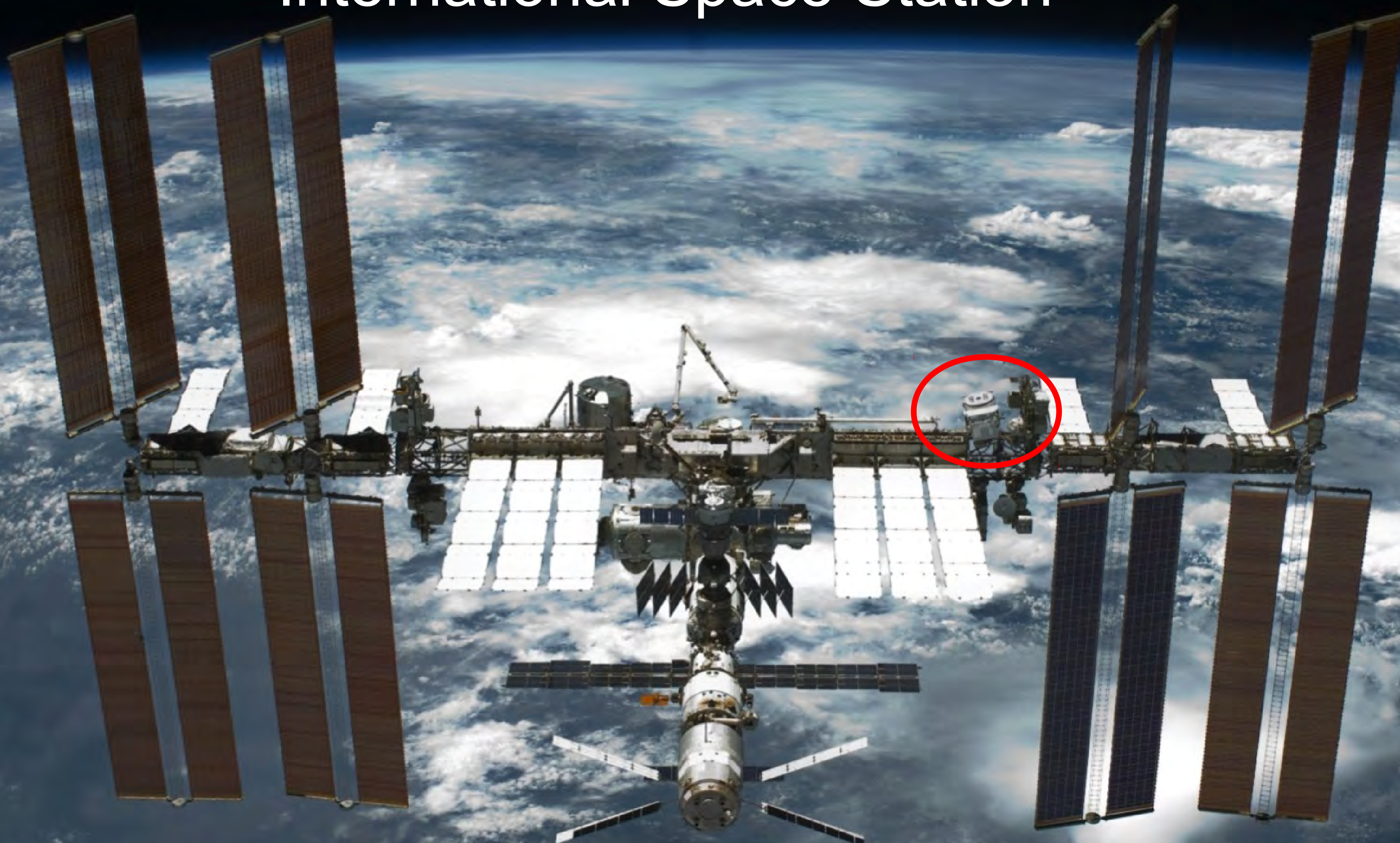
New results from the AMS experiment on the International Space Station



Henning Gast
RWTH Aachen

Questions to AMS-02:

Are there galaxies made of anti-matter in the Universe?
What is the nature of Dark Matter?
How do cosmic rays propagate in the Galaxy?

Overview

- Physics with AMS-02
- The AMS-02 detector
- New data from AMS-02:
    - positrons and electrons
    - protons and light nuclei
    - B/C
    - antiprotons

The search for antimatter in the Universe

AMS on the ISS

The Universe was created in the Big Bang.

After the Big Bang, there must have been equal amounts of matter and anti-matter.

The search for antimatter in the Universe

AMS on the ISS

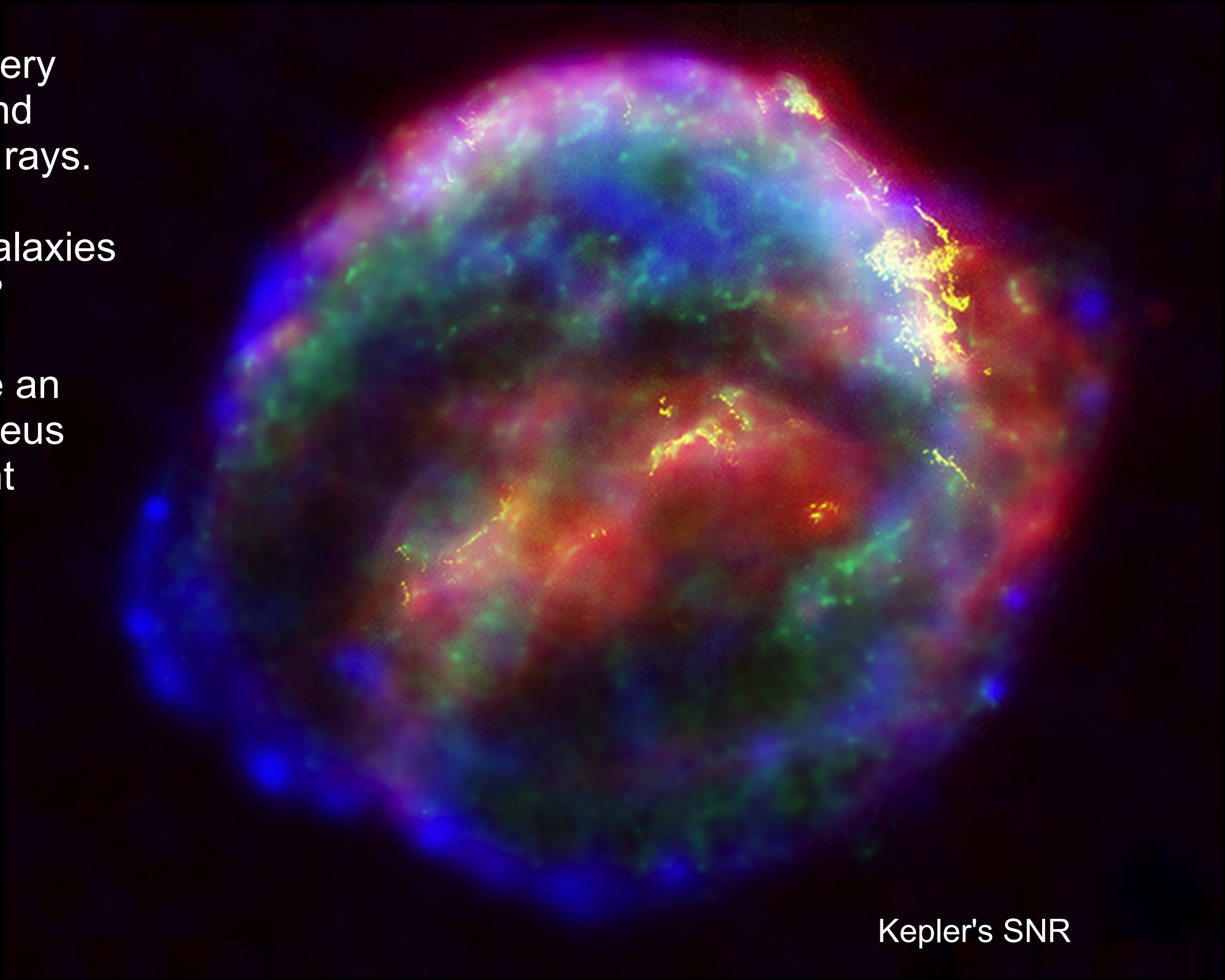
The Universe was created in the Big Bang.

After the Big Bang, there must have been equal amounts of matter and anti-matter.

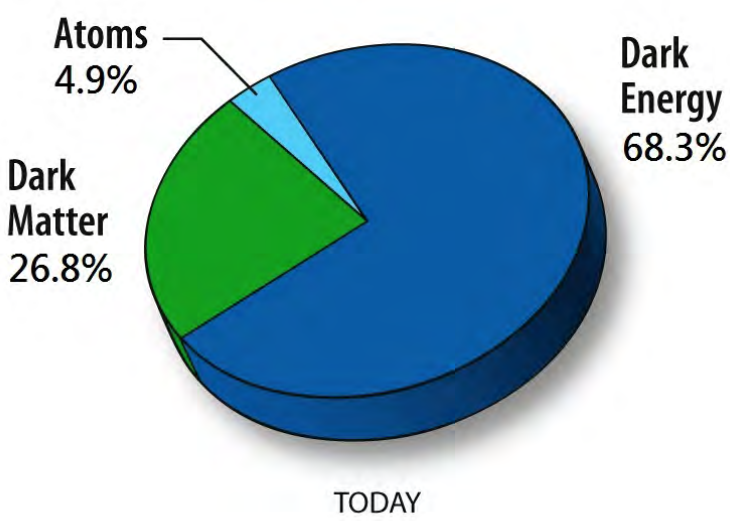
Atomic nuclei are accelerated in supernovae to very high energies and become cosmic rays.

Are there anti-galaxies in the Universe?

Can we observe an anti-carbon nucleus from a far distant supernova?

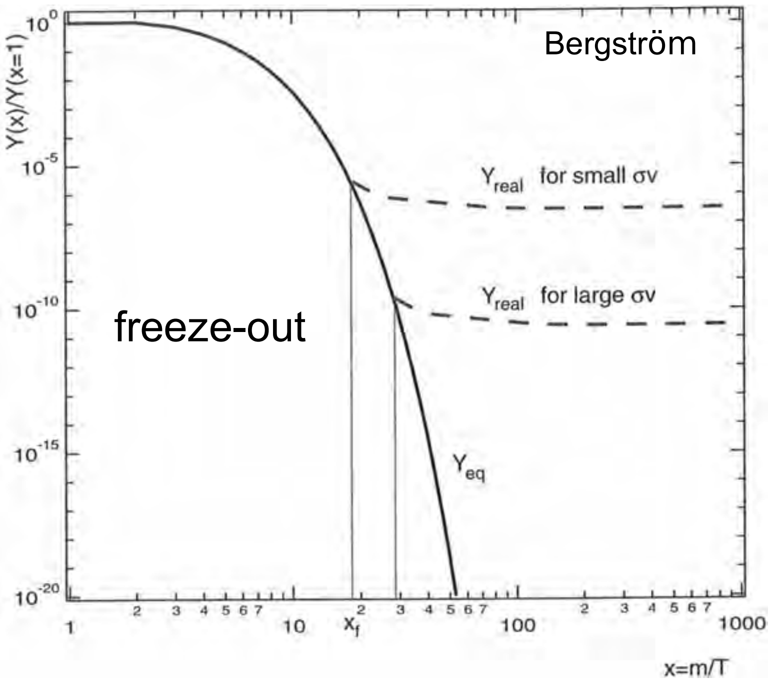


Relic Dark Matter



Dark matter makes up a substantial fraction of the energy density of the Universe. But what is its nature?

Freeze-out in the early Universe:

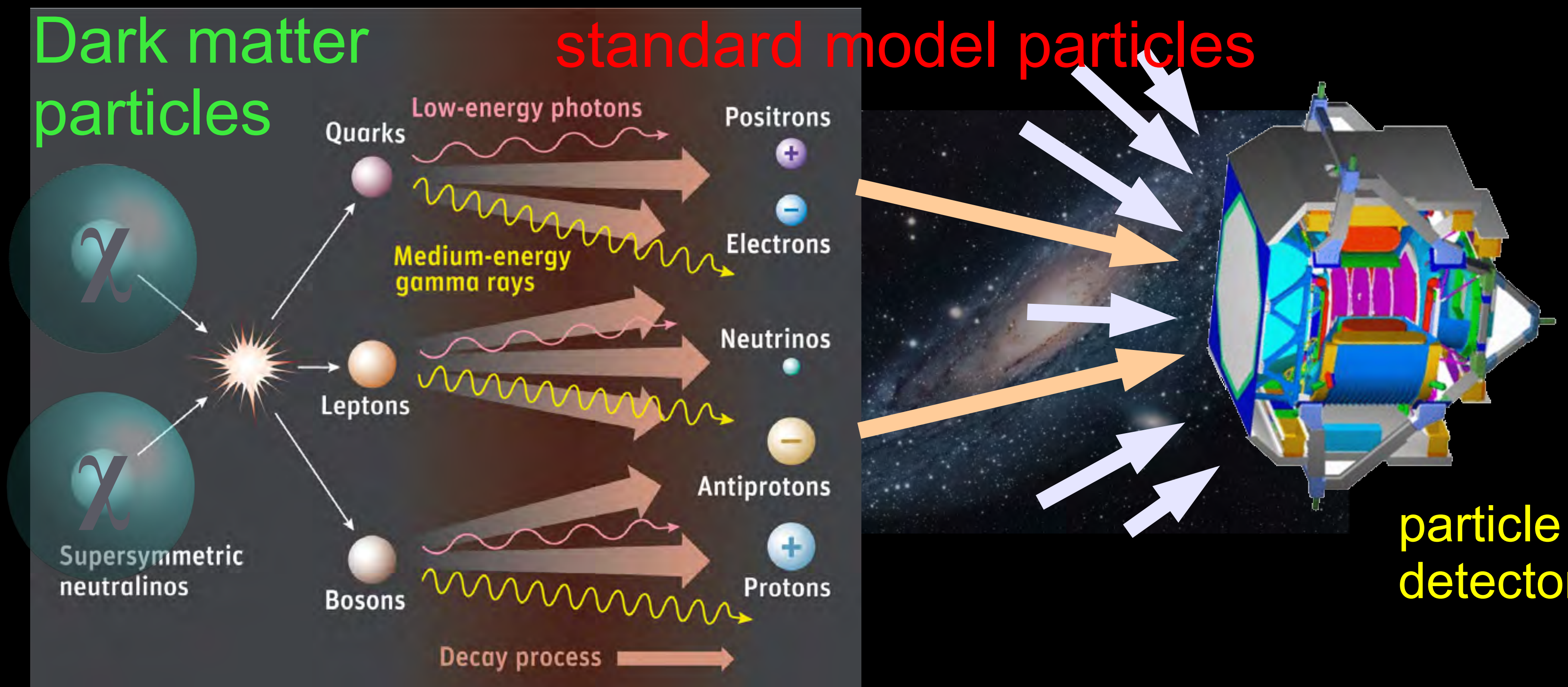


$$\Omega_\chi h^2 \approx \frac{3 \cdot 10^{-27}\,\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma v \rangle}$$

relic density ↔ annihilation cross section

Dark Matter annihilation

Products of Dark Matter annihilations get injected into the cosmic-ray sea:



most promising channels: e^+, $\bar{p}$, $\bar{D}$, ($\overline{He}$), (and photons)

Cosmic ray physics in a nutshell

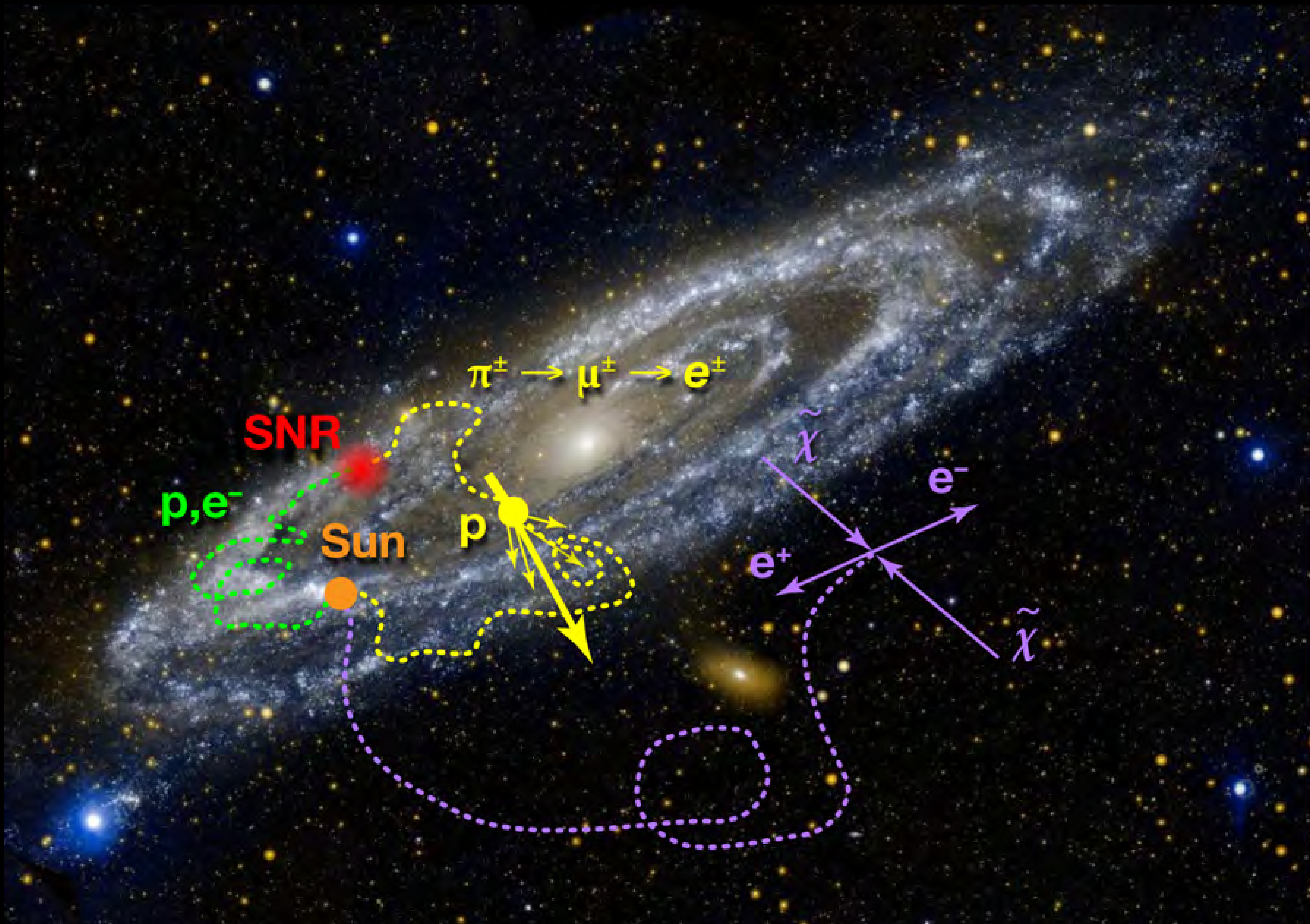


Image: GALEX, JPL-Caltech, NASA;
Drawing: APS/Alan Stonebraker

Excellent results from PAMELA

- Results span 4 decades in energy and 13 in fluxes

Contents lists available at ScienceDirect

Physics Reports

journal homepage: www.elsevier.com/locate/physrep

The PAMELA Mission: Heralding a new era in precision cosmic ray physics

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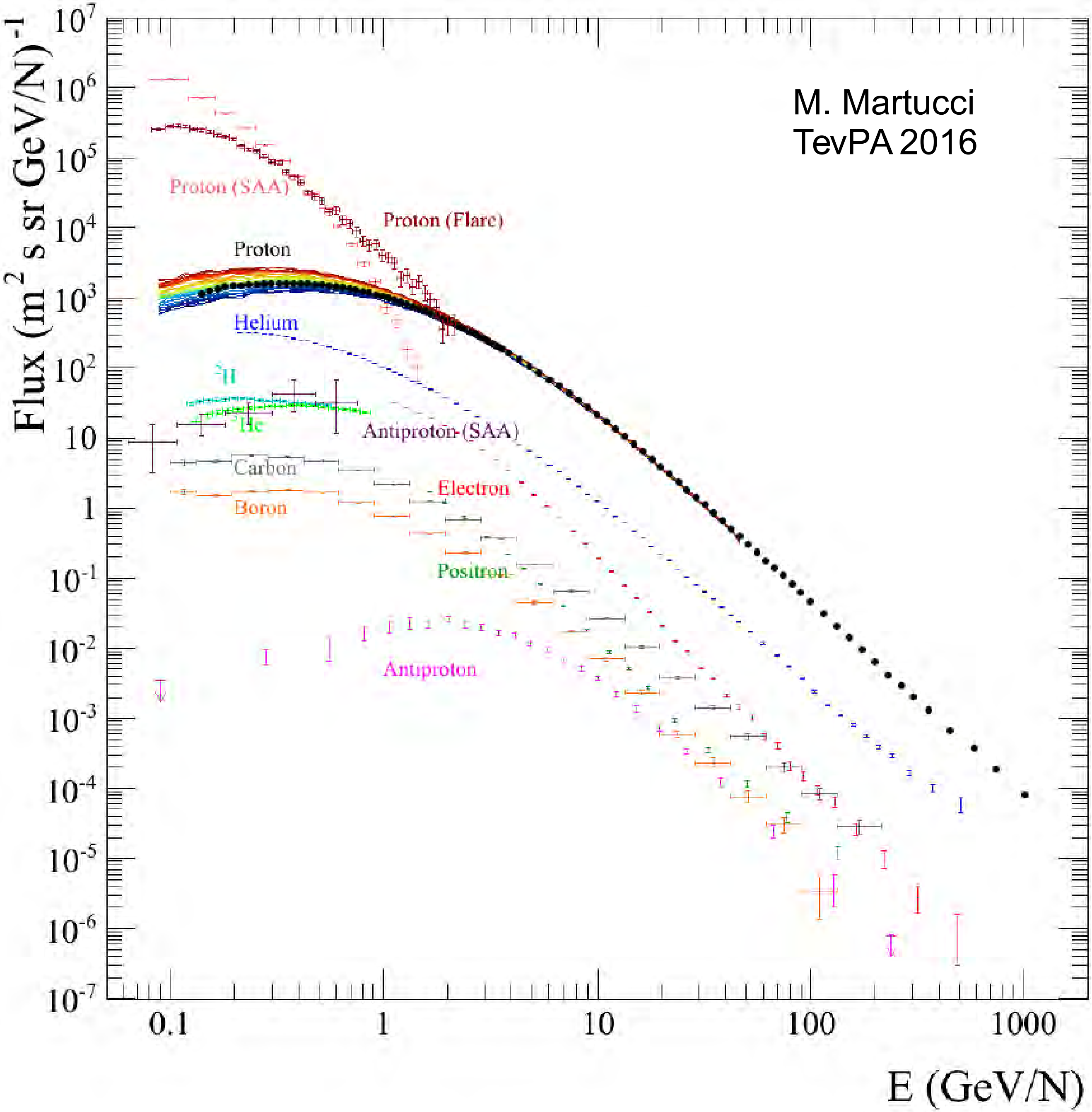
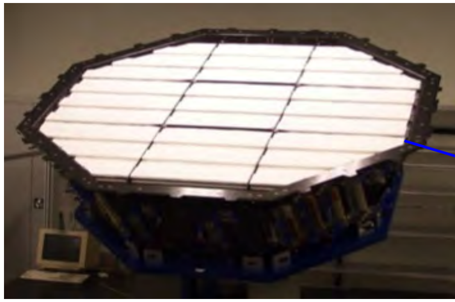


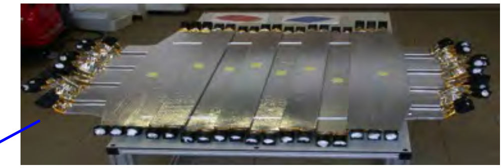
AMS-02: A TeV precision, multi-purpose spectrometer

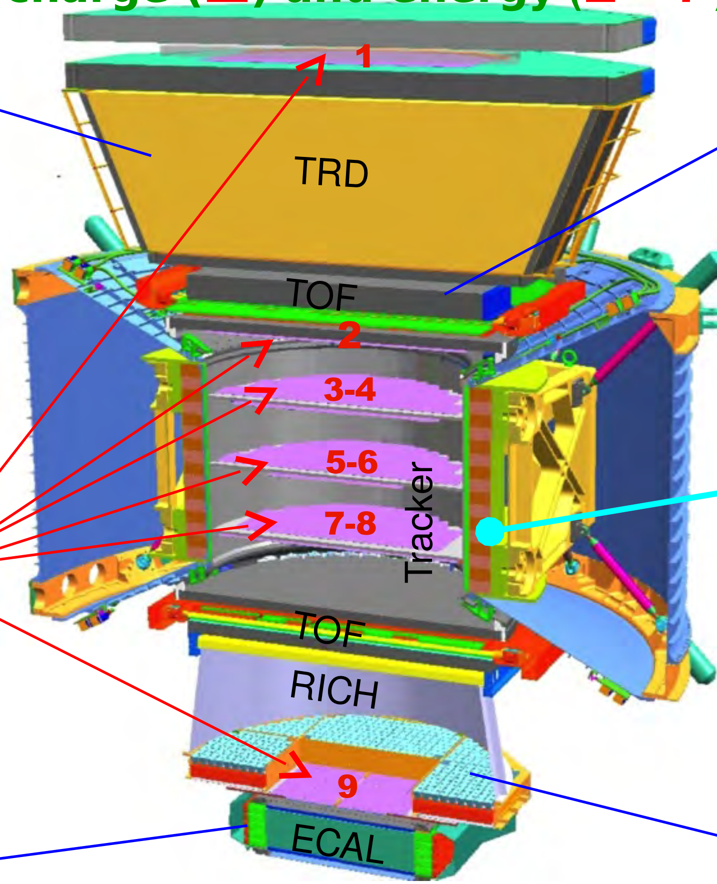
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TRD
Identify e+, e-

