Precision Measurement of the Energy Dependence of Primary and Secondary Cosmic Rays with the Alpha Magnetic Spectrometer on the International Space Station

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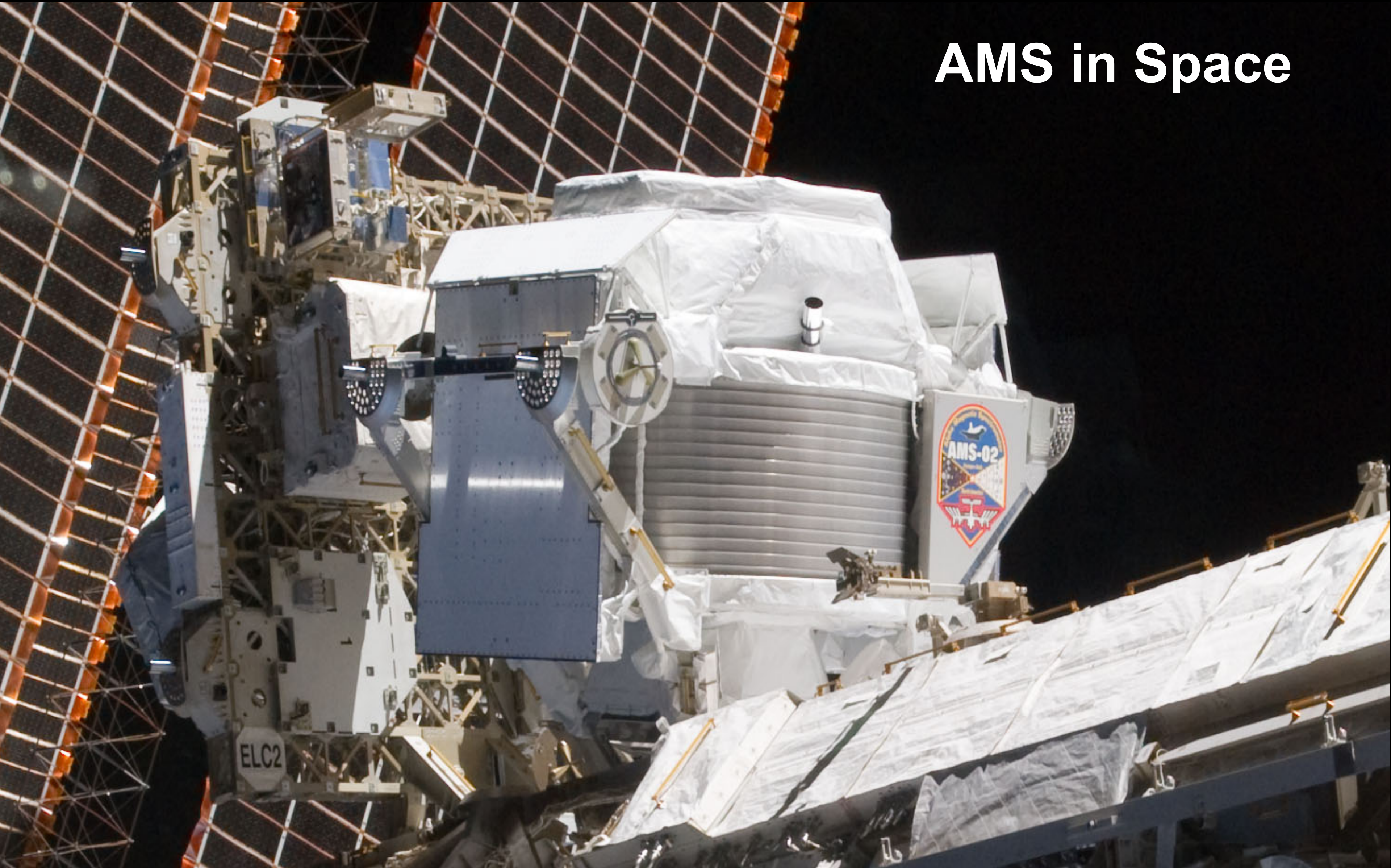
On behalf of AMS Collaboration

WIN2019 Bari, June 5, 2019

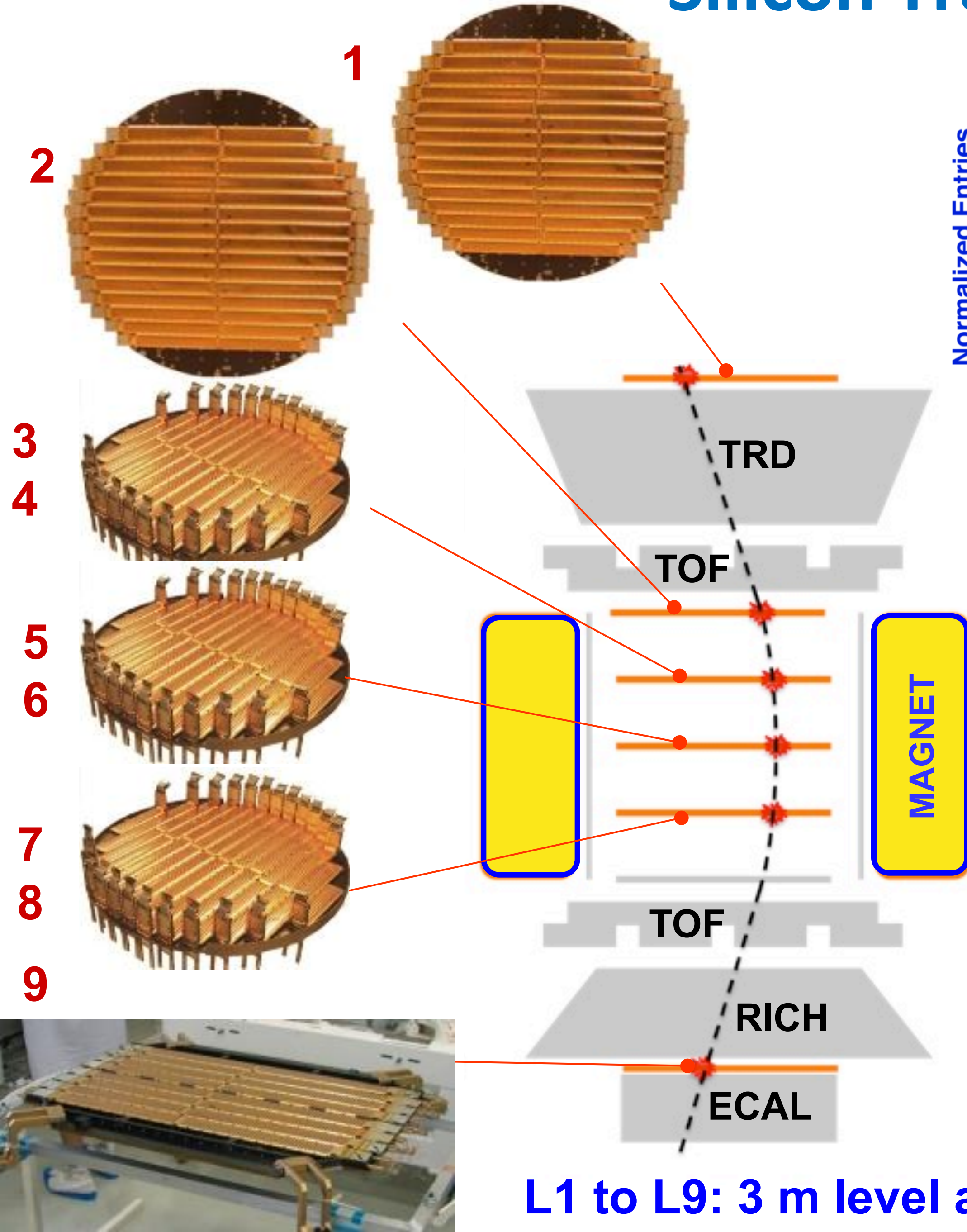
AMS in Space



300,000 electronics channels
650 processors

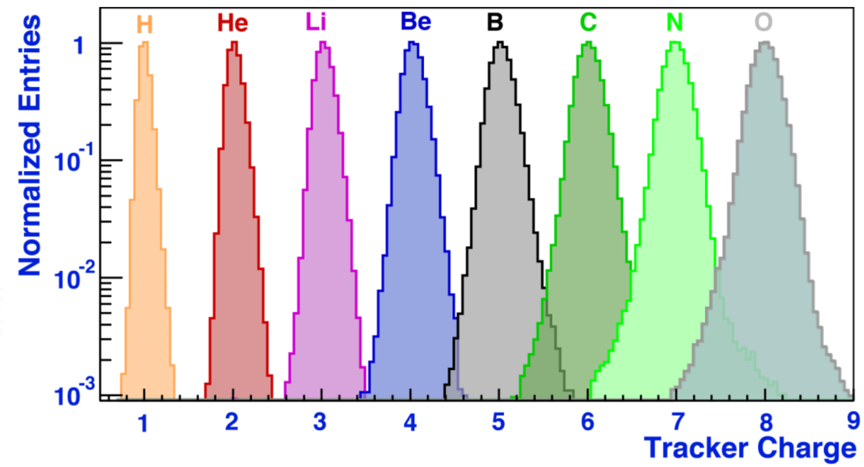
5m x 4m x 3m
7.5 tons

Silicon Tracker

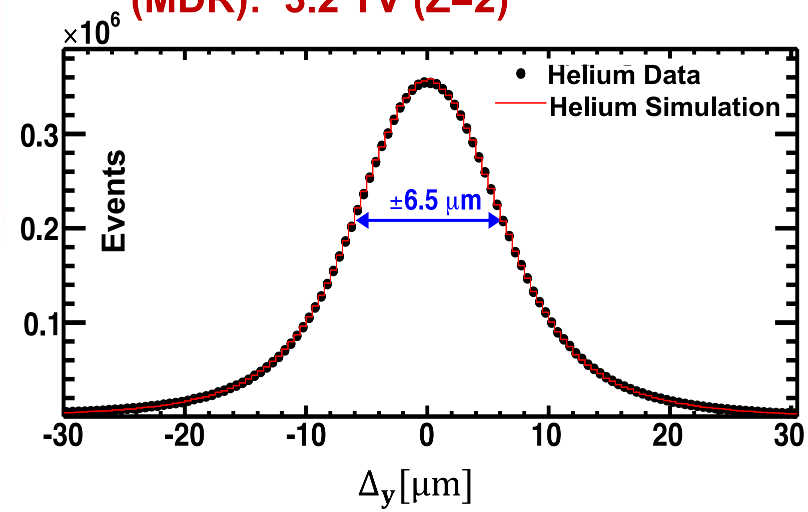


L1 to L9: 3 m level arm

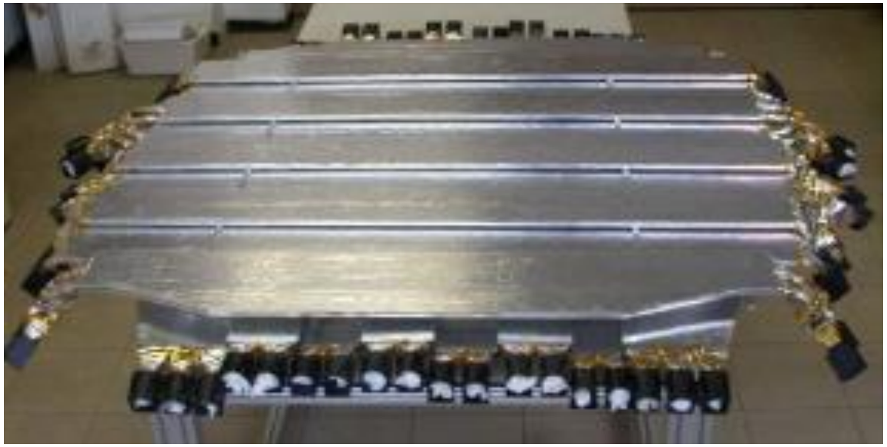
Charge Measurement: ΔZ=0.12 (Z=6)



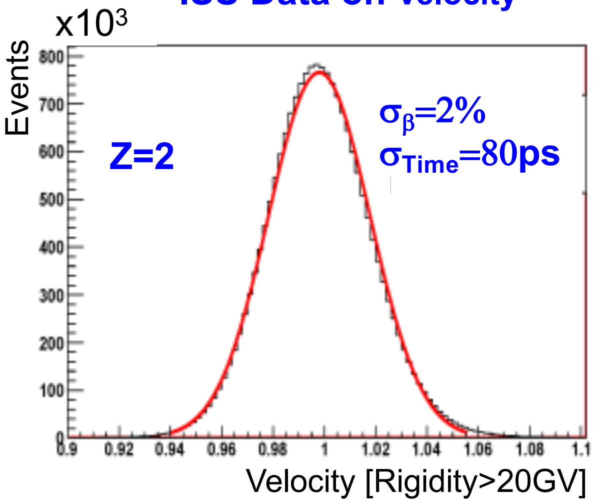
Maximum Detectable Rigidity (MDR): 3.2 TV (Z=2)

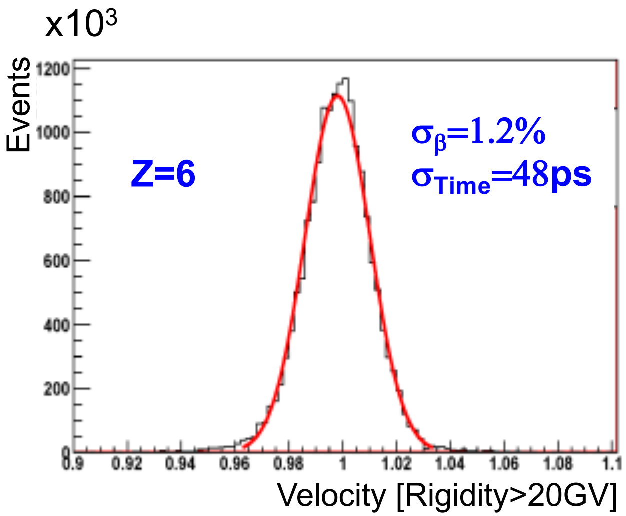


Time of Flight (TOF)



ISS Data on Velocity

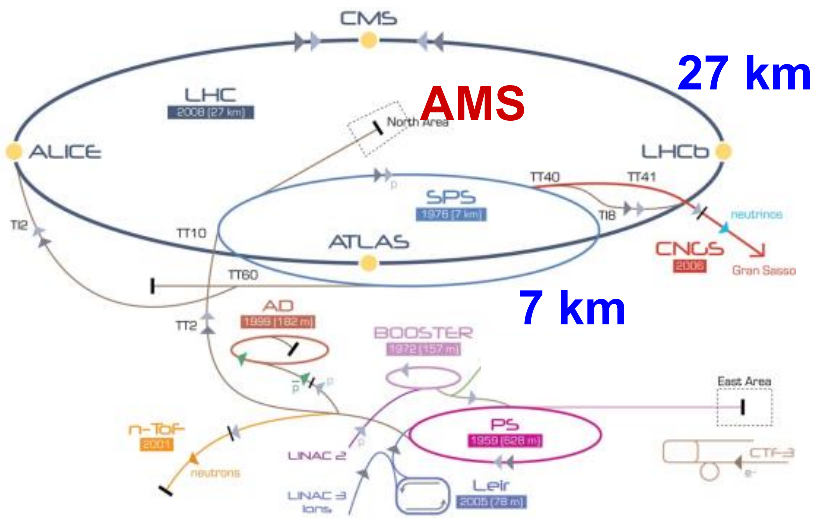




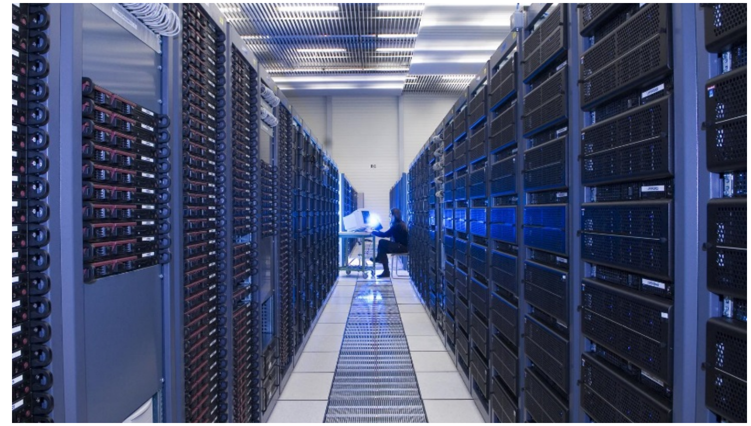
The TOF system serves as a high-efficiency trigger

