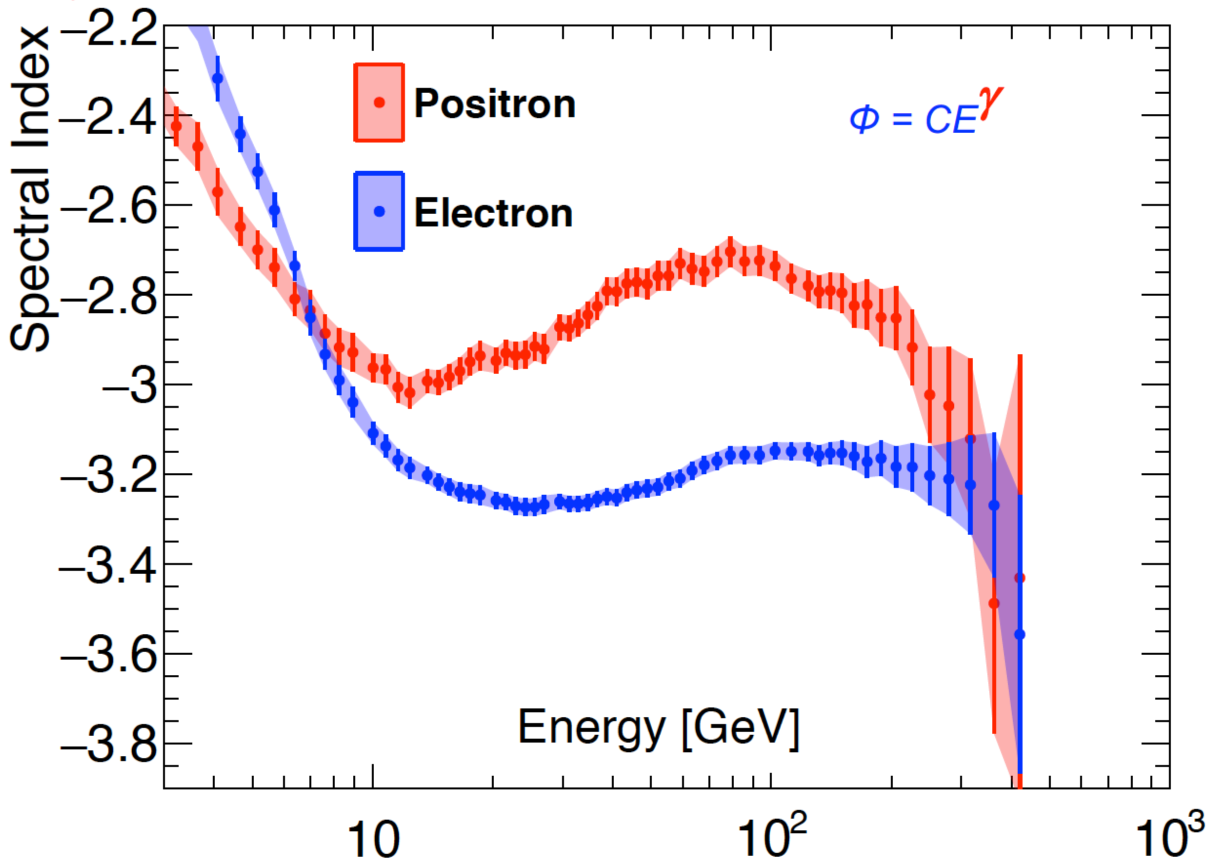
The electron flux and the positron flux are different in their magnitude and energy dependence



Physics Results 1: The Electron and Positron spectral indices

Traditionally, the spectrum of cosmic rays is characterized by a single power law function $\Phi = CE^{\gamma}$ where γ is the spectral index and E is the energy.

Before AMS, γ was assumed to be **constant** for the electron and positron spectra.

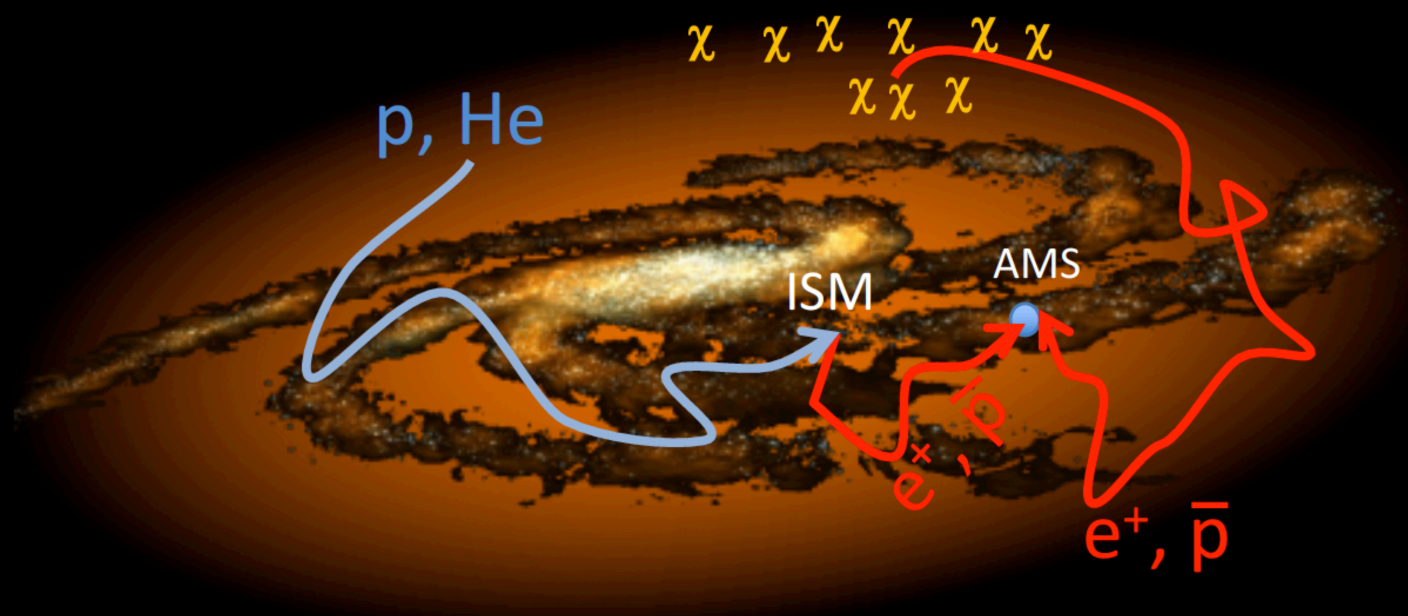


- ➢ The electron and positron spectral indices are not constant.
- ➢ They are different in their magnitude and energy dependence

Search Dark Matter

Collision of Cosmic Rays with the Interstellar Media will produce e^+, $\bar{p}$…

p, He + ISM → e^+, $\bar{p}$ + …



Dark Matter (χ) annihilations $\chi + \chi \rightarrow e^+, \bar{p} + \ldots$

The excess of e^+, $\bar{p}$ from Dark Matter (χ) annihilations can be measured by AMS

M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001; J. Ellis 26th ICRC (1999)

Search Dark Matter: Strategies

Indirect Detection by Annihilation

AMS, Fermi, CALET … **(Detectors in Space)**

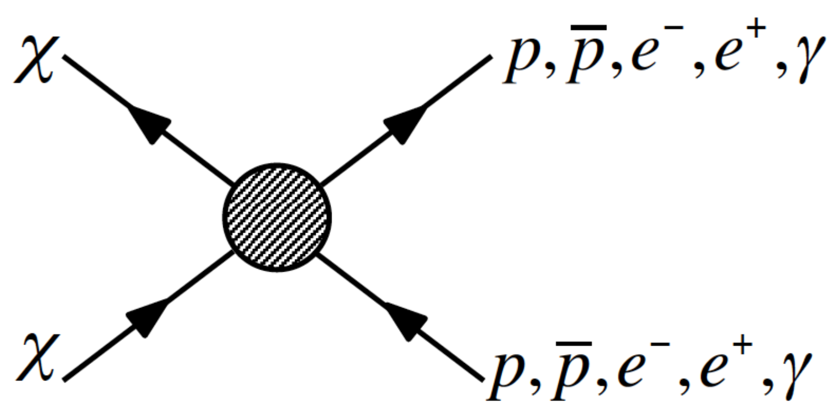
$\chi + \chi \rightarrow e^{+}, \bar{p}, \gamma, \ldots$

(Detectors in Underground)

Direct Detection by Scattering

XMASS
LUX
DARKSIDE
XENON 100
CDMS II
…

$\chi + N \rightarrow \chi + N$



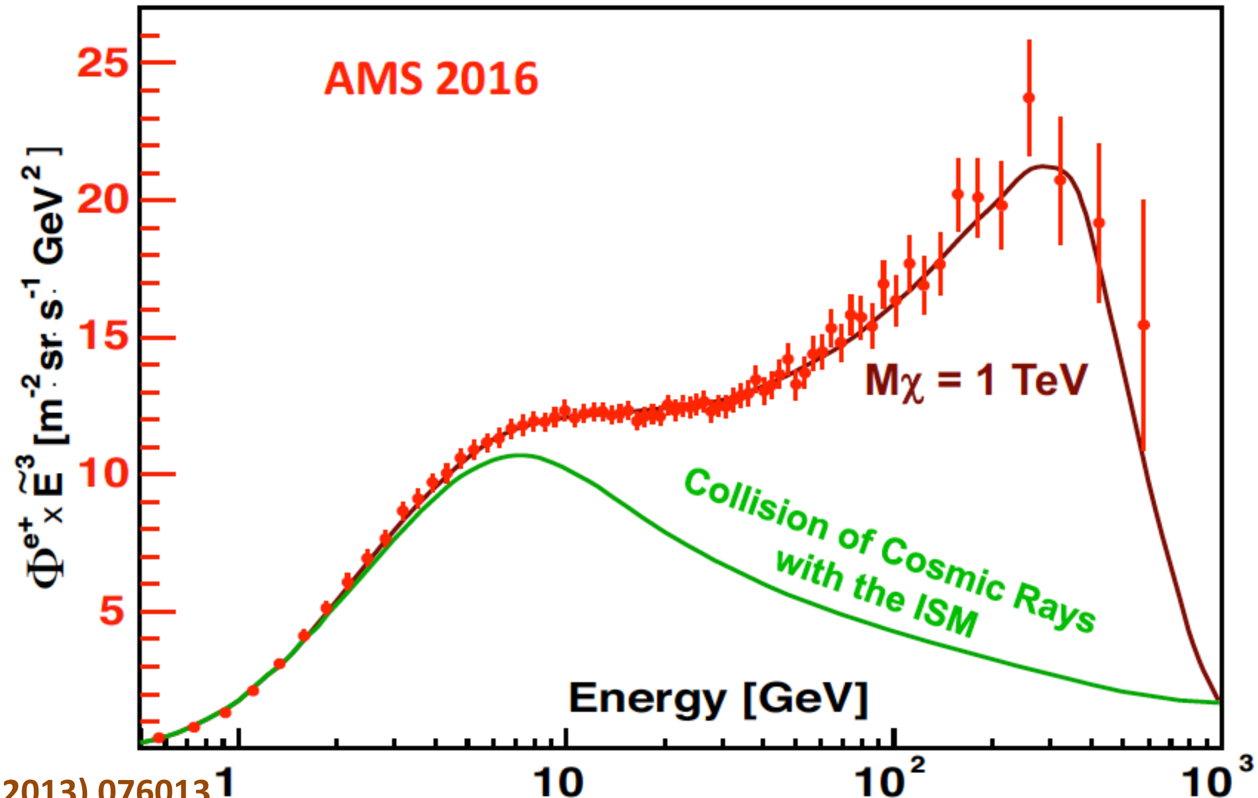
$\ldots + \chi + \chi \leftarrow p + p$

LHC **(Detectors in Colliders)**

Detection by Production

Physics Results 2: The origin of the AMS positron spectrum

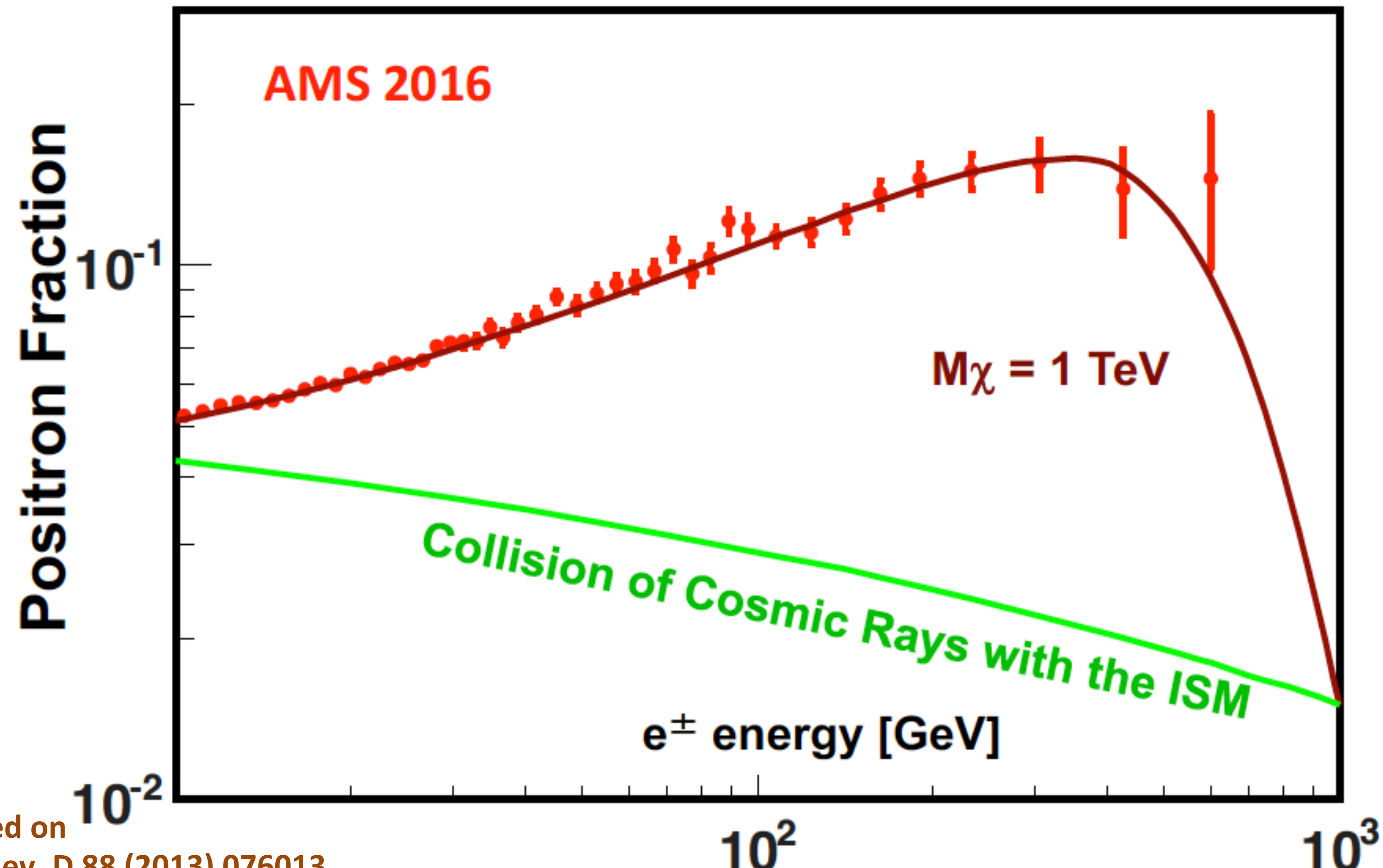
- **Collision of Cosmic Rays with the Interstellar Media produce e+**
- **Unexpectedly, starting from ~8GeV, the AMS e+ data show an excess above ordinary Cosmic Ray collisions.**
- **Annihilation of Dark Matter produces additional e+ which are characterized by a sharp drop off at the mass of dark matter.**



DM model based on J. Kopp, Phys. Rev. D 88 (2013) 076013

Physics Results 3: The origin of the AMS positron fraction

The excess of the Positron fraction $e^+/(e^+ + e^-)$ is an alternative way to search for signal of Dark Matter



DM model based on
J. Kopp, Phys. Rev. D 88 (2013) 076013

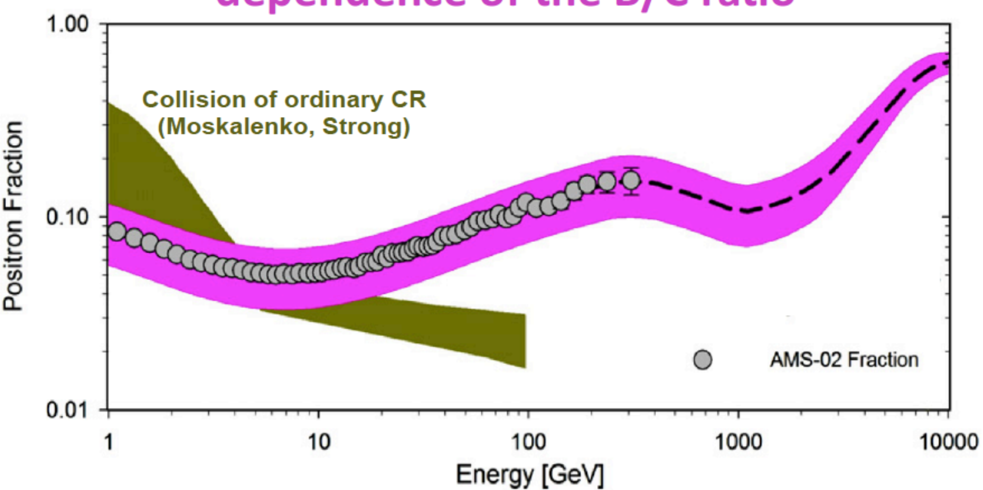
Alternative Models to explain the AMS positron flux and positron fraction

- **Modified Propagation of Cosmic Rays**
- **Supernova Remnants**
- **Pulsars**

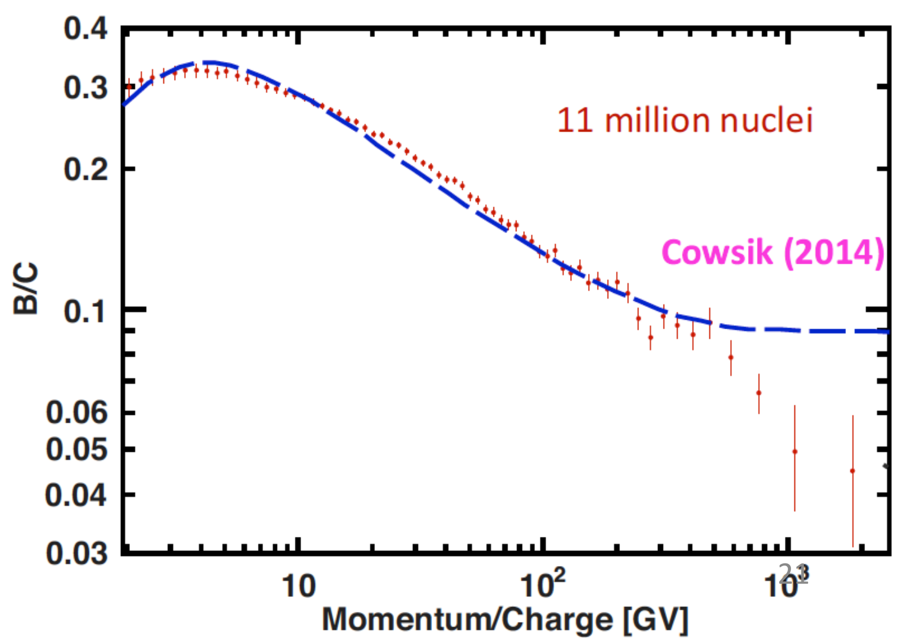
Examples:

R. Cowsik *et al.*, Ap. J. 786 (2014) 124, (pink band) explaining that the AMS positron fraction (gray circles) above 10 GV is due to propagation effects.

However, this requires a specific energy dependence of the B/C ratio



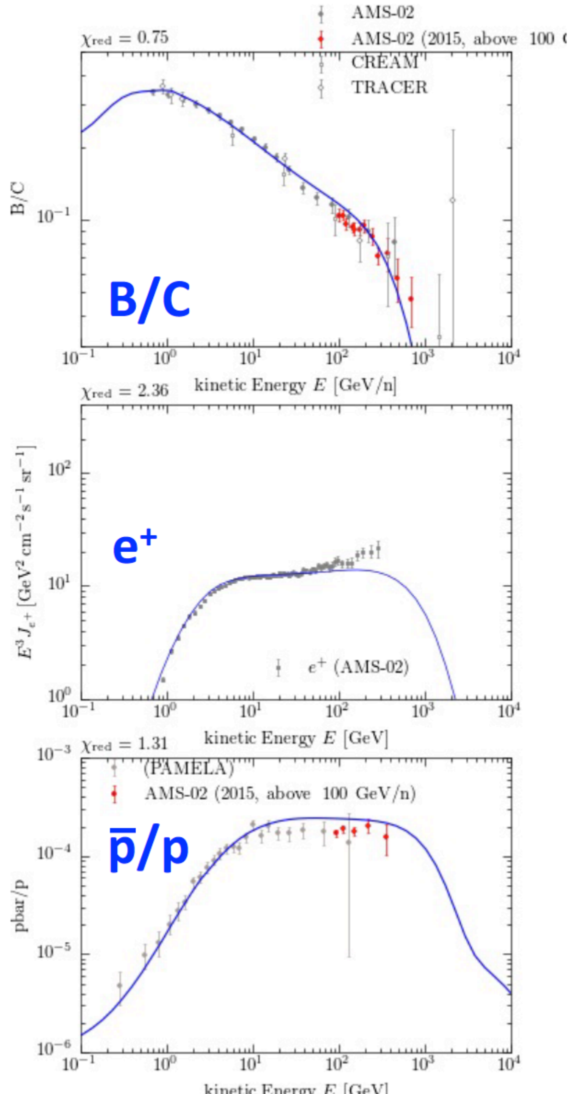
The AMS Boron-to-Carbon (B/C) flux ratio



Alternative Models to explain the AMS positron flux and positron fraction

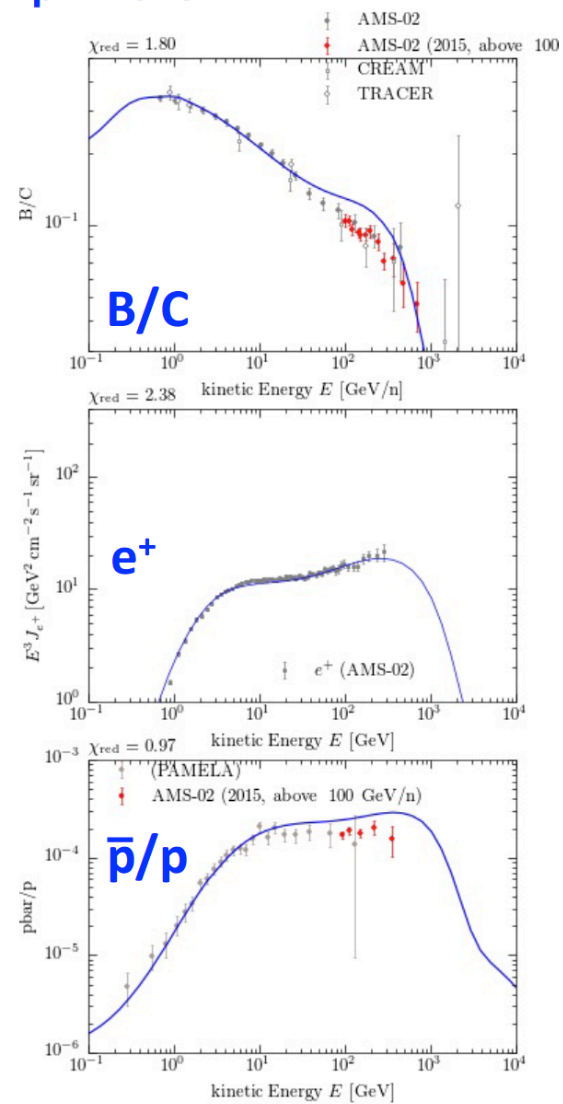
Example: Supernova Remnants

Subir Sarkar: AMS Days@CERN, April 2015



We have been trying (late last night!) to get better fits to the new data but it is not easy ... perhaps our model is *too* simple and some further refinements are necessary.

