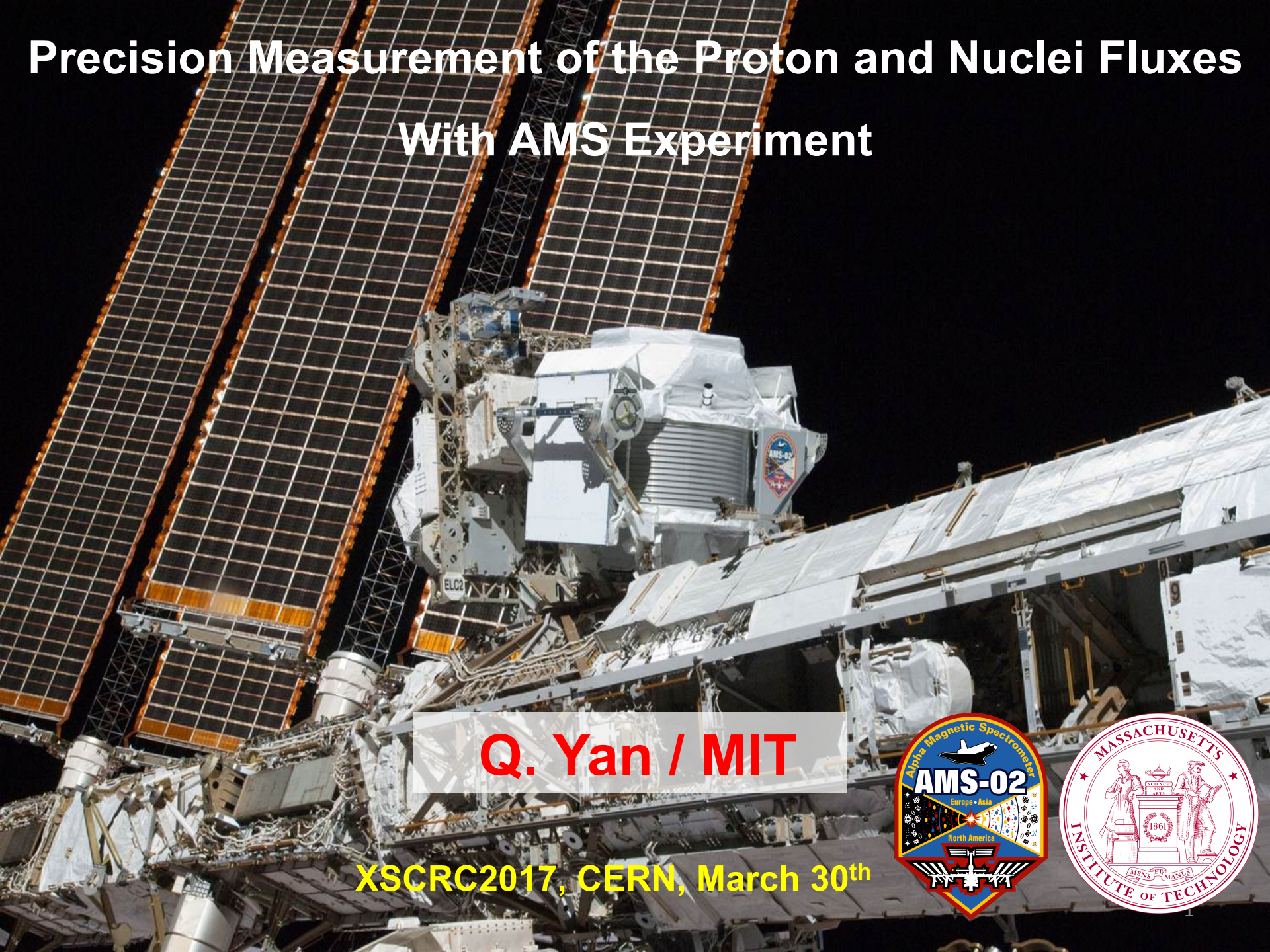
Precision Measurement of the Proton and Nuclei Fluxes With AMS Experiment



Q. Yan / MIT

XSCRC2017, CERN, March 30th

Cosmic Rays Nuclei Measurements

One of the fundamental measurements in cosmic rays is the determination of the rigidity dependence of spectra of cosmic ray primary nuclei H, He, C, O, Ne, Mg, Si and Fe. These are thought to be produced and accelerated in the supernova remnants in our Galaxy. Their spectra carry the information about their acceleration and propagation.

Another class of nuclei (^{3}He, Li, Be, B, F …) is produced by nuclear interactions of the primary nuclei during their propagation in the Galaxy.The spectra and relative abundances of these nuclei reveal the propagation parameters, like amount of matter traversed by cosmic rays and the time it took.

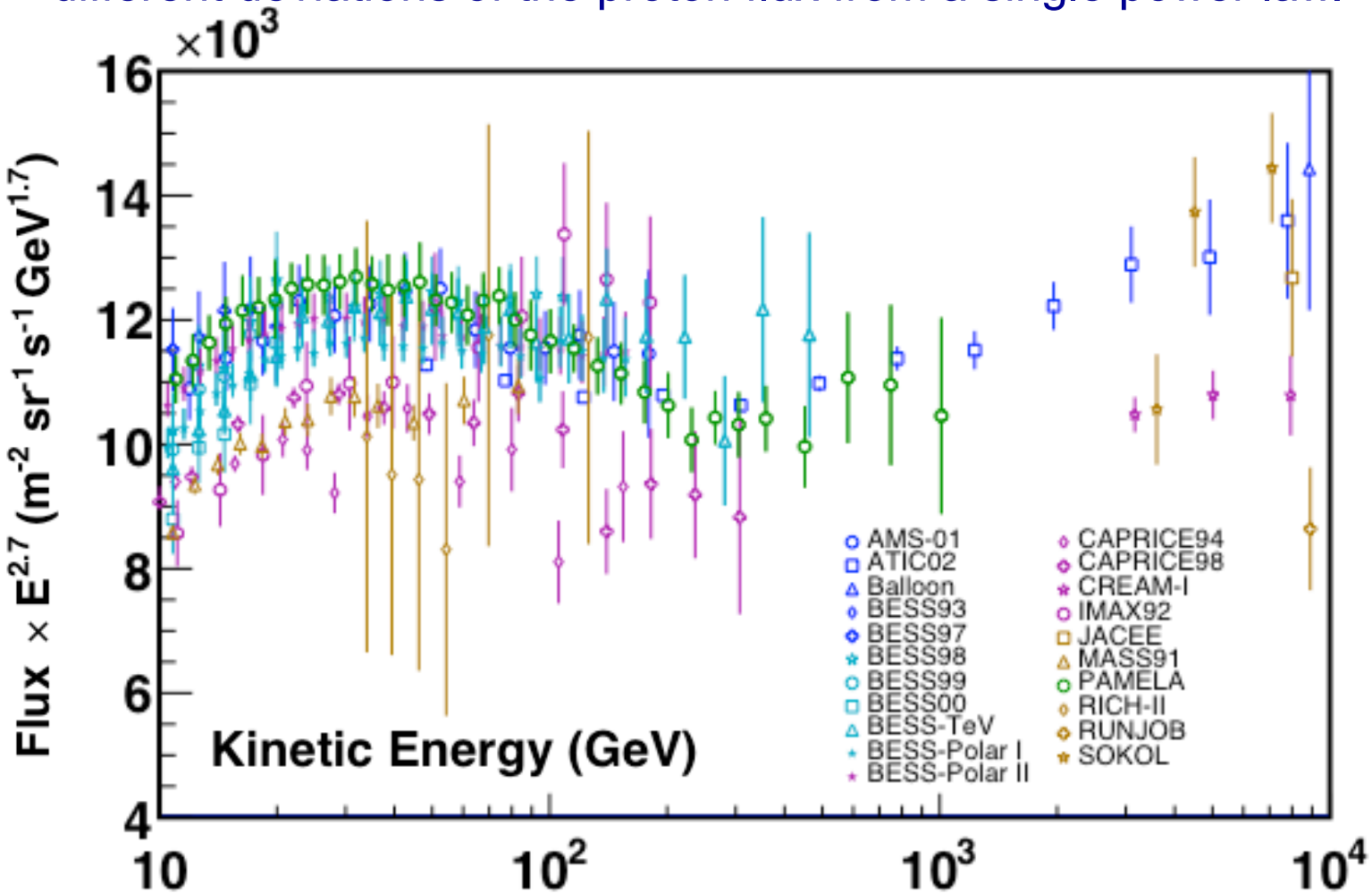
Proton Flux

Protons are the most abundant charged particles in cosmic rays. Knowledge of the precise behavior of the proton spectrum is important in understanding the origin, acceleration, and propagation of cosmic rays.

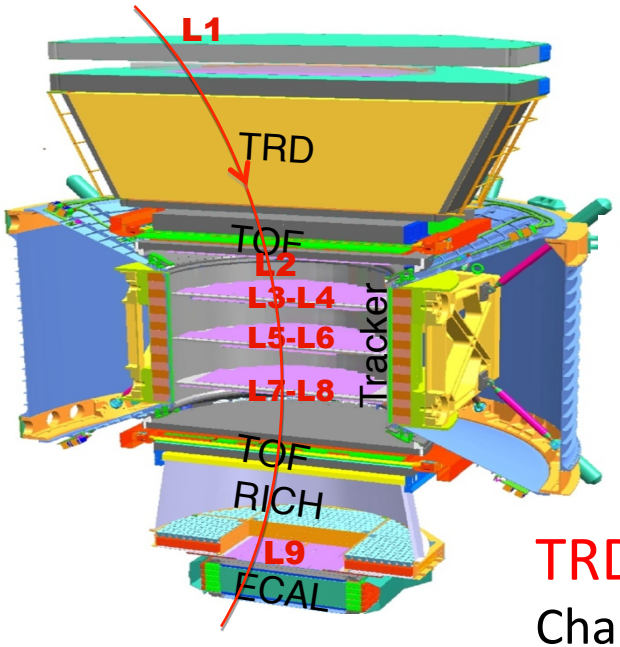
AMS made the precise measurement of the proton flux in primary cosmic rays in the rigidity range from 1 GV to 1.8 TV based on 300 million events.

Measurements of the proton flux before AMS

Previous measurements of the proton flux in cosmic rays have reported different variations of the flux with energy. In particular, experiments showed different deviations of the proton flux from a single power law.



AMS Cosmic Ray Proton Flux Measurement



Tracker (9 Layers) + Magnet

Rigidity and Charge Magnitude

Bending Coordinate Resolution ≈ 10 μm

MDR ≈ 2 TV

ToF (4 Layers)

Velocity and Direction

$\Delta\beta/\beta^2 \approx 4\%$

TRD, Tracker, RICH ,TOF, ECAL

Charge Along Particle Trajectory $\Delta Z \approx 0.05\text{-}0.2$

Residual Background (He, e^+) 0.5% @ 1GV and <0.1% above 10 GV

Flux Measurement

Assuming flux above geomagnetic cutoff is isotropic the differential rigidity flux can be defined as

$$\Phi_i(R) = \frac{N_i}{T_i\, A_i\, \varepsilon_i\, \Delta R_i}$$

Events Corrected for Bin to Bin Migration due to Tracker Rigidity Resolution

Bin width

Time ~63,000,000 sec
R>30 GV

i=1,72
Rigidity 1-1800 GV

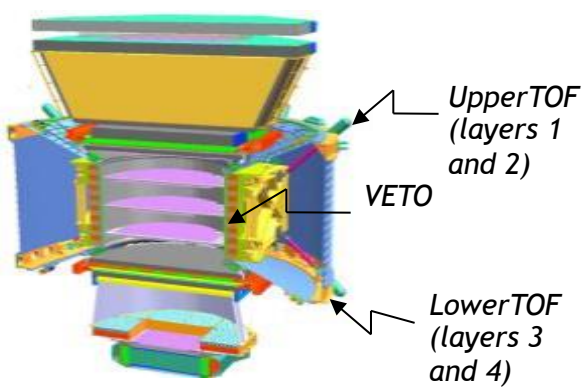
Trigger Efficiency from Data

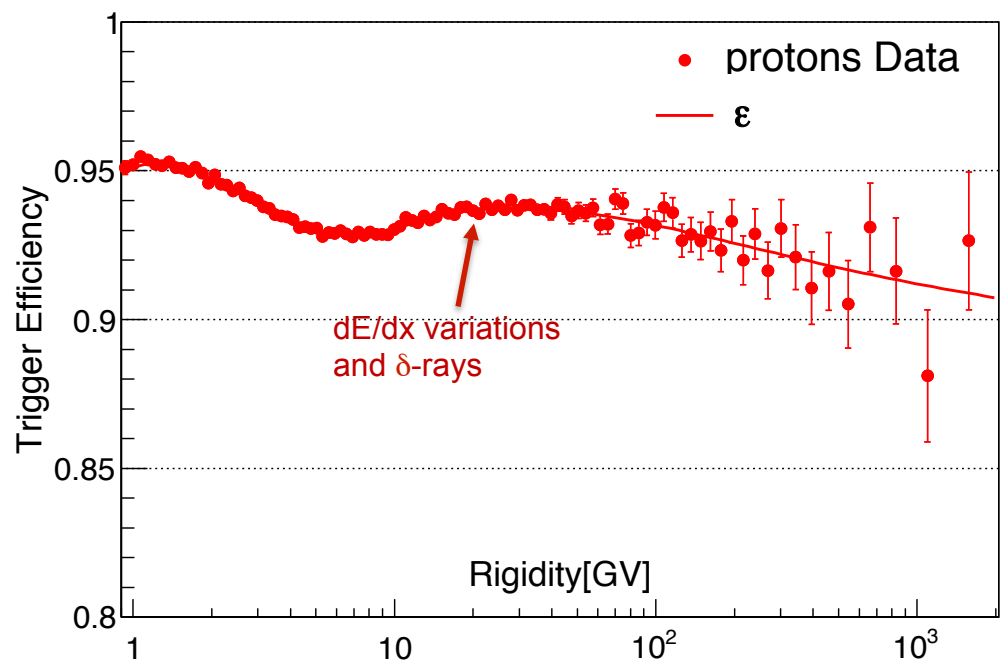
Effective Acceptance from MC, Verified with Data

Flux statistical errors are very small (0.1-0.7%), so the final accuracy is defined by systematic errors on trigger efficiency, acceptance, migration and rigidity scale.

(i) Systematic errors on trigger efficiency

Trigger efficiency [4/4 TOF + VETO , 90-95%] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger. The error is dominated by the statistics available from the unbiased trigger.

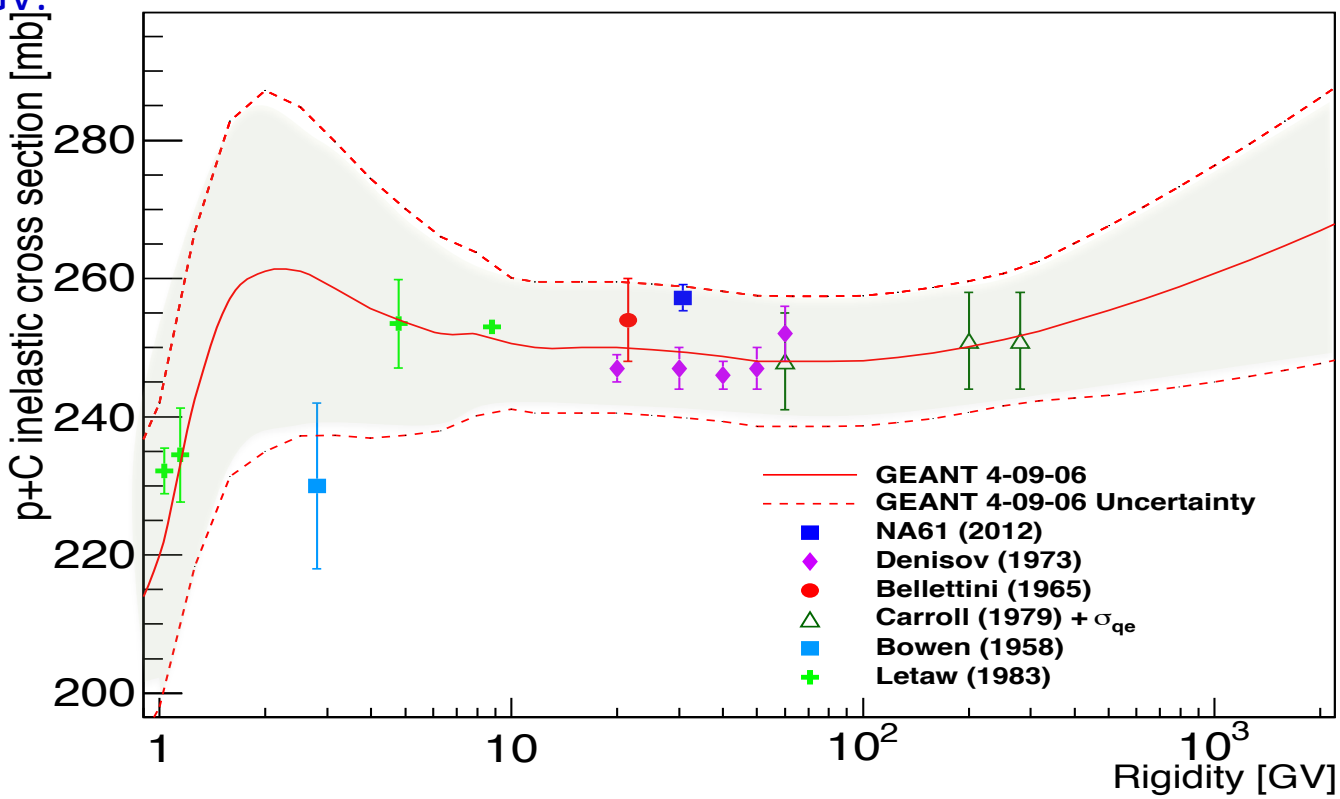




This systematic error is negligible below 100GV and reaches 1.5% at 1.8TV.

(ii) Systematic errors on acceptance due to interactions

The detector components traversed by the particles (TRD, TOF, Tracker, RICH) are mostly made of C and Al. The inelastic cross sections of *p* + C and *p* + Al are measured to few percent between 1 and 300 GV.

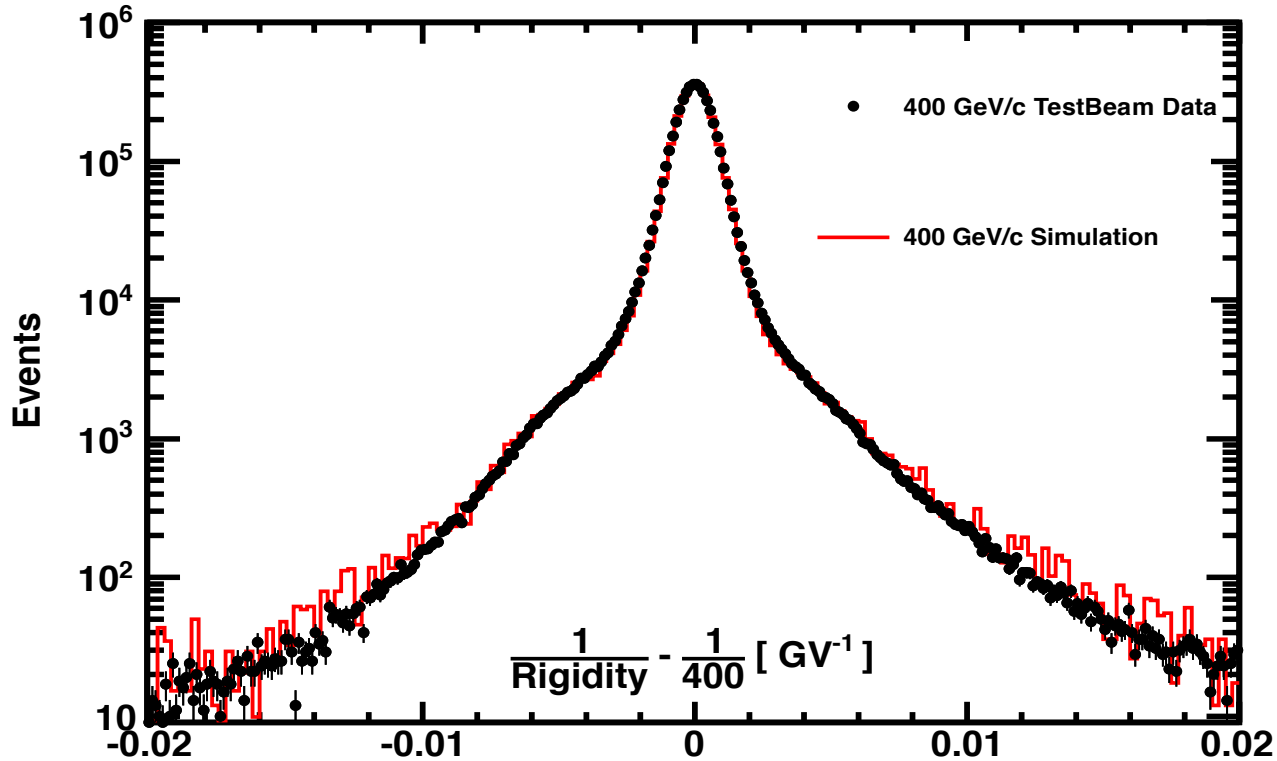


Using MC samples with cross sections varied by ±10%, we found that the errors on the flux due to uncertainty in inelastic cross sections are

1% [1GV] 0.6% [10-300GV] 0.8% [1.8 TV]

(iii) Systematic errors on the rigidity resolution function

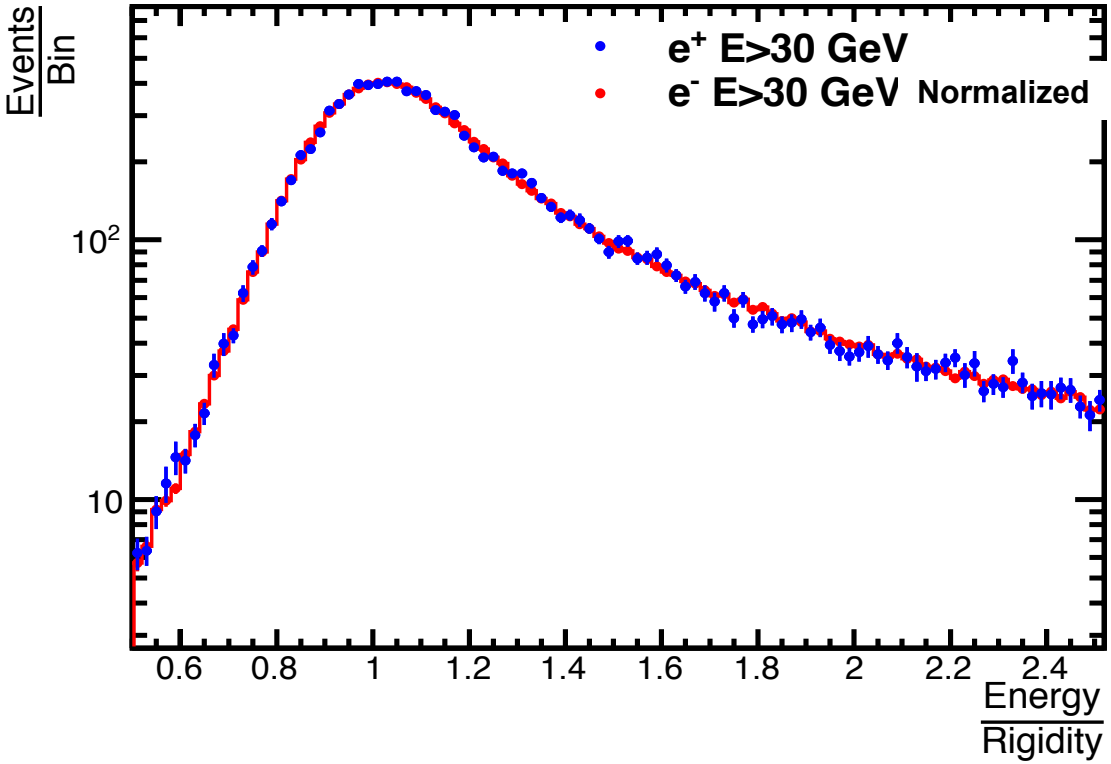
The rigidity resolution function was measured with 400 GeV proton beam and verified with the ISS data. The unfolding errors were obtained by varying the width of the Gaussian core of the resolution function by 5% [due to uncertainty of 1μm of L1,9 alignment] and amplitudes of the non-Gaussian tails by 20% [due to uncertainty in large angle p-Nuclei scattering] and found : 1% below 200GV and 3% at 1.8TV.