Calibration of the AMS Detector

Test beam at CERN SPS:
p, $e^{\pm}$, $\pi^{\pm}$, 10−400 GeV

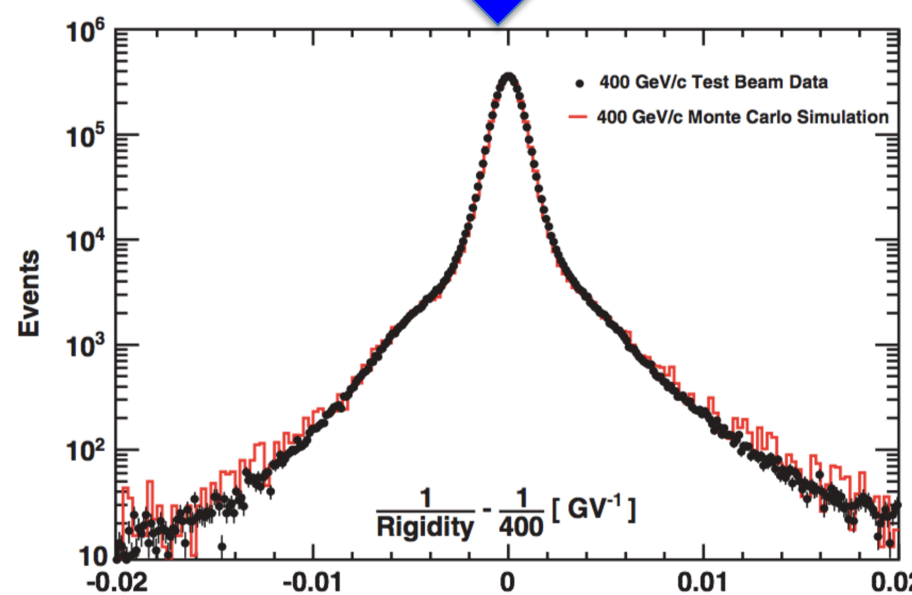


12,000 CPU cores at CERN



Computer simulation:
Interactions, Materials, Electronics

2000 positions

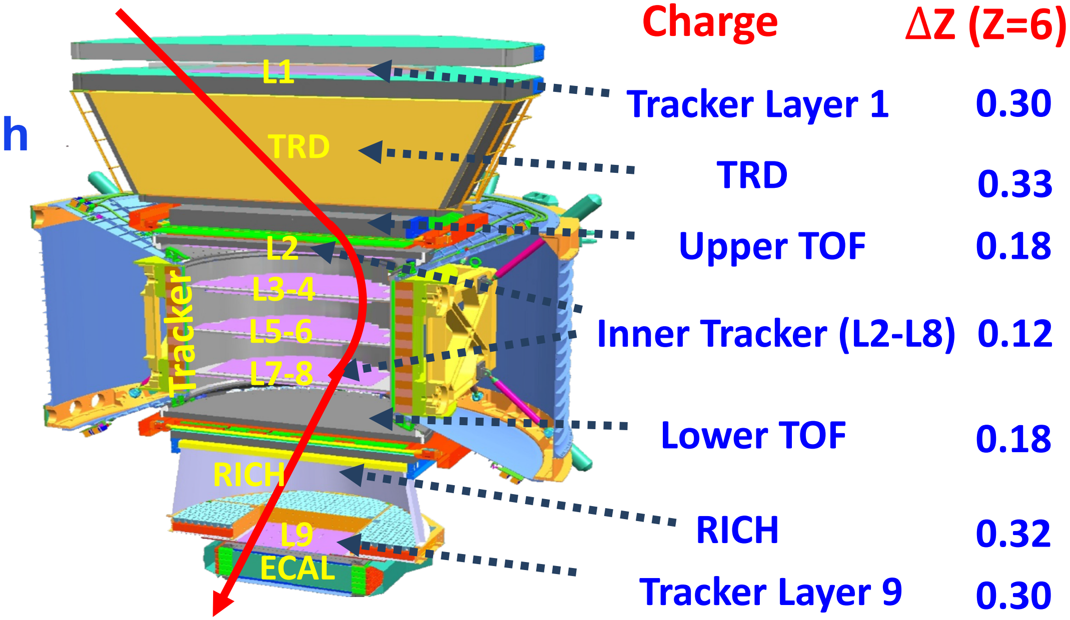


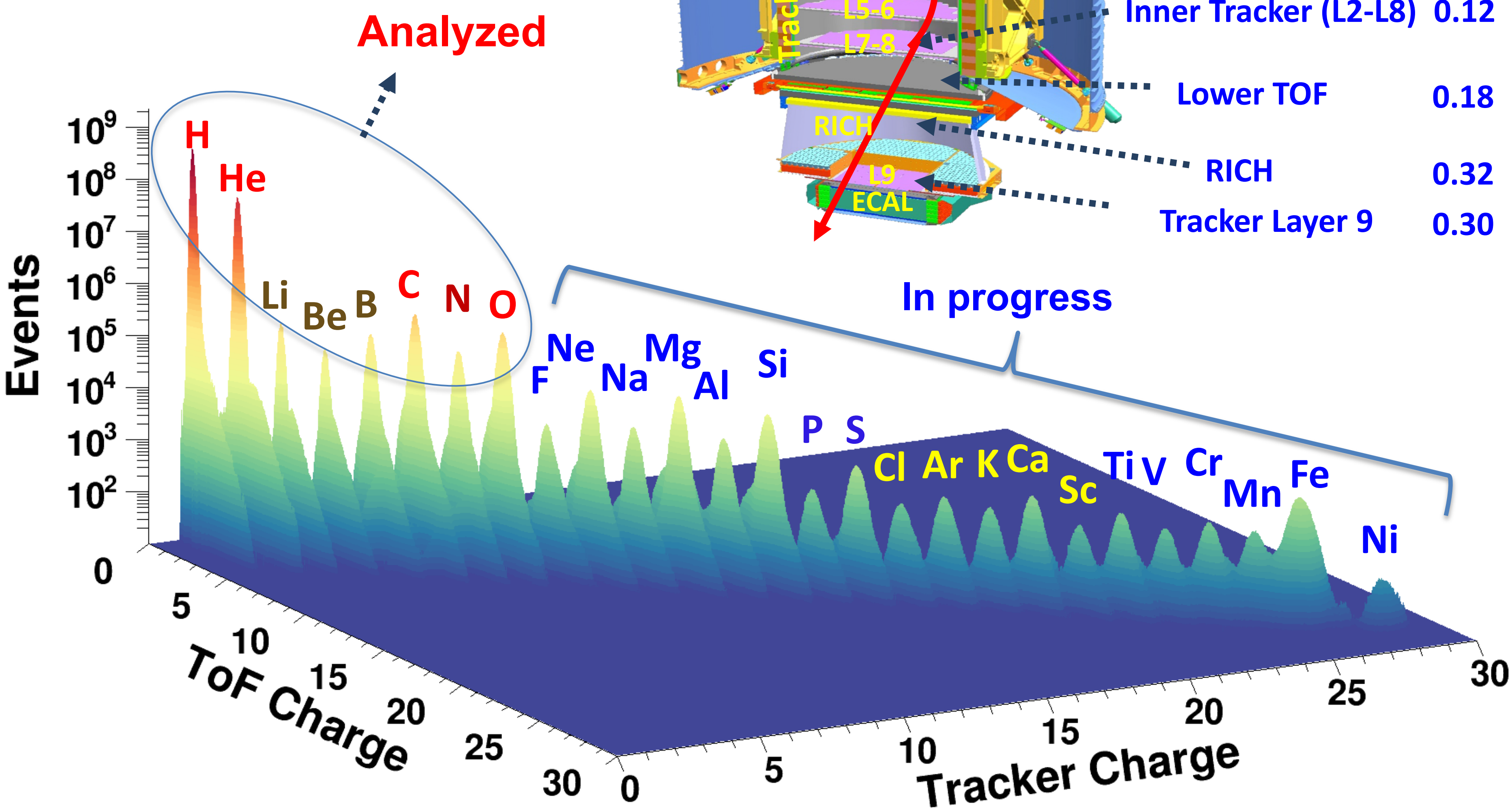
AMS was installed on the ISS in May 2011

In 8 years, 140 billion charged particles have been measured by AMS

Precision Measurements of Cosmic Rays

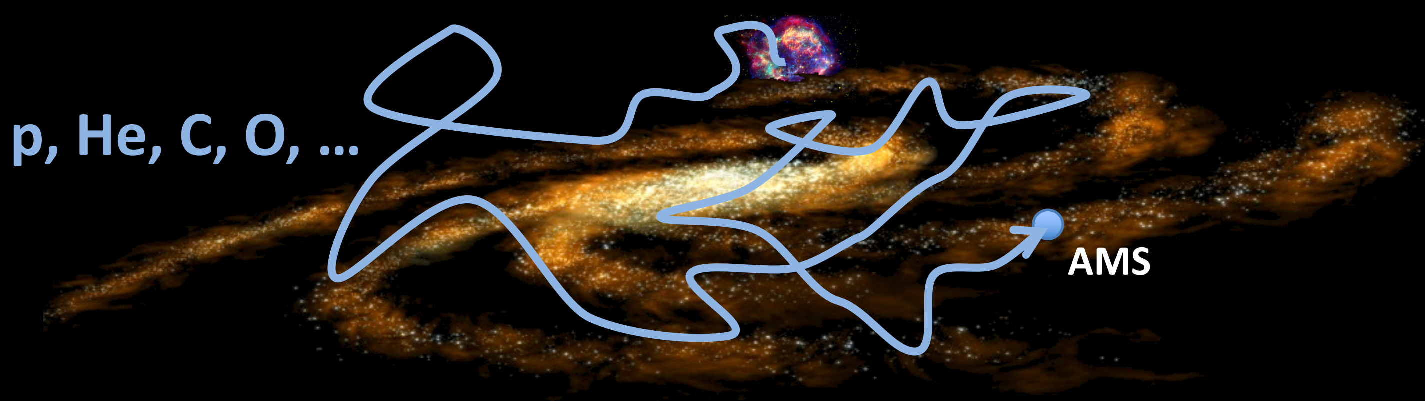
AMS has seven instruments which independently measure Cosmic Nuclei





Traditionally, there are two prominent classes of cosmic rays:

Primary Cosmic Rays (p, He, C, O, …)
are produced and accelerated at the source (such as SNR) and travel through space, and are directly detected by AMS. They carry information on their sources and the history of travel.



Flux Measurement

Isotropic flux in the i^{th} rigidity bin $(R_i, R_i + \Delta R_i)$

Number of selected events (subtracted for backgrounds and corrected for bin-to-bin migration)

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

Bin width (68 bins between 2 GV to 3 TV)

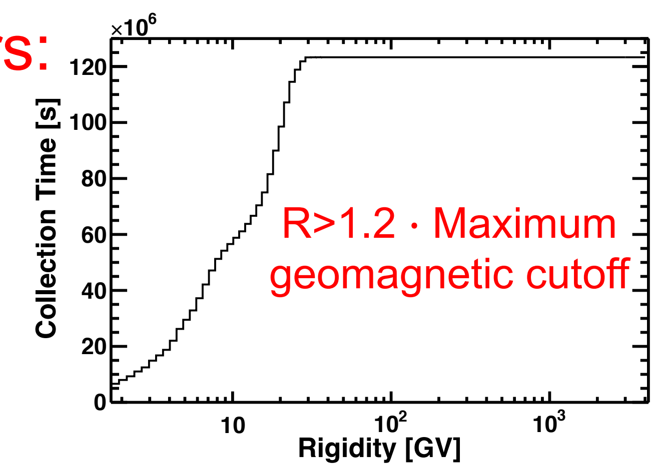
Effective acceptance (from MC, verified with data)

Trigger efficiency (>97% over entire R range)

Collection time (5 years, 1.23×10^8 s for R>30 GV)

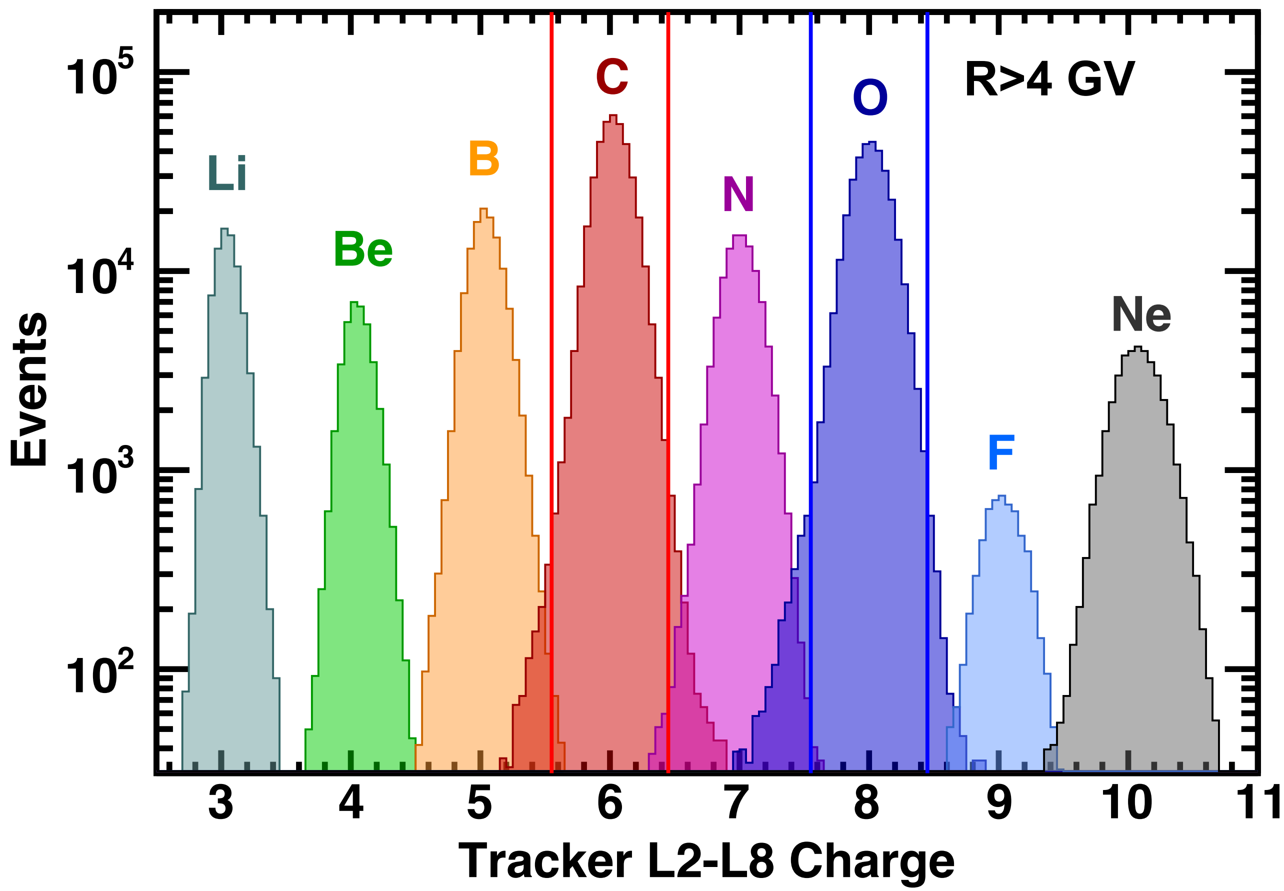
Extensive studies of the systematic errors:

- Background estimations
- Rigidity resolution function
- Acceptance and Trigger efficiency
- Absolute rigidity scale



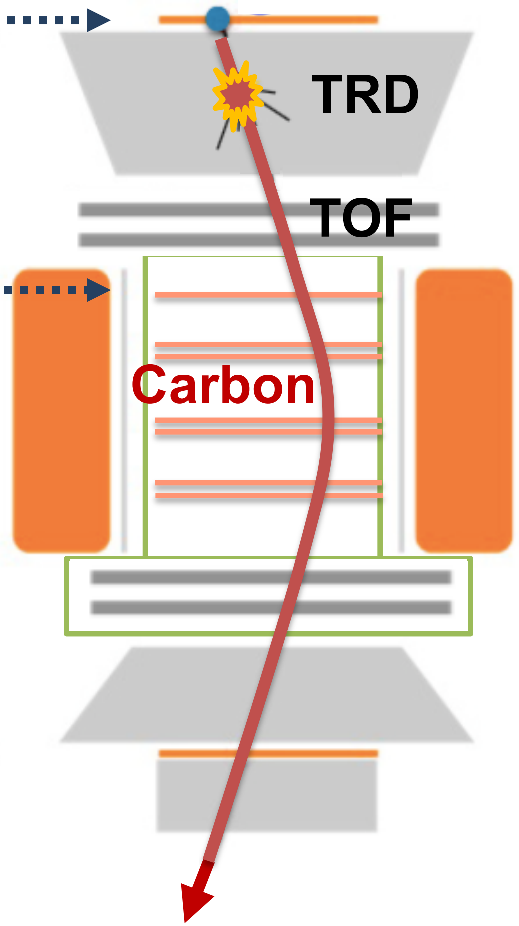
Accuracy on N_i: Nuclei Charge Identification

The tracker L2-L8 charge has a very fine resolution of
ΔZ=0.07-0.12 (2≤Z≤8).

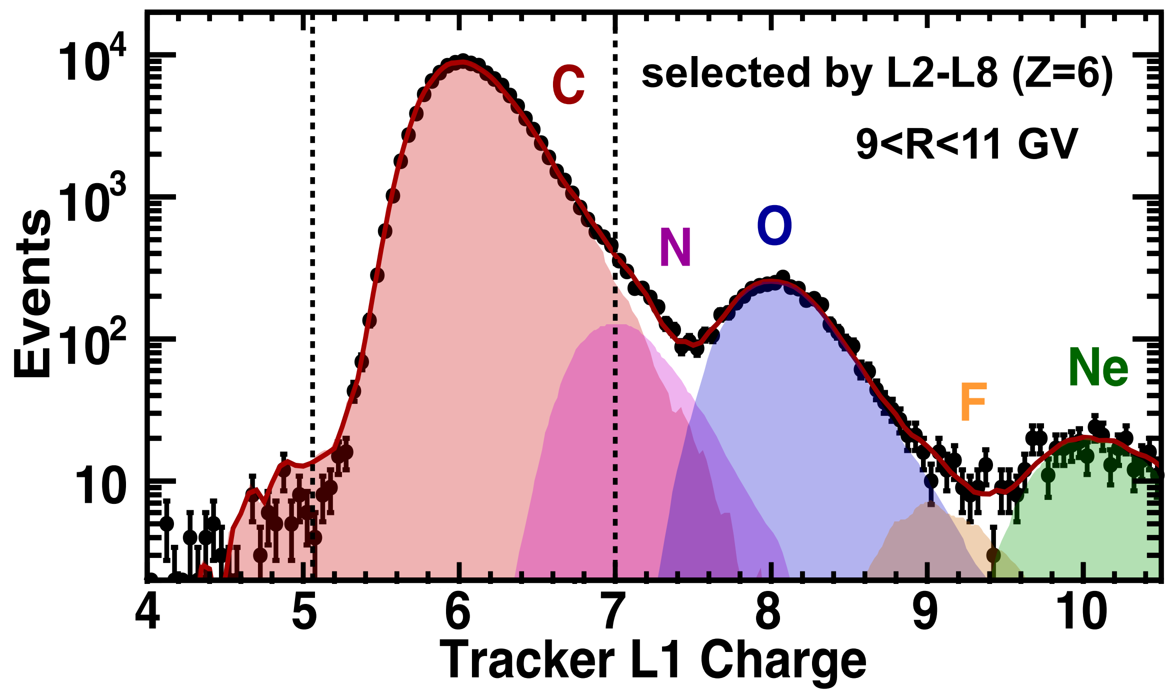


The charge misidentification from noninteracting nuclei is negligible.

Accuracy on N_i: Background from interactions between L1 and L2



N,O,F,Ne + AMS → C + X



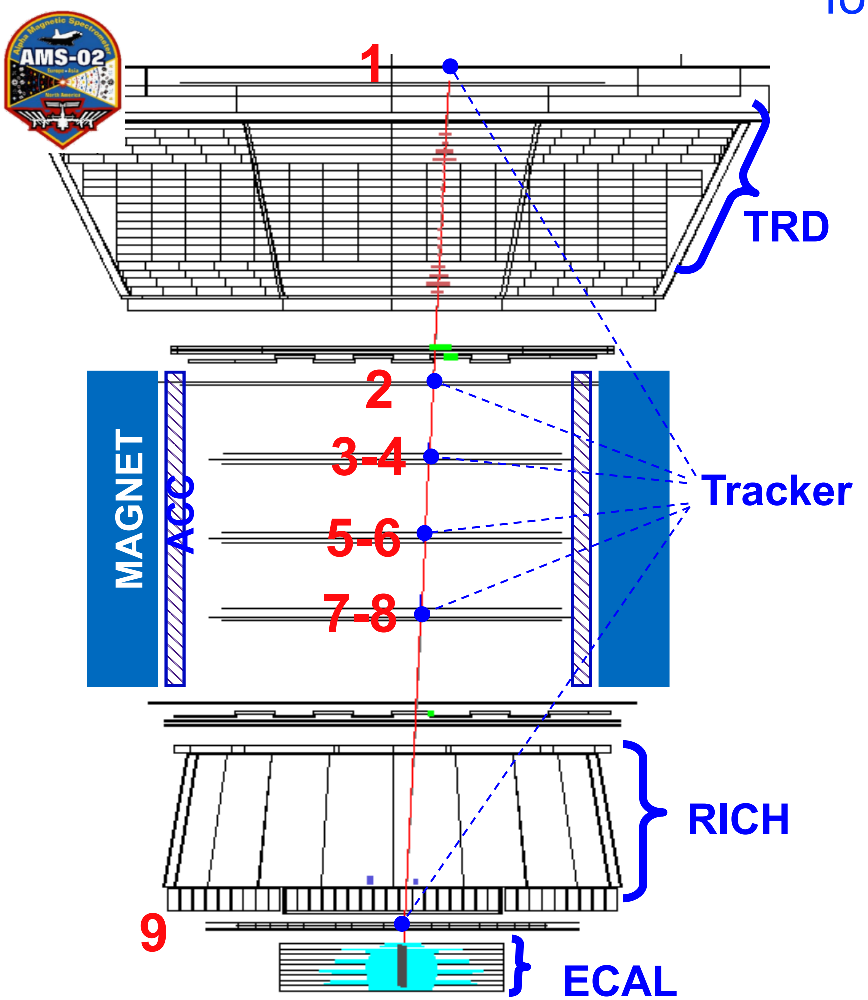
evaluated by fitting the charge distribution of tracker L1

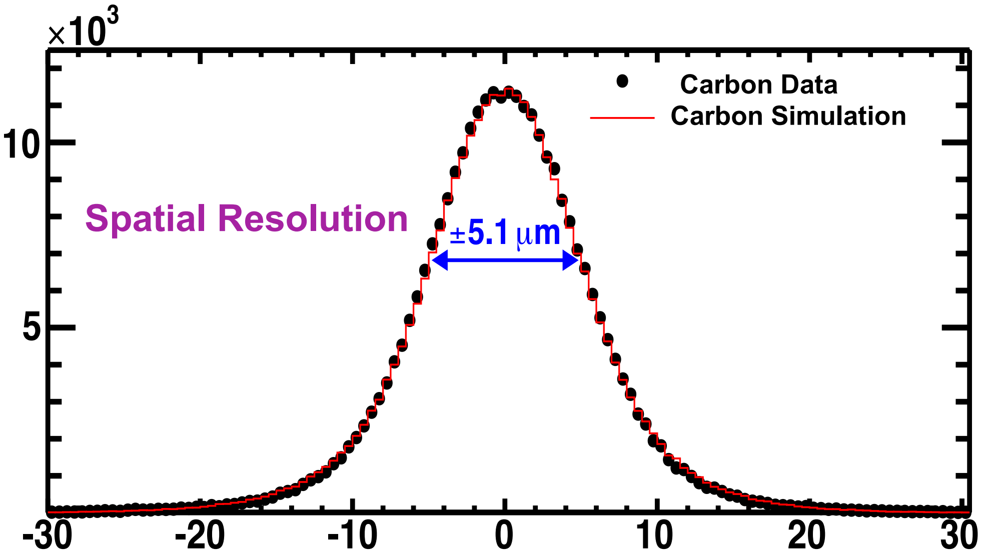
This background is <0.5% for Carbon and negligible for Helium and Oxygen.

