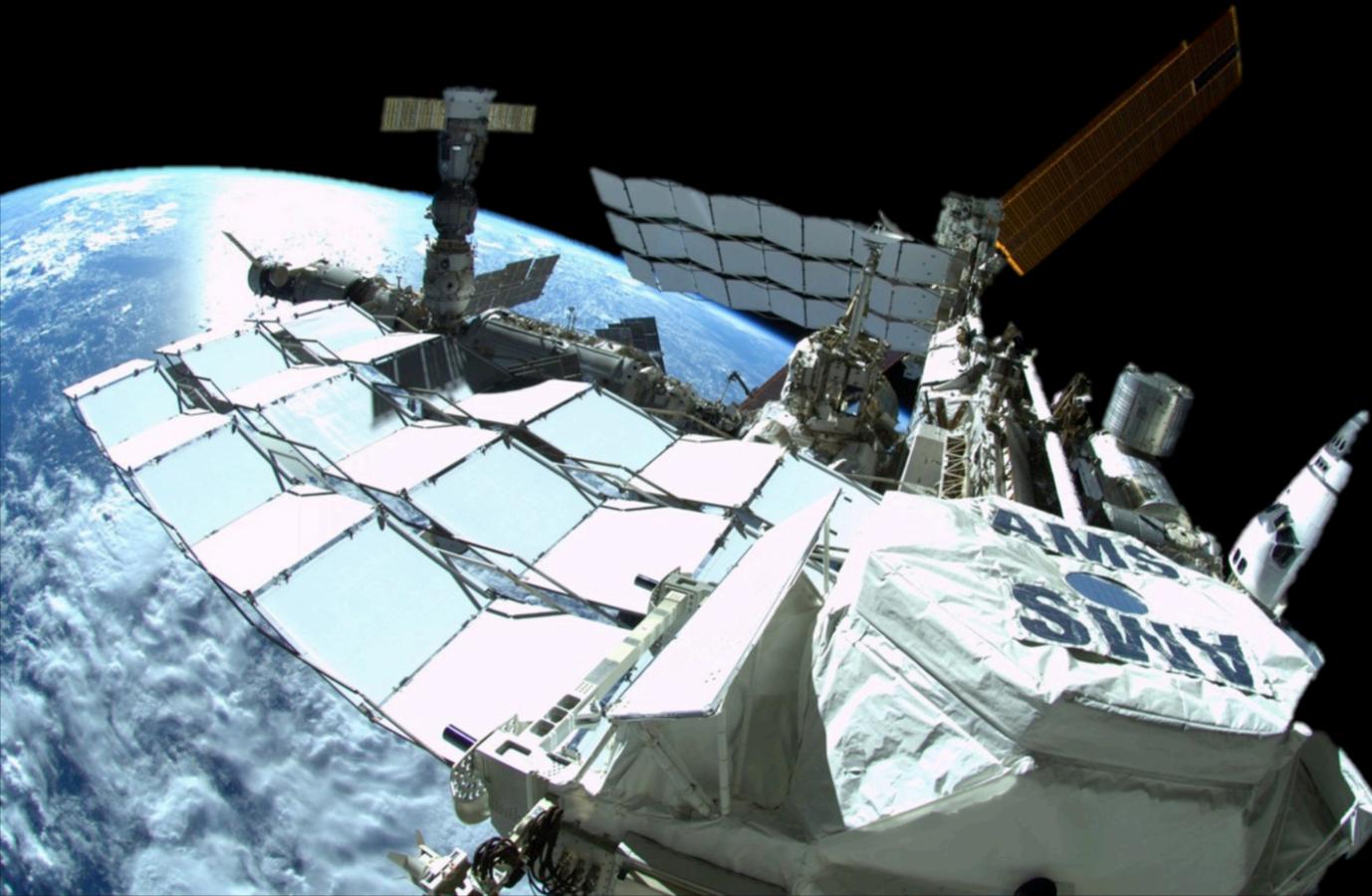


# *Observation of Properties of Primary and Secondary Cosmic Rays by the Alpha Magnetic Spectrometer on the International Space Station*

*A. Oliva\* on behalf of the AMS-02 Collaboration.*

*\*Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain*



*ISVHECRI 2018,  
24/05/2018,  
Nagoya, Japan*

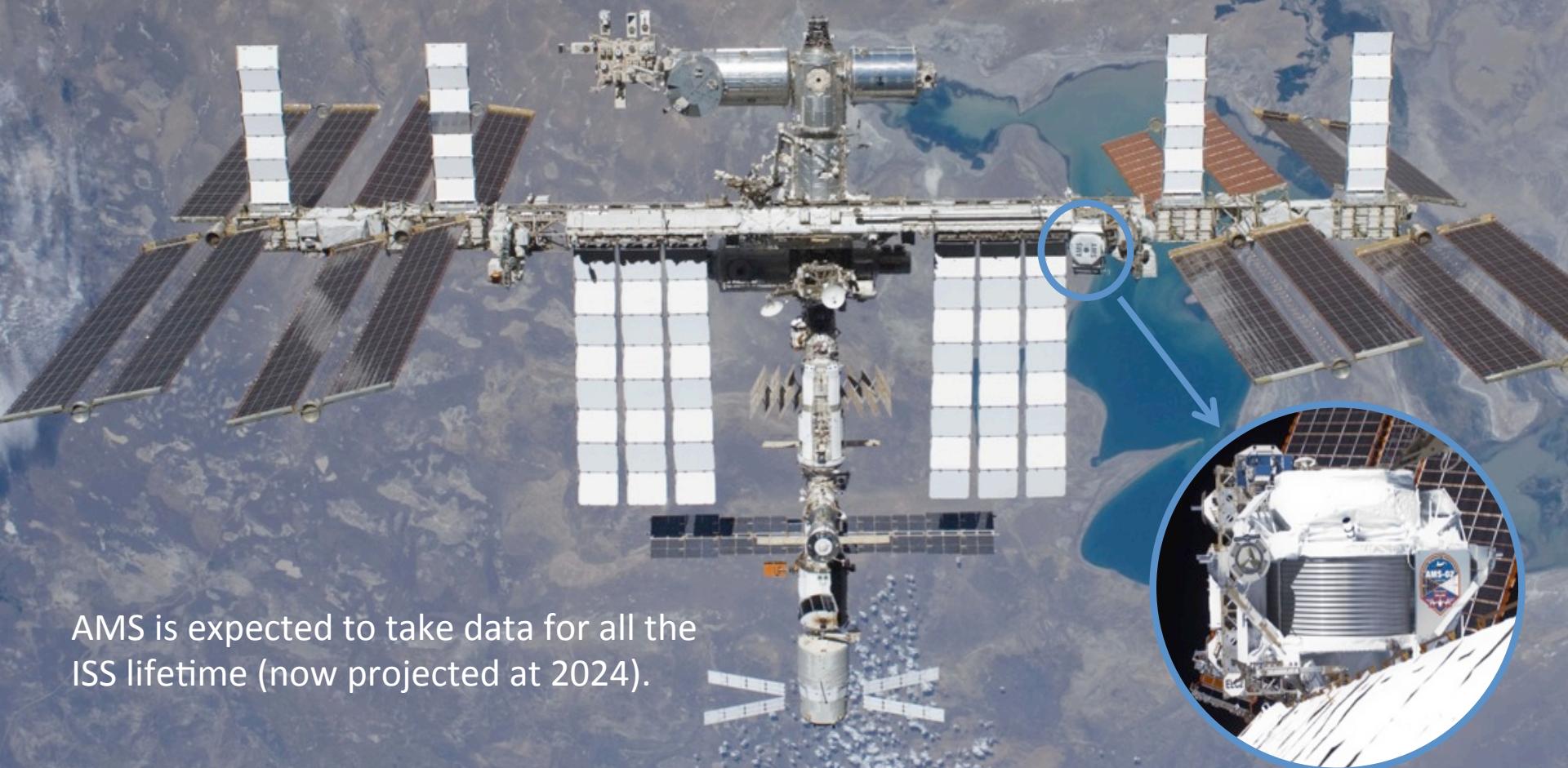


# AMS-02 On Orbit

From May 19<sup>th</sup> 2011 active on ISS, operating continuously since then.

AMS has collected >117 billion cosmic rays in 7 years.

With such a statistics the most rare components of the cosmic rays are visible.

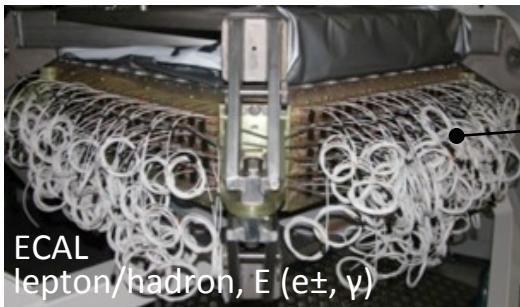
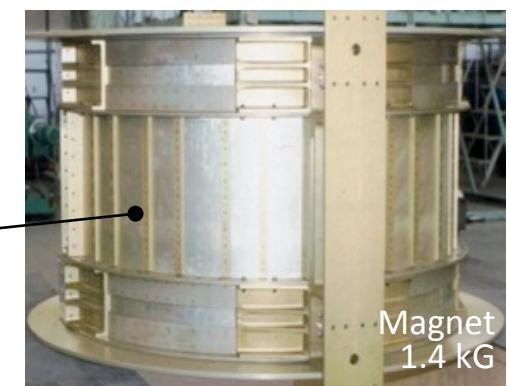
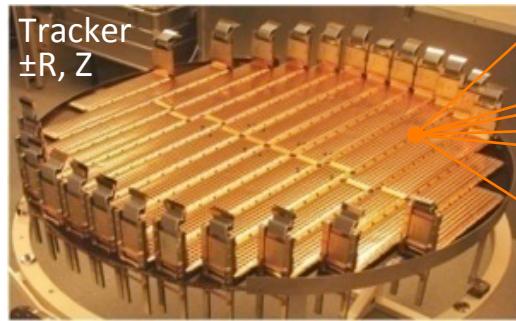
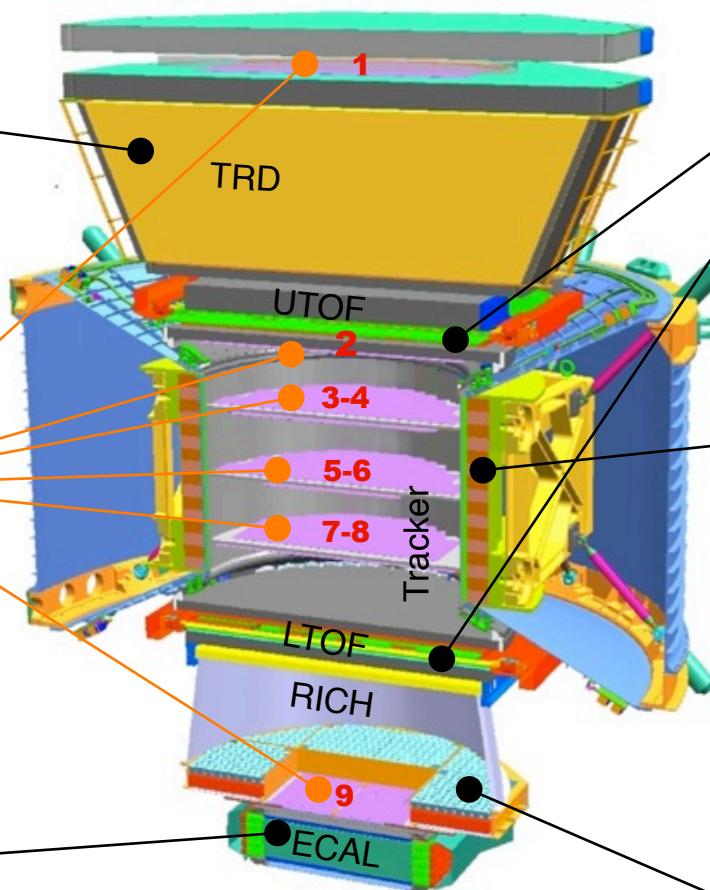
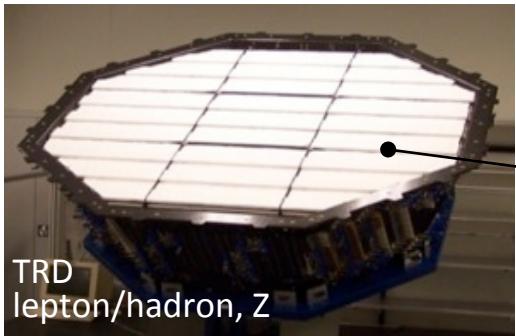


AMS is expected to take data for all the  
ISS lifetime (now projected at 2024).

