The Latest Results from AMS-02

29 - 31 December 2016 @ 4th Intl. Workshop on DM and DE

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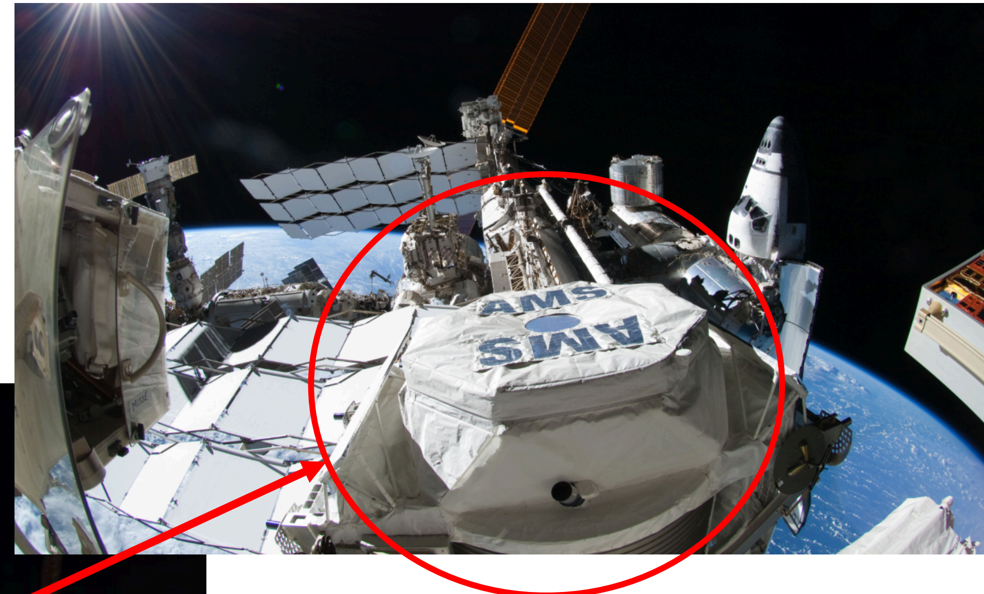
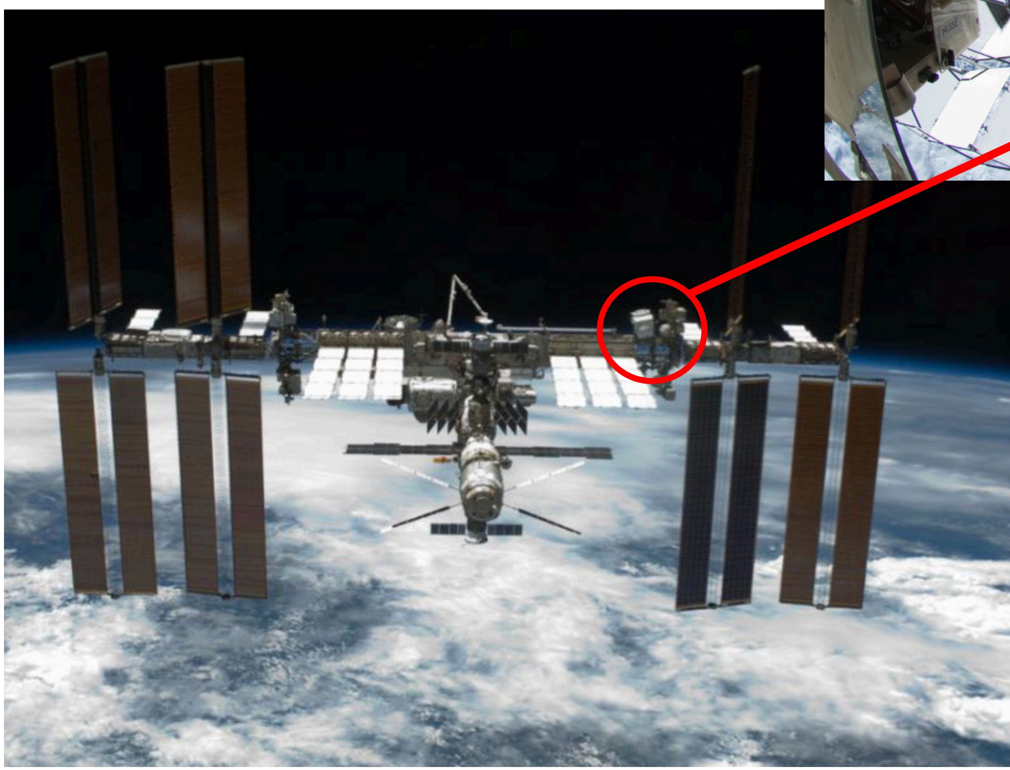
National Cheng Kung University

Outline

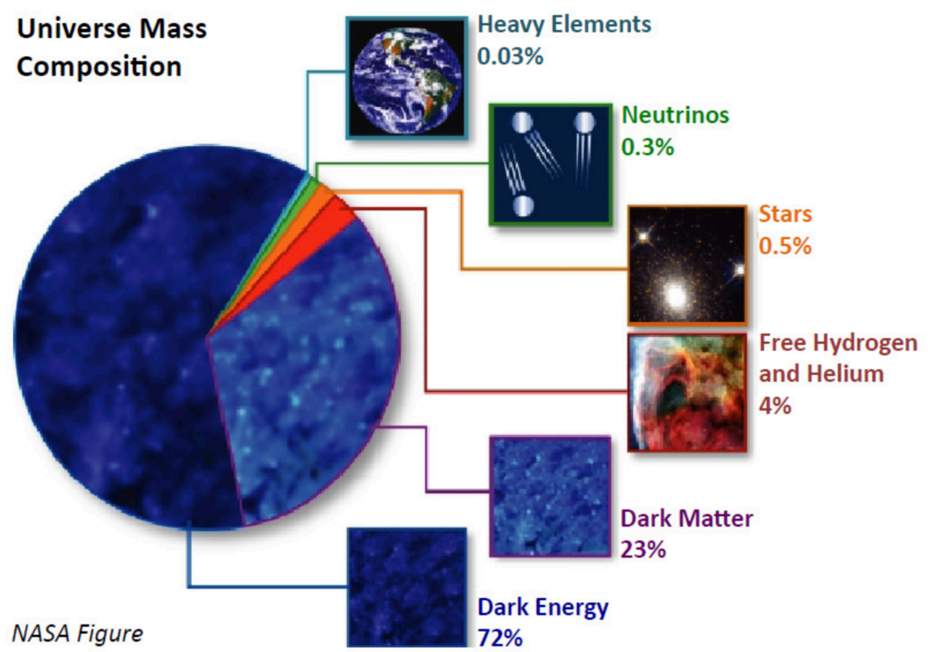
- Introduction
- The AMS-02 Detector
- Physics Analysis
- Summary

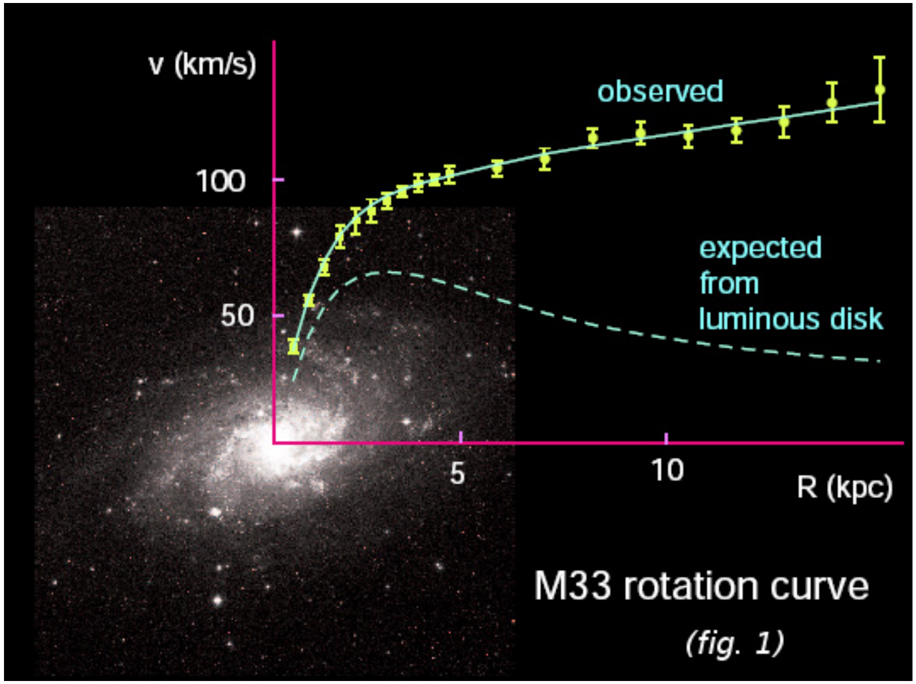




Introduction

- The Standard Model of Particle Physics is not perfect, there are many unsolved problems
- Some very important and mysterious questions in physics are the origin of ***Dark Matter*** and ***Dark Energy***, and ***particle-antiparticle asymmetry***





Dr. Vera Rubin (1928 - 2016)

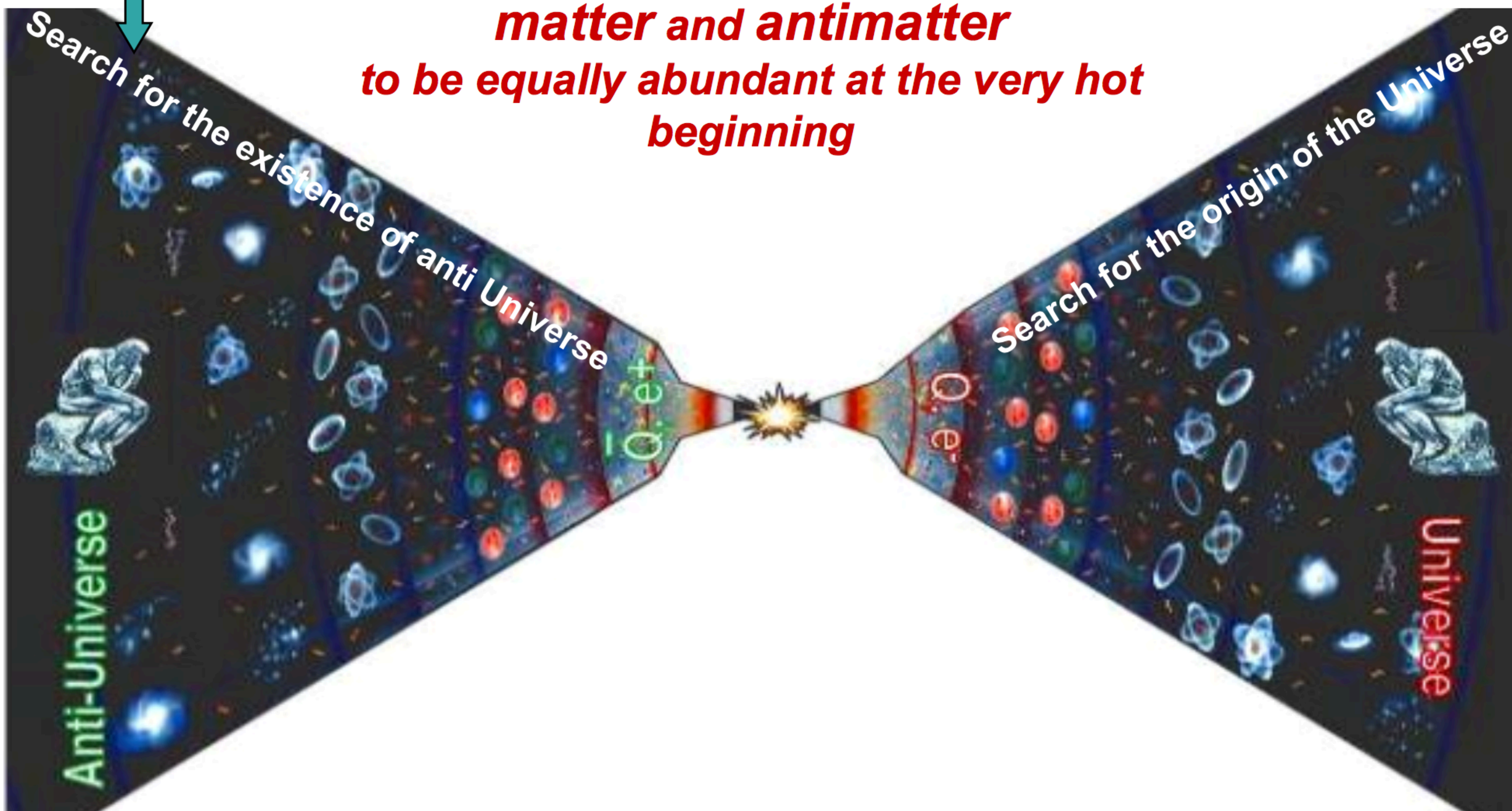
- The pioneer who opened our world!

Introduction

- The mystery of matter-and-antimatter asymmetry

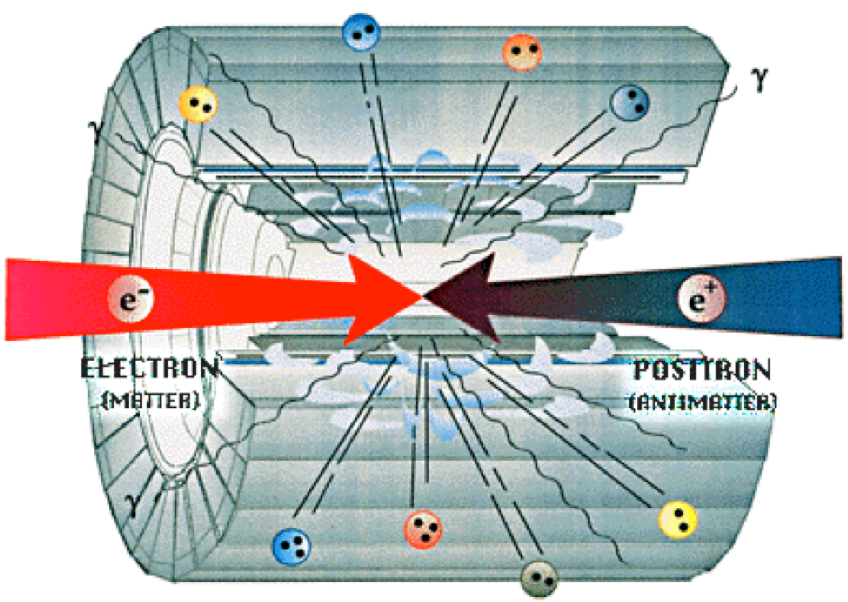
AMS in Space

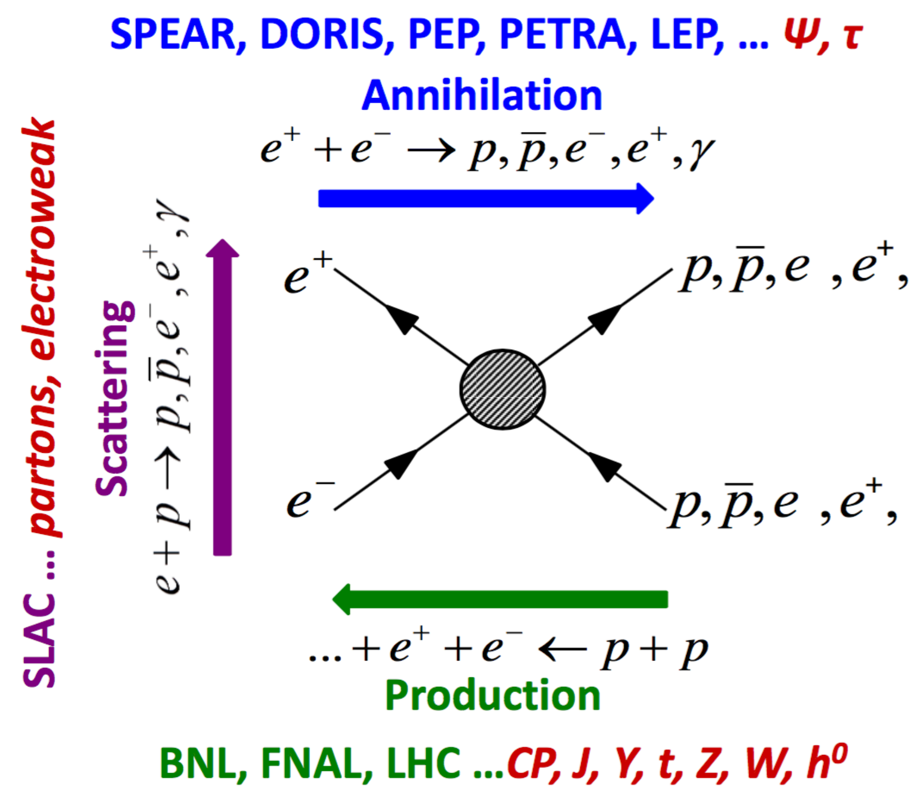
The Big Bang origin of the Universe requires
matter and antimatter
to be equally abundant at the very hot beginning



Introduction

- **There are two ways to study particle physics**
  1. Collide two particles to each other with high energy to create different particles
  2. Use the high energy particles from Nature: cosmic rays





Introduction

- **There are two ways to study particle physics**
  1. Collide two particles to each other with high energy to create different particles
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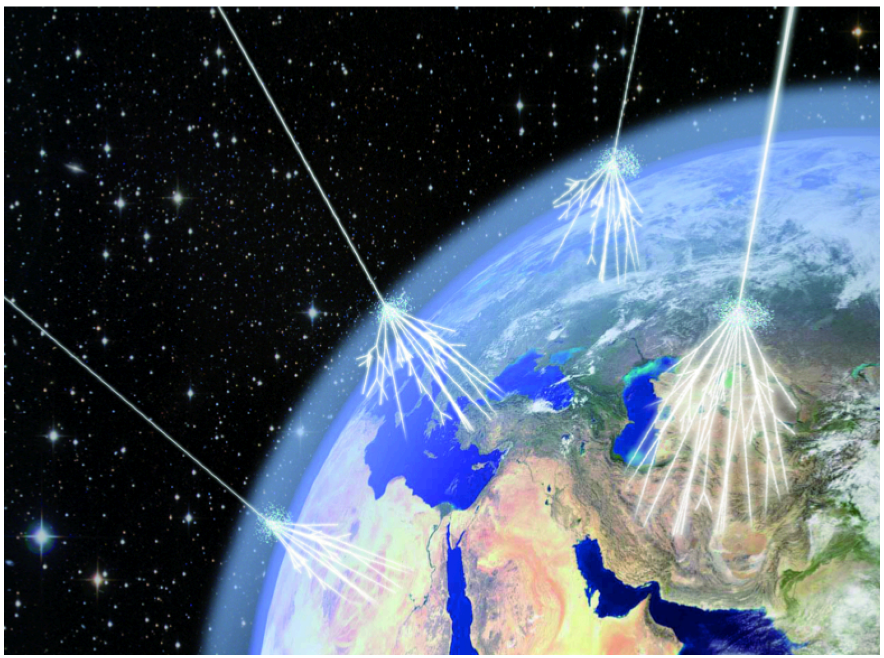
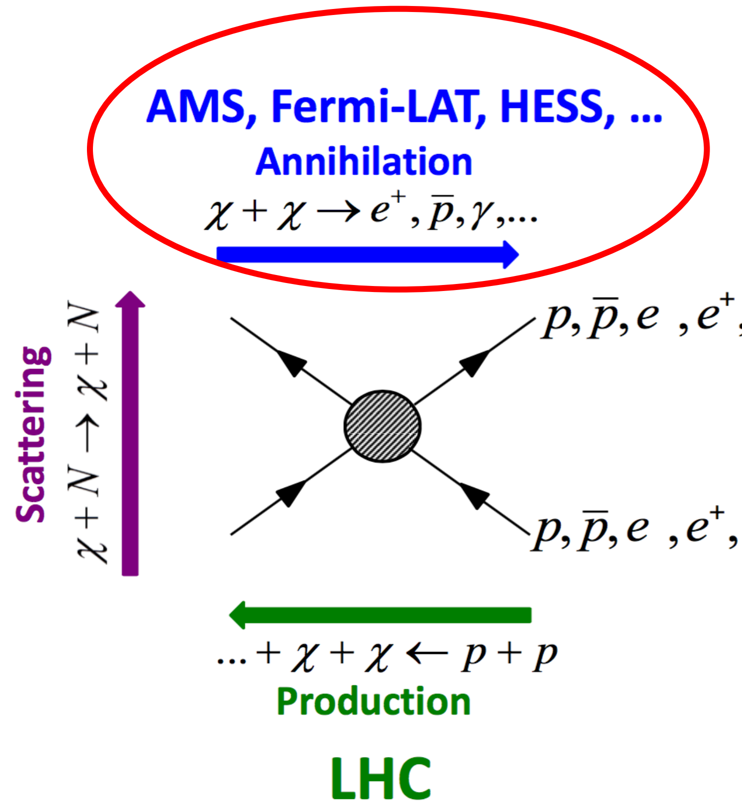
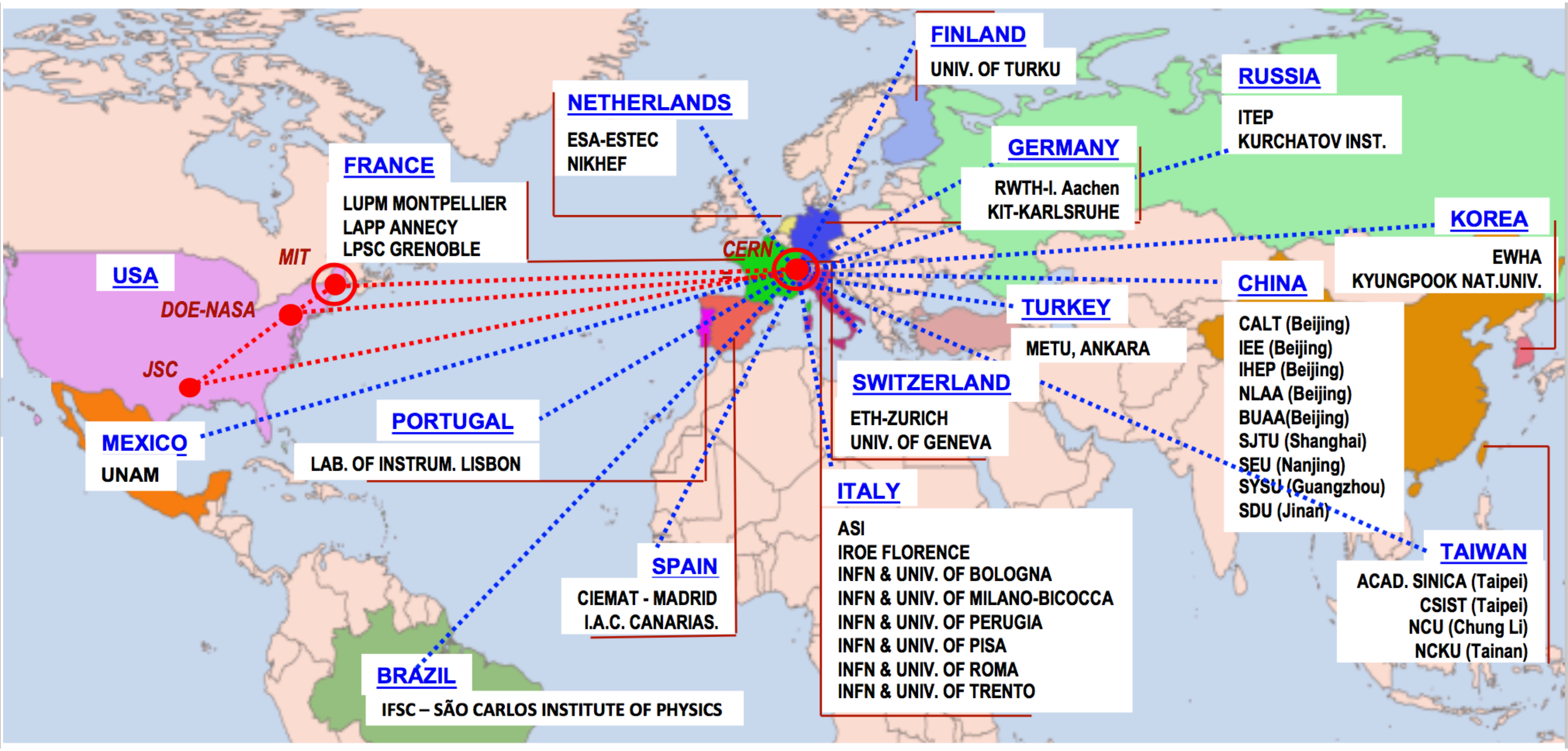


LUX
DARKSIDE
XENON 100
CDMS II
...