Systematic error on the fluxes is < 0.5% in the entire rigidity range

Accuracy on N_i : Tracker Rigidity Resolution

The systematics associated with the tracker rigidity resolution is well understood. The tracker spatial resolution is **6.5 μm** for Helium, **5.1 μm** for Carbon, and **6.3 μm** for Oxygen.



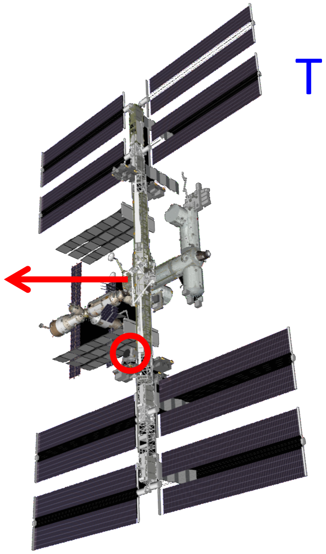


L1 to L9: 3 m level arm

maximum detectable rigidity ≈ 3.7 TV

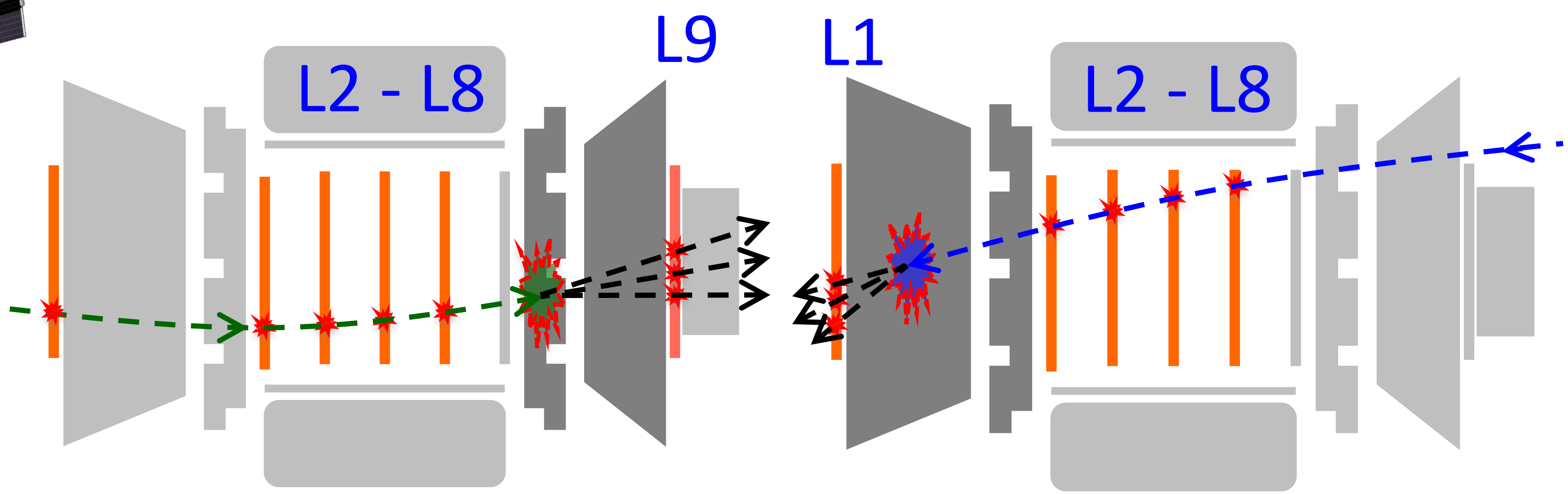
The resulting systematic errors on the fluxes are **< 1% below 300 GV** and **4% @ 3 TV**

Accuracy on A_i: Measurements of Nuclei Cross Section by AMS



The detector components are mostly made of Carbon and Aluminum.

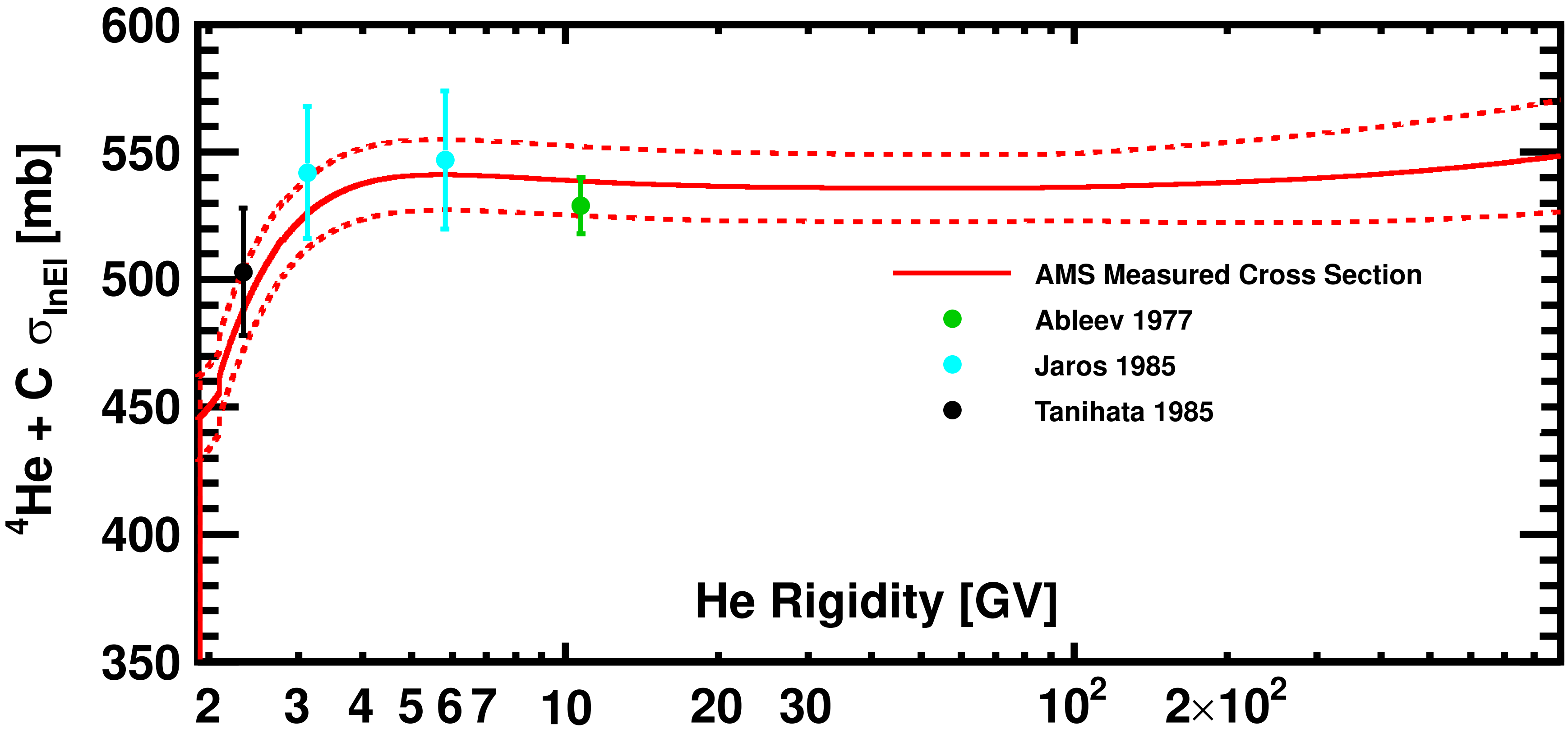
AMS measured the nuclei survival probability using data acquired when AMS pointing in horizontal direction (~10^5 sec exposure), in which cosmic rays can enter AMS both **left to right** and **right to left**.



Most importantly, by flying horizontally, AMS was able to make Interaction cross sections measurements which were not available from accelerators.

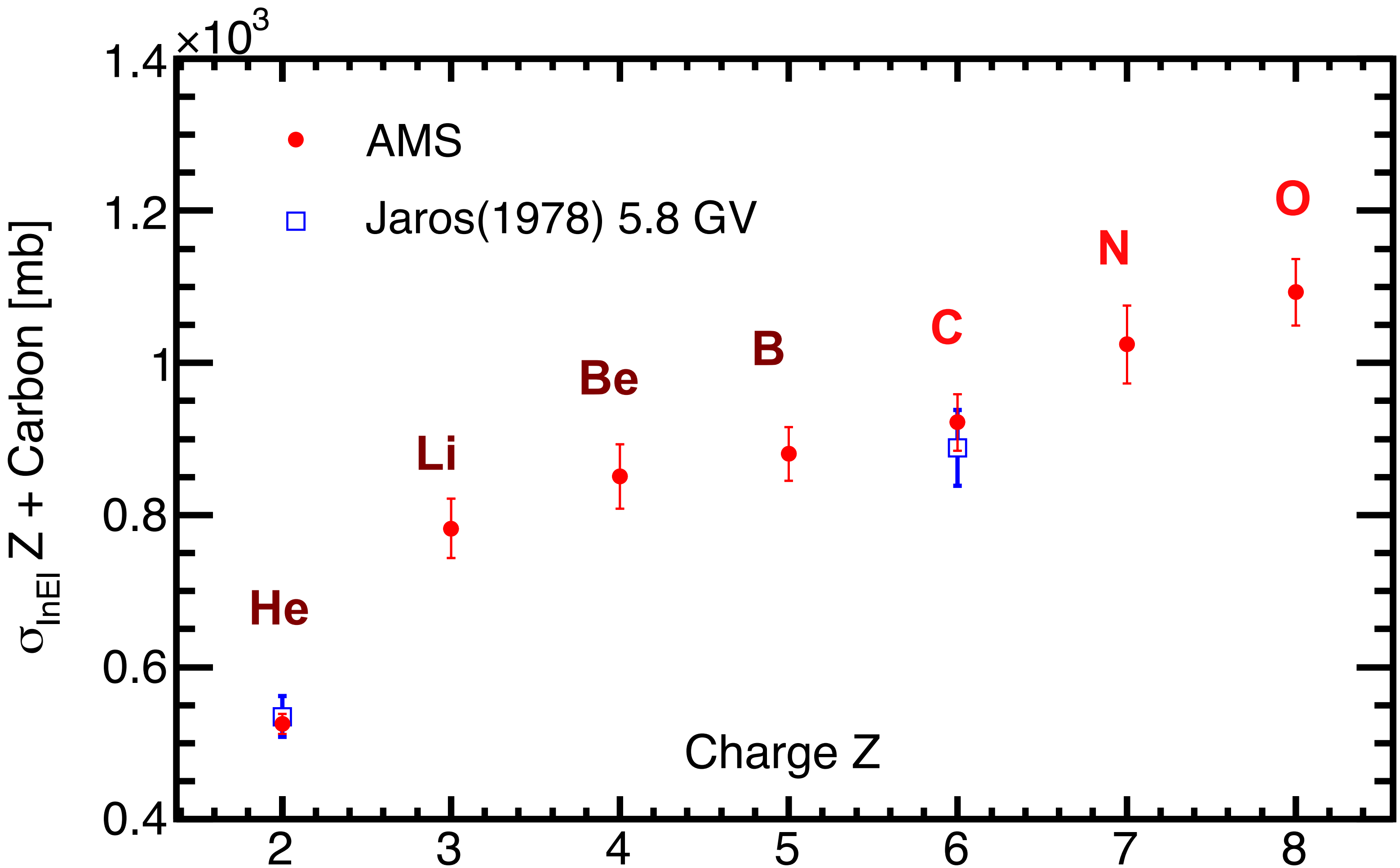
Accuracy on A_i:

AMS He + C Inelastic Cross Section Measurement
AMS Materials C(73%) Al(20%)



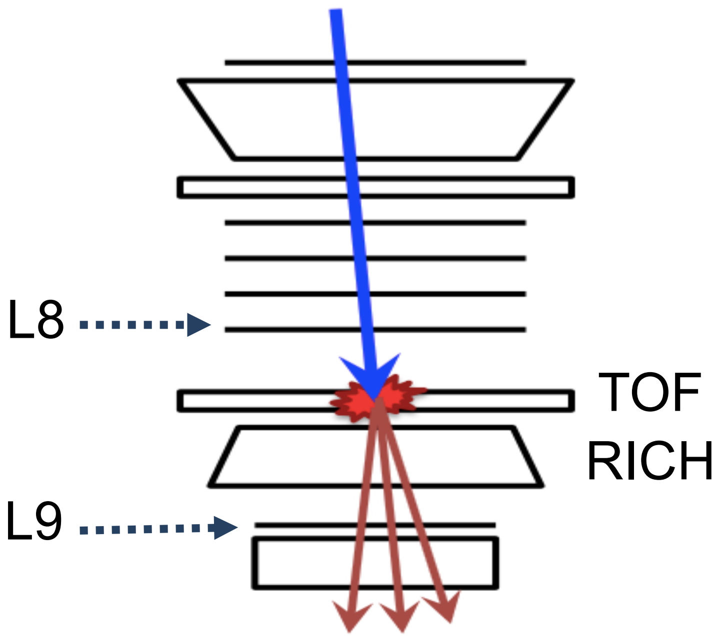
The **dashed curve** indicates the corresponding systematic errors.

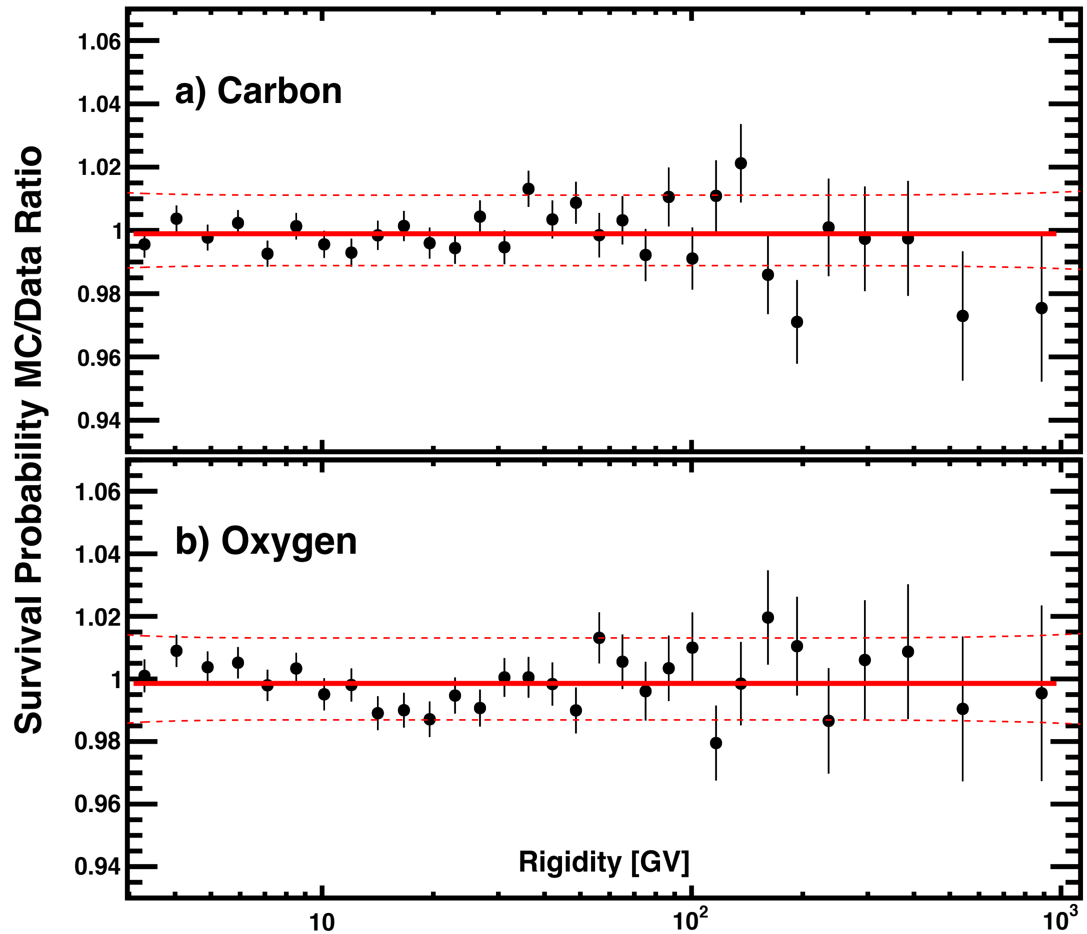
Accuracy on A_i:
AMS Nuclei + C Inelastic Cross Section measurements average in 5-100 GV



Accuracy on A_i: Survival Probability MC/Data Comparison

The nuclei survival probability after traversing the material between L8 and L9 is used to verify the inelastic cross section

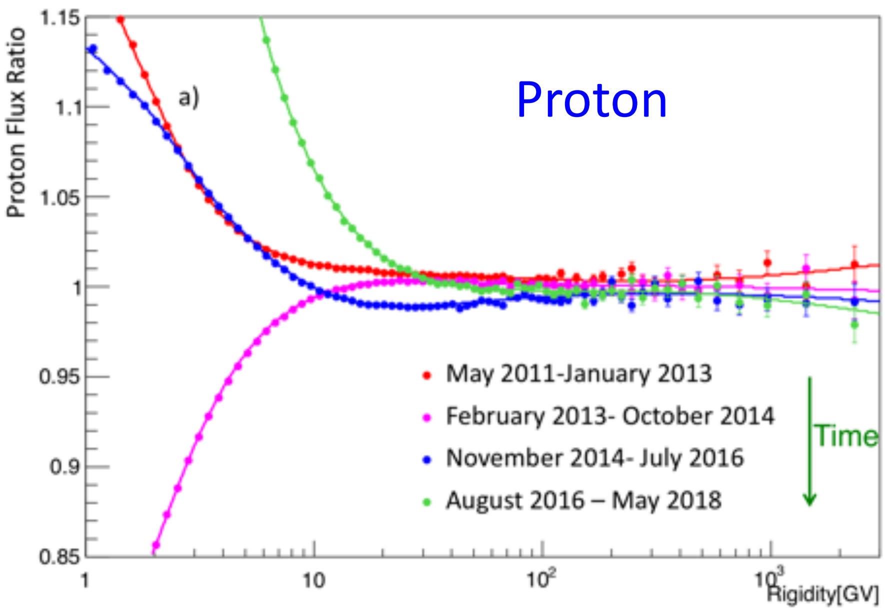


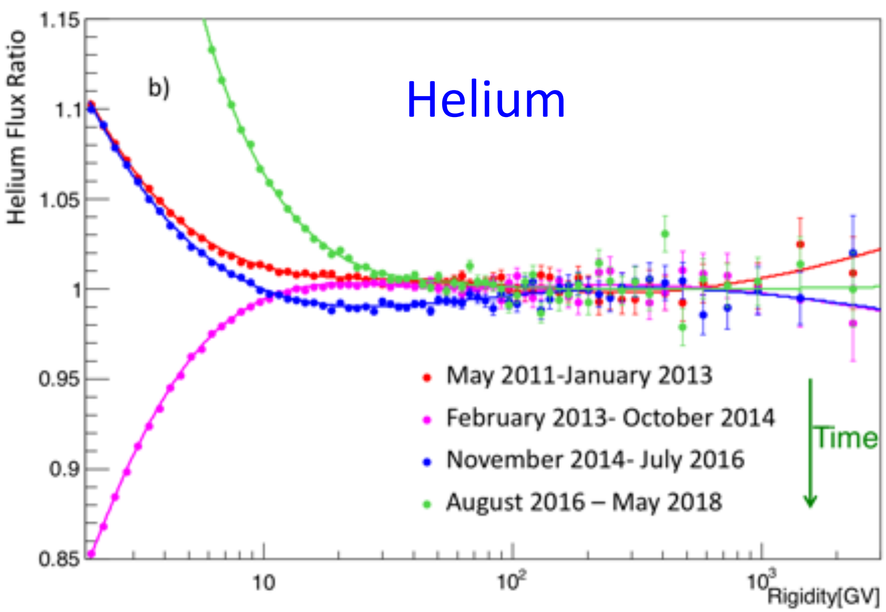


The systematic errors on the fluxes due to uncertainties of inelastic cross sections are ~ 2% up to 100 GV and ~ 3% at 3 TV.