# AMS-02: A TeV Multi-purpose Spectrometer

3

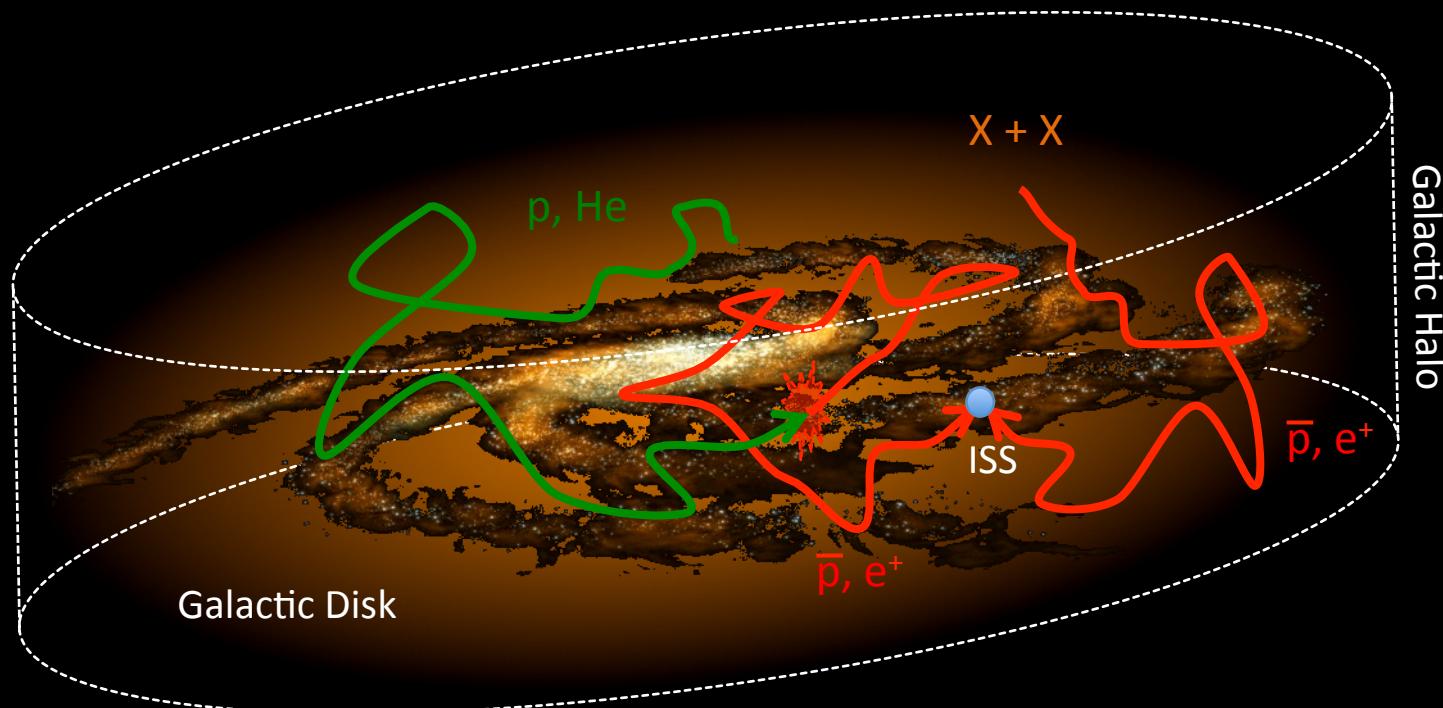
Separates hadrons from leptons, matter from anti-matter and able to do CRs chemical and isotopic composition in GeV to TeV range.



Multiple and Independent Measurement of Charge (Z), Energy ( $\beta, p, E$ ) and Charge Sign ( $\pm$ ).

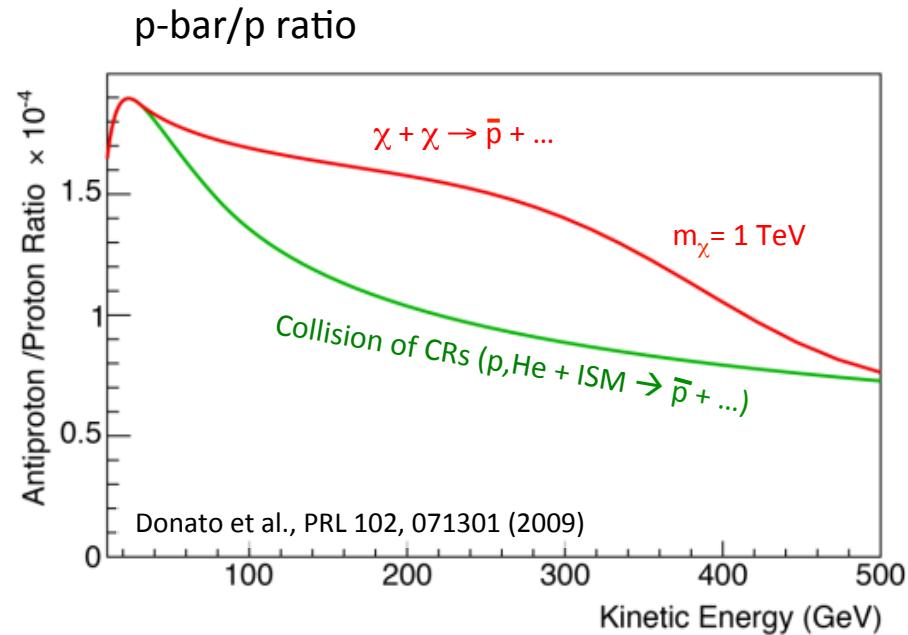
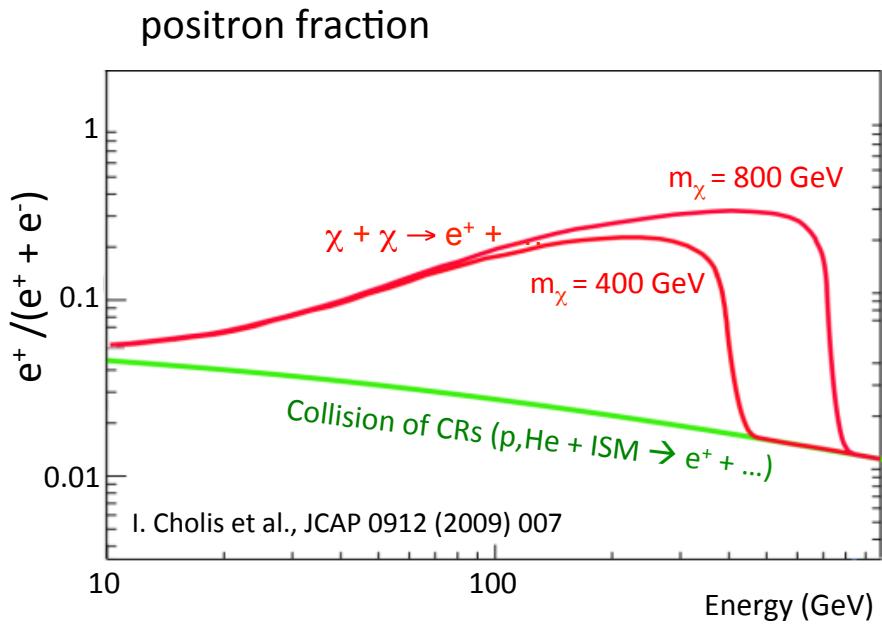
# Indirect Search of Dark Matter in CRs

Collisions of Dark Matter particles (ex. neutralinos) may produce a signal of  $e^+$ ,  $\bar{p}$ ,  $\bar{D}$  ...  
Detected above the background from the collisions of CRs on interstellar medium (ISM)



# Indirect Search of Dark Matter in CRs

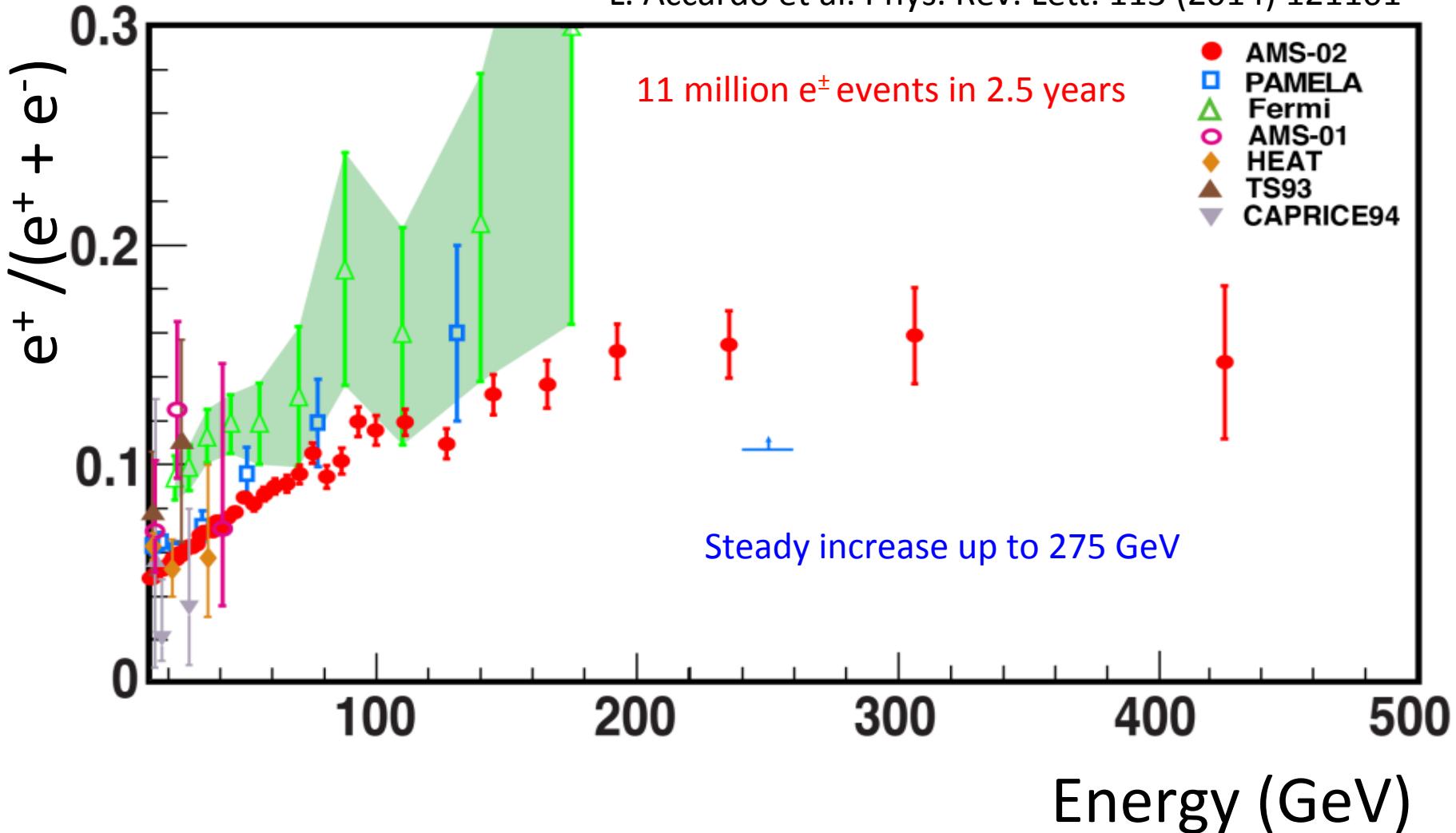
Collisions of Dark Matter particles (ex. neutralinos) may produce a signal of  $e^+$ ,  $\bar{p}$ ,  $\bar{D}$  ...  
 Detected above the background from the collisions of CRs on interstellar medium (ISM)



(other scenarios include pulsar production, secondary production, ...)