The AMS Collaboration

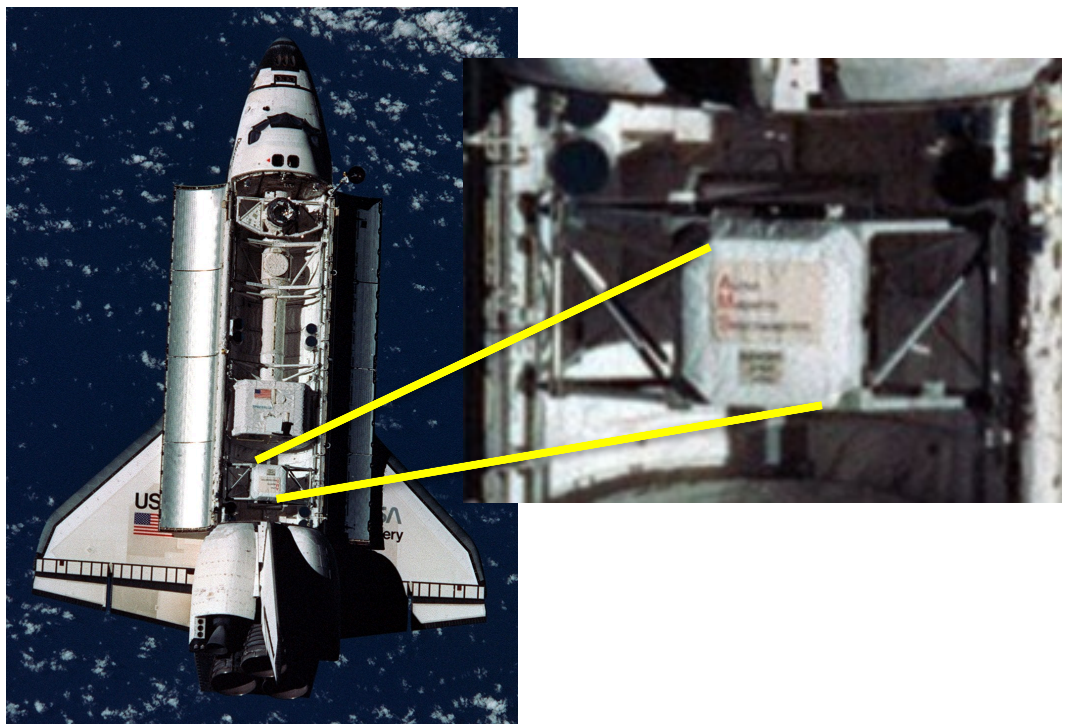
- International collaboration: 16 countries, ~60 institutions, and ~600 scientists



The AMS-01 Experiment

- **A**lpha **M**agnetic **S**pectrometer is particle detector in the Space
  - AMS project was proposed in ***1995***
  - The prototype (AMS-01) flew with Space Shuttle ***Discovery*** for 10 days (6/2 - 6/18 ***1998***)

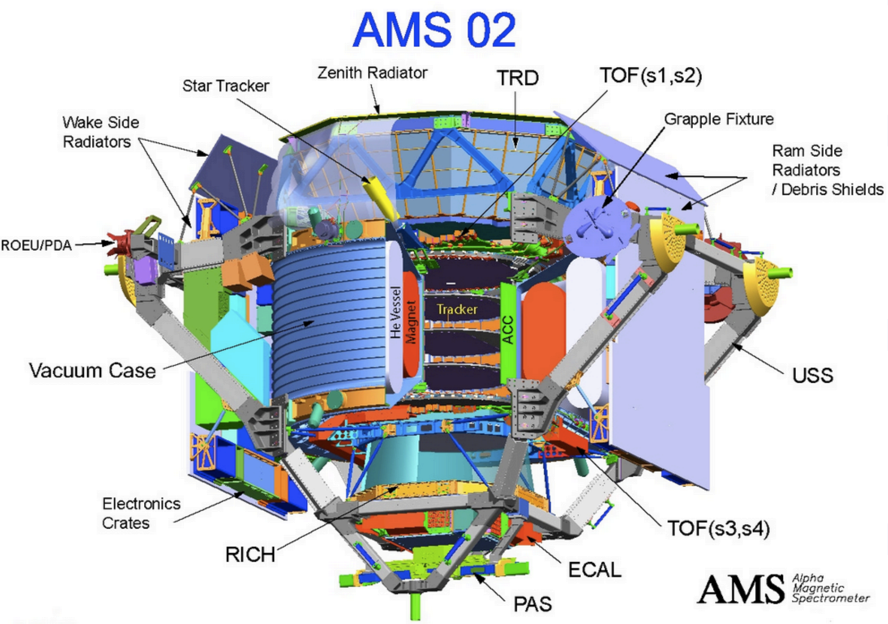
➔ The main goal for AMS -01 was to prove the detector concept worked in space



The AMS-02 Detector

- Particle physics detector
- A TeV precision, multipurpose spectrometer
- Launched with ***Space Shuttle Endeavour*** on ***16 May 2011*** and installed on ***ISS*** on ***19 May 2011***
- First result was reported in 2012
- ***Main goals: Antiparticle-particle asymmetry and new physics***

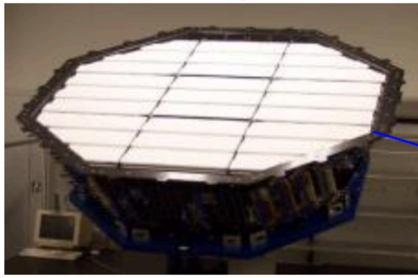
The AMS-02 Detector



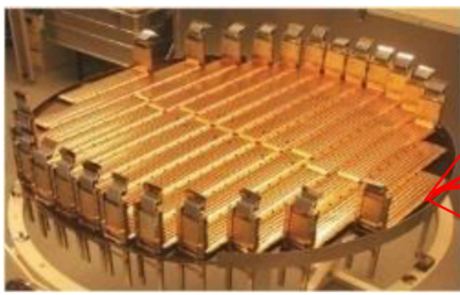
- **Magnet** bends in opposite directions charged particles/antiparticles
- **Transition Radiation Detector (TRD)** identifies electrons and positrons among other cosmic-rays
- **Time-of-Flight System (ToF)** warns the sub-detectors of incoming cosmic-rays
- **Silicon Tracker (Tracker)** detects the particle charge sign, separating matter from antimatter
- **Ring-Imaging Cherenkov Detector (RICH)** measures with high precision the velocity of cosmic-rays
- **Electromagnetic Calorimeter (ECAL)** measures energy of incoming electrons, positrons and γ-rays
- **Anti-Coincidence Counter (ACC)** rejects cosmic rays traversing the magnet walls
- **Tracker Alignment System (TAS)** checks the Tracker alignment stability
- **Star Tracker and GPS** defines the position and orientation of the AMS-02 experiment

The AMS-02 Detector

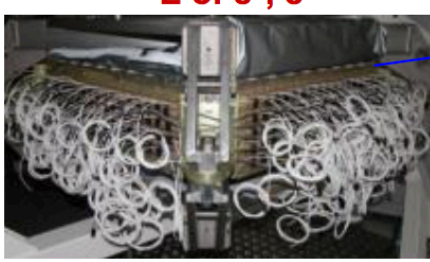
Transition Radiation Detector (TRD)
Identify e^+, e^-

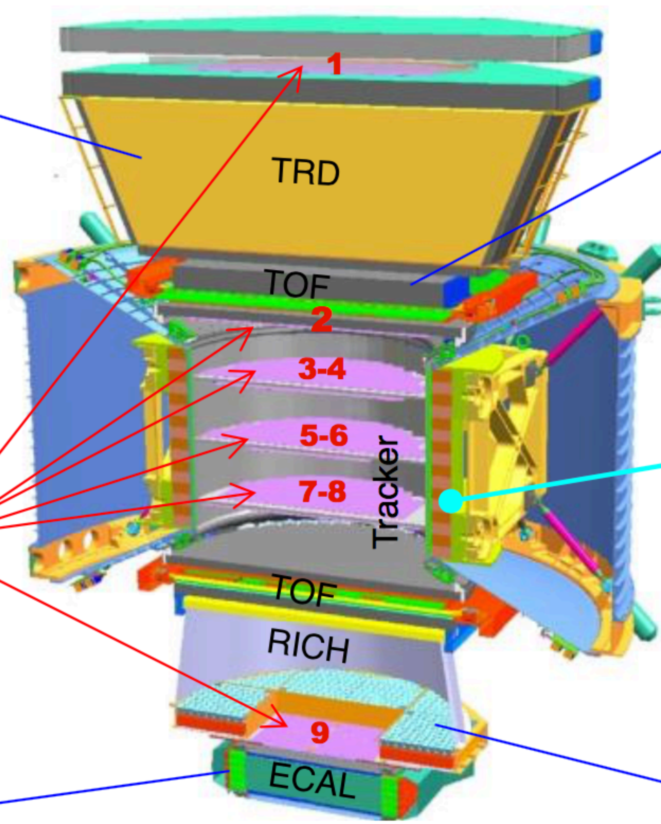


Silicon Tracker
Z, P or R=P/Z



Electromagnetic Calorimeter (ECAL)
E of e^+, e^-

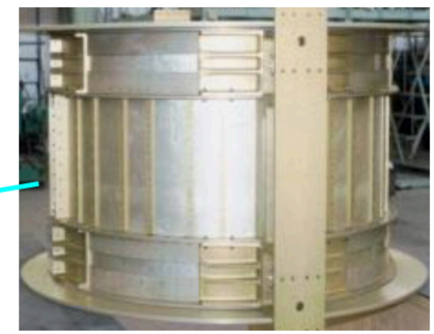




Z and P, E or R are measured independently by Tracker, ECAL, TOF and RICH

Time of Flight (TOF)
Z, E

Magnet
±Z



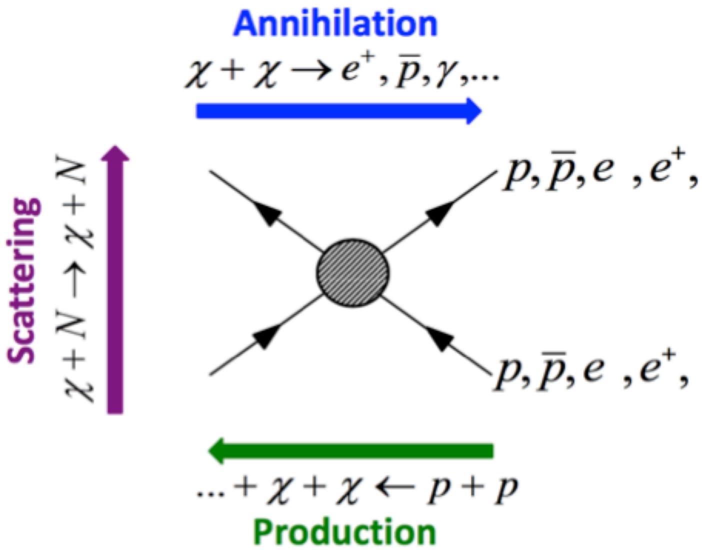
Ring Imaging Cherenkov (RICH)
Z, E

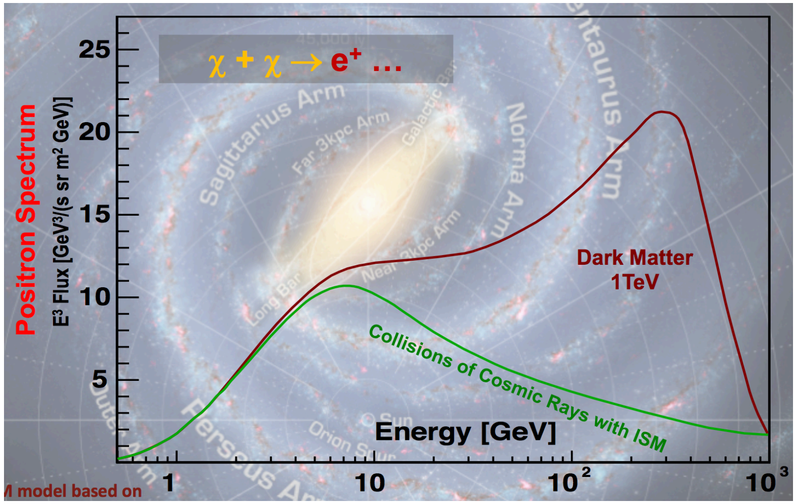
The AMS-02 Results

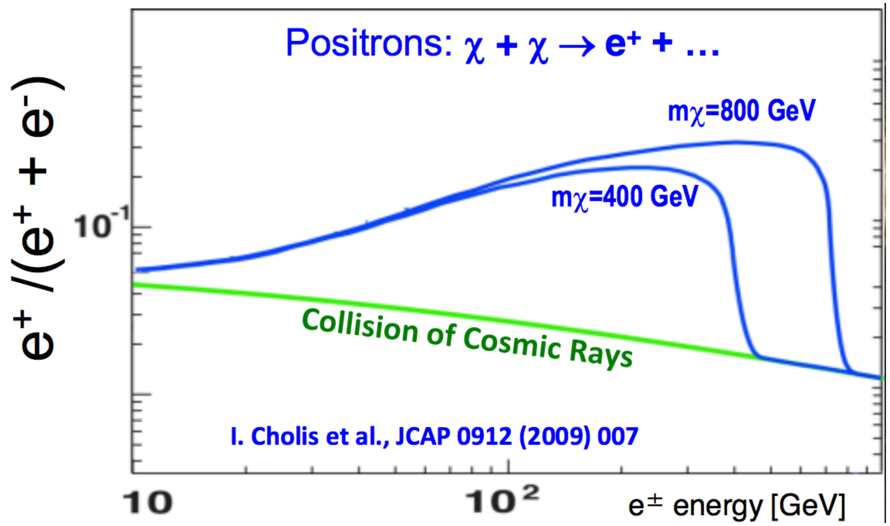
- In ***5 years*** on ISS, AMS-02 has collected ***> 90 billion cosmic rays***
- With this large statistics, the systematic uncertainty is very important now

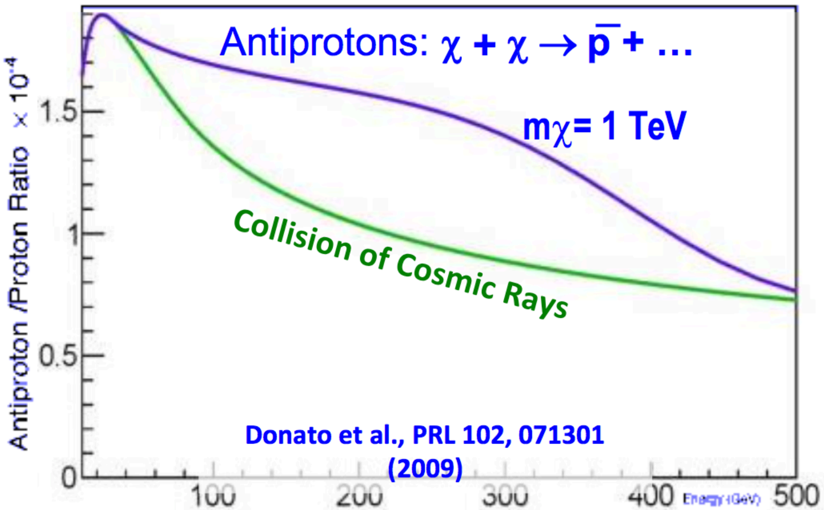
Dark Matter Search with AMS

- Dark Matter annihilation will produce **extra positrons** and **protons**









The first Positron fraction result

THE ASTROPHYSICAL JOURNAL, Vol. 158, November 1969

CHARGE COMPOSITION AND ENERGY SPECTRUM OF PRIMARY COSMIC-RAY ELECTRONS*

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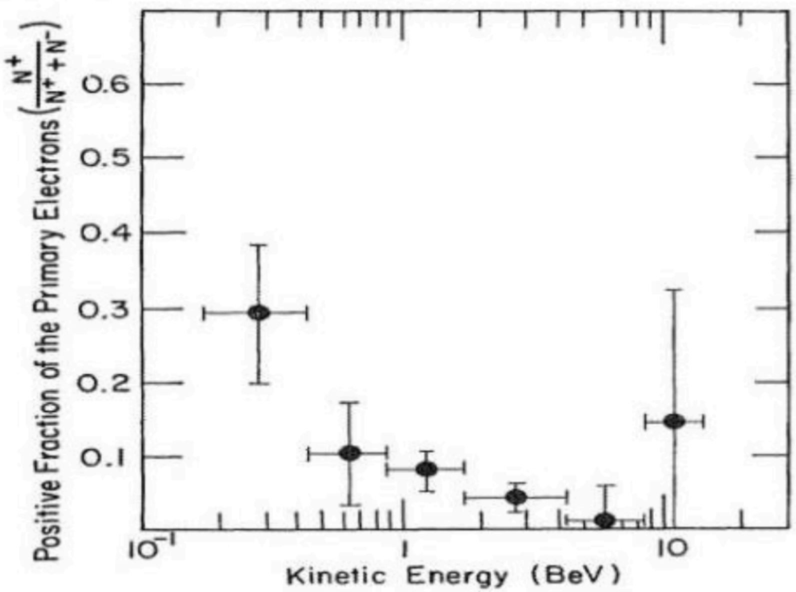
Enrico Fermi Institute, University of Chicago
Received 1969 April 29

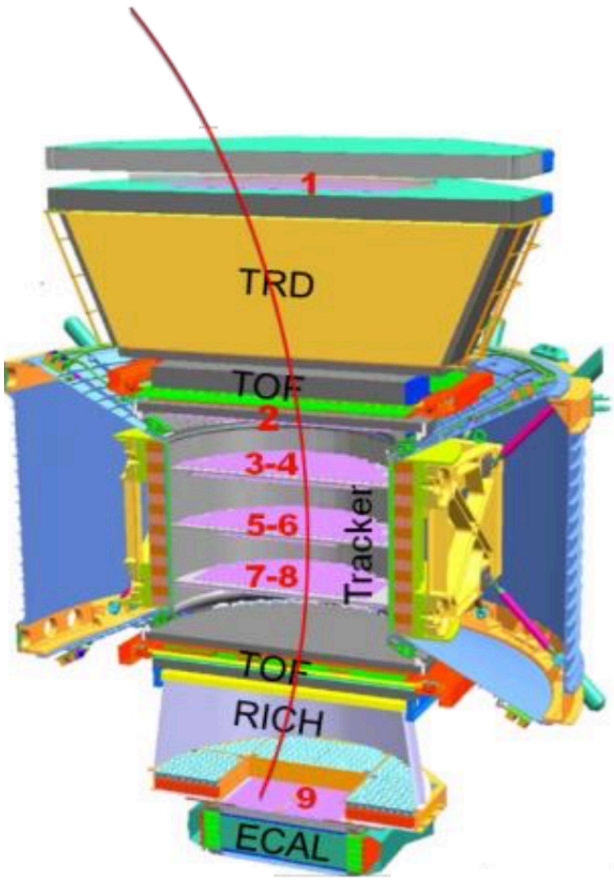
ABSTRACT

The flux, energy spectrum, and charge composition of the electron component of primary cosmic rays was measured in 1965 and 1966 in the range from 170 MeV to 14.3 BeV, and a finite flux of positrons was observed up to 4 BeV. The positron fraction $N^+/(N^+ + N^-)$ is shown to decrease as a function of energy. For the first time, it has been possible to determine the energy spectrum of primary positrons above 220 MeV. To approximate this observed spectrum above 860 MeV by a power law requires an exponent of 2.6 ± 0.5, consistent with negligible modification of the source spectrum below 10 BeV by energy-loss processes. Comparison of the differential energy spectrum of positrons with calculations based on a collision origin leads to a reasonable agreement for a disk model with passage of cosmic rays through 3–4 g cm^{-2} of interstellar material and modulation parameters $\eta = 0.6$ BV and $R_0 = 0.3$ BV.

