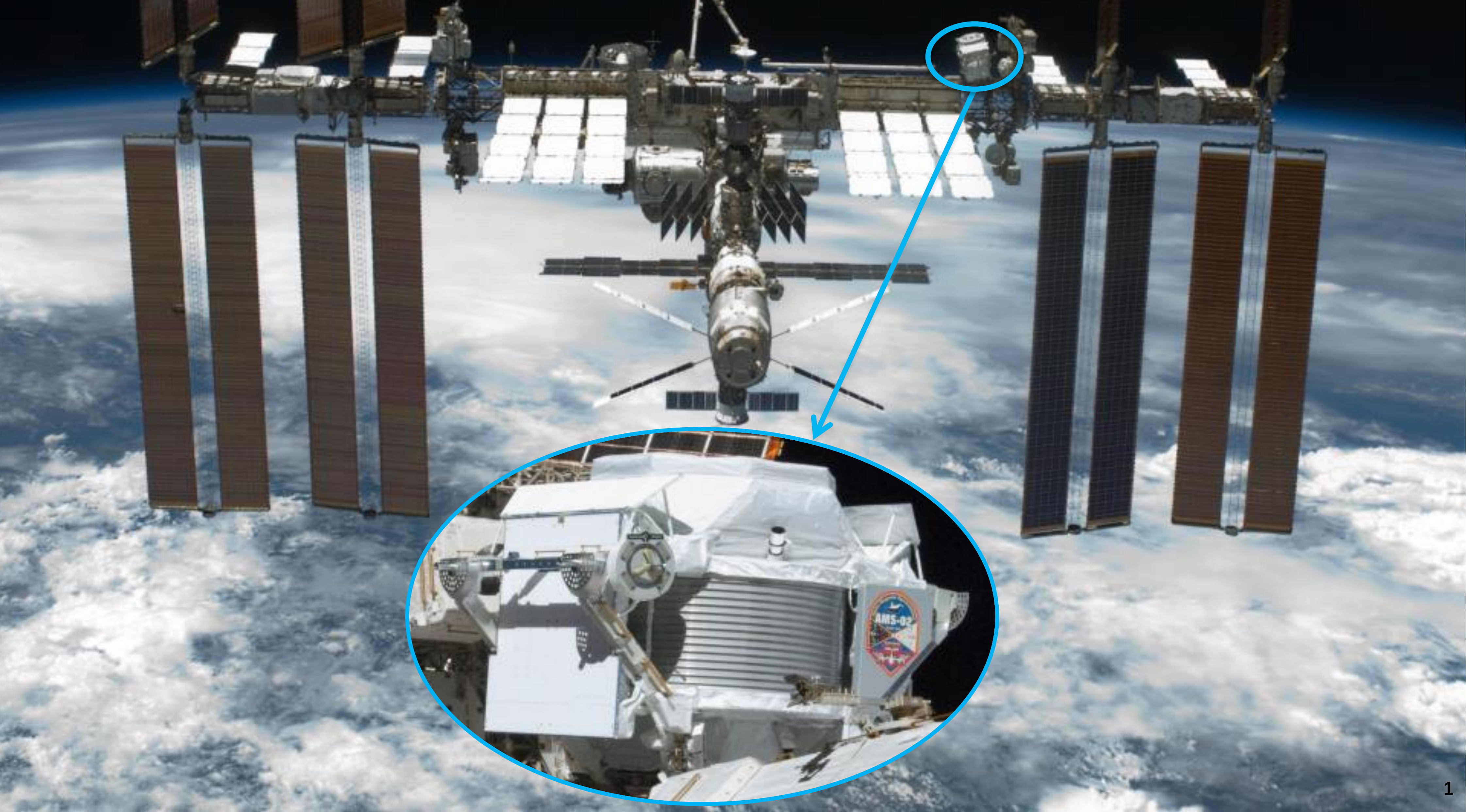
Latest Physics Results from the AMS Experiment on the ISS

Siarhei Vaurynovich / MIT

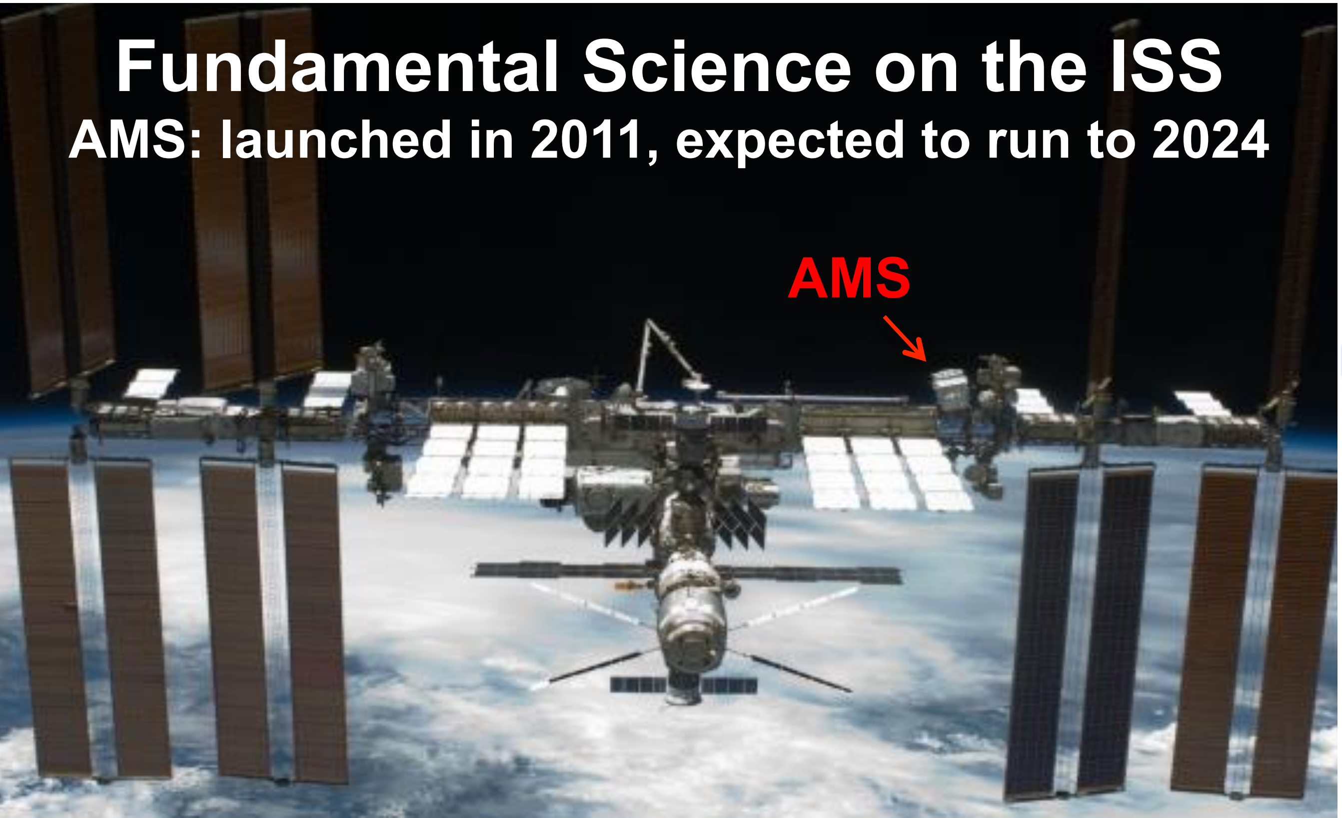
The XXII International Workshop on High Energy Physics and Quantum Field Theory
June 30th, 2015, Samara, Russia



Two kinds of cosmic rays

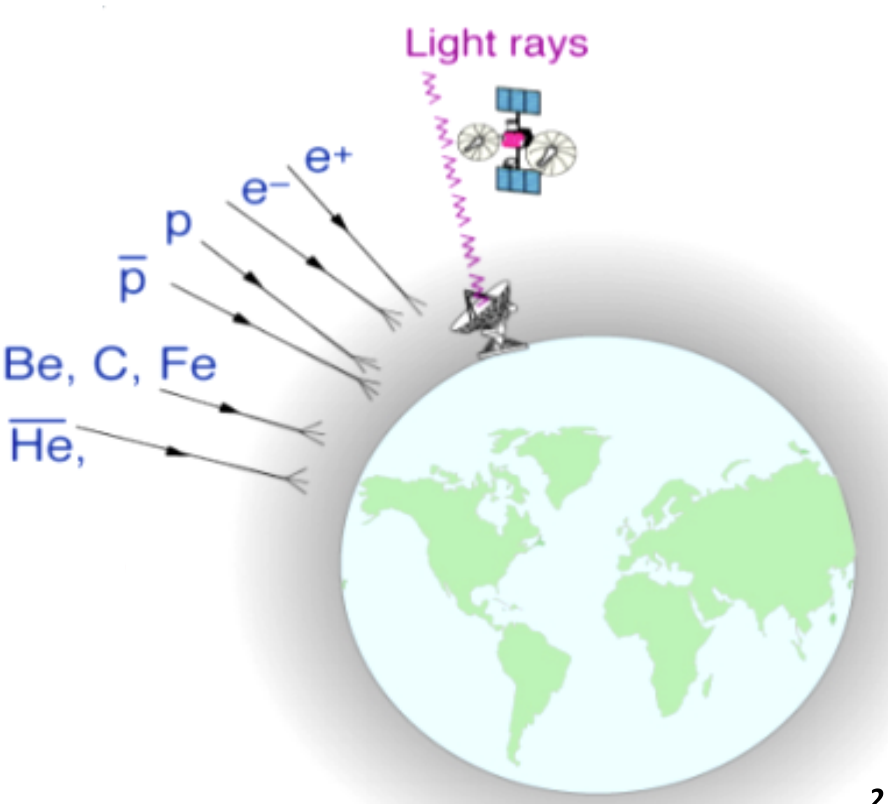
A. Neutral cosmic rays (γ-rays and neutrinos): have been measured for many years (Hubble, COBE, EGRET, WMAP, Planck, Fermi-LAT, Super Kamiokande, IceCube, HESS, …). Fundamental discoveries have been made.

B. Charged cosmic rays: Following the pioneering experiments with balloons and satellites (ACE/CRIS, ATIC, BESS, CREAM, HEAT, PAMELA, …), using a magnetic spectrometer (AMS) on ISS is a unique way to provide precision long term (10-20 years) measurements of primordial high energy charged cosmic rays.

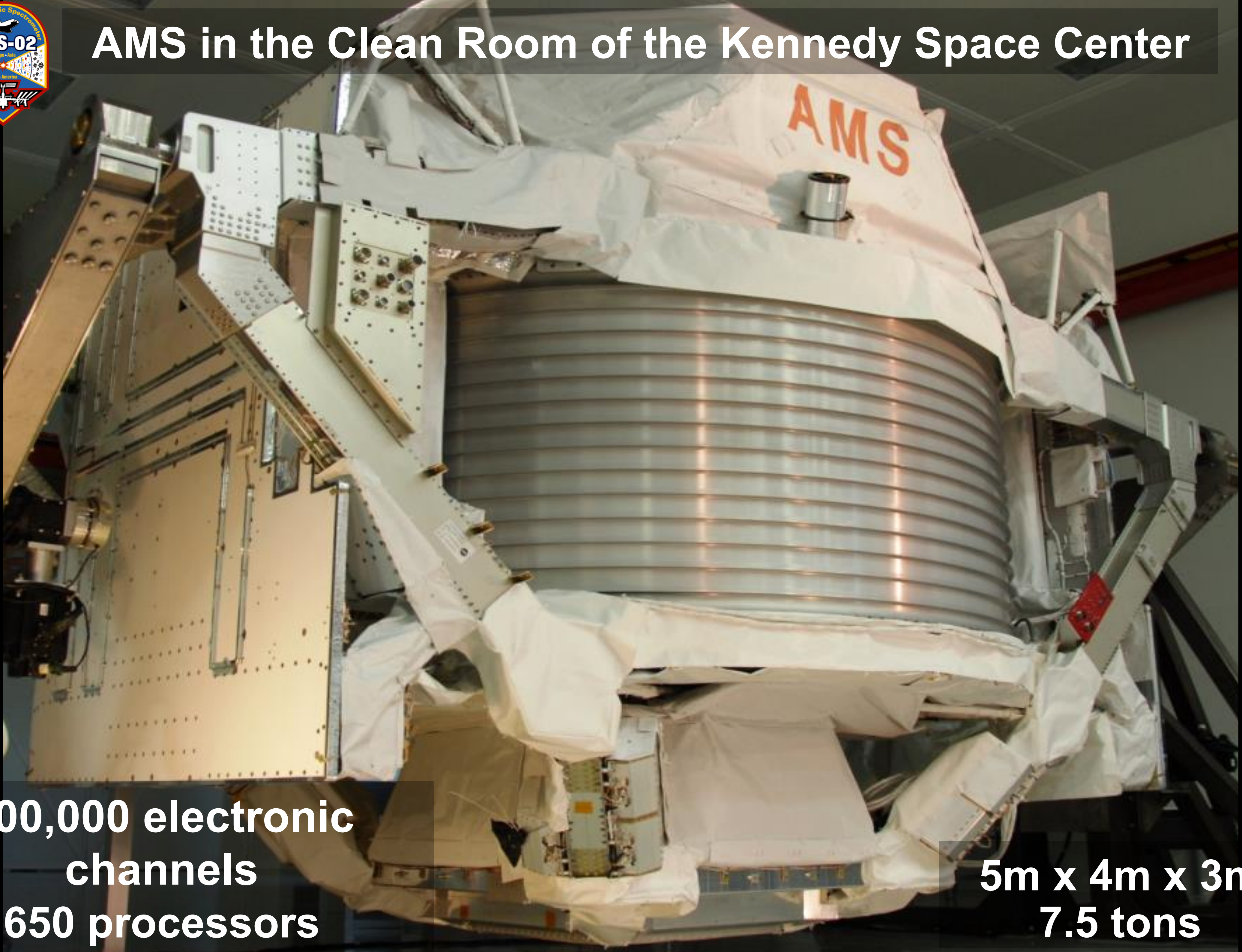


Fundamental Science on the ISS

AMS: launched in 2011, expected to run to 2024



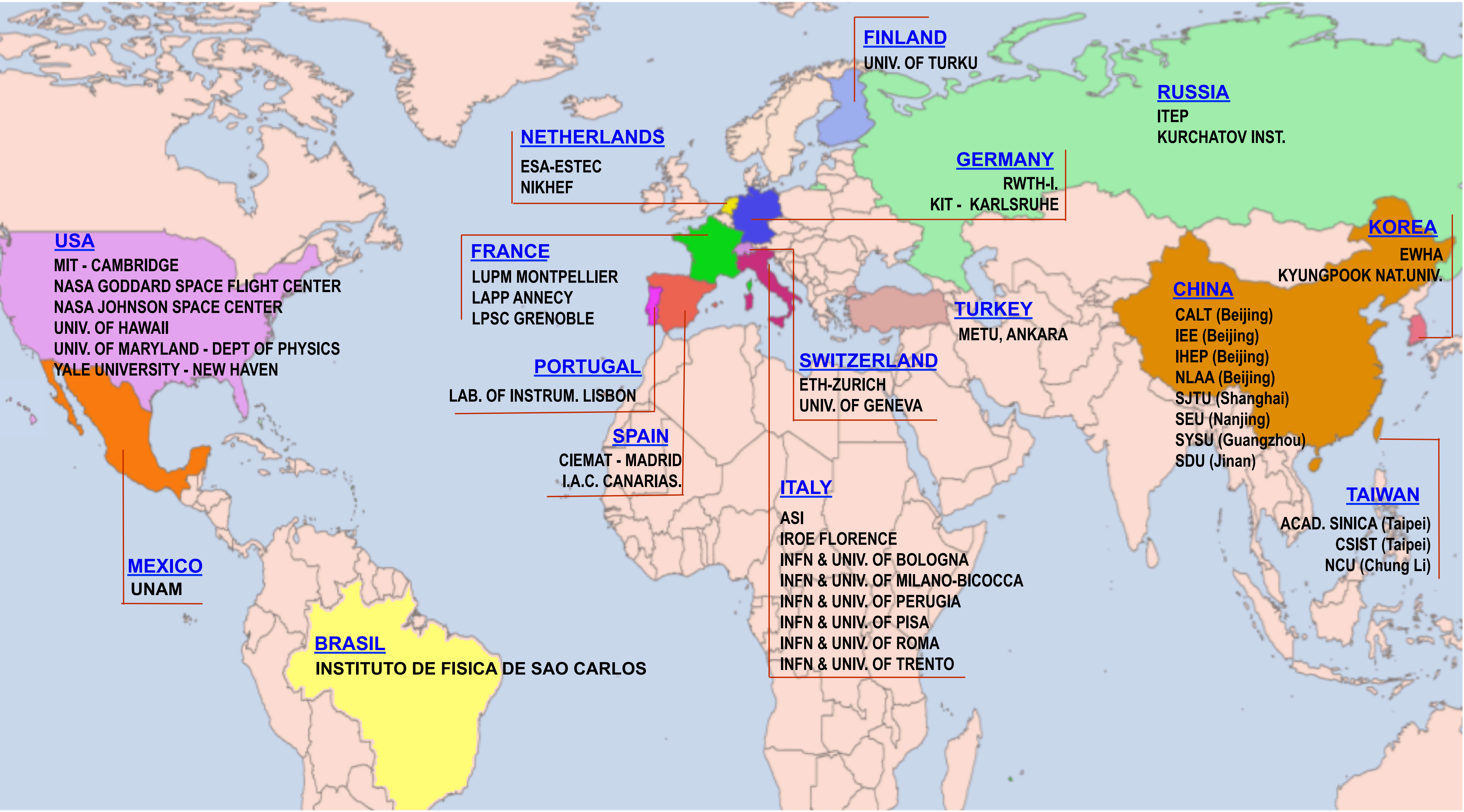
AMS in the Clean Room of the Kennedy Space Center



300,000 electronic channels
650 processors

5m x 4m x 3m
7.5 tons

AMS Is an International Collaboration of 300 Scientists Working in 45 Universities and Institutes Located in 16 Countries



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

MEXICO
UNAM

BRASIL
INSTITUTO DE FISICA DE SAO CARLOS

NETHERLANDS
ESA-ESTEC
NIKHEF

FRANCE
LUPM MONTPELLIER
LAPP ANNECY
LPSC GRENOBLE

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SDU (Jinan)

TAIWAN
ACAD. SINICA (Taipei)
CSIST (Taipei)
NCU (Chung Li)

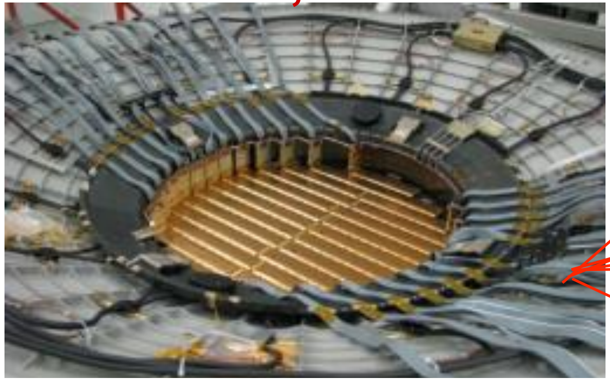
AMS: A TeV precision, multipurpose spectrometer

TRD

Z, Identify e^+, e^-

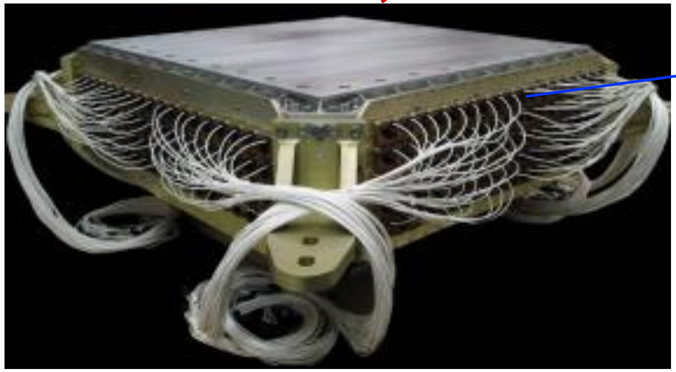
Silicon Tracker

Z, P

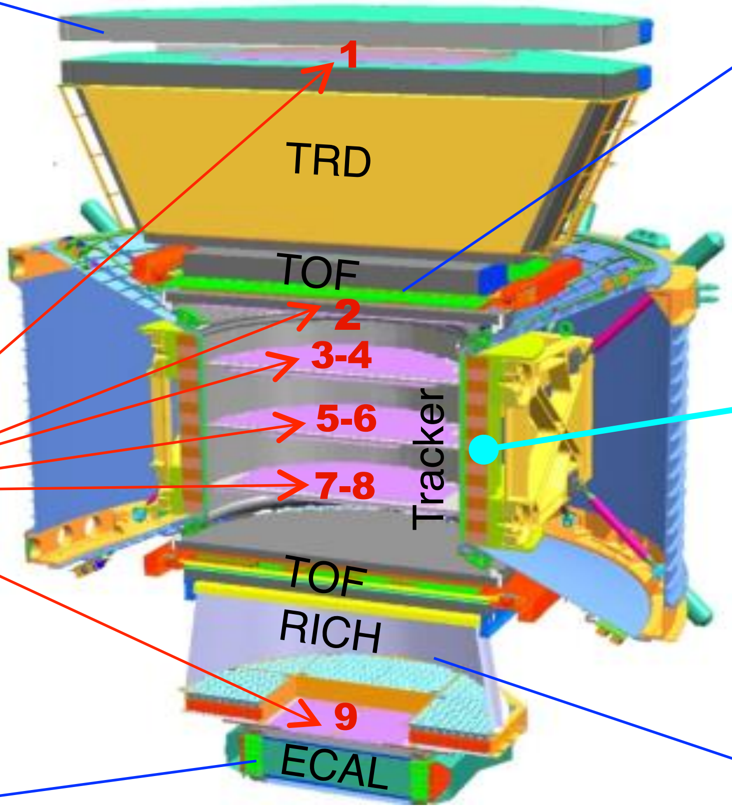


ECAL

E of e^+, e^-



Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



Z and P

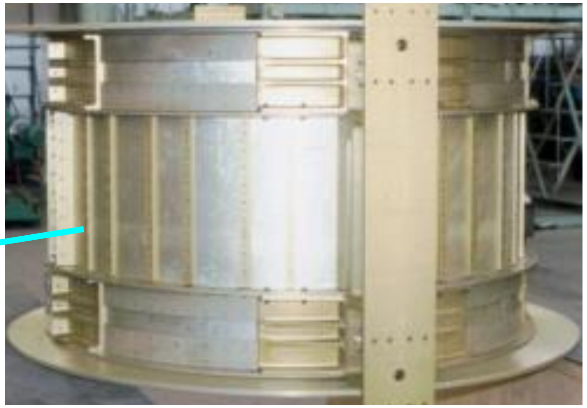
are measured independently by the Tracker, RICH, TOF and ECAL

TOF

Z, E

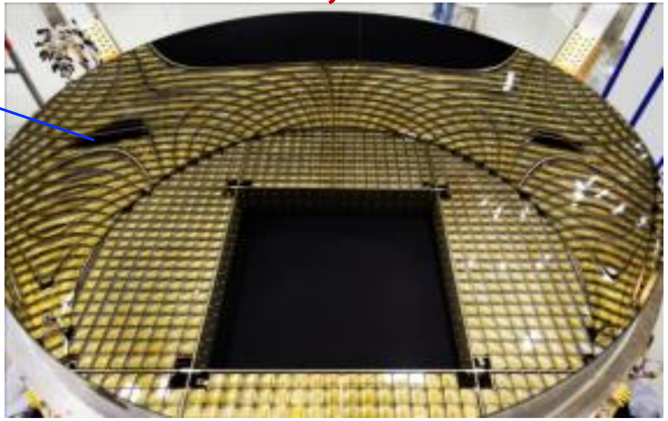
Magnet

±Z



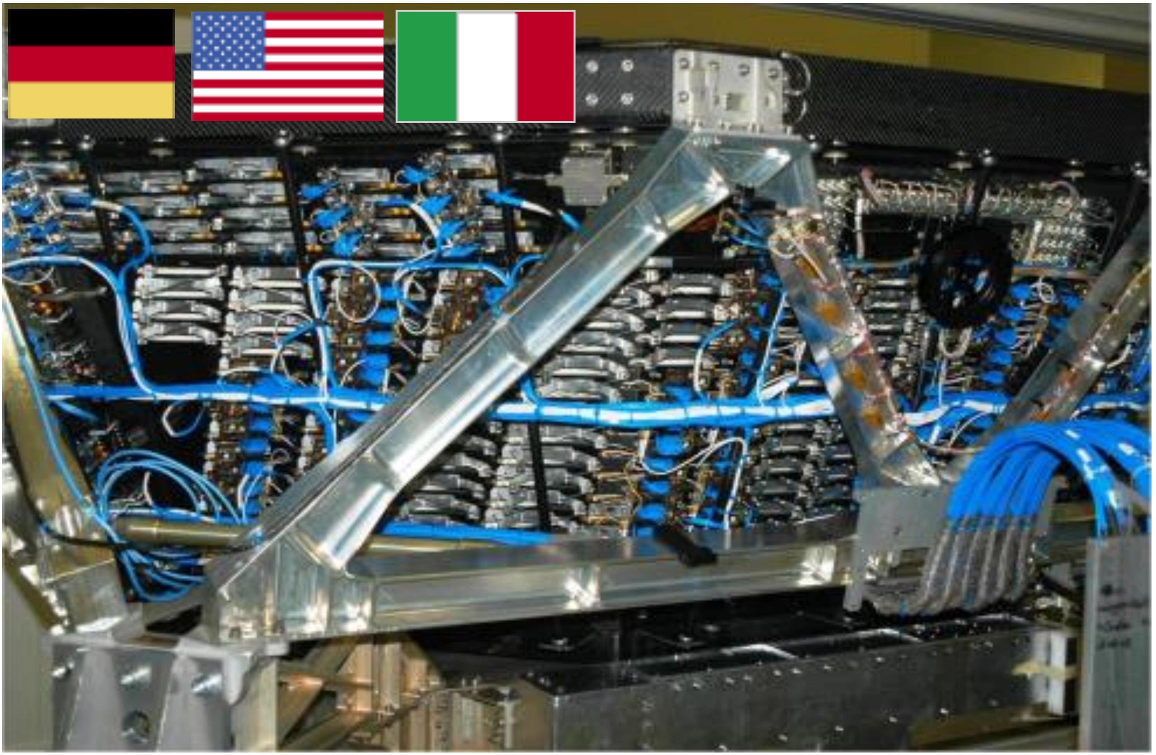
RICH

Z, E

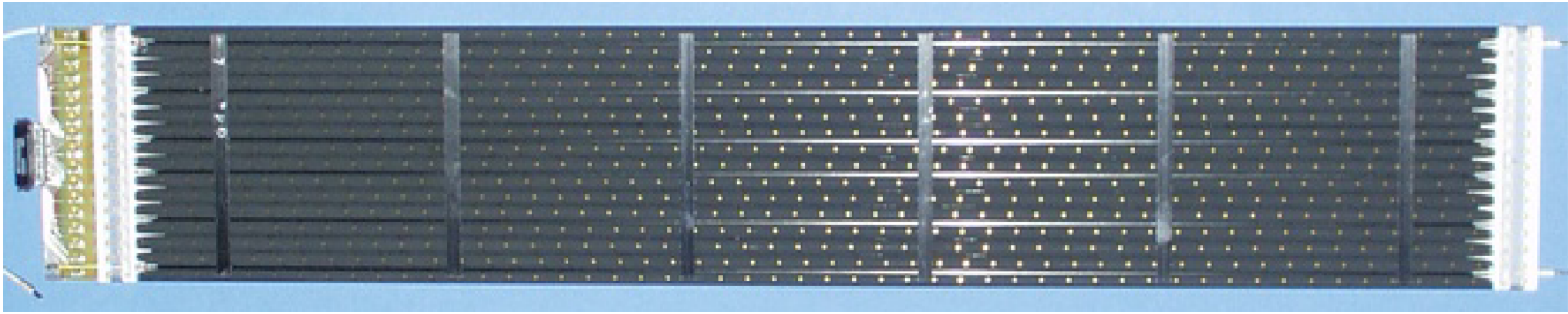


Transition Radiation Detector (TRD)