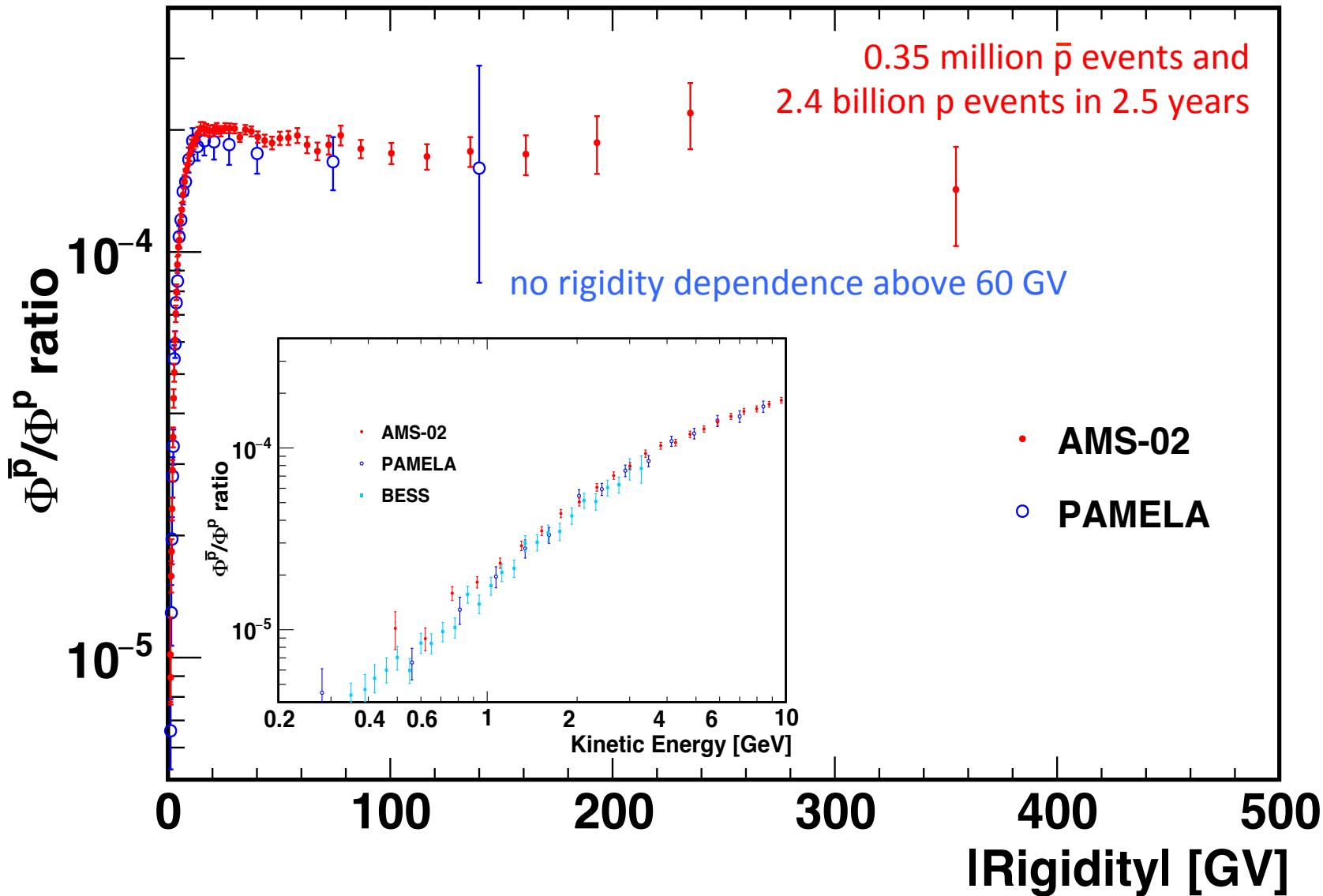
# AMS Positron Fraction

L. Accardo et al. Phys. Rev. Lett. 113 (2014) 121101



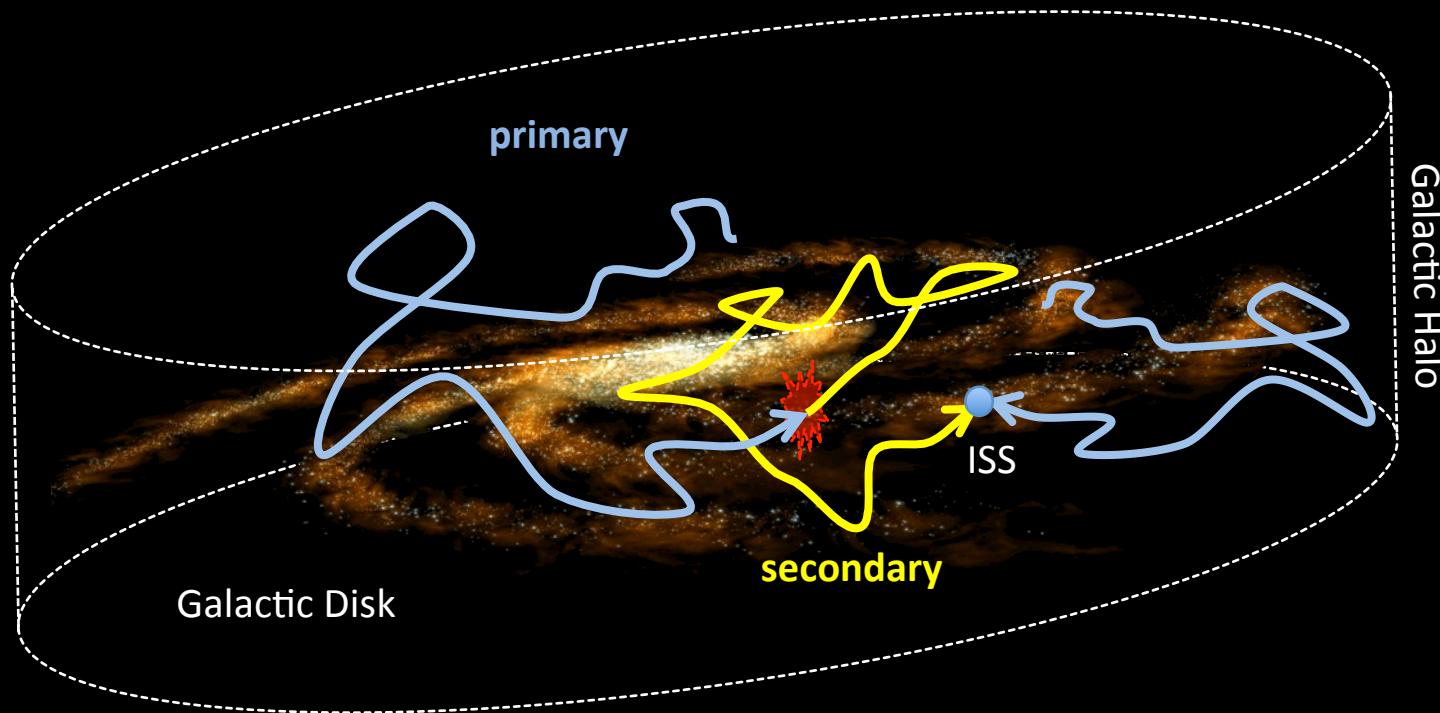
# AMS $\bar{p}/p$ Flux Ratio

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



# Cosmic Rays Nuclei

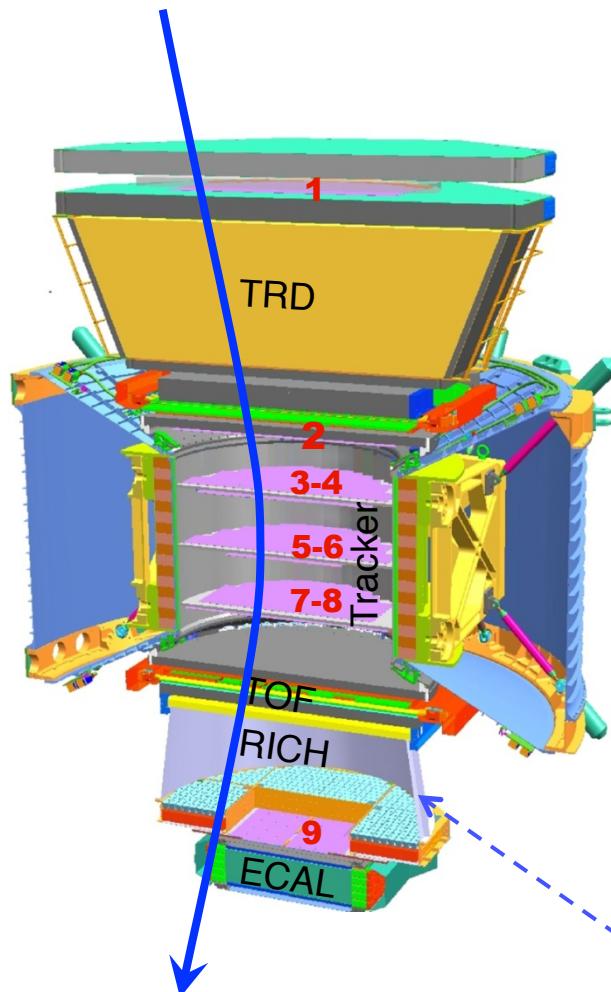
Cosmic rays **primaries** are mostly produced at astrophysical sources (ex. p, He, C, O, ...), **secondaries** (ex. Li, Be, B, ...) are mostly produced by the collision of cosmic rays with the ISM.



The understanding of primary and secondary cosmic rays reveal details of sources and propagation of all CRs species. In particular with respect to secondary production of  $e^+$  and  $p\bar{p}$

- The cosmic ray fluxes of their “parents” (p, He)
- Behaviour of their propagation in the Milky Way (B/C, Be/B, ...)