Absolute Rigidity Scale Verification

The ratio of the fluxes measured using data from each 21-month period to the flux measured over 7 years





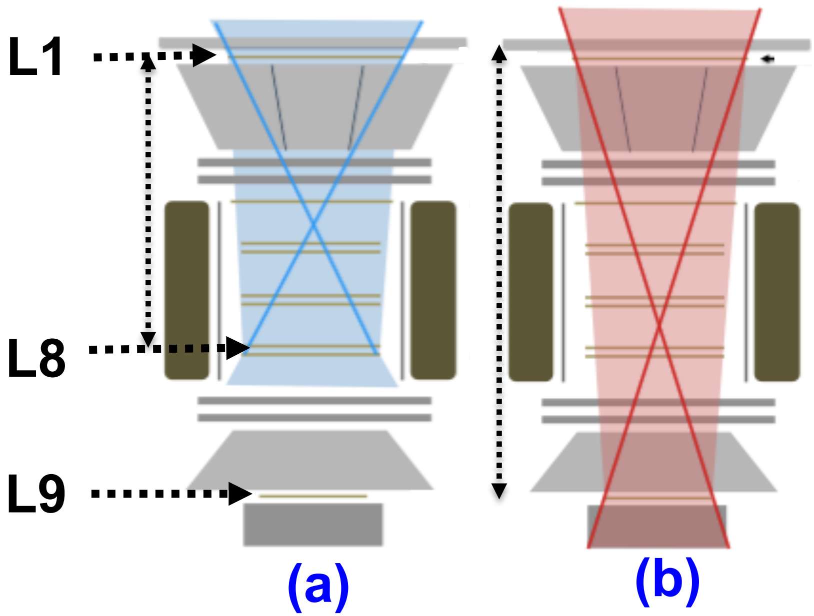
Differences at low rigidities are due to solar modulation.

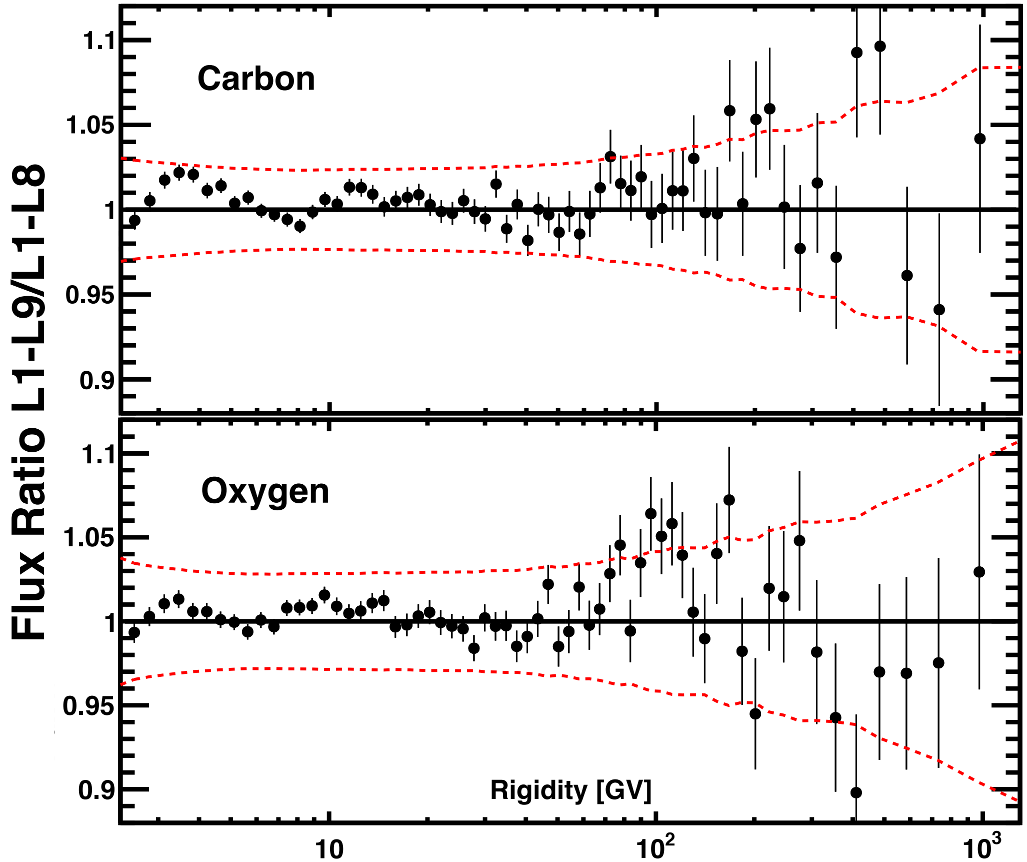
At high rigidities (>50 GV), the fluxes are constant within measurement errors

Flux Measurement Verification Example

The ratio of the fluxes with different acceptances using events

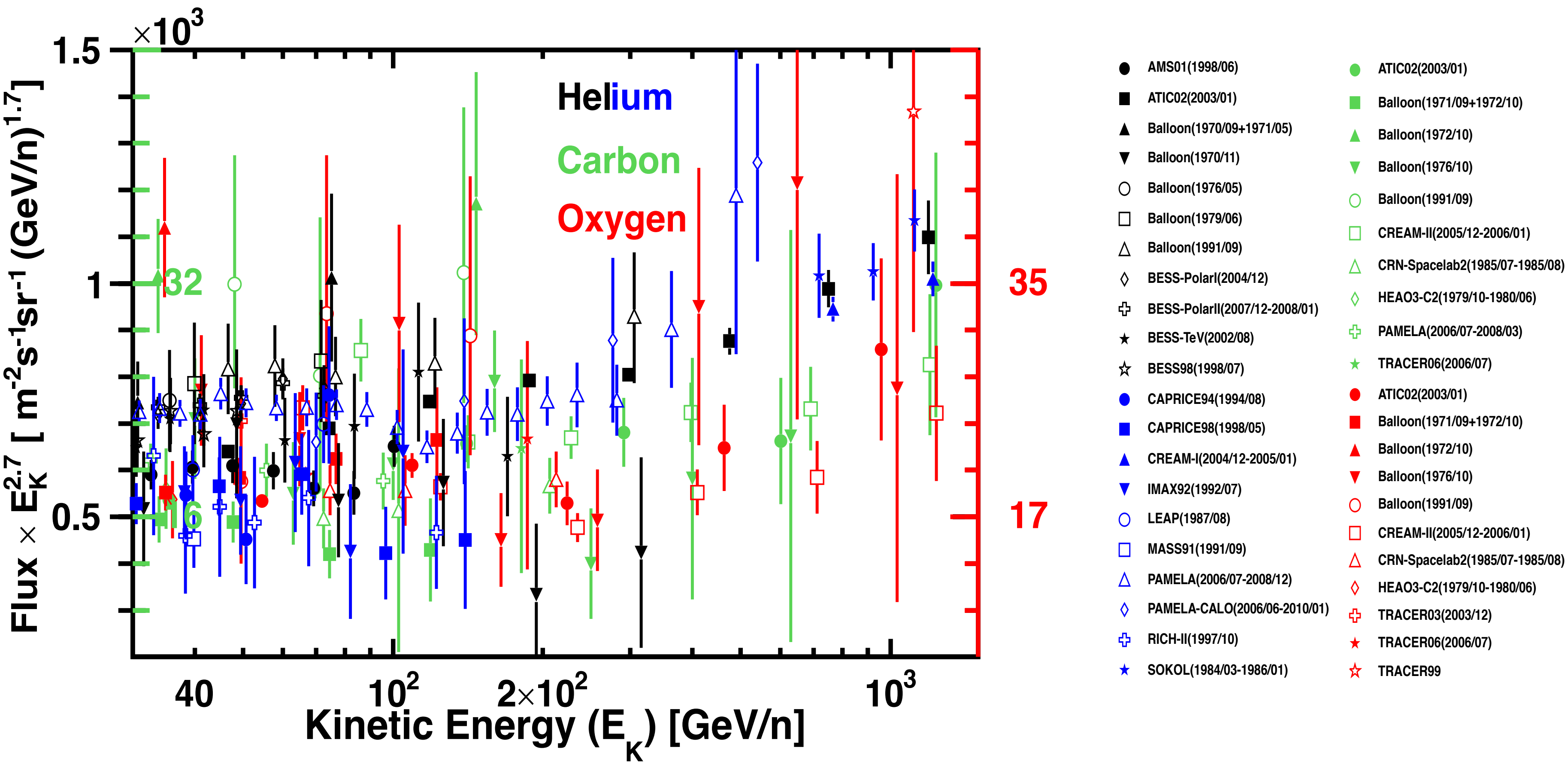
(a) passing through **L1 to L8**
(b) passing through **L1 to L9**



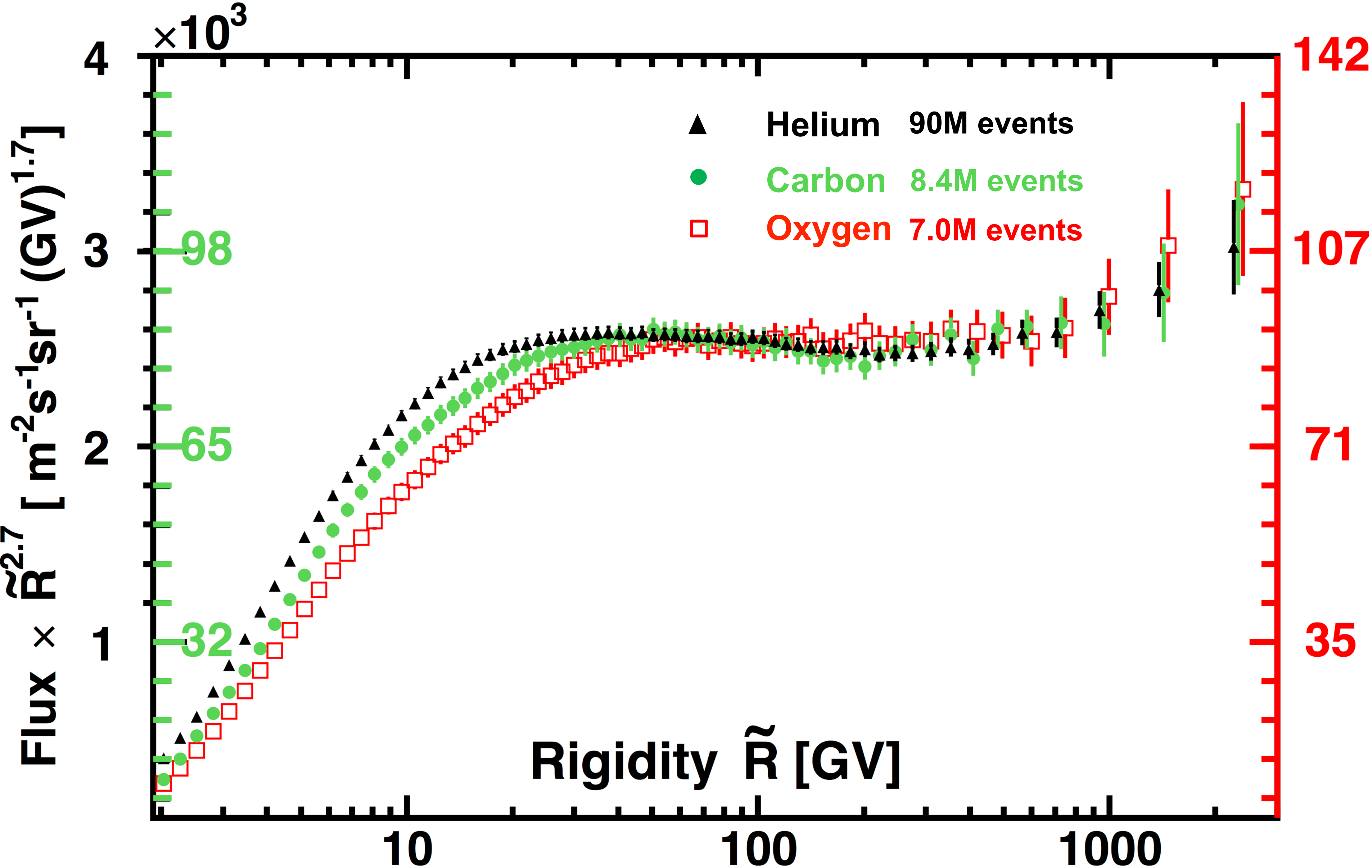


The good agreement verifies the systematic errors on unfolding and acceptance.

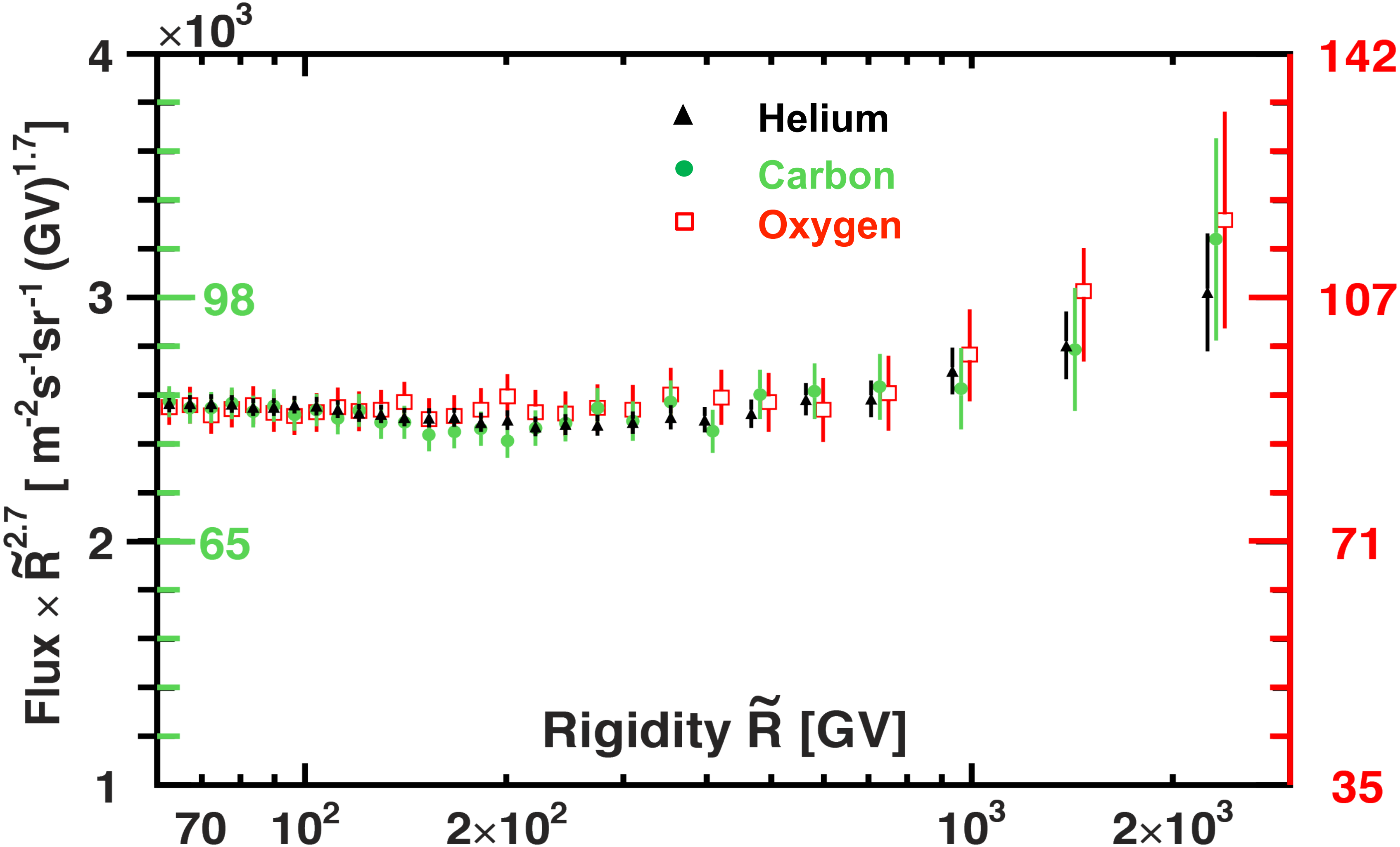
Before AMS: Results on Primary Cosmic Rays
(Helium, Carbon, Oxygen)
from balloon and satellite experiments



The AMS Results on Primary Cosmic Rays He, C, and O.



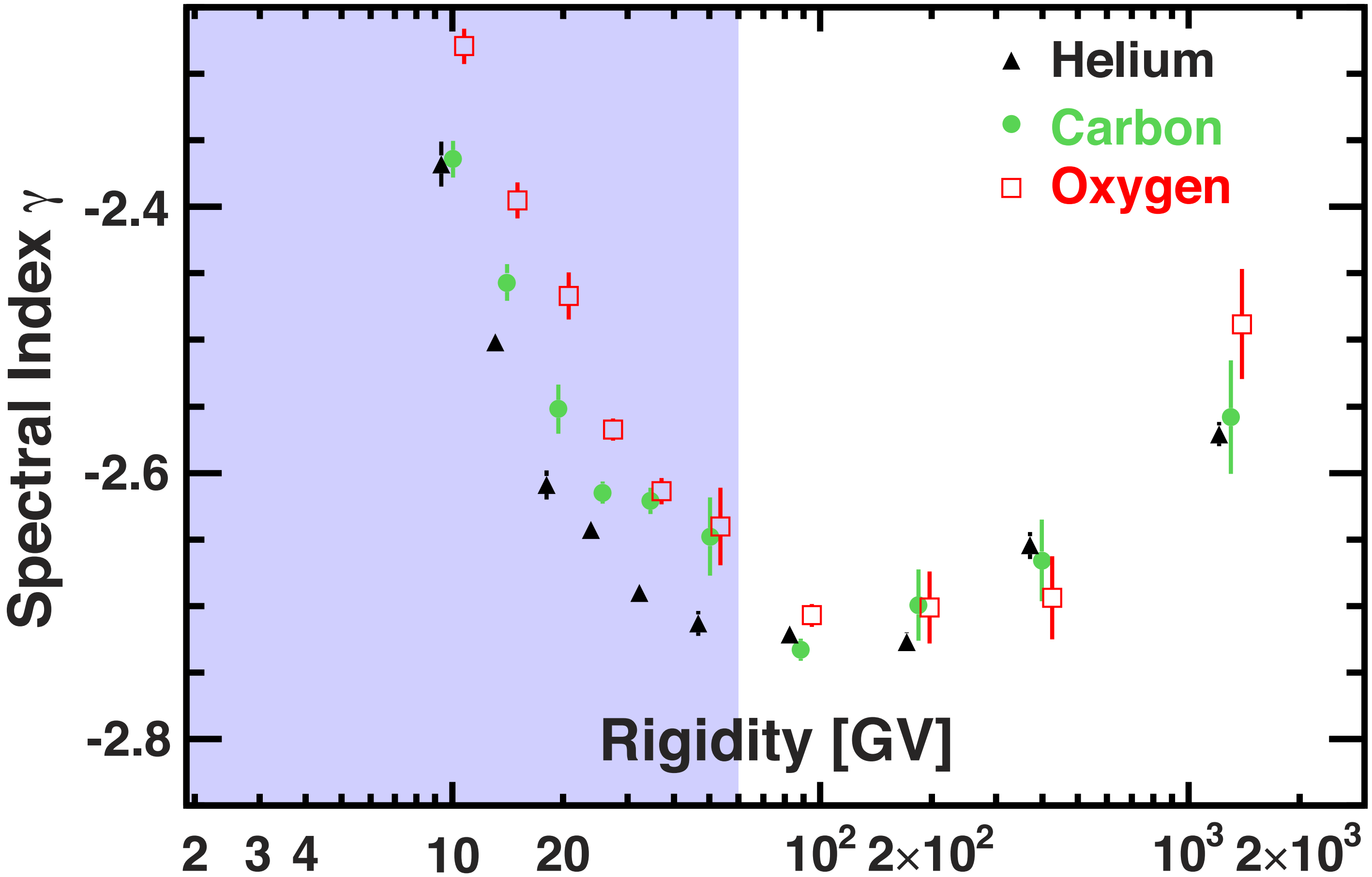
AMS Result: Surprisingly, above 60 GV, these fluxes have identical rigidity dependence.