The resolution function for 400 GeV/*c* protons measured in test beam compared with simulation

(iv) Systematic errors on the absolute rigidity scale

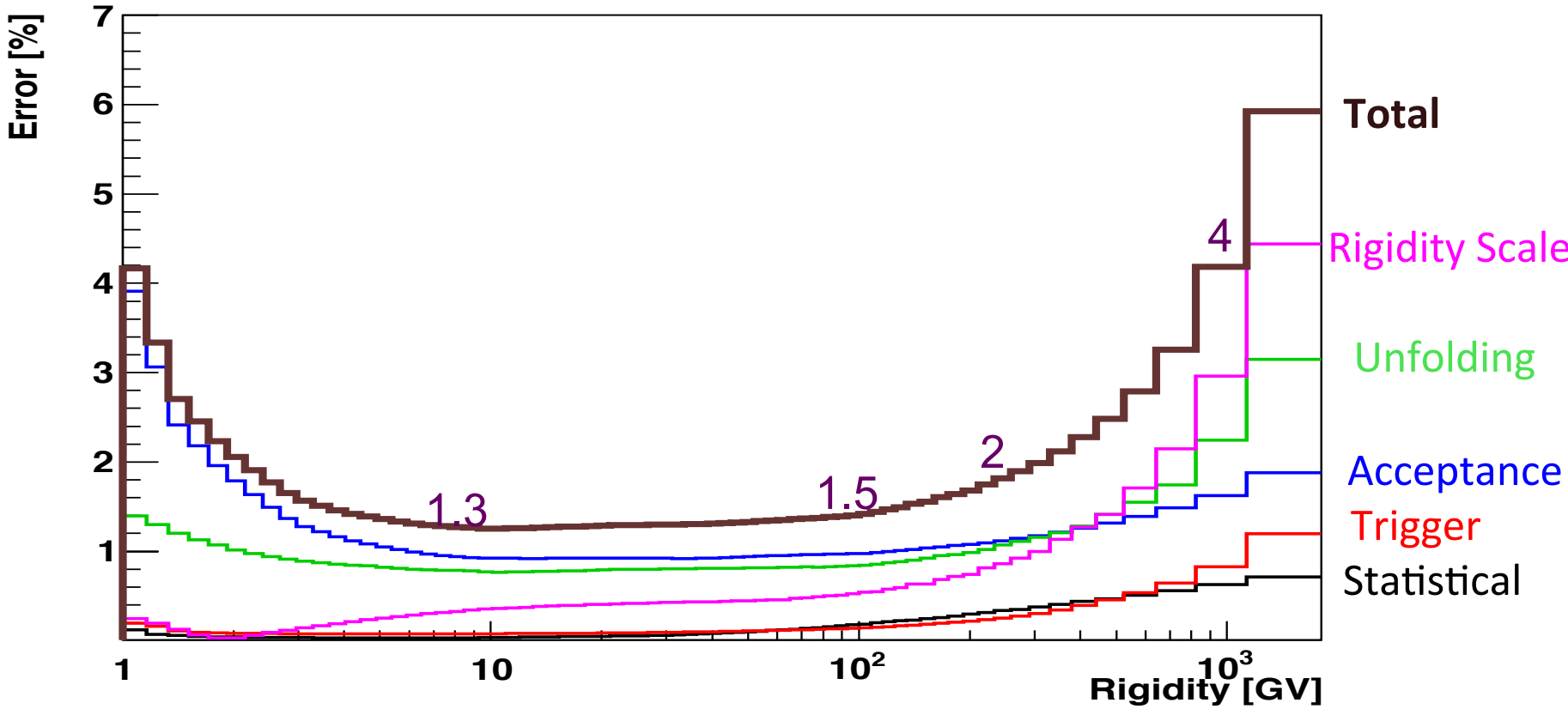
a) Residual tracker misalignment, i.e. how the measured average inverse rigidity of straight tracks ($1/\Delta$) differs from zero. This was measured by comparing the *Energy*[E, Measured by ECAL]/*Rigidity*[R, Measured by Tracker] ratio for electron and positron events and was found to be less than 1/(26TV), limited mostly by the high energy positron statistics. The corresponding flux error is 5% @1.8 TV.



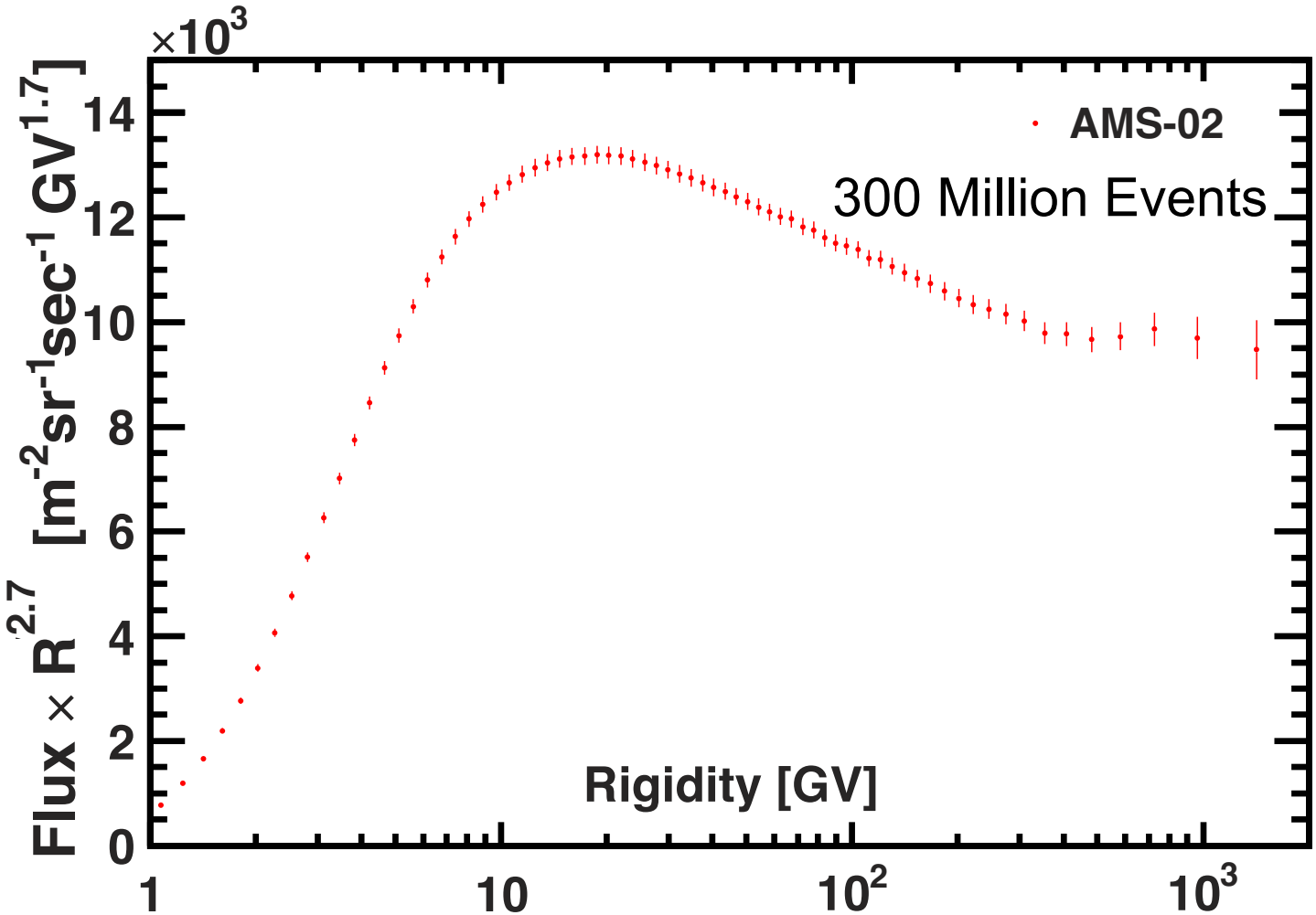
$$\frac{1}{\Delta} = \frac{\overline{(E/R)}_{e^+} - \overline{(E/R)}_{e^-}}{\overline{E}_{e^+} + \overline{E}_{e^-}}$$

$1/\Delta \sim 0 \quad \sigma(1/\Delta) = 1/26\ \mathrm{TV}^{-1}$

Proton Flux Errors Breakdown



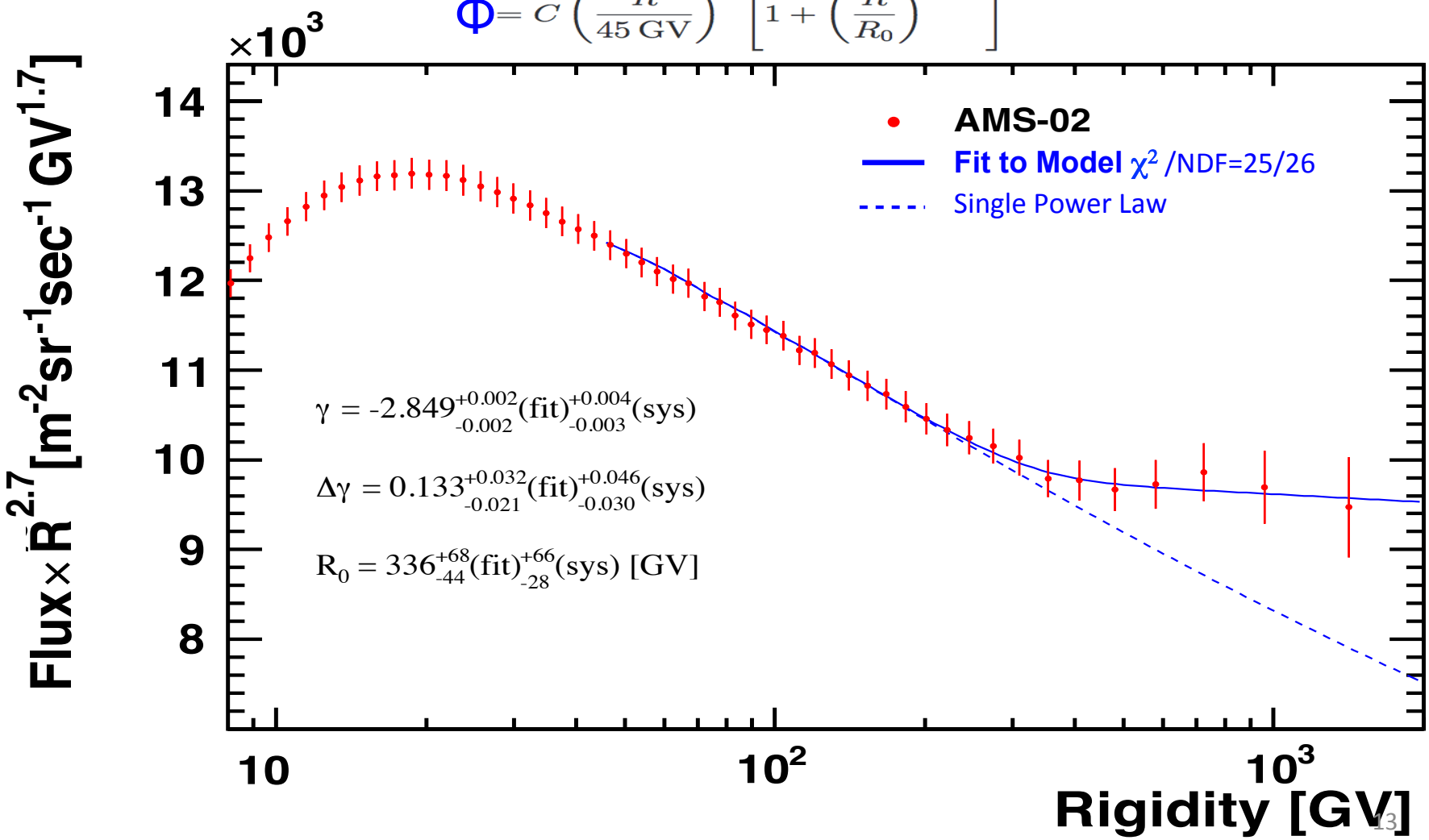
Proton Flux


×10^3
Flux × R^2.7 [m^-2sr^-1sec^-1 GV^1.7]
14
12
10
8
6
4
2
0
AMS-02
300 Million Events
Rigidity [GV]
1
10
10^2
10^3

Fitting Proton Flux with the Double Power Law Model

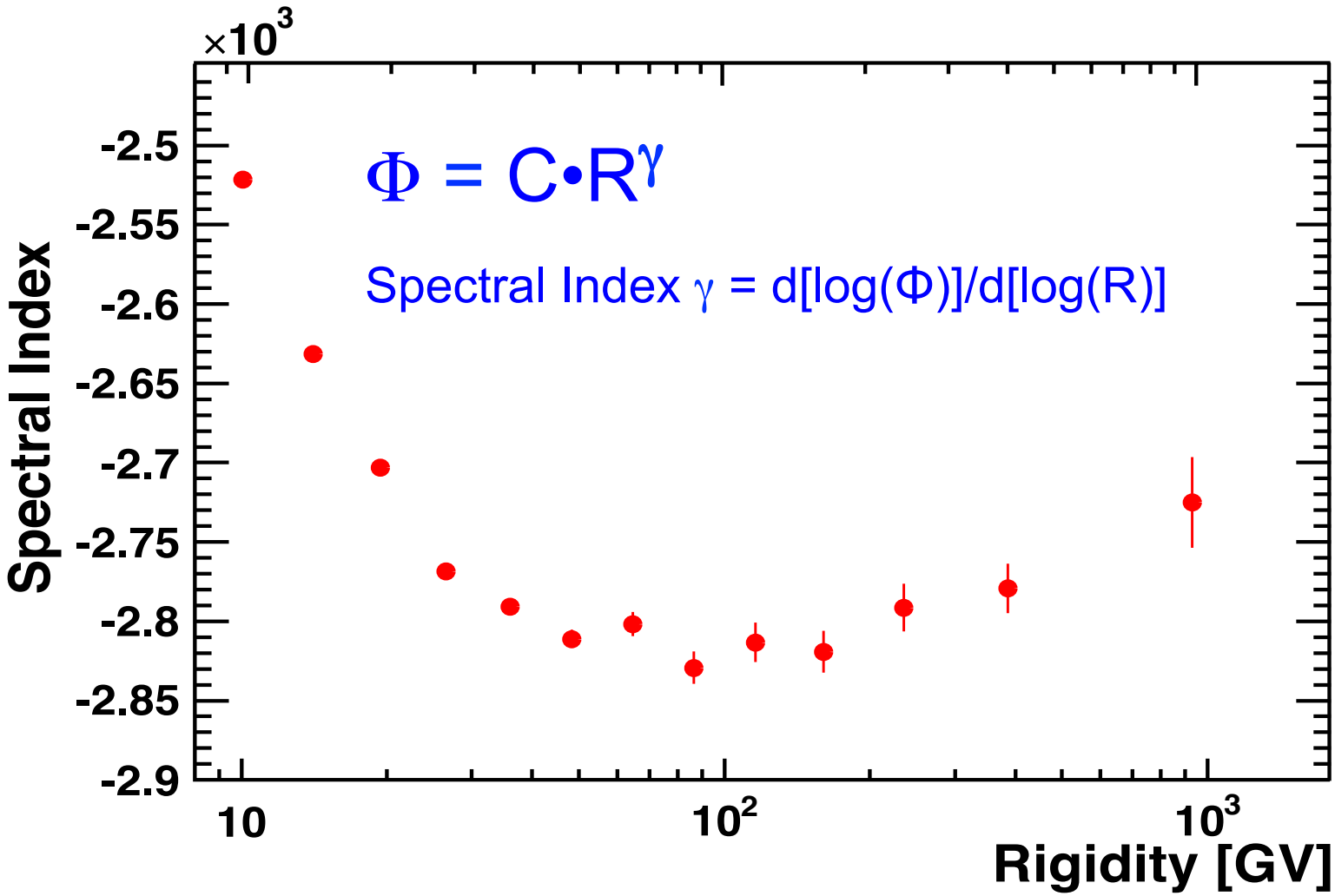
R^{γ} below R_0, $R^{\gamma+\Delta\gamma}$ above R_0 (transition rigidity) and transition smoothness s

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

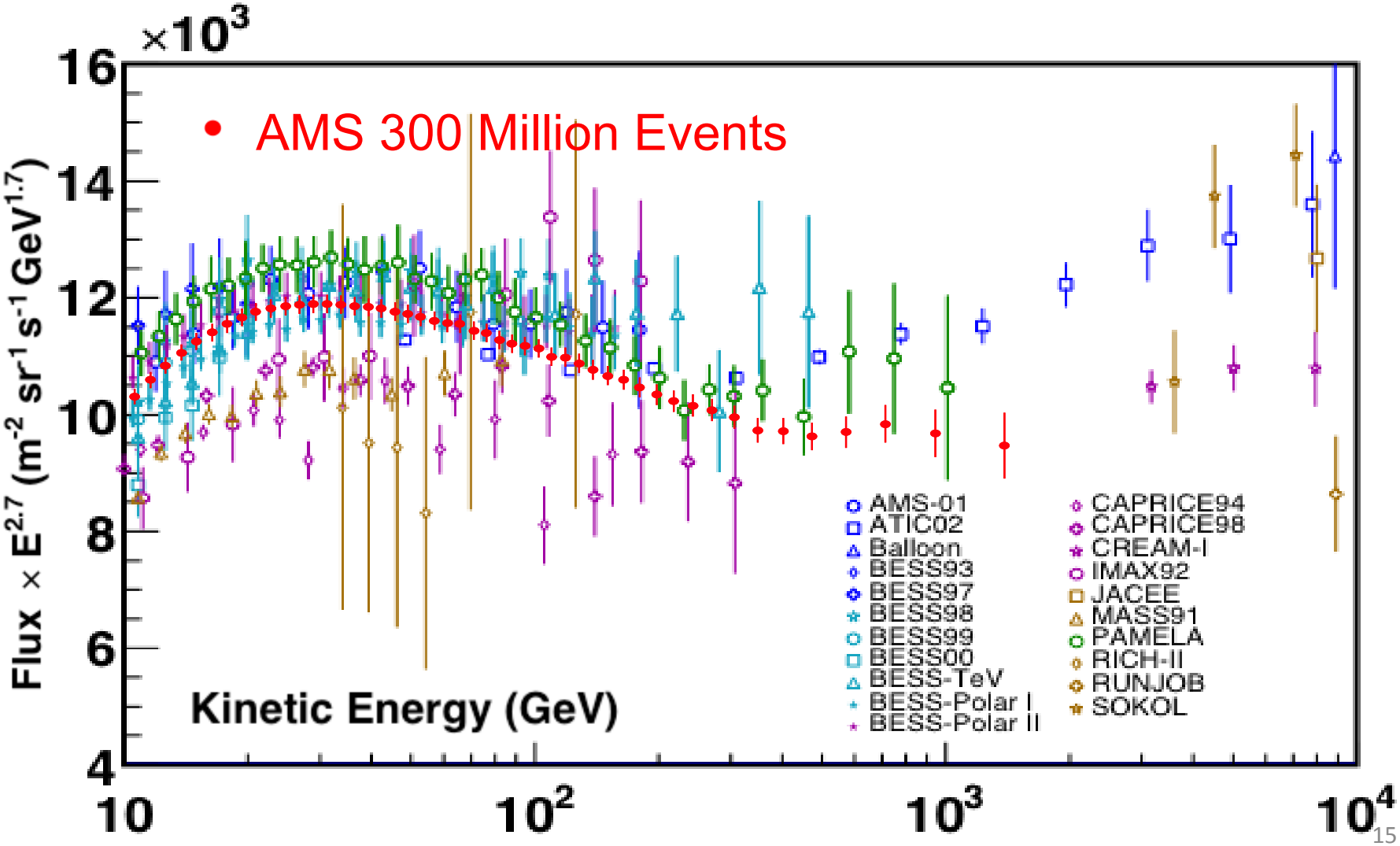


Spectral Index Rigidity Dependence

The spectral index varies with rigidity. In particular, the spectral index is progressively hardening with rigidity above ~100 GV.



Proton Flux Comparison with Earlier Measurements



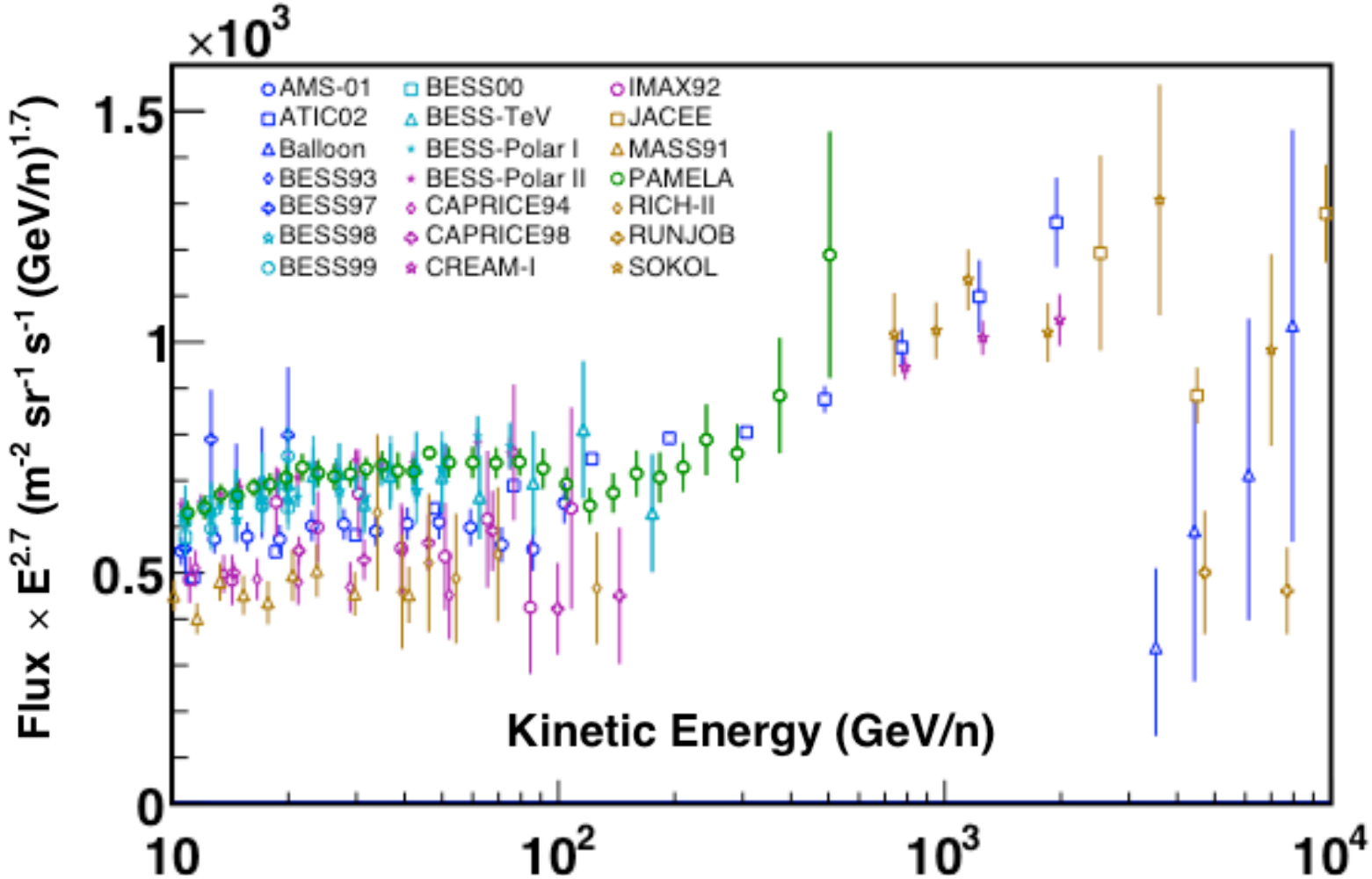
Helium Flux

Helium nuclei are the second most abundant charged particles in cosmic rays

AMS made the precise measurement of the helium flux in primary cosmic rays in the rigidity range from 1.9 GV to 3 TV based on 50 million events.

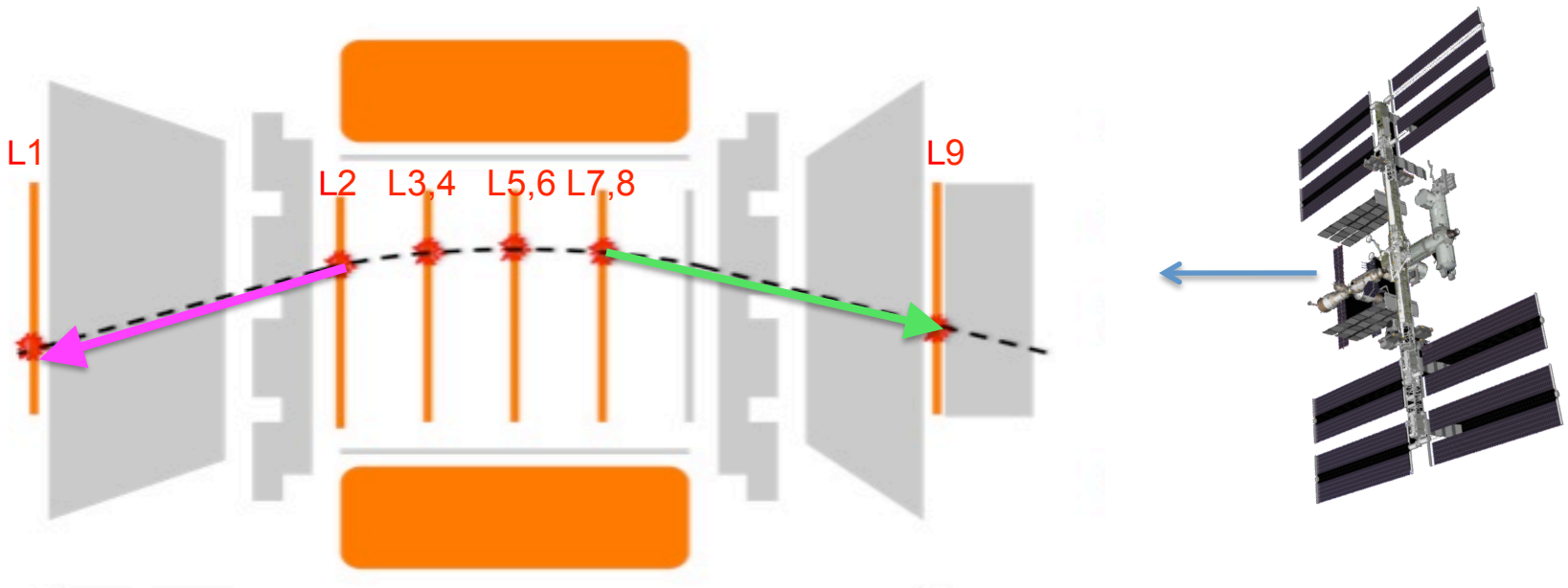
Measurements of the Helium flux before AMS

Previous measurements of the helium flux in cosmic rays have reported different variations of the flux with energy. These were the best data before AMS



(ii) Helium acceptance due to interactions

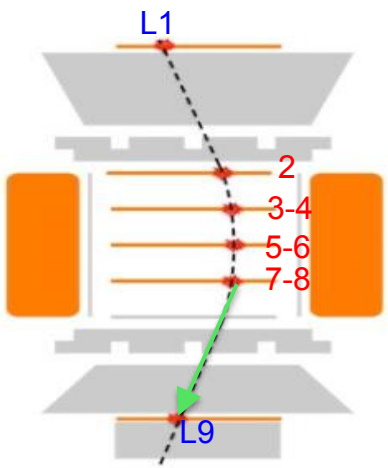
The inelastic cross sections of *He*+ C,Al are only measured below few GV



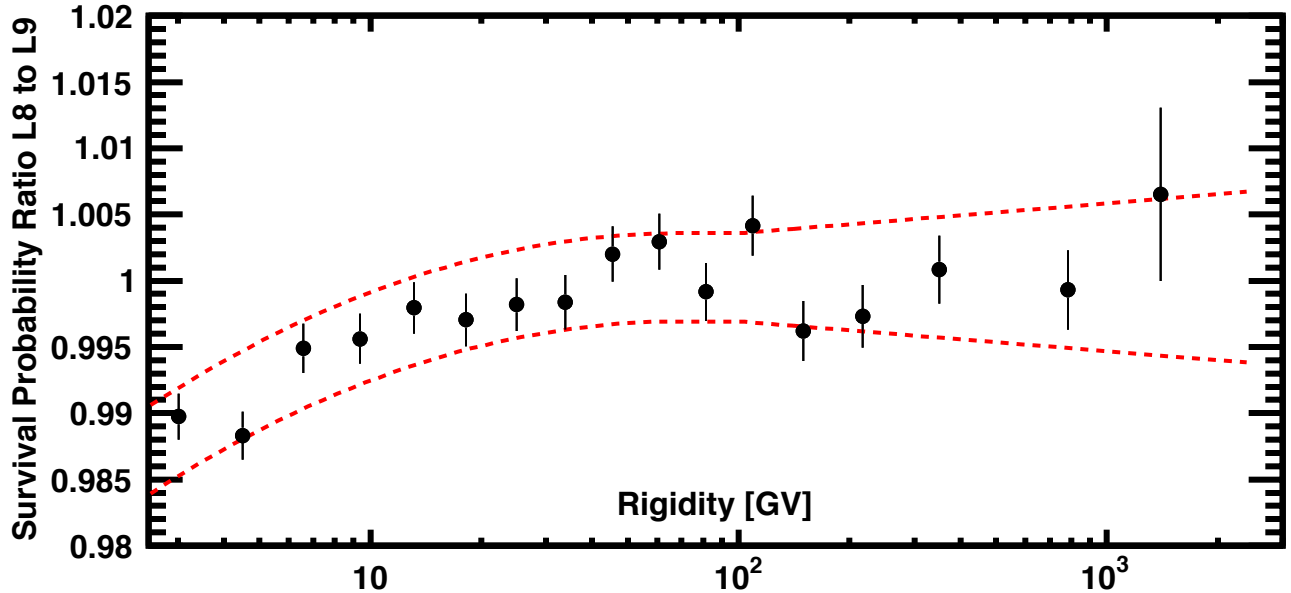
AMS measured the Survival Probabilities L2 to L1 and L8 to L9 during "Horizontal" runs [~10^5 sec exporsure] in which CRs can enter AMS both right to the left and left to the right. L8->L9 can also be measured in ECAL acceptance during usual conditions.

