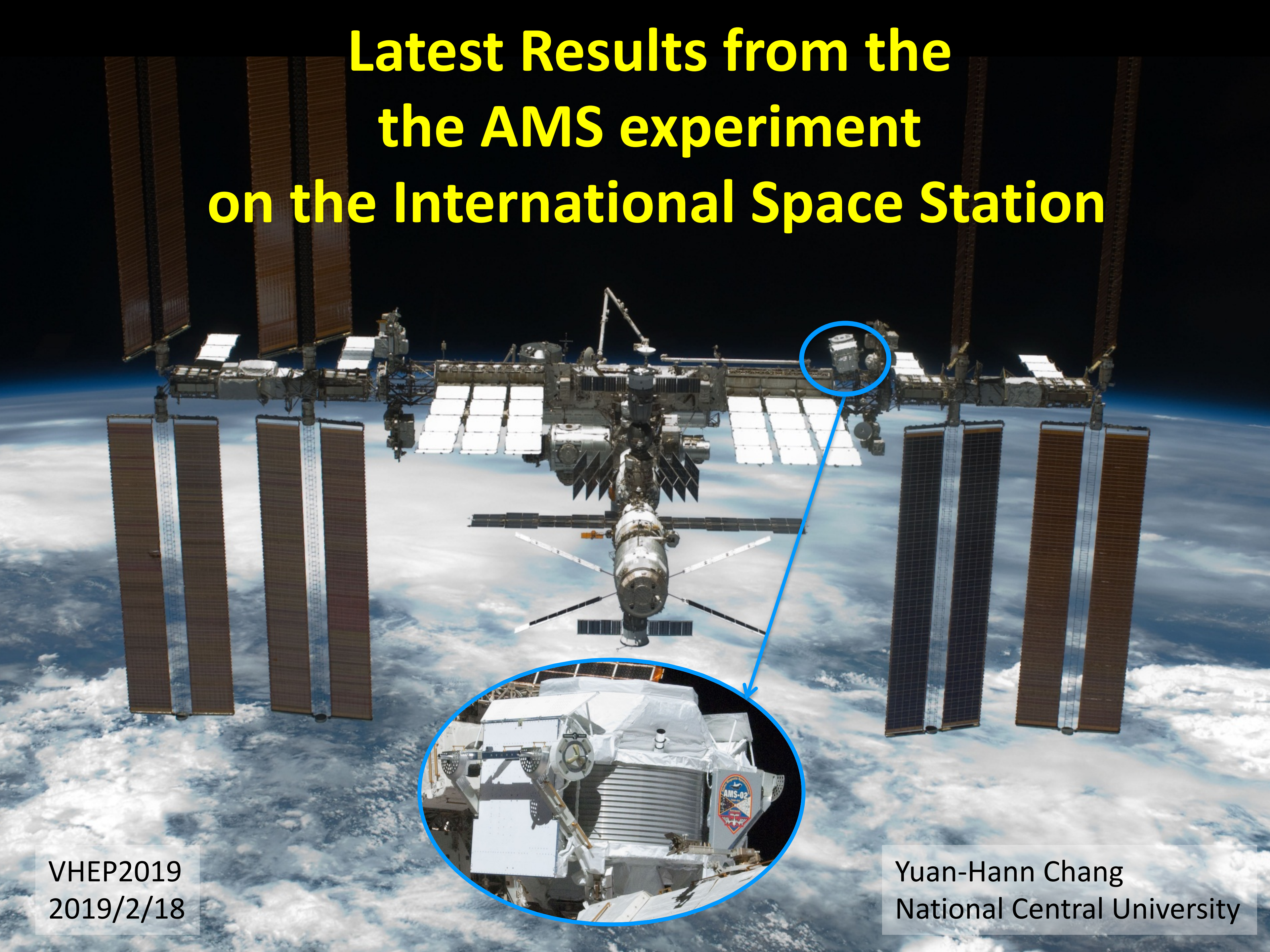
Latest Results from the the AMS experiment on the International Space Station



VHEP2019
2019/2/18

Yuan-Hann Chang
National Central University

Contents:

- The AMS experiment
- AMS results on cosmic nuclei
- AMS results on elementary particles
- Status of anti-Helium events

Extensive measurements of the cosmic ray nuclei have been carried out in the range of ~GeV to 100 TeV energy range:

Advantage of measurement in this range:

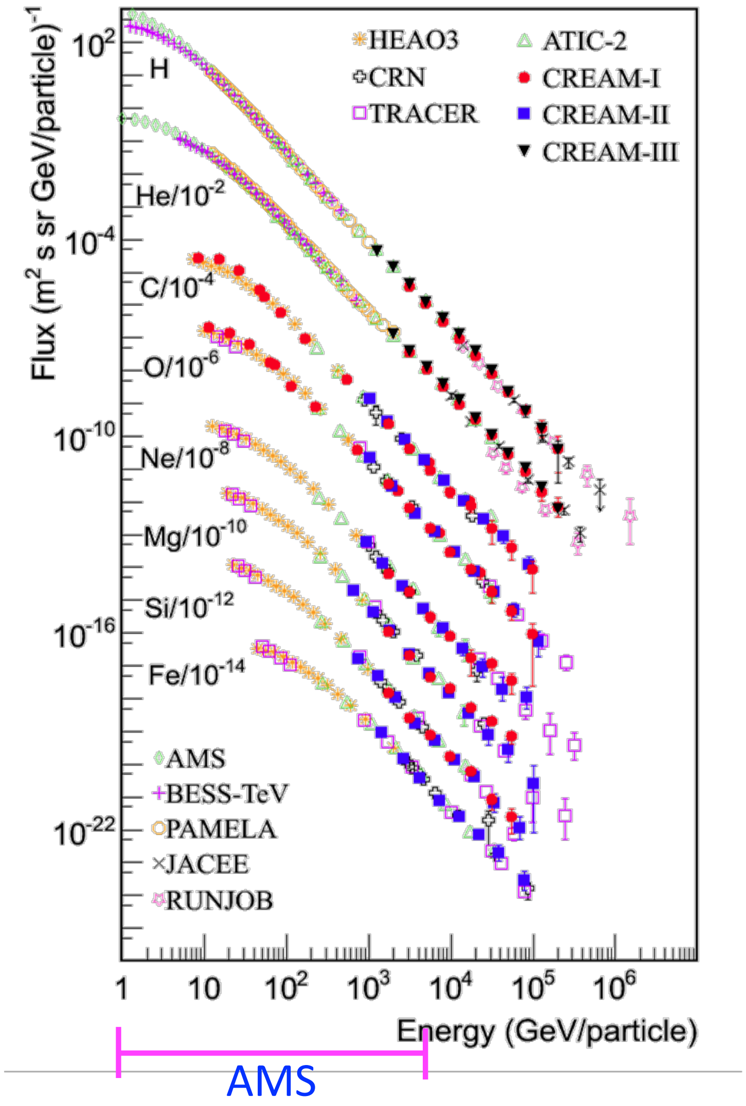
- The charge of the particles can be measured precisely.

  ➔ Nuclei are well identified.

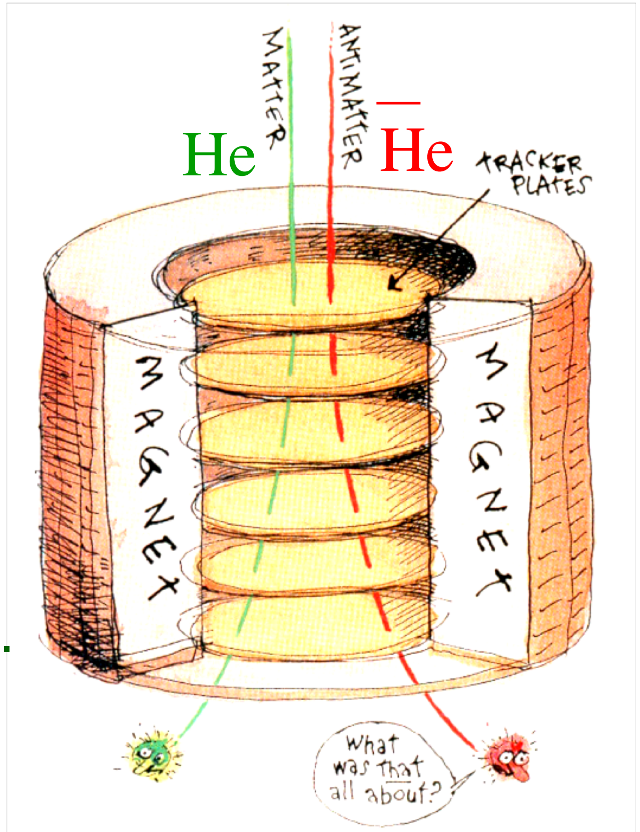
- The flux is large enough for precision spectra measurements with relatively small detector

  ➔ Search for new physics.

- Anti-particle measurements possible with magnetic spectrometer.

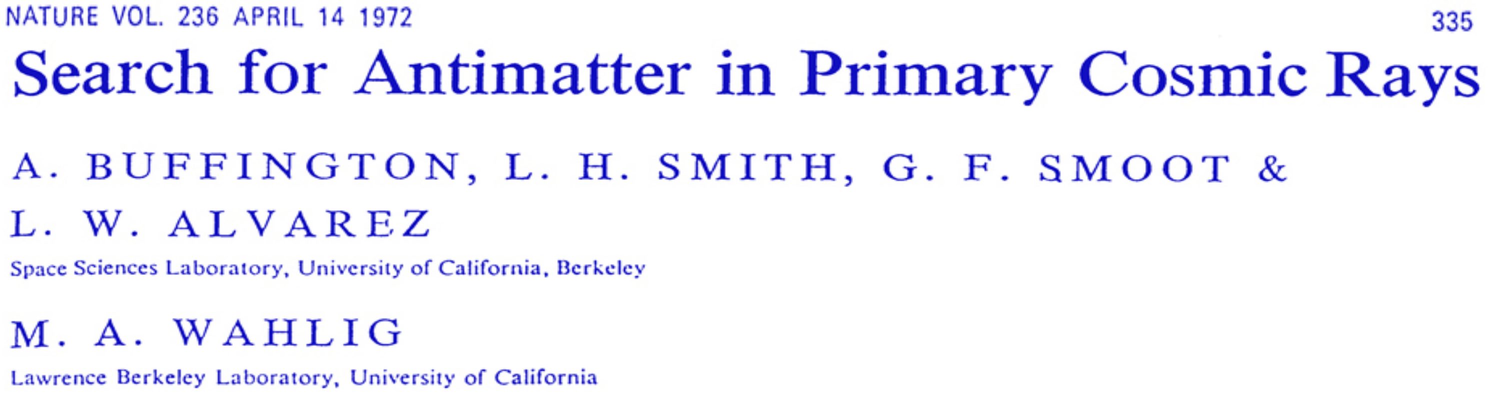


AMS: A magnetic spectrometer in Space with large acceptance.



Matter and antimatter have opposite electric charges;

we need a magnetic detector to measure the charge of antimatter.



NATURE VOL. 236 APRIL 14 1972 335

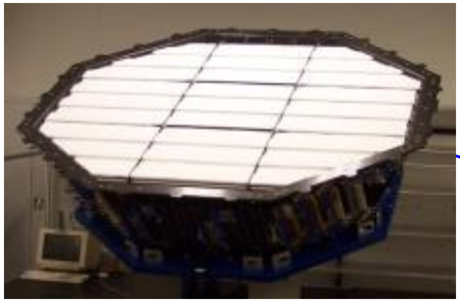
Search for Antimatter in Primary Cosmic Rays

A. BUFFINGTON, L. H. SMITH, G. F. SMOOT & L. W. ALVAREZ
Space Sciences Laboratory, University of California, Berkeley

M. A. WAHLIG
Lawrence Berkeley Laboratory, University of California

AMS: A TeV precision, multipurpose magnetic spectrometer

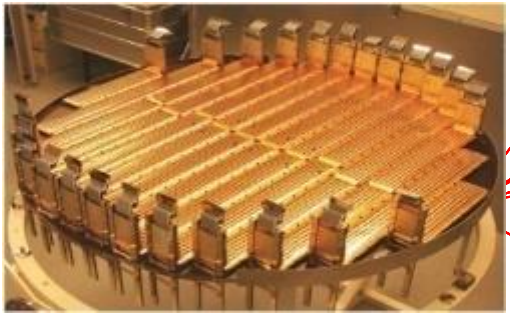
Transition Radiation Detector
Identify e^+, e^-

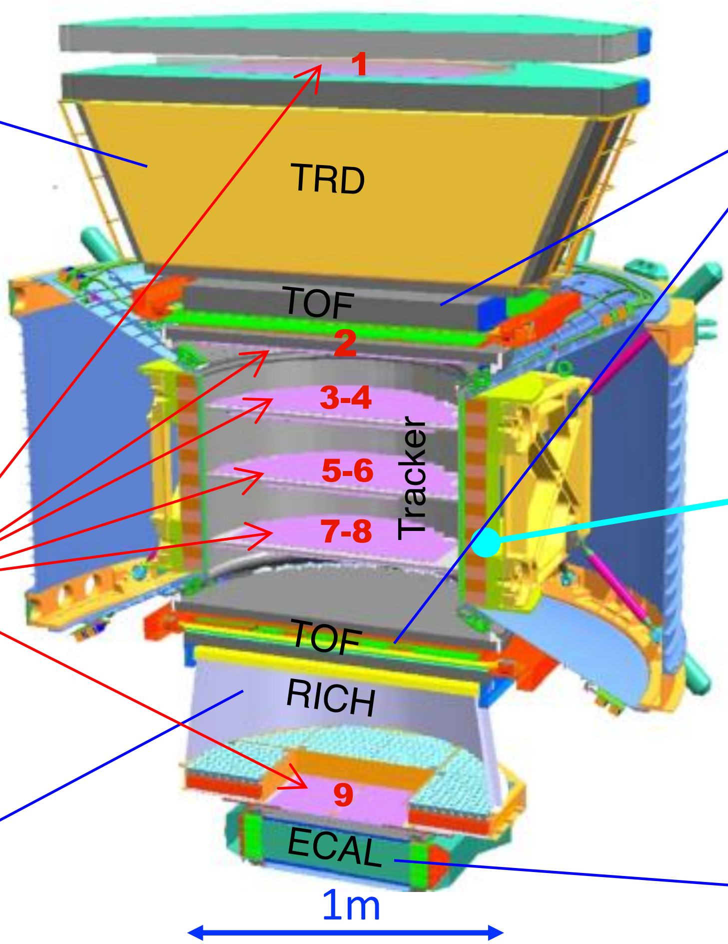


Particles and nuclei are defined by their charge (Z) and energy (E) or (P)

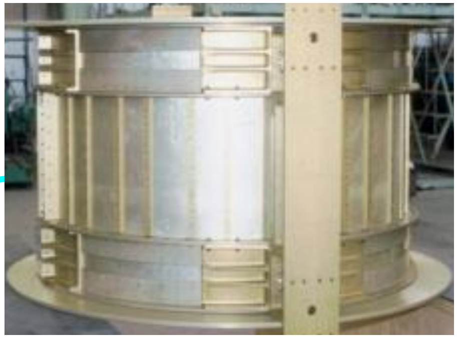
Time of Flight
Z, E

Silicon Tracker
Z, P





Magnet
±Z



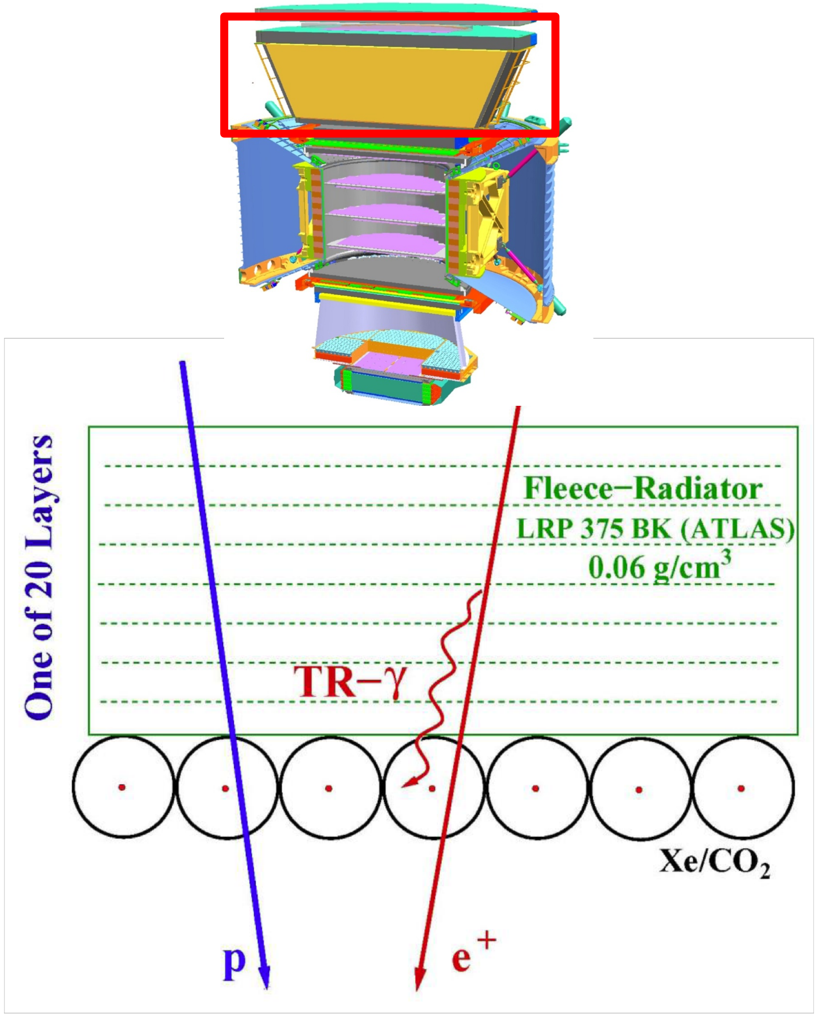
Ring Imaging Cherenkov
Z, E

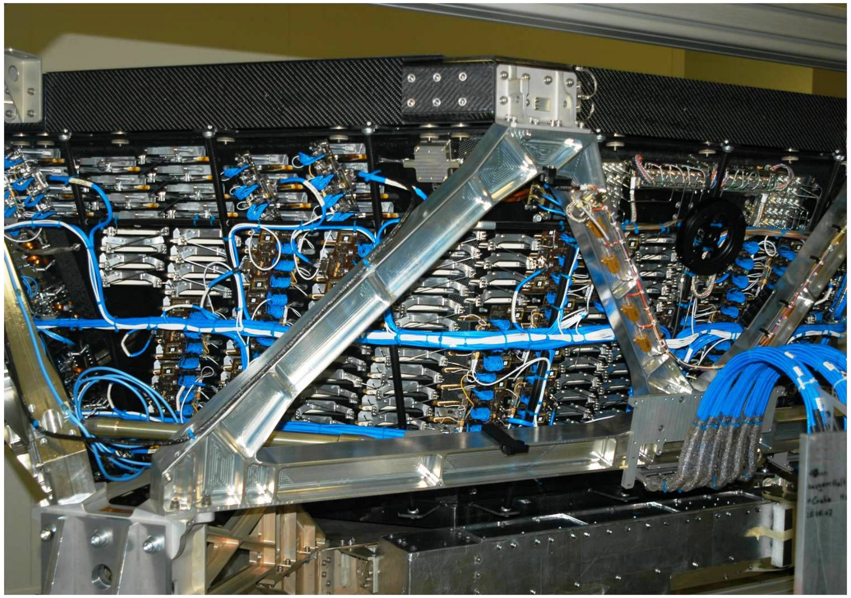
Electromagnetic Calorimeter
E of e^+, e^-

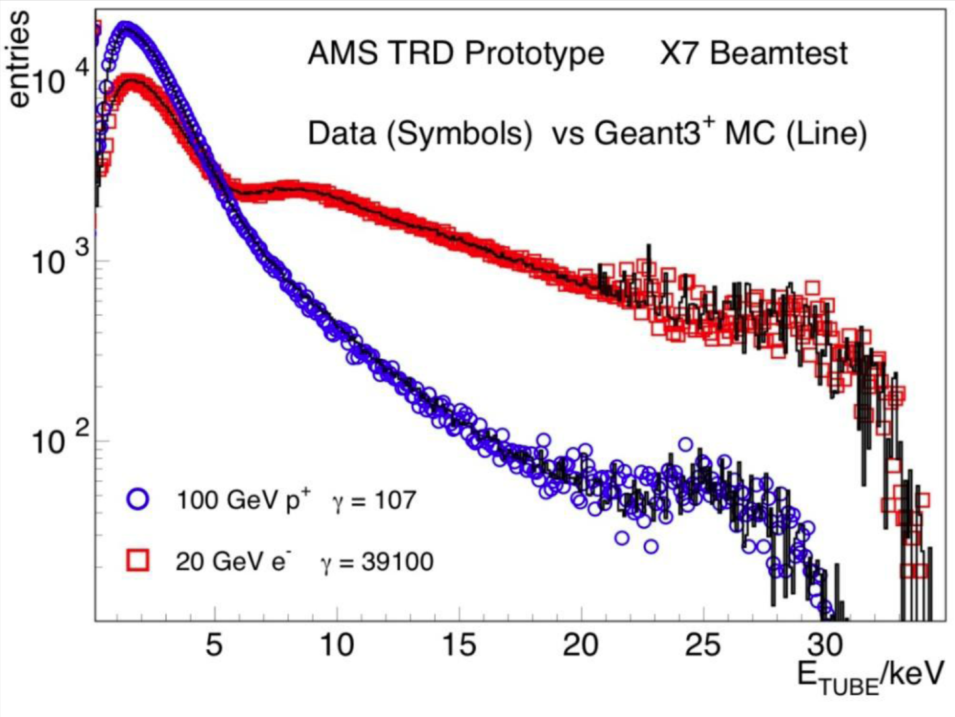
The Charge and Energy are measured independently by many subdetectors

Transition Radiation Detector (TRD) :

Identify e^+, reject P





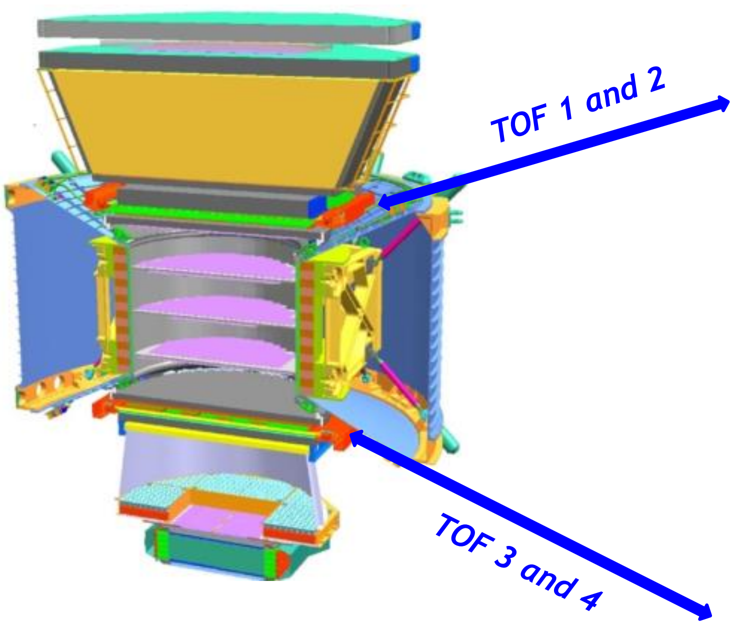


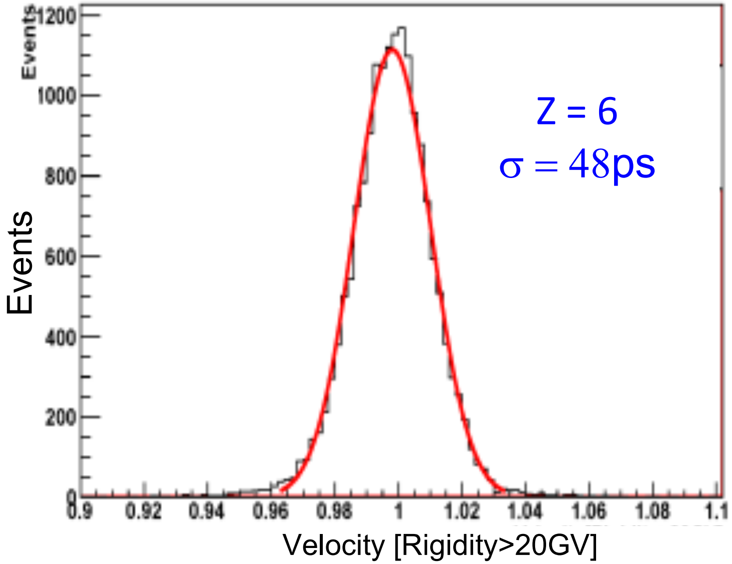
Prob. of radiation ∝ $\gamma = E/mc^2$ ➔

Proton radiate ~2000 less than $e^{\pm}$.

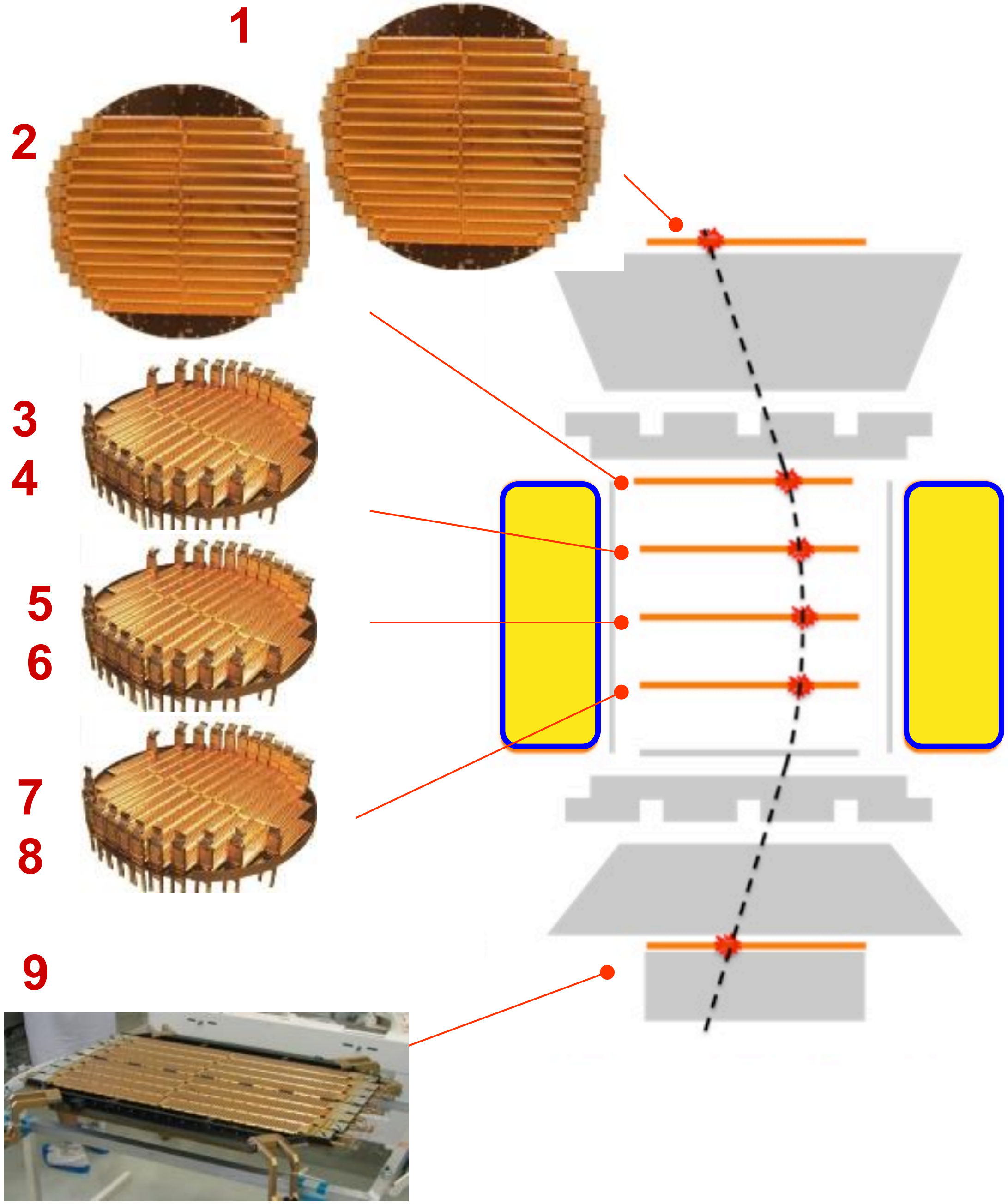
Time of Flight System (TOF)

Measures Velocity and Charge of particles

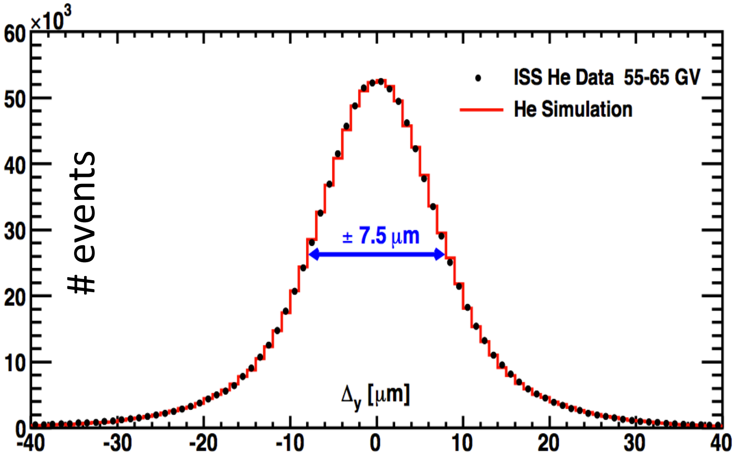




Silicon Tracker



9 planes reconstructing the particle trajectory with 5-10 micron coordinate resolution