# Multiple Measurement of Energy

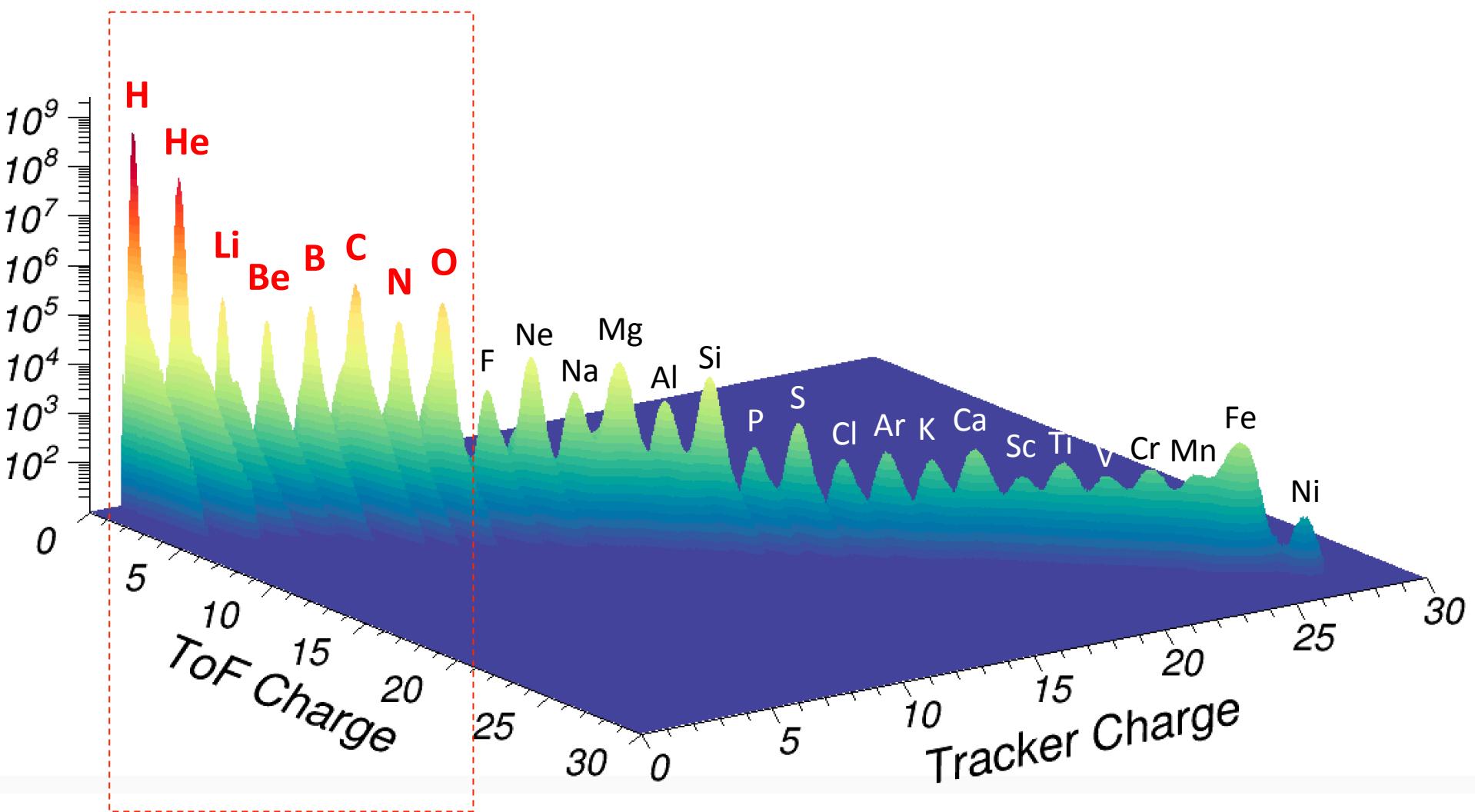


**Tracker,  $R = p/Z$**   
Full Span MDR  $\approx 2 \div 3$  TV

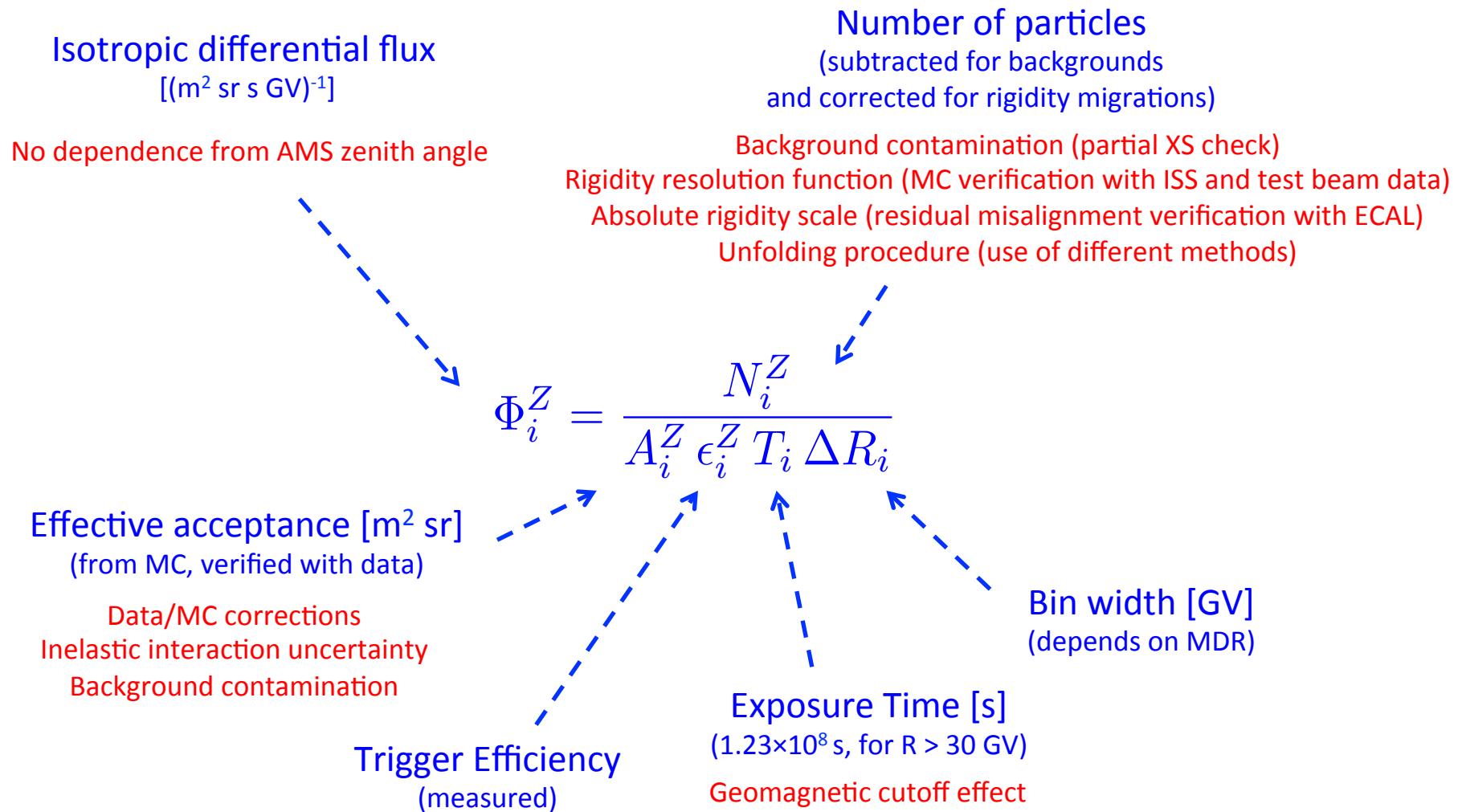
**TOF,  $\beta$**   
 $\Delta\beta$  ( $\beta=1$ )  $\approx 0.01 \div 0.04$

**RICH,  $\beta$**   
 $\Delta\beta$  ( $\beta=1$ )  $\approx 1 \div 5 \times 10^{-4}$

# Chemical Composition with AMS



# Flux Measurement / Systematics

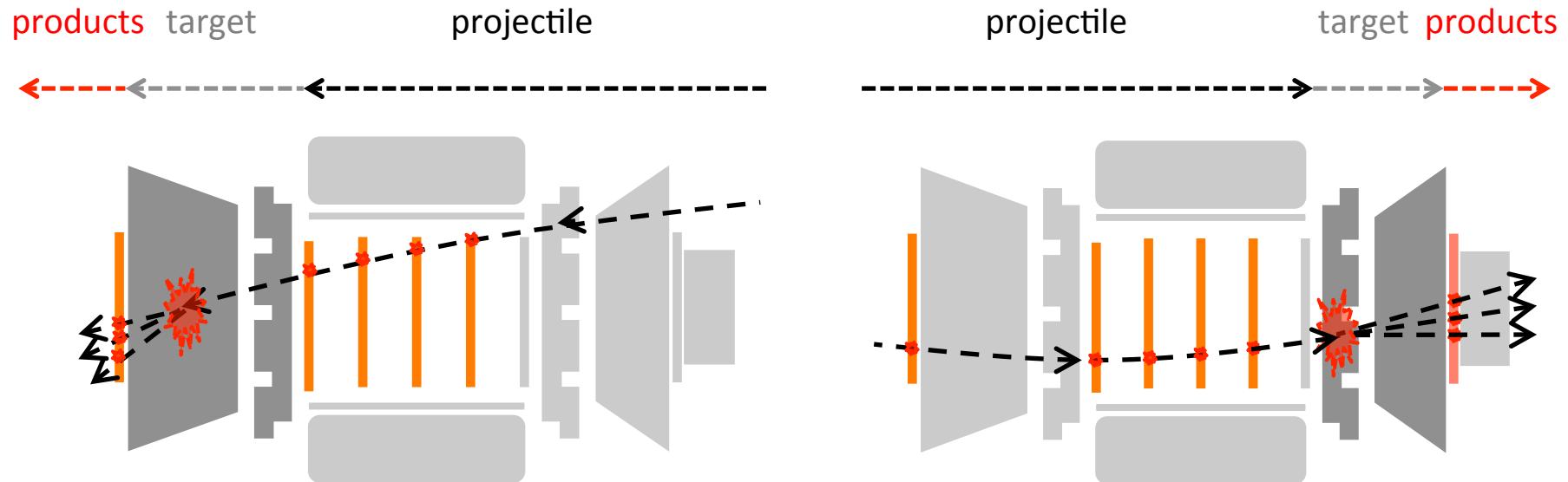


To match the statistics (<% error), extensive systematic errors studies have been made.

# Inelastic Cross Section Estimation with AMS

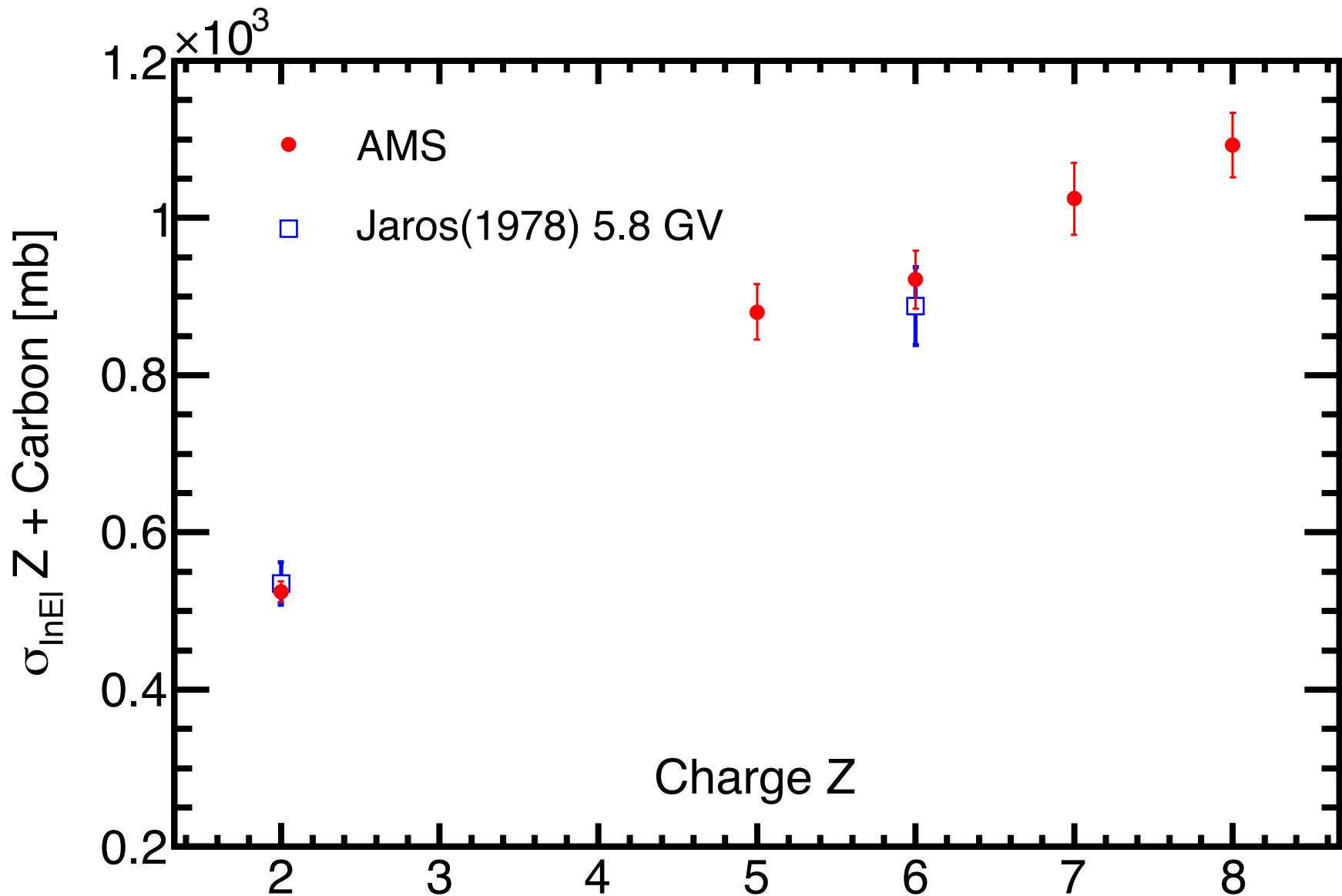
Inelastic XS of Light Nuclei on C and Al (that represent AMS materials for 73% and 17% in weight respectively) are known with large uncertainties only below 10 GV and represent a large source of errors for the flux determination.