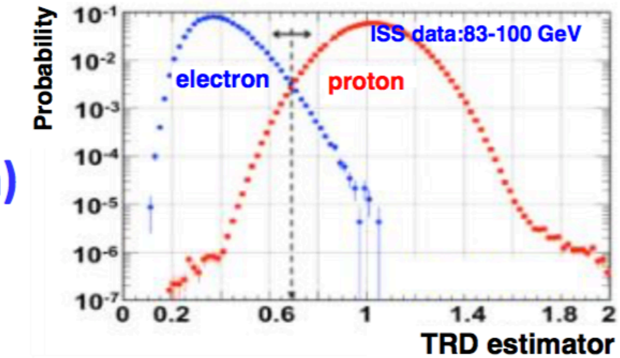


-The positron fraction $N^+/(N^+ + N^-)$ as a function of energy

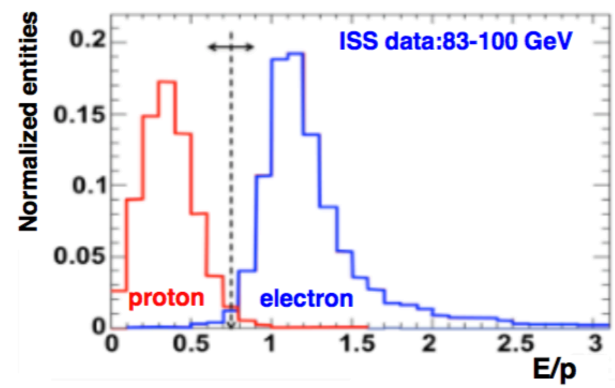
Electron and Positron



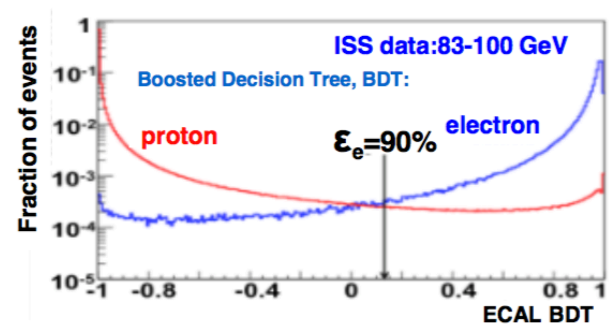
TRD
(transition radiation)
to identify $e^{\pm}$



ECAL measures E
Tracker measures p
$e^{\pm}$: E=p
proton: E<p

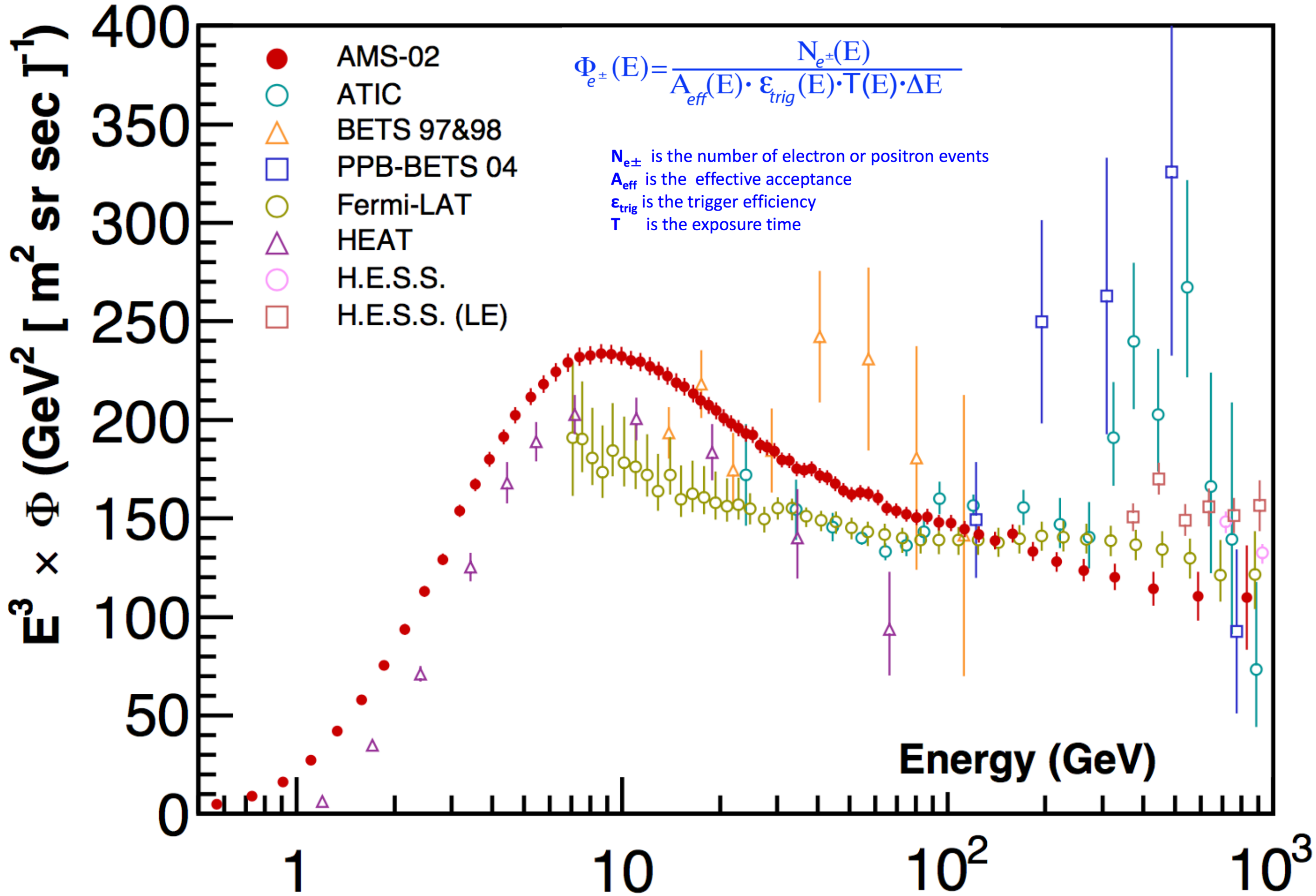


ECAL
(shower shape)
to separate $e^{\pm}$
from protons

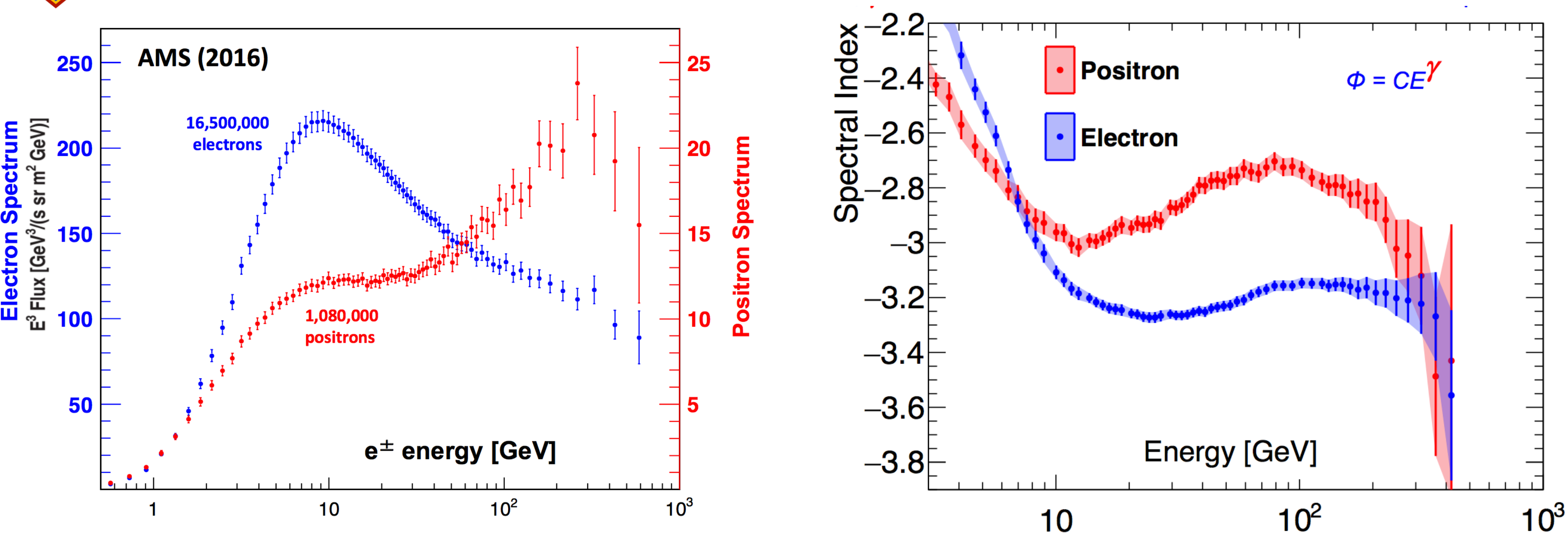


Electron + positron flux (2014)

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



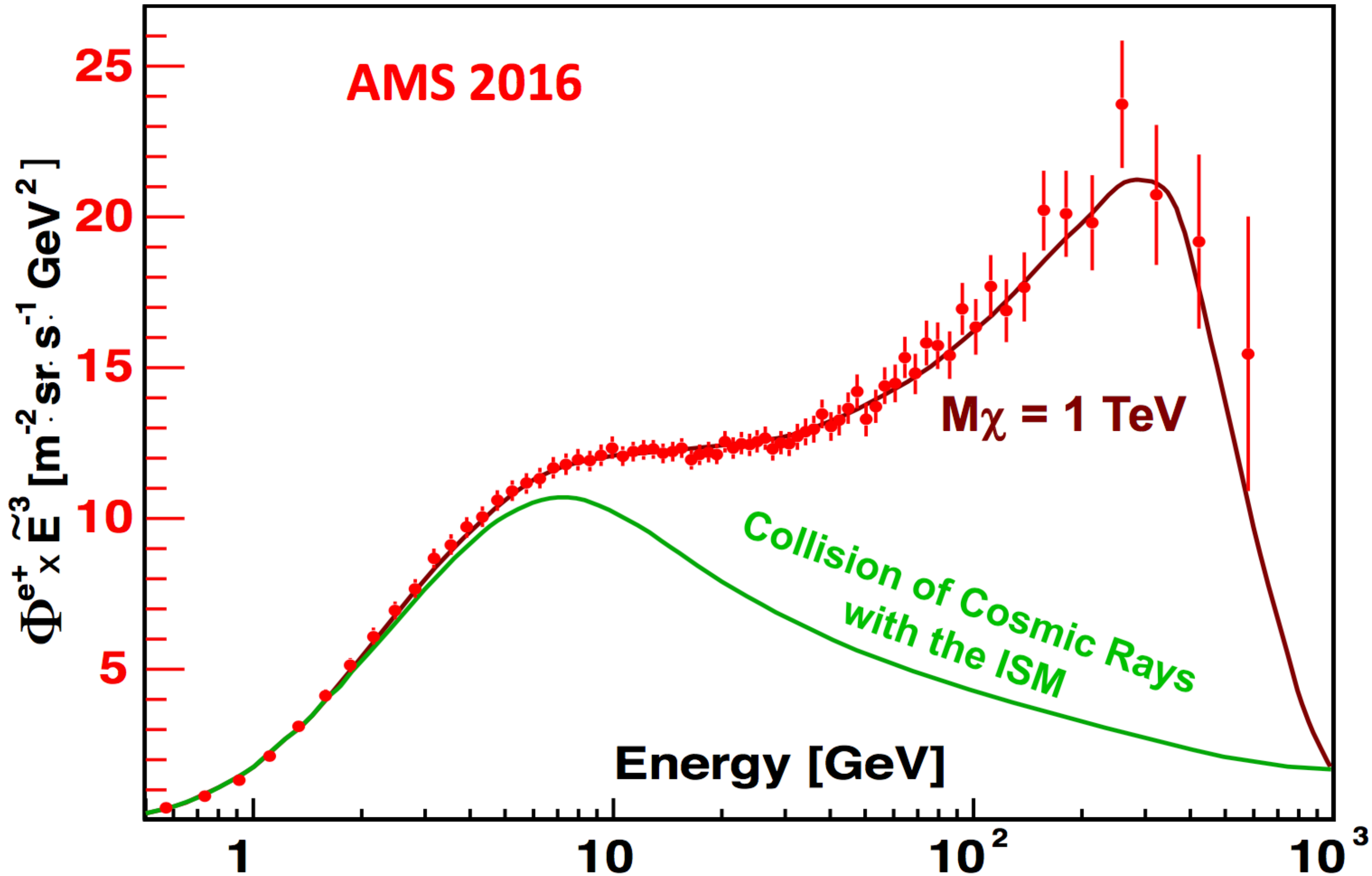
Electron and Positron Flux (2016)



- The electron flux and the positron flux are different in their ***magnitude*** and ***energy*** dependence
- Both spectra ***cannot*** be described by **single power laws**
- The ***spectral indices*** of electrons and positrons are different
- 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).

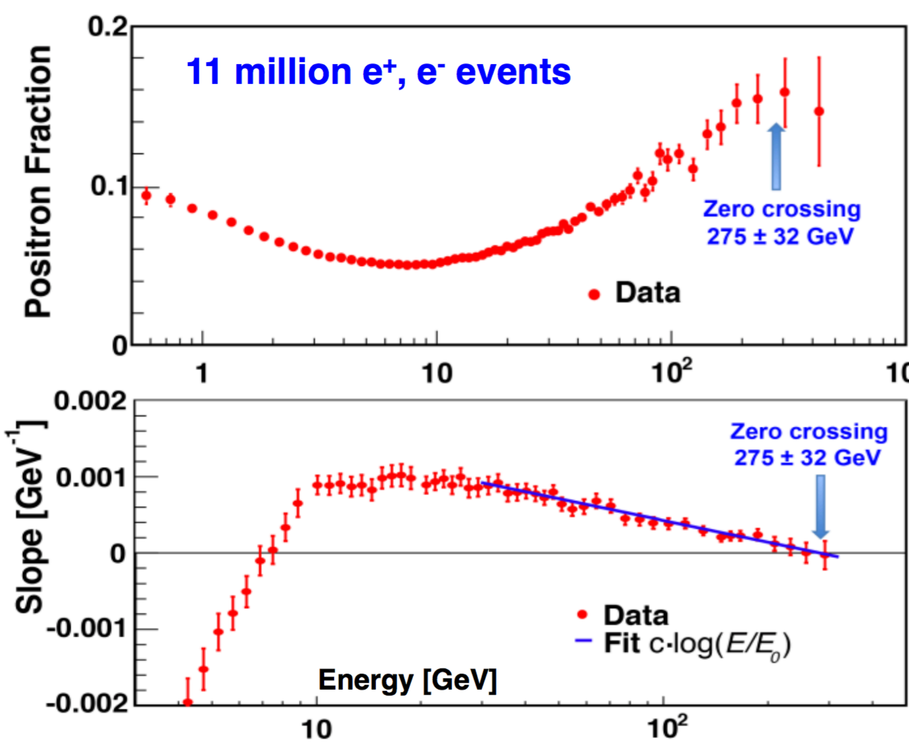
Positron Flux (2016)

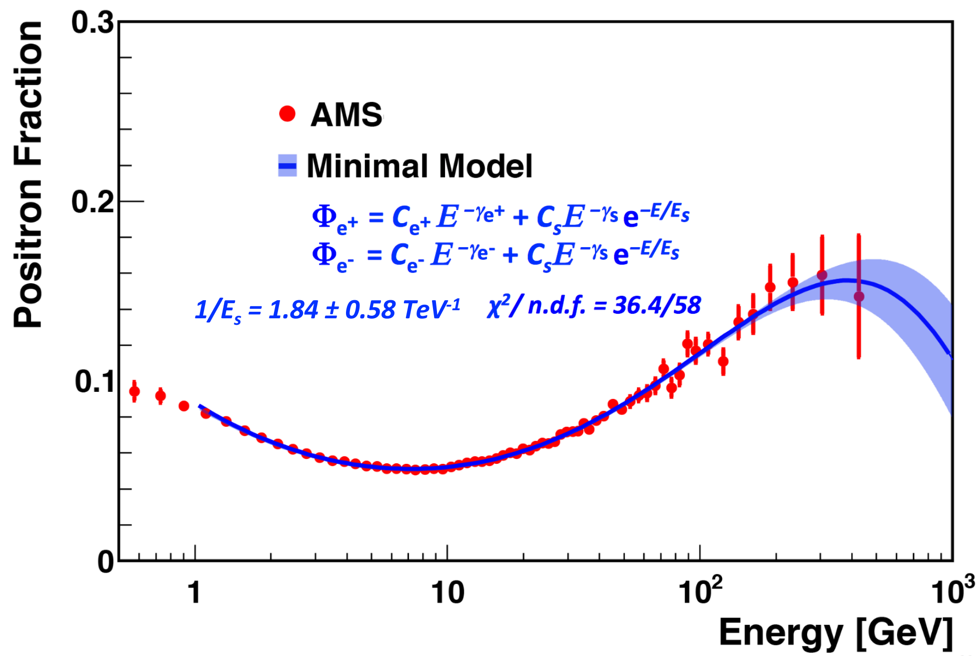
- The AMS results are in excellent agreement with a Dark Matter Model



Positron Fraction (2014)

- Precision measurement from 0.3 to 500 GeV
- The slope reaches zero at 275 (±32) GeV ➔ Go flat or down
- Consistent with the minimal model with an extra common source

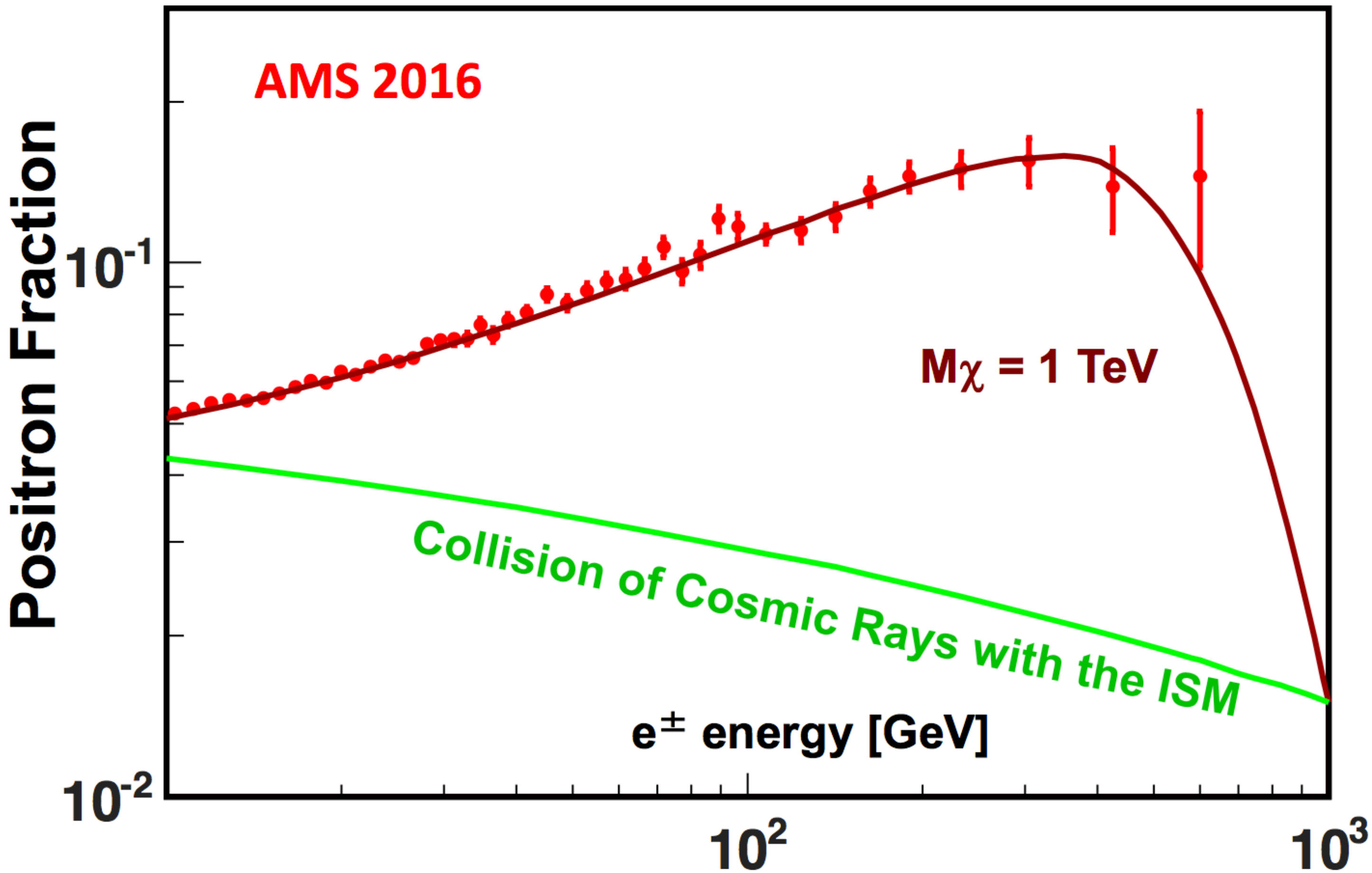




Positron Fraction (2016)

- Also consistent with a simple Dark Matter model with 1 TeV mass and the Pulsar model

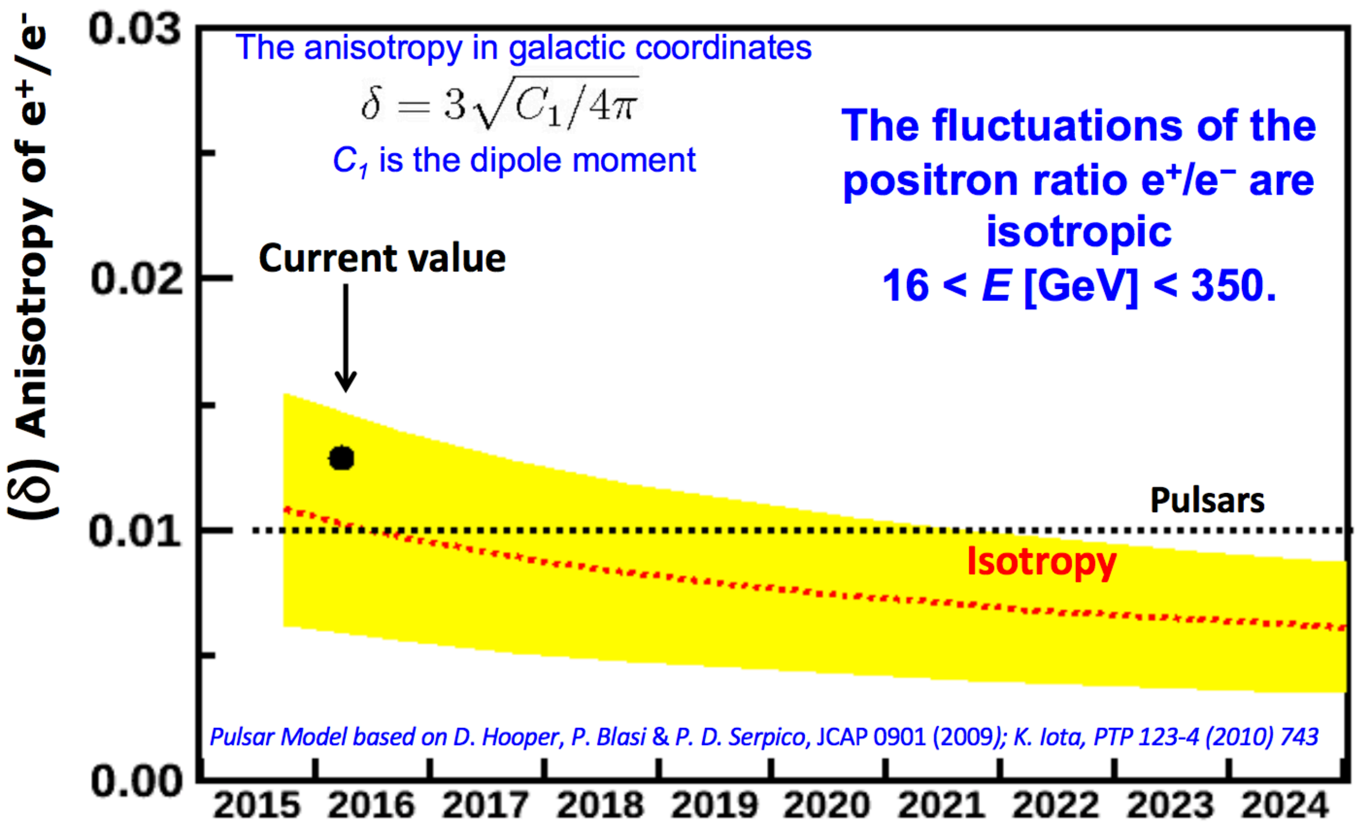
➔ **It is too early to make any solid conclusion**



Anisotropy (2014)

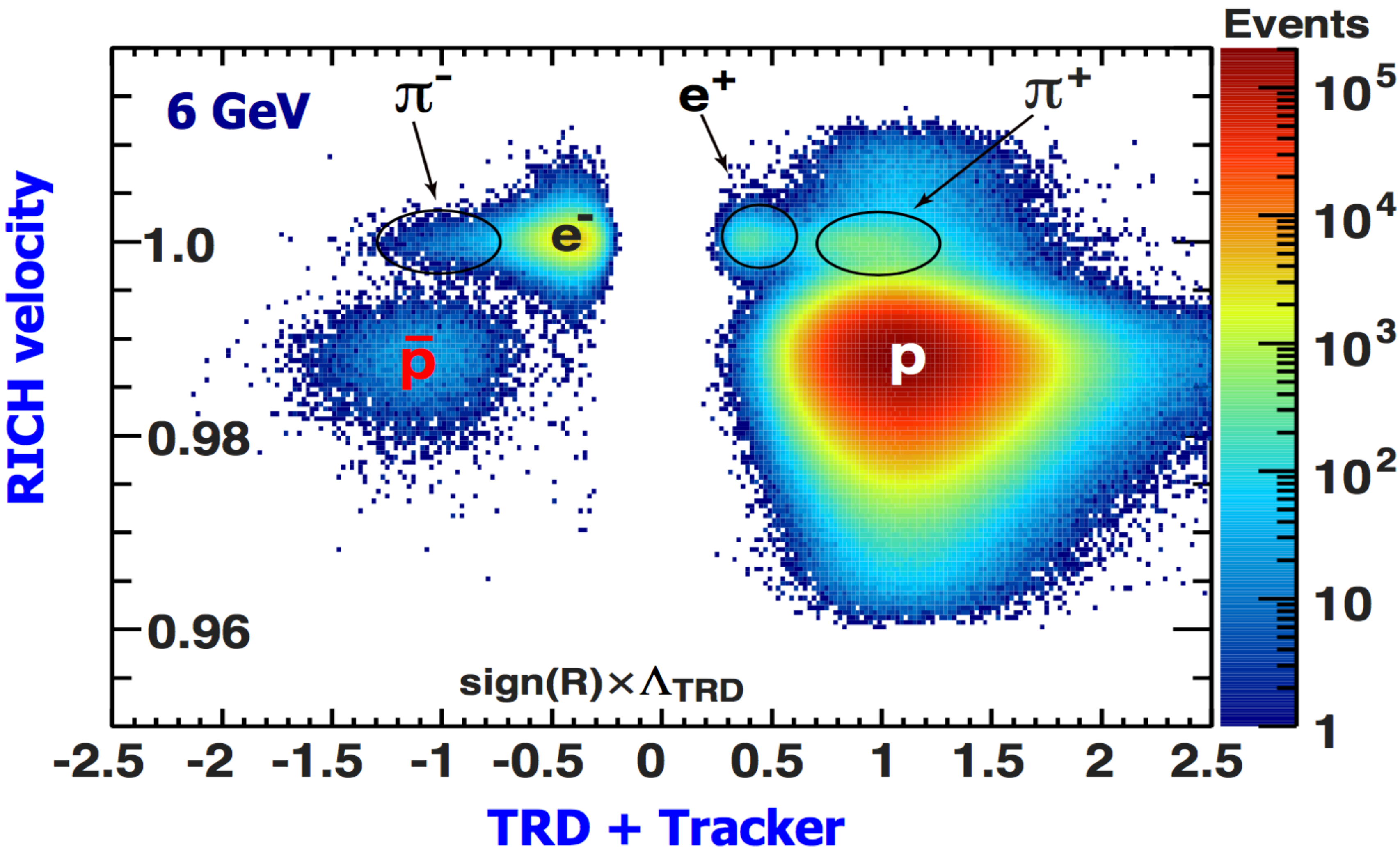
- Astrophysical point sources like pulsars will imprint a higher level of anisotropy on the arrival directions of energetic positrons than a smooth dark matter halo.

