The Latest Results from AMS on the International Space Station
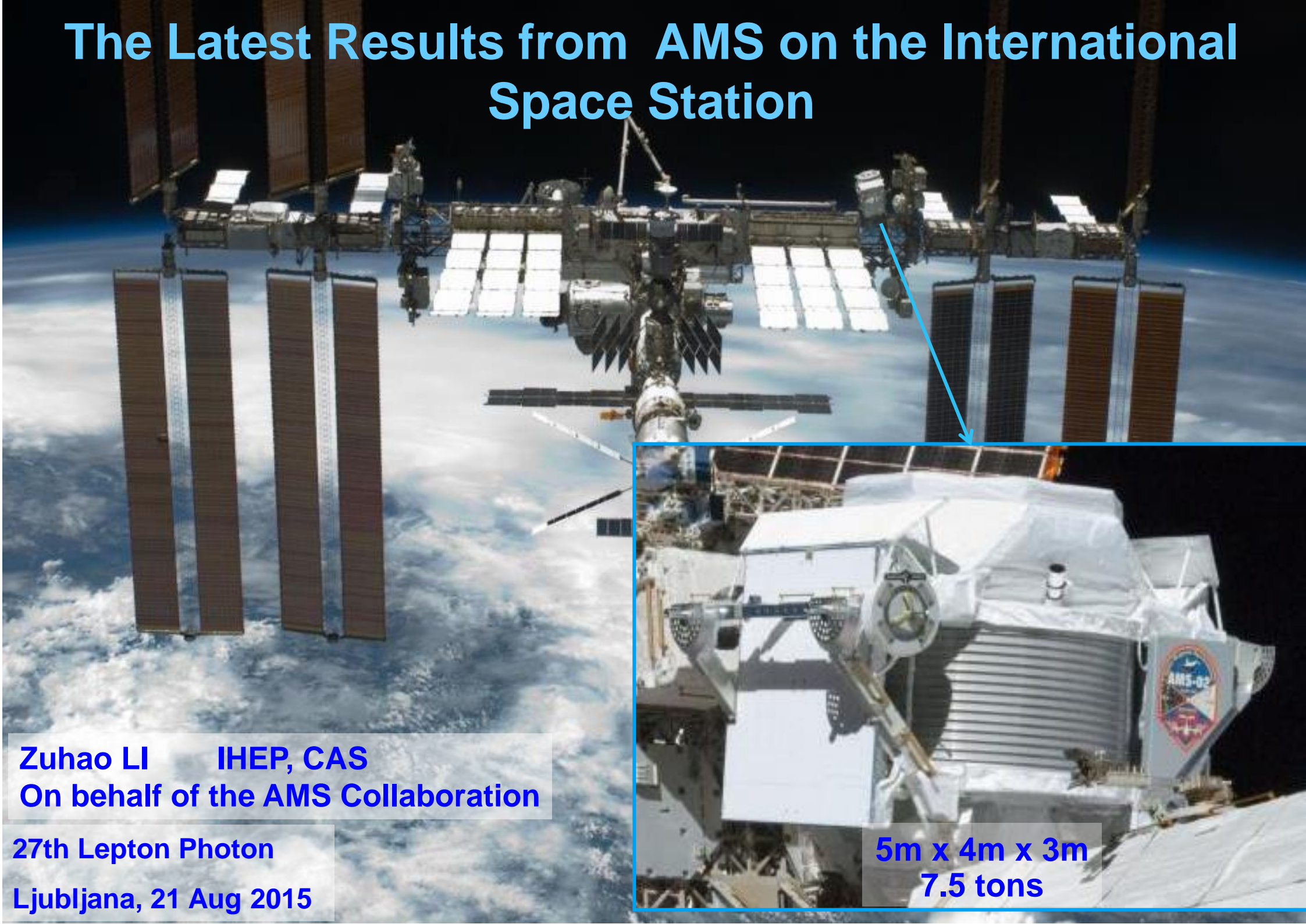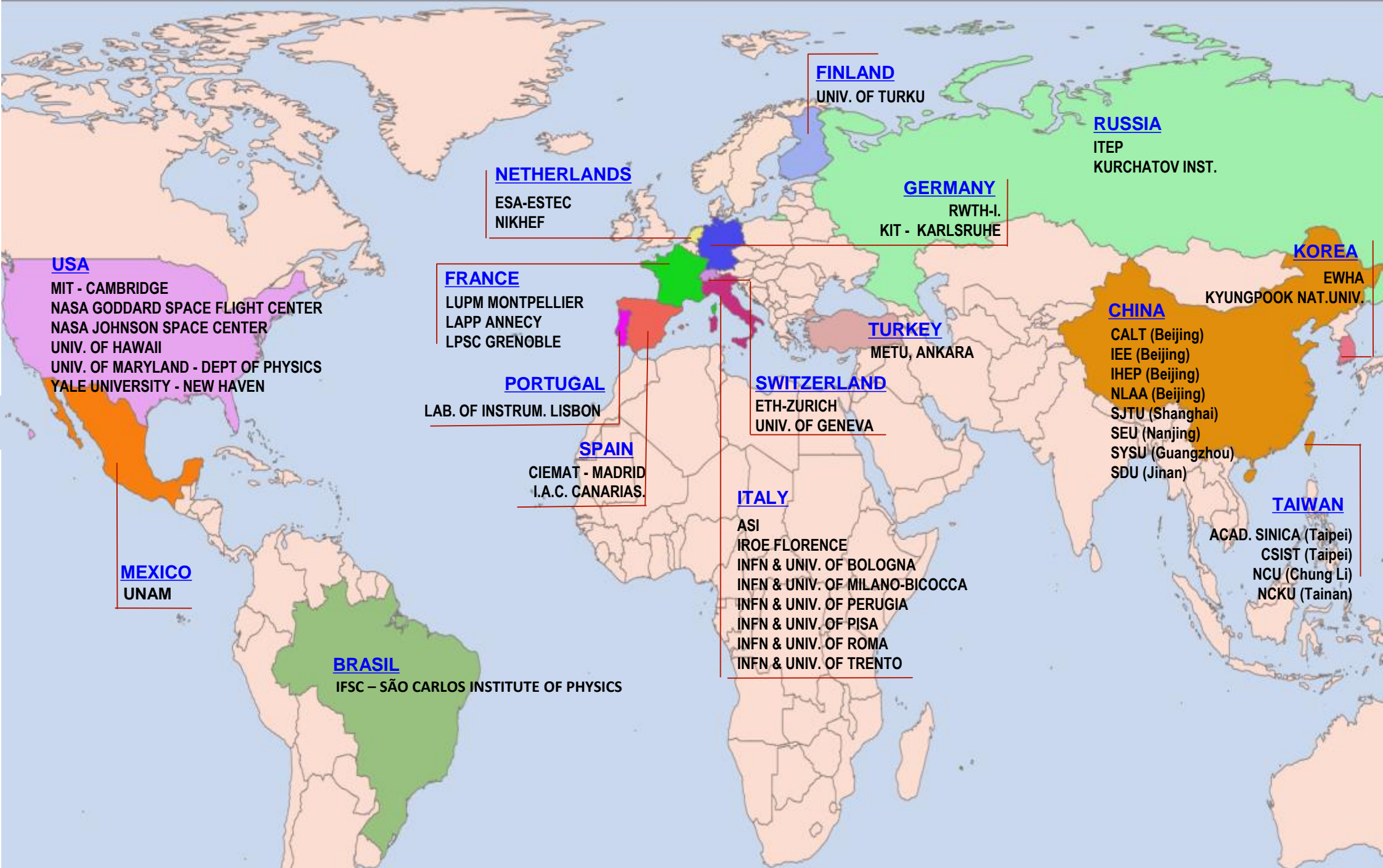
Zuhao LI   IHEP, CAS
On behalf of the AMS Collaboration

27th Lepton Photon

Ljubljana, 21 Aug 2015

5m x 4m x 3m
7.5 tons

FINLAND
UNIV. OF TURKU

RUSSIA
ITEP
KURCHATOV INST.

NETHERLANDS
ESA-ESTEC
NIKHEF

GERMANY
RWTH-I.
KIT - KARLSRUHE

KOREA
EWHA
KYUNGPOOK NAT.UNIV.

USA
MIT - CAMBRIDGE
NASA GODDARD SPACE FLIGHT CENTER
NASA JOHNSON SPACE CENTER
UNIV. OF HAWAII
UNIV. OF MARYLAND - DEPT OF PHYSICS
YALE UNIVERSITY - NEW HAVEN

FRANCE
LUPM MONTPELLIER
LAPP ANNECY
LPSC GRENOBLE

CHINA
CALT (Beijing)
IEE (Beijing)
IHEP (Beijing)
NLAA (Beijing)
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SEU (Nanjing)
SYSU (Guangzhou)
SDU (Jinan)

TURKEY
METU, ANKARA

PORTUGAL
LAB. OF INSTRUM. LISBON

SWITZERLAND
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TAIWAN
ACAD. SINICA (Taipei)
CSIST (Taipei)
NCU (Chung Li)
NCKU (Tainan)

SPAIN
CIEMAT - MADRID
I.A.C. CANARIAS.

ITALY
ASI
IROE FLORENCE
INFN & UNIV. OF BOLOGNA
INFN & UNIV. OF MILANO-BICOCCA
INFN & UNIV. OF PERUGIA
INFN & UNIV. OF PISA
INFN & UNIV. OF ROMA
INFN & UNIV. OF TRENTO

MEXICO
UNAM

BRASIL
IFSC – SÃO CARLOS INSTITUTE OF PHYSICS

AMS is a large international collaboration

2

AMS: A TeV precision, multipurpose spectrometer
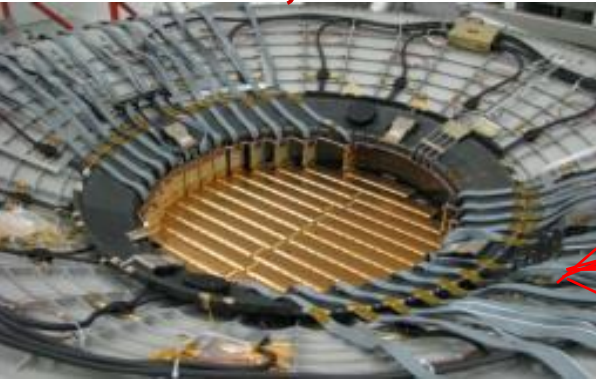
TRD
Identify e^+, e^-
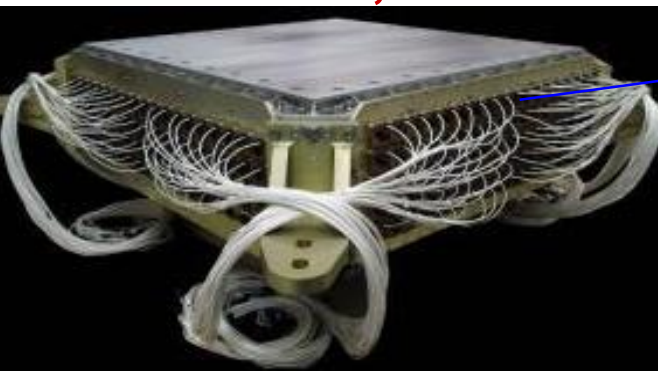
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TOF
Z, E

Silicon Tracker
Z, P

Magnet
±Z

ECAL
E of e^+, e^-

RICH
Z, E

TRD

TOF

1

2

3-4

5-6

7-8

Tracker

TOF

RICH

9
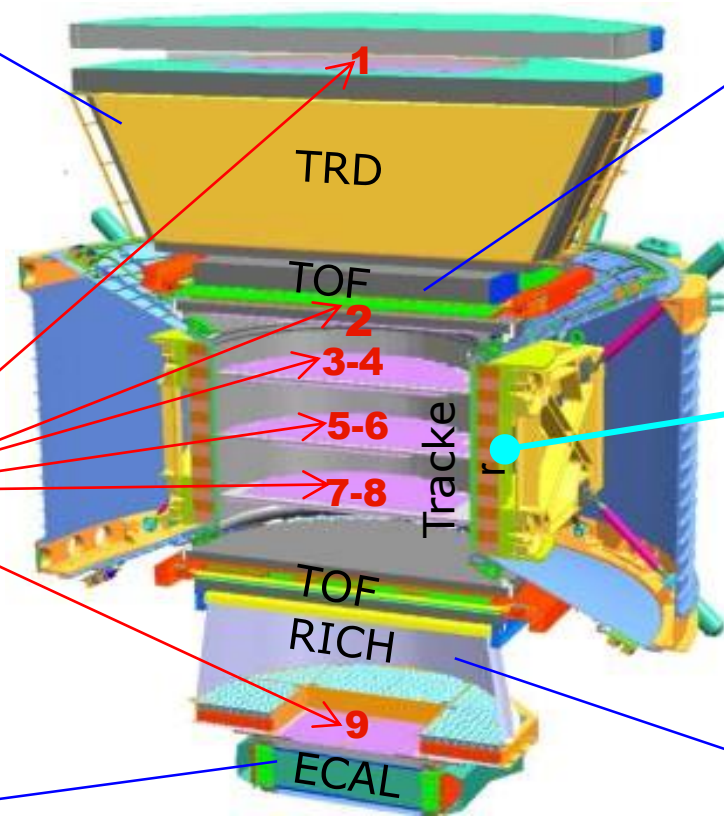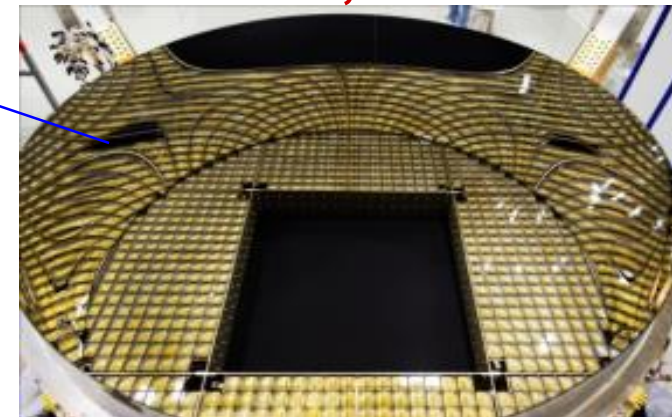
ECAL

*Z and P ~ E
are measured independently by the
Tracker, RICH, TOF and ECAL*

Transition Radiation Detector

p **e$^\pm$**

One of 20 layers

radiator

Measurement with 1 of the 20 TRD Layers

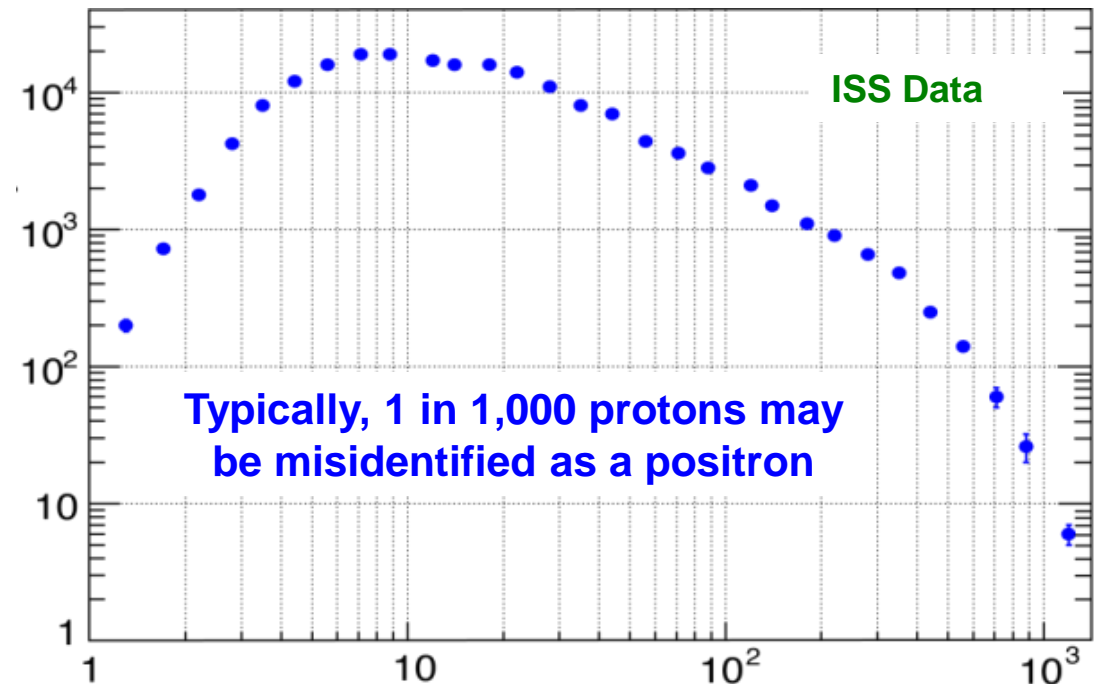Electrons

Transition Radiation

Protons

ISS Data

1/N dn/2 ADC

Amplitude [ADC]

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

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

TRD estimator = -ln(P_e/(P_e+P_p))
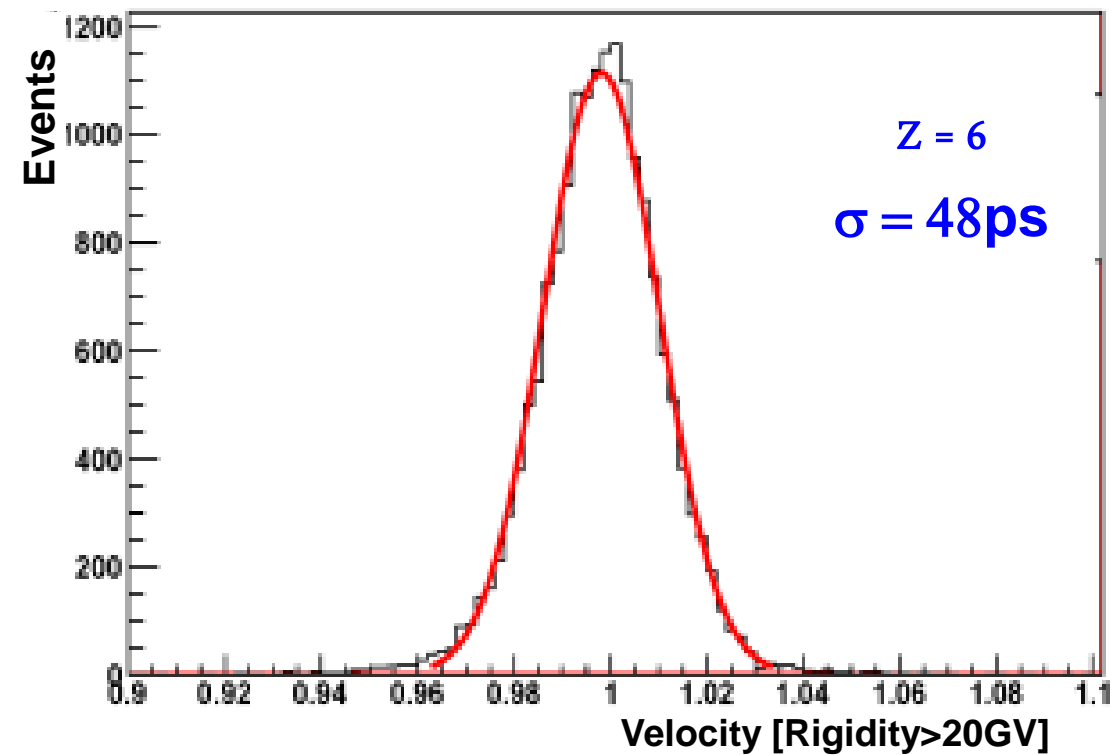
20 layers: fleece radiator and proportional tubes

ISS Data

Typically, 1 in 1,000 protons may be misidentified as a positron

Proton rejection at 90% e$^+$ efficiency
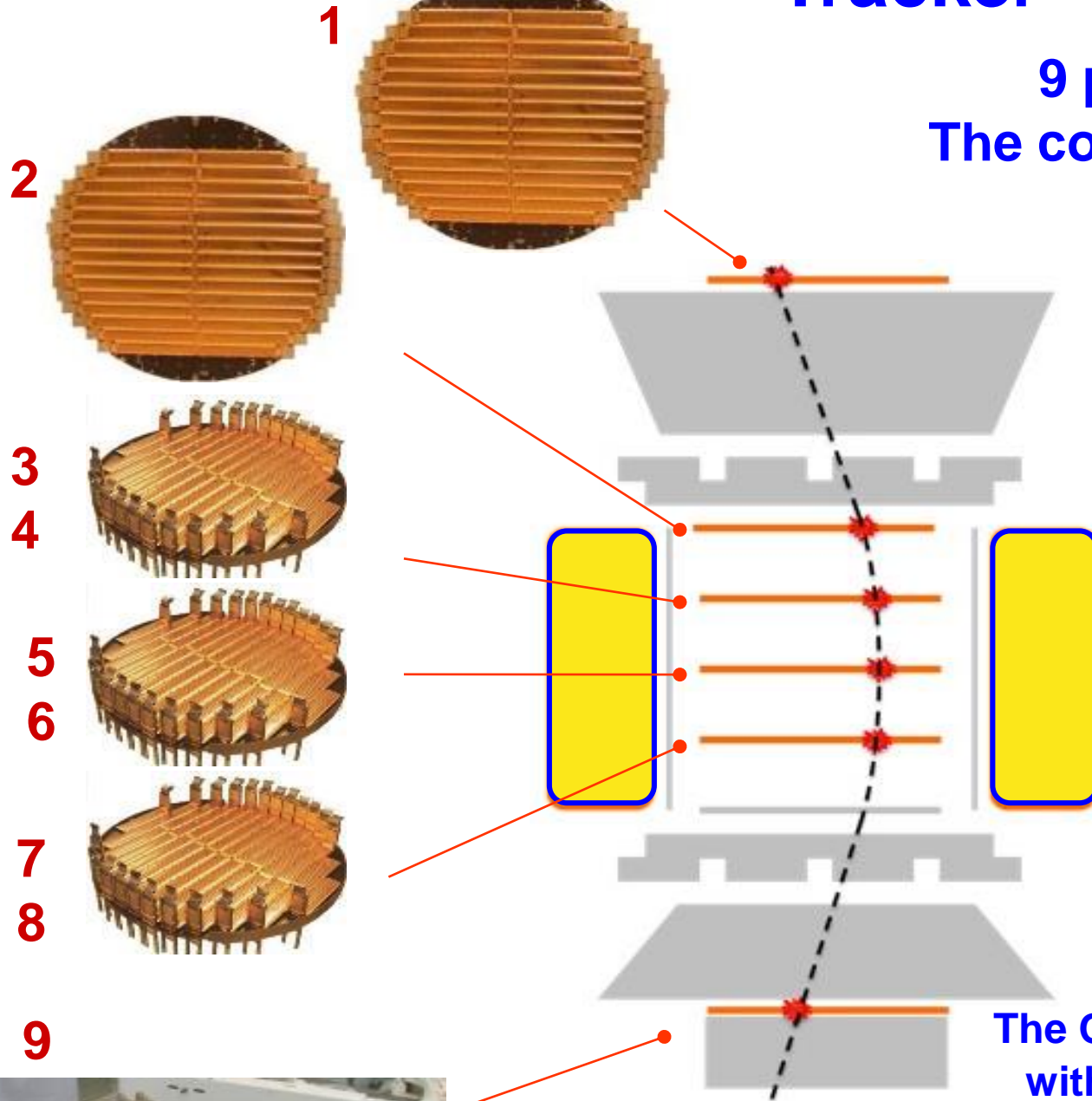
Rigidity (GV)

Time of Flight System

Measures Velocity and Charge of particles

PMs
Conical light guides
Curved light guides
Scintillator
Clear plastic

Events

Z = 6

$\sigma = 48ps$

Velocity [Rigidity>20GV]
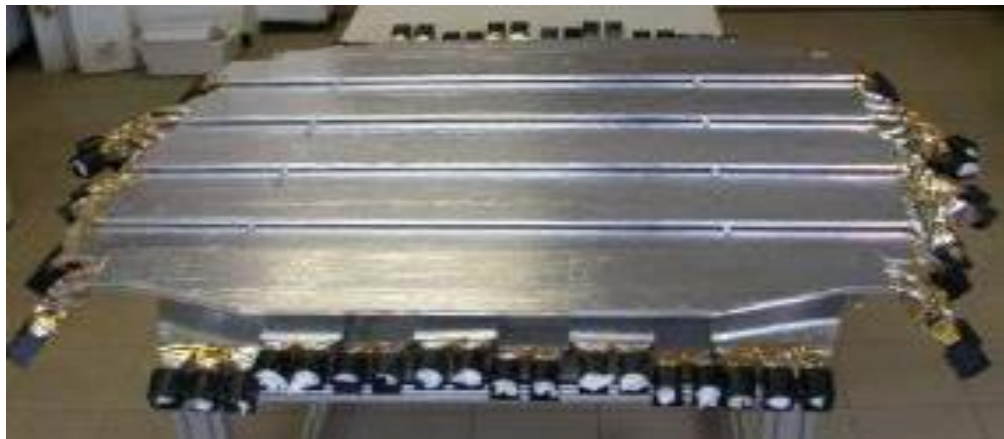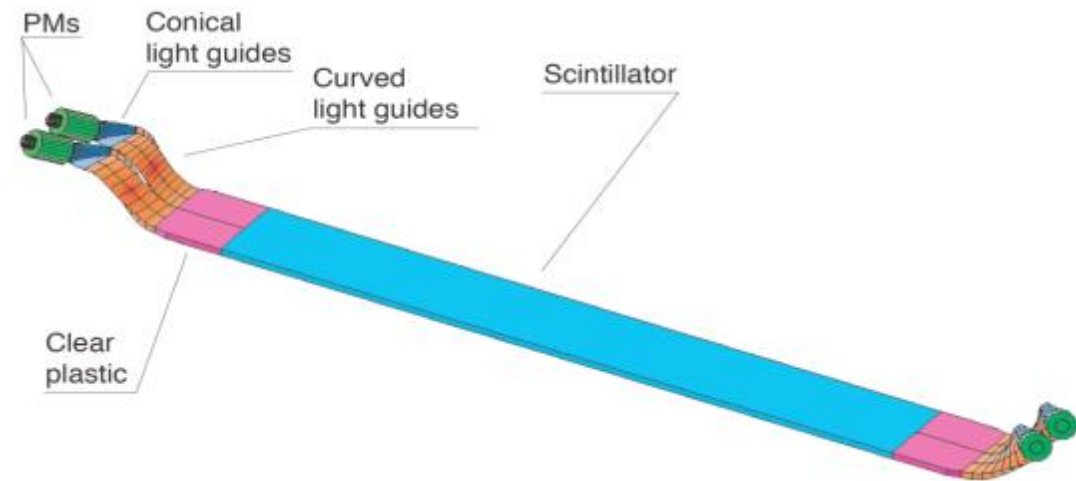
Tracker