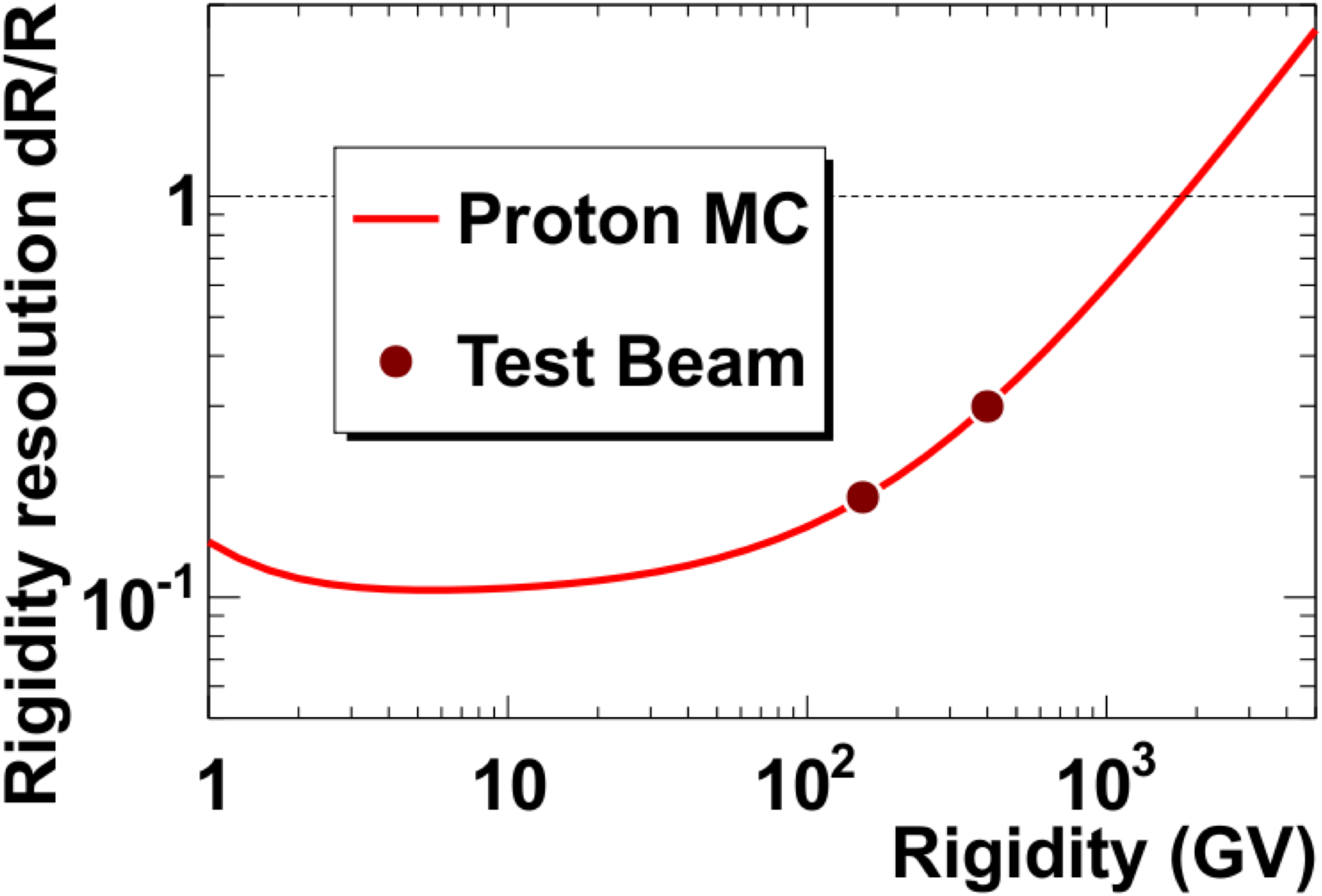


This provides a maximum detectable rigidity (momentum/charge) :

2 TV for |Z|=1 particles

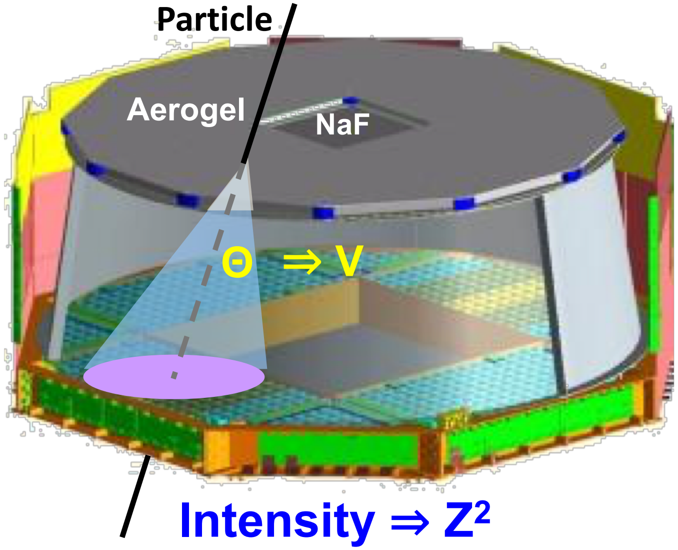
and

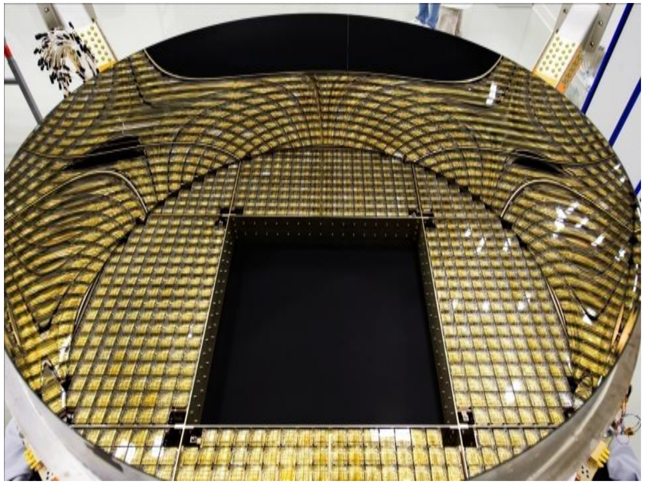
3.3 – 3.6 TV for |Z|=2-8 nuclei

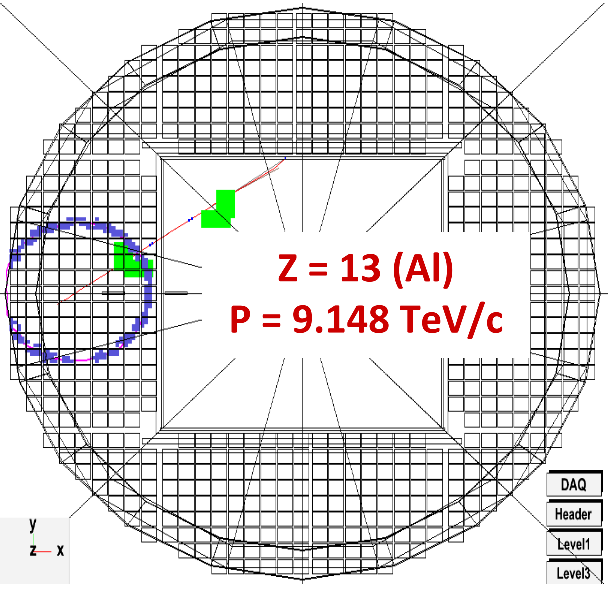

Rigidity resolution dR/R
1
10^{-1}
1
10
10^{2}
10^{3}
Rigidity (GV)
Proton MC
Test Beam

AMS Ring Imaging CHerenkov (RICH)

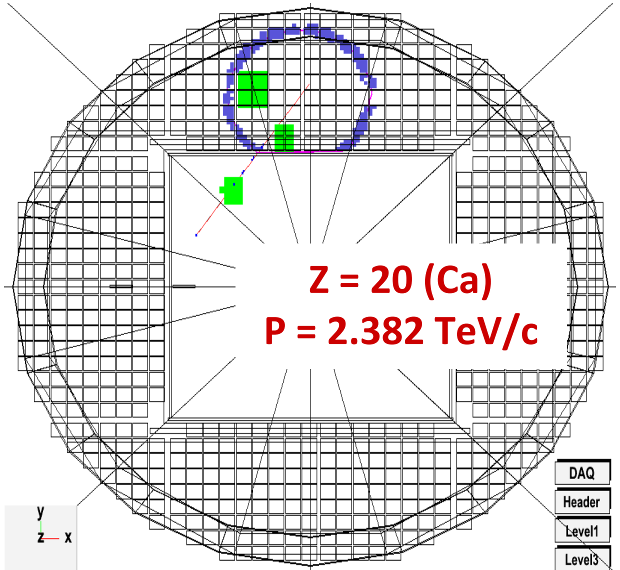
Measurement of Nuclear Charge (Z^2) and Velocity to 1/1000



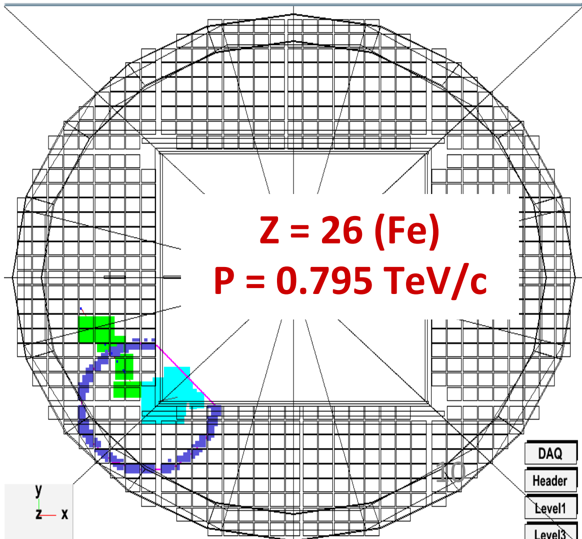




Z = 13 (Al)
P = 9.148 TeV/c



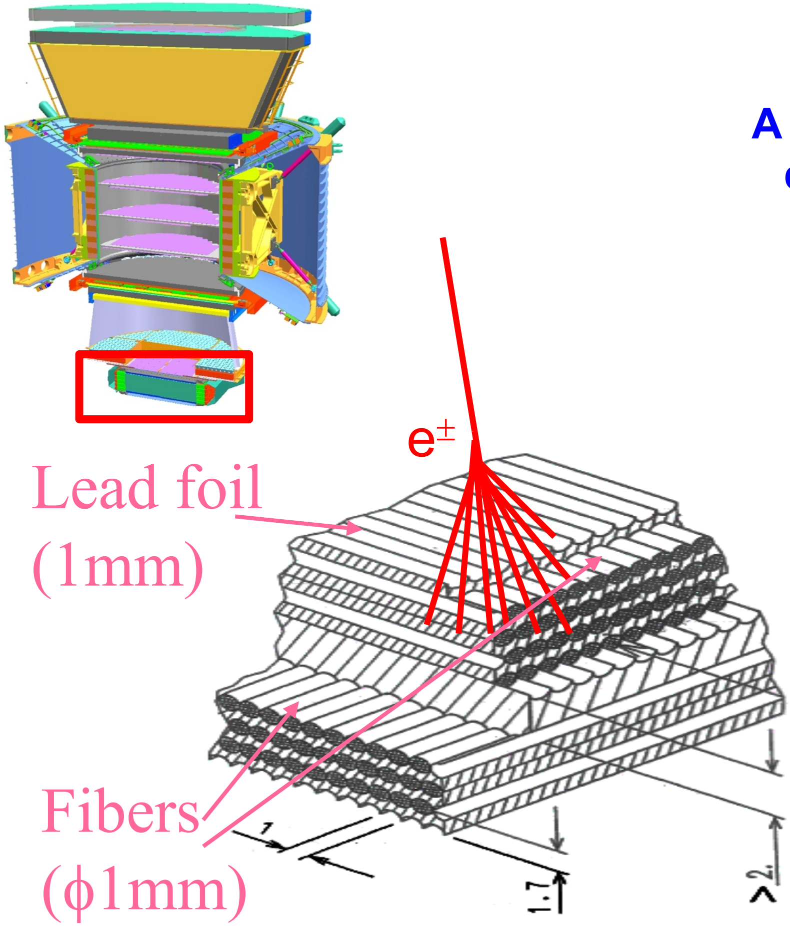
Z = 20 (Ca)
P = 2.382 TeV/c

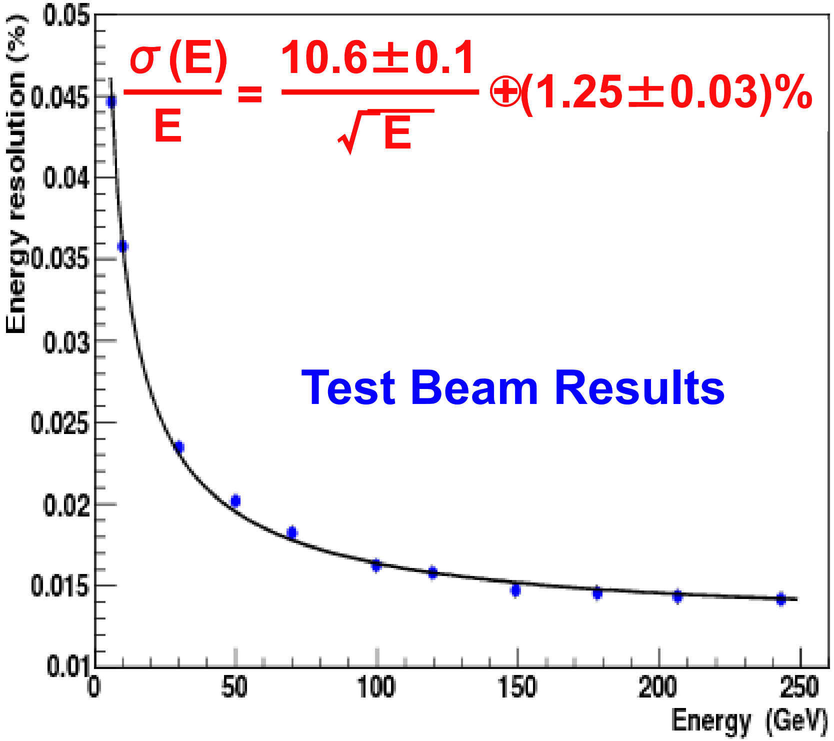


Z = 26 (Fe)
P = 0.795 TeV/c

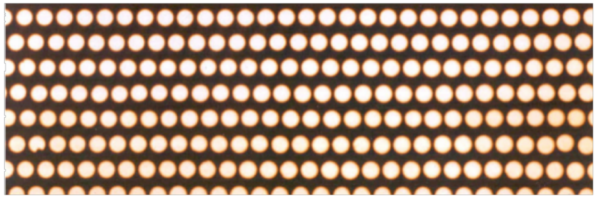
Calorimeter (ECAL)

A precision, 17 X_0, 3-dimensional measurement of the directions and energies of light rays and electrons





$$\frac{\sigma(E)}{E} = \frac{10.6\pm0.1}{\sqrt{E}} \oplus (1.25\pm0.03)\%$$



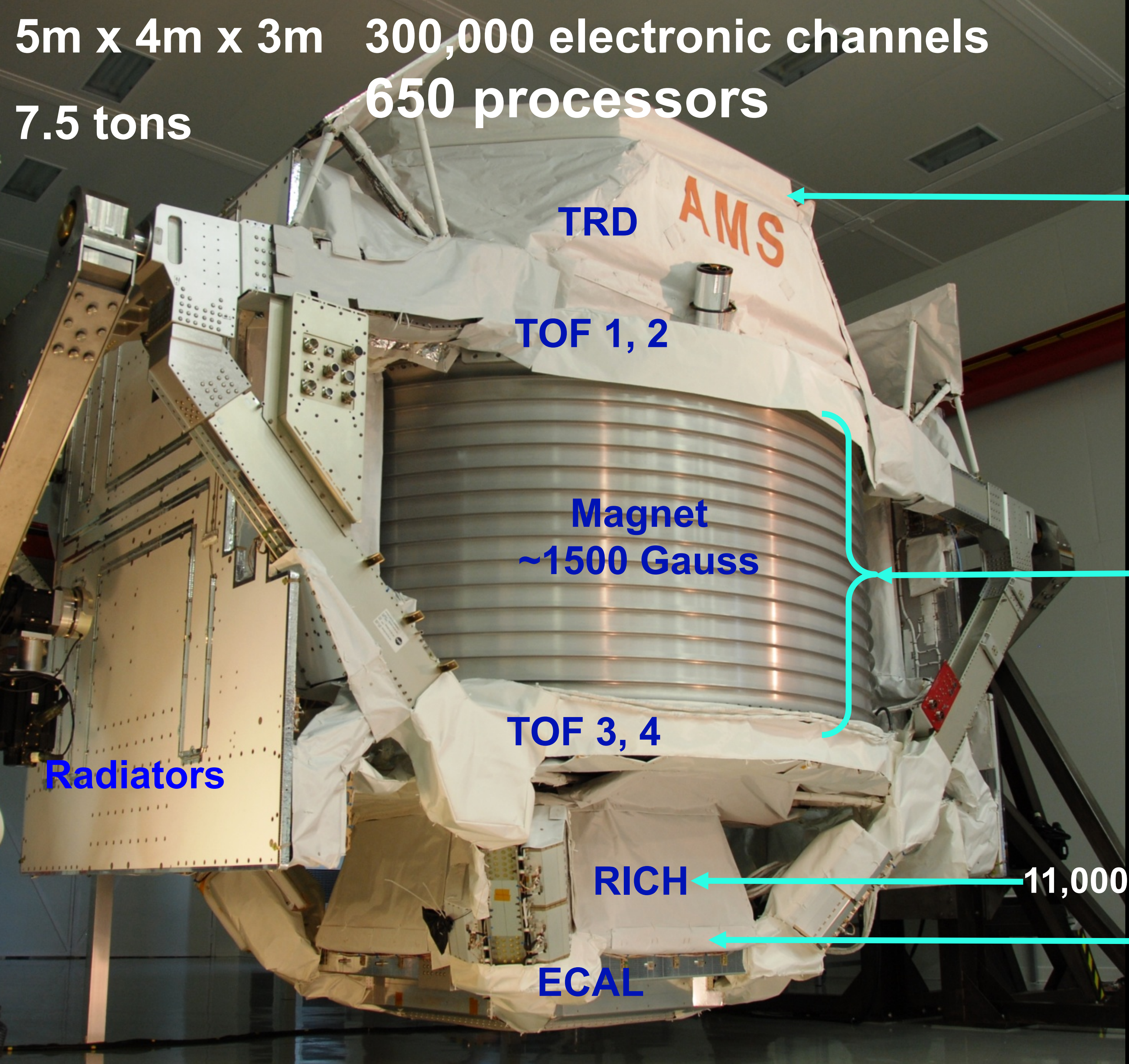
50 000 fibers, $\phi = 1$ mm distributed uniformly Inside 600kg of lead

5m x 4m x 3m

7.5 tons

300,000 electronic channels

650 processors



TRD

TOF 1, 2

Magnet

~1500 Gauss

TOF 3, 4

Radiators

RICH

ECAL

Silicon layer

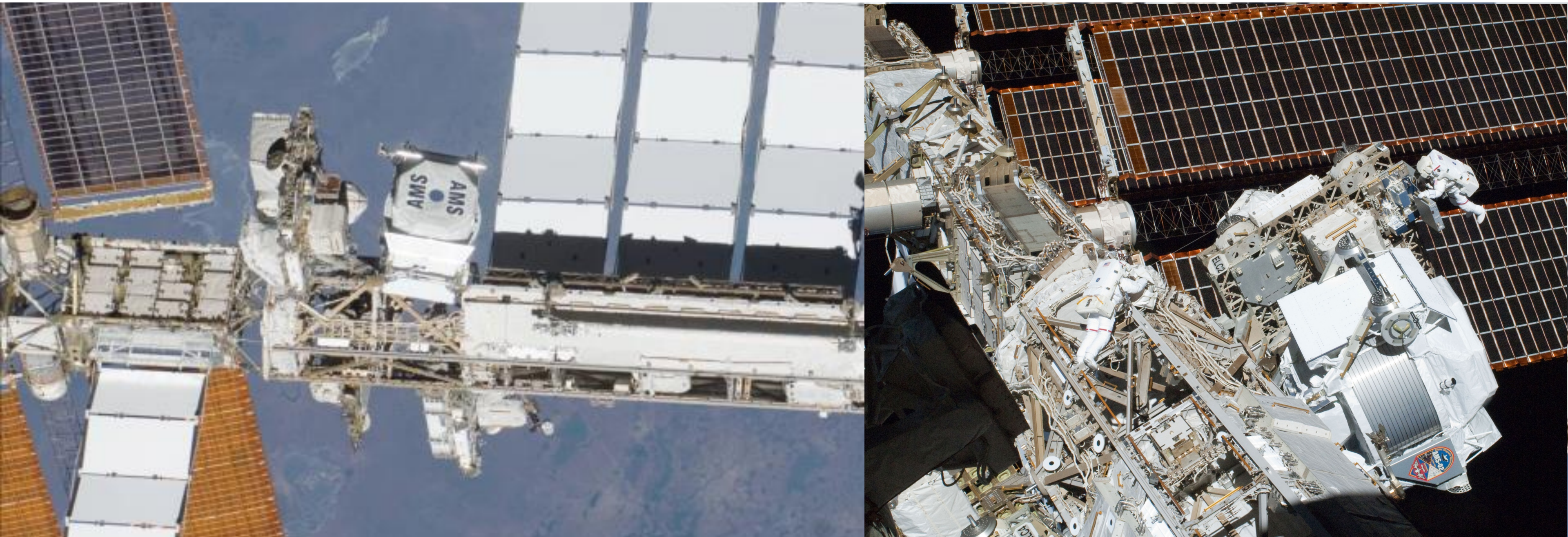
7 Silicon layers

11,000 Photo Sensors

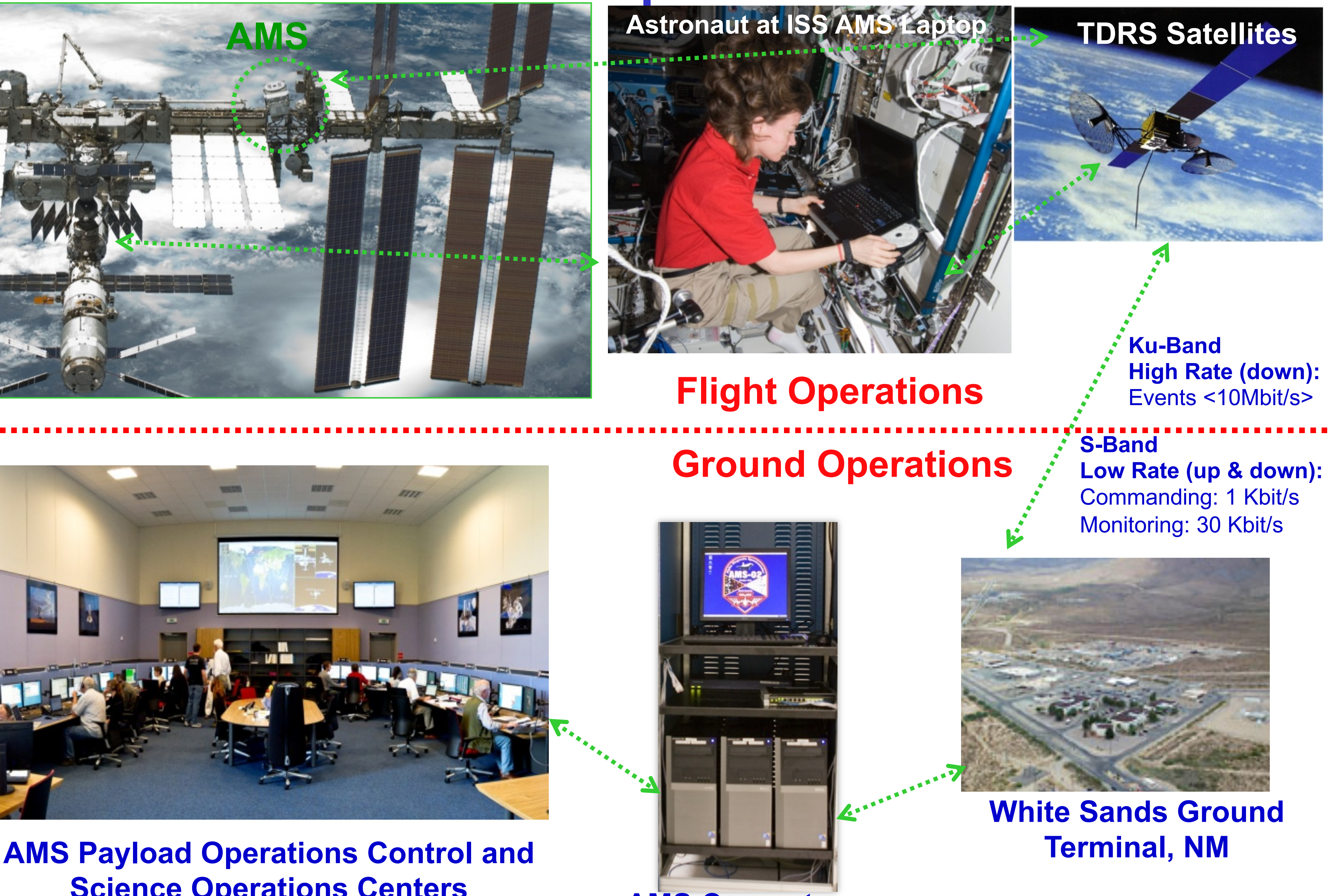
Silicon layer

May 16, 2011

May 19, 2011: AMS is installed on the ISS and data taking started



AMS Operations



Astronaut at ISS AMS Laptop

TDRS Satellites

Flight Operations

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

Ground Operations

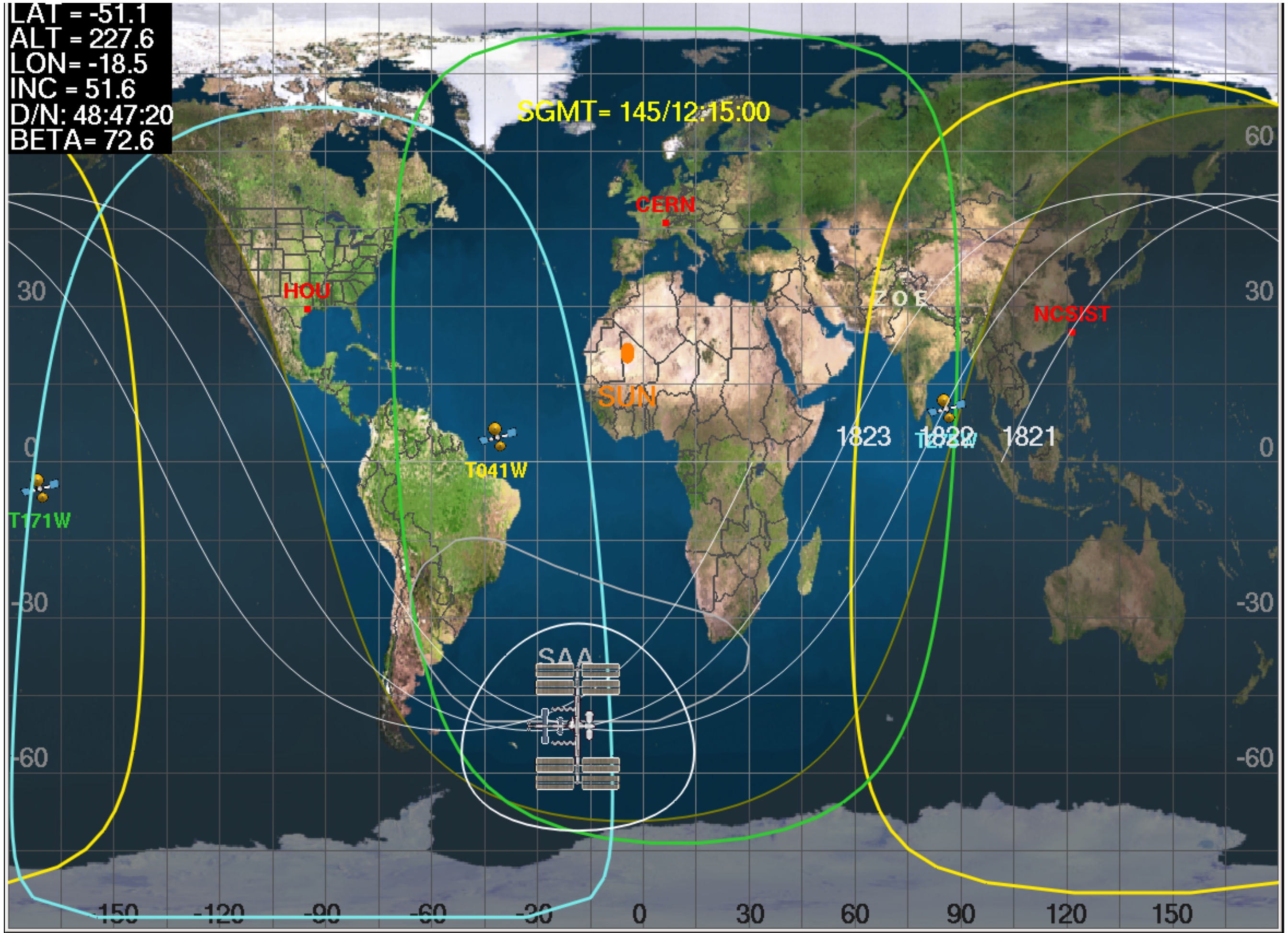
S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

AMS Payload Operations Control and Science Operations Centers (POCC, SOC) at CERN

AMS Computers at MSFC, AL

White Sands Ground Terminal, NM

May 25, 2017: AMS measured its 100 billionth cosmic ray event



100,879,440,121

Goals of AMS:

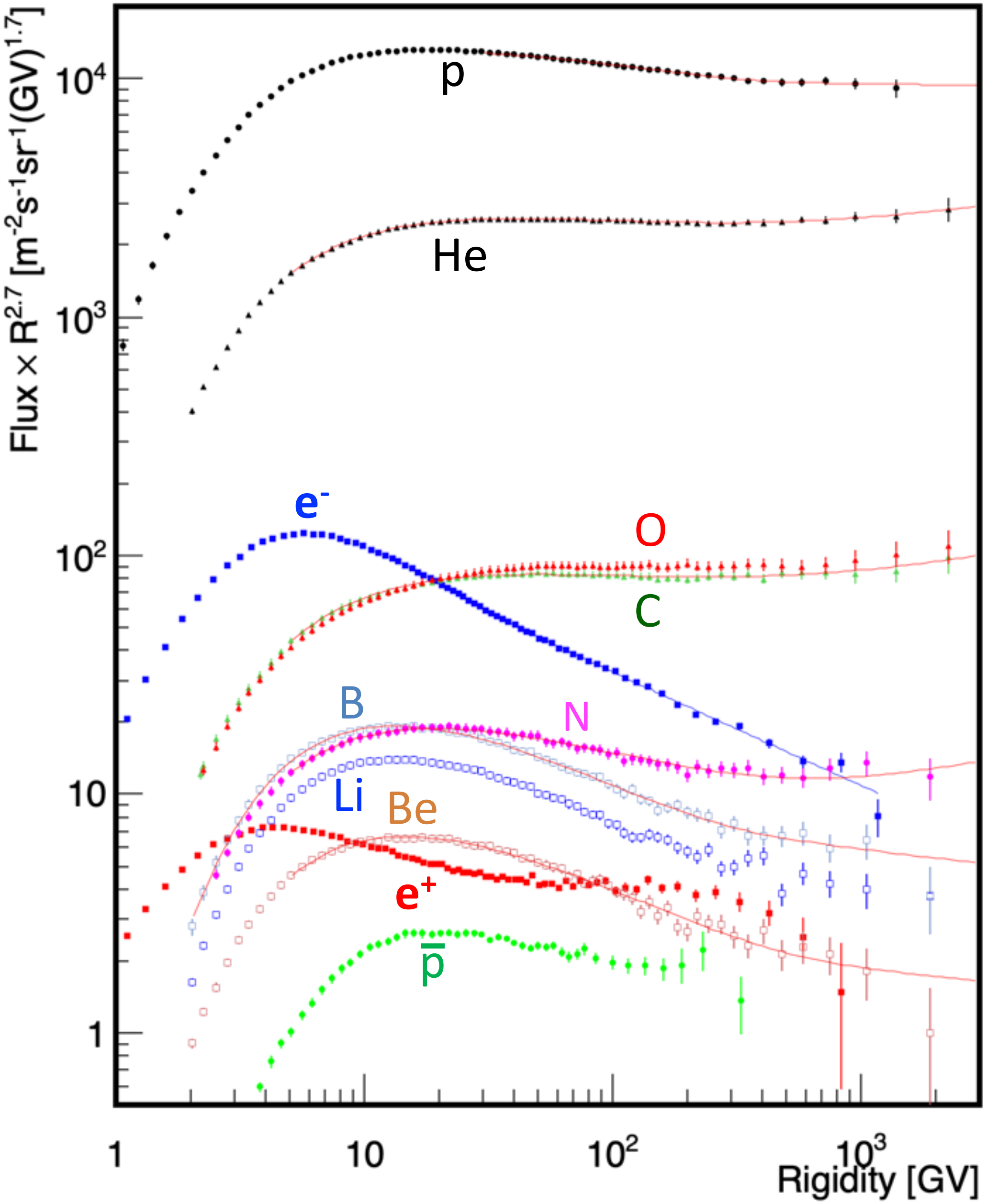
1. Search for the signature of Dark Matter in Cosmic Rays fluxes.
2. Search for the anti-matter signals in the Cosmic Rays.
3. Search for unexpected new phenomena.
4. Understanding the production and propagation of cosmic rays.