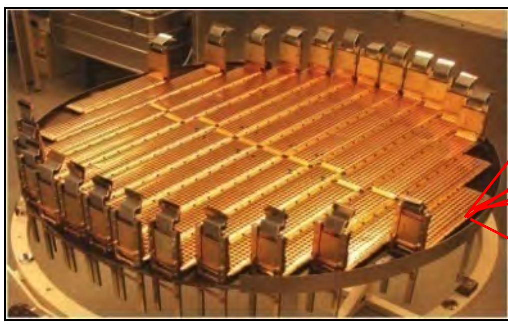


TOF
Z, E

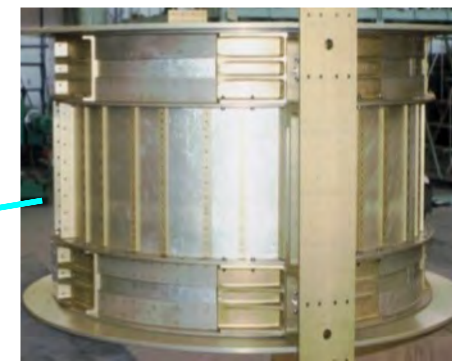




Silicon Tracker
Z, P



Magnet
±Z



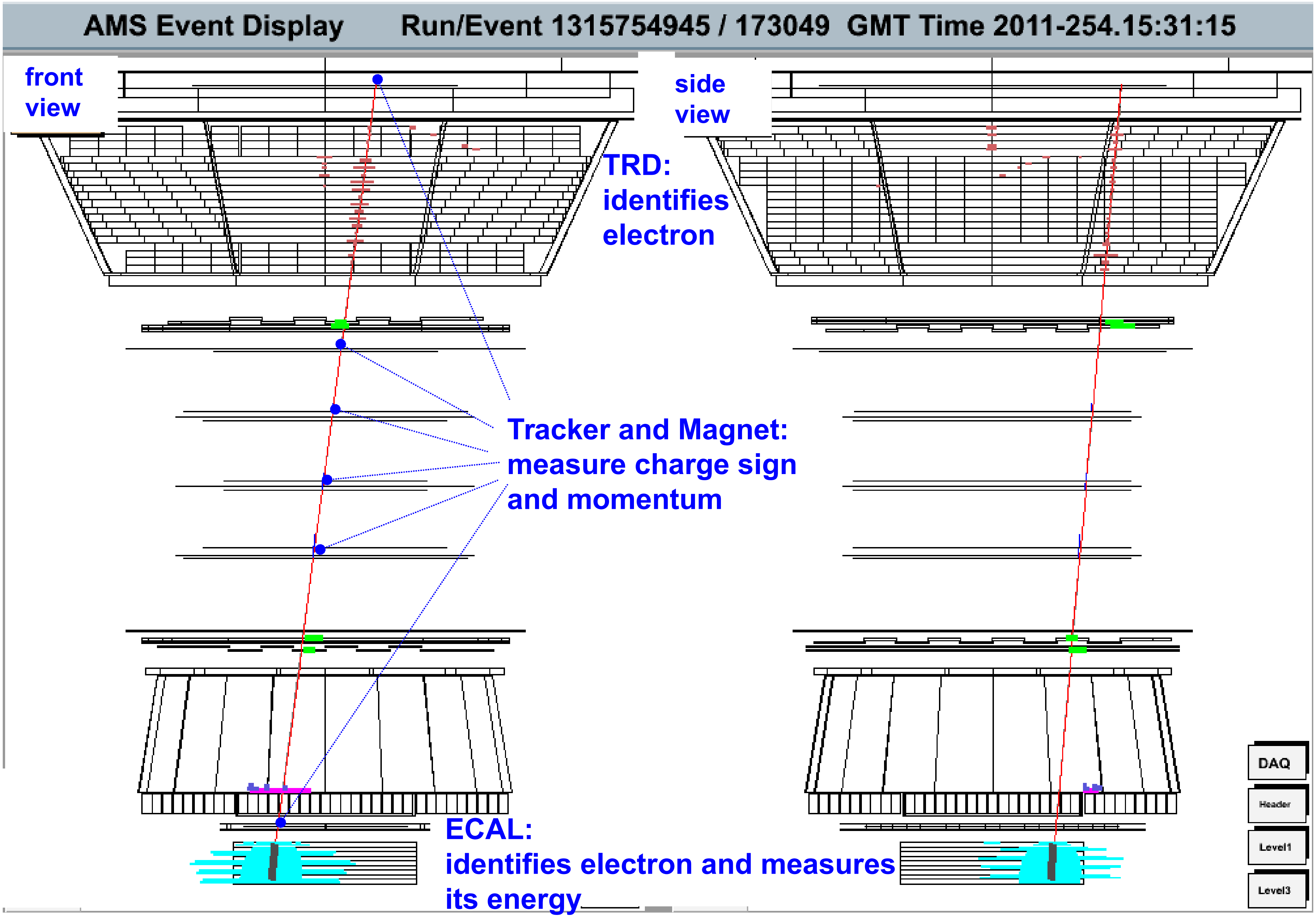
ECAL
E of e+, e-, γ

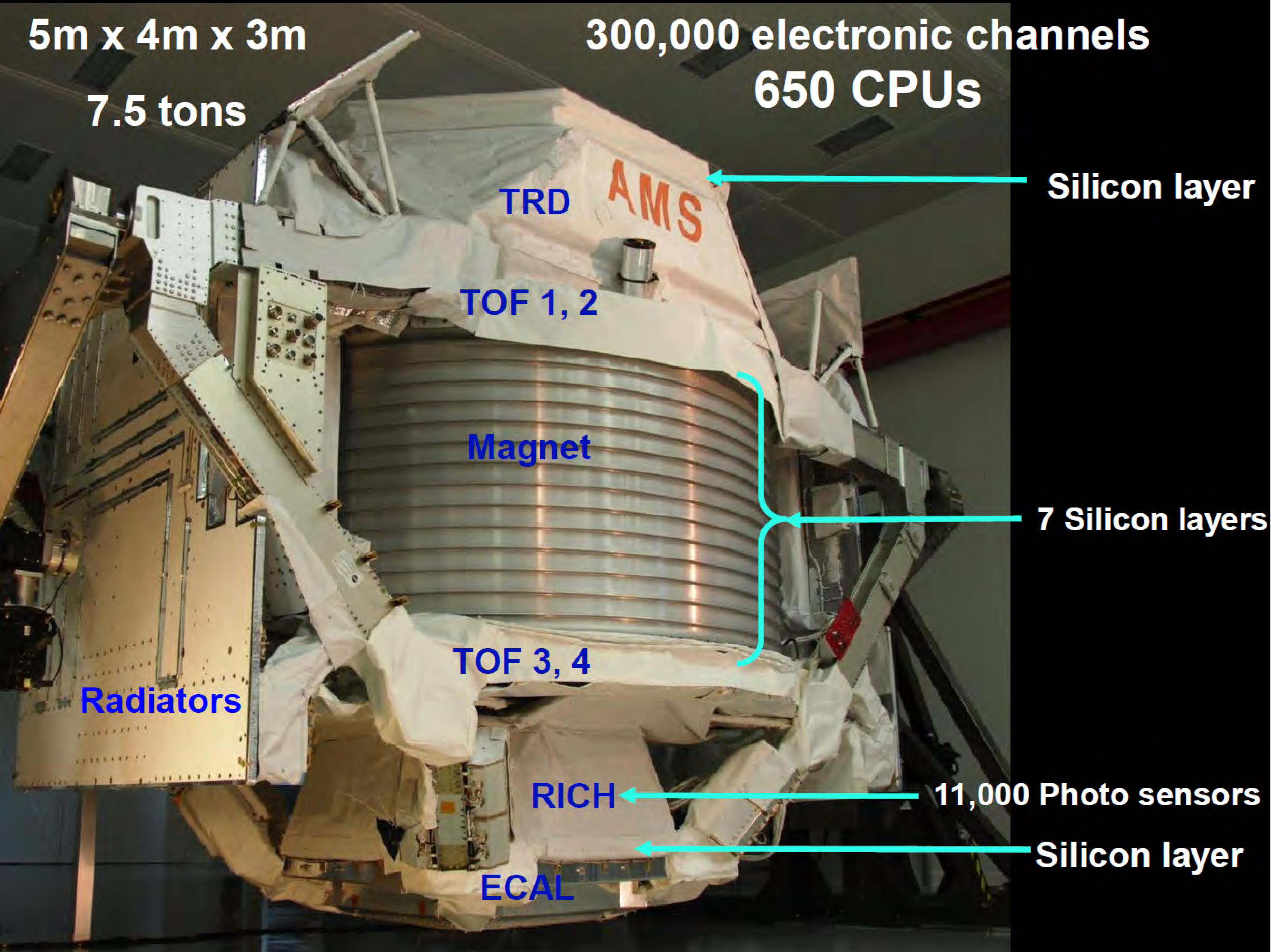
RICH
Z, E

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

1 out of more than 80,000,000,000 events:

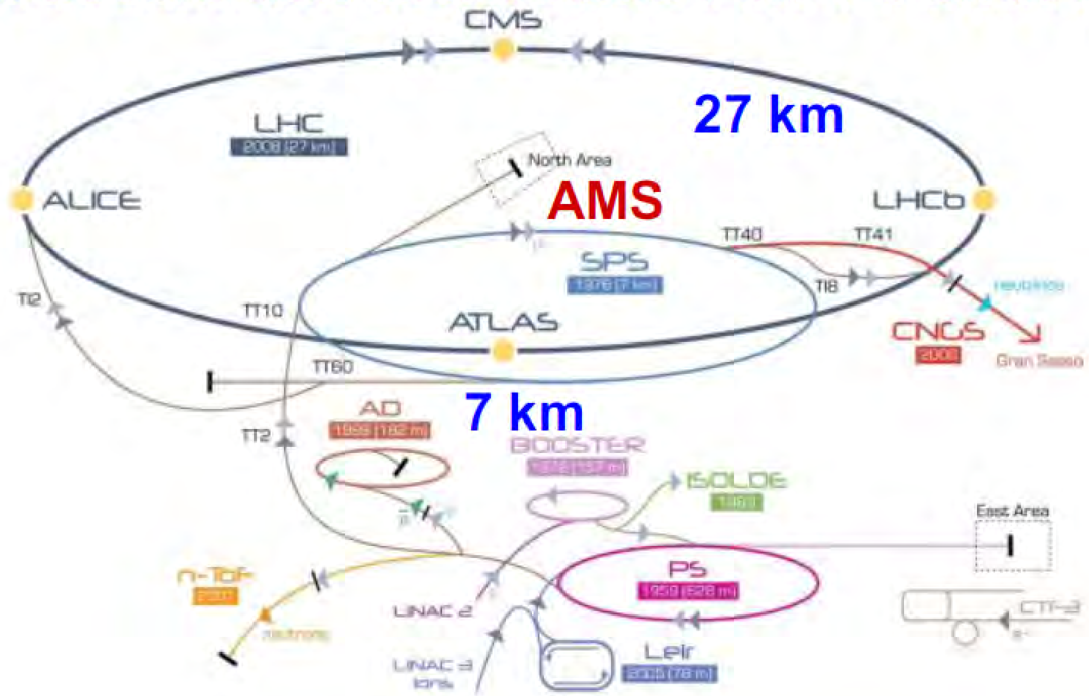
1.03 TeV electron





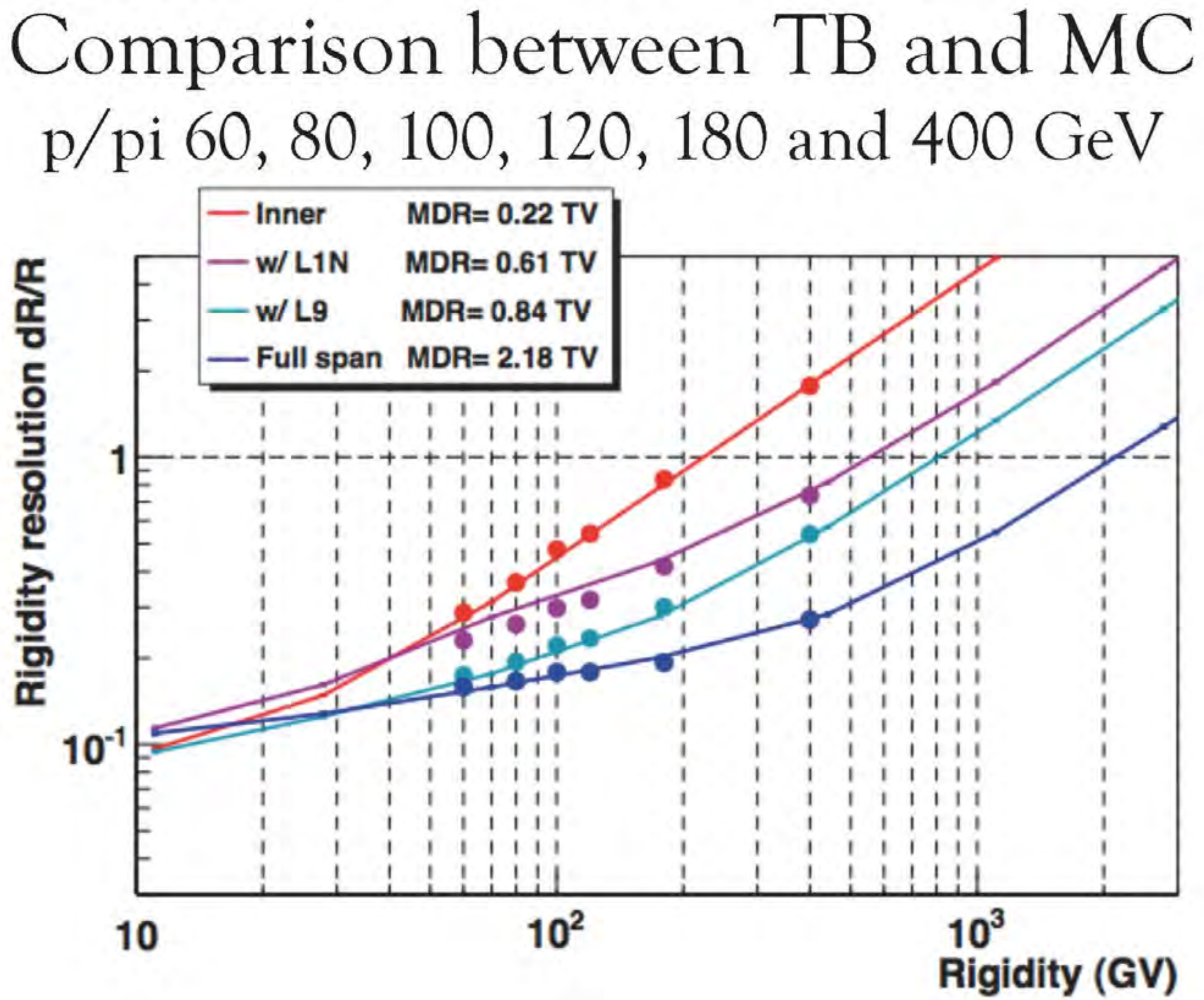
5m x 4m x 3m
7.5 tons
300,000 electronic channels
650 CPUs
AMS
TRD
Silicon layer
TOF 1, 2
Magnet
7 Silicon layers
TOF 3, 4
Radiators
RICH
11,000 Photo sensors
Silicon layer
ECAL

Tests at CERN
AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010

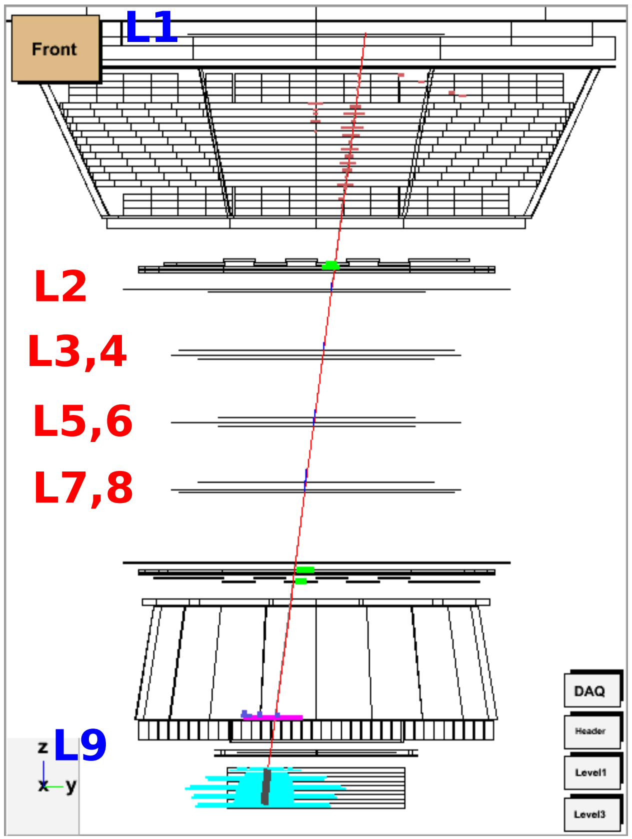


Particle	Momentum (GeV/c)	Positions
Protons	180, 400	1,650
Electrons	100, 120, 180, 290	7 each
Positrons	10, 20, 60, 80, 120, 180	7 each
Pions	20, 60, 80, 100, 120, 180	7 each

Tracker: Rigidity resolution

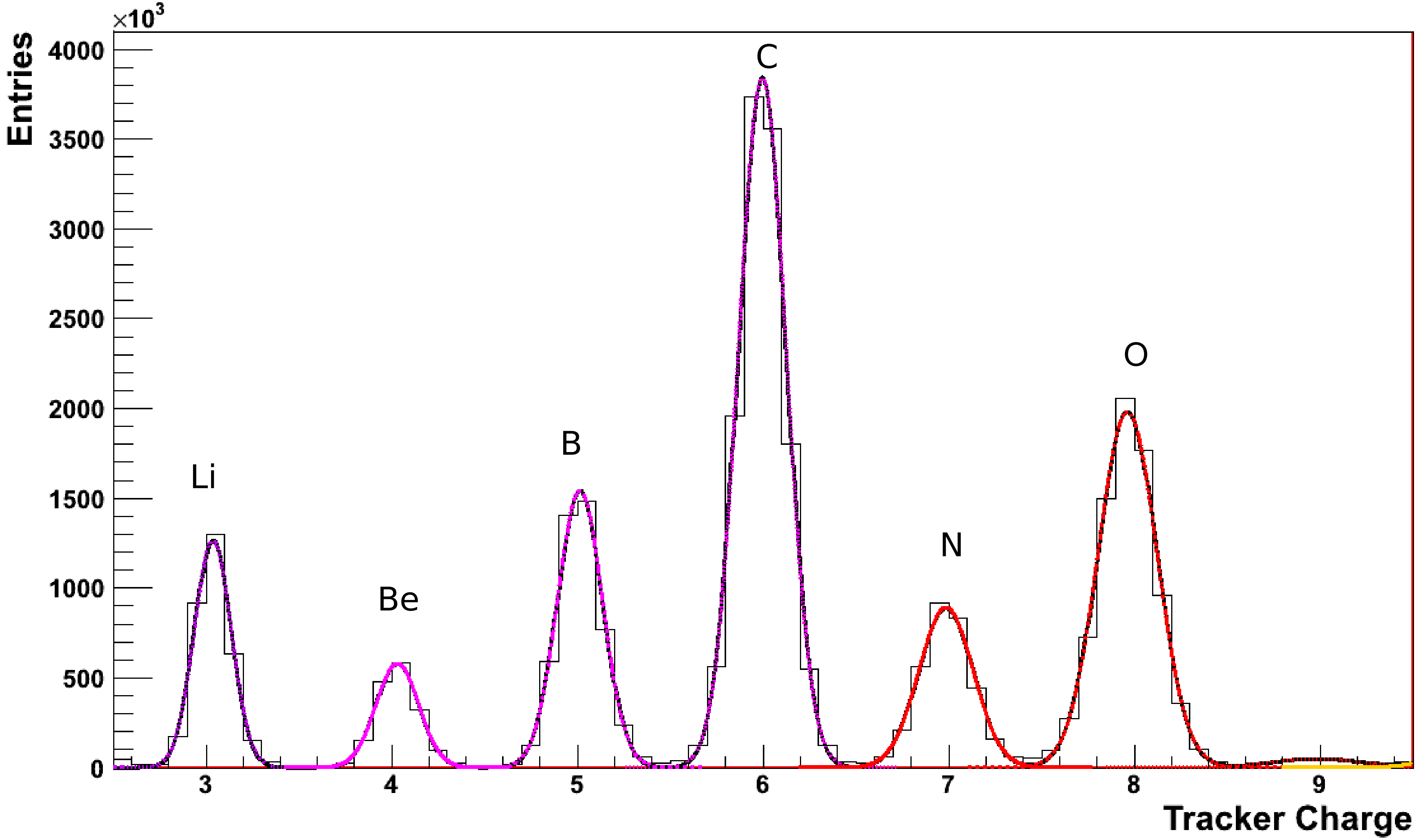


CERN beamtest data



Rigidity = momentum / charge

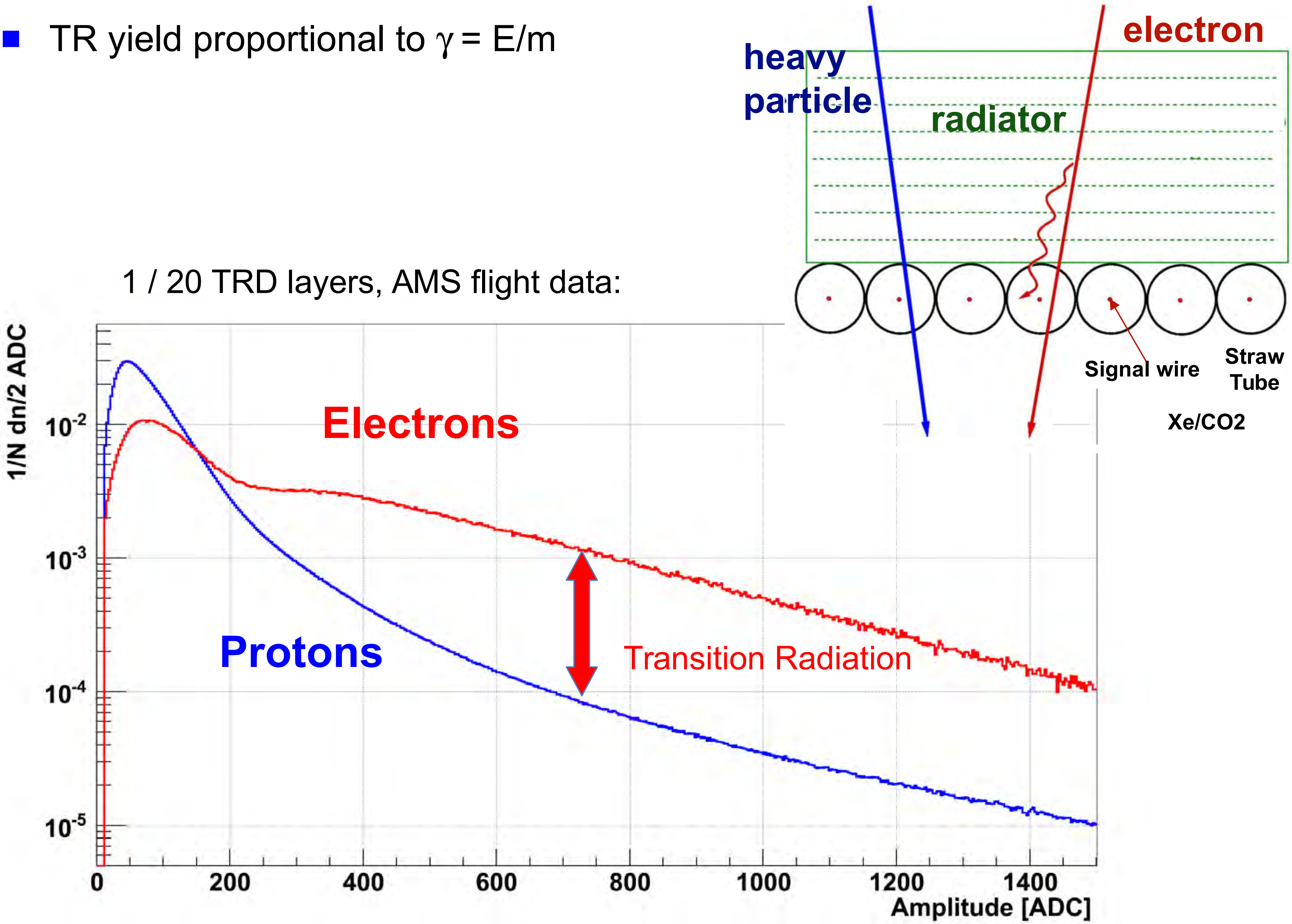
Tracker: Charge measurement



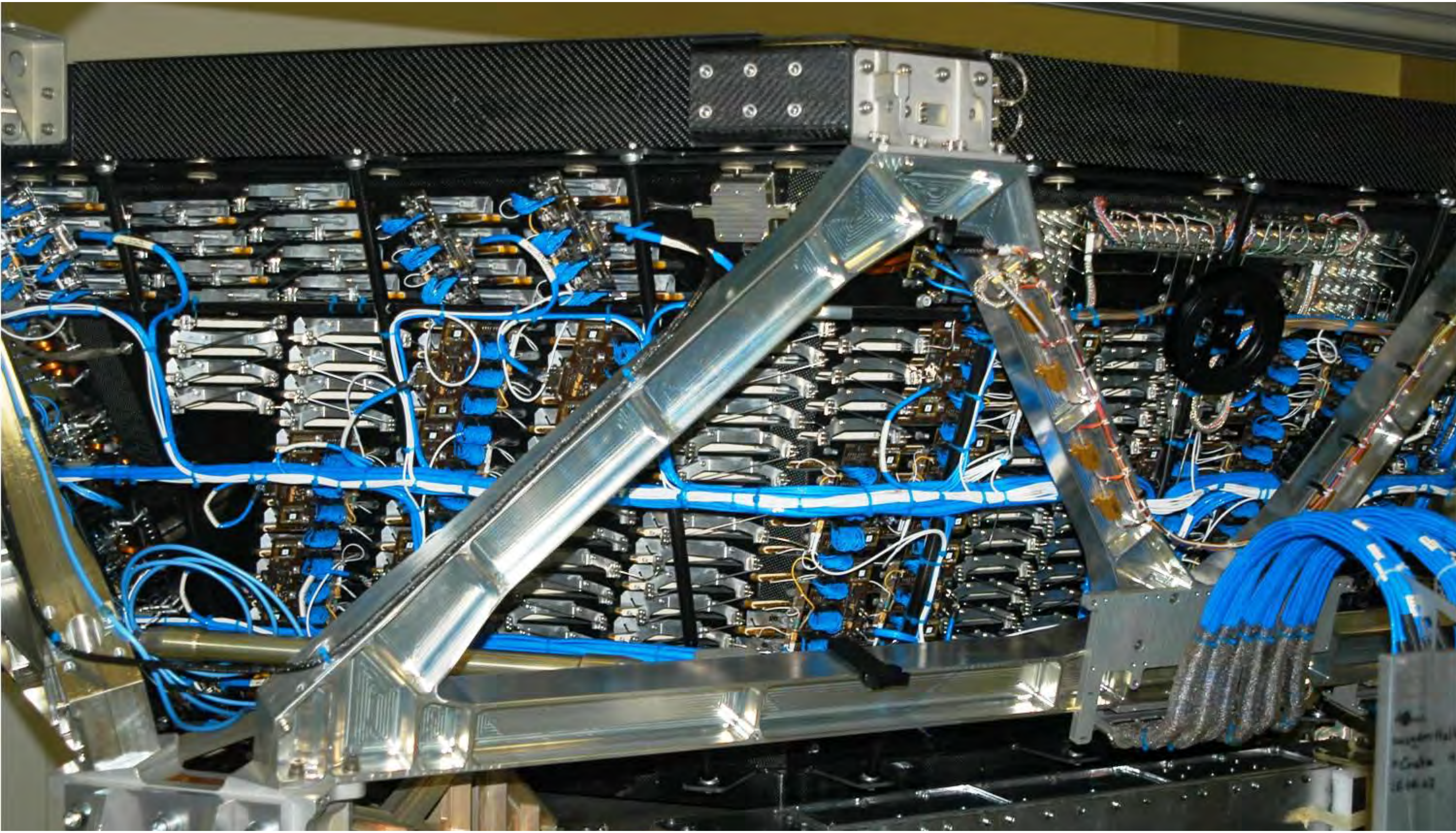
TRD: Transition radiation detector

- TR yield proportional to $\gamma = E/m$

1 / 20 TRD layers, AMS flight data:



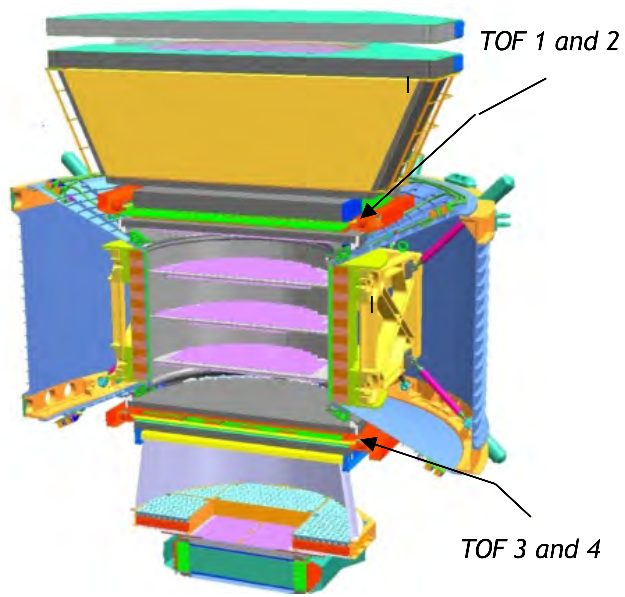
AMS-02 Transition Radiation Detector

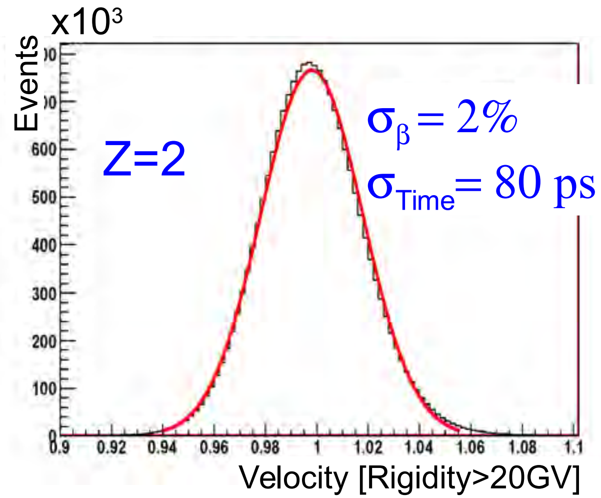


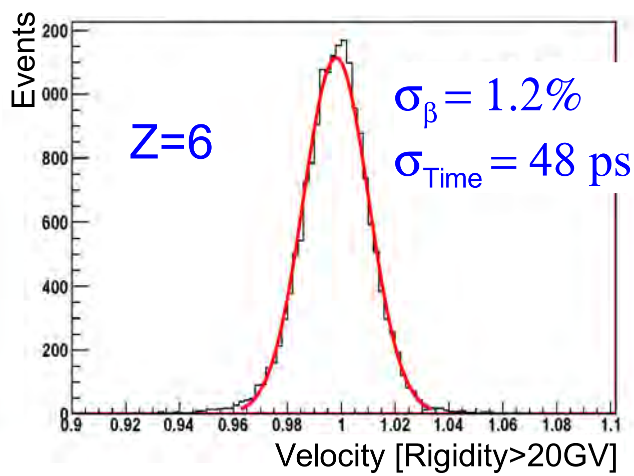
Misidentifies only 1 in 10000 protons as a positron.