They all deviate from a single power law above 200 GV

Primary Cosmic Ray Spectral Indices

$\gamma = d[\log(\Phi)/d[\log(R)]$ (Φ is the flux; γ is the spectral index)

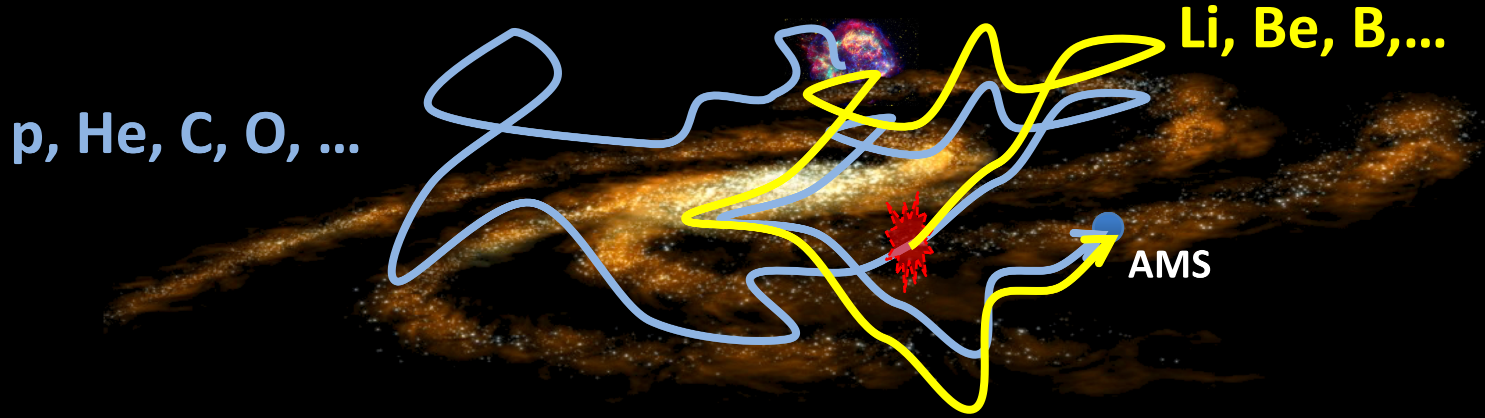


All spectral indices are identical above 60 GV and harden above 200 GV.

Traditionally, there are two prominent classes of cosmic rays:

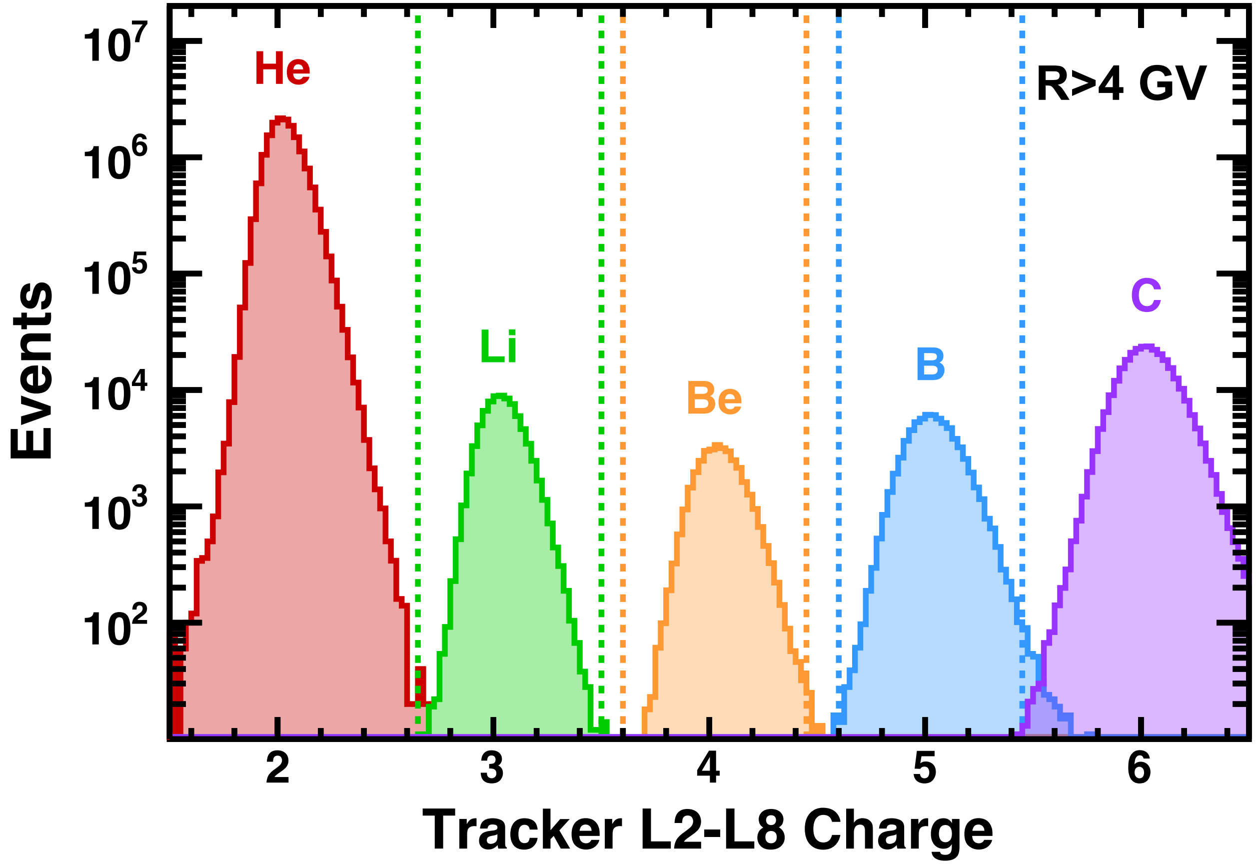
Primary and Secondary (Li, Be, B, …).

Secondary Cosmic Rays are produced in the collisions of primary cosmic rays. They carry information on the history of the travel and on the properties of the interstellar matter.



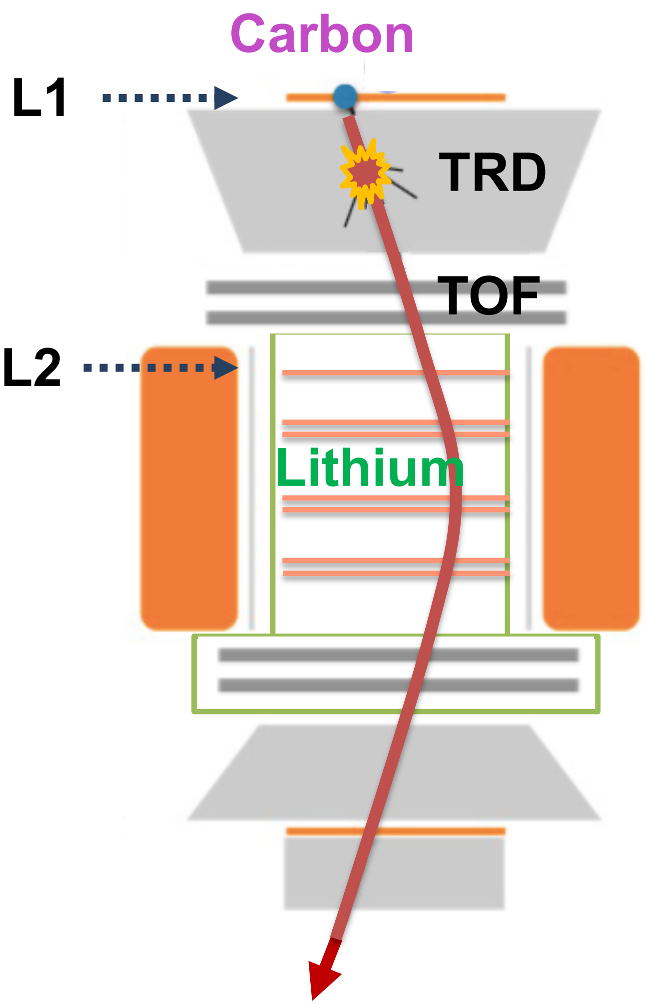
Accuracy on N_i: Nuclei Charge Identification

The tracker L2-L8 charge has a very fine resolution of ΔZ=0.08-0.12 ($3 \leq Z \leq 5$).

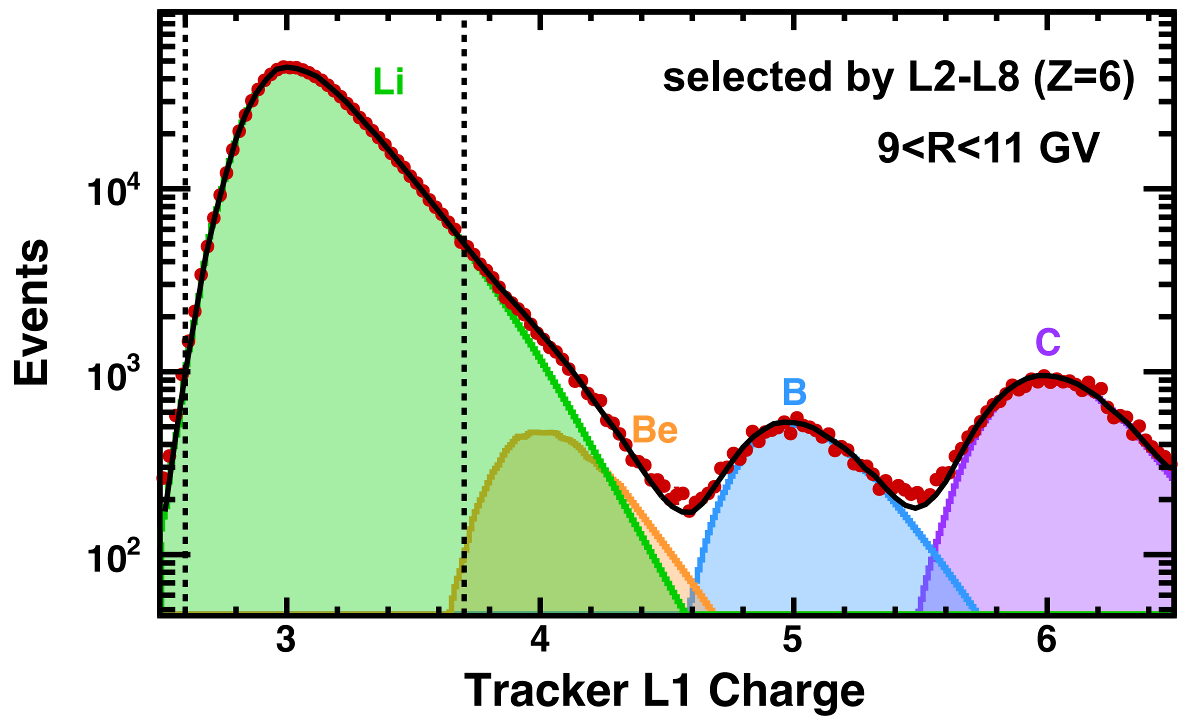


The charge misidentification from noninteracting nuclei is negligible.

Background from interactions between L1 and L2



O,N,C,B,Be + AMS → Li + X



evaluated by fitting the charge distribution of tracker L1

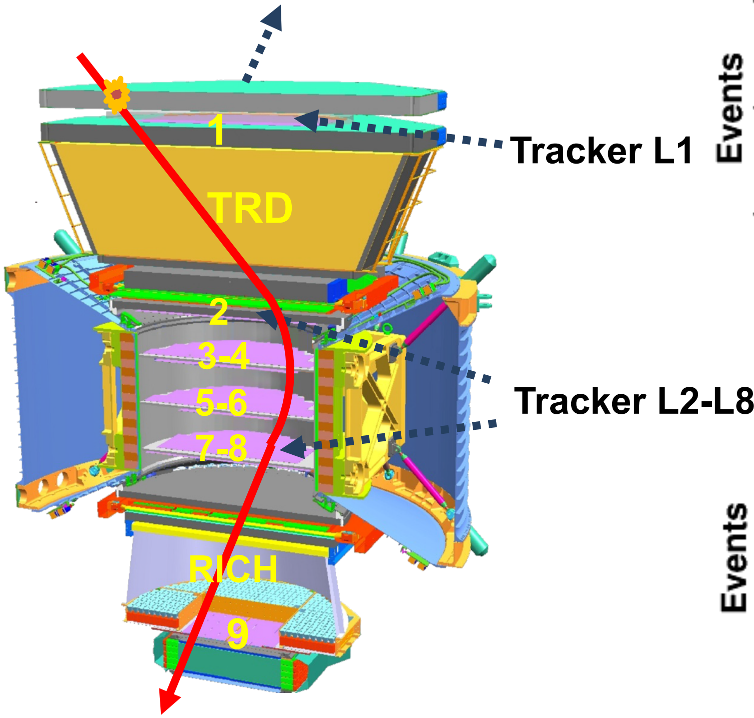
This background is <0.5% for Lithium and Beryllium, <3% for Boron.

Systematic error on the fluxes is < 0.5% in the entire rigidity range

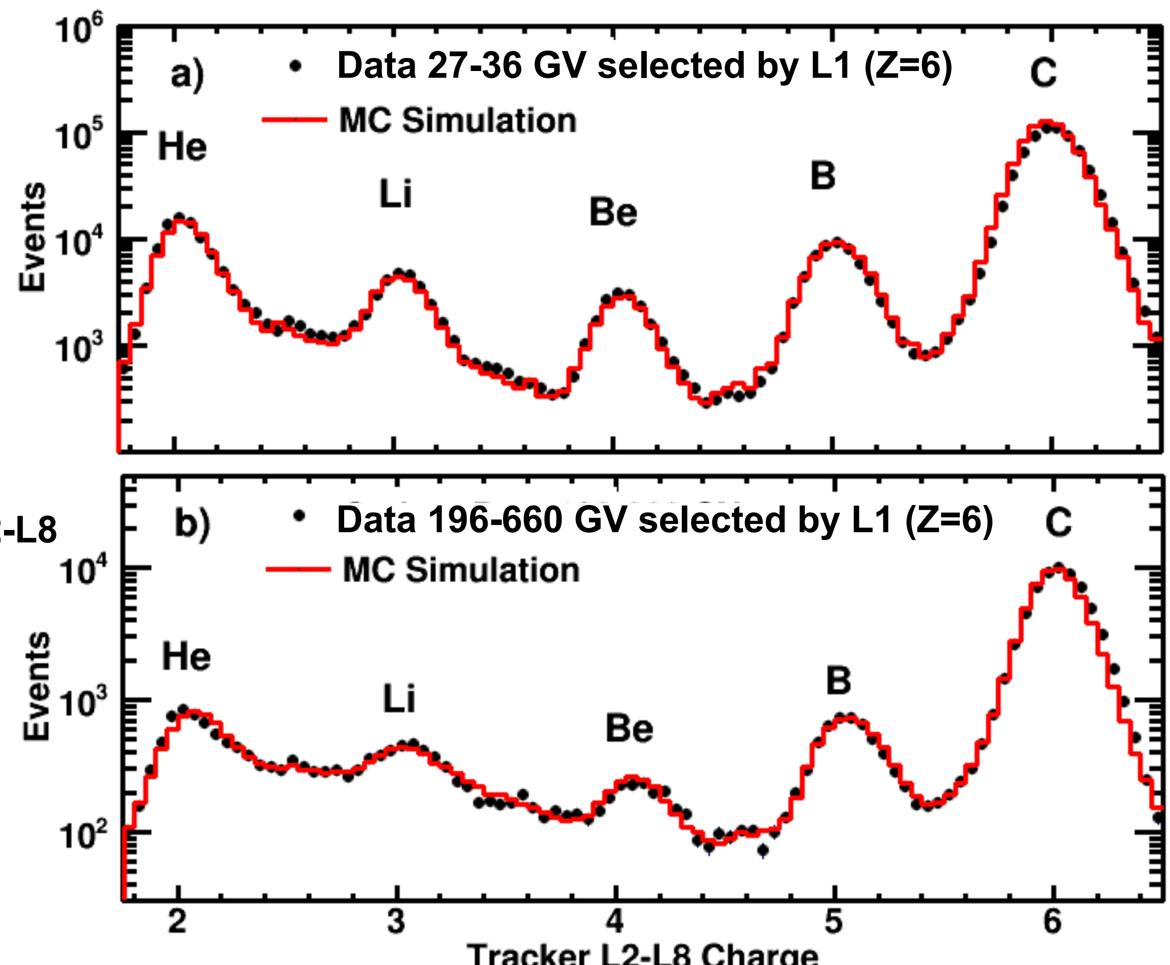
Background from interactions above L1

estimated from MC simulations which have been validated using data,

thin L1 support structures made by carbon fiber and aluminum honeycomb

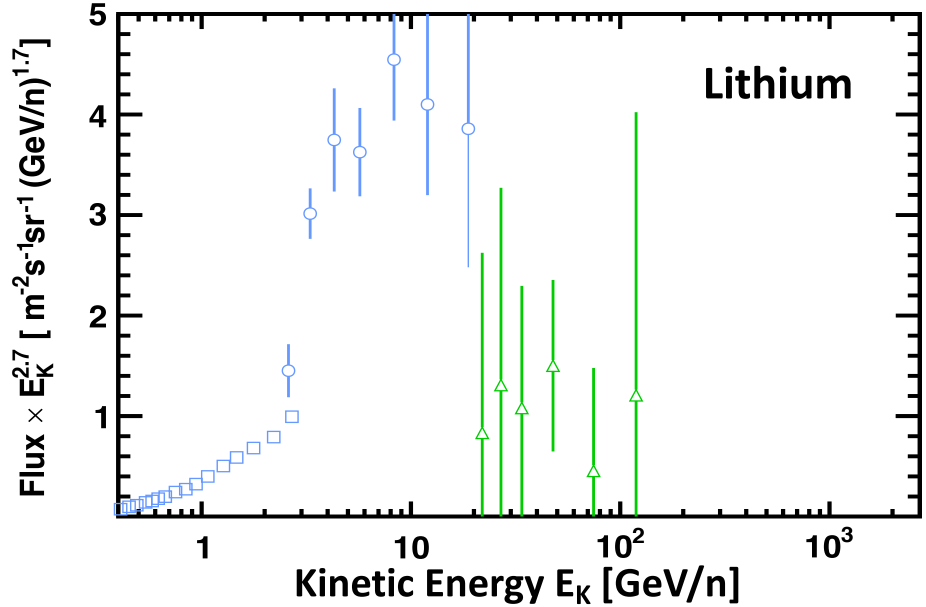


for examples:

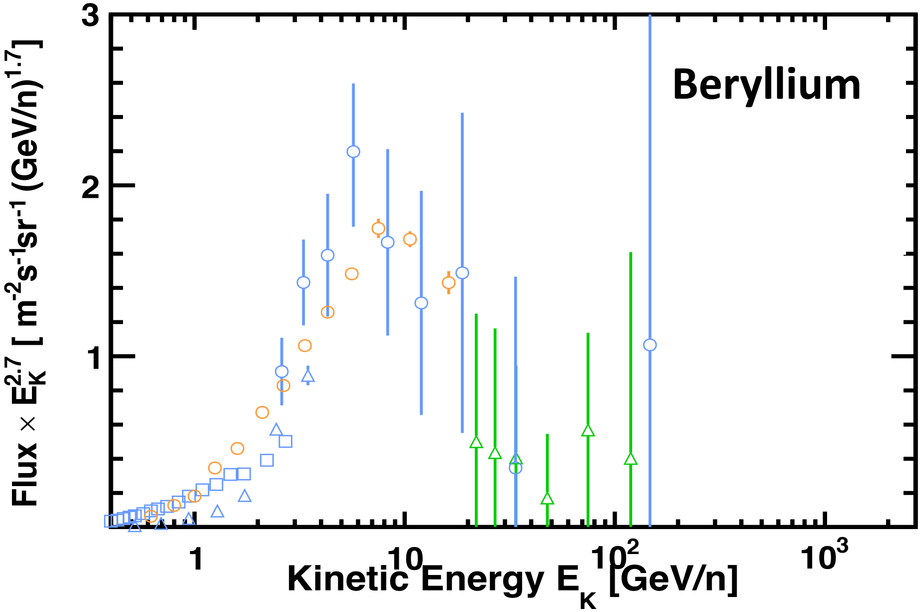


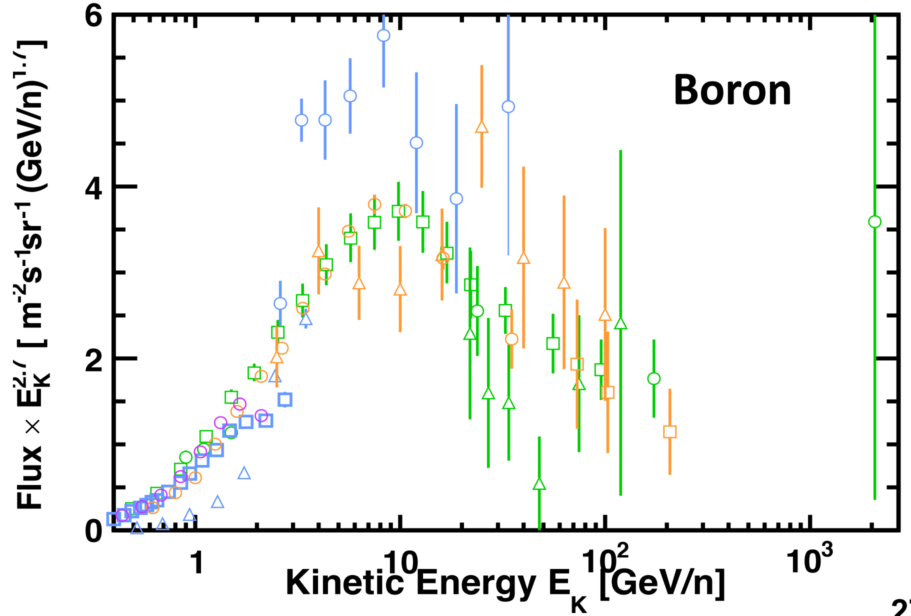
For secondaries, this background can reach up to 10% at 3 TV.
The systematic error on the fluxes is **<1.5 %** in the entire rigidity range