Experimental results:

- Fluxes of various cosmic ray components as functions of Rigidity (spectrum).
- Flux ratios between cosmic ray components as functions of Rigidity.

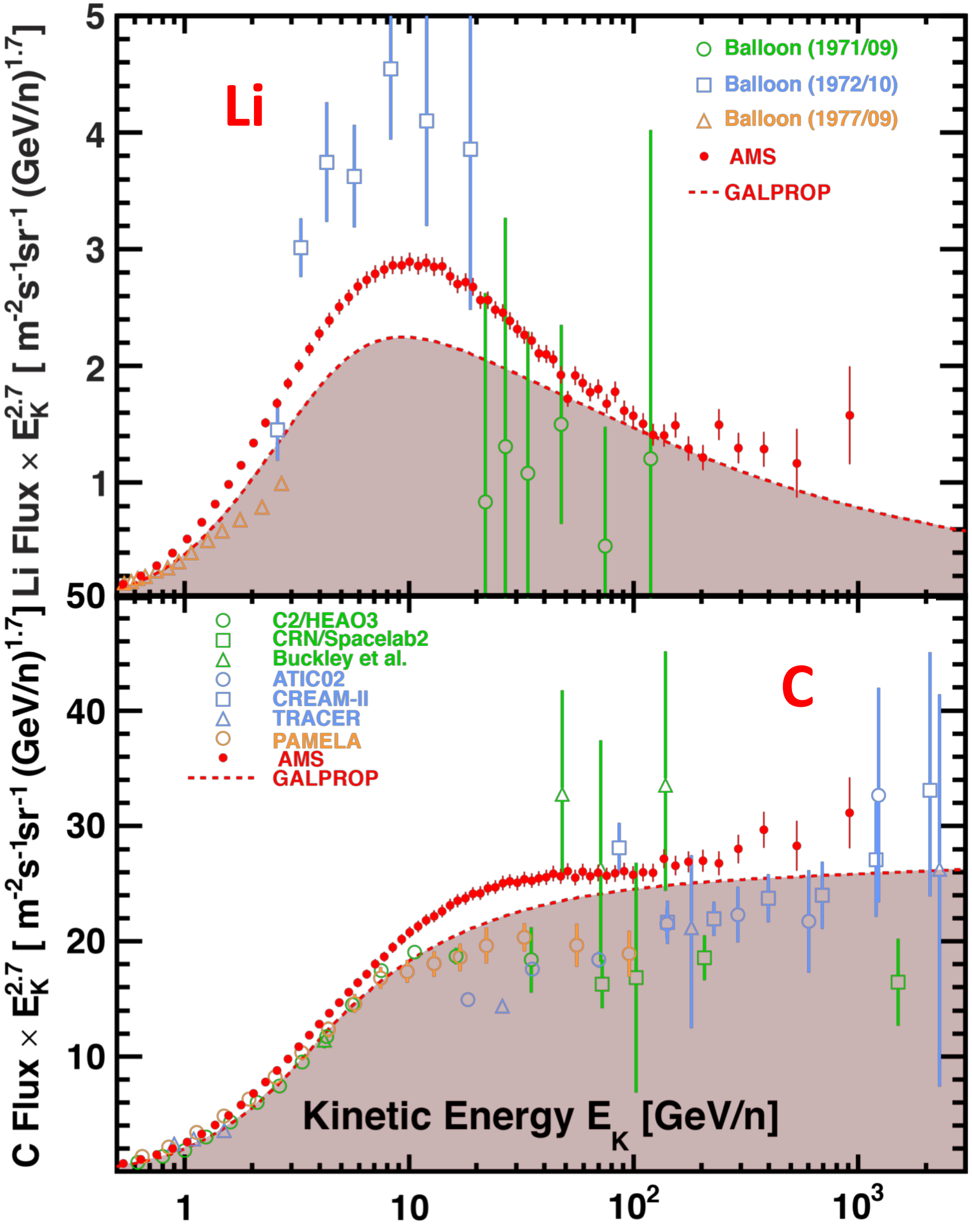
(Rigidity = Momentum/Charge = P/Z, unit: GV=GeV/Z)

AMS cosmic ray spectra ($\Phi \times R^{2.7}$)



Ref:
p: PRL 114.171103
He: PRL 115.211101
e+: PRL 122.041102
$\bar{p}$: PRL 117.091103
C,O: PRL 119.251101
Li, Be, B: PRL 120.021101
e^-: Preliminary

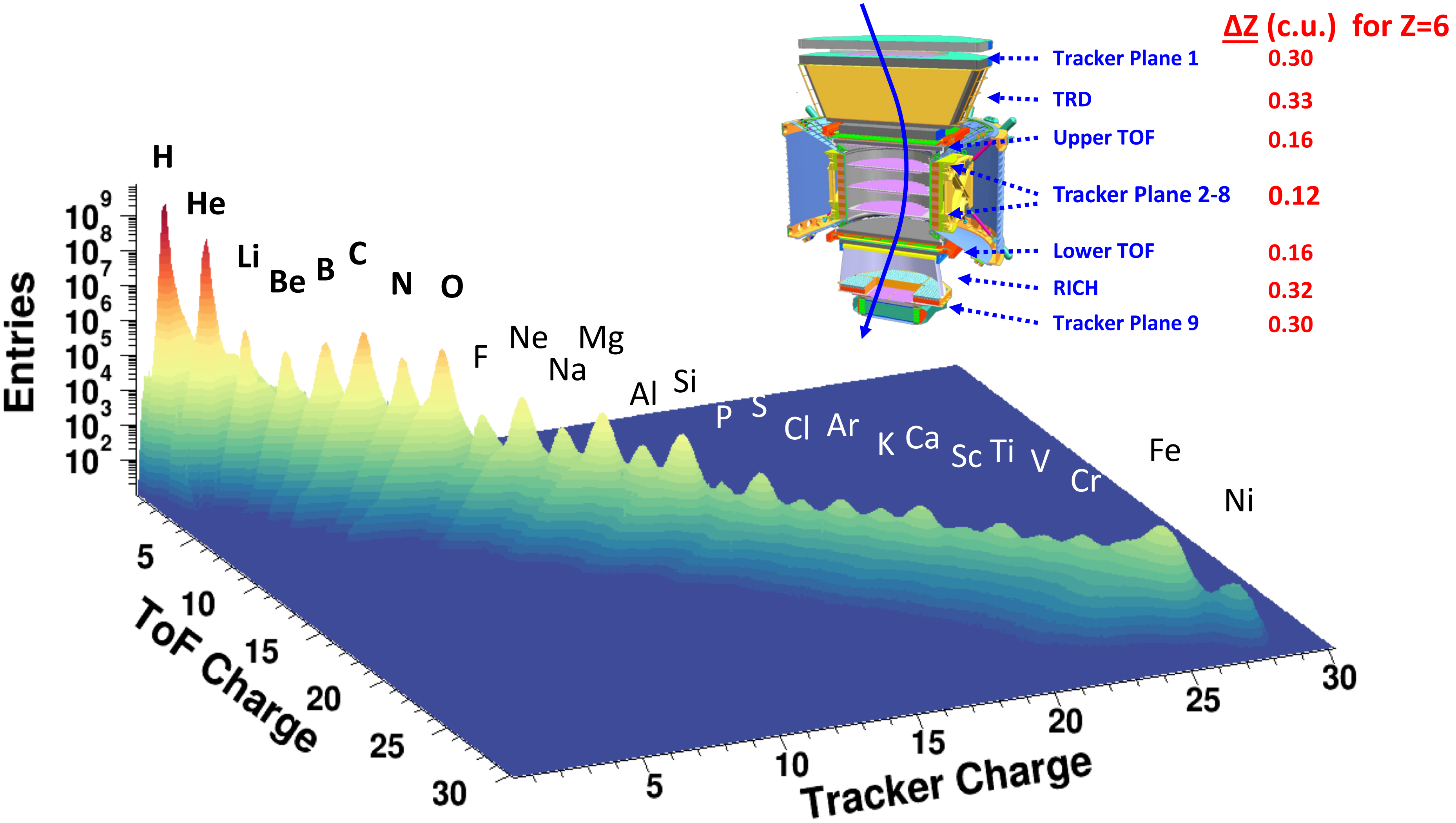
AMS results greatly improved the precision of cosmic ray spectra measurements. As in the following Examples:



Spectra of cosmic ray nuclei (Z>1)

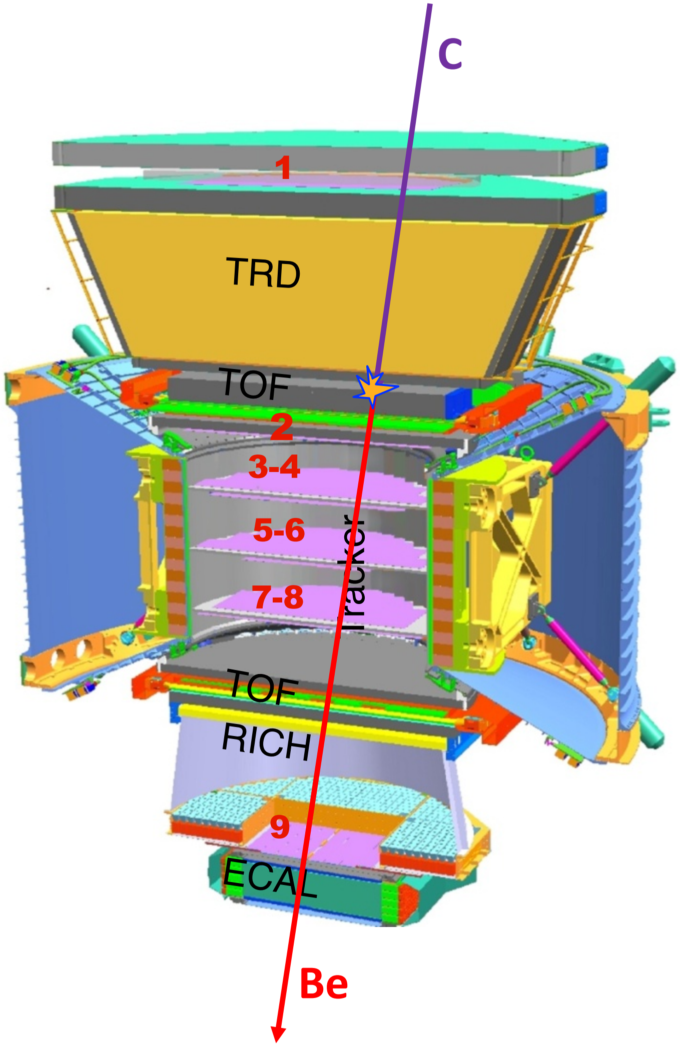
Cosmic Nuclei

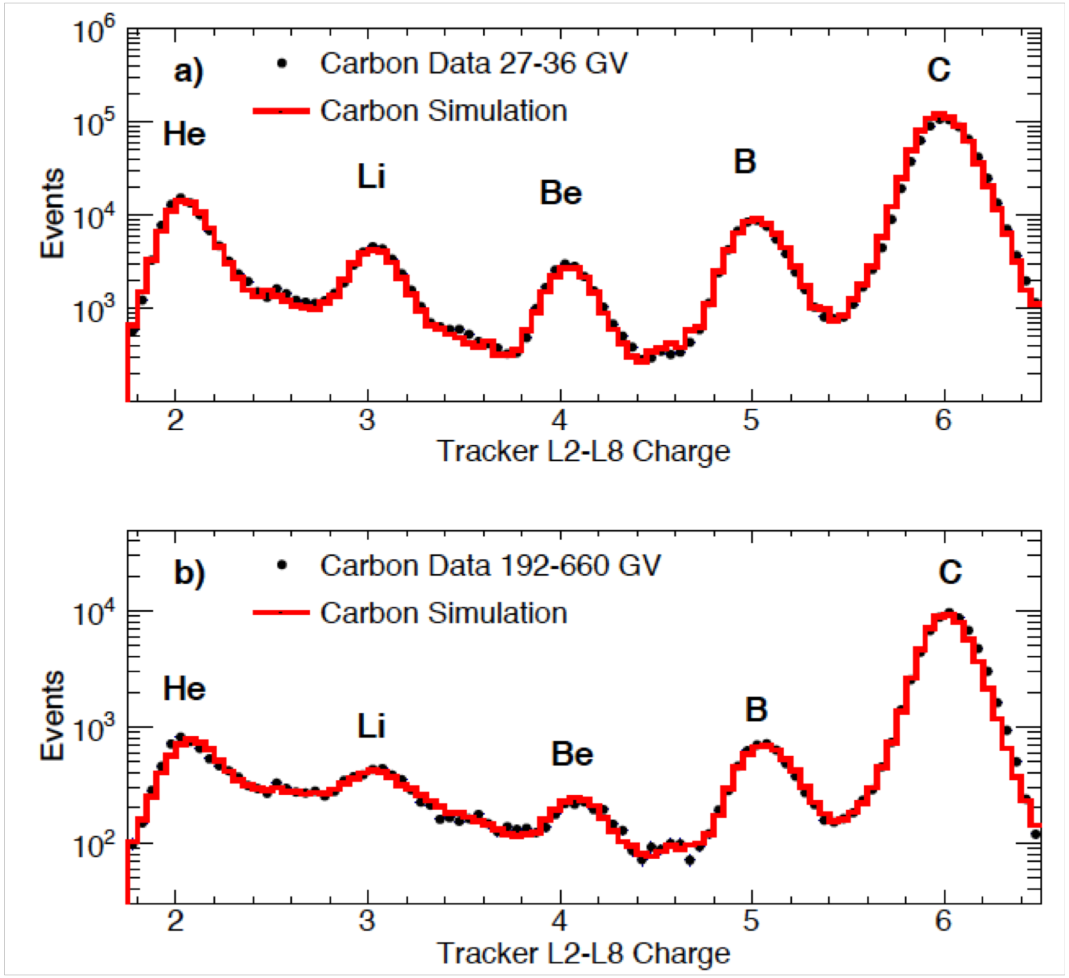
AMS has seven instruments which independently identify different elements



	ΔZ (c.u.) for Z=6
Tracker Plane 1	0.30
TRD	0.33
Upper TOF	0.16
Tracker Plane 2-8	0.12
Lower TOF	0.16
RICH	0.32
Tracker Plane 9	0.30

For nuclei, it is critical to understand the probability that the nuclei breaks up while passing through the detectors.



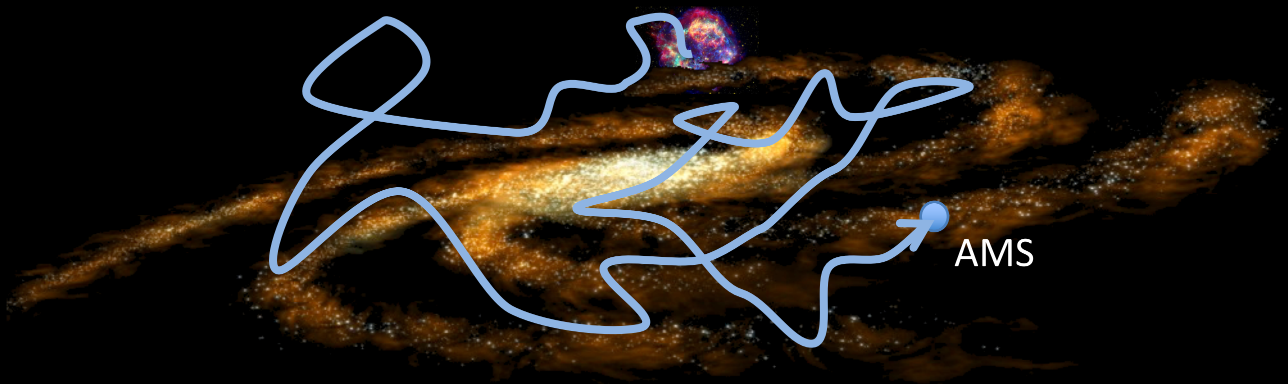


Charge measured by Tracker L1

Spectra of nuclei provide crucial information of cosmic ray propagation. Important features:

- Do not expect exotic sources.
- In the collision of primary cosmic rays with ISM, the secondaries are produced with the same velocity. In the nuclei we studied, this implies that the secondary nuclei are produced with roughly the same rigidity (p/Z) as the parent nuclei.
- Nuclei with the same rigidity follow the same path during propagation in the galactic magnetic field.

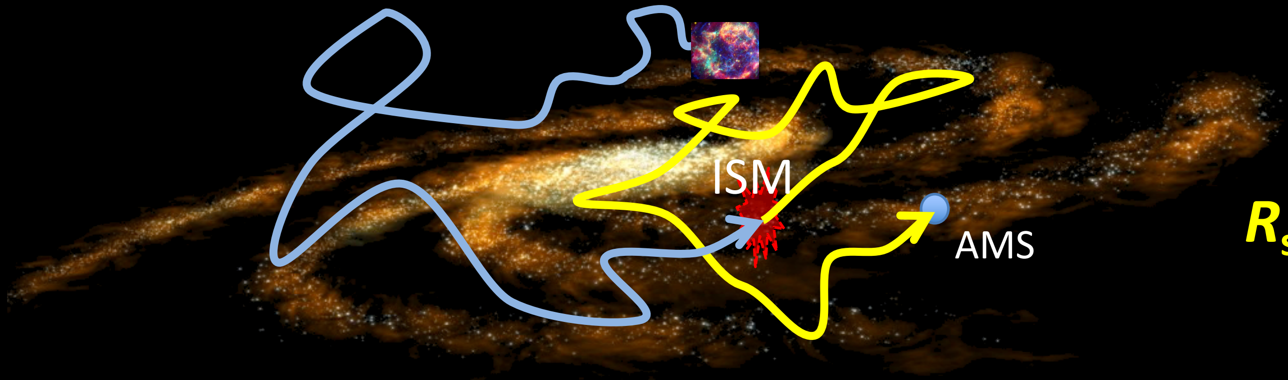
Primary Cosmic Rays (p, He, C, O, …)



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

Secondary Cosmic Rays (Li, Be, B, …)

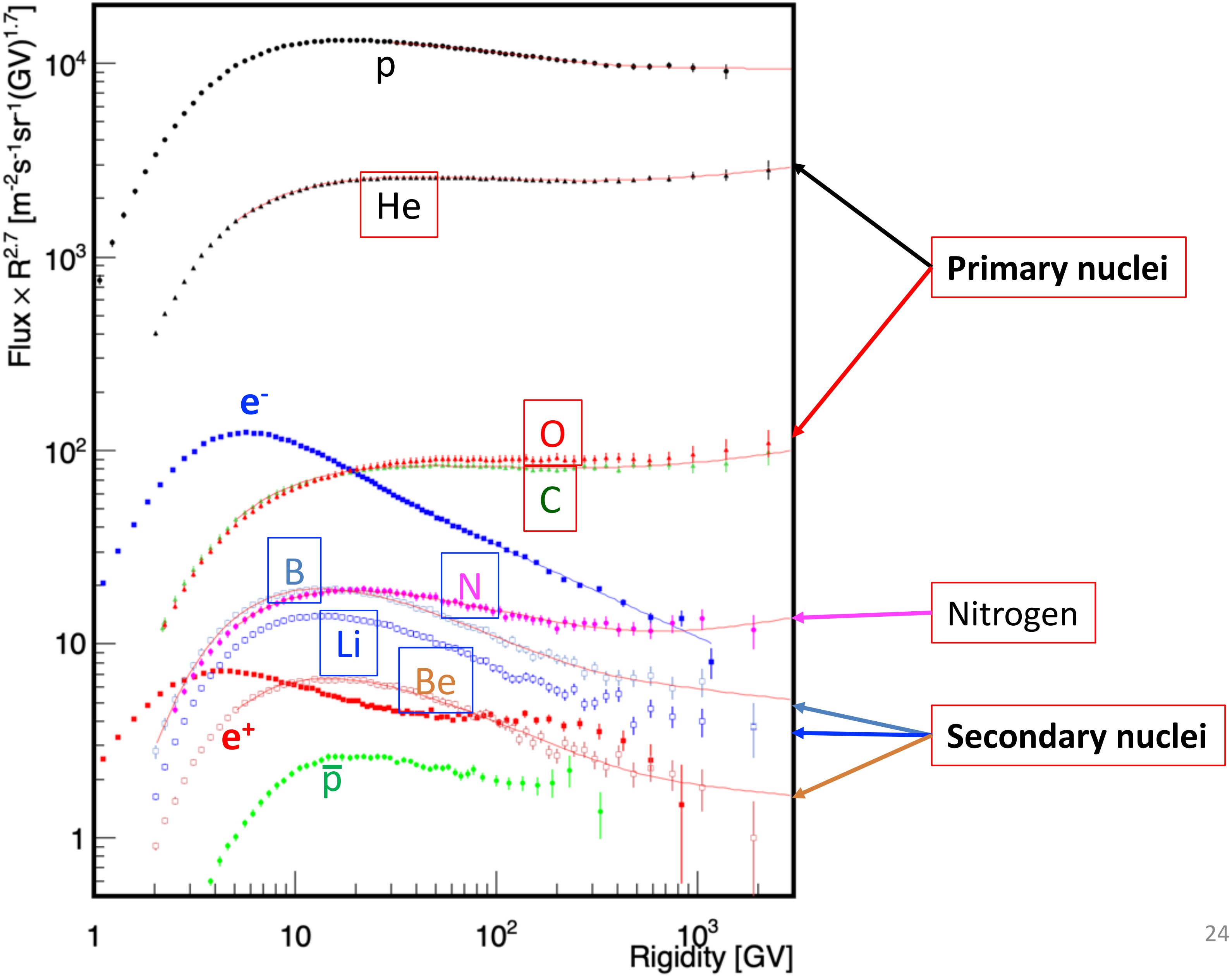
C, O, …, Fe + ISM → Li, Be, B + X



$R_{sec} \approx R_{parent}$

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

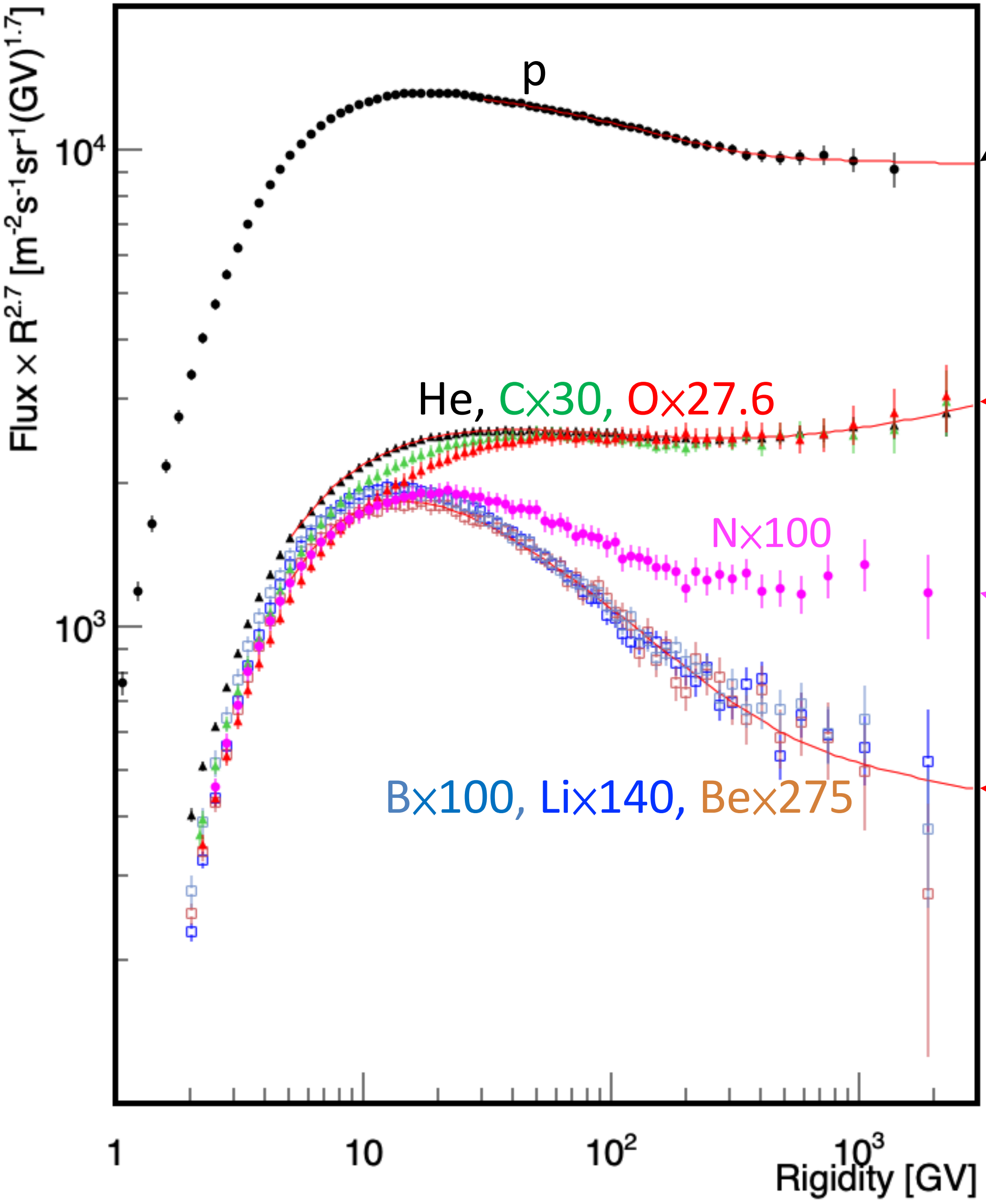
Spectra of cosmic ray nuclei



Primary nuclei

Nitrogen

Secondary nuclei



Proton

Primary nuclei

- Identical behavior above 20 GV in rigidity.
- Differences below 20 GV are mainly due to solar modulation.

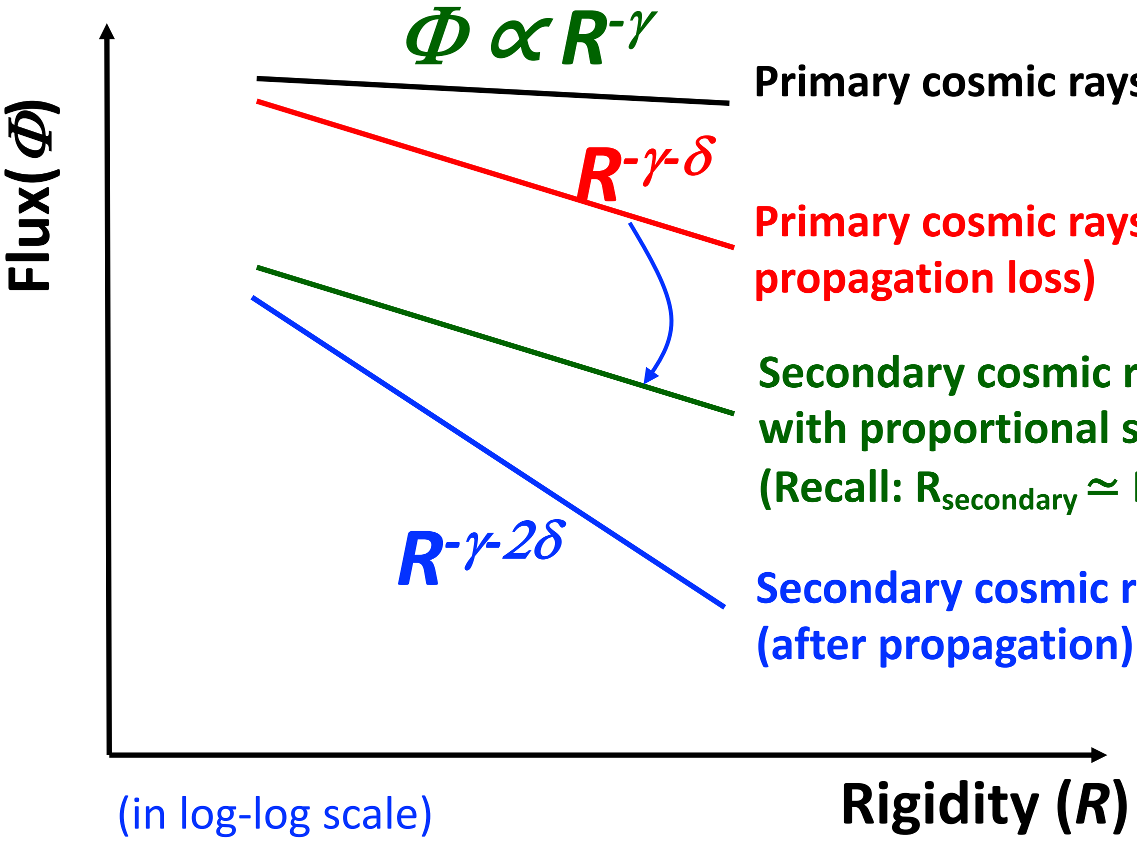
Nitrogen is unique in its spectrum behavior

Secondary nuclei

(produced by collision of primary cosmic rays with ISM)

- Li, Be, B have the same spectrum.
- distinctively different from the primaries.