Identifies Positrons, Electrons by transition radiation and Nuclei by dE/dx

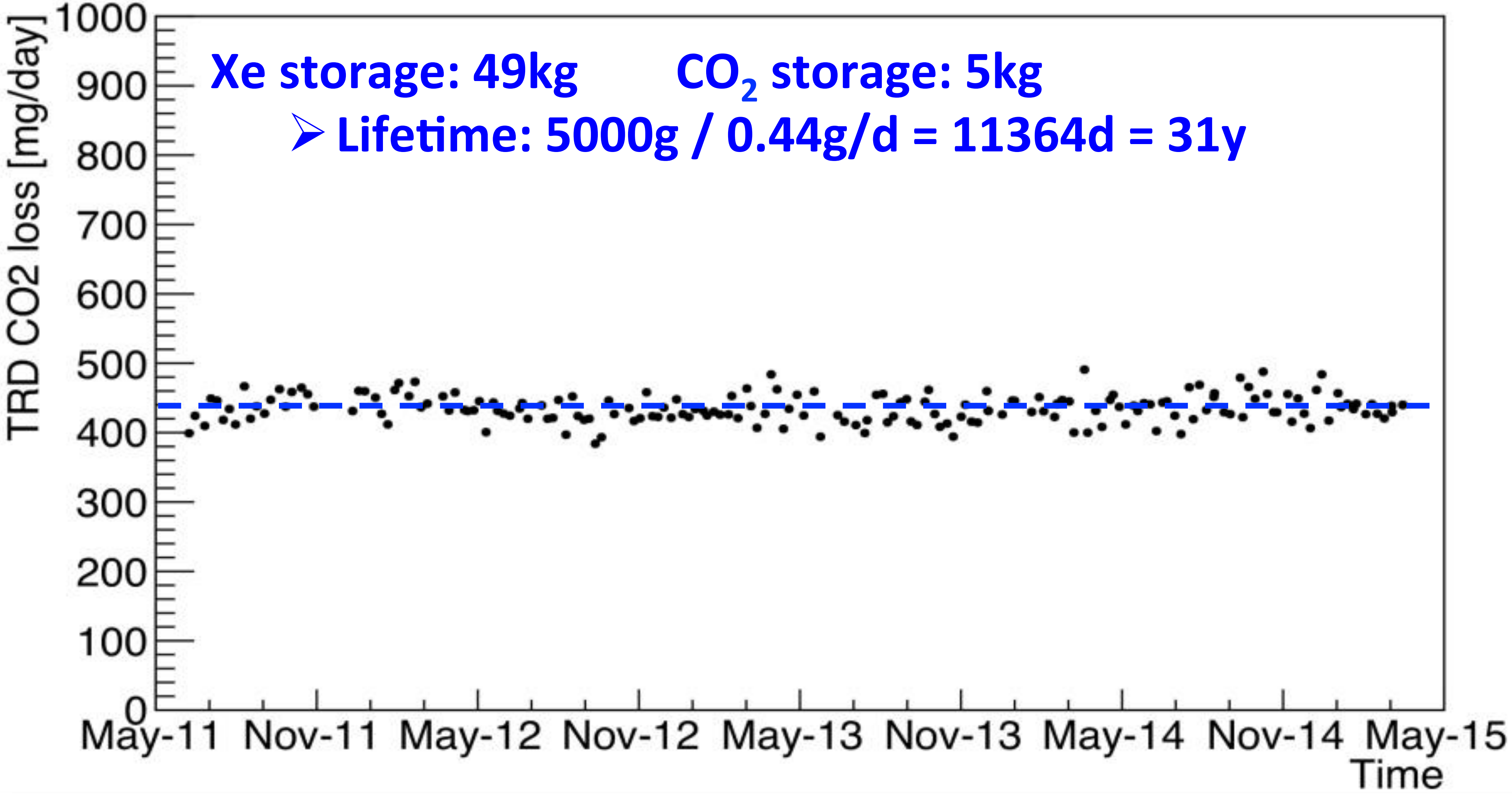


Completion of the TRD: a 10 year effort



- 5000 proportional straw tubes (filled with Xe/CO_2) are arranged in 20 layers
- Error on the central wire position of each tube is <100 µm
- Each layer has almost 100% efficiency

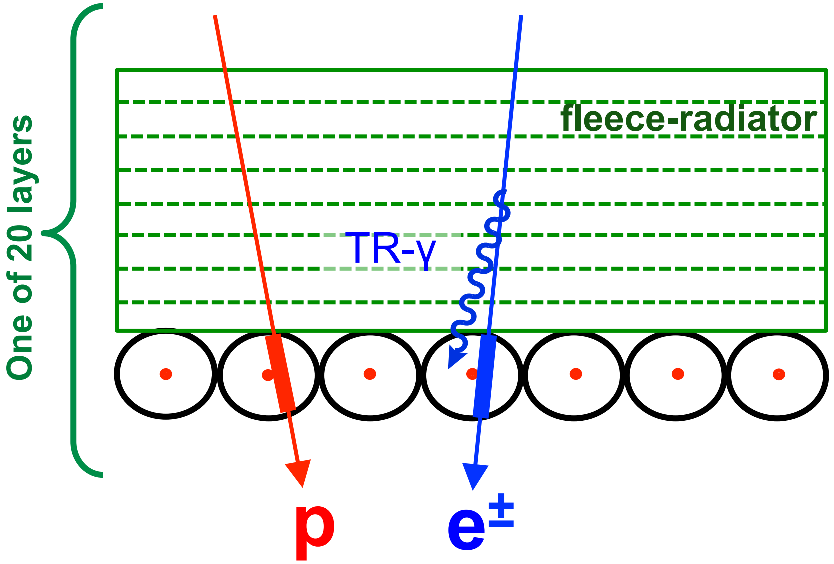
TRD Lifetime on the ISS

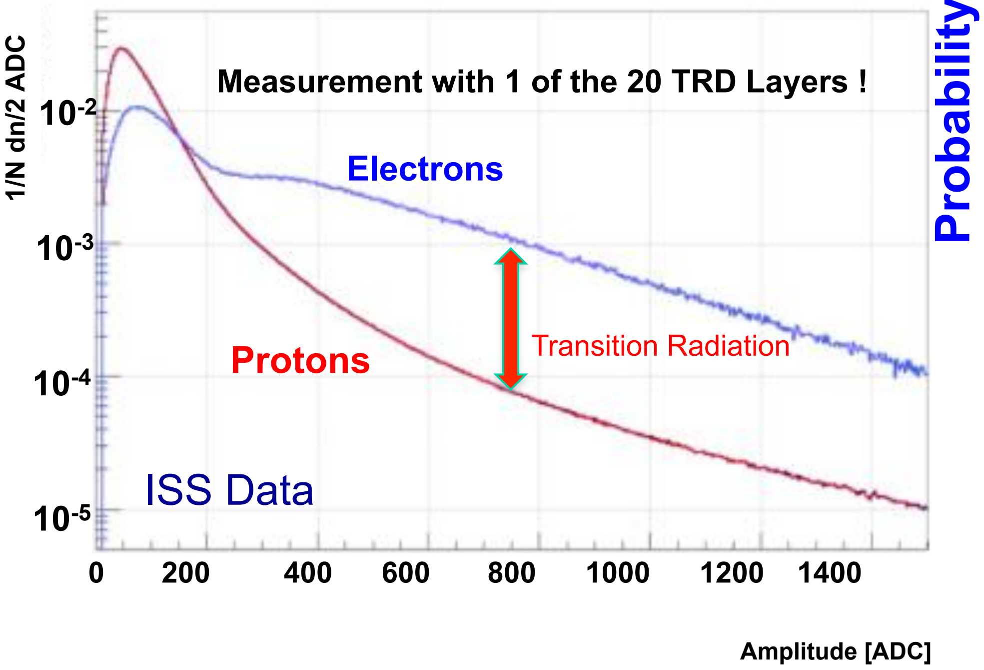


Xe storage: 49kg **CO_2 storage: 5kg**

- ➢ **Lifetime: 5000g / 0.44g/d = 11364d = 31y**

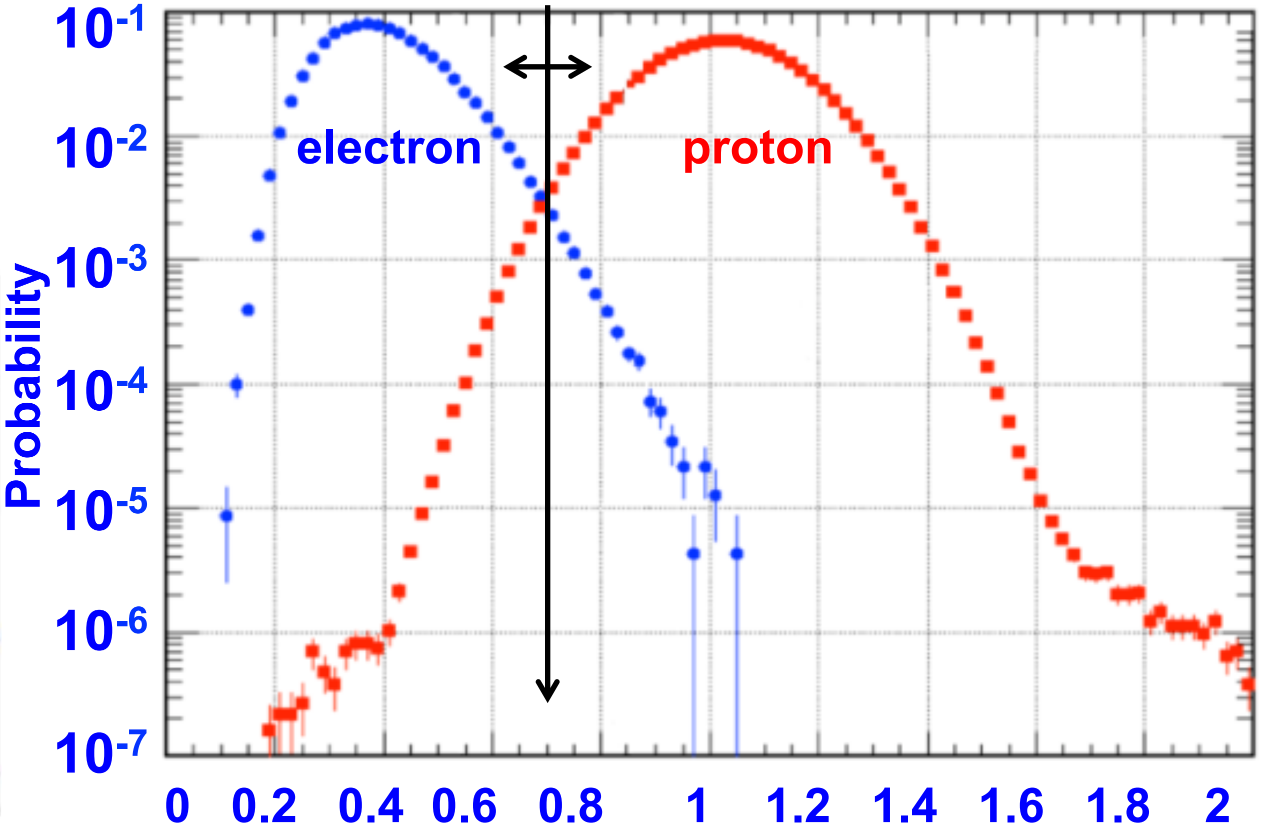
TRD performance on the Space Station





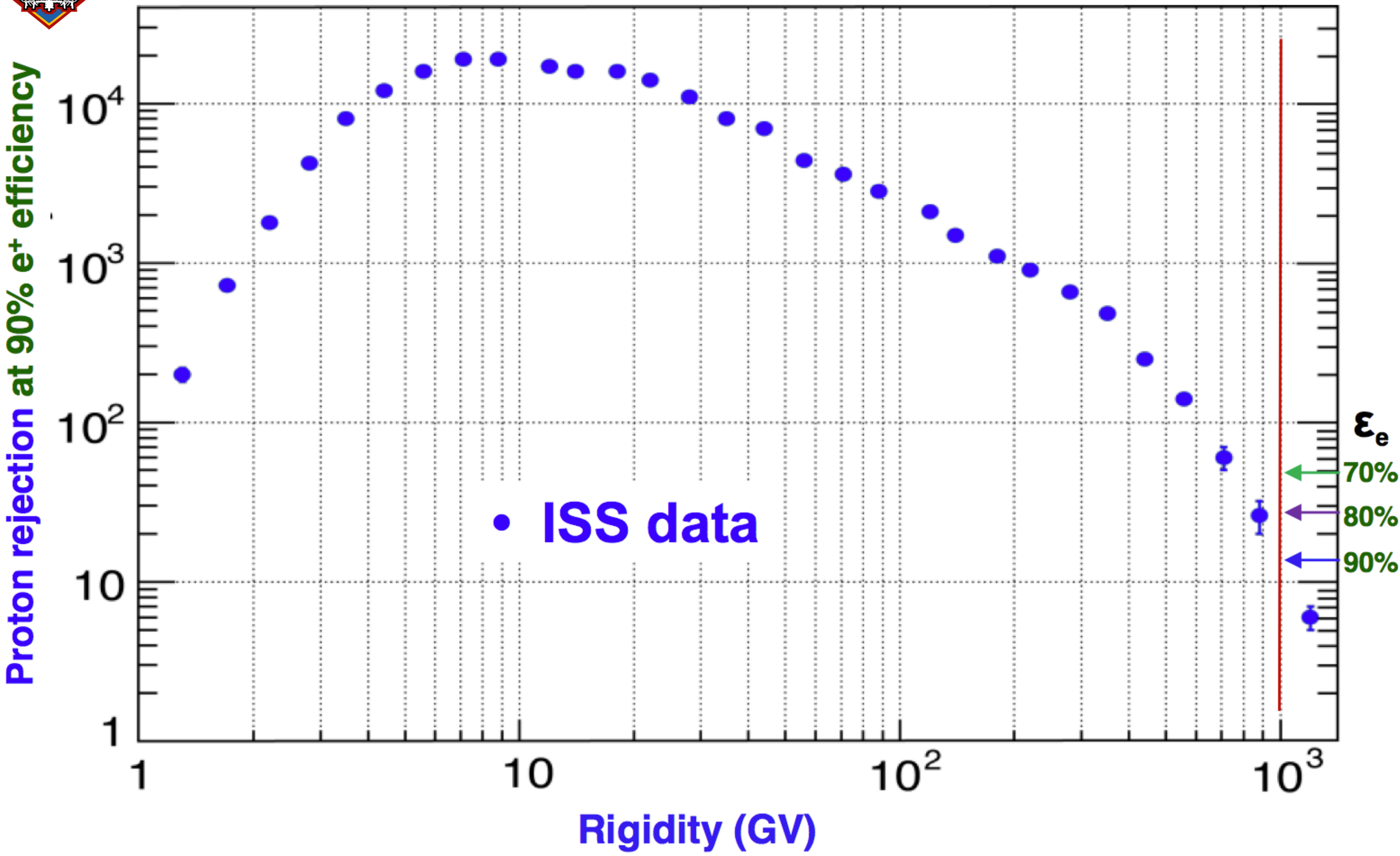
Normalized probabilities:

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



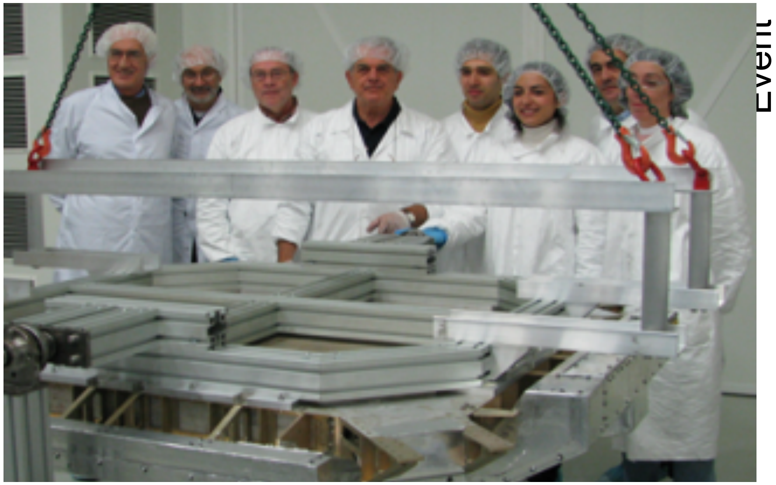
TRD estimator = $-\ln(P_e/(P_e+P_p))$

TRD performance on the Space Station



Time of Flight System

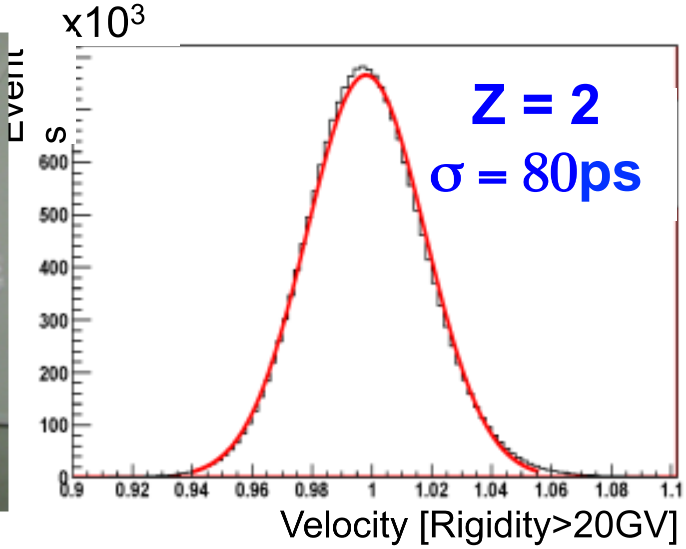
Measures Velocity and Charge of particles