This is justified now that we have *precision* data from AMS!



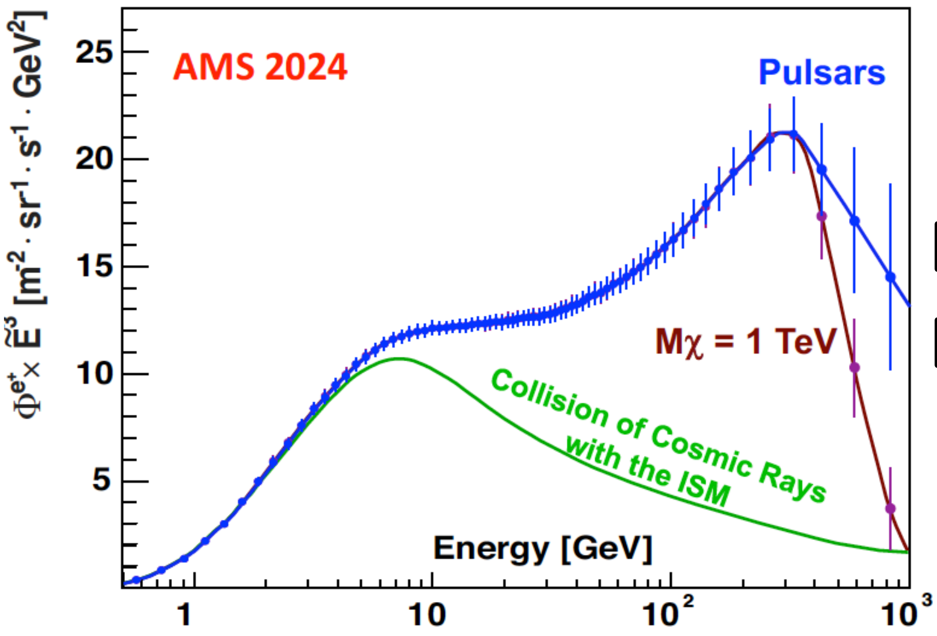
Alternative Models to explain the AMS positron flux and positron fraction

- **Modified Propagation of Cosmic Rays**
- **Supernova Remnants**
- **Pulsars**

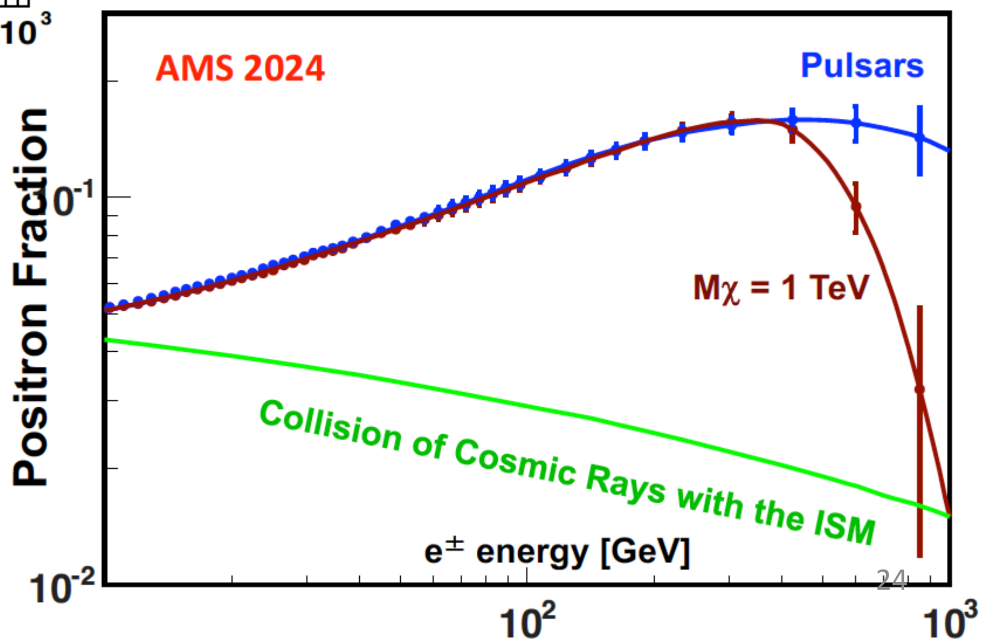
Excess of Positron flux and Positron fraction can be also explained by Pulsar sources

<u>AMS also observes excess on Antiproton/Proton ratio and this is cannot be explained by Pulsars</u>

The AMS positron spectrum and fraction expected by 2024

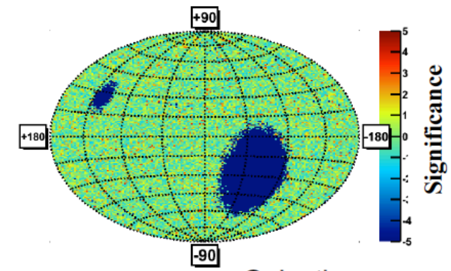


By 2024, AMS will distinguish Dark Matter from Pulsars

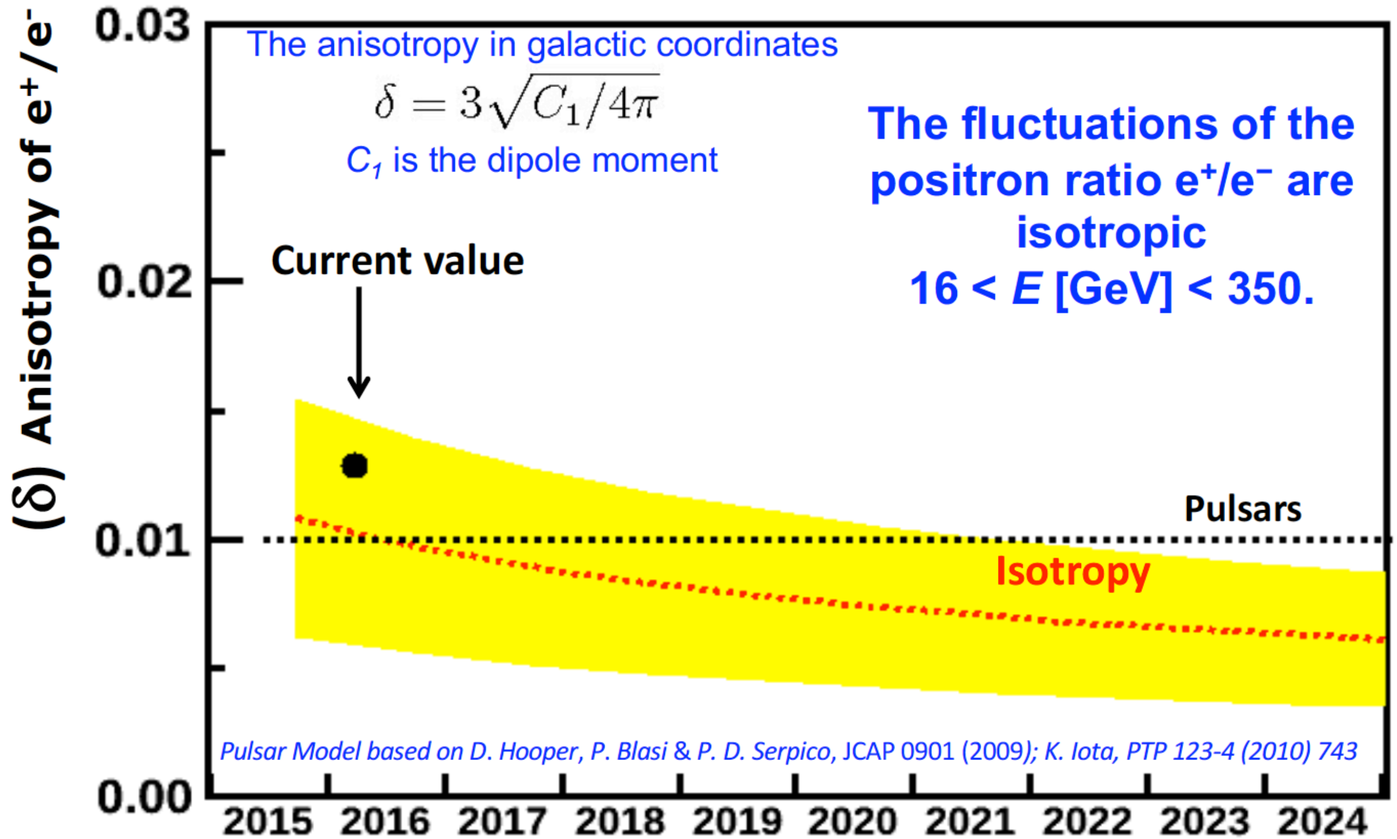


Physics Results 4: Measurement of Anisotropy

Astrophysical point sources like pulsars will imprint a higher level of anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.



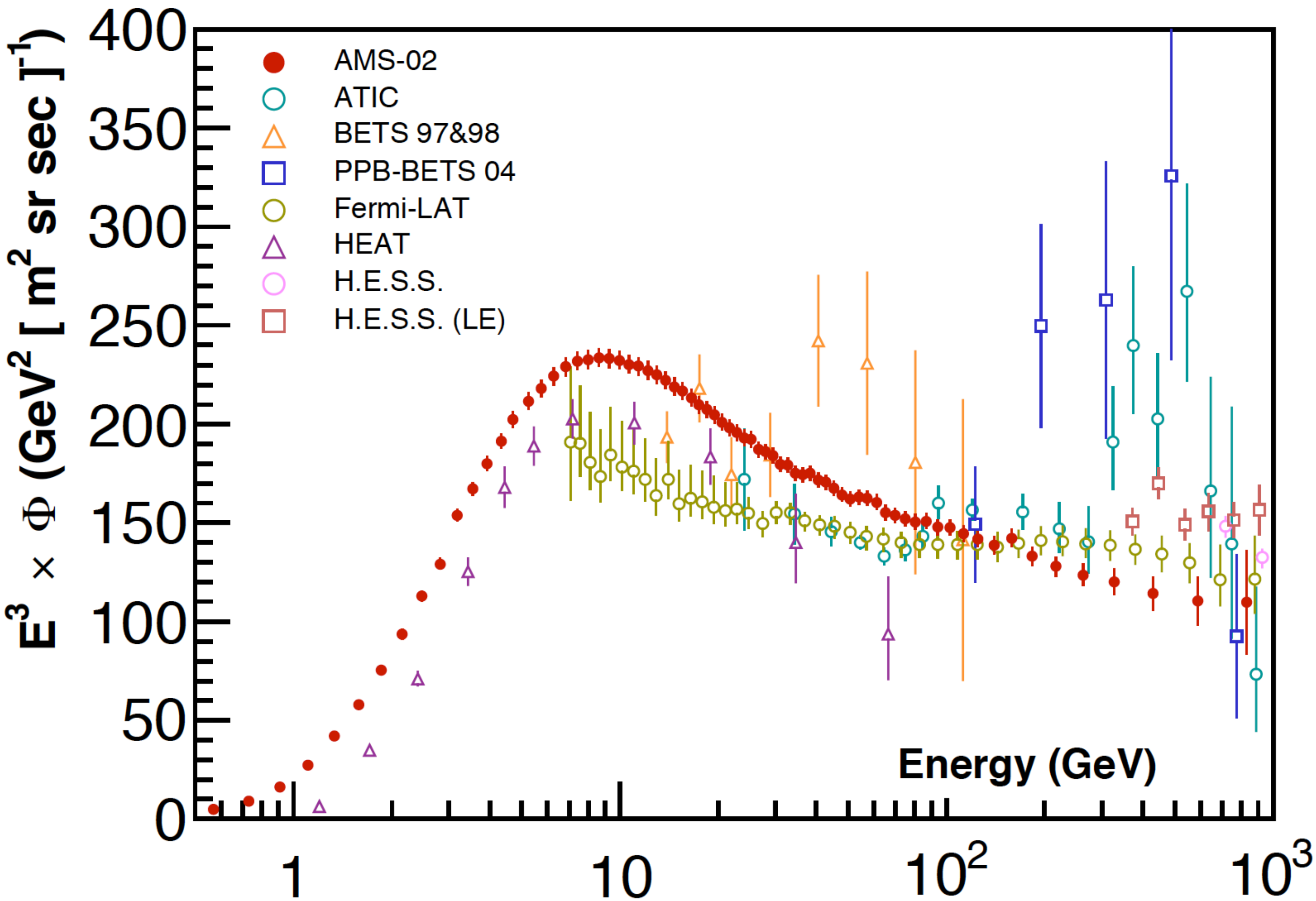
Galactic coordinates (b,l)



Data taking to 2024 will allow to explore anisotropies of 1%

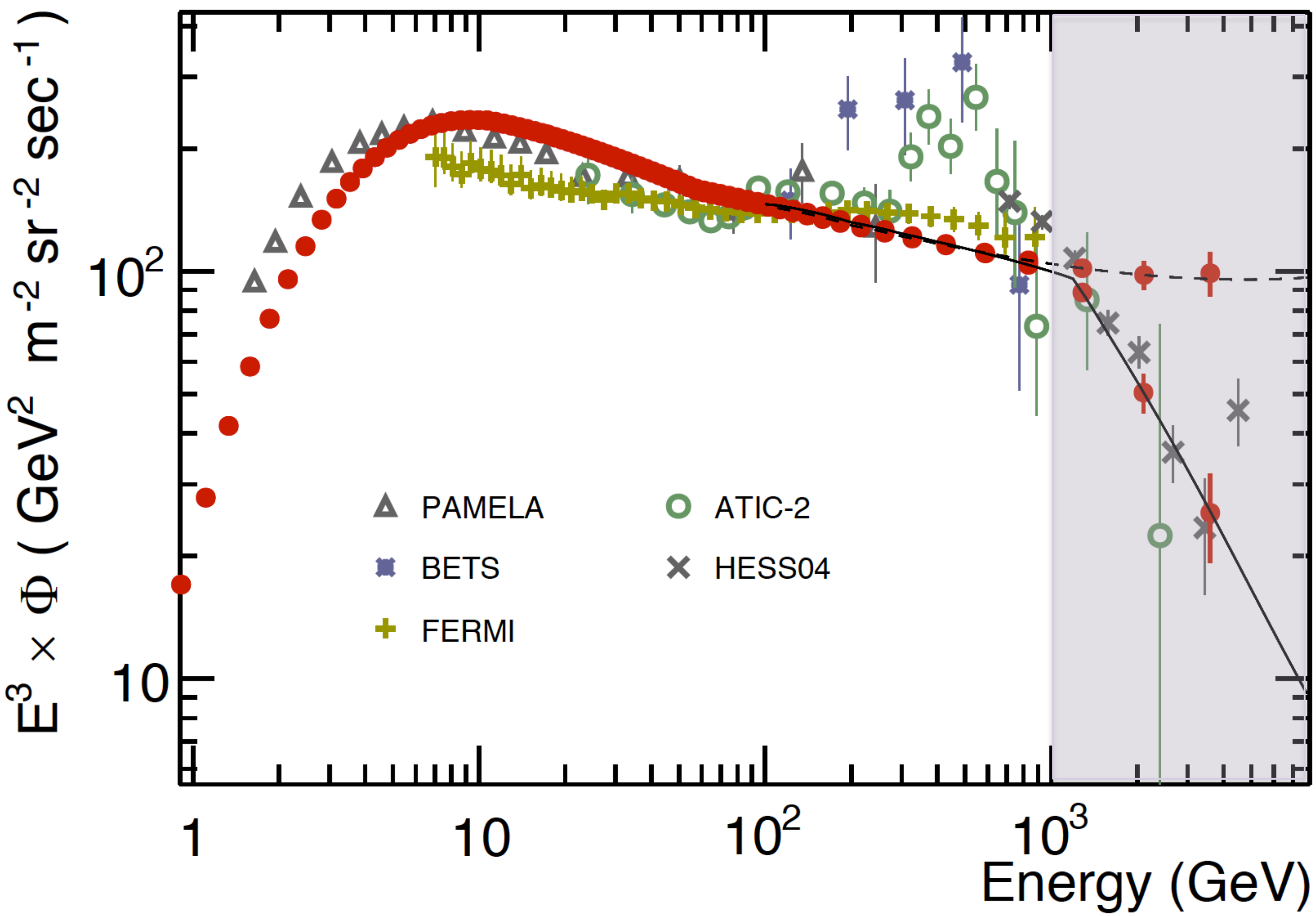
Physics Results 5: The ($e^+ + e^-$) flux

The precision AMS measurement of the ($e^+ + e^-$) flux contradicts all previous measurements and previous models



The ($e^+ + e^-$) flux projected in 2024

AMS will be able to distinguish the ($e^+ + e^-$) flux behavior above 1 TeV

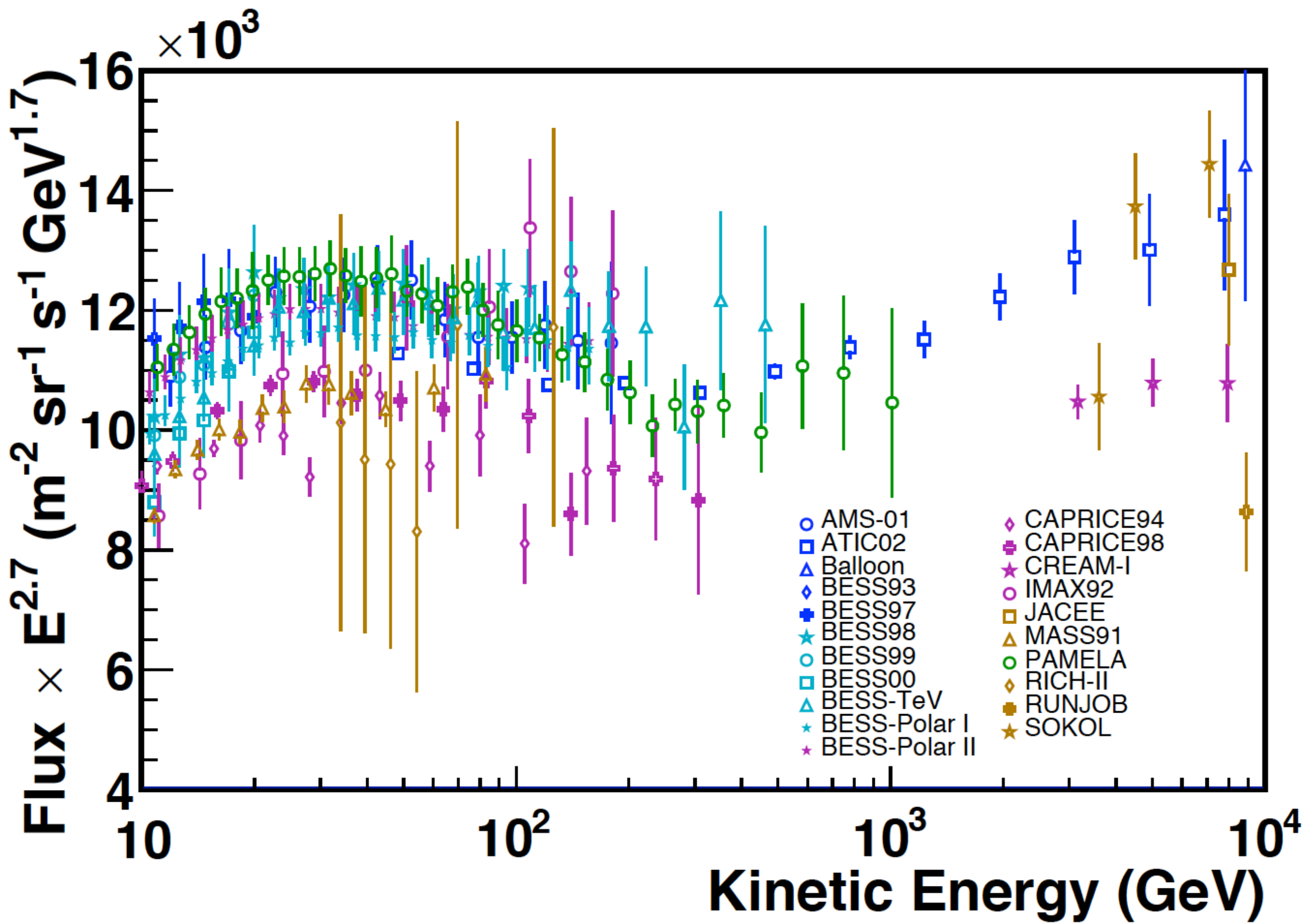


CALET: Exploring the TeV region

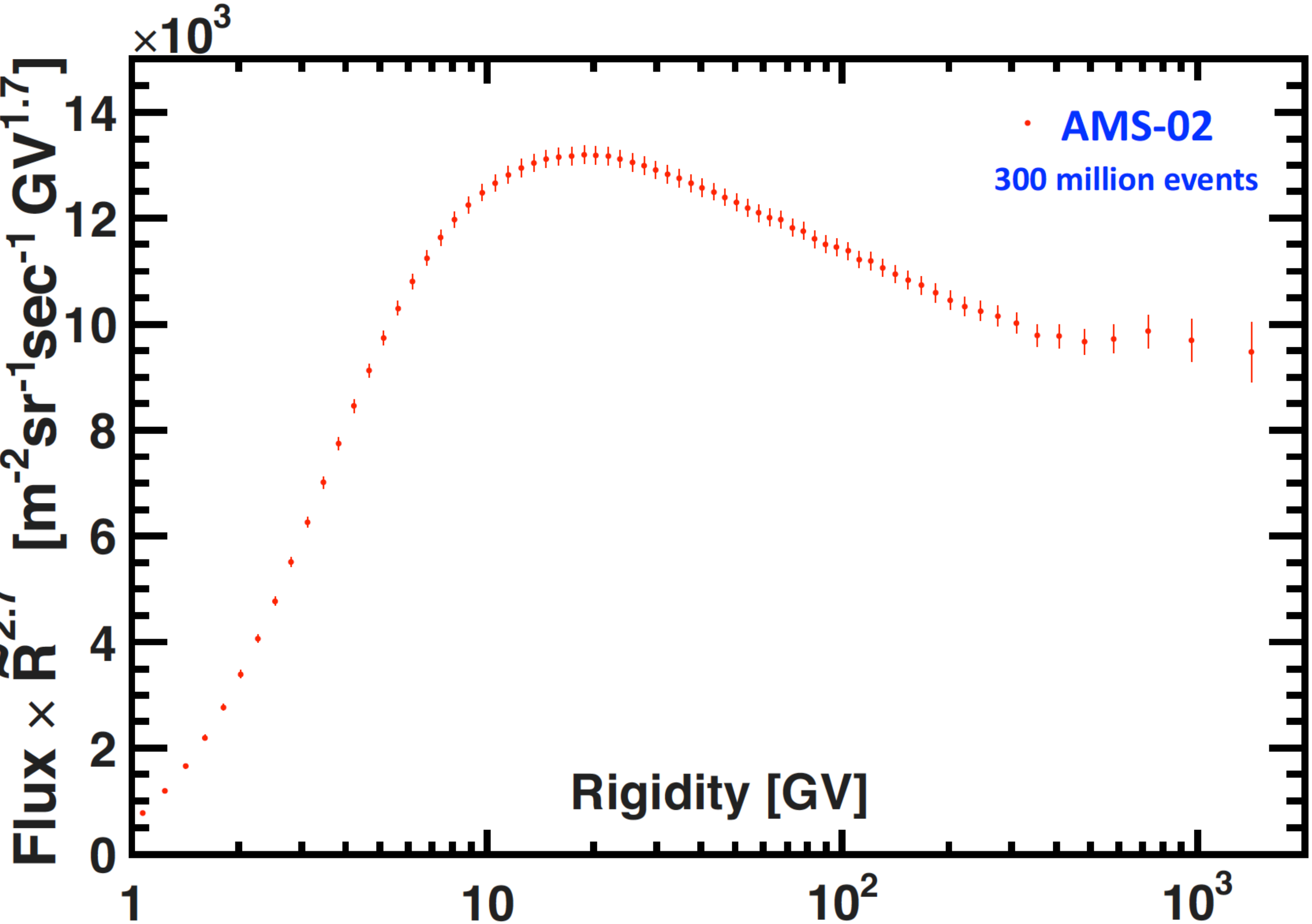
Before AMS: Proton Flux Measurement

- **Protons are the most abundant cosmic rays.**
- **Before AMS there have been many measurements of the proton spectrum.**
- **In cosmic rays models, the proton spectral function was assumed to be a single power law $\Phi = CE^{\gamma}$ with γ = -2.7**