General expectations of Standard Cosmic rays models:



$\Phi \propto R^{-\gamma}$

Primary cosmic rays at production (He, C, O)

$R^{-\gamma-\delta}$

Primary cosmic rays detected. (after propagation loss)

Secondary cosmic rays (Li, Be, B) produced with proportional spectrum

(Recall: $R_{secondary} \simeq R_{parent}$)

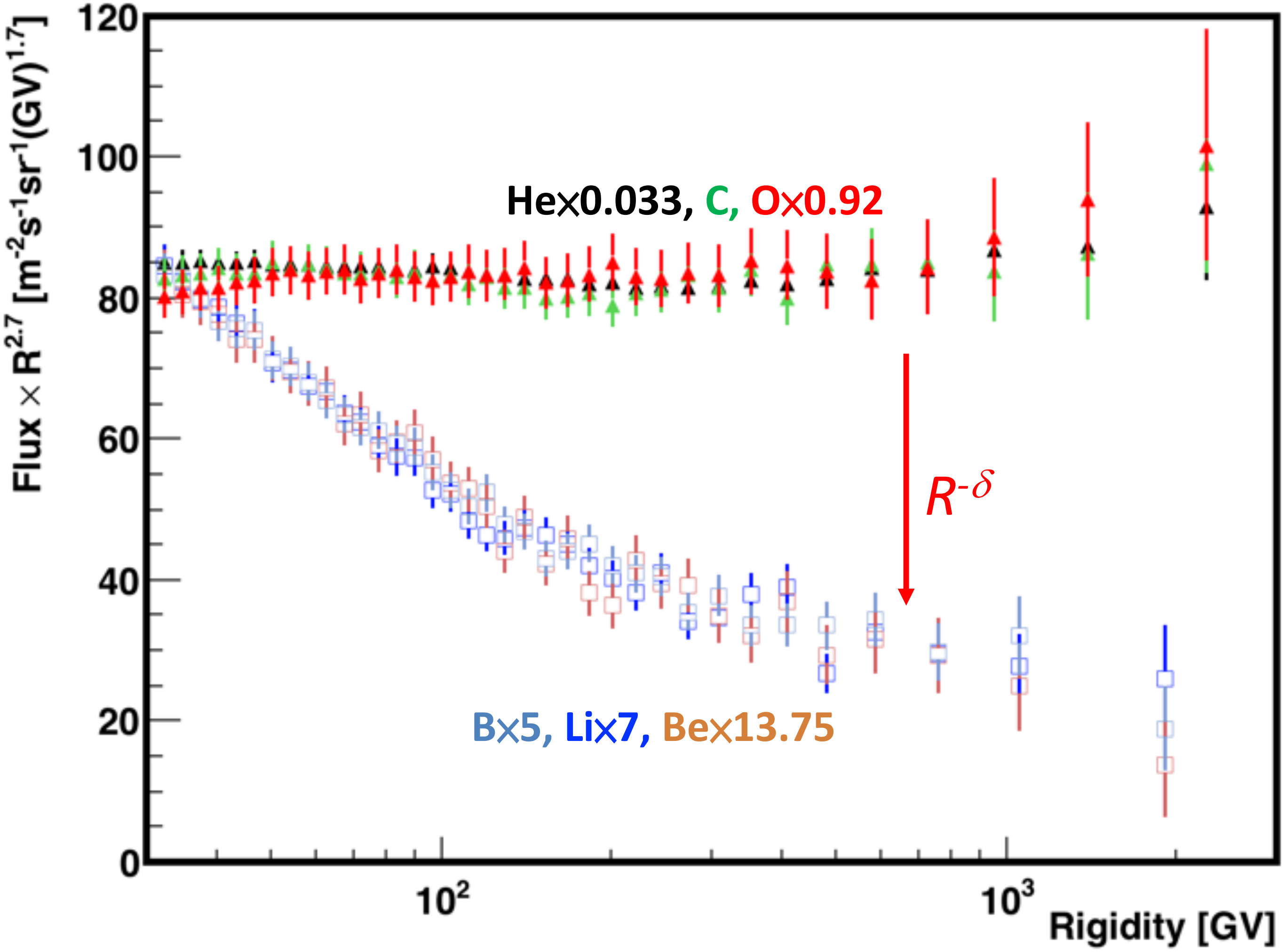
$R^{-\gamma-2\delta}$

Secondary cosmic rays detected. (after propagation)

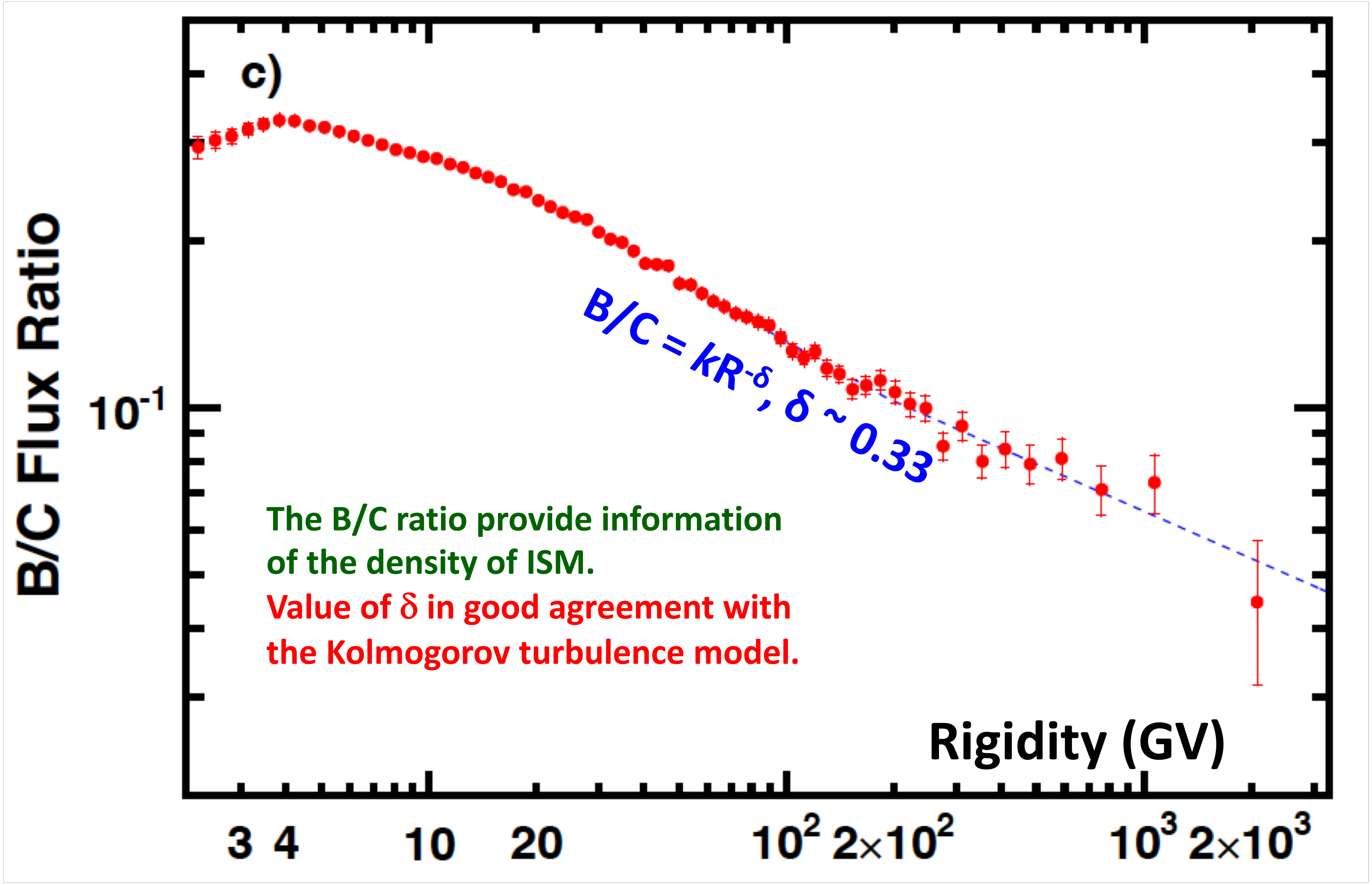
(in log-log scale)

Propagation effect: high rigidity particles escape from the galaxy faster.

Observed spectra strongly support our understanding of cosmic ray nuclei



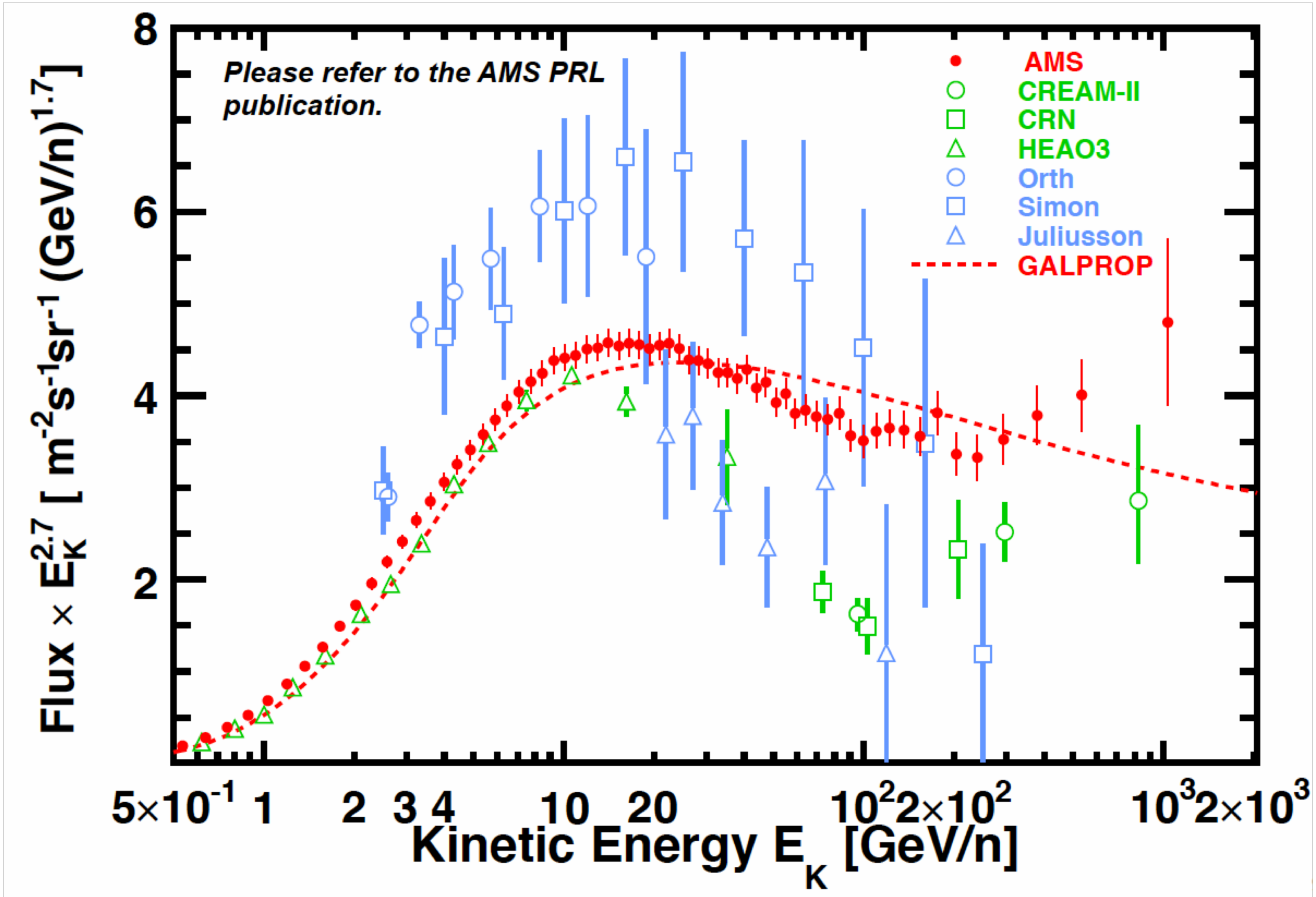
Secondary to Primary ratio



The B/C ratio provide information of the density of ISM.

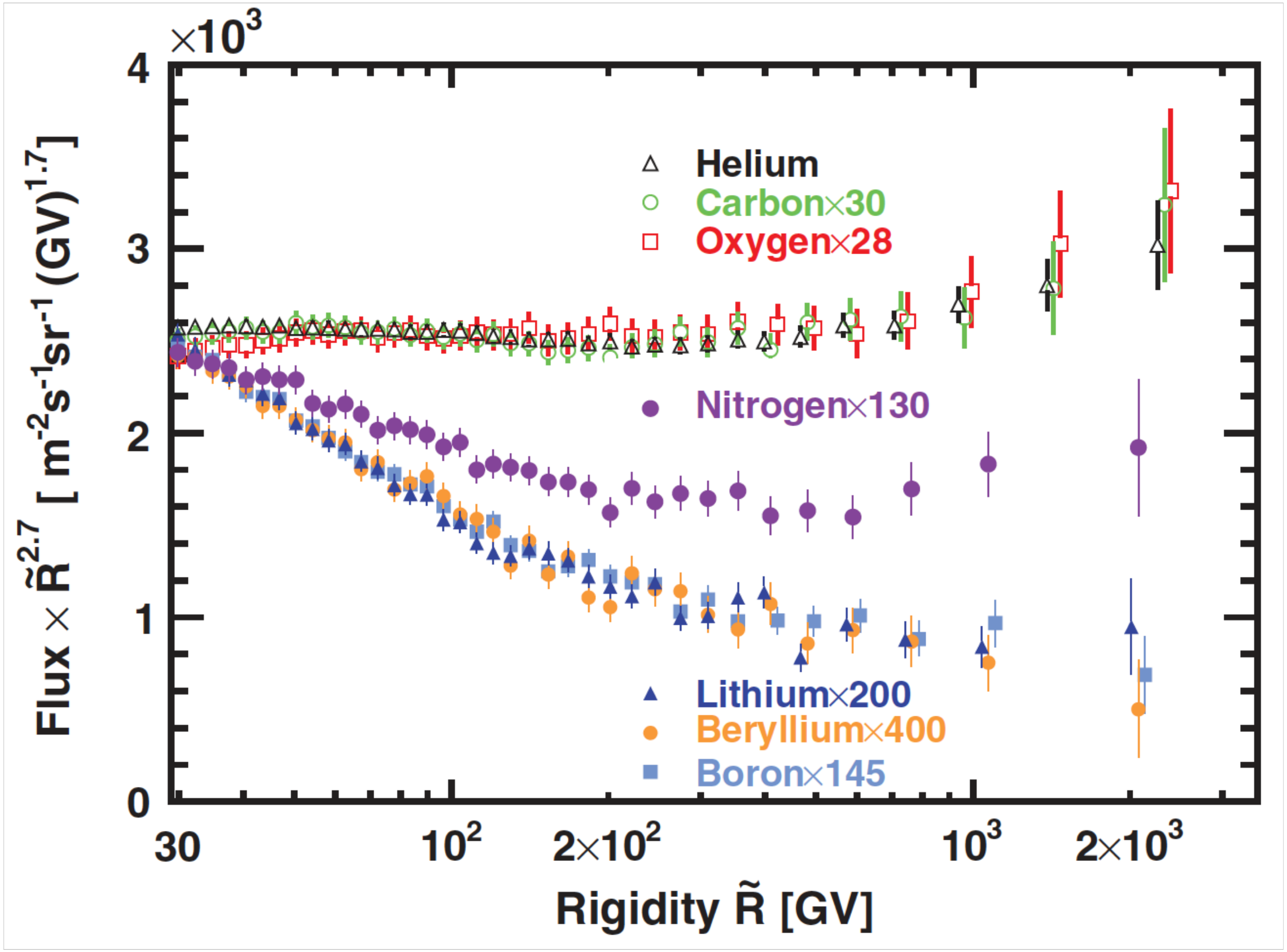
Value of δ in good agreement with the Kolmogorov turbulence model.

The AMS Result on the Nitrogen Flux Converted from Rigidity assuming $^{14}N/^{15}N = 1$



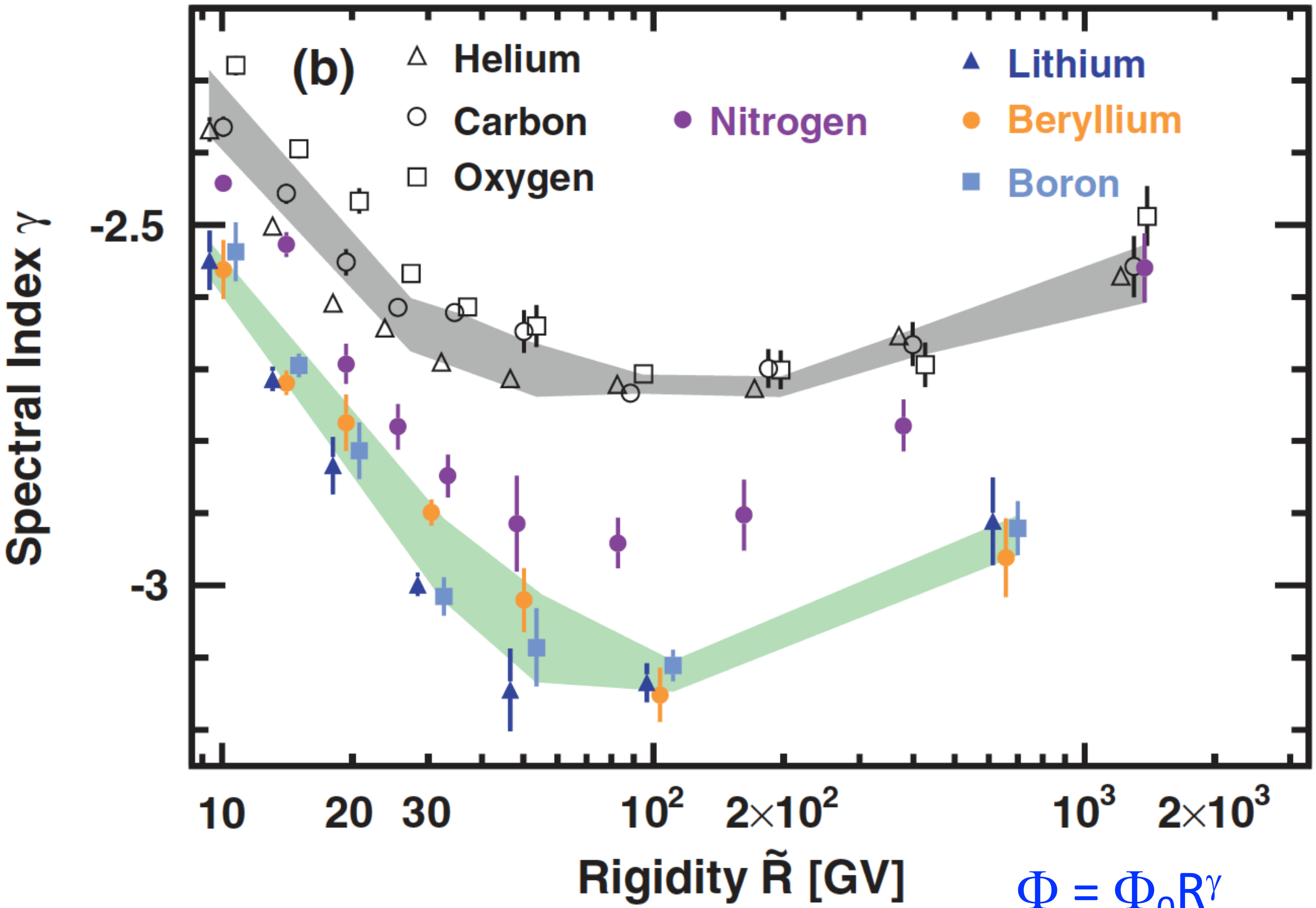
Nitrogen:

Nitrogen contains both primary and secondary components
The spectrum is a mix of primary and secondary spectra.



PRL 121.051103

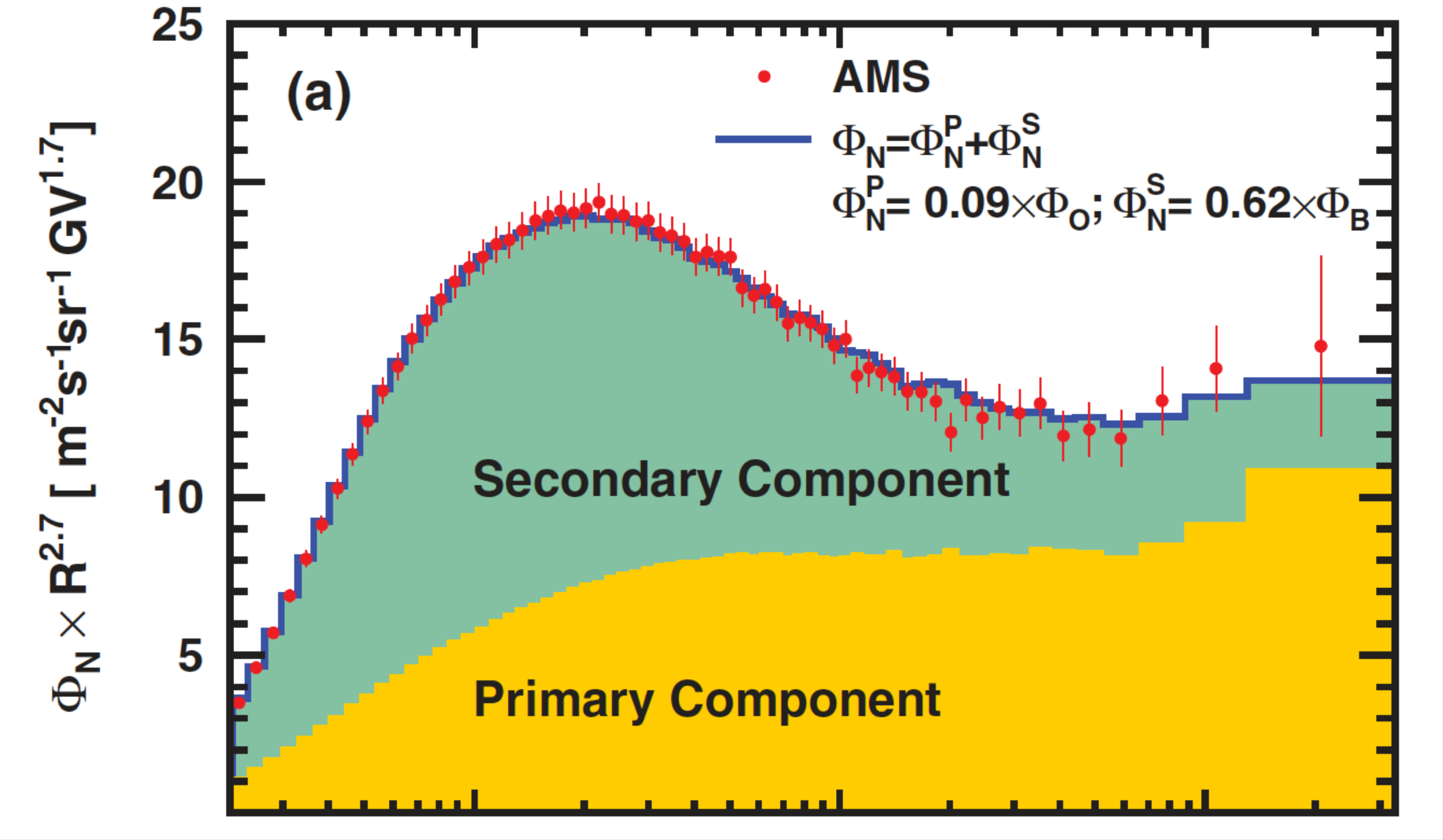
The spectra index γ indicates that N spectrum is closer to secondary at low rigidity, and become primary at high rigidity.



$\Phi = \Phi_0 R^\gamma$

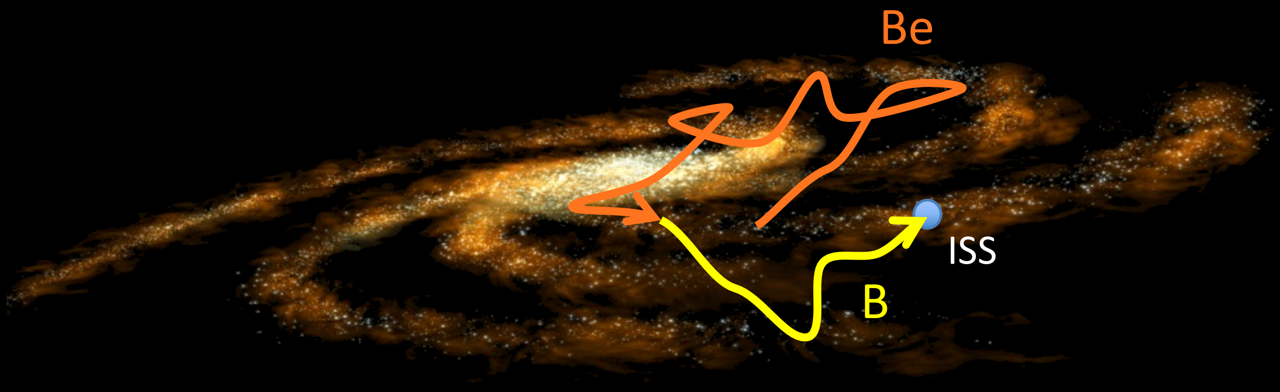
A fit is performed to express Nitrogen flux as linear sum of Oxgen (primary) and Boron (secondary) fluxes, and the spectrum agrees very well with

$\Phi_N = 0.09\ \Phi_O + 0.62\ \Phi_B$.



Note: N/O ~ 0.12 in the Sun

Beryllium-to-Boron and the age of cosmic rays

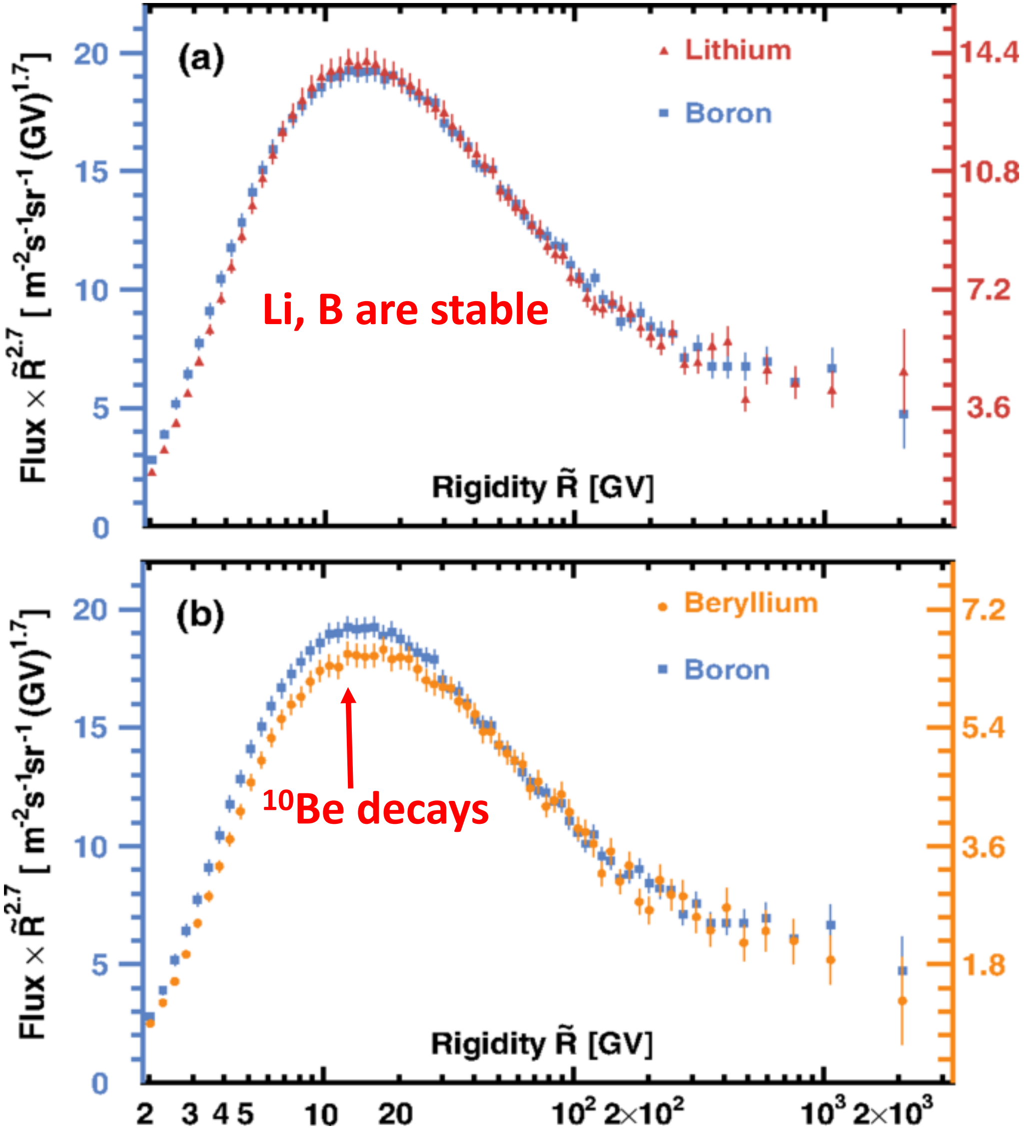


$$ {}^{10}\mathrm{Be} \rightarrow {}^{10}\mathrm{B} + e^{-} + \bar{\nu}_e $$

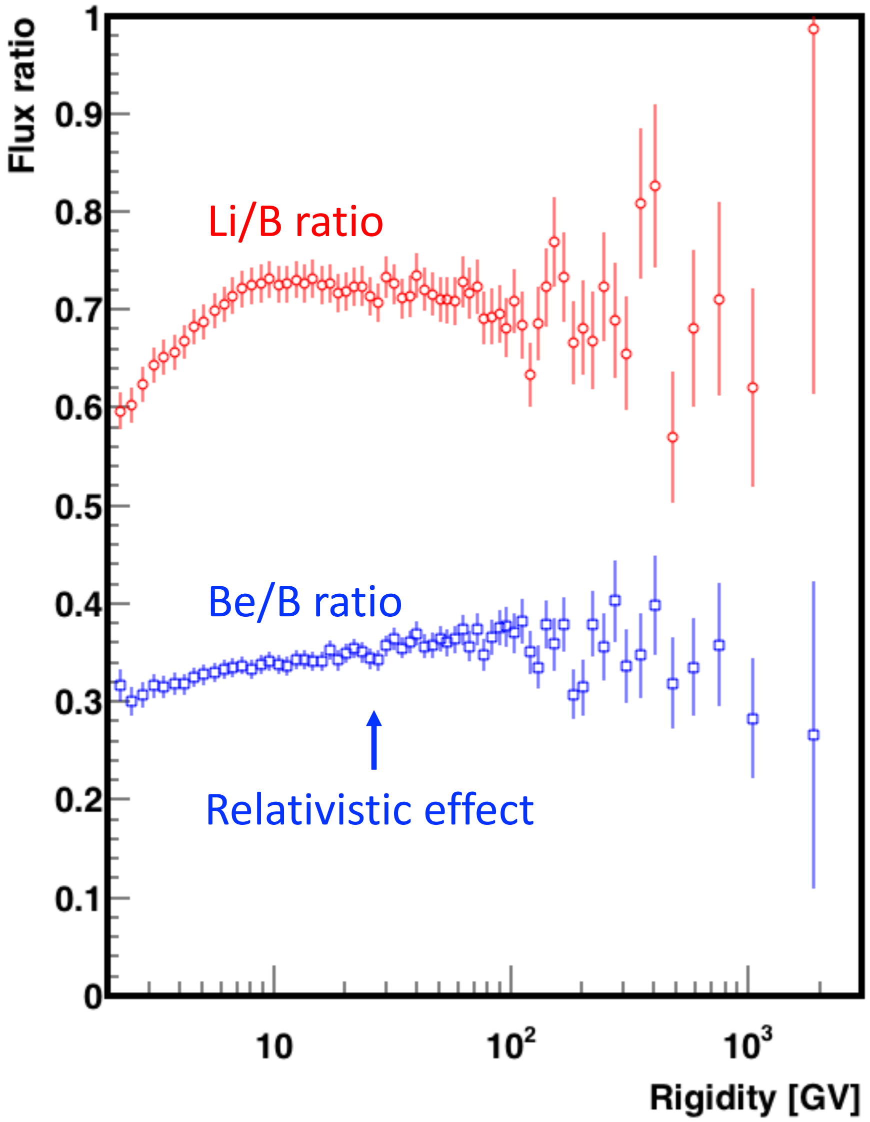
The ^{10}Be half-life is 1.35×10^6 years.

The Be/B ratio rises with energy due to relativistic time dilation. Be/B provides information on the age of cosmic rays in the Galaxy.

Looking closer to the secondary spectra, we notice that Be flux shows deficit below 30GV.