We developed a method to verify the effect of interactions on AMS acceptance using ISS data using with data acquired when AMS pointing in horizontal direction (2 days up to now)



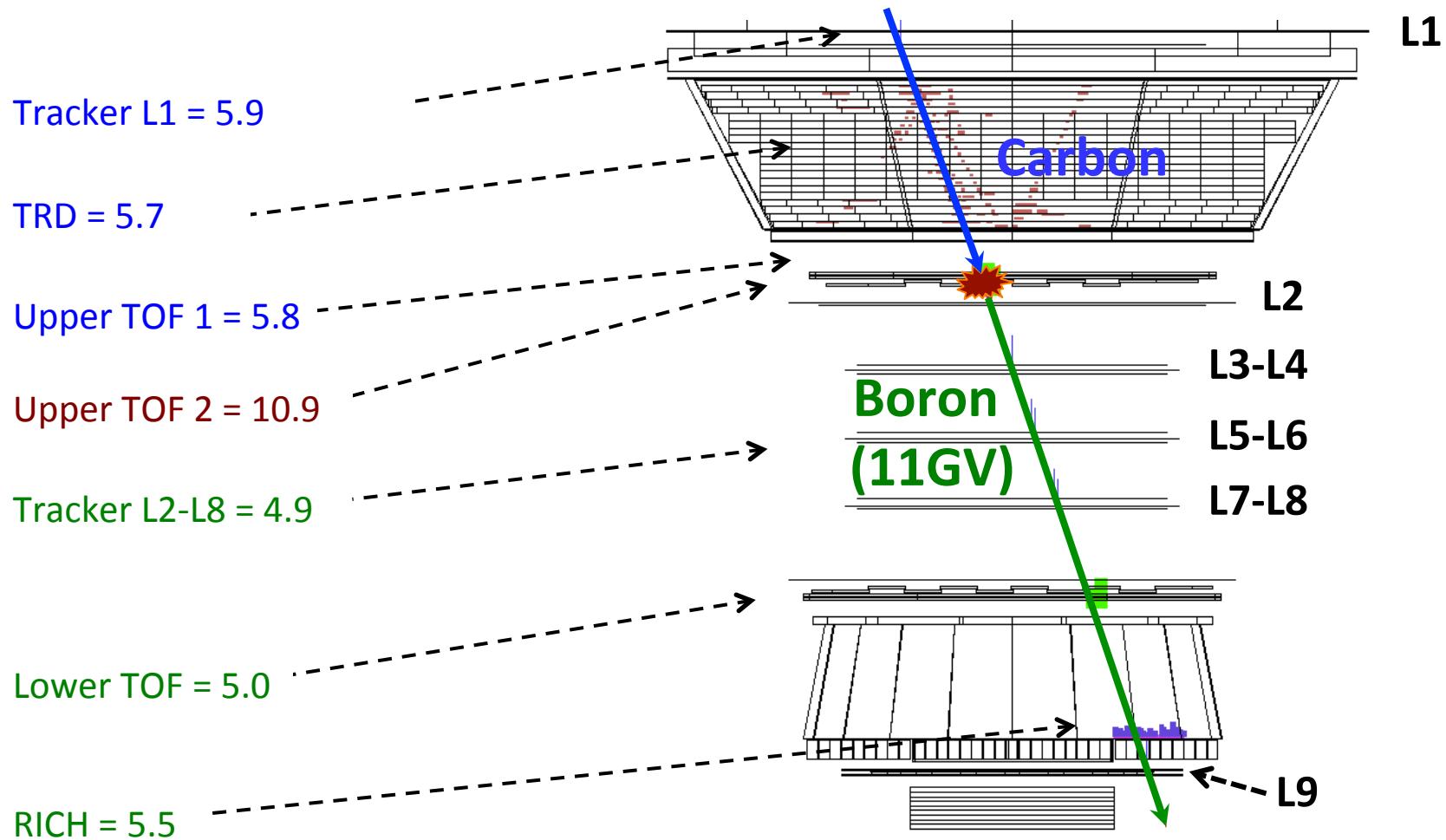
What is needed for flux estimation normalization is just the survival probability in AMS materials in a model dependent way, is possible to derive the inelastic cross section.

# Inelastic Cross Section Estimation with AMS



# Partial Cross Section Validation with AMS

Nuclei interact in AMS (ex. C + AMS  $\rightarrow$  B), this background is controlled with the top detectors.  
Interactions in materials above the first detection plane can be only estimated with MC.

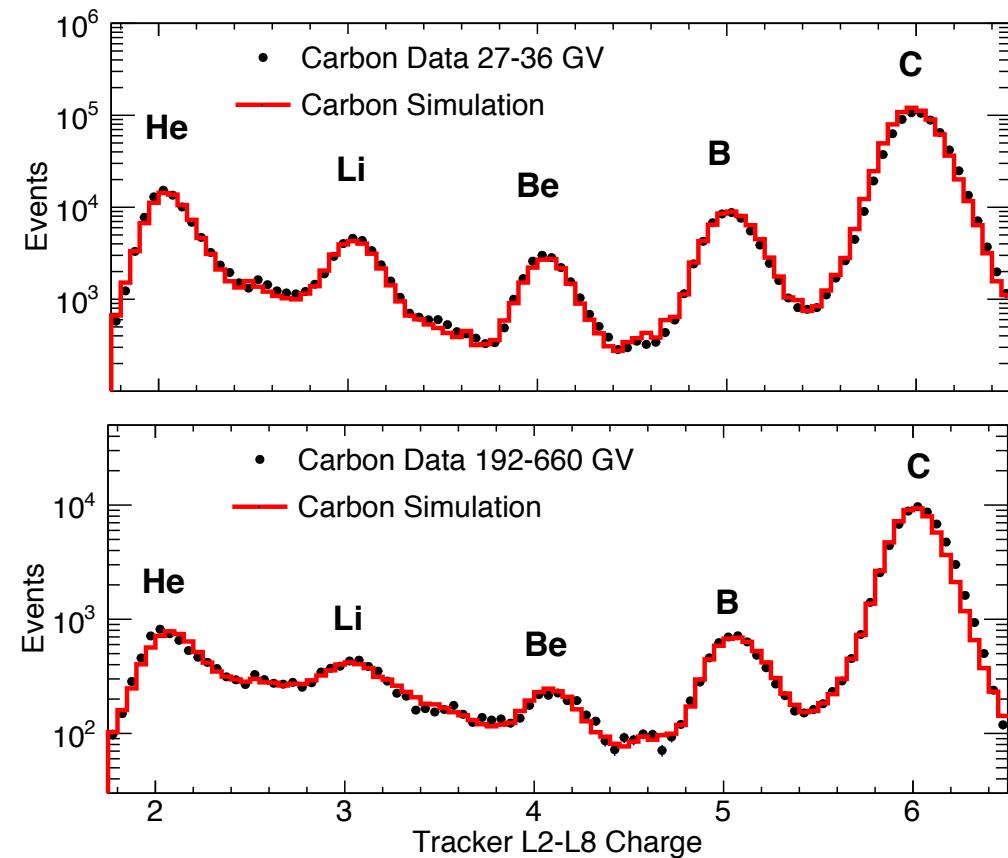
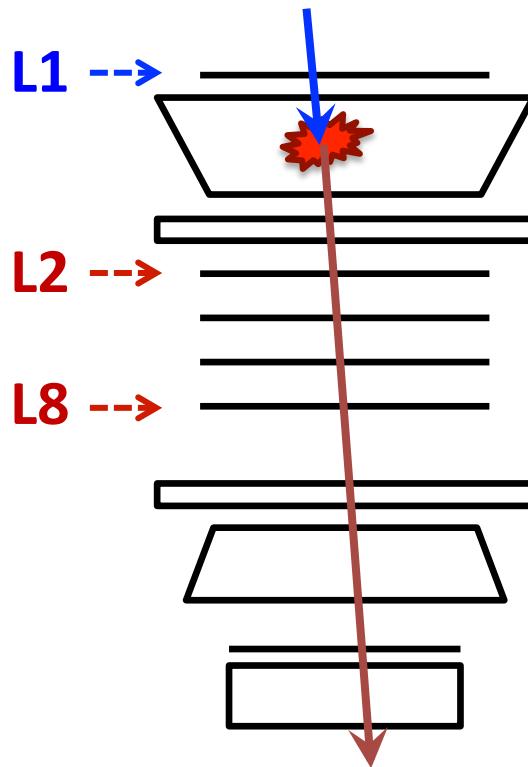


# Partial Cross Section Validation with AMS

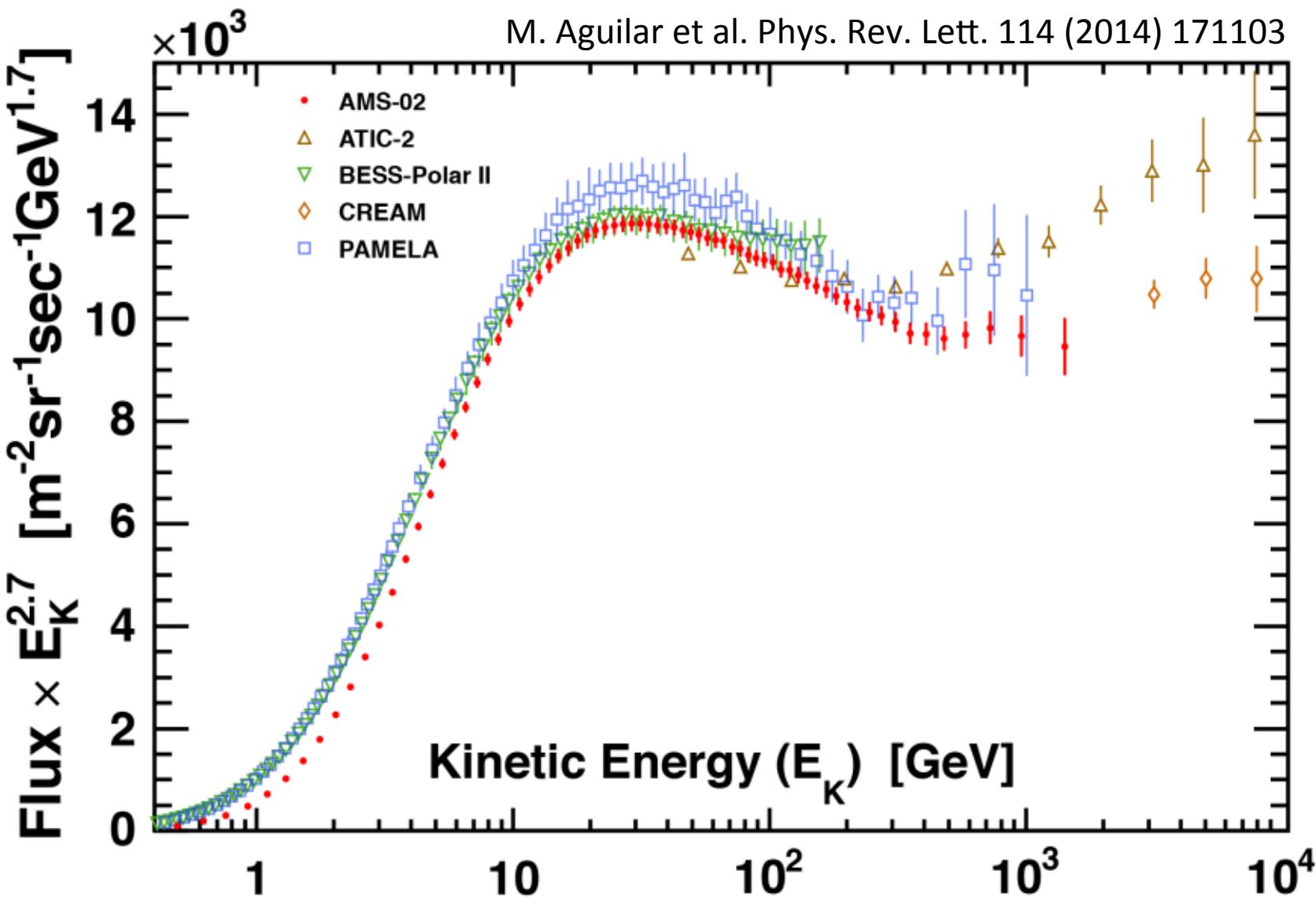
Bkg. generated above L1 is calculated using MC and nuclei fluxes measured by AMS.