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

(ii) He Survival Probability L8 to L9 MC GEANT 4.1 Glauber-Gribov Scaled Model to Data Comparison



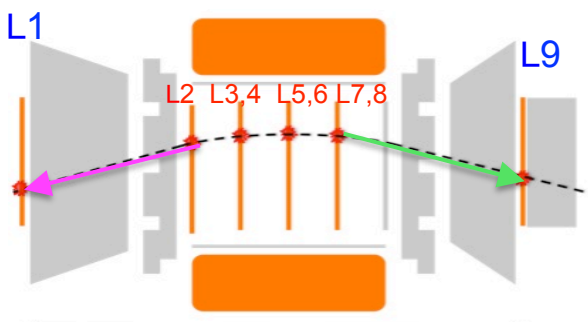
normal condition



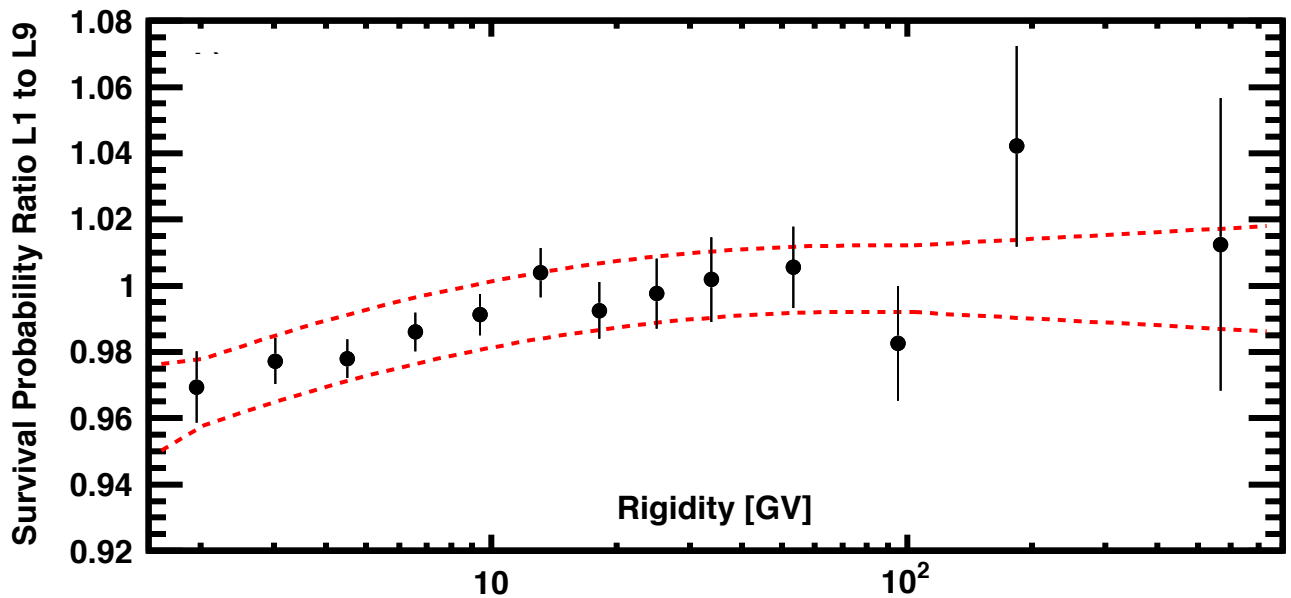
Ratio of the He survival probabilities from L8 to L9 between the best scaled simulation and data when traversing the lower TOF and RICH. The dashed curve indicates the corresponding systematic errors.

GG model rigidity dependence still need to be modified below ~30 GV.

(ii) He Survival Probability L1 to L9 MC to Data Comparison



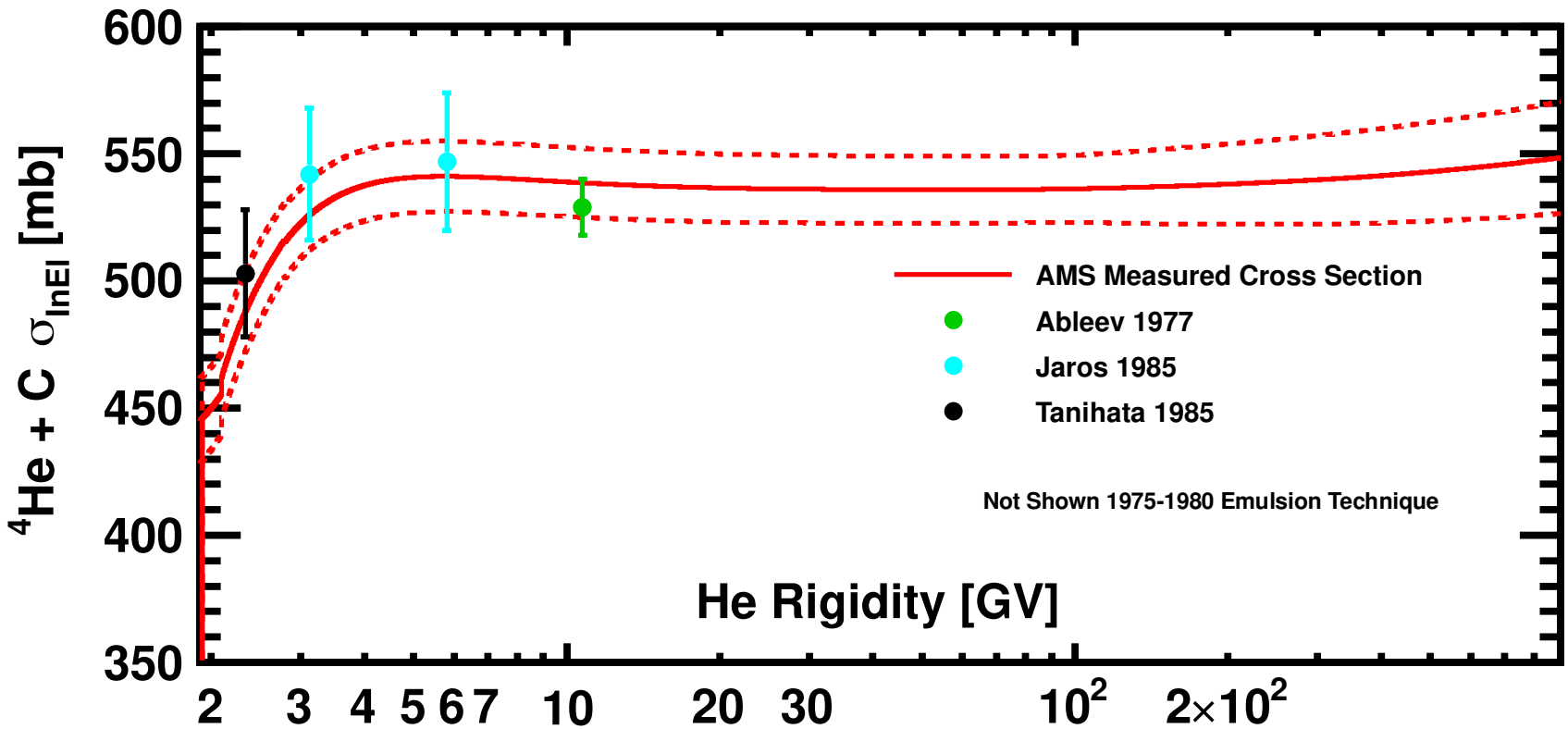
"Horizontal" AMS



Ratio of the He survival probabilities from L1 to L9 between the best scaled simulation and data when traversing the entire detector. The dashed curve indicates the corresponding systematic errors.

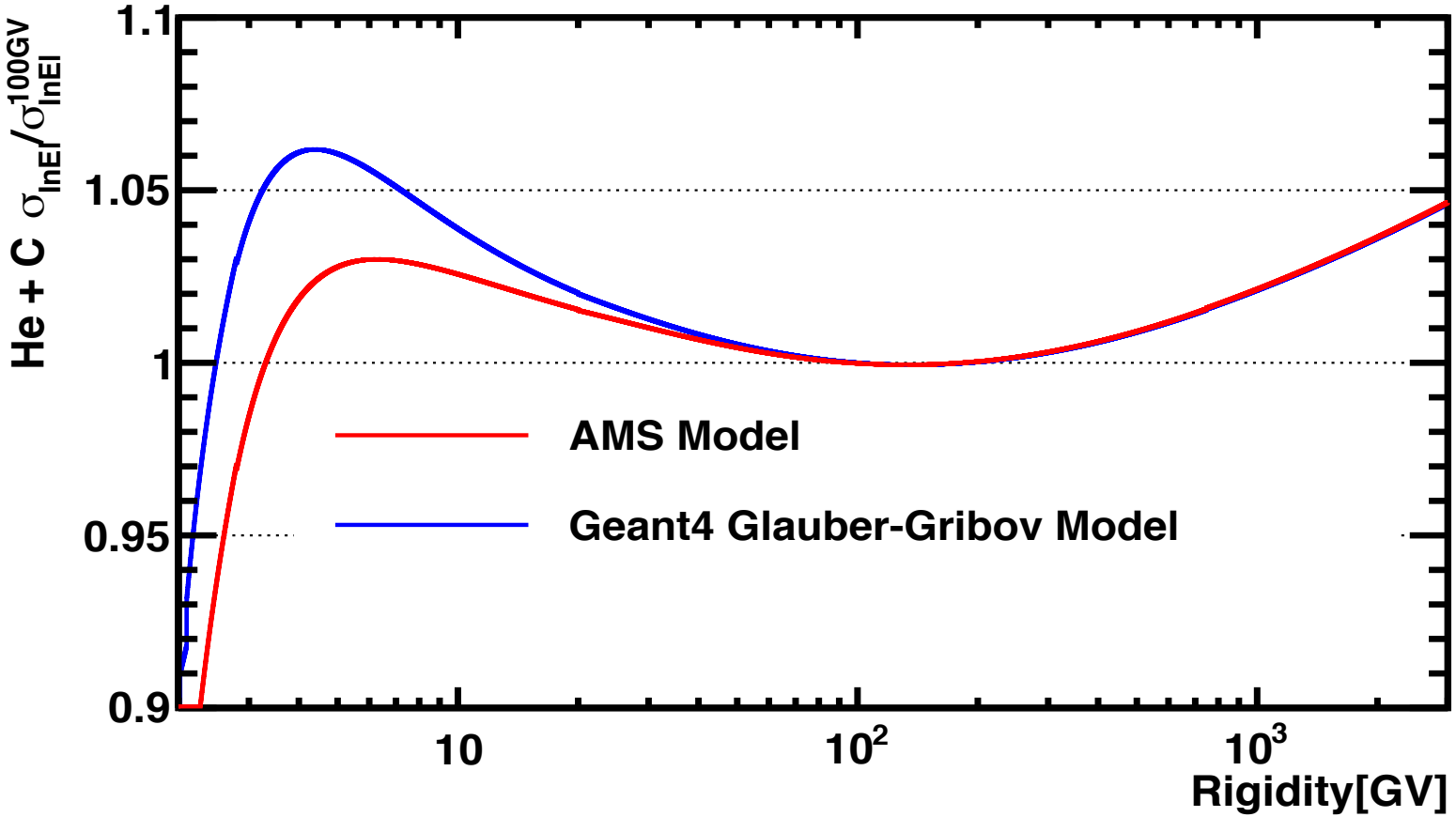
GG model rigidity dependence still need to be modified below ~30 GV.

(ii) AMS measured He+C cross section AMS Materials C(73%) Al(20%)



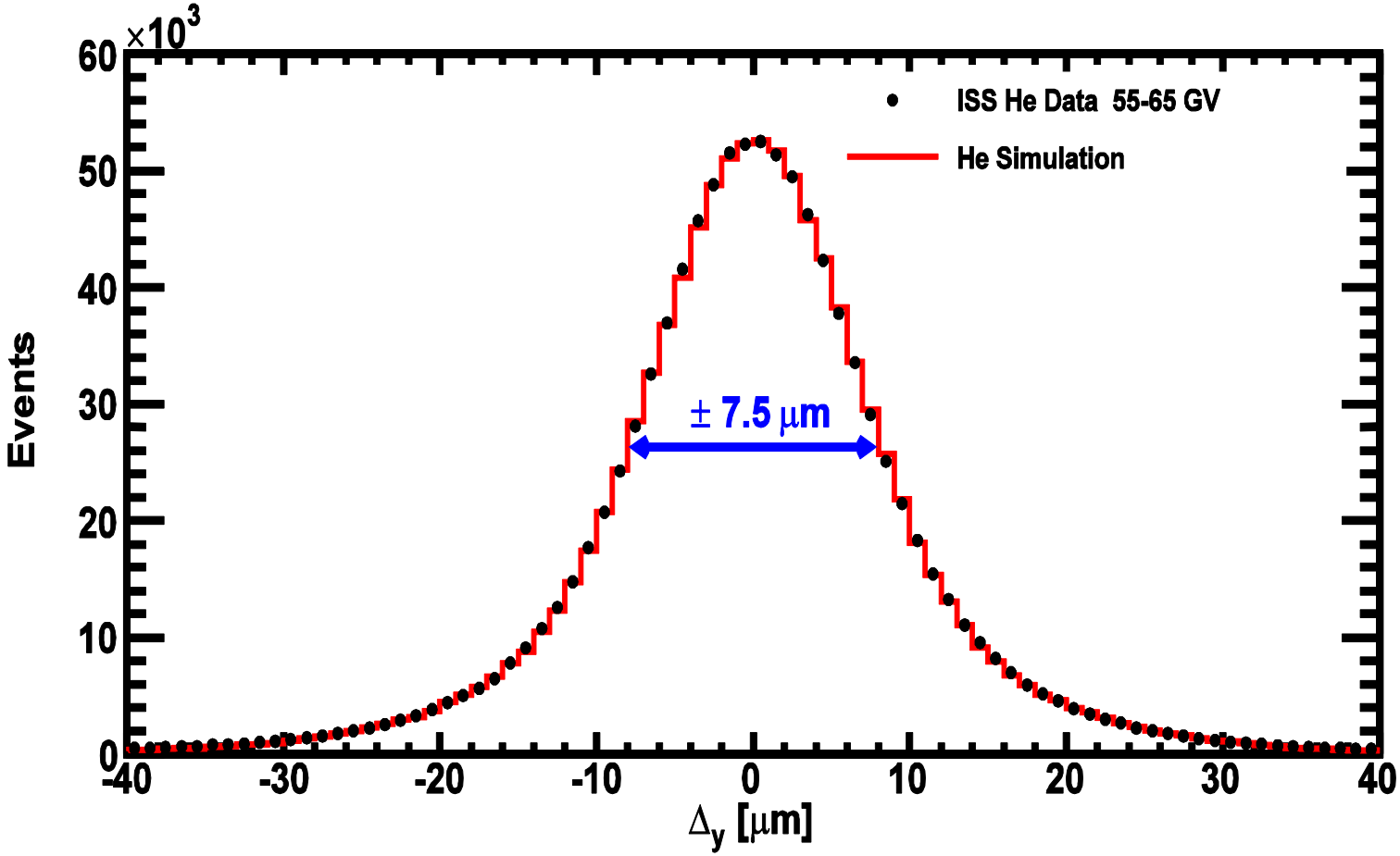
The AMS measured He+C inelastic cross section in comparison with experimental results. The dashed curve indicates the corresponding systematic errors.

(ii) AMS Tuned He+C cross section Energy Dependence

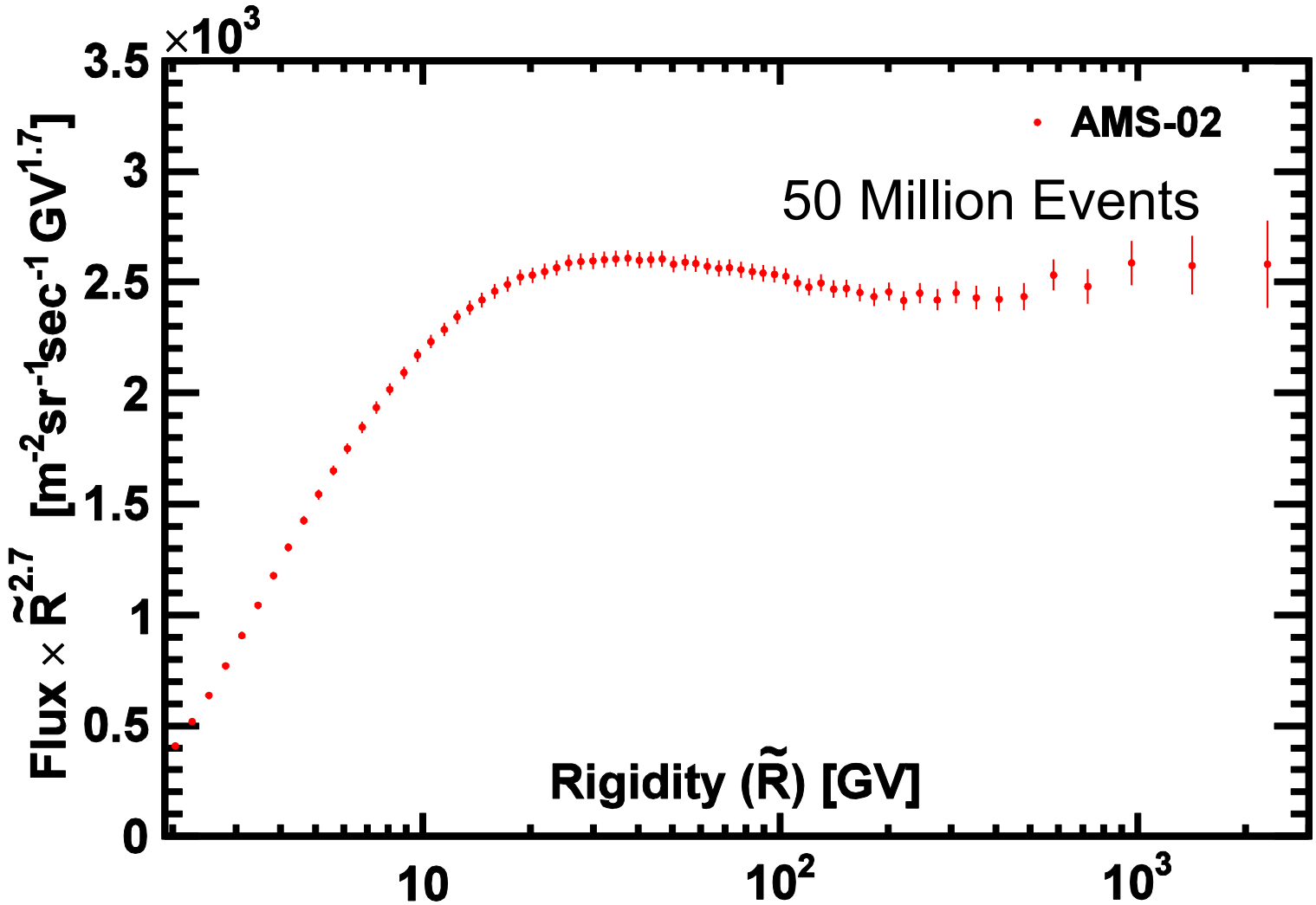


GG model rigidity dependence still need to be modified below ~30 GV.