Ratios of secondary cosmic ray fluxes



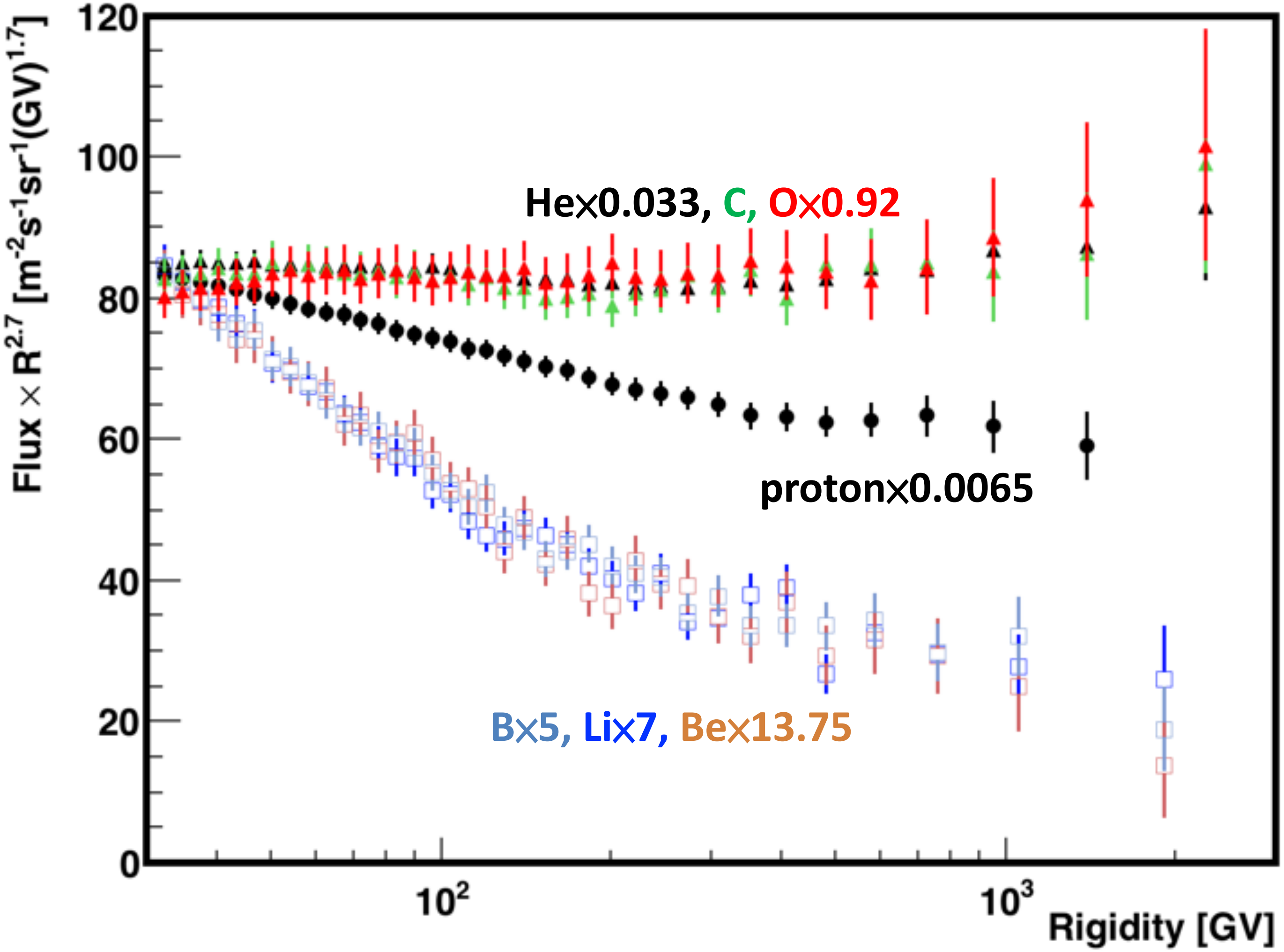
- Li and B are stable, and are produced through the same mechanism. Li/B ratio are basically constant.

- ^{10}Be (~10% in production) decays. ^{10}Be with larger rigidity has longer life time due to relativistic time dilation. ➔Be/B ratio rises with rigidity.

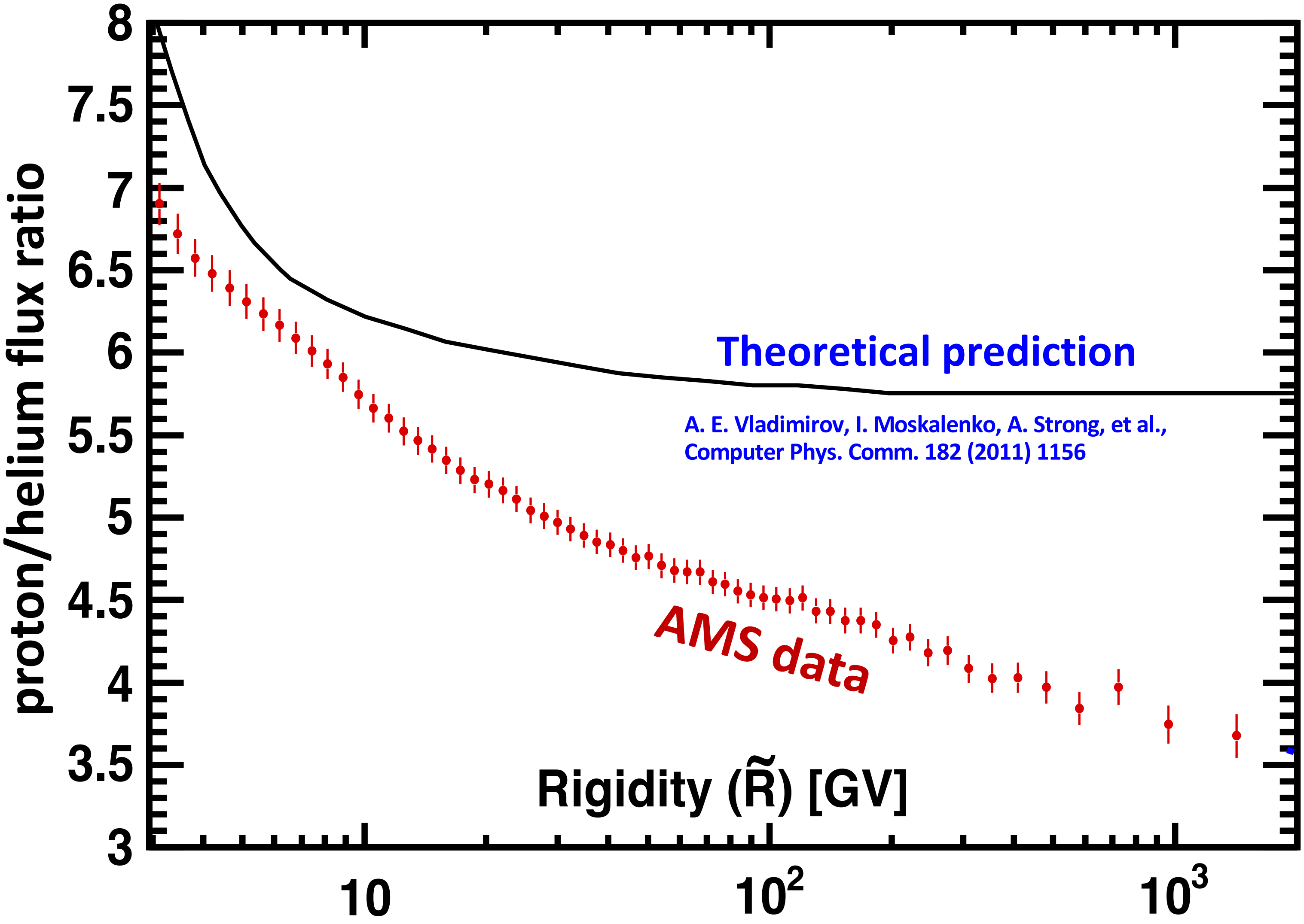
- **The mean escape time of cosmic ray nuclei can be derived from Be/B ratio.**

There are also unsolved problems of the nuclei spectra:

1. What about Proton? Proton is also primary!
2. The flux cannot be described by a single power law. Power law index changes at ~300GV.



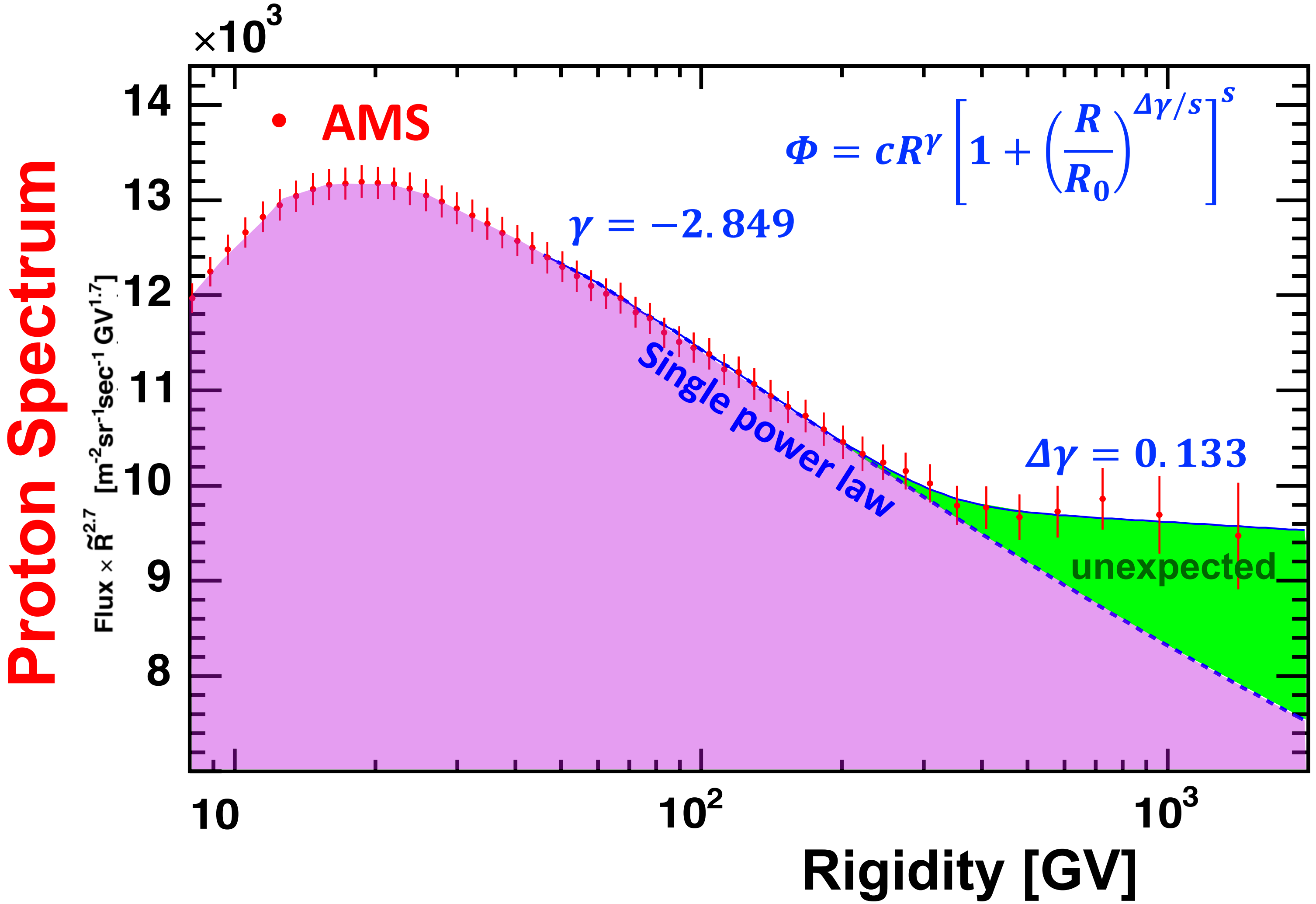
Protons and helium are both “primary” cosmic rays. Traditionally, they are assumed to be produced in the same sources and, therefore, their flux ratio should be rigidity independent.



A. E. Vladimirov, I. Moskalenko, A. Strong, et al., Computer Phys. Comm. 182 (2011) 1156

Break of cosmic nuclei spectrum

The Flux cannot be described by a single power law as has traditionally been assumed

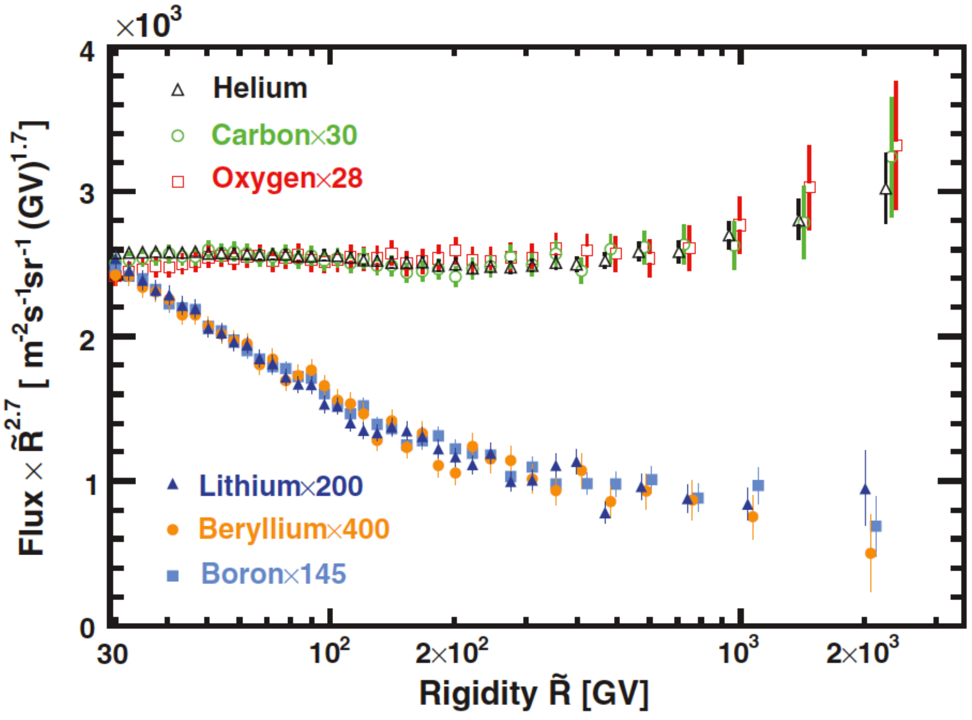


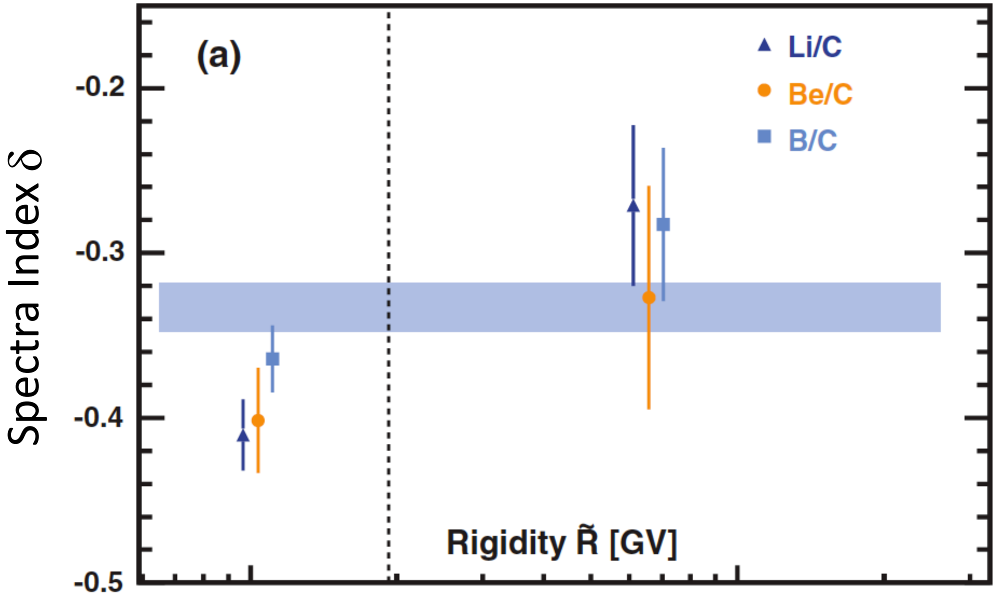
Nuclei spectra changes power law index (Break) at ~300GV.

- The Secondary spectra index change more than primary spectra.

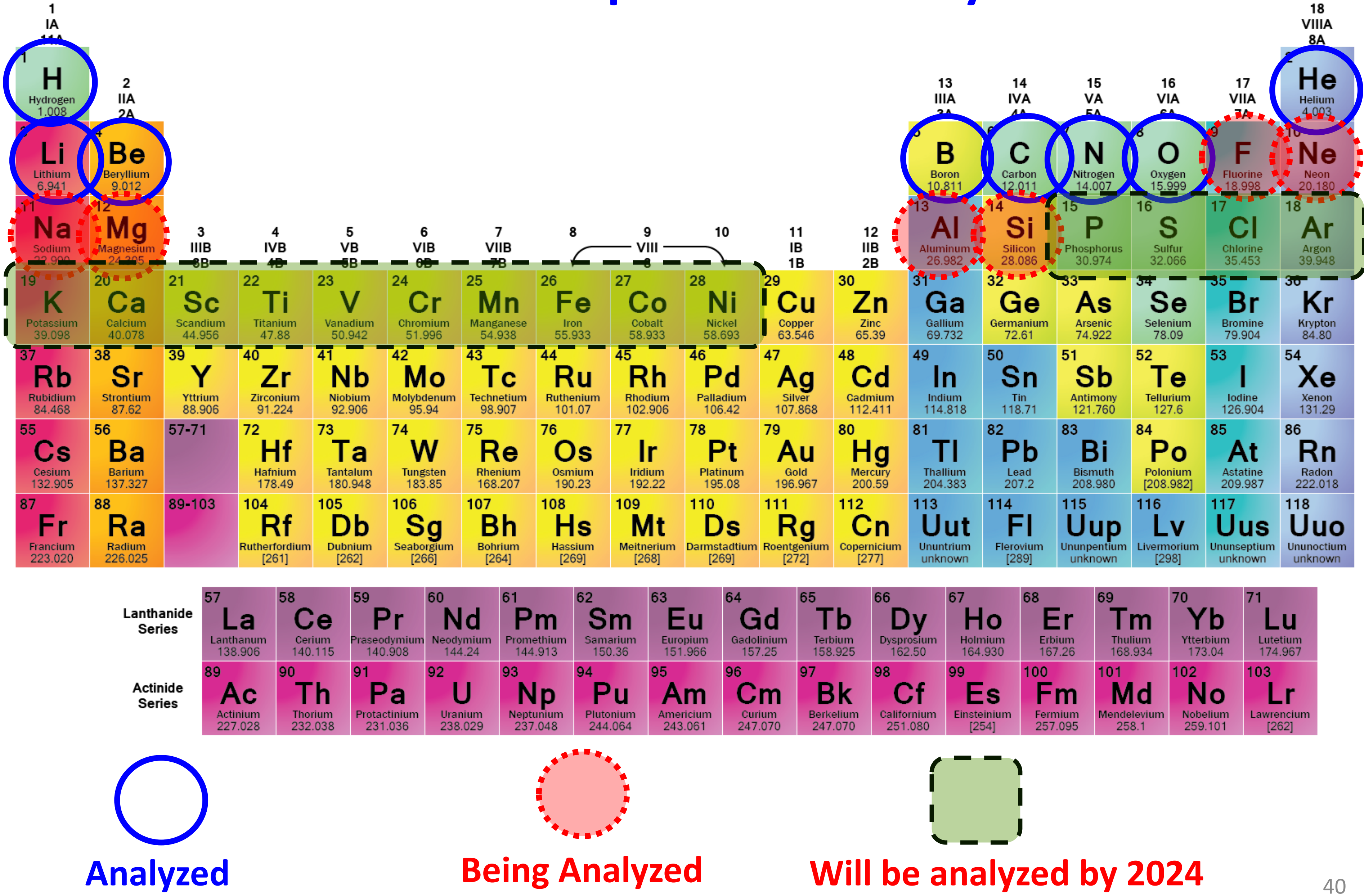
- Possible scenario:
  - Propagation
  - Injection spectrum
  - Local source at LE or HE

- ***$\Delta\gamma$* of secondary is larger than *$\Delta\gamma$* of primary -> Break of the spectra is likely a propagation effect.**





With increasing statistics through 2024, we will measure the elements up to iron and beyond.



1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.09	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 168.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

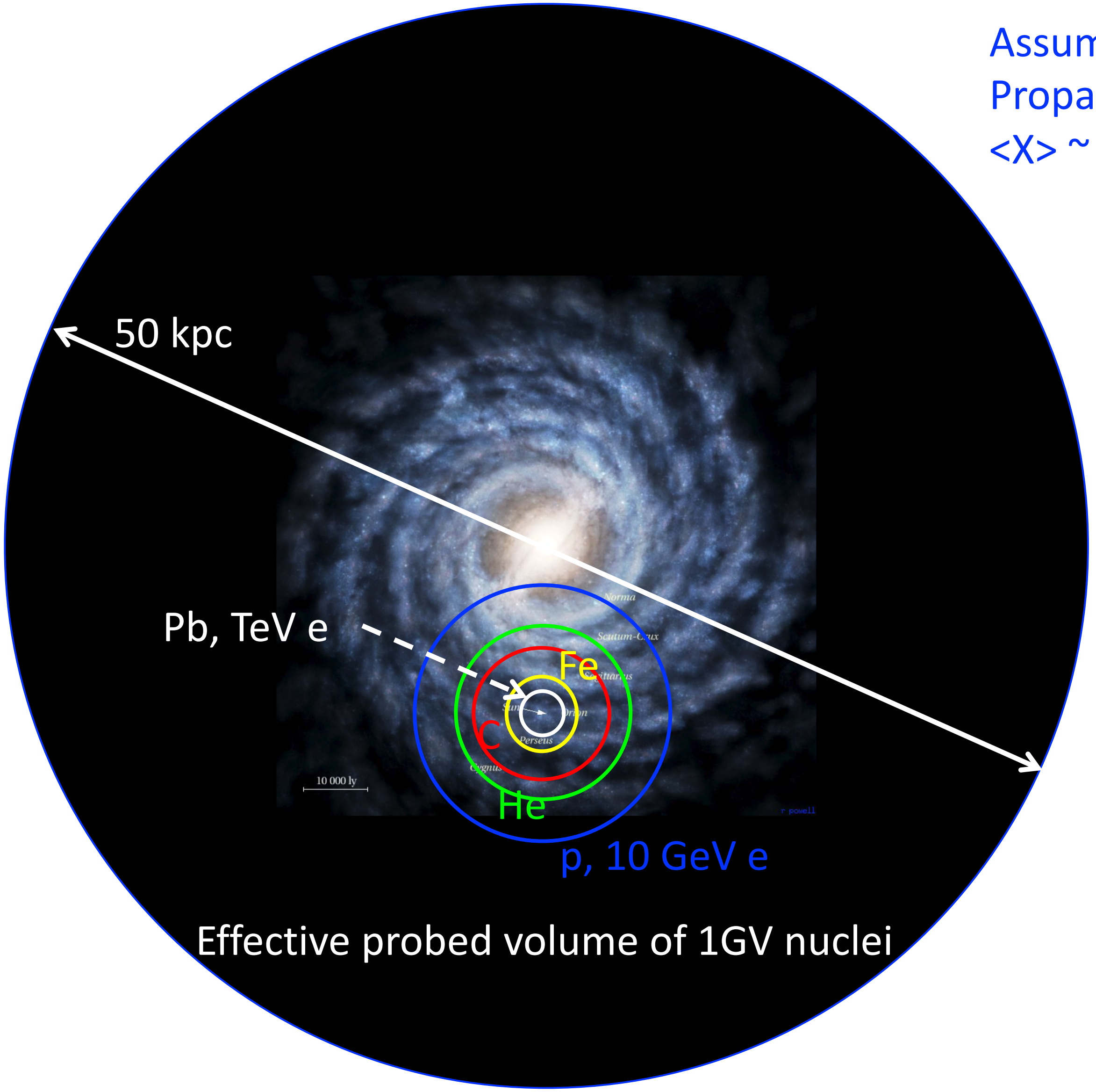
Lanthanide Series	57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Analyzed

Being Analyzed

Will be analyzed by 2024

Measurements of CR species probes different Galactic volumn



Assuming Kolmogorov model
Propagation distance:
$\langle X \rangle \sim 2.7\ \text{kpc}\ R^{\delta/2}\ (A/12)^{-1/3}$

I. Moskolenko, AMS days 2018

Elementary Particles in Space

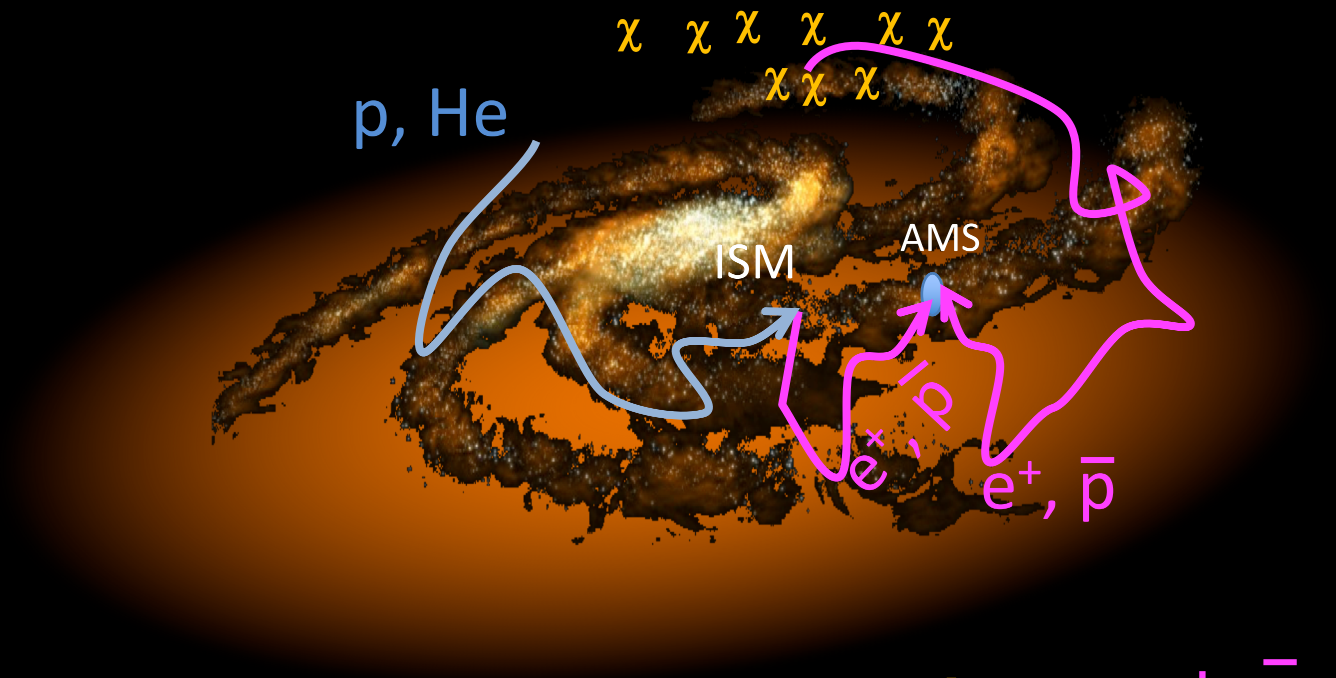
e^-, e^+, p, $\bar{p}$ are the only stable elementary particles in the cosmic rays

Elementary particles in the cosmic rays are uniquely important because, in addition to probing the production and propagation of cosmic rays, they are also sensitive to the fundamental physics processes.

Example: Dark Matter χ

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

p, He + ISM → e^{+}, $\bar{p}$ + …



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

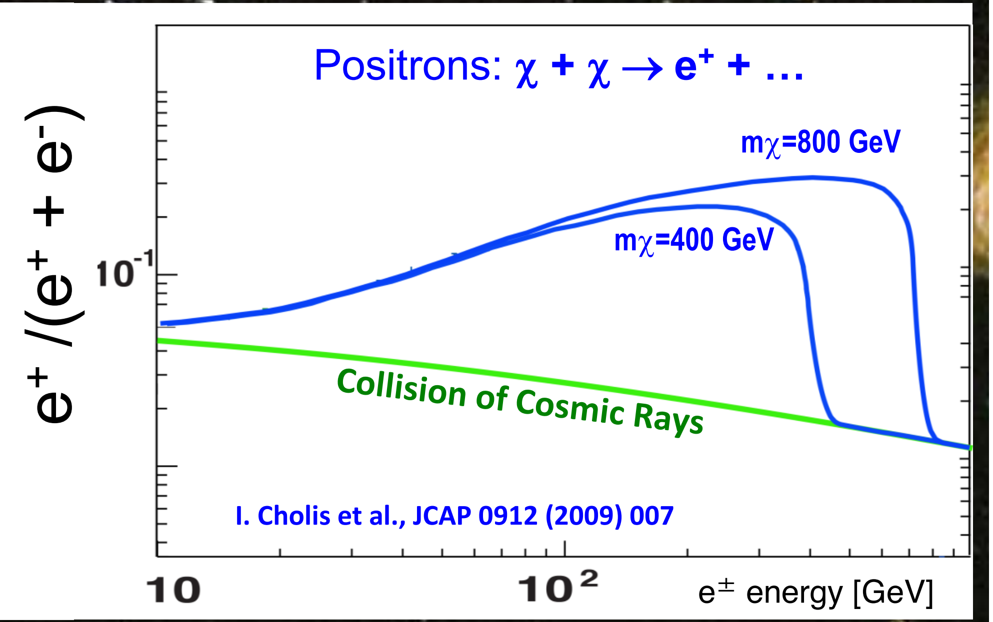
create extra e^+ and $\bar{p}$

Dark Matter

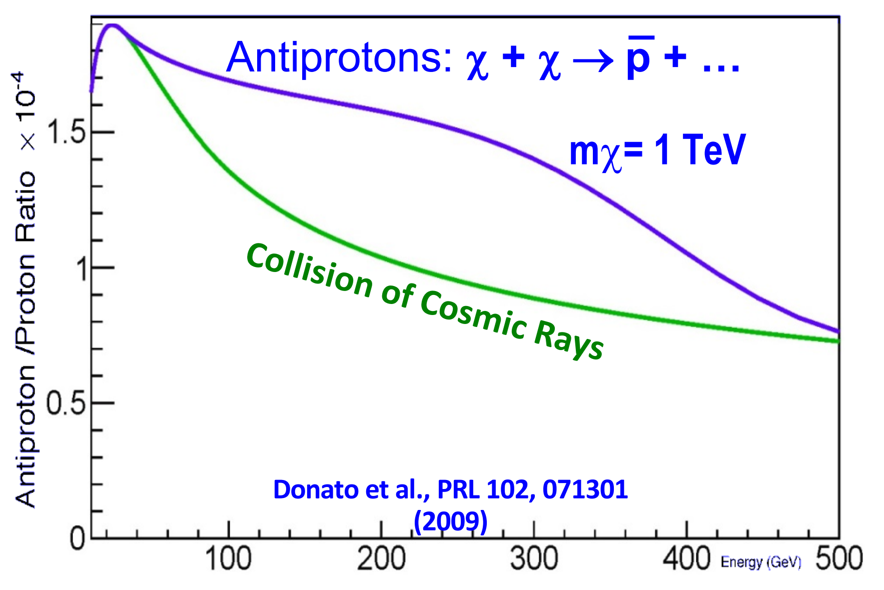
Collision of “ordinary” Cosmic Rays produce e+, $\bar{p}$…

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

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



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



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

First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV, PRL 110 (2013) 141102

Selected by APS as a Highlight of the Year 2013

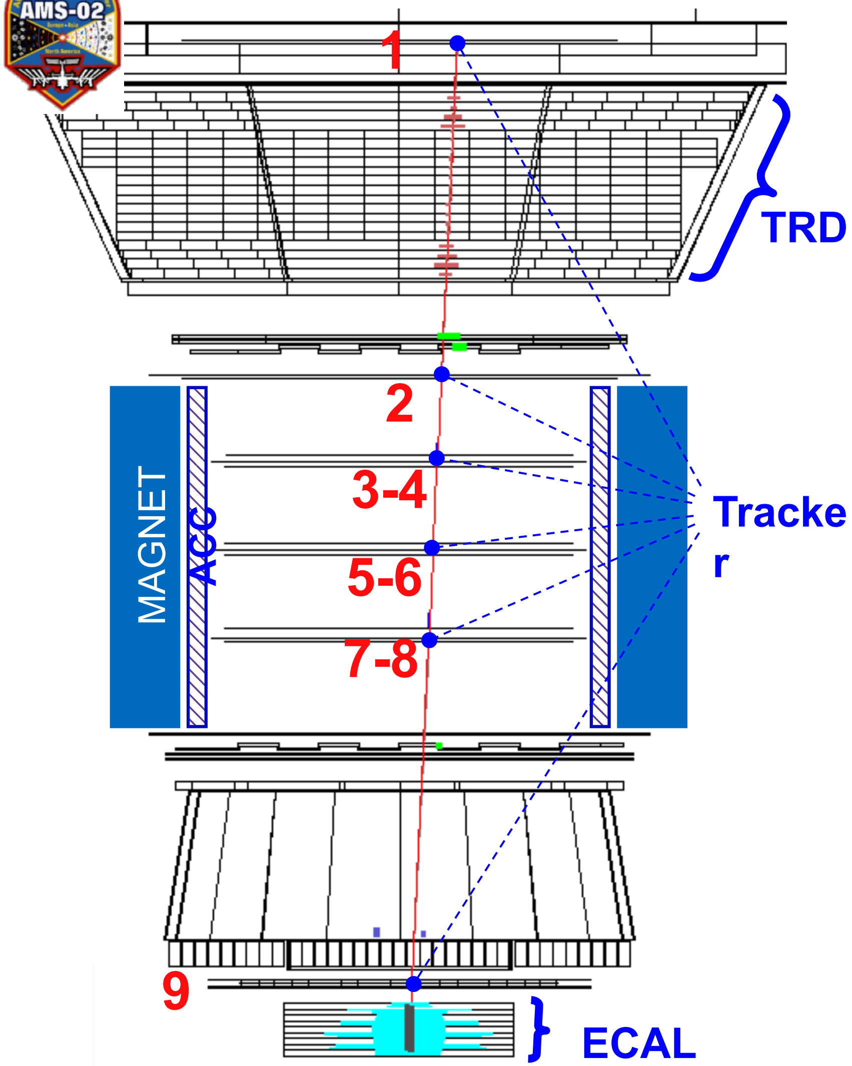
p, $\bar{p}$, e^-, e^+ are all charge 1 particles, the key issues for measurement are:

1. **e/p separation:**
   - $p : e^+ \sim 2000$, $e^- : \bar{p} \sim 10\text{-}100$,
   - proton rejection at 10^6 is needed.