9 planes, 200,000 channels
The coordinate resolution is 10 μm.
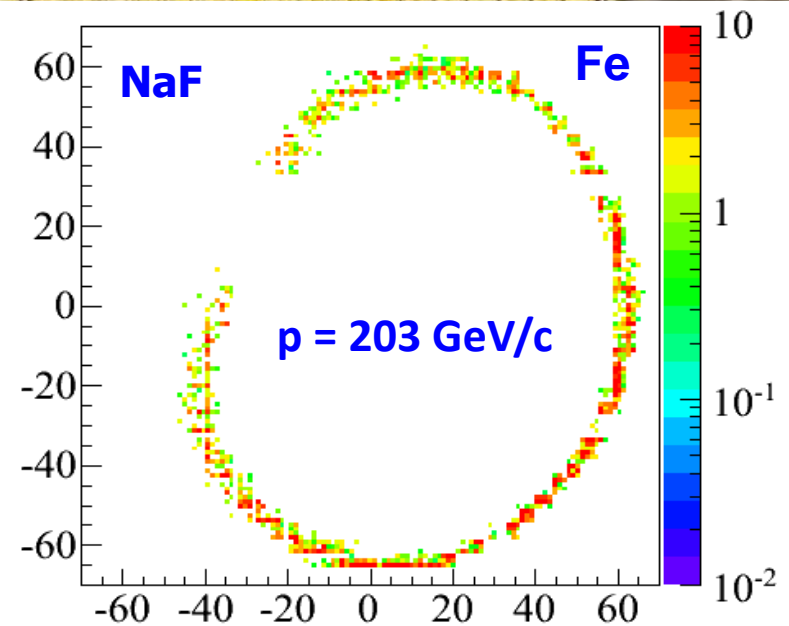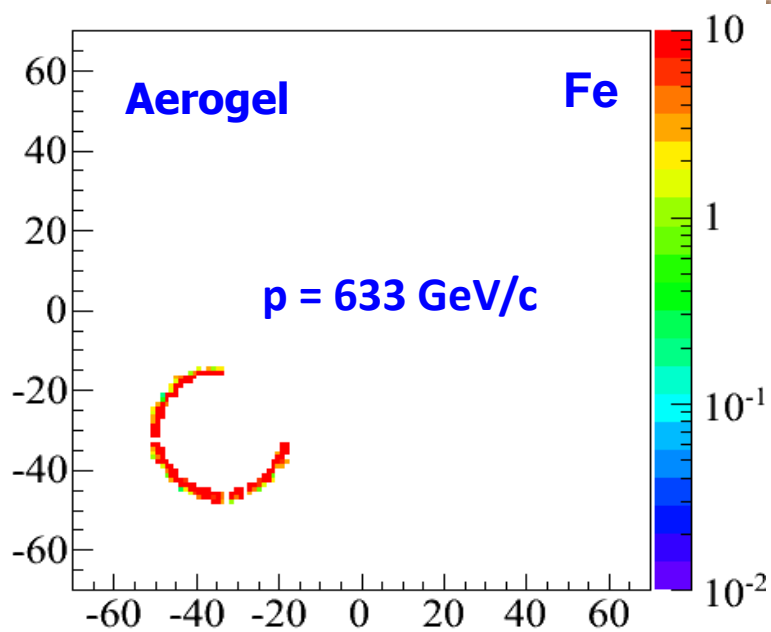
1

2

3
4

5

6

7
8

9
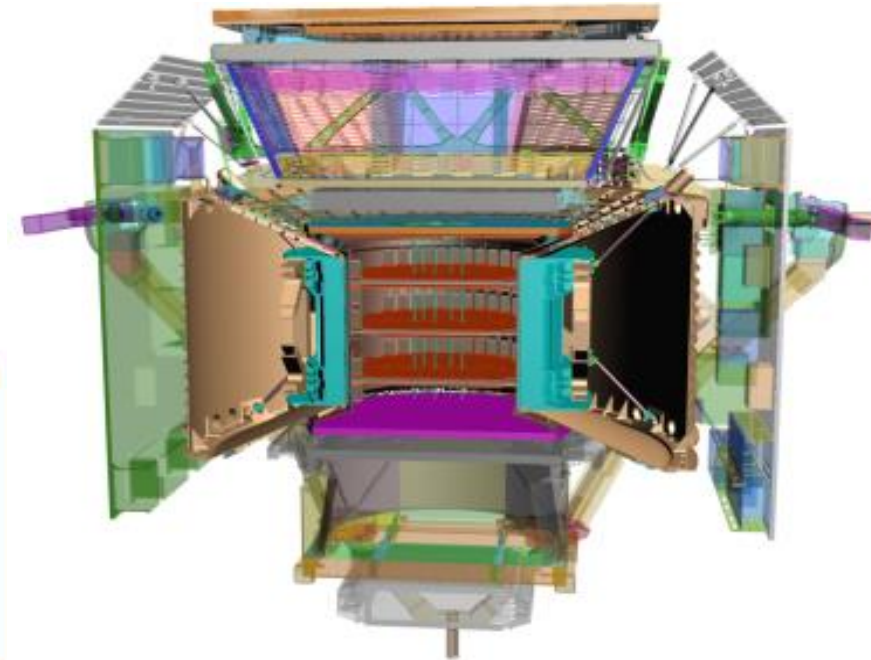
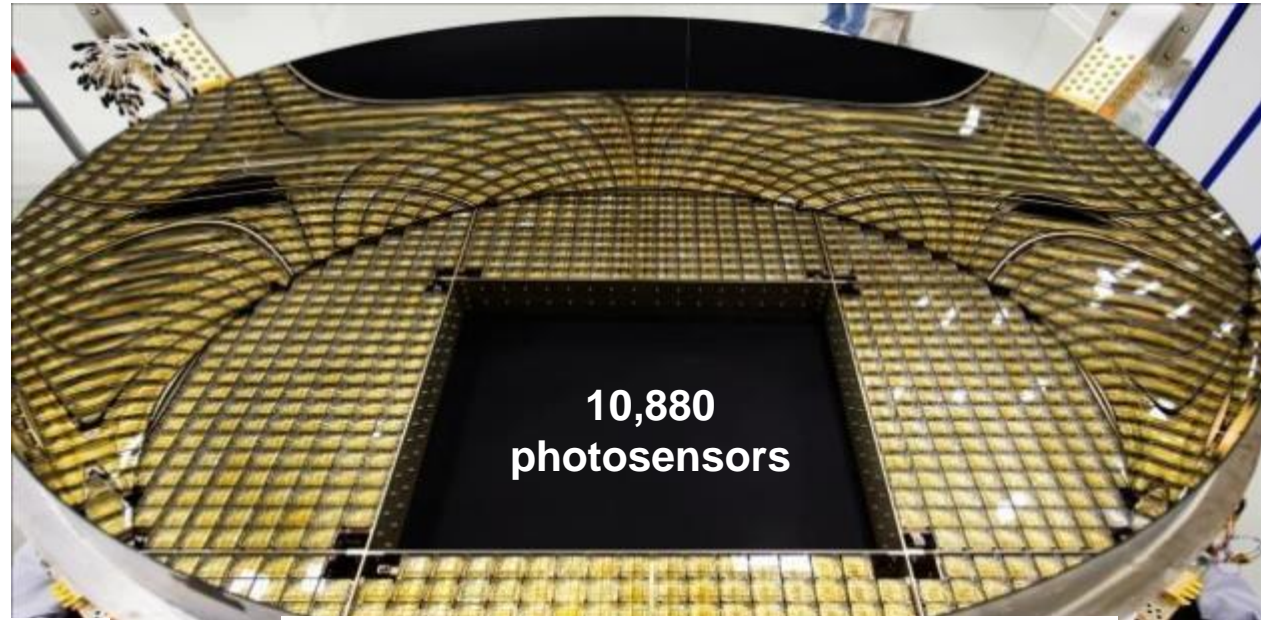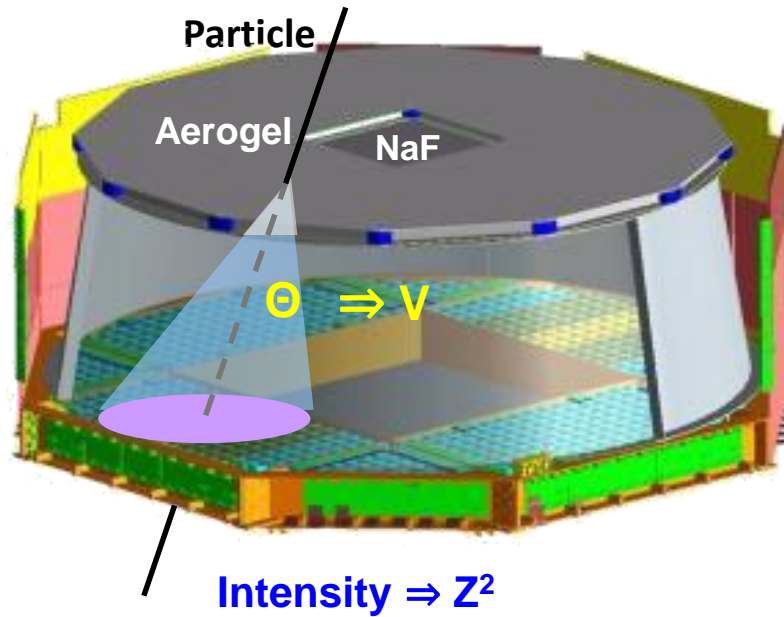**Inner tracker alignment stability monitored with IR Lasers.**

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

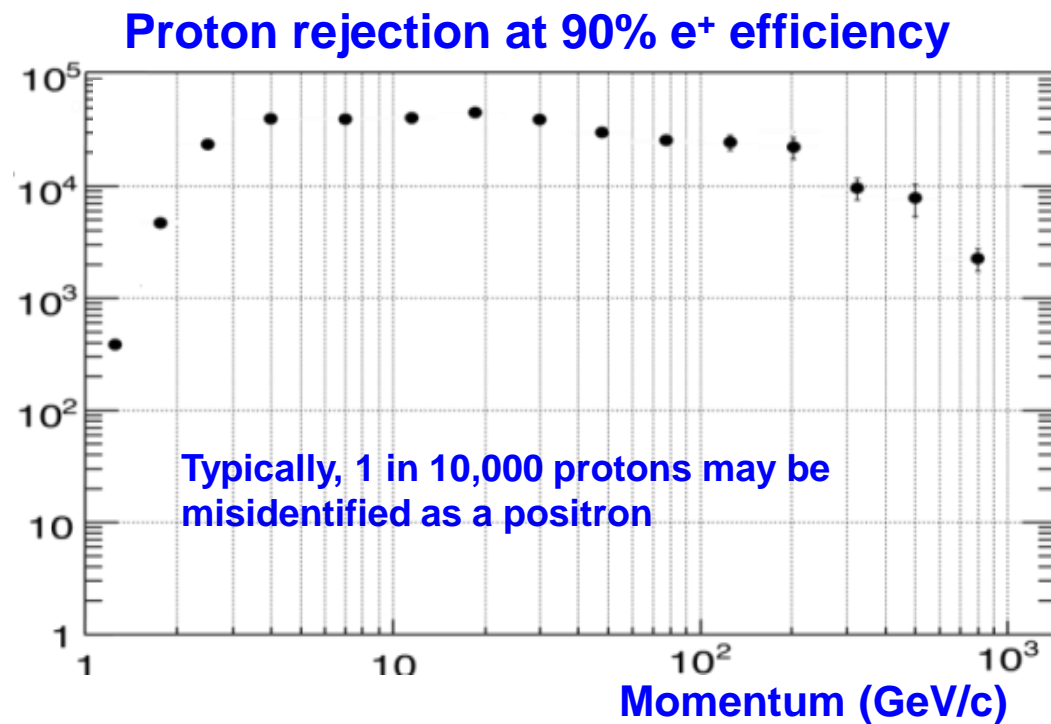# Ring Imaging CHerenkov (RICH)

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

Particle

Aerogel

NaF

$\Theta \Rightarrow V$

Intensity $\Rightarrow Z^2$

10,880 photosensors

Aerogel   Fe

p = 633 GeV/c

NaF   Fe

p = 203 GeV/c

Electromagnetic Calorimeter

Provides a precision, 17 X$_0$, TeV, 3-dimensional measurement of the directions and energies of electrons and positrons, seperate e$^\pm$ from protons

**Boosted Decision Tree (BDT):
3D shower shape**

protons

$\varepsilon_e = 90\%$

electrons

Fraction of events

ECAL estimator

Test beam result

$$\sqrt{\frac{(10.4)^2}{E} + (1.4)^2}$$

Energy Resolution(%)

Energy(GeV)

Proton rejection at 90% e$^+$ efficiency

Typically, 1 in 10,000 protons may be misidentified as a positron

Momentum (GeV/c)
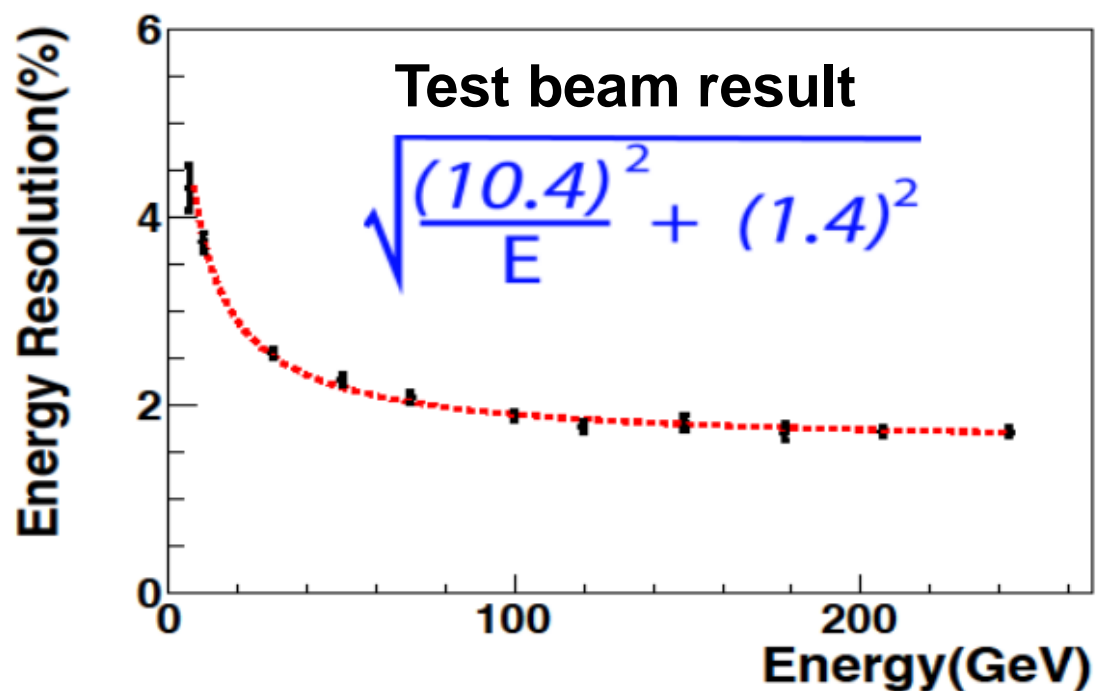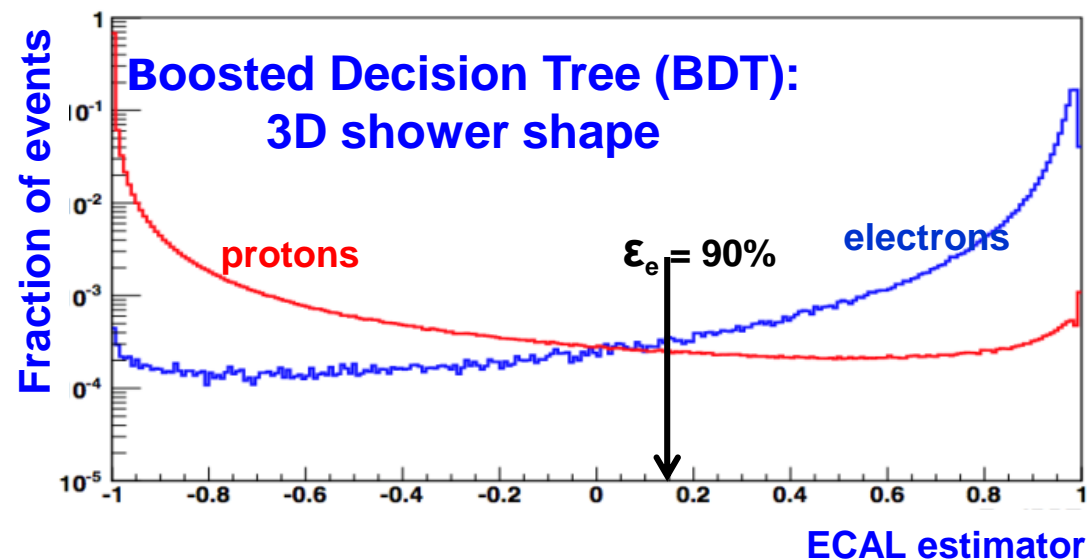
Extensive tests and calibration at CERN

27 km

AMS

7 km

p, e⁺, e⁻, π   20…400 GeV

2000 positions

Beam

θ

Φ

Z

X
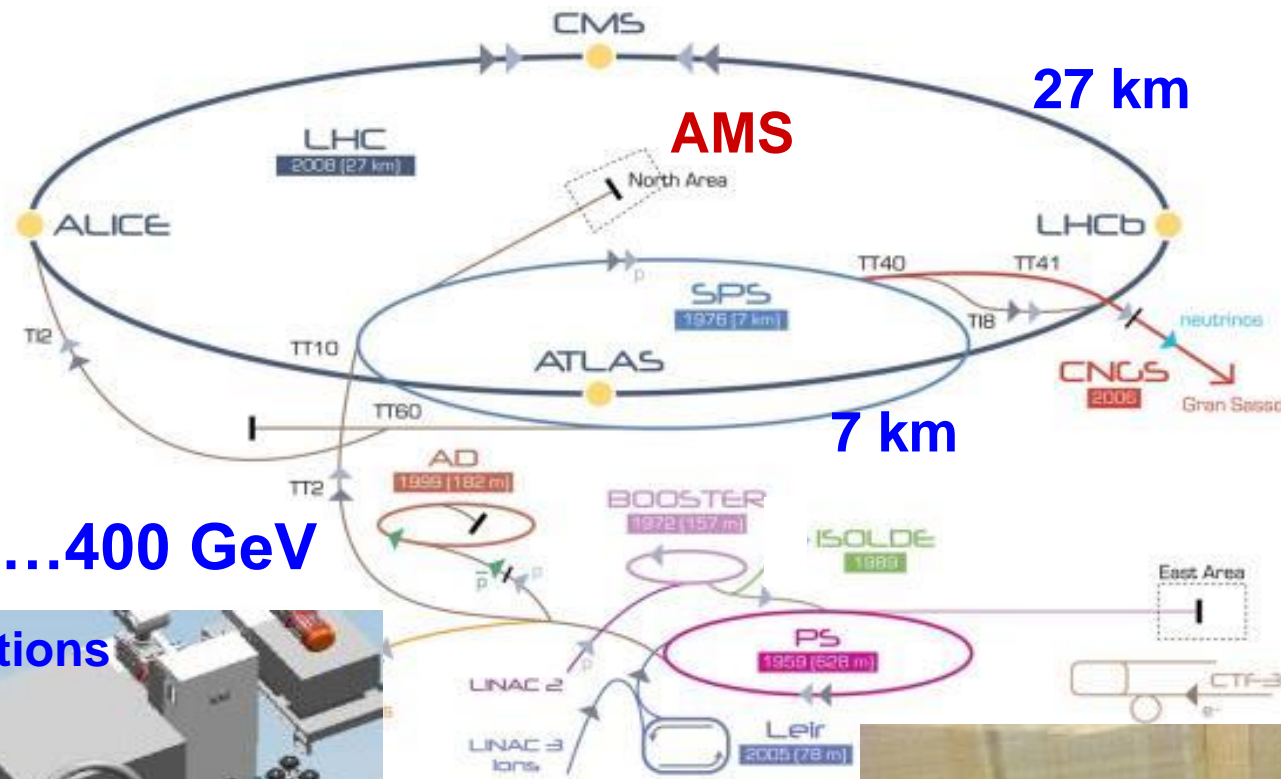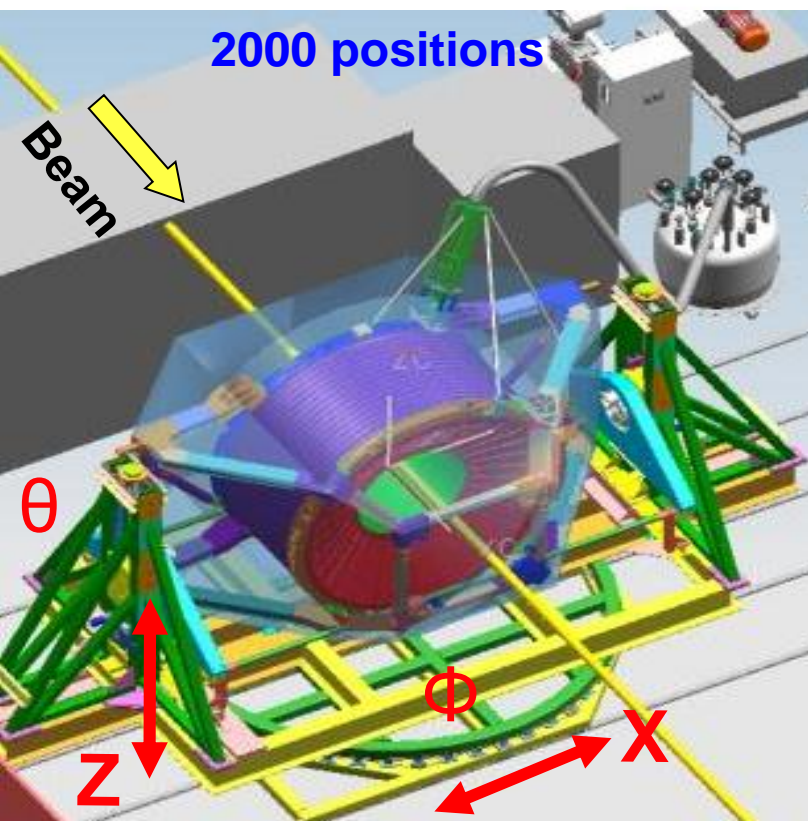
May 16, 2011

In 4 years on ISS,

AMS has collected >68 billion cosmic rays.

To match the statistics,

systematic error studies have become important.

The Search for the Origin of Dark Matter

Collisions of Dark Matter (neutralinos, χ) will produce a signal of e+, $\bar{p}$, …

above the background from the collisions of "ordinary" cosmic rays

Positrons: $\chi + \chi \rightarrow e^+ + …$
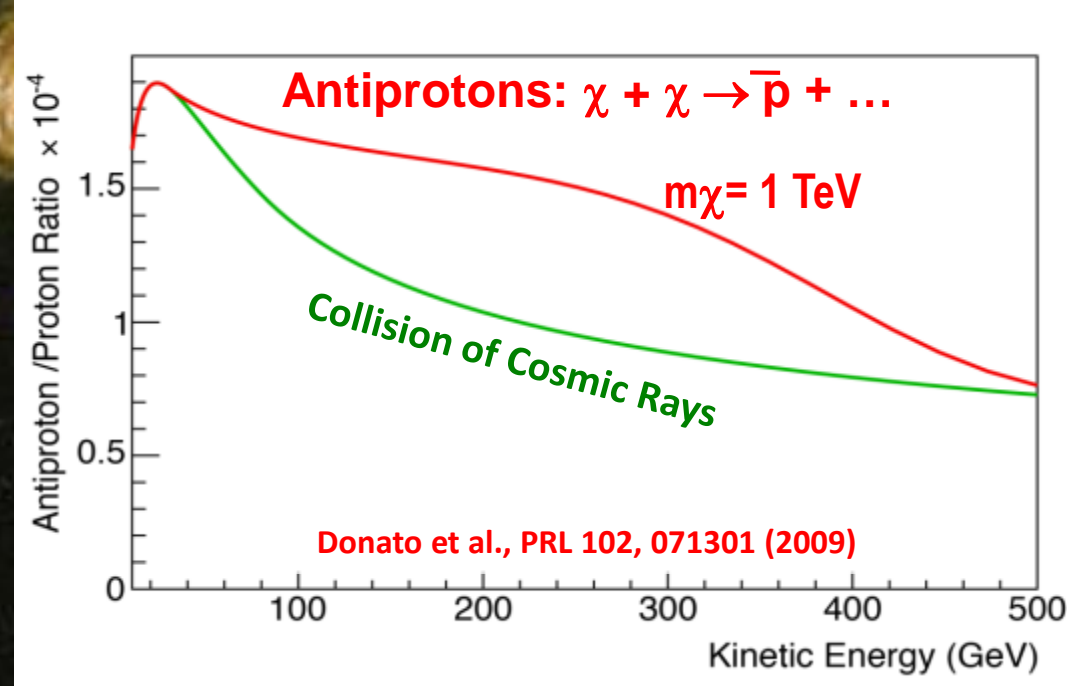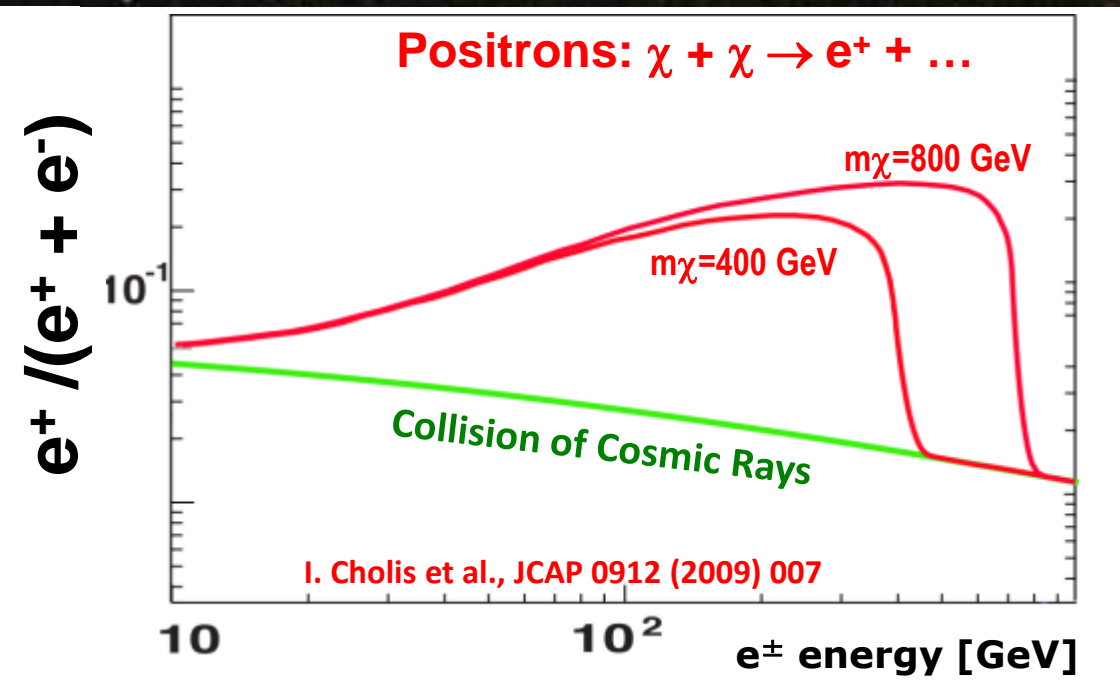
$e^+ / (e^+ + e^-)$

mχ=800 GeV

mχ=400 GeV

Collision of Cosmic Rays

I. Cholis et al., JCAP 0912 (2009) 007

$e^\pm$ energy [GeV]

Antiprotons: $\chi + \chi \rightarrow \bar{p} + …$

Antiproton /Proton Ratio $\times 10^{-4}$

mχ= 1 TeV

Collision of Cosmic Rays

Donato et al., PRL 102, 071301 (2009)

Kinetic Energy (GeV)

M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001;
J. Ellis, 26th ICRC Salt Lake City (1999) astro-ph/9911440;
……………

Selected for a Viewpoint in *Physics*
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,[32,20] G. Alberti,[42,43] B. Alpat,[42] A. Alvino,[42,43] G. Ambrosi,[42] K. Andeen,[28] H. Anderhub,[54] L. Arruda,[30]

6.8 million events

Dear Sam,

this is just to let you know that your article the first AMS data has been selected in our 2013 APS Physics Highlights (http://physics.aps.org/articles/v6/139).
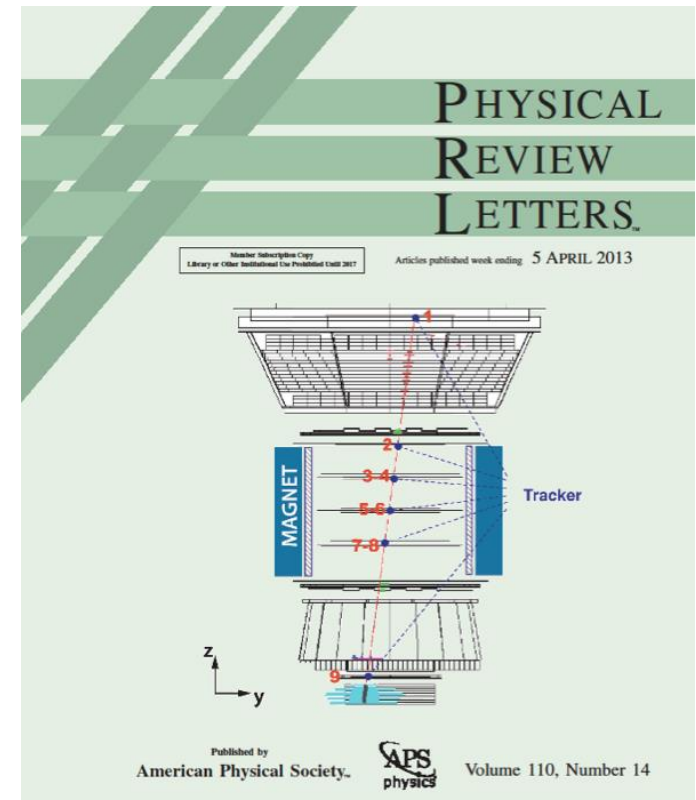
Congratulation on this work, which has generated a lot attention among our readers, the press and the scientific community.