Proton Spectrum

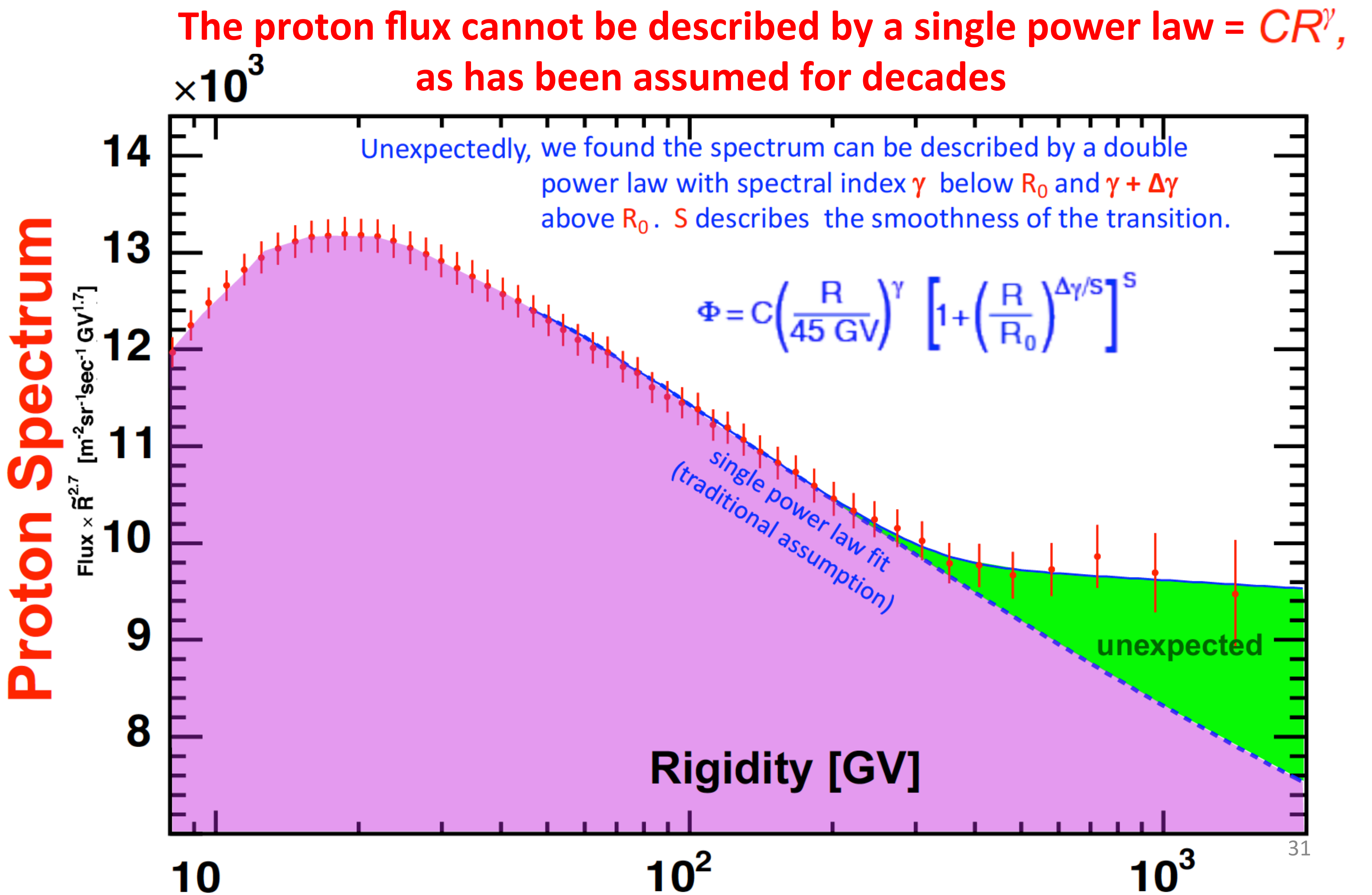


Physics Results 6: Precision measurement of proton flux to an accuracy of 1%

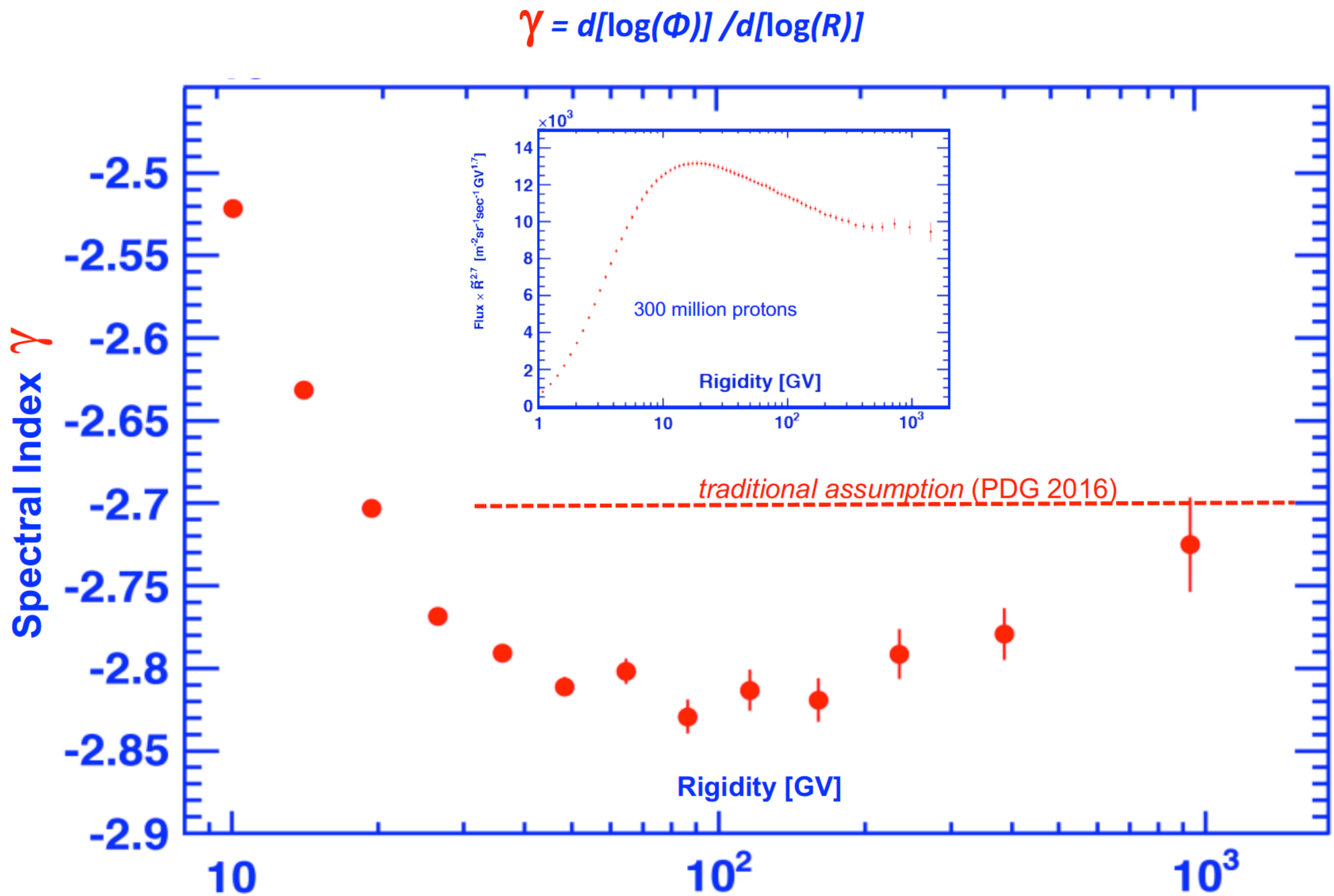


M. Aguilar *et al.*, Phys. Rev. Lett. **114**, 171103 (2015)

New information on AMS Proton flux

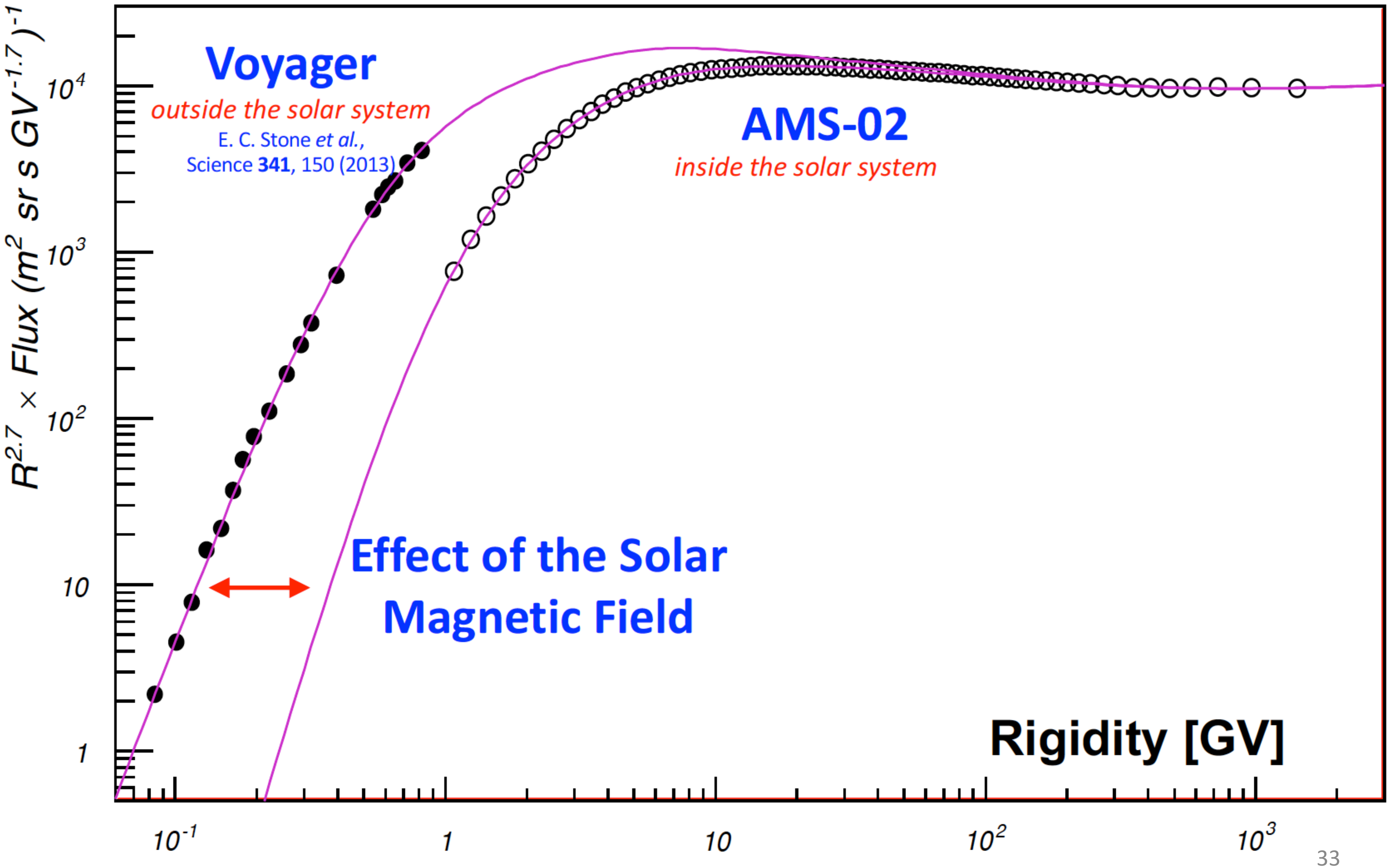


Proton spectral index changing with momentum



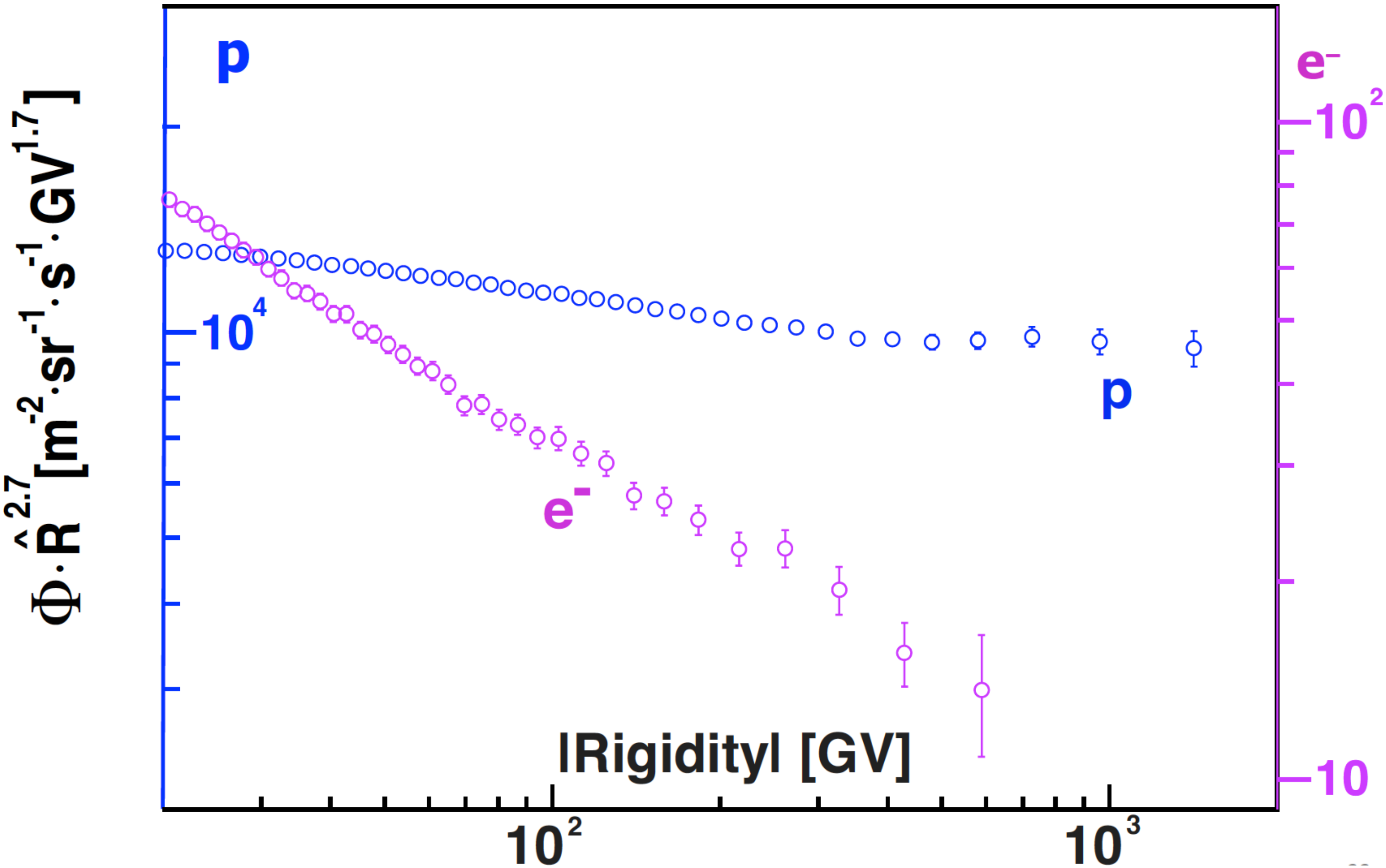
γ is not a constant -2.7

Understanding of the Solar Magnetic field



Spectra of elementary particles

e- and e+ have much smaller mass than p and $\bar{p}$, so they lose much more energy in the galactic magnetic field due to synchrotron radiation.

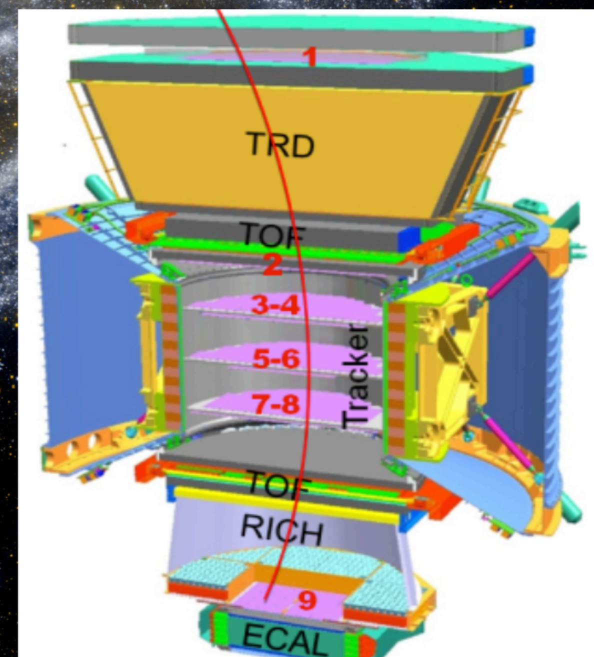


Dark Matter: Antiproton channel

Cosmic ray + ISM $\rightarrow \bar{p}$ + …

$\chi + \chi \rightarrow \bar{p}$ + …

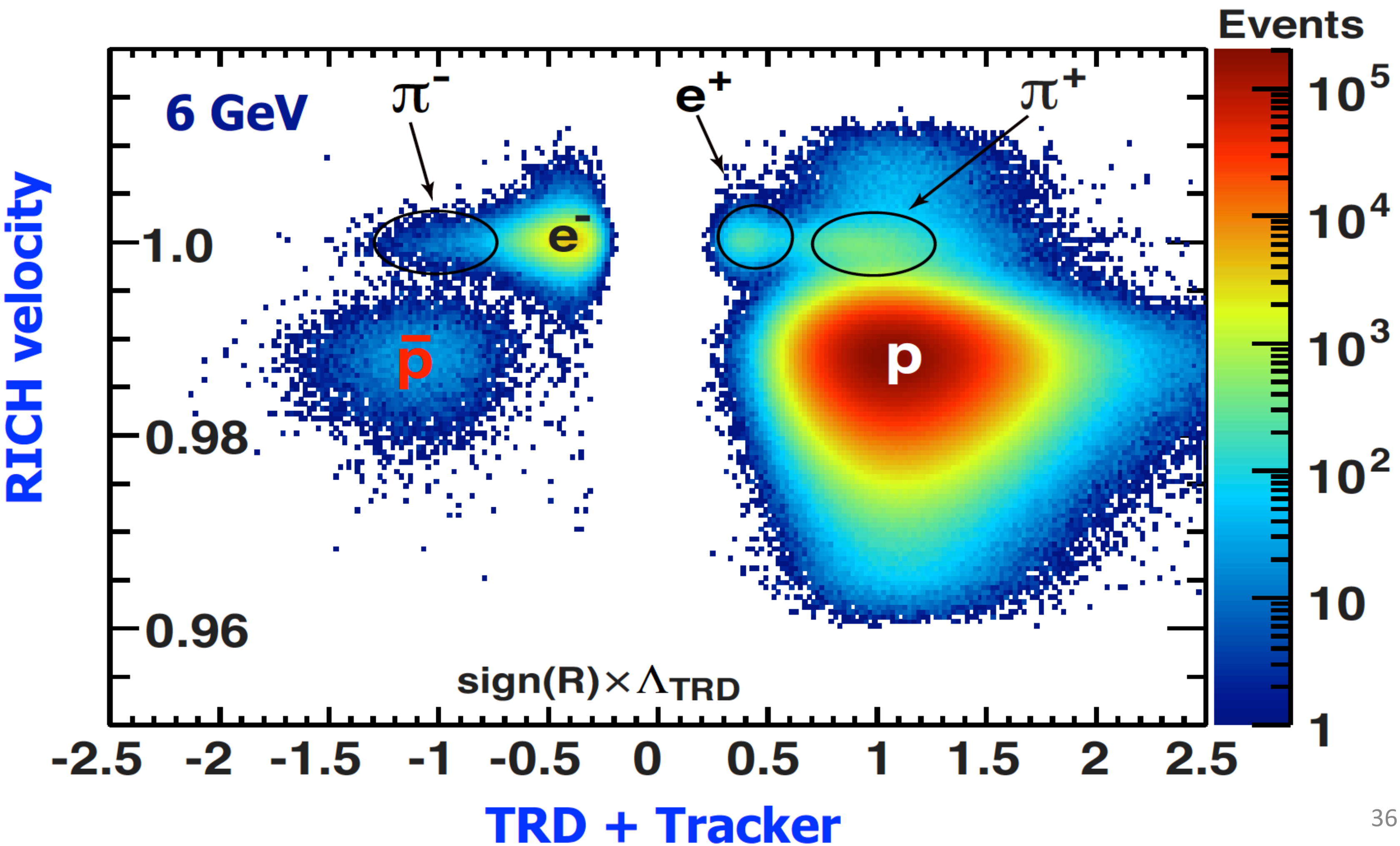
There is only 1 Antiproton for 10,000 Protons.