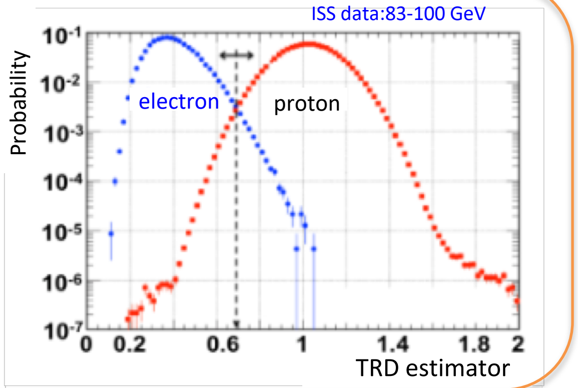
2. **Charge confusion estimator:**
   Rejecting charged confused p and e^- in the measurements of $\bar{p}$ and e^+.

Electron/positron identification

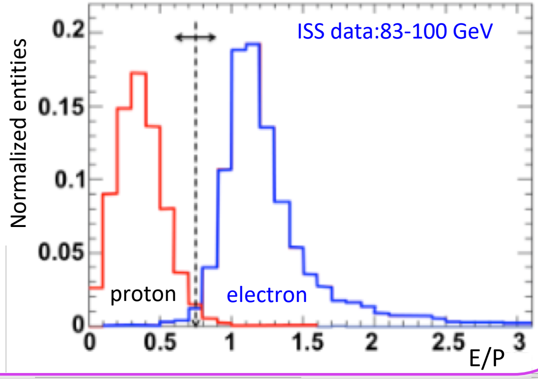
424 GeV positron



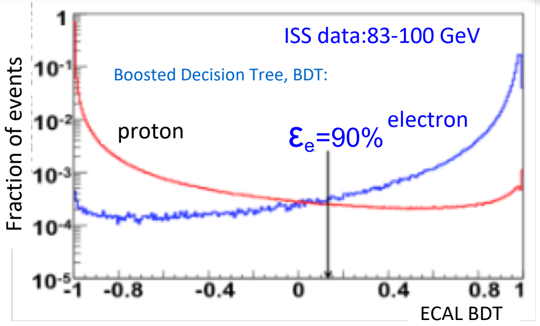
TRD
identifies e±



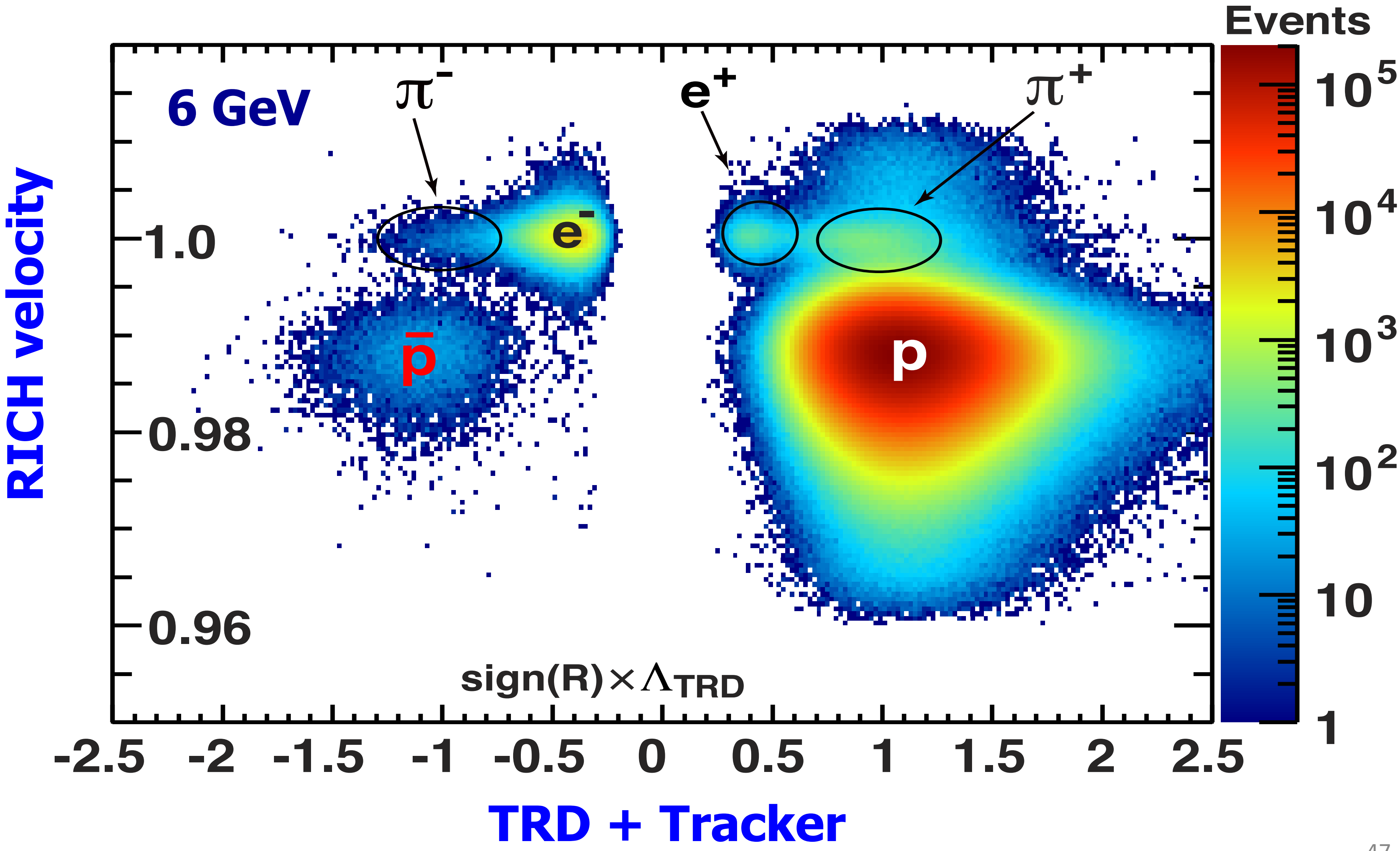
TRACKER
measures P
ECAL measures E
e±: E=P
proton: E<P



ECAL
measures
shower shape
to separate e±
from protons

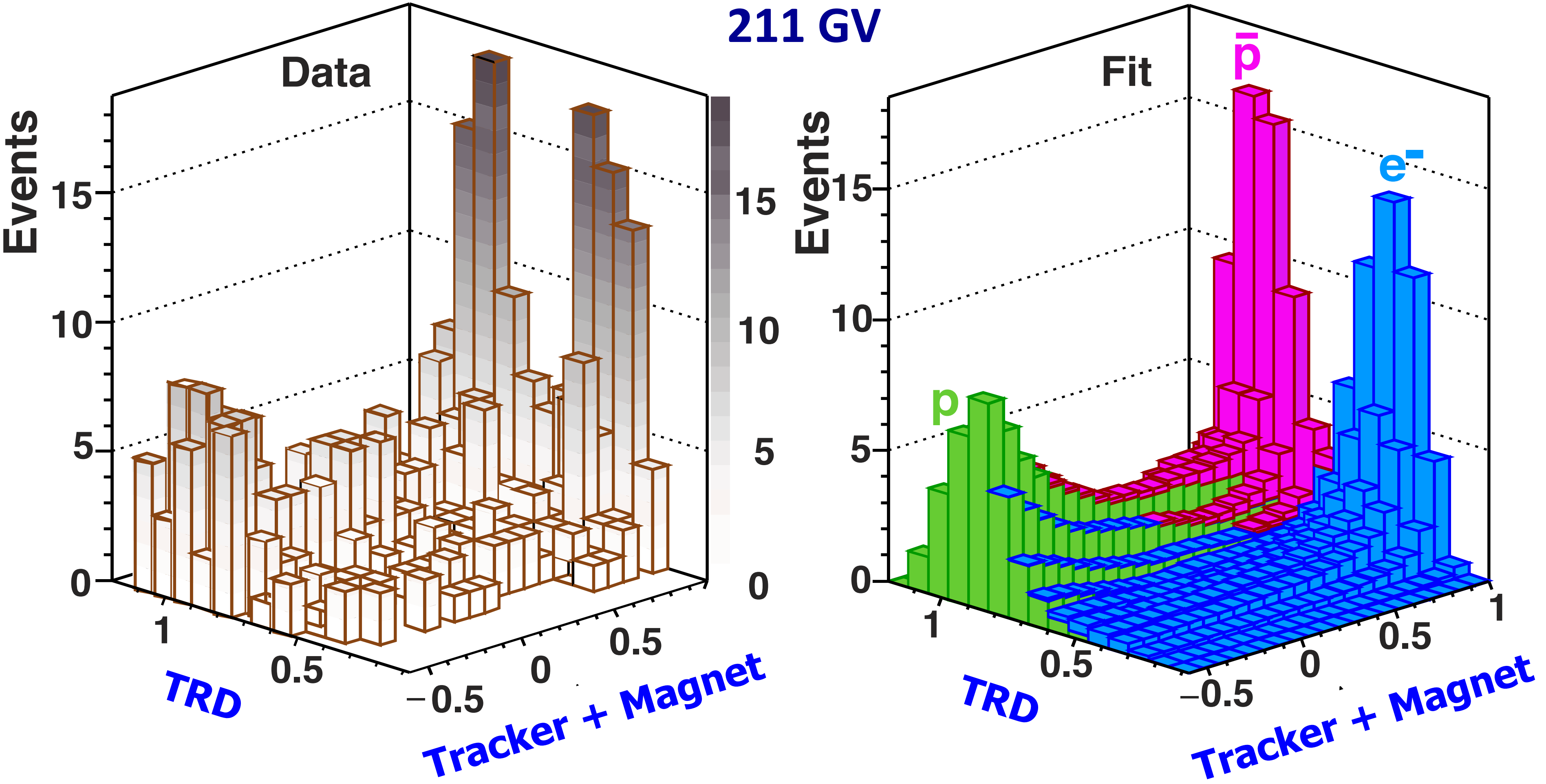


Selection of the signal:
The $\bar{p}$ signal is well separated from the backgrounds.



Selection of the signal at high rigidities. Background rejection close to 1 part in a million.

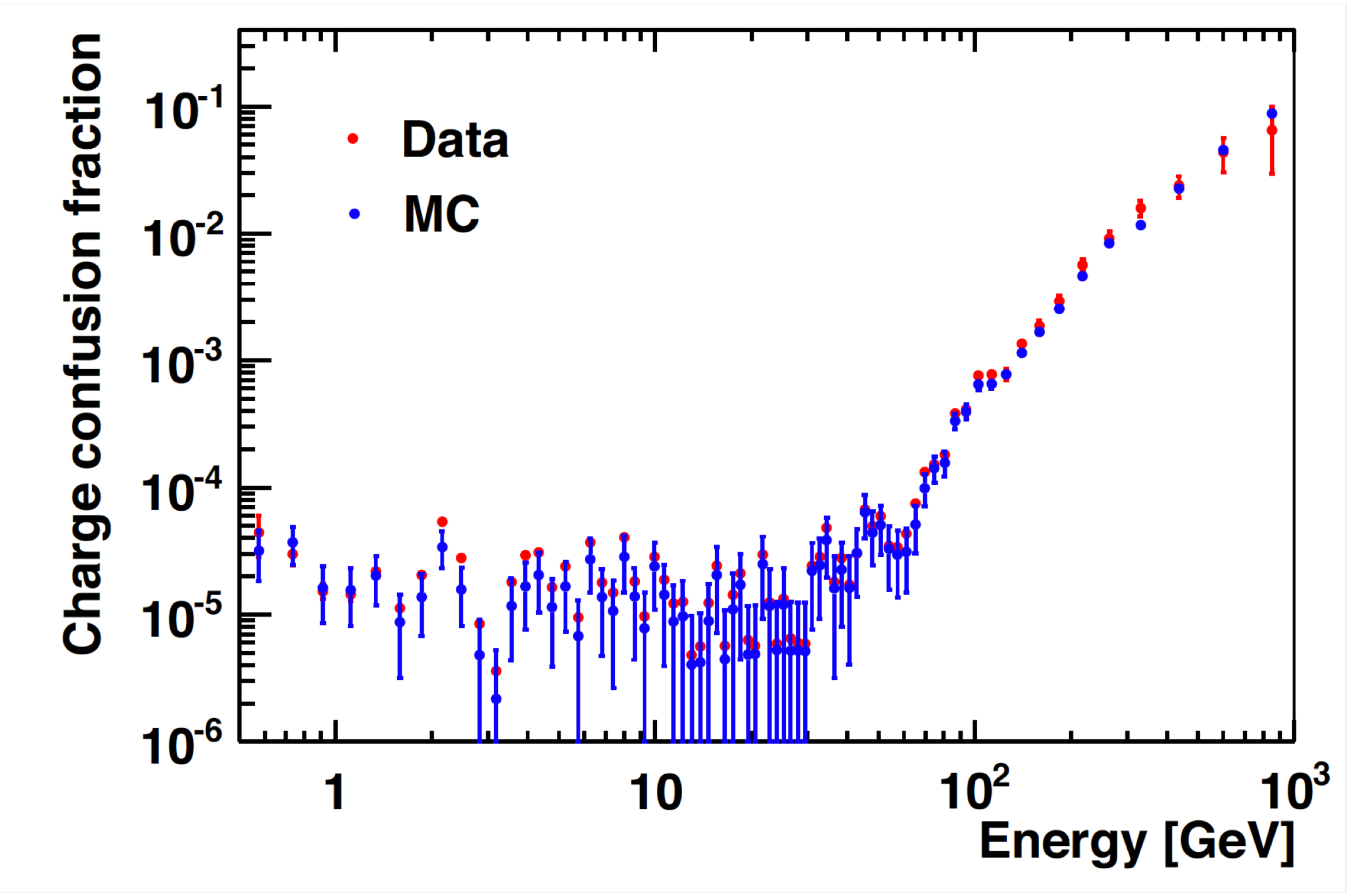
Absolute Rigidity range 175-211 GV



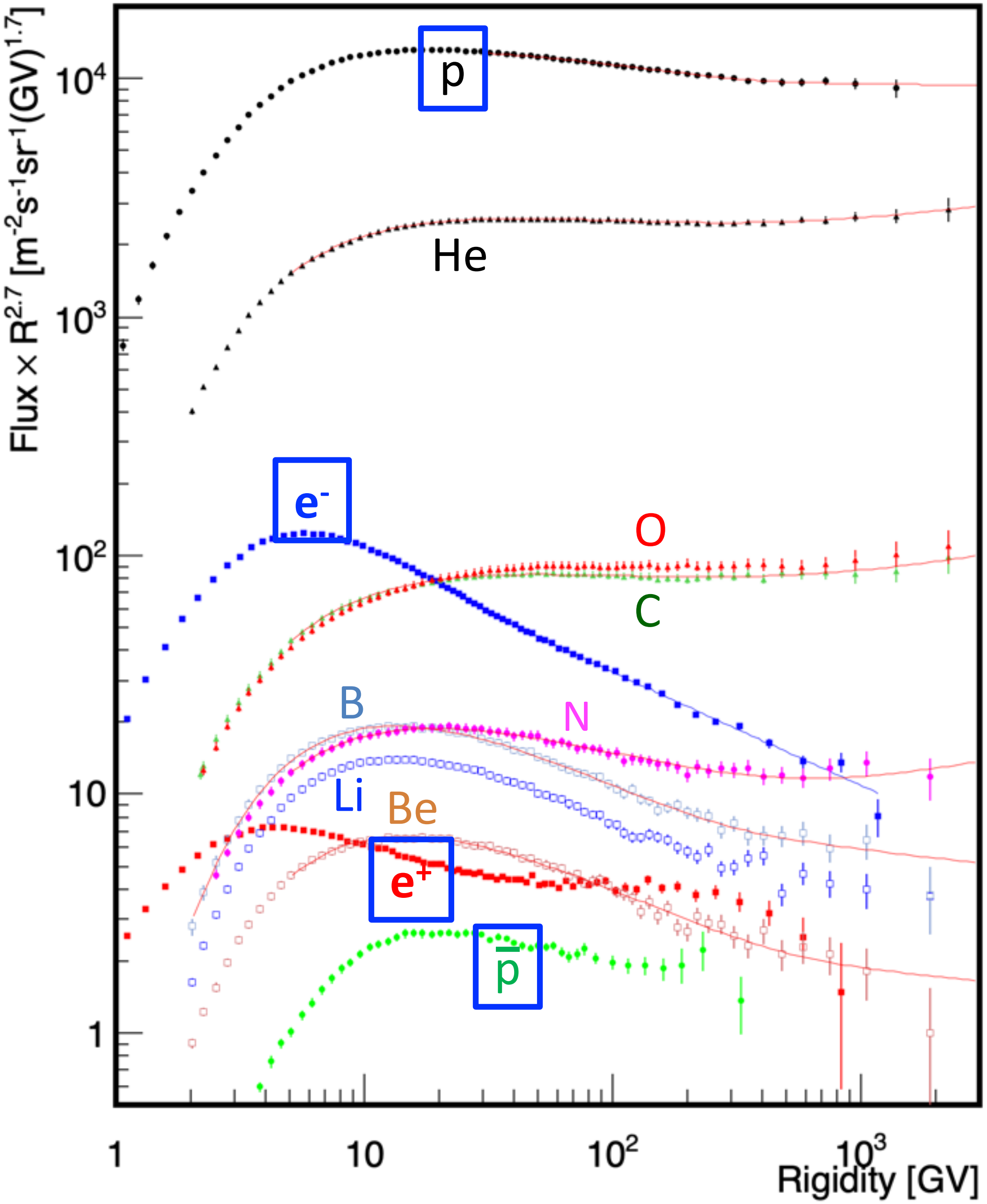
χ^2/d.f.=138/154

Charge confusion is estimated by building an Charge Confusion estimator, Λ_{CC}.

Λ_{CC} is based on E/p, track fitting quality, extra hits, signals amplitude of Tof and Tracker.



AMS cosmic ray spectra ($\Phi \times R^{2.7}$)



Ref:

p: PRL 114.171103

He: PRL 115.211101

e^+e^-: PRL 113.121102

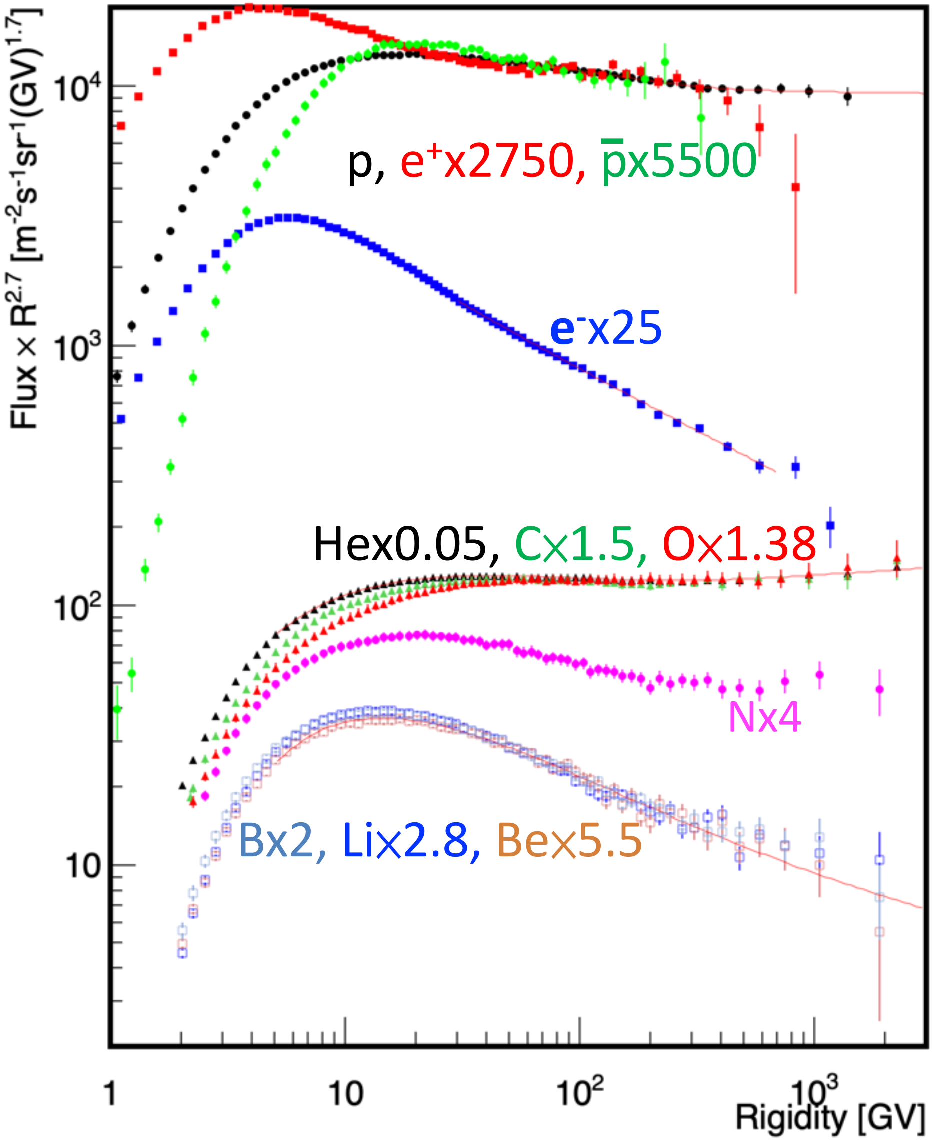
p̄: PRL 117.091103

C,O: PRL 119.251101

Li, Be, B: PRL 120.021101

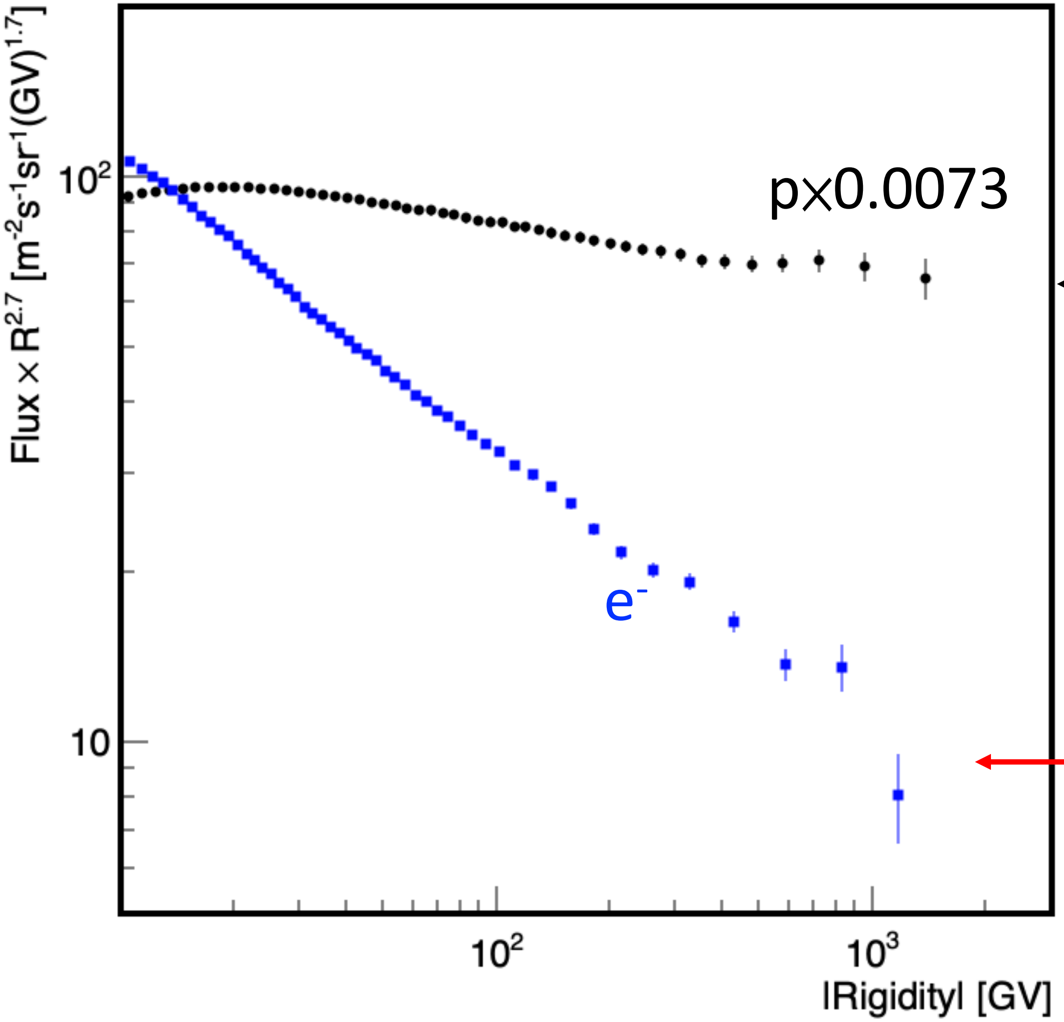
Unexpected Result:

e^+ and antiproton exhibit same spectra behavior as proton from ~40 - ~450 GV.



e^- spectrum is distinctively different.

Electrons show a much softer spectrum, with spectra index γ ~-3.1

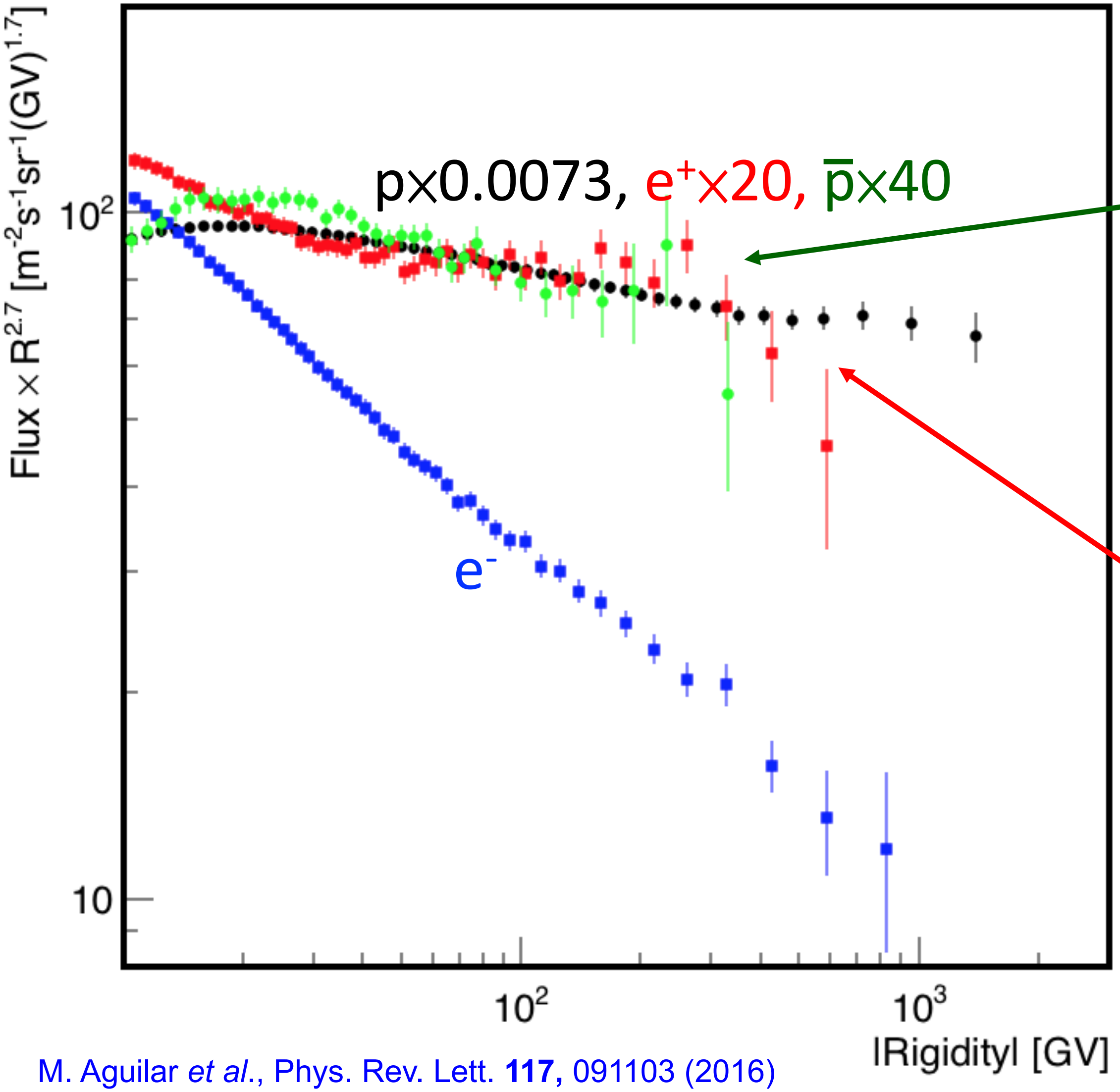


M. Aguilar *et al.*, Phys. Rev. Lett. **117,** 091103 (2016)

Protons are primary cosmic rays.