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



Proton and Antiproton

- The antiproton signal is well separated from the backgrounds

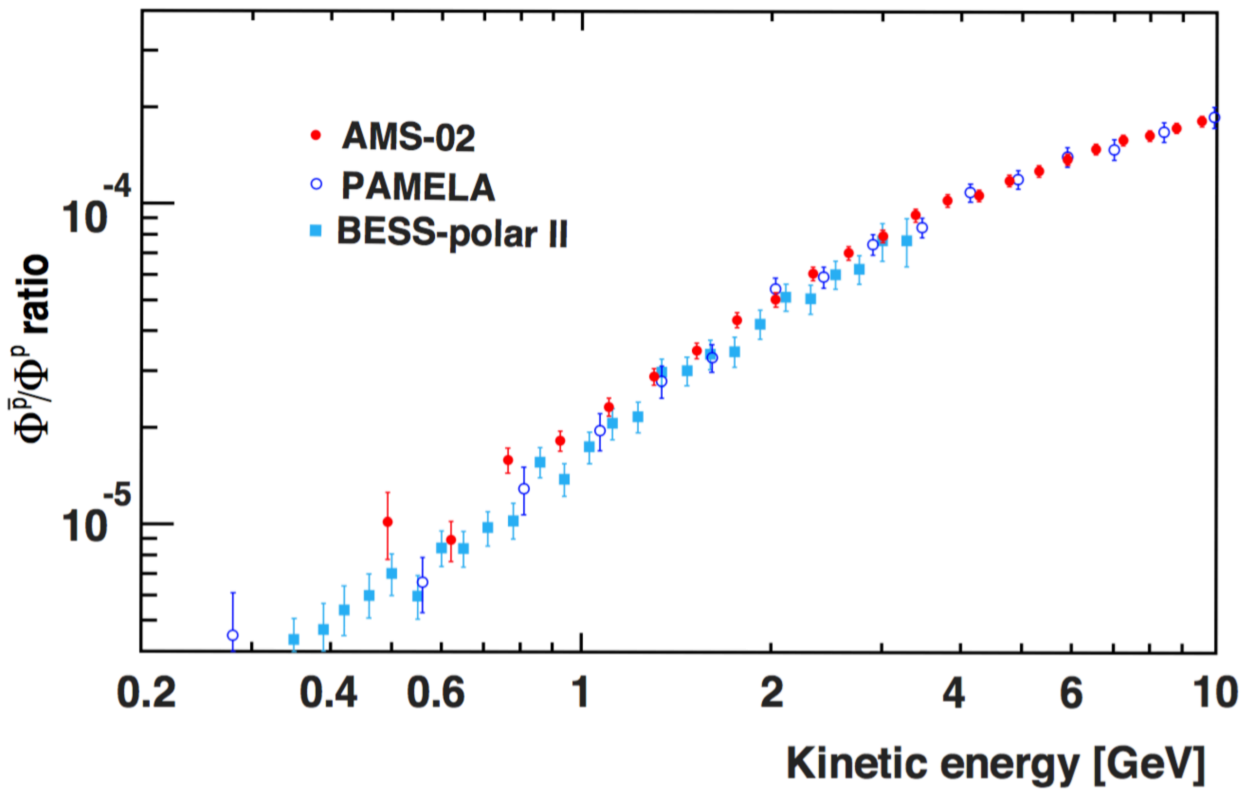


Antiproton-to-Proton Ratio

- Ratio definition: $$\left(\frac{\bar{p}}{p}\right)_i \equiv \frac{\Phi_i^{\bar{p}}}{\Phi_i^{p}} = \frac{\tilde{N}_i^{\bar{p}}}{\tilde{N}_i^{p}} \frac{\tilde{A}_i^{p}}{\tilde{A}_i^{\bar{p}}}$$

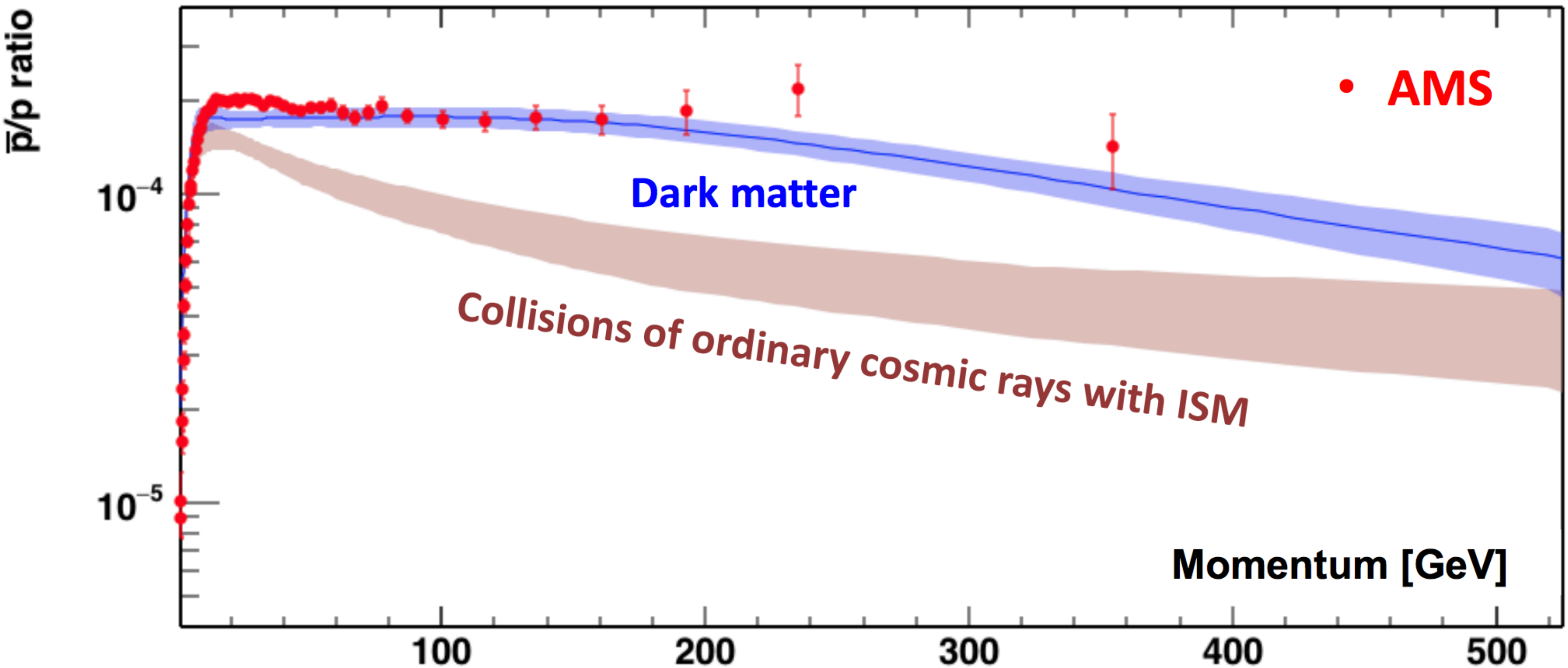
  → Most of the systematic uncertainties cancel out

- Good agreement with other experiments in low energy



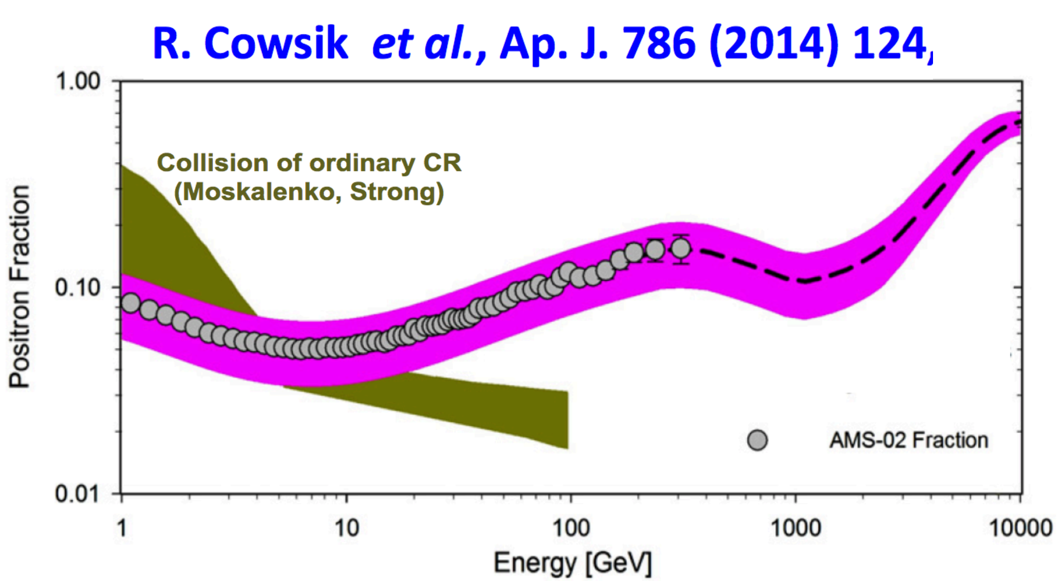
Antiproton-to-Proton Ratio (2016)

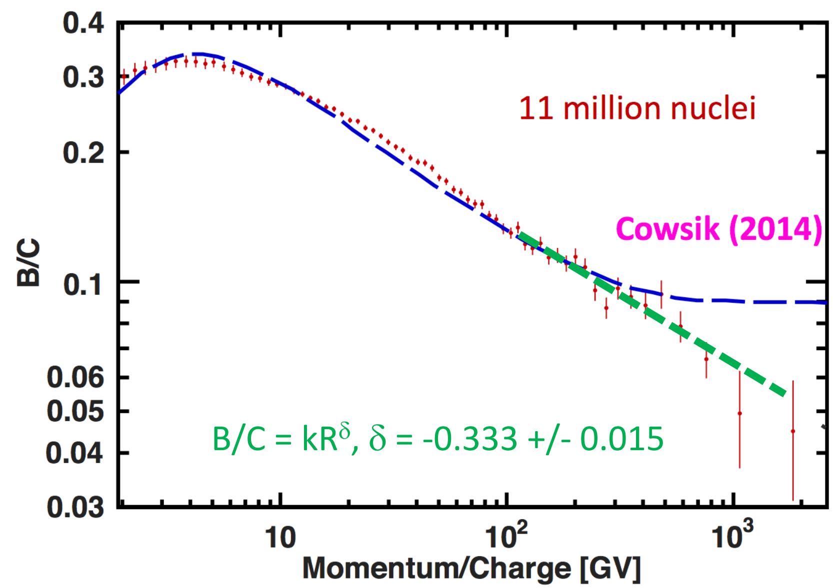
- The excess of antiprotons observed by AMS cannot come from pulsars.
- It can be explained by Dark Matter collisions or by new astrophysics phenomena



Boron-to-Carbon Ratio (2016)

- The flux ratio between primaries (C) and secondaries (B) provides information on propagation and the ISM
- Some models (ex: Cowsik) can explain the AMS positron fraction above 10 GeV (propagation effects), but it also requires a specific energy dependence of the B/C ratio
- The AMS result shows no significant structure in high regidity

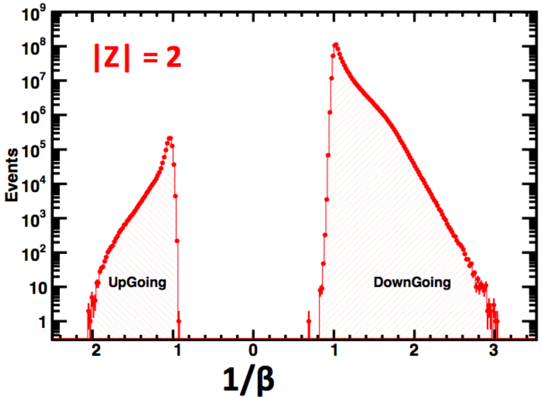




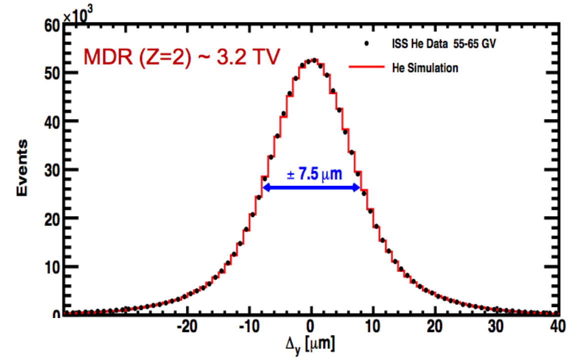
Search for Anti-Helium

- To date we have observed a few events with Z = -2 and with mass around ^{3}He

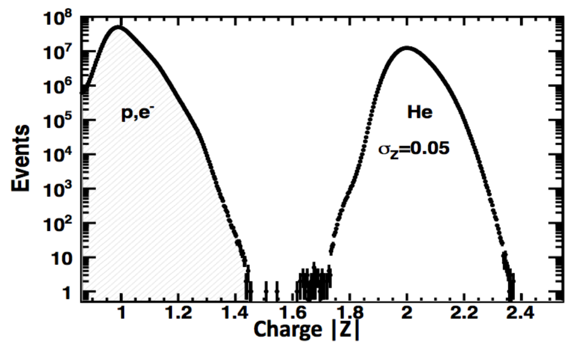
1. Determine direction with TOF.



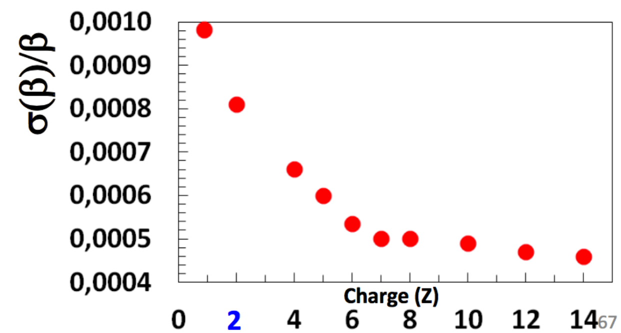
3. To measure momentum and sign of the charge, use Tracker



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



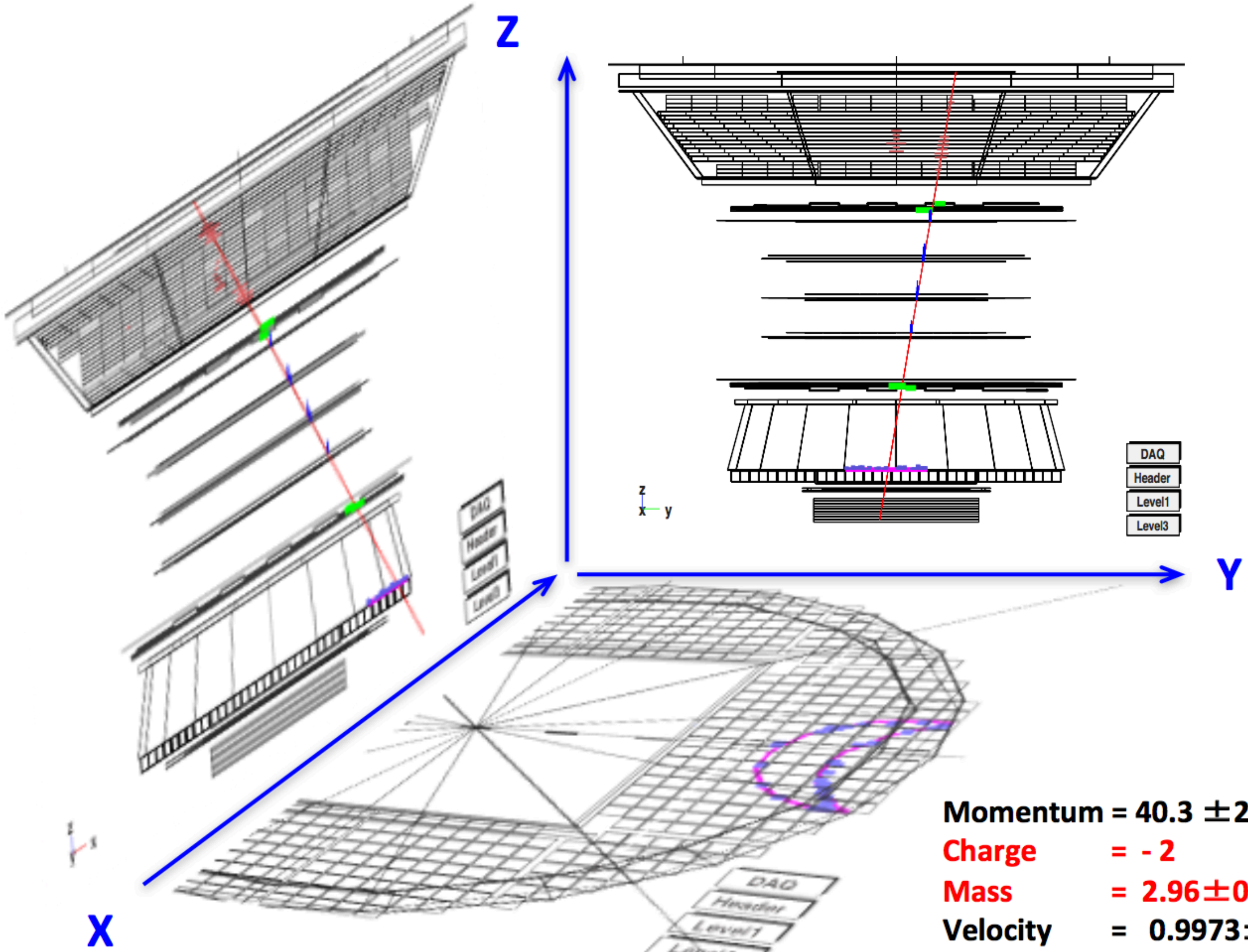
4. To determine mass, use the RICH to measure the velocity.



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

Search for Anti-Helium (2016)

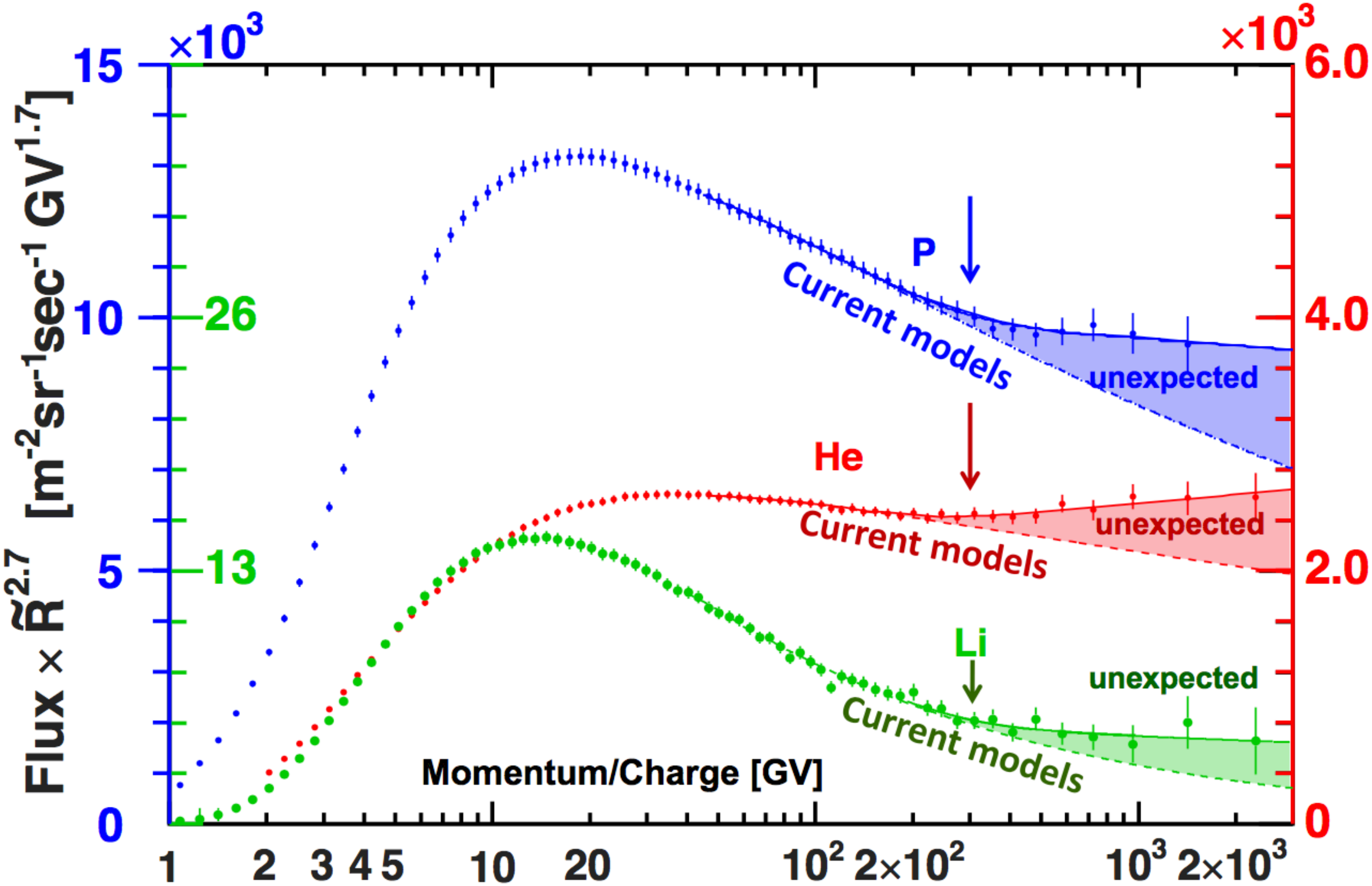
An anti-Helium candidate:



Momentum = 40.3 ±2.9 GeV/*c*
Charge = - 2
Mass = 2.96±0.33 GeV/*c*²
Velocity = 0.9973±0.0005 *c*

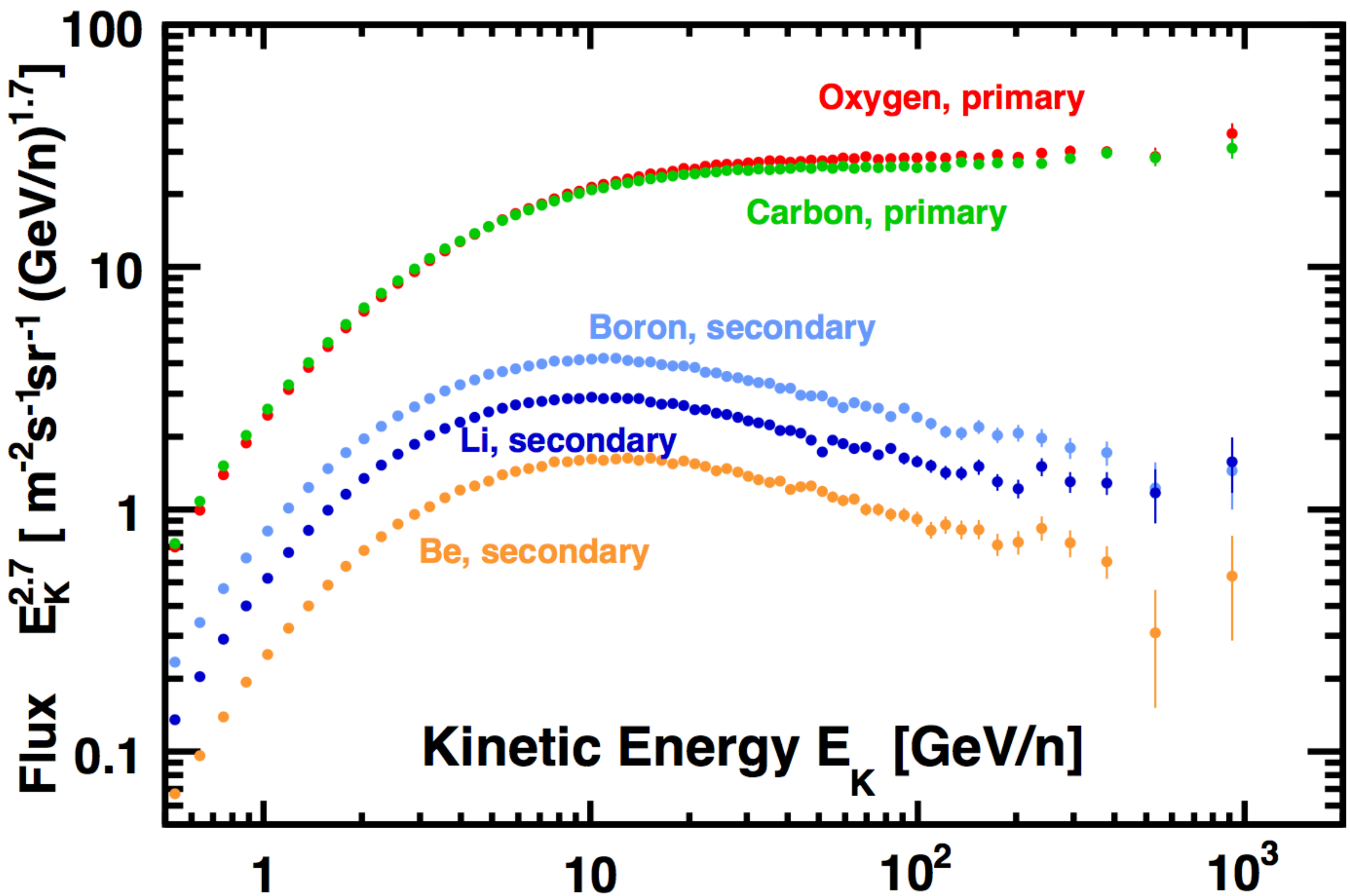
P, He and Li Fluxes

- Do not follow the traditional single power law
- Their behaviors change at the same energy



Primary vs. Secondary Cosmic Rays

- Characteristically different rigidity dependence

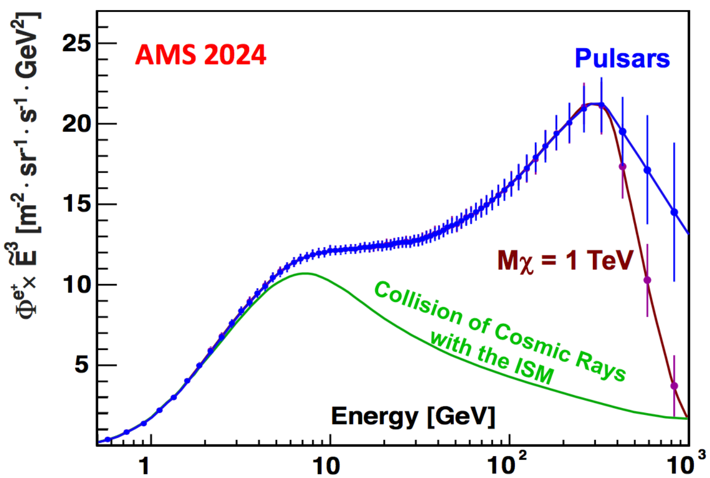


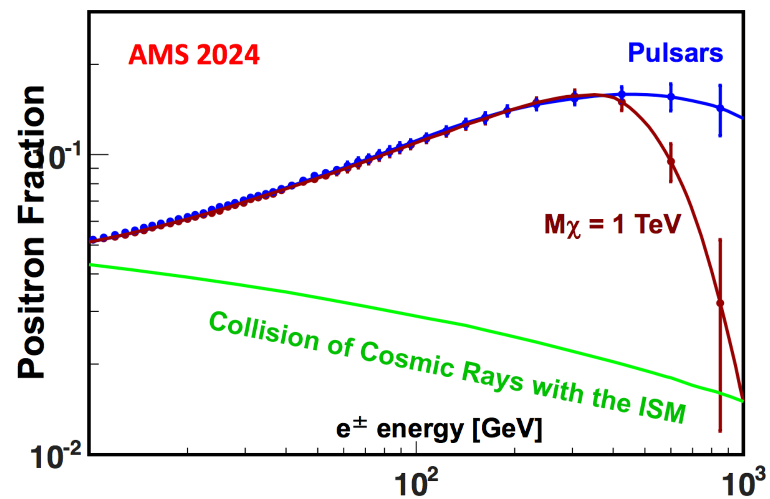
Summary

- AMS-02 is a TeV precision and multipurpose **spectrometer**
- The positron spectrum, positron fraction and antiproton-to-proton ratio are in excellent agreement with a Dark Matter
  - ➔ Need more data to draw a solid conclusion
- A few anti-Helium candidates are observed
  - ➔ Need to be extremely careful on the detector verification

Positron Spectrum **Positron Fraction**

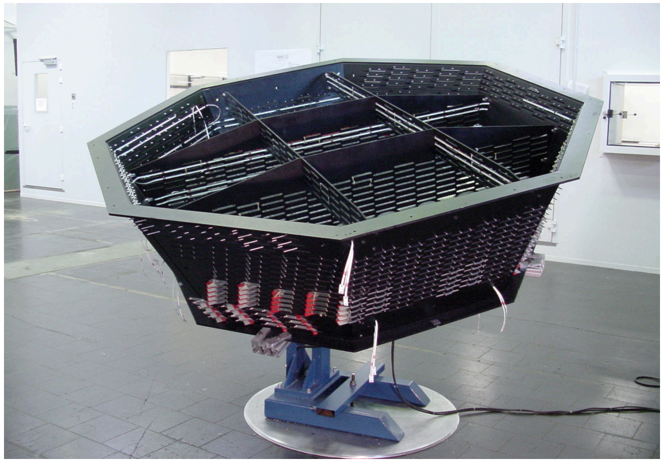
By 2024 we will should be able understand the origin of this unexpected data.

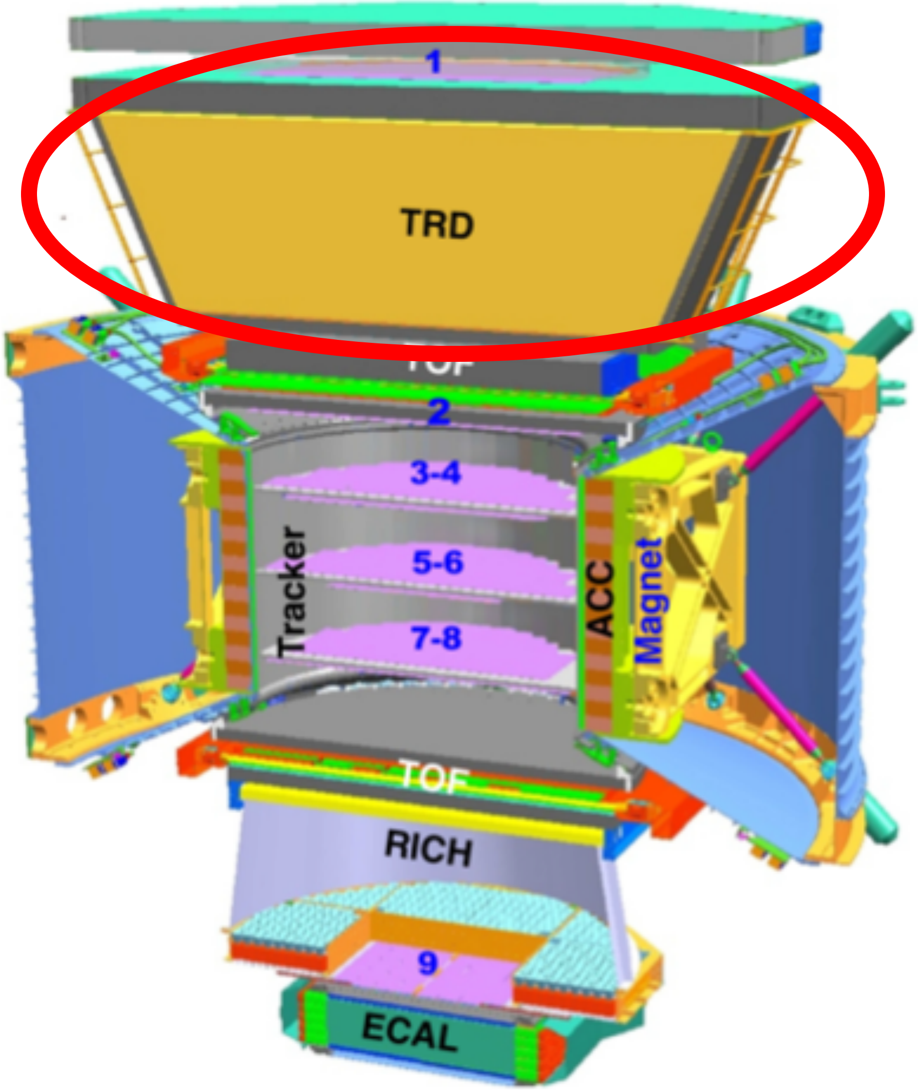




Backup

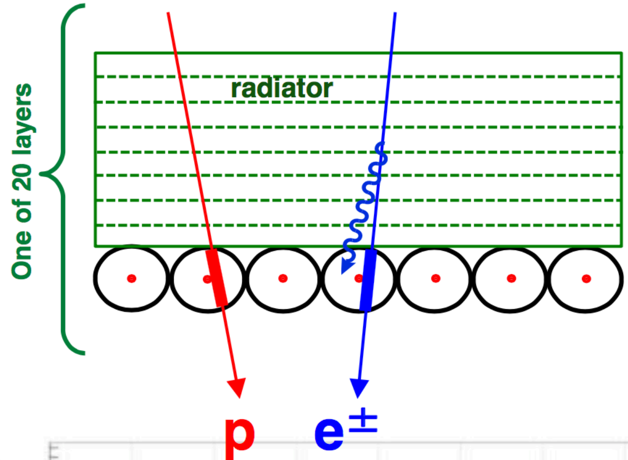
The AMS-02 Detector - TRD

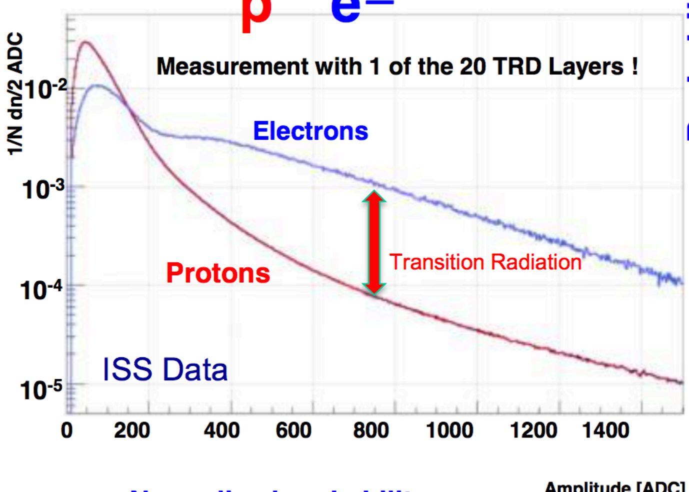


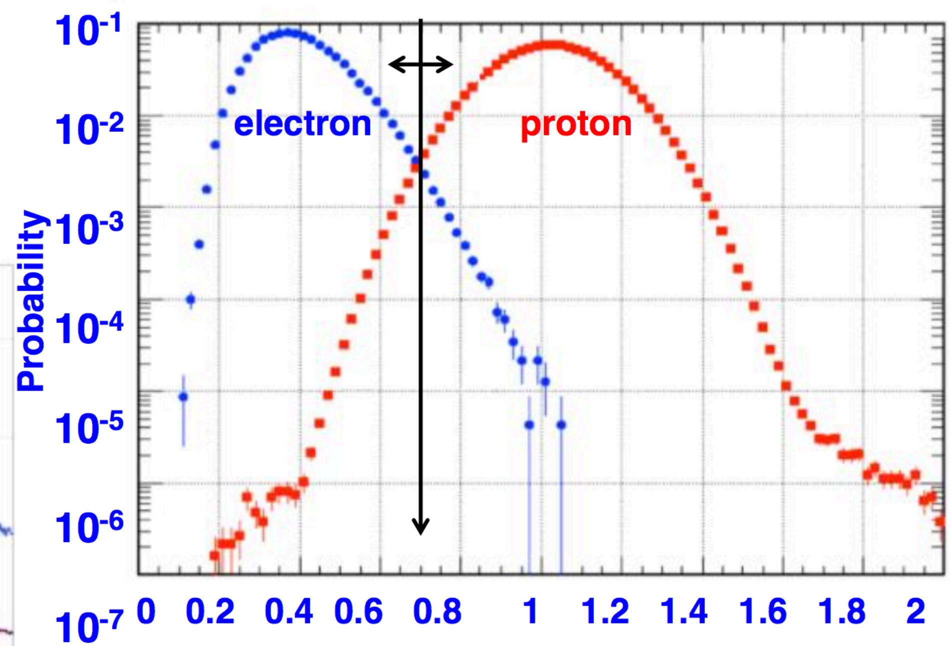


The AMS-02 Detector - TRD

Transition Radiation Detector (TRD)







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

Normalized probability

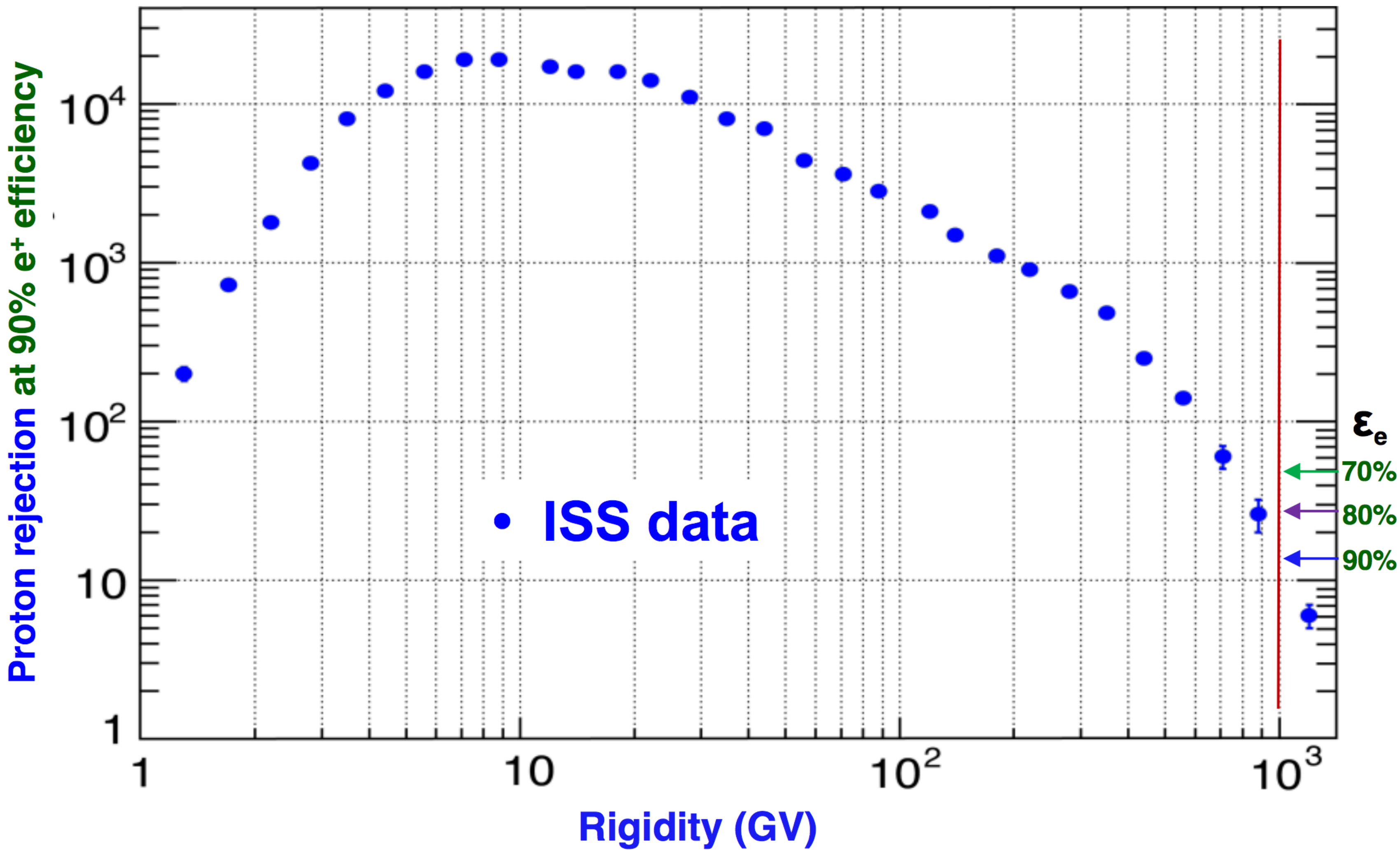
$$P_p = \sqrt[n]{\prod_{i}^{n} P_p^{(i)}(A)} \qquad P_e = \sqrt[n]{\prod_{i}^{n} P_e^{(i)}(A)}$$

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

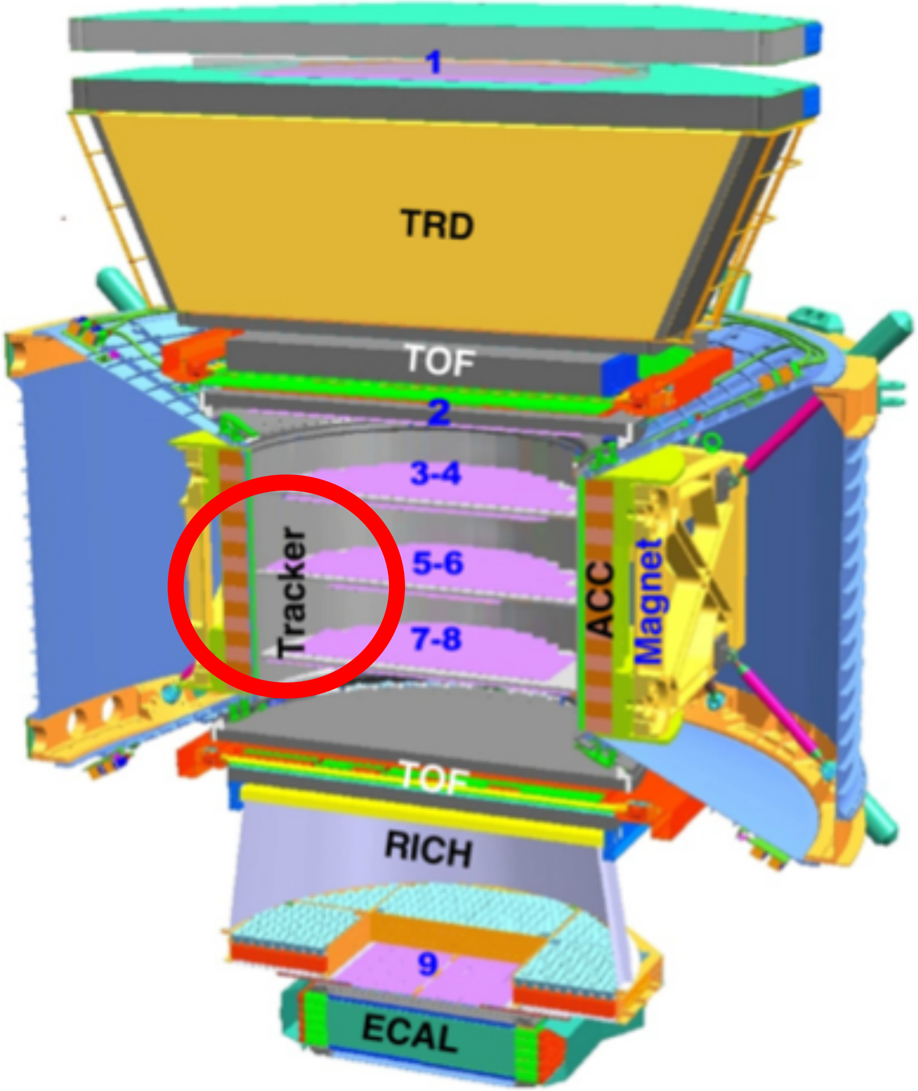
TRD classifier = $-\mathrm{Log}_{10}(P_e)-2$