MC interaction channels (ex. C + C, Al  $\rightarrow$  Li, Be, B + X) have been verified with data.

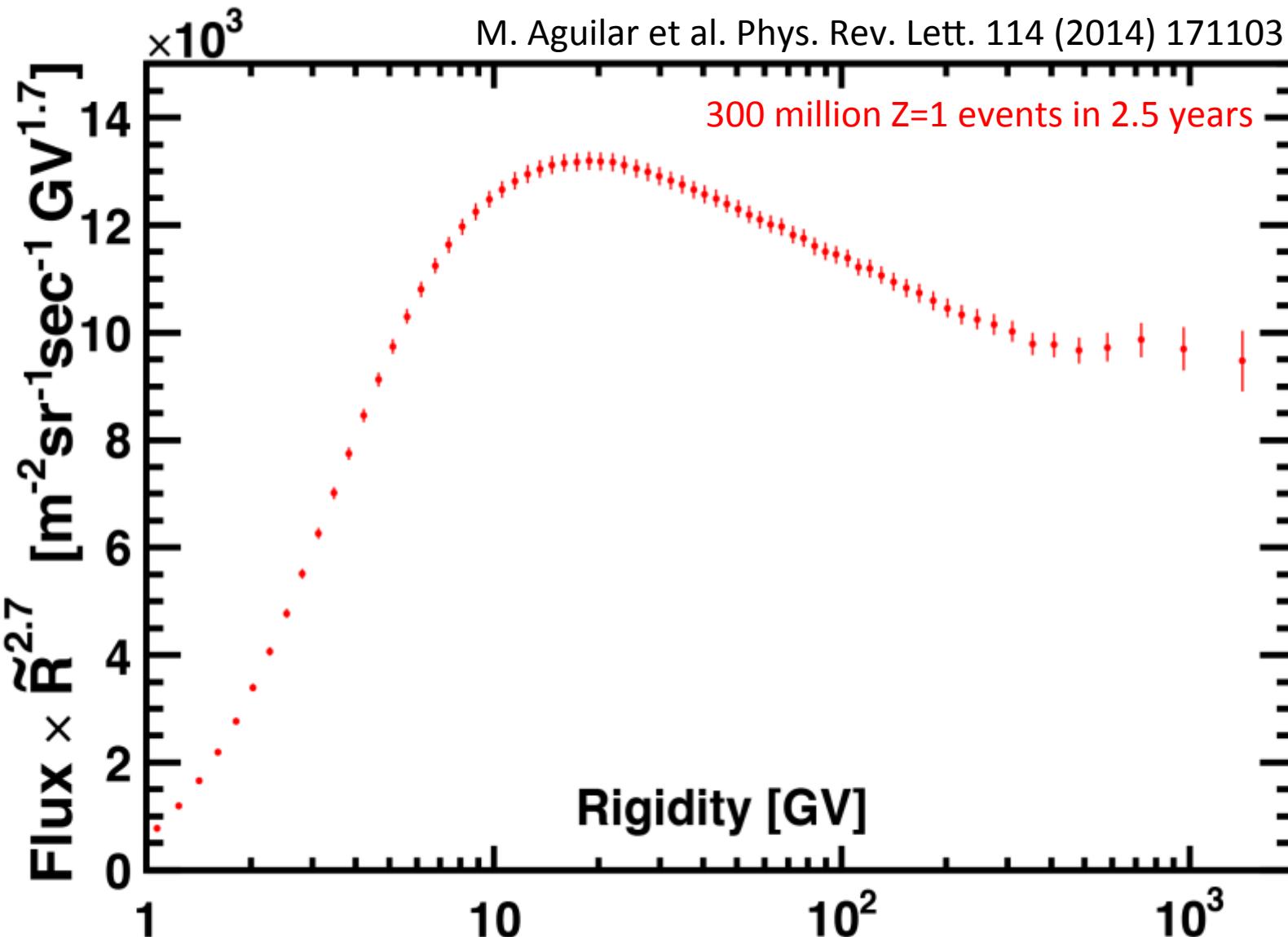
Systematics due to interactions on top of AMS are < 1.5%.