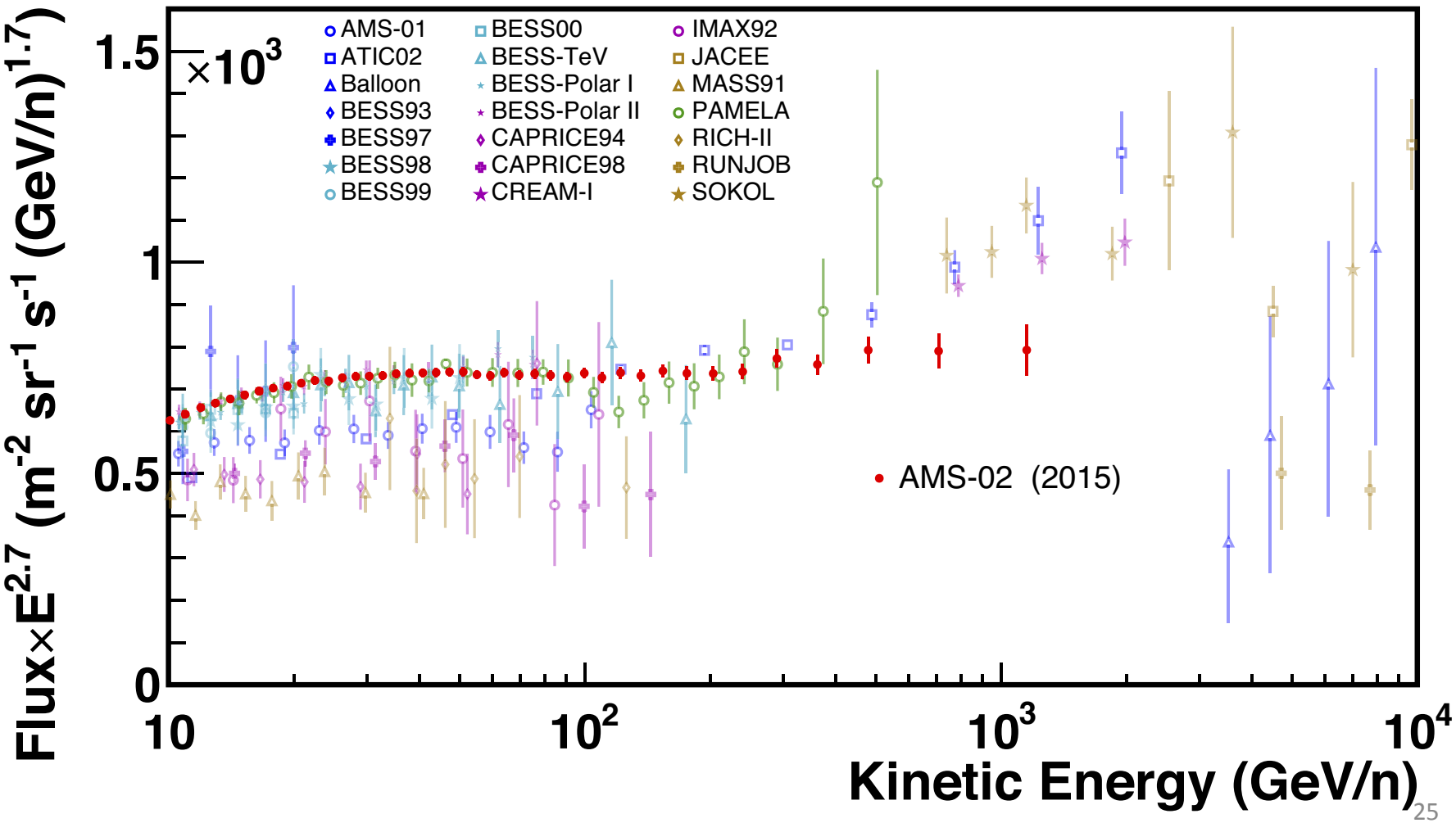
(iii) Helium Tracker Resoultion



Helium Flux 2.5 Years

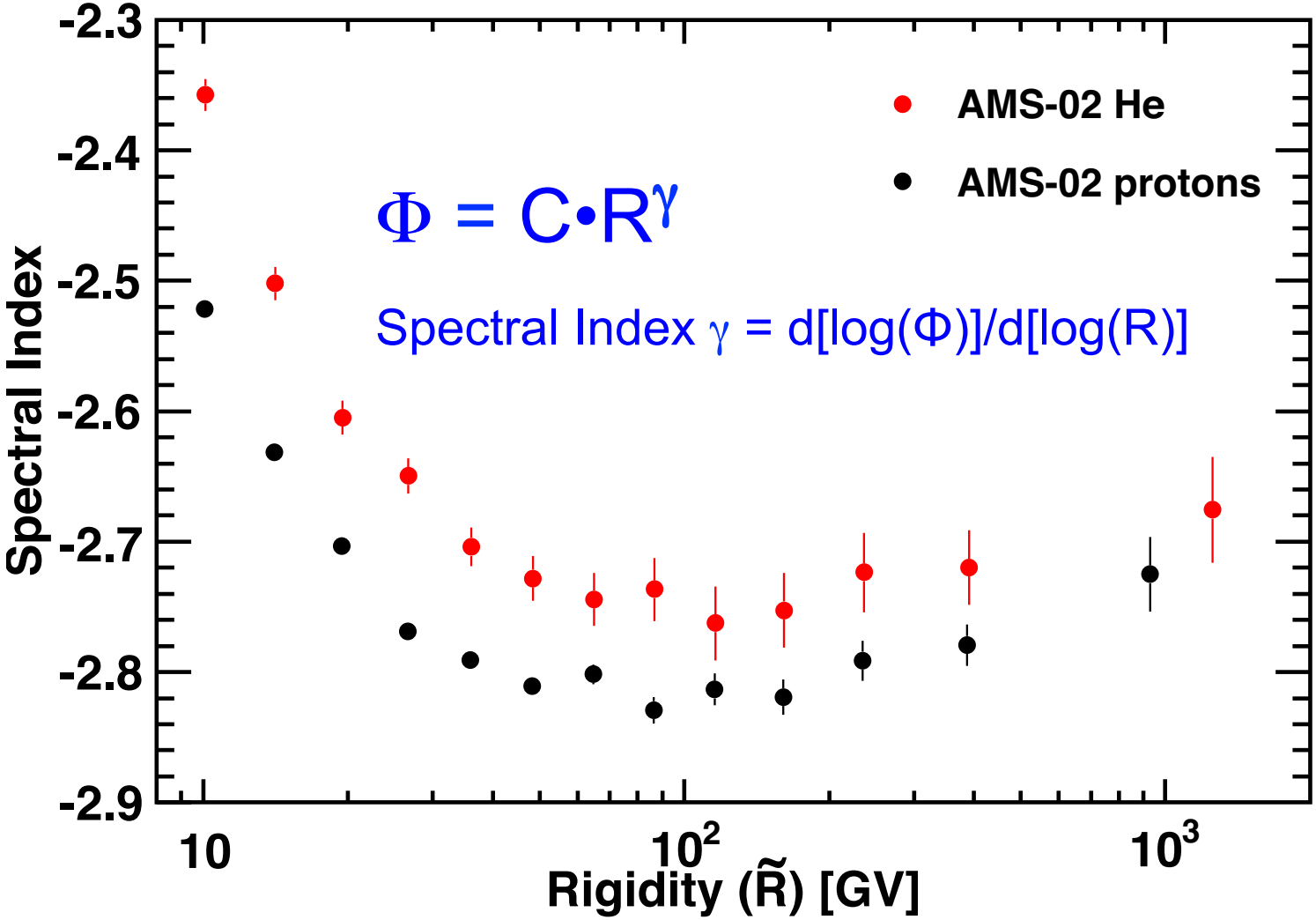


Helium Flux Comparison with Earlier Measurements

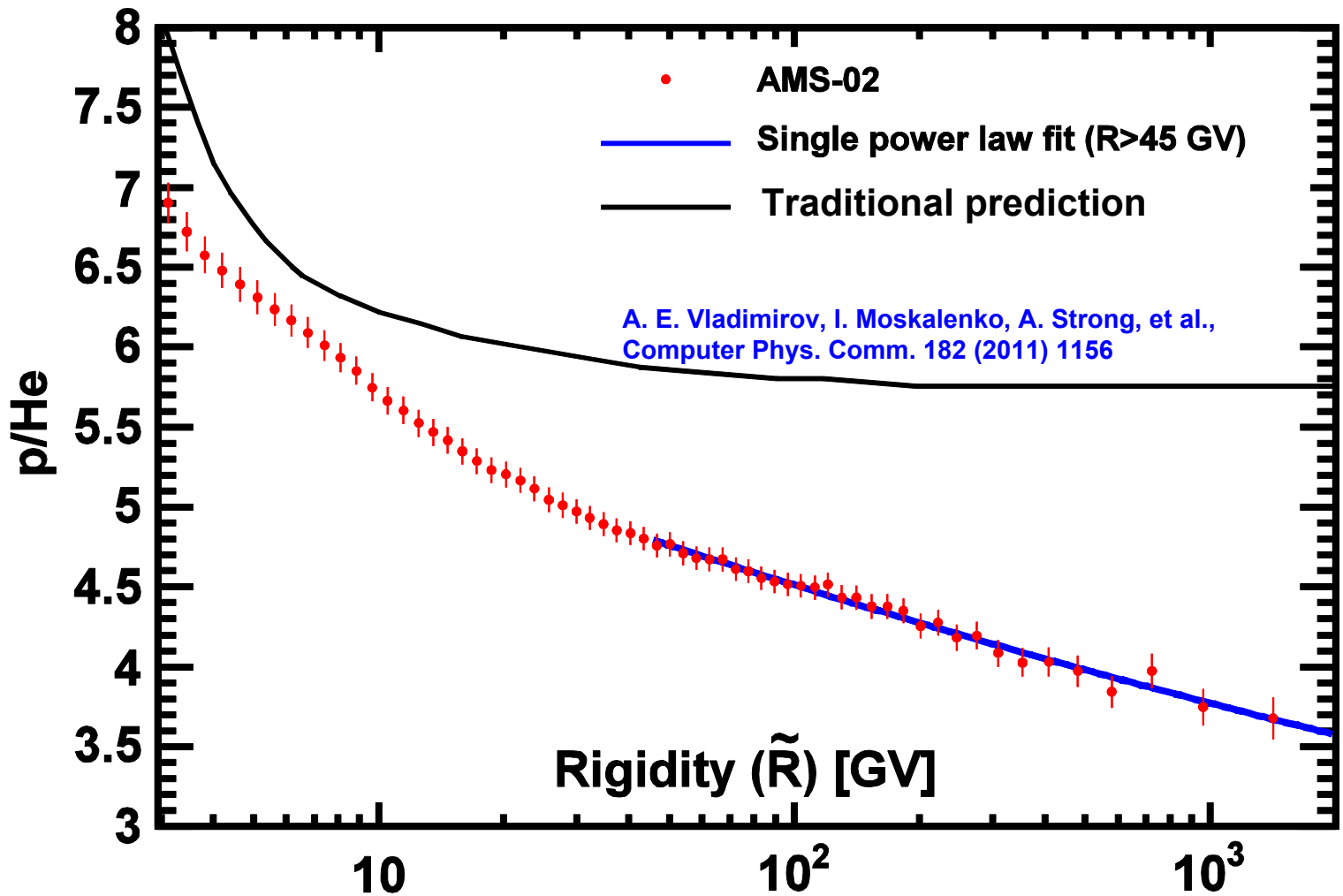


Spectral Index Rigidity Dependence

The spectral index varies with rigidity. In particular, the spectral index is progressively hardening with rigidity above ~100 GV.



Proton/Helium Flux Ratio

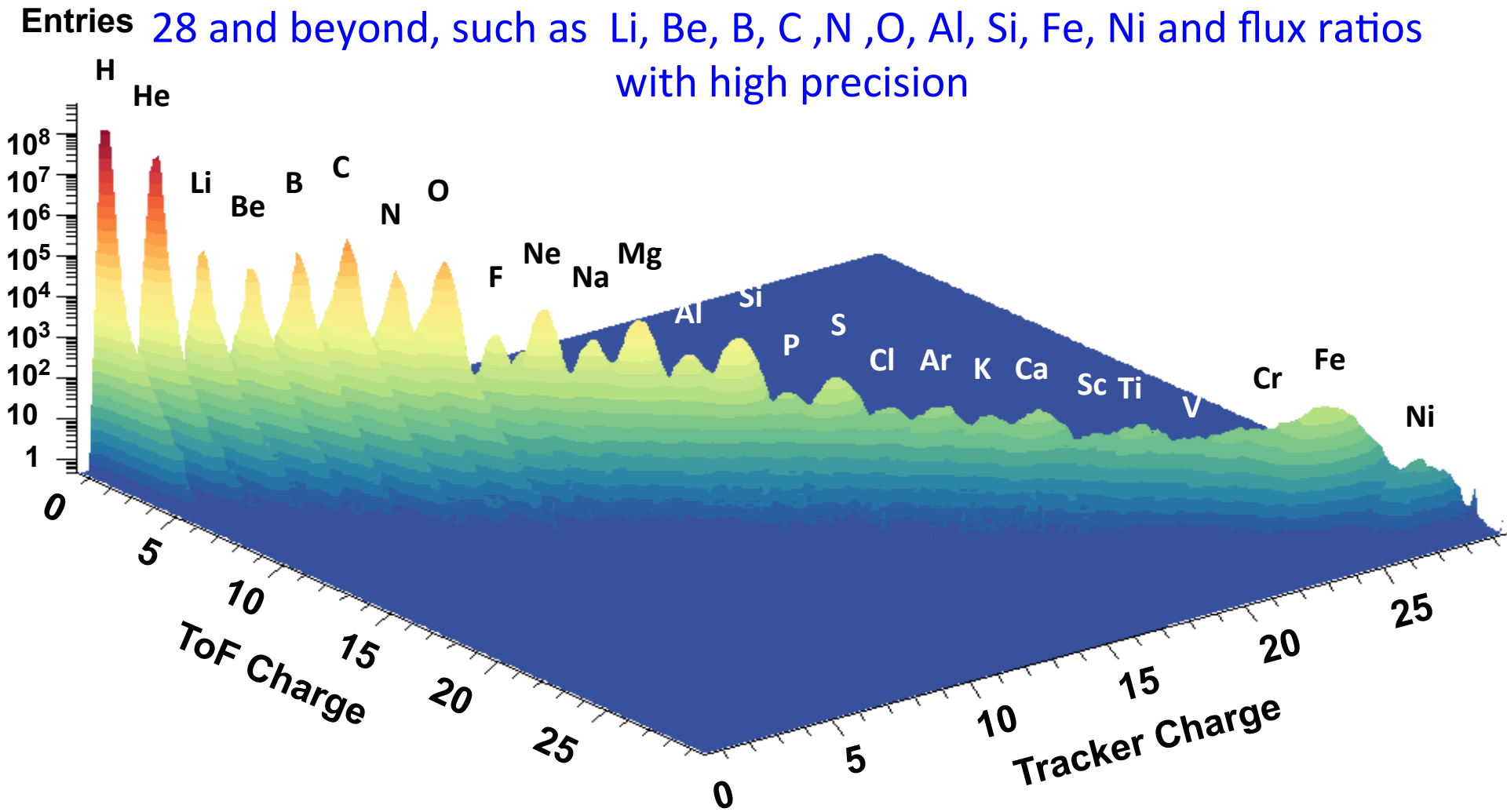


Summary Proton and Helium Flux

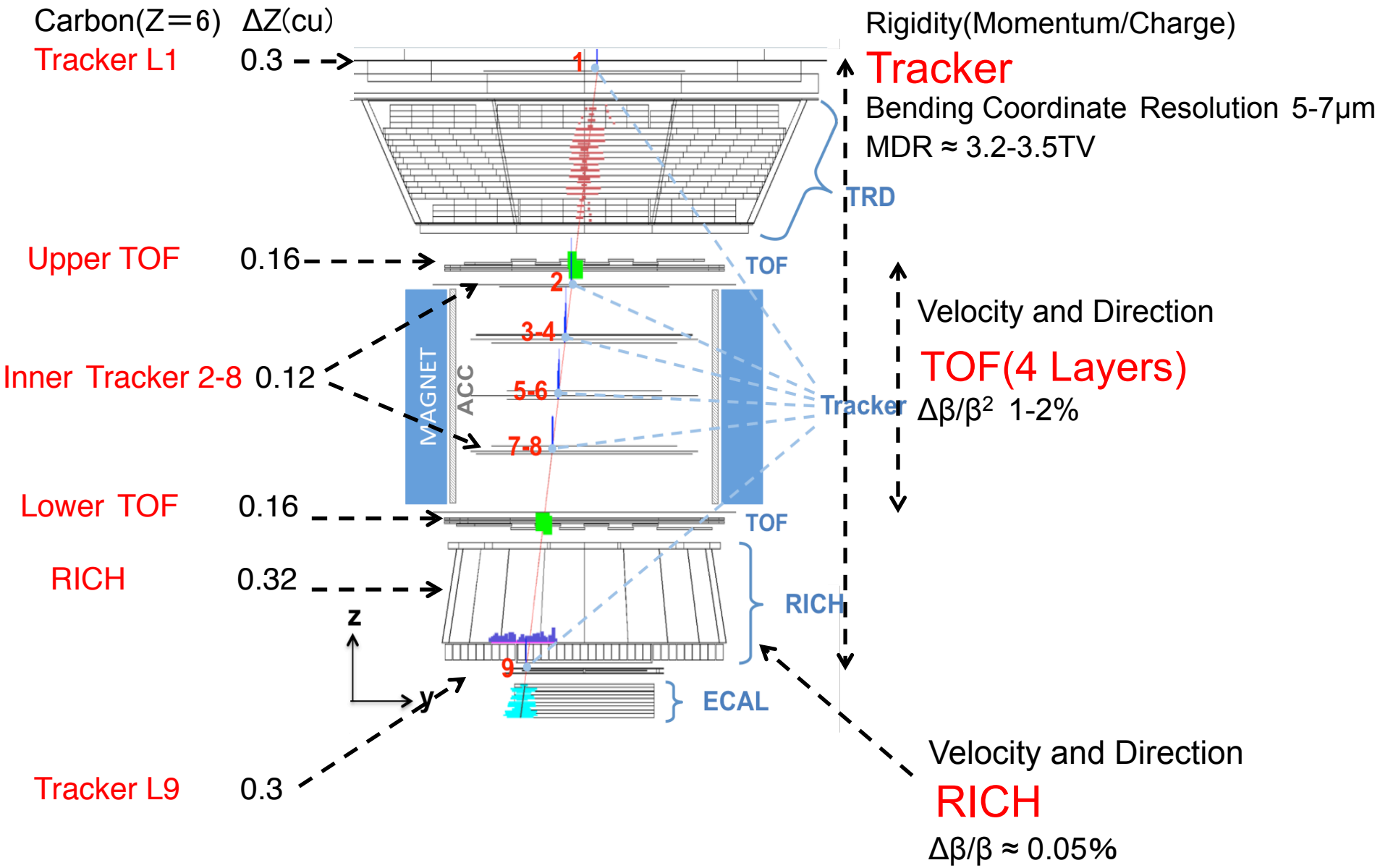
- Precision measurement of proton flux from 1 GV to 1.8 TV, and helium flux from 1.9 GV to 3 TV with AMS:
  - The detailed variation with rigidity of the flux spectral index is presented
  - The spectral index is progressively hardening at high rigidities

AMS Nuclei Fluxes Measurements

AMS is capable of measuring the fluxes of all Cosmic Nuclei from Z 3 to 28 and beyond, such as Li, Be, B, C ,N ,O, Al, Si, Fe, Ni and flux ratios with high precision



AMS Light (Z up to 8) Nuclei Fluxes Measurement



Flux Measurement

Isotropic flux above geomagnetic cutoff in rigidity is defined as

$$\Phi_i(R) = \frac{N_i}{T_i \, A_i \, \varepsilon_i \, \Delta R_i}$$

Events Corrected for Background and for Bin to Bin Migration due to Tracker Rigidity Resolution

Bin width

Time ~123,000,000 sec (R>30 GV, 5Years)

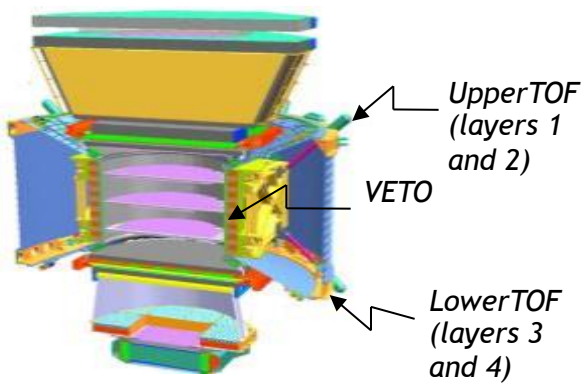
Rigidity 2-3000 GV

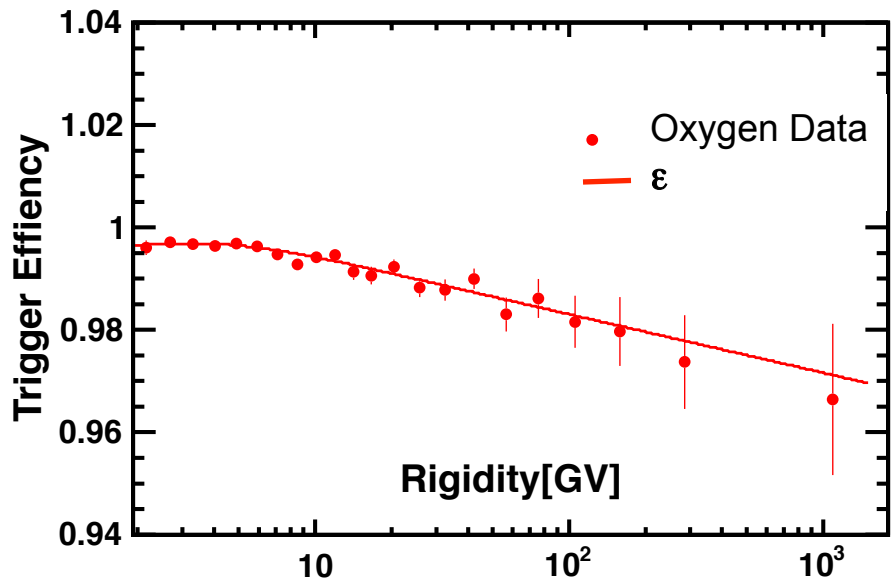
Trigger Efficiency from Data

Effective Acceptance from MC, Corrected for Nuclei Interactions Verified with Data

(i) Trigger efficiency for Nuclei

Trigger efficiency [4/4 TOF + VETO 4/8] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger. The error is dominated by the statistics available from the unbiased trigger.

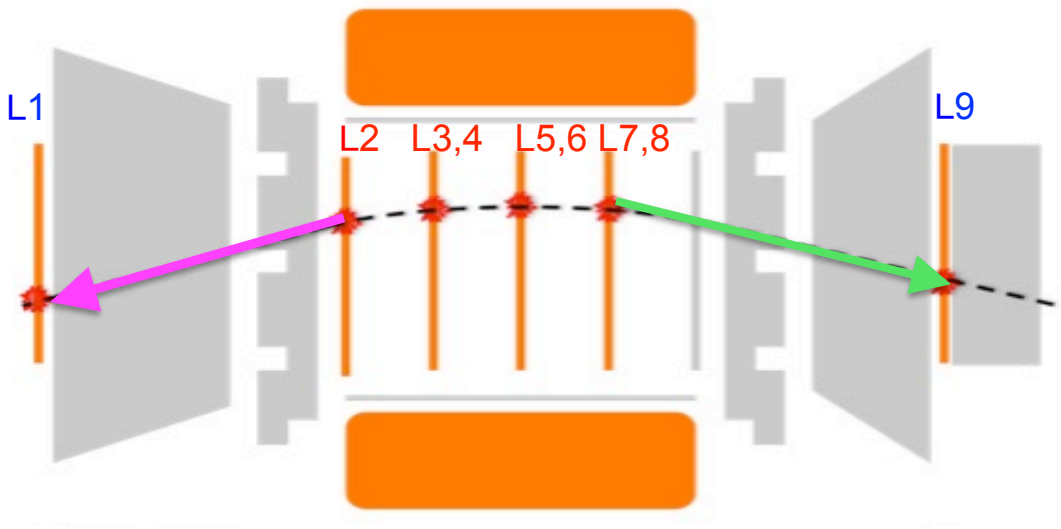


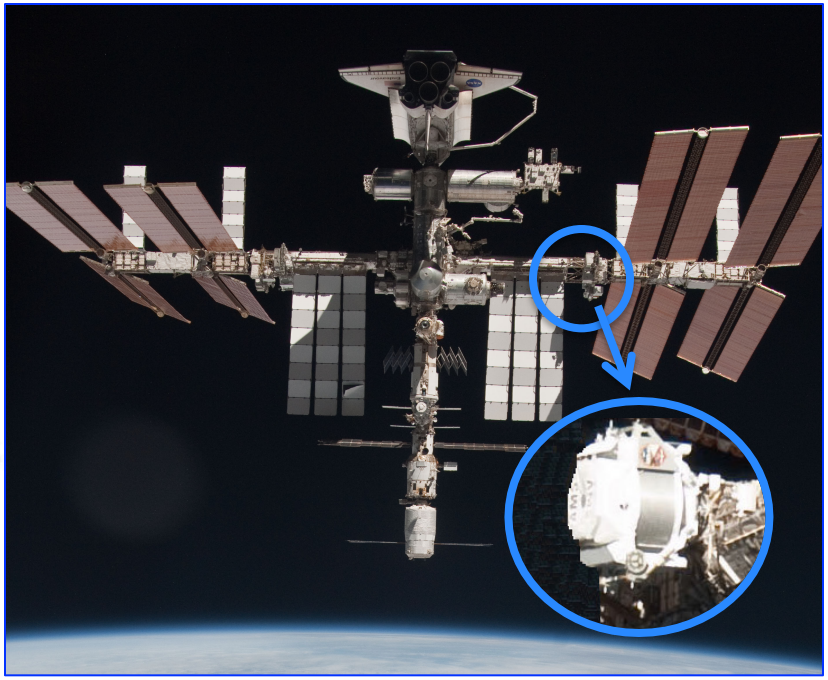


This systematic error is small (less than 1%) for Z = 3 to 8, as trigger efficiency exceeds 95% in all measurement range.

(ii) Nuclei acceptance due to interactions

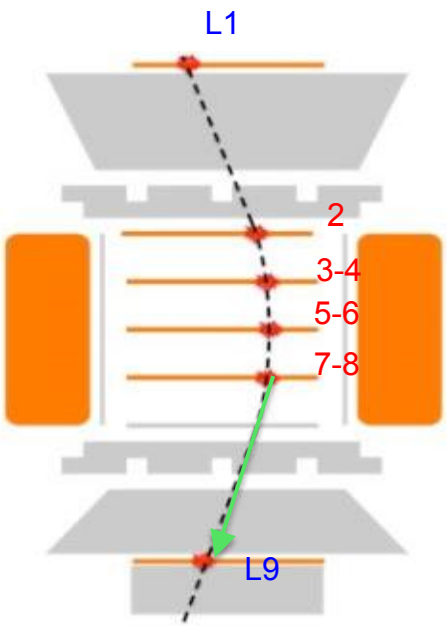
The inelastic cross sections of *N* + C, *N* + Al are only measured below few GV (C,O) or not measured (Li,Be,B,N)



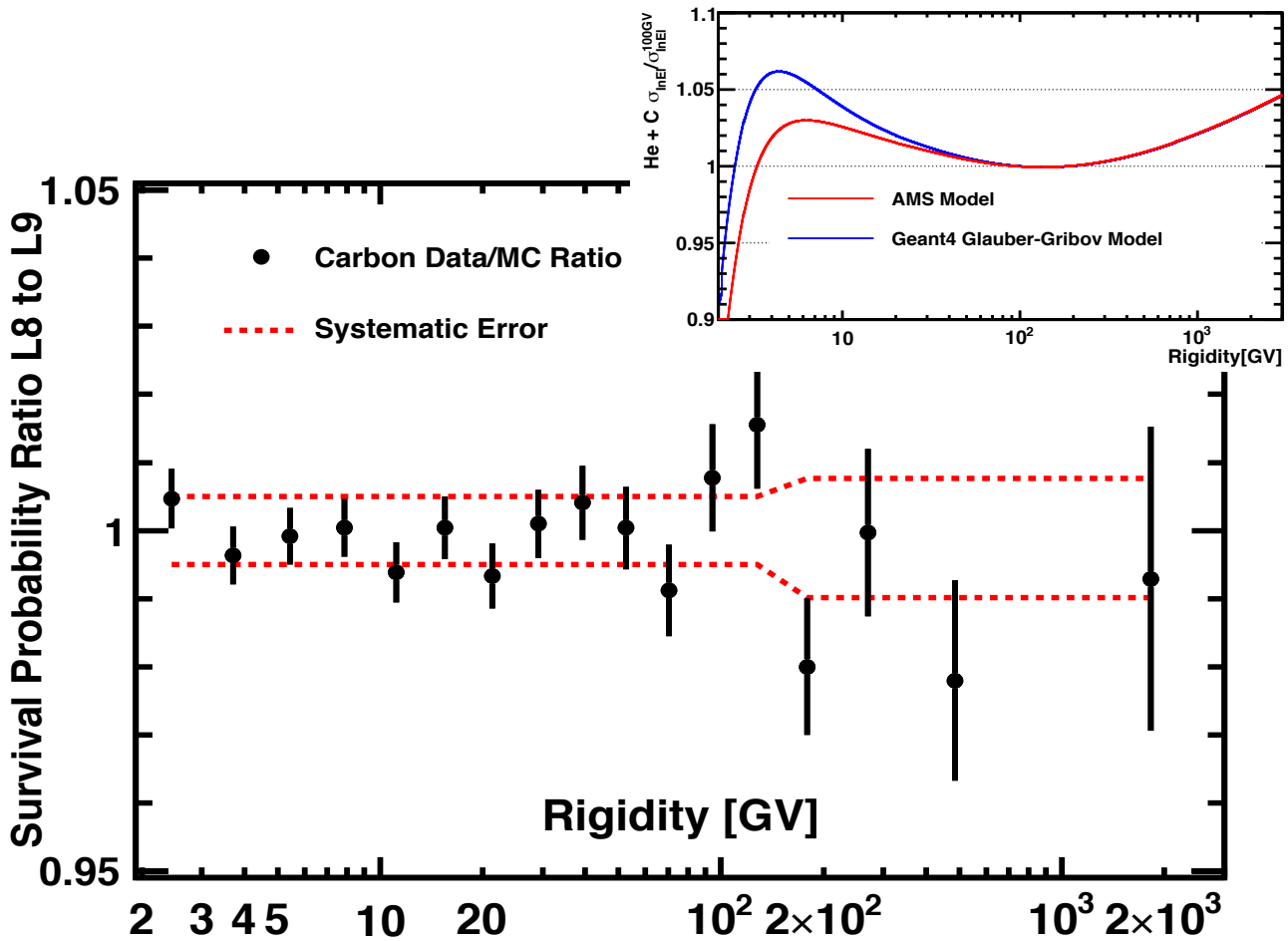


AMS measured the nuclei Survival Probabilities L2 to L1 and L8 to L9 during "Horizontal" runs [~10^5 sec exporsure] in which nuclei can enter AMS both right to the left and left to the right. L8->L9 Survival Probabilities can also be measured in ECAL acceptance during normal conditions.