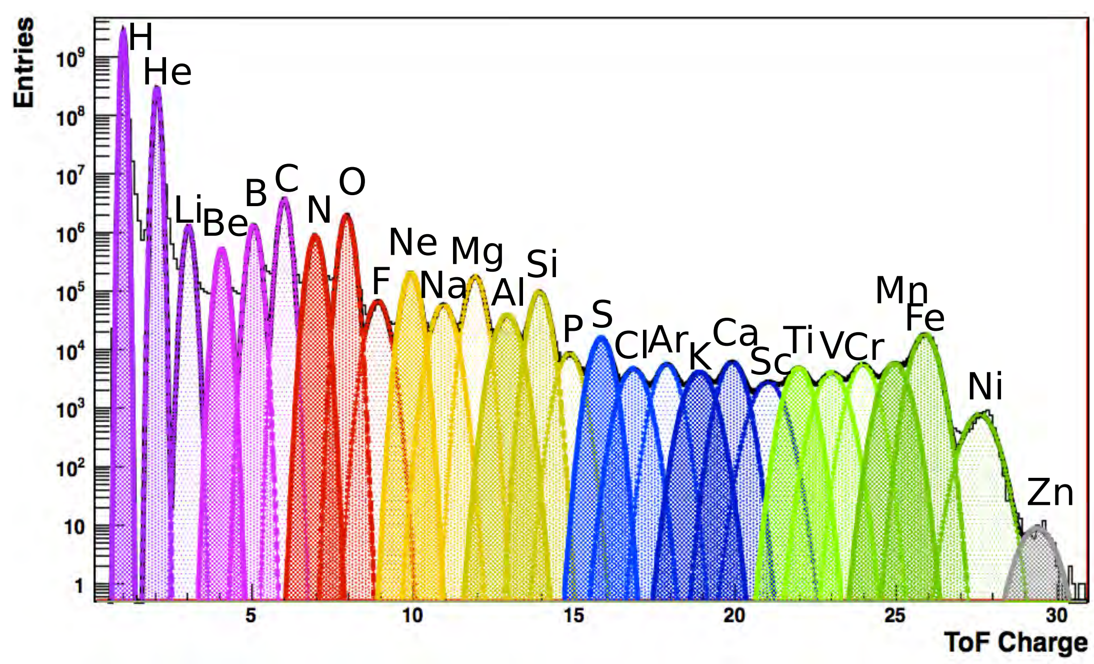
TOF: Time-of-Flight system

- Measures velocity and charge:







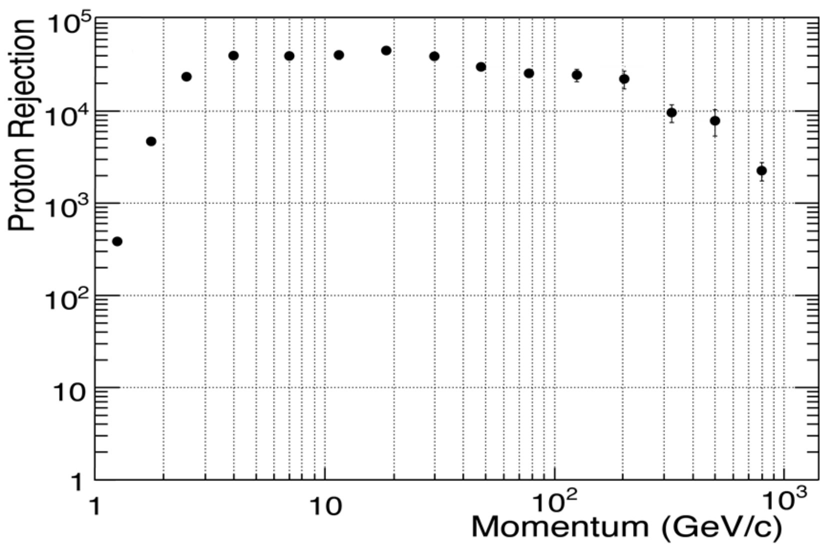


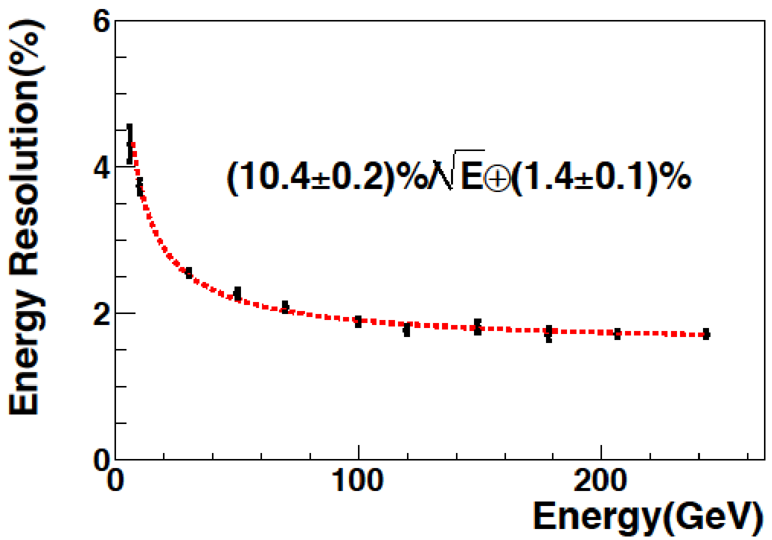
ECAL: Electromagnetic calorimeter

Precision, 3-D measurement of the directions and energies of light rays and electrons up to 1 TeV.

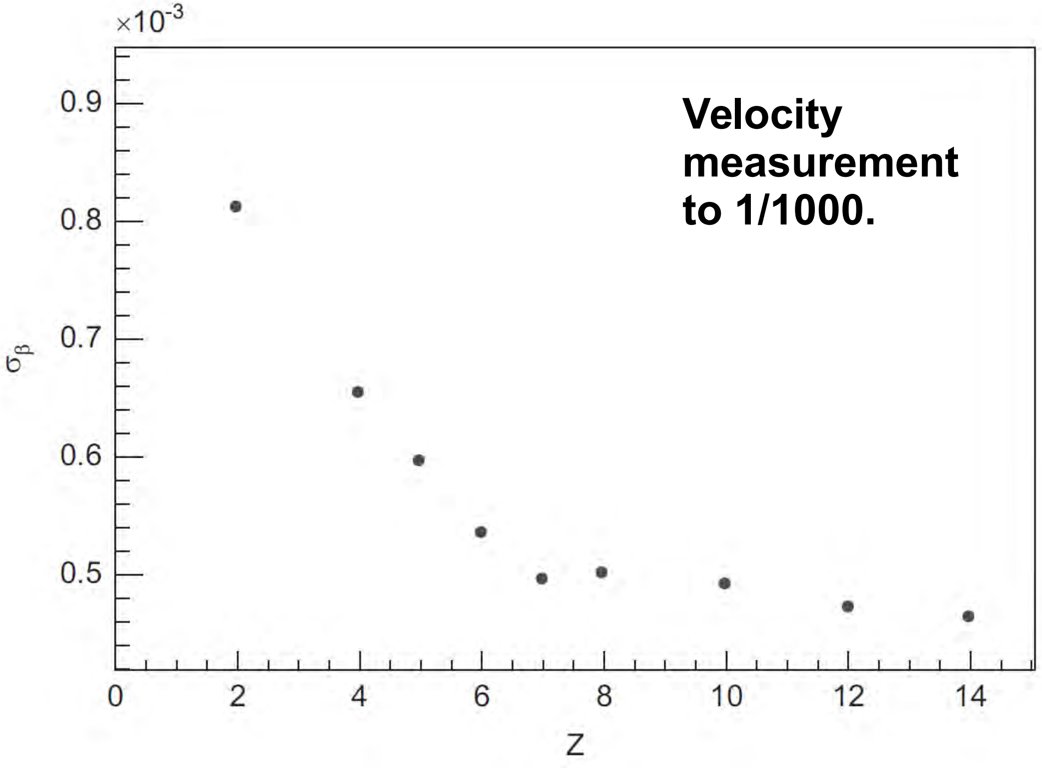
50,000 fibers, $\phi = 1$ mm distributed uniformly inside 600 kg of lead

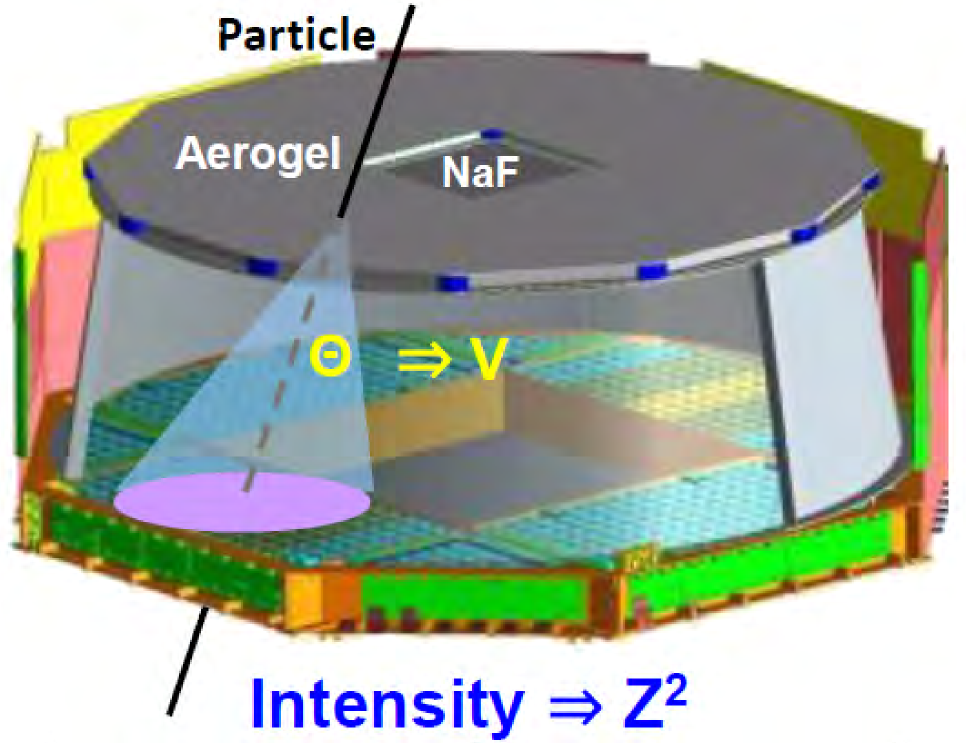
Total: 17 X_0

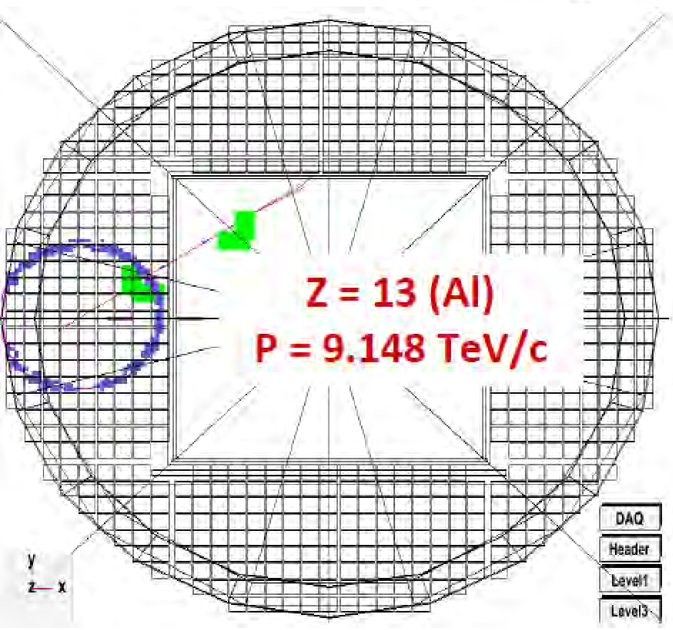


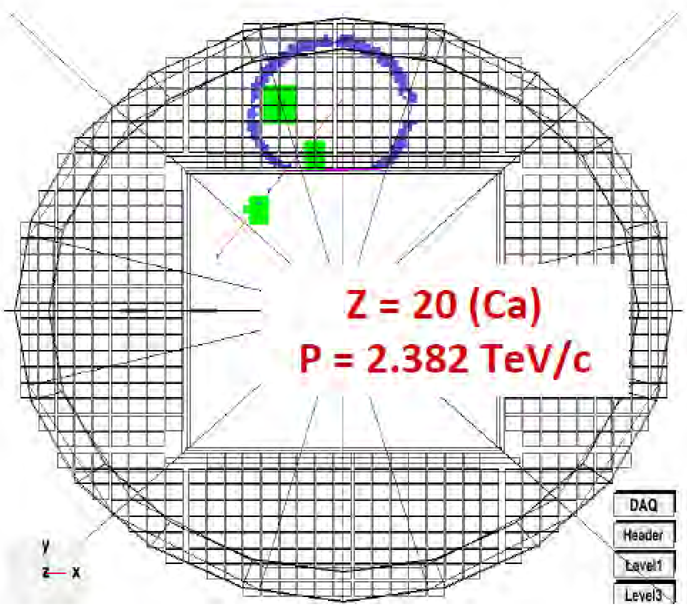


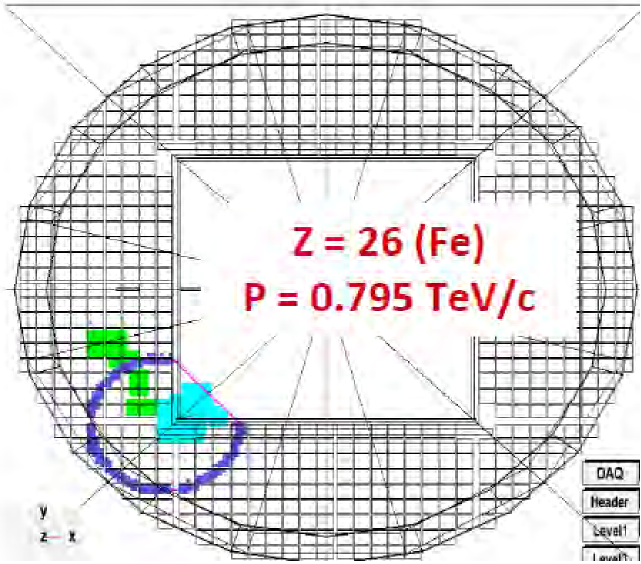
RICH: Ring-imaging Cherenkov counter



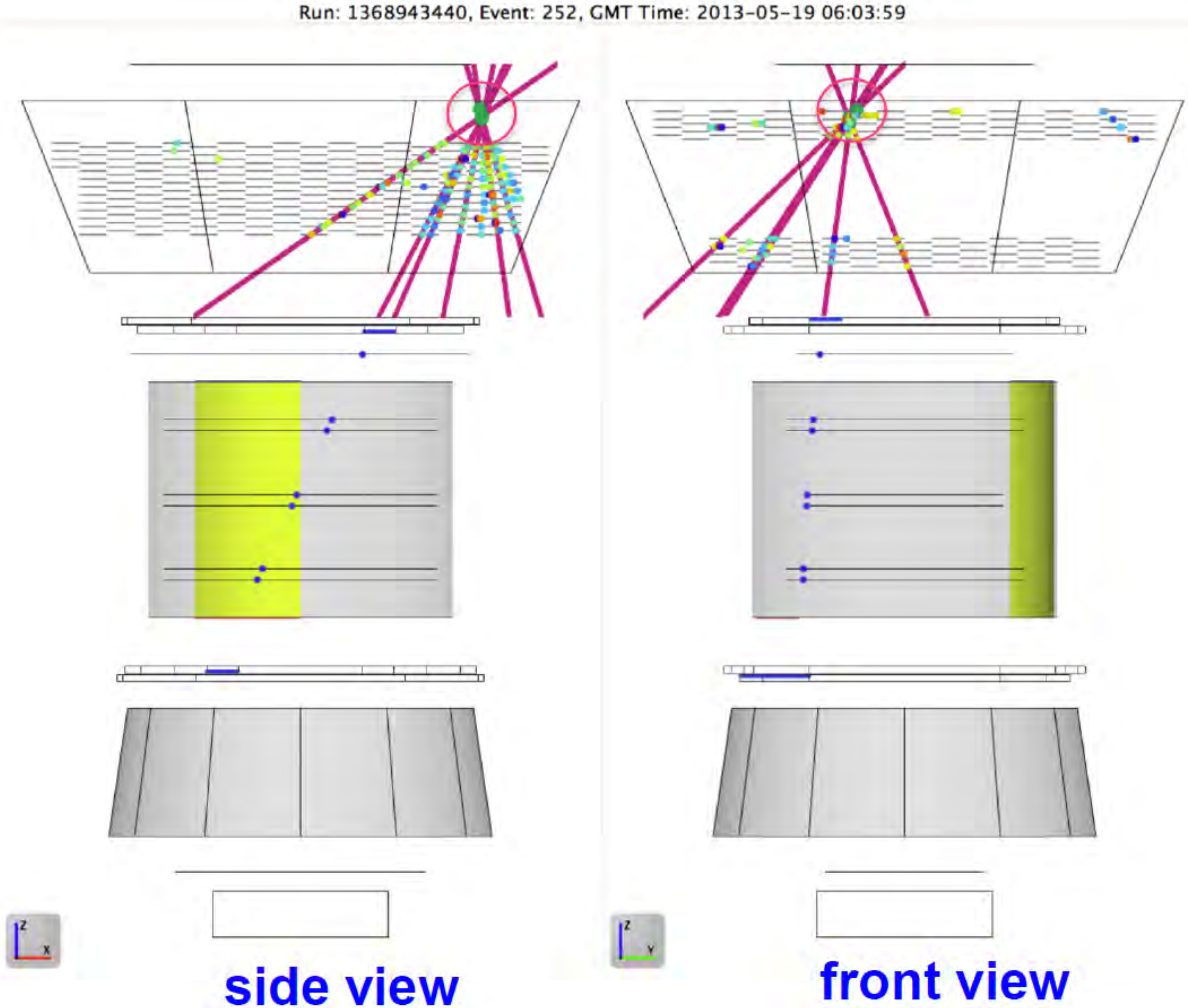






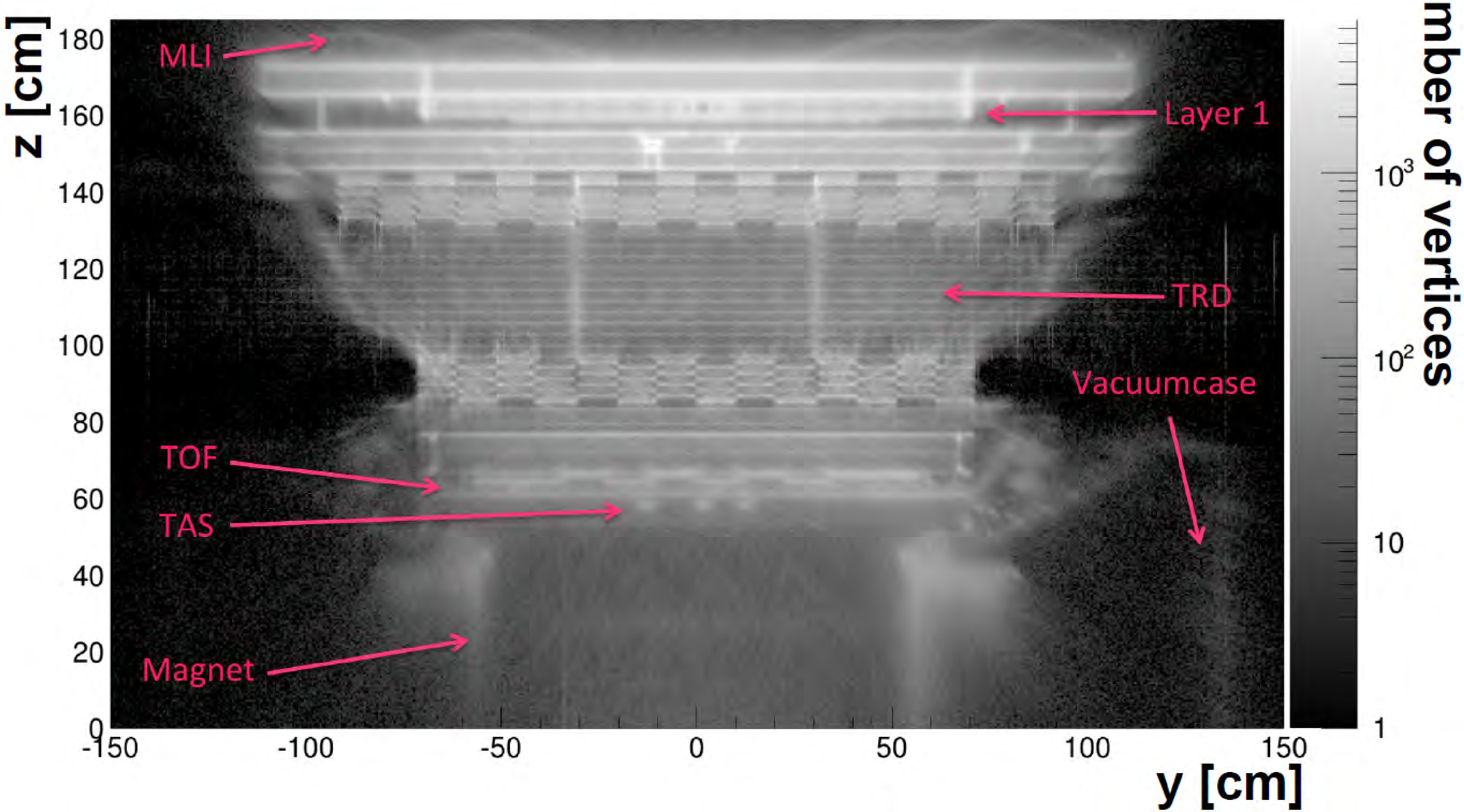


Use rare nuclear interaction events to optimize the material description in the Monte Carlo

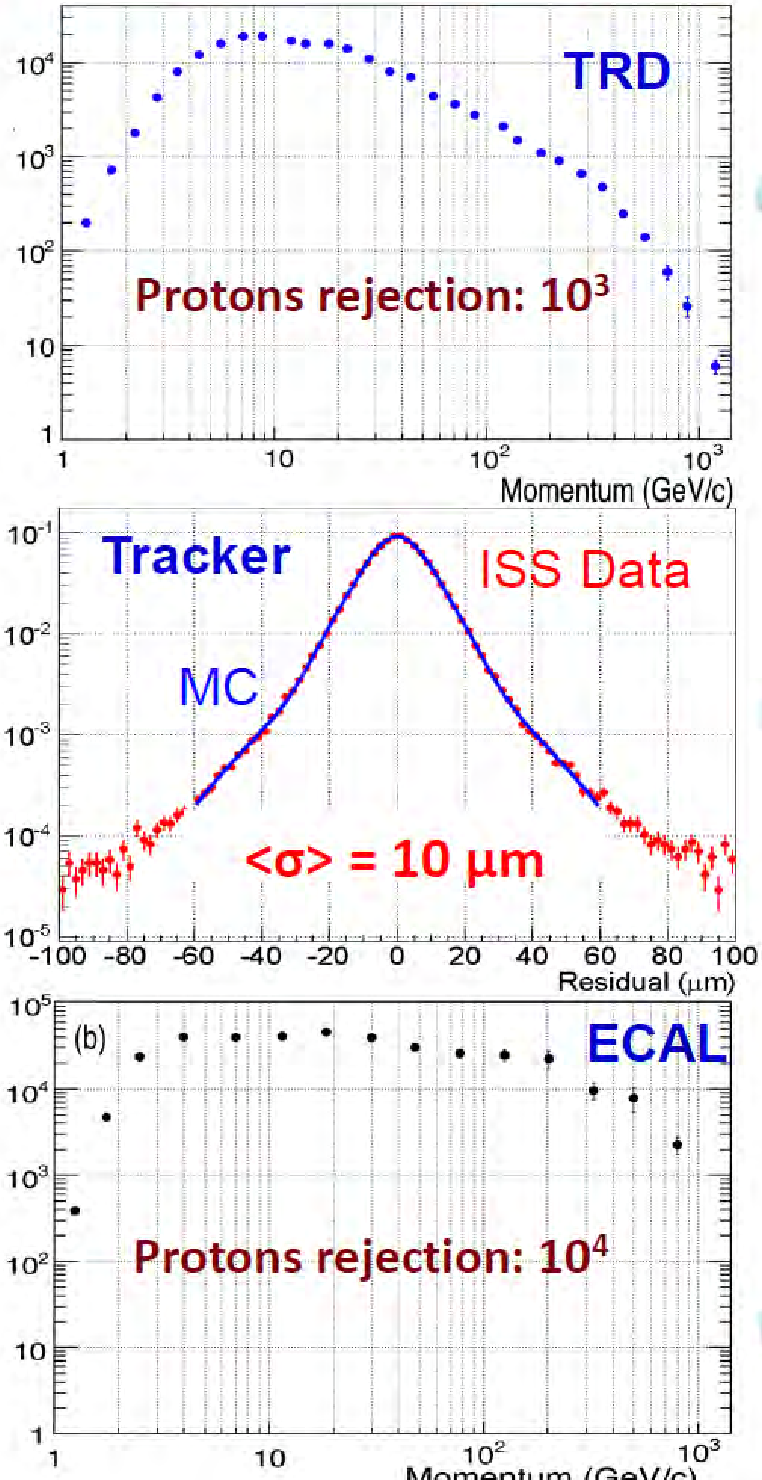


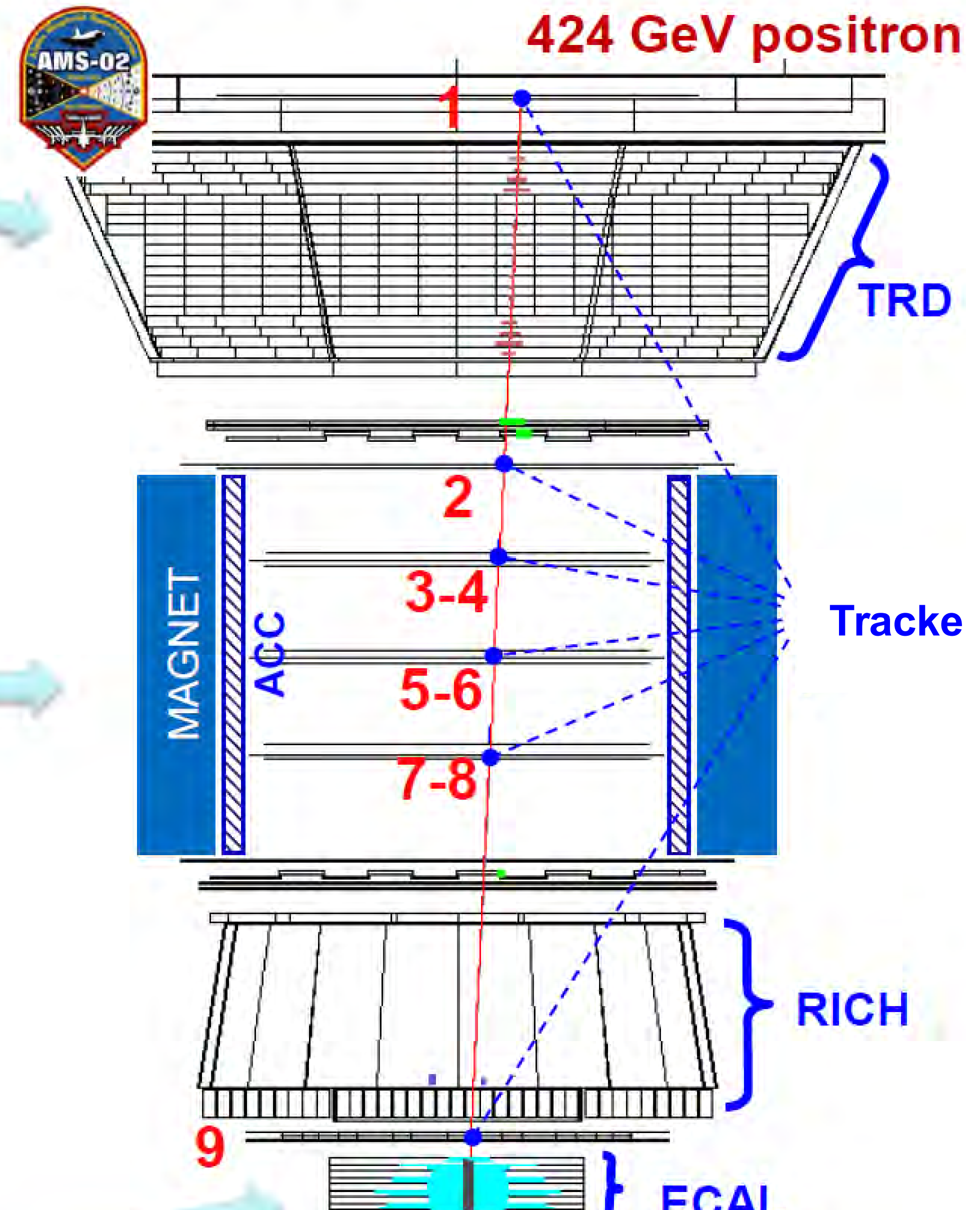
X-Ray of AMS on the ISS from rare nuclear interaction events

The gray scale is proportional to the number of vertices found.