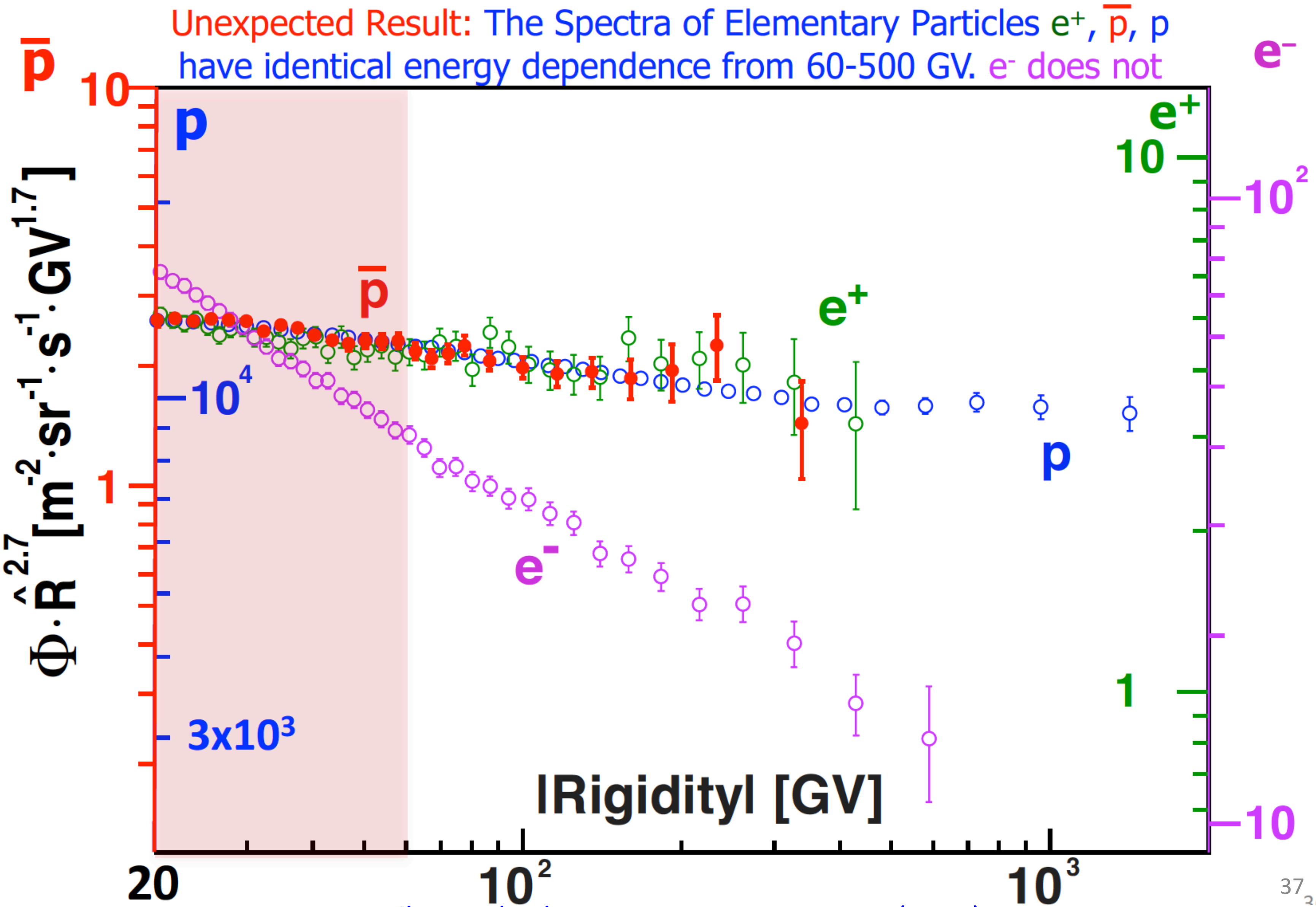
A percent precision experiment requires background rejection close to 1 in a million.

Signal Selection

The p̄ signal is well separated from the backgrounds.



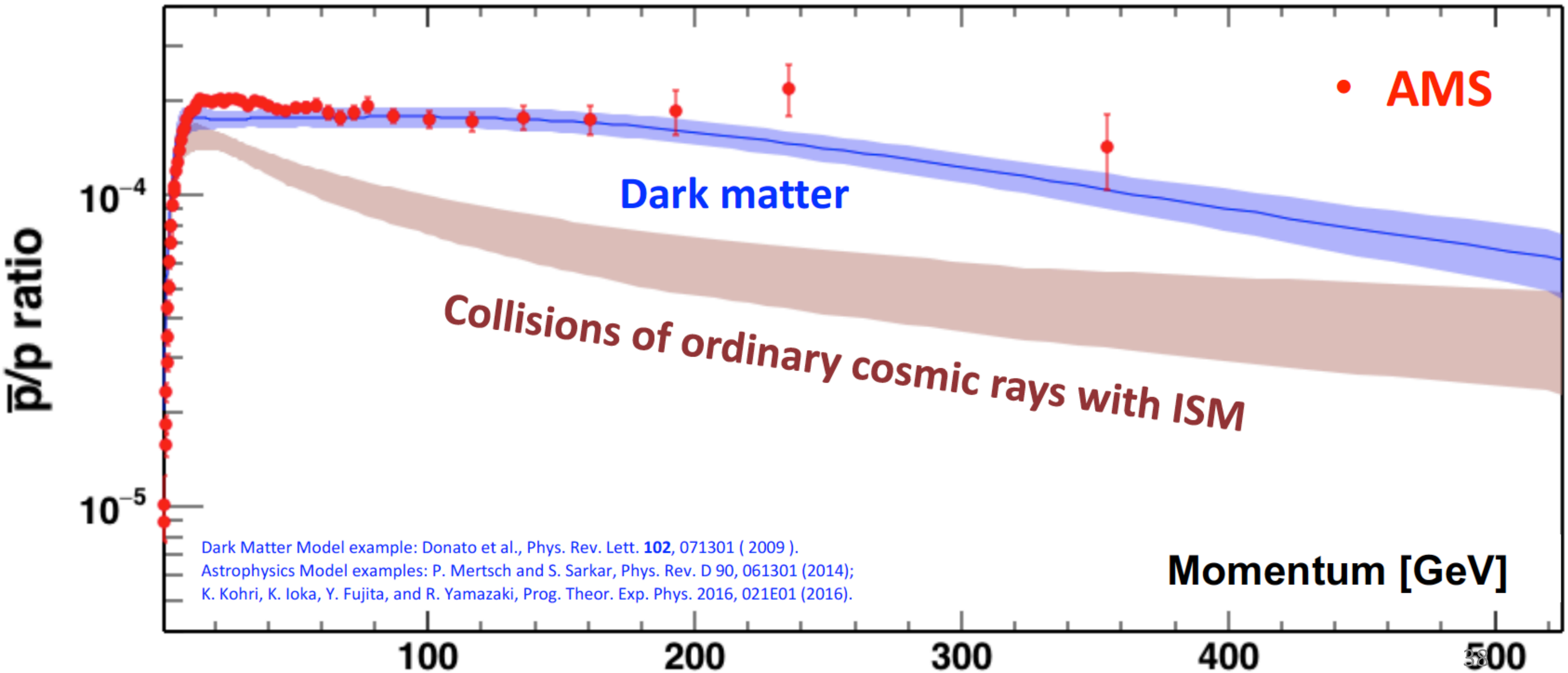
Physics Results 7: The antiproton flux and properties of elementary particle fluxes



M. *Aguilar et al.*, Phys. Rev. Lett. **117**, 091103(2016)

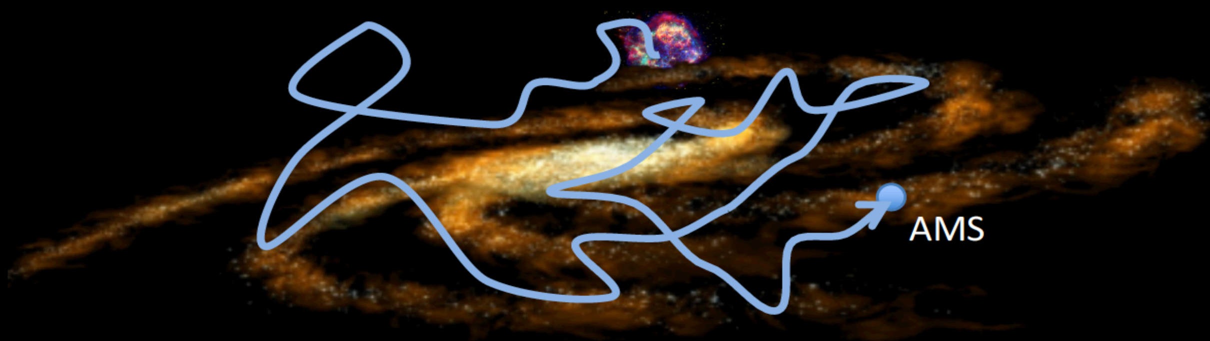
Antiproton-to-proton ratio

- **Excess of antiproton is observed by AMS!!!**
- **Cannot be explained by Pulsars**
- **Can be explained by Dark Matter Annihilation or by new astrophysics phenomena**



Cosmic Rays Interaction

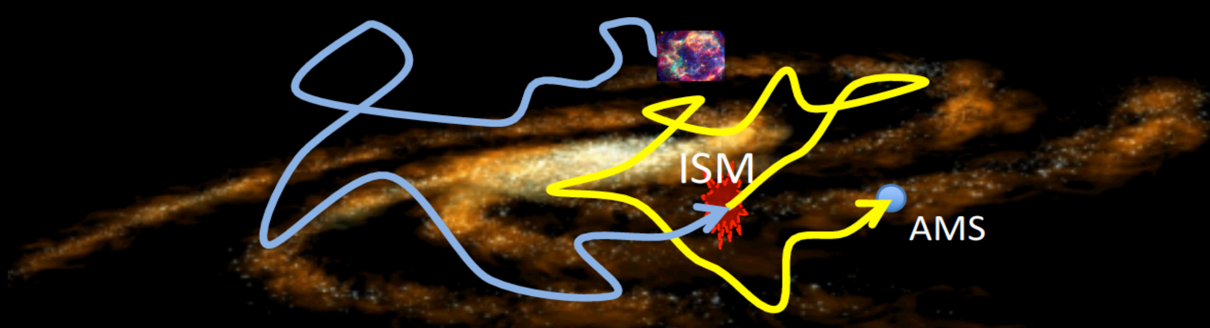
Primary Cosmic Rays (p, He, C, O, …)



Primary cosmic rays carry information about their original spectra and propagation.

Secondary Cosmic Rays (Li, Be, B, …)

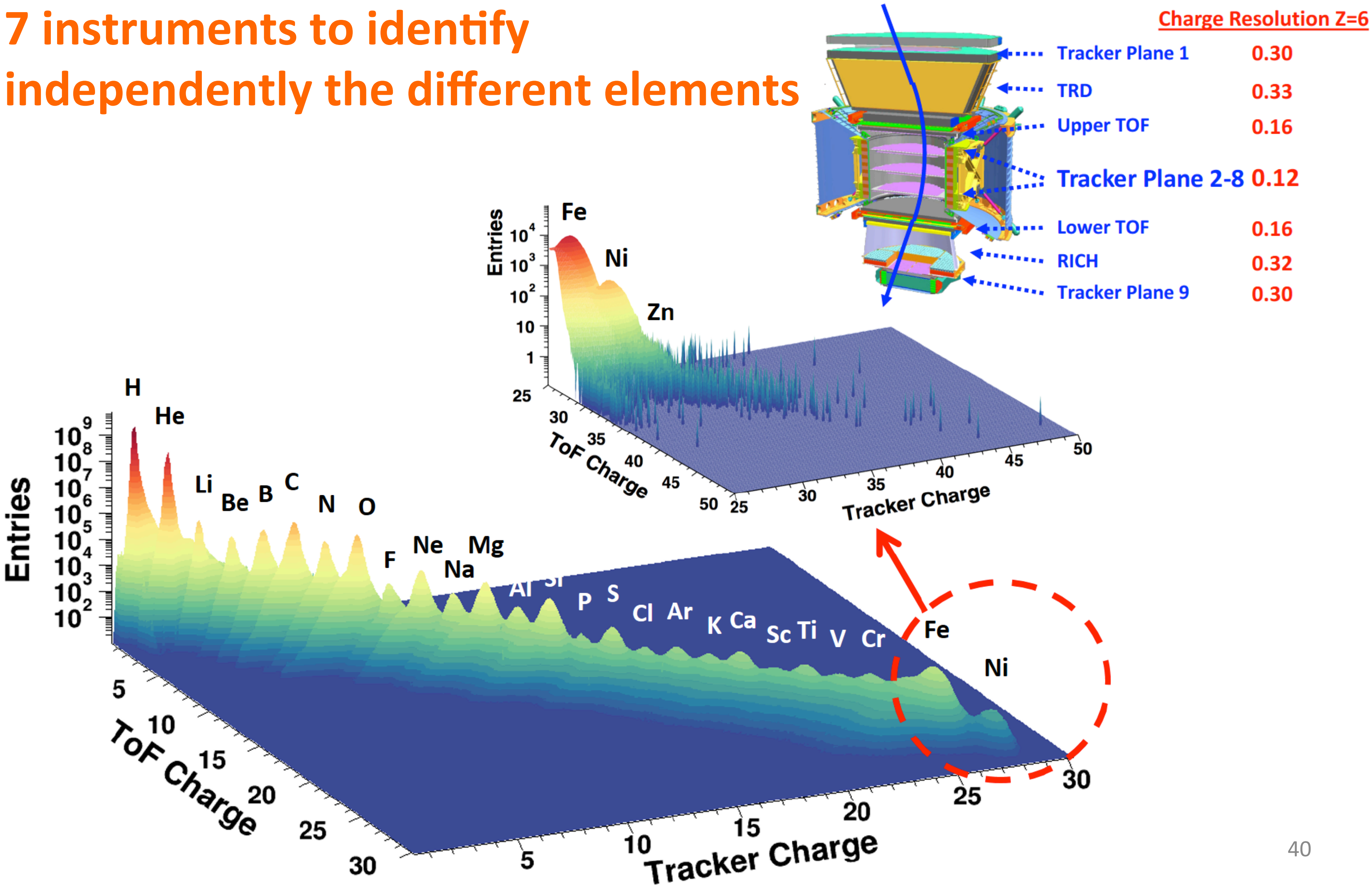
C, O, …, Fe + ISM → Li, Be, B + X



Secondary cosmic rays carry information about propagation of primaries, secondaries and the ISM.

AMS Nuclei Fluxes Measurements

7 instruments to identify independently the different elements



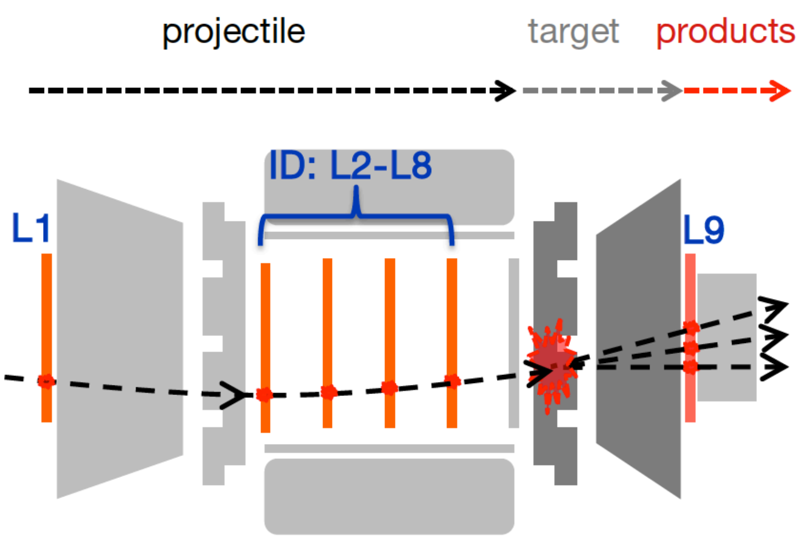
Measuring the interaction of nuclei within AMS: Method

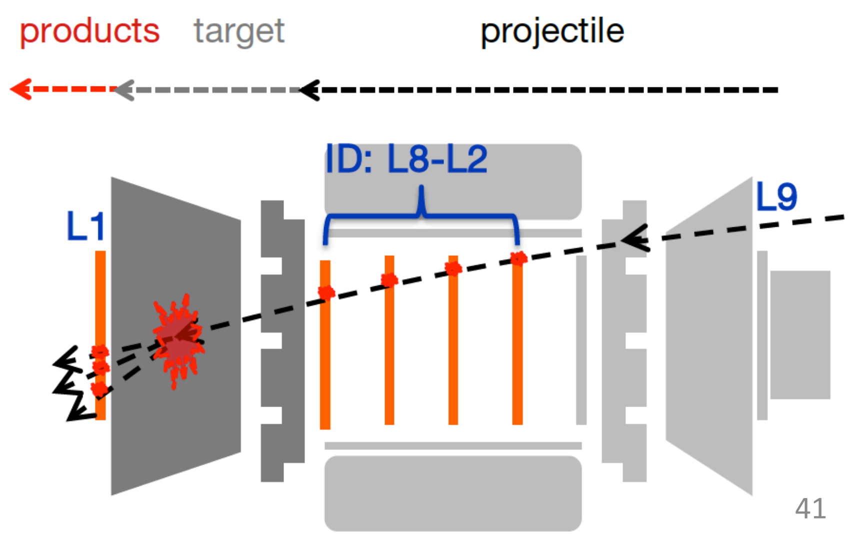
AMS in horizontal position

First, we use the seven inner tracker layers, L2-L8, to define beams of nuclei: Li, Be, B, …

Second, we use left-to-right particles to measure the nuclear interactions in the lower part of the detector.

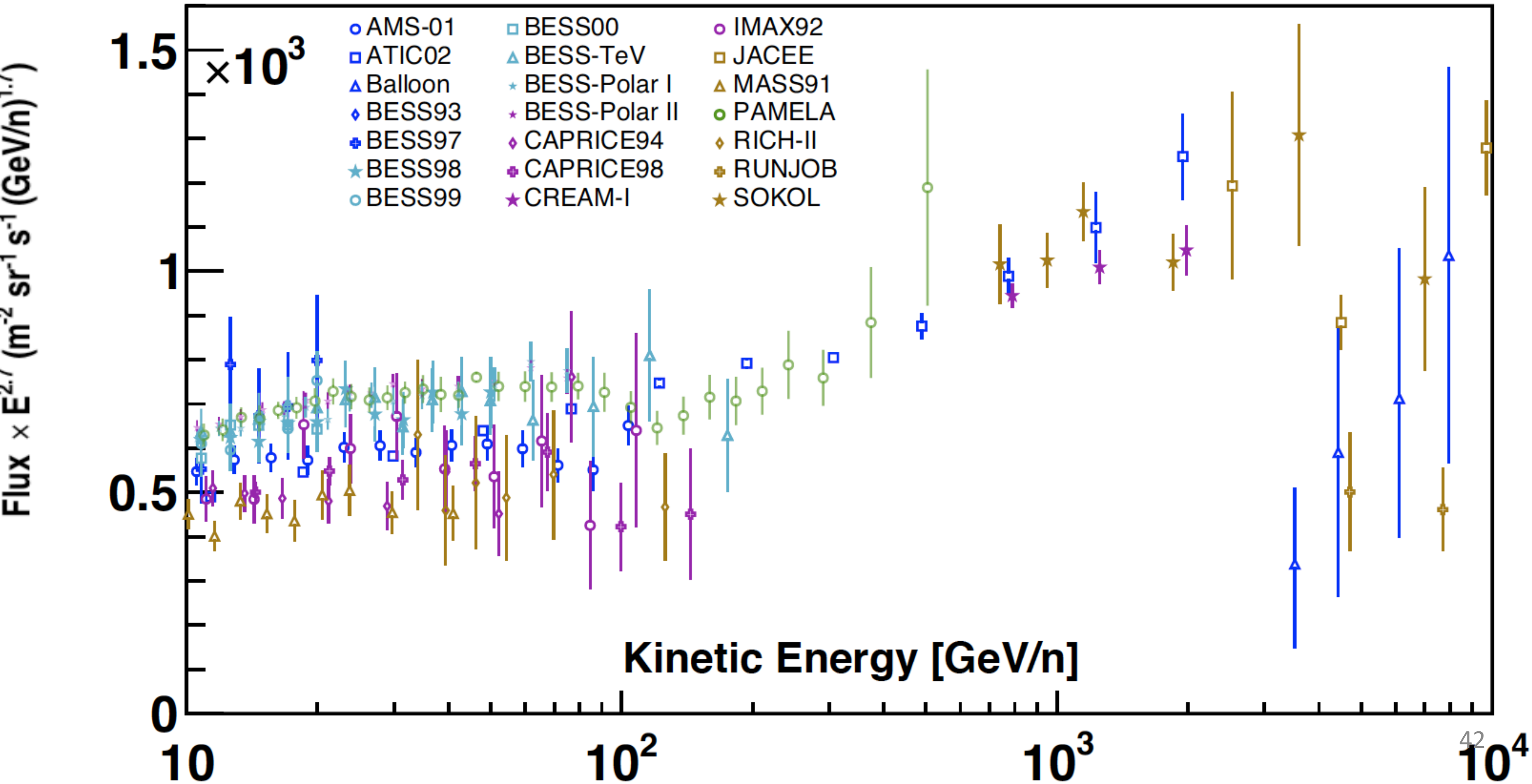
Third, we use right-to-left particles to measure the nuclear interactions in the upper part of detector.