Best regards,

Matteo

--
Matteo Rini, PhD
Deputy Editor, Physics
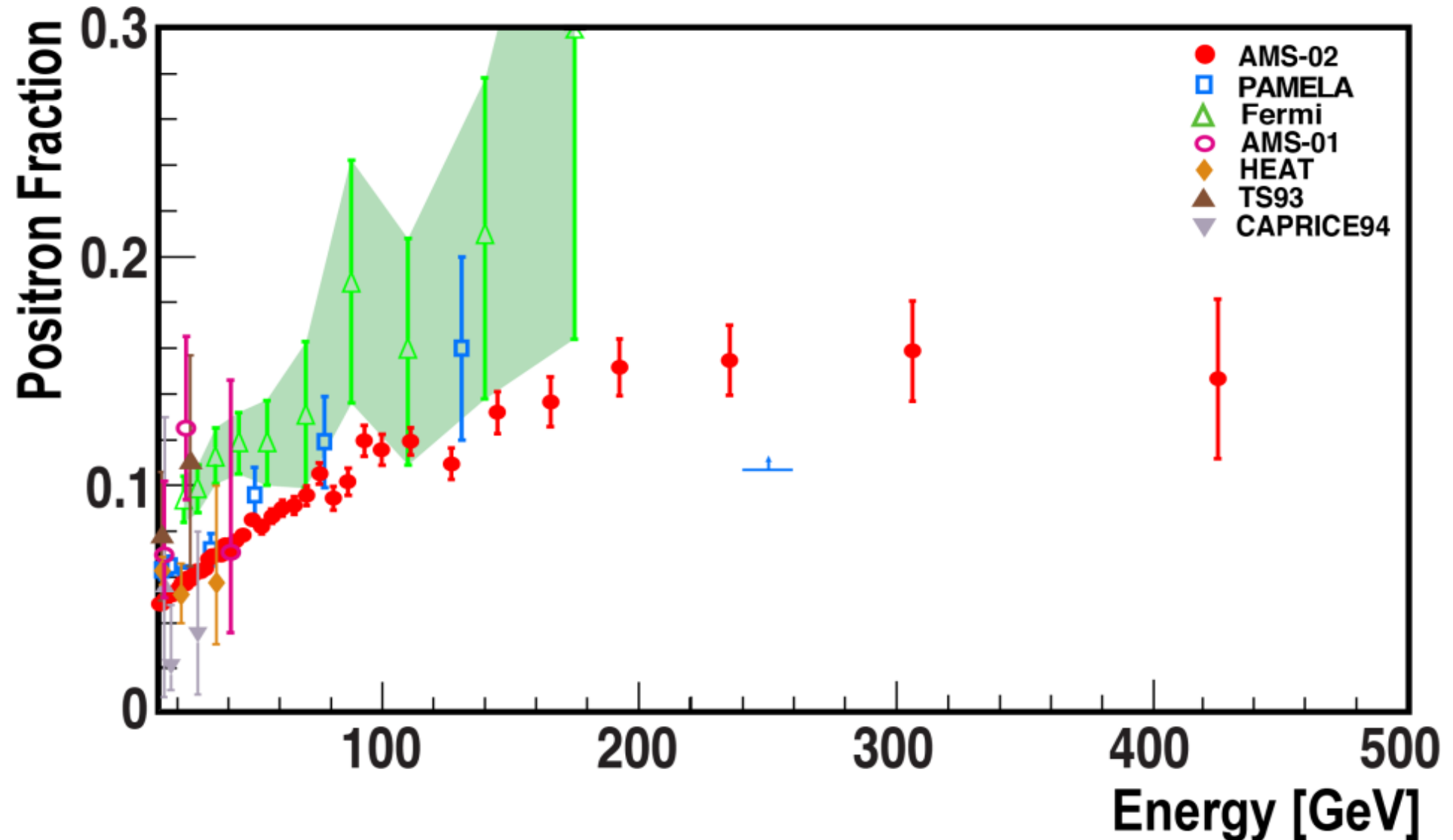mrini@aps.org
http://physics.aps.org

13

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

10.9 million e+ and e- events

2. The rate of increase with energy

3. The existence of sharp structures.

4. The energy beyond which it ceases to increase.

5. Isotropy.
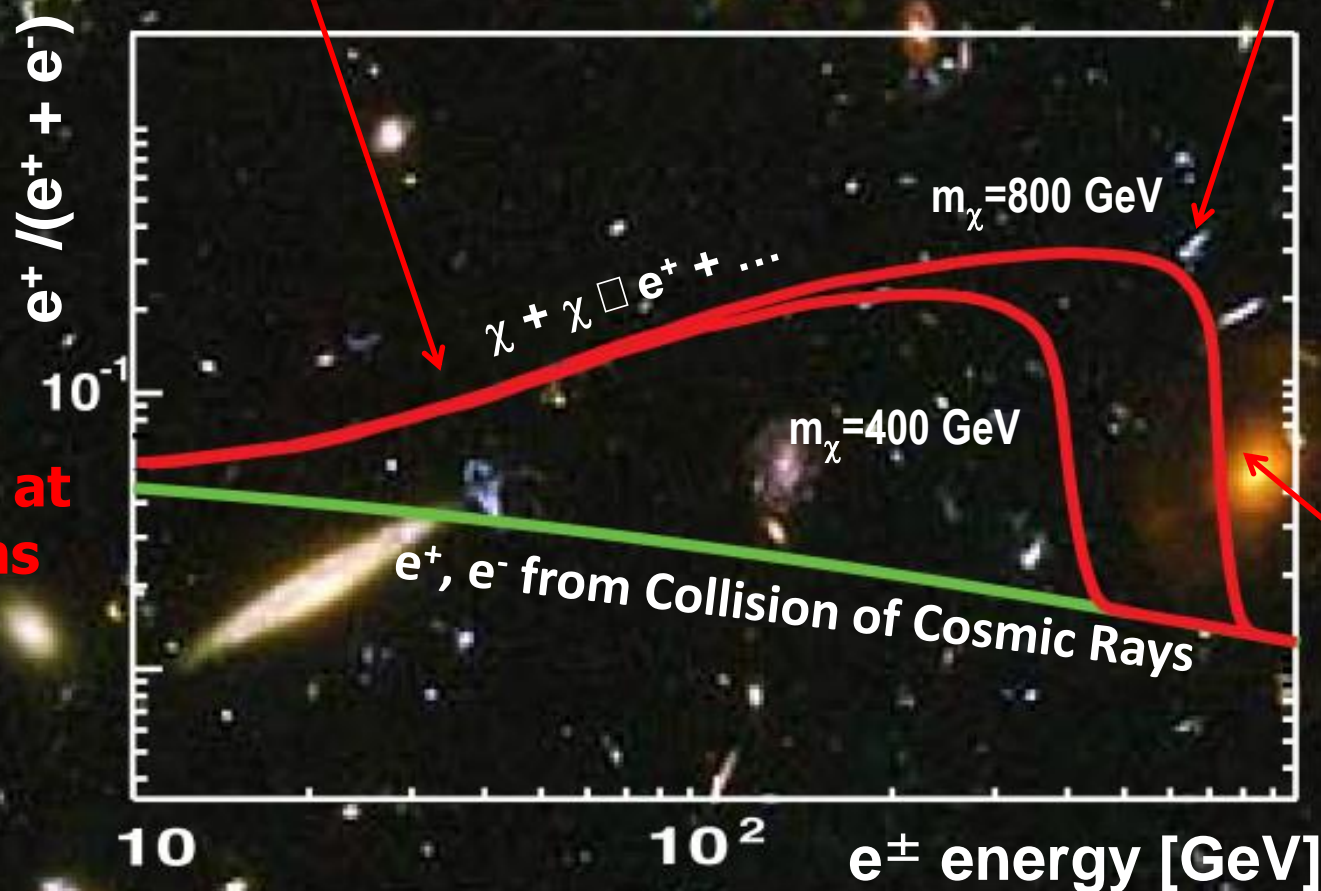
m_χ=800 GeV

$\chi + \chi \square e^+ + \ldots$

m_χ=400 GeV

1. The energy at which it begins to increase.

e^+, e^- from Collision of Cosmic Rays

6. The rate at which it falls beyond the turning point.

$e^+ /(e^+ + e^-)$

10^{-1}

10   10^2 $e^\pm$ energy [GeV]

1. The energy at which it begins to increase.
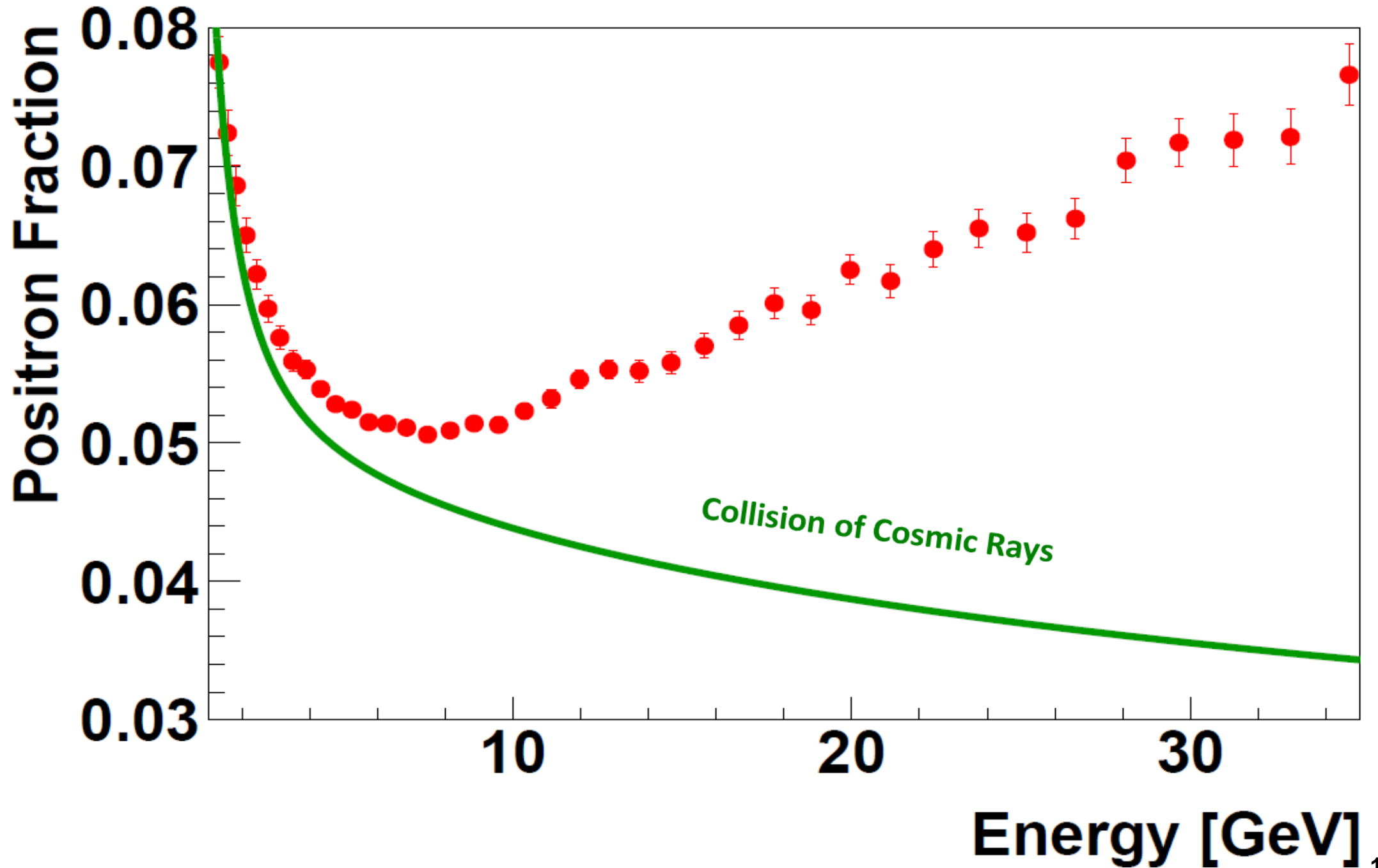
2. **The rate of increase with energy.**

3. **The non-existence of sharp structures.**

10.9 million e+, e- events

Data
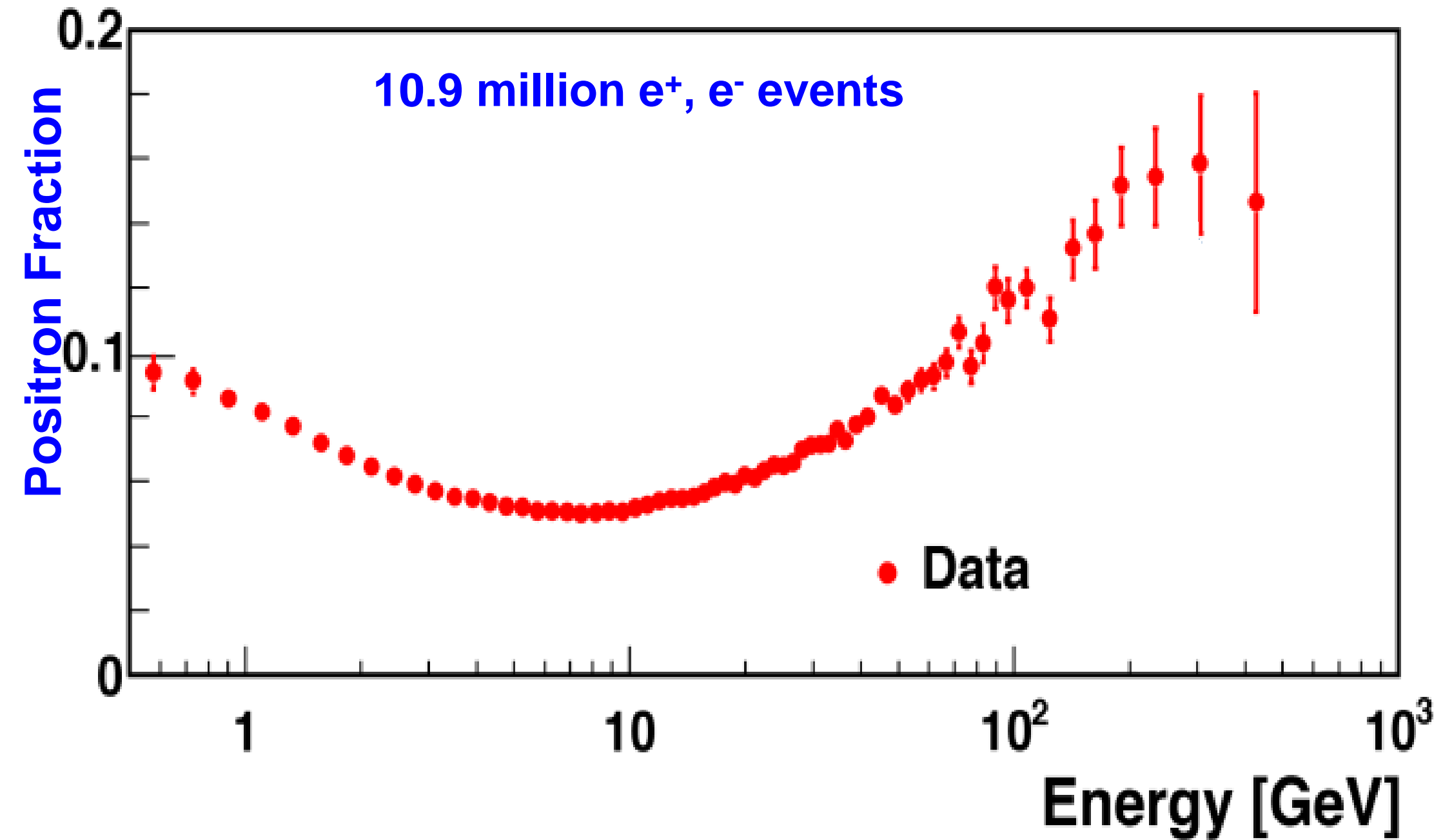
4. The energy beyond which it ceases to increase.

5. The isotropy.
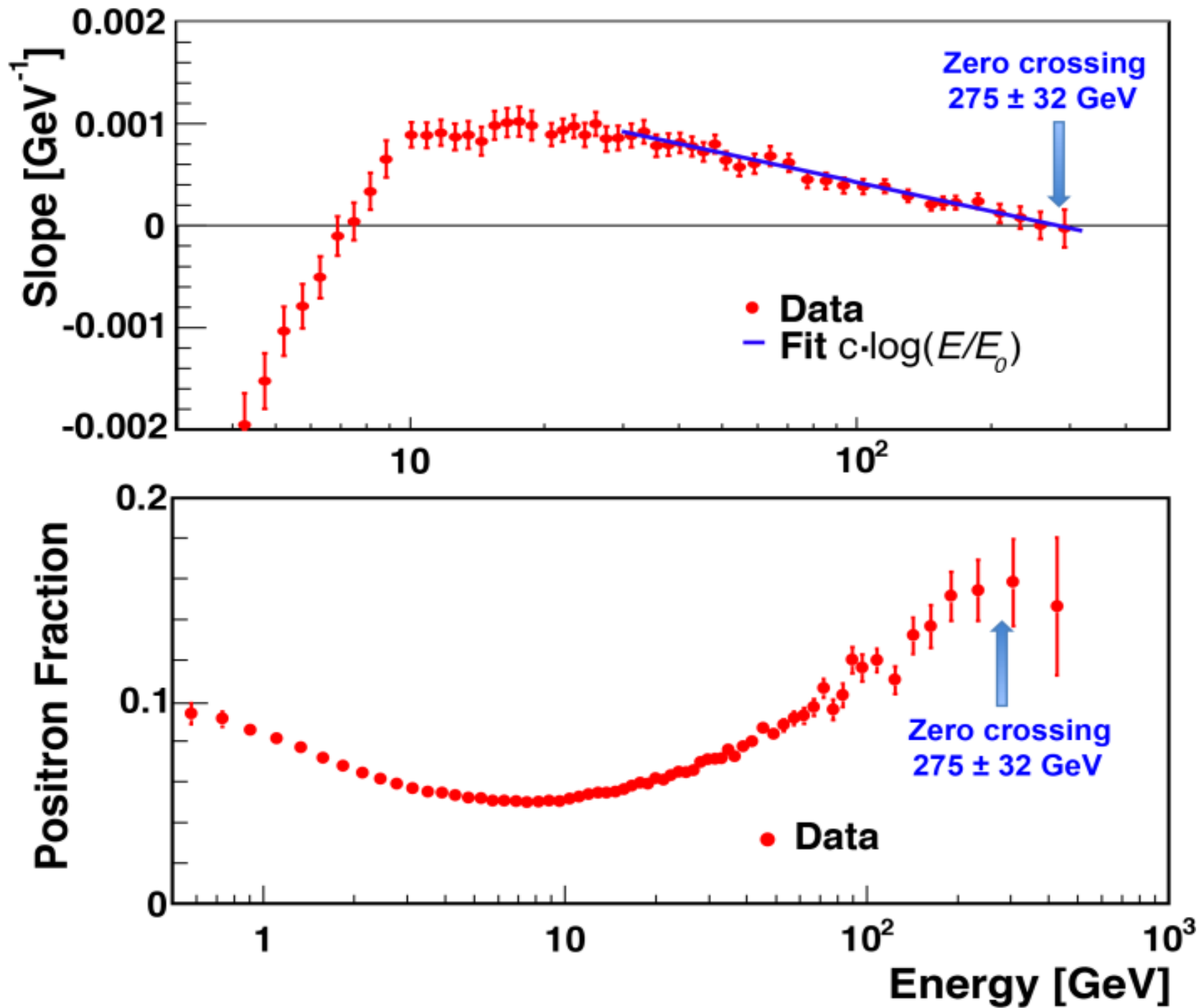
Galactic coordinates (b,l)
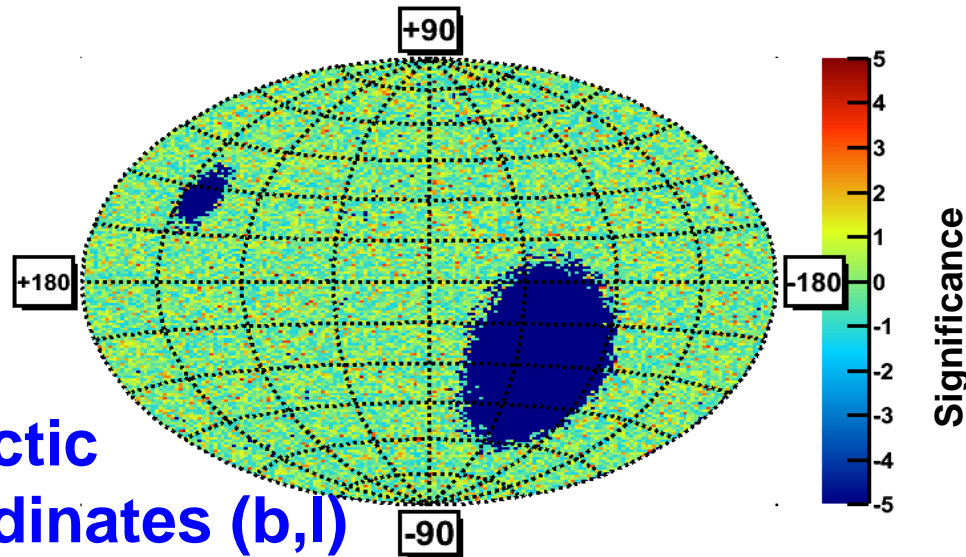
The fluctuations of the positron ratio e^+/e^- are isotropic.