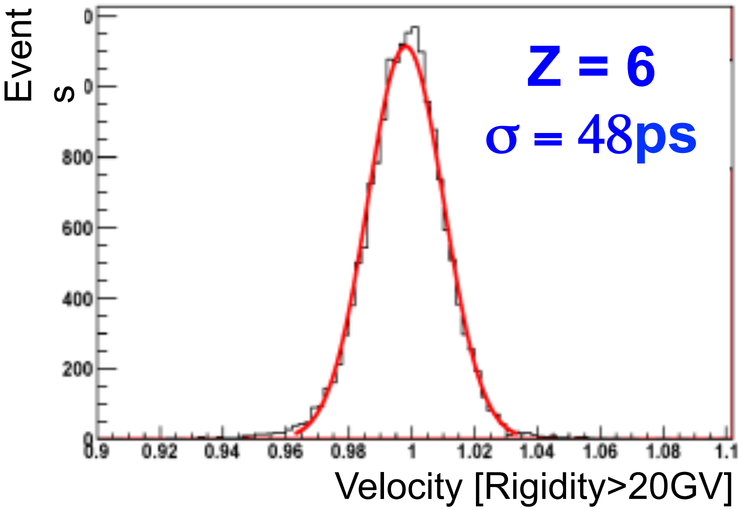
Bologna

Prof. A. Contin, G. Laurenti, F. Palmonari

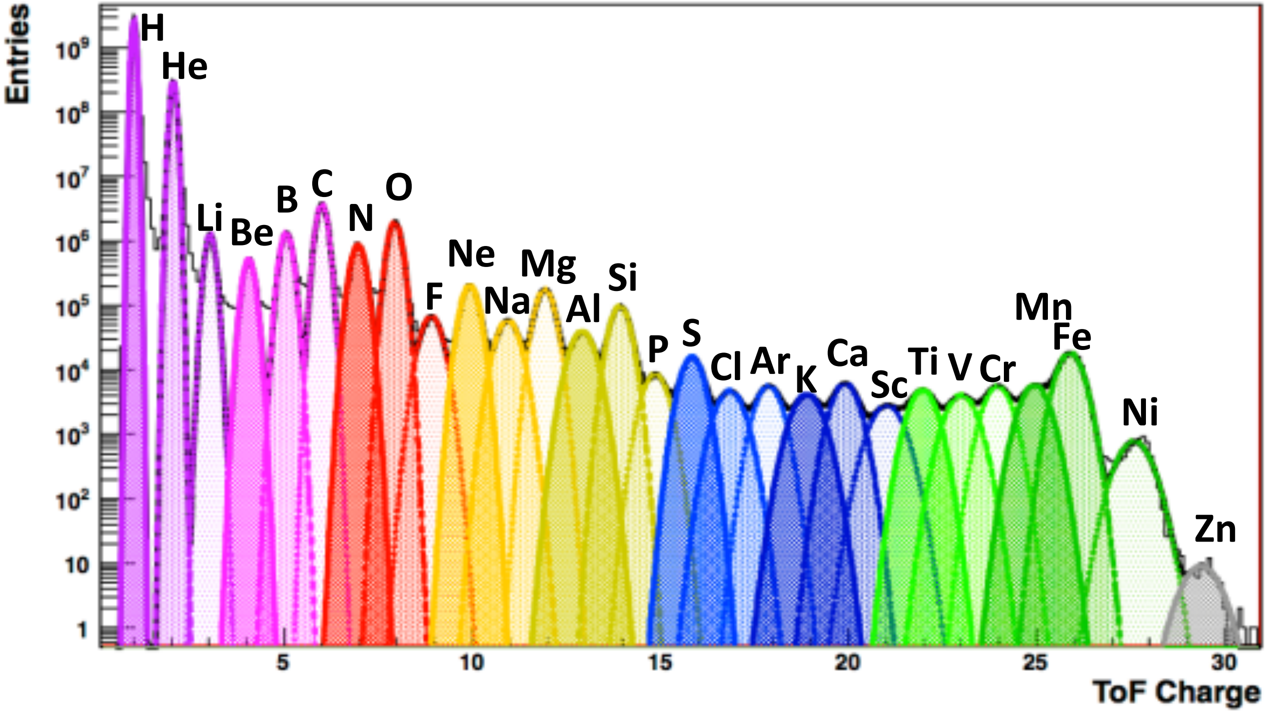
Professors A. Zichichi and V. Bindi



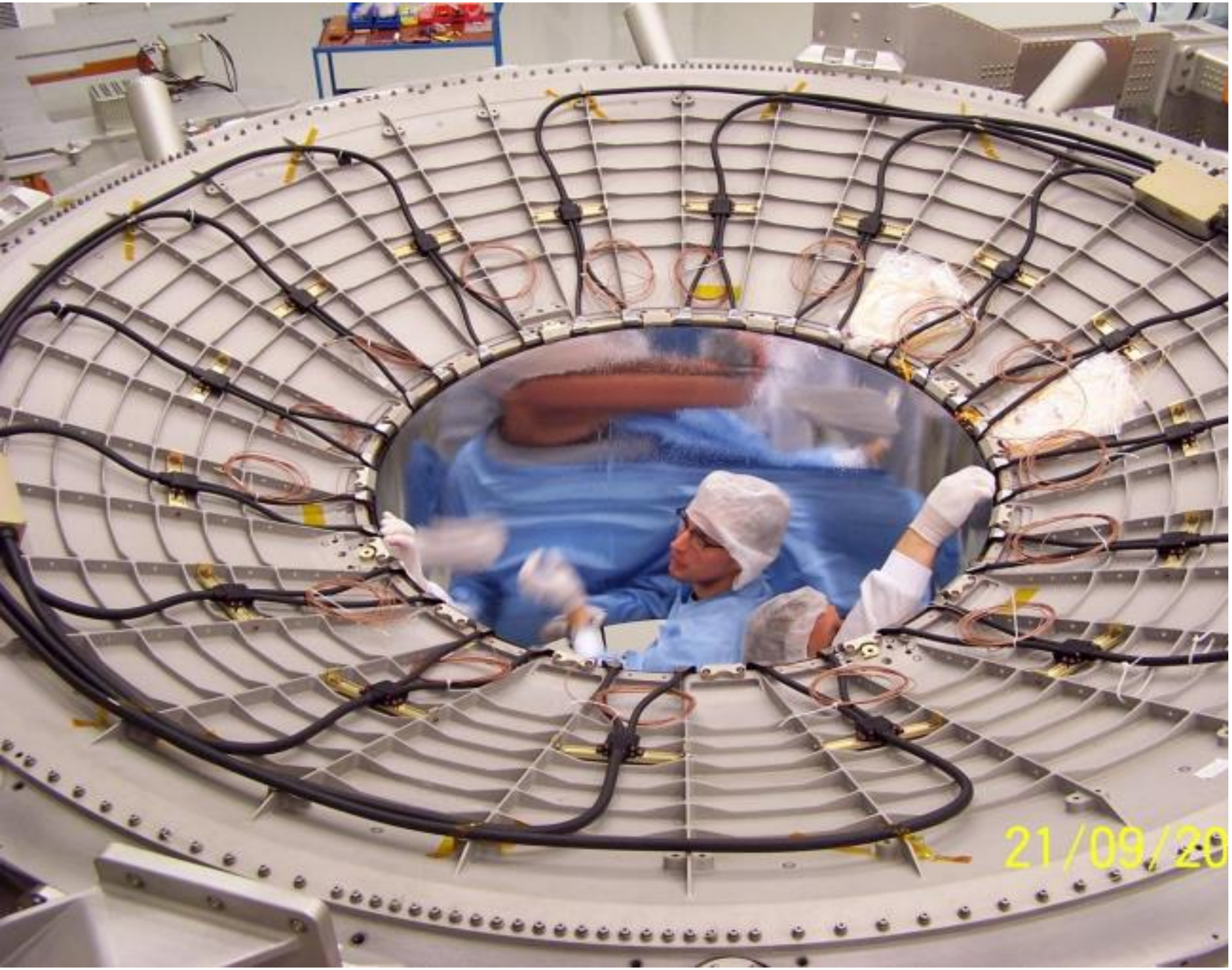
Z = 2
σ = 80ps

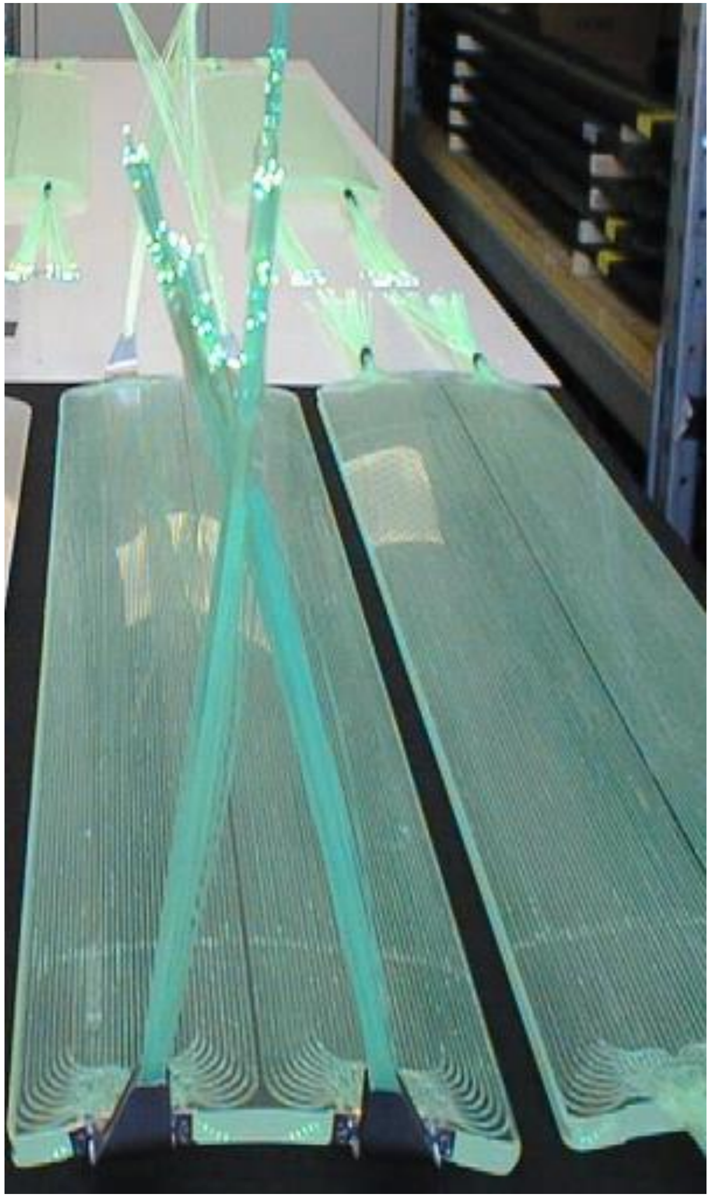


Z = 6
σ = 48ps



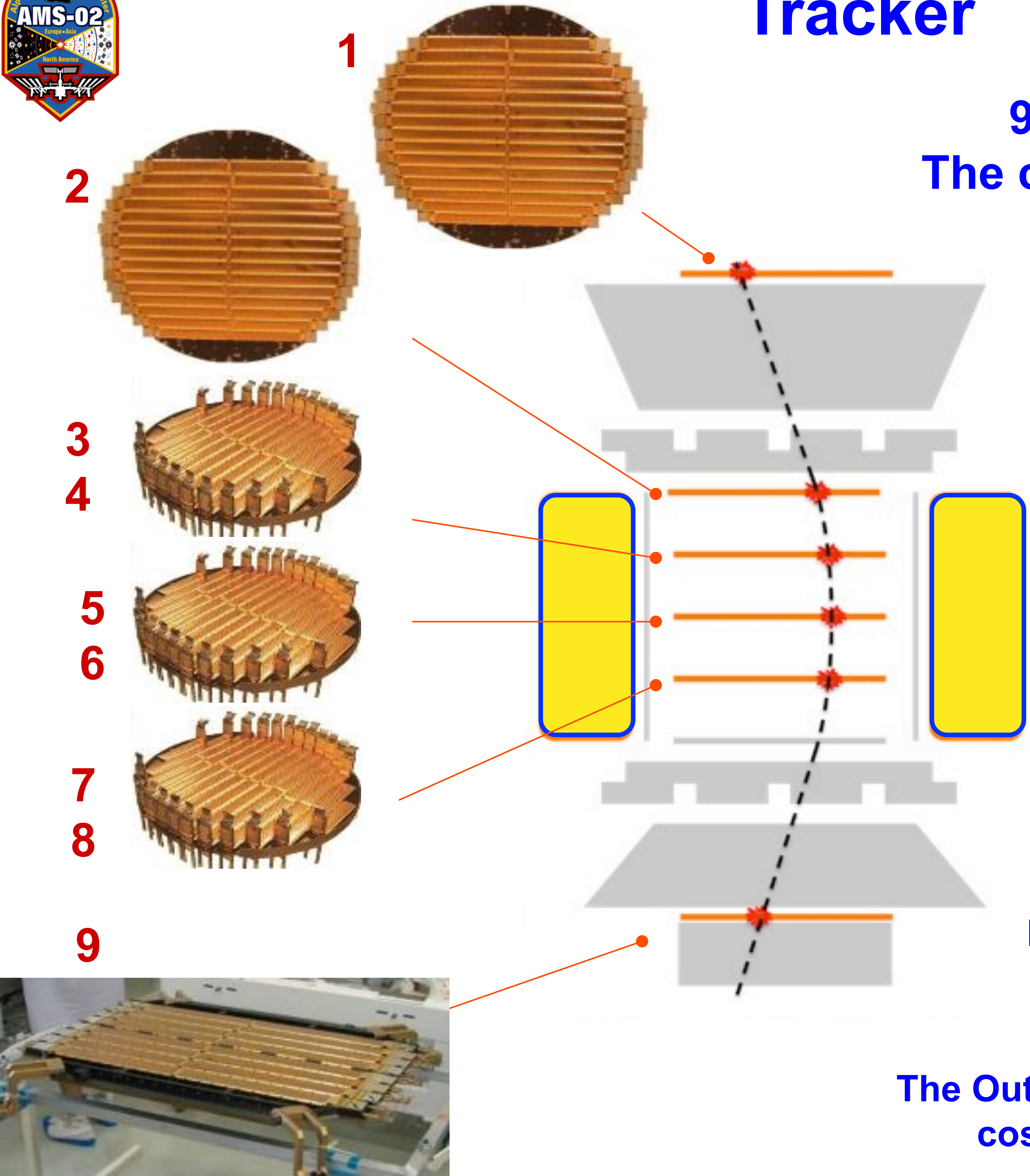
Veto System Rejects Random Cosmic Rays



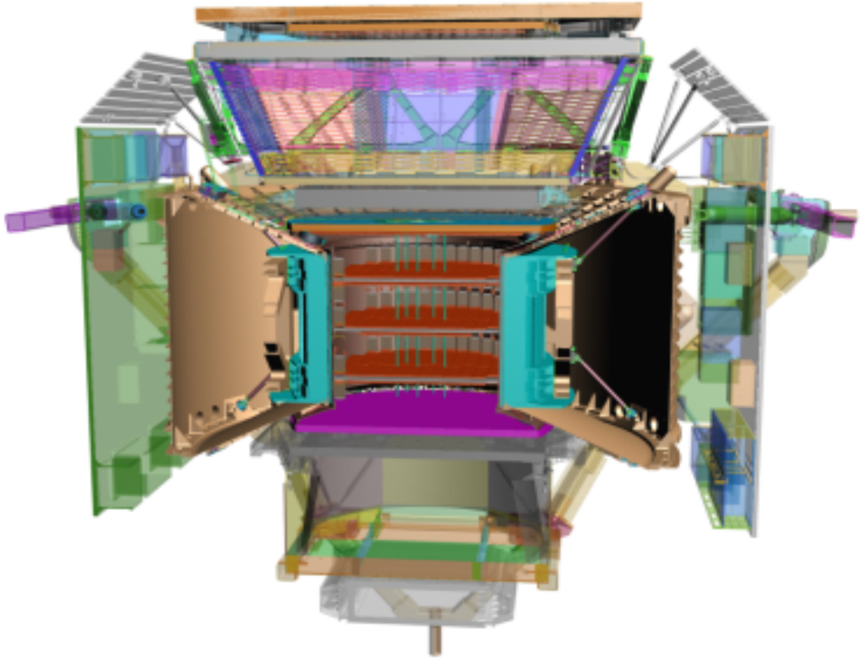


Measured veto efficiency better than 0.99999

Tracker



9 planes, 200,000 channels
The coordinate resolution is 10 μm
($MDR_{Z=1} \approx 2$ TV)



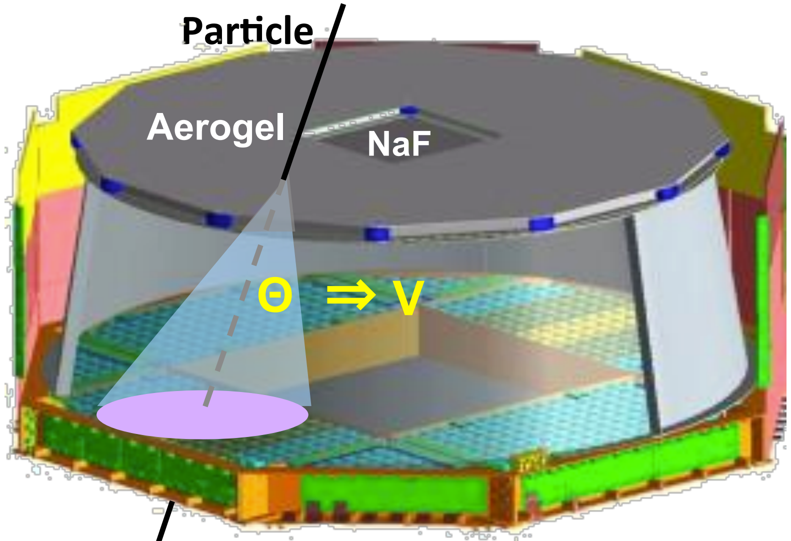
Inner tracker alignment stability monitored with IR Lasers.

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

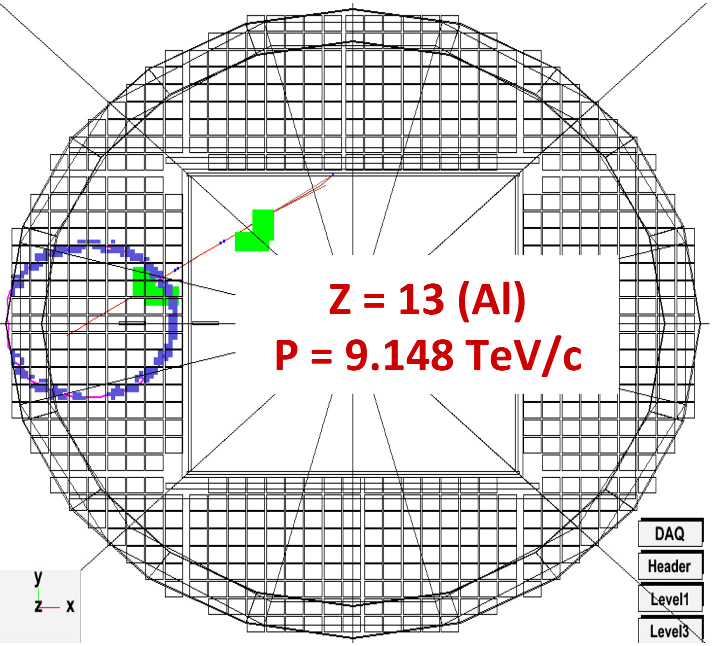
AMS Ring Imaging CHerenkov (RICH)

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

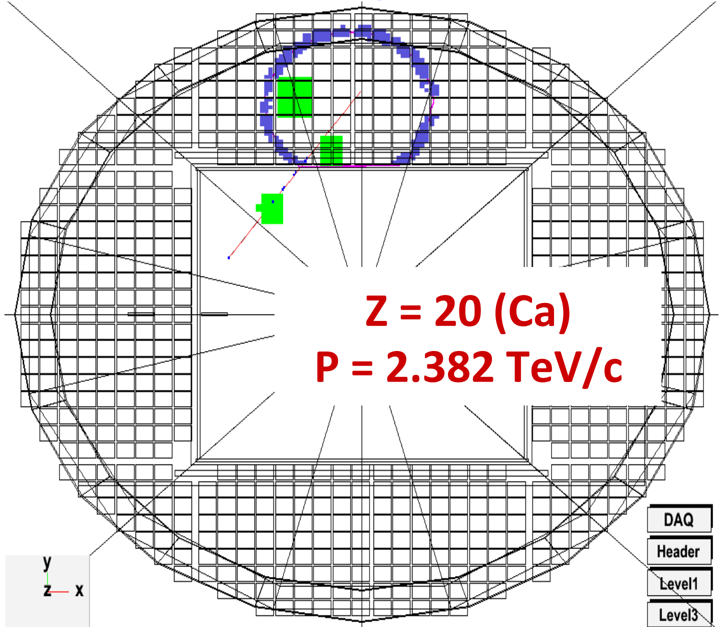
Readout done by 10,880 PMTs



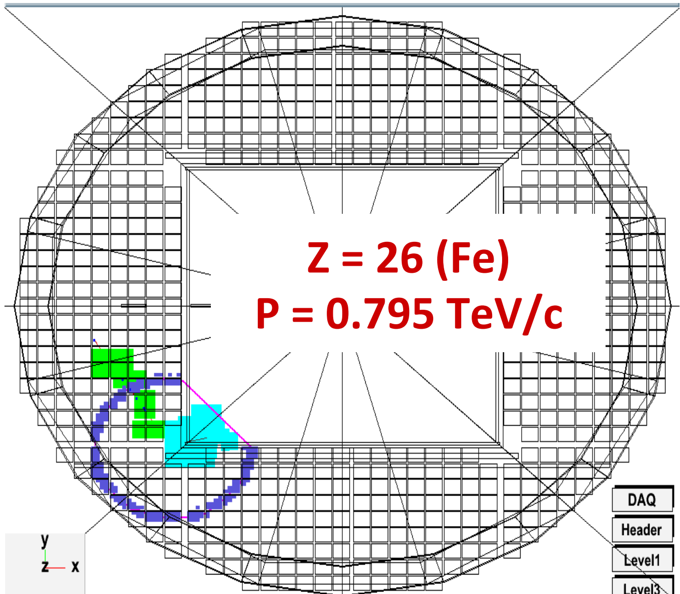
Intensity ⇒ Z^2



Z = 13 (Al)
P = 9.148 TeV/c

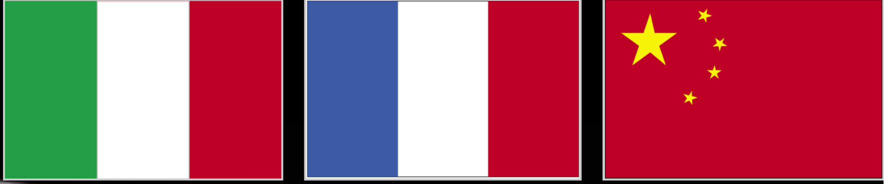


Z = 20 (Ca)
P = 2.382 TeV/c

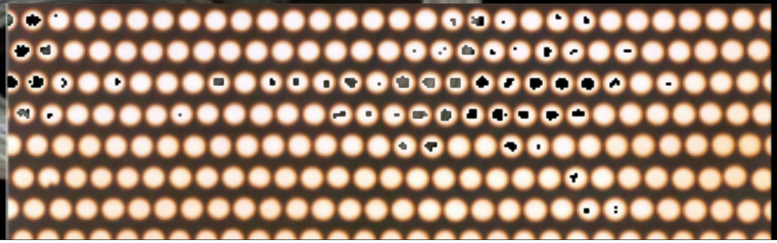


Z = 26 (Fe)
P = 0.795 TeV/c

Calorimeter (ECAL)



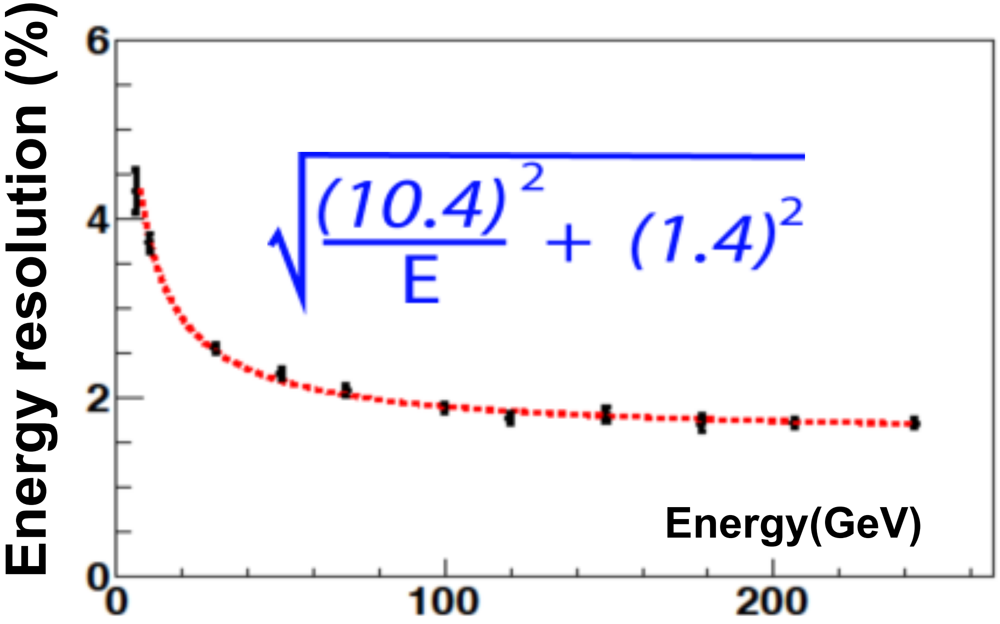
Prof. F. Cervelli, M. Incagli,

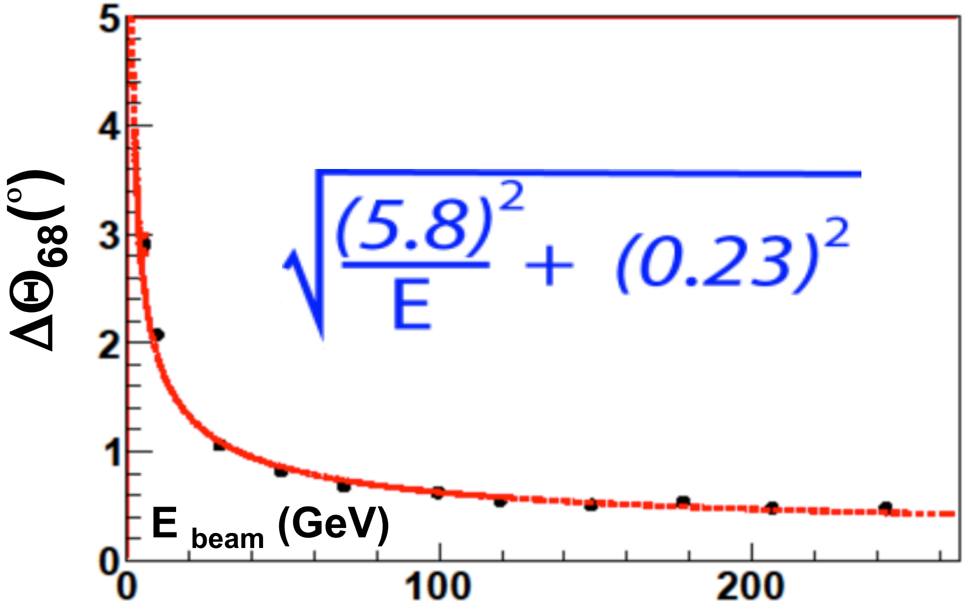


LAPP (S. Rosier, J.P. Vialle,..), IHEP (H. S. Chen, ...)

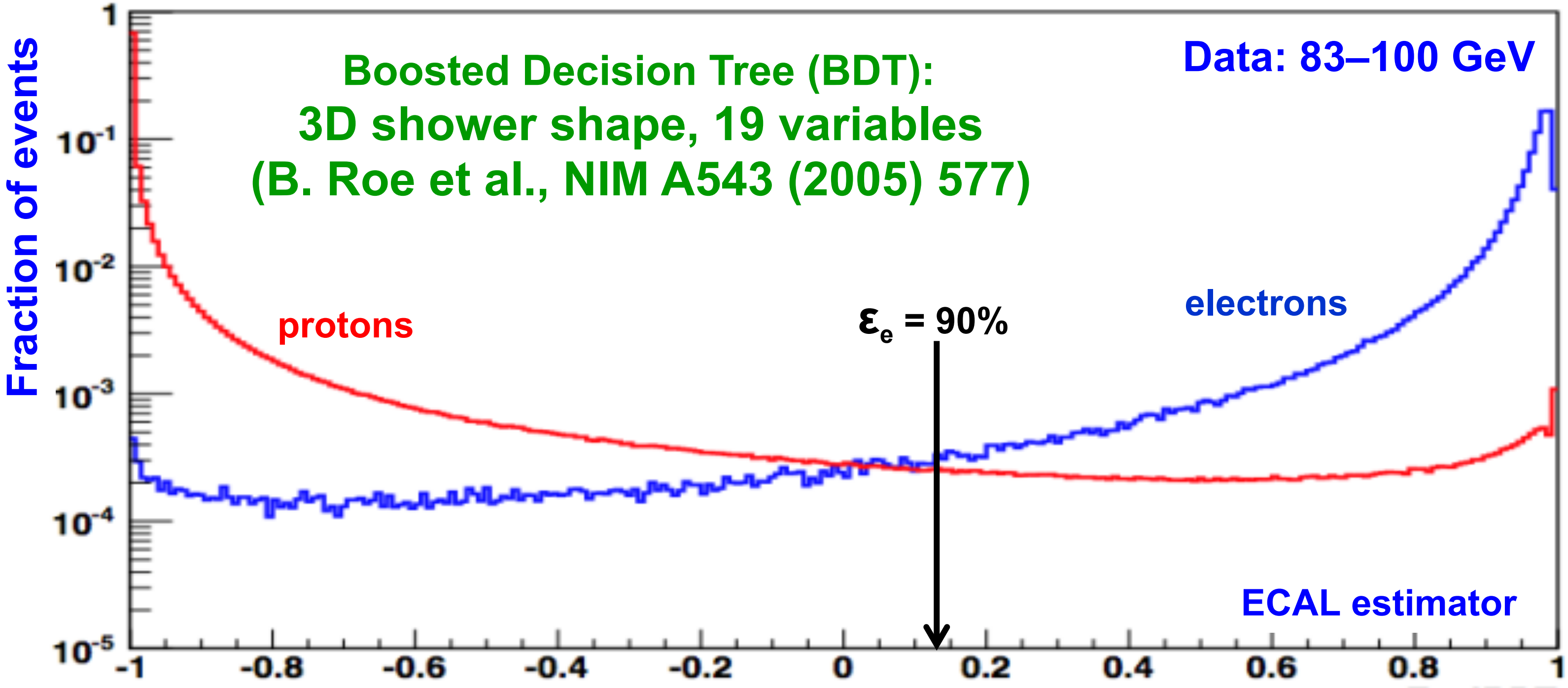
50,000 fibers, $\phi = 1$mm, distributed uniformly inside 600 kg of lead which provides a precision, 3-D, $17X_0$ measurement of the directions and energies of $e^\pm$ to TeV

Calorimeter (ECAL): Test beams at CERN


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


$$\sqrt{\frac{(5.8)^2}{E} + (0.23)^2}$$

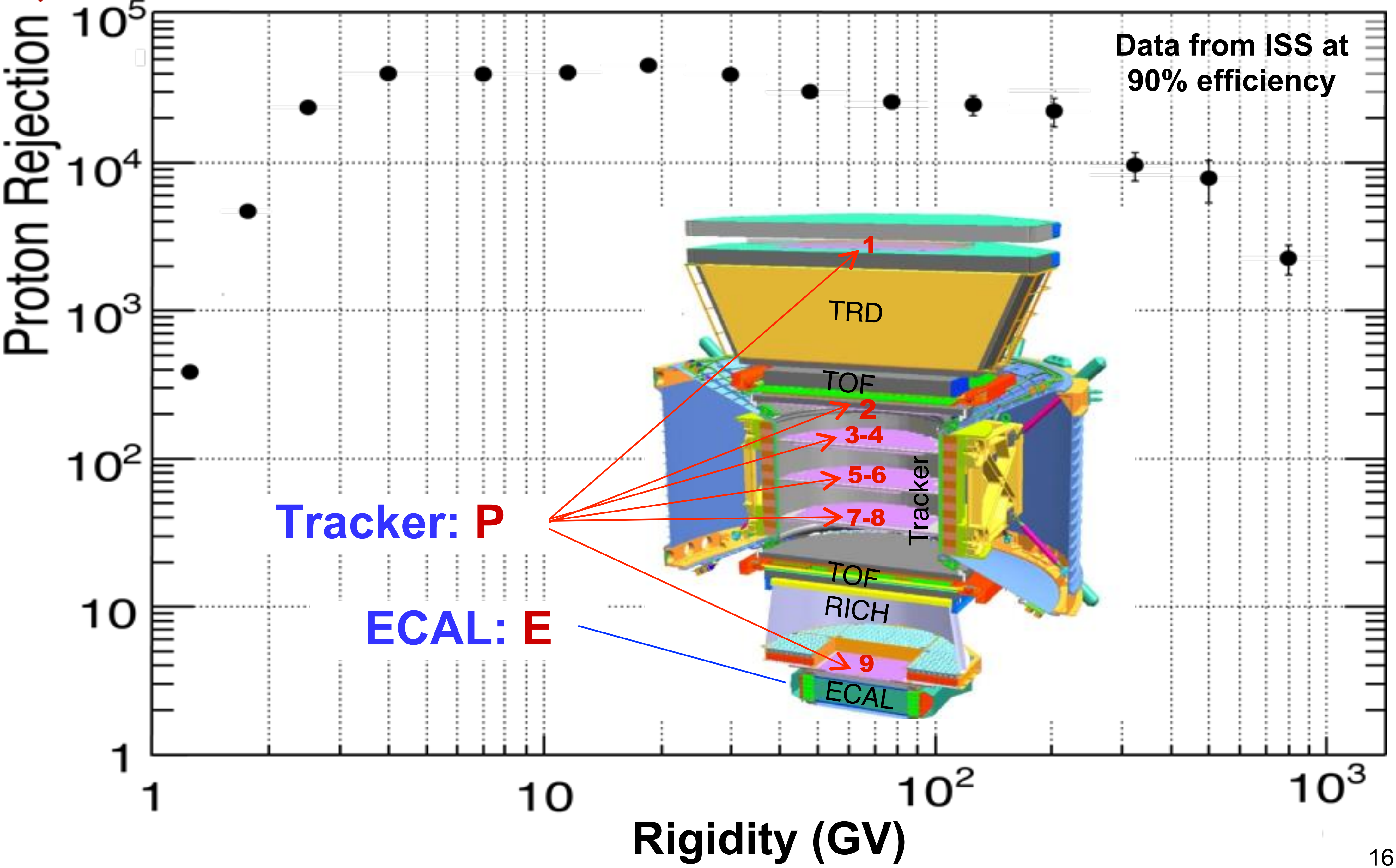
Electron/Proton Separation on ISS


Boosted Decision Tree (BDT):
3D shower shape, 19 variables
(B. Roe et al., NIM A543 (2005) 577)

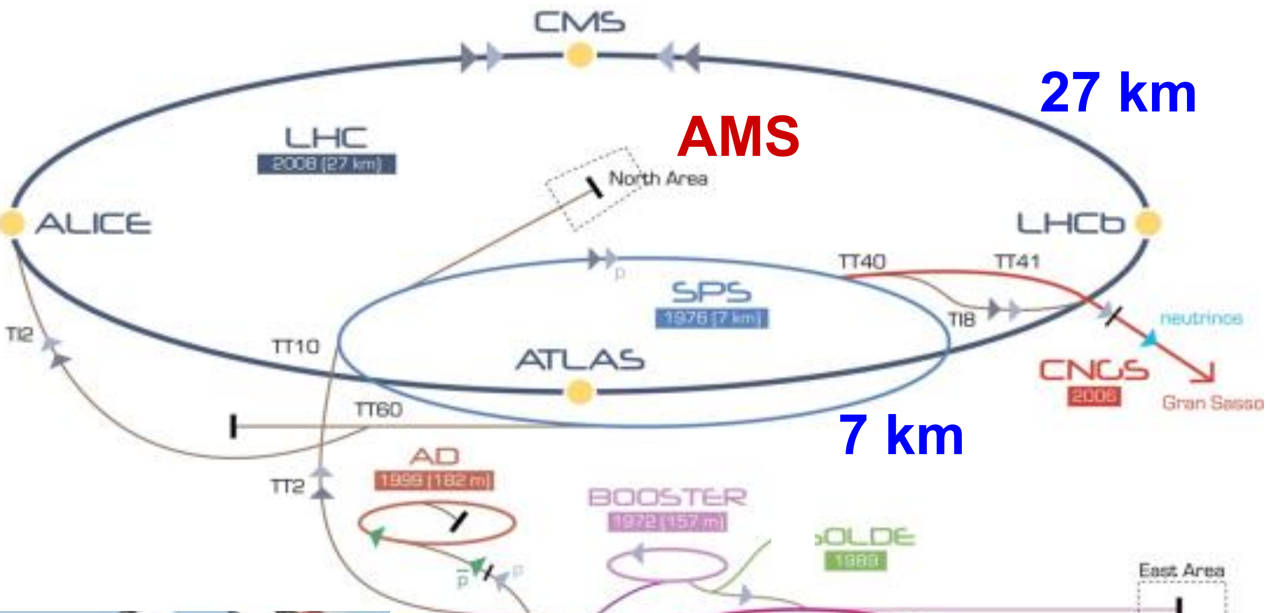
Data: 83–100 GeV

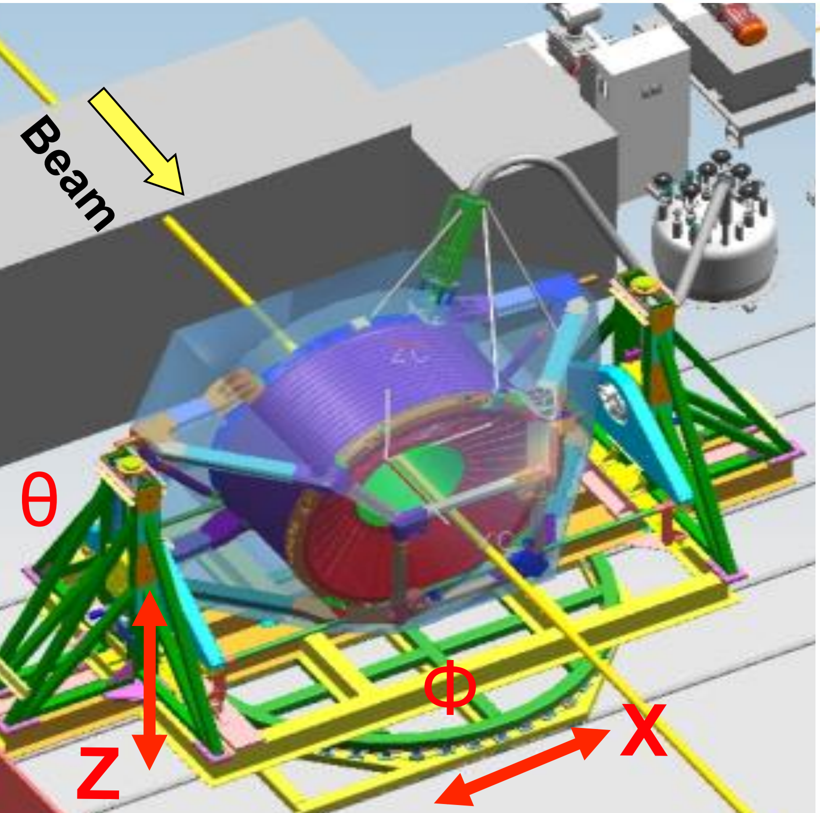
ε_e = 90%

Proton rejection: 1. ECAL 3-D Shower Shape of $e^{\pm}$
2. P from the Tracker = E from ECAL