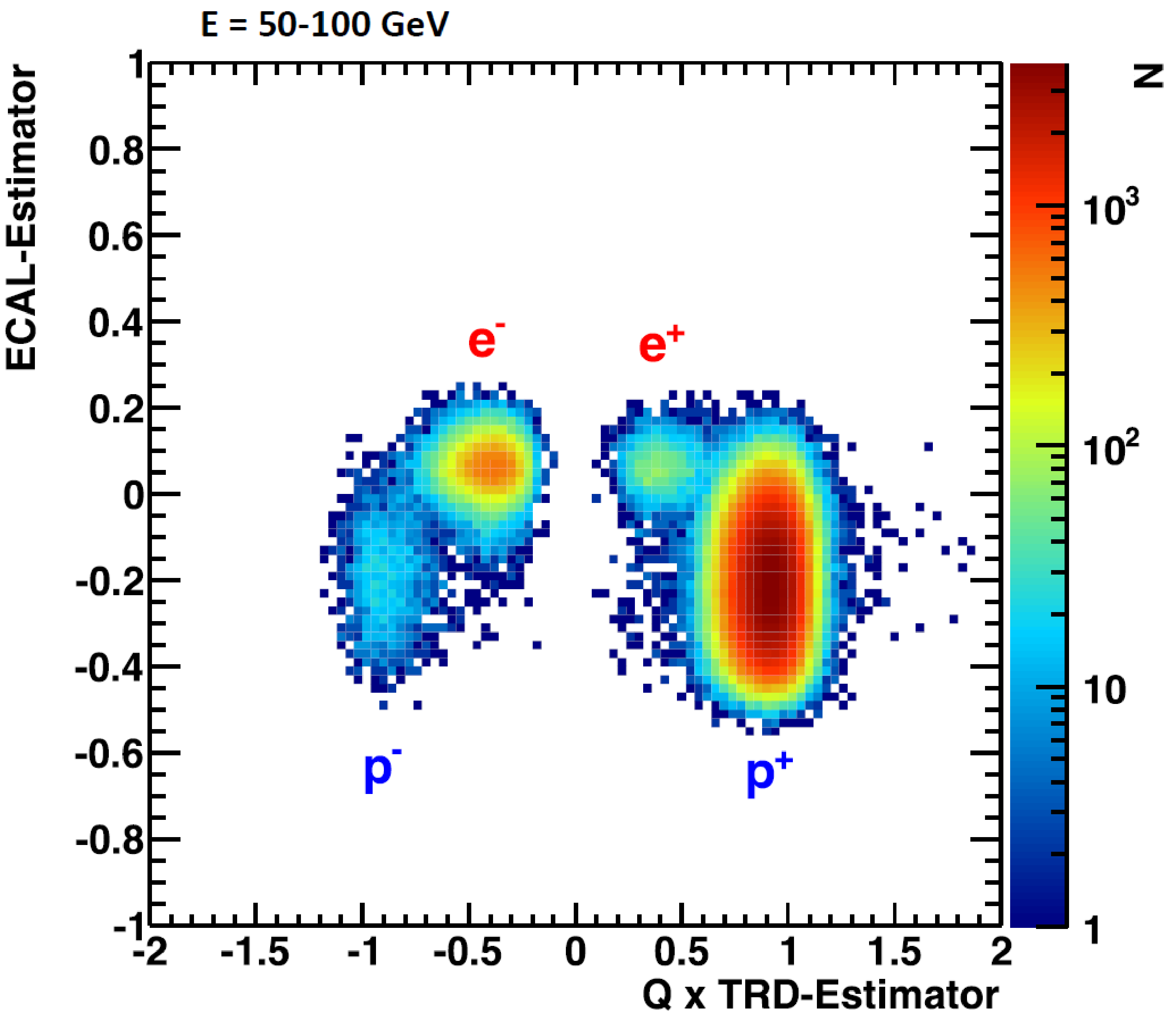
Positron fraction analysis: update 5 years data ⇔ ~85 10^9 cosmic rays



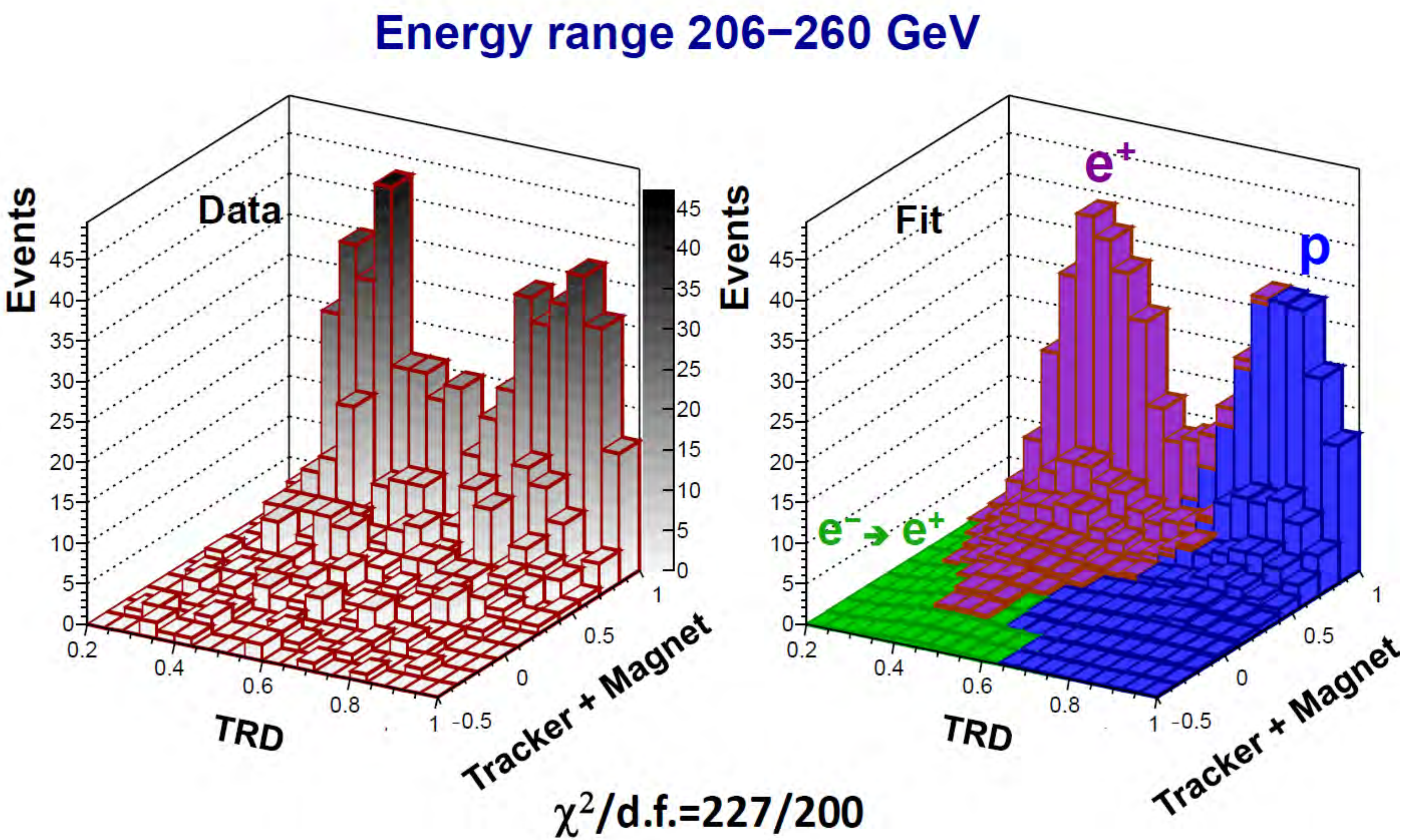


20 million of $e^{\pm}$ events are selected in the energy range 0.5–700 GeV

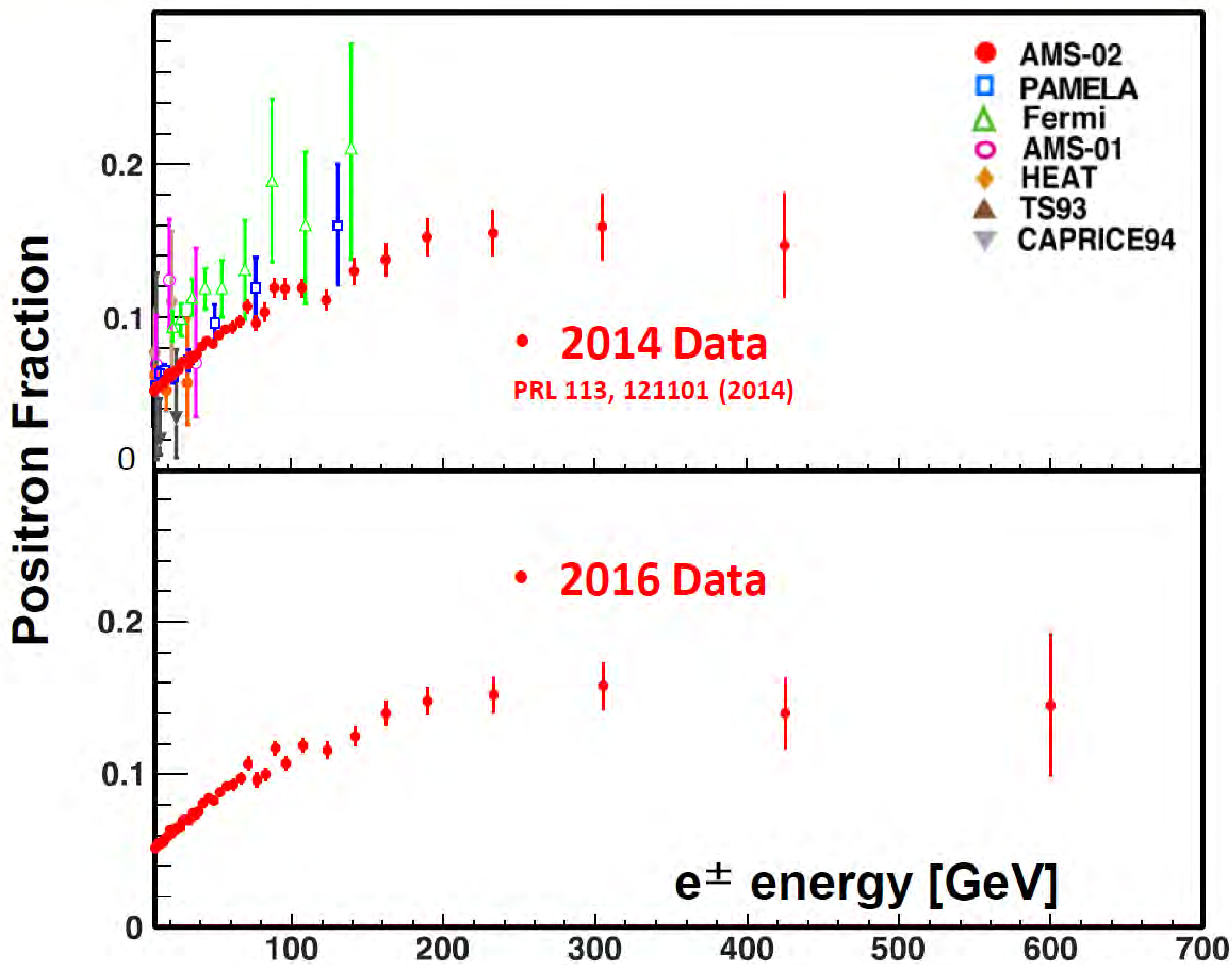
In our data sample we identify four components using an ECAL Estimator and a TRD Estimator.

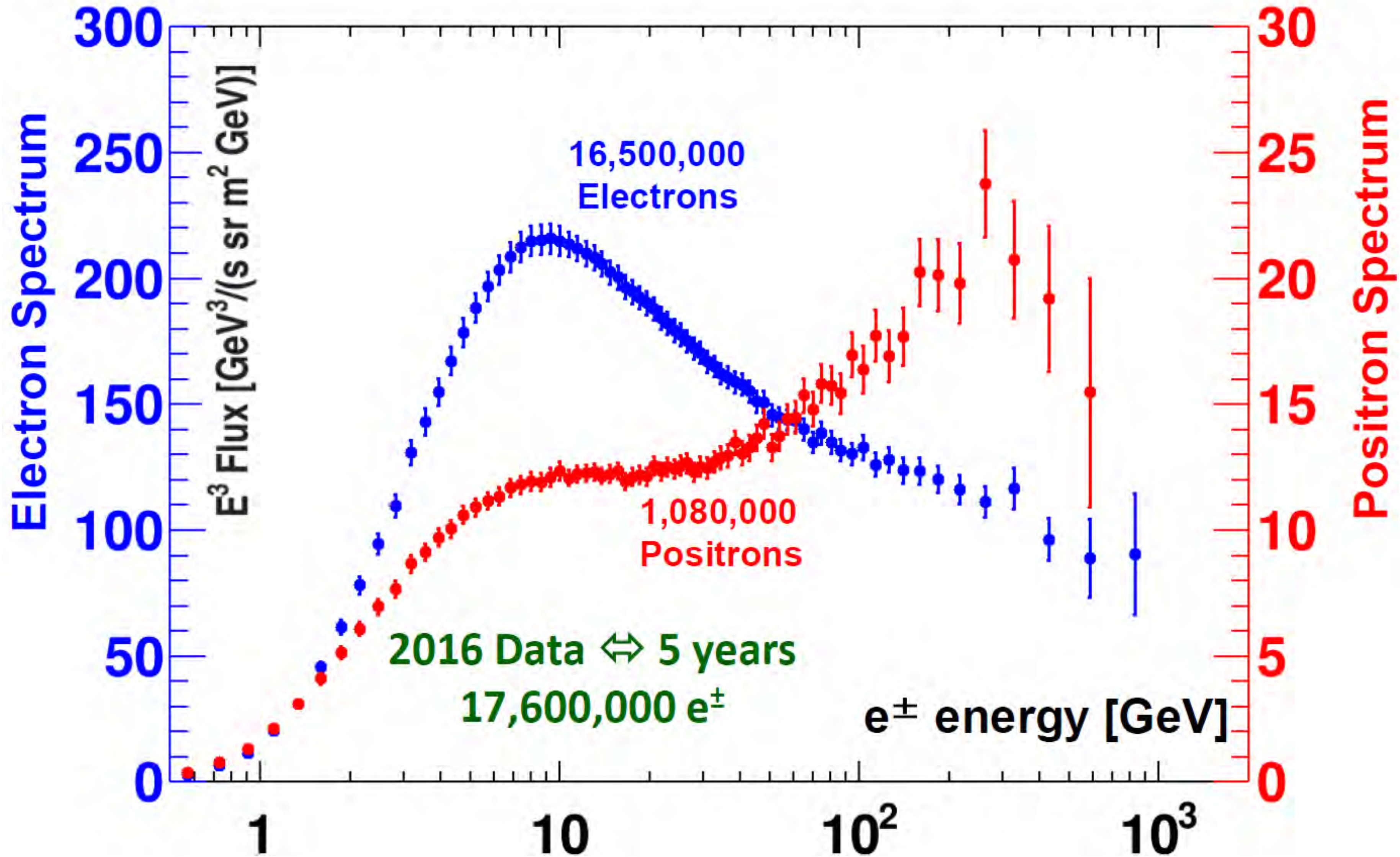


TRD Estimator shows clear separation between positrons and protons with a small charge confusion background



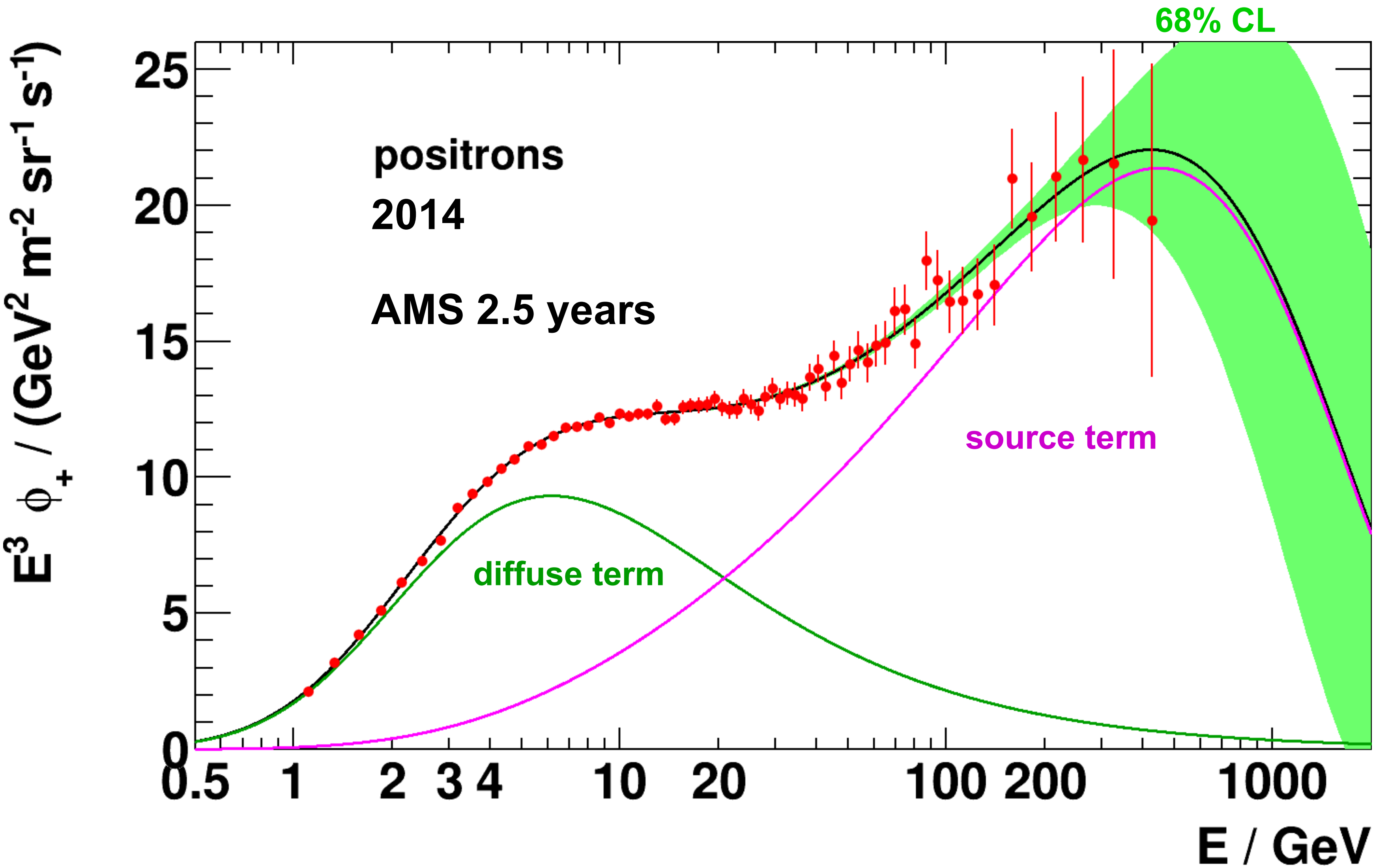
Compared to our publication in 2014 the energy range has been increased up to 700 GeV and the statistics has been increased from11 Million e± to 20 Million e±.





- Electrons and positrons have a different origin.
- A „Standard Model“ to describe all our data does not exist.
- Therefore we have to use simple phenomenological models.

Simple phenomenological model for AMS electrons, positrons



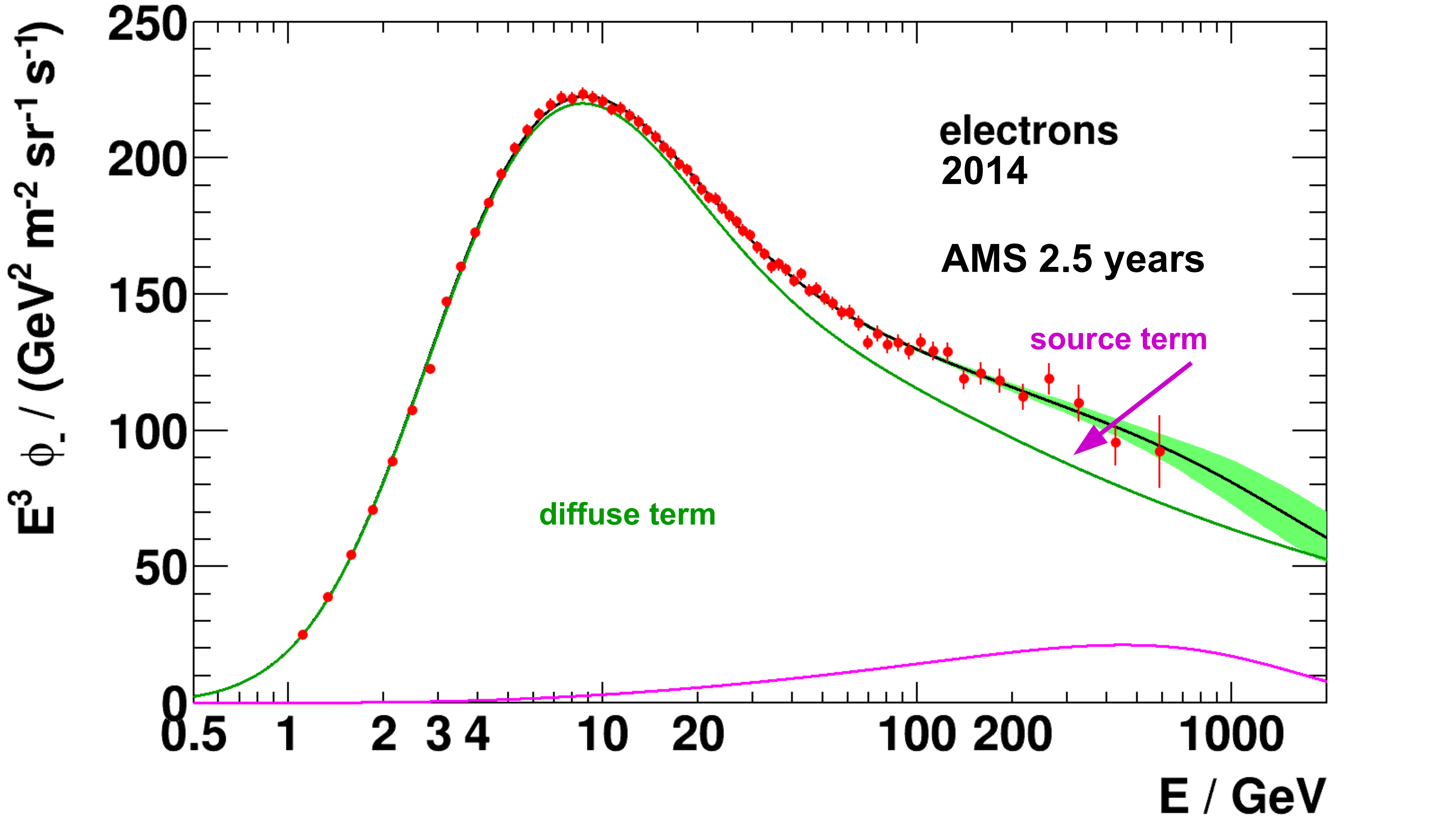
$$\Phi_+(E) = (E^2/\hat{E}^2)(C_+(\hat{E}/E_0)^{-\gamma_+} + C_S(\hat{E}/E_1)^{-\gamma_S}\exp(-\lambda_S\hat{E}))$$

$$\Phi_-(E) = (E^2/\hat{E}^2)(C_-(\hat{E}/E_0)^{-\gamma_-}(1+(\hat{E}/E_B)^{\Delta\gamma_-/b})^b + C_S(\hat{E}/E_1)^{-\gamma_S}\exp(-\lambda_S\hat{E}))$$