The anisotropy in galactic coordinates:
$\delta \leq 0.030$ at the 95% confidence level

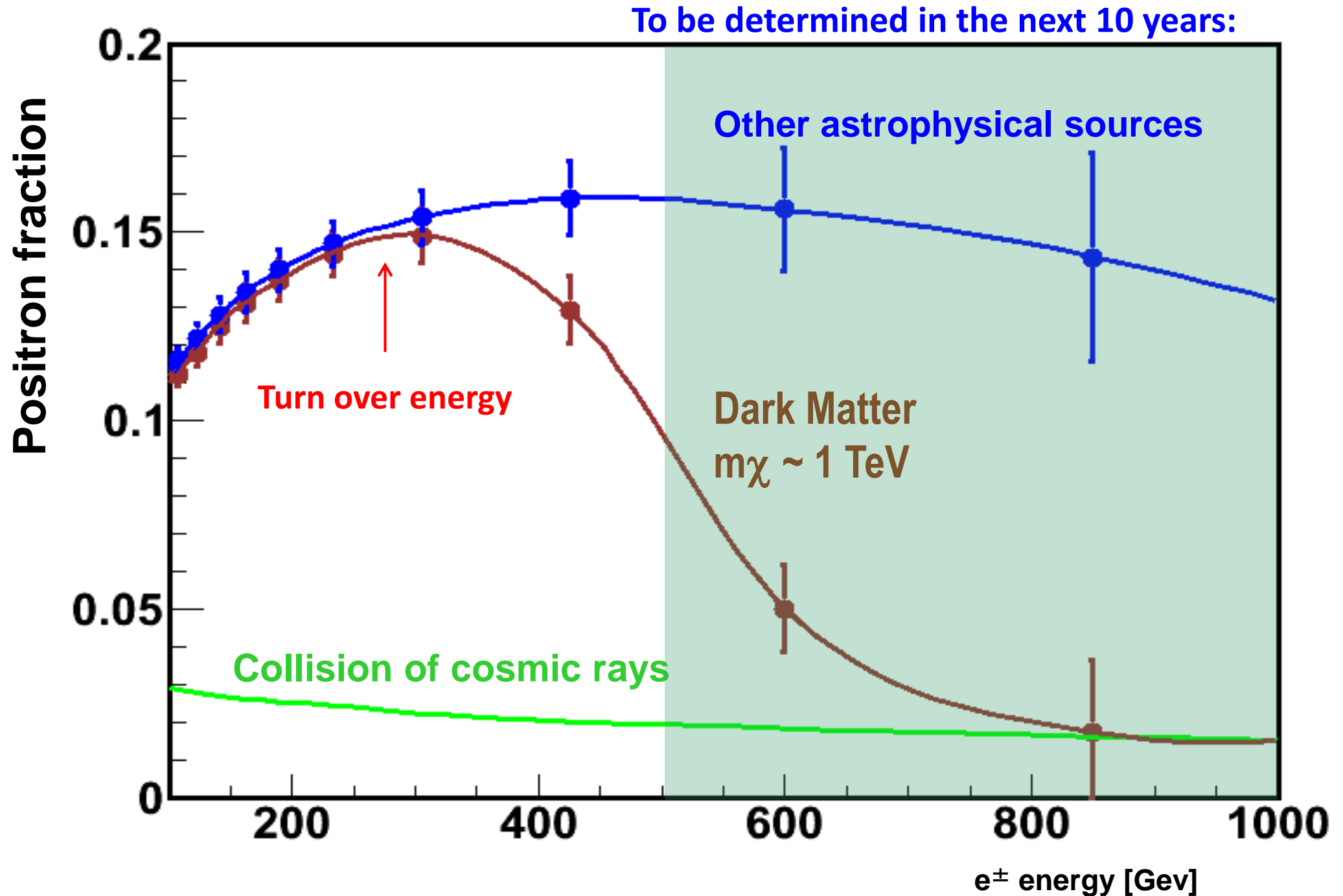$$\delta = 3\sqrt{C_1/4\pi}$$

C_1 is the dipole moment

Arrival directions of electrons and positrons are used to build a sky map in galactic coordinates, (b,l), containing the number of observed positrons and electrons. The fluctuations of the observed positron ratio are described using a spherical harmonic expansion

$$\frac{r_e(b,l)}{<r_e>} - 1 = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} \, Y_{\ell m}(\pi/2 - b, l),$$

where $r_e(b,l)$ denotes the positron ratio at (b,l); $<r_e>$ is the average ratio over the sky map; $Y_{\ell m}$ are spherical harmonic functions and $a_{\ell m}$ are the corresponding weights. The coefficients of the angular power spectrum of the fluctuations are defined as

$$C_\ell = \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2. \qquad \delta = 3\sqrt{C_1/4\pi}$$

6. The expected rate at which it falls beyond the turning point.

To be determined in the next 10 years:

Other astrophysical sources

Dark Matter
$m\chi \sim 1$ TeV

Turn over energy

Collision of cosmic rays

Positron fraction

$e^{\pm}$ energy [Gev]

Electron and Positron flux (before AMS)
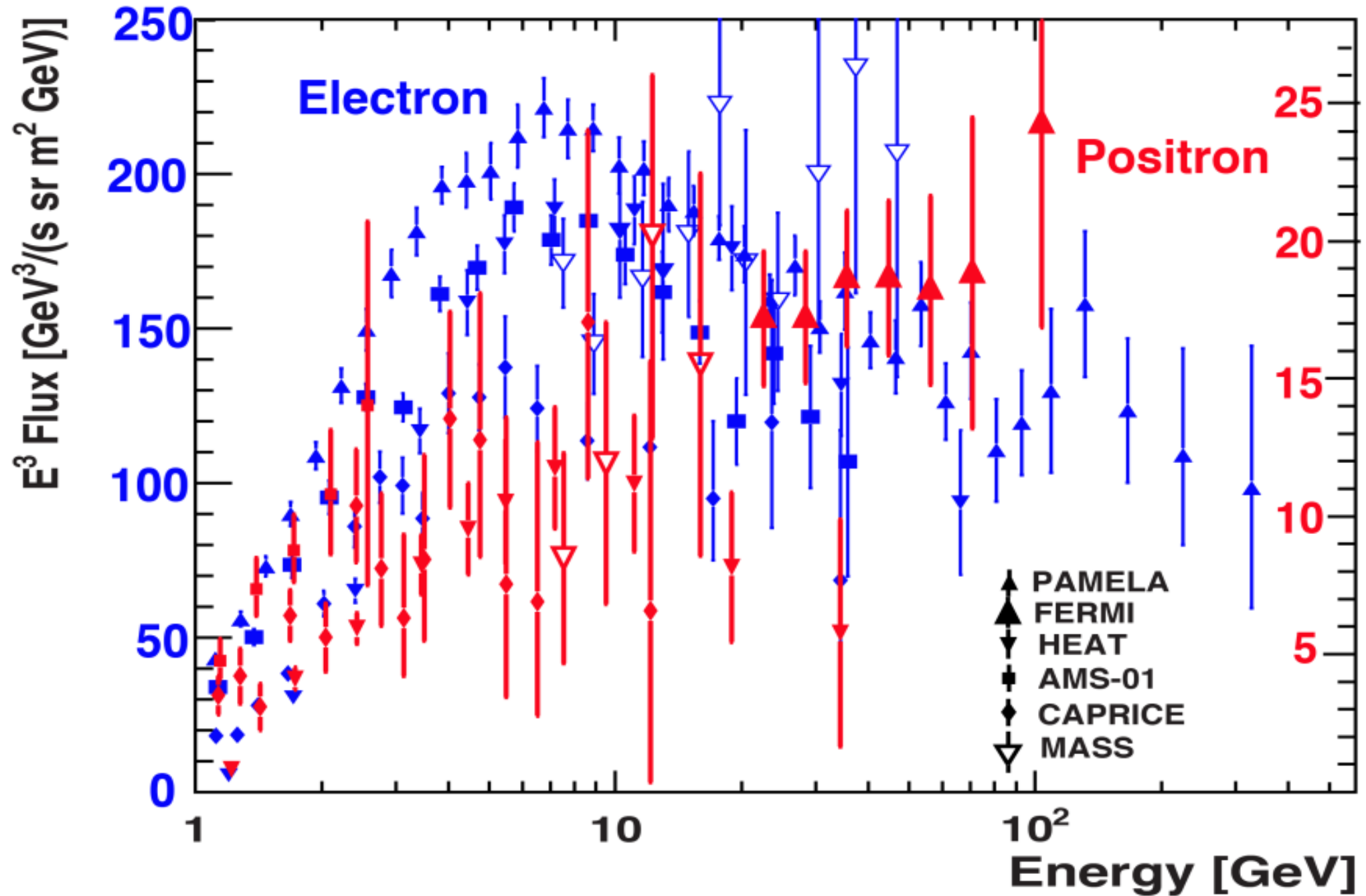
AMS, Electron Flux and the Positron Flux

Electrons
9.2 M

Positrons
0.6 M

The Electron Flux and the Positron Flux

spectral index = d log (Φ)/ d log (E)
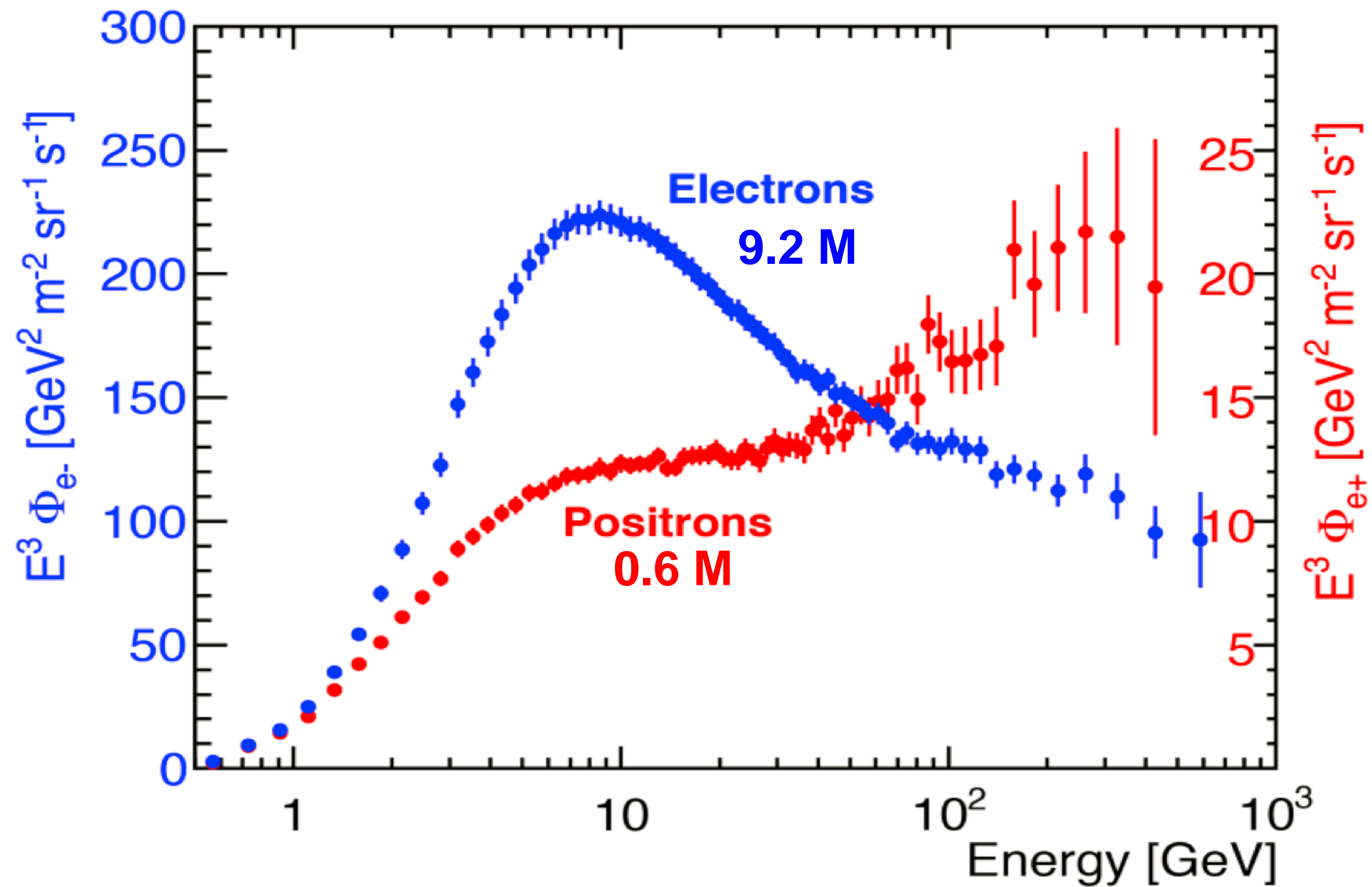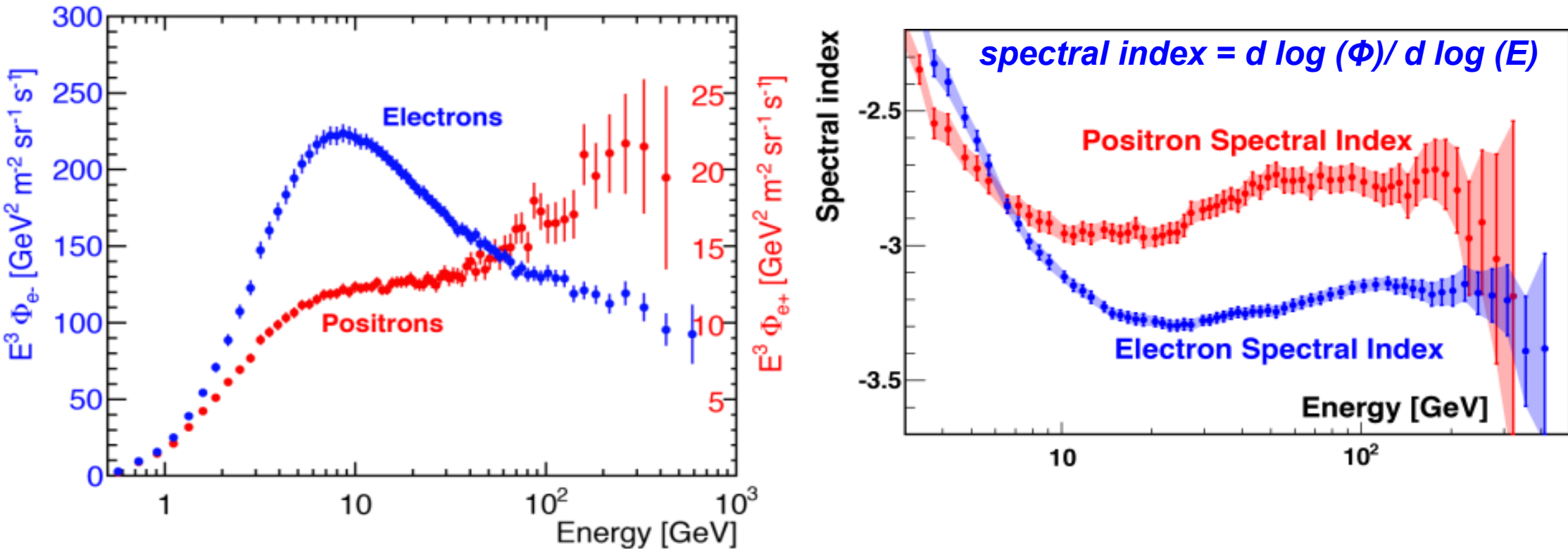
Observations:

1. **The electron flux and the positron flux are different in their magnitude and energy dependence.**
2. **Both spectra cannot be described by single power laws.**
3. **The spectral indices of electrons and positrons are different.**
4. **Both change their behavior at ~30GeV.**
5. **The rise in the positron fraction from 20 GeV is due to an excess of positrons, not the loss of electrons (the positron flux is harder).**

AMS Results: (e⁺ + e⁻) flux

10.6 M events

Independent of charge **sign** measurement → no charge confusion
Small systematics on acceptance: 2% @ TeV

Legend:
- AMS-02
- ATIC
- BETS 97&98
- PPB-BETS 04
- Fermi-LAT
- HEAT
- H.E.S.S.
- H.E.S.S. (LE)

$E^3 \cdot F \ (GeV^2 \ [m^2 \ sr \ sec]^{-1})$

Energy (GeV)
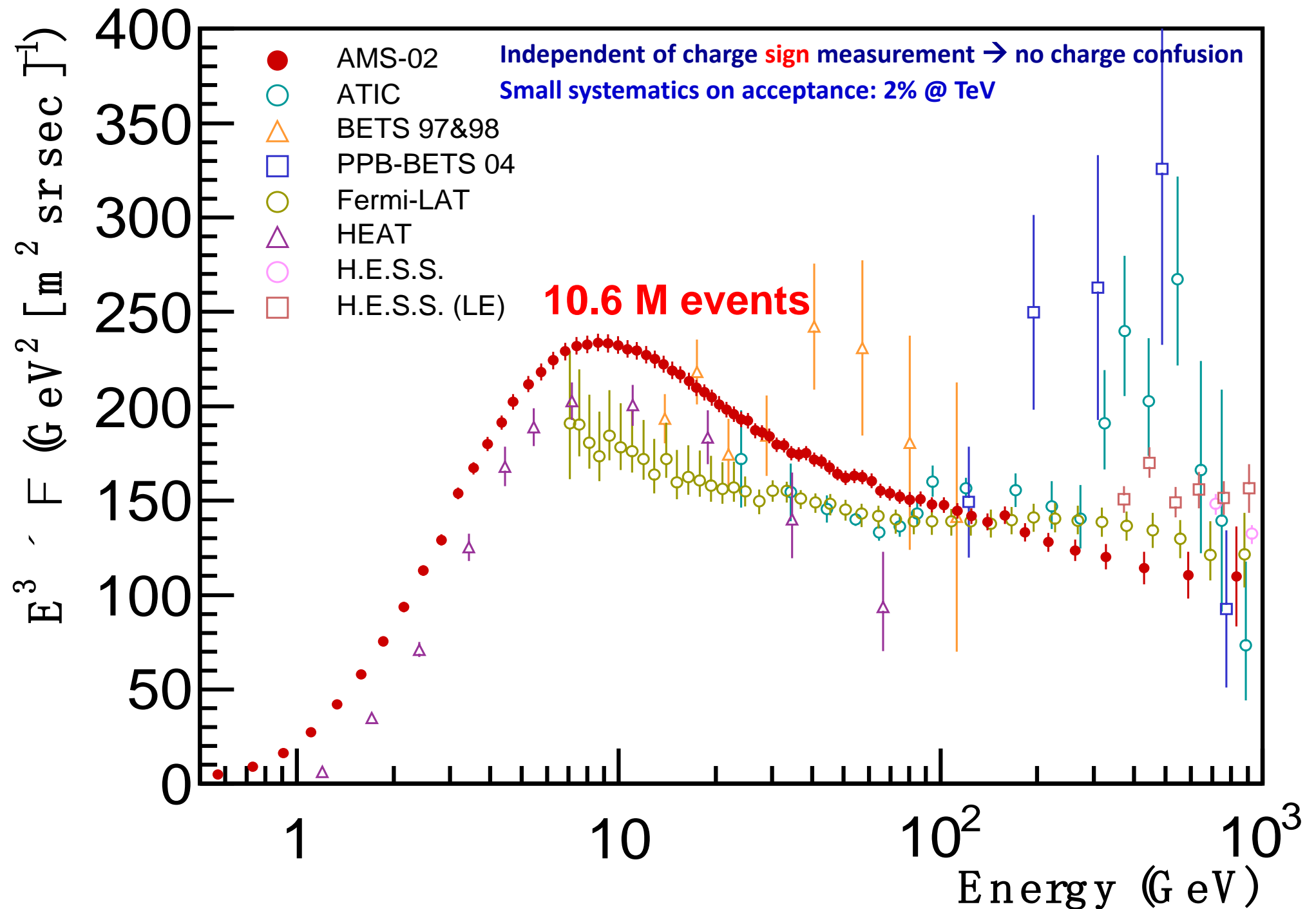
Spectral Indices of electrons, positrons, and (electrons + positrons)
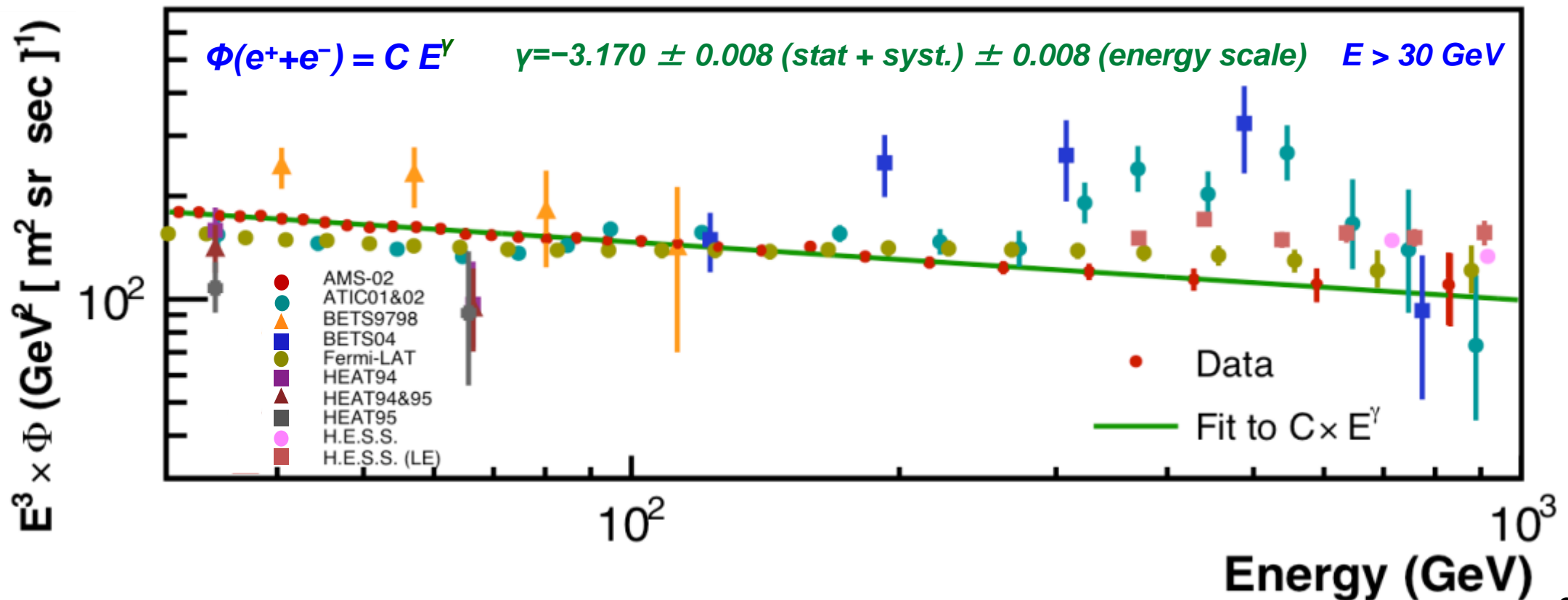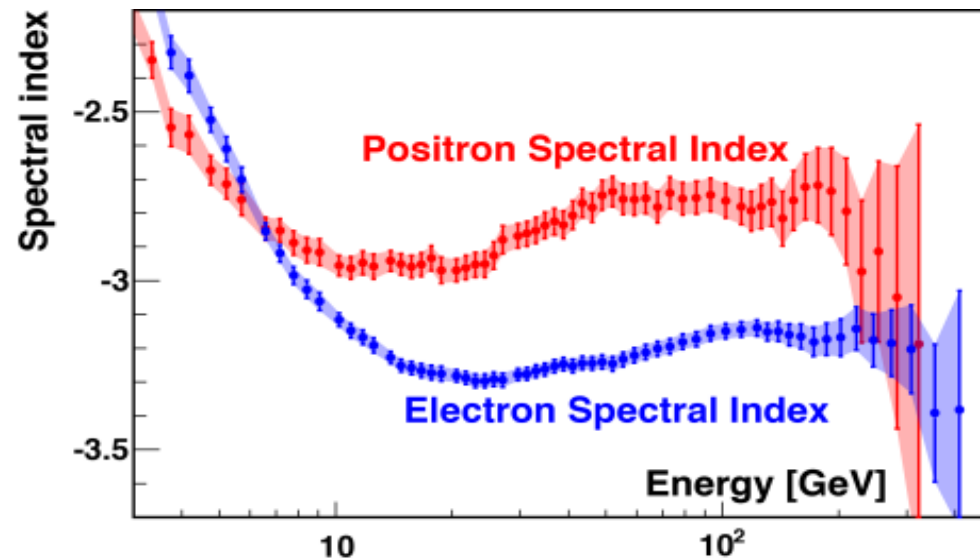
$$\Phi(e^+ + e^-) = C\, E^\gamma \qquad \gamma = -3.170 \pm 0.008\ (stat + syst.) \pm 0.008\ (energy\ scale) \qquad E > 30\ GeV$$

Legend:
- AMS-02
- ATIC01&02
- BETS9798
- BETS04
- Fermi-LAT
- HEAT94
- HEAT94&95
- HEAT95
- H.E.S.S.
- H.E.S.S. (LE)

- Data
- Fit to $C \times E^\gamma$

The Search for the Origin of Dark Matter

Collisions of Dark Matter (neutralinos, χ) will produce a signal of e^+, $\bar{p}$, …

above the background from the collisions of "ordinary" cosmic rays

Positrons: $\chi + \chi \rightarrow e^+ + \ldots$

$m\chi=800$ GeV

$m\chi=400$ GeV

Collision of Cosmic Rays

$e^+/(e^+ + e^-)$

$e^\pm$ energy [GeV]

I. Cholis et al., JCAP 0912 (2009) 007

Antiprotons: $\chi + \chi \rightarrow \bar{p} + \ldots$

$m\chi= 1$ TeV

Collision of Cosmic Rays

Antiproton /Proton Ratio $\times 10^{-4}$

Kinetic Energy (GeV)

Donato et al., PRL 102, 071301 (2009)
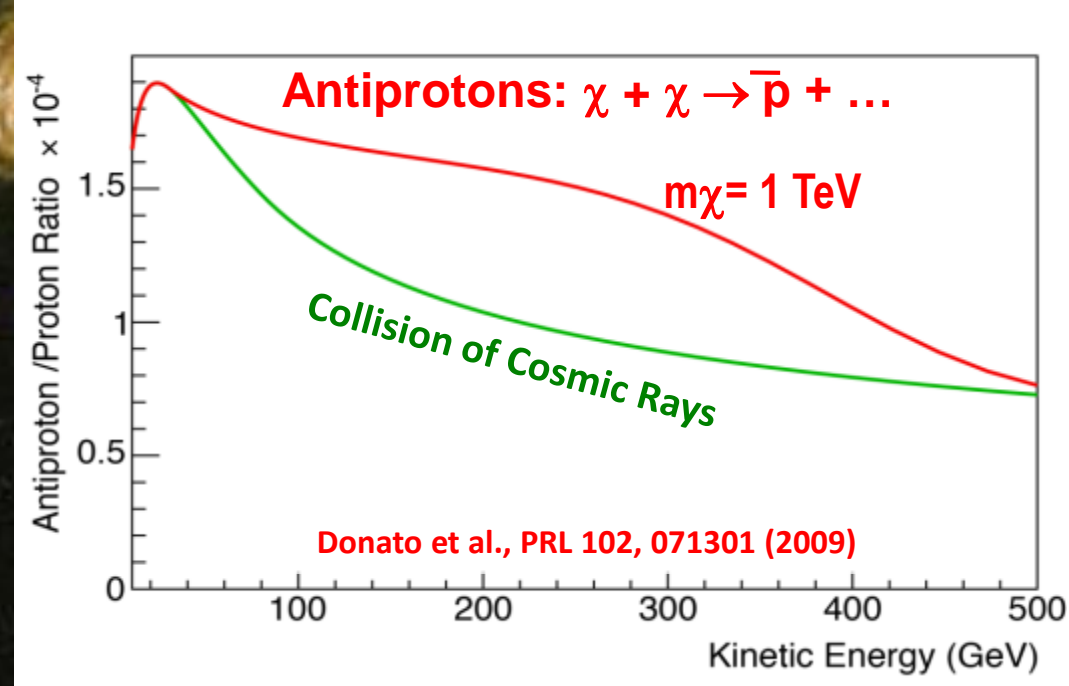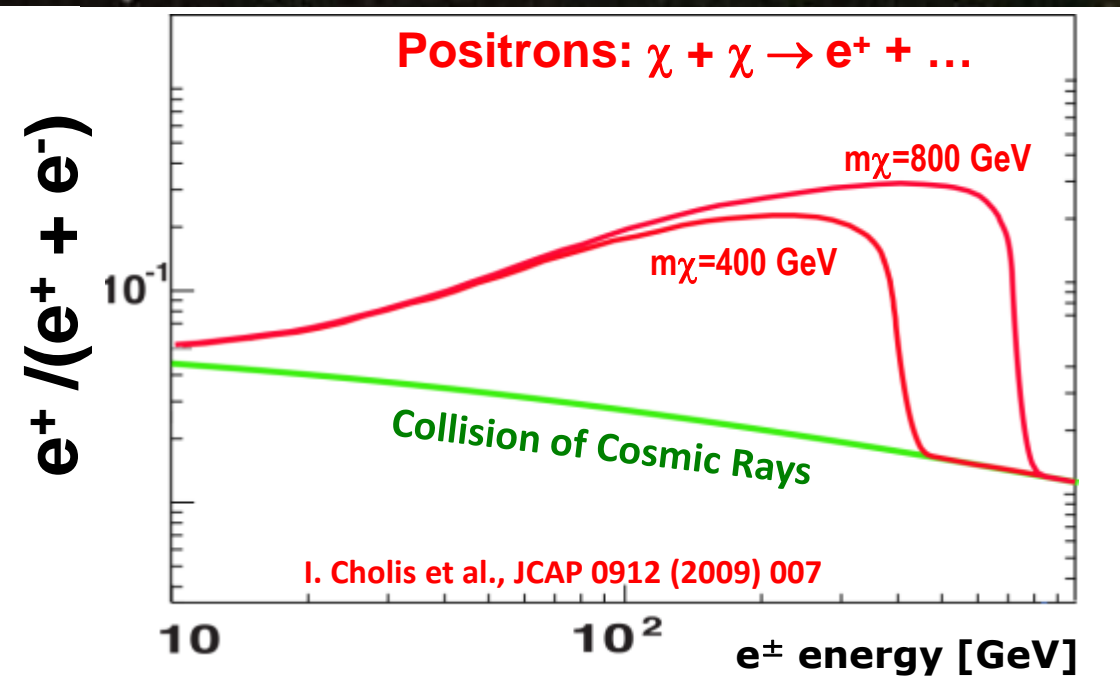
M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001;
J. Ellis, 26th ICRC Salt Lake City (1999) astro-ph/9911440;
…………….