Extensive tests and calibration at CERN





AMS in SPS Test Beam, 2010

Particle	Momentum (GeV/c)	Positions	Purpose
Protons	400 + 180	1,650	Full Tracker alignment, TOF calibration, ECAL uniformity
Electrons	100, 120, 180, 290	7 each	TRD, ECAL performance study
Positrons	10, 20, 60, 80, 120, 180	7 each	TRD, ECAL performance study
Pions	20, 60, 80, 100, 120, 180	7 each	TRD performance to 1.2 TeV

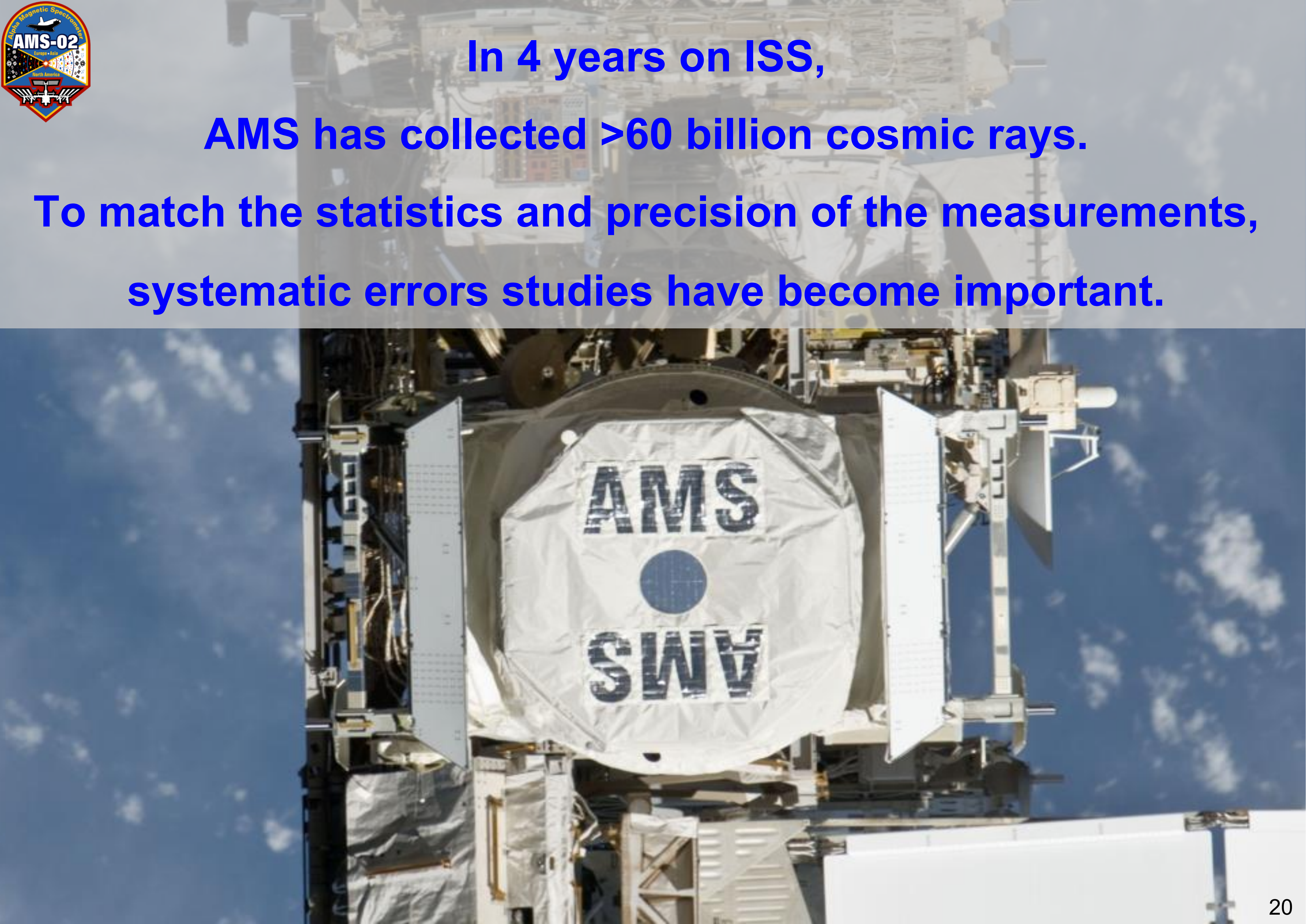
May 16, 2011

In 4 years on ISS,

AMS has collected >60 billion cosmic rays.

To match the statistics and precision of the measurements,

systematic errors studies have become important.



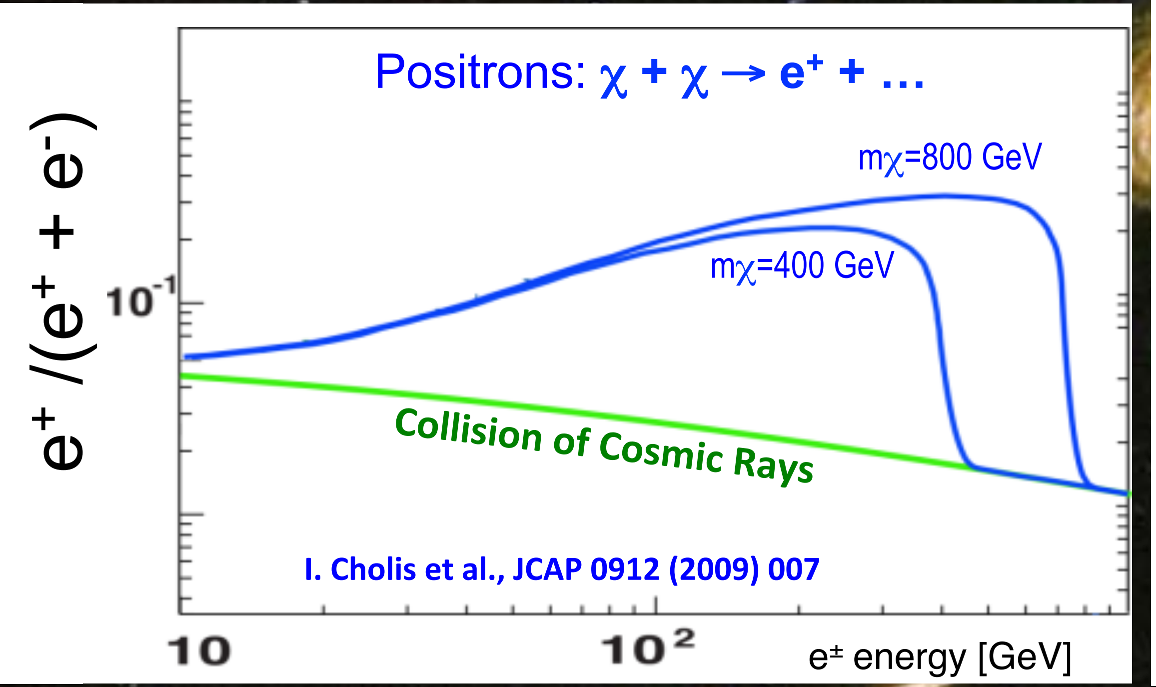
The Origin of Dark Matter

~ 85% of Matter in the Universe is not visible and is called Dark Matter

Collision of “ordinary” Cosmic Rays produce e+, $\bar{p}$..

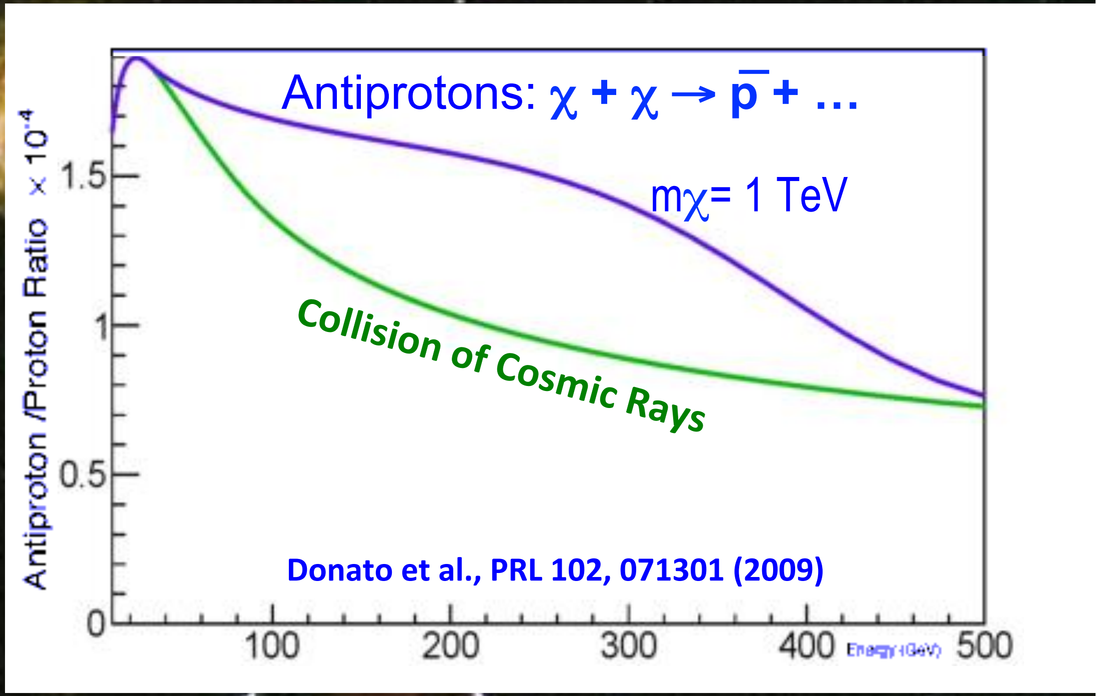
Collisions of Dark Matter (neutralinos, χ) will produce additional e+, $\bar{p}$, …

(M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001)



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

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



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

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

To identify the Dark Matter signal we need

1. Measurement of e^+, e^- and $\bar{p}$.
2. Precise knowledge of the cosmic ray fluxes (p, He, C, …)
3. Propagation and Acceleration (Li, B/C, …)

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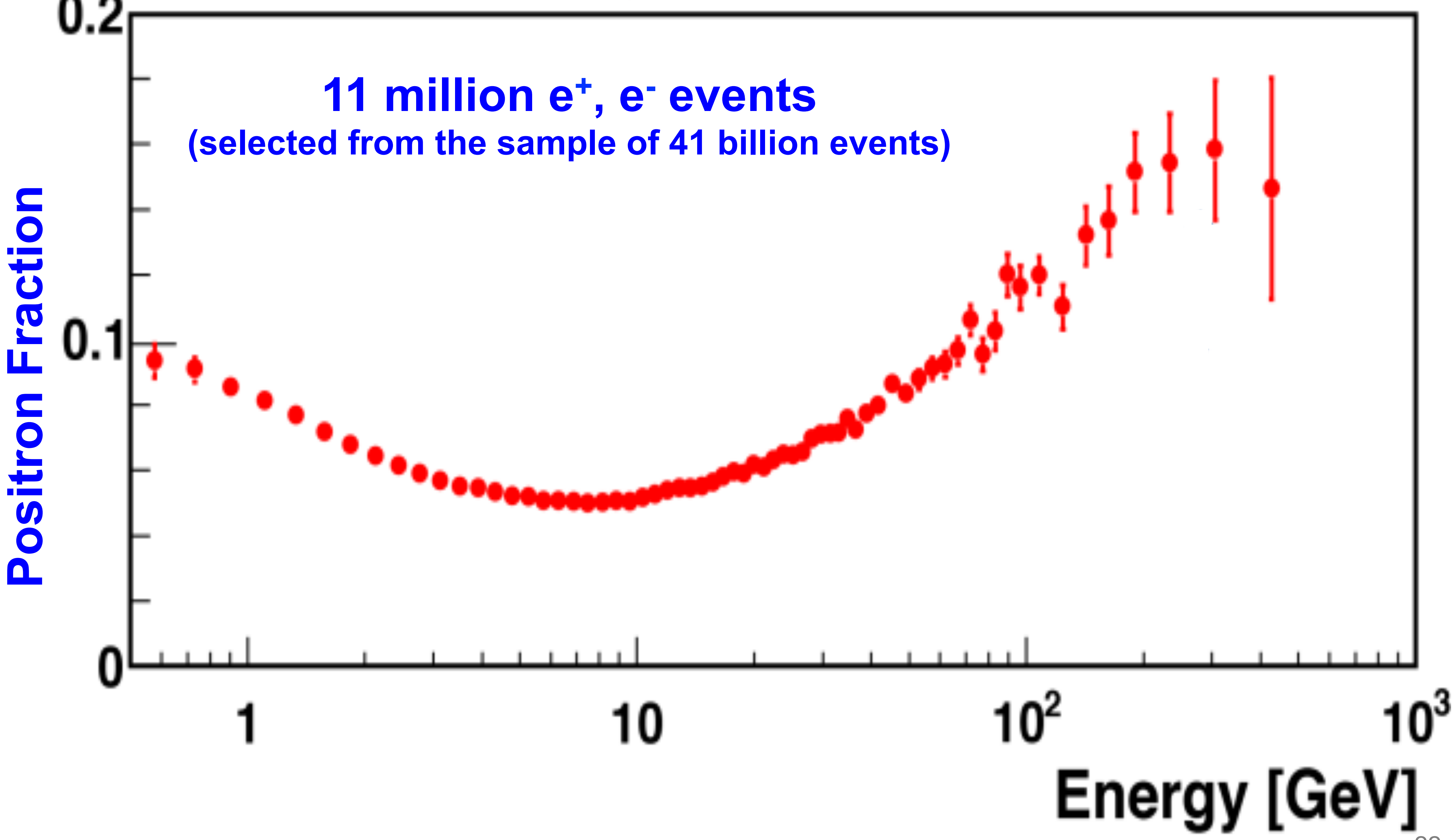
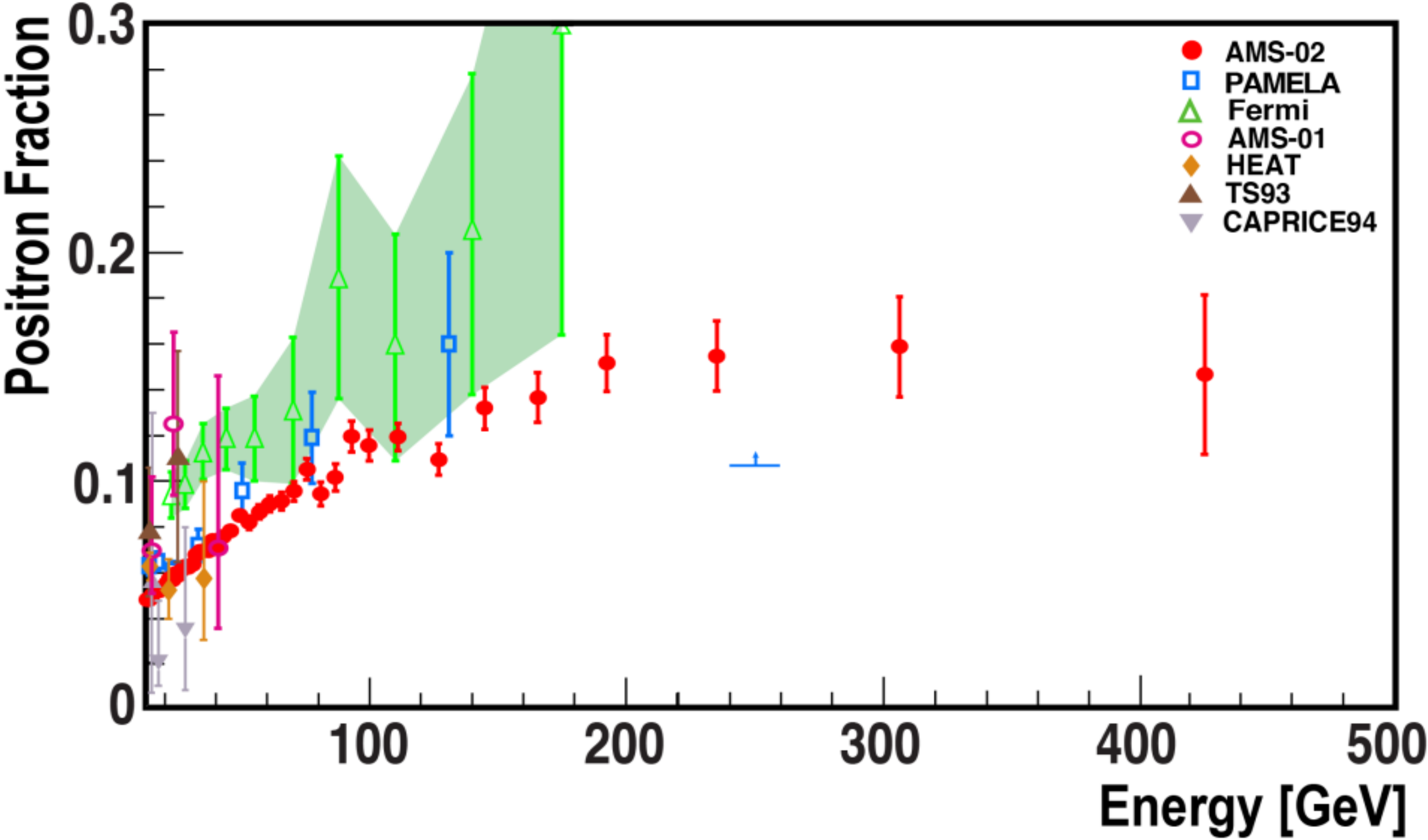
High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5–500 GeV with the Alpha Magnetic Spectrometer on the International Space Station



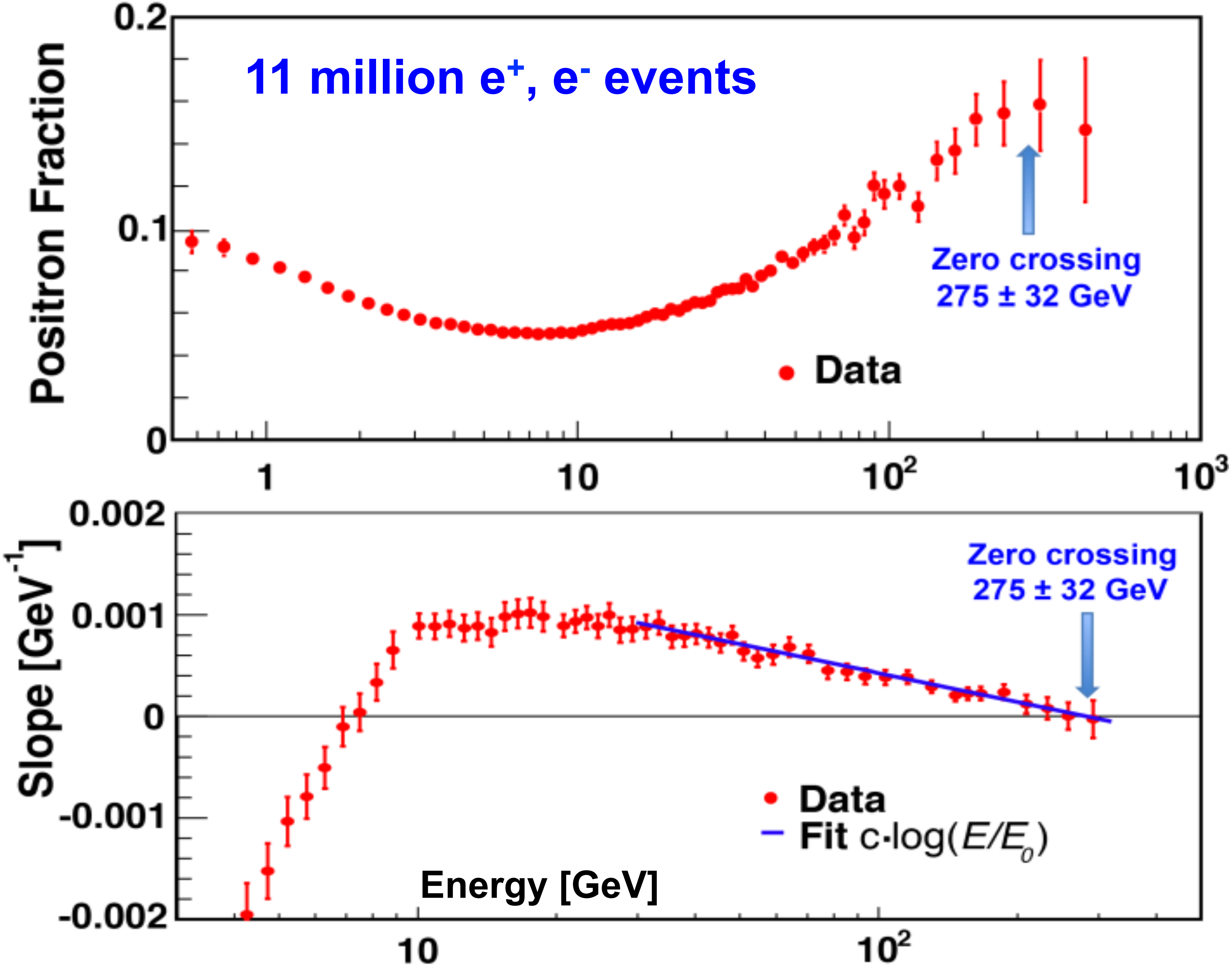
11 million e^+, e^- events

(selected from the sample of 41 billion events)

Positron Fraction from AMS



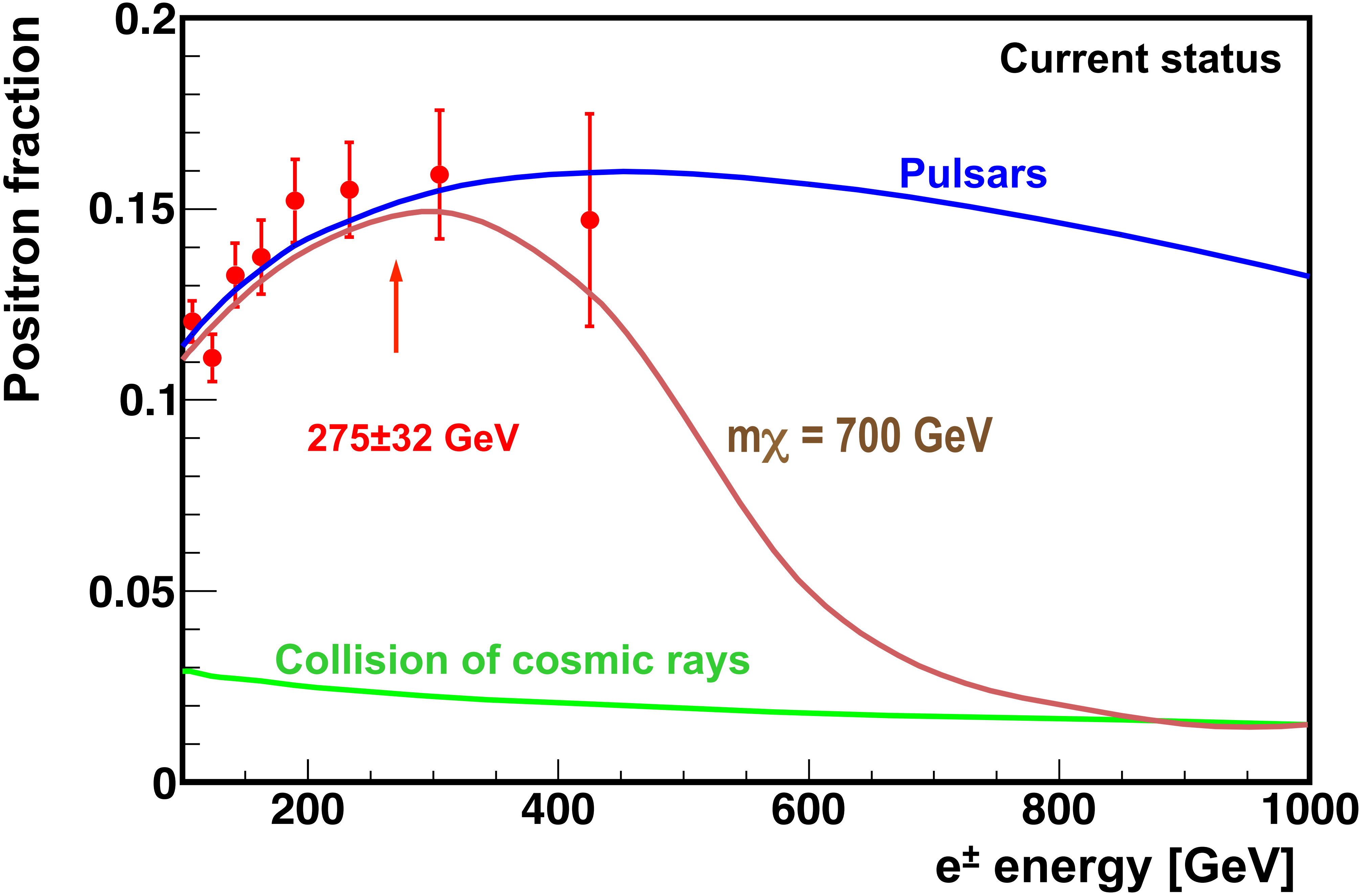
The energy beyond which it ceases to increase.