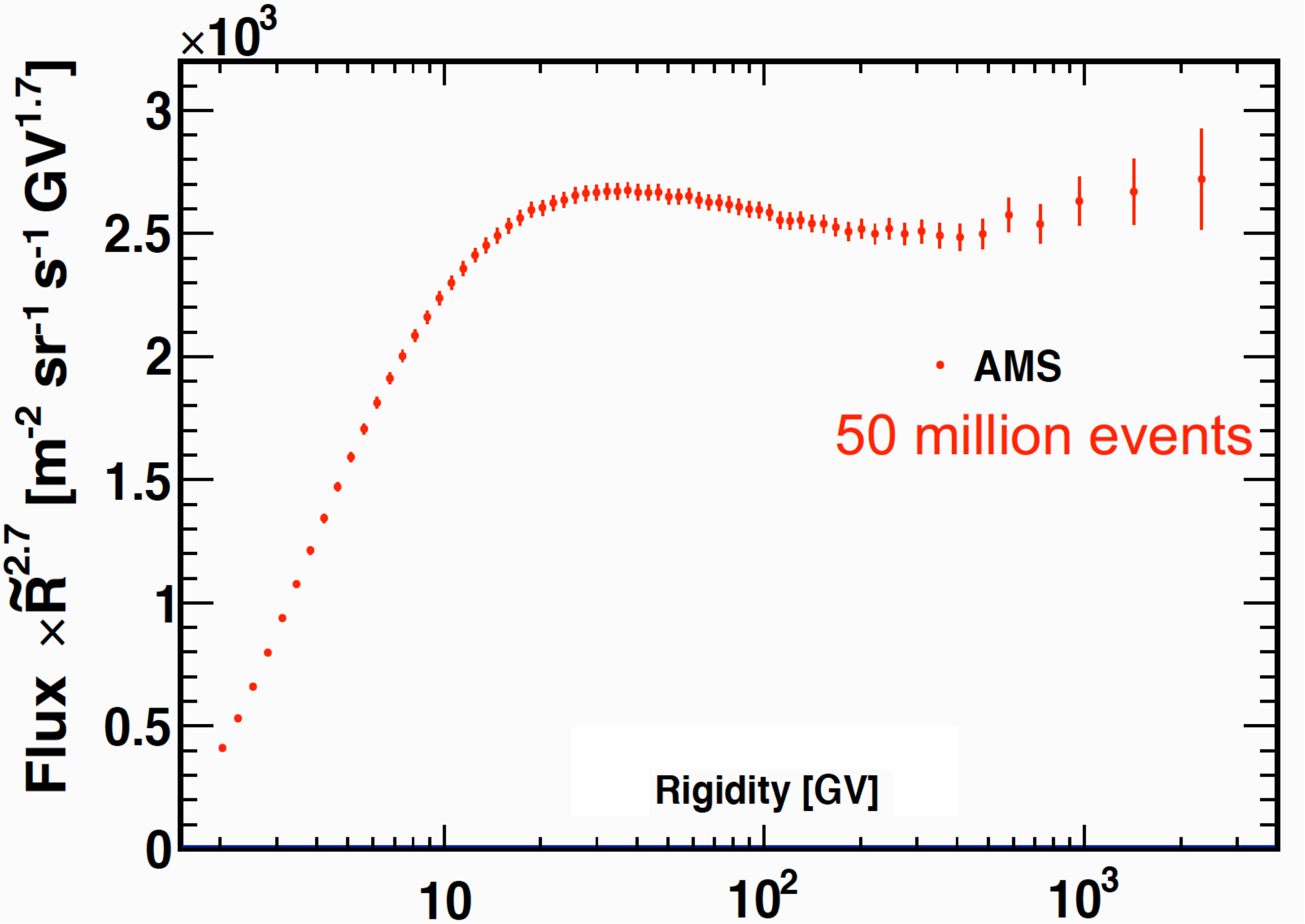


Before AMS : Helium Flux Measurement

- **2^{nd} most abundant cosmic rays**
- **He produced by Supernovas**
- **As for Protons He spectral function was assumed to be a single power** $(\gamma = -2.7)$



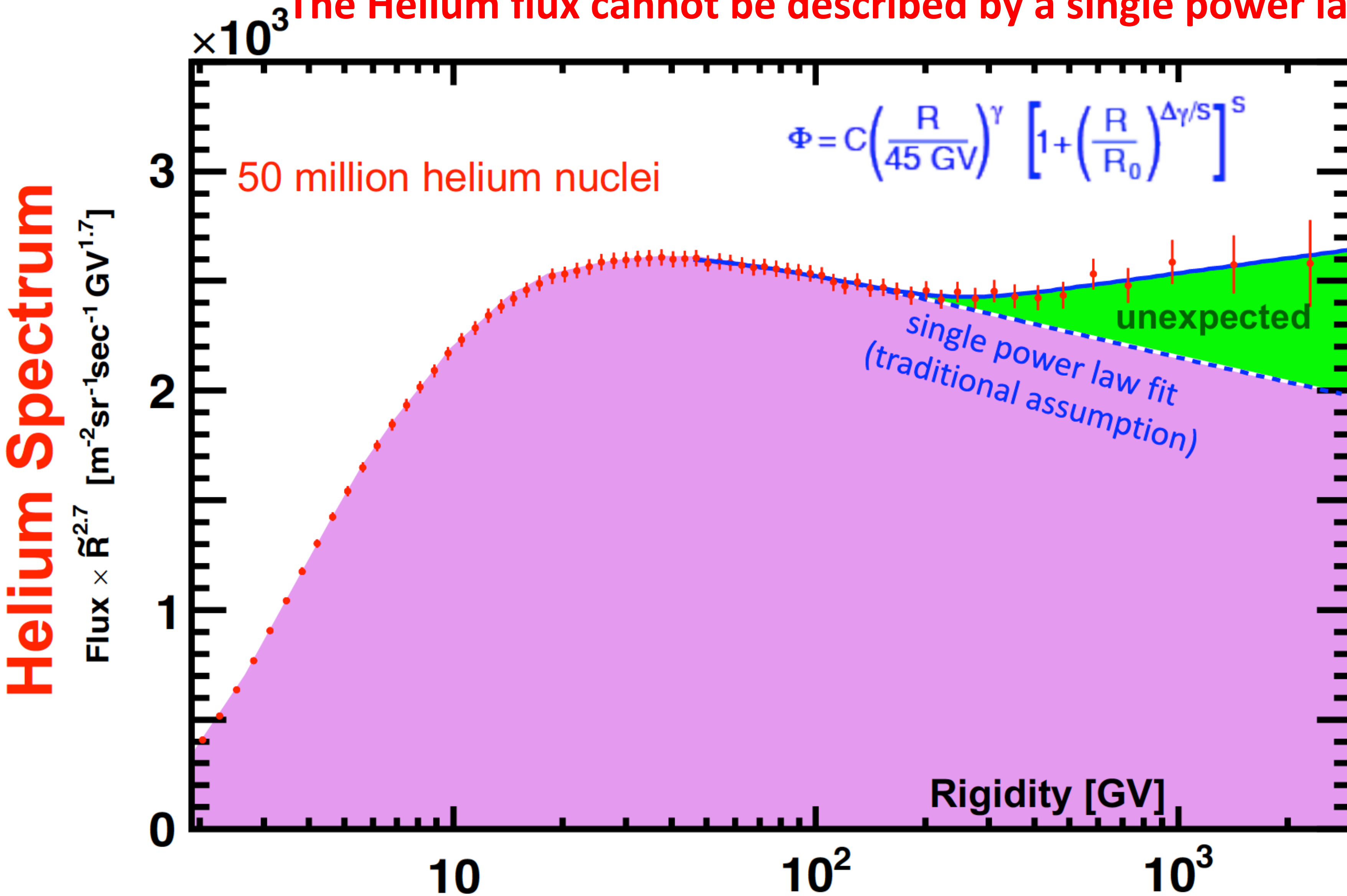
Physics Results 8: Precision measurement on the Helium flux



M. Aguilar *et al.*, Phys. Rev. Lett. **115**, 211101 (2015)

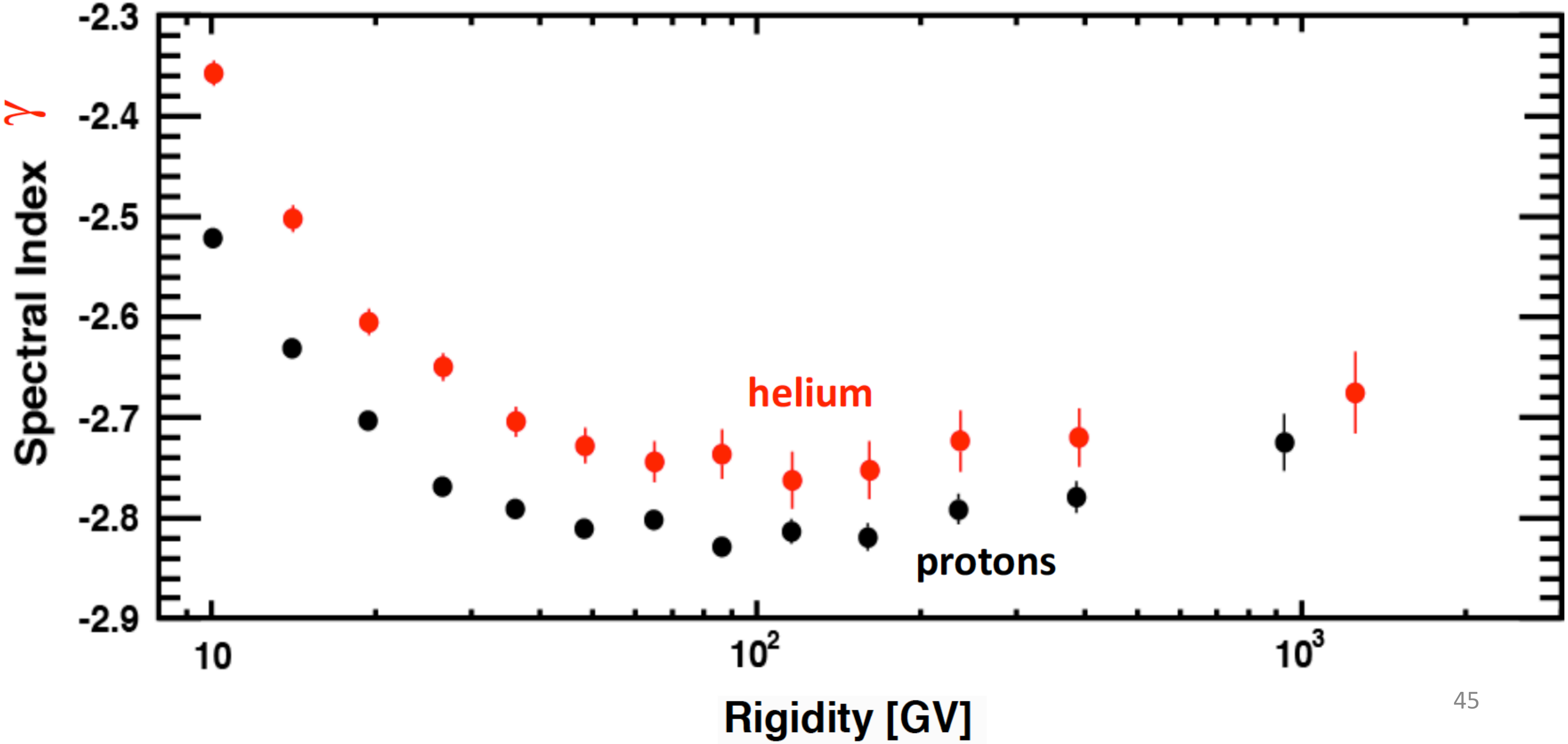
New information on AMS Helium flux

The Helium flux cannot be described by a single power law



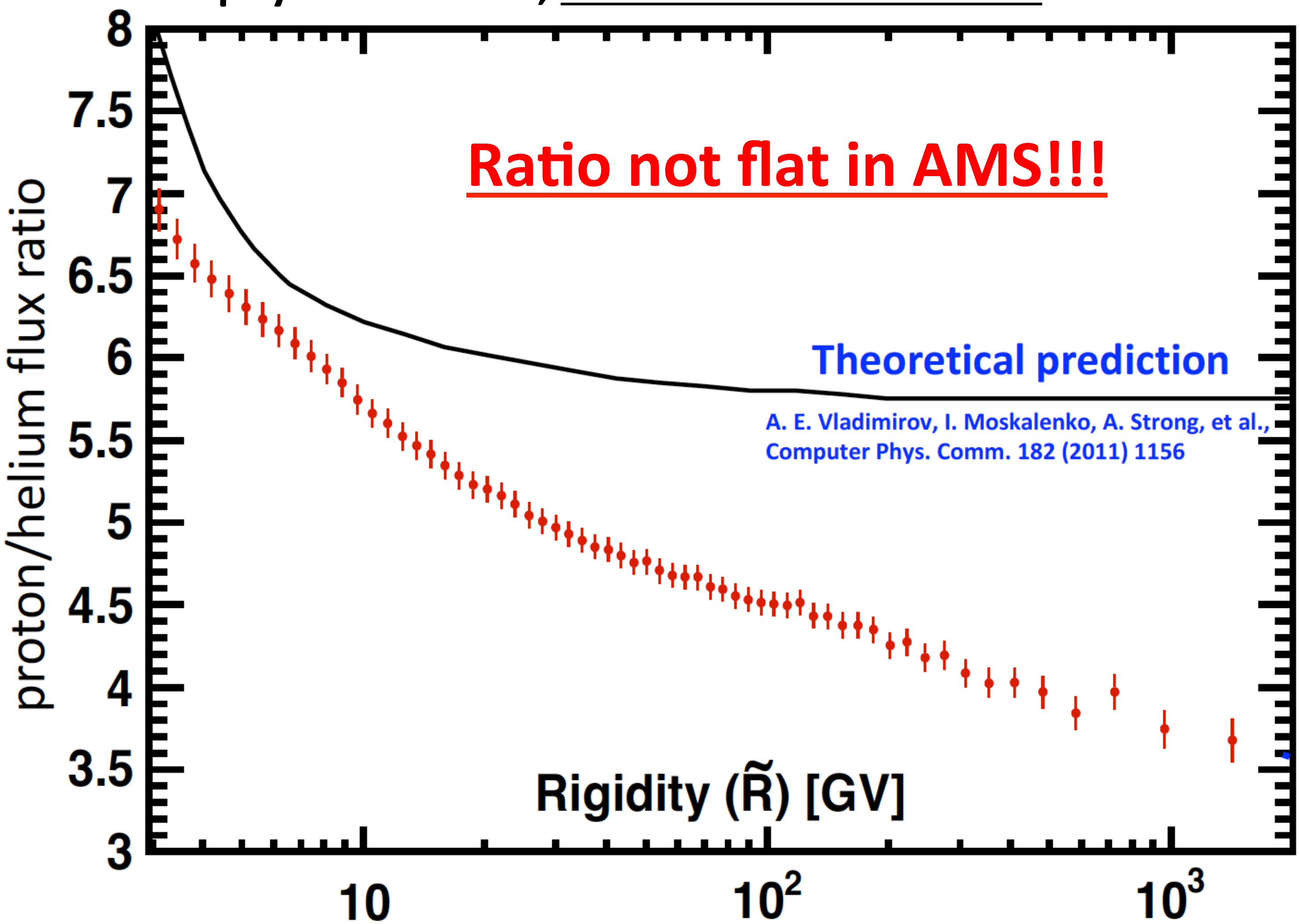
Helium spectral index

Unexpectedly the Helium index change with the rigidity in the similar way as for the Proton spectral index but the values are different!!

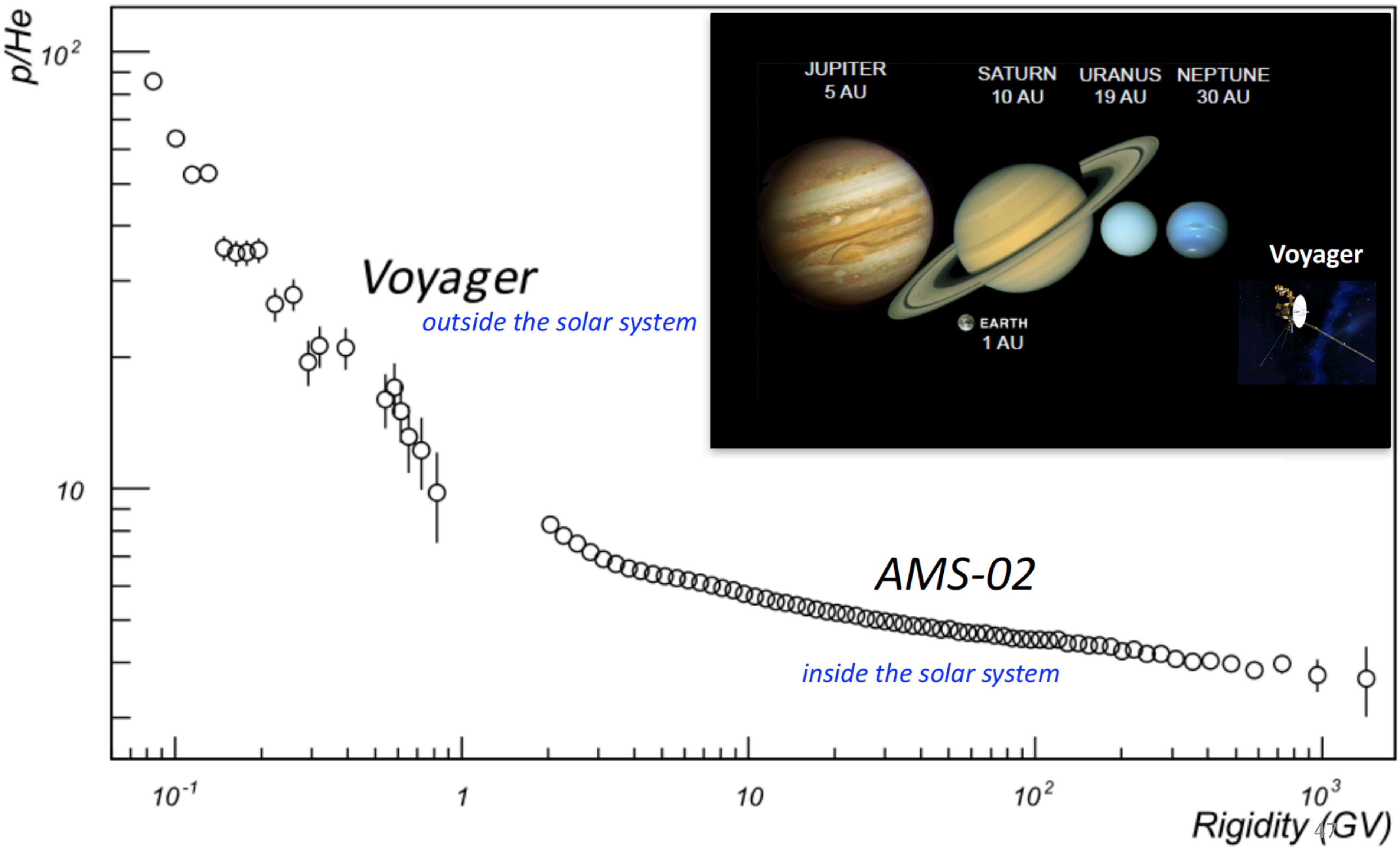


Physics Results 9: The AMS proton/helium flux ratio

Proton and Helium are "Primary" Cosmic Rays.
Since Proton and Helium are assumed to be produced by the same Astrophysical sources, <u>their ratio should be flat</u>.



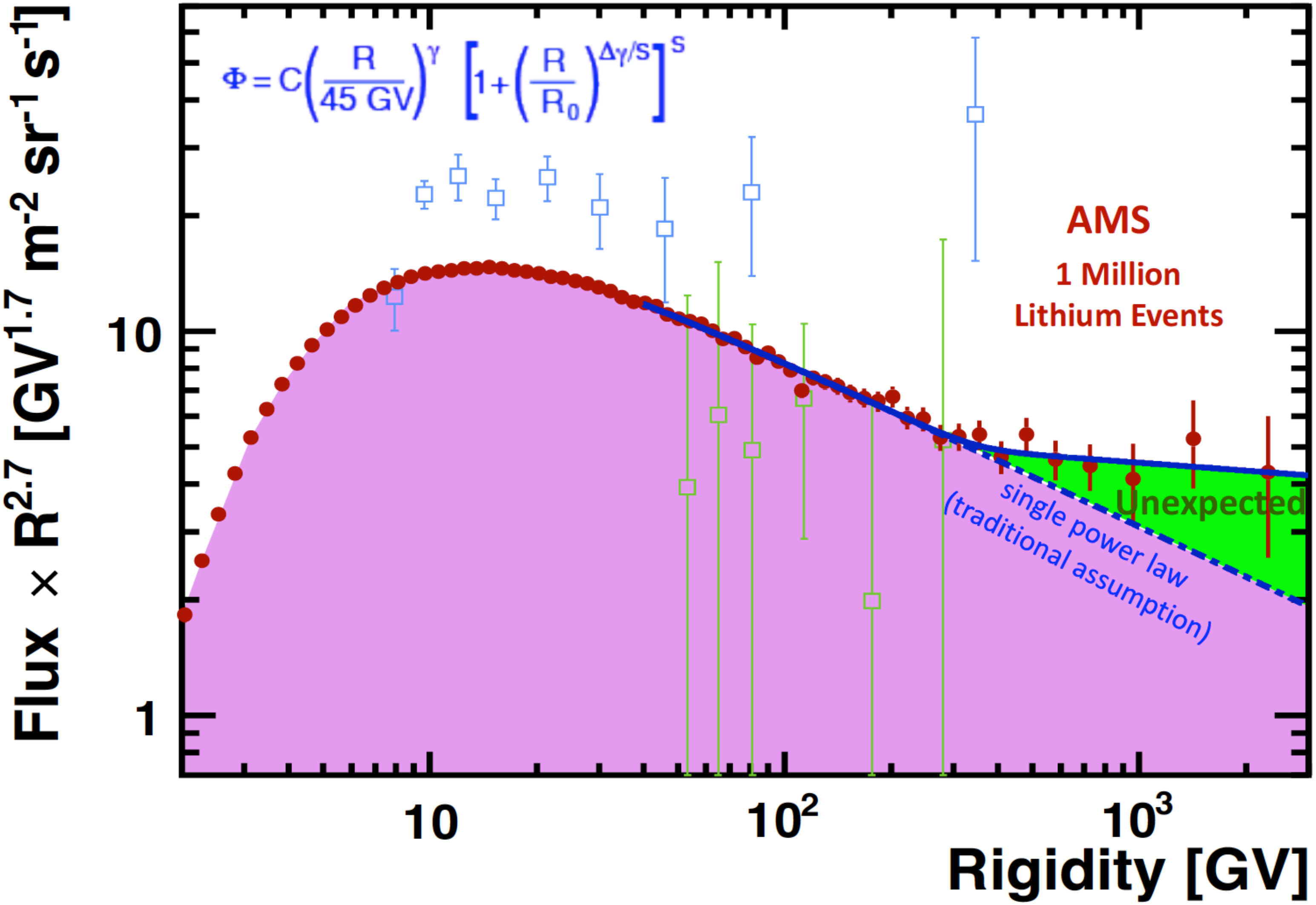
Proton-Helium ratio: independent of the solar activity