solar modulation: $\hat{E} = E + \varphi_\pm$

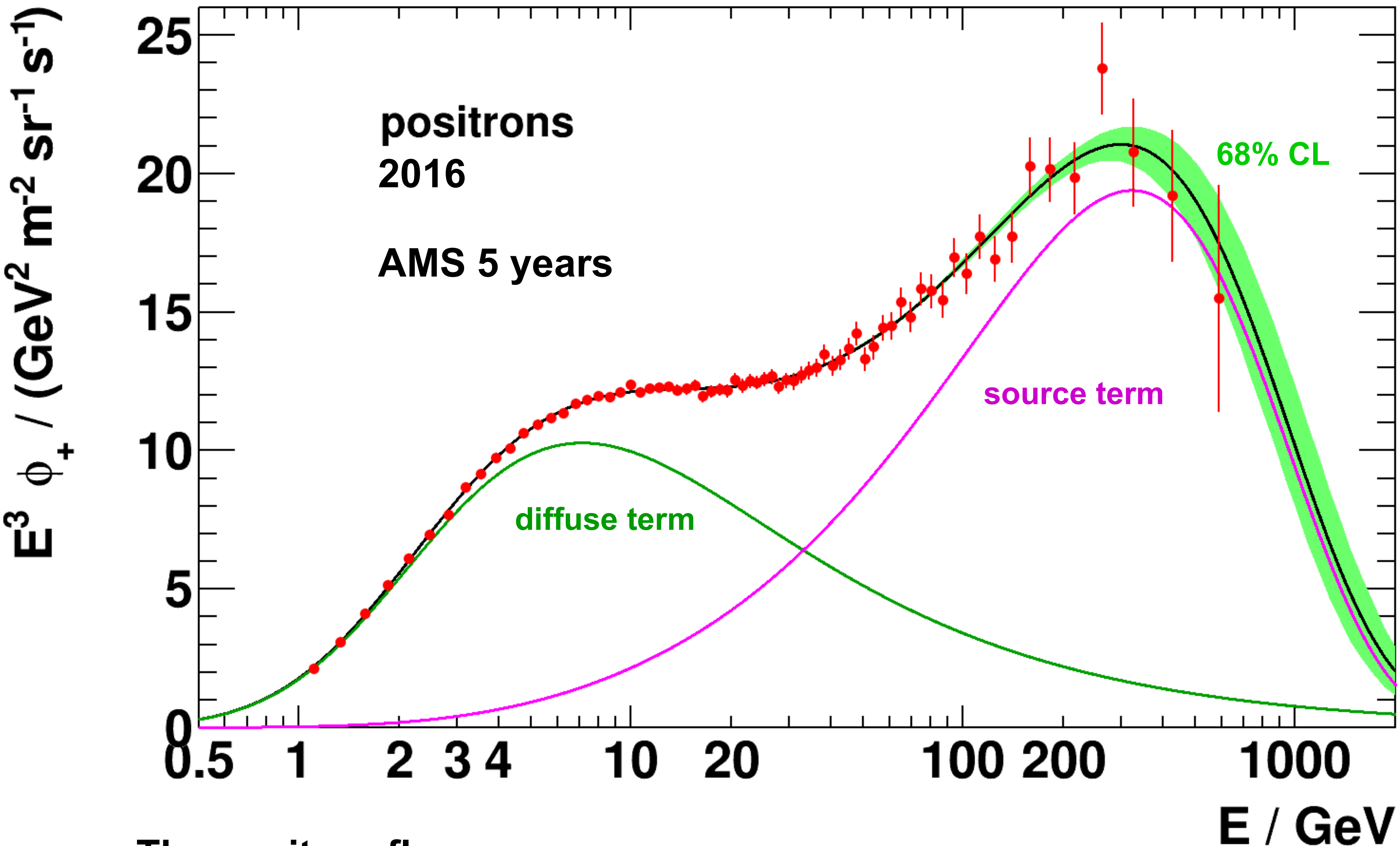
“diffuse” term

common “source” term



The electron flux

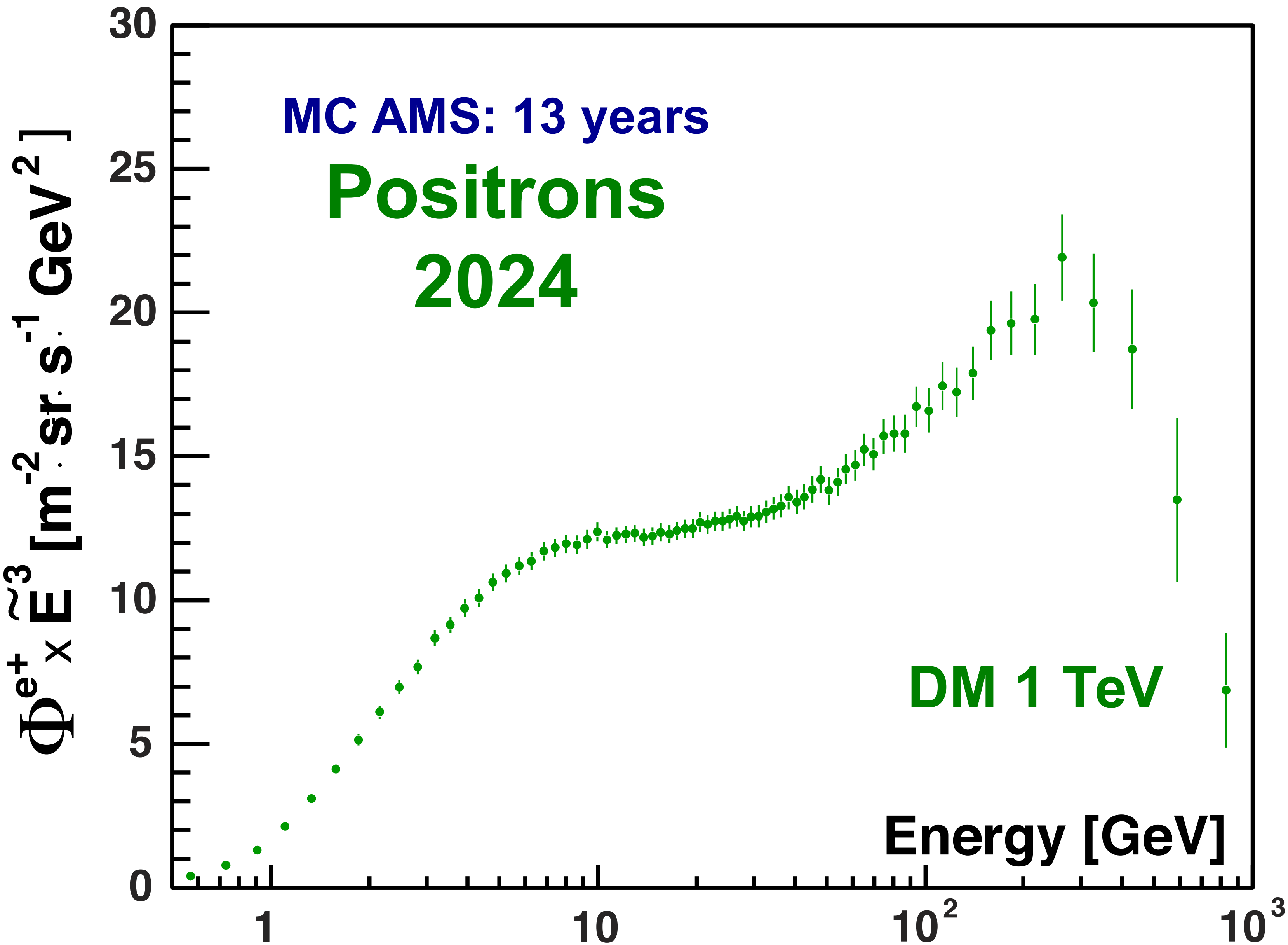
- has no sharp structures and is dominated by the diffuse term,
- is consistent with a charge-symmetric source term.



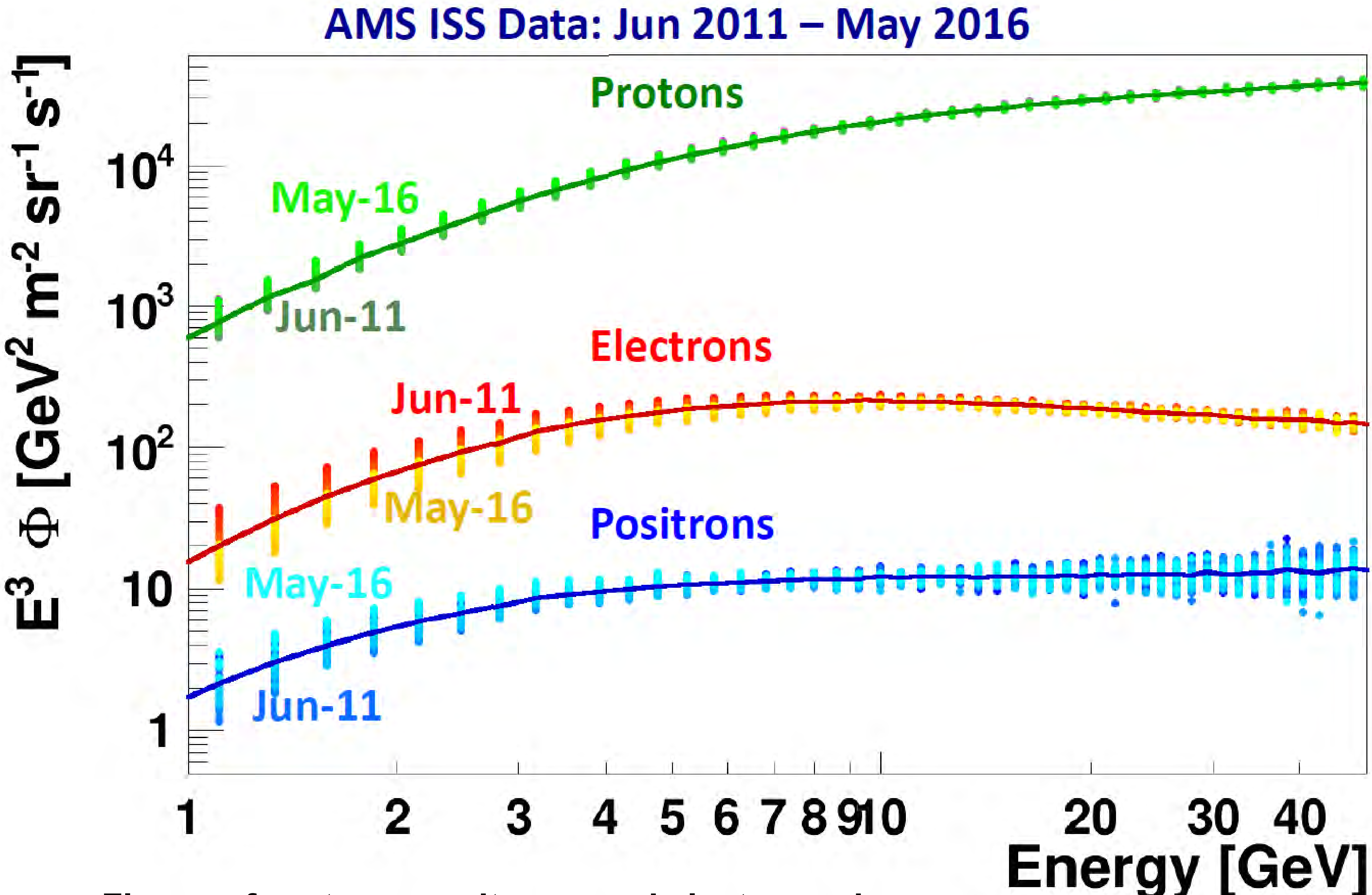
The positron flux

- has no sharp structures,
- is dominated by the source term.

The significance for the cutoff is 3σ with the data up to 2016.

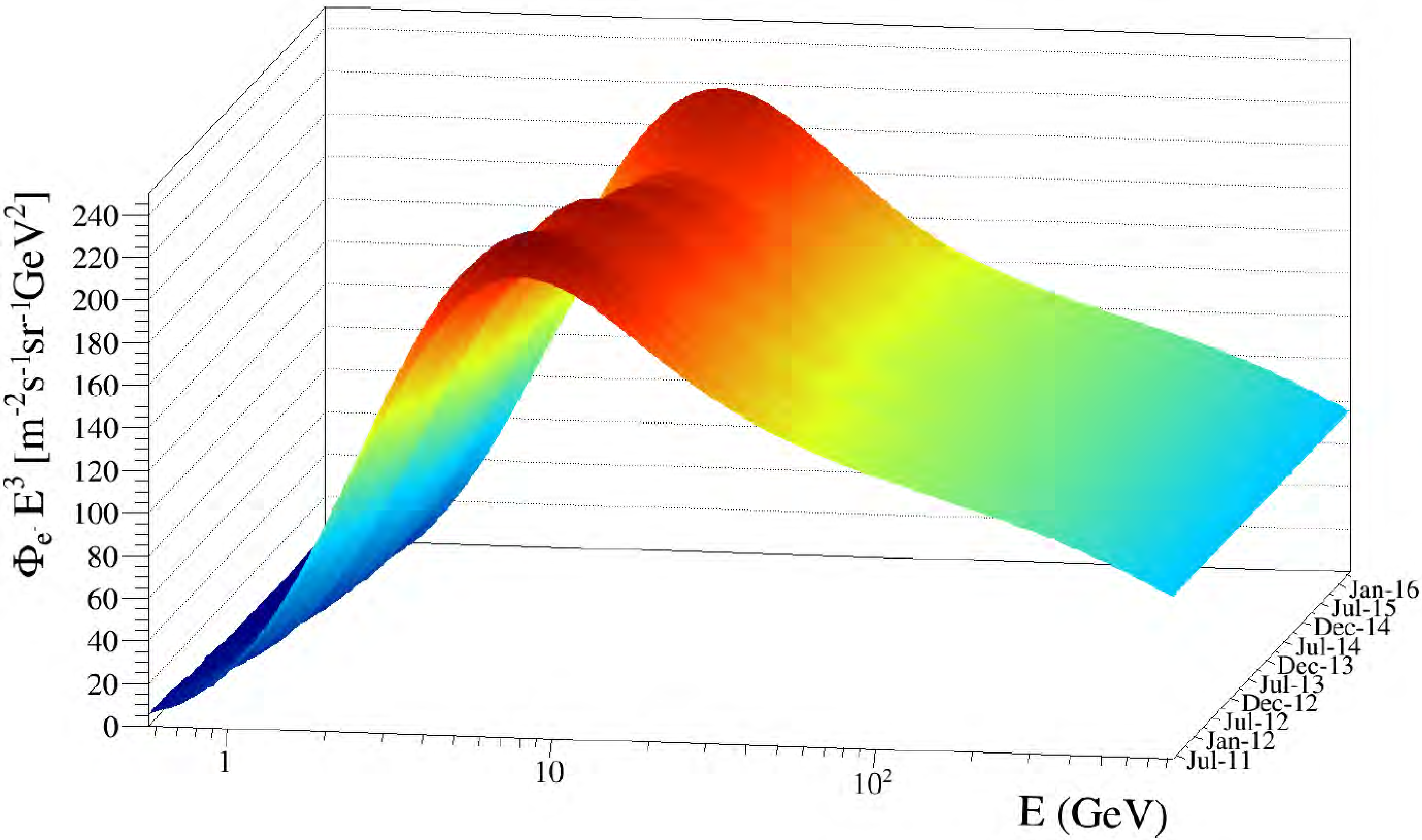


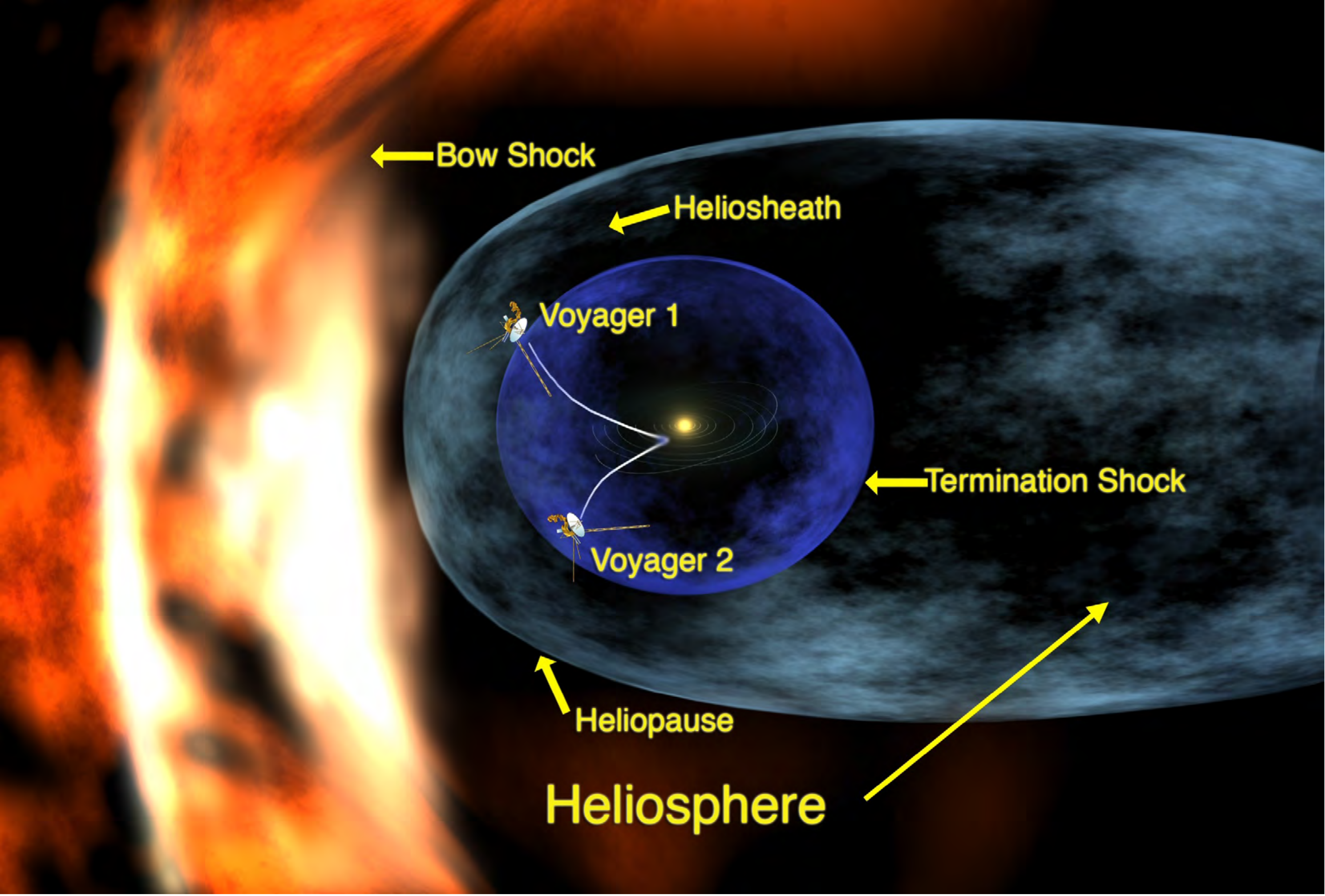
The significance of the energy cutoff of the source term will have increased to >5σ in 2024.



Fluxes of protons, positrons, and electrons show a characteristic time dependence below ~20 GeV.

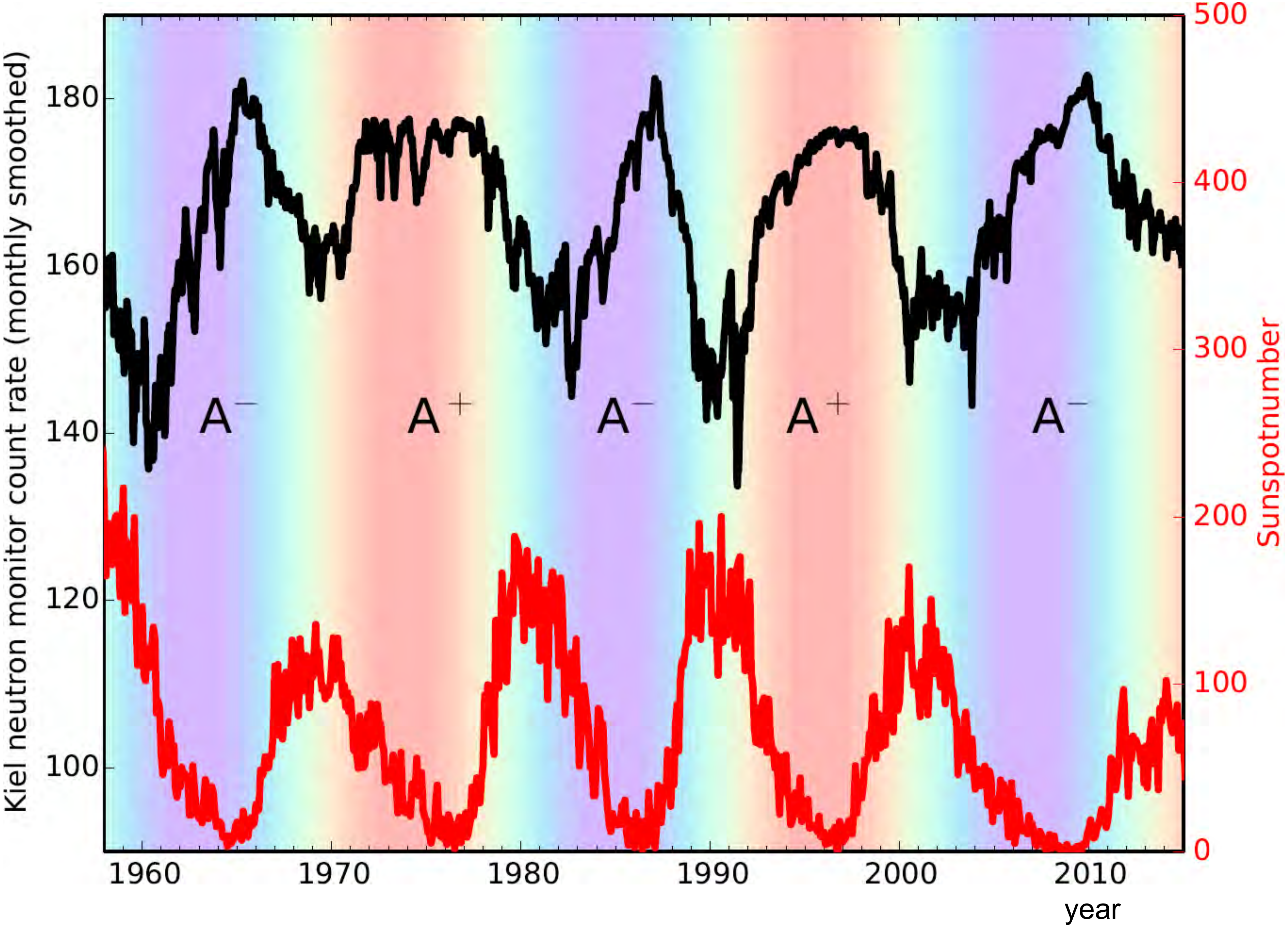
AMS electron flux: June 2011 – May 2016



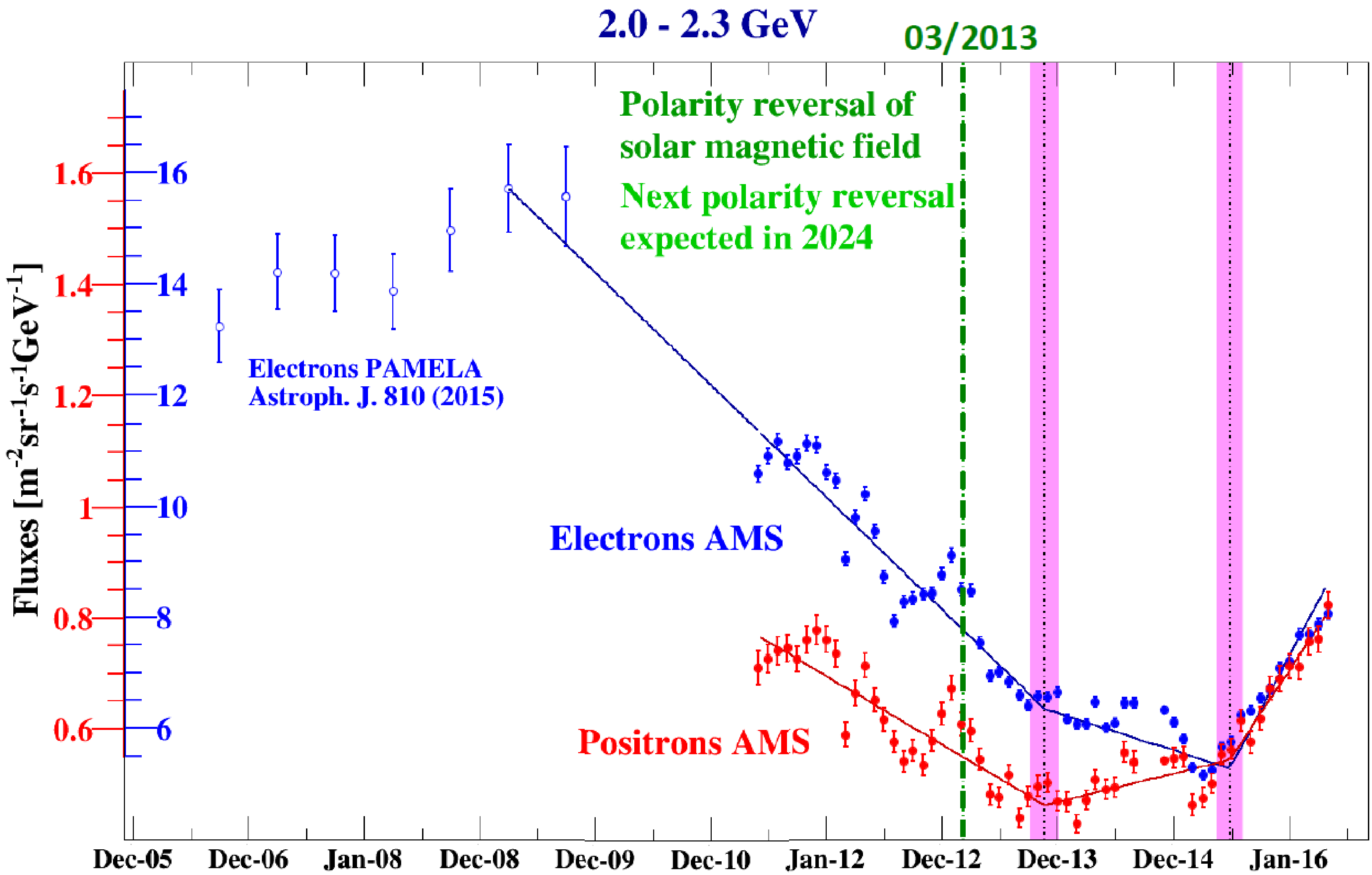


Cosmic rays interact with the heliosphere, which evolves with time.