Flux Measurements of Li, Be, B before AMS



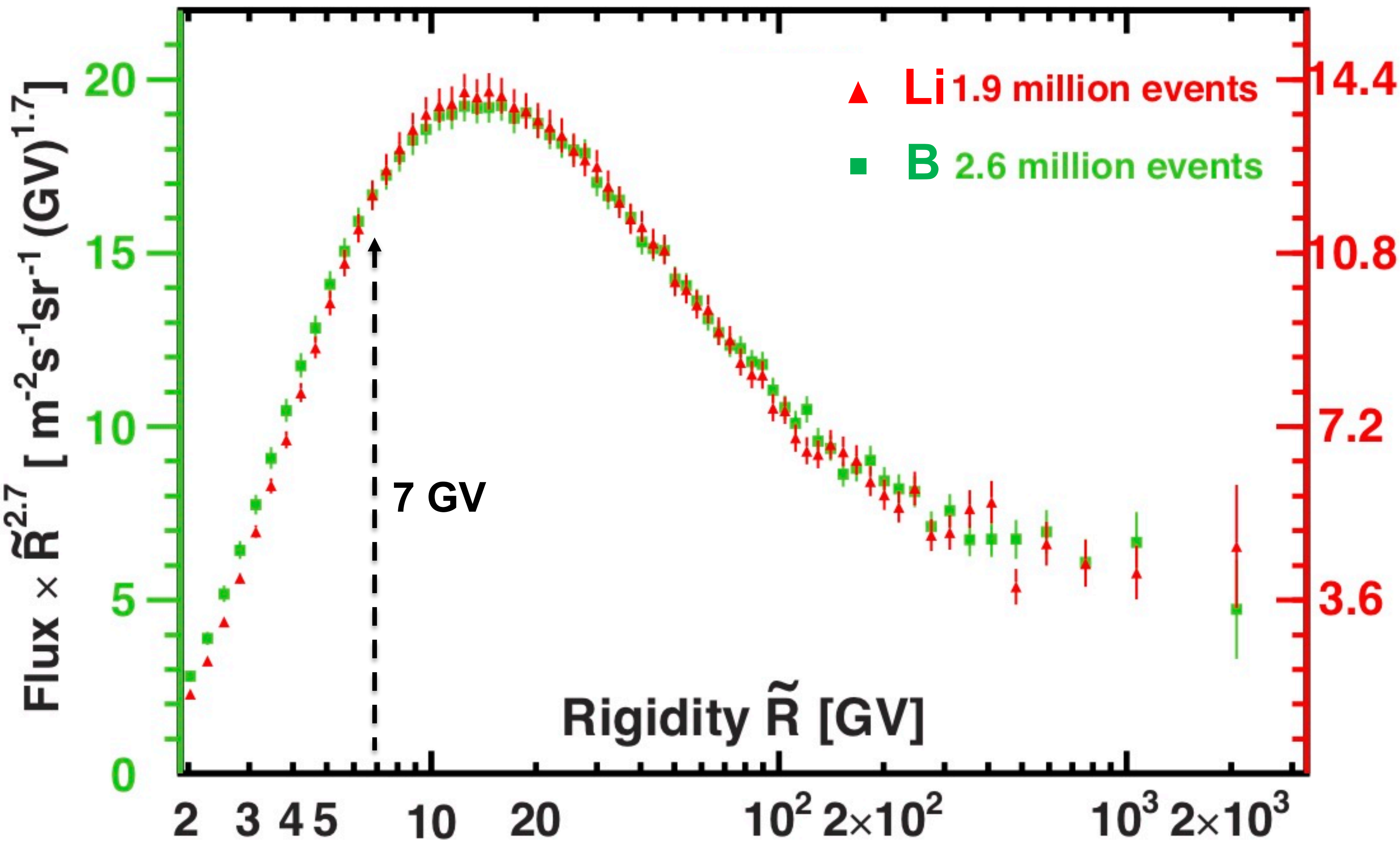
Typically, the error on each flux is larger than 50% at 100 GV





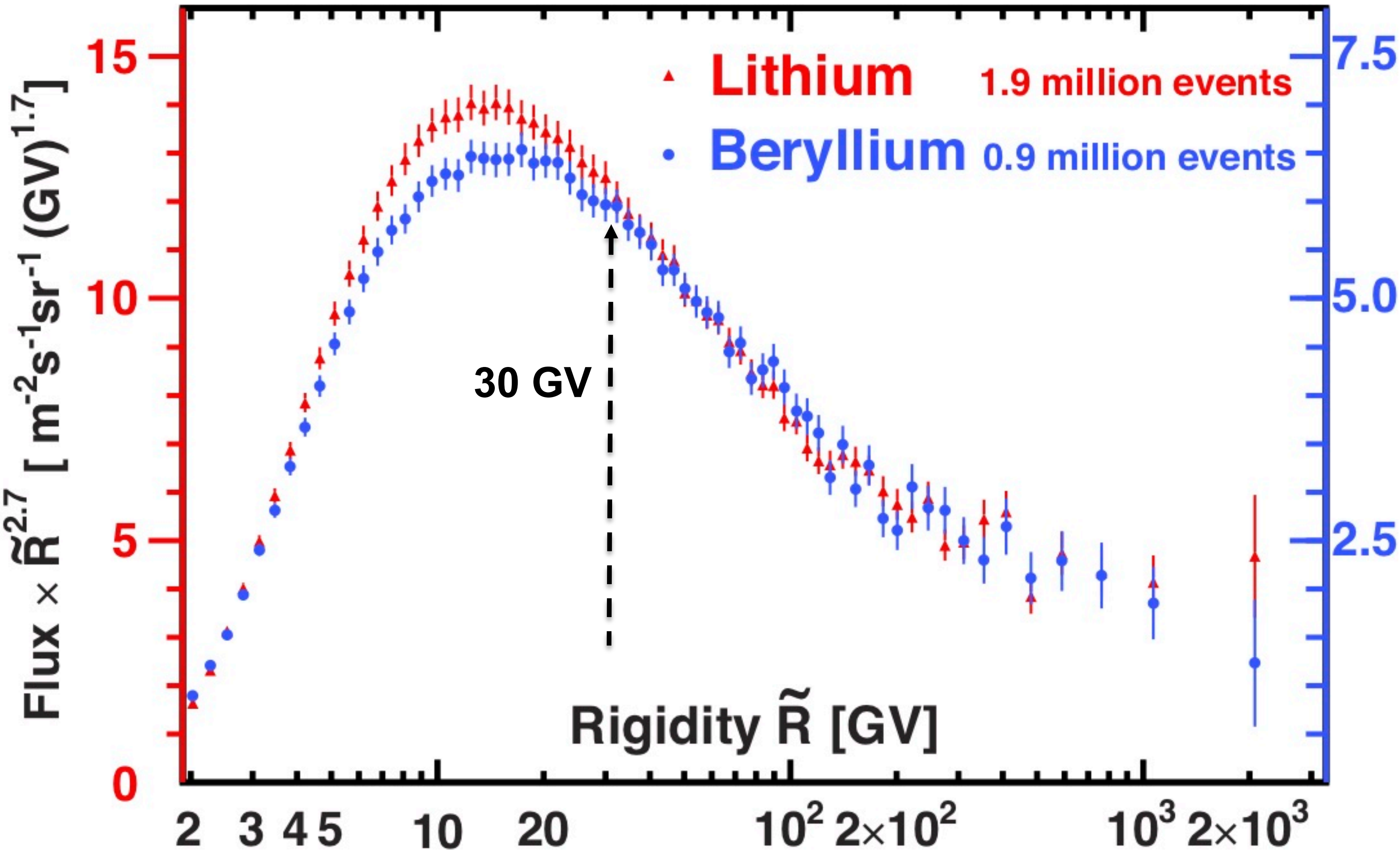
AMS Secondary Cosmic Rays: Lithium and Boron

Above 7 GV Li and B have identical rigidity dependence



AMS Secondary Cosmic Rays: Lithium and Beryllium

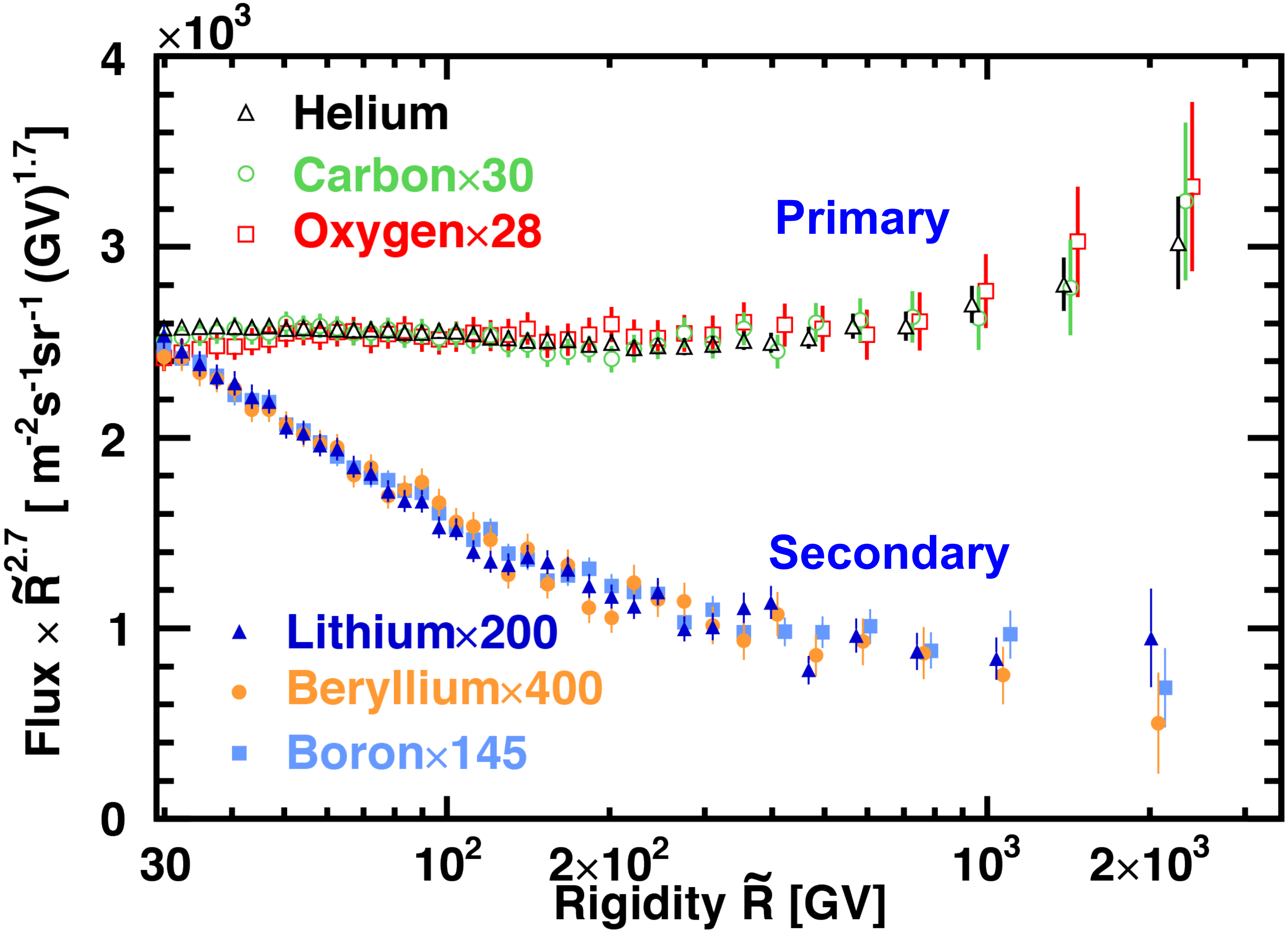
Above 30 GV Li and Be have identical rigidity dependence.
The fluxes are different by a factor of 2.



Rigidity dependence of Primary and Secondary Cosmic Rays

Both deviate from a single power law above 200 GV.

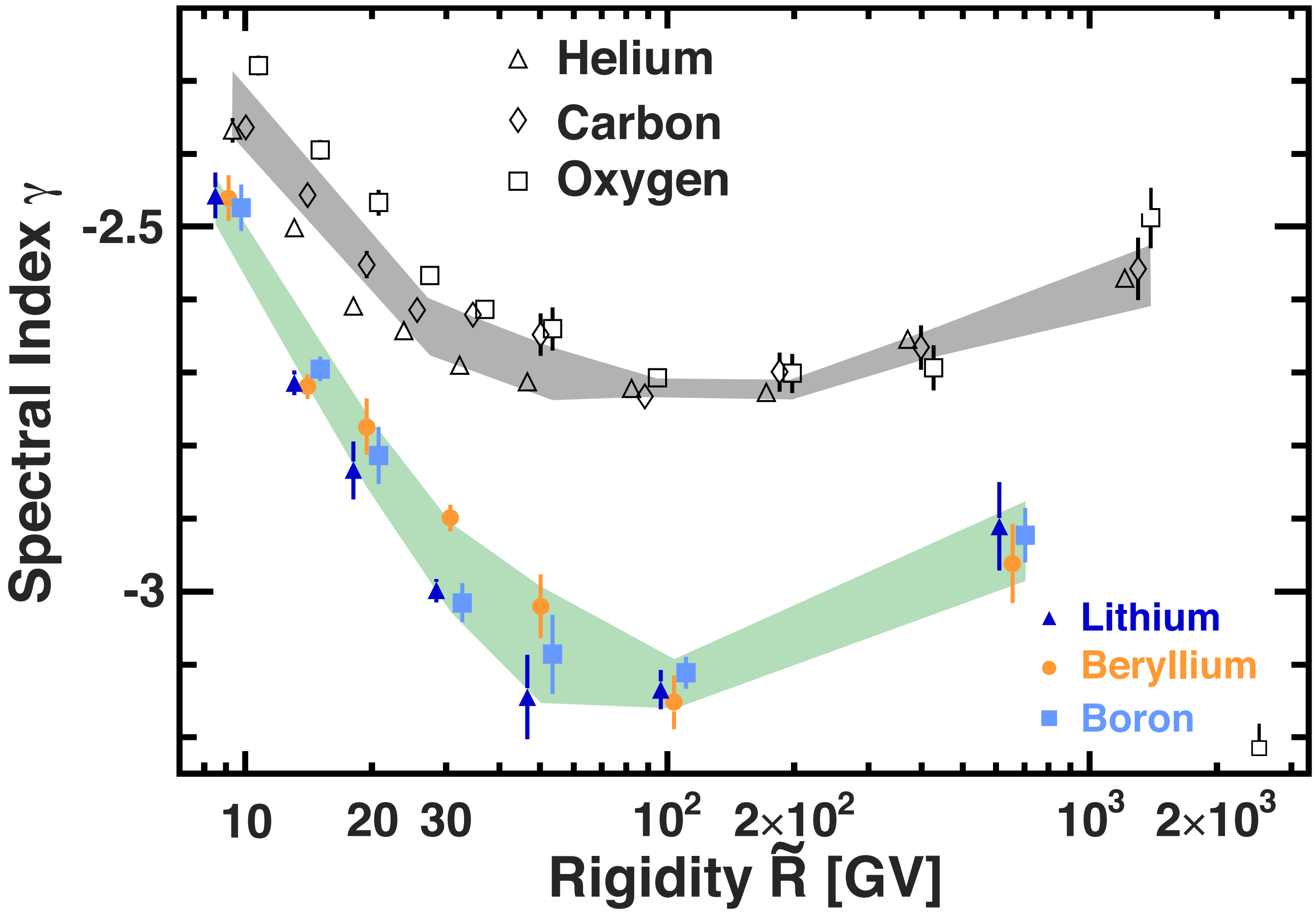
But their rigidity dependences are distinctly different.



Primary and Secondary Cosmic Ray Spectral Indices

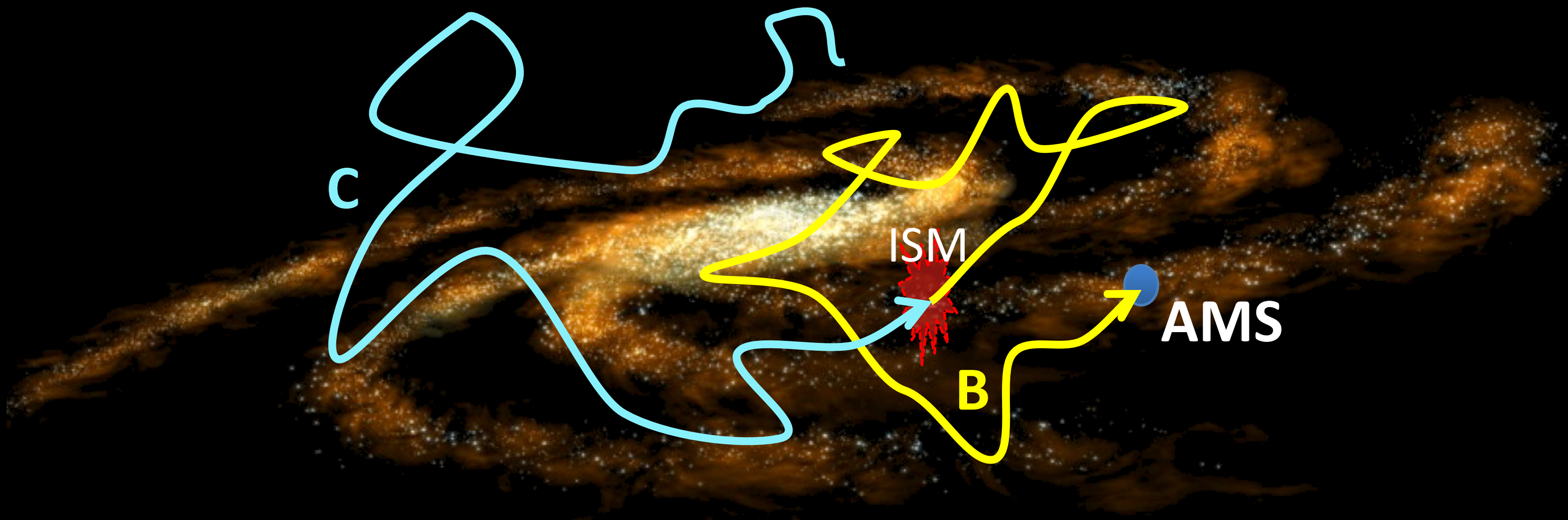
$\gamma = d[\log(\Phi)/d[\log(R)]$ (Φ is the flux; γ is the spectral index)

The secondary cosmic ray spectral indices are nearly identical, but **distinctly different** from the rigidity dependence of the primary cosmic rays.



Above 200 GV, Li, Be, B all harden more than He, C, and O.