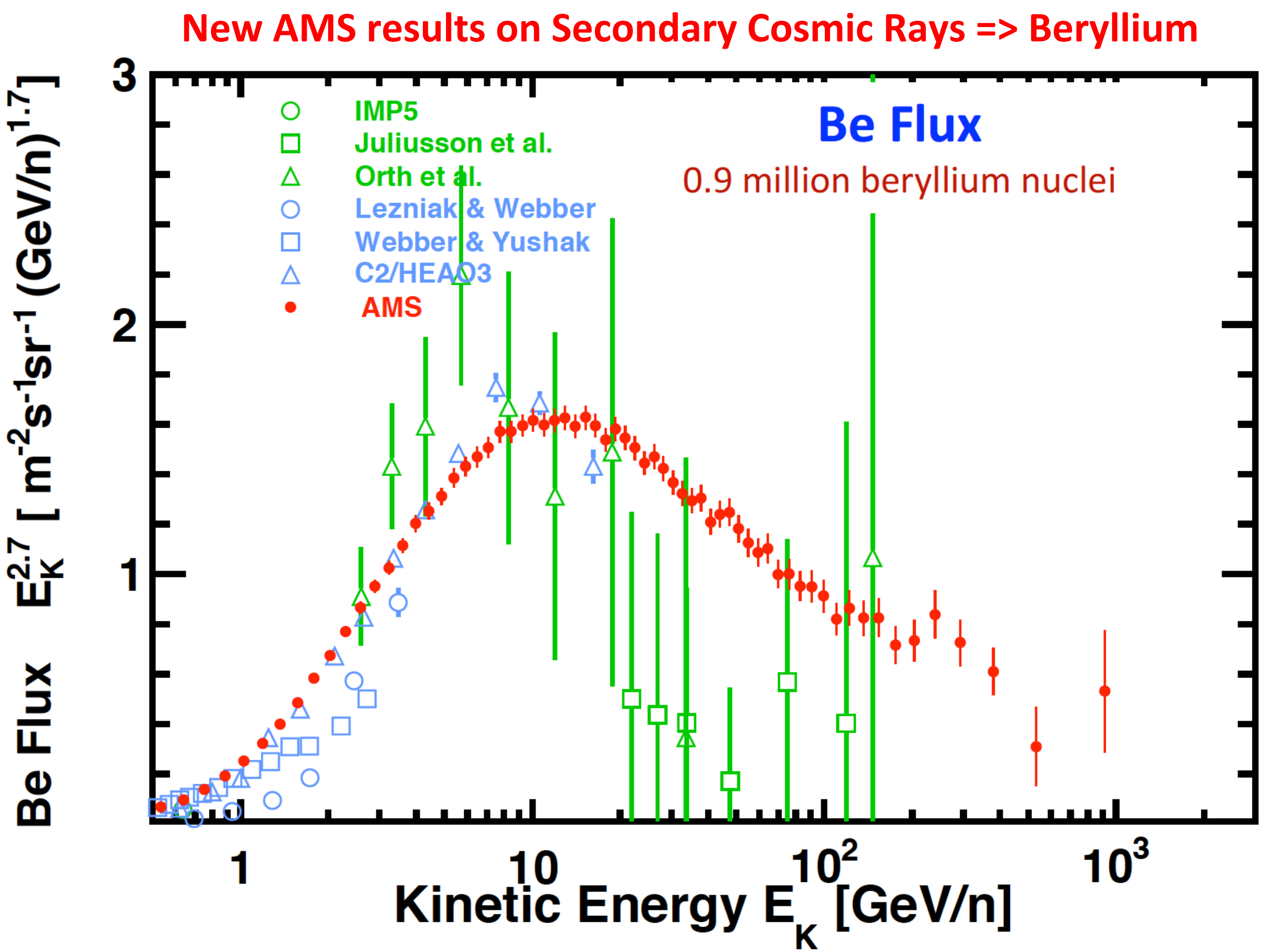
Physics Results 10: The Lithium flux

New AMS results on Secondary Cosmic Rays => Lithium

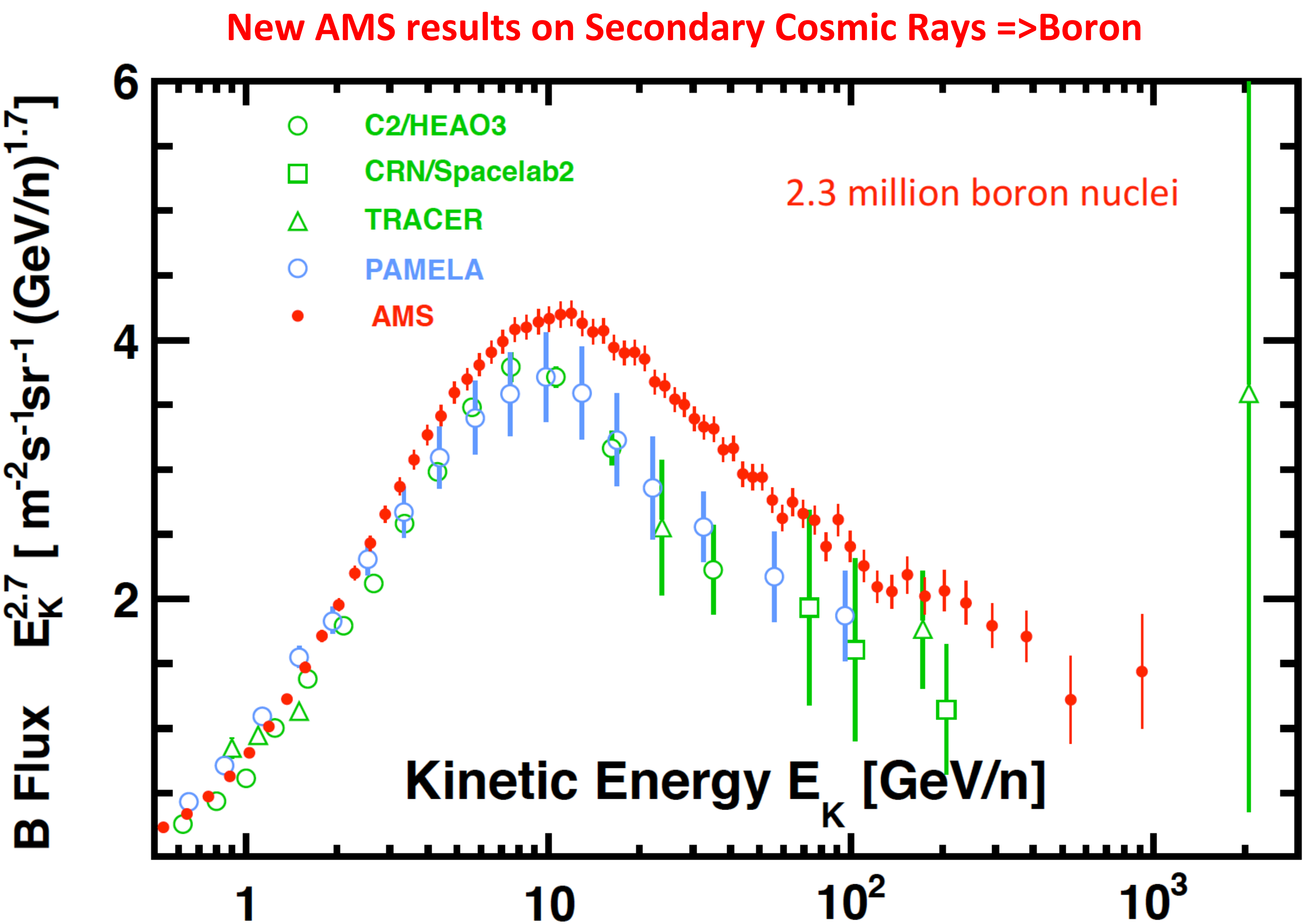
Similar as Proton and Helium fluxes, Lithium flux cannot be explain by a single power law.



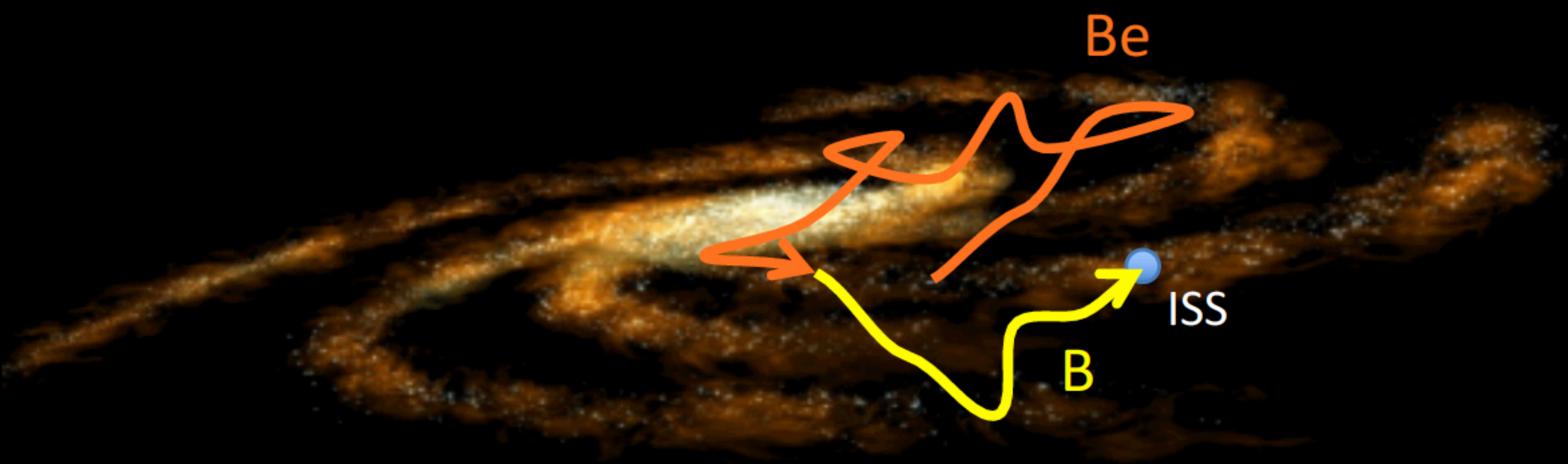
Physics Results 11: The Beryllium flux



Physics Results 12: The Boron flux



Beryllium to Boron fluxes ratio and age of Cosmic Rays

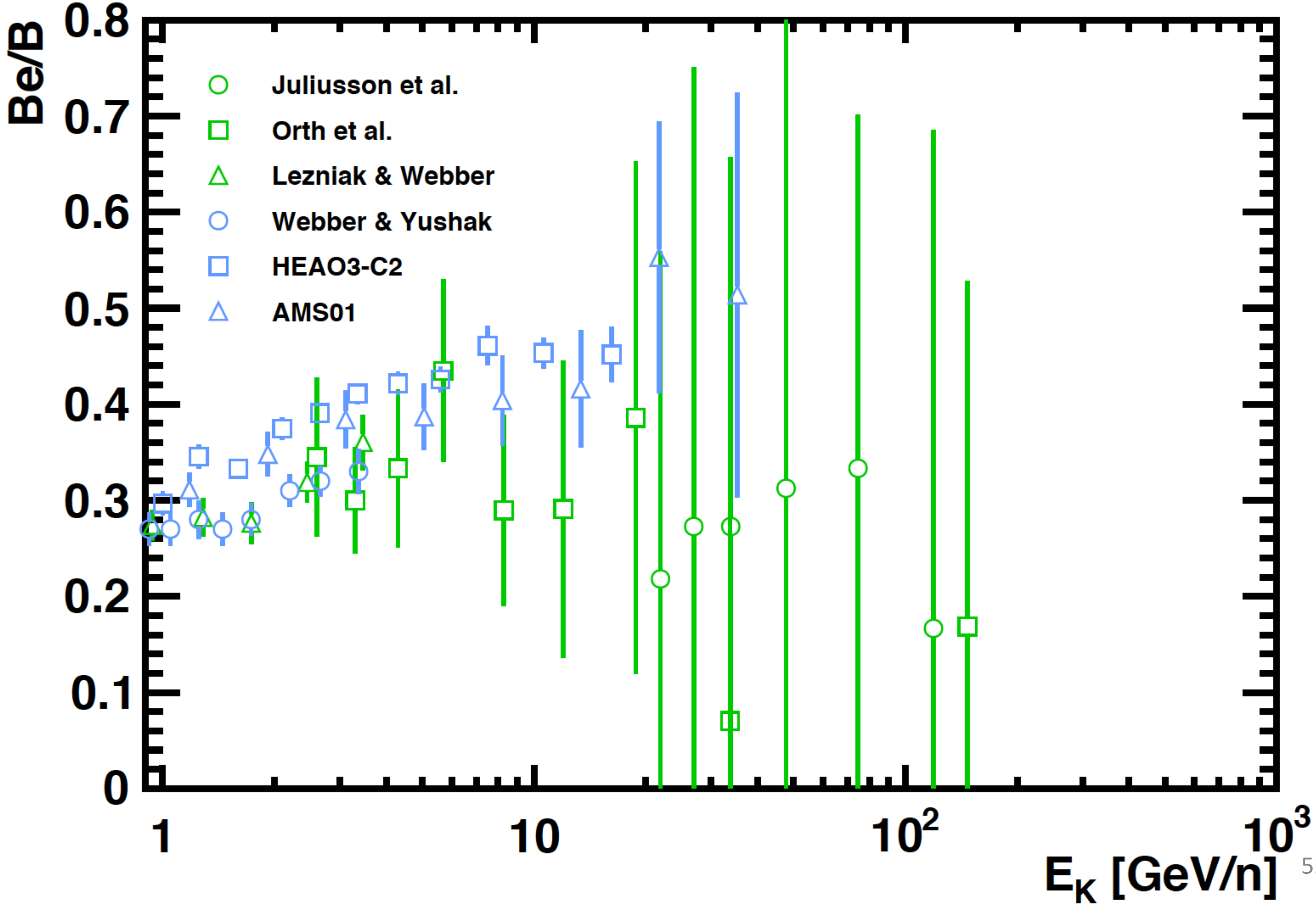


$$^{10}Be \rightarrow {}^{10}B + e^{-} + \bar{\nu}_e$$

The ^{10}Be half-life is 1.5×10^6 years.

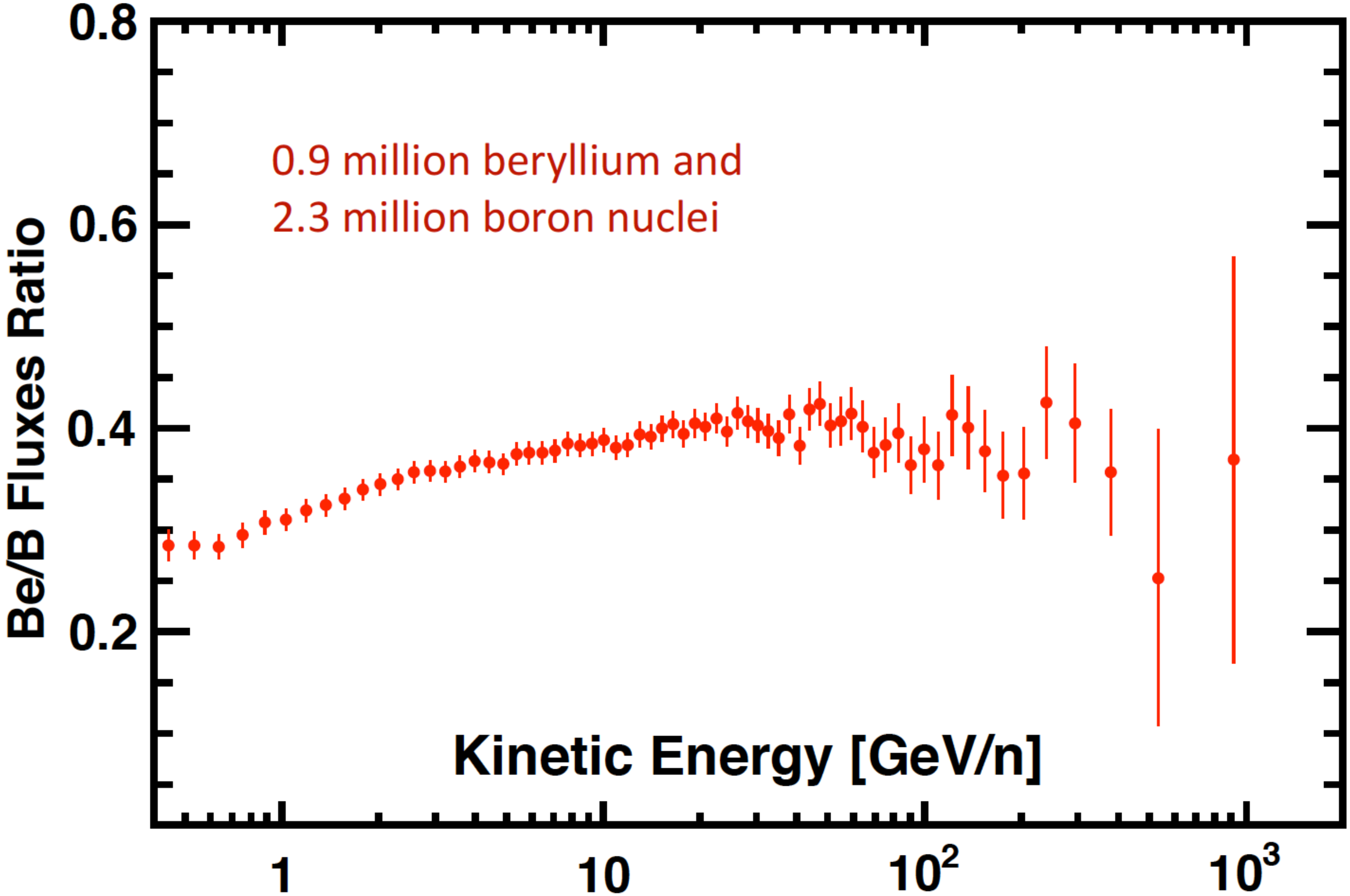
Be/B ratio increases with energy due to relativistic time dilation and provides information about the age of Cosmic Rays in the Galaxy

Before AMS: Beryllium to Boron flux ratio measurement



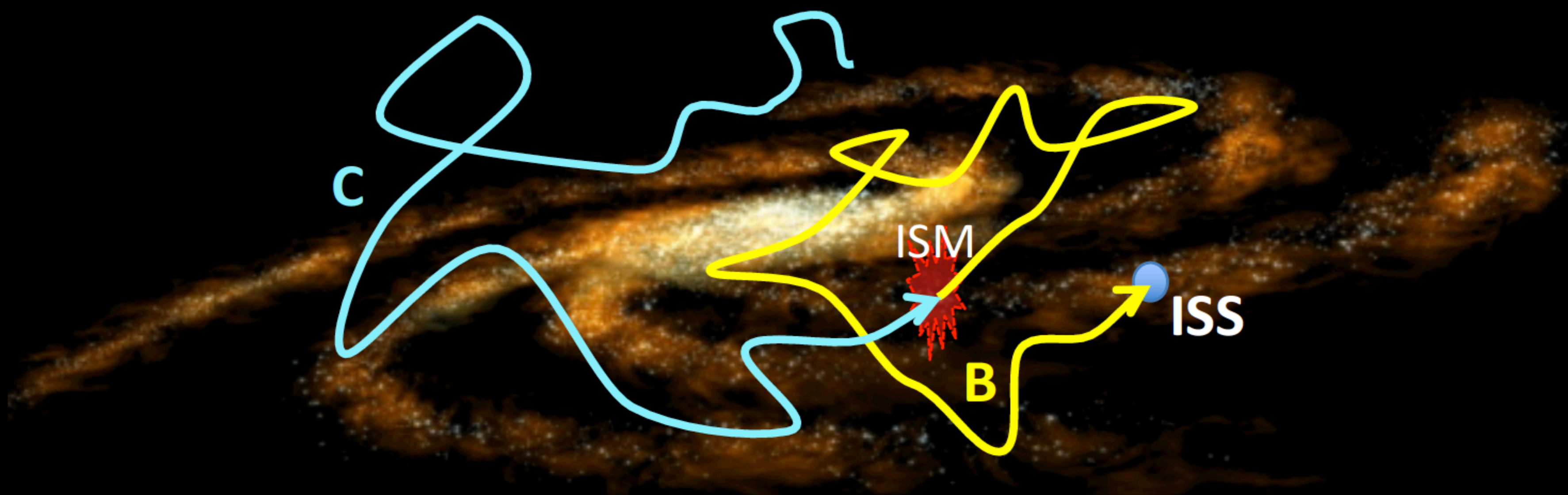
Physics Results 13: Berylllium to Boron flux ratio

Age of the cosmic rays in the galaxy ~ 12 millions years



Ratio between primaries (C) and secondaries (B)

Provides information on the cosmic propagation and ISM.
In general cosmic rays propagation is modeled as a fast moving gas diffusing through magnetized plasma.



For high rigidities, the magnetized plasma model shows different behavior.

$$B/C = kR^{\delta}$$

$\delta = -1/3$ => Kolmogorov turbulence model

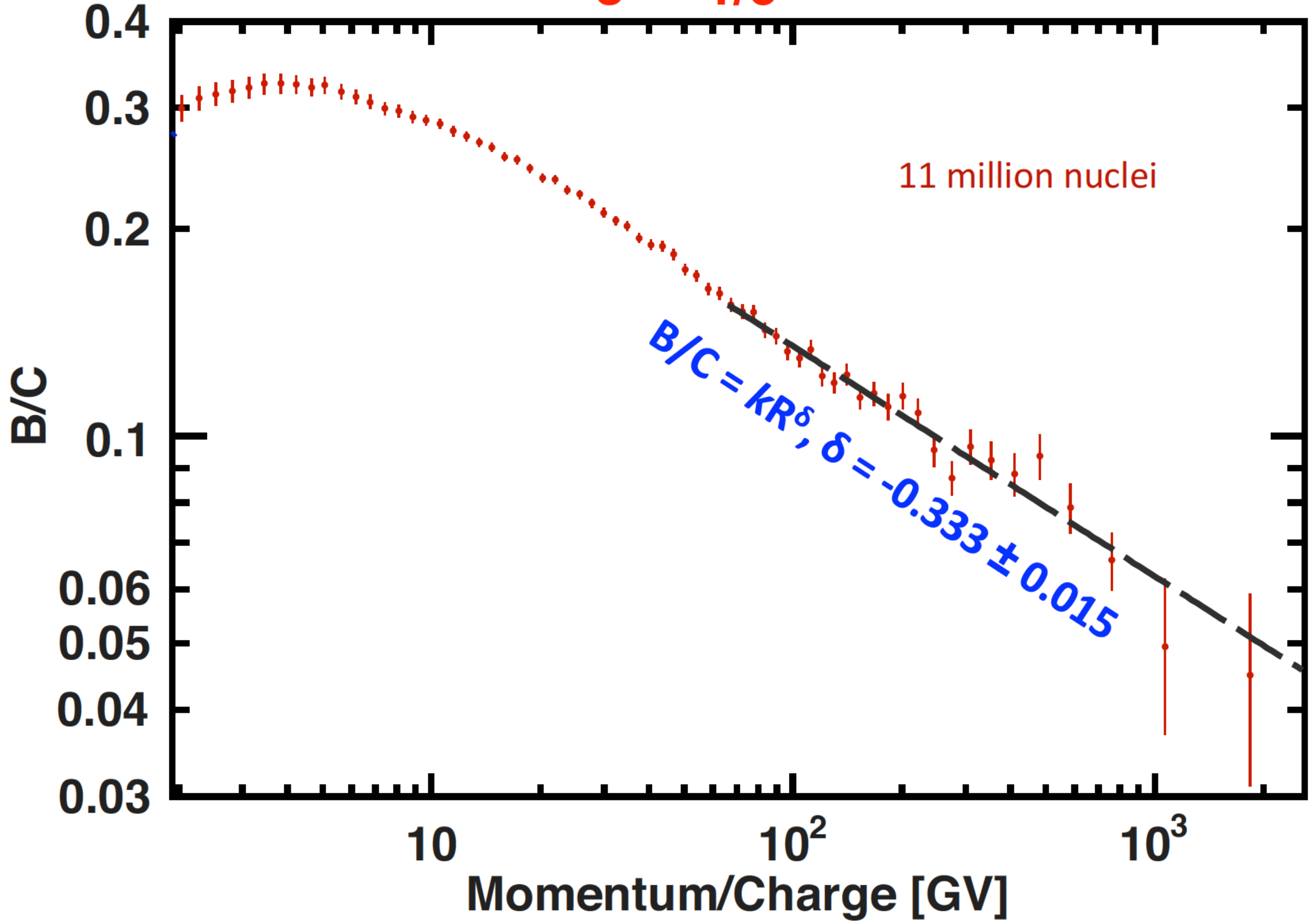
$\delta = -1/2$ => Kraichnan theory

Physics Results 14: Boron to Carbon flux ratio

Above 65 GeV, the B/C is well described by the single power law.