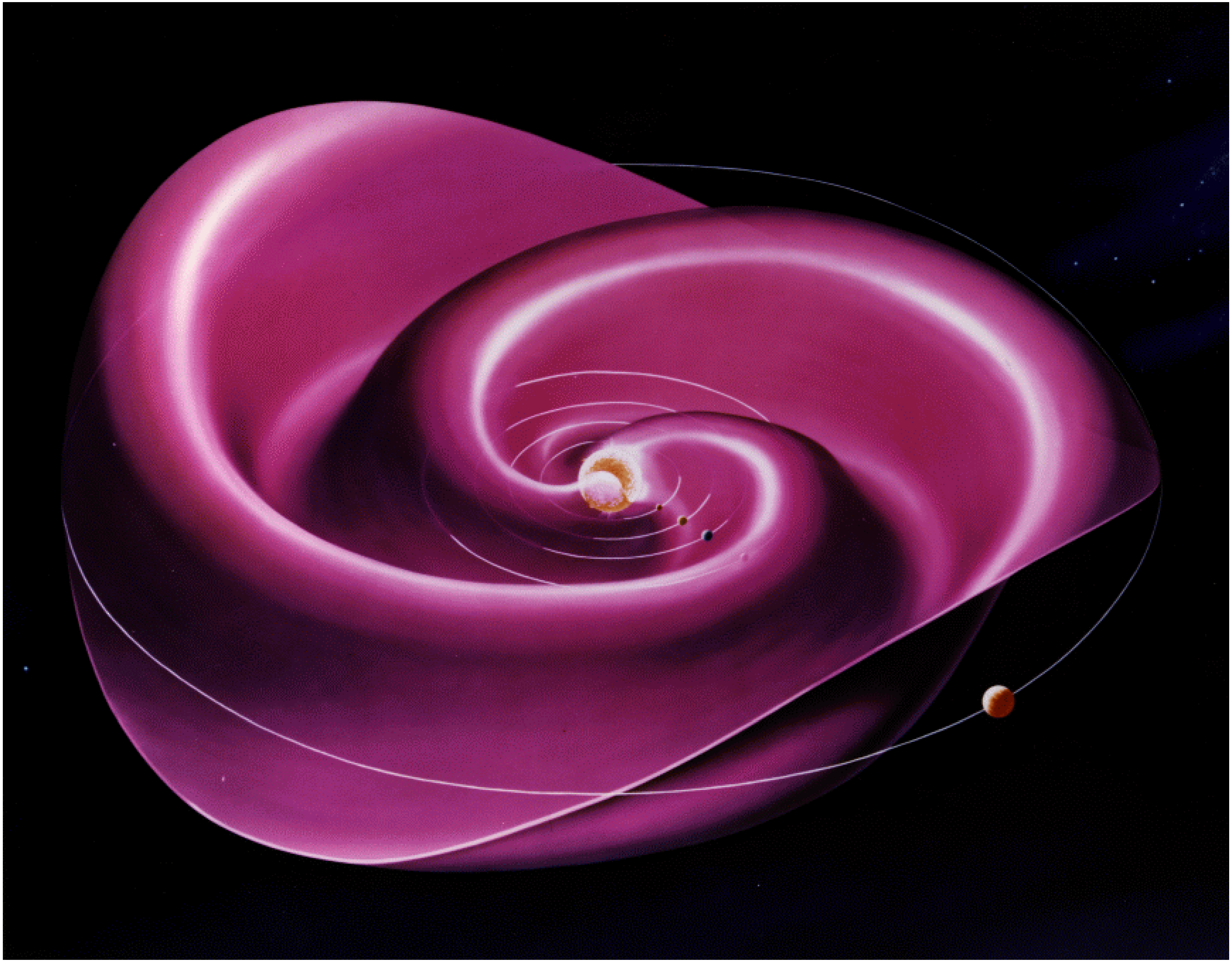
Solar modulation



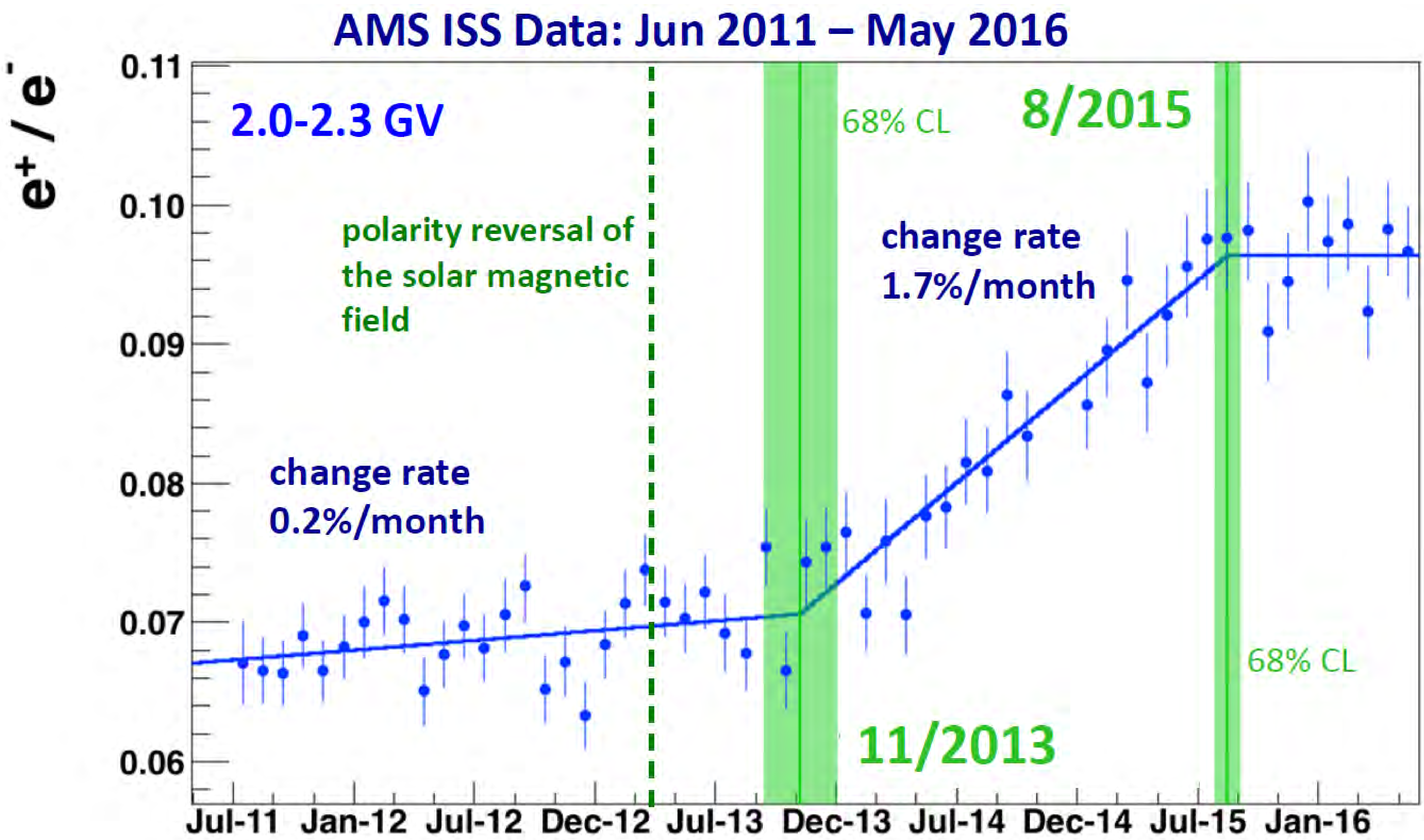
AMS ISS Data: Jun 2011 – May 2016



Positrons and electrons reveal charge-sign dependent solar modulation.

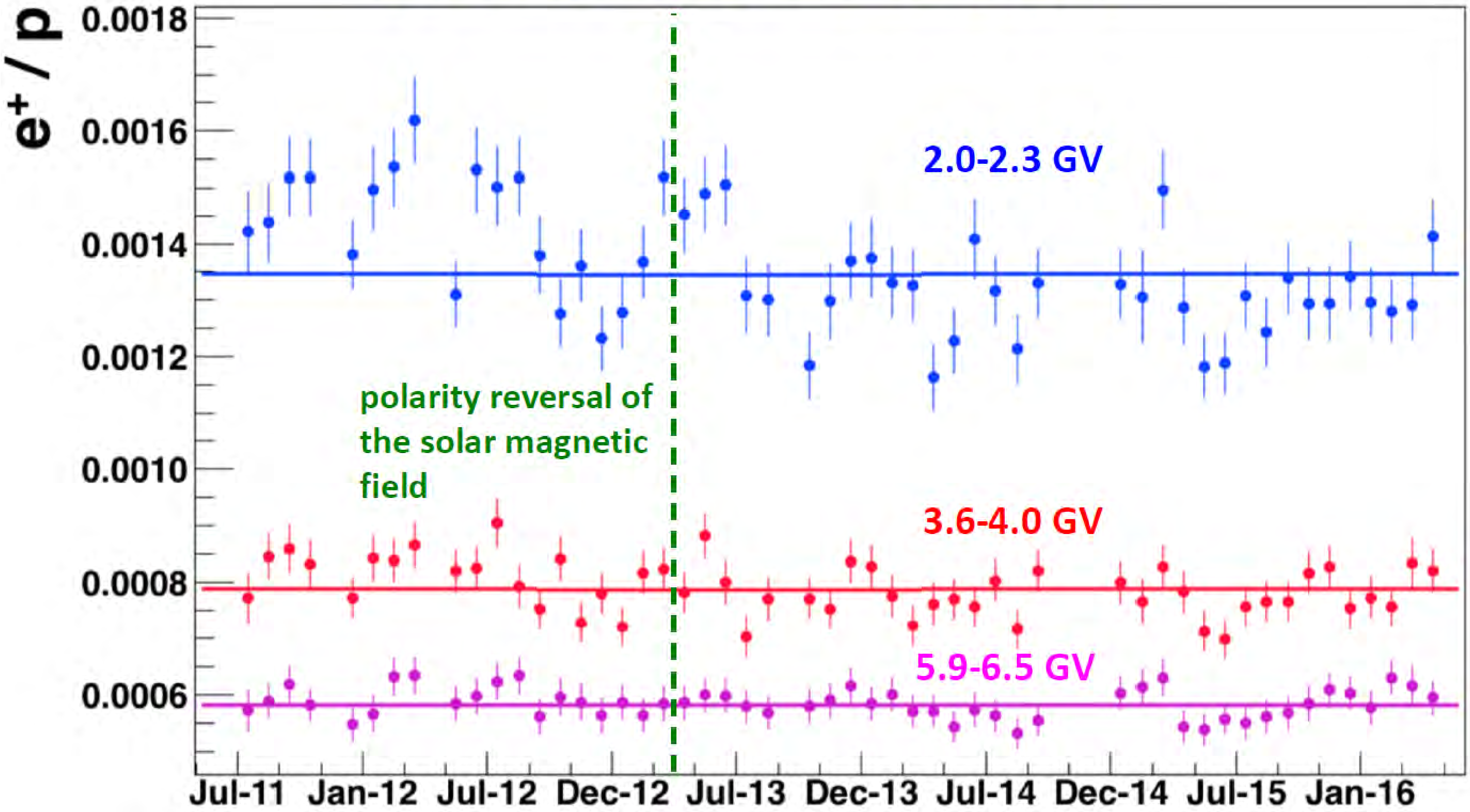


Complex structure of the solar magnetic field causes charge-dependent modulation effects.



AMS ISS Data: Jun 2011 – May 2016
e+ / e-
2.0-2.3 GV
68% CL
8/2015
polarity reversal of the solar magnetic field
change rate 1.7%/month
change rate 0.2%/month
68% CL
11/2013
0.11
0.10
0.09
0.08
0.07
0.06
Jul-11 Jan-12 Jul-12 Dec-12 Jul-13 Dec-13 Jul-14 Dec-14 Jul-15 Jan-16

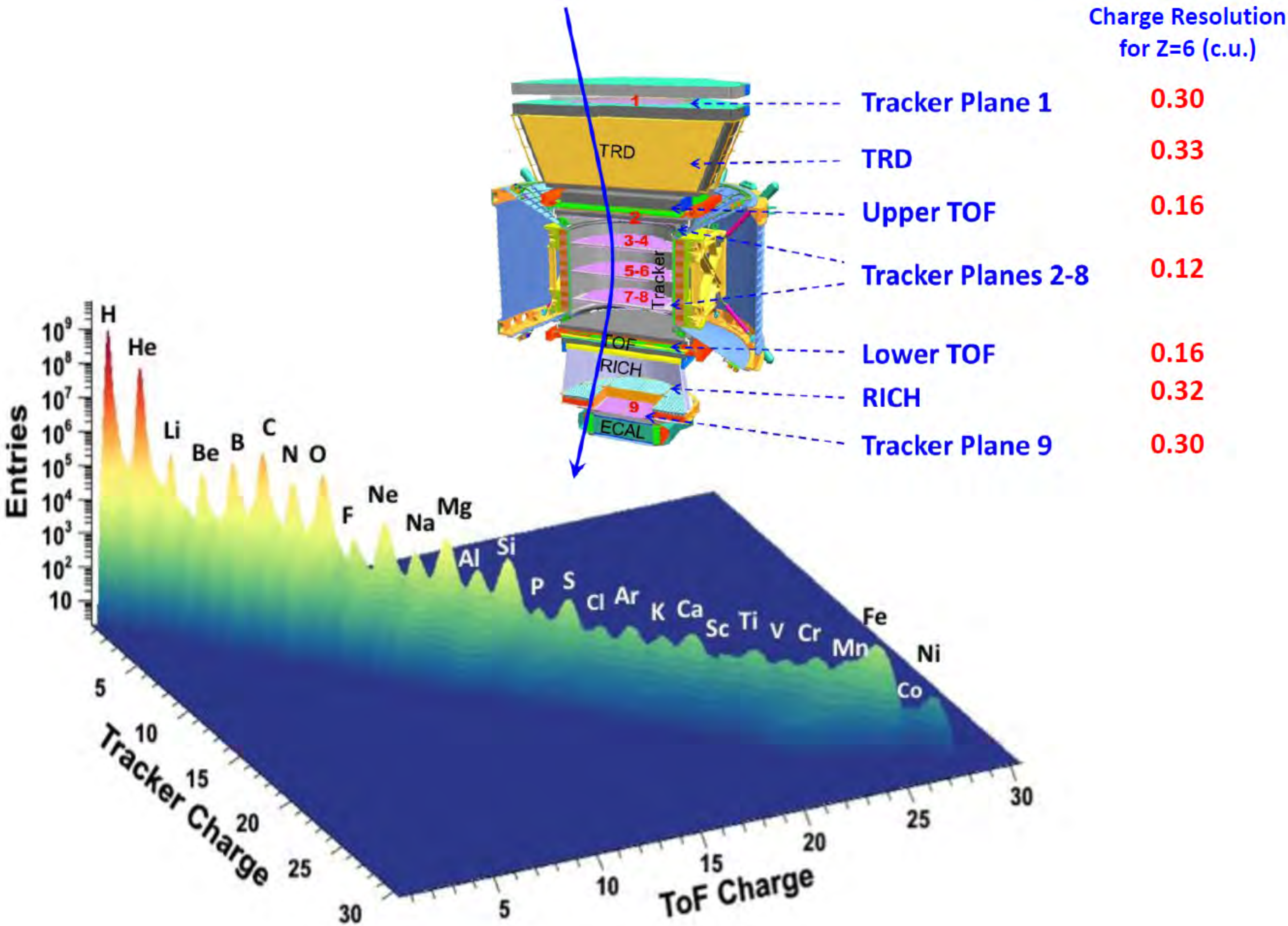
AMS ISS Data: Jun 2011 – May 2016



The e^+/p ratio does not show large variations as a function of time.

The full power of the high precision AMS data sets can only be explored after time-dependent effects are extracted and the data can be used to constrain the local interstellar spectra.

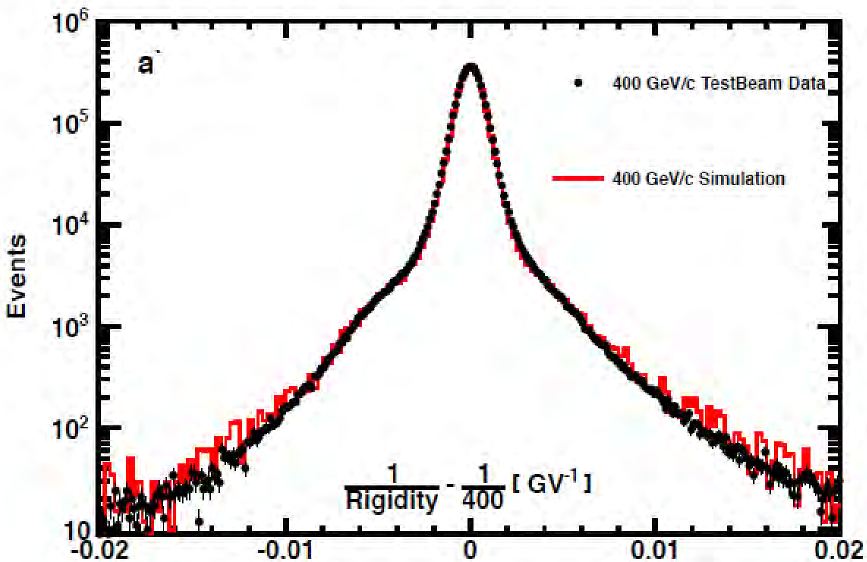
Multiple measurements of charge



Tracker resolution

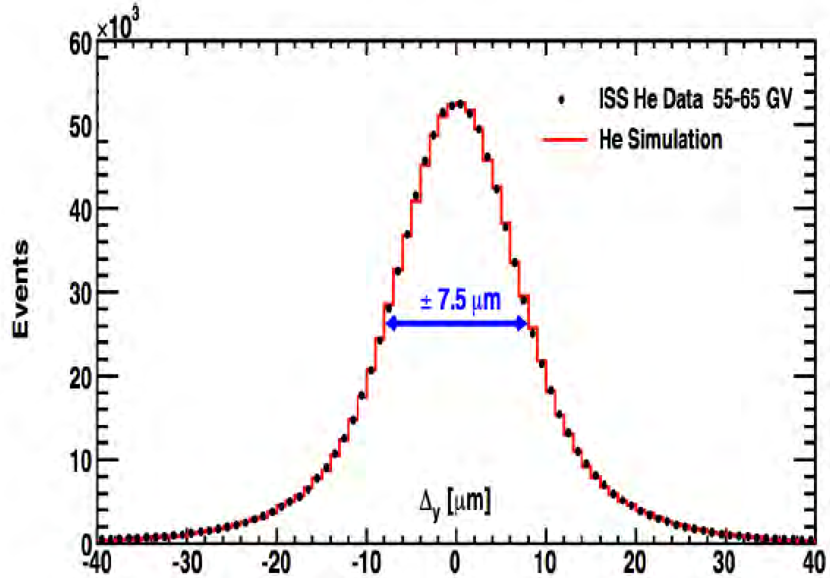
Protons:

- Resolution function from MC simulation
- Verified with:
  - 400 GeV/c Test Beams data
  - ISS data: tracker residuals, rigidity reconstruction (L1-L8) vs. (L2-L9)

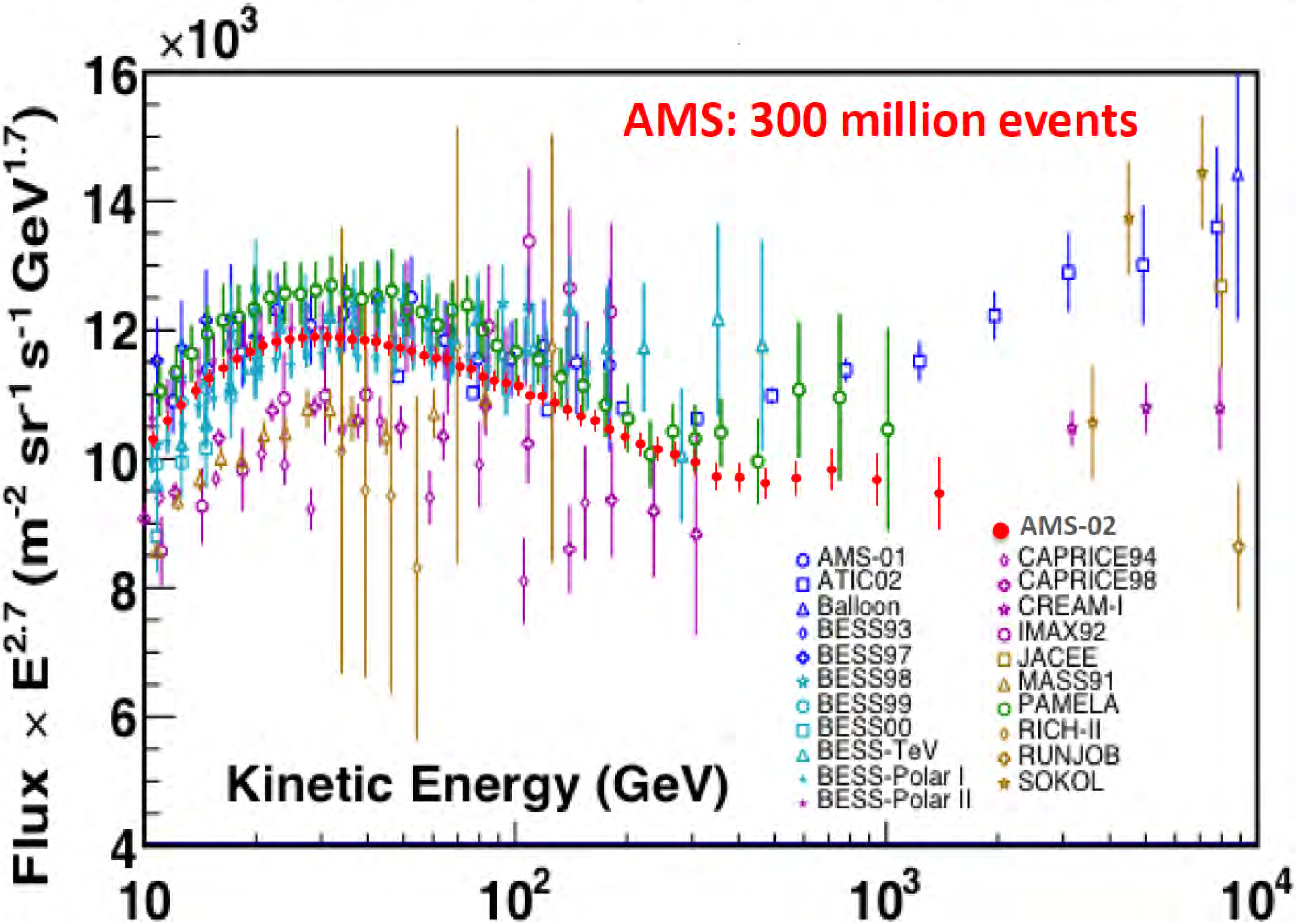


Helium:

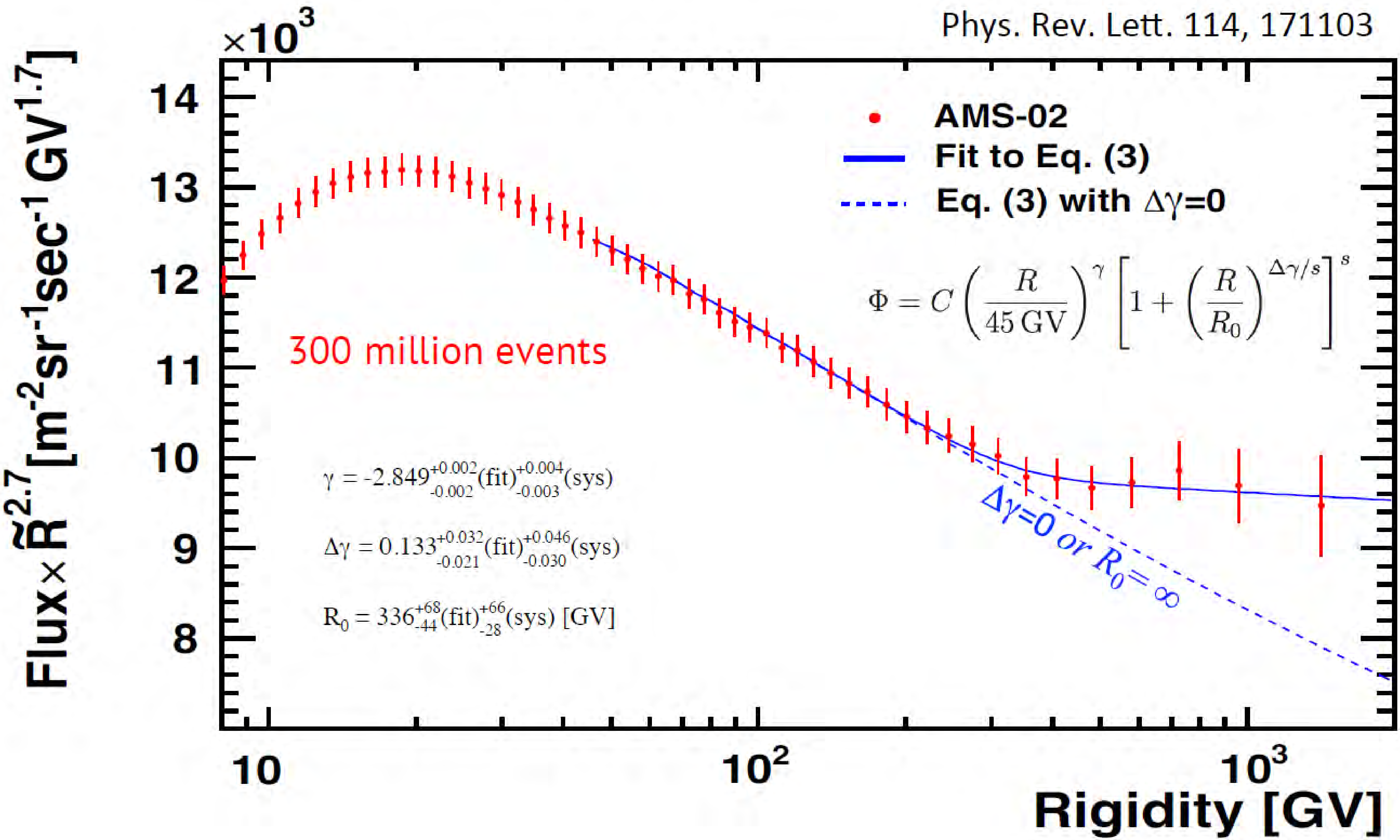
- Resolution function from MC simulation
- Verified with ISS data:
  - Tracker residuals
  - Rigidity reconstruction (L1-L8) vs. (L2-L9)



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

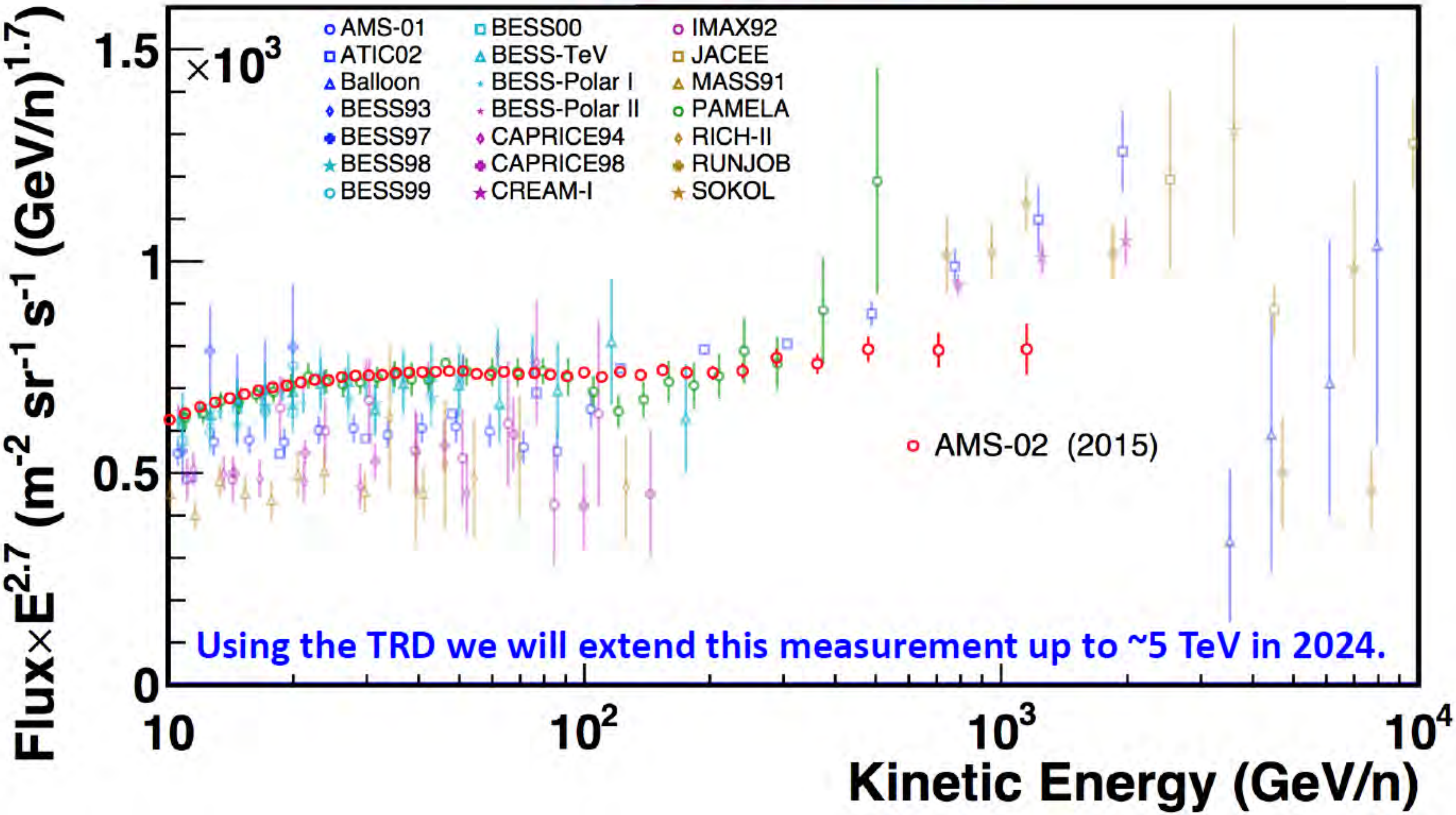


It was expected that the proton spectrum could be described by a simple power law with spectral index γ = -2.7