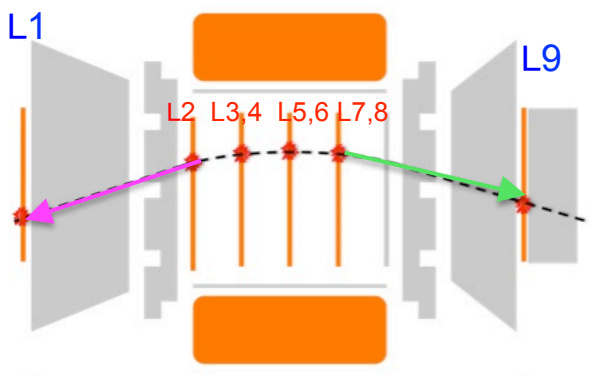
(ii) Carbon Survival Probability L8 to L9 Data to MC Comparison



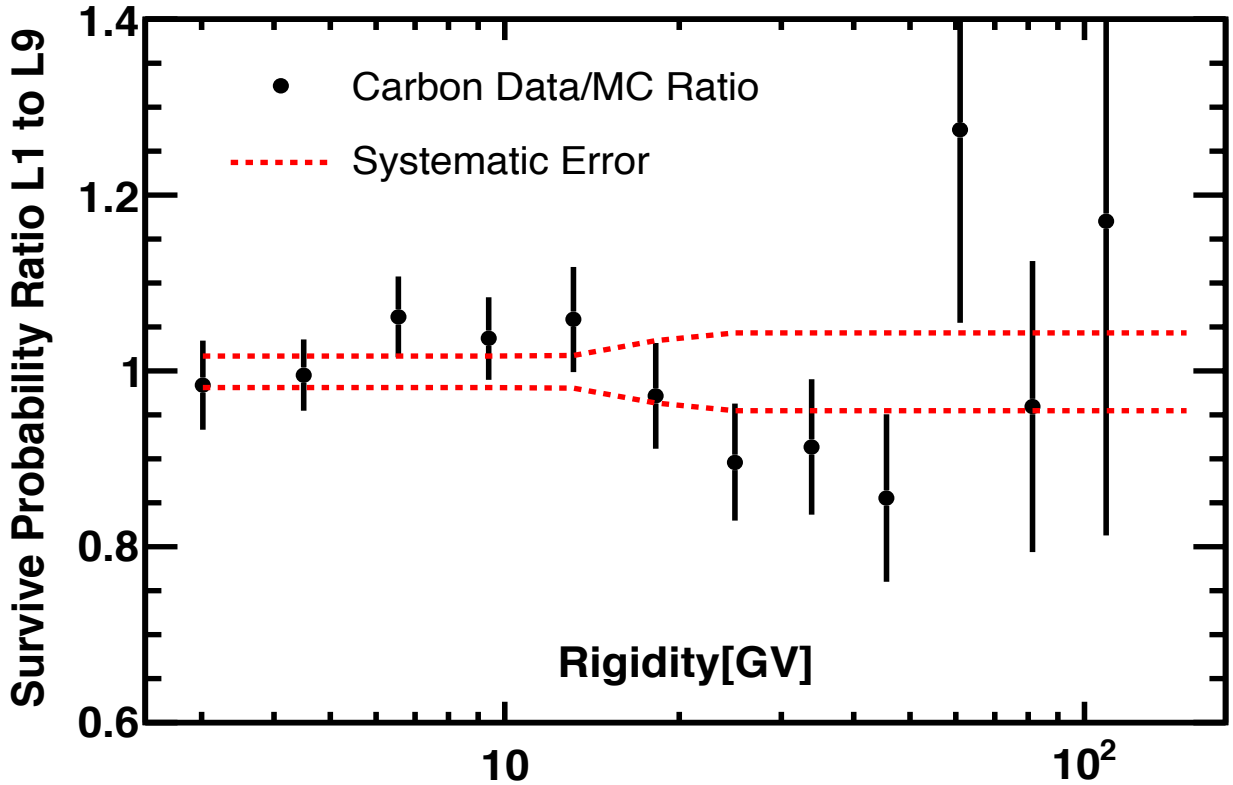
normal condition



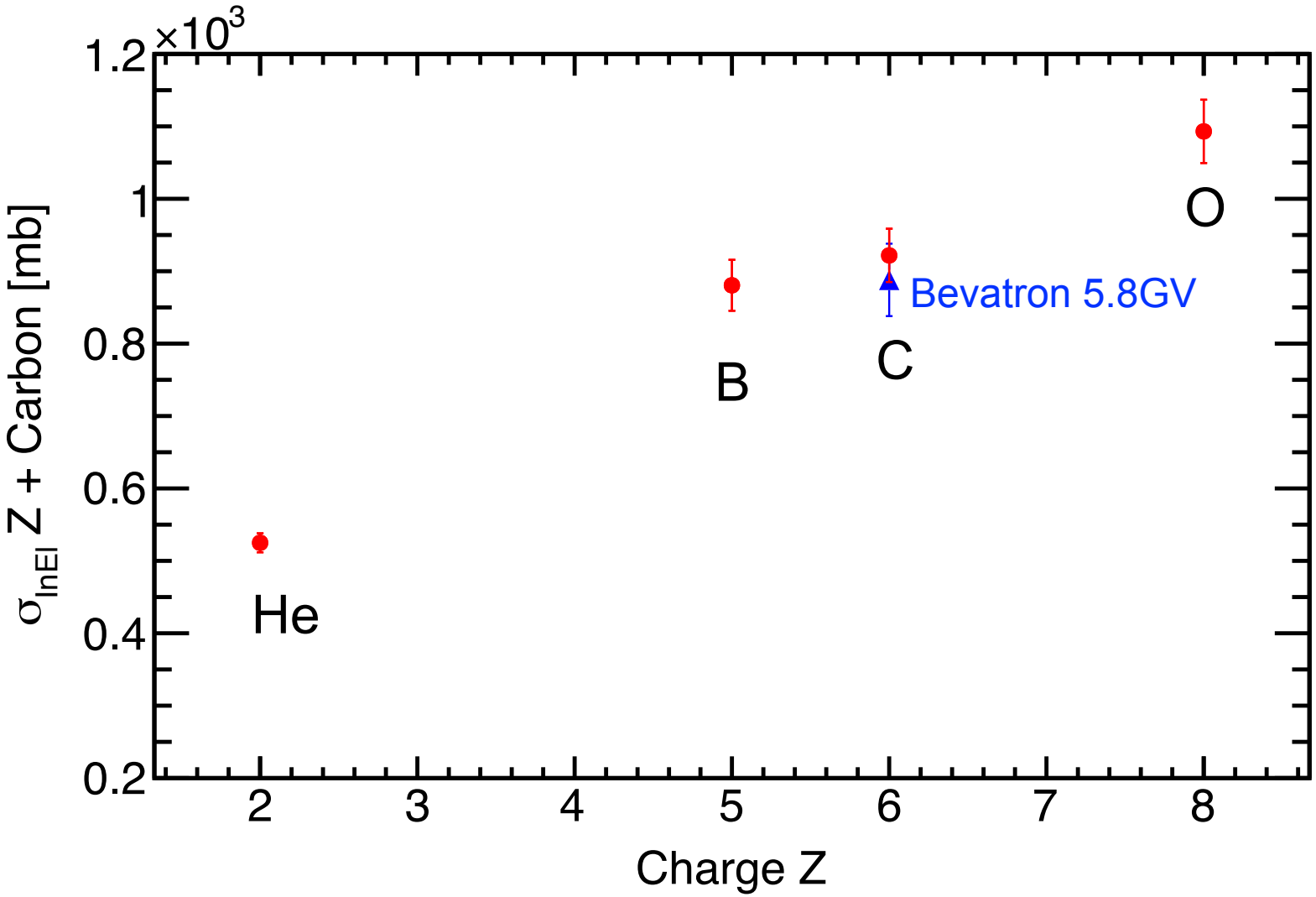
(ii) Carbon Survival Probability L1 to L9 Data to MC Comparison



"Horizontal" AMS

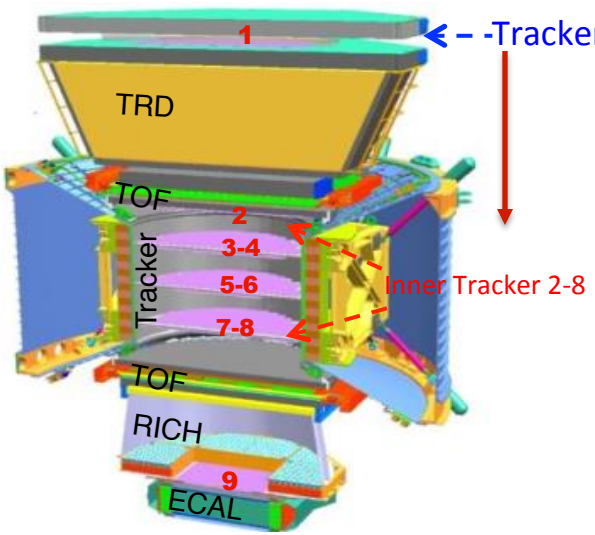


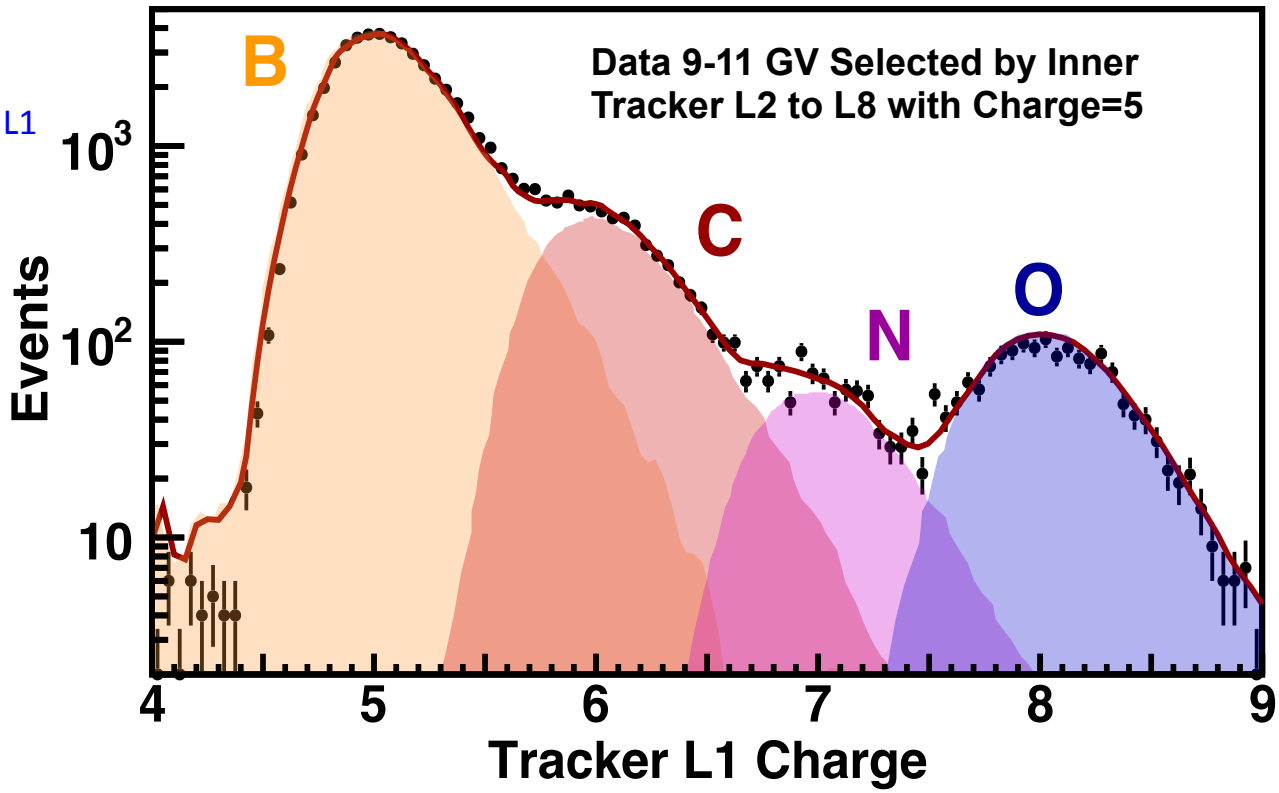
(iii) AMS Nuclei + C Inelastic Cross Section Measurements, 5-100GV Rigidity



(iv) Background to Nuclei Fluxes Measurement

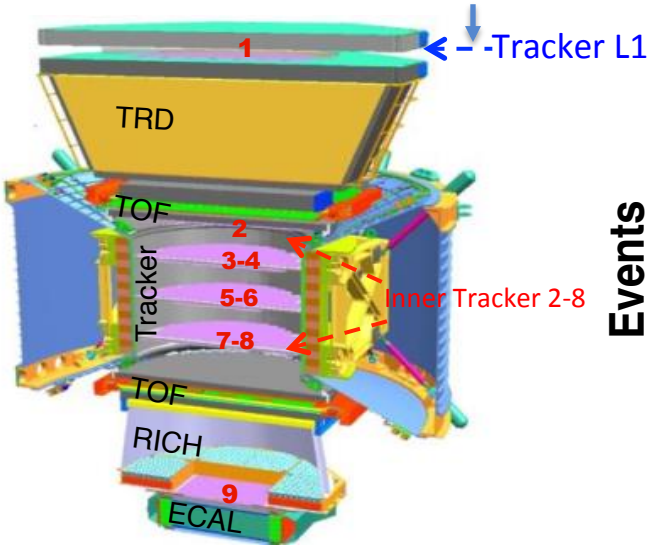
background from elements of higher charges, which interact between Tracker L1 and Tracker L2 can be measured from Data by fitting the Charge Distribution in L1. This systematic error is typically <0.5%

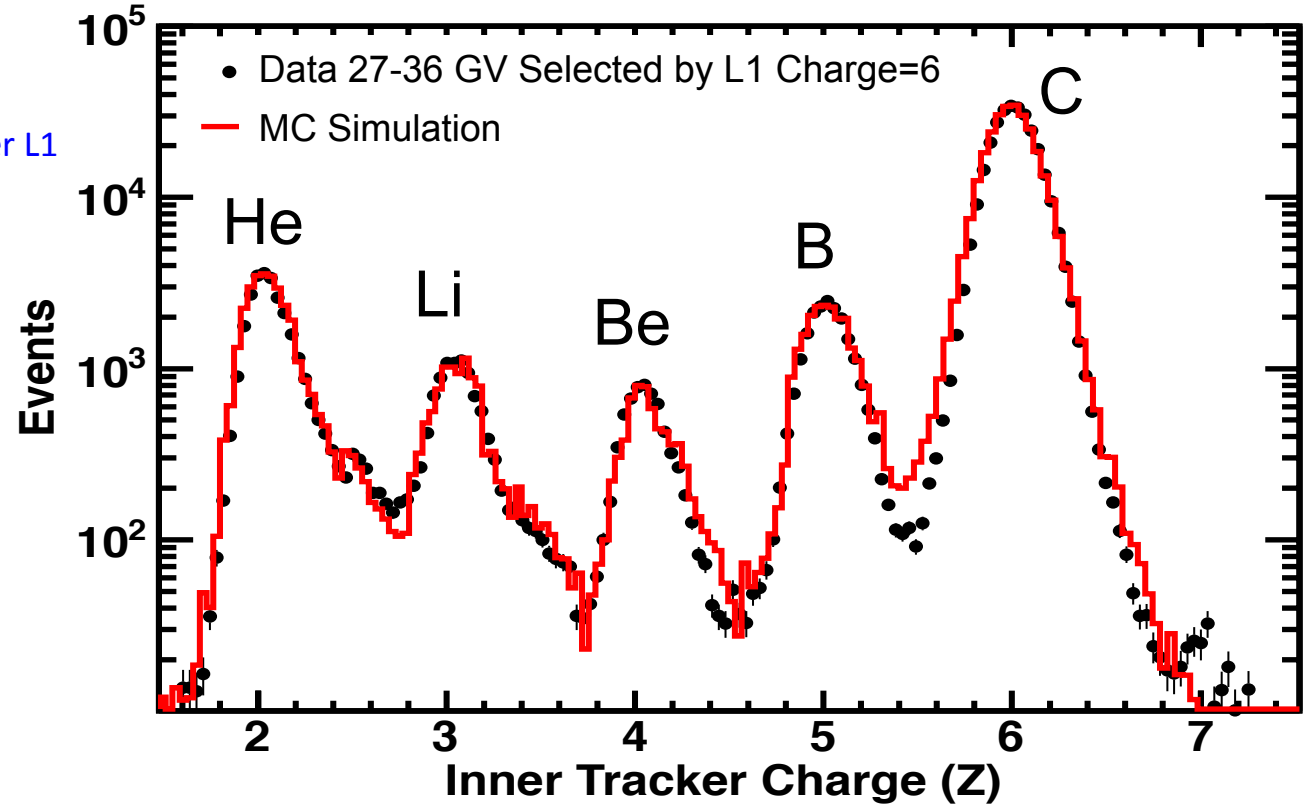




(iv) Background to Nuclei Fluxes Measurement

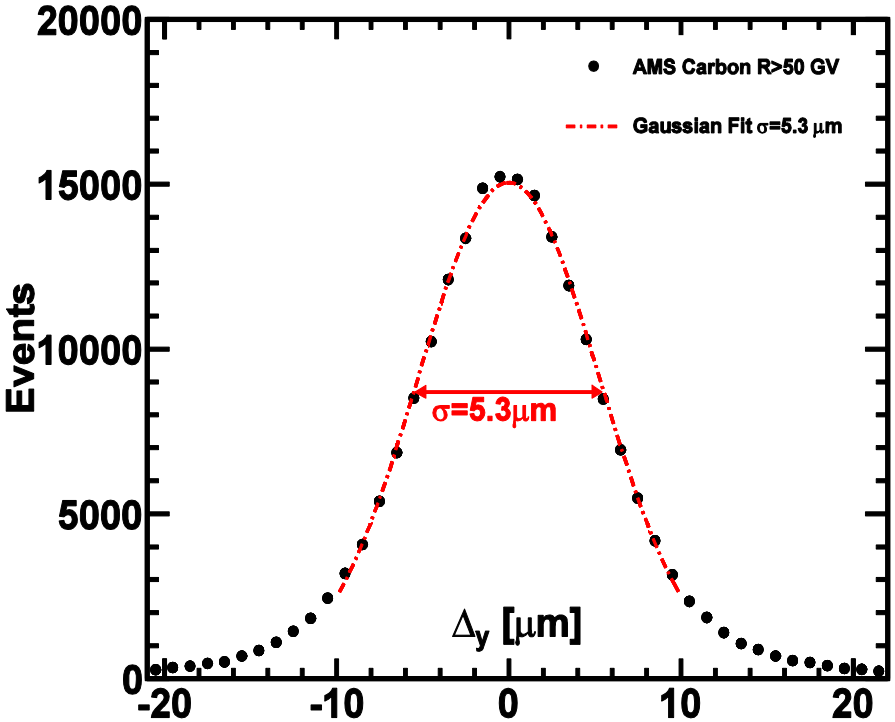
background from elements of higher charges, which interact at very top of AMS , i.e. above Tracker L1 is important for secondary nuclei like Li, Be, B, N where it can reach up to 10% @MDR. MC break-up channels have been verified with data, background systematic error <1 %.

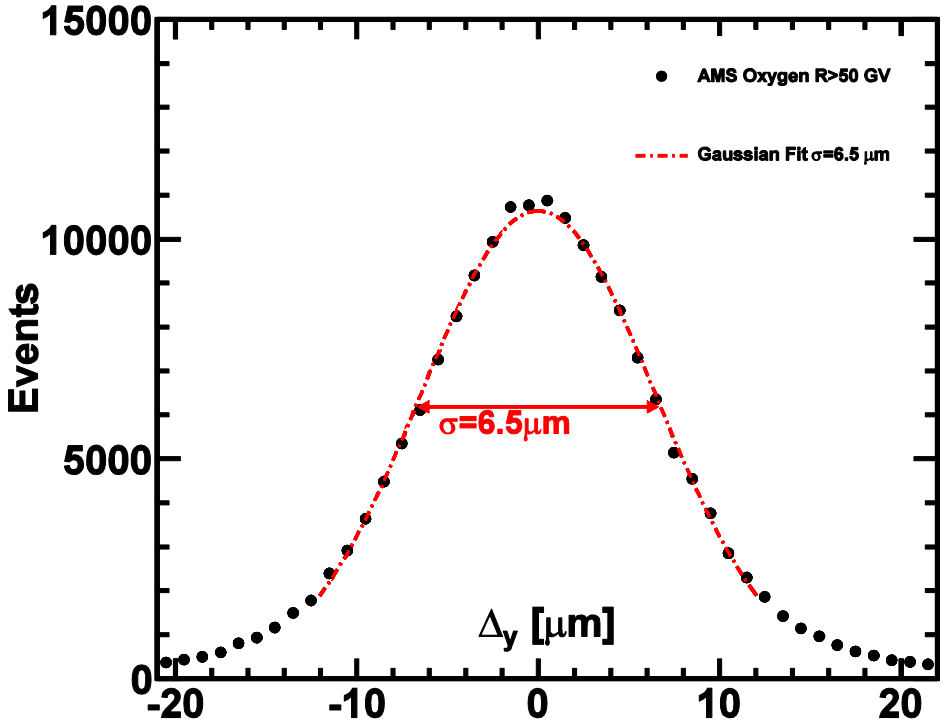




(v) Systematic errors on the rigidity resolution function

The rigidity resolution functions were verified with the ISS data. The unfolding errors were obtained by varying the width of the Gaussian core of the resolution function by 5% [due to uncertainty of 1μm of L1,9 alignment] and amplitudes of the non-Gaussian tails by 20% [due to uncertainty in large angle N-N scattering] and found to be typically 1% below 200GV and 3% to 5% at MDR.



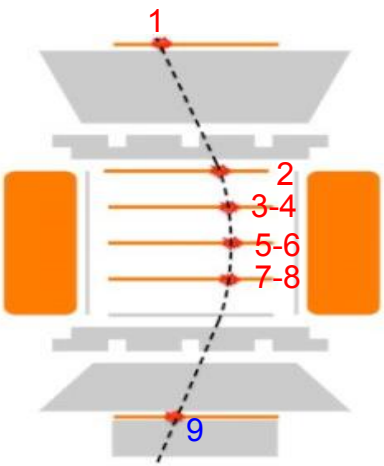


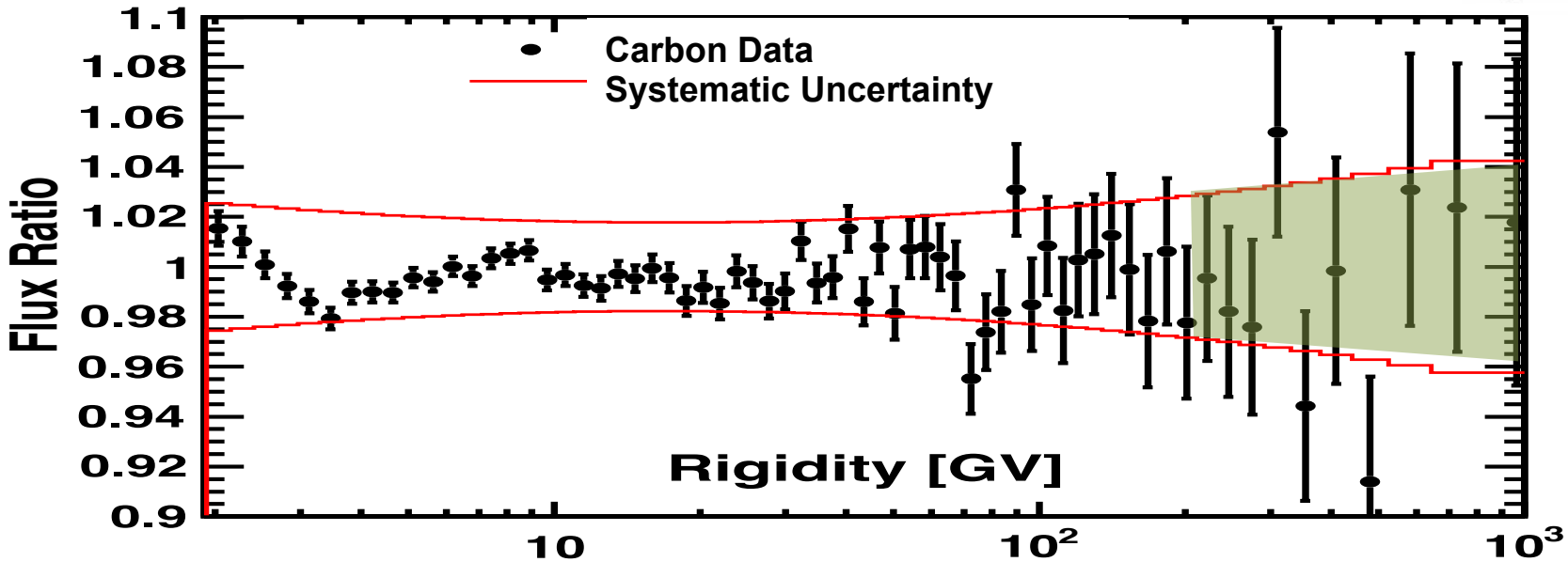
Difference between measured coordinates in L3-L6 and whose interpolated from fitted track

(v) Verification of the Systematic Error of Unfolding, Acceptance and Rigidity Resolution

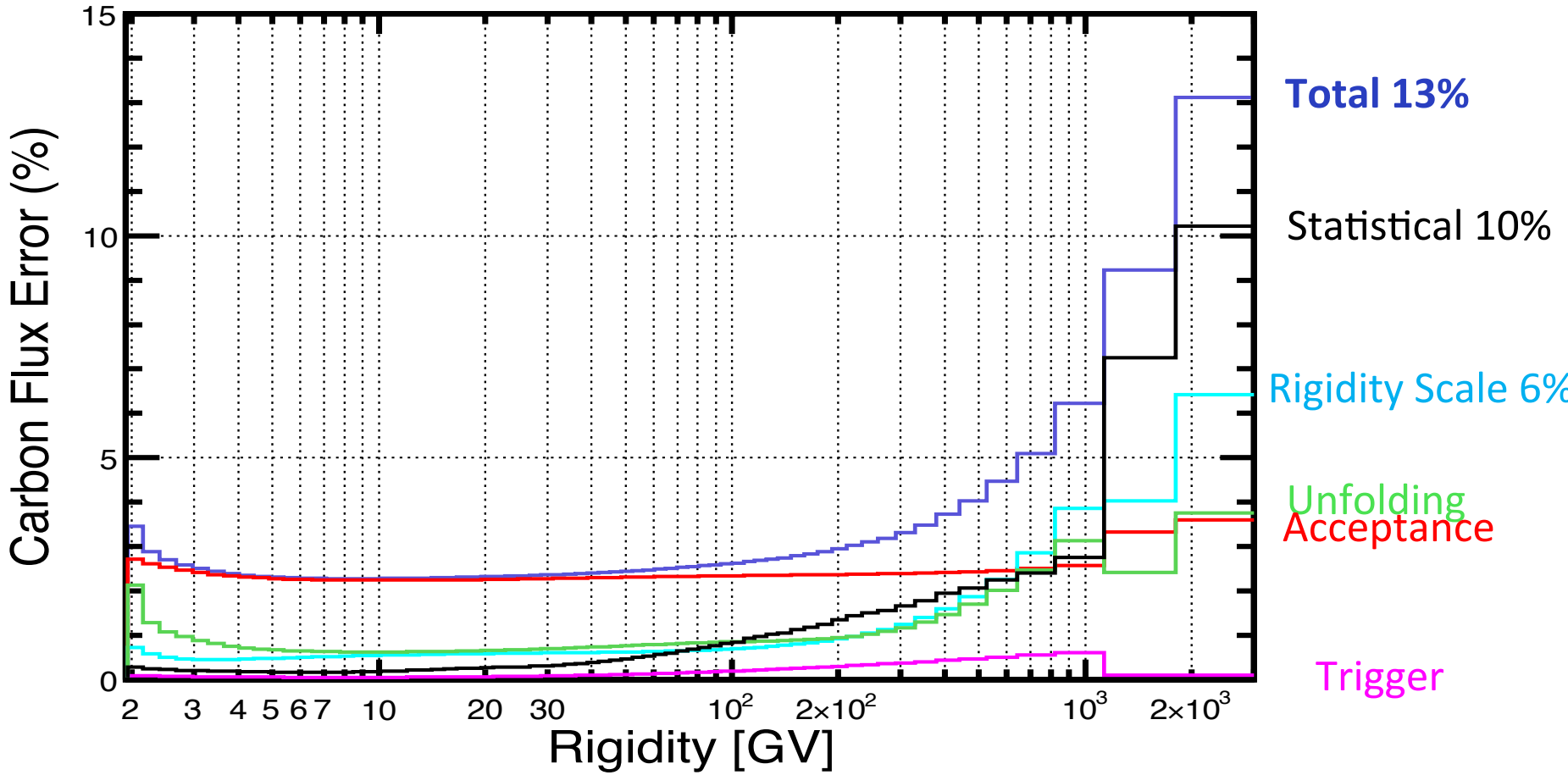
Carbon Flux obtained using the rigidity measured by only the L1+inner tracker in a larger acceptance is in very good agreement with the flux measured using the full lever arm, specifically at

-high rigidities (200 to 1000GV) where the unfolding effects and resolution functions of the L1+inner tracker (1.3 TV MDR) and the full lever arm one (3.5 TV MDR) are very different.