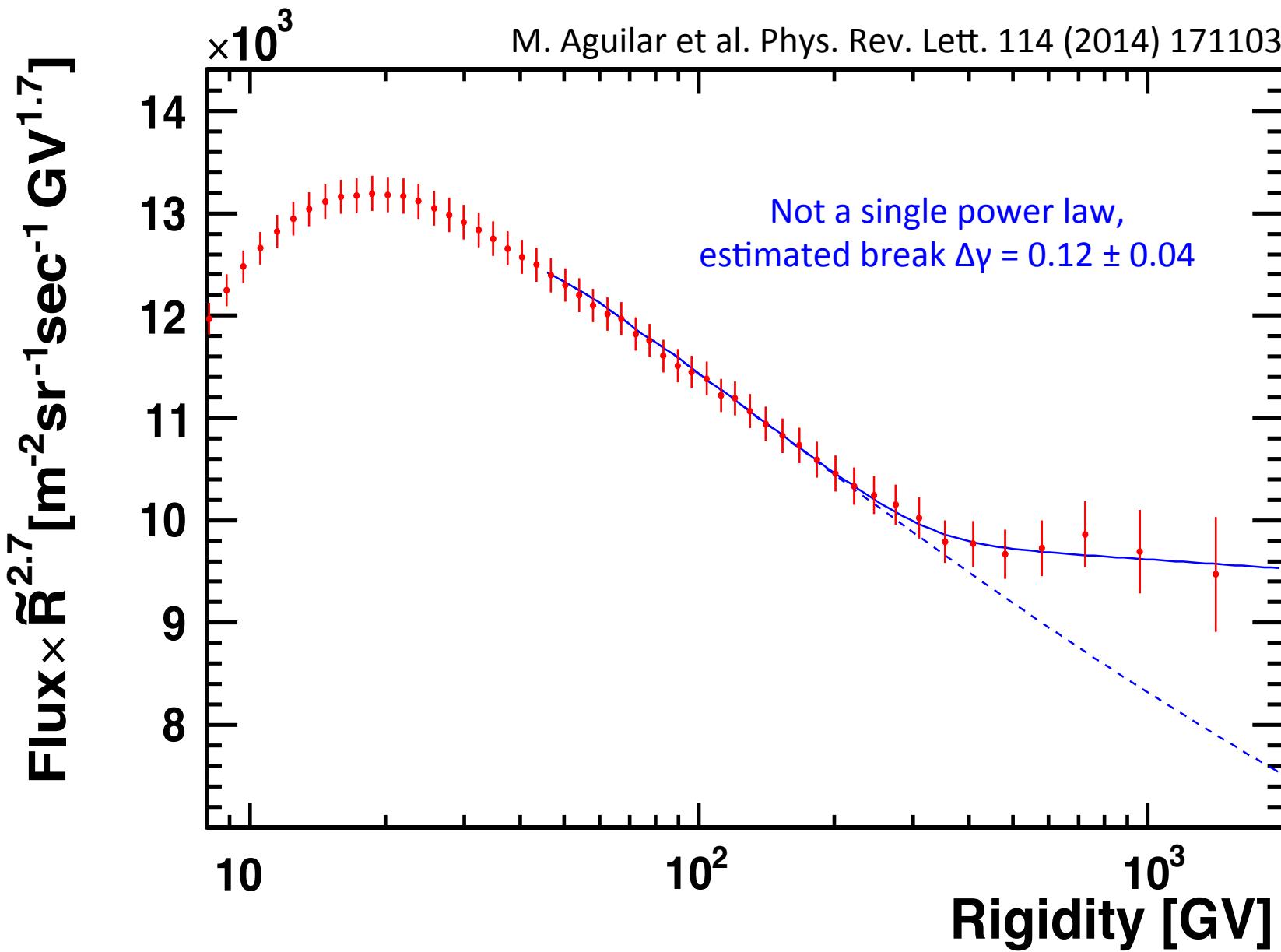
# Proton Flux



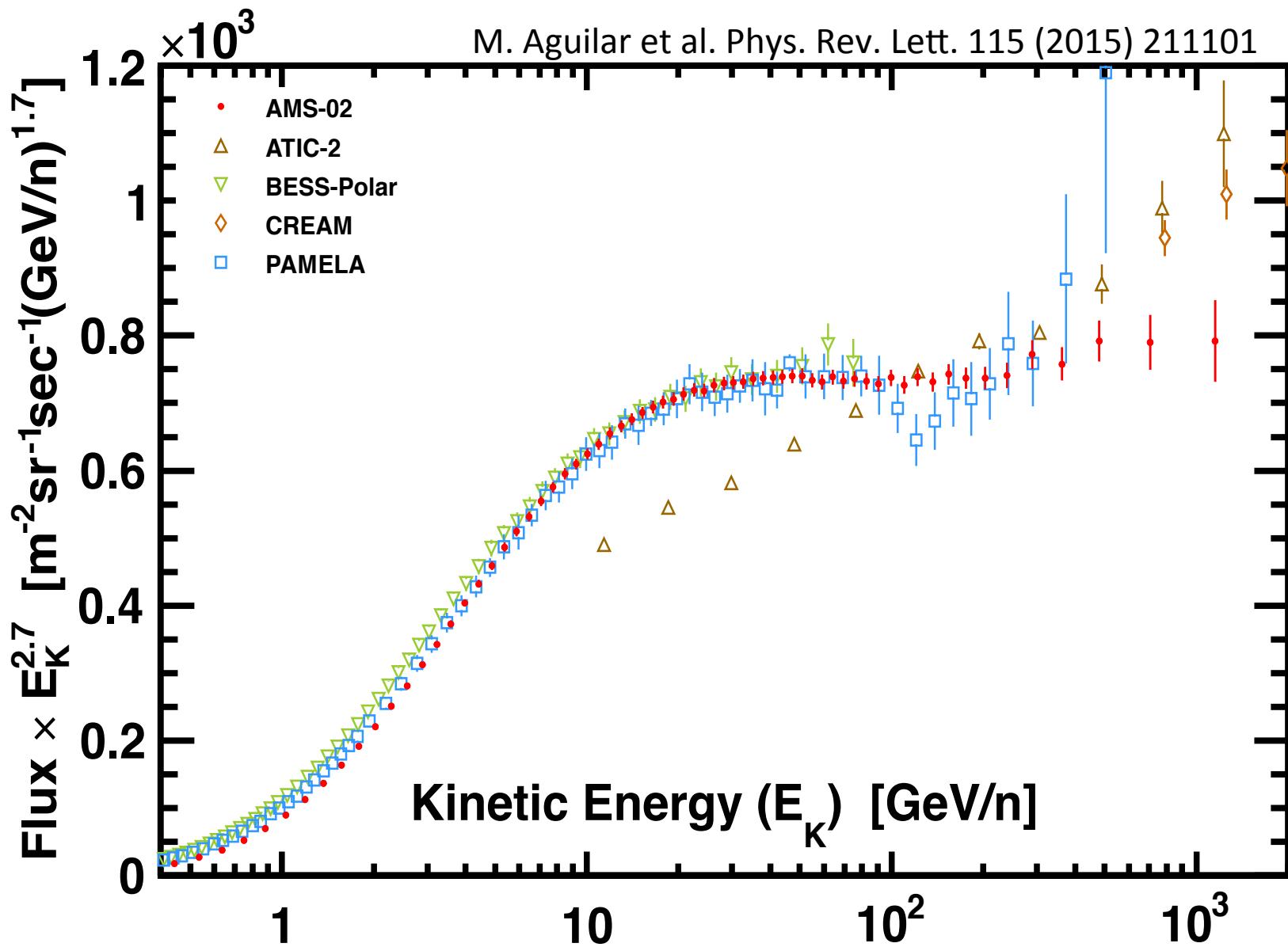
# Proton Flux



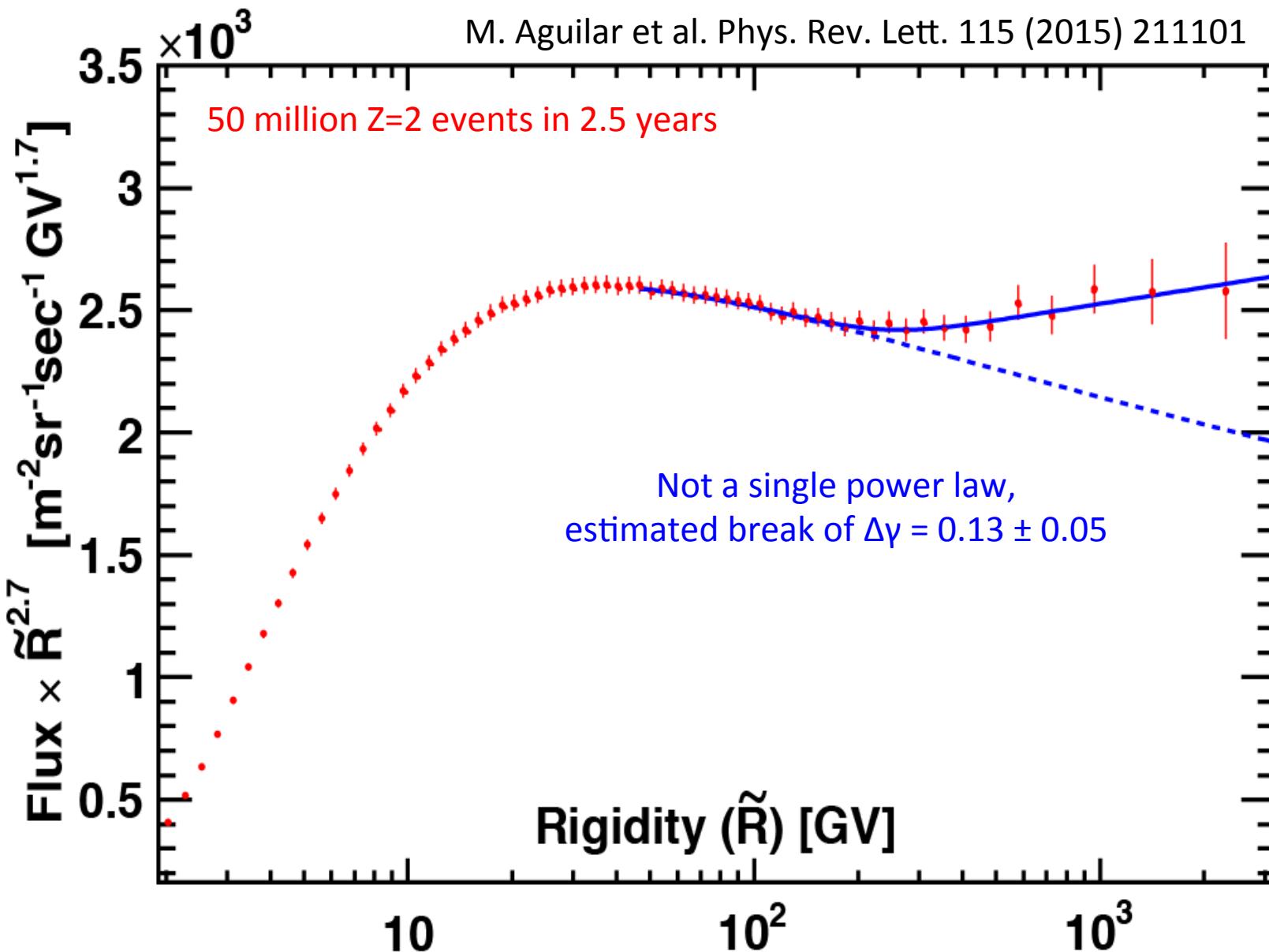
# Proton Flux



# Helium Flux

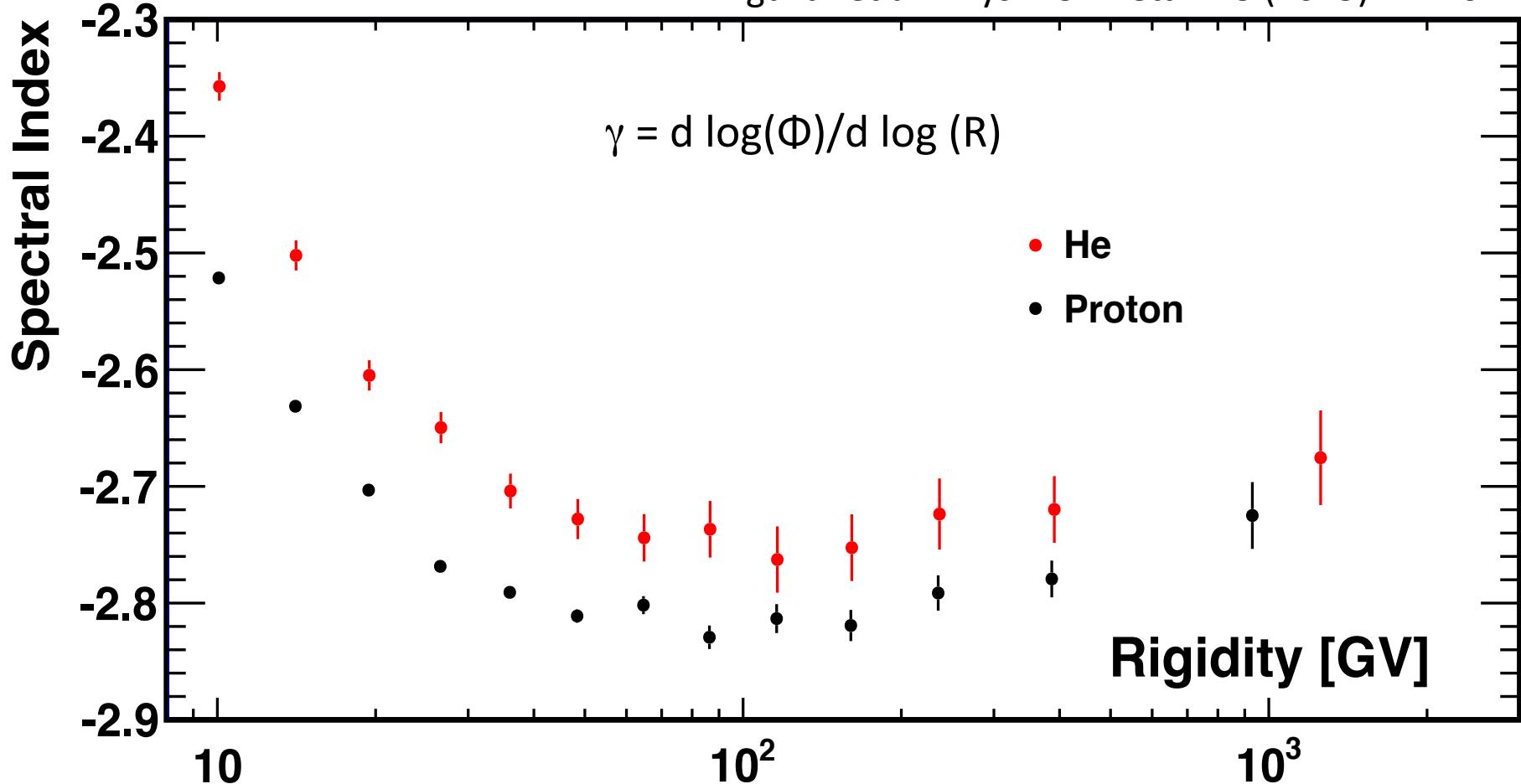


# Helium Flux



# Proton and Helium Spectral Index

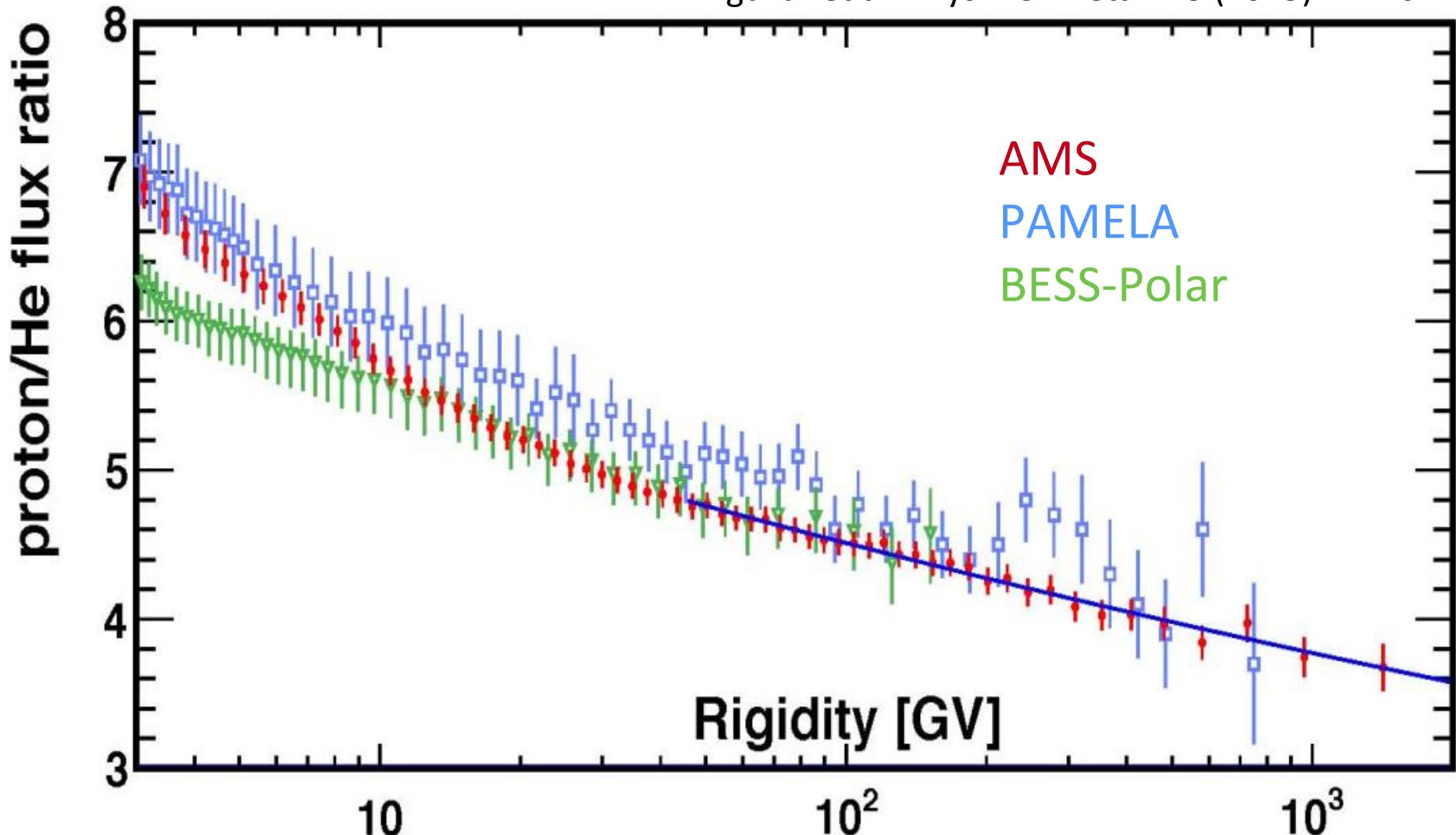
M. Aguilar et al. Phys. Rev. Lett. 115 (2015) 211101



Different magnitude, similar behavior.