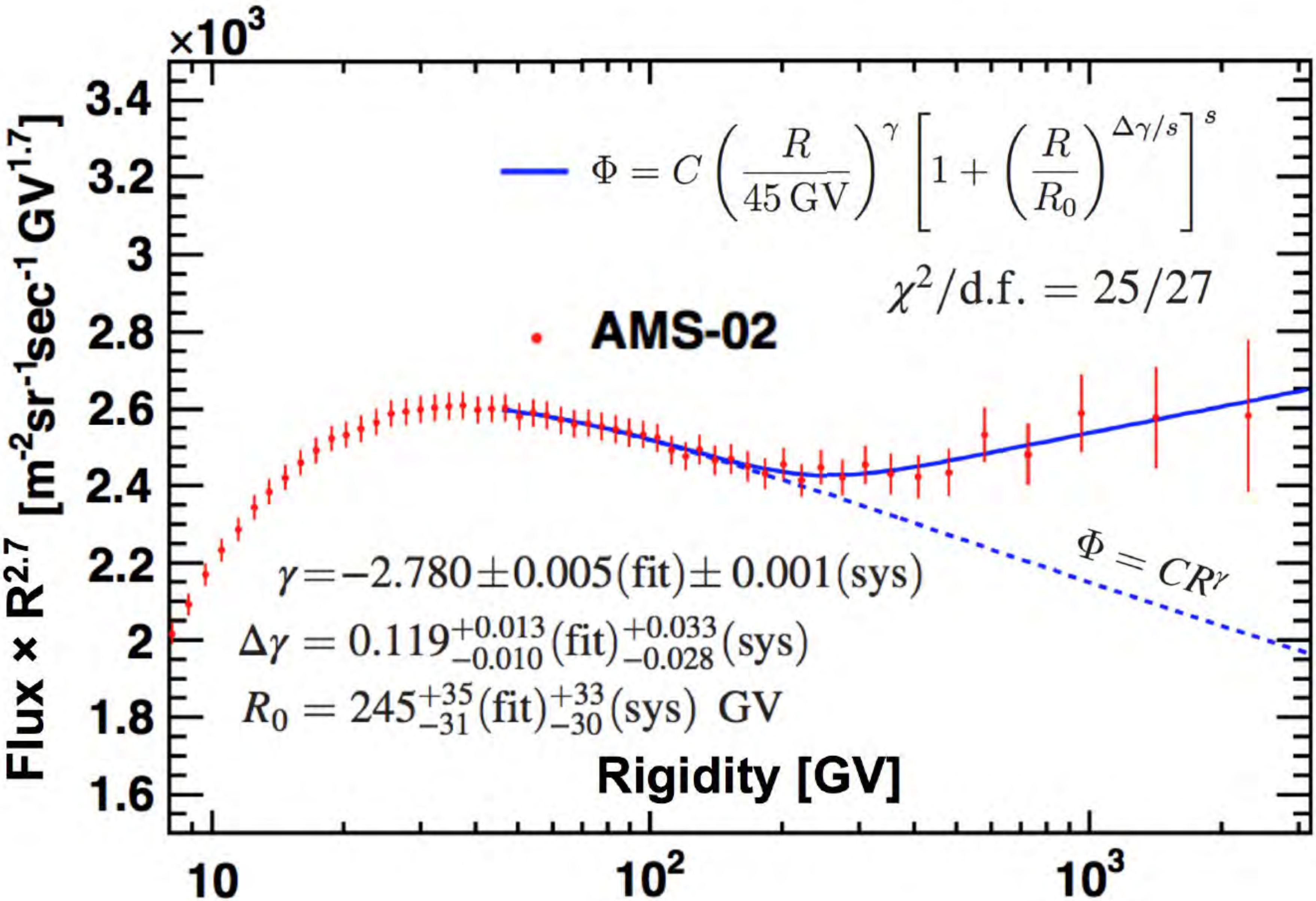
Precision Measurement of the Helium Flux in Primary Cosmic Rays of Rigidities 1.9 GV to 3 TV with the Alpha Magnetic Spectrometer on the International Space Station

50 million helium nuclei

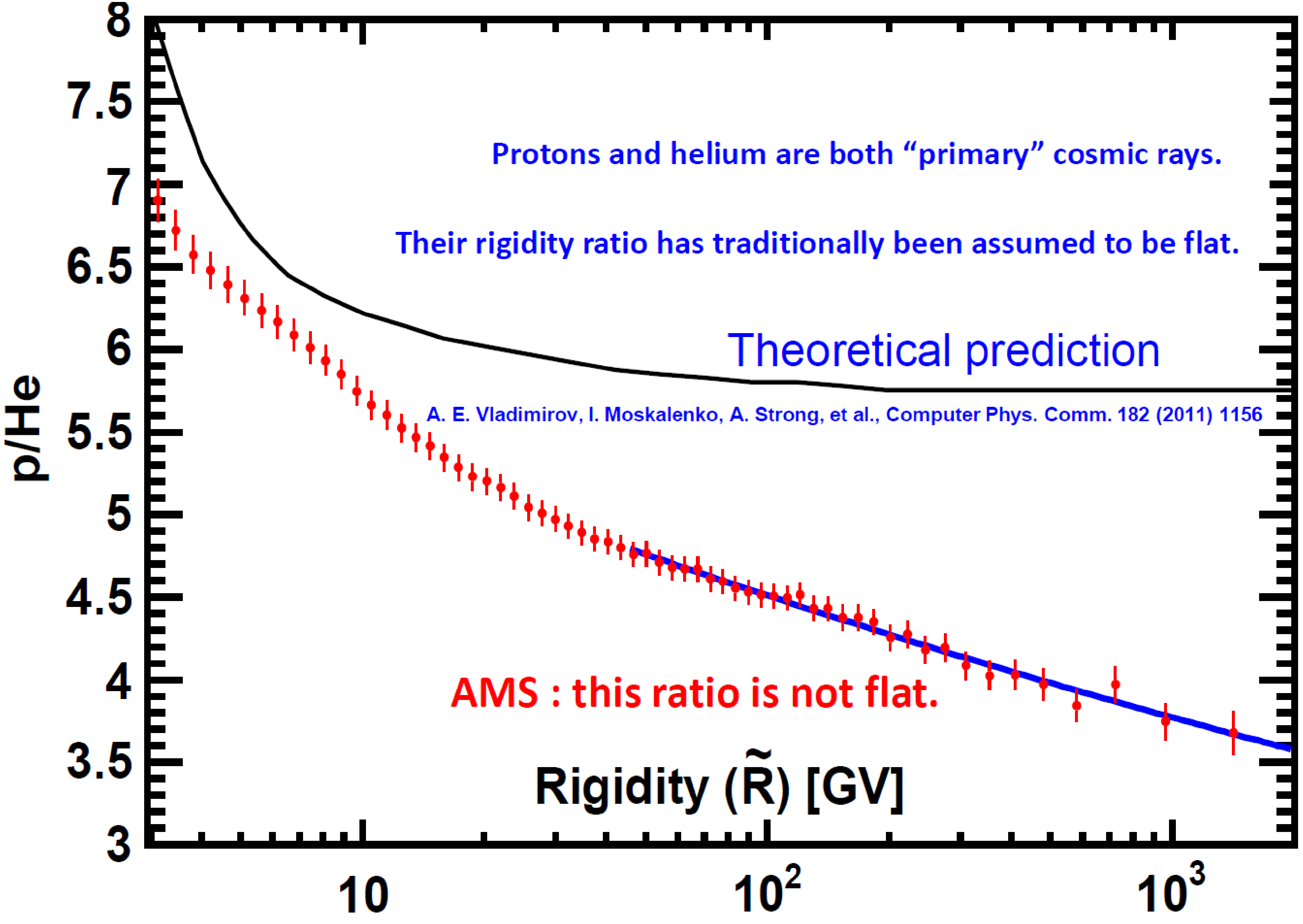


Using the TRD we will extend this measurement up to ~5 TeV in 2024.

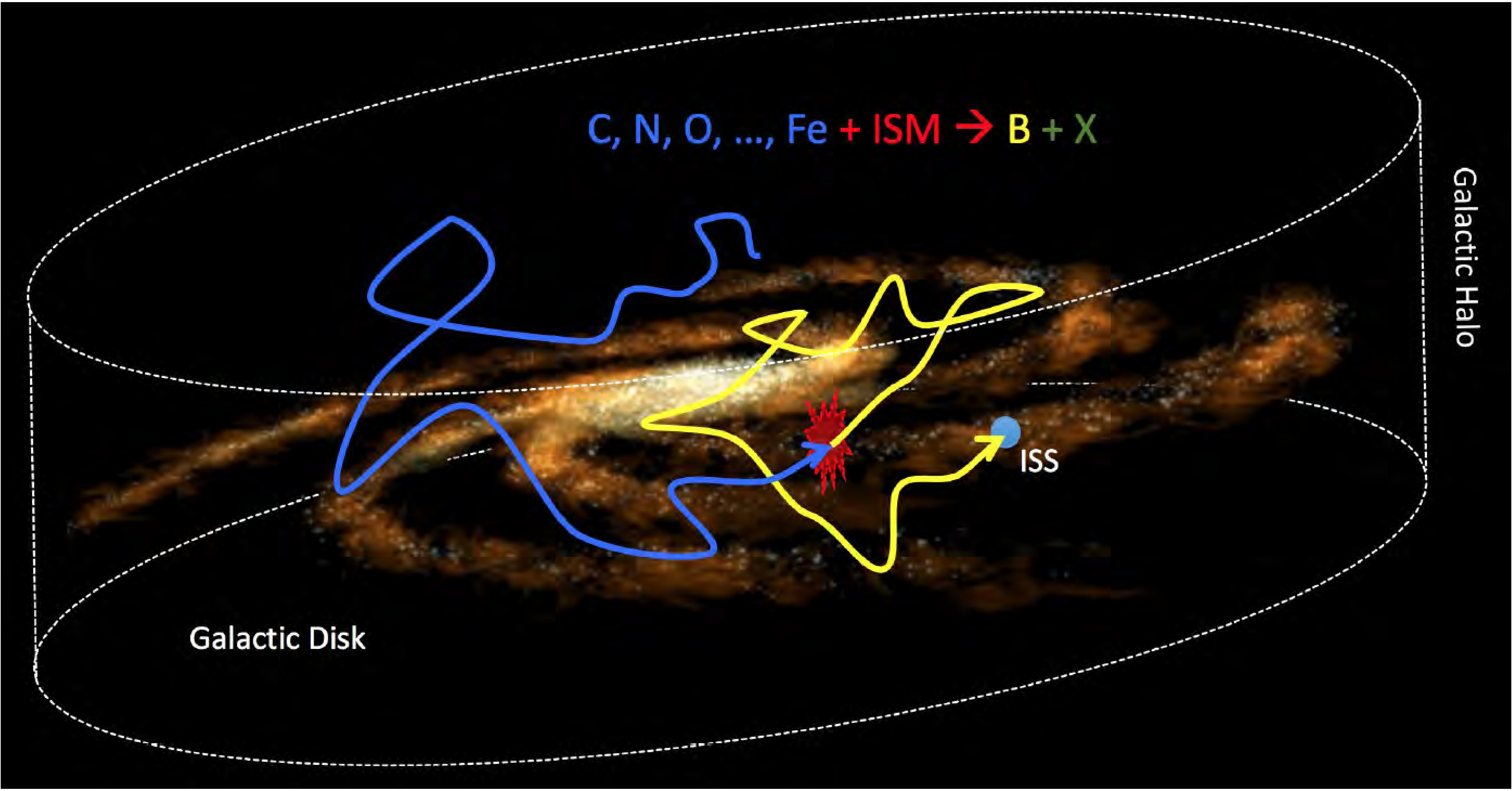
It was expected that the helium spectrum could be described by a simple power law with spectral index γ = -2.7



The AMS proton/helium flux ratio

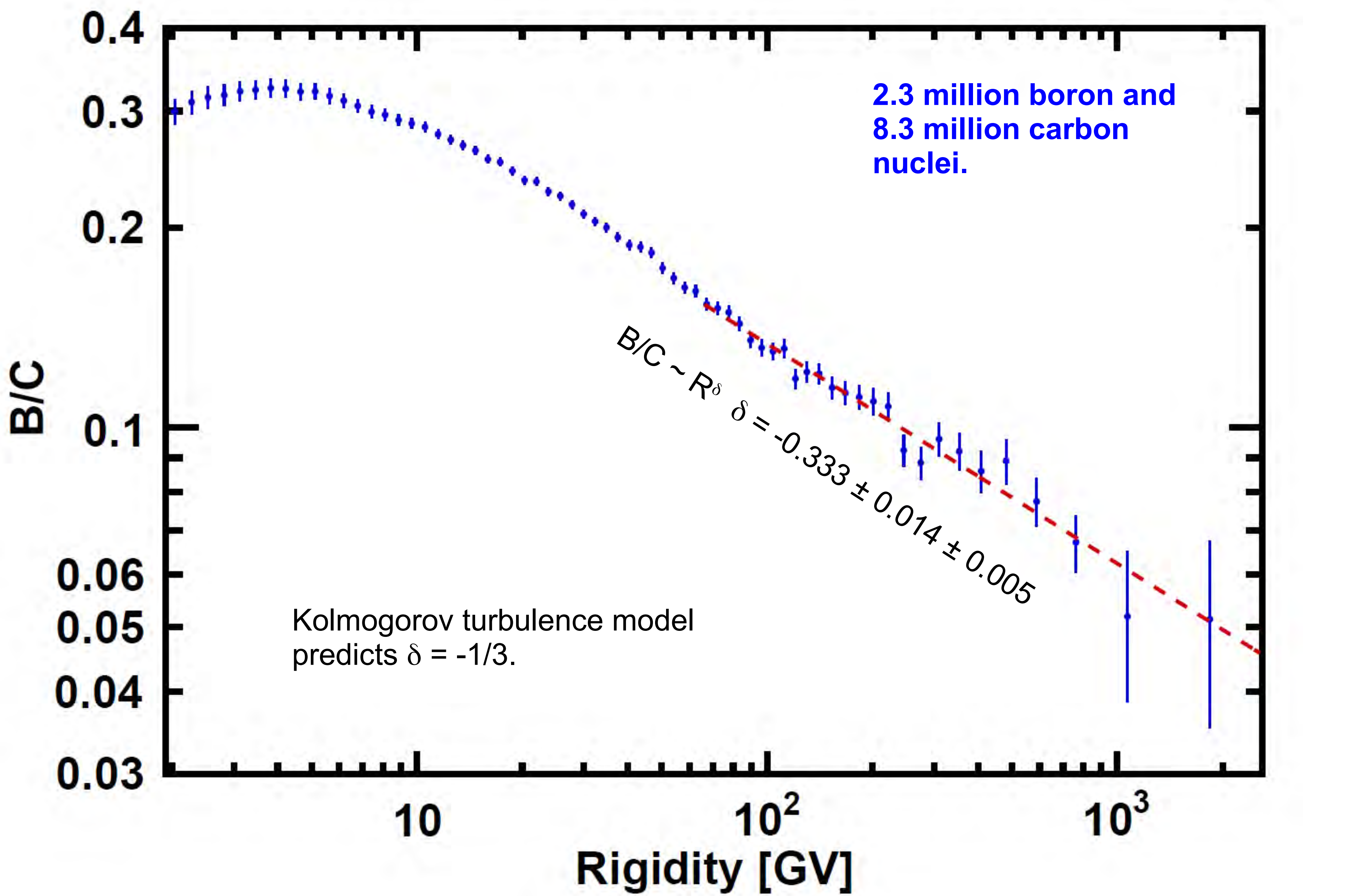


Flux ratios: boron/carbon and cosmic-ray propagation



The boron-to-carbon ratio (B/C) is important in the determination of cosmic-ray propagation. Boron is assumed to be produced in the collision of primary cosmic rays, such as carbon, with the interstellar medium (ISM), hence the B/C ratio provides information on cosmic-ray propagation.

B/C ratio measured by AMS

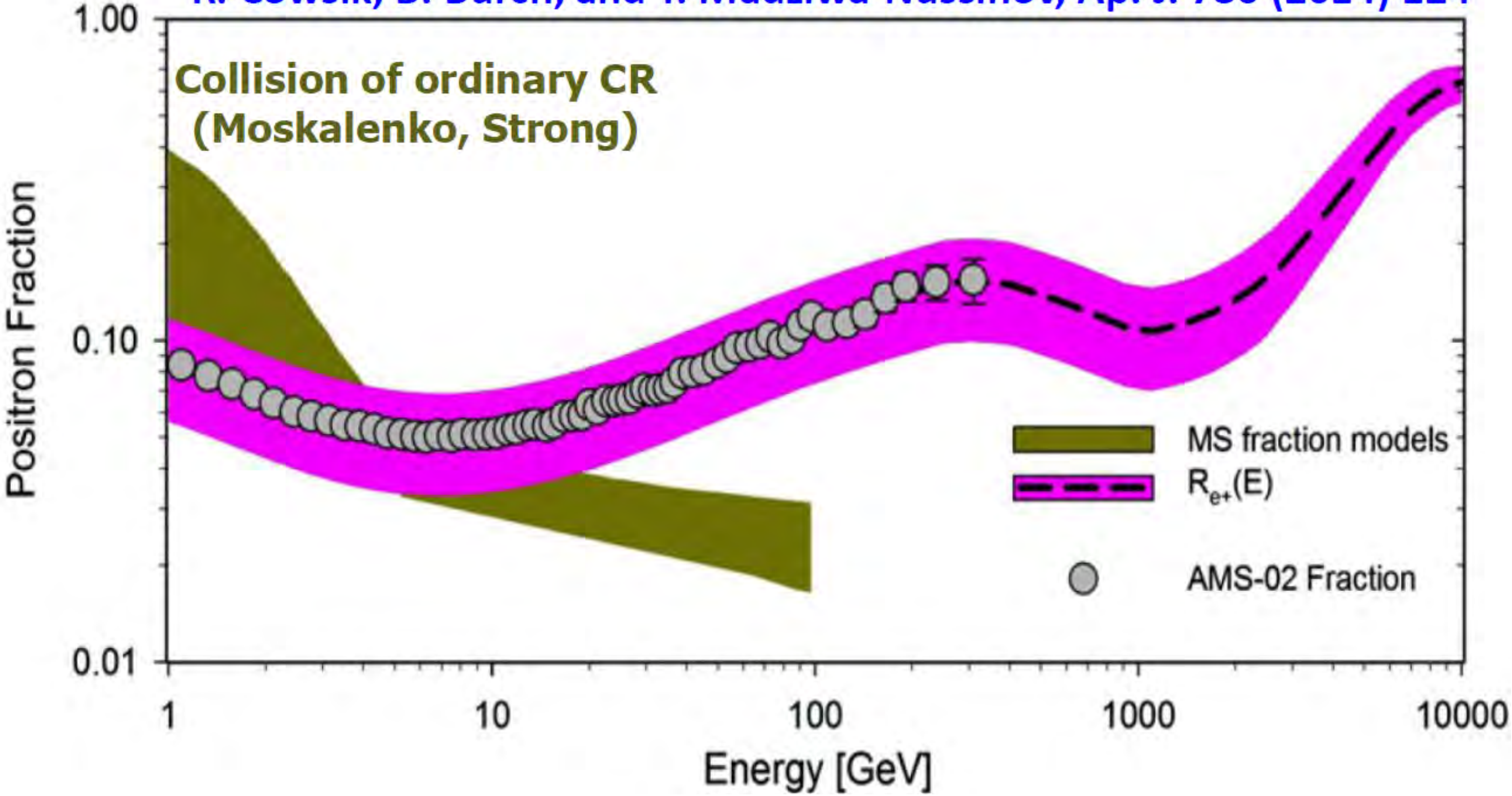


Theoretical models to explain the AMS positron fraction.
Among the 100's of models there are three classes:

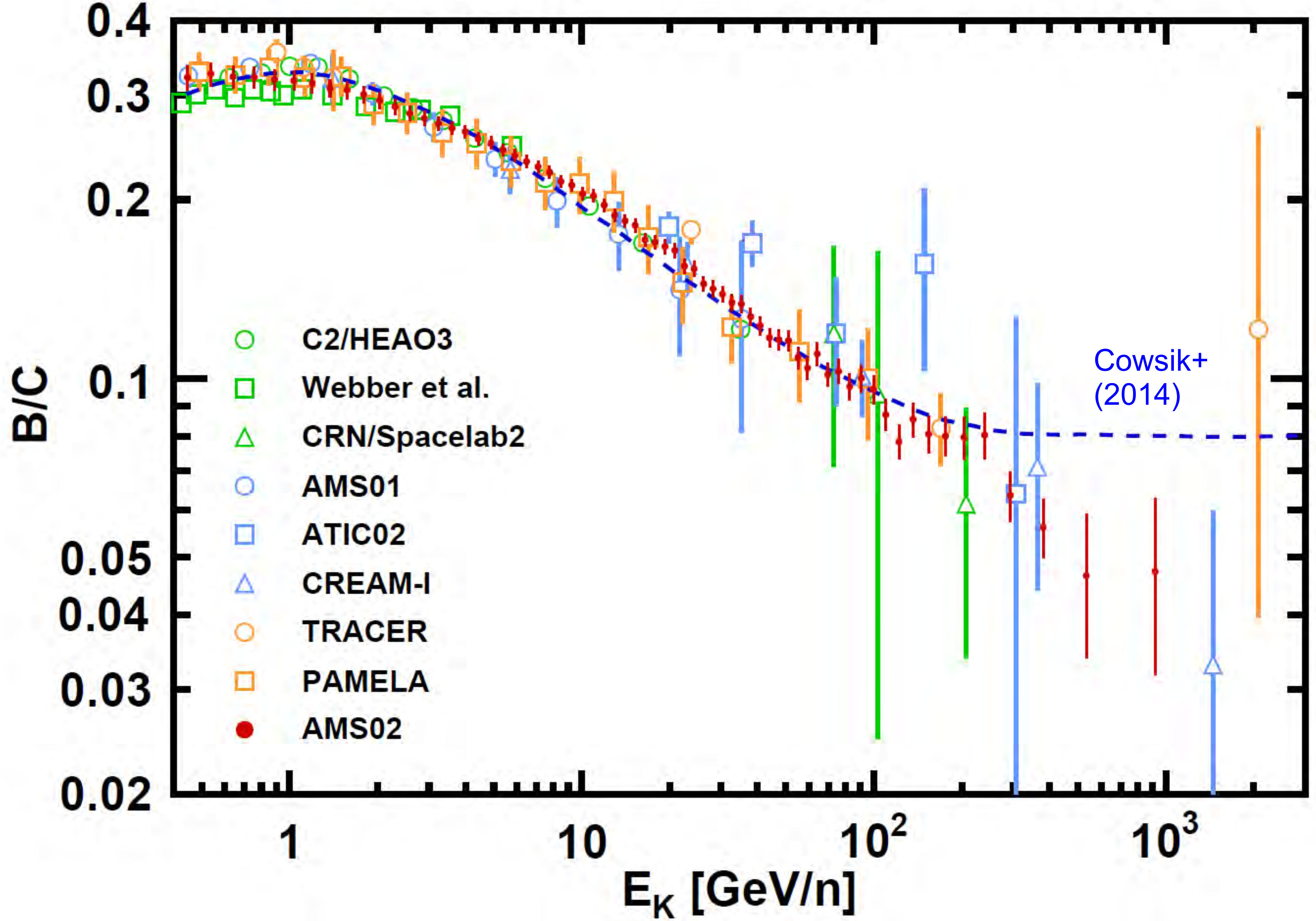
a) dark matter
b) new forms of propagation
c) pulsars.

b) An example of new propagation:

R. Cowsik, B. Burch, and T. Madziwa-Nussinov, Ap. J. 786 (2014) 124

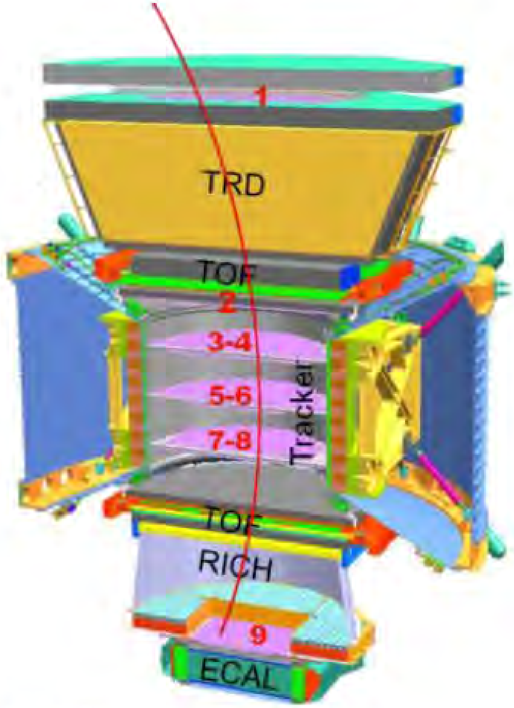


B/C ratio measured by AMS

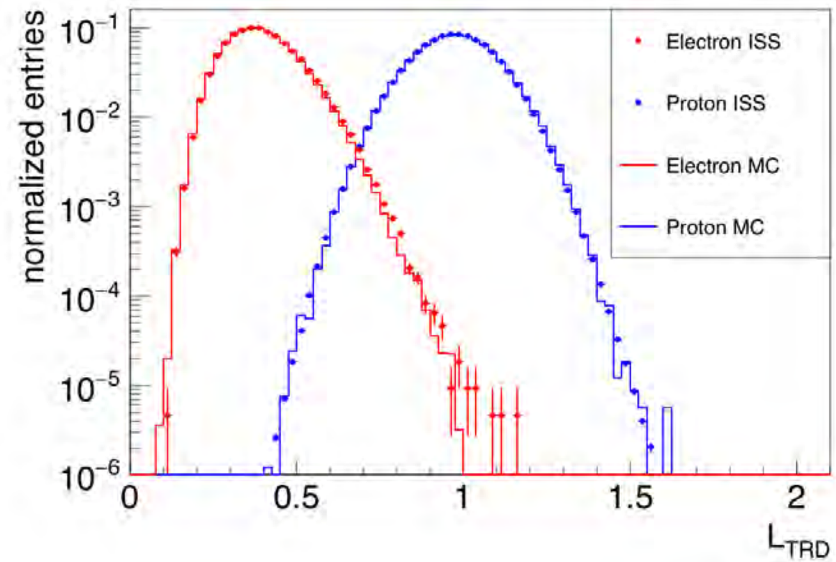


Antiproton analysis

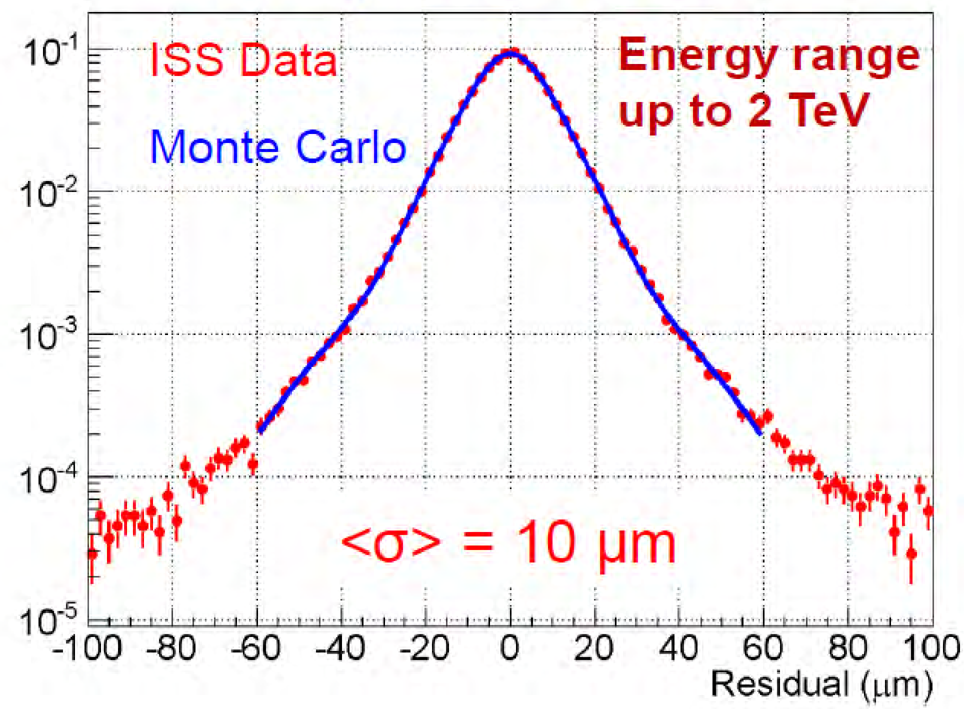
6.5 · 10^{10} cosmic rays
3.49 · 10^{5} antiprotons
2.42 · 10^{9} protons