The AMS-02 Detector - TRD

❑ The performance of TRD: proton rejection



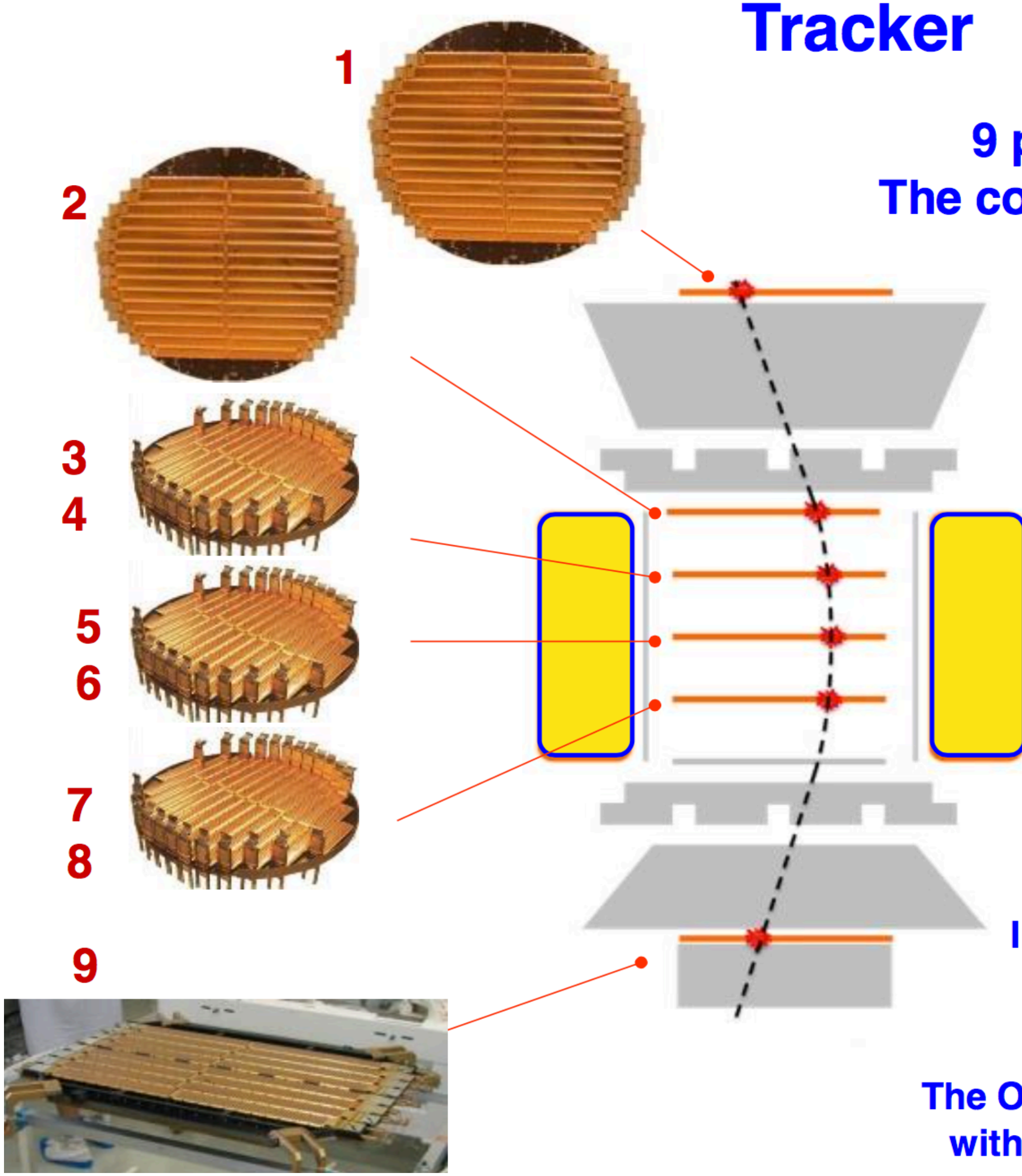
The AMS-02 Detector - Tracker

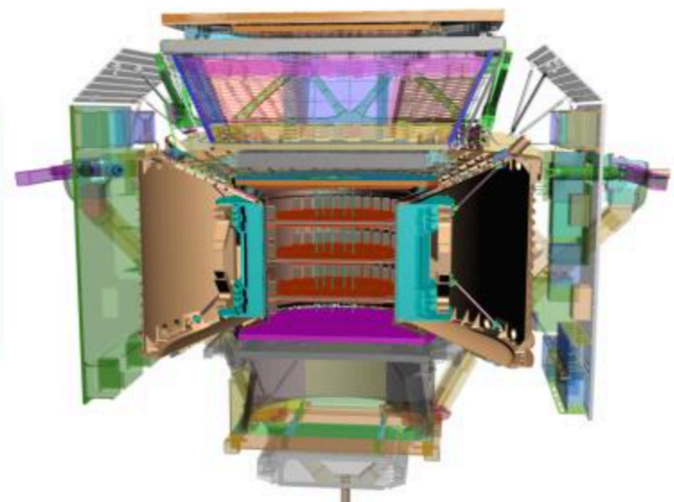


The AMS-02 Detector - Tracker

Tracker

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



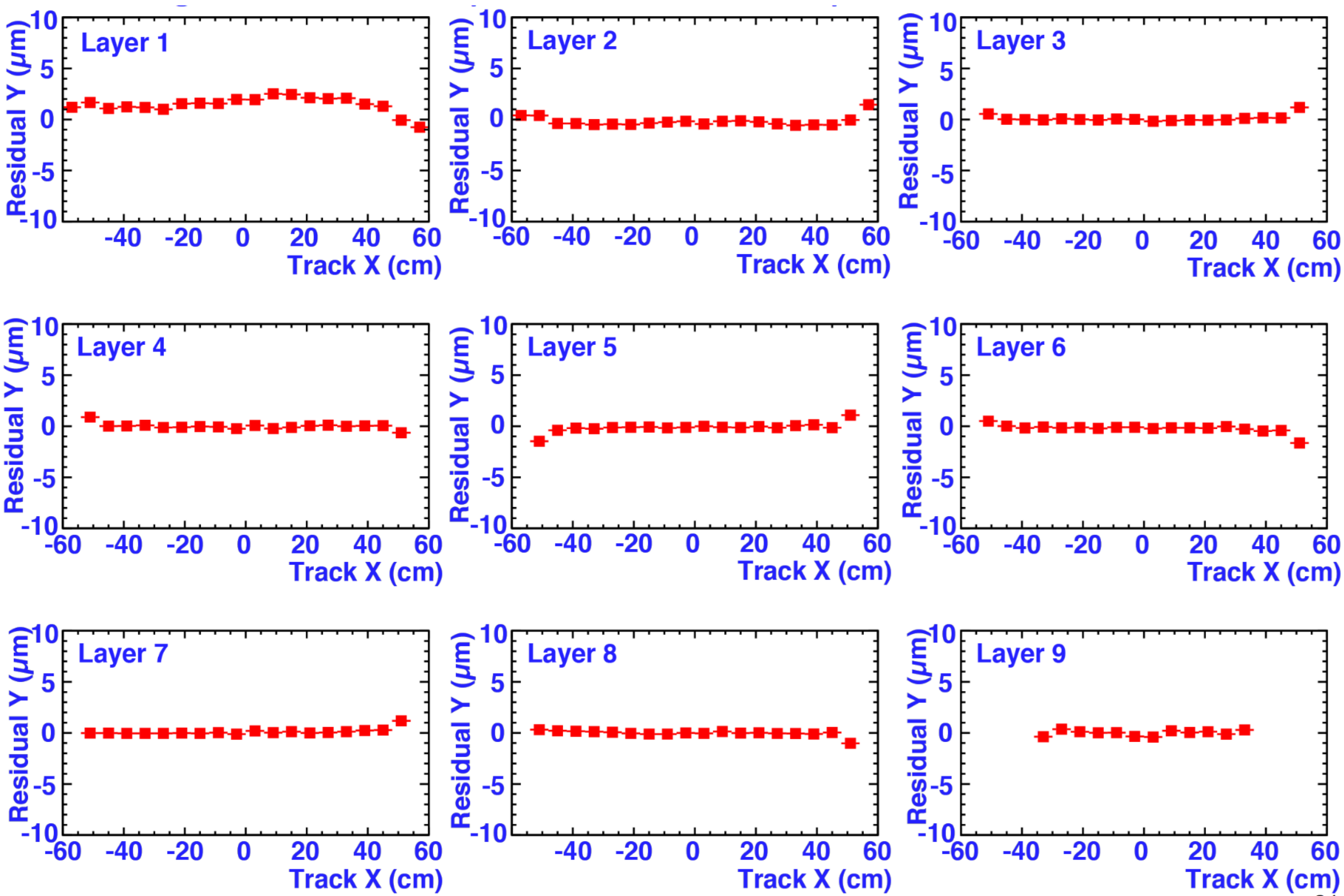


Inner tracker alignment stability monitored with IR Lasers.

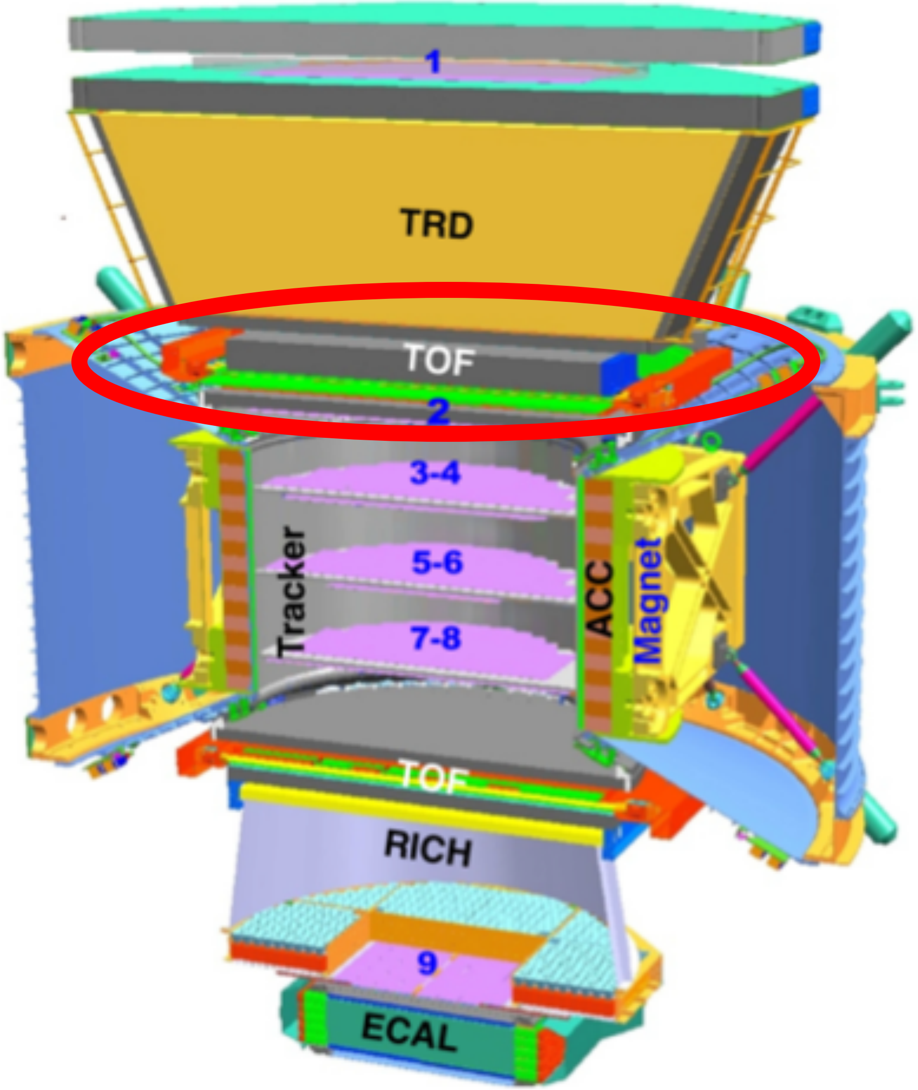
The Outer Tracker is continuously aligned with cosmic rays in a 2 minute window

The AMS-02 Detector - Tracker

- **Alignment accuracy of the 9 Tracker layers over 40 months**



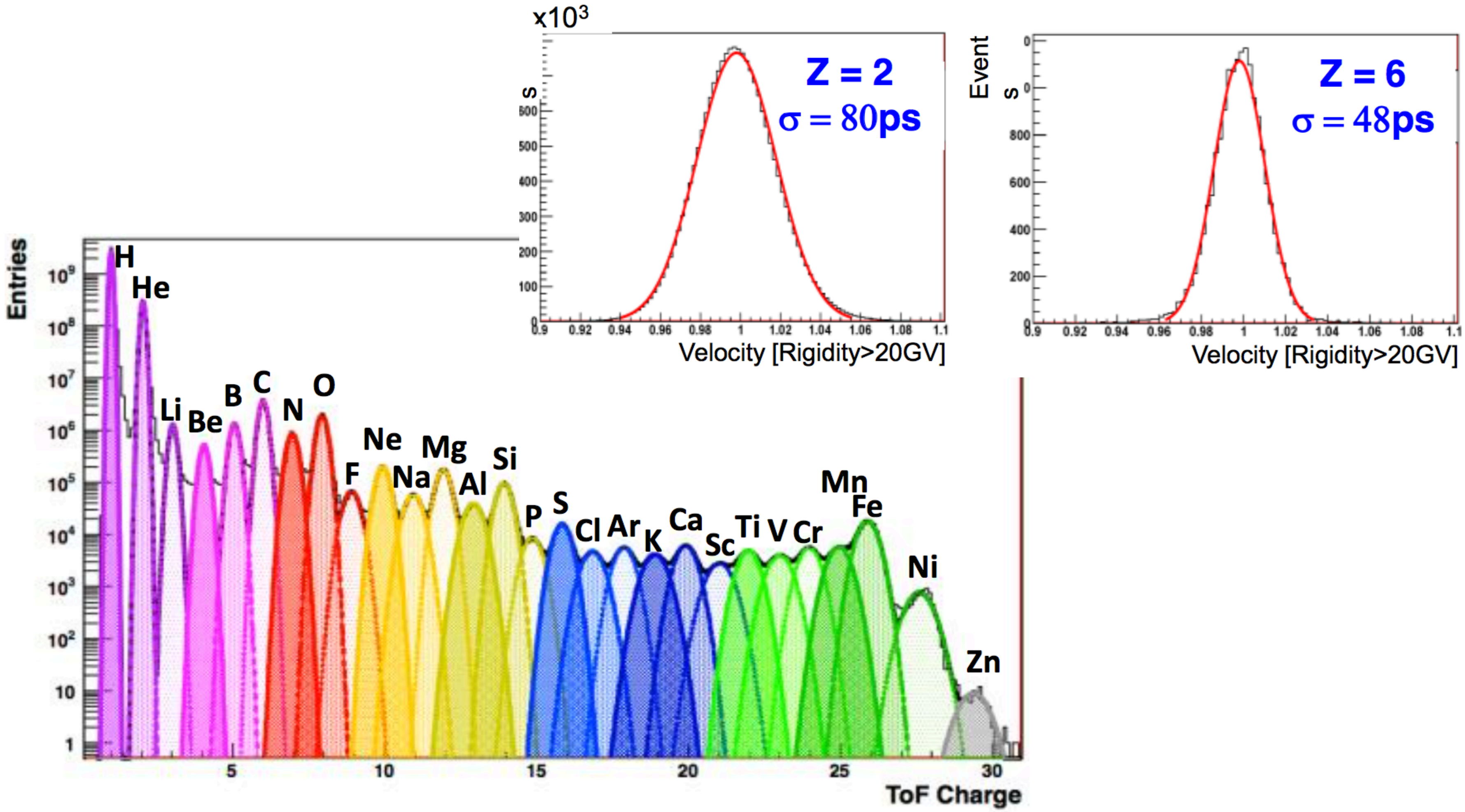
The AMS-02 Detector - ToF



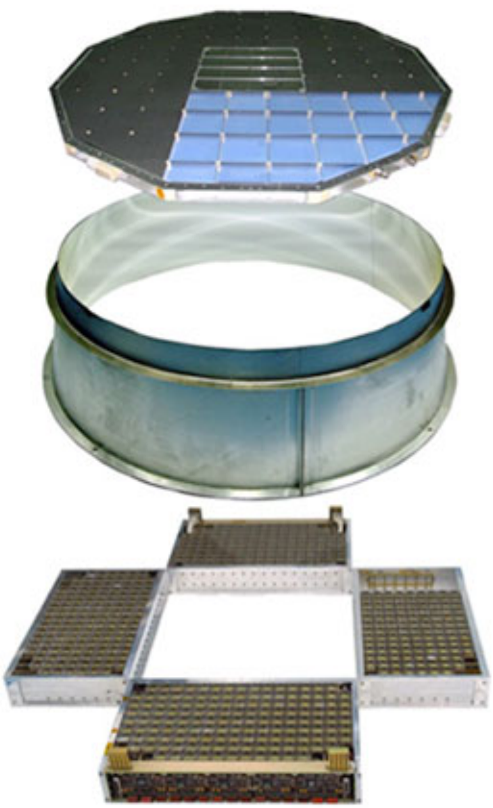
The AMS-02 Detector - ToF

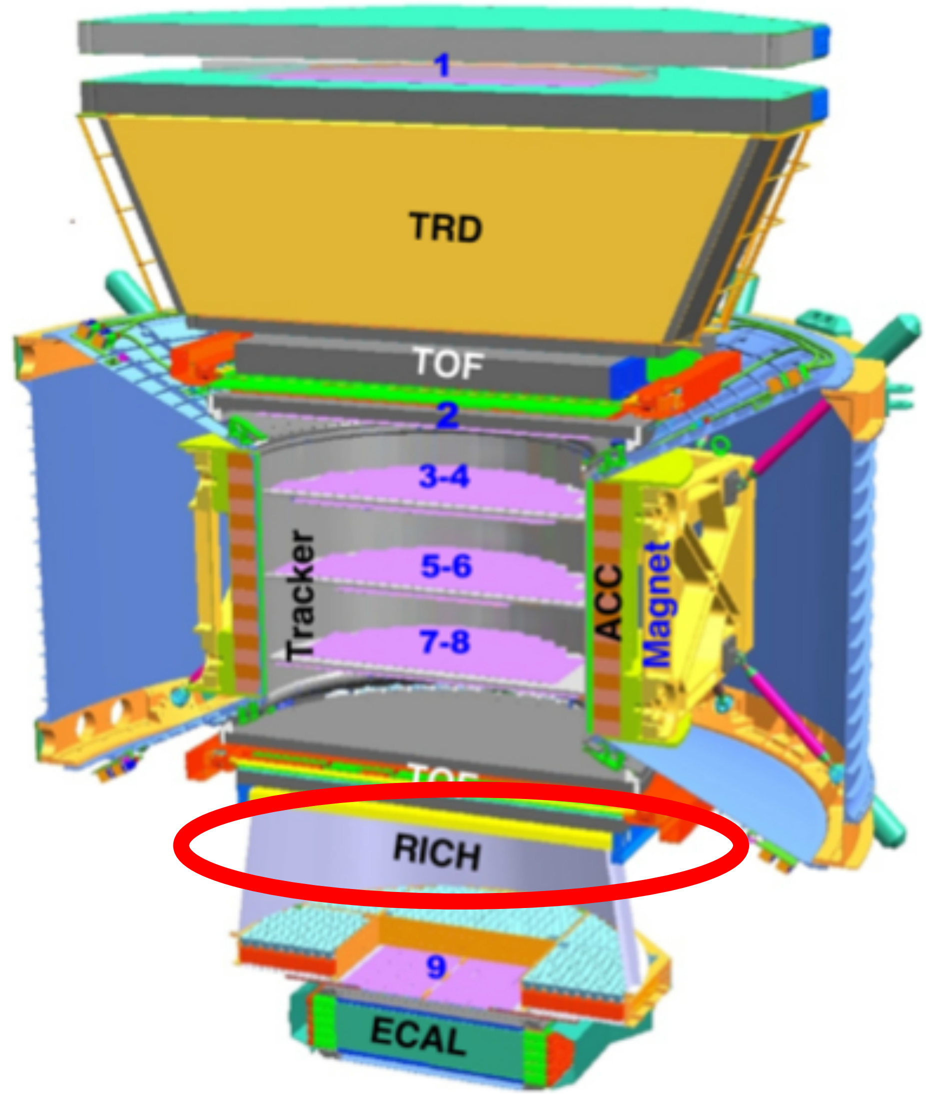
❑ Time-of-Flight

- ***Measures Velocity*** and ***Charge*** of particles



The AMS-02 Detector - RICH

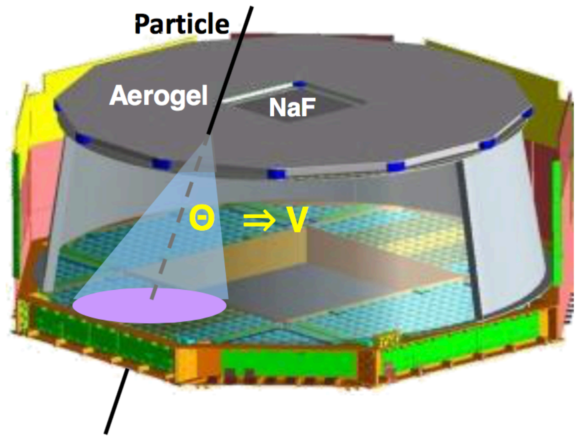


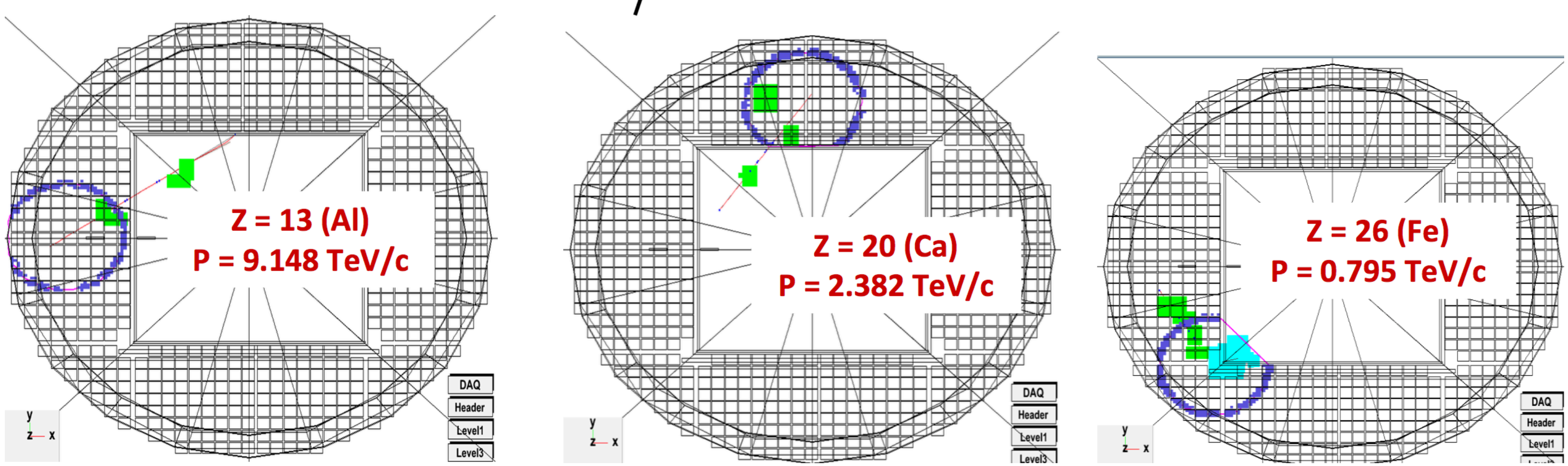


The AMS-02 Detector- RICH

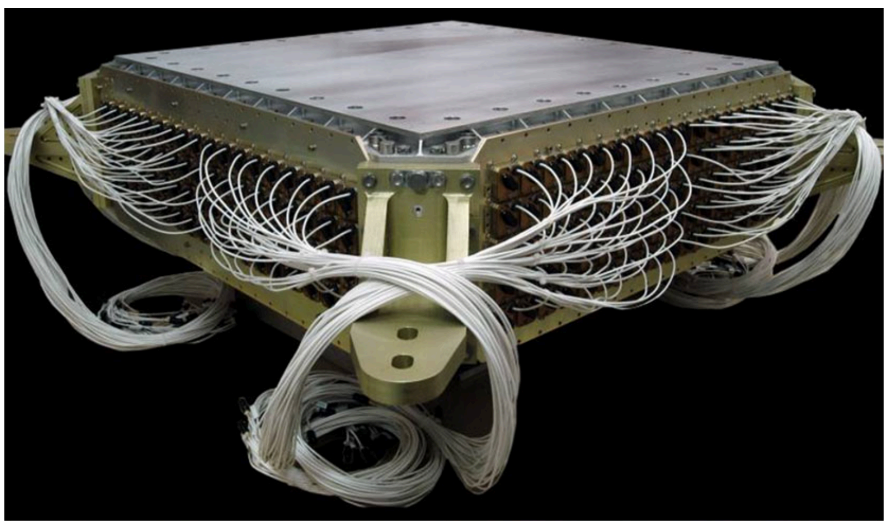
❑ Ring-Imaging Cherenkov Detector (RICH)