AMS p̄/p results

290,000 p̄ events

- ● AMS-02
- ○ PAMELA
- △ BESS

p̄/p ratio

Kinetic Energy (GeV)
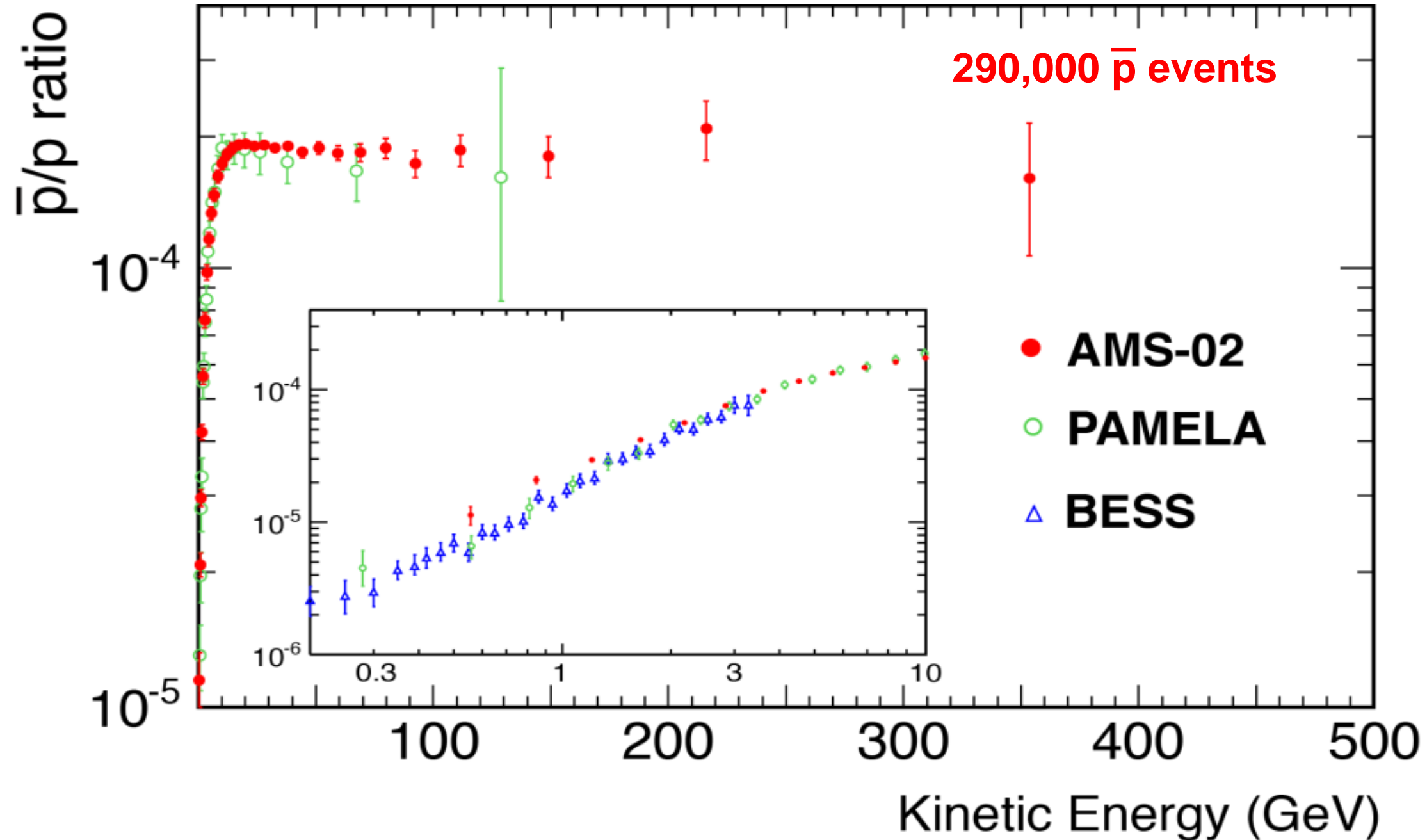
AMS p̄/p results

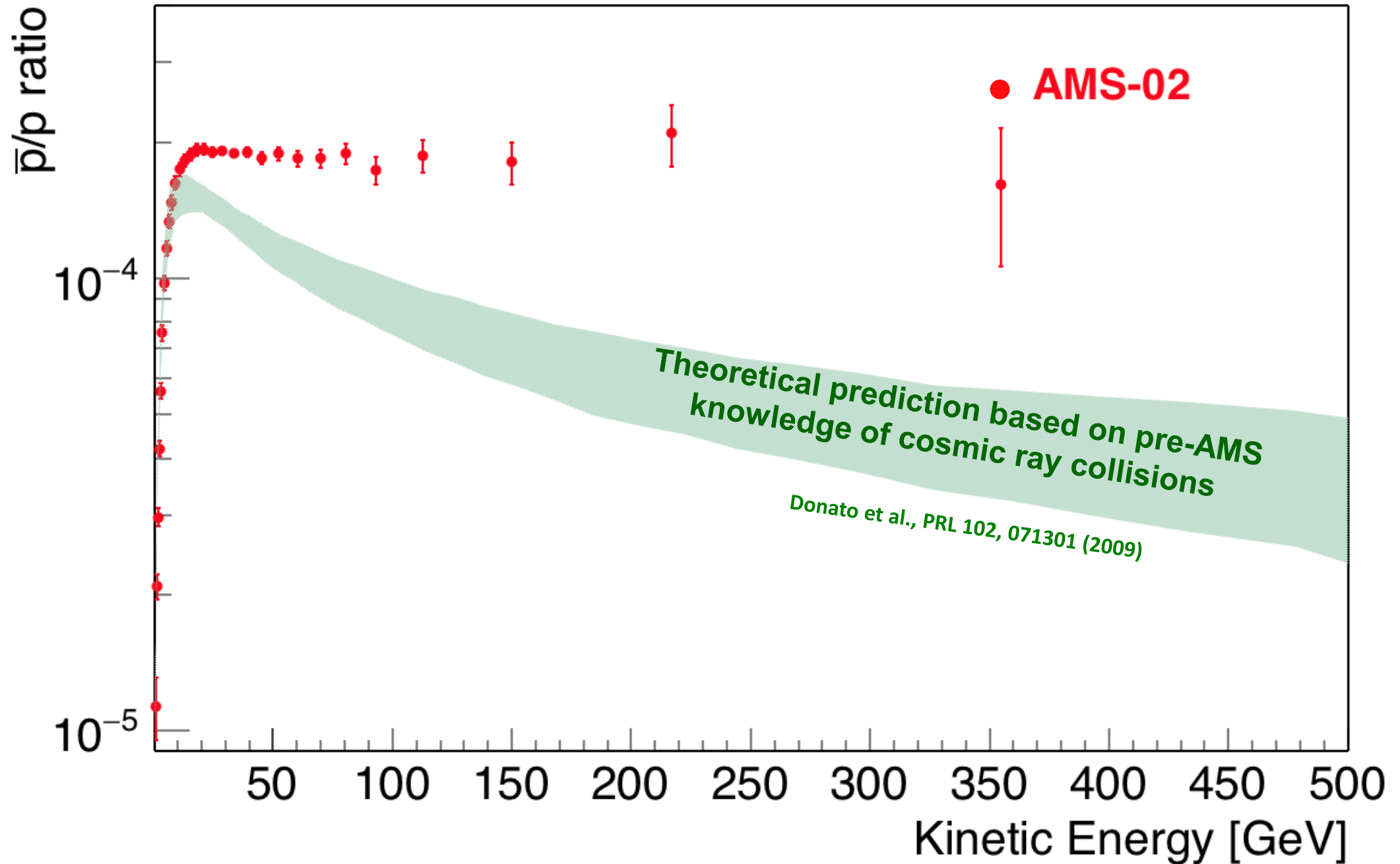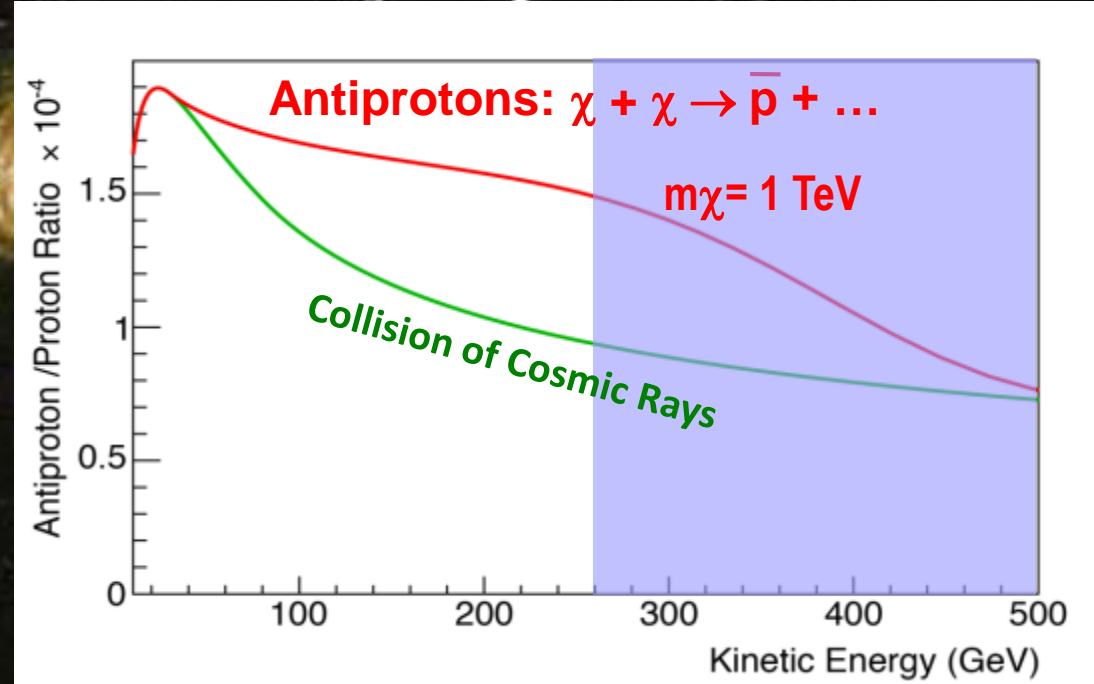# The Search for the Origin of Dark Matter

To identify the Dark Matter signal we need

to measure the e^+, e^- and $\bar{p}$ signal accurately until 2024.

Positrons: $\chi + \chi \rightarrow e^+ + \dots$

$m\chi$=800 GeV

$m\chi$=400 GeV

Collision of Cosmic Rays

$e^+ /(e^+ + e^-)$

$e^\pm$ energy [GeV]

Antiprotons: $\chi + \chi \rightarrow \bar{p} + \dots$

$m\chi$= 1 TeV

Collision of Cosmic Rays

Antiproton /Proton Ratio $\times 10^{-4}$

Kinetic Energy (GeV)
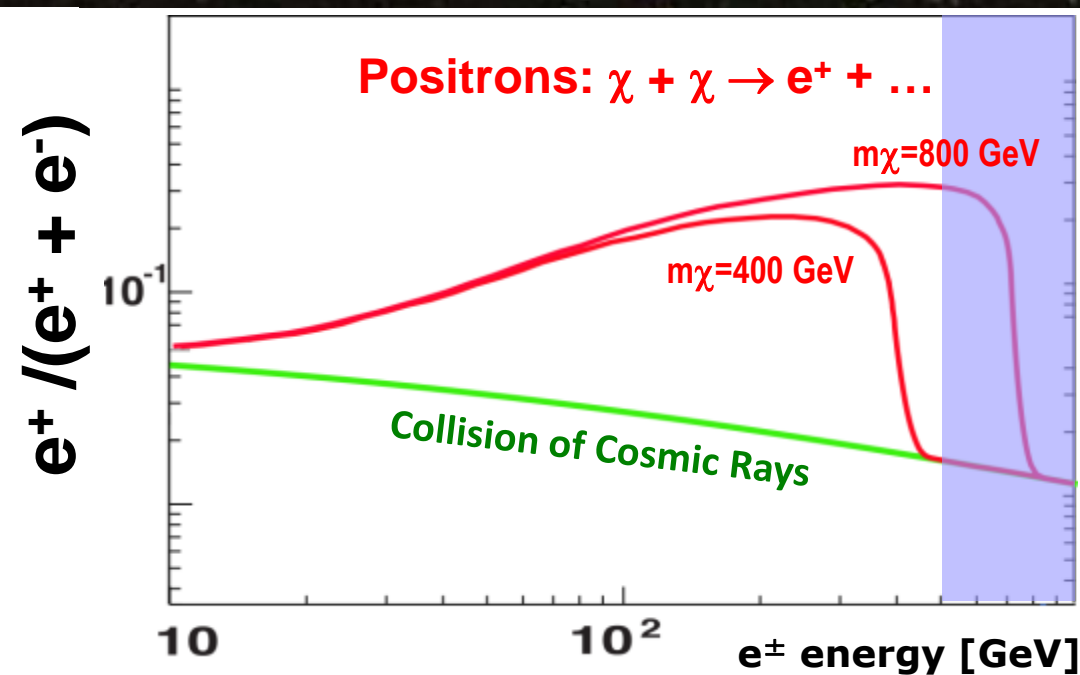
To understand background, we need precise knowledge of:

1. The cosmic ray fluxes (p, He, C, …)

2. Propagation and Acceleration (Li, B/C, …)

AMS: Multiple Measurements of Nuclear Charge

Charge Resolution (Z=6)

Detector	Resolution
Tracker Plane 1	0.30
TRD	0.33
Upper TOF	0.16
Inner Tracker 2-8	0.12
Lower TOF	0.16
RICH	0.32
Tracker Plane 9	0.30
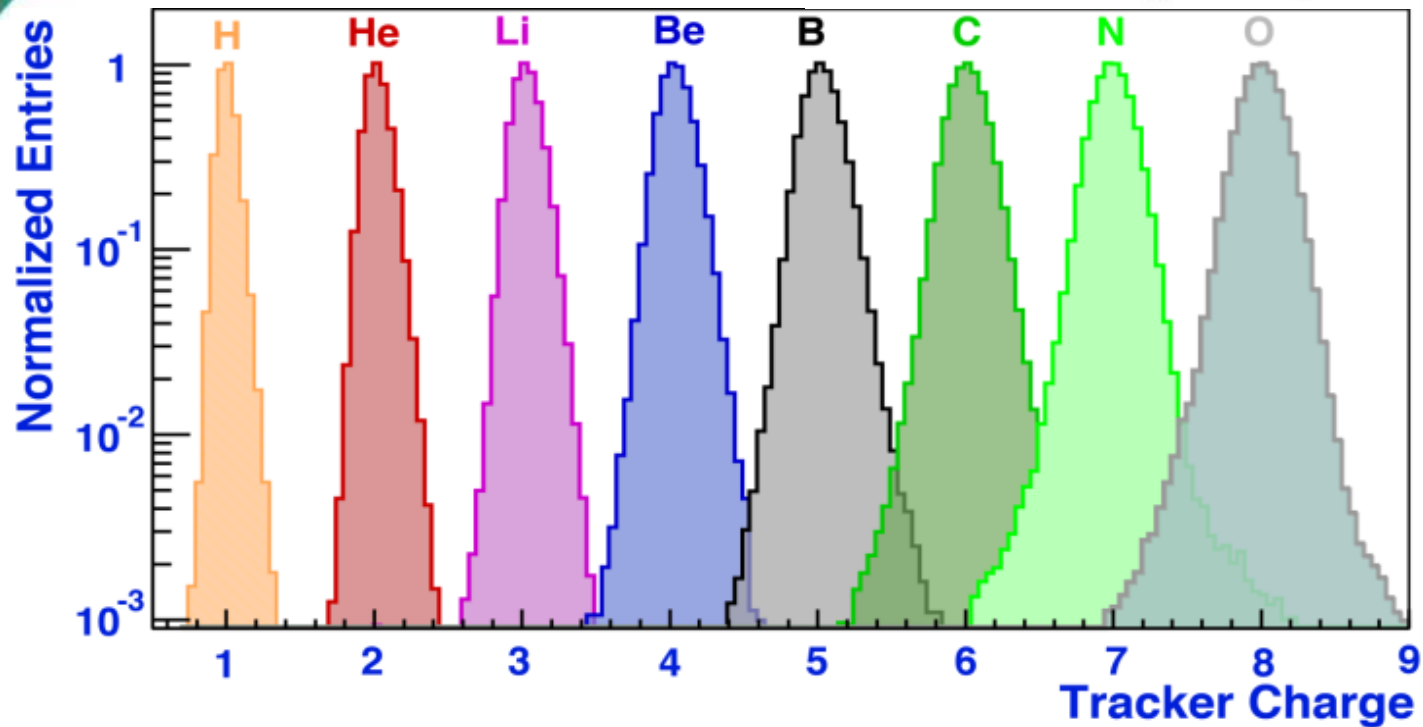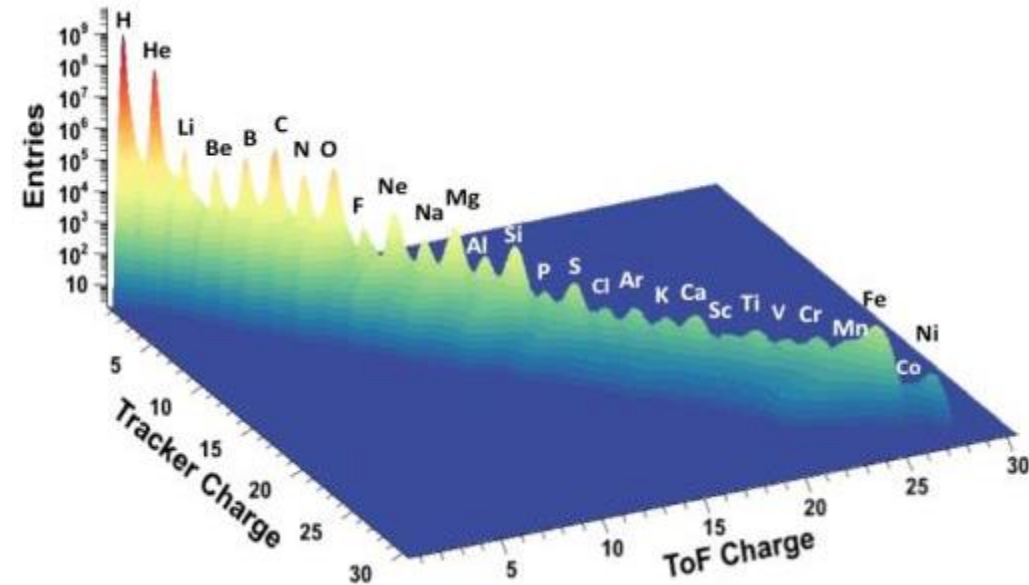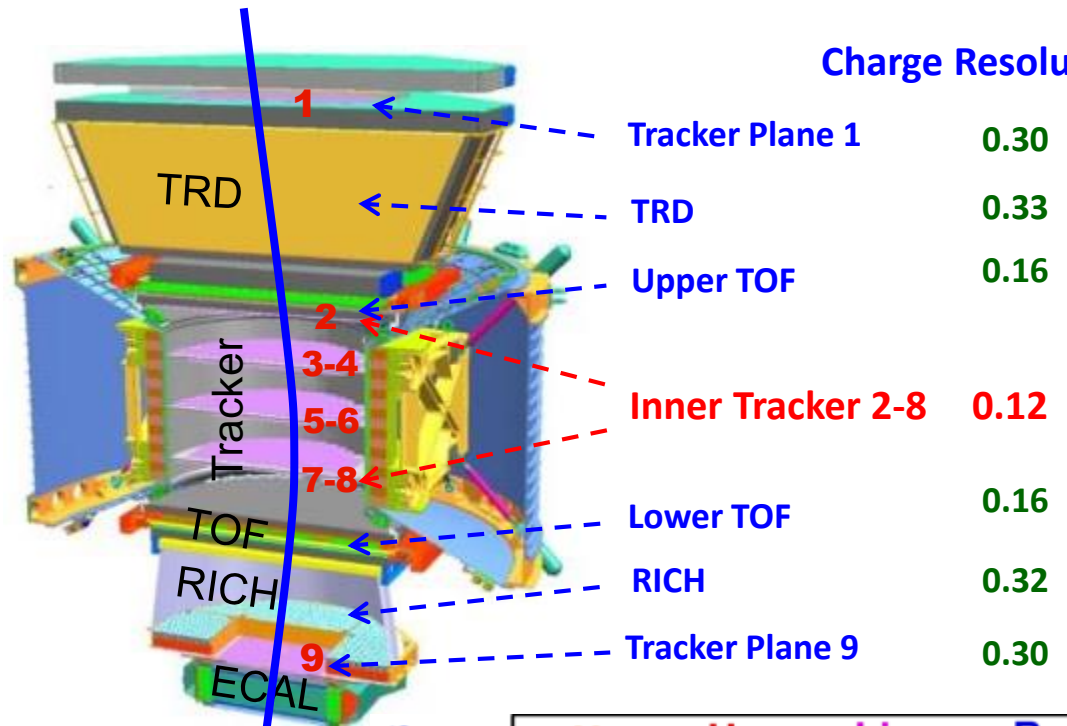
Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station

The isotropic protonflux Φ_i for the ith rigidity bin (R_i , $R_i + \Delta R_i$) is:

$$\Phi_i = \frac{N_i}{A_i \, \varepsilon_i \, T_i \, \Delta R_i}$$

To match the statistics of 300 million events, extensive systematic errors studies have been made.