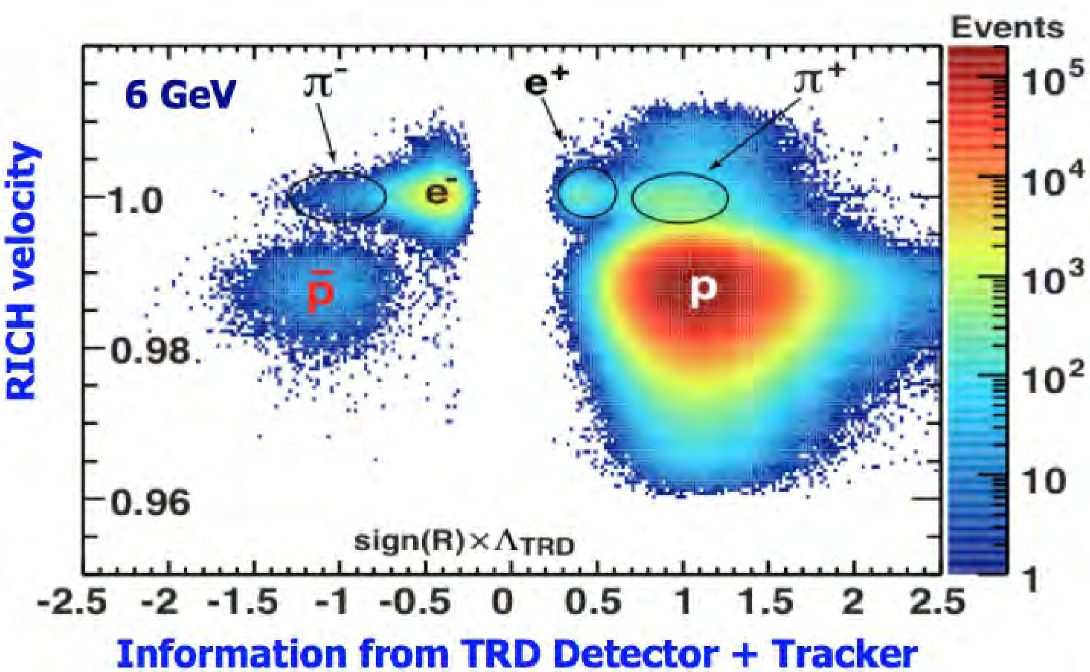
1. TRD (transition radiation) to separate $e^{\pm}$ from $p^{\pm}$



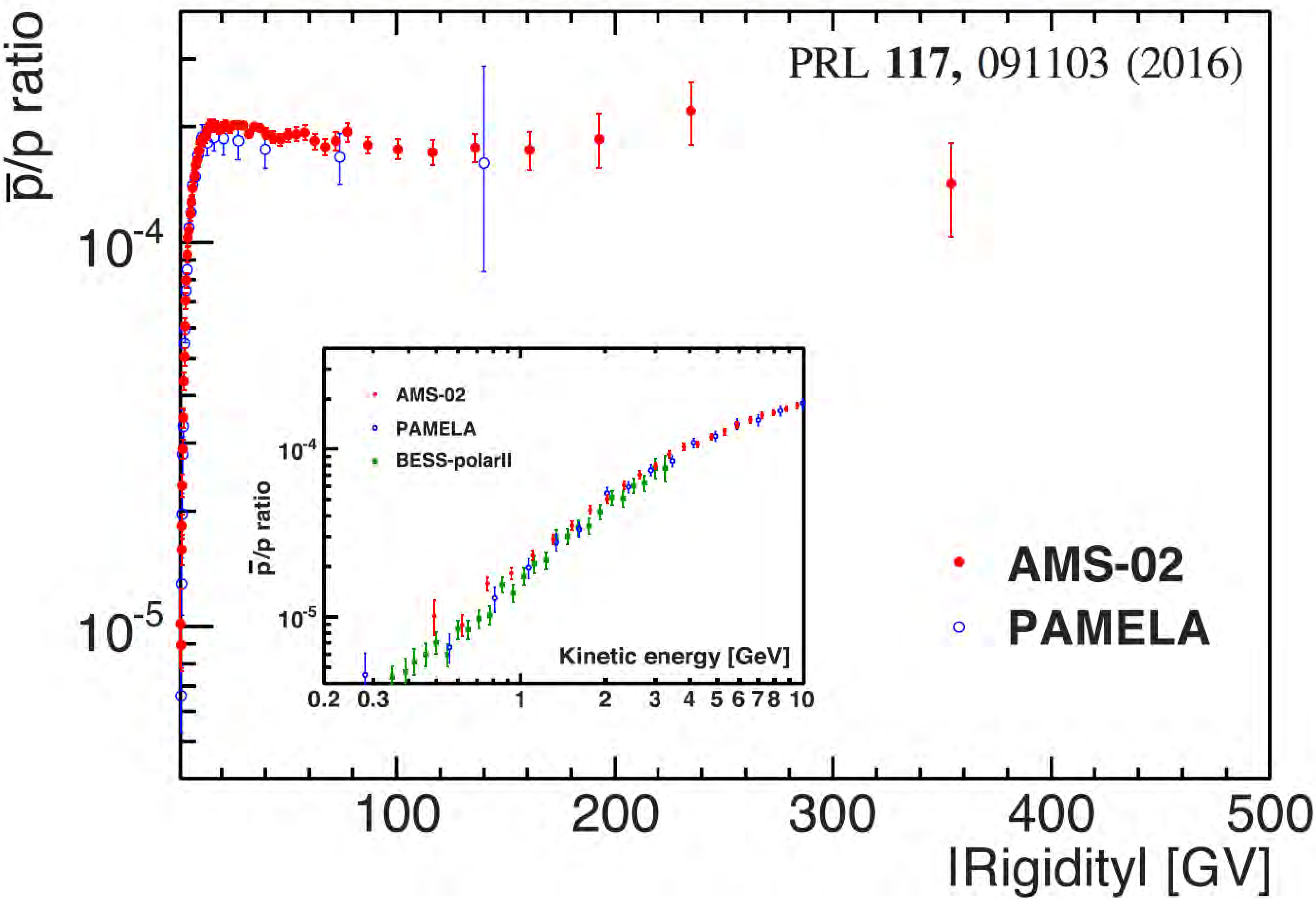
2. Tracker measures momentum and separates + from −



3. RICH measures velocity,

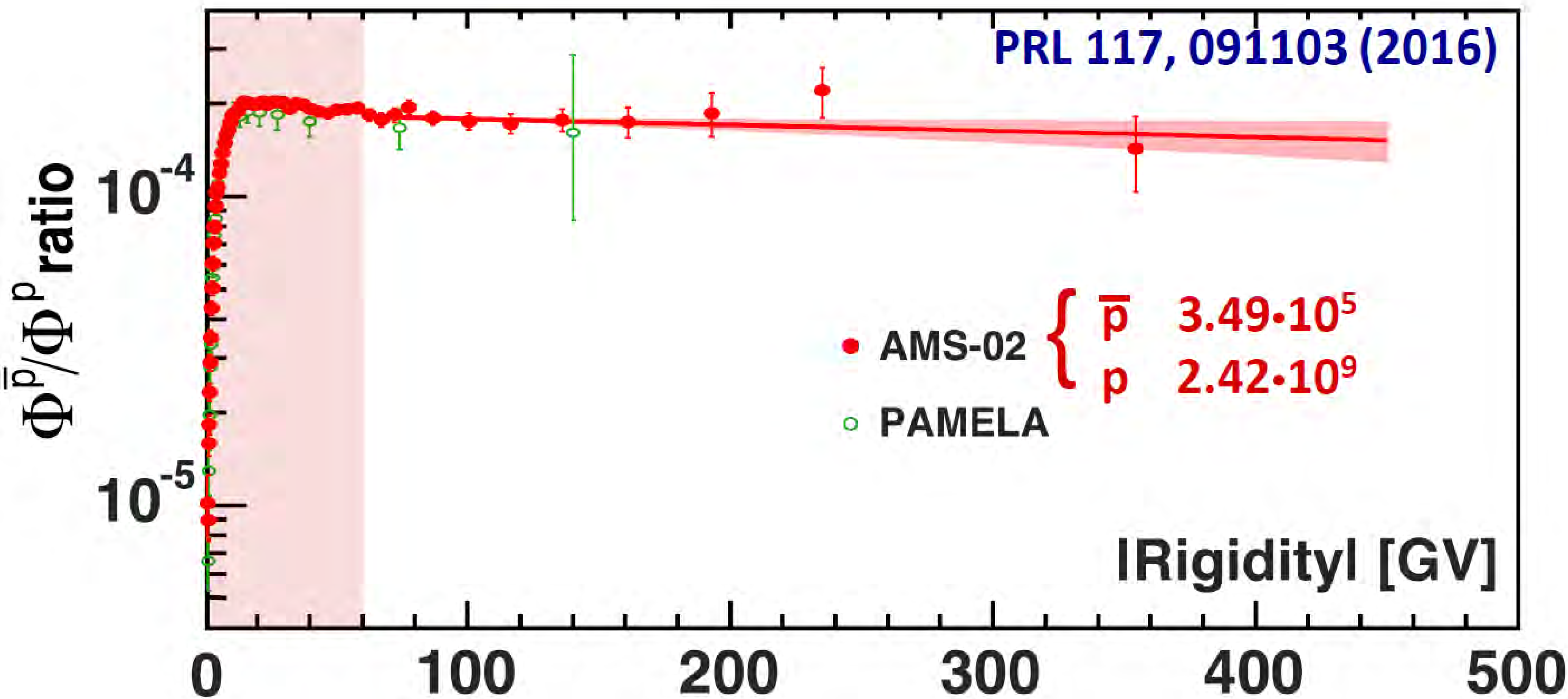


AMS results on the $\bar{p}/p$ flux ratio

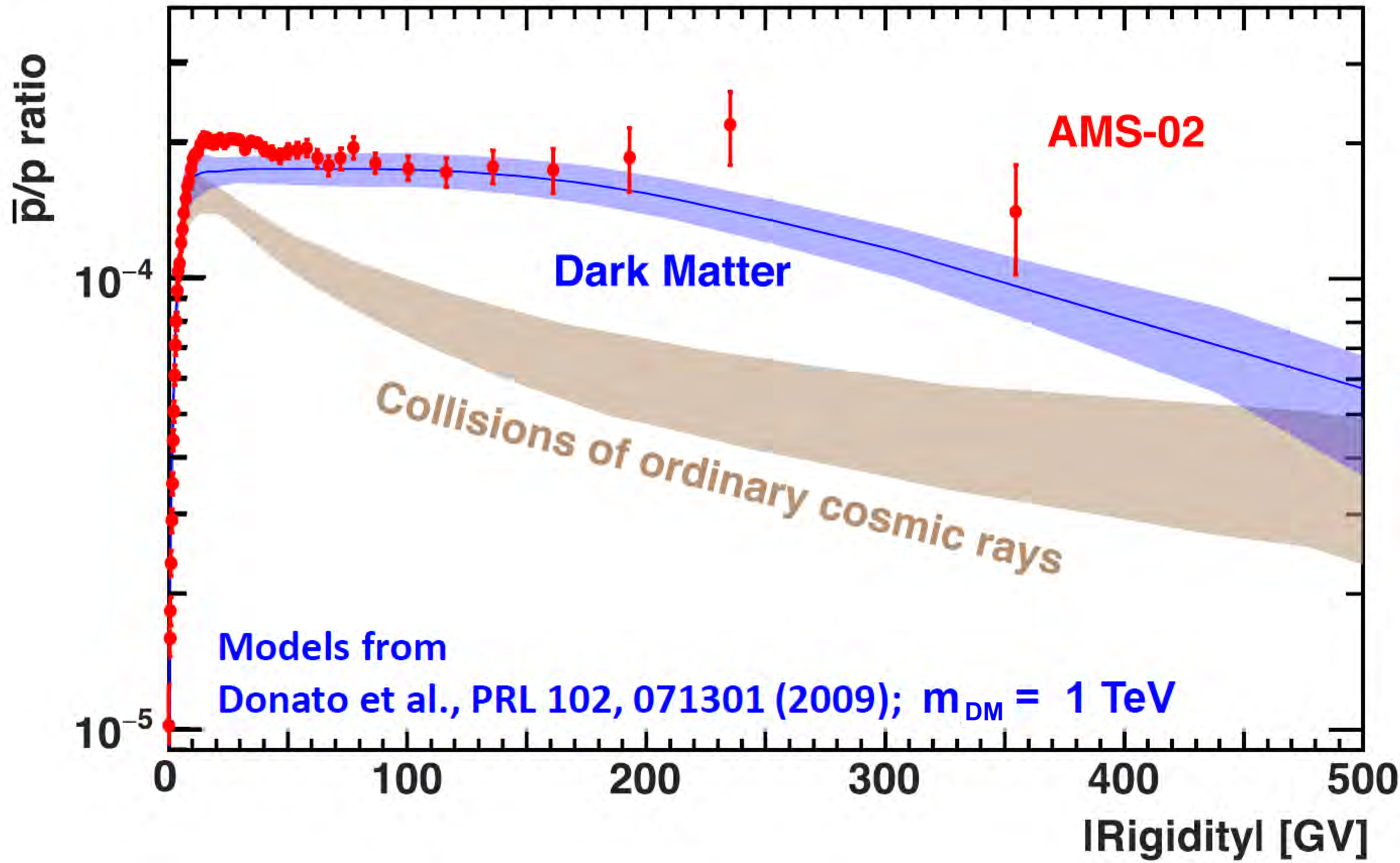


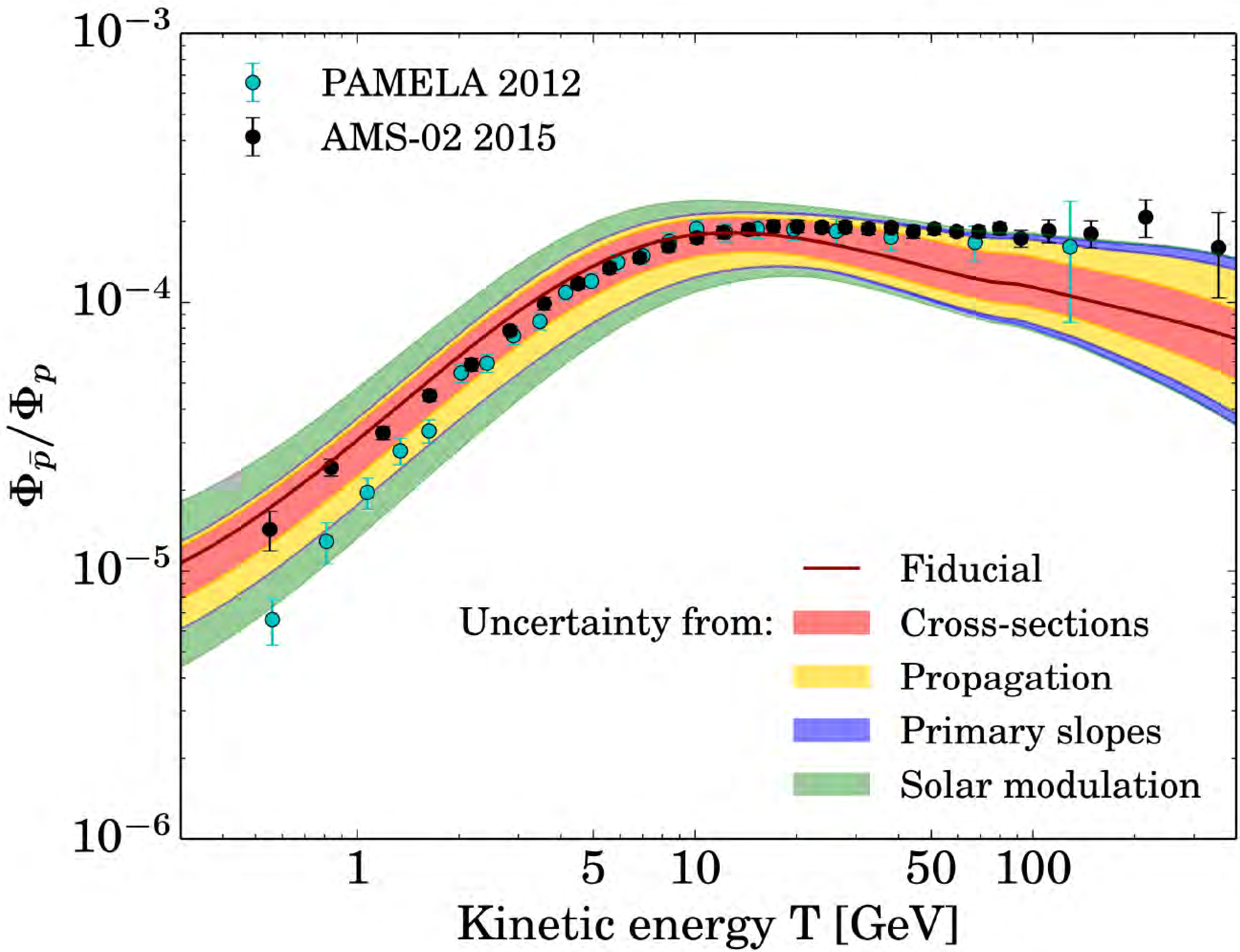
Unexpected Result

Flux Ratio of Elementary Particles $\bar{p}/p$ is energy independent above 60 GeV



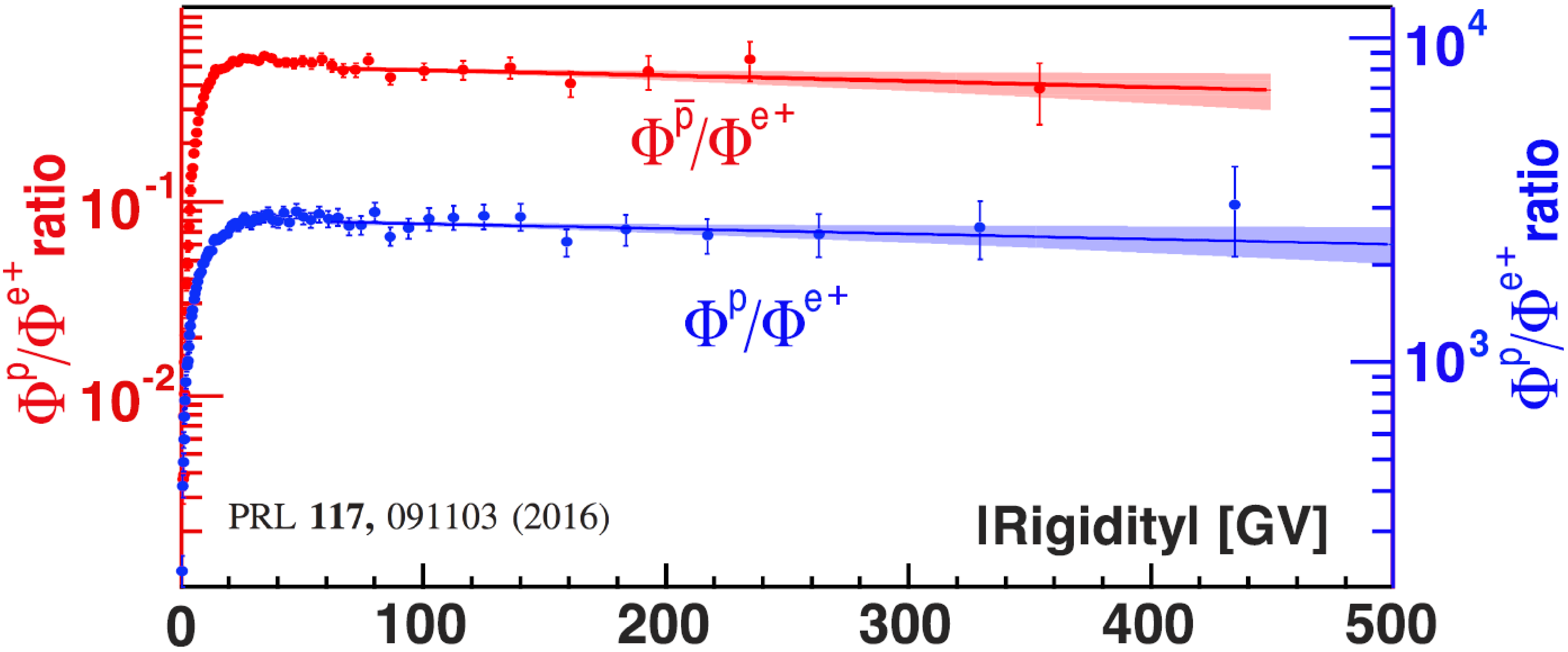
AMS $\bar{p}/p$ results and modeling



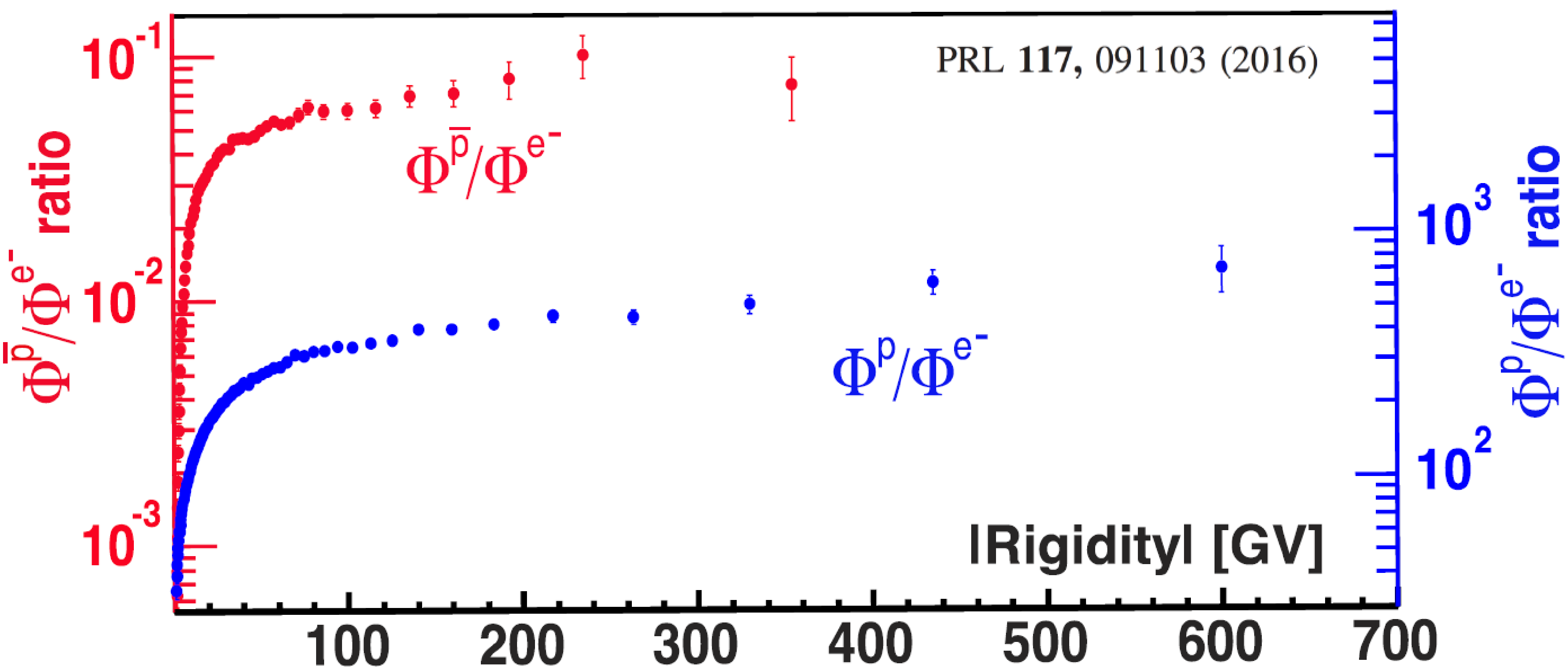


G.Giesen et al., JCAP09 (2015) 023

Flux Ratios $\bar{p}/e^+$ and p/e^+ are also energy independent in the interval 60–450 GV

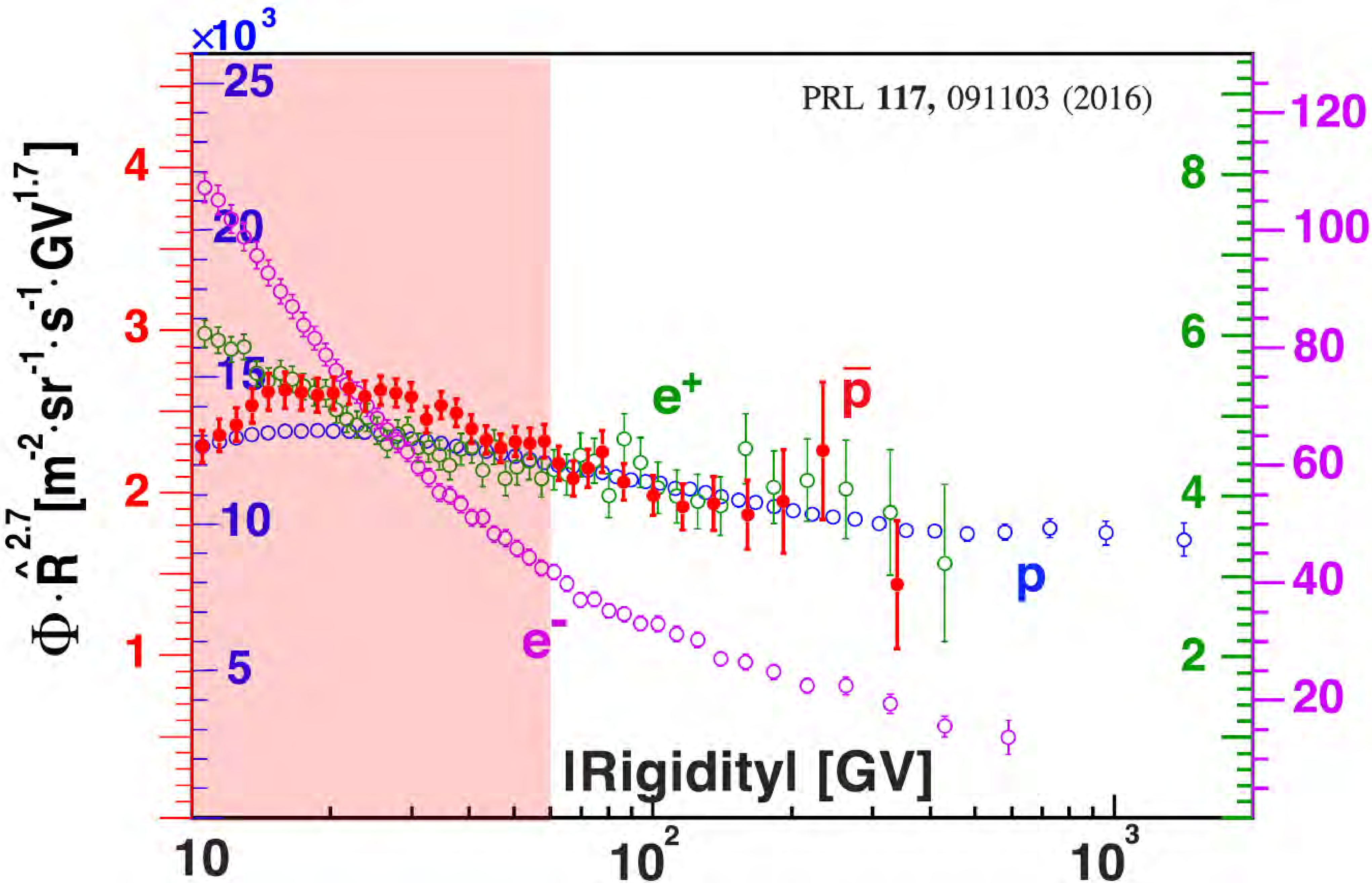


Flux Ratios $\bar{p}/e^-$ and p/e^- are not energy independent in the interval 60–450 GV



As expected: significant energy losses of e^- due to synchrotron radiation

Summary: AMS results on fluxes of elementary particles



Summary

- Proton and helium show power-law fluxes for E > ~30 GeV.
- Both have a spectral break at E~300 GeV, and p/He is not constant.
- Strong constraints on models for cosmic-ray propagation from B/C data.

- Electron flux is smaller and significantly softer than the proton flux.
- Evidence for charge-sign dependent solar modulation.
- Above E~30 GeV, antiprotons and positrons approximately exhibit power-law behaviour. Intriguingly,

$$\gamma_{e^+} \simeq \gamma_{\overline{p}} \approx \gamma_p + \frac{\Delta\gamma_p}{2}$$

$$\left.\frac{\phi_{e+}(E)}{\phi_{\overline{p}}(E)}\right|_{E\in[30,350]\ \mathrm{GeV}} \simeq (2.04 \pm 0.04) \times \left(\frac{E}{50\ \mathrm{GeV}}\right)^{0.015\pm0.045}$$

According to Lipari (2016), expected antiproton-to-positron ratio for common origin in secondary production is 1.8 ± 0.5.