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

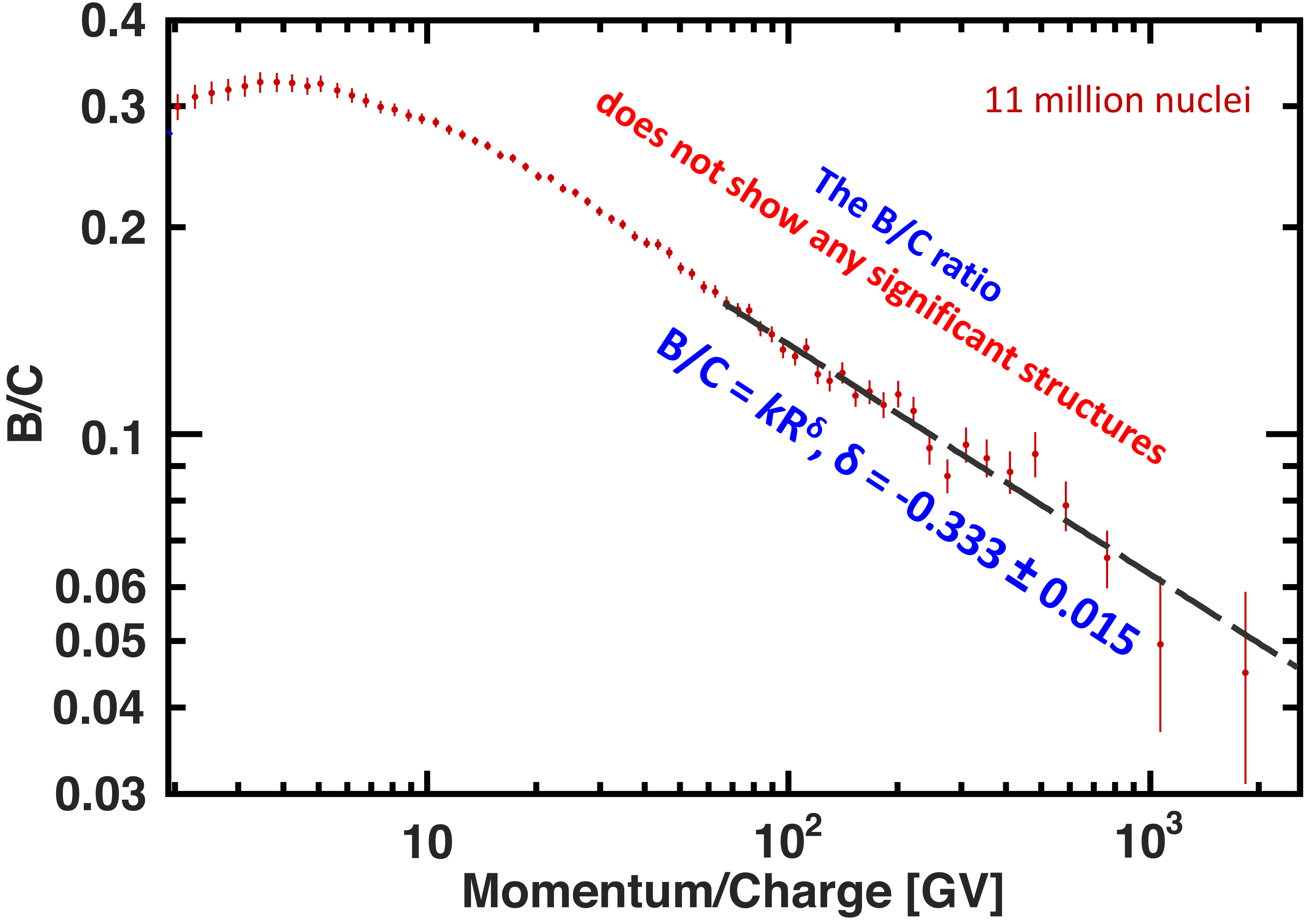


Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

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

With the Kolmogorov turbulence model $\delta = -1/3$

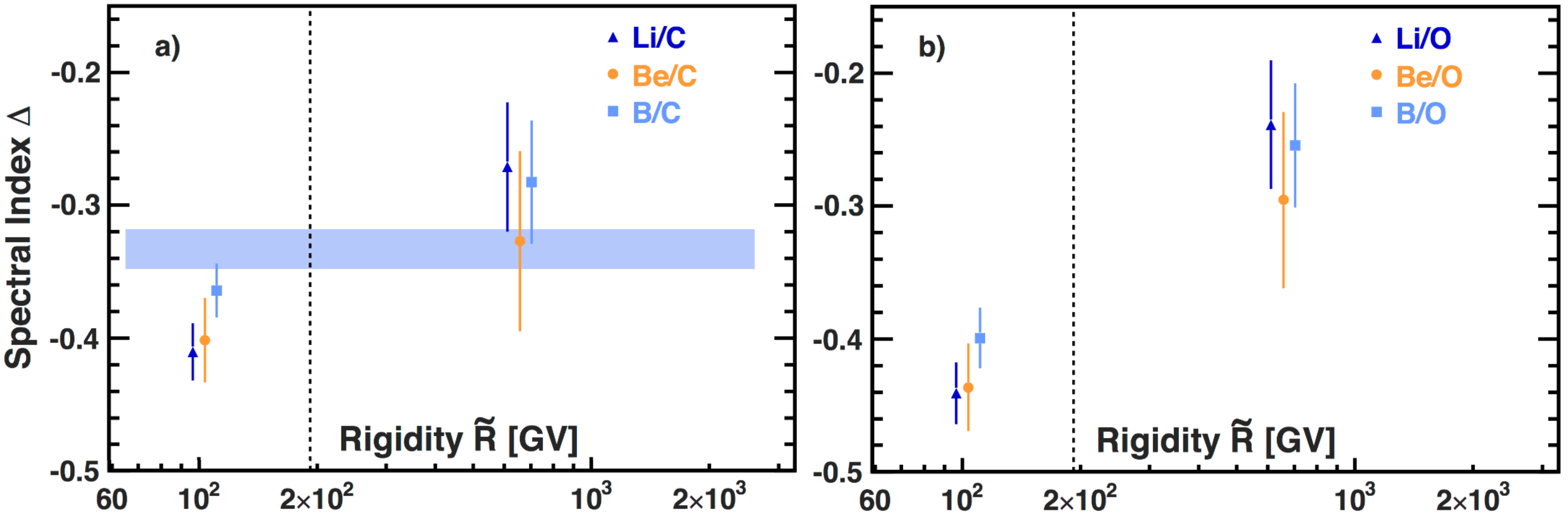
The AMS Boron-to-Carbon (B/C) flux ratio



Earlier AMS publication M. Aguilar *et. al*., Phys. Rev. Lett. 117 (2016) 231102.

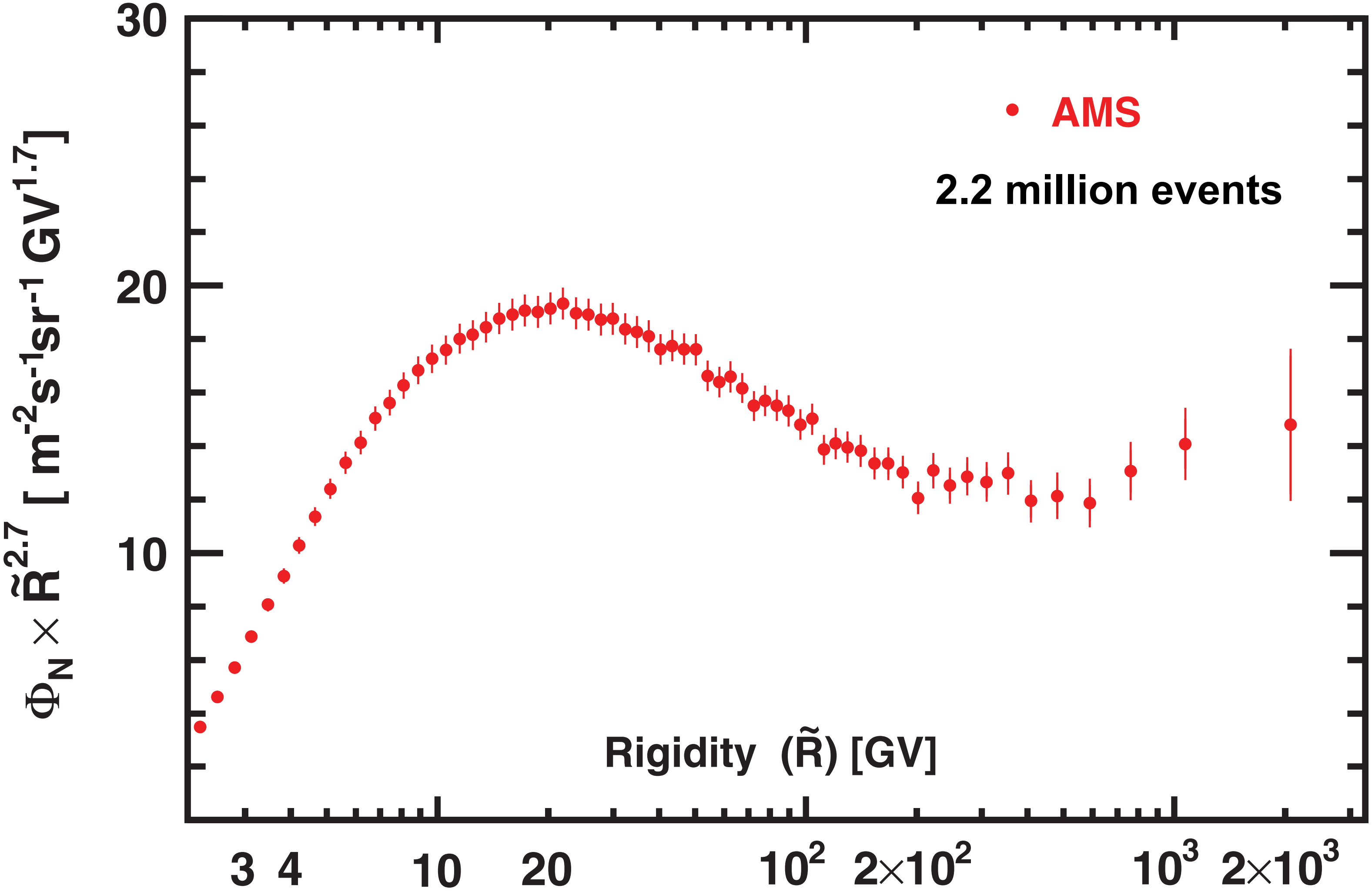
Secondary to Primary Flux Ratio Spectral Indices

$$\Delta = d[\log(\Phi_S/\Phi_P)]/d[\log(R)]$$



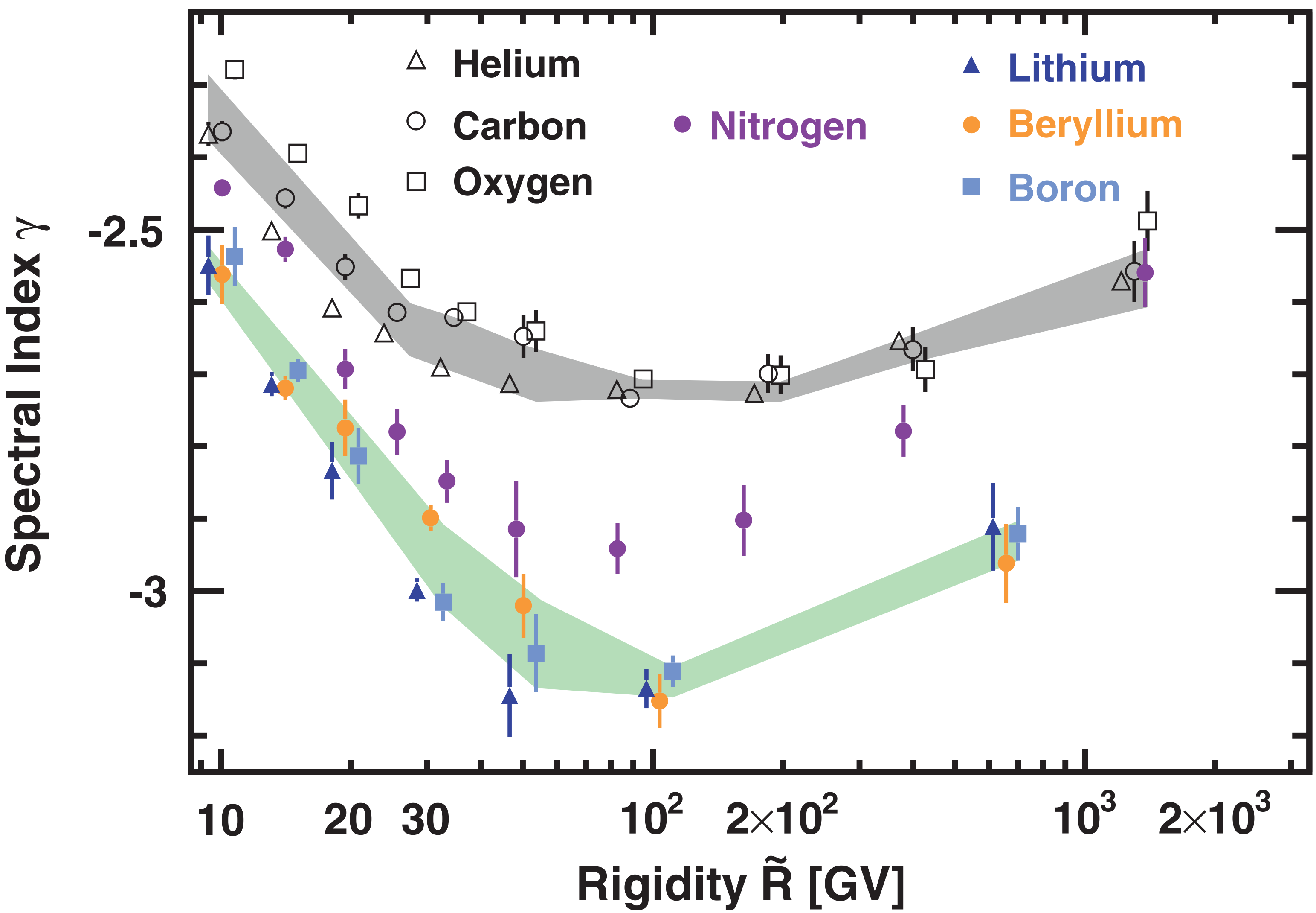
Combining the six ratios, the secondary over primary flux ratio (B/C, …) deviates from single power law above 200 GV by 0.13±0.03

The AMS Result on Nitrogen Flux

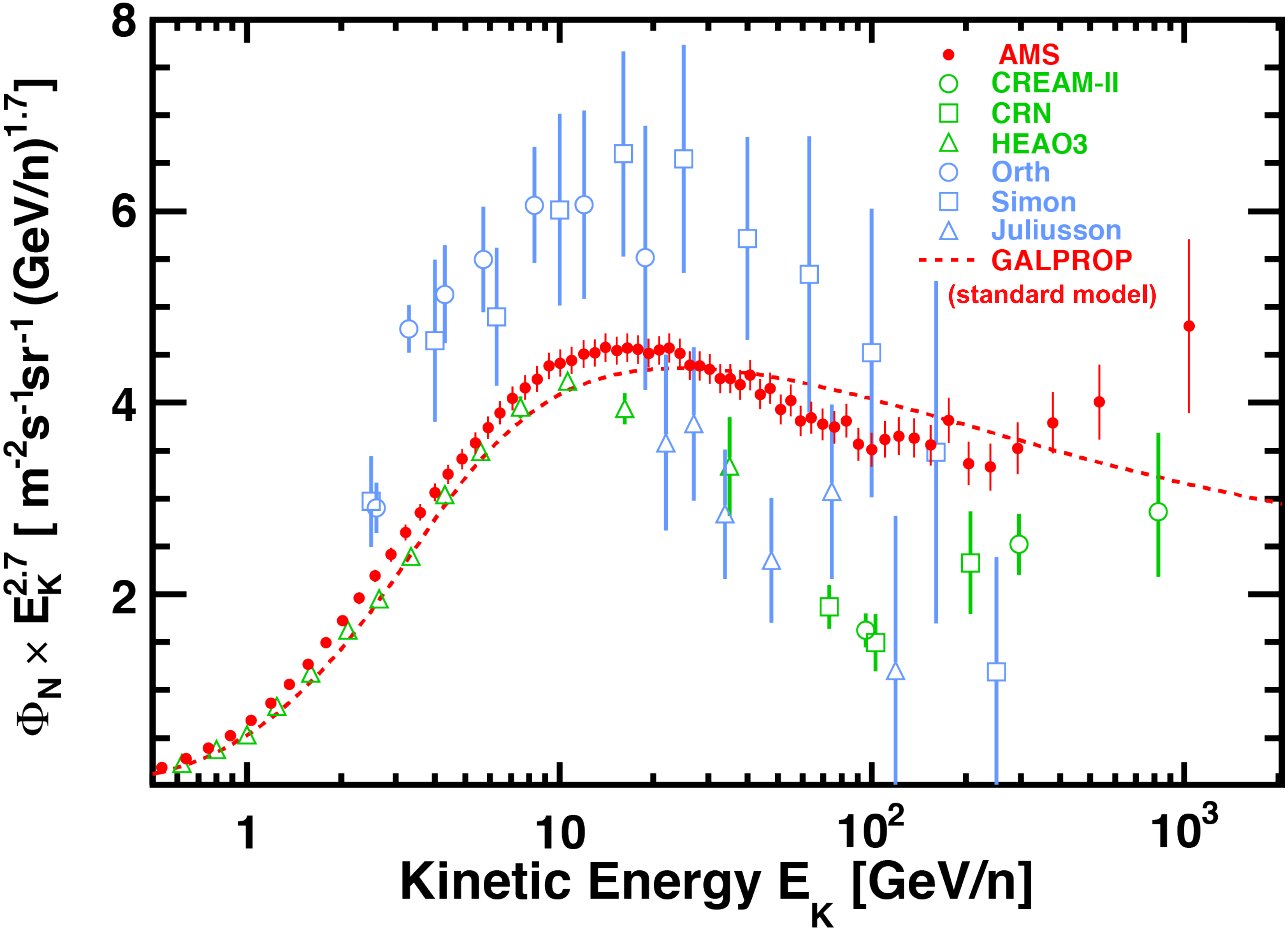


Nitrogen Spectral Indices

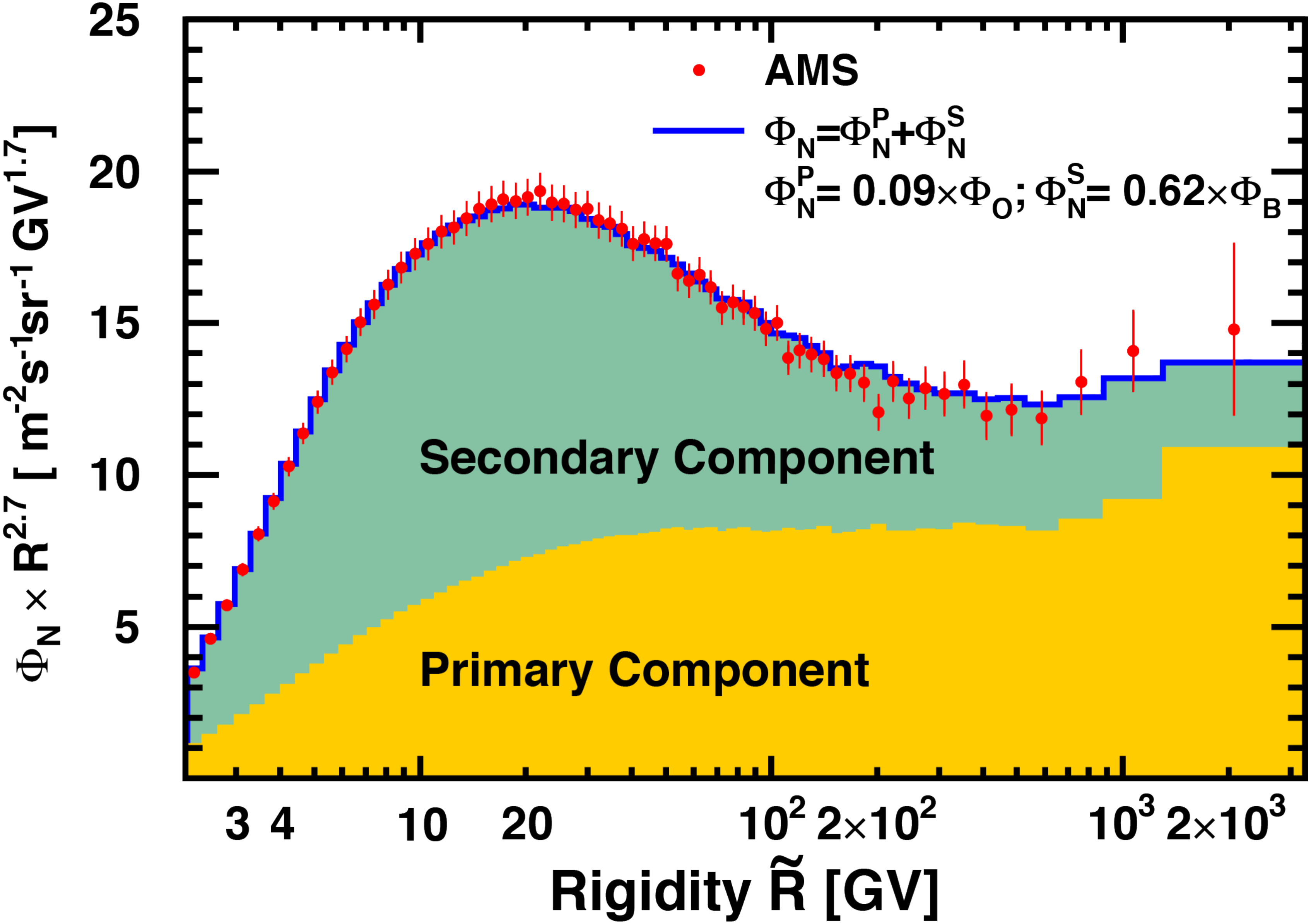
$\gamma = d[\log(\Phi)/d[\log(\mathrm{R})]$ (Φ is the flux; γ is the spectral index)