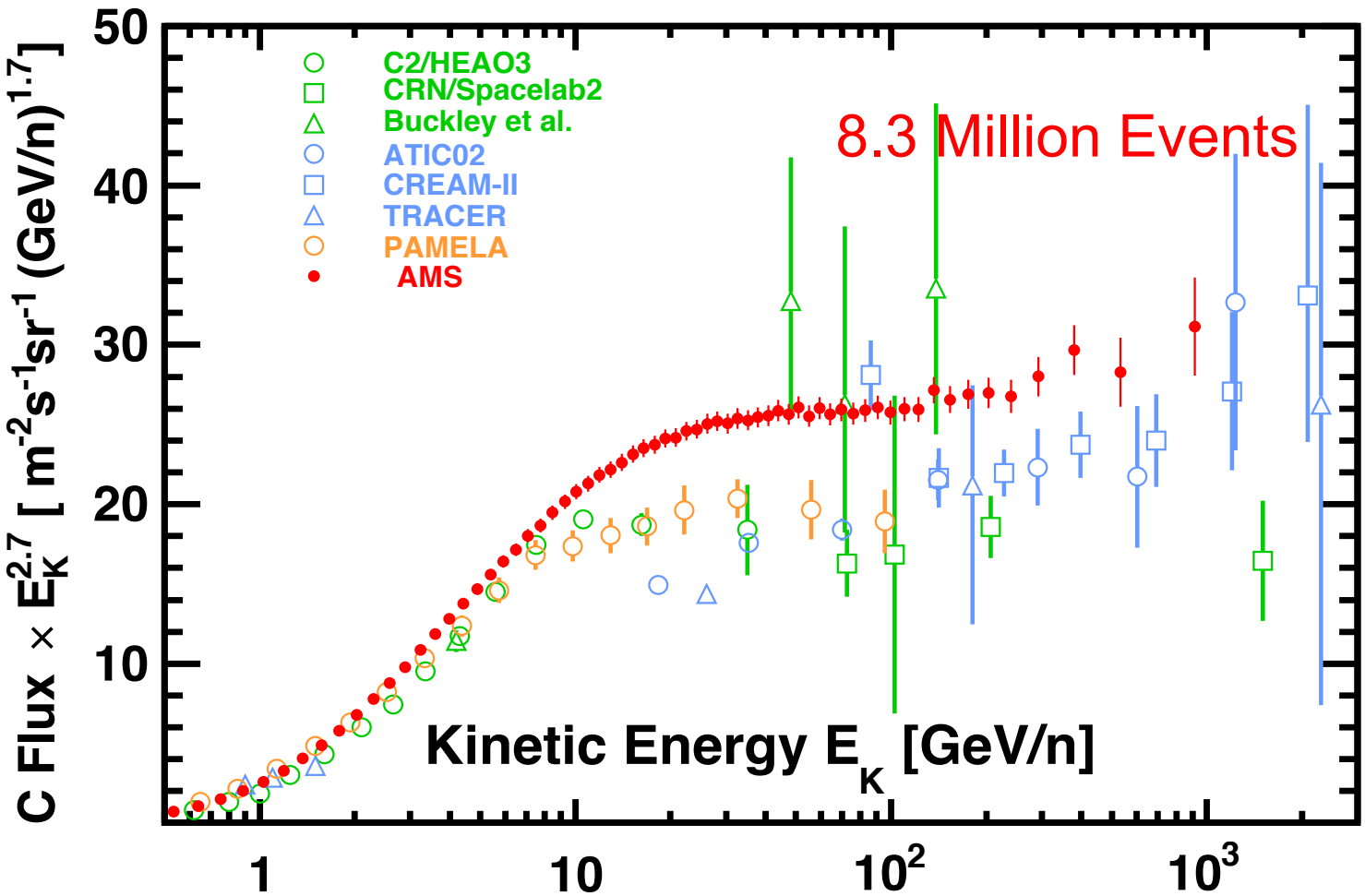


Carbon Flux Errors Breakdown

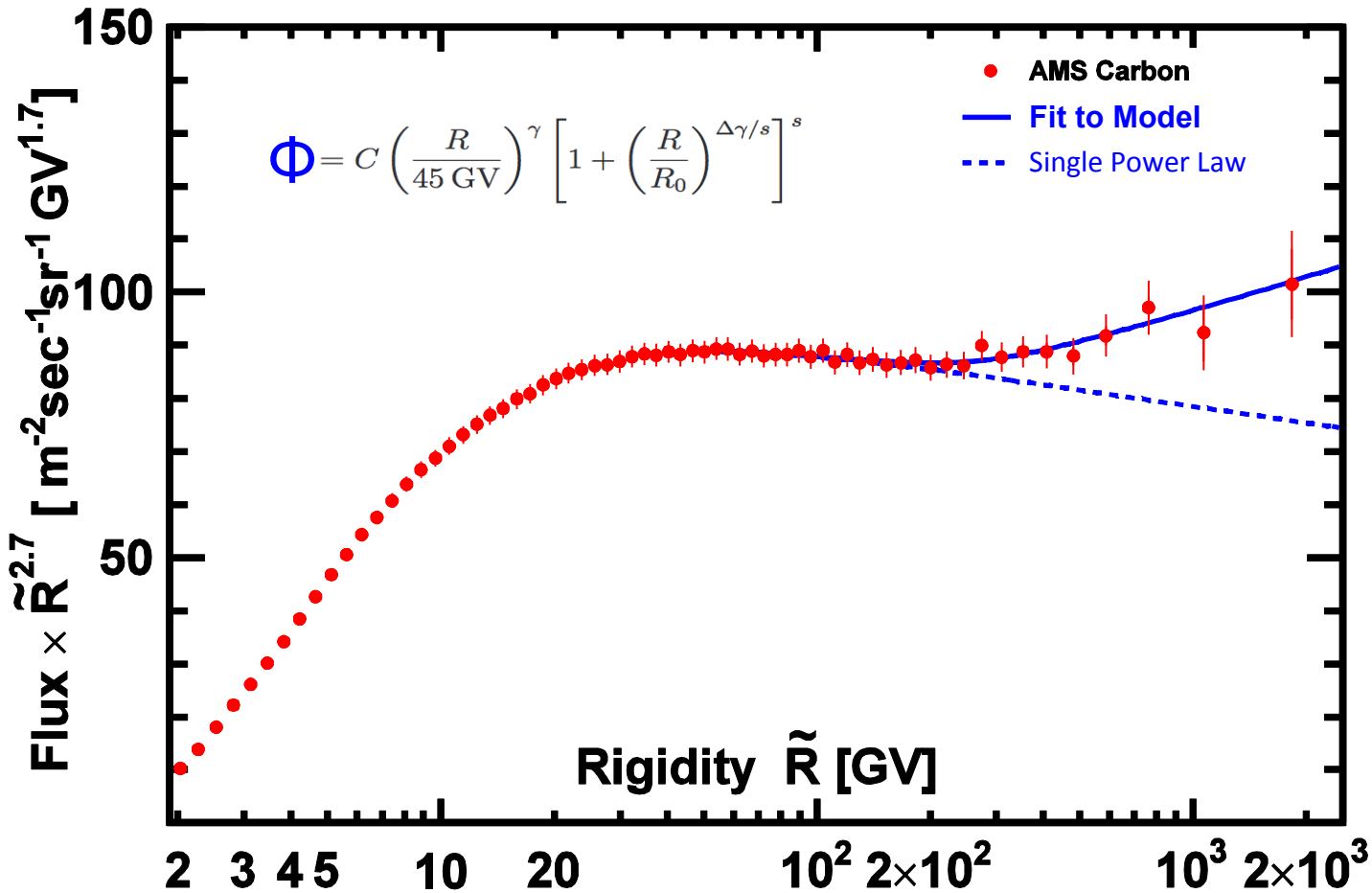


Carbon Flux

The current precision of the data at highest energies is limited by statistics.

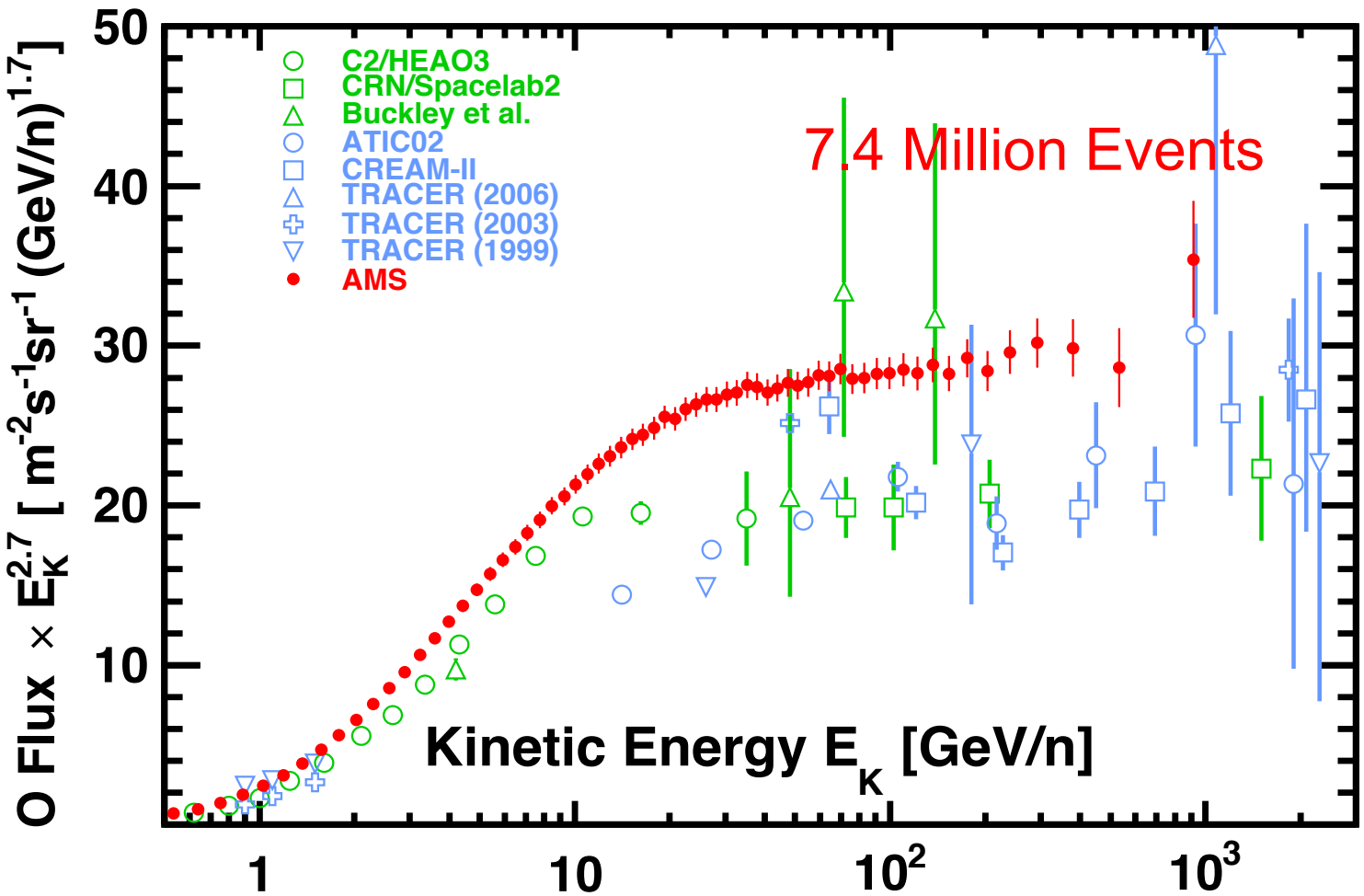


The High Rigidity Behavior of Carbon Flux

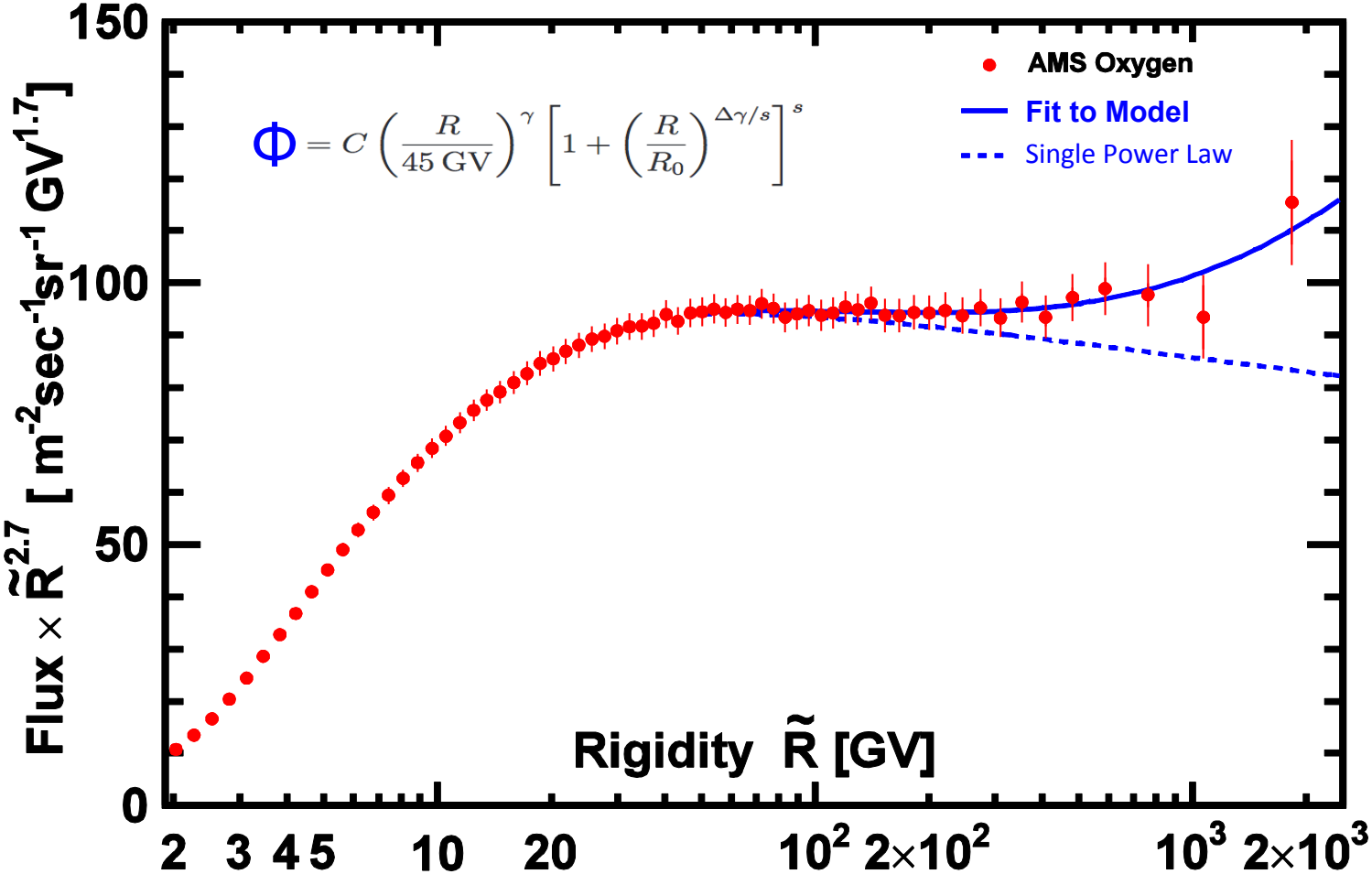


Oxygen Flux

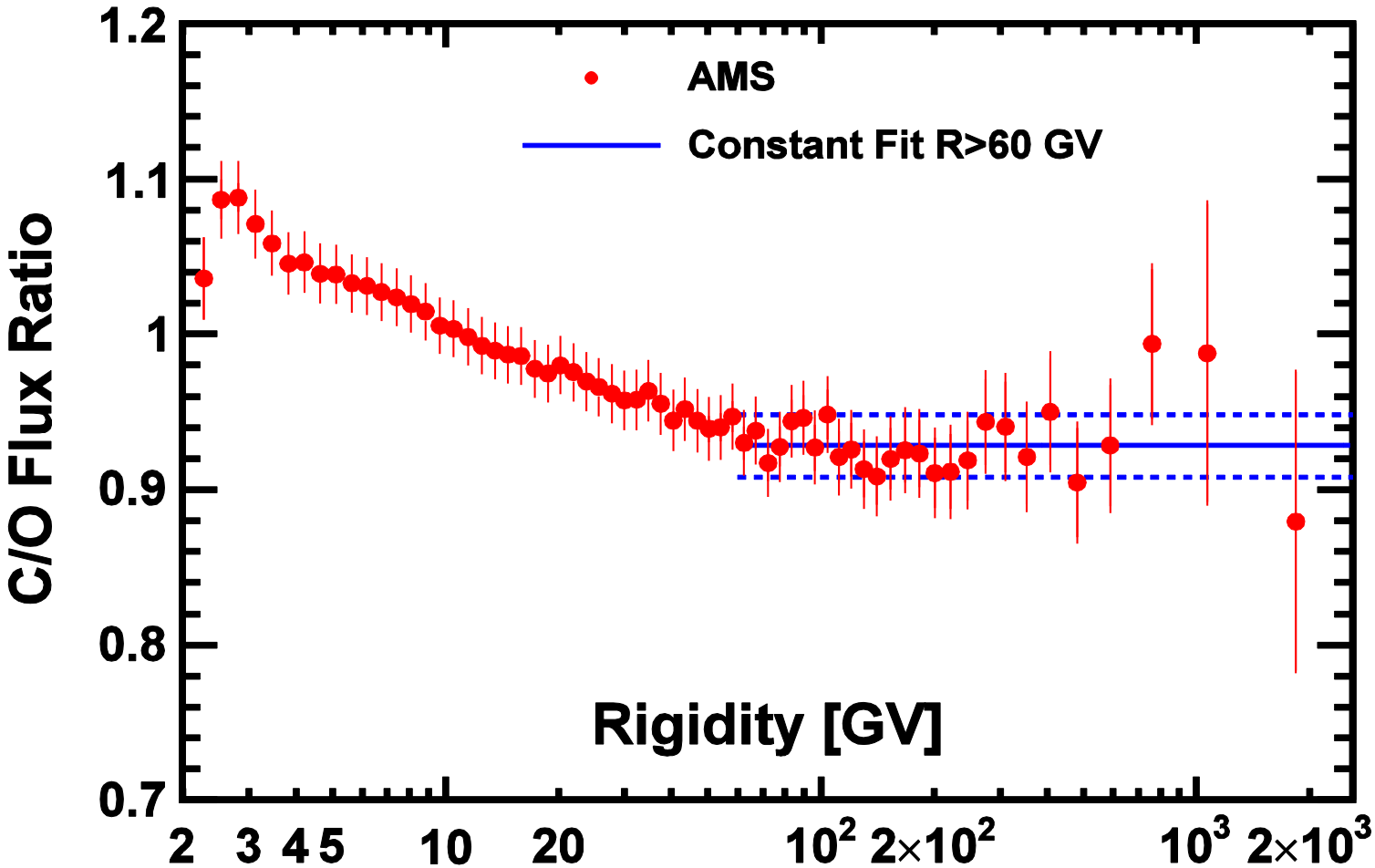
The current precision of the data at highest energies is limited by statistics.



The High Rigidity Behavior of Oxygen Flux

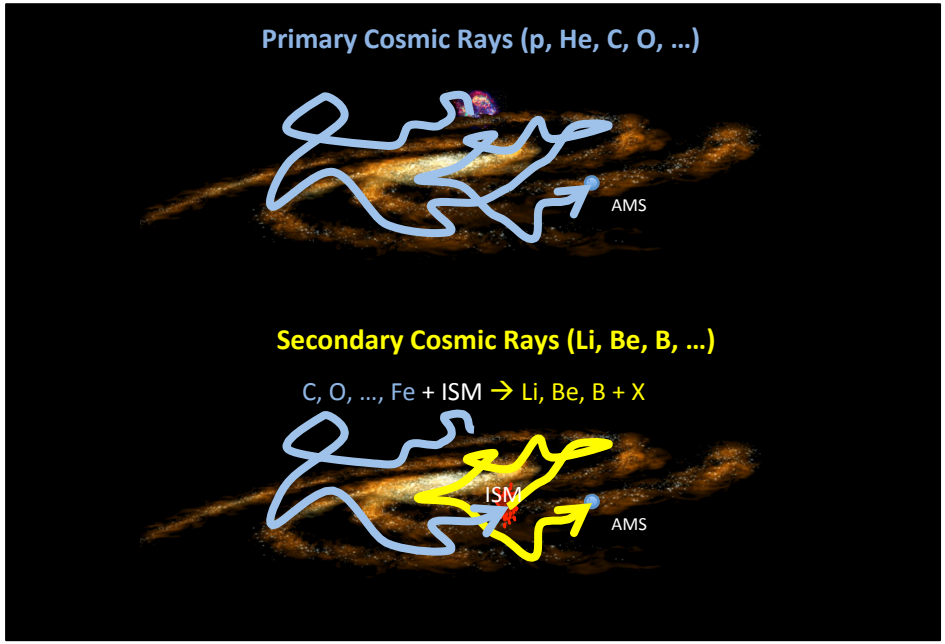


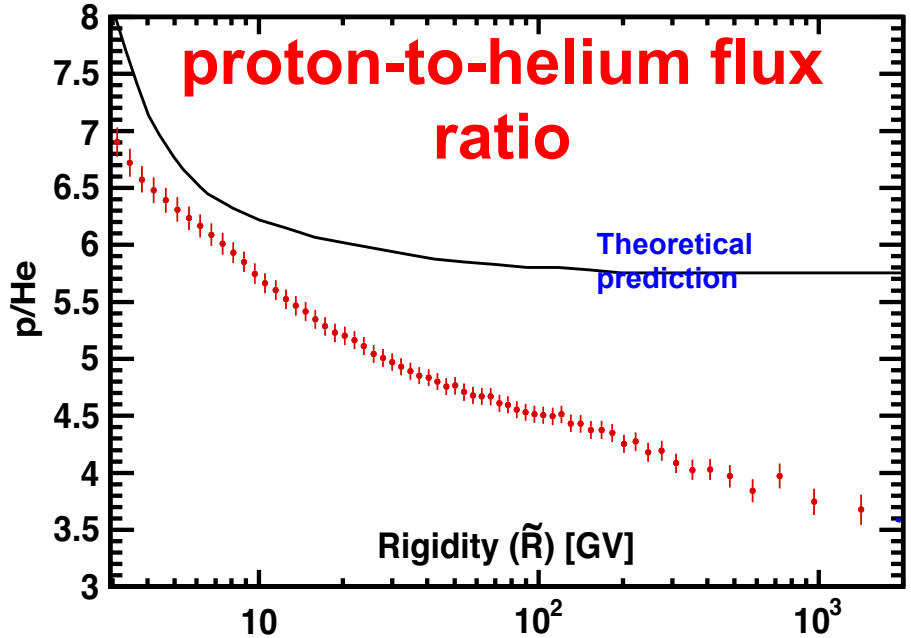
Carbon/Oxygen Flux Ratio

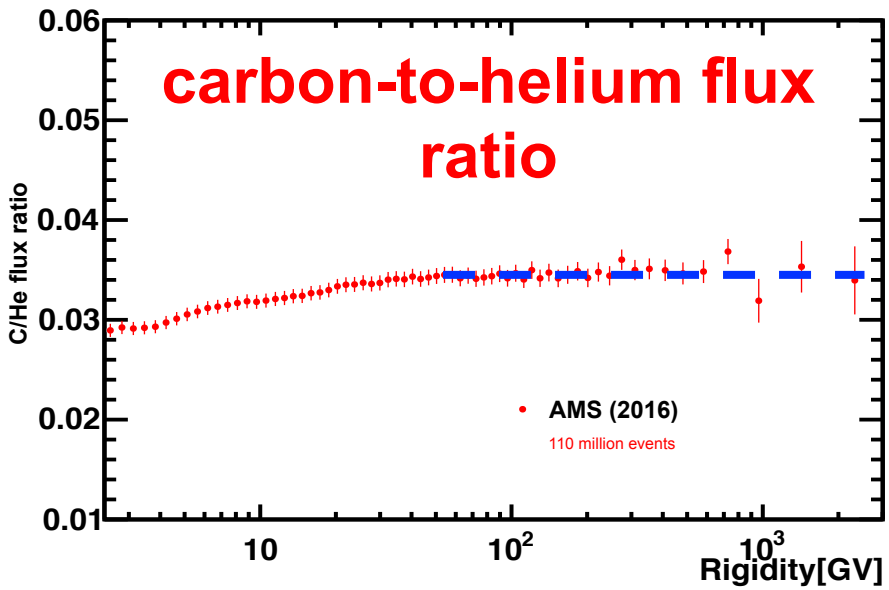


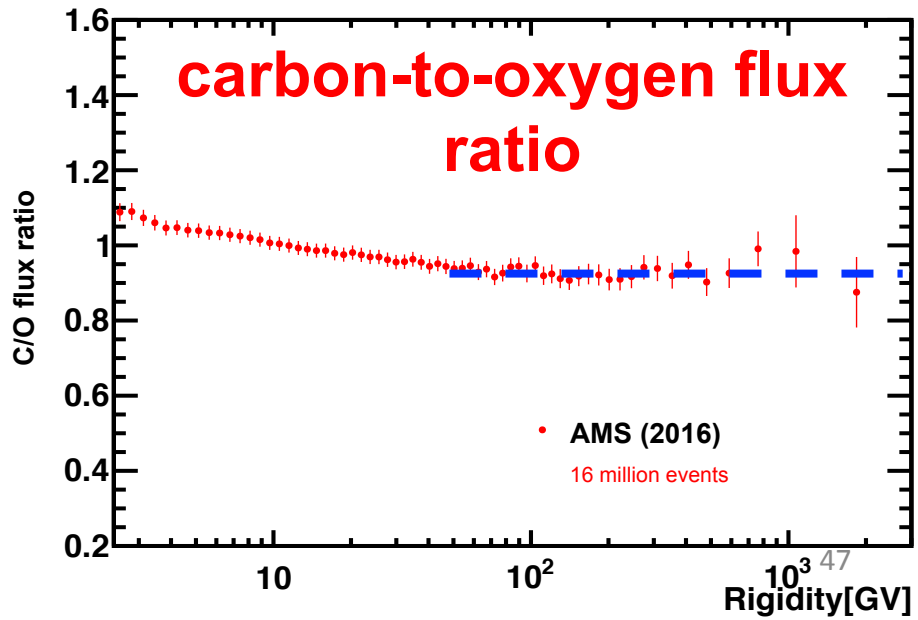
Summary (on nuclei)