1) $\sigma_{trig.}$: trigger efficiency

2) $\sigma_{acc.}$:
   a. the acceptance and event selection
   b. background contamination
   c. geomagnetic cutoff

3) σ_{unf} :
   a. unfolding
   b. the rigidity resolution function

4) $\sigma_{scale.}$: the absolute rigidity scale

TABLE I: The proton flux Φ as a function of rigidity

Rigidity [GV]	Φ	$\sigma_{stat.}$	$\sigma_{trig.}$	$\sigma_{acc.}$	$\sigma_{unf.}$	σ_{scale}	$\sigma_{syst.}$
100 − 108	(4.085	0.007	0.006	0.040	0.035	0.022	0.058)$\times 10^{-2}$
108 − 116	(3.294	0.007	0.005	0.033	0.028	0.018	0.047)$\times 10^{-2}$
116 − 125	(2.698	0.006	0.004	0.027	0.023	0.016	0.039)$\times 10^{-2}$
125 − 135	(2.174	0.005	0.004	0.022	0.019	0.013	0.032)$\times 10^{-2}$

31

AMS proton flux

AMS-02

300 million events
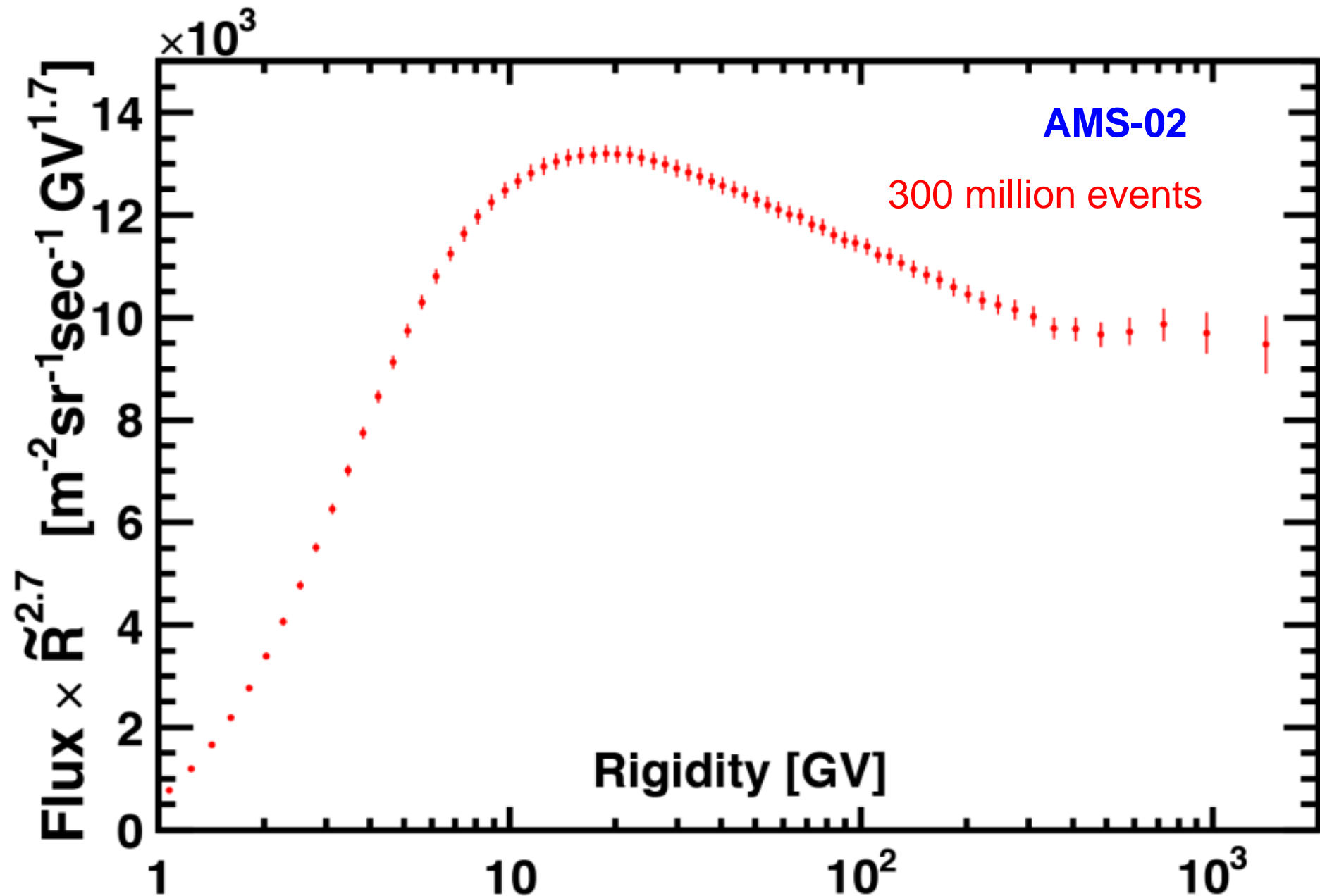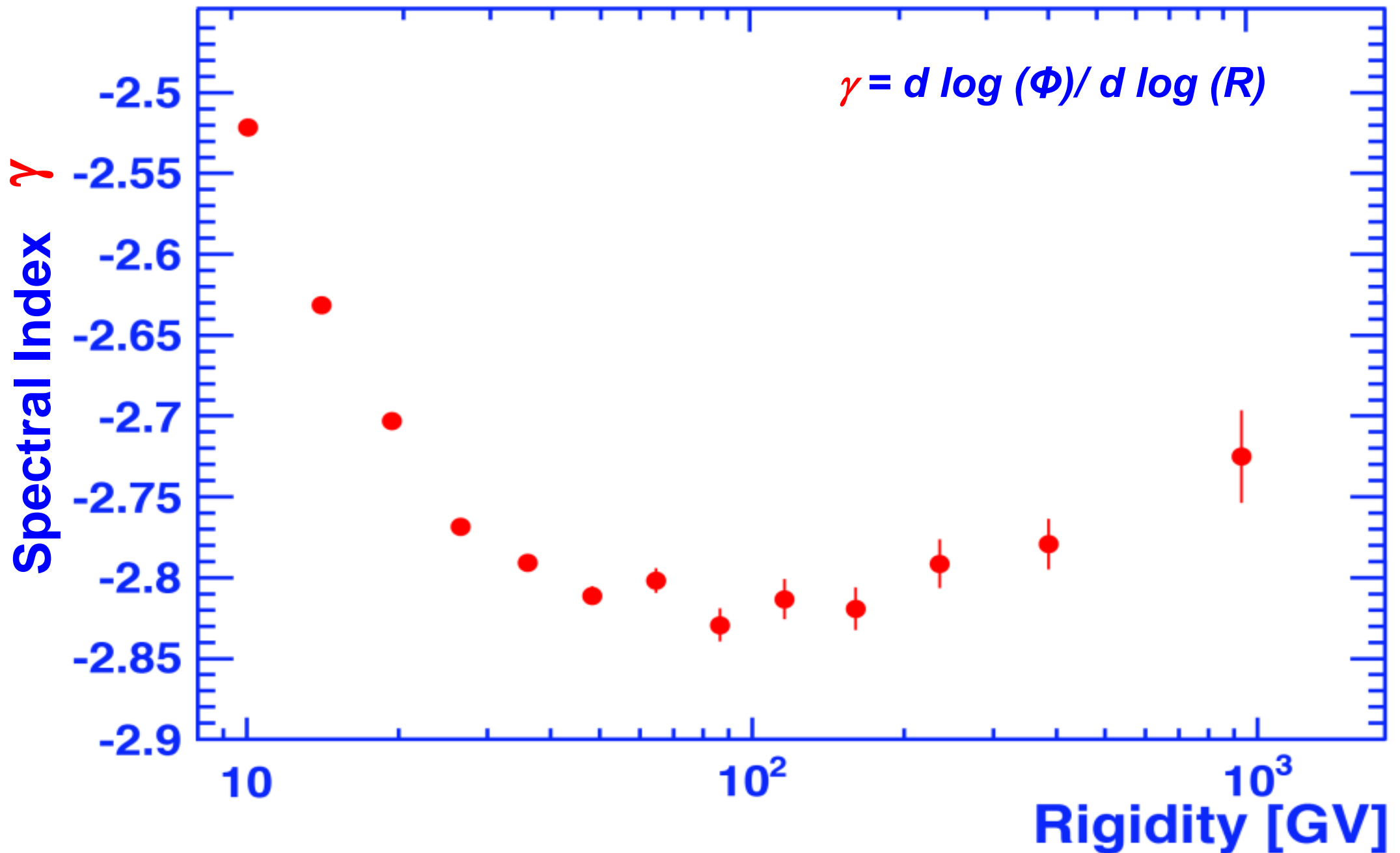
AMS proton flux

two power laws: R^γ, $R^{\gamma+\Delta\gamma}$ with a characteristic transition rigidity R_0 and smoothness s

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

$\Delta\gamma = 0$

Soide curve is the fit to the data above 45 GV: $\chi^2/\text{d.f.}= 25\,/26$
Dashed curve uses the same fit values but with $\Delta\gamma$ set to zero.

Flux $\times \tilde{R}^{2.7}$ [m^{-2}sr^{-1}sec^{-1}GV$^{1.7}$]

Rigidity [GV]
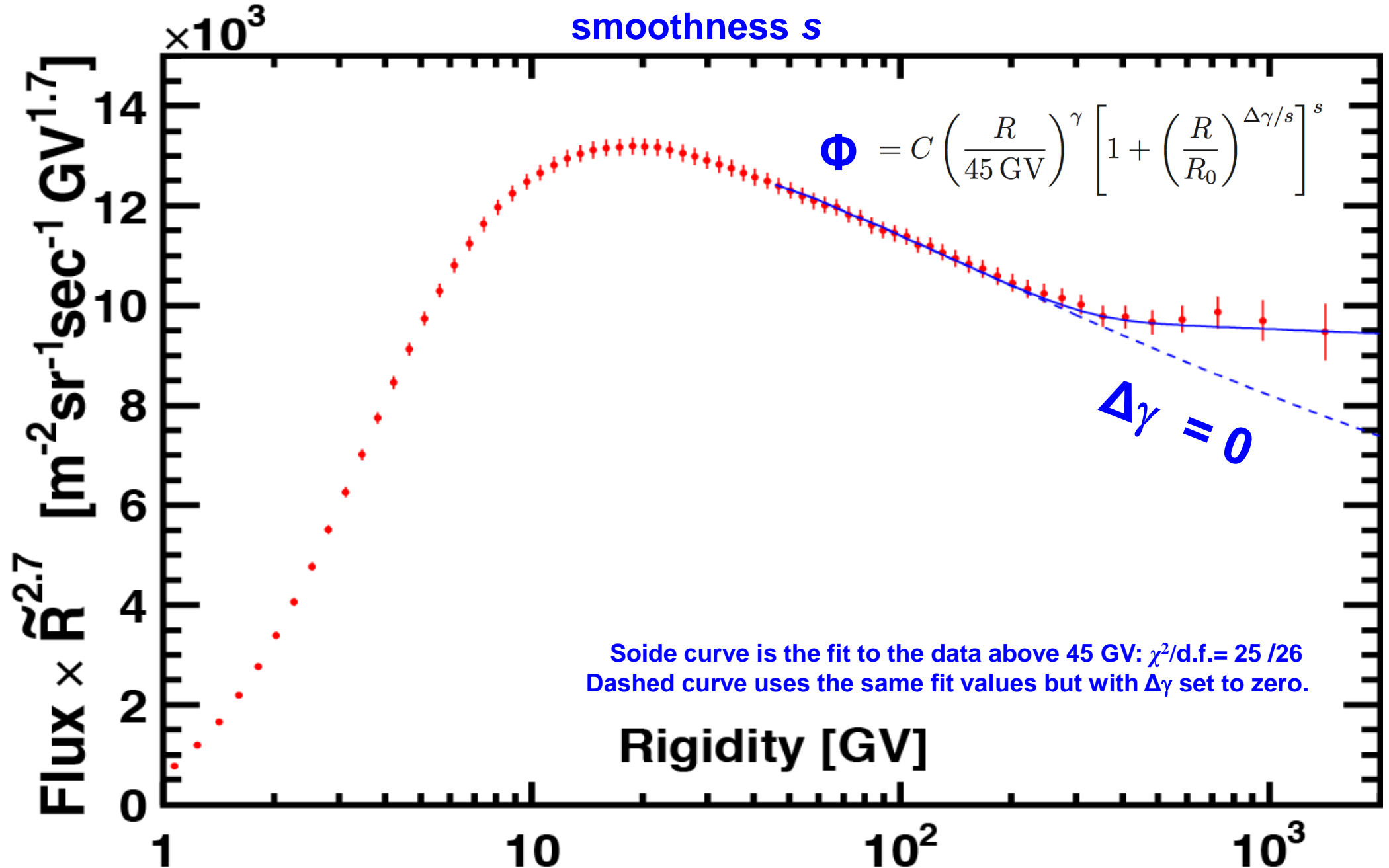
AMS proton spectral index variation:
Model independent measurement of spectral index

$\gamma = d \log (\Phi)/ d \log (R)$

AMS proton flux

Legend:
- AMS-02
- ATIC-2
- BESS-Polar II
- CREAM
- PAMELA

Y-axis: Flux $\times E_K^{2.7}$ $[m^{-2}sr^{-1}sec^{-1}GeV^{1.7}]$, $\times 10^3$

X-axis: Kinetic Energy (E_k) [GeV]
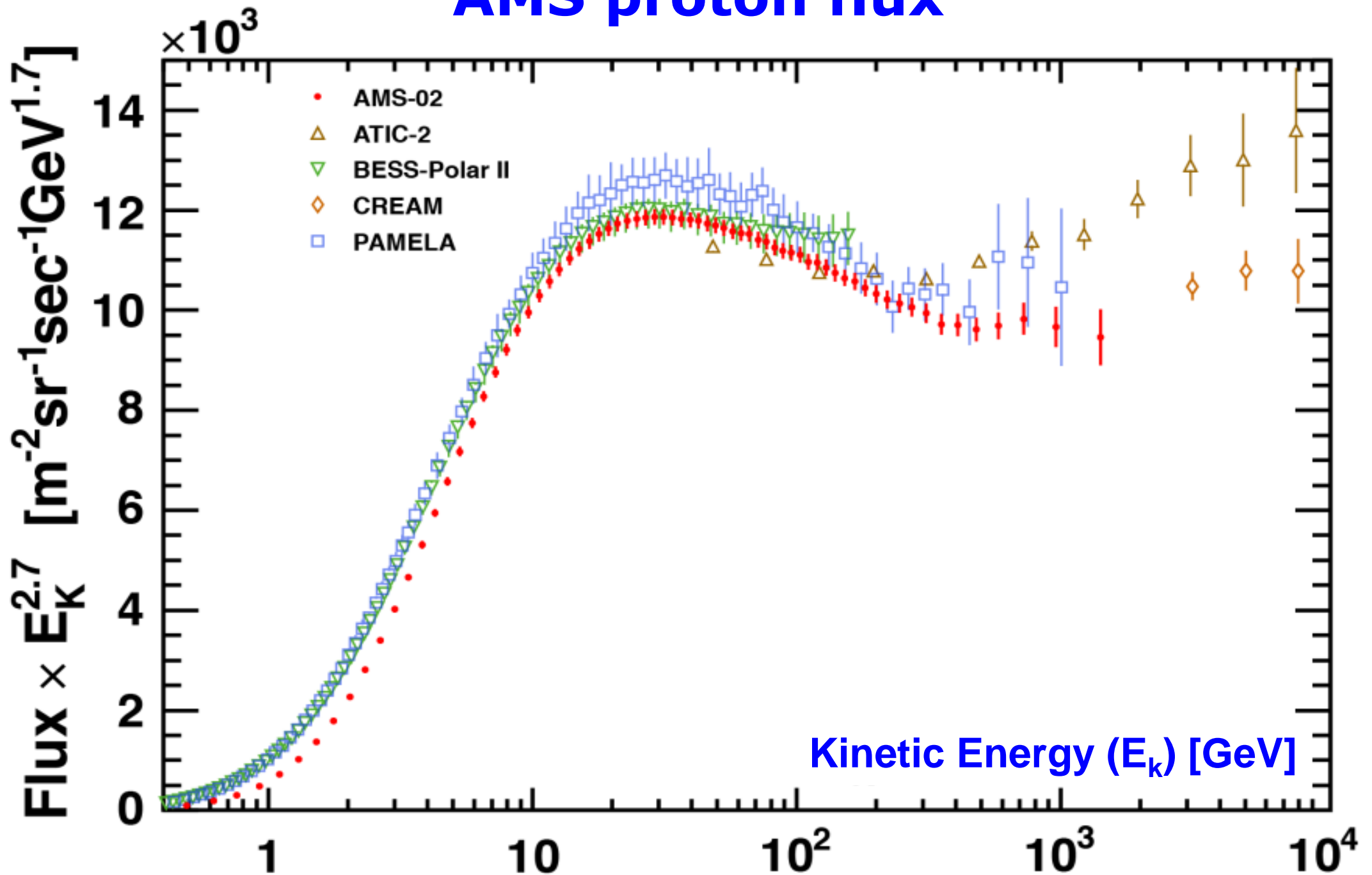
# Accurate measurement of the flux of nuclei on the ISS.

A new method:

To measure the flux of nuclei (He, Li, Be, B, C, O, …) accurately, we need to know the interaction cross section of these nuclei with the materials in AMS.

Unfortunately, the interactions of nuclei with the materials in AMS could not be measured on the ground. This limits the accuracy to which we could measure the fluxes.

On ISS we have now a method to measure these interactions in space accurately.
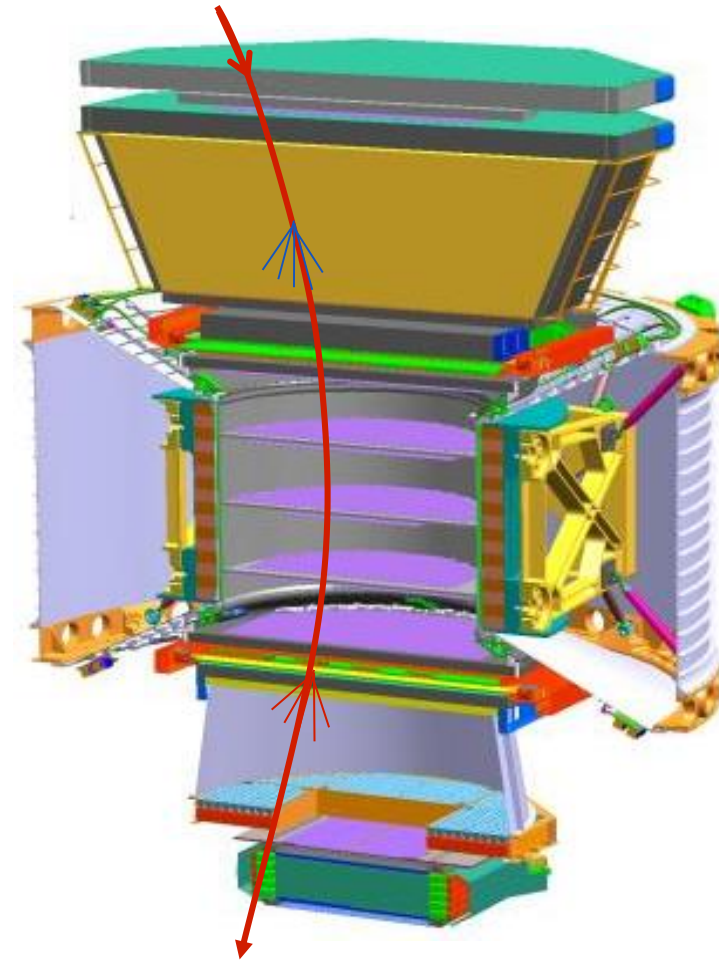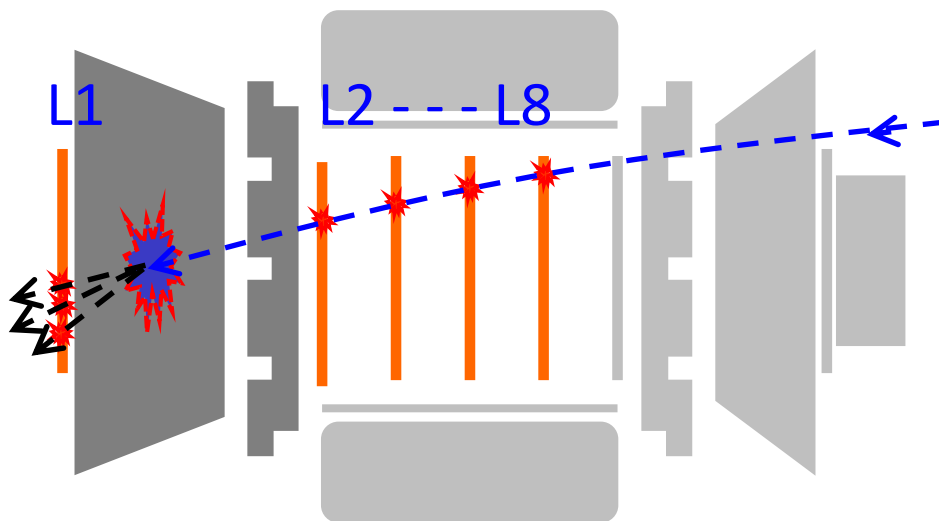
Measuring the interactions of nuclei within AMS
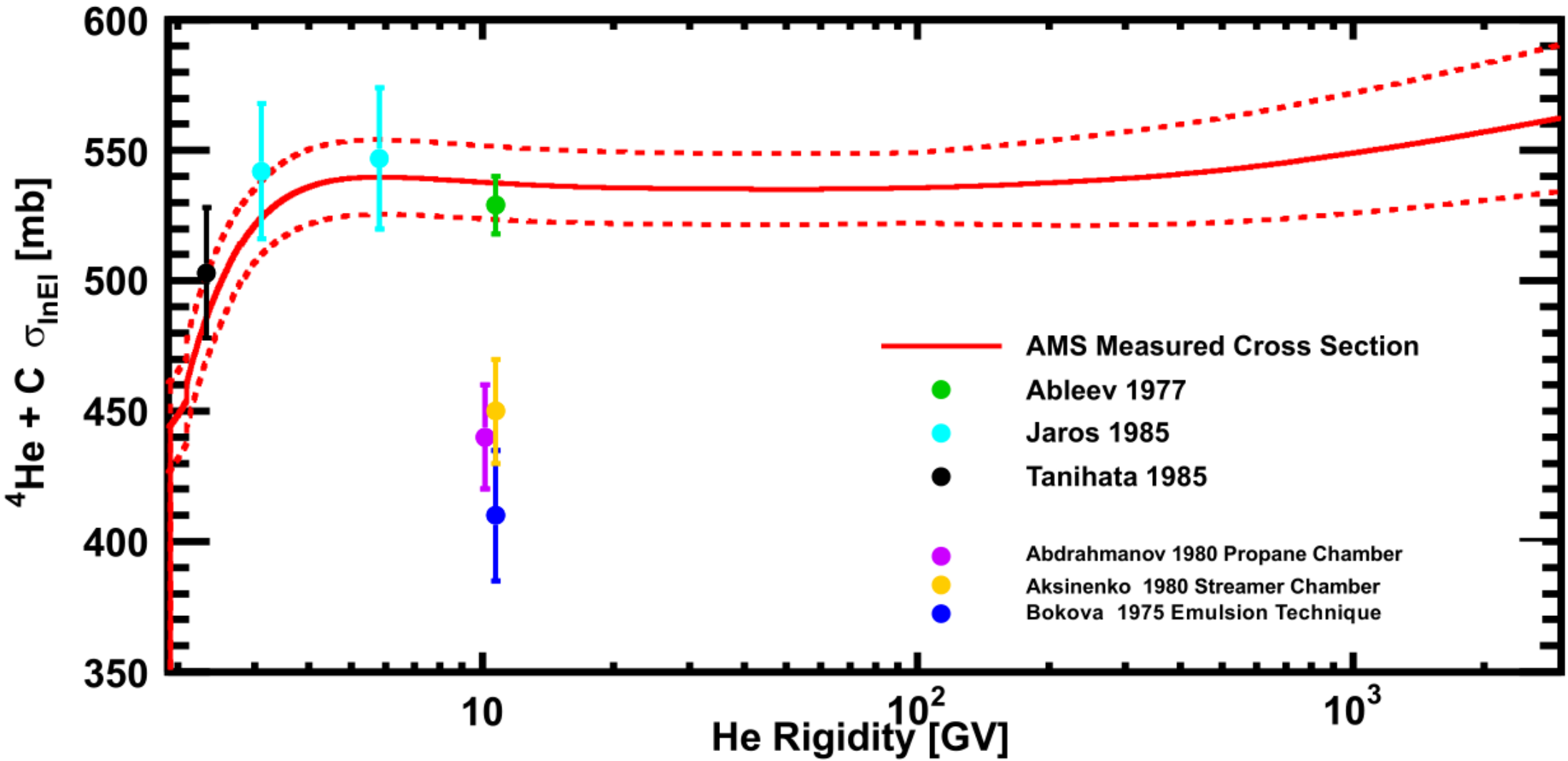## when AMS is flying horizontal

L2 - - - L8   L9

L1   L2 - - - L8
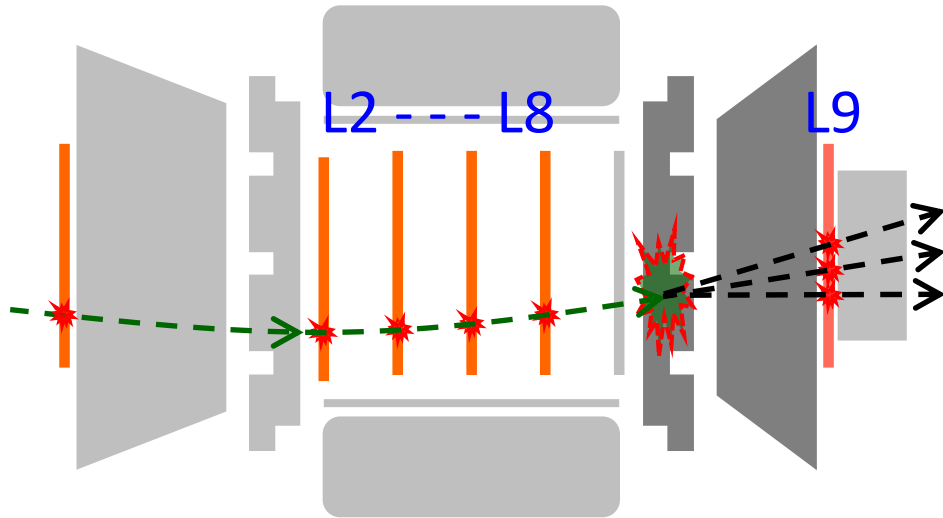
First, we use the seven inner tracker layers, L2-L8, to define beams of nuclei: He, Li, Be, B, …

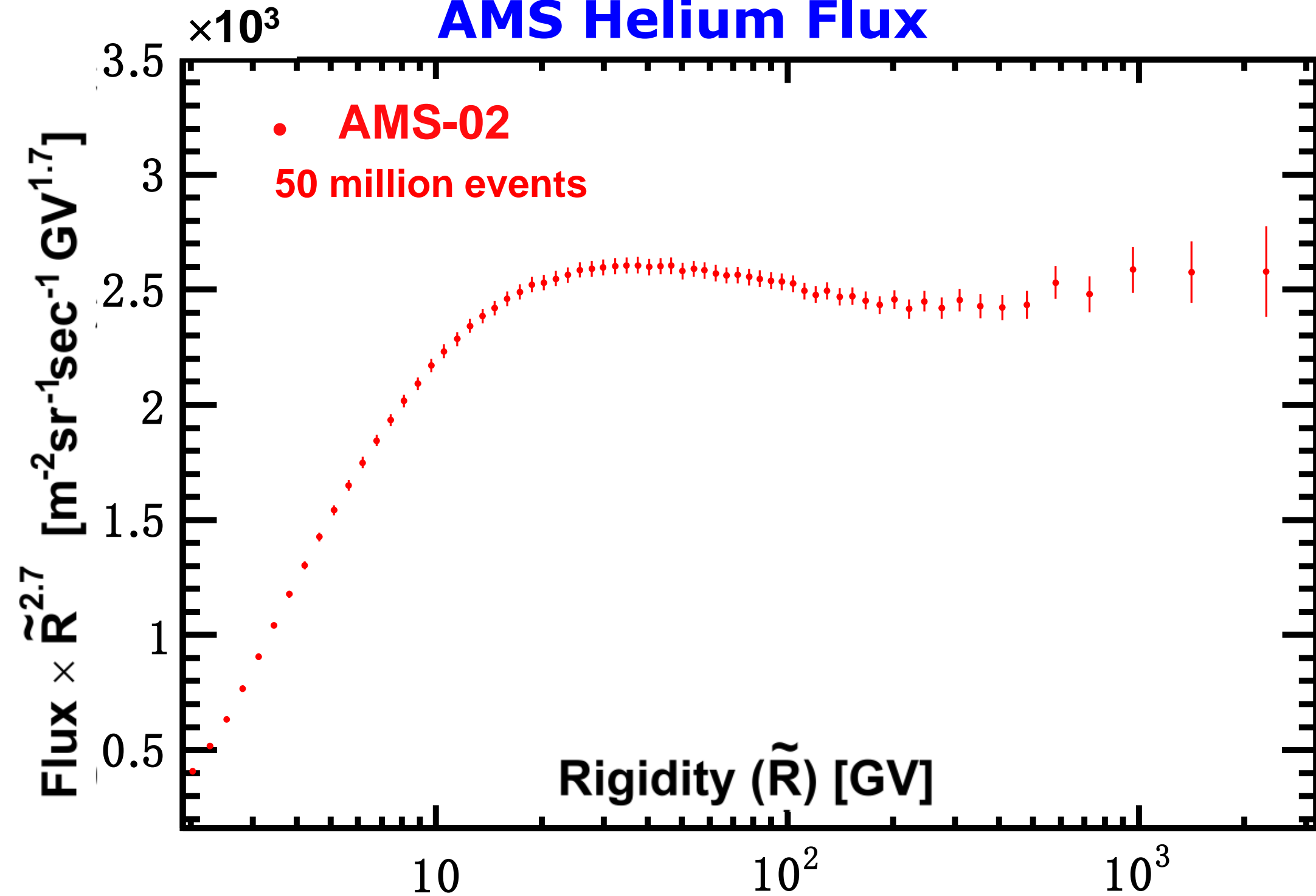Second, we use left-to-right particles to measure the nuclear interactions in the lower part of the detector.