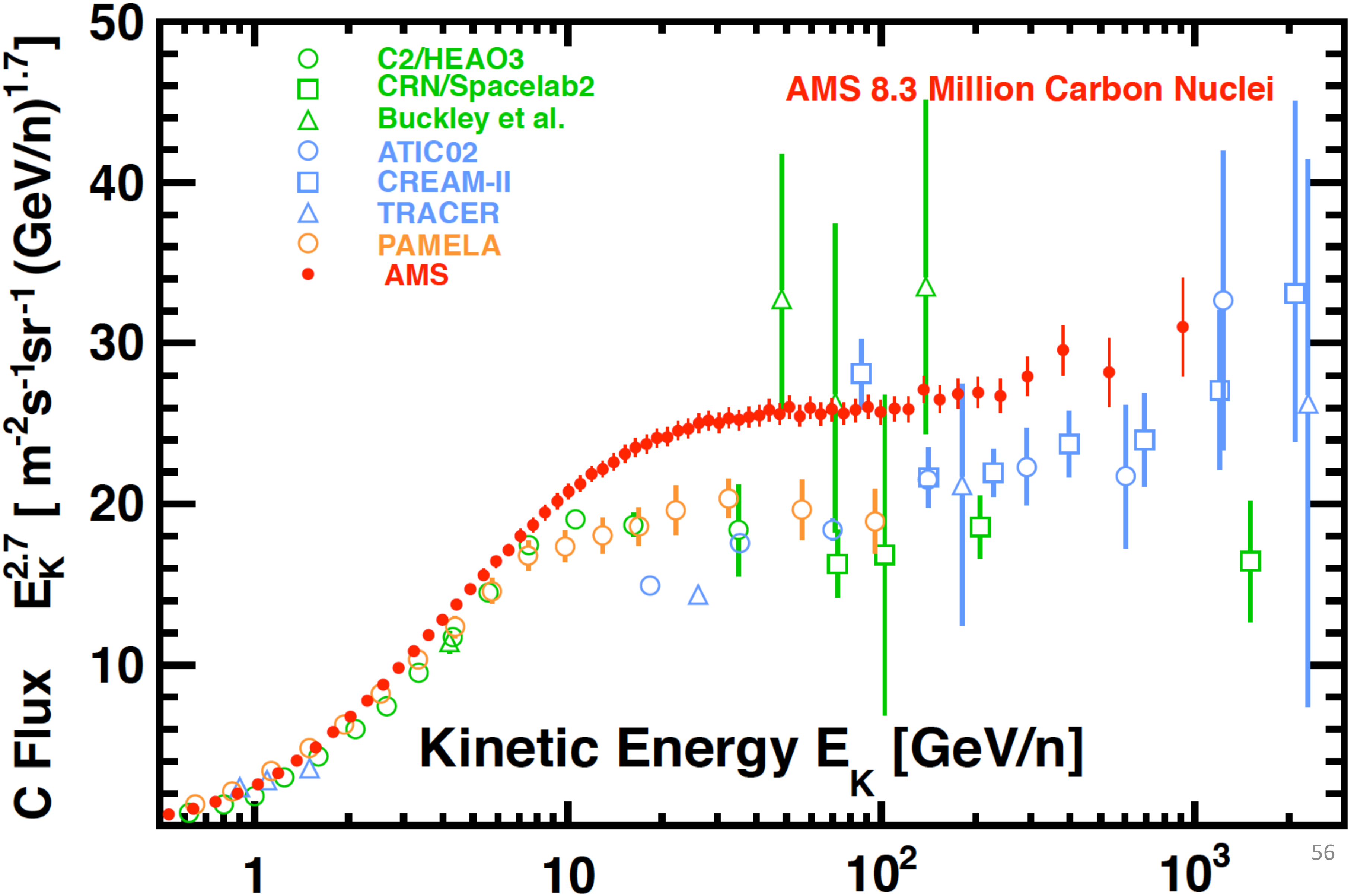
In agreement with the Kolmogorov turbulence model of magnetized plasma

δ = -1/3

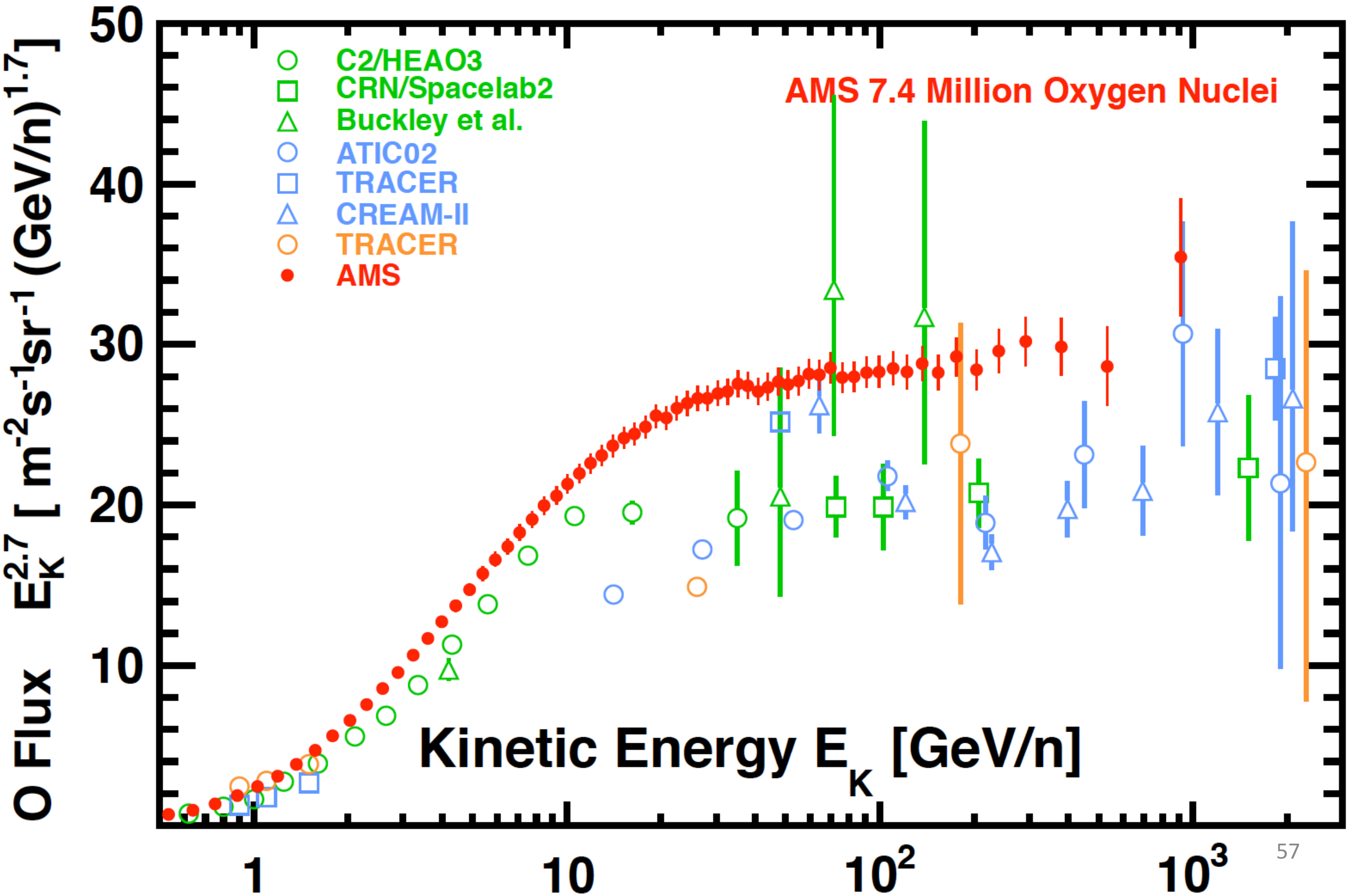


M. Aguilar *et al.*, Phys. Rev. Lett. **117**, 231101 (2016)

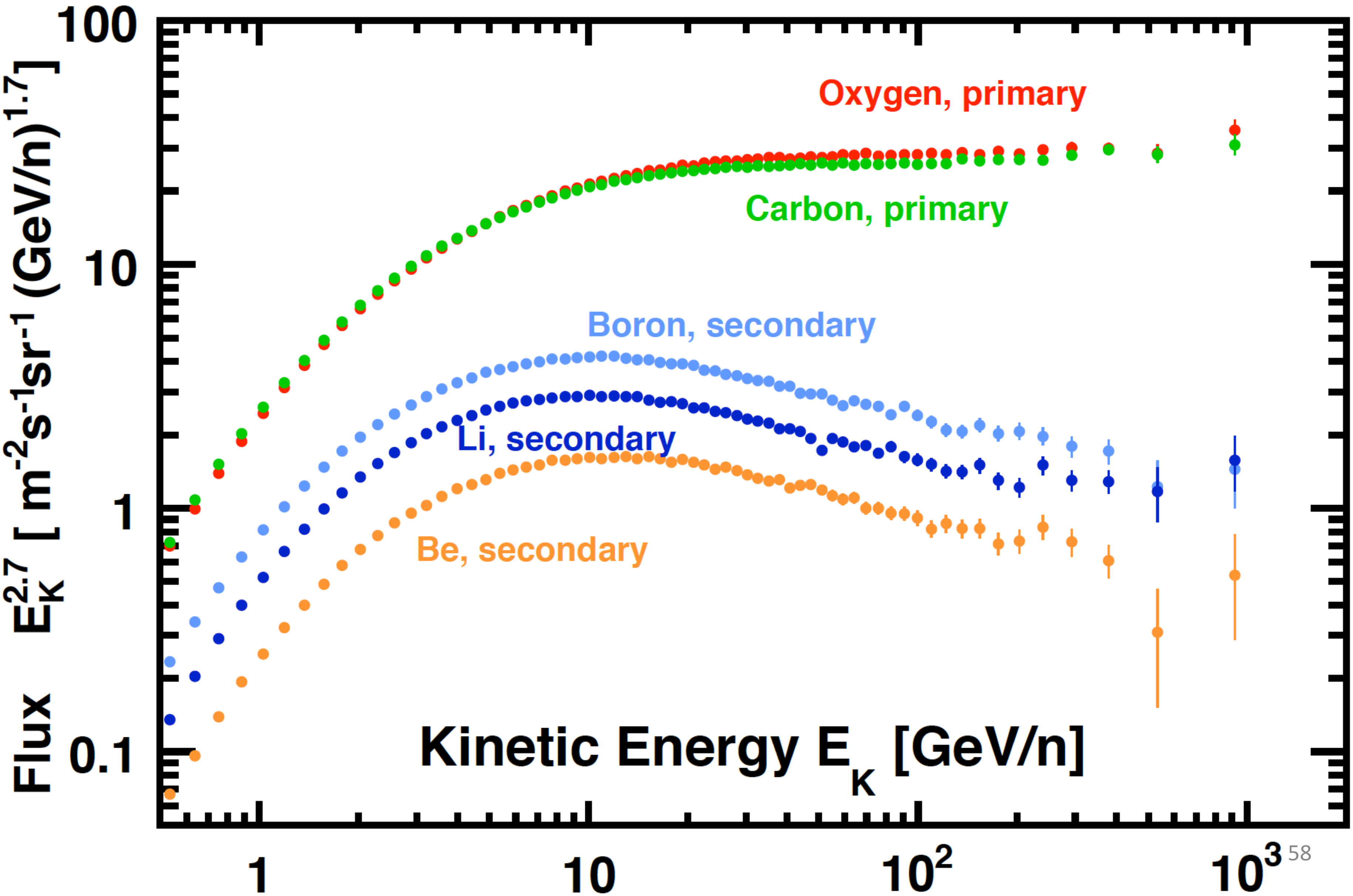
Physics Results 15: The Carbon flux (primary)



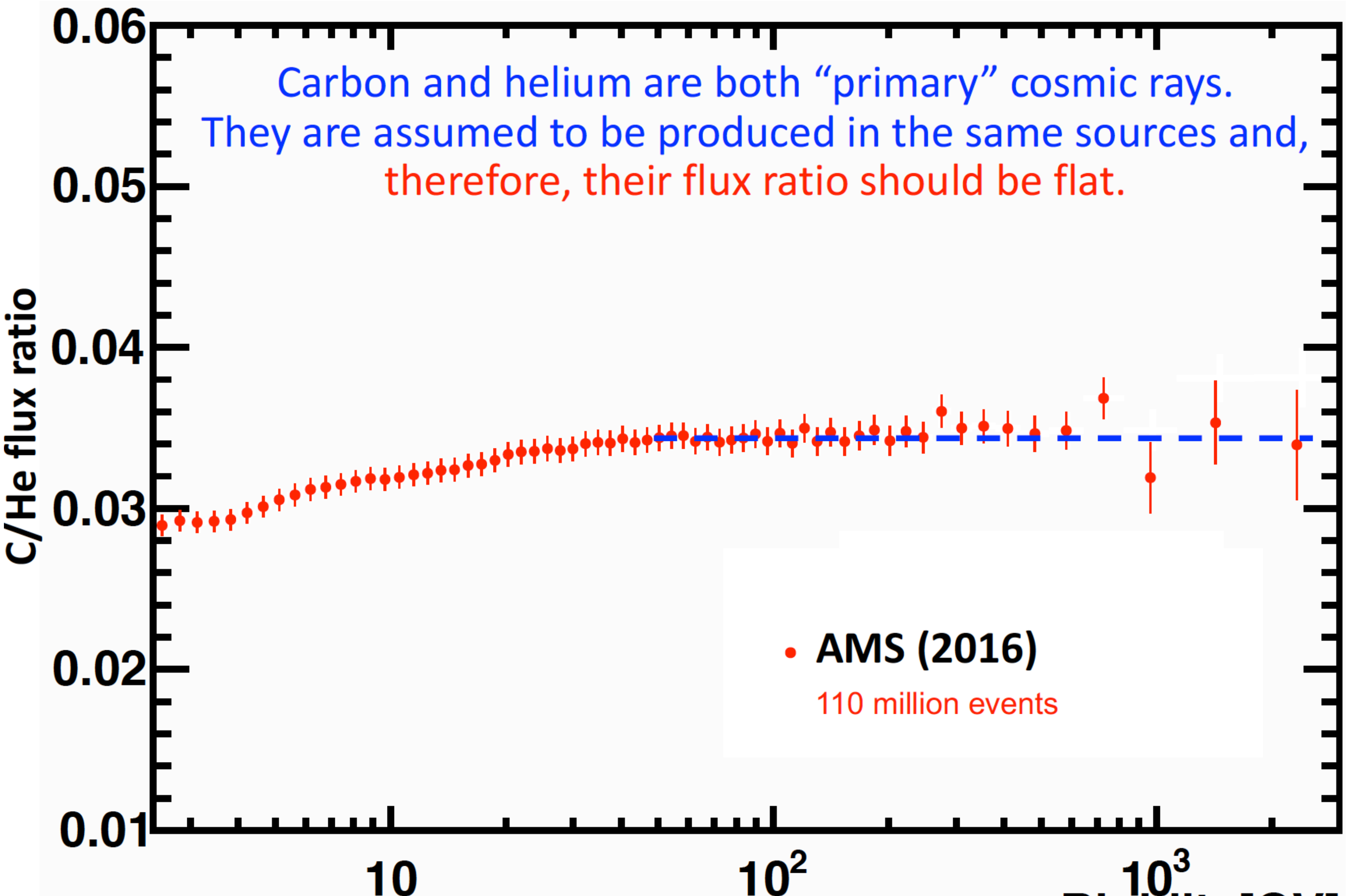
Physics Results 16: The Oxygen flux (primary)



Physics Results 17: Different momentum dependence for primaries and secondaries cosmic rays

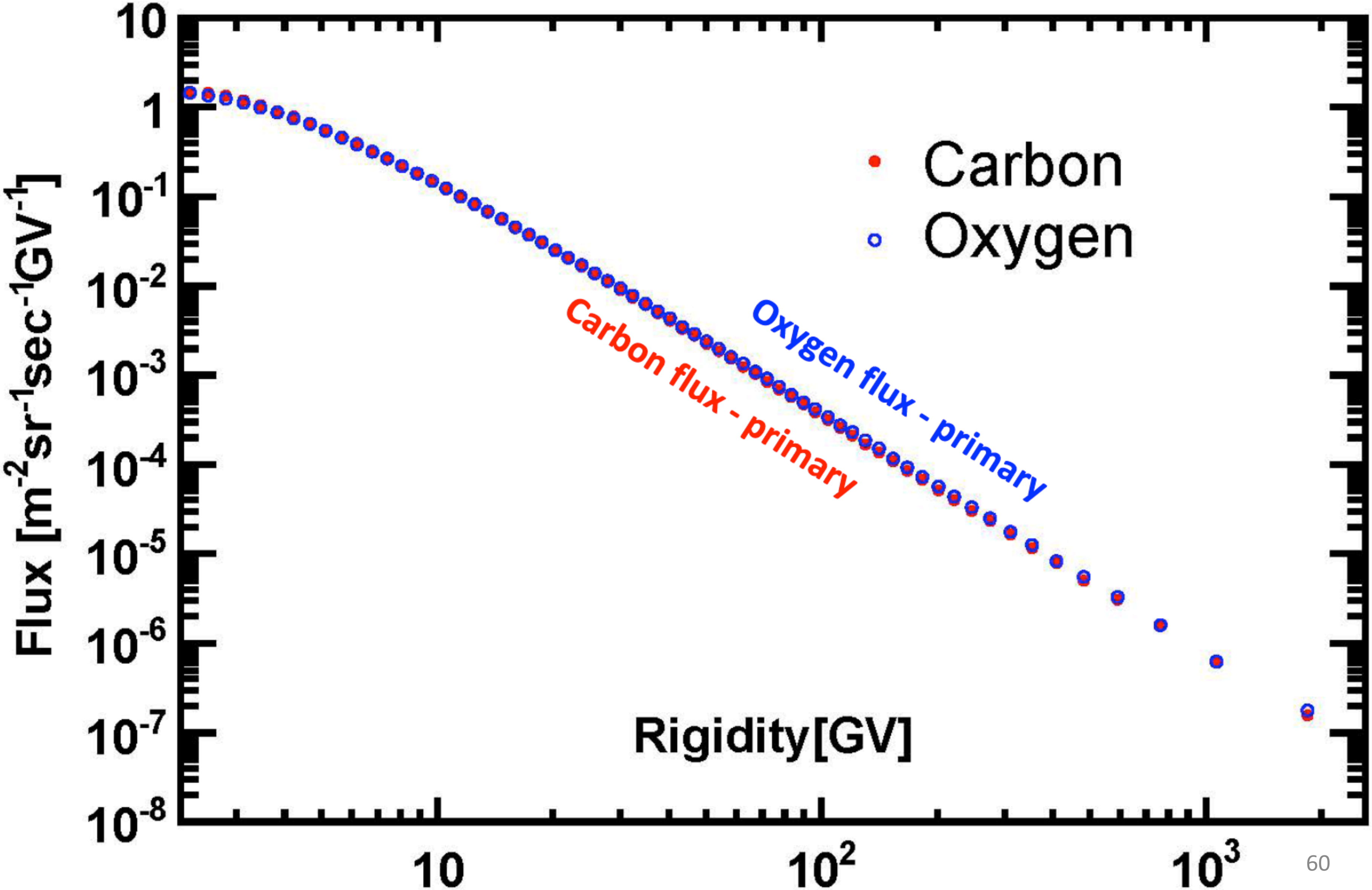


Physics Results 18: The AMS Carbon/Helium flux ratio

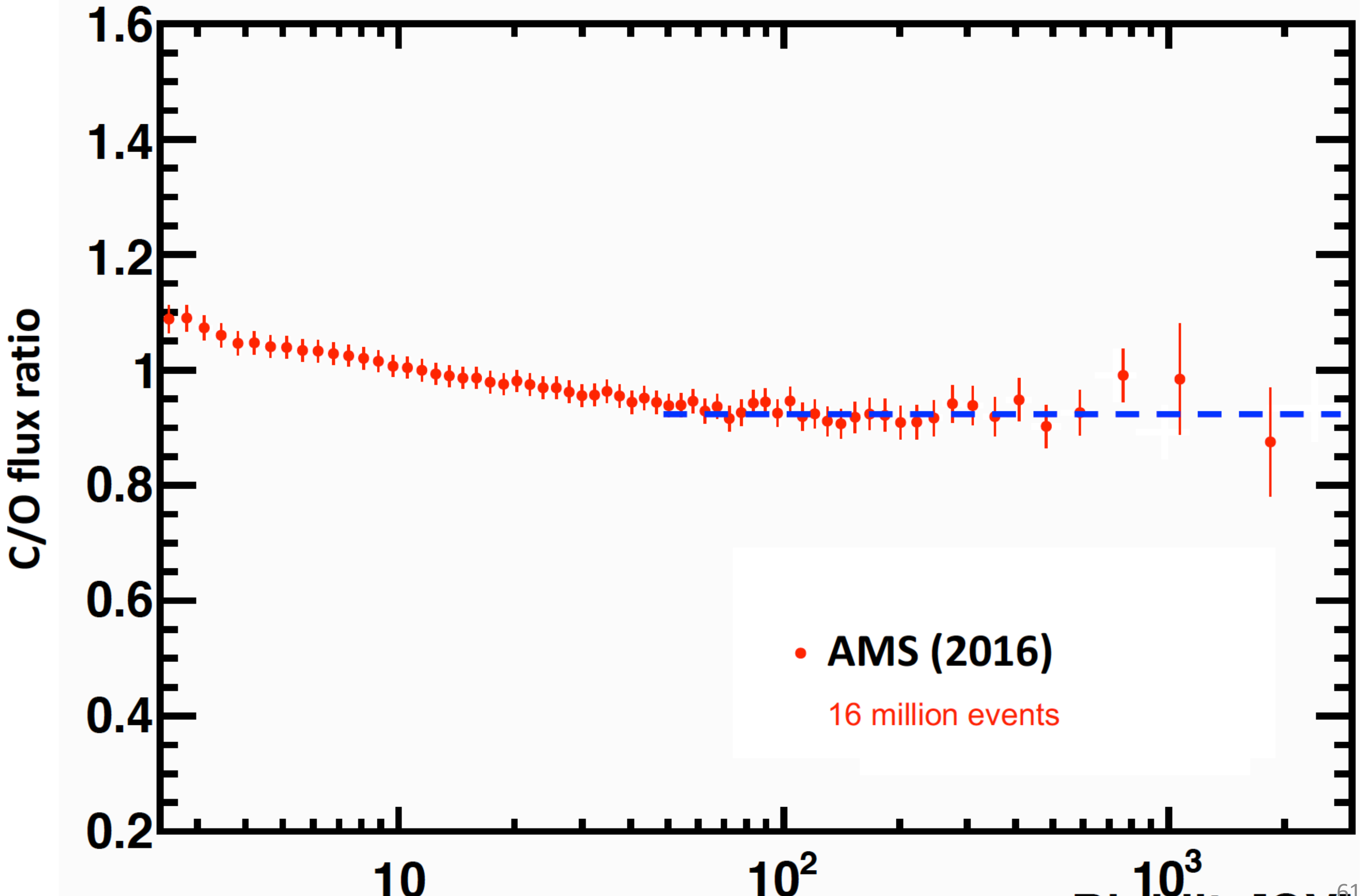


AMS result: the flux ratio is flat.

Physics Results 19: Identical momentum dependence for primary cosmic rays Carbon and Oxygen

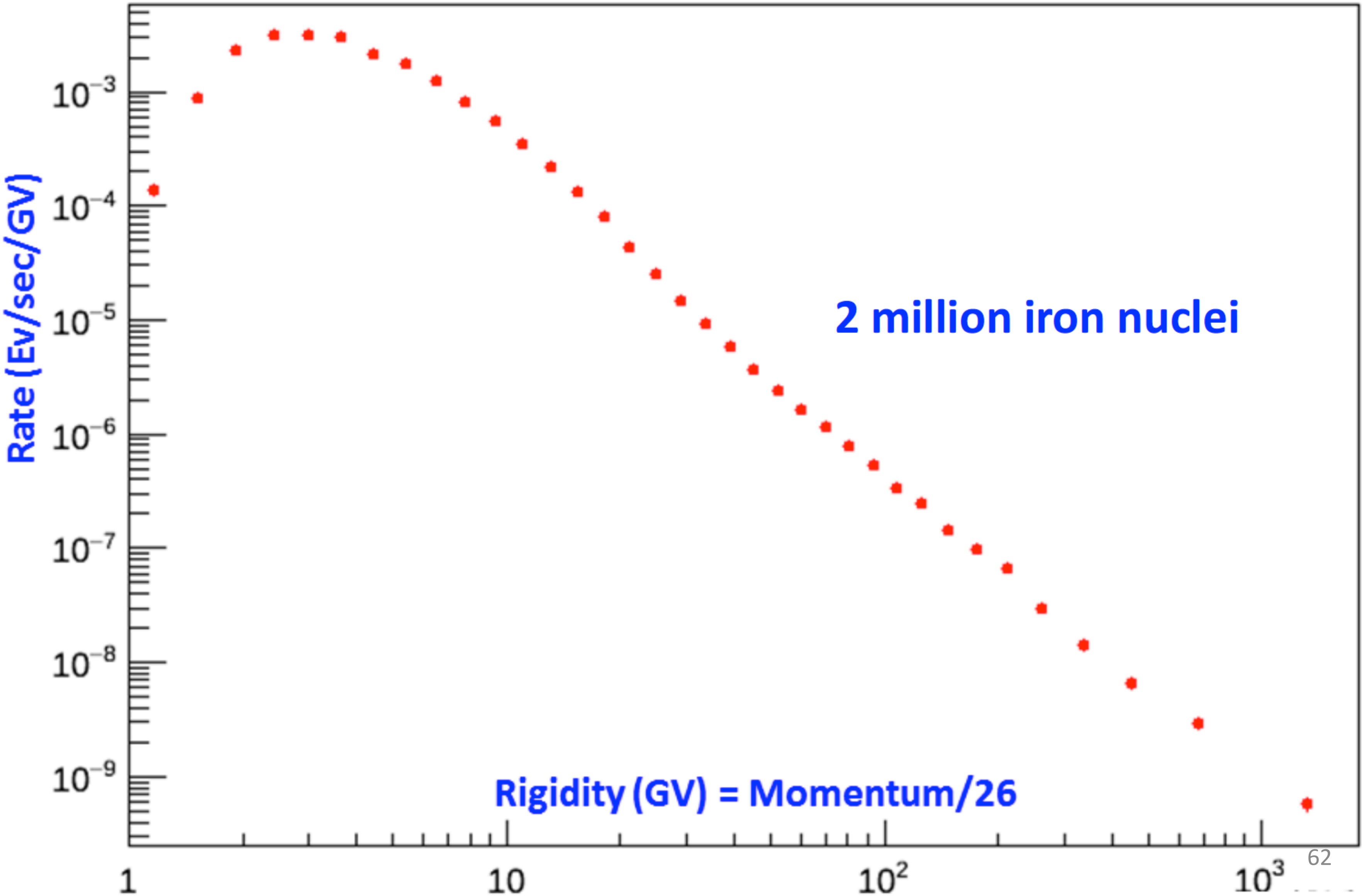


The Carbon/Oxygen flux ratio



AMS result: the flux ratio is flat.