The flux ratios of primary cosmic rays are energy independent except p/He



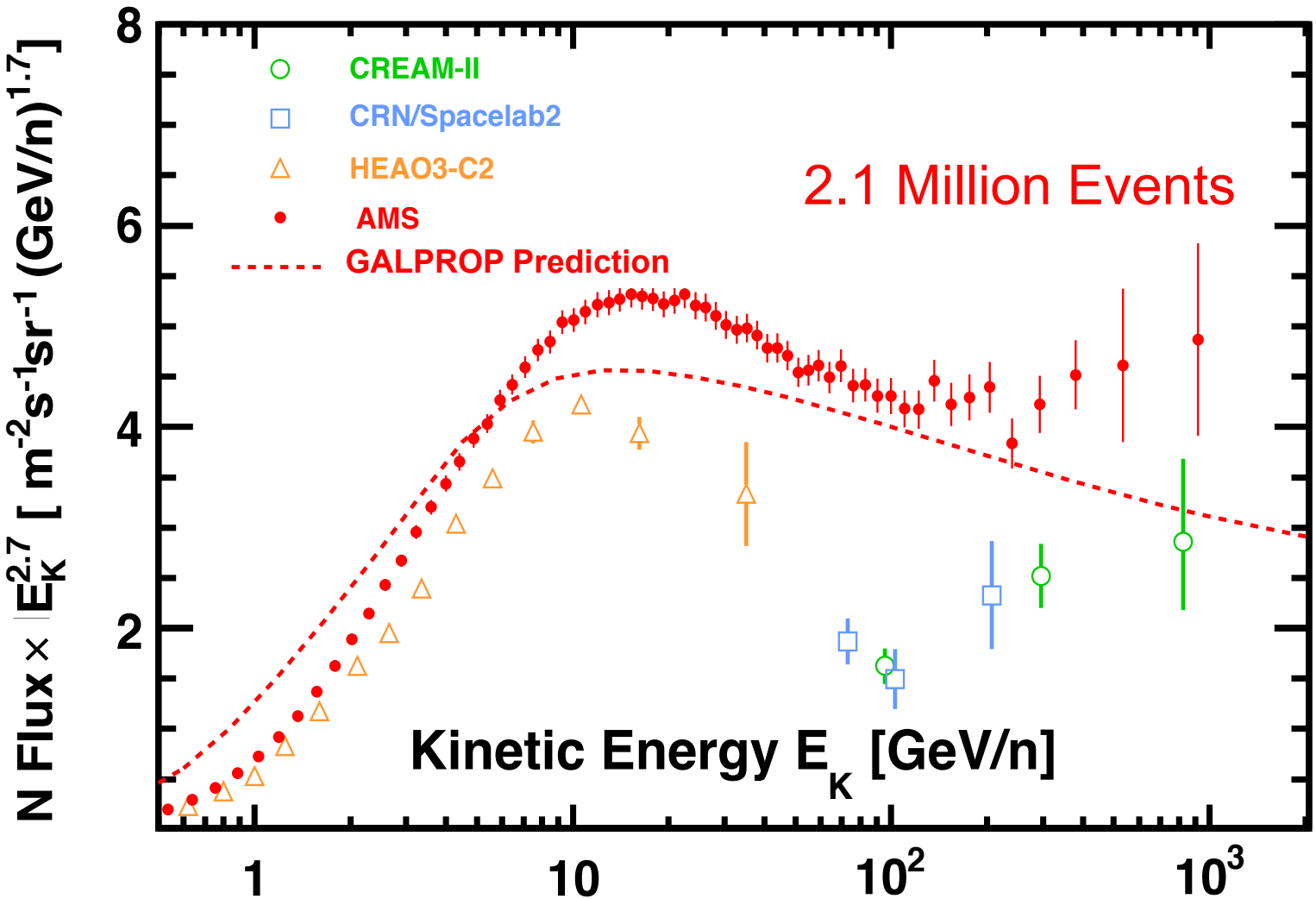




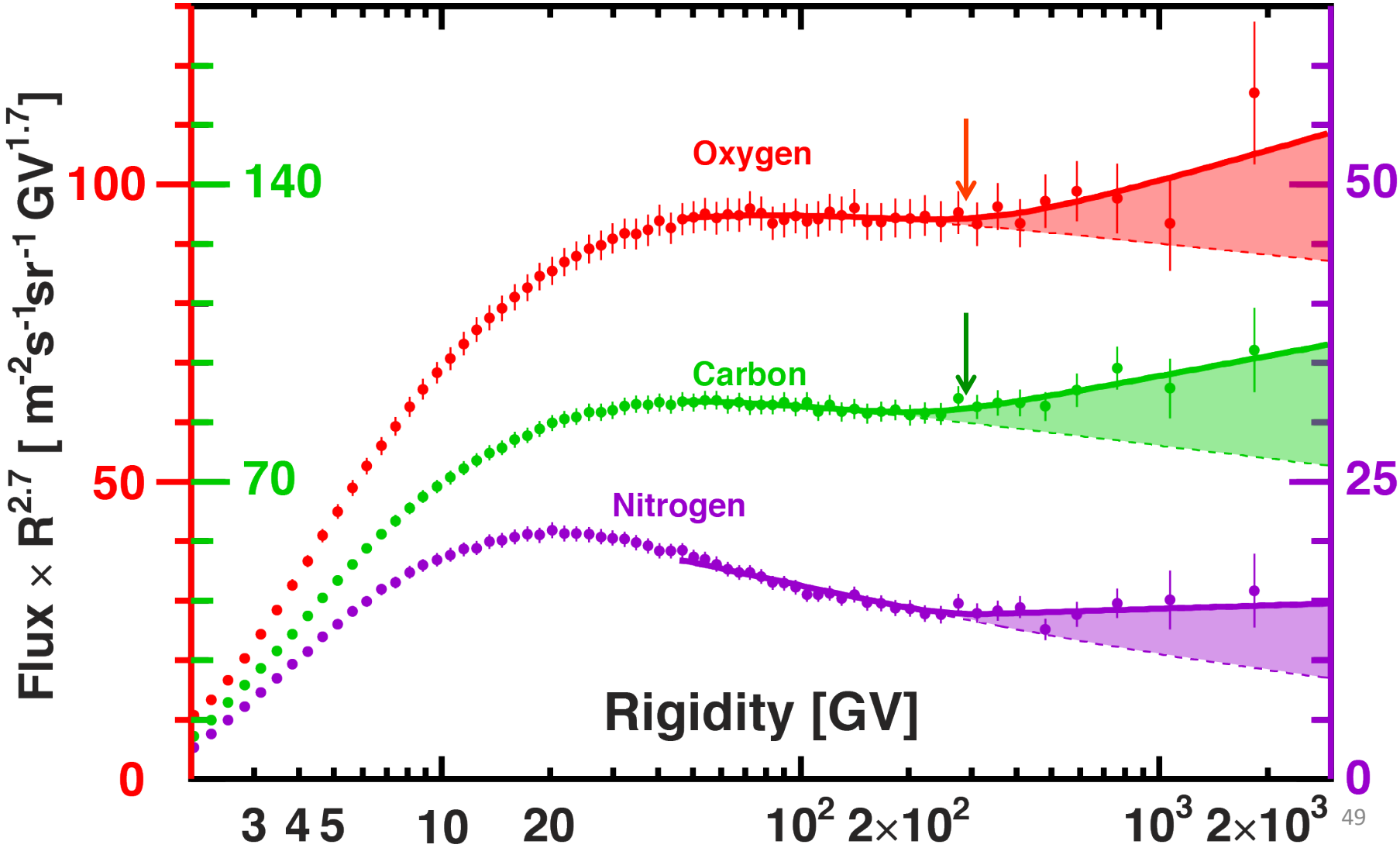


Nitrogen Flux

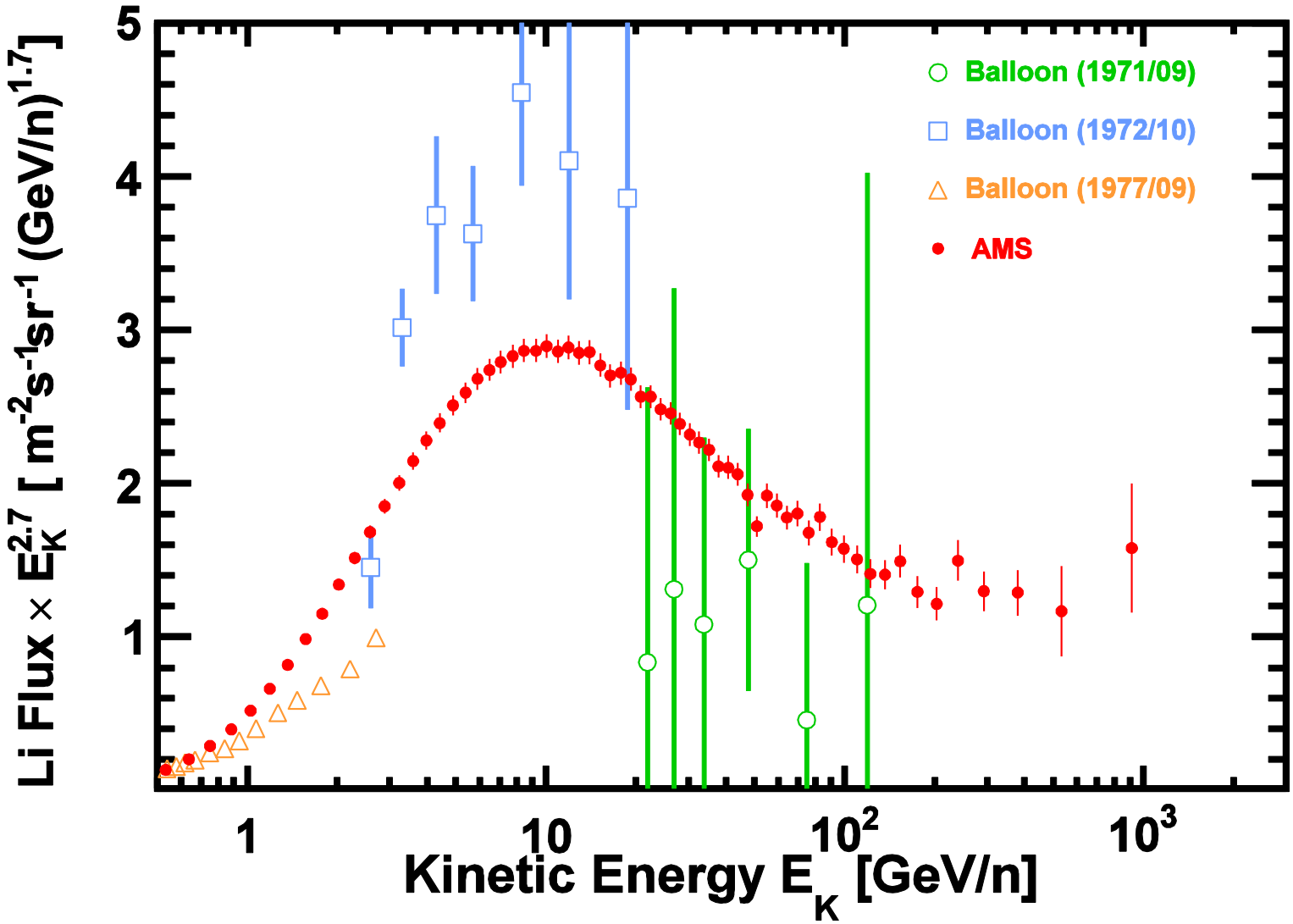
The current precision of the data at high energies is limited by statistics.



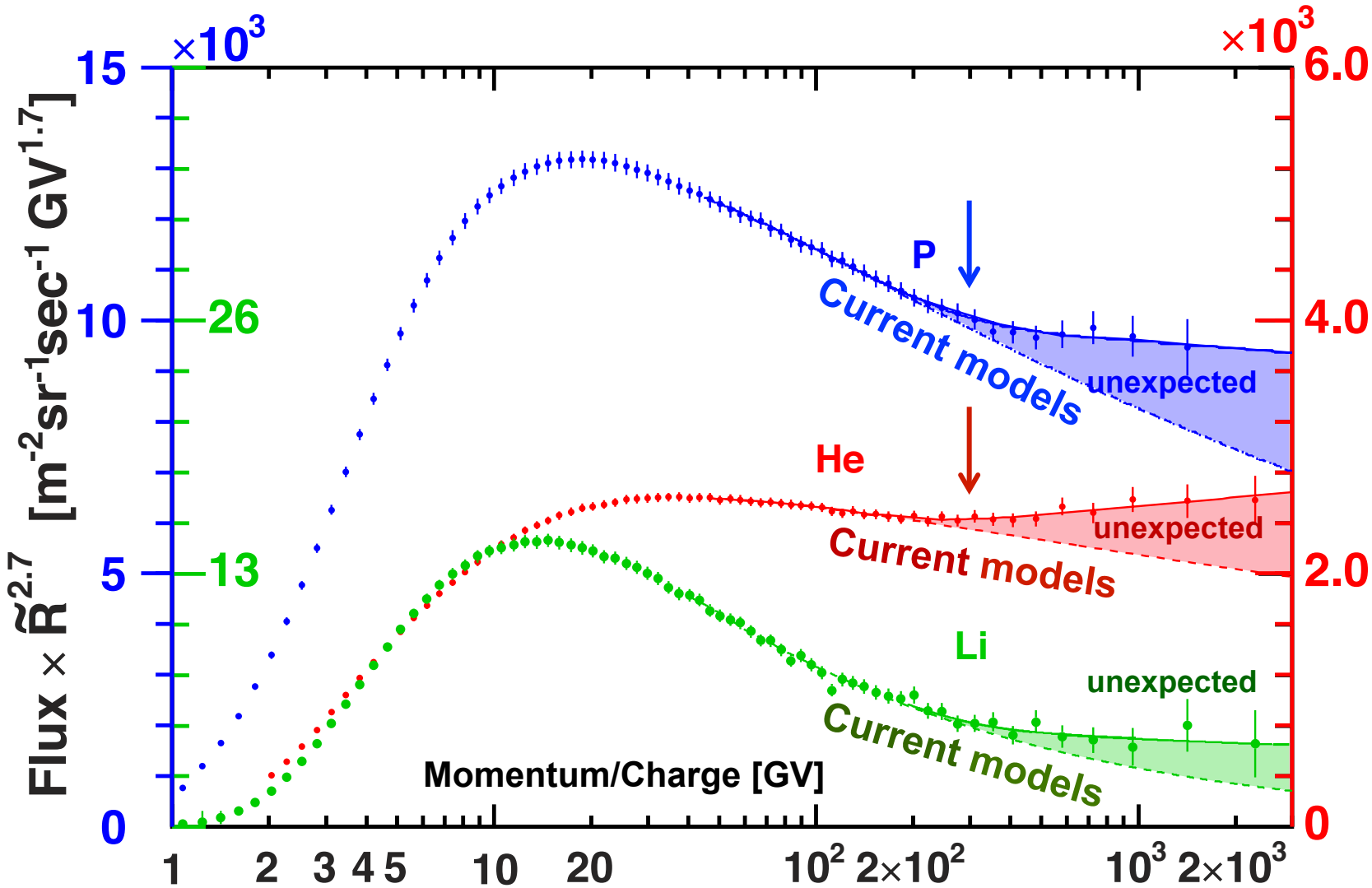
The spectra of oxygen, carbon and nitrogen do not follow the traditional single power law.



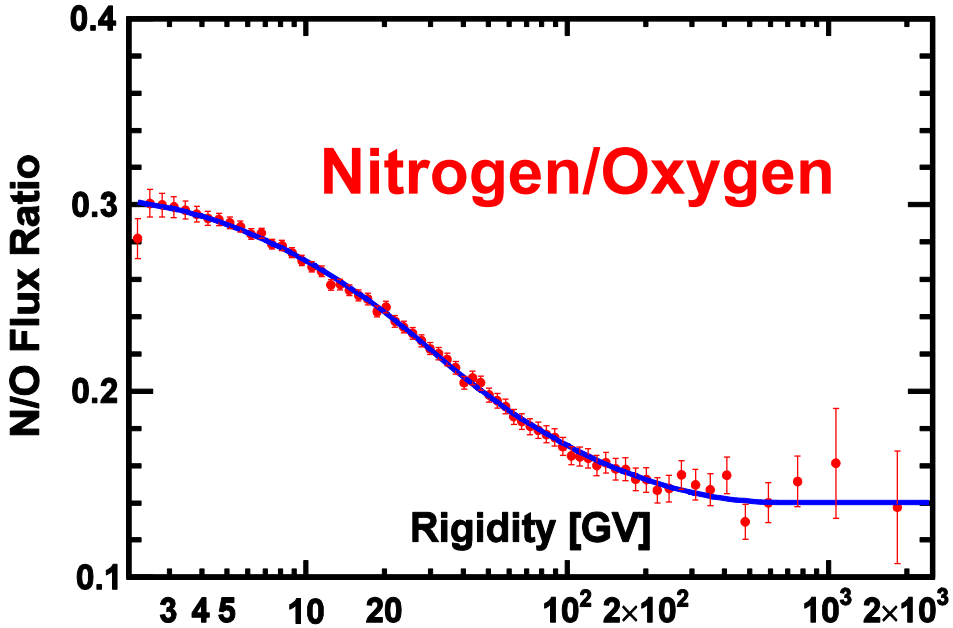
Lithium Flux

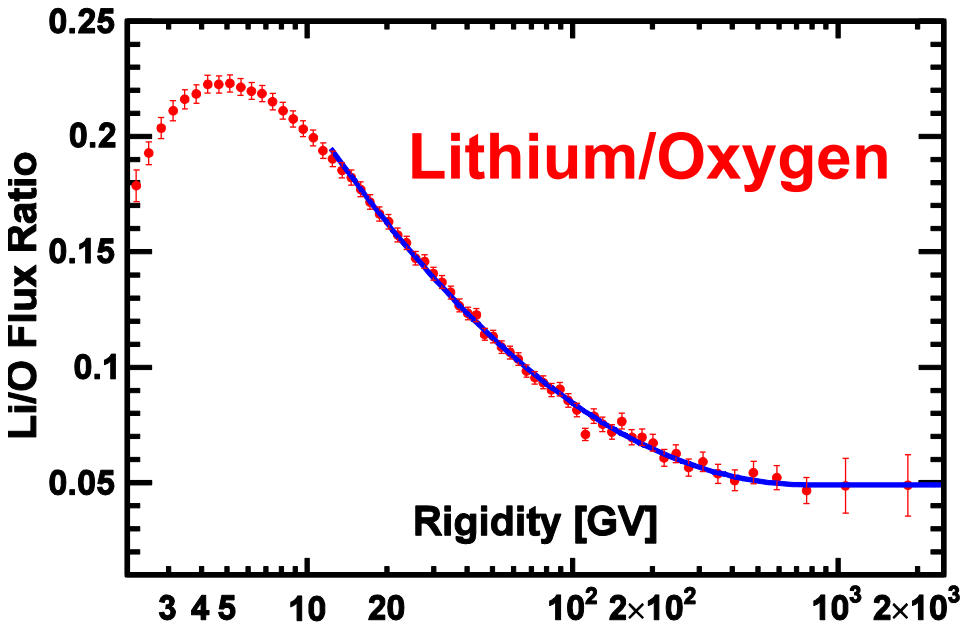


The spectra of protons, helium and lithium do not follow the traditional single power law.

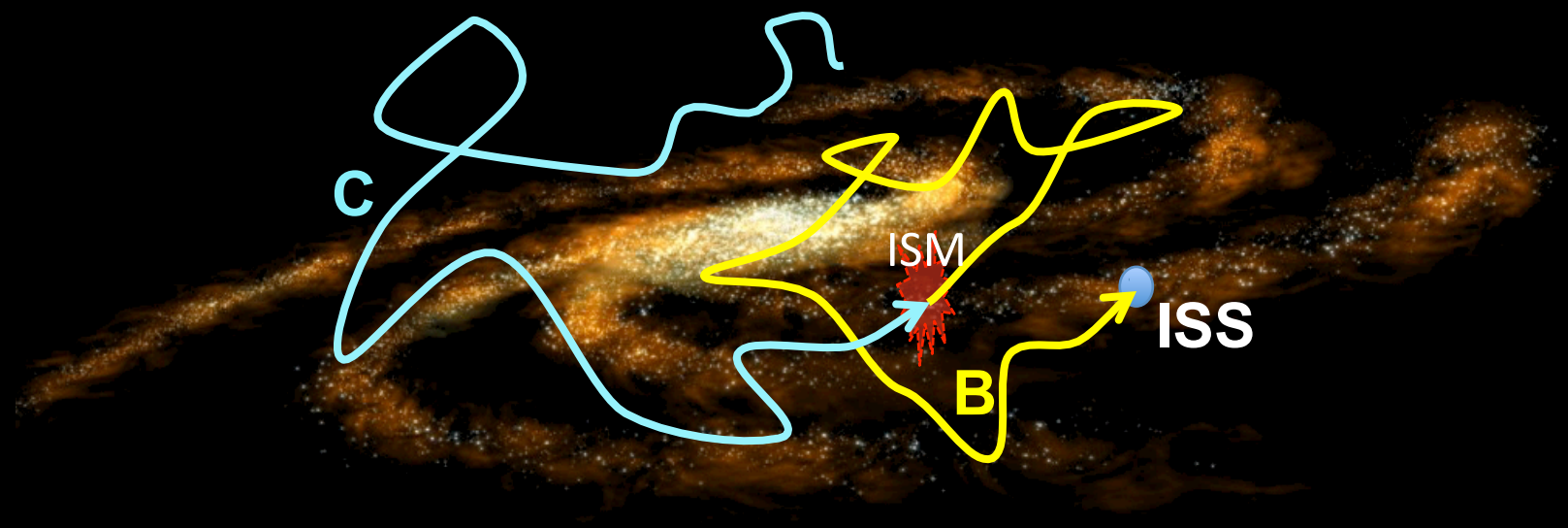


Nitrogen-to-Oxygen and Lithium-to Oxygen Ratio Approaches constant at High rigidities





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

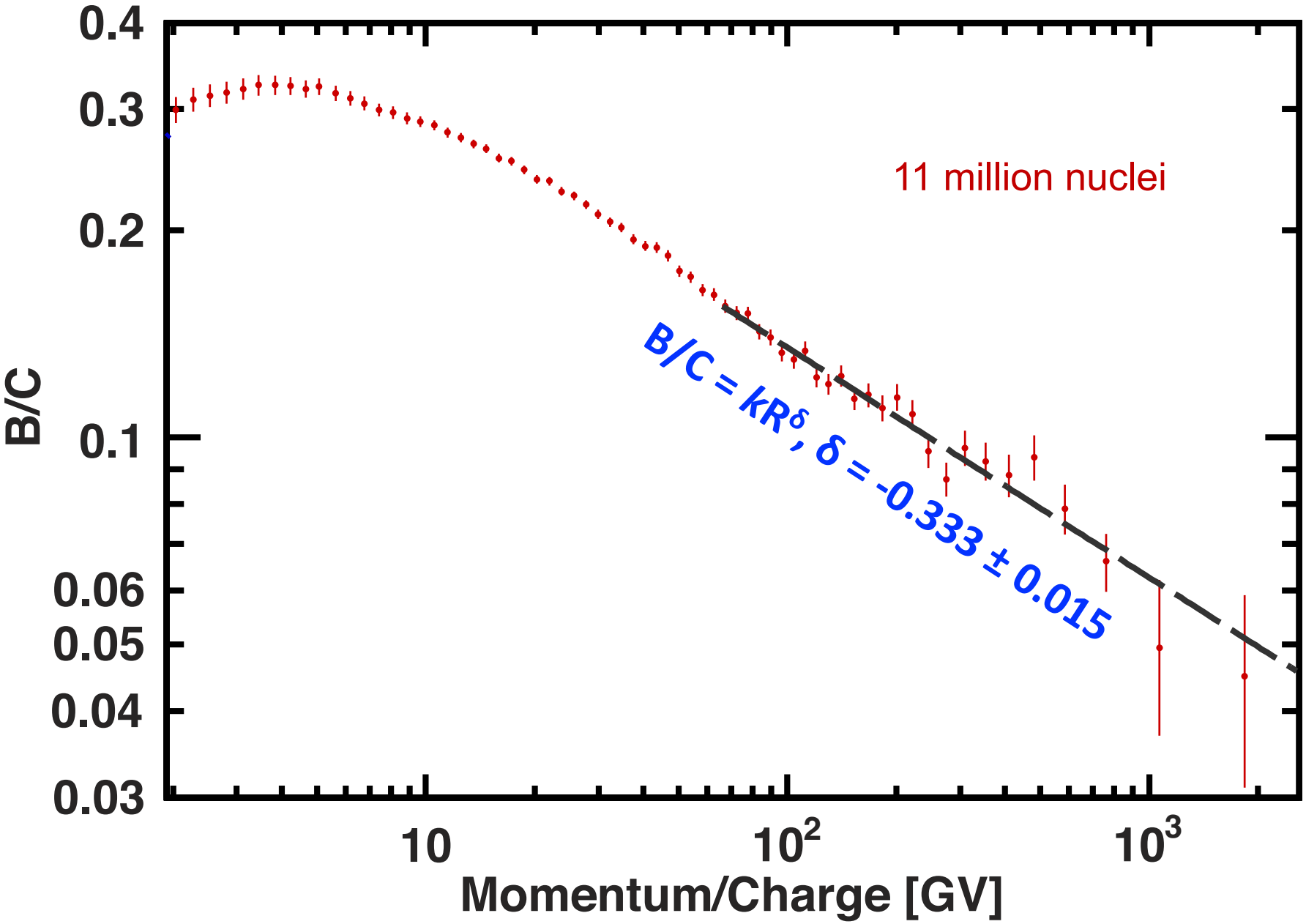


Cosmic ray propagation is commonly modeled as a fast moving gas diffusing through a magnetized plasma.