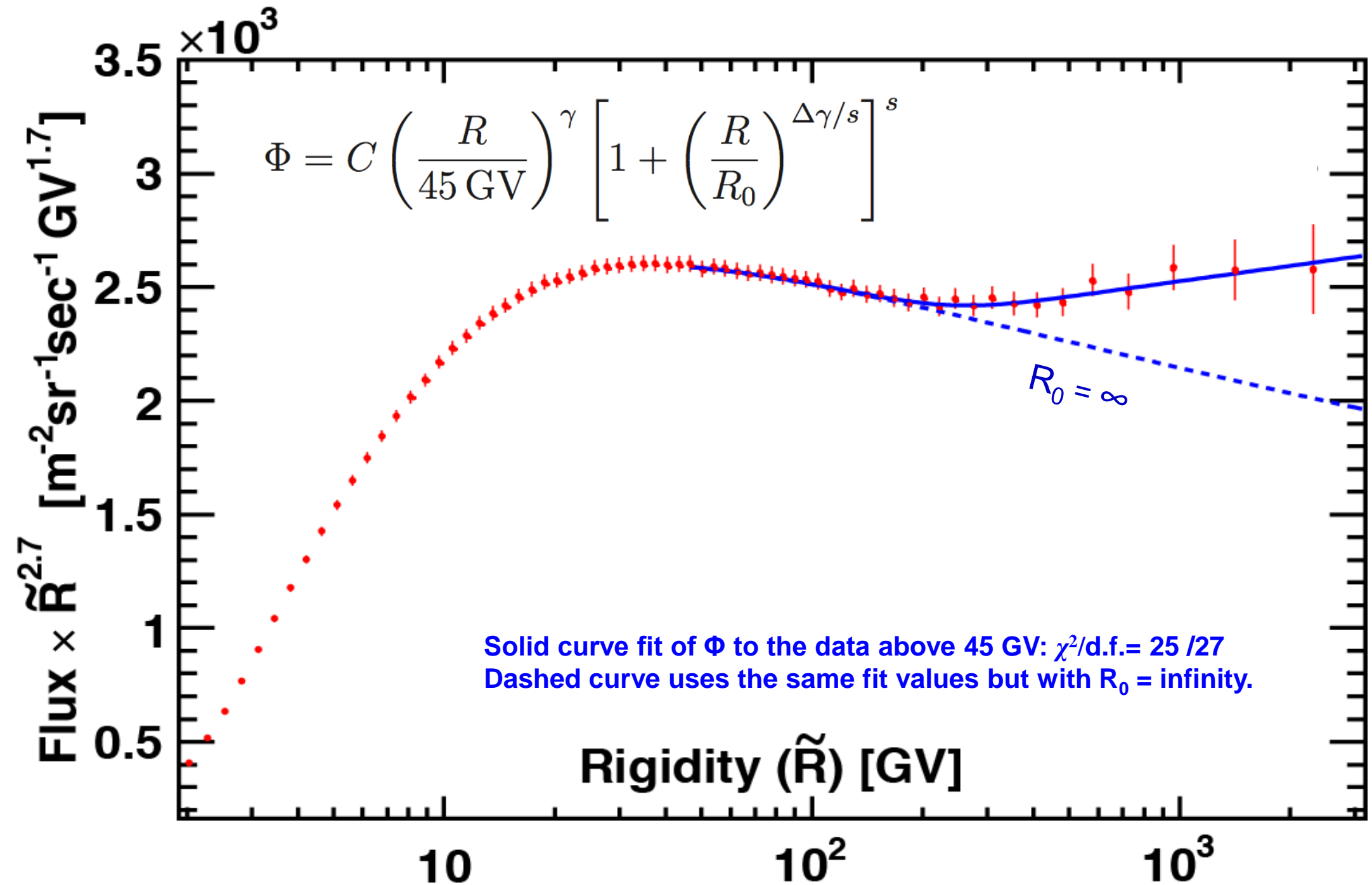Third, we use right-to-left particles to measure the nuclear interactions in the

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AMS Measurement of He+C Cross Section

AMS Helium Flux

AMS-02

50 million events

Flux $\times$ $\tilde{R}^{2.7}$ [m^{-2}sr^{-1}sec^{-1} GV$^{1.7}$]

Rigidity ($\tilde{R}$) [GV]

$\times 10^3$

AMS Helium Flux

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

$R_0 = \infty$

Solid curve fit of Φ to the data above 45 GV: χ^2/d.f.= 25 /27
Dashed curve uses the same fit values but with R_0 = infinity.

Flux × $\tilde{R}^{2.7}$ [m^{-2}sr^{-1}sec^{-1} GV$^{1.7}$]

Rigidity ($\tilde{R}$) [GV]

AMS Helium Flux

- AMS-02
- ATIC-2
- BESS-Polar
- CREAM
- PAMELA

Flux × $E_K^{2.7}$ [m^{-2}sr^{-1}sec^{-1}(GeV/n)$^{1.7}$]

Kinetic Energy (E_K) [GeV/n]

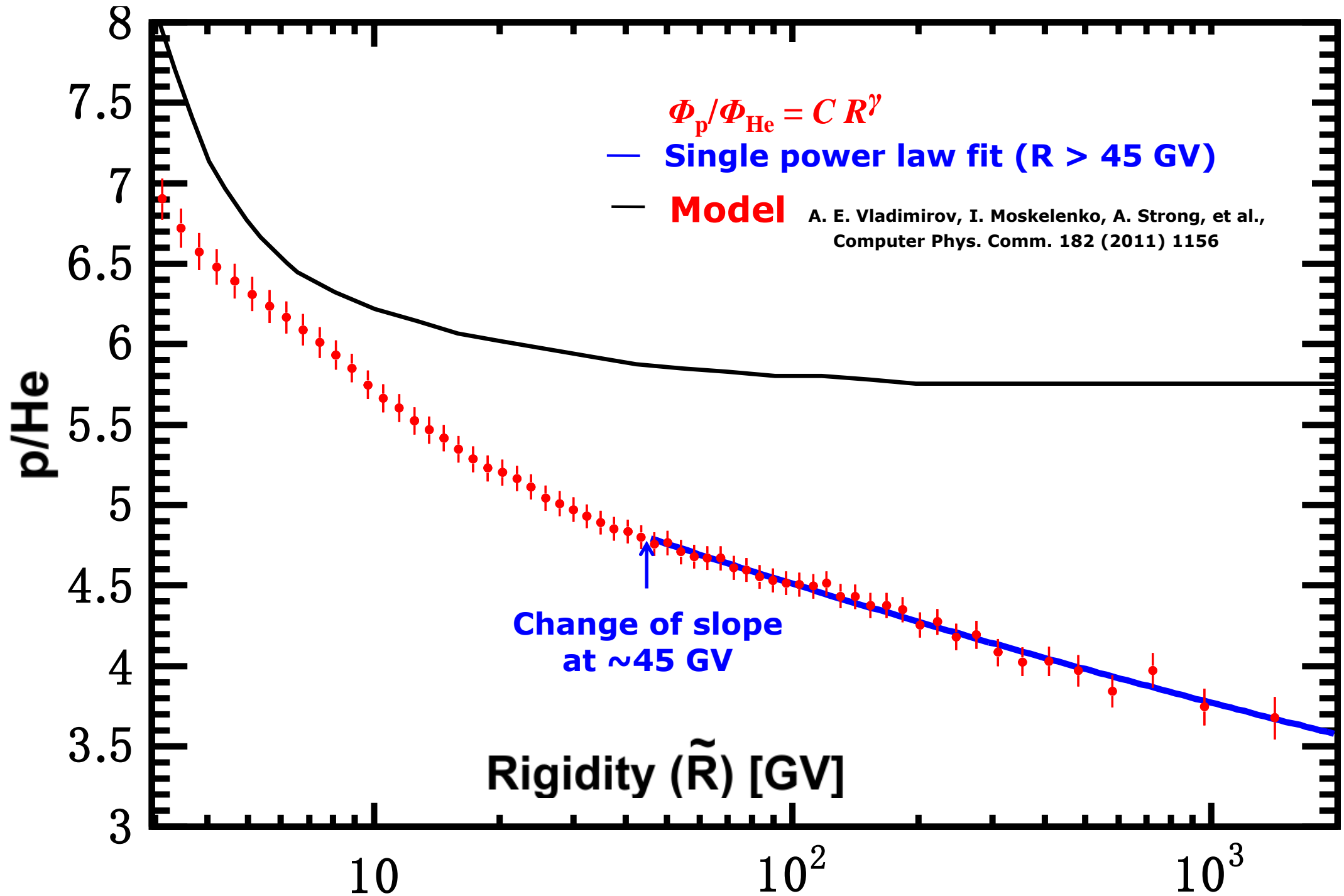# Model Independent Spectral Indices Comparison

$$\gamma = d \log (\Phi)/ d \log (R)$$
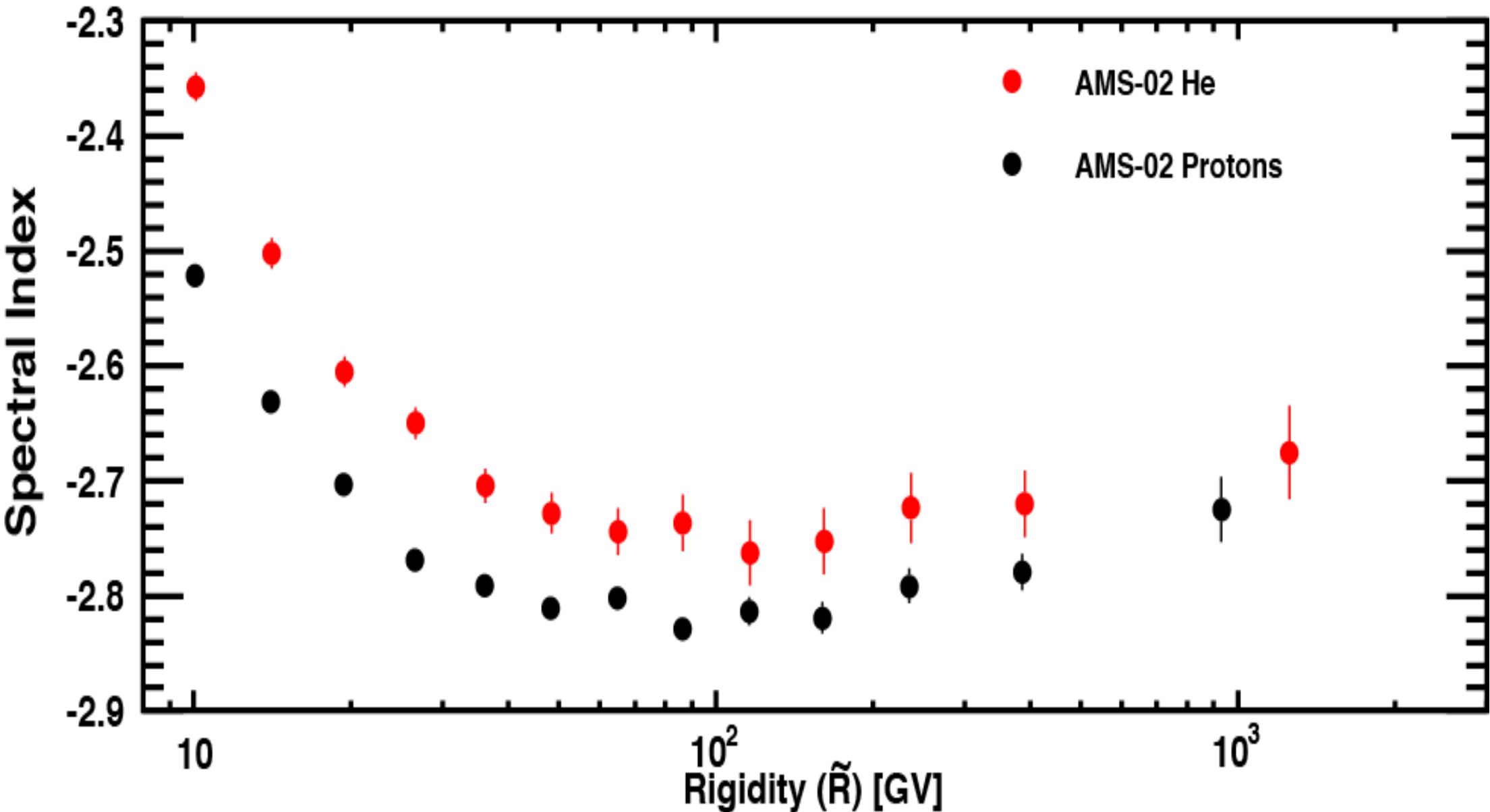
The AMS proton/helium ratio

$$\Phi_p/\Phi_{He} = C\,R^{\gamma}$$

— **Single power law fit (R > 45 GV)**

— **Model** A. E. Vladimirov, I. Moskelenko, A. Strong, et al., Computer Phys. Comm. 182 (2011) 1156

Change of slope at ~45 GV

p/He

Rigidity ($\tilde{R}$) [GV]

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proton/He flux ratio

proton/He flux ratio vs Rigidity [GV]

- AMS-02
- Fit to $\Phi_p/\Phi_{He} = C\,R^\gamma$
- □ PAMELA
- ▽ BESS-Polar

Change of slope at ~45 GV
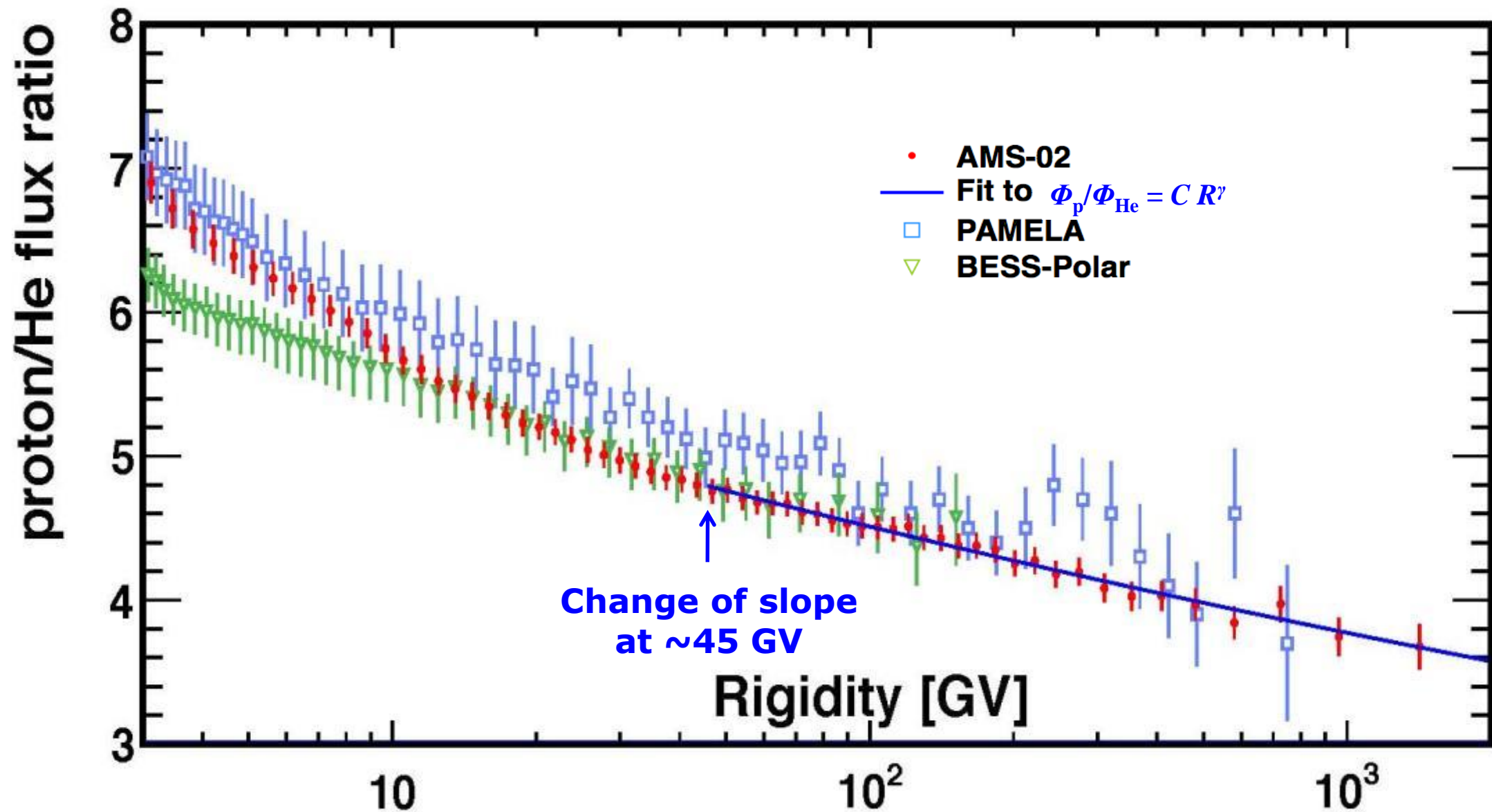
Spectral index of p/He ratio

$$p/He \; ratio = C \, R^{\gamma}$$

$$p/He \; spectral \; index \; (\gamma) = d \log (p/He \; ratio)/ d \log (R)$$

Constant above 45 GV

$\gamma_{p/He} = -0.077 \pm 0.0073$
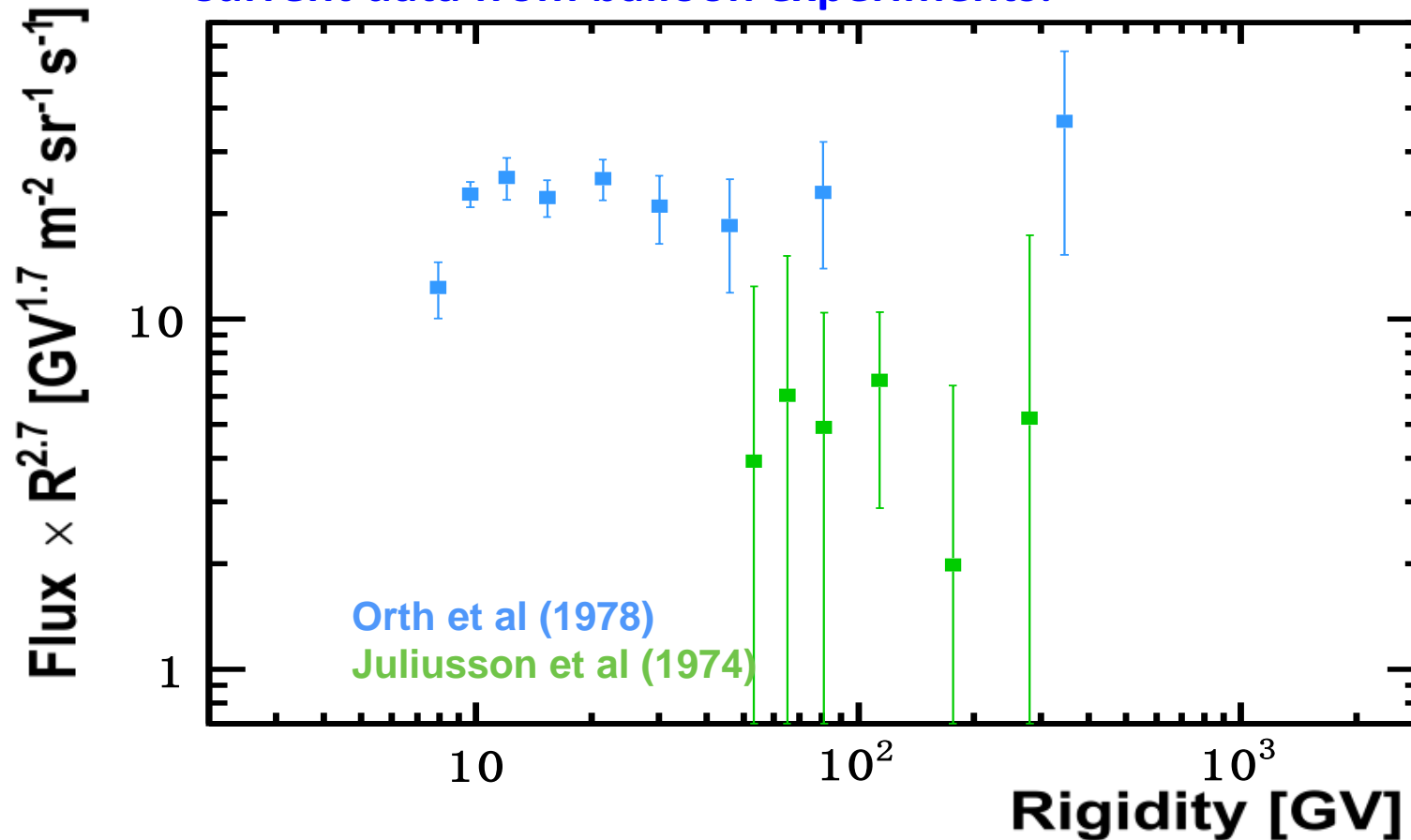
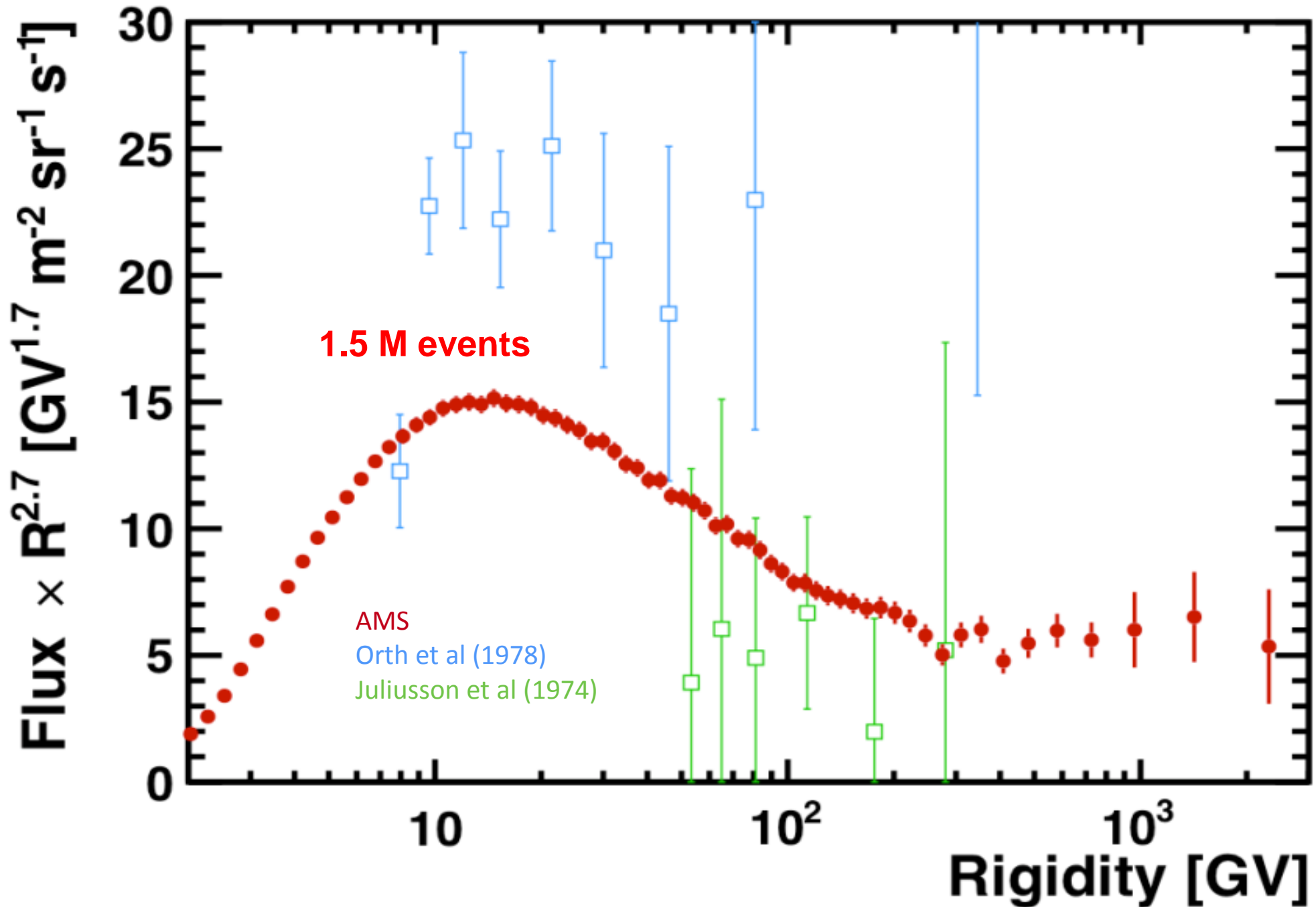Rigidity ($\tilde{R}$) [GV]
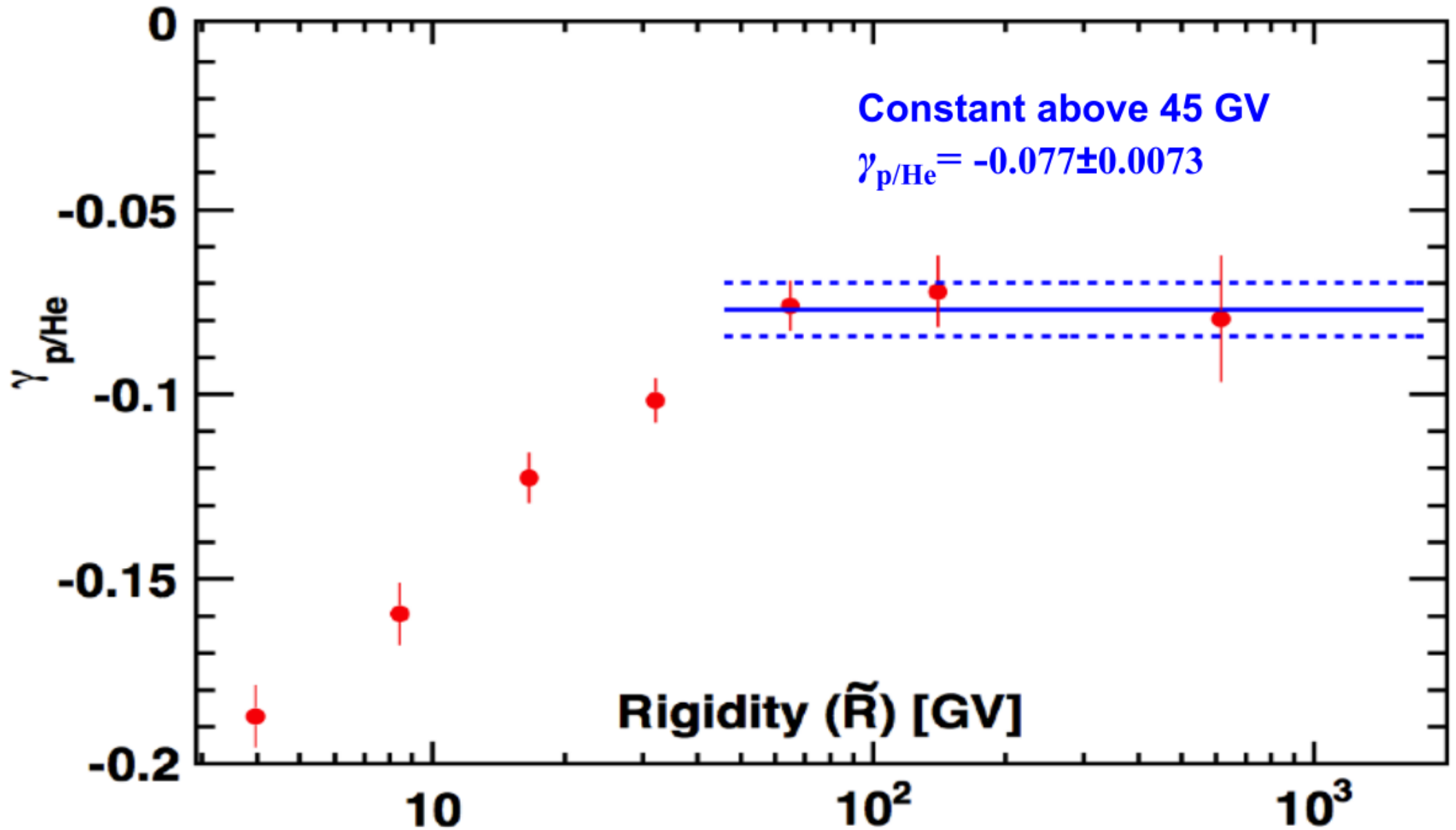
Lithium in Cosmic Rays