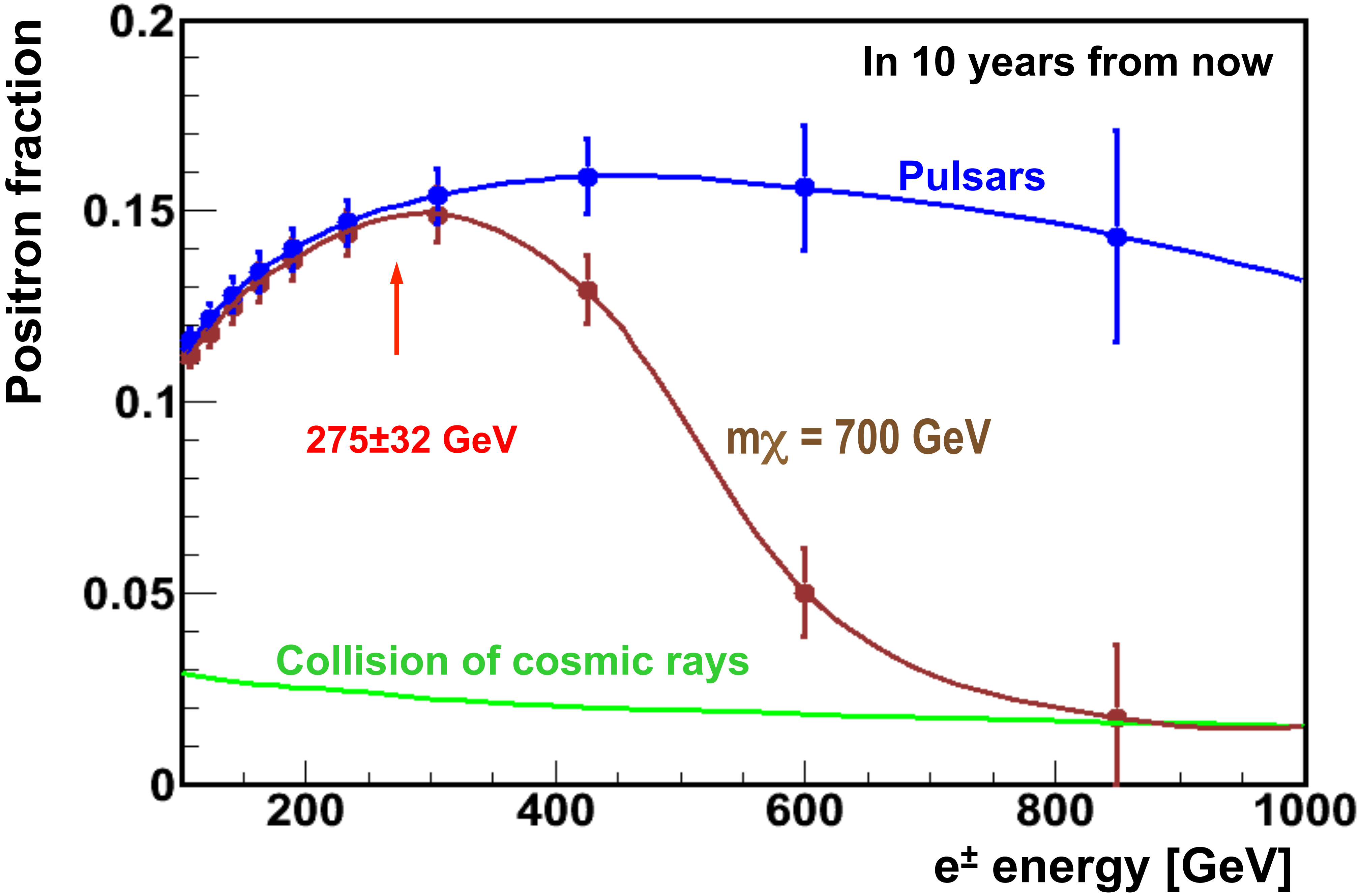
11 million e^+, e^- events

Zero crossing
275 ± 32 GeV

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



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



Measurement of the flux of electrons and positrons

$$\Phi_{e^\pm}(E)=\frac{N_{e^\pm}(E)}{A_{eff}(E)\cdot\varepsilon_{trig}(E)\cdot T(E)\cdot\Delta E}$$

$N_{e\pm}$ is the number of electron or positron events

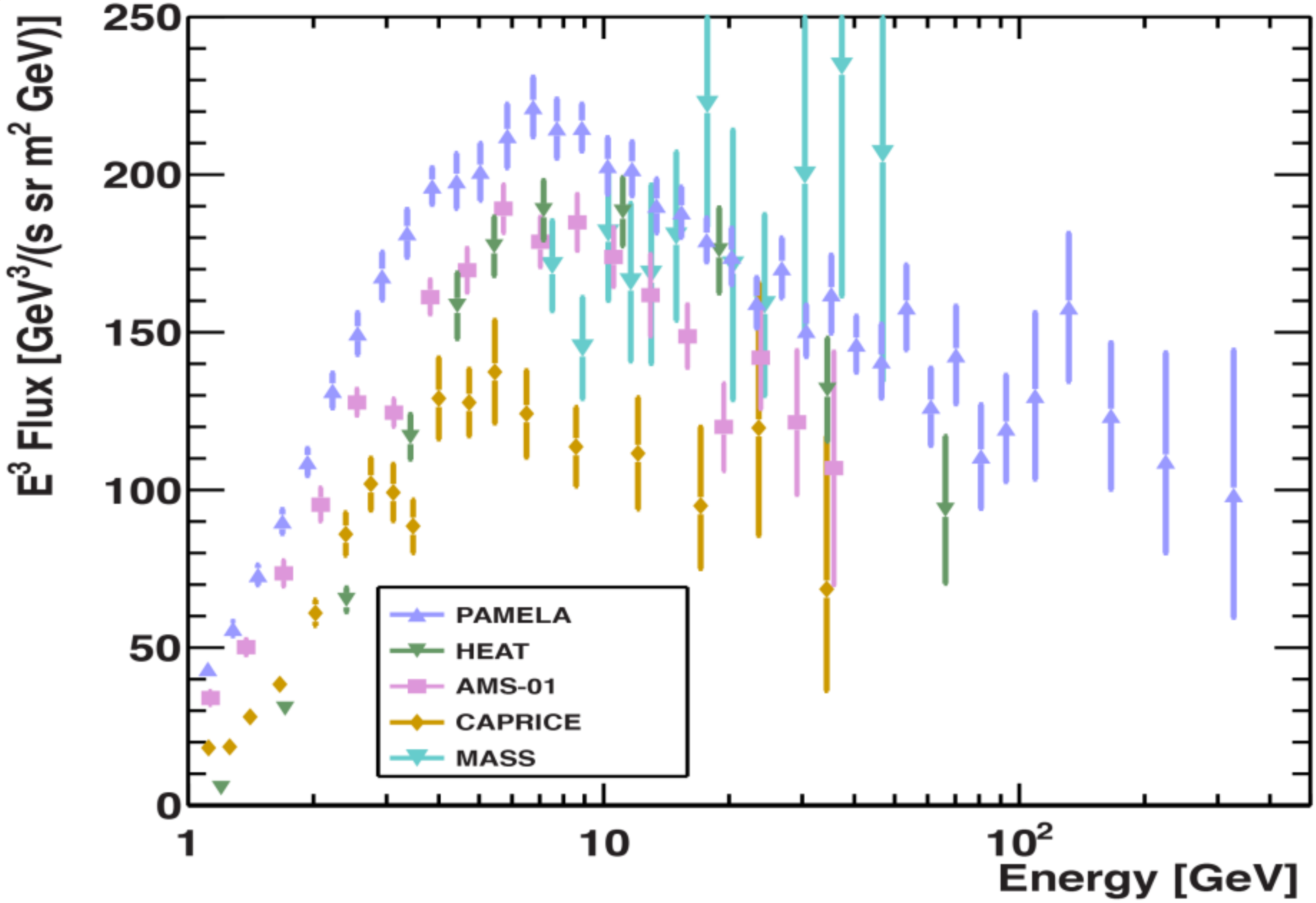
A_{eff} is the effective acceptance

ε_{trig} is the trigger efficiency

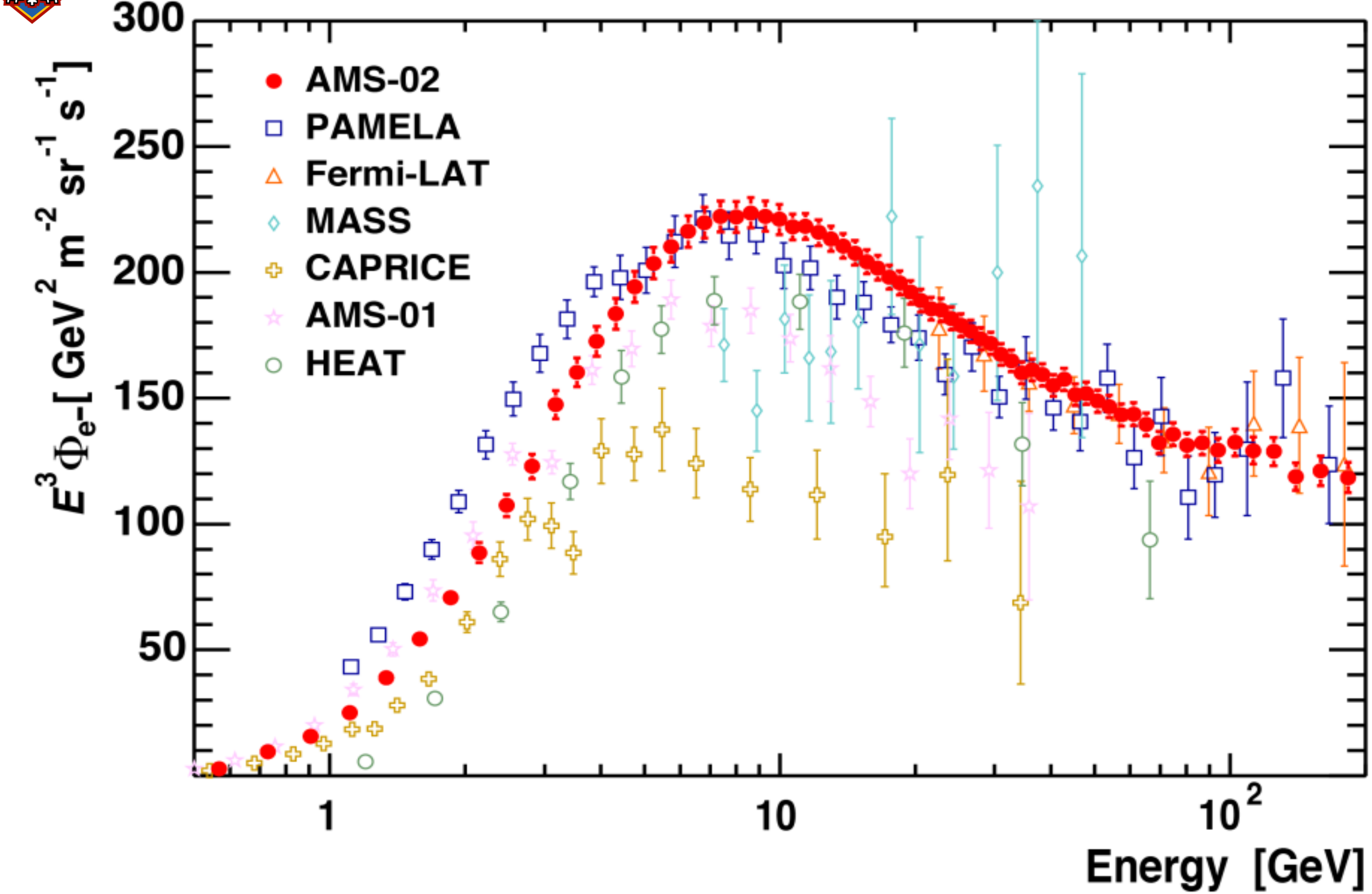
T is the exposure time

Electron Flux

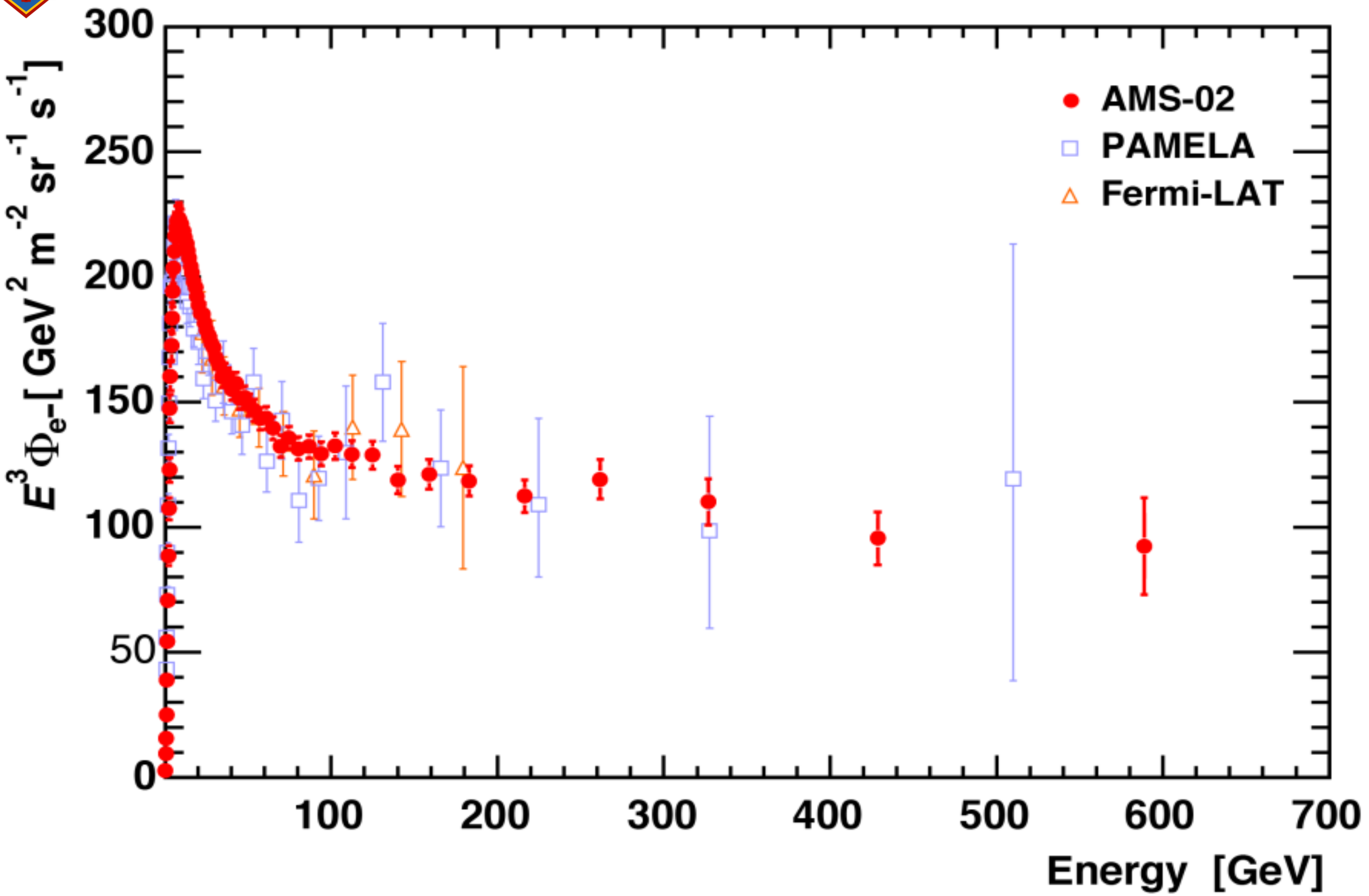
(before AMS)