Electrons are primary, but they loss energy due to synchrotron radiation during propagation. The spectrum of electron is expected to be softer than other particles in CR.

Proton, antiproton, positron have very different production and propagation properties. It is unexpected that they share the same spectra behaviour.



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

Antiprotons are secondary particles, should have different spectrum than proton.

Positron loss energy equally in the Galactic magnetic field as electron, but shows very different spectrum.

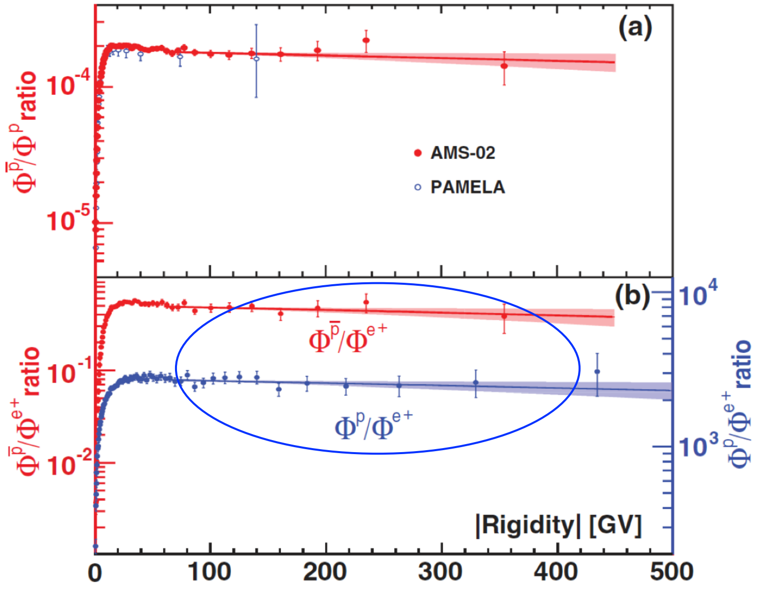
Many models proposed to explain the physics origin of the observed behavior

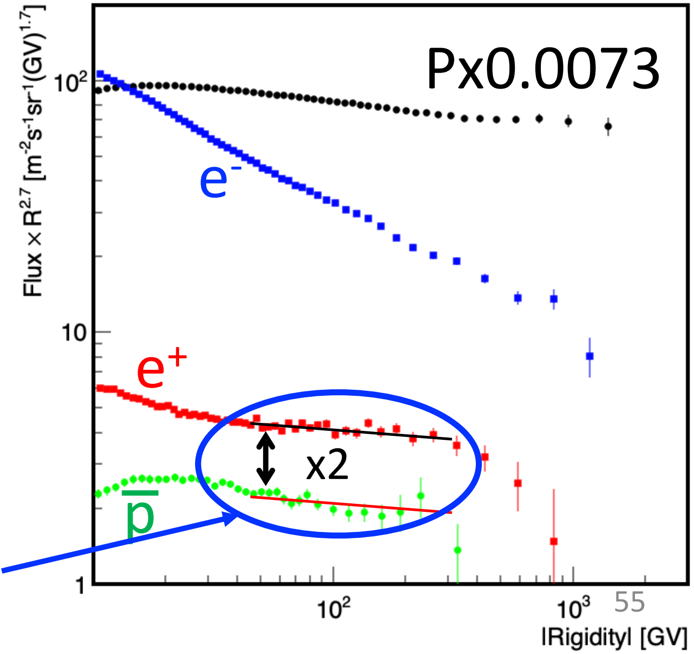
1) **Secondaries: production in propagation**
2) **Particle origin: Dark Matter**
3) **Astrophysics origin: Pulsars, PWNe, SNRs**

Interpretation based on Secondary production:

- The same rigidity dependence of e^+, $\bar{p}$, p is intriguing, suggesting a secondary production of e+ and $\bar{p}$
- **Evidence of secondary production:** The ratio of e^+ to $\bar{p}$ is in agreement with the production ratio in high energy proton-proton collision, indicating they are both from high energy proton collision with ISM?

  (S. Ahlen, G. Tarle, arXiv 1410.7239; P. Lipari, PRD 95, 063009; B. Katz et.al., MNRAS 405, 1458 (2010); K. Blum et. al., PRL 111.211101)
- Problem: It is very challenging for any model to describe simultaneously all four spectra and the nuclei spectra.





Production rate up to 1TeV

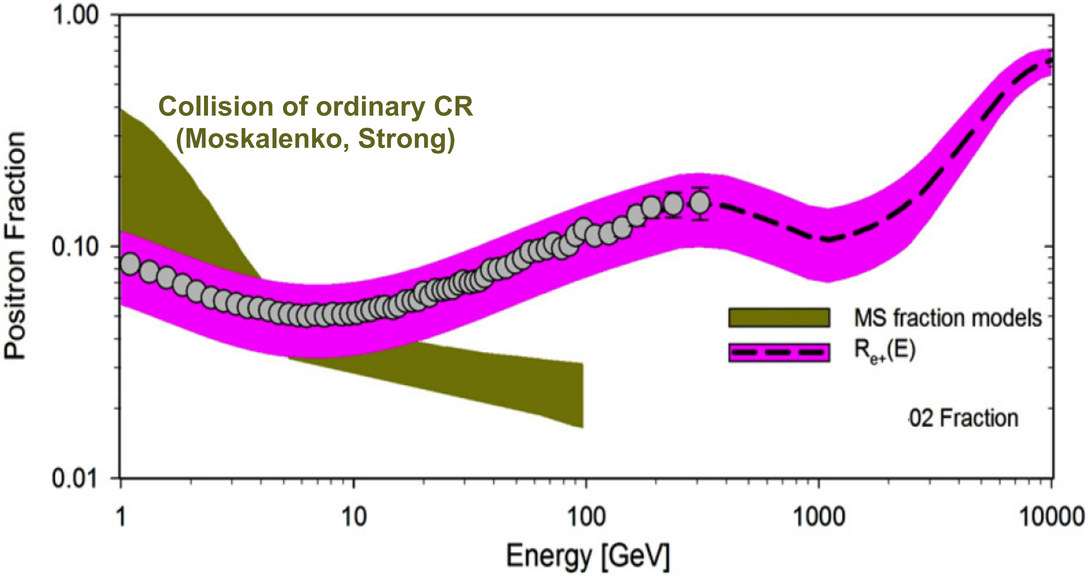
$e^+/\bar{p} \approx 1.8$

Propagation: R. Cowsik *et al.*, Ap. J. 786 (2014) 124

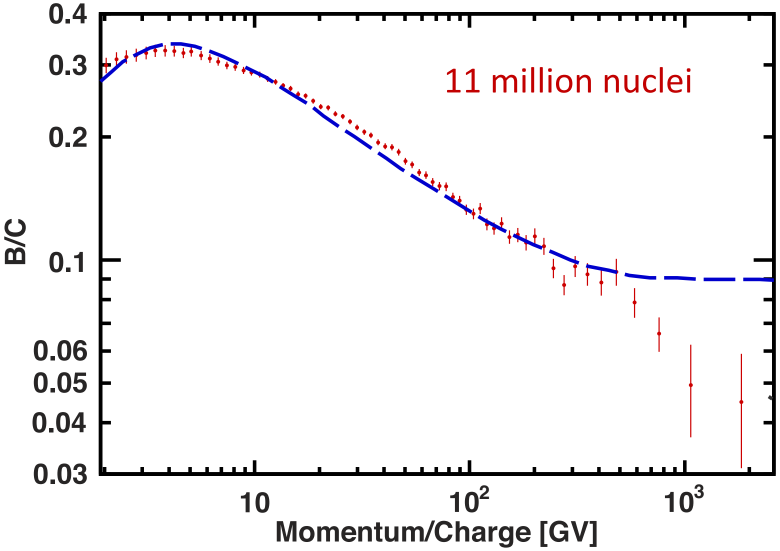
The model (pink band) fits well the AMS positron fraction (gray circles)

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

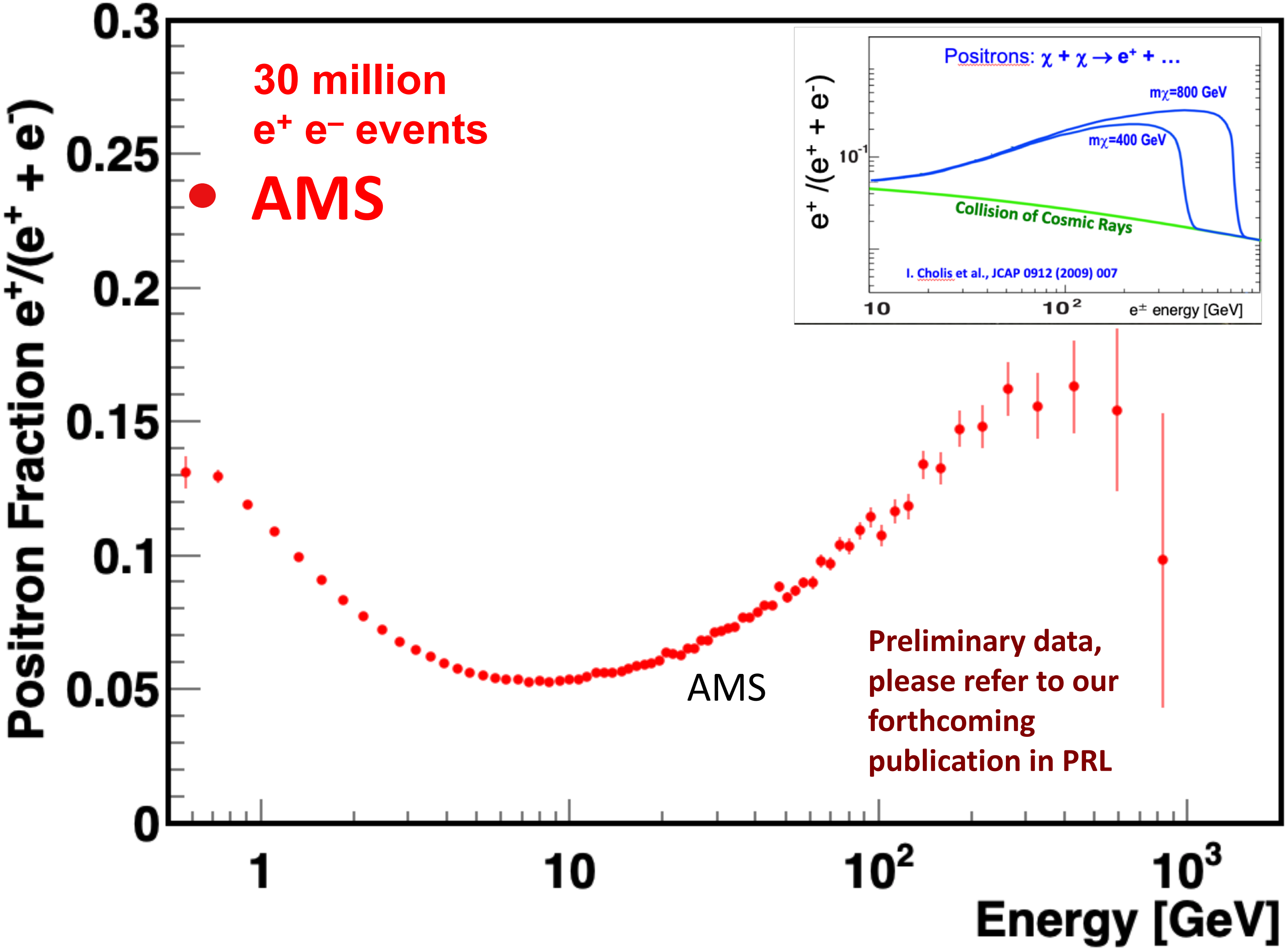
The AMS positron fraction



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

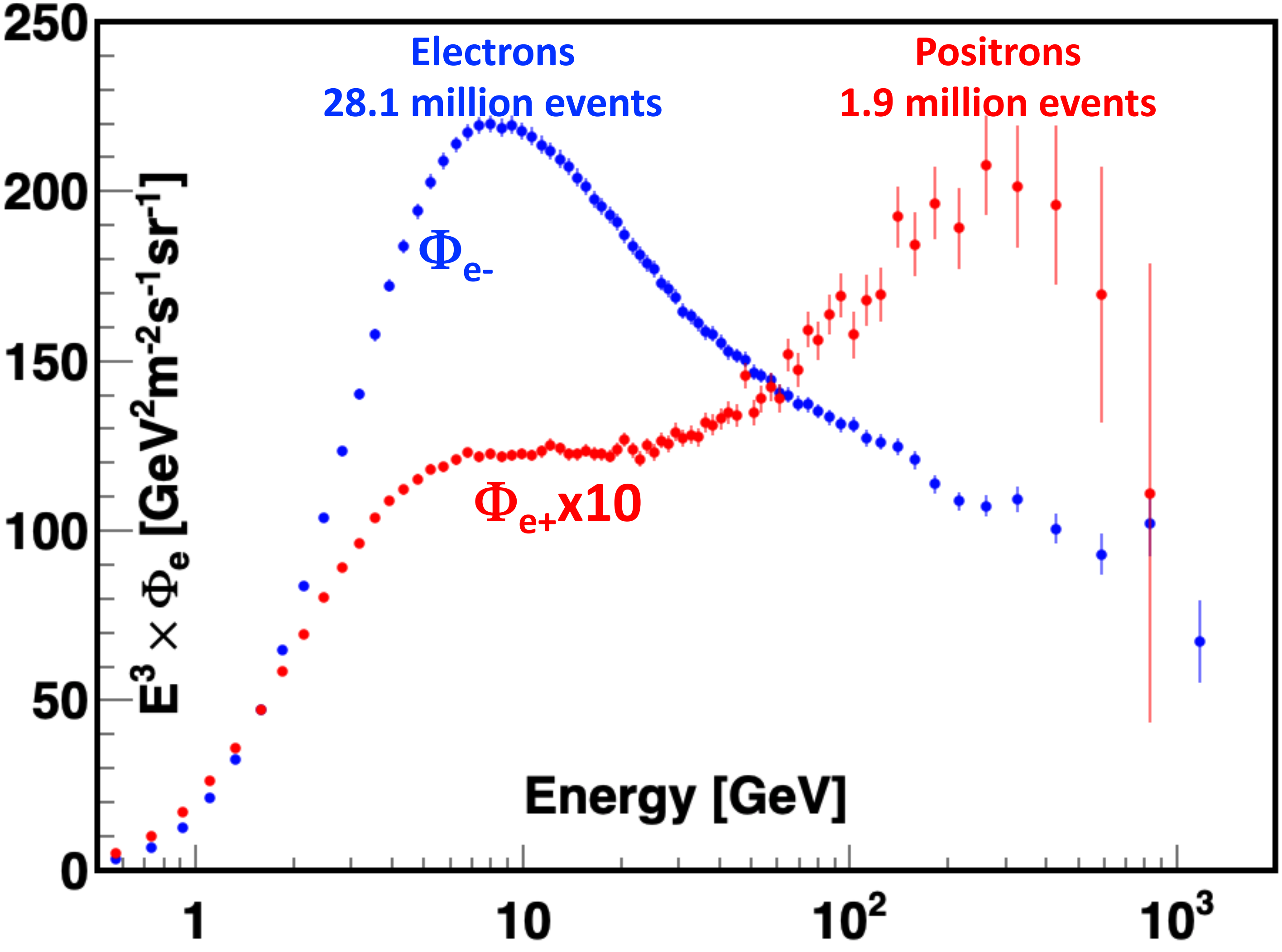


Alternative explanation of Positron excess: the smoking gun of an unknown source of positrons: Dark matter, pulsar, PWNe, …



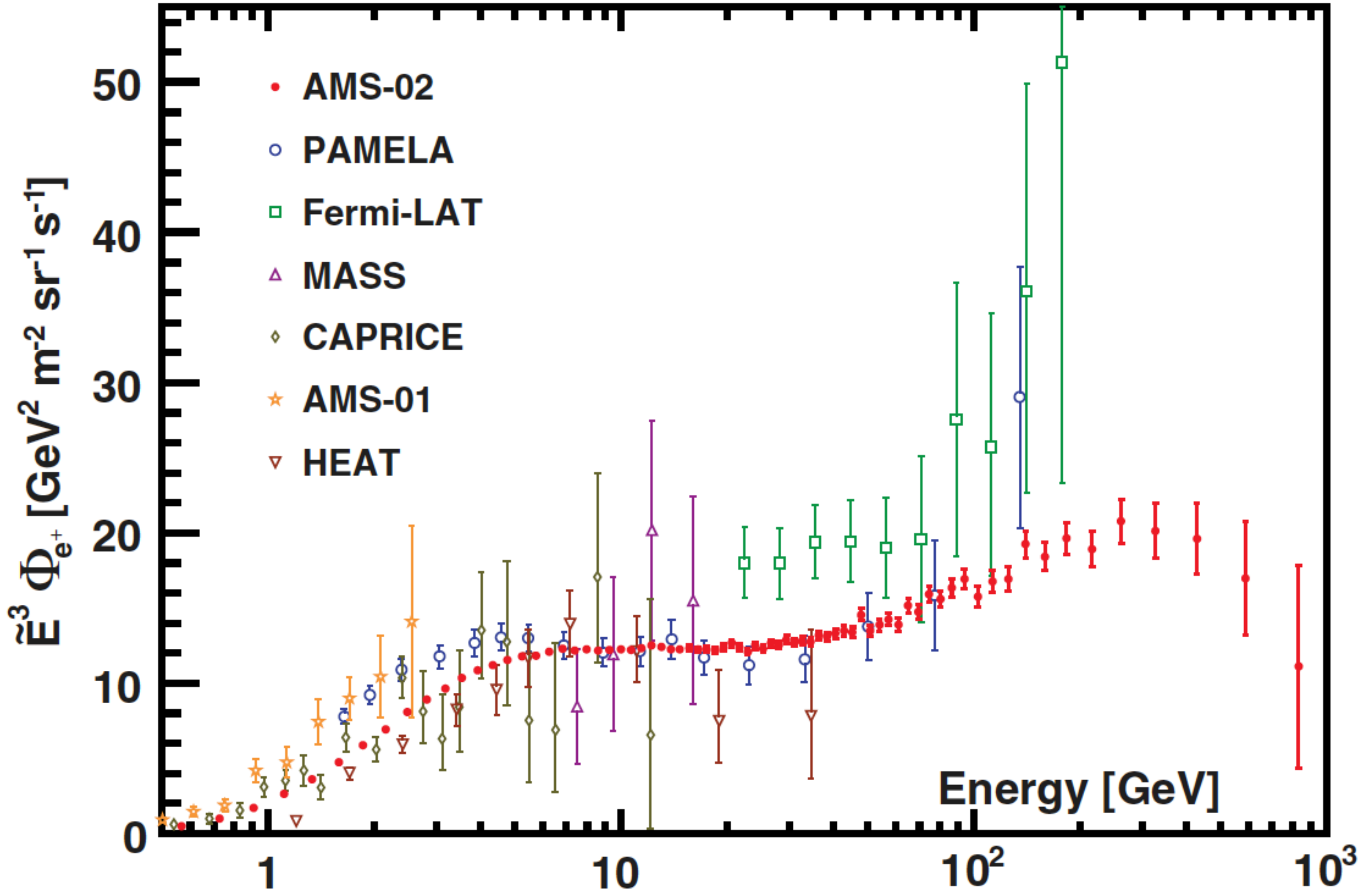
Preliminary data, please refer to our forthcoming publication in PRL

AMS data is precise enough to look into details of Electron and Positron spectra separately



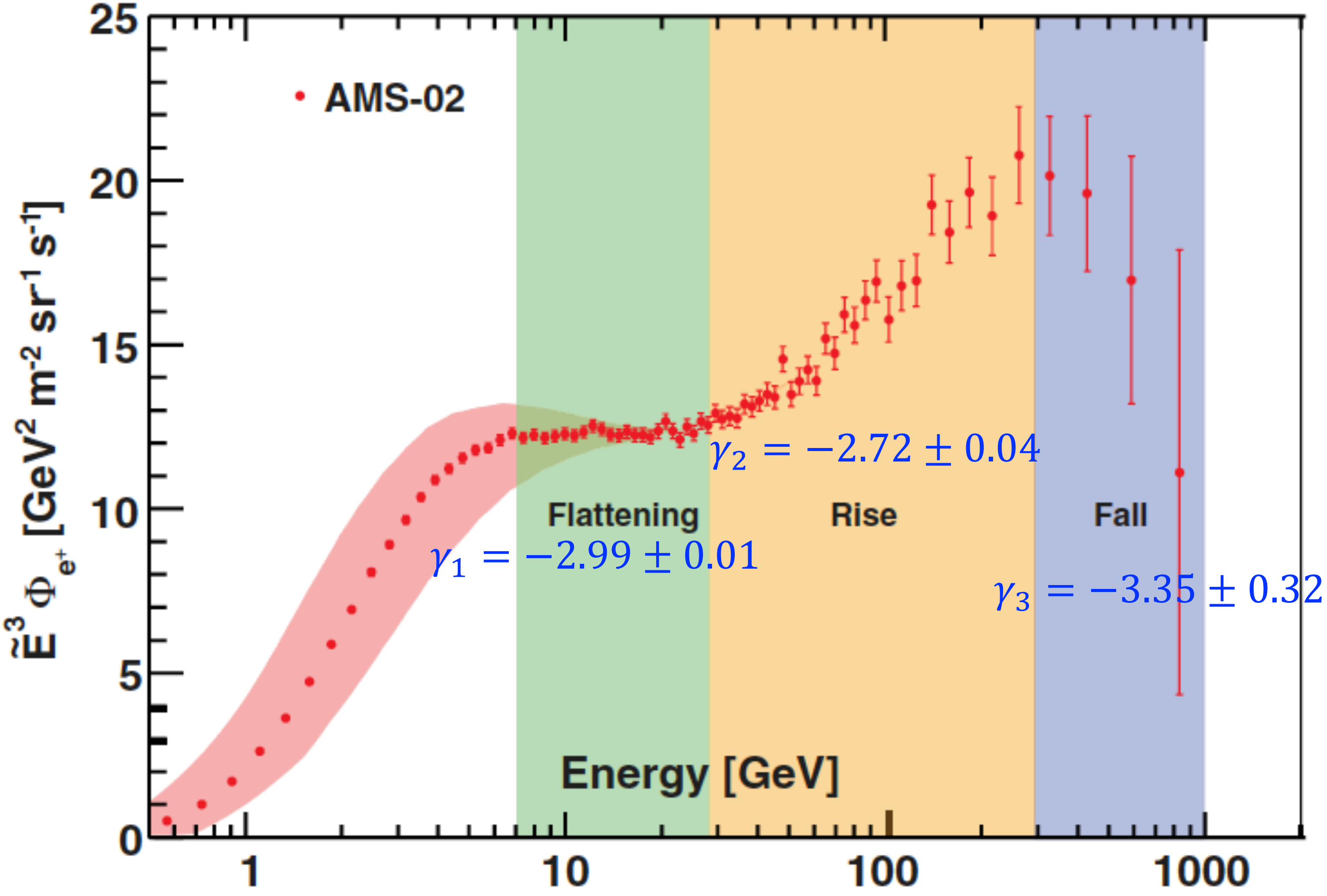
Positron and electron spectra are distinctively different.

The positron spectrum is now extended to 1TeV



Analysis of the positron data:

1. Three distinctively different power spectrumat E > 10 GeV



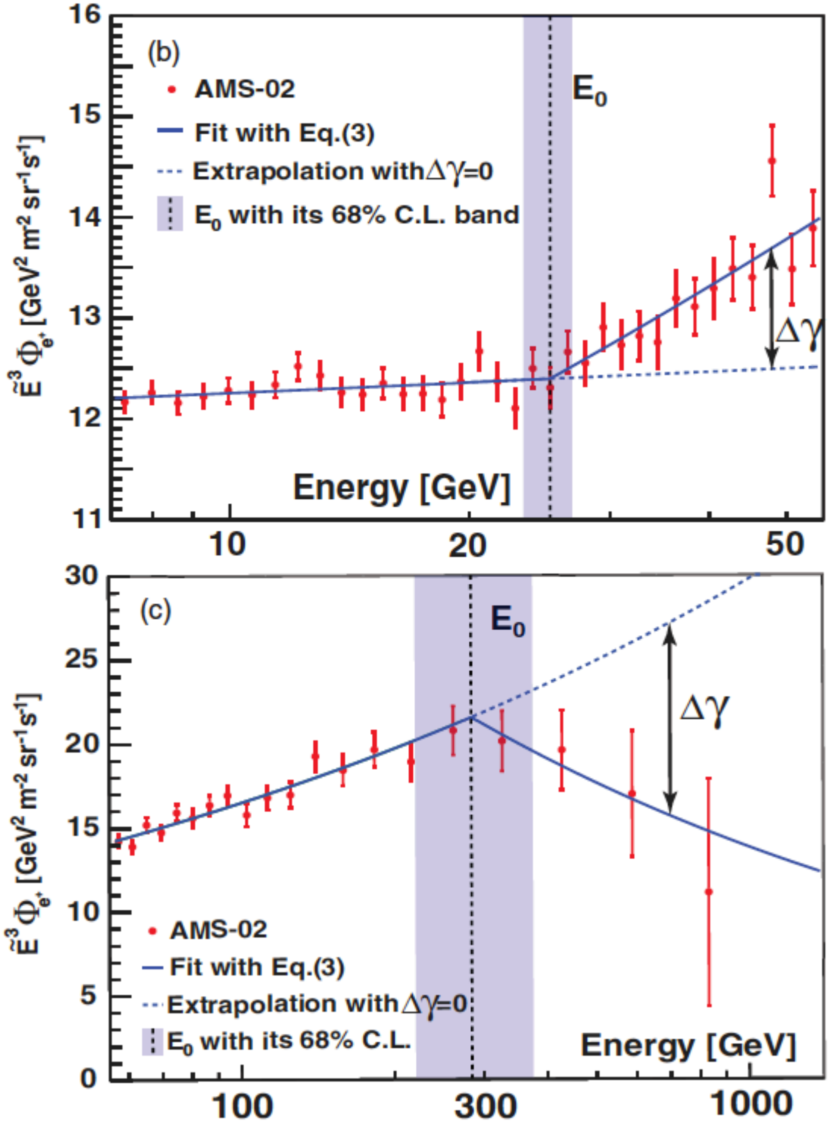
$\gamma_1 = -2.99 \pm 0.01$

$\gamma_2 = -2.72 \pm 0.04$

$\gamma_3 = -3.35 \pm 0.32$

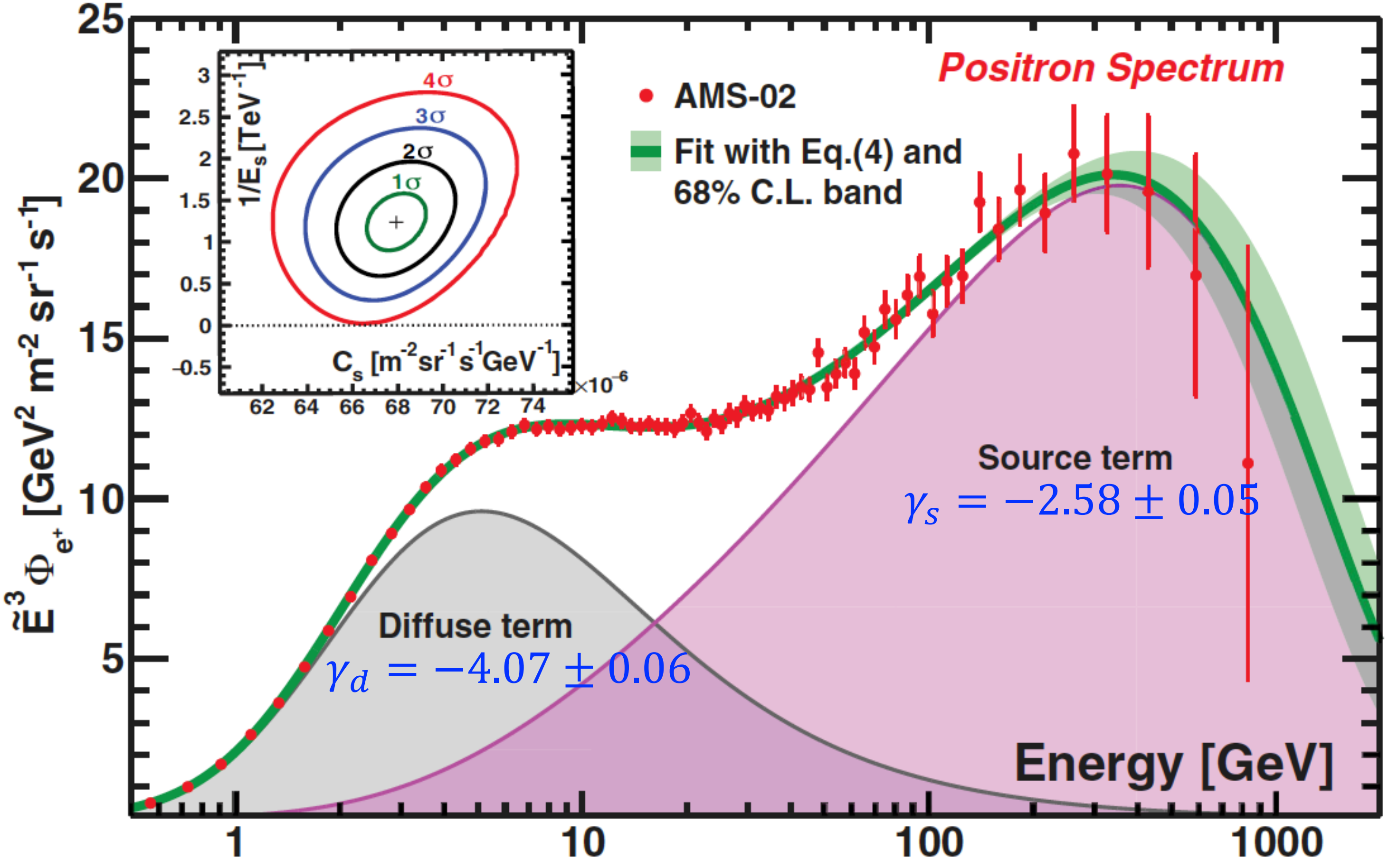
Spectrum break at 25.2 ± 1.8 GeV and 284^{+91}_{-64} GeV

The break at 284 GeV is established with 3σ significance.