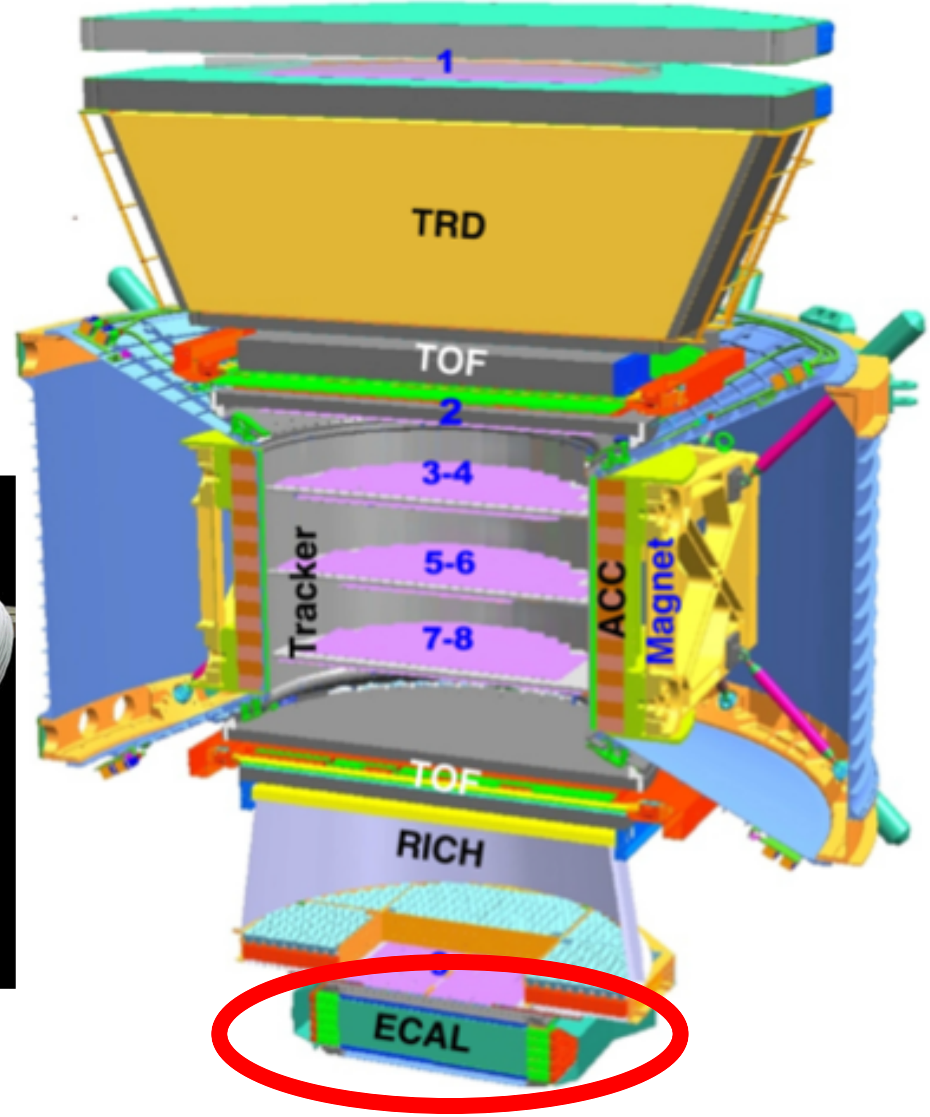
- Use the Cherenkov light to measurement the Nuclear Charge, Z^2, (Intensity) and its Velocity to 1/1000





The AMS-02 Detector - ECAL

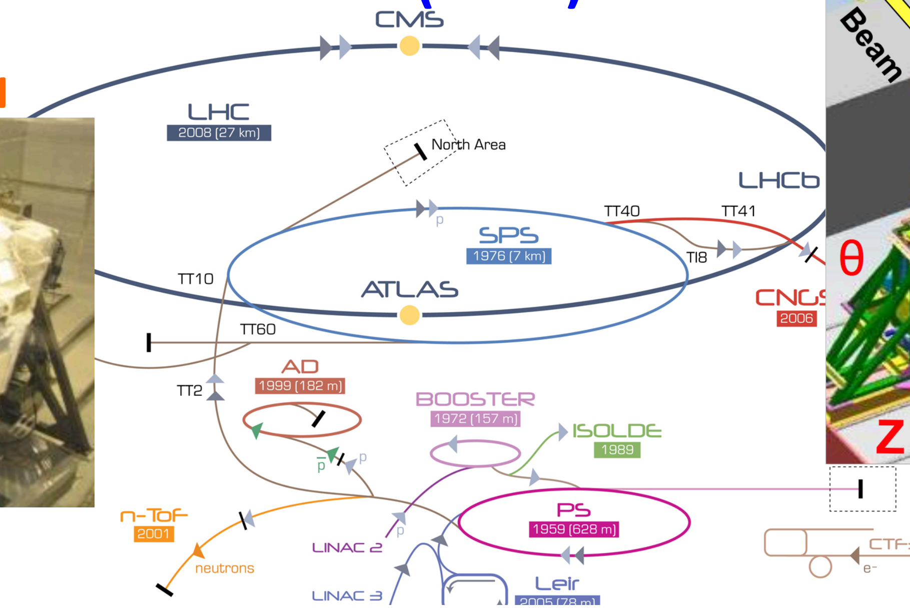


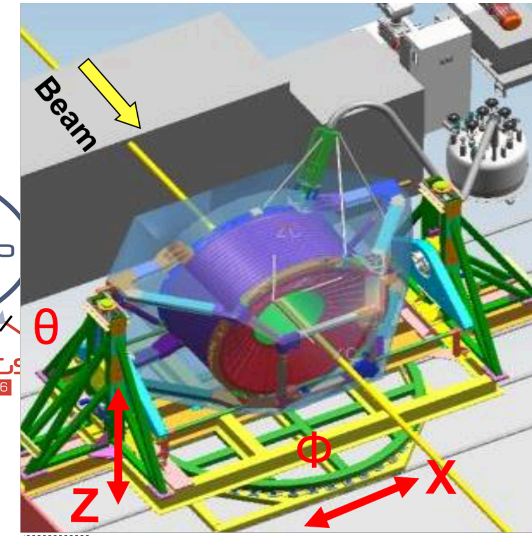


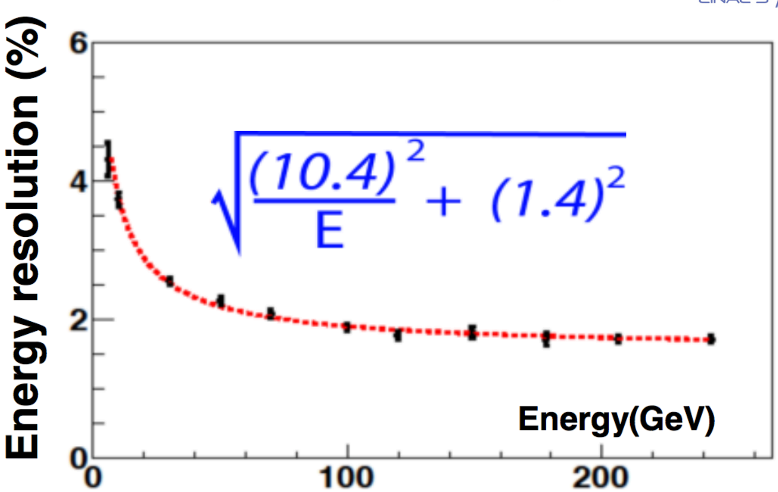
The AMS-02 Detector - ECAL

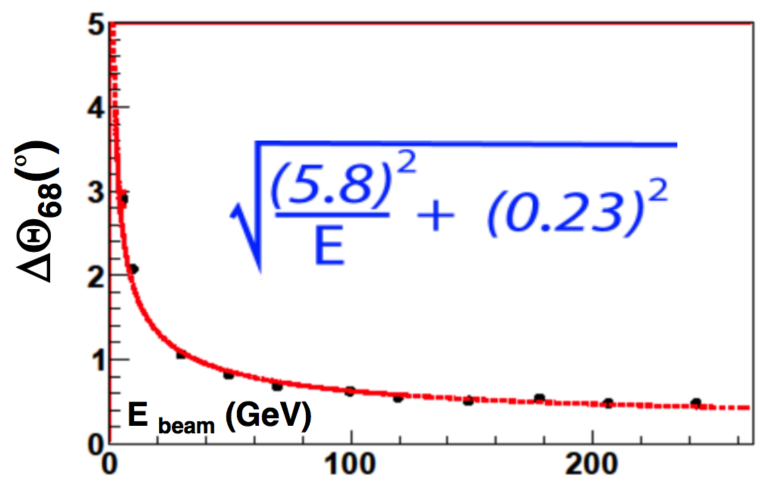
❑ Electromagnetic Calorimeter (ECAL)

Test-Beam at CERN



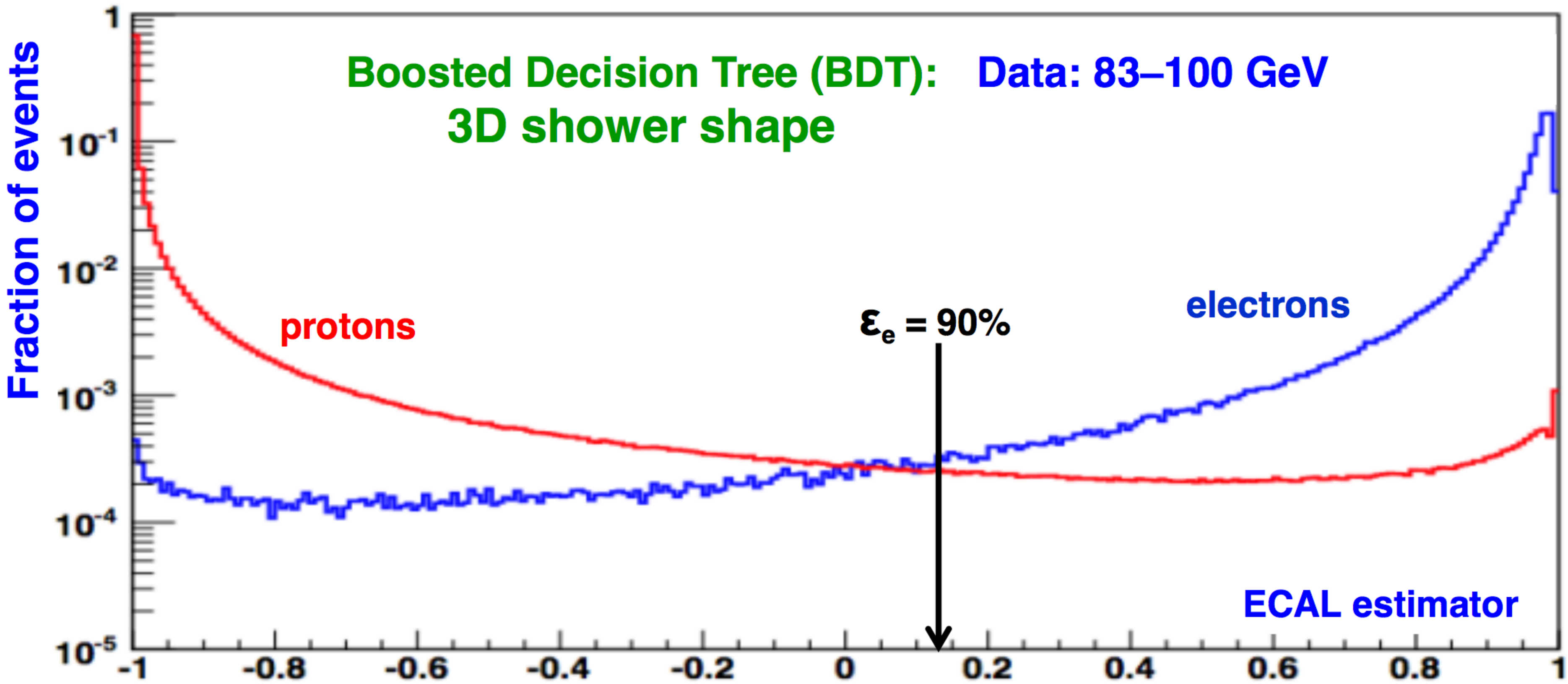






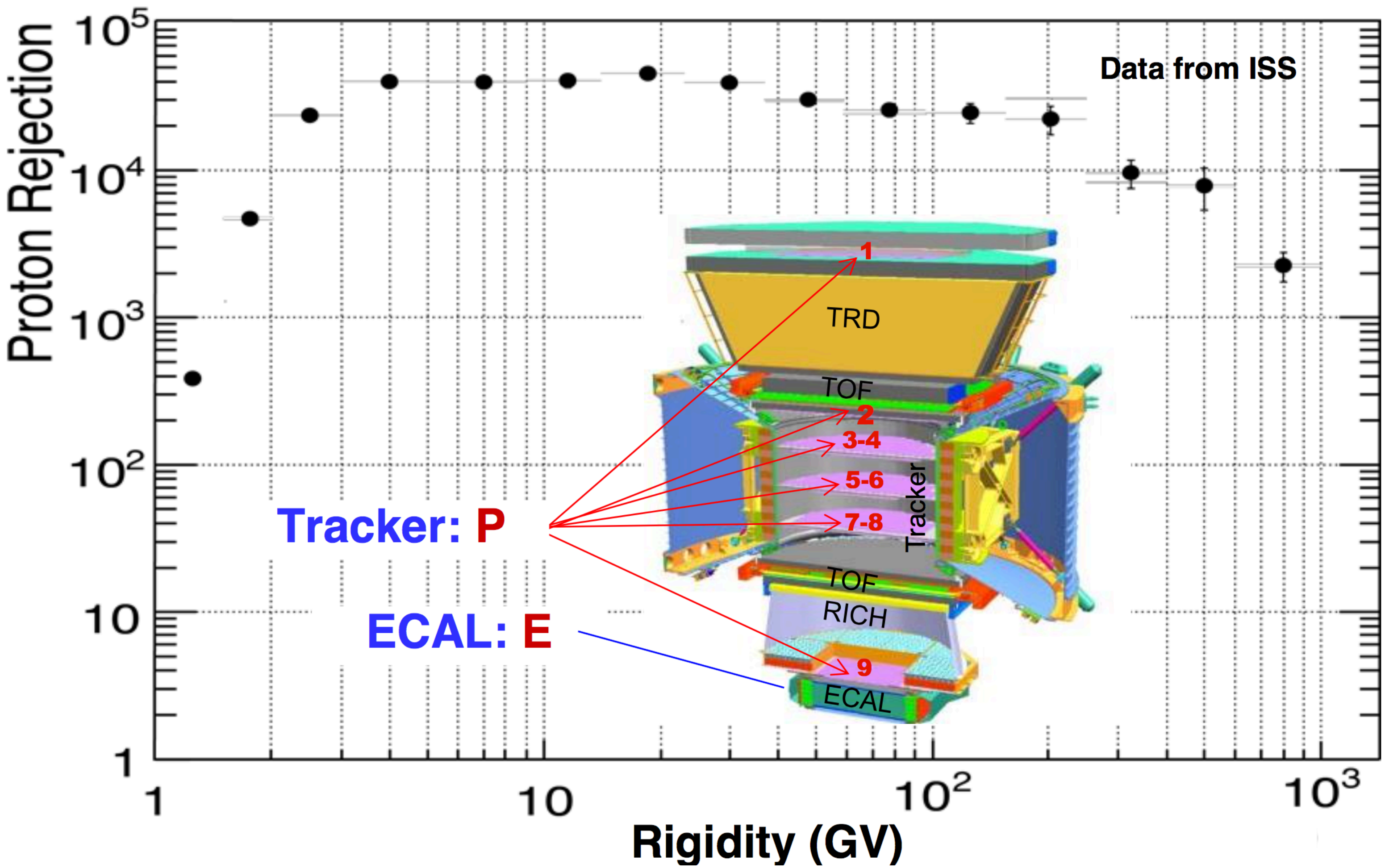
The AMS-02 Detector - ECAL

❑ The performance of ECAL: Electron and Proton Separation



The AMS-02 Detector - ECAL

❑ The performance of ECAL: proton rejection



Examples of Theoretical Models for positrons and antiprotons

From Dark Matter

1) J. Kopp, Phys. Rev. D 88, 076013 (2013);
2) L. Feng, R.Z. Yang, H.N. He, T.K. Dong, Y.Z. Fan and J. Chang Phys.Lett. B728 (2014) 250
3) M. Cirelli, M. Kadastik, M. Raidal and A. Strumia ,Nucl.Phys. B873 (2013) 530
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5) Y. Kajiyama and H. Okada, Eur.Phys.J. C74 (2014) 2722
6) K.R. Dienes and J. Kumar, Phys.Rev. D88 (2013) 10, 103509
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From Astrophysical Sources

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3) I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013
4) A. Erlykin and A.W. Wolfendale, Astropart.Phys. 49 (2013) 23
5) P.F. Yin, Z.H. Yu, Q. Yuan and X.J. Bi, Phys.Rev. D88 (2013) 2, 023001
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7) E. Amato, Int.J.Mod.Phys.Conf.Ser. 28 (2014) 1460160
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9) D. Gaggero, D. Grasso, L. Maccione, G. DiBernardo and C Evoli, Phys.Rev. D89 (2014) 083007
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From Secondary Production

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2) K. Blum, B. Katz and E. Waxman, Phys.Rev.Lett. 111 (2013) 211101
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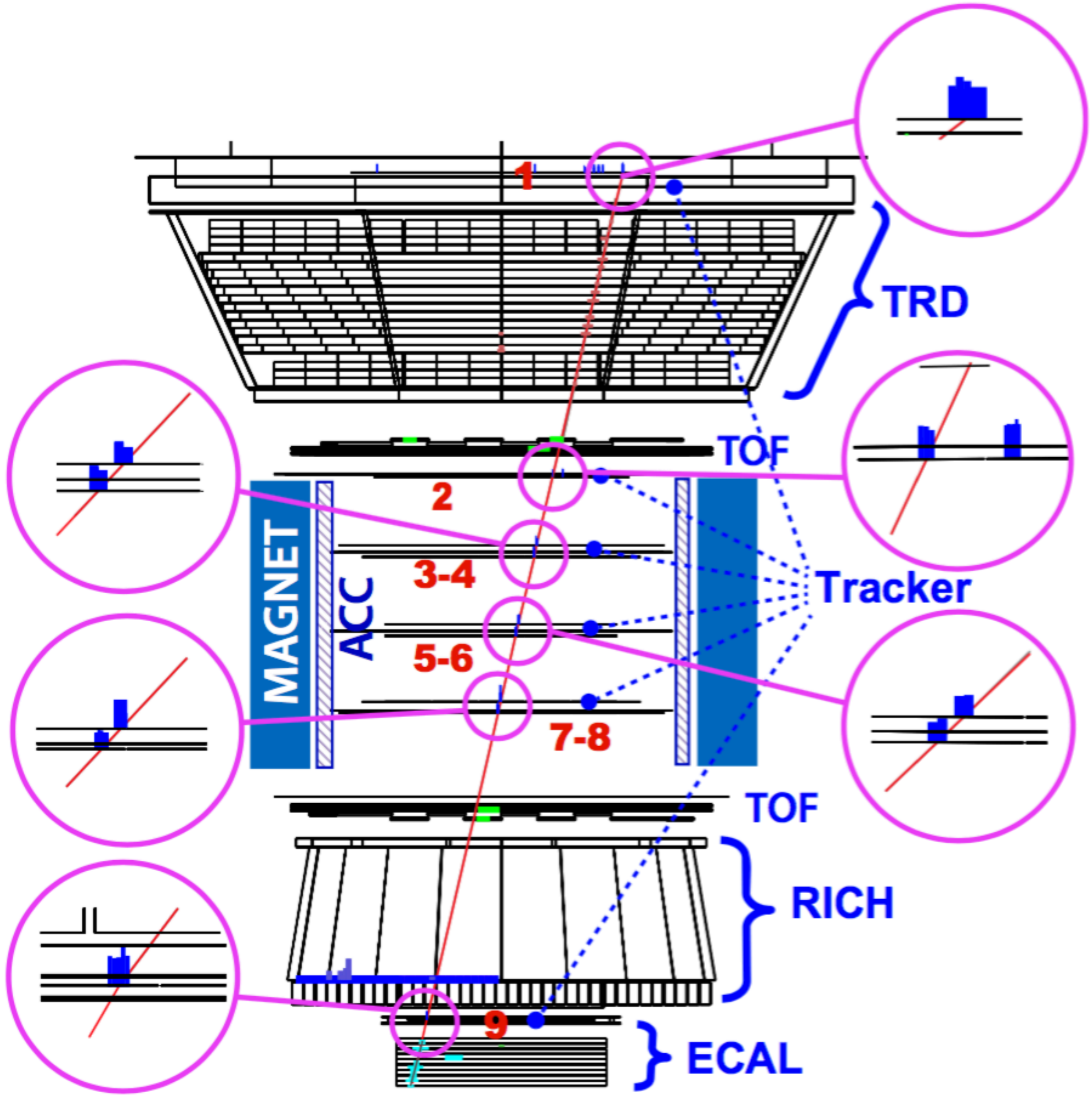
4) G.Giesen, M.Boudaud, Y.Gènolini, V.Poulin, M.Cirelli, P.Salati and P.D.Serpico, JCAP09 (2015) 023;
5) C.Evoli, D.Gaggero and D.Grasso, JCAP 12 (2015) 039.
6) R.Kappl, A.Reinertand, and M.W.Winkler, arXiv:1506.04145 (2015)

Event Display



Proton Flux

- 300 M proton events
- The isotropic proton flux is defined

$$\Phi_i(R_i) = \frac{N_i}{T_i \epsilon_i A_i \Delta R_i}$$

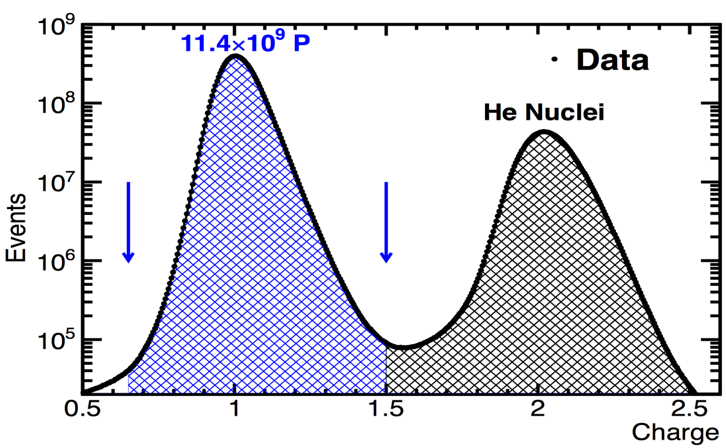
N_i → Number of events with corrected bin-to-bin migration effect