- **Like B and Be, Li is produced by the spallation of heavier nuclei during their propagation.**
- **Sensitive to CR propagation parameters (diffusion, convection, reacceleration…).**

C, N, O,…Fe + ISM → Li
→ B, Be + ISM → Li
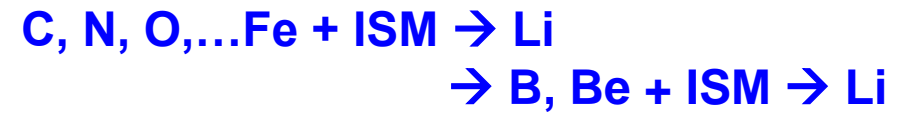
Current data from balloon experiments:

Orth et al (1978)
Juliusson et al (1974)

AMS Lithium flux – current status

Flux × R$^{2.7}$ [GV$^{1.7}$ m^{-2} sr^{-1} s^{-1}] vs Rigidity [GV]

1.5 M events

AMS
Orth et al (1978)
Juliusson et al (1974)

Lithium flux with two power law fit

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

$R_0 = \infty$
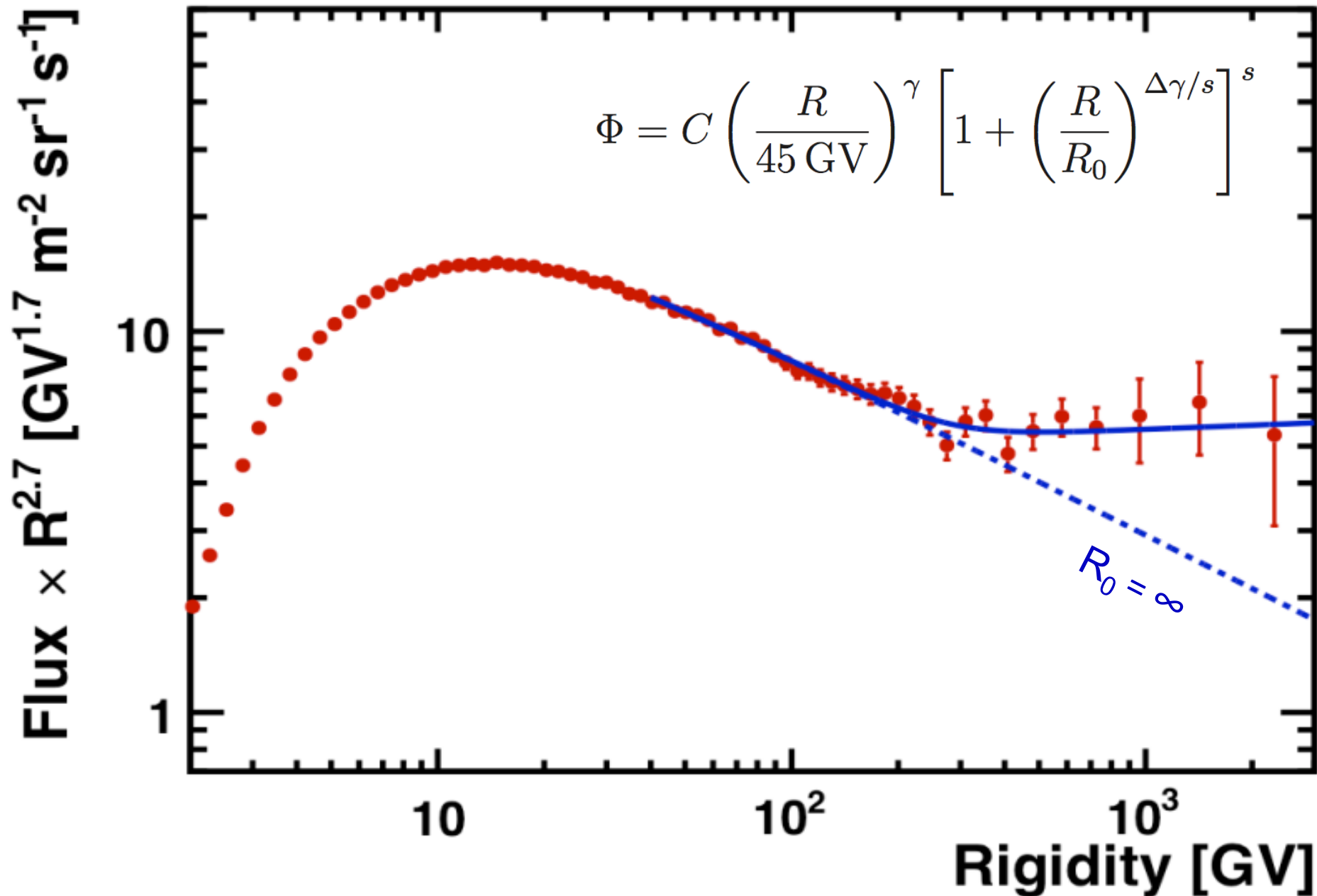
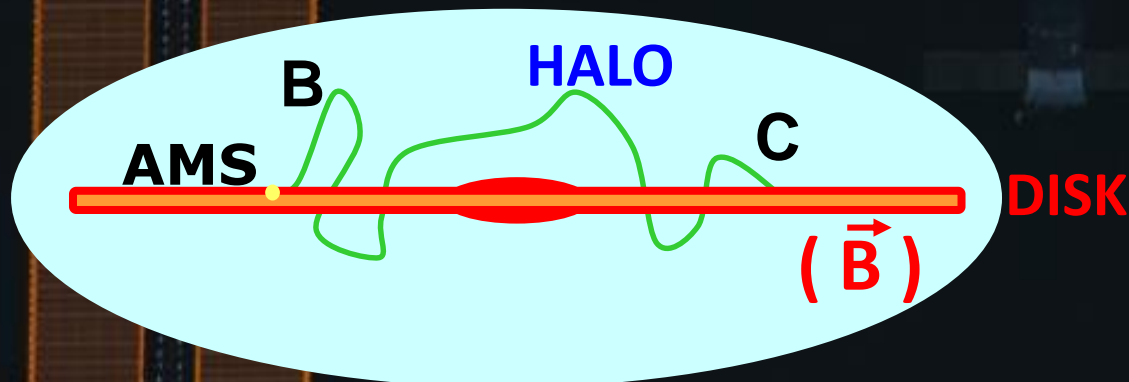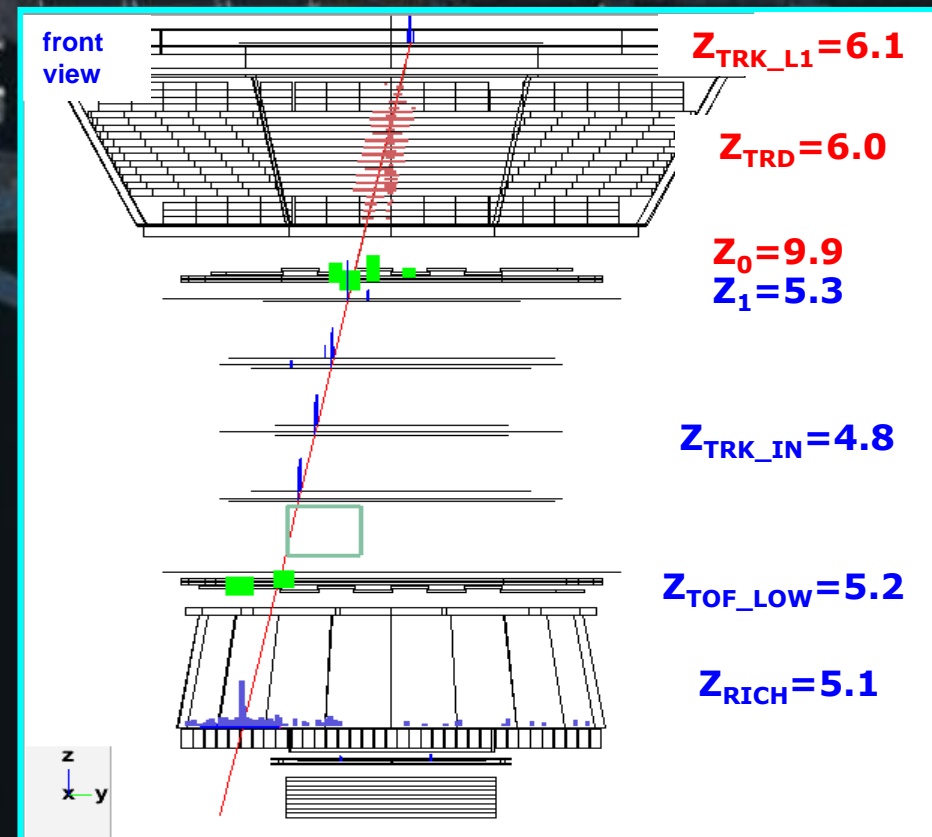**Slope changes at about the same rigidity as for protons and helium**

Precise measurement of the rigidity spectra of B/C provides information on Cosmic Ray Interactions and Propagation
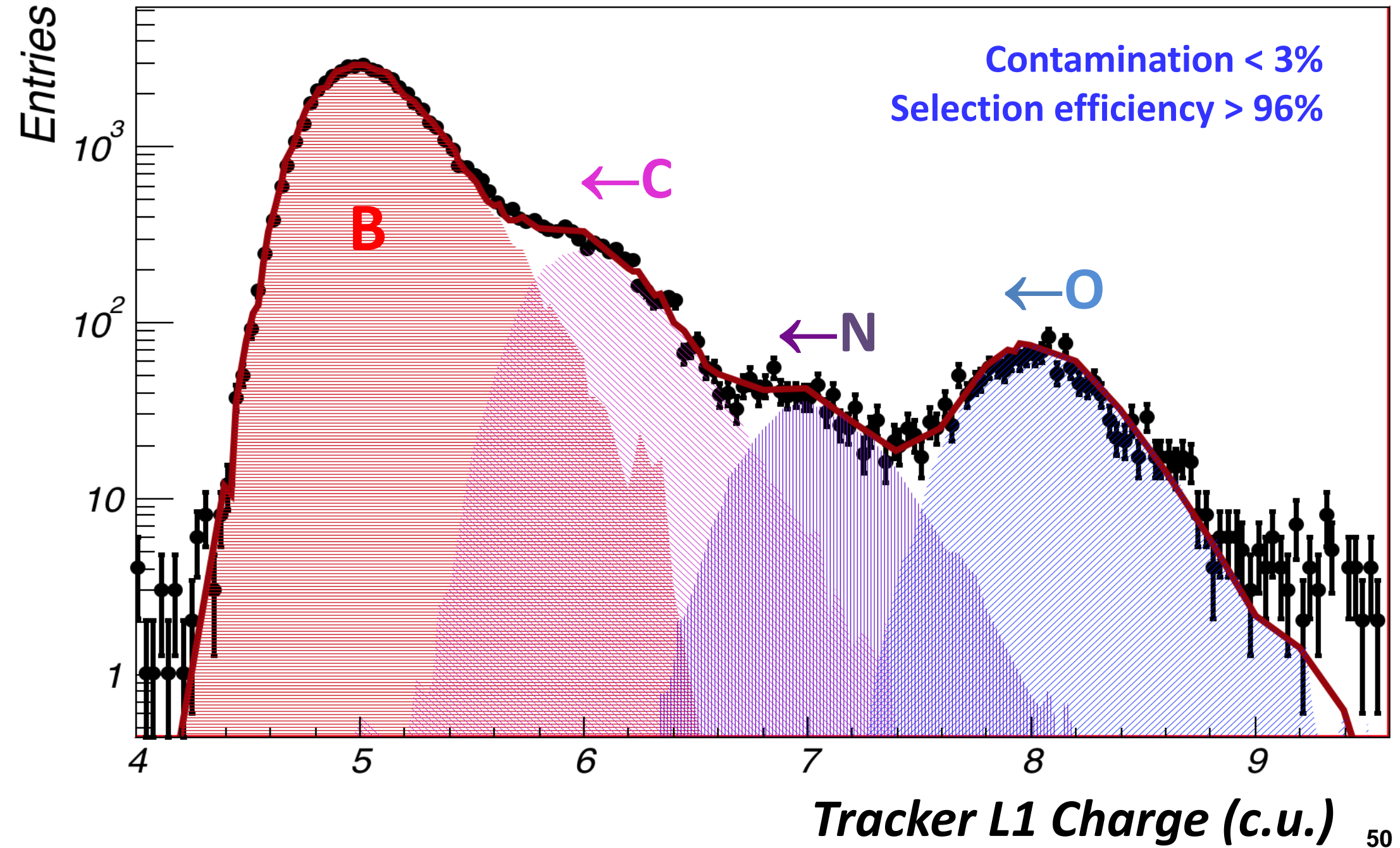

Carbon Fragmentation to Boron R = 10.6 GV

The propagation of cosmic rays and their interactions with the Interstellar Medium (ISM) is measured through the B/C ratio.

HALO

B

AMS

C

DISK

$(\vec{B})$

front view

$Z_{TRK\_L1}=6.1$

$Z_{TRD}=6.0$

$Z_0=9.9$
$Z_1=5.3$

$Z_{TRK\_IN}=4.8$

$Z_{TOF\_LOW}=5.2$

$Z_{RICH}=5.1$

z
x—y

Boron and Carbon: Sample composition

Contamination < 3%
Selection efficiency > 96%

B

←C

←N

←O

Entries

Tracker L1 Charge (c.u.)

AMS B/C Ratio

Exposure time of 40 months
7M Carbons, 2M Borons

Boron-to-Carbon Ratio

Rigidity (GV)

● *AMS-02*
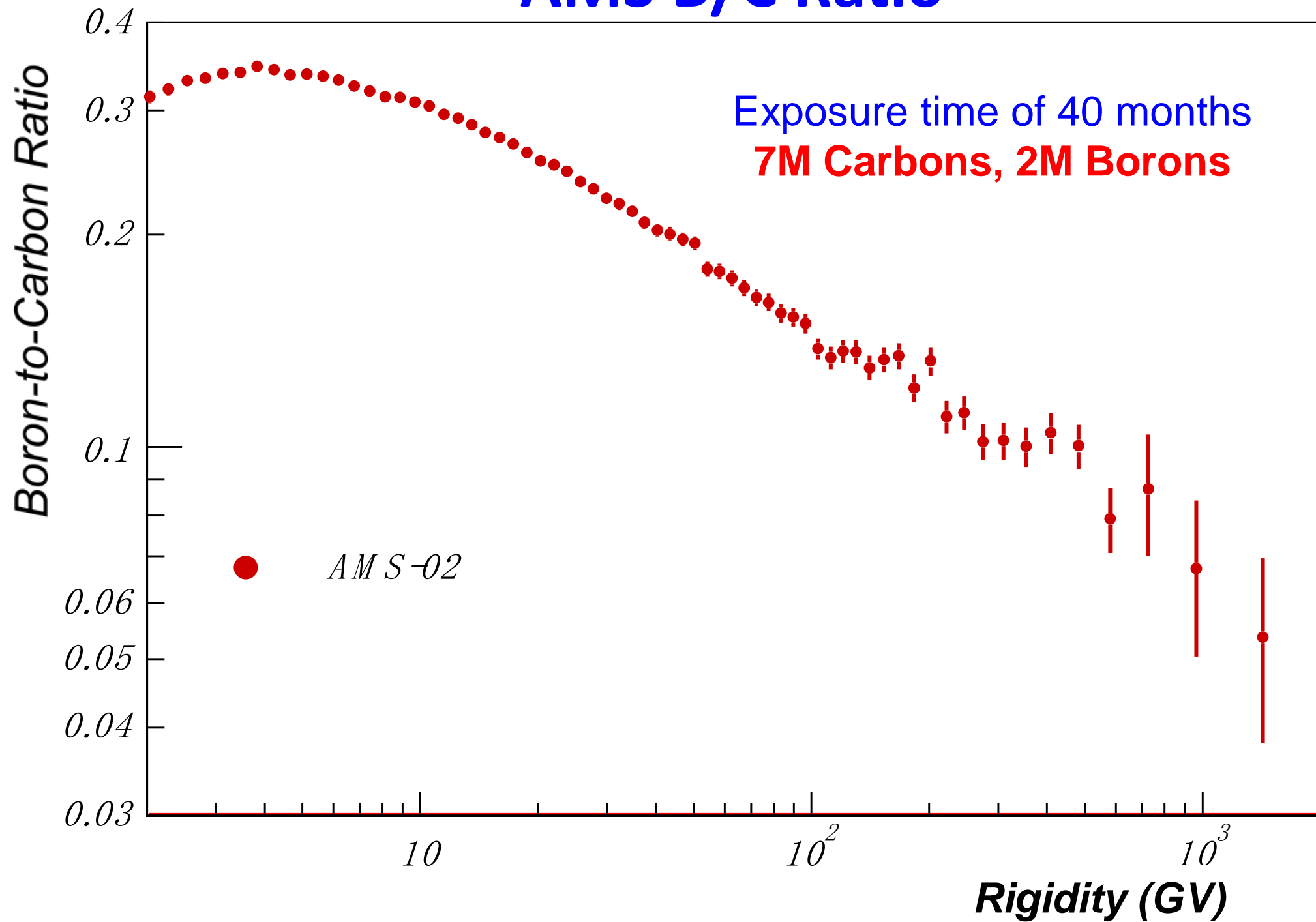
AMS B/C Ratio converted in Kinetic Energy

7 M Carbon events
2 M Boron events

comparison with measurements from 0.5 GeV/n to 3 TeV/n

Boron-to-Carbon Ratio

Kinetic Energy (GeV/n)

- AMS-02
- PAMELA (2014)
- TRACER (2006)
- CREAM-I (2004)
- ATIC-02 (2003)
- AMS-01 (1998)
- Buckley et al. (1991)
- CRN-Spacelab2 (1985)
- Webber et al. (1981)
- HEAO3-C2 (1980)
- Simon et al. (1974-1976)
- Dwyer & Meyer (1973-1975)
- Orth et al. (1972)
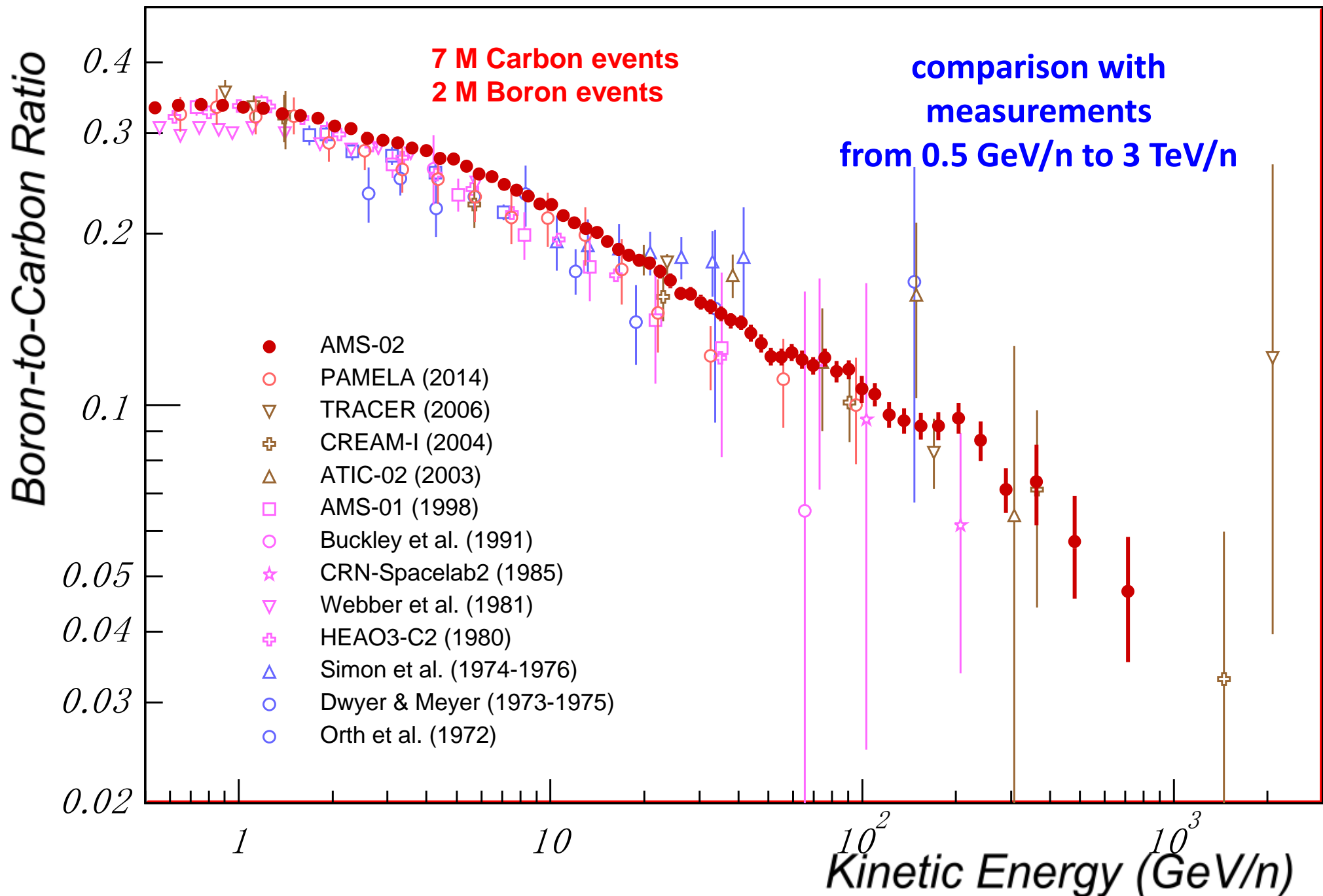
The latest AMS measurements of the positron fraction, the antiproton/proton ratio, the behavior of the fluxes of electrons, positrons, protons, helium, and other nuclei is providing new, precise, and unexpected information.

The accuracy and characteristics of the data, simultaneously from many different types of cosmic rays, will soon determine the true nature of the new phenomena we observe.
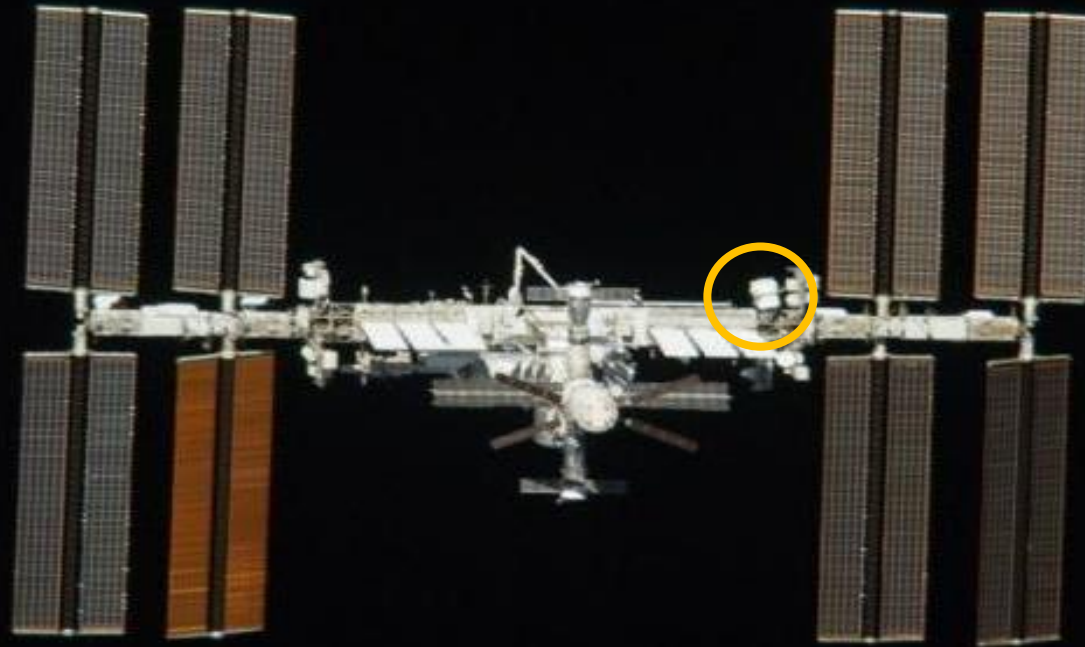
AMS physics for the lifetime of the Space Station

Accurate measurement (~1%) of Cosmic Rays to higher energies including:

a. Continue the study of Dark Matter

b. Search for the Existence of Antimatter

c. Search for New Phenomena, ...

In the past hundred years, measurements of charged cosmic rays by balloons and satellites have typically contained ~30% accuracy.

AMS is providing cosmic ray information with ~1% accuracy. The improvement in accuracy will provide new insights.

The Space Station is now a unique platform for fundamental physics research.