2. Describe the positron spectrum by a Diffuse term plus a source with exponential cutoff:

$$\Phi_{e+}(E) = \frac{E^2}{\hat{E}^2}[\underbrace{C_d(\hat{E}/E_1)^{\gamma_d}}_{\text{Diffuse term}} + \underbrace{C_s(\hat{E}/E_2)^{\gamma_s}\exp(-\hat{E}/E_s)}_{\text{Source term with exponential cutoff}}]$$



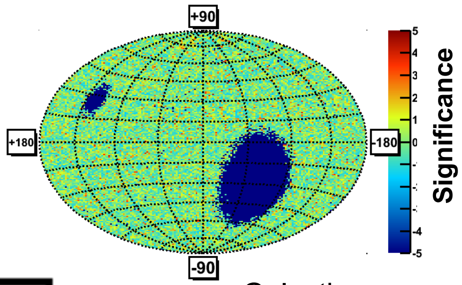
$\gamma_s = -2.58 \pm 0.05$

$\gamma_d = -4.07 \pm 0.06$

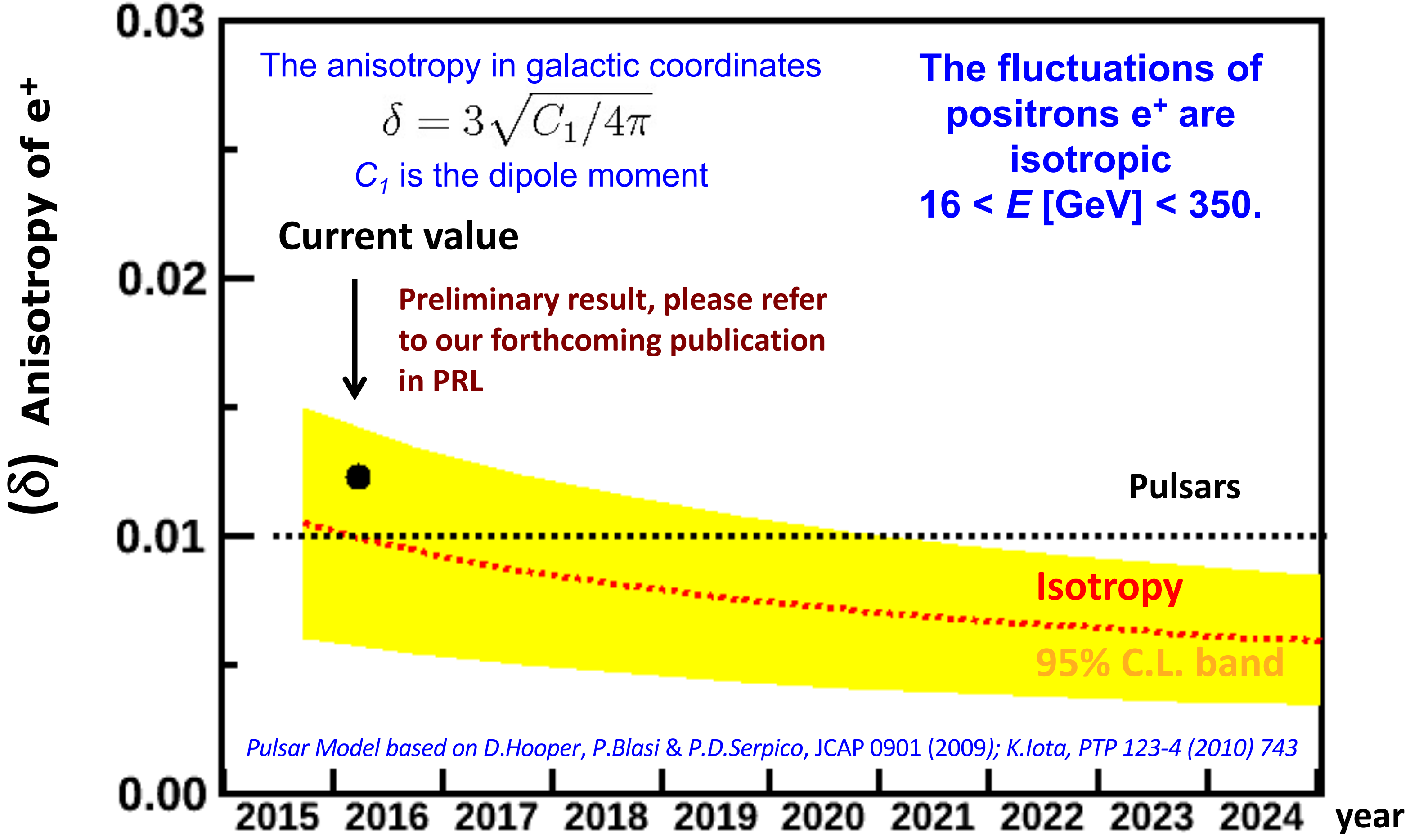
$1/E_s = 1.23 \pm 0.34$ TeV^{-1},

the cutoff is established with 4σ significance

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



Galactic coordinates (b,l)



The anisotropy in galactic coordinates

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

C_1 is the dipole moment

Current value

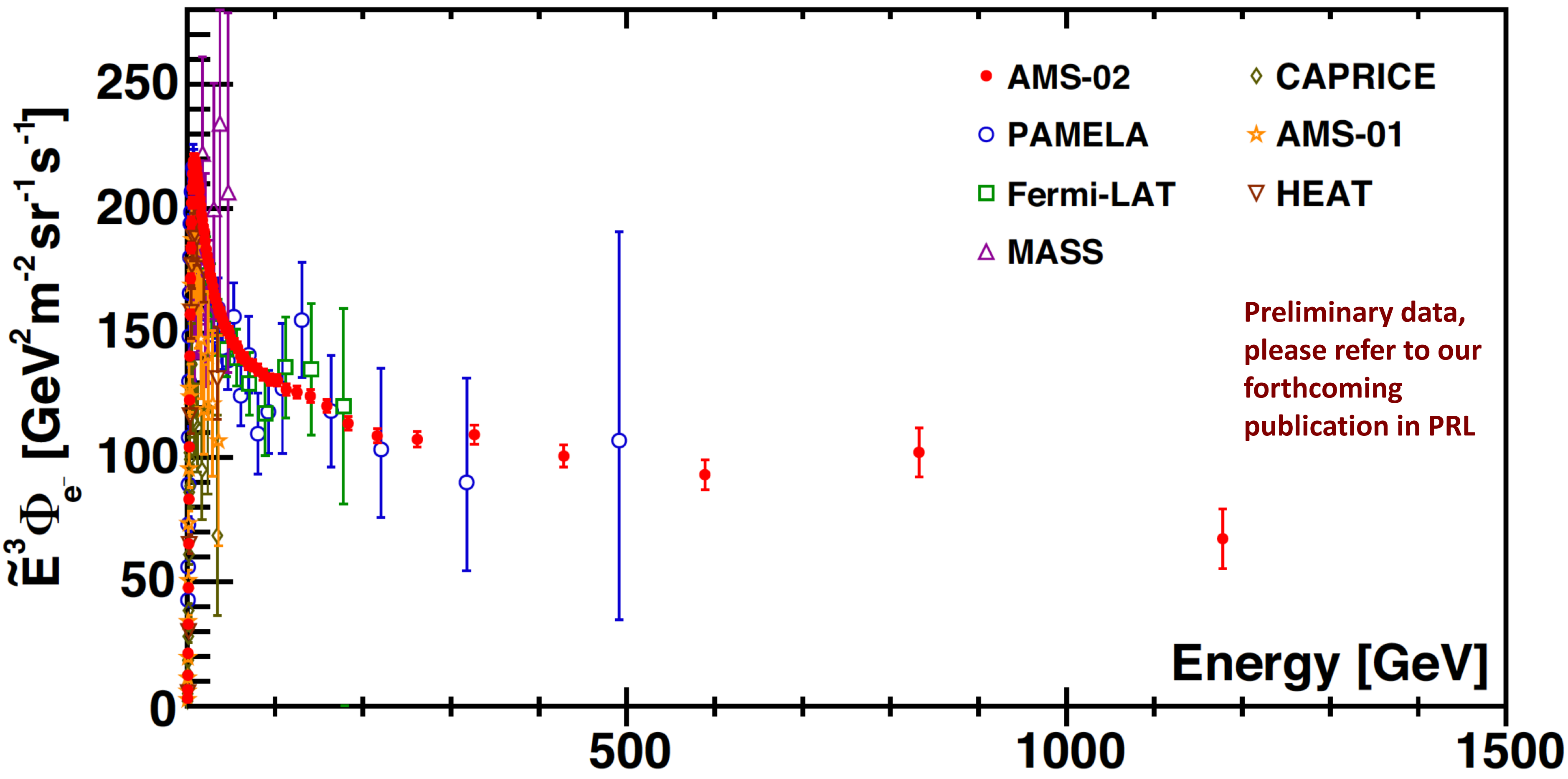
Preliminary result, please refer to our forthcoming publication in PRL

The fluctuations of positrons e^+ are isotropic
$16 < E$ [GeV] < 350.

Pulsar Model based on D.Hooper, P.Blasi & P.D.Serpico, JCAP 0901 (2009); K.Iota, PTP 123-4 (2010) 743

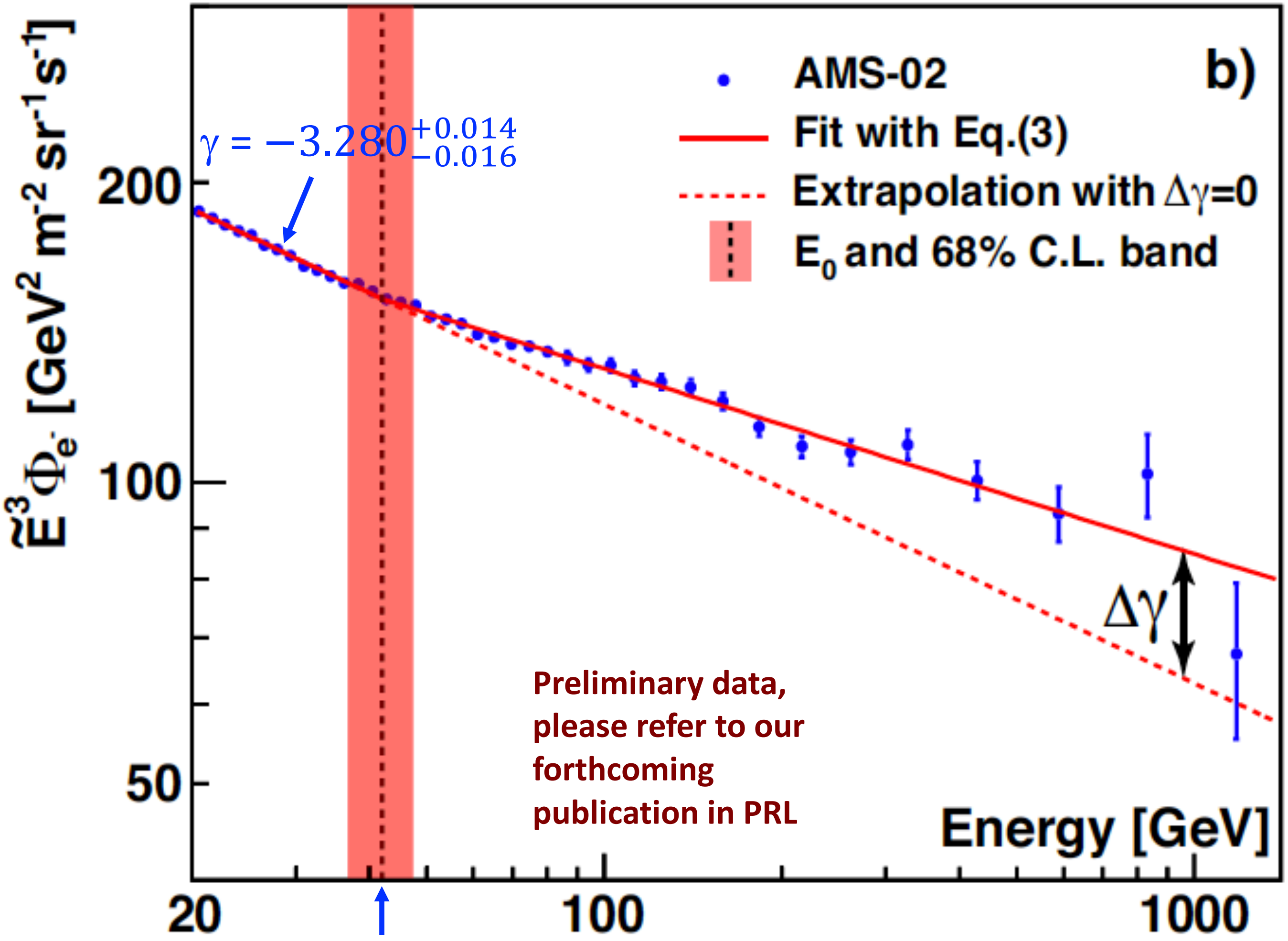
Data taking to 2024 will allow to explore anisotropies of < 1%

Analysis of Electron data:



Preliminary data, please refer to our forthcoming publication in PRL

1. Two region of different power law spectrum:



$\gamma = -3.280^{+0.014}_{-0.016}$

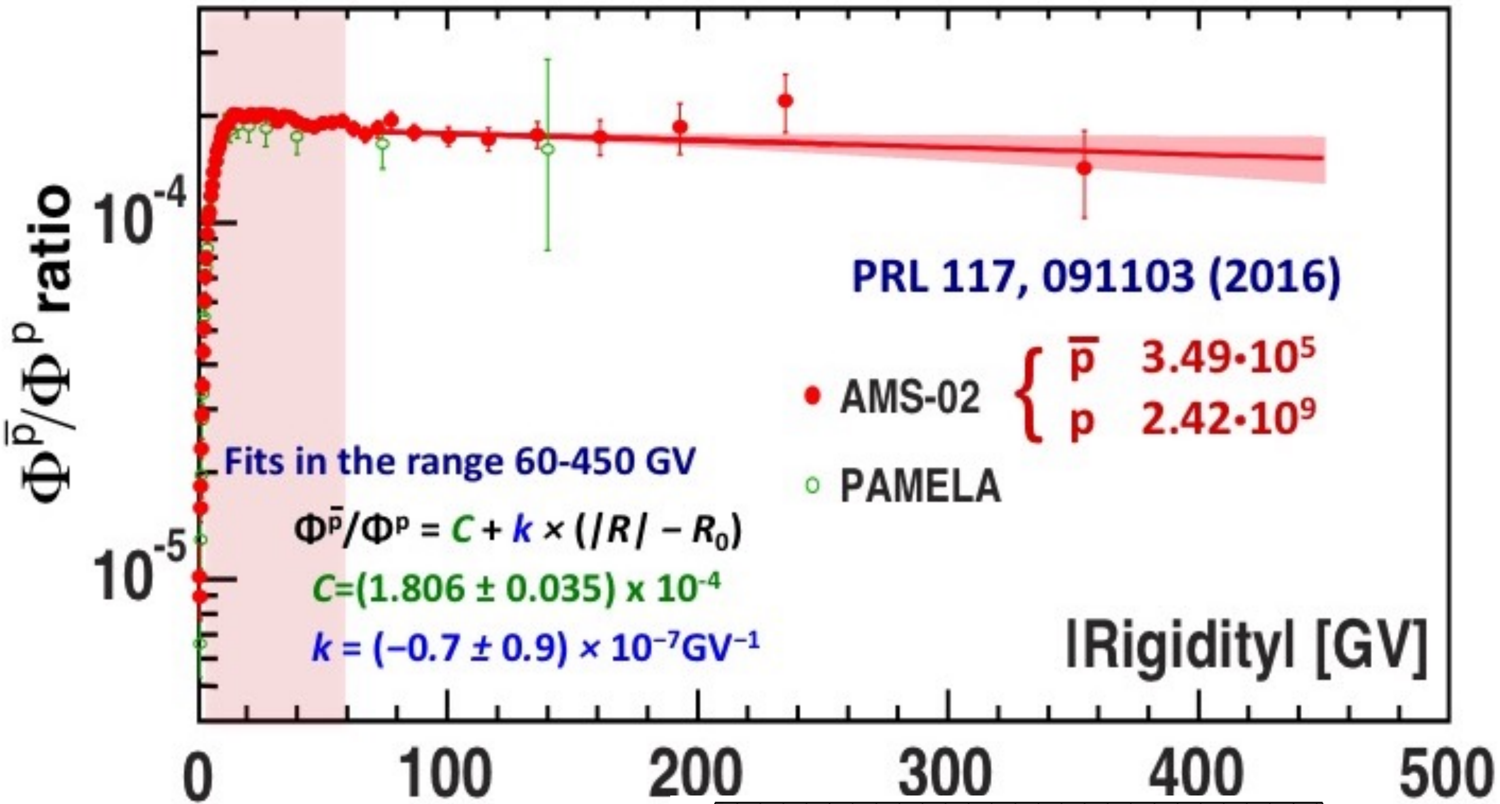
Preliminary data, please refer to our forthcoming publication in PRL

$E_0 = 42.1^{+5.4}_{-5.2}$ GeV

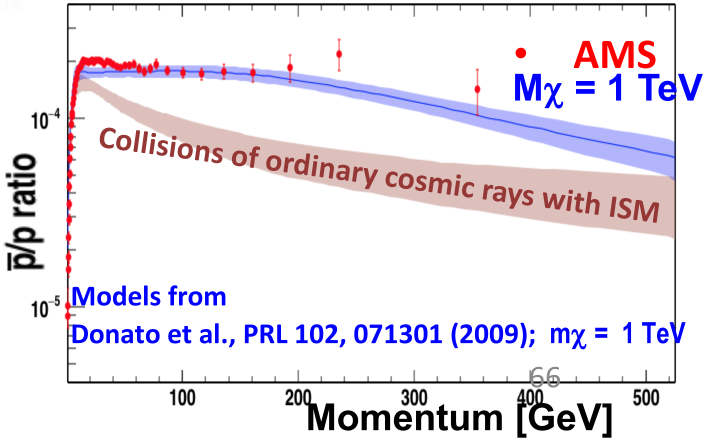
$\Delta\gamma = 0.094 \pm 0.014$

No drop-off above 284 GeV as in positron spectrum.

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



Before AMS data, it was generally believed that the secondary should have softer spectrum.



Electrons and positrons in the cosmic rays show different behavior, they originated from different sources?

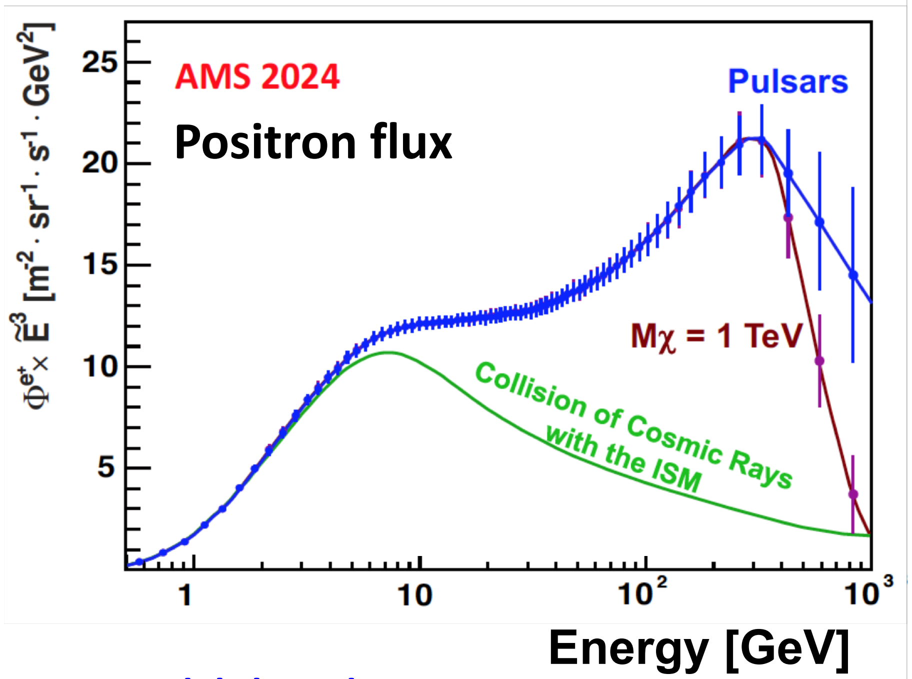
Flat antiproton/proton ratio : coincidence or some physics reason behind?

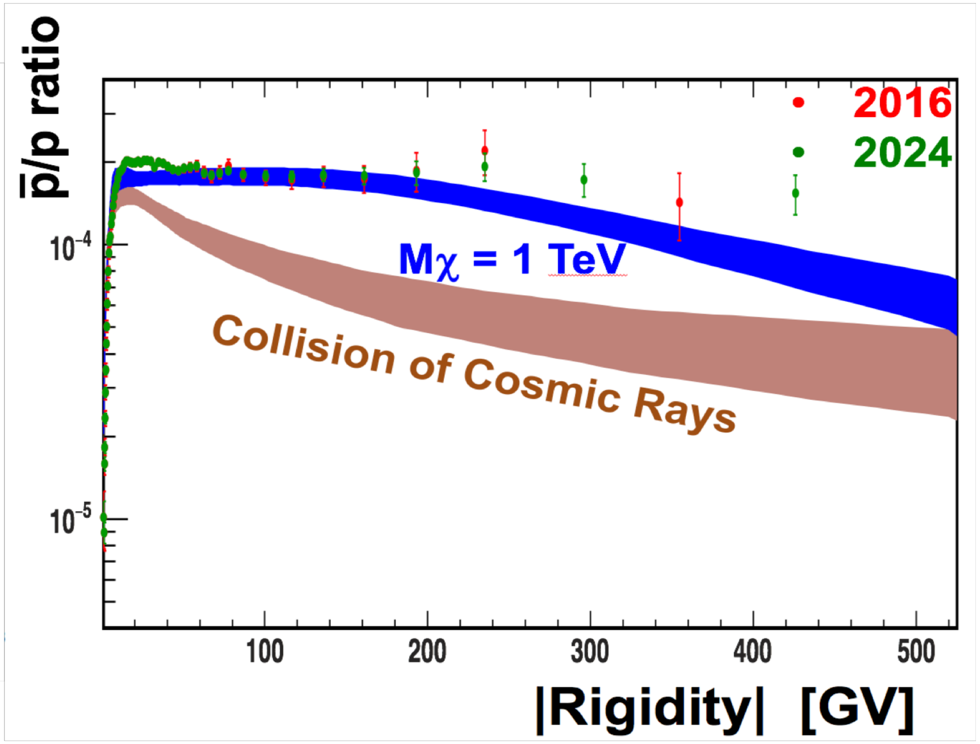
At present, there is no single model that describes all data simultaneously.

To understand the true nature of the positron and antiproton spectra, we need:

- Tune cosmic ray models by latest nuclei data.
- More statistics to extend the rigidity range.
- Combine other measurements.
- Advances in theory

By 2024, AMS will have enough data to extend the positron and antiproton spectra, and provide stronger constraint on cosmic ray models





Models based on

I. Cholis and D. Hooper, Phys.Rev. D88 (2013) 023013

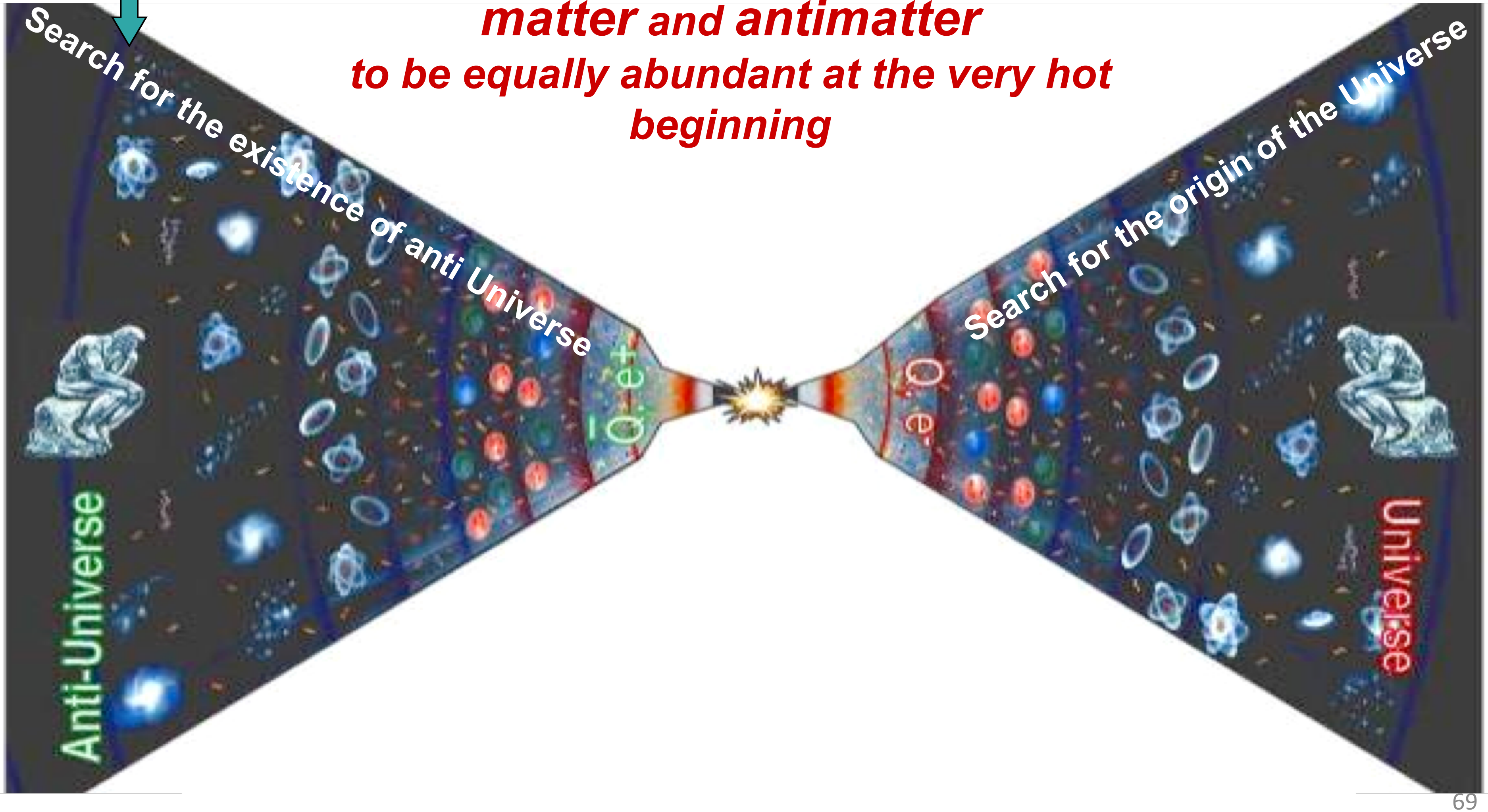
J. Kopp, Phys. Rev. D 88 (2013) 076013

Complex Antimatter in Cosmic Rays

A Status Report

AMS in Space

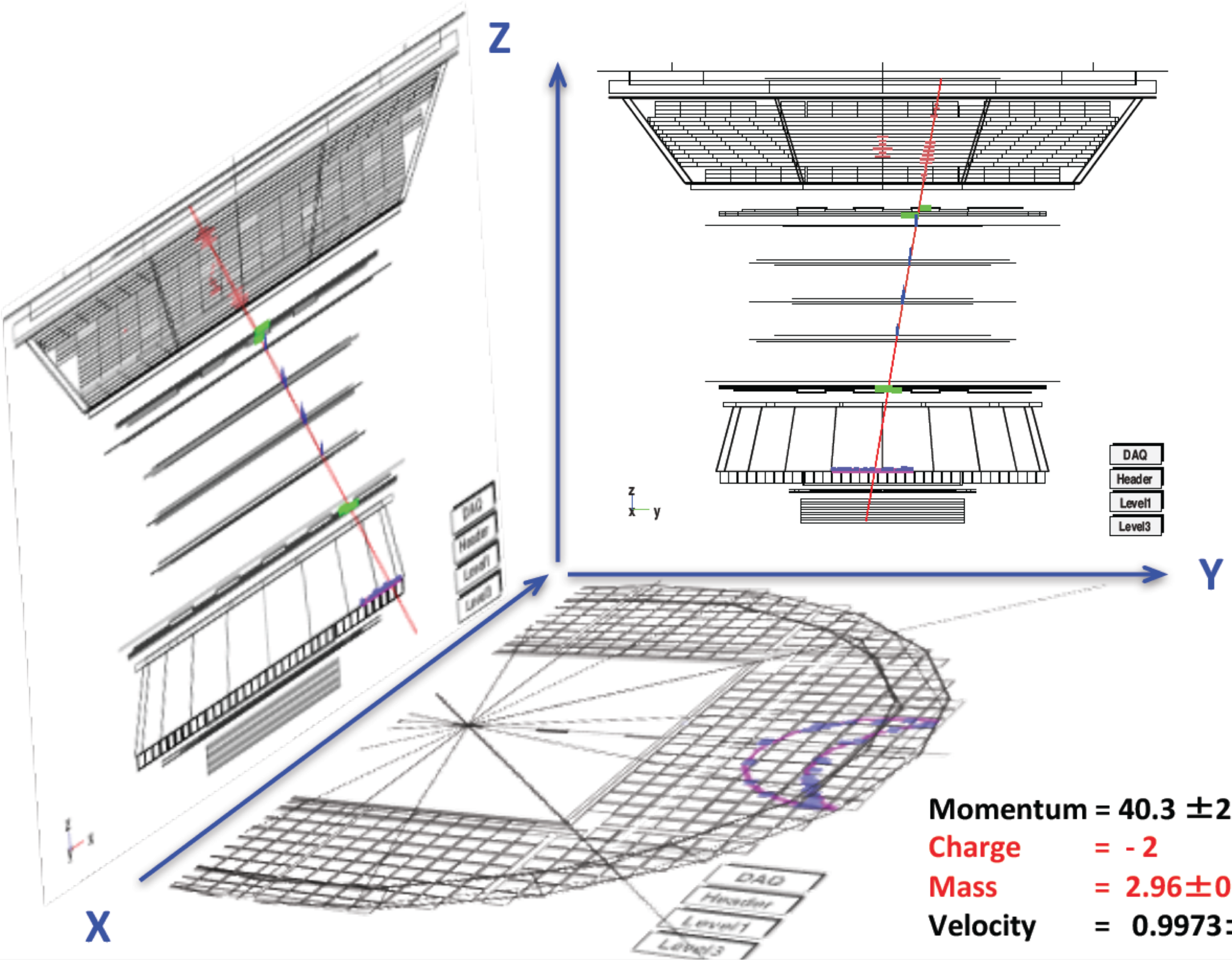
The Big Bang origin of the Universe requires ***matter*** *and* ***antimatter*** *to be equally abundant at the very hot beginning*



To date we have observed
a few events with $Z = -2$
and
with mass around ^{3}He
at a rate of ~1 anti-helium
in 100 million helium

S. Ting, Colloquium at CERN, Dec. 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*

Antihelium and AMS

At a signal to background ratio of $1/10^9$,
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: 2.2 million CPU-Days,
   10 times more events than He data

The few events have mass 2.8 GeV and charge -2 like ^{3}He.
Their existence has fundamental implication in physics.

We are developing systematic checks on the detector to ensure that the events are not from detector effects.

Conclusions:

- AMS has made precision measurement of CR spectra from 1GV to 3TV. Primary and secondary nuclei spectra provides new understanding of CR propagation.
- Unprecedented precision reveals new features in cosmic ray spectra:
  - Proton spectrum differs significantly from other primary particles.
  - Change of nuclei spectrum index at ~300 GV.
  - Same spectra behavior of proton, antiproton, and positron in 40 – 450GV rigidity.
  - Positron excess.
- Operation of AMS for the lifetime of the ISS will extend AMS measurements in rigidity range, to resolve some of the mysteries of the CR.