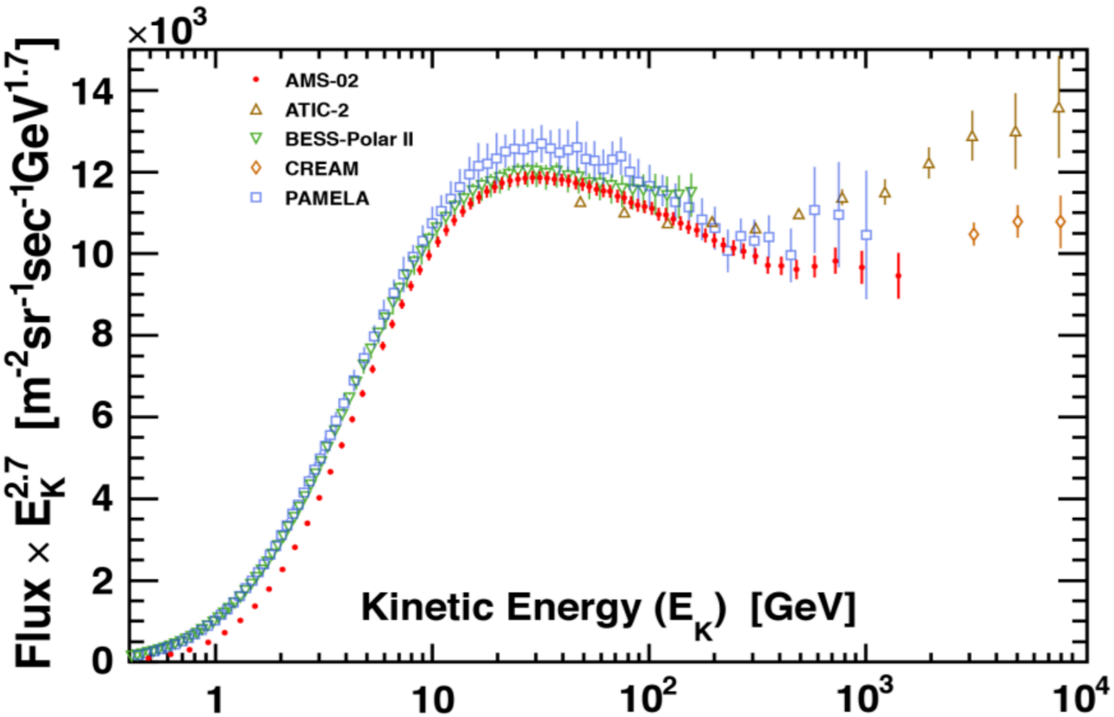
ΔR_i → Bin width

T_i → Exposure time

ϵ_i → Trigger efficiency

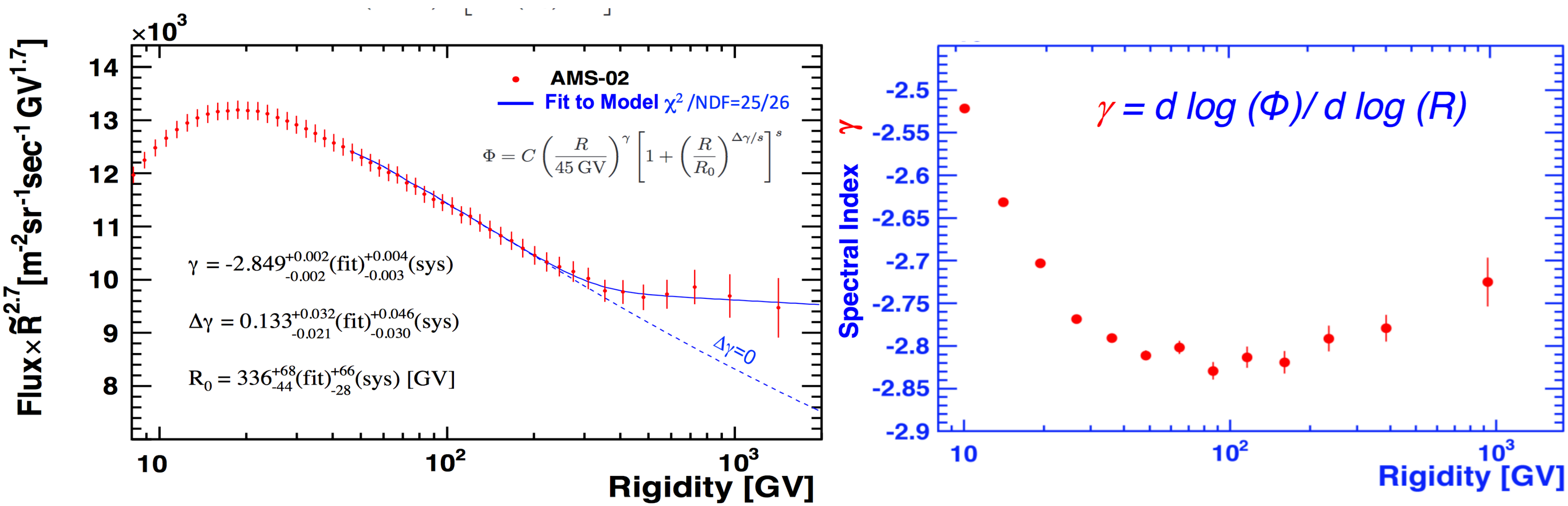
A_i → Acceptance





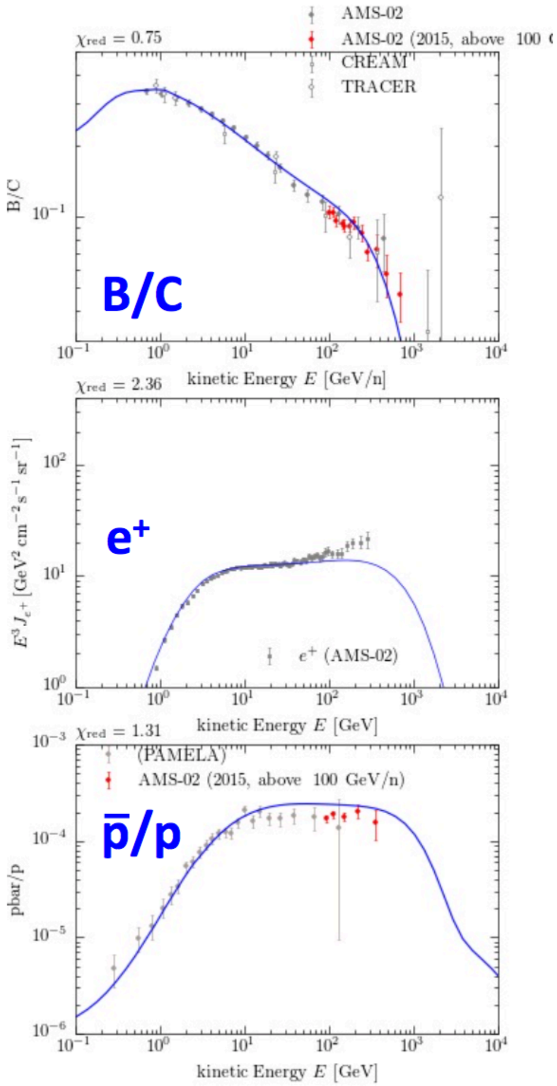
Proton Flux

- Precision measurement of proton flux from 1 GV to 1.8 TV with 300 million events
- The spectral index is progressively hardening at high rigidities



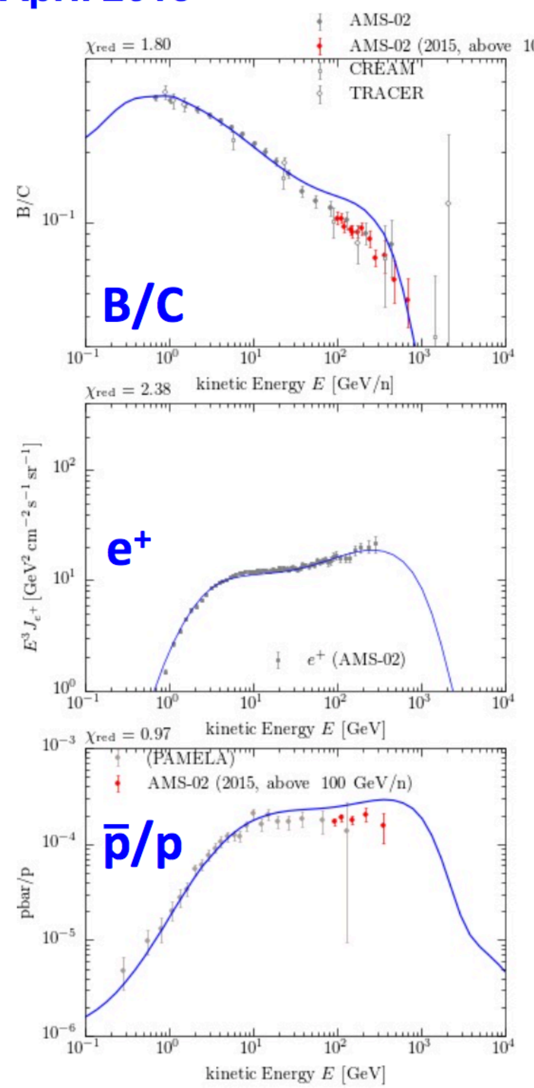
Example: Supernova Remnants

Subir Sarkar: AMS Days@CERN, April 2015



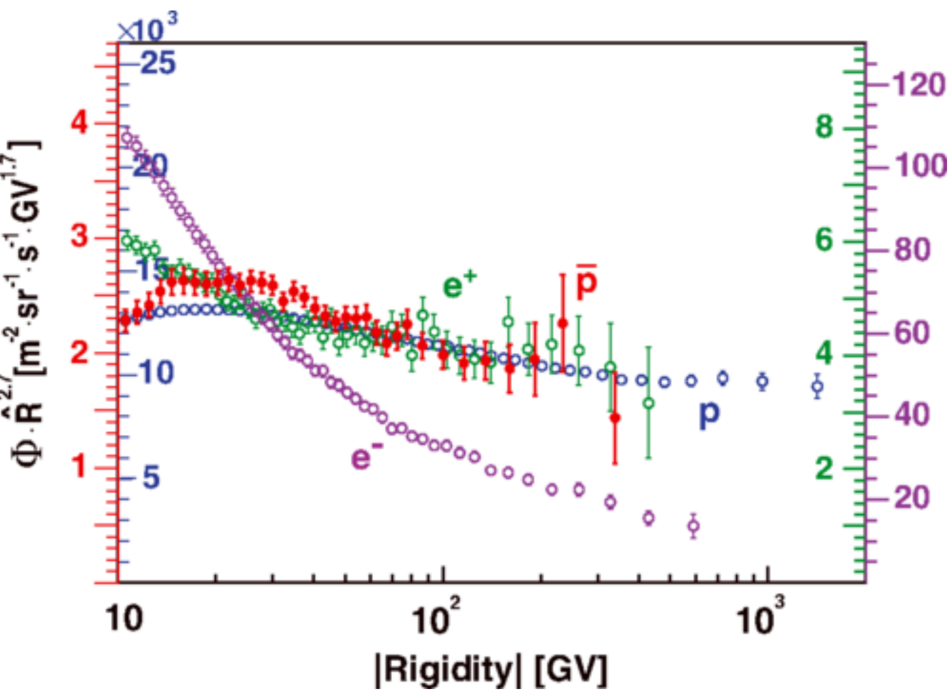
We have been trying (late last night!) to get better fits to the new data but it is not easy ... perhaps our model is *too* simple and some further refinements are necessary.

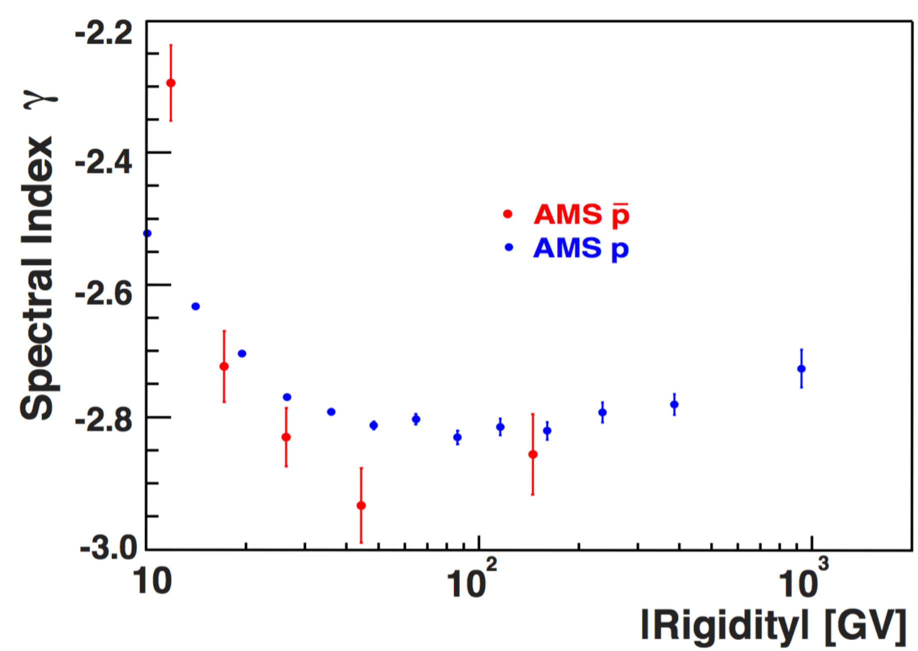
This is justified now that we have *precision* data from AMS!



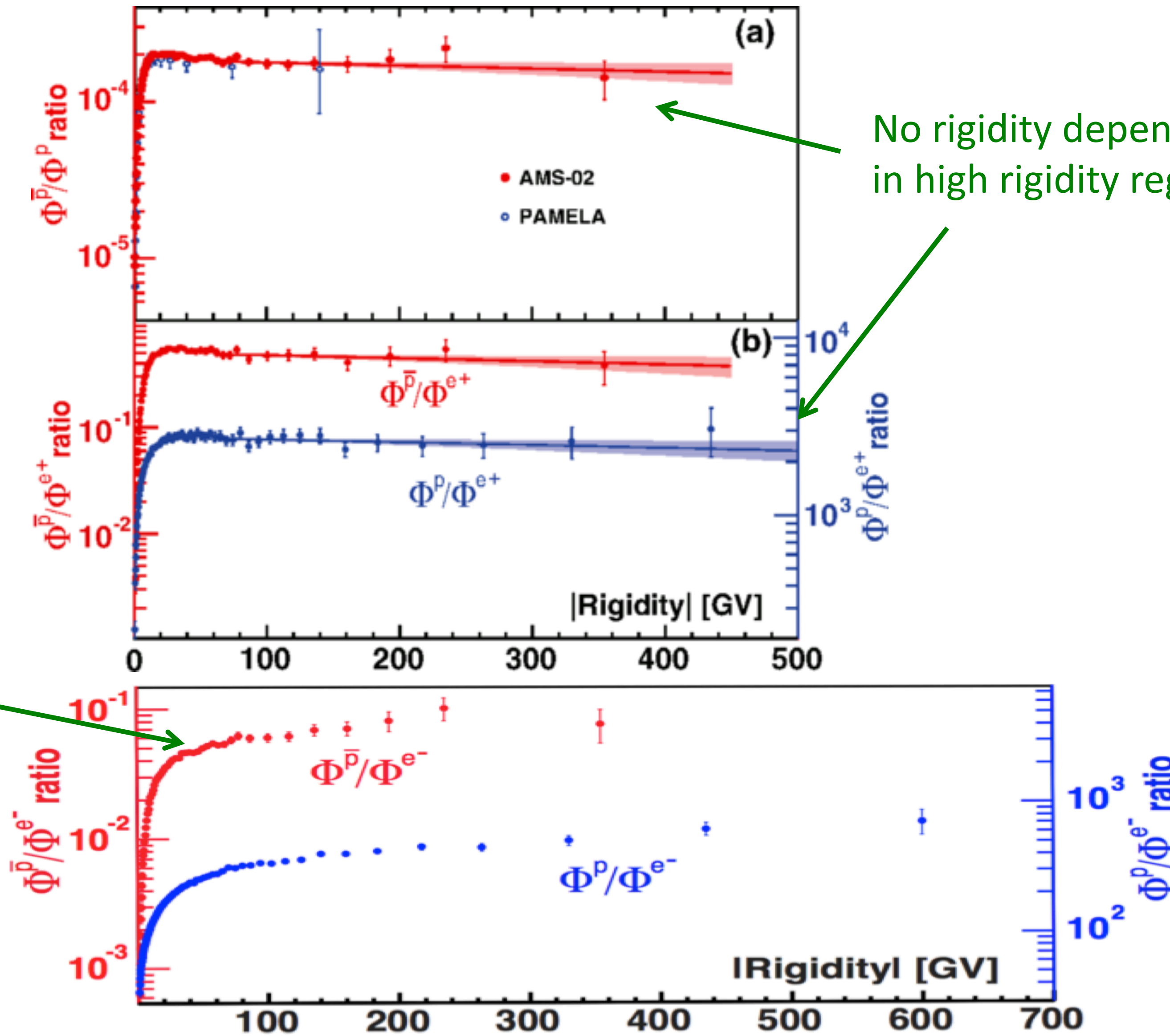
Flux Results

- The most precise measurements of the elementary particles
- Very similar rigidity dependence for proton, antiproton and position, but electron behaves very differently
- Similar spectral index for proton and antiproton after 60.3 GV





Antiproton-to-Proton Ratio



No rigidity dependence in high rigidity region

Different behavior for electron

Antihelium and AMS

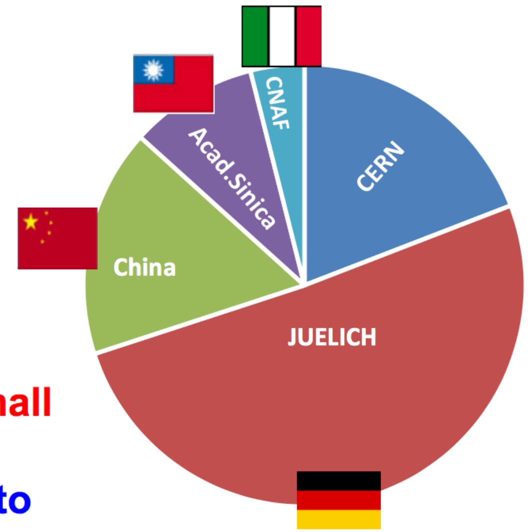
At a signal to background ratio of one in one billion, detailed understanding of the instrument is required.

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 $^{3}\overline{He}$.

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

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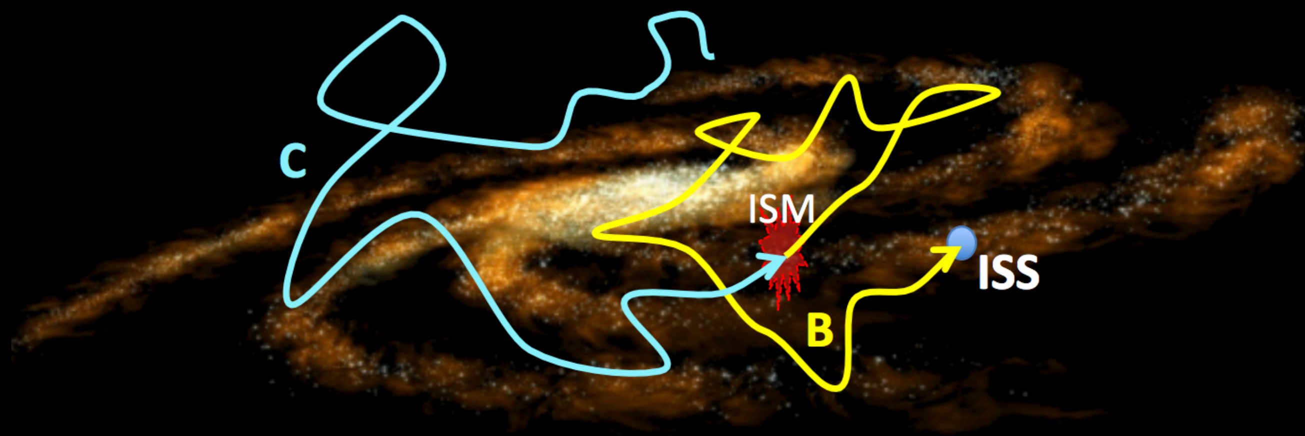
B/C ratio

The flux ratio between primaries (C) and secondaries (B) provides information on propagation and the ISM



Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

At high rigidities, models of the magnetized plasma predict different behavior for B/C = kR^{δ}.

With the Kolmogorov turbulence model $\delta = -1/3$ while the Kraichnan theory leads to $\delta = -1/2$.

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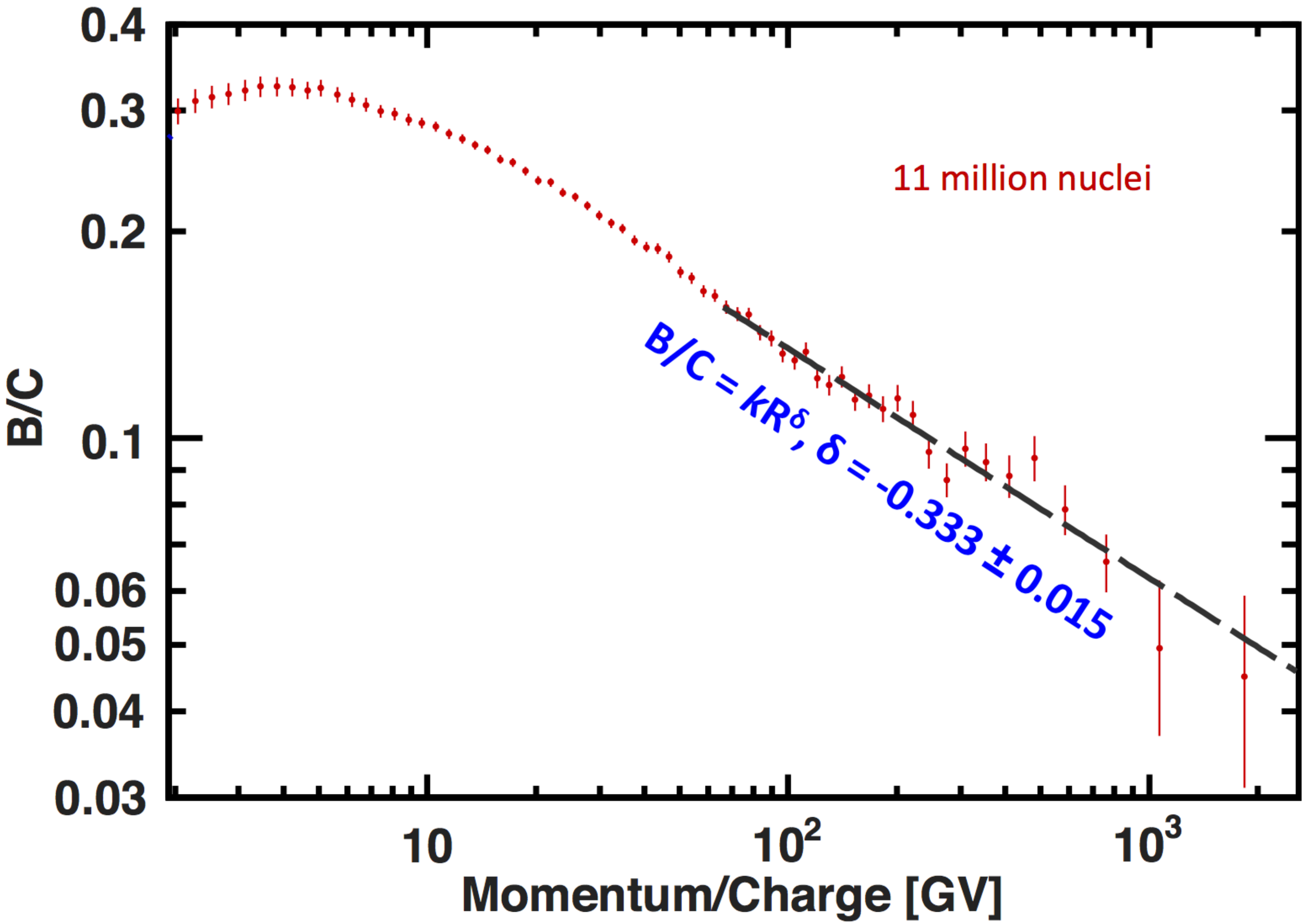
B/C



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