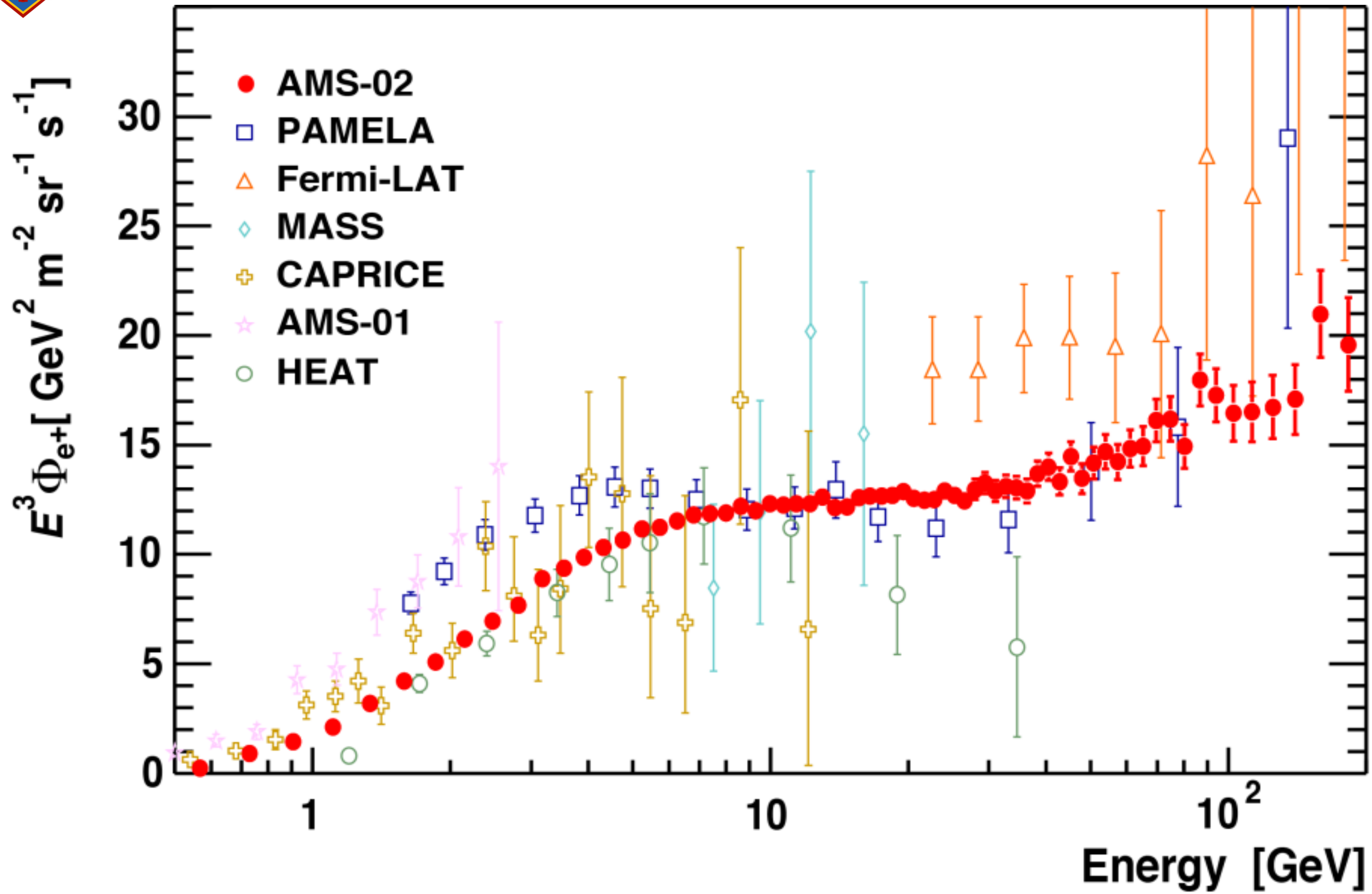
Electron Flux



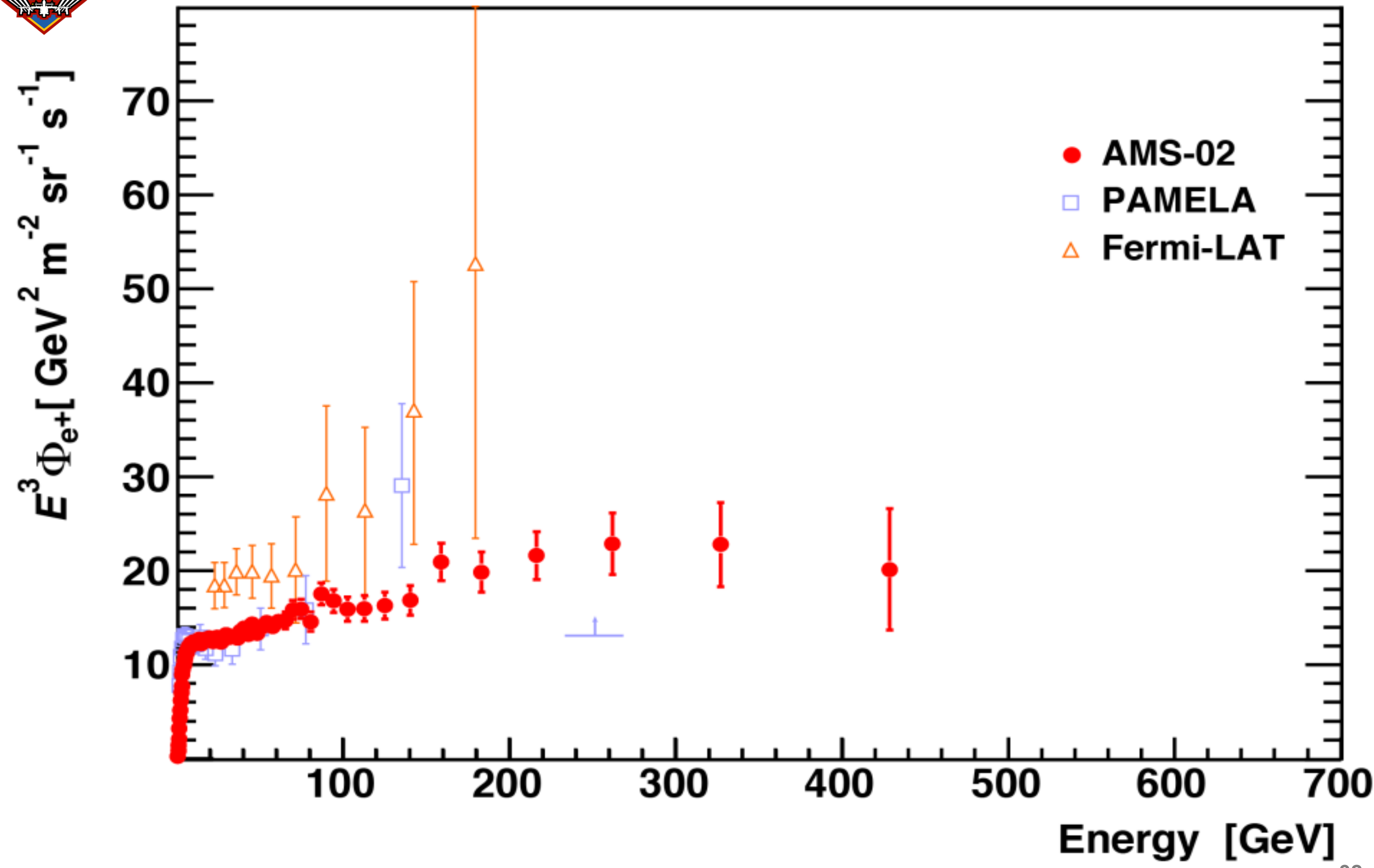
Electron Flux



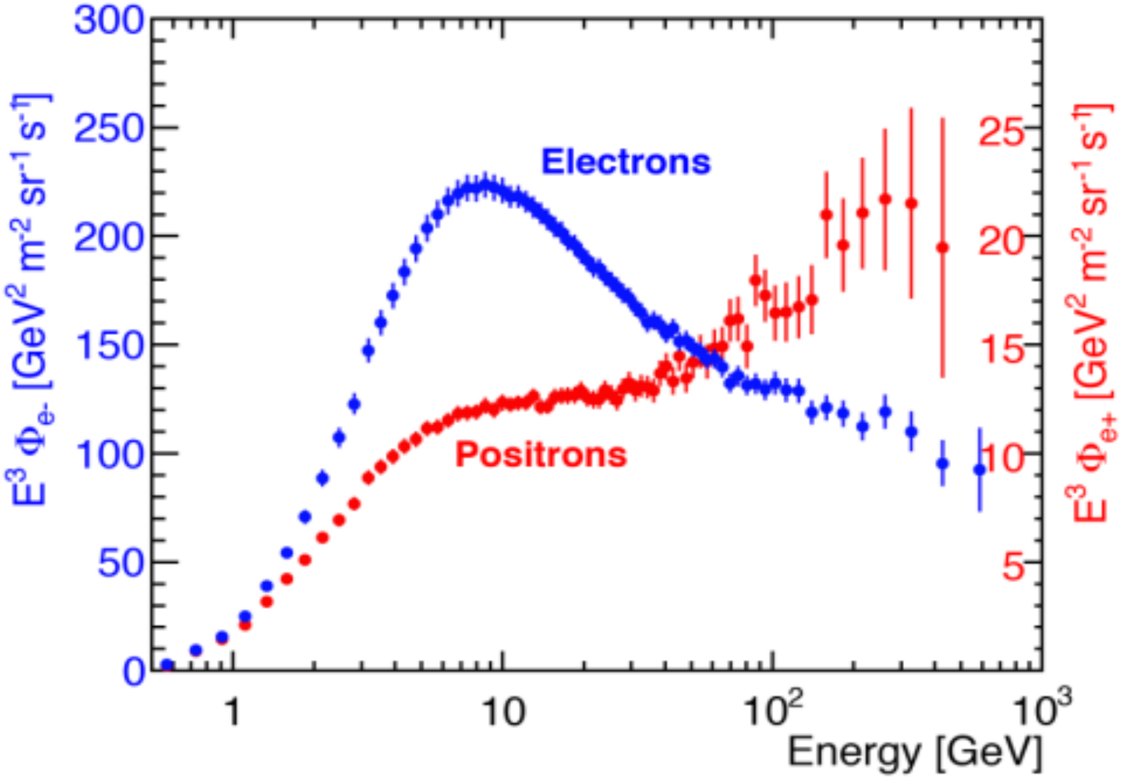
Positron Flux

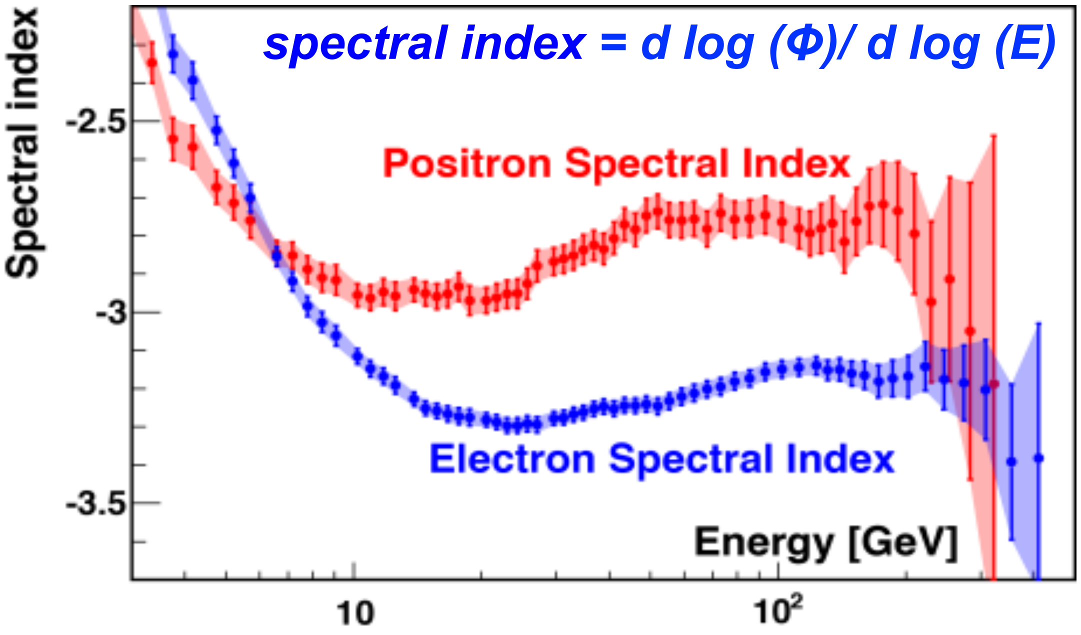


Positron Flux



The Electron Flux and the Positron Flux

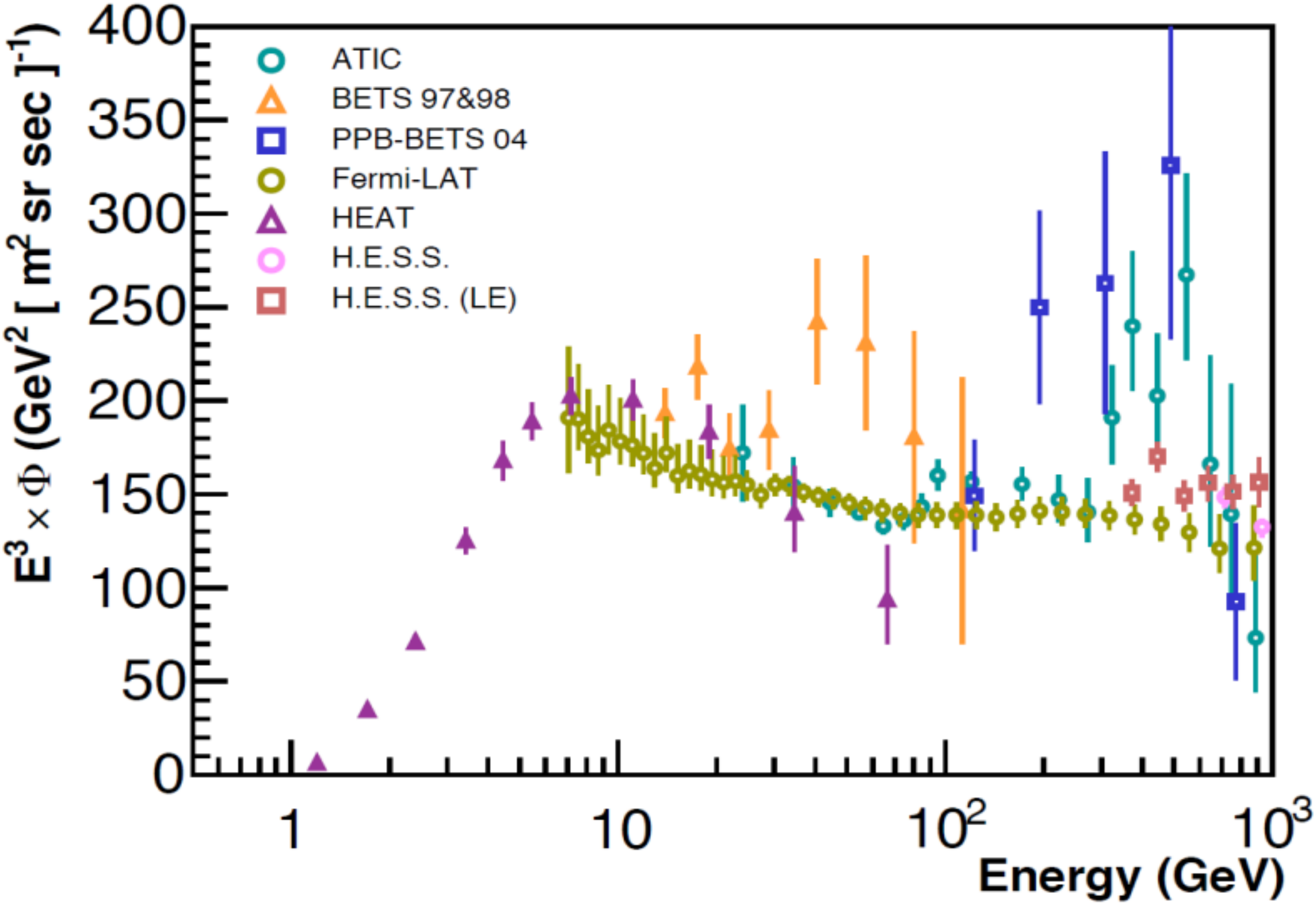




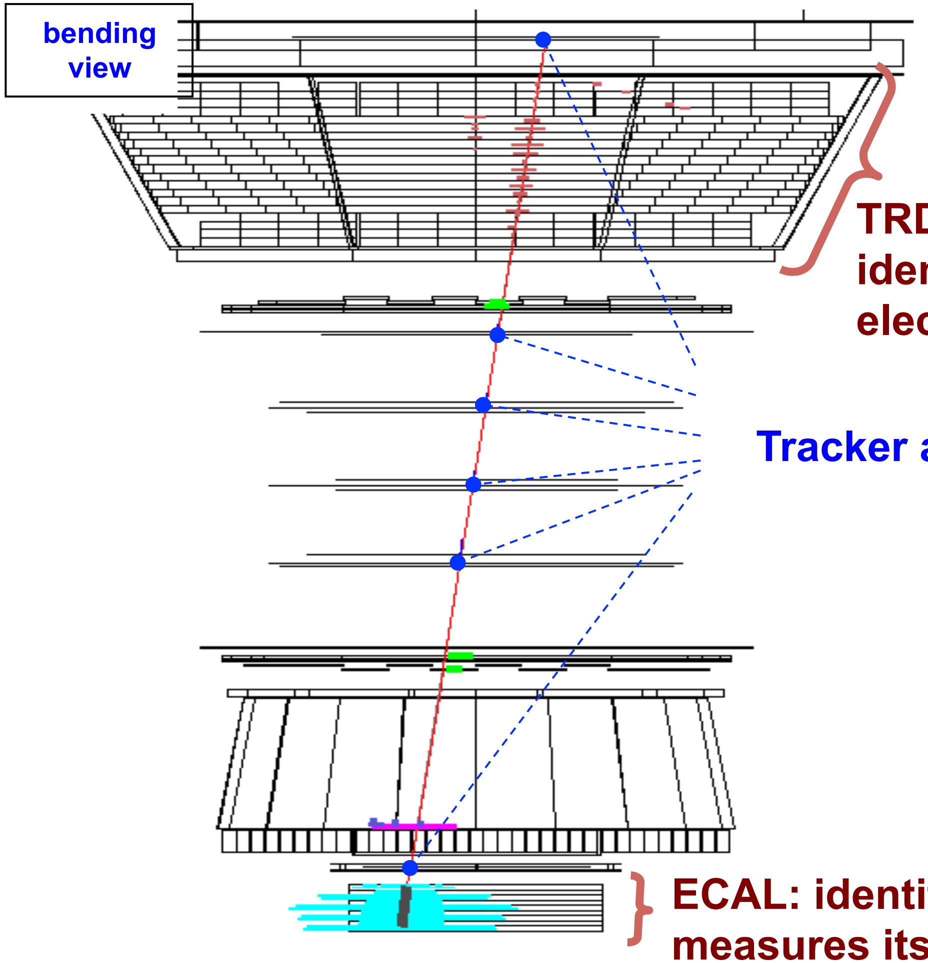
Observations:

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).

The $(e^+ + e^-)$ flux before AMS



Combined ($e^+ + e^-$) Flux: event selection



bending view

TRD: identifies electron

Tracker and Magnet:

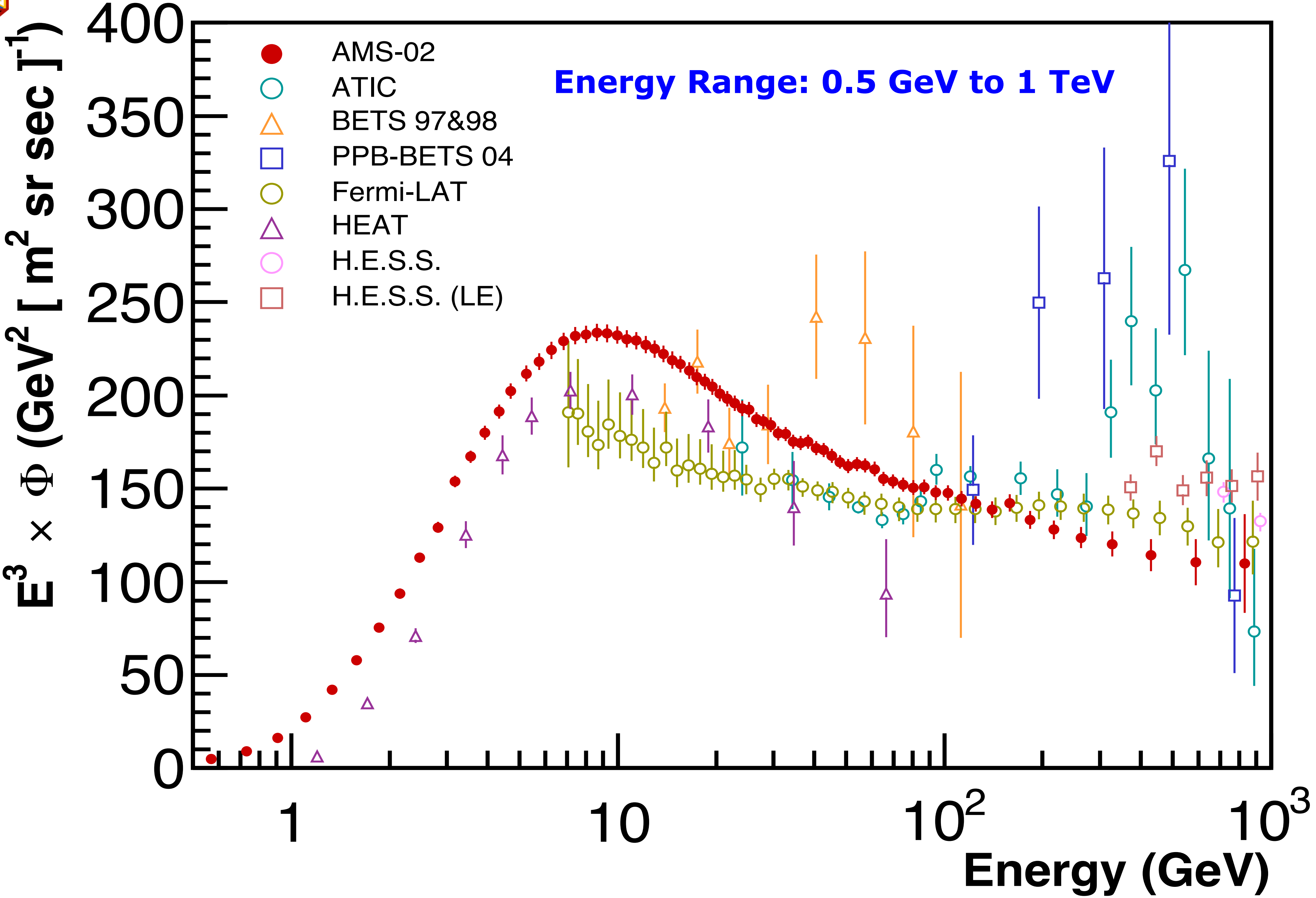
ECAL: identifies electron and measures its energy

Independent of charge sign measurement → no charge confusion

High selection efficiency : 70% @ TeV

Small systematics on acceptance: 2% @ TeV

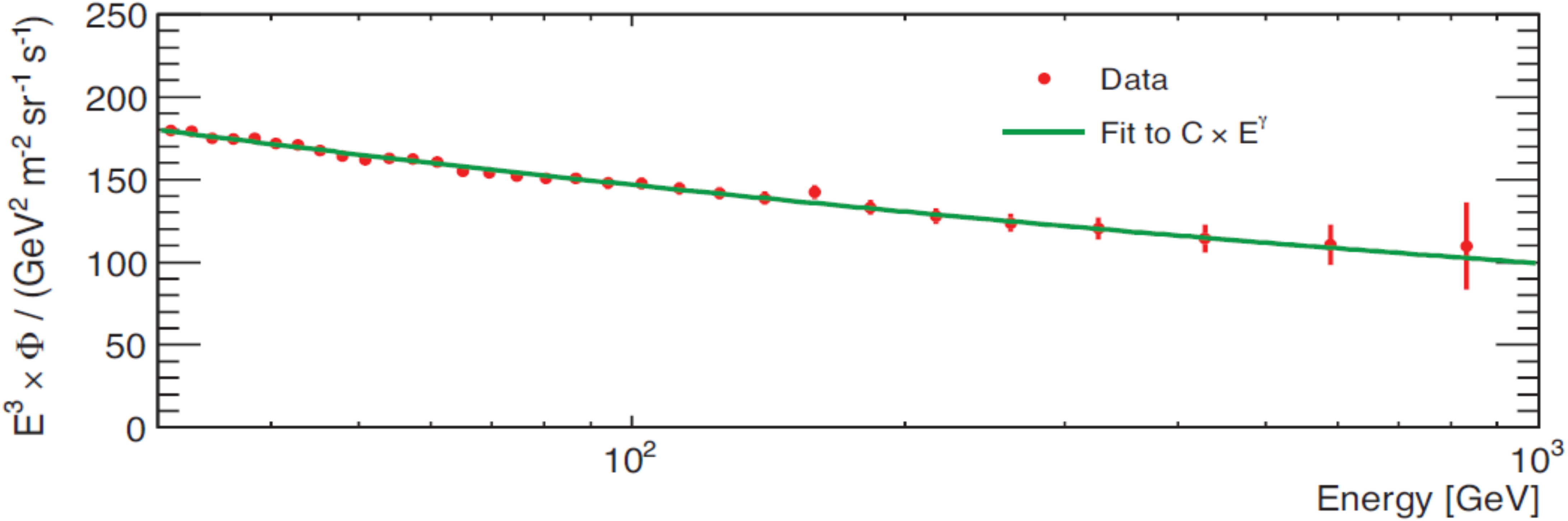
AMS Results: $(e^+ + e^-)$ Flux



$\Phi(e^{+}+e^{-}) = C\,E^{\gamma}$

$\gamma = -3.170 \pm 0.008$ (stat + syst.) $\pm\ 0.008$ (energy scale)

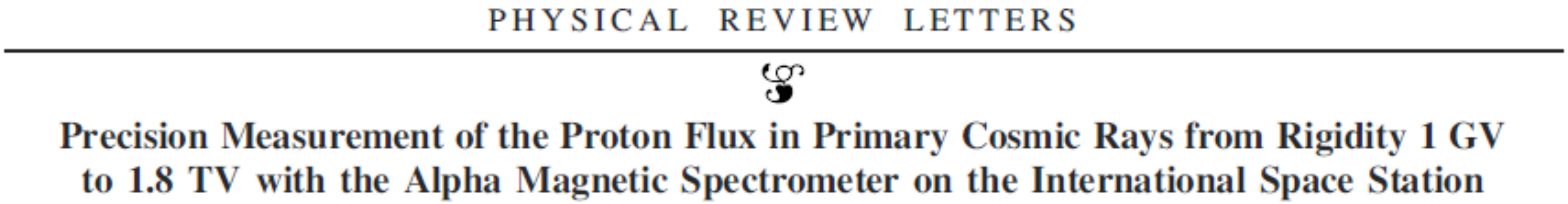
$E > 30$ GeV



The flux is consistent with a single power law above 30 GeV.

An unexpected observation which does not have a theoretical explanation

(remember, the individual e+/e- fluxes can not be described with single power laws)



PHYSICAL REVIEW LETTERS

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

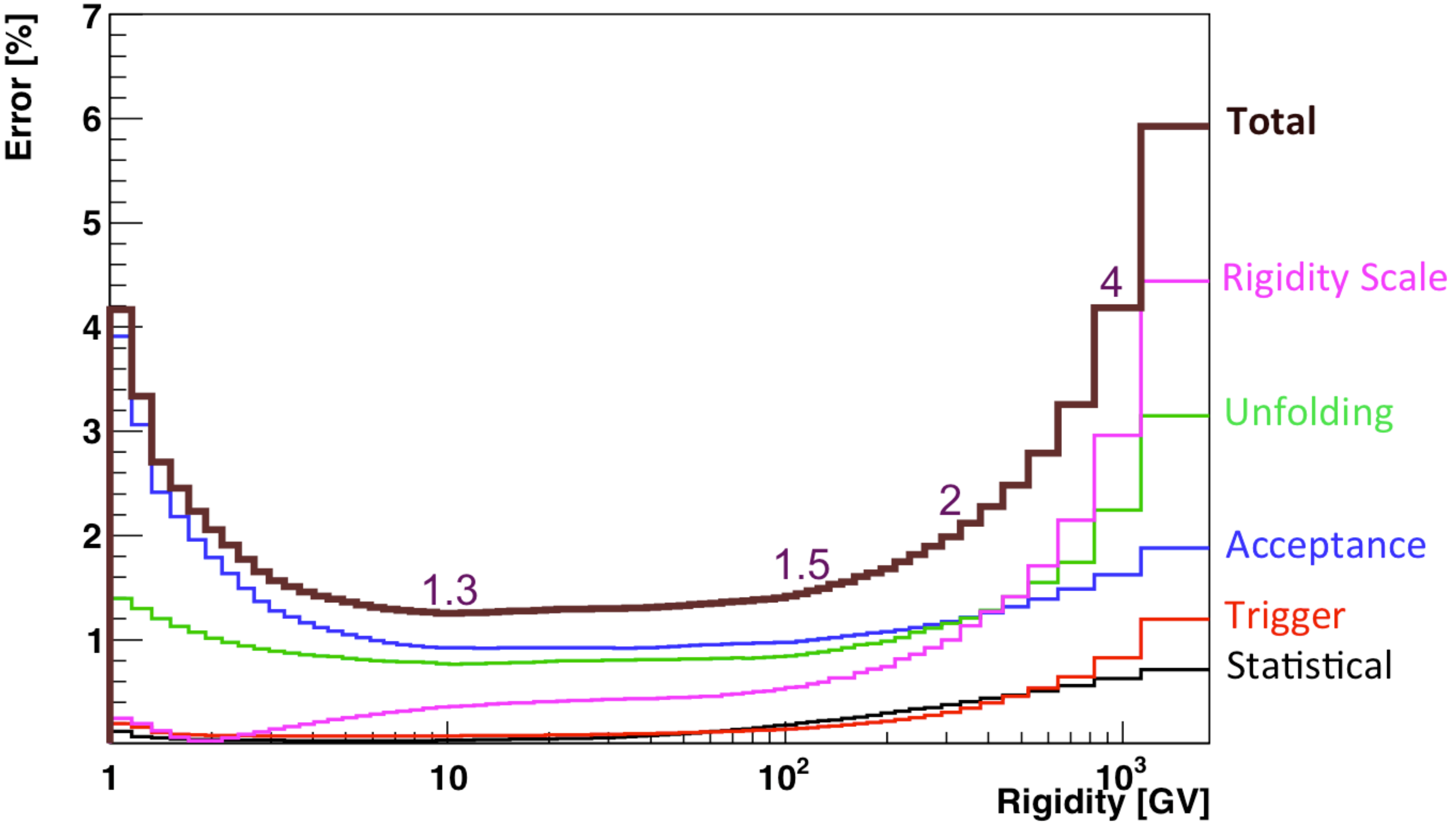
The isotropic proton flux Φ_i for the i th rigidity bin (R_i , $R_i + \Delta R_i$) is

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

N_i is the number of events, corrected for the tracker resolution
A_i is the effective acceptance
ε_i is the trigger efficiency
T_i is the collection time (which depends on the geomagnetic cutoff)

300 million proton events have been selected

Systematic Errors of the Proton Flux (An Example of the Systematic Error Sources)



1) trigger efficiency

2) acceptance

- a. the acceptance and event selection
- b. background contamination
- c. geomagnetic cutoff