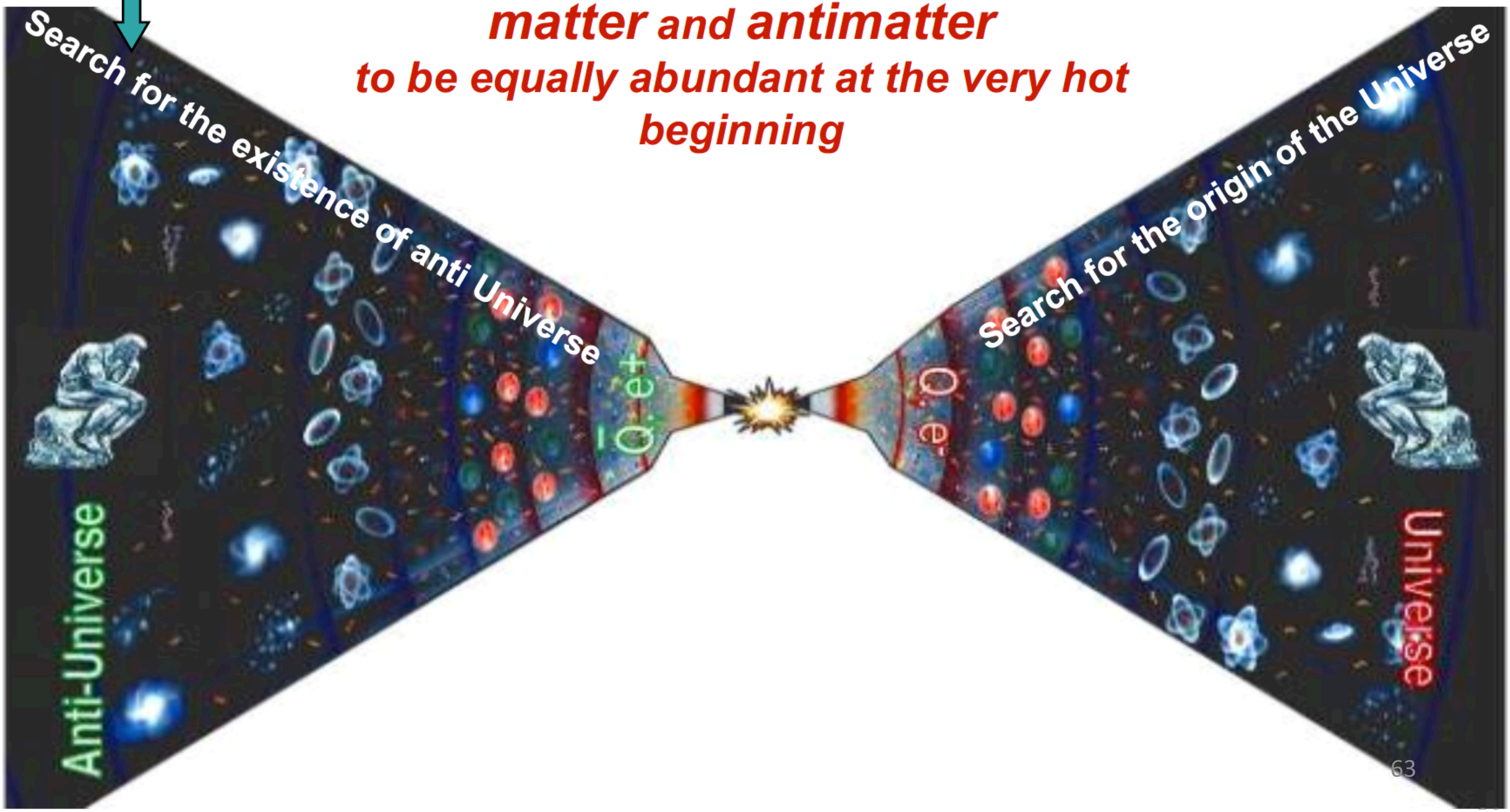
Physics Results 20: Iron rate



Physics Results 21: Search for complex antimatter in cosmic rays (status report)

AMS in Space

The Big Bang origin of the Universe requires
matter and antimatter
to be equally abundant at the very hot beginning



Search for Baryogenesis

Two requirements for the Baryogenesis:

Strong Symmetry Breaking

BELLE, BaBar
FNAL: KTeV, CDF, D0, NOvA
CERN NA-48
T2K,
LHC: LHC-b, ATLAS,CMS

Proton has a finite lifetime

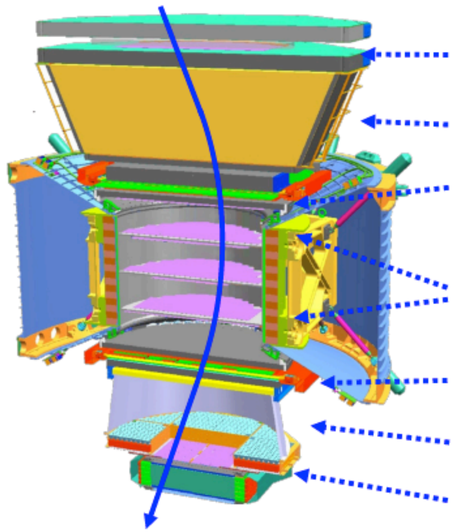
underground experiments

Super Kamiokande

No evidence for strong symmetry breaking nor proton decay have been found so far!!!

Searching antihelium

In five years, 3.7 billion helium events have been collected by AMS when both the Upper and Lower TOF measure |Z| = 2 with an accuracy of 0.08



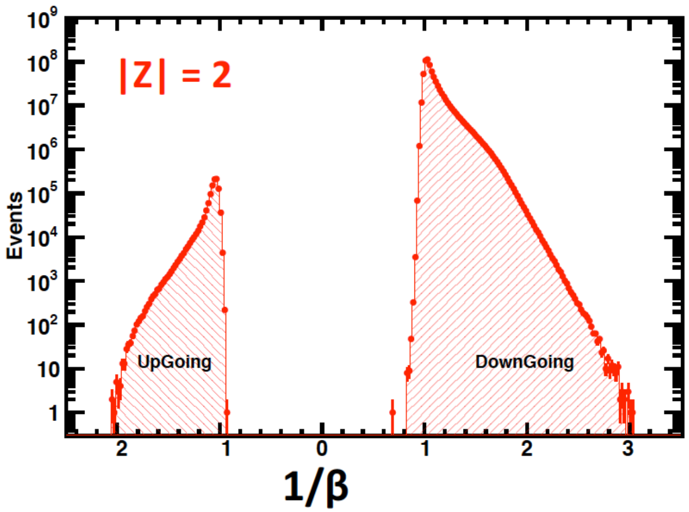
Of these, 100 million passed through the full lever arm (L1 to L9) and are used in the analysis of the helium spectrum.

In our helium publication we used the first 2.5 years of data (50 million events).

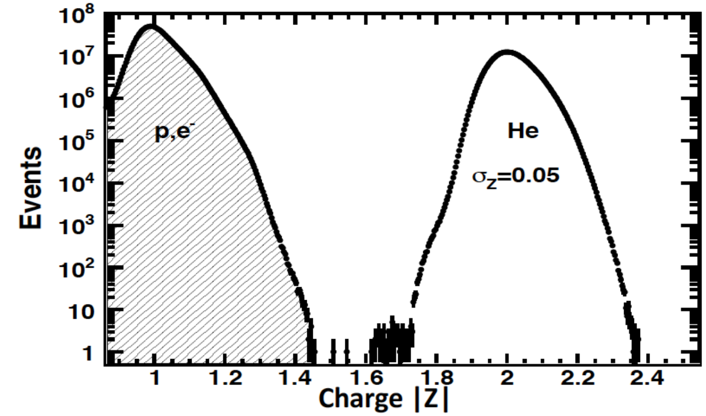
In searching for antihelium we use a larger acceptance (L2 to L8) with 700 million helium events to date.

Identification of antihelium

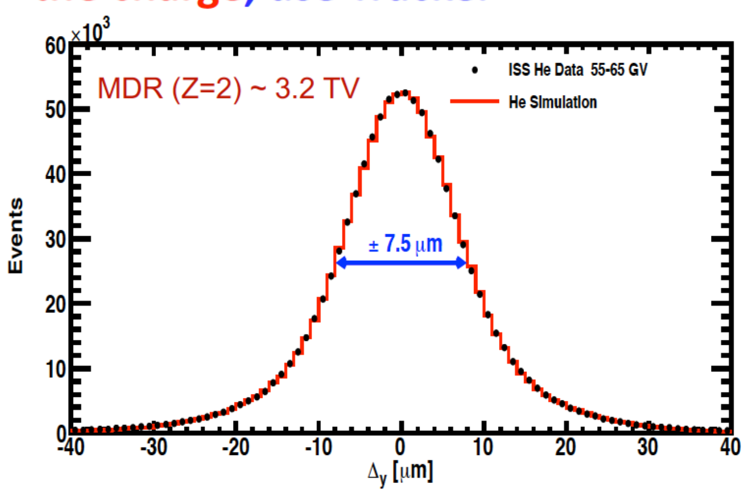
1. Determine direction with TOF.



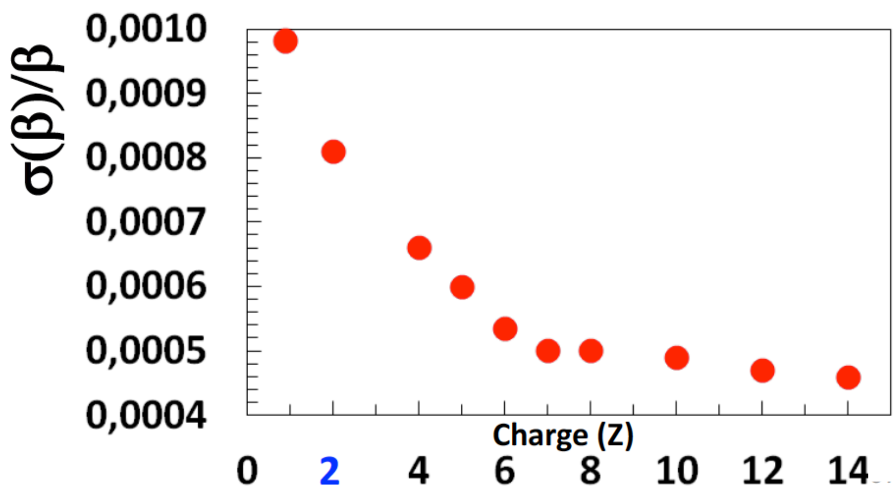
2. To measure |Z|, use the TOF+Tracker+RICH to separate p,e$^{\pm}$ from He



3. To measure momentum and sign of the charge, use Tracker



4. To determine mass, use the RICH to measure the velocity.



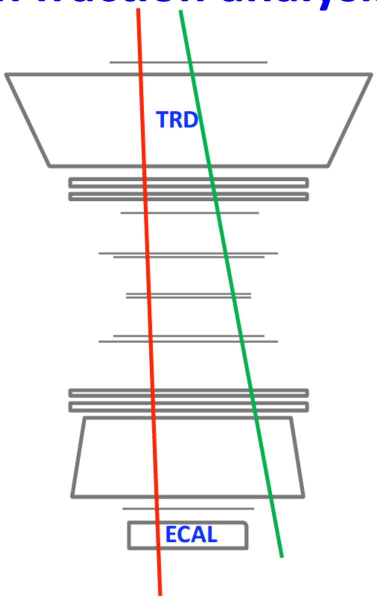
Antihelium Candidates

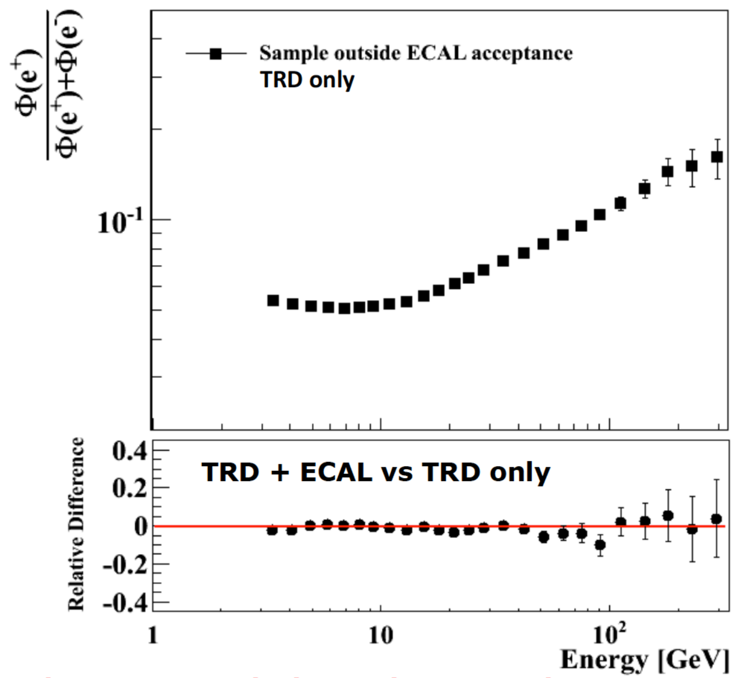
AMS observed few events with z = -2 and with mass around ^{3}He!!!

At a signal to background ratio of $1/10^9$, a detailed understanding of the instrument is required.

Example: Precision measurement of Positron Fraction requires e and p separation of $1/10^6$

Positron fraction analysis with TRD+ECAL compared with TRD Only





Good agreement between two independent samples

Antihelium and AMS

At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.

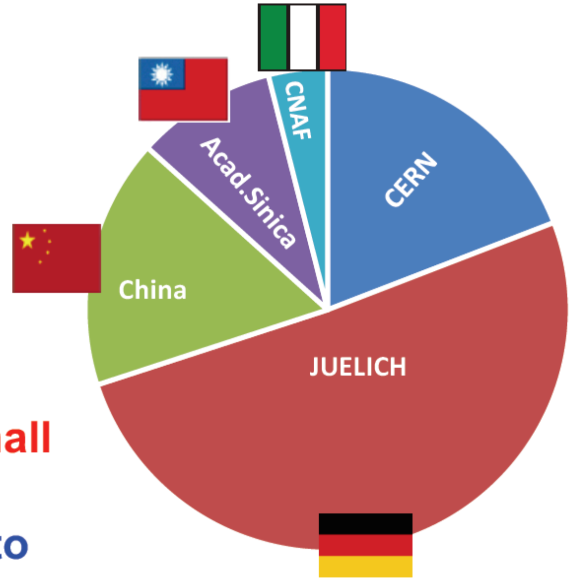
Detector verification is difficult.

1. The magnetic field cannot be changed.

2. The rate is ~1 per year.

3. Simulation studies:

Helium simulation to date:
2.2 million CPU-Days =
35 billion simulated helium events:
Monte Carlo study shows the background is small



How to ensure that the simulation is accurate to one in one billion?

The few candidates have mass 2.8 GeV and charge -2 like $^{3}\overline{\mathrm{He}}$.

It will take a few more years of detector verification and to collect more data to ascertain the origin of these events.

Summary

1) Precise measurement on the Electron and Positron flux => Spectral indexes not constant

2) Excess on Positron flux and Positron fraction => Our dat fits with the DM model

3) Measurement of the Anisotropy

4) Measurement on the $e^+ + e^-$ flux

5) Proton and Helium fluxes described by a double power law function => Spectral indexes not constant

6) Proton/Helium ratio not constant

7) Positron flux has the same energy dependence as the Antiproton and Proton fluxes

8) Excess on Antiproton/Proton ratio

9) Age of the Cosmic rays (Be/B) => ~ 12 million years

Summary

10) Measurement on B/C in agreement with the Kolmogorov turbulence model of a magnetized plasma

11) Different momentum dependence between primaries and secondaries cosmic rays

12) Identical momentum dependence for primary cosmic rays Carbon and Oxygen

13) Iron rate

14) Search for complex antimatter (status report)

Thank you for your attention

Akemashite Omedetou Gozaimasu!!!

Back up Slides

Coming experiments

Payload (Launching Date)	Energy Region (GeV)	Energy Resolution	e/p separation	Instruments*	Exposure in 5 years** (m^2 sr day)	Total Weight (kg)
AMS-02 (2011)	1-2,000 (~800)	~10 % @100 GeV	10^4 - 10^5	Magnet Spectrometer (0.15T) + Sampling Calorimeter (SciFi + Pb: $17X_0$) +TOF+TRD+RICH	55@2TeV (170@800GeV)	7,000
CALET (2015)	1-20,000	~2 % (>10 GeV)	~10^5 Mostly Energy Independent	Imaging Calorimeter (W+SciFi: 3 X_0) + Total Absorption Cal. (PWO : 27 X_0) +Charge Detector (SCN)	220	650
DAMPE* (China : 2015?)	5-10,000	~1.5 %	~10^5	Silicon Tracker +Total Absorption Cal. (BGO: ~31 X_0) +ACD Detector +Neutron Detector	900	1,500
GAMMA-400* (Russia : 2017?)	1-sevral 10,000	~1 % (>100GeV)	~$4x10^5$	Imaging Calorimeter ($2X_0$) + Main Calorimeter- calocube (25 X_0)	730(vertical) x10 (all)	1,700

Table by S. Torii

Can we explain AMS-02 antiproton and positron excesses simultaneously by nearby supernovae without pulsars or dark matter? (Kohri *et al.* Prog. Theor. Exp. Phys. **2016** , 021)

. . . .

We explain the excess of the antiproton fraction recently reported by the AMS-02 experiment by considering collisions between cosmic-ray protons accelerated by a local supernova remnant and the surrounding dense cloud. The same "*pp* collisions" provide the right ratio of daughter particles to fit the observed positron excess simultaneously in the natural model parameters. The supernova happened in relatively lower metallicity than the major cosmic-ray sources. The cutoff energy of electrons marks the supernova age of $\sim 10^5$ years, while the antiproton excess may extend to higher energy. Both antiproton and positron fluxes are completely consistent with our predictions in an earlier paper [Y. Fujita et al., Phys. Rev. D **80**, 063003 (2009) [arXiv:0903.5298 [astro-ph.HE]]].

. . . .

Can we explain AMS-02 antiproton and positron excesses simultaneously by nearby supernovae without pulsars or dark matter? (Kohri *et al.* Prog. Theor. Exp. Phys. **2016** , 021)

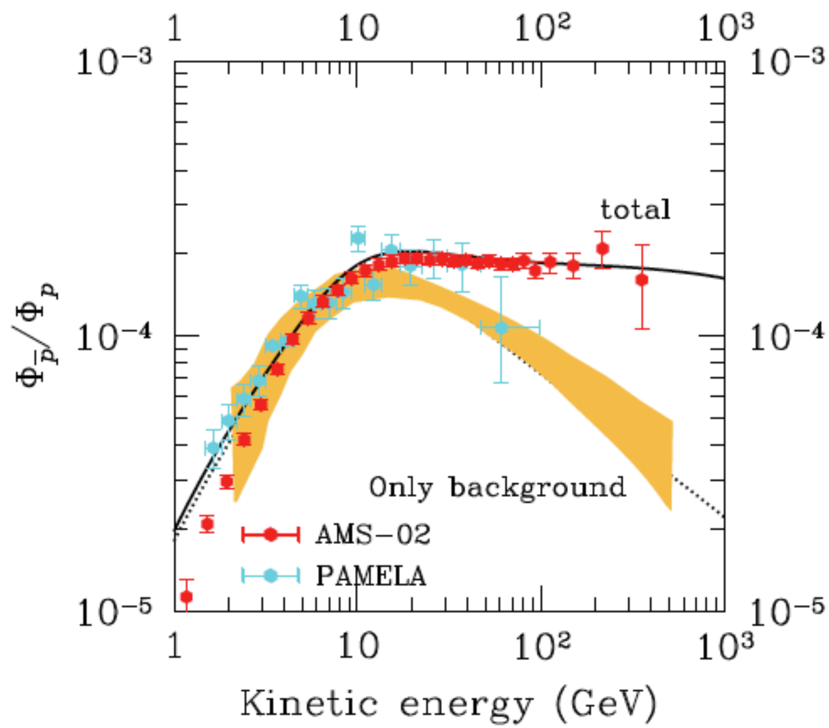


Fig. 1. Antiproton fraction fitted to the data. The data points are taken from Ref. [1] for AMS-02, and from Ref. [17] for PAMELA. The dotted line is plotted only by using the background flux [42]. The shaded region represents the uncertainties of the background flux among the propagation models shown in Ref. [1]. Cosmic rays below an energy $\lesssim$10 GeV are affected by the solar modulation. We choose the background line and its uncertainty band only for demonstration purposes. This choice is not essential for our conclusion (see our discussion of Fig. 3).

ANOMALOUS GALACTIC COSMIC RAYS IN THE FRAMEWORK OF AMS-02
(Khiali *et al.*)

In this paper “ we argued that a transition from diffuse shock acceleration (DSA) to Superdiffuse Shock acceleration (SSA) in SNRs is an acceptable explanation for the recent results of AMS-02, especially the proton and helium hardenings at 300 GV. We proposed that the observed break in proton and helium spectra originates from the source due to different acceleration mechanisms and finally with different injection forms.”

“the He/p ratio decreases with a single power law and indicates that solar modulation and interaction of He nuclei with ISM reduces the flux at lower energies. Furthermore, this figure shows that the abundances of the CR helium are larger than the solar abundance (see Lodders 2003).”

“In addition, this model can be used for recent observed carbon spectrum by the AMS-02 experiment which is similar to that of helium, and for heavier nuclei, which will be provided in the near future.”

Cosmic-ray hardenings in light of AMS-02 data
(Ohira *et al.*)

Recent precise observations of cosmic rays (CRs) by AMS-02 experiment clearly show (1) harder spectra of helium and carbon compared to protons by $\propto R^{0.08}$, and (2) concave breaks in proton and helium spectra at a rigidity $R \sim 300$ GV. In particular the helium and carbon spectra are exactly similar, pointing to the same acceleration site. We examine possible interpretations of these features and identify a chemically enriched region, that is, superbubbles as the most probable origin of Galactic CRs in high rigidity $R > 30$ GV. The similar spectra of CR carbon and helium further suggest that the CRs with $R > 30$ GV originate from the supernova ejecta in the superbubble core, mixed with comparable or less amount of interstellar medium. We predict similar spectra for heavy nuclei.