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

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

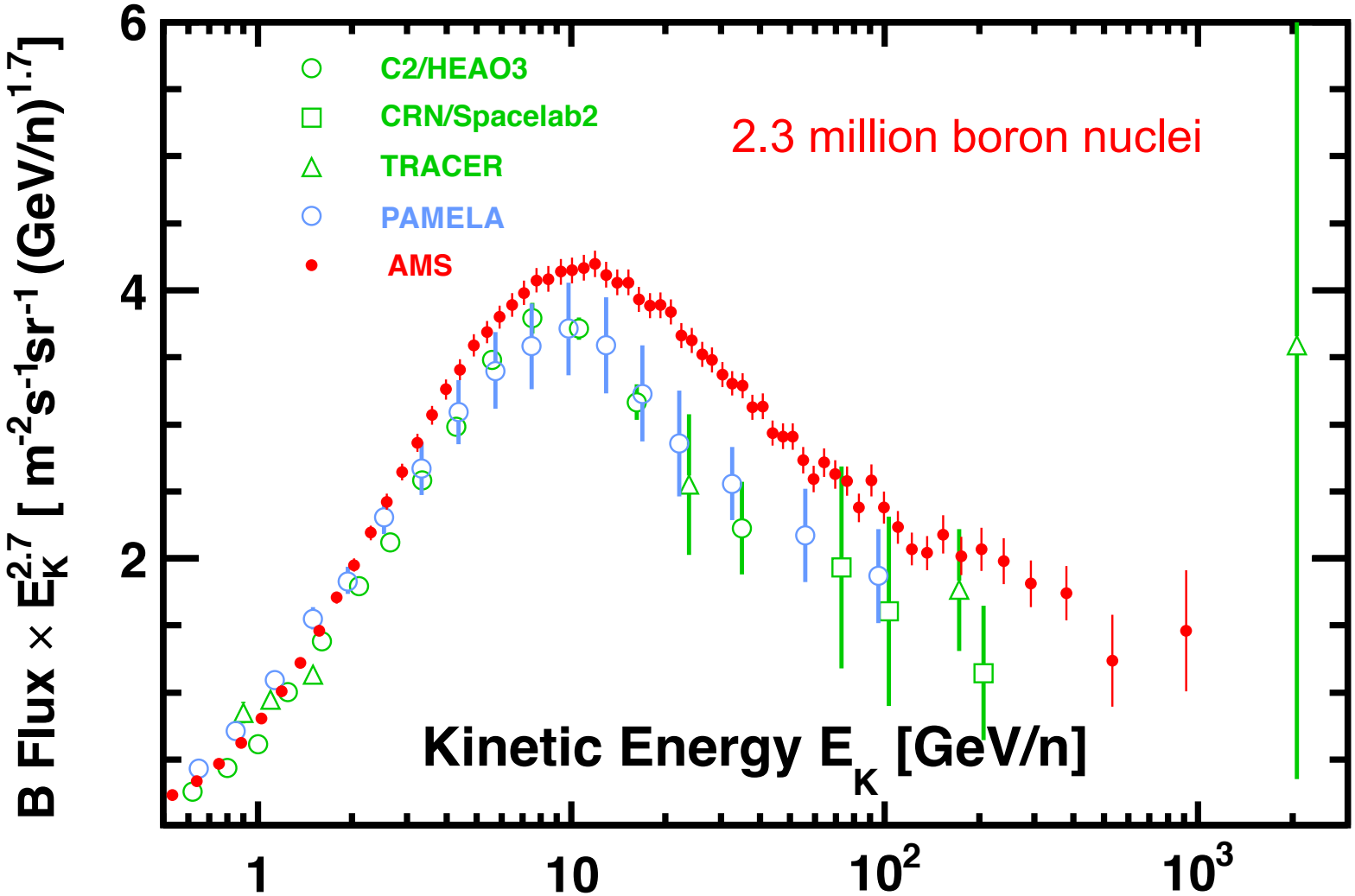
Boron-to-Carbon Ratio



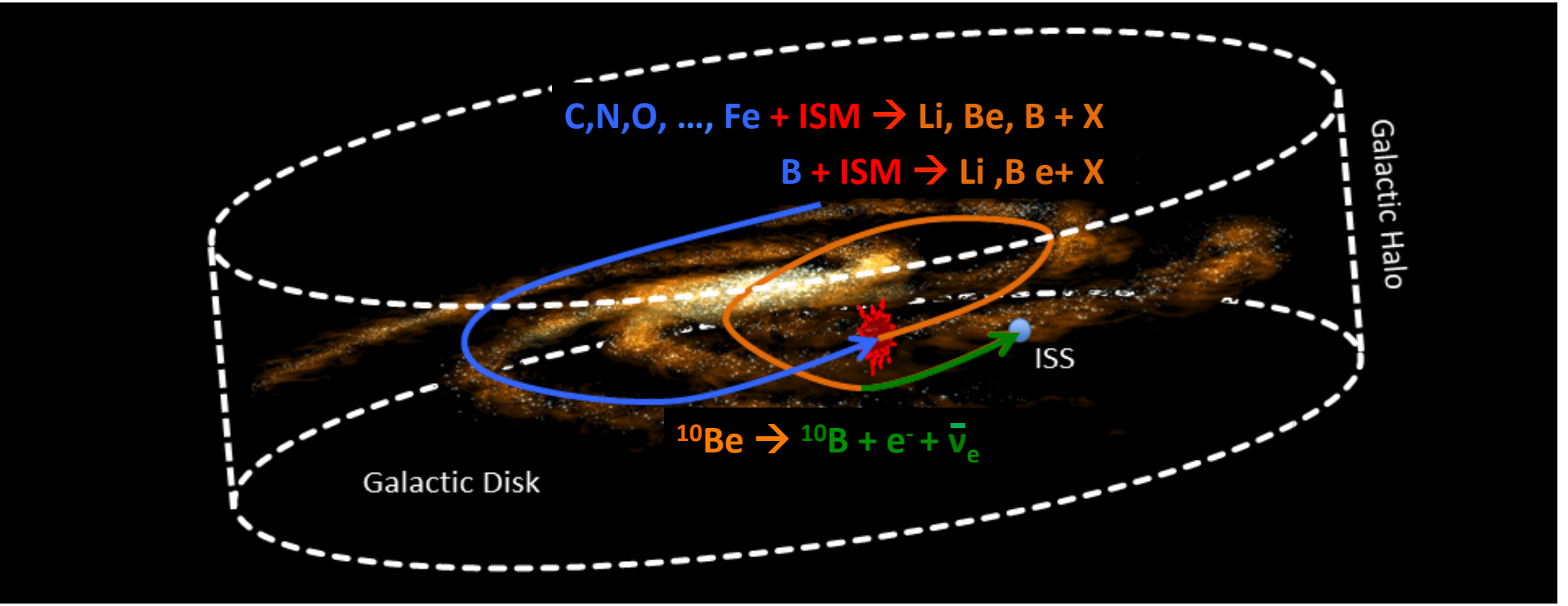
M. Aguilar *et al.*, Phys. Rev. Lett. **117,** 231101 (2016)

Boron Flux

The current precision of the data at high energies is limited by statistics.

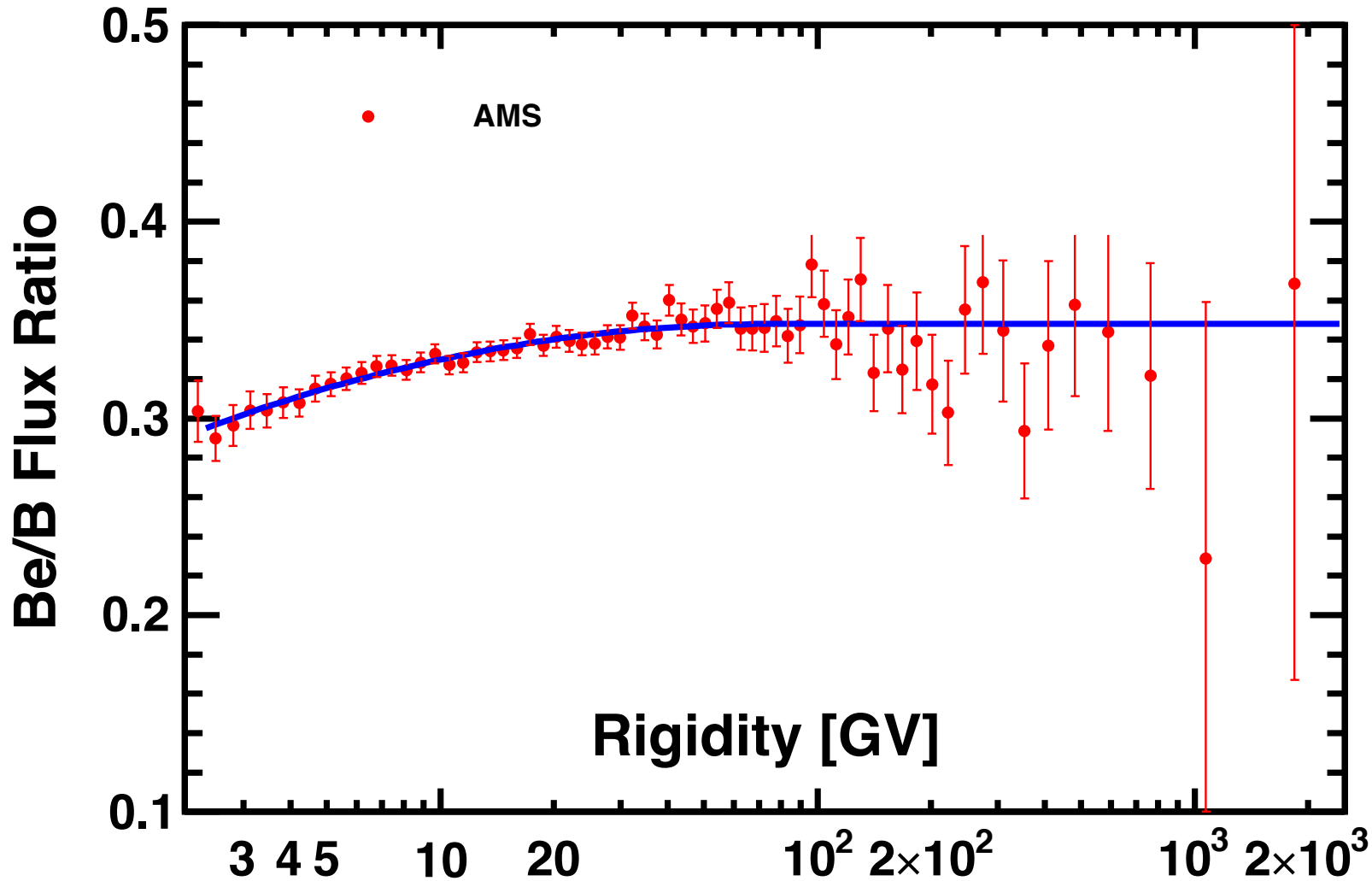


Be/B Flux Ratio Measurement

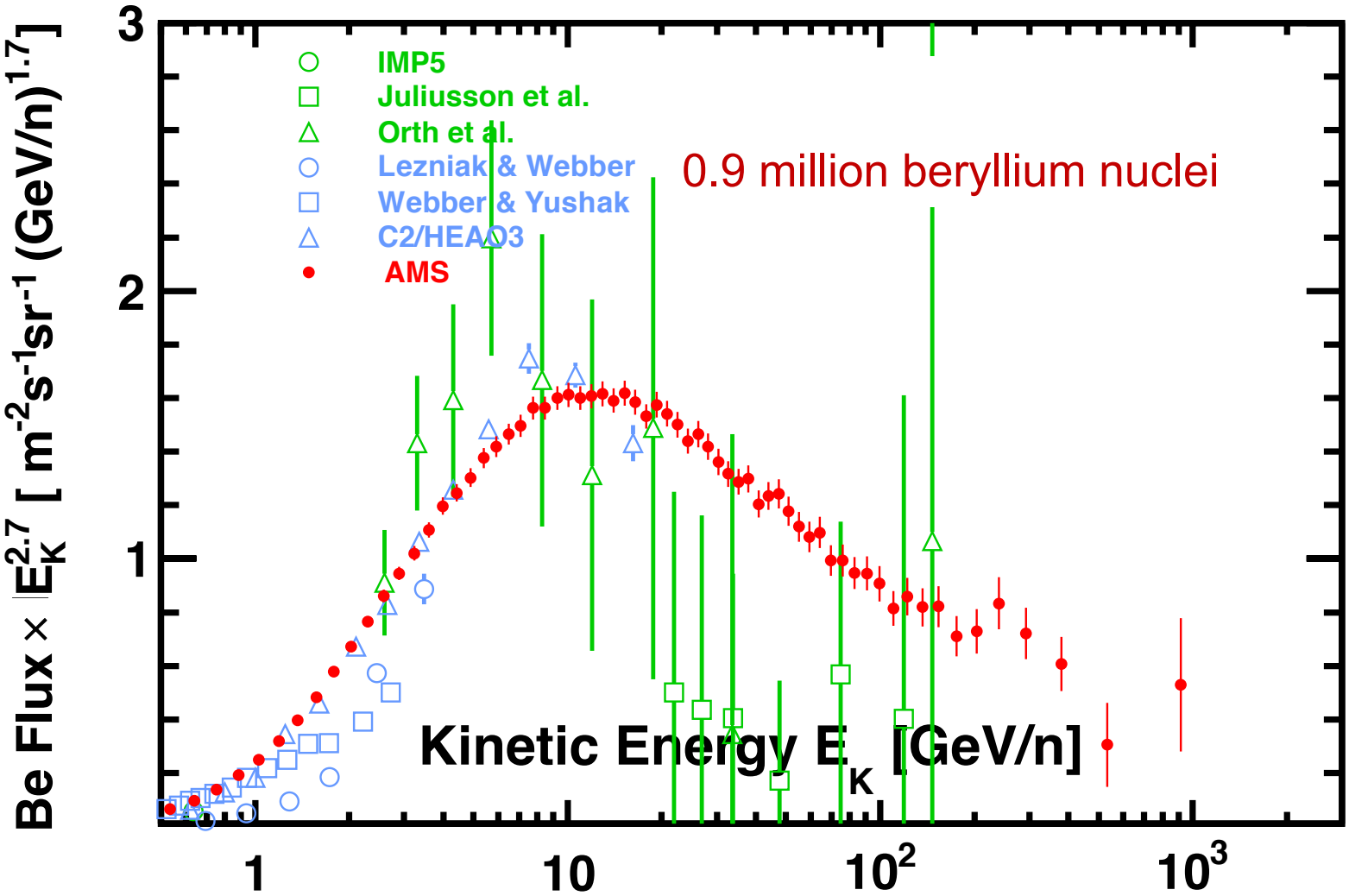


Be isotopes (^{7}Be, ^{9}Be, ^{10}Be) are generated by spallation of B, C,N,O …
^{10}Be is not stable, decays into ^{10}B with half-life of 1.5 M years.
Due to relativistic time dilation, the fraction of ^{10}Be increase with energy, so the raising energy dependence of Be/B reveals the characteristic lifetime of cosmic rays in the Galaxy.

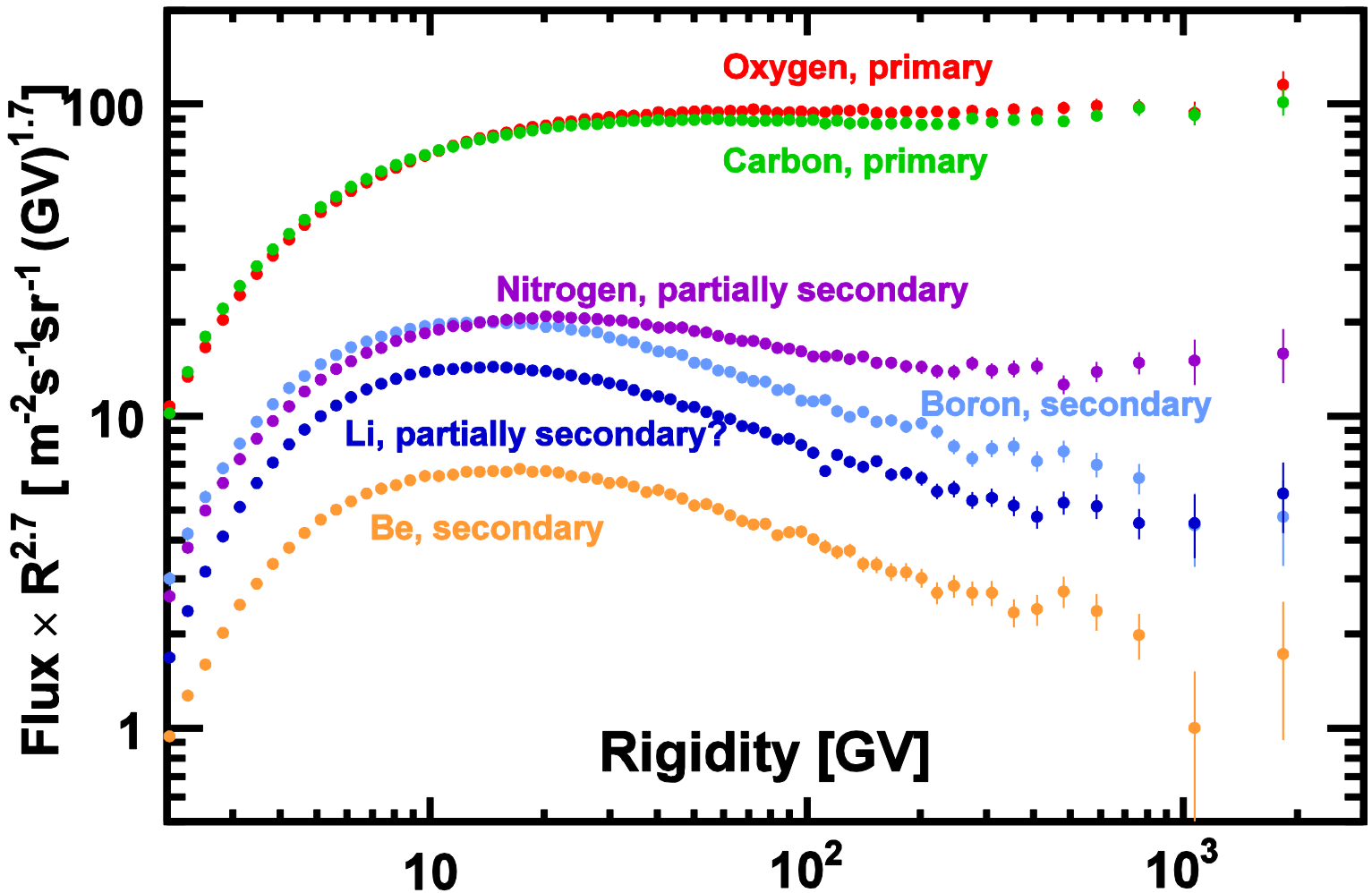
Be-to-Boron Ratio
Rigidity Dependence is seen



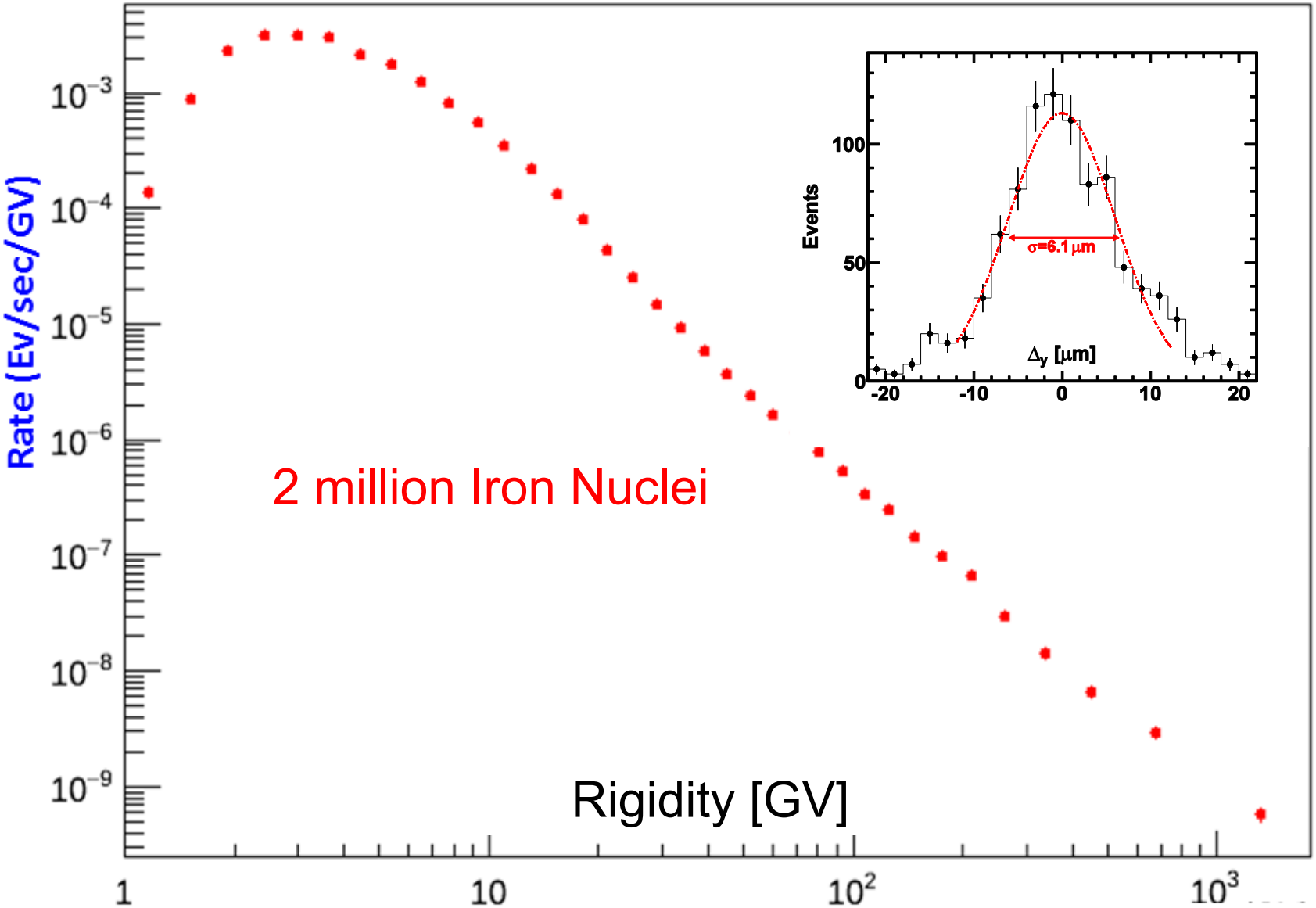
Be Flux


IMP5
Juliusson et al.
Orth et al.
Lezniak & Webber
Webber & Yushak
C2/HEAO3
AMS
0.9 million beryllium nuclei
Kinetic Energy E_K [GeV/n]
Be Flux × $E_K^{2.7}$ [$m^{-2}s^{-1}sr^{-1}$ $(GeV/n)^{1.7}$]
3
2
1
1
10
10^2
10^3

Primary and Secondary Nuclei Energy Dependence Summary



Future Examples: Iron



Summary Nuclear Fluxes

- Precise measurements of nuclear fluxes for Li, Be, B, C, N and O as well as the flux ratio measurement based on 5 Years AMS Data were presented:
  - The detailed variations of fluxes dependence with rigidity are being studied.
  - The measurements are still limited by statistics, and are expected to be significantly improved towards 2024.

Summary Nuclear Fluxes

- To Year 2024 AMS will provide precision measurements of nuclear fluxes up to Z=28 … from GV to few TV:
  - The detailed variations of fluxes dependence with rigidity will be studied.
  - The flux ratios measurements will allow to extract precise information about cosmic ray propagation.

backup

Lithium-to-Boron Ratio
No rigidity dependence 10-100 GV