The AMS nitrogen flux compared with earlier measurements



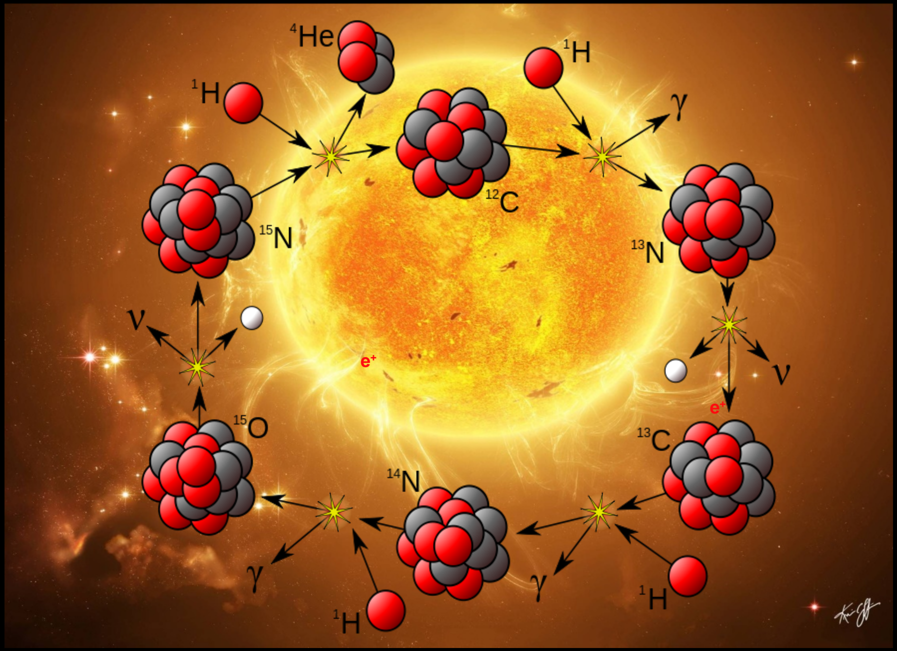
The Nitrogen flux Φ_N is composed of a Primary flux Φ_N^P and a Secondary flux Φ_N^S

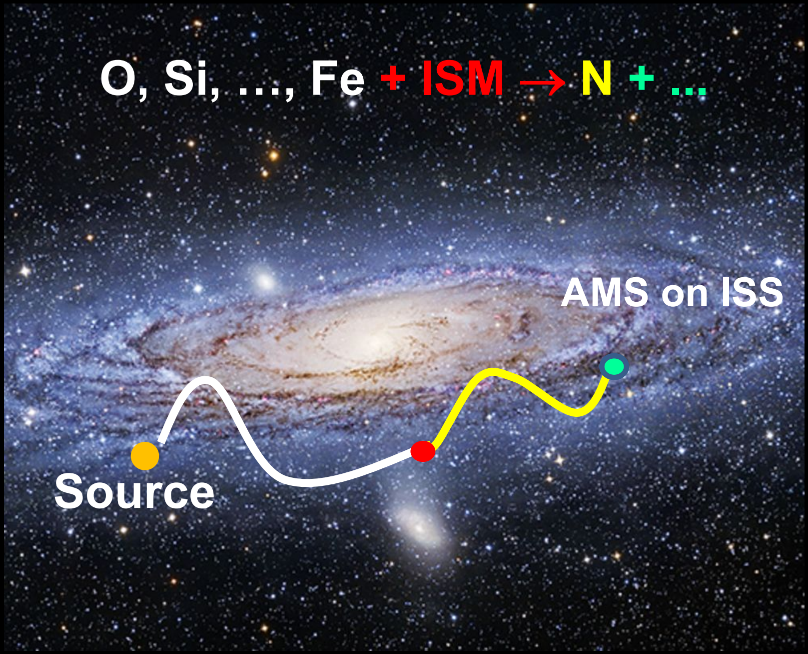


Nitrogen nuclei in cosmic rays: both primary and secondary

Astrophysical sources, mostly via the CNO cycle

Collisions of heavier nuclei with the interstellar medium





In the Solar System:

$N/O \approx 0.14^{+0.05}_{-0.04}$

$C/O \approx 0.46^{+0.09}_{-0.08}$

AMS measurement in the Galaxy

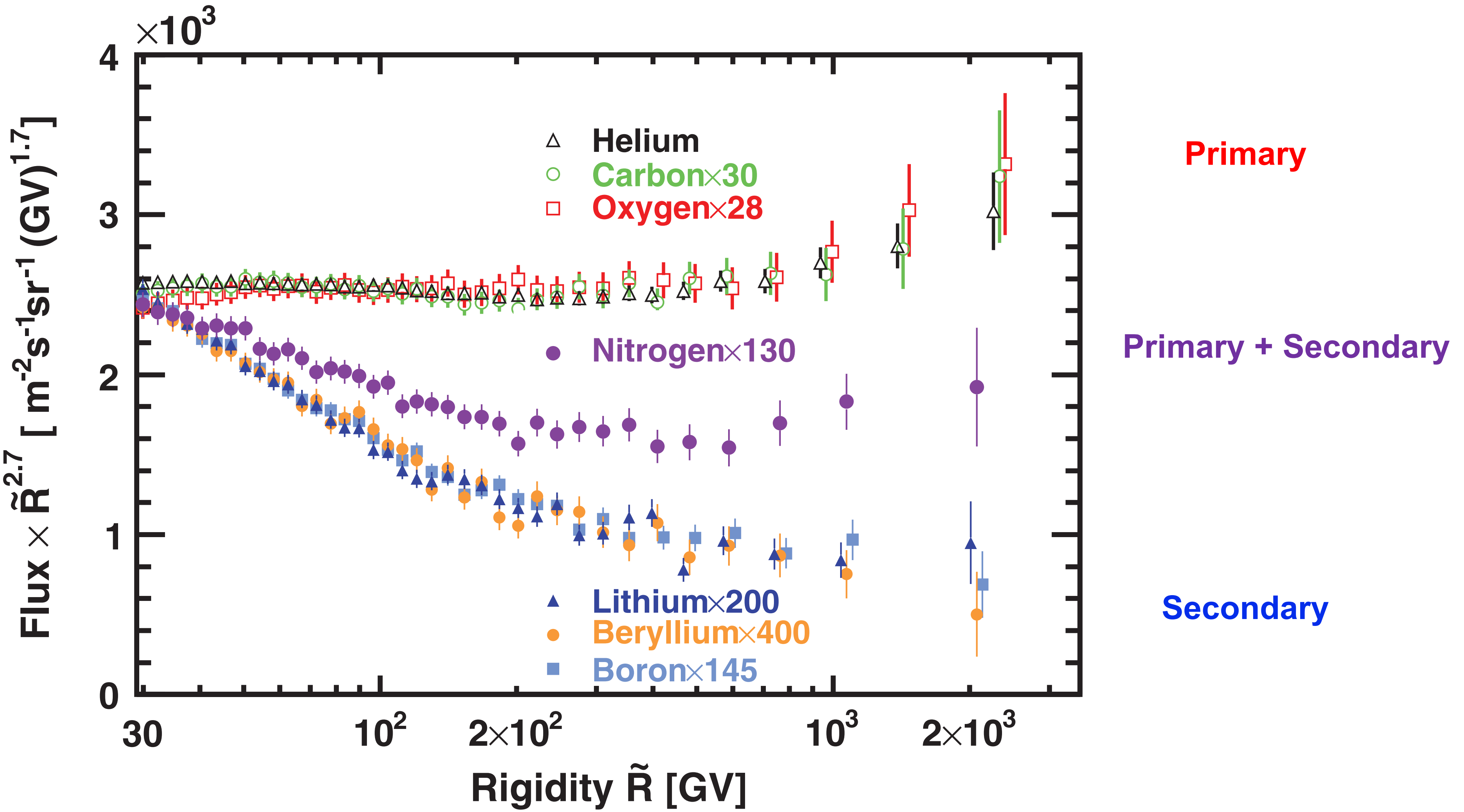
(primary component)

$N/O = 0.090 \pm 0.002$

$C/O = 0.91 \pm 0.02$

Synthesis of Elements in Stars , Lodders, K. , Springer-Verlag Berlin Heidelberg p. 379-417 (2010)

Summary of Flux of Elements



Conclusions and Outlook

- AMS **precision** measurements of cosmic ray nuclei up to **multi-TeV energies** are challenging our understanding of cosmic ray physics.

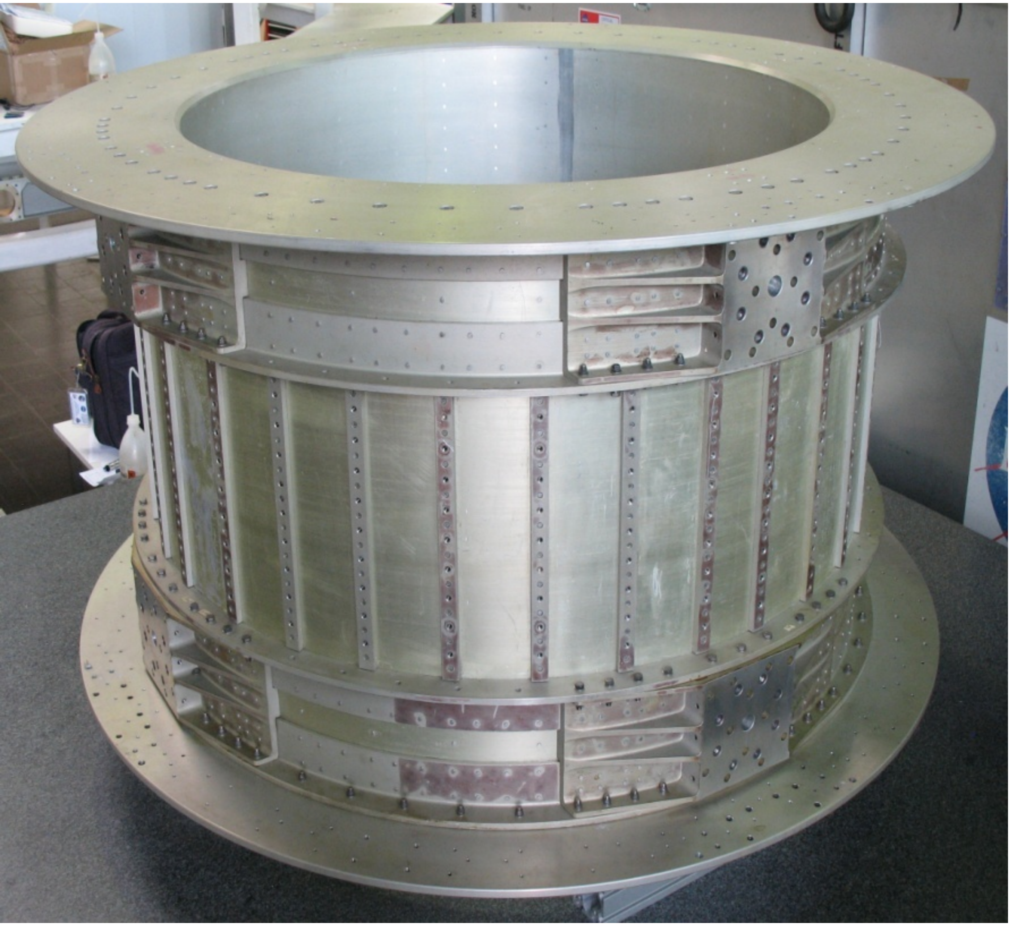
- **Identical rigidity dependences** are observed for both primary cosmic rays (He, C, O) and secondary cosmic rays (Li, Be, B). But they are distinctly different from each other.

- The AMS results on cosmic-ray fluxes Z<=8 do not follow the traditional single power law. **They all have a break at ~200 GV.**

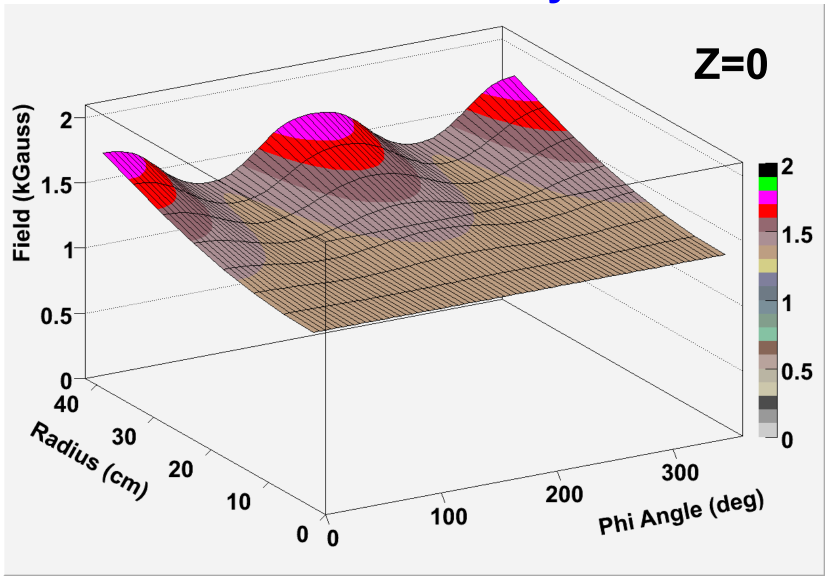
- AMS will **continue taking data** for the lifetime of the International Space Station (beyond 2024). Measurements of heavier species, Z>8, will enable us to explore a new region in cosmic rays.

Back up

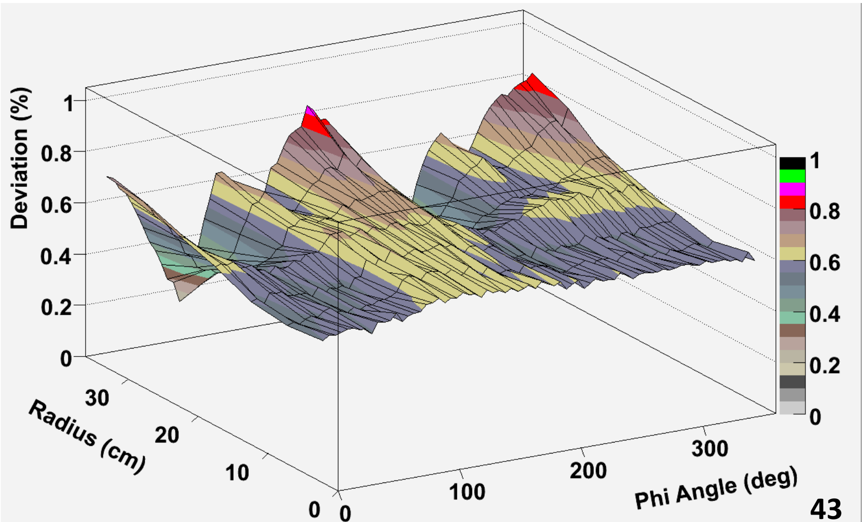
The Magnet



The detailed 3D field map (120k locations) was measured in May 2010

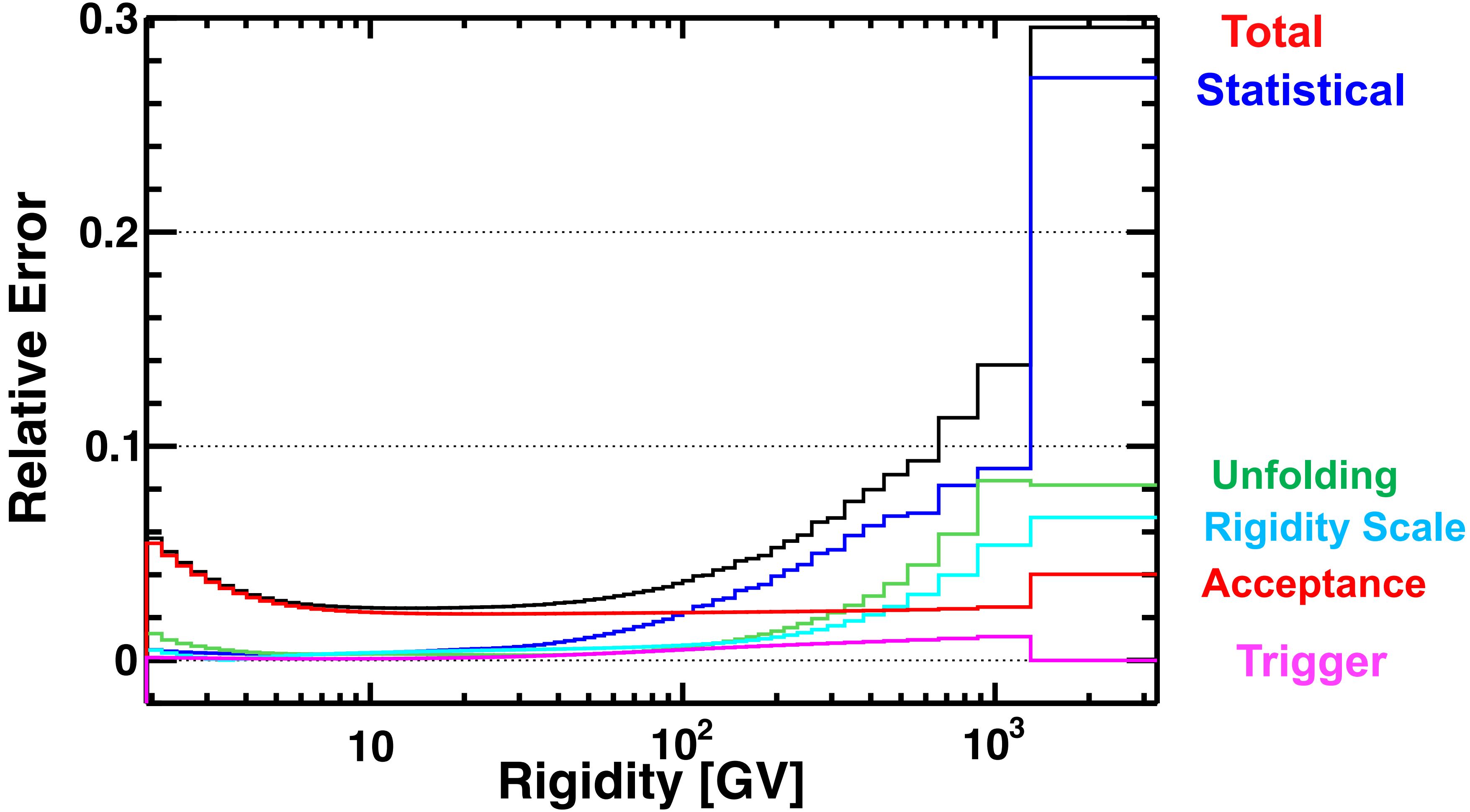


Deviation from 1997 measurement



In 12 years the field has remained the same to <1%

Flux Errors Breakdown (Boron)



The systematic errors include the uncertainties in the background estimations, the trigger efficiency, the geomagnetic cutoff factor, the acceptance calculation, the rigidity resolution function, and the absolute rigidity scale.

Carbon Flux Errors Breakdown