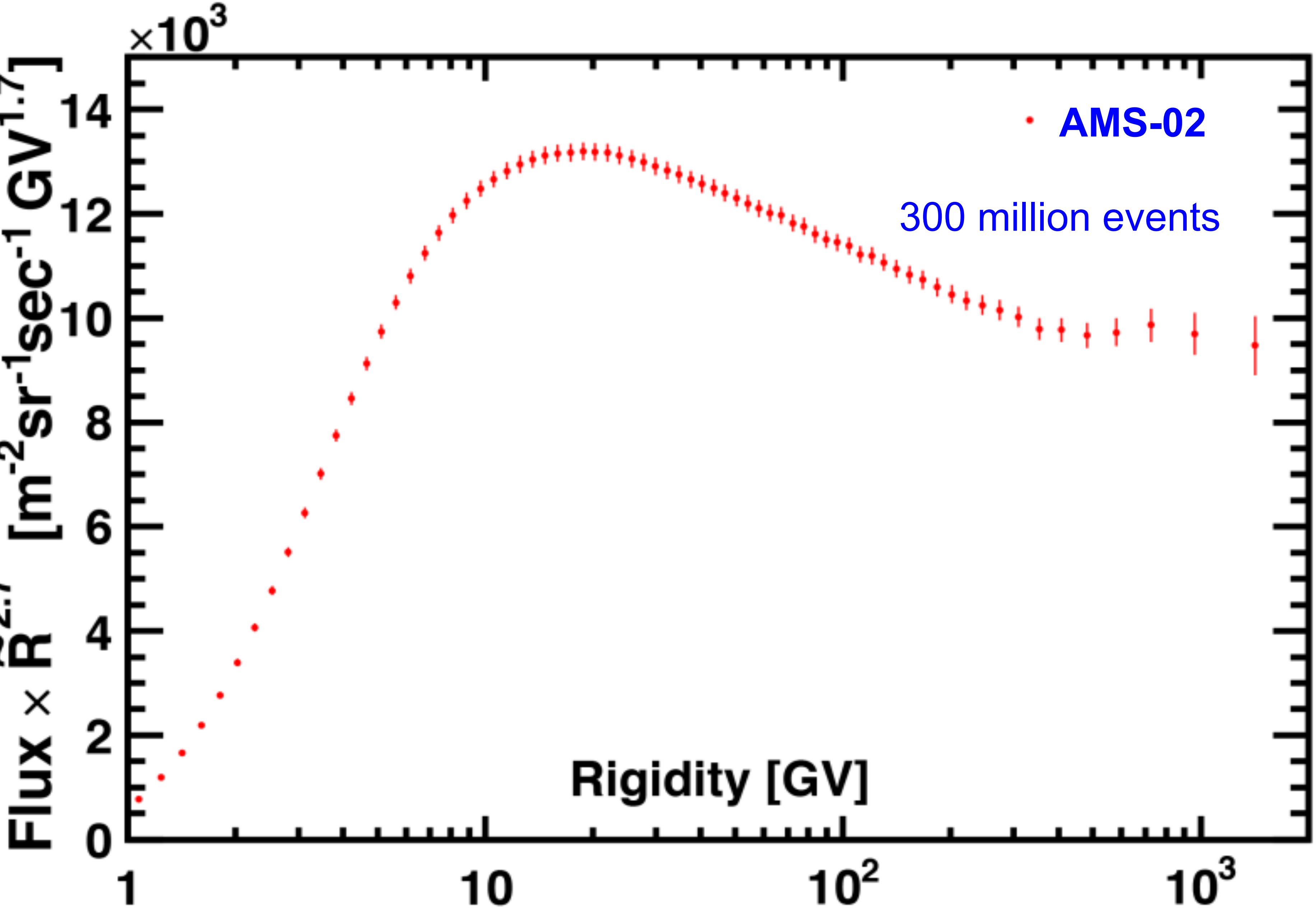
3) unfolding

- a. unfolding algorithm
- b. rigidity resolution function

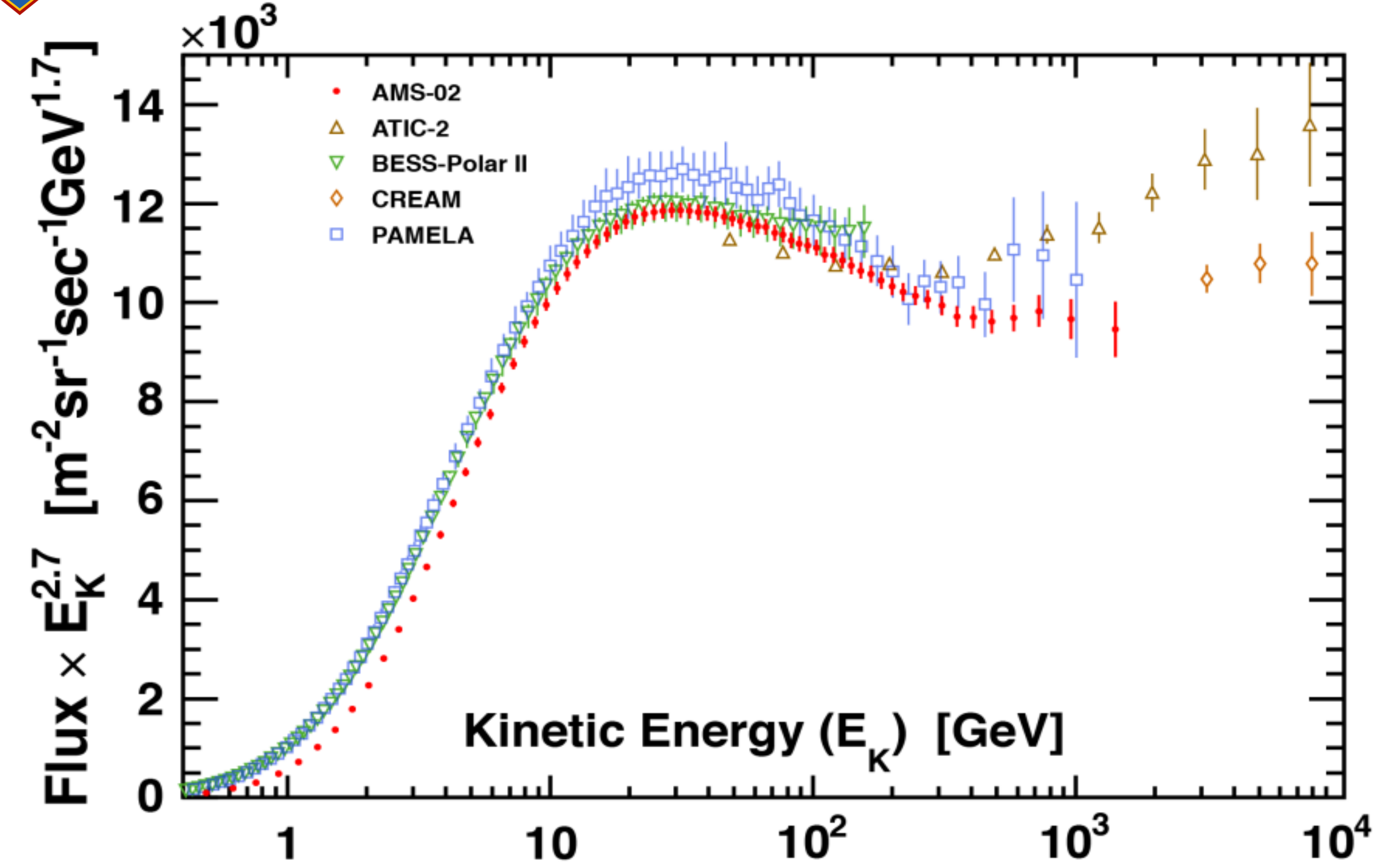
4) absolute rigidity scale

- a. residual tracker misalignment
- b. magnetic field uncertainty

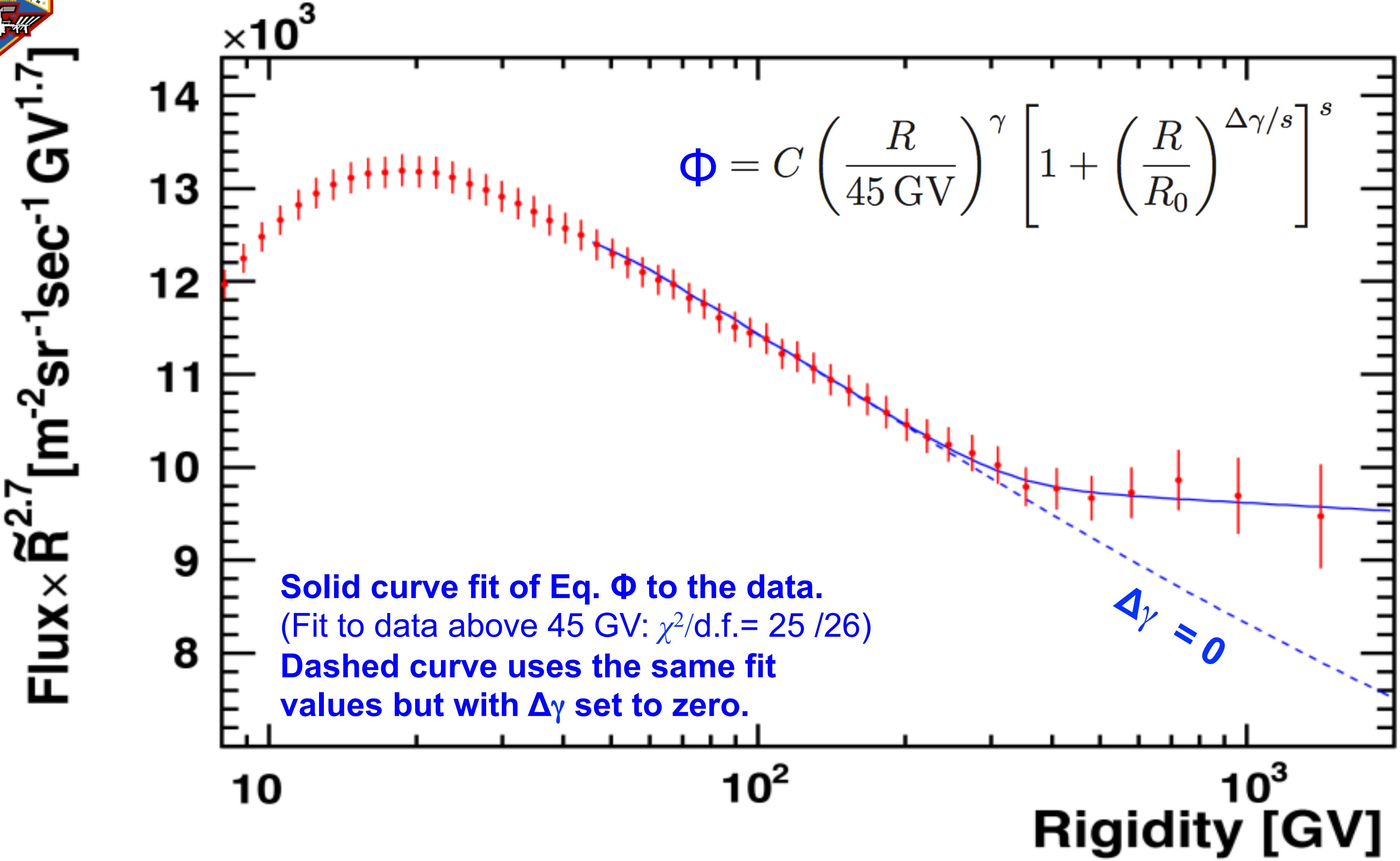
AMS Proton Flux



AMS Proton Flux



AMS Proton Flux: Fit with Double Power Law

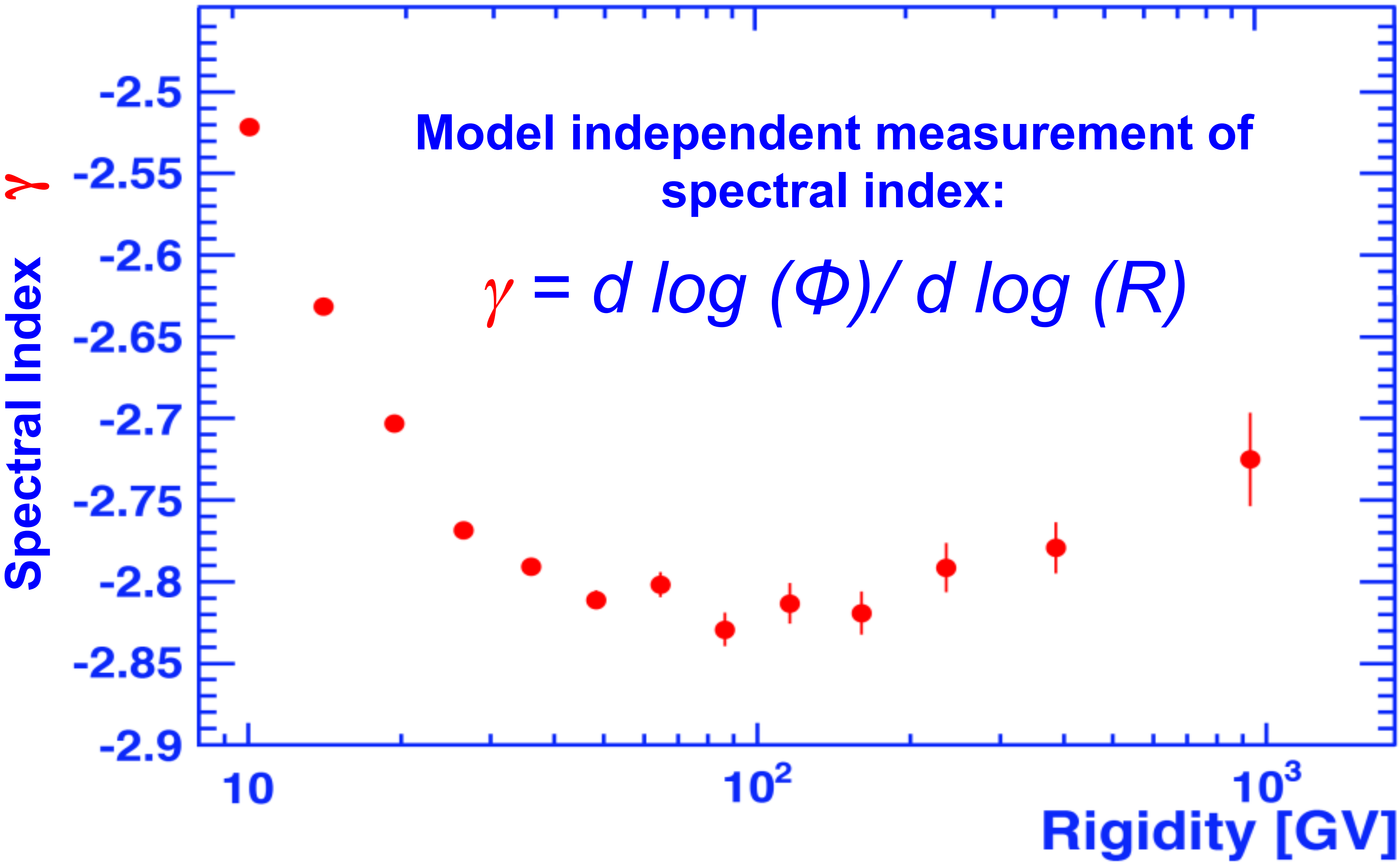


$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

Solid curve fit of Eq. Φ to the data.
(Fit to data above 45 GV: χ^2/d.f.= 25 /26)
Dashed curve uses the same fit values but with Δγ set to zero.

Proton flux can not be described with a single power law: no theoretical explanation

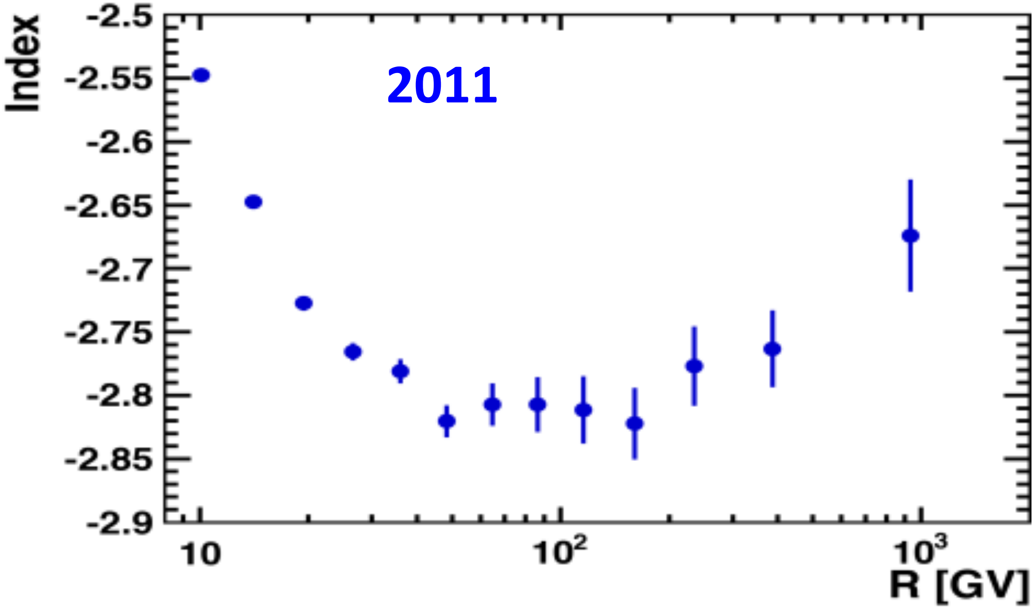
AMS Proton Spectral Index Variation

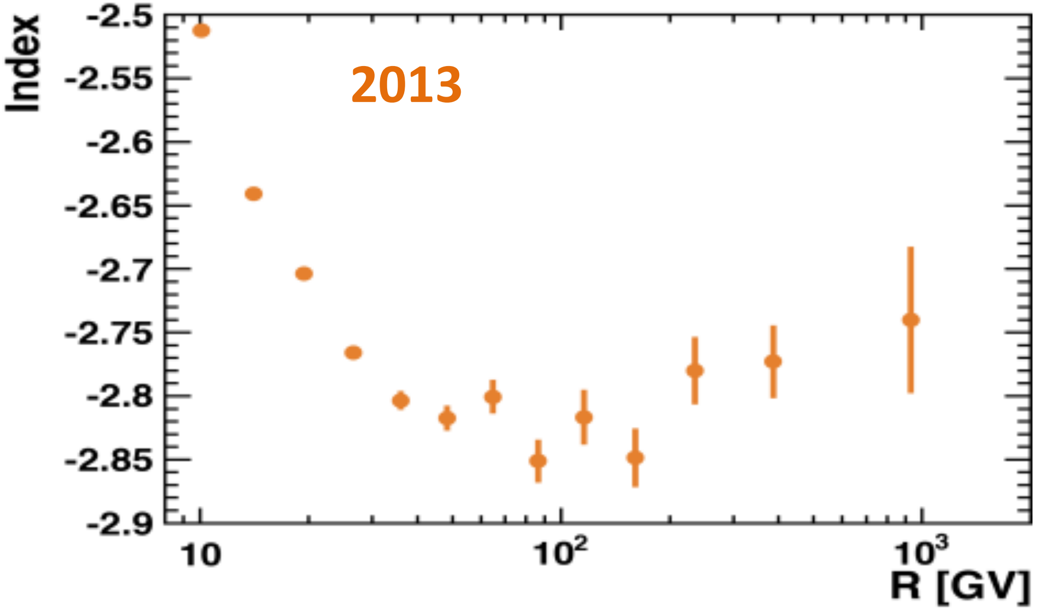


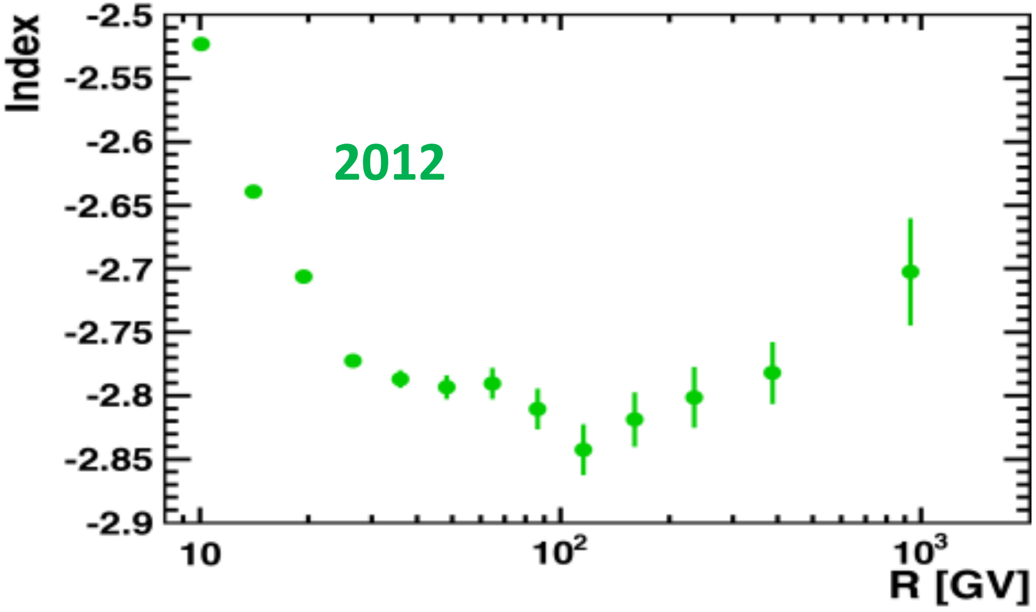
Model independent measurement of spectral index:

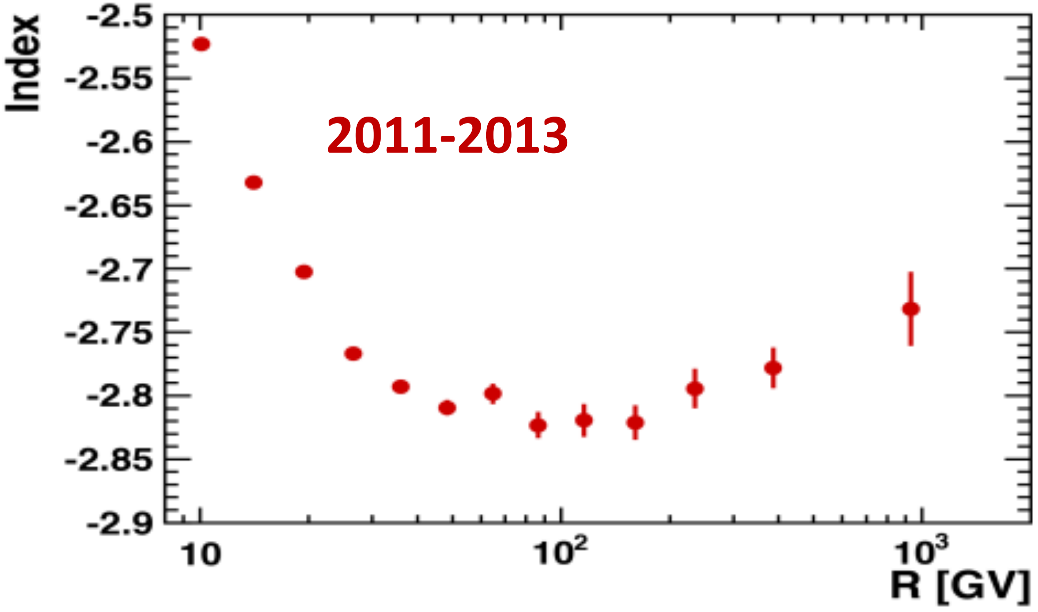
$$\gamma = d\log(\Phi) / d\log(R)$$

Spectral index of the proton flux for 2011 to 2013



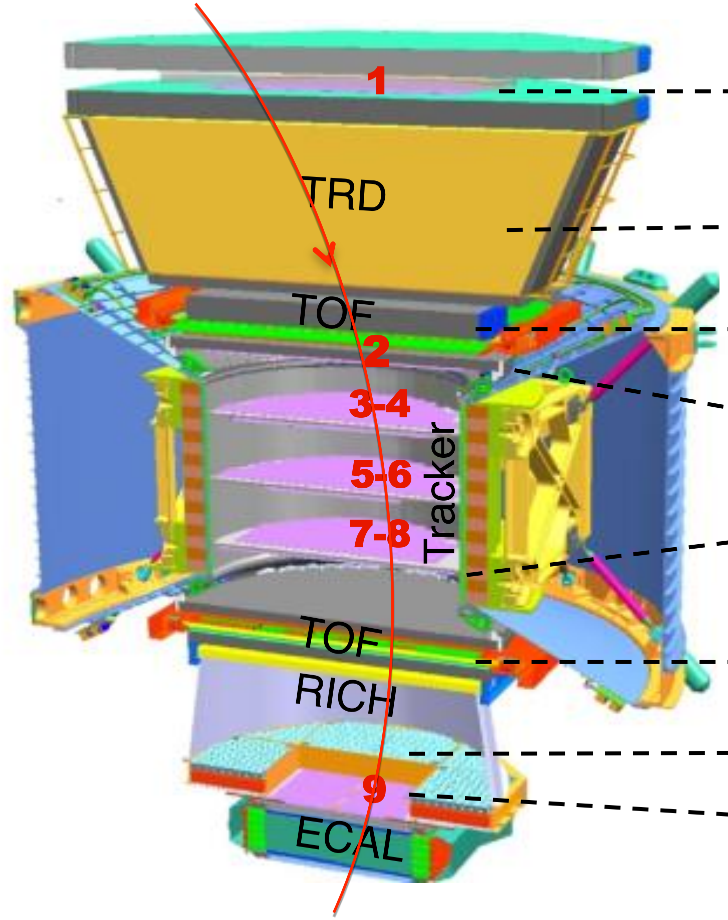






Measurement of Nuclei with AMS

Multiple Independent Measurements of the Charge (|Z|)

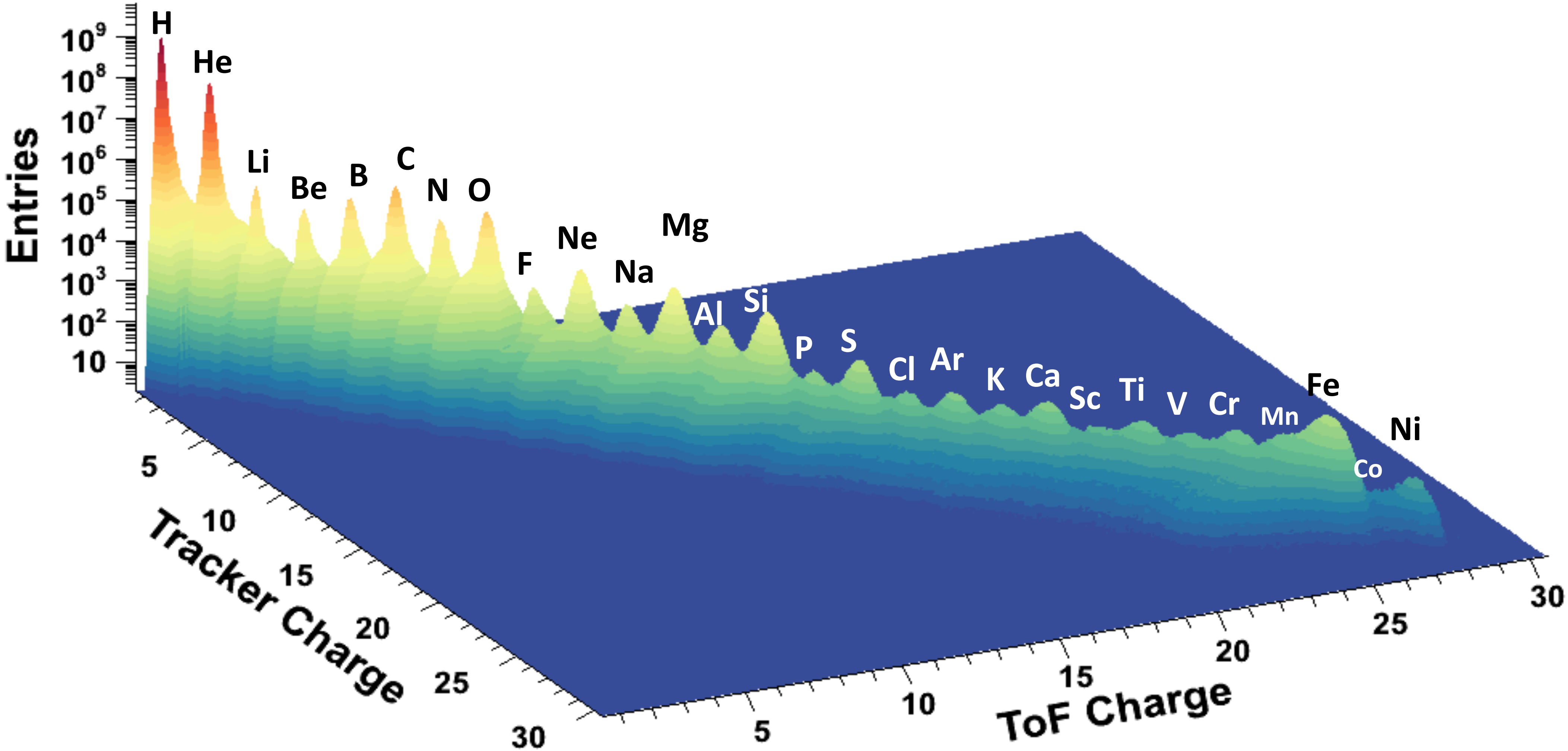


Carbon (Z=6)

	ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30

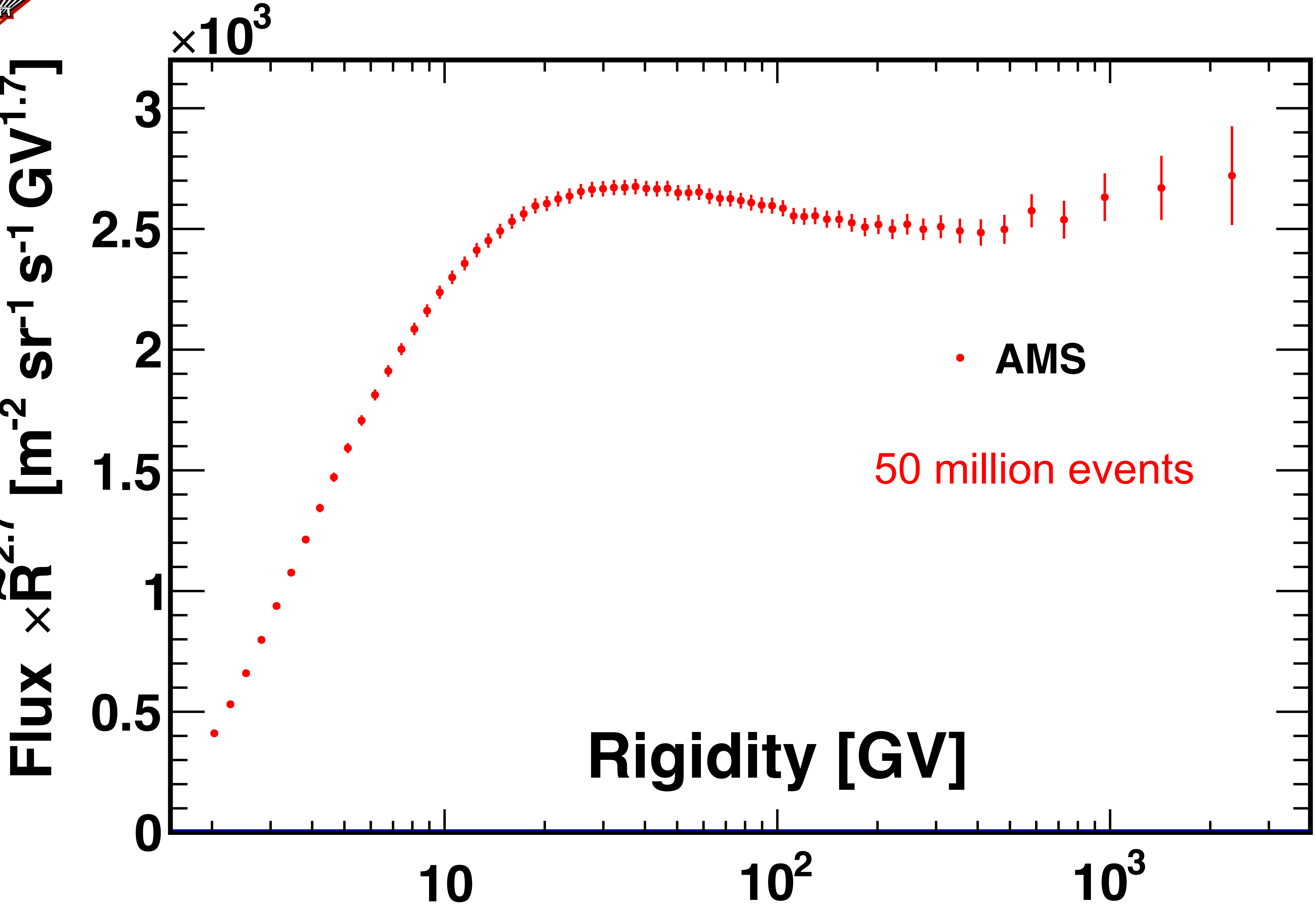
Allows for precise tuning of our MC using ISS data: inelastic, (quasi-)elastic, multiple scattering x-sections, etc.

AMS Nuclei Measurement on ISS

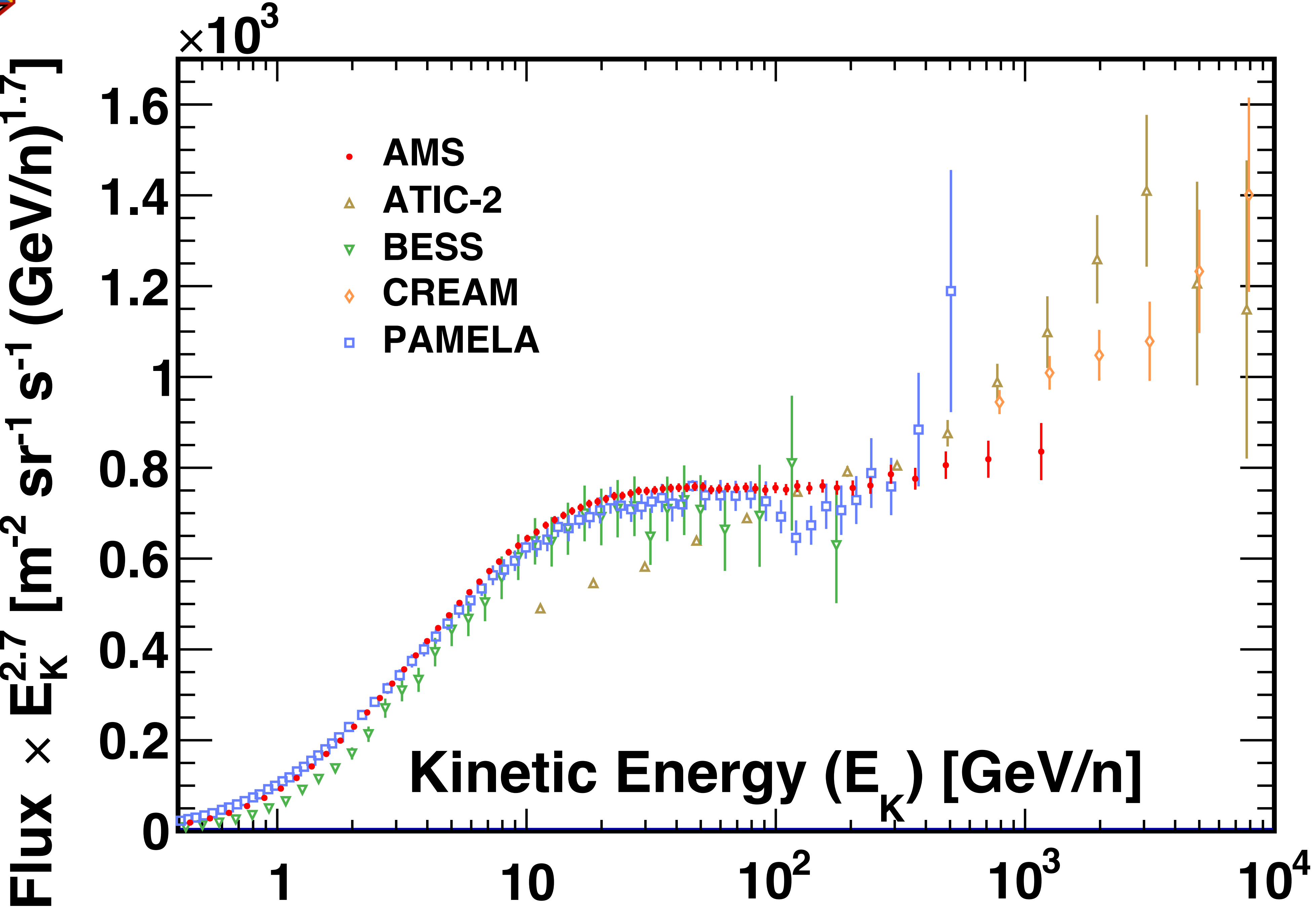


Constraining Cosmic Ray Propagation Parameters:
In addition to the traditionally measured B/C ratio, AMS is capable of providing precise data on many other secondary and tertiary nuclei

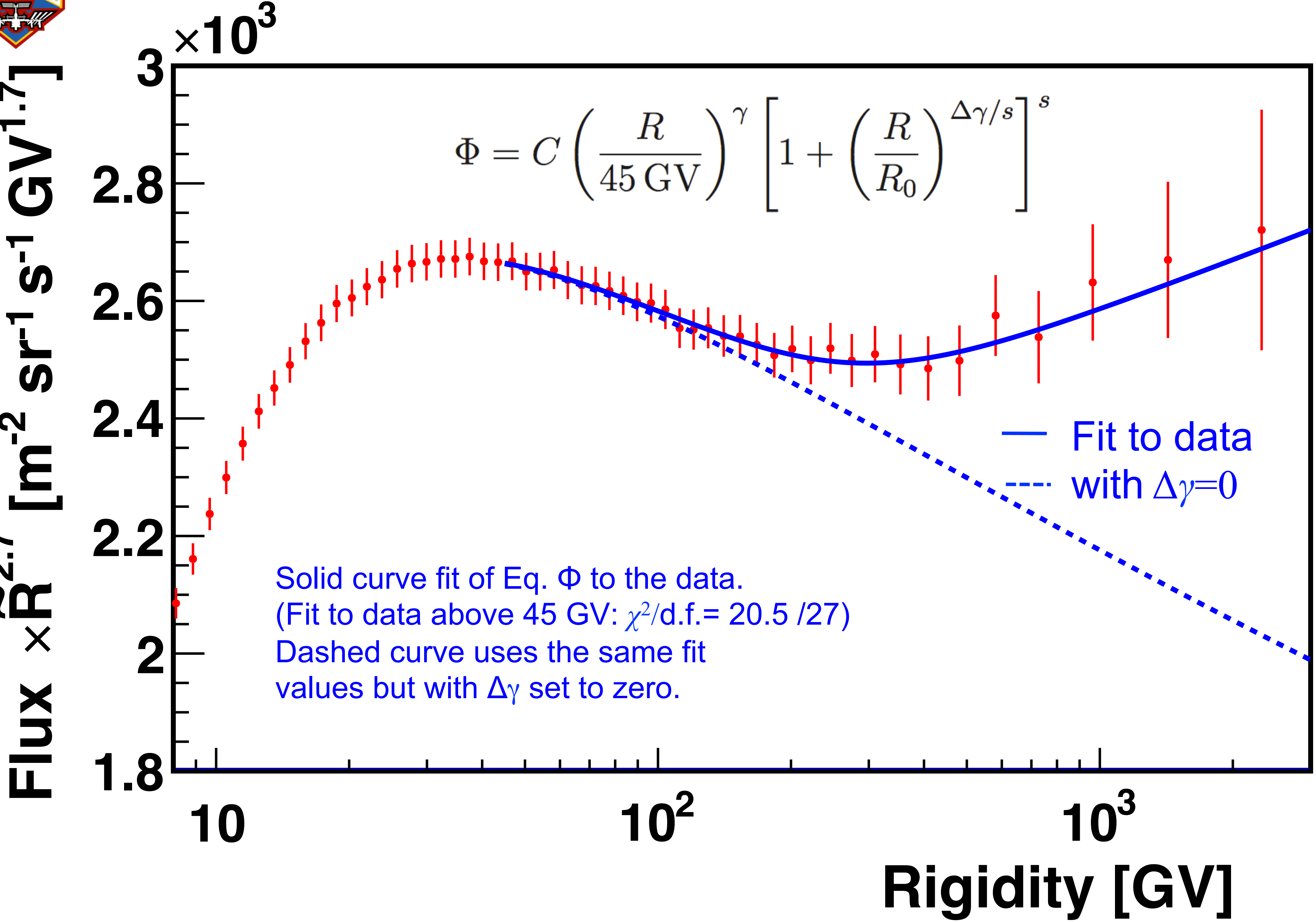
AMS Helium Flux



AMS Helium Flux



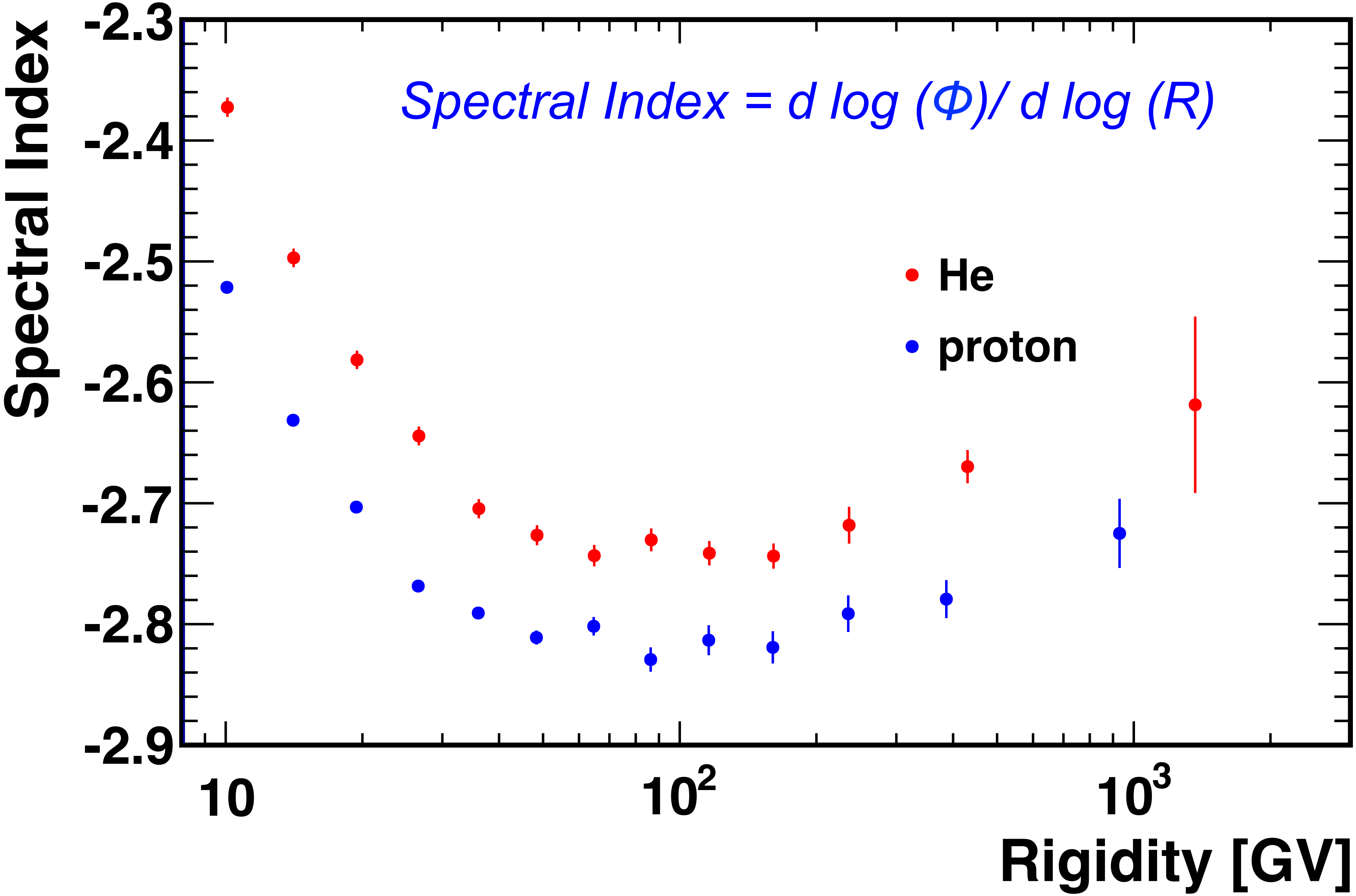
AMS HeFlux: Fit with Double Power Law



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

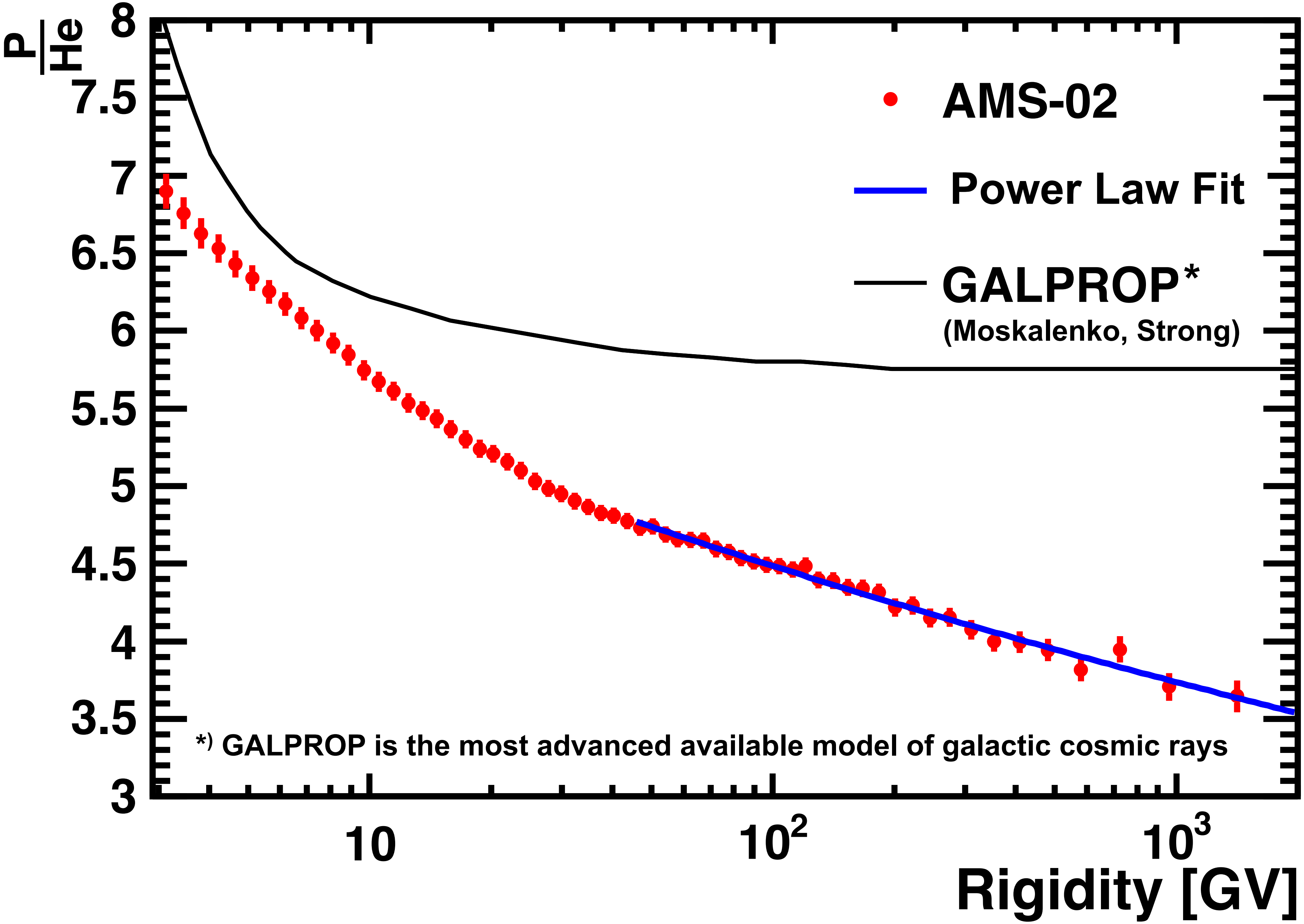
Solid curve fit of Eq. Φ to the data.
(Fit to data above 45 GV: χ^2/d.f.= 20.5 /27)
Dashed curve uses the same fit
values but with Δγ set to zero.

Model Independent Spectral Indices Comparison



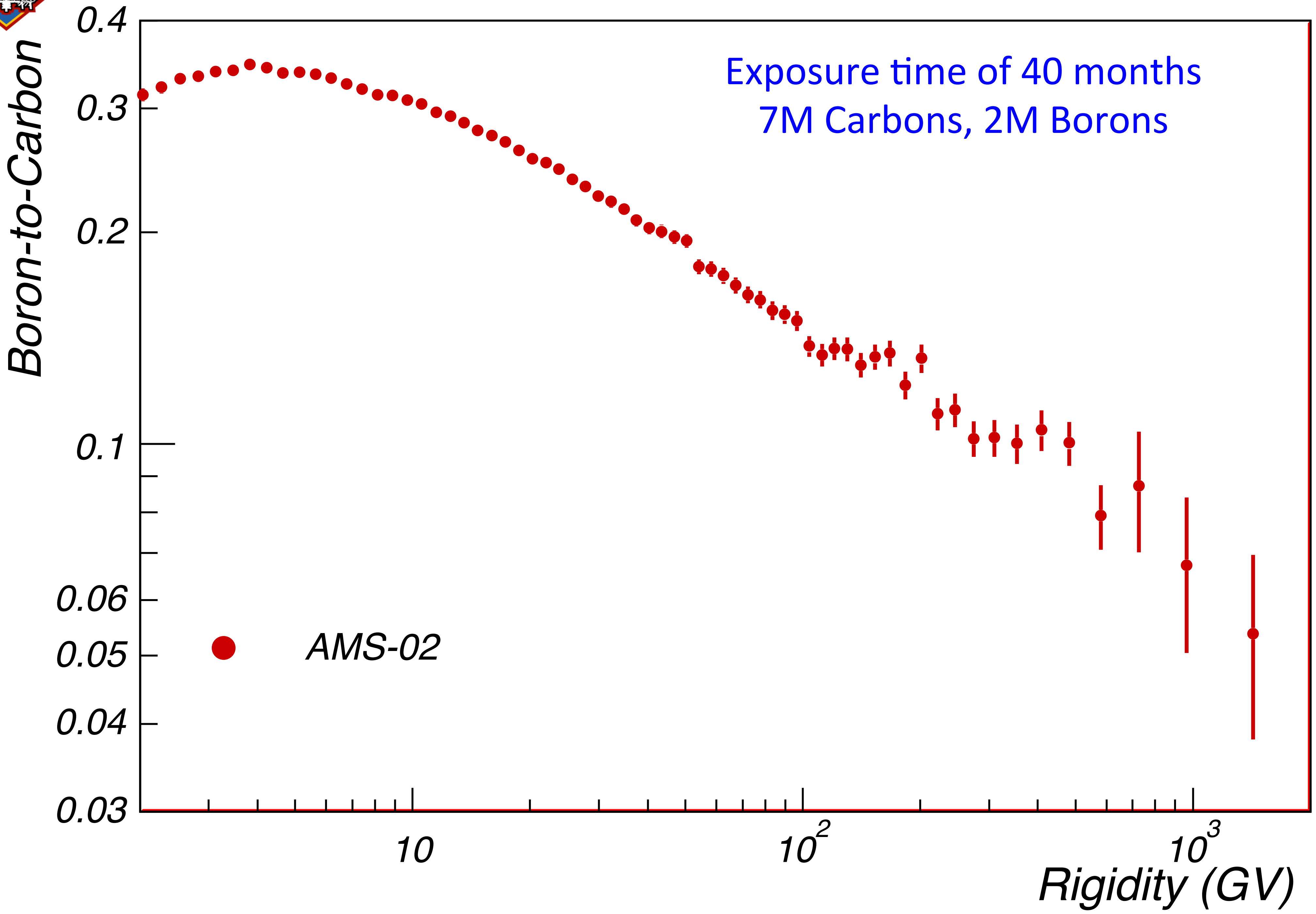
Proton and He fluxes have different spectral indices: no theoretical explanation

Proton/He Flux Ratio

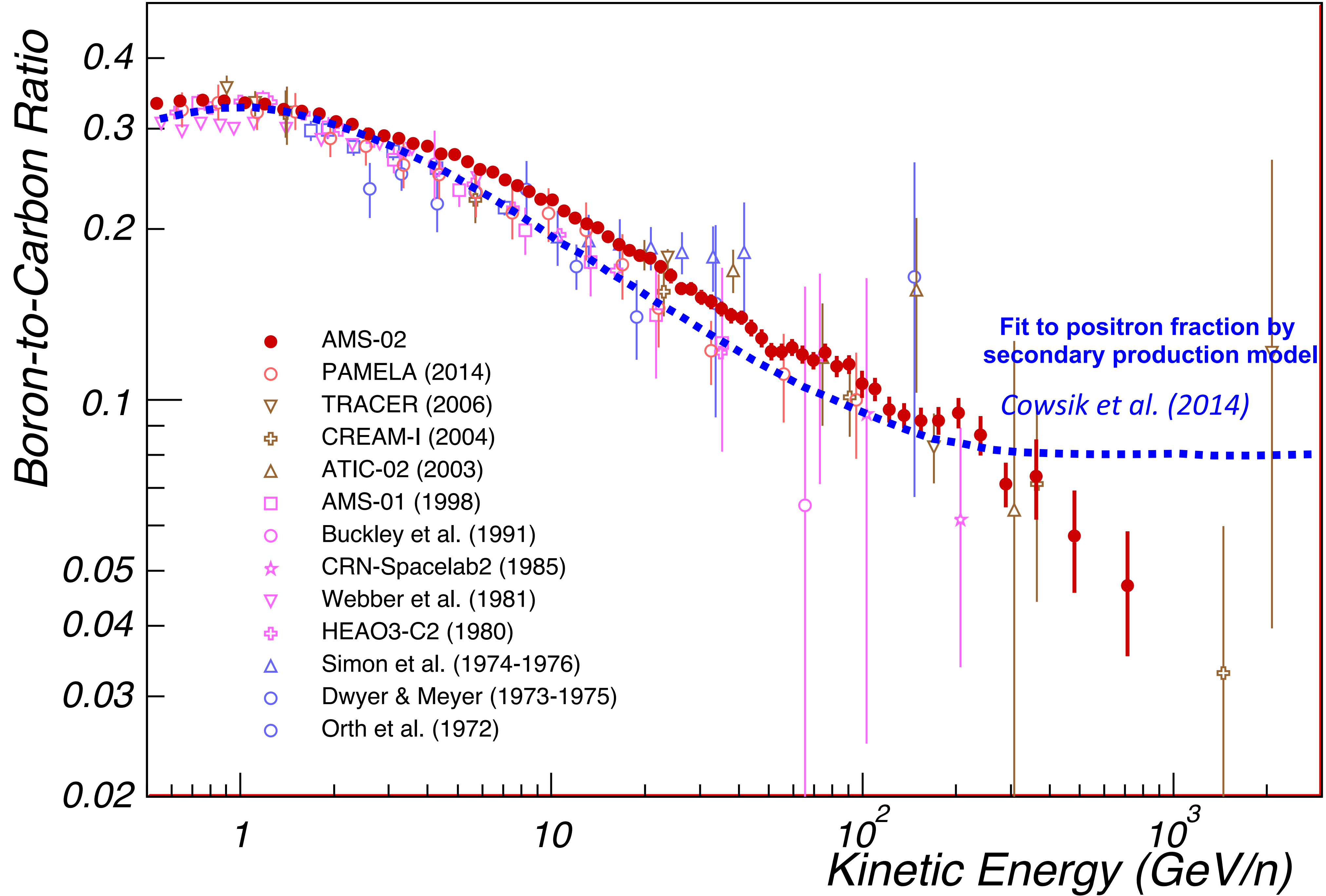


*) GALPROP is the most advanced available model of galactic cosmic rays

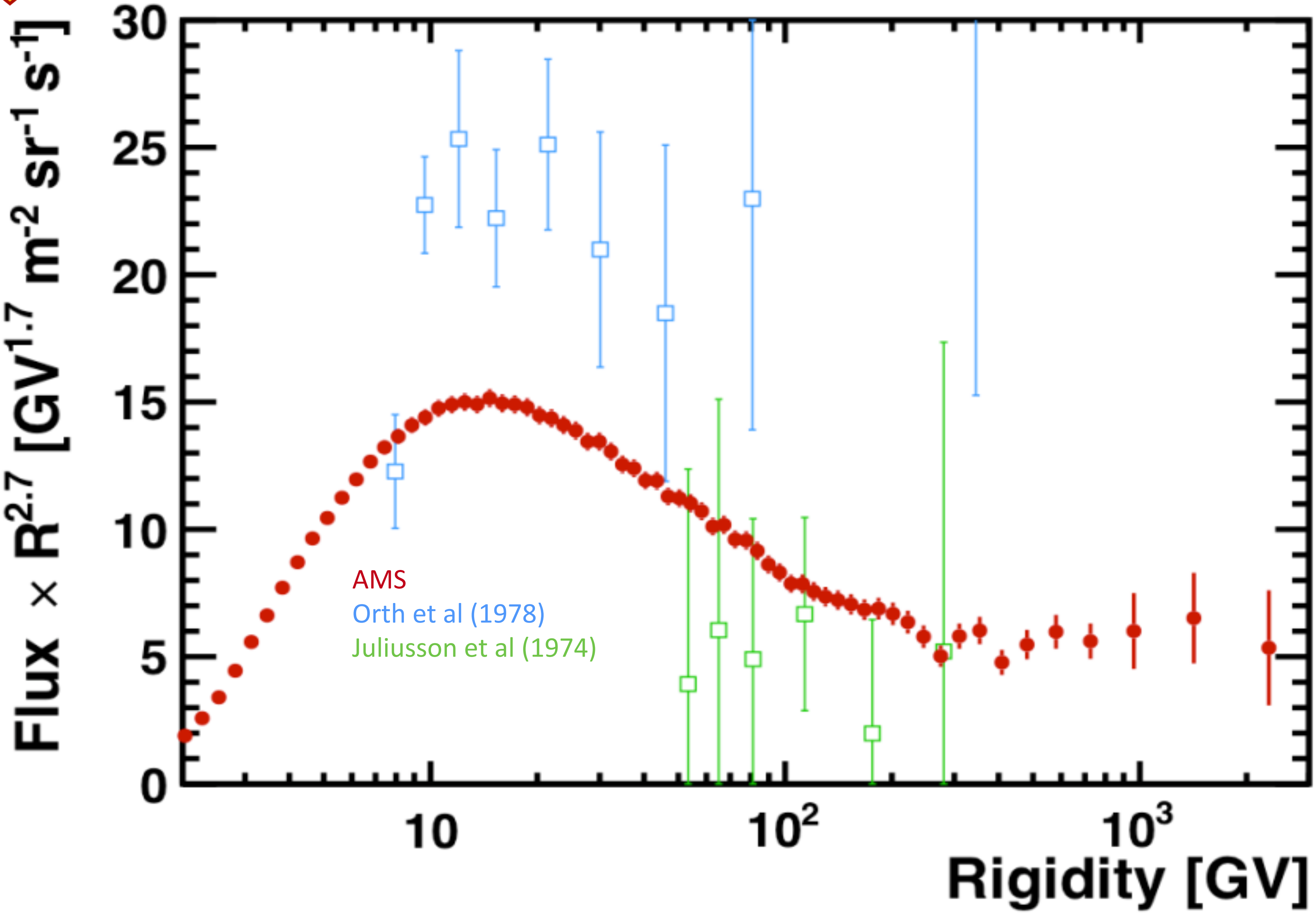
B/C Ratio


Boron-to-Carbon
0.4
0.3
0.2
0.1
0.06
0.05
0.04
0.03
Exposure time of 40 months
7M Carbons, 2M Borons
● AMS-02
10
10^2
10^3
Rigidity (GV)

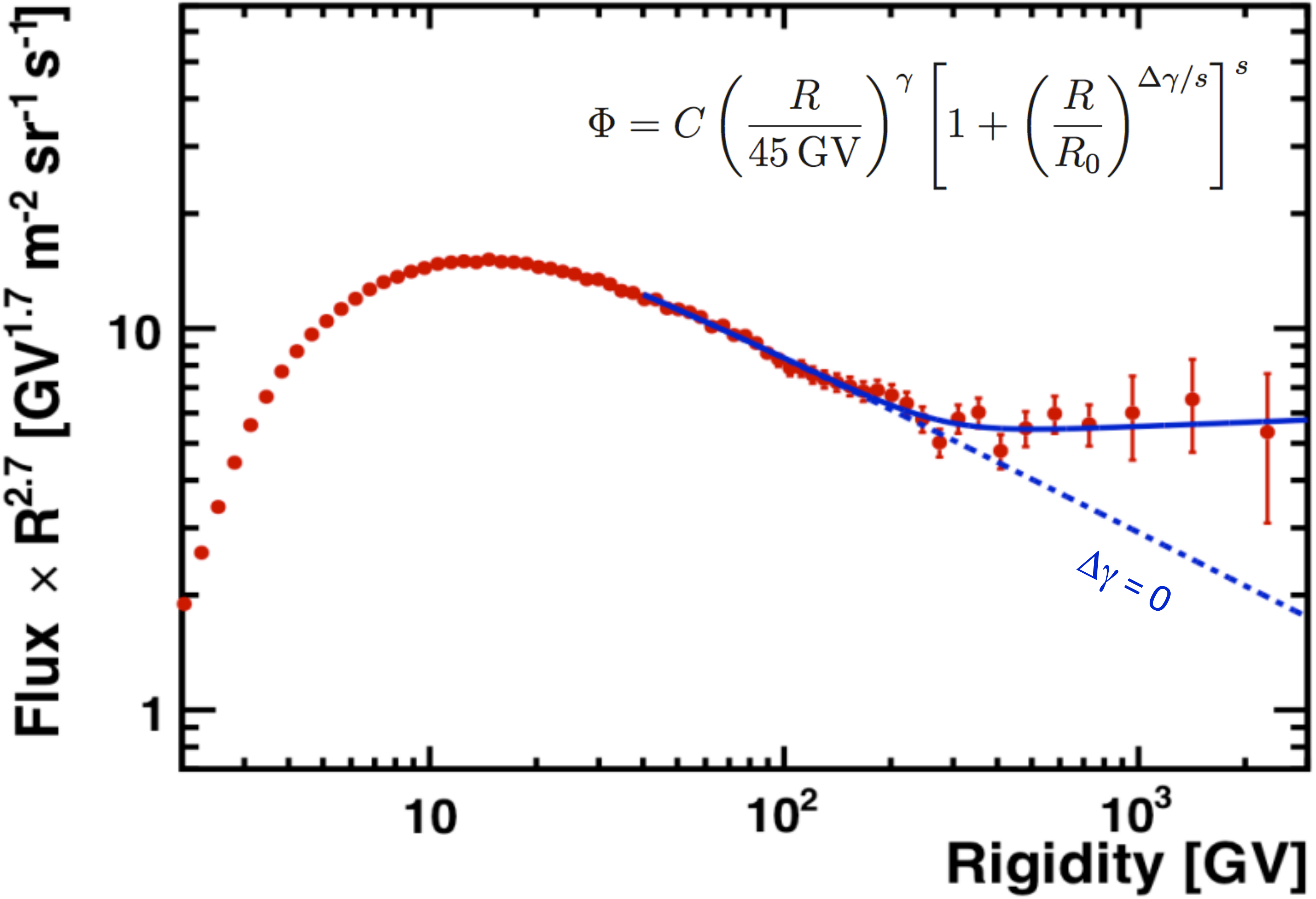
B/C Ratio converted in Kinetic Energy



AMS Lithium flux – current status



Lithium flux with two power law fit



Slope changes at about the same rigidity as for protons and helium

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

AMS is providing cosmic ray information with ~1% uncertainty.

The improvement in accuracy will provide new insights.

The Space Station has become a unique platform for precision physics research.

The latest AMS measurements of the positron fraction, the behavior of the fluxes of electrons, positrons, protons, helium, and other nuclei provide precise and unexpected information. A comprehensive model able to accommodate the accuracy and the observed features of the data simultaneously from many different types of cosmic rays is needed to check if their origin is from dark matter, astrophysical sources, propagation mechanisms or from their combination.