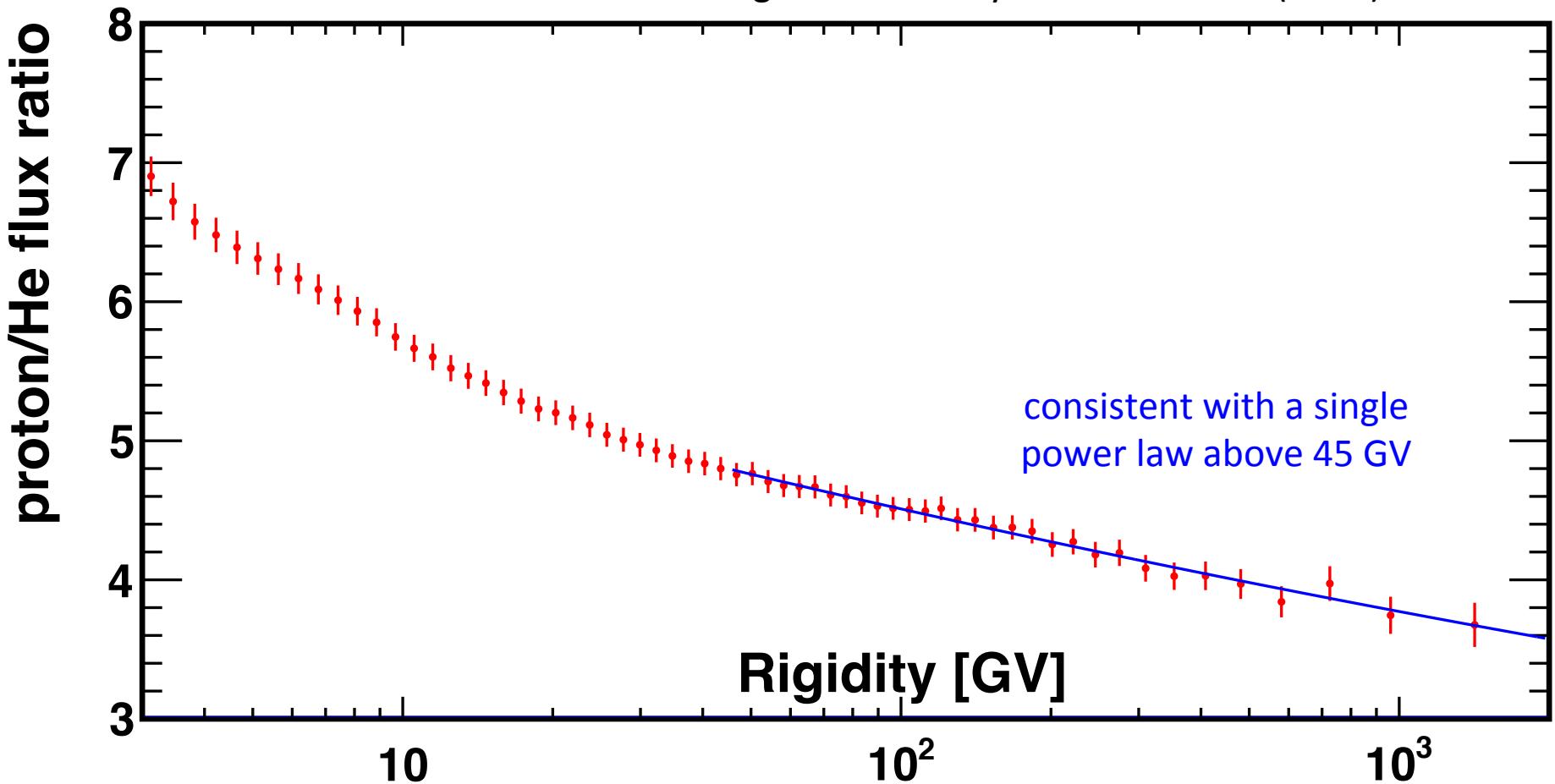
# AMS p/He Flux Ratio Comparison

M. Aguilar et al. Phys. Rev. Lett. 115 (2015) 211101



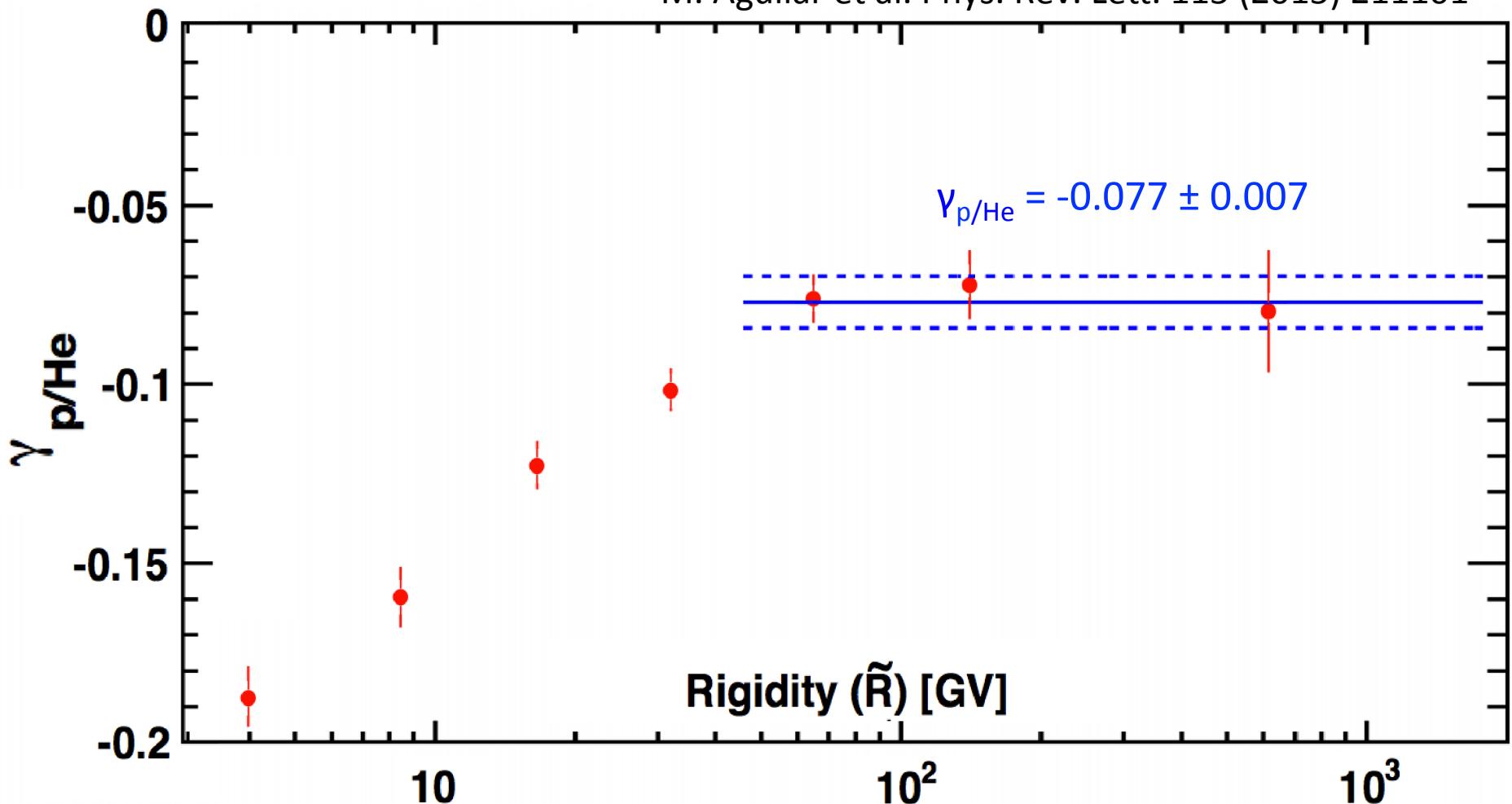
# p/He Flux Ratio

M. Aguilar et al. Phys. Rev. Lett. 115 (2015) 211101



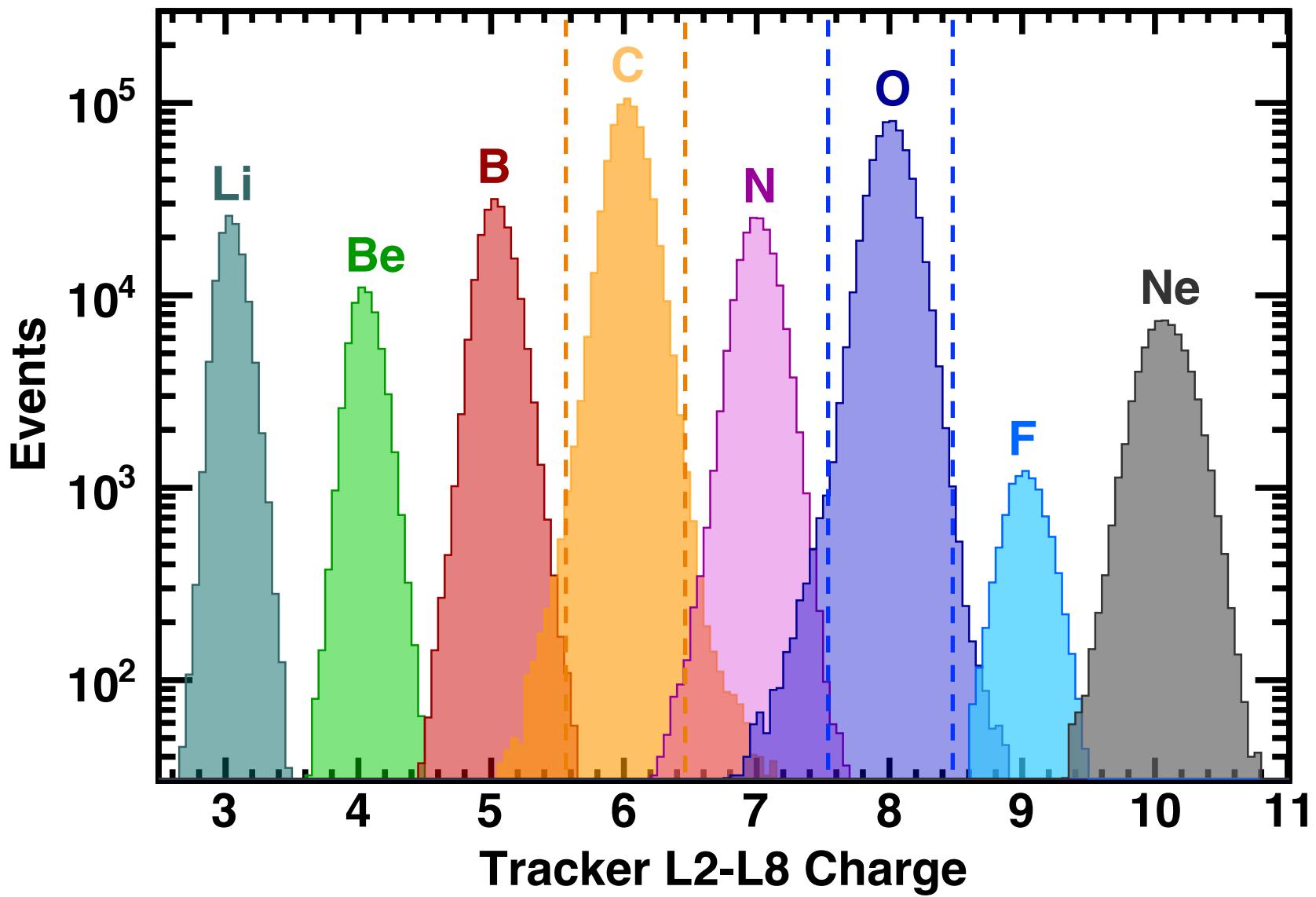
# p/He Spectral Index

M. Aguilar et al. Phys. Rev. Lett. 115 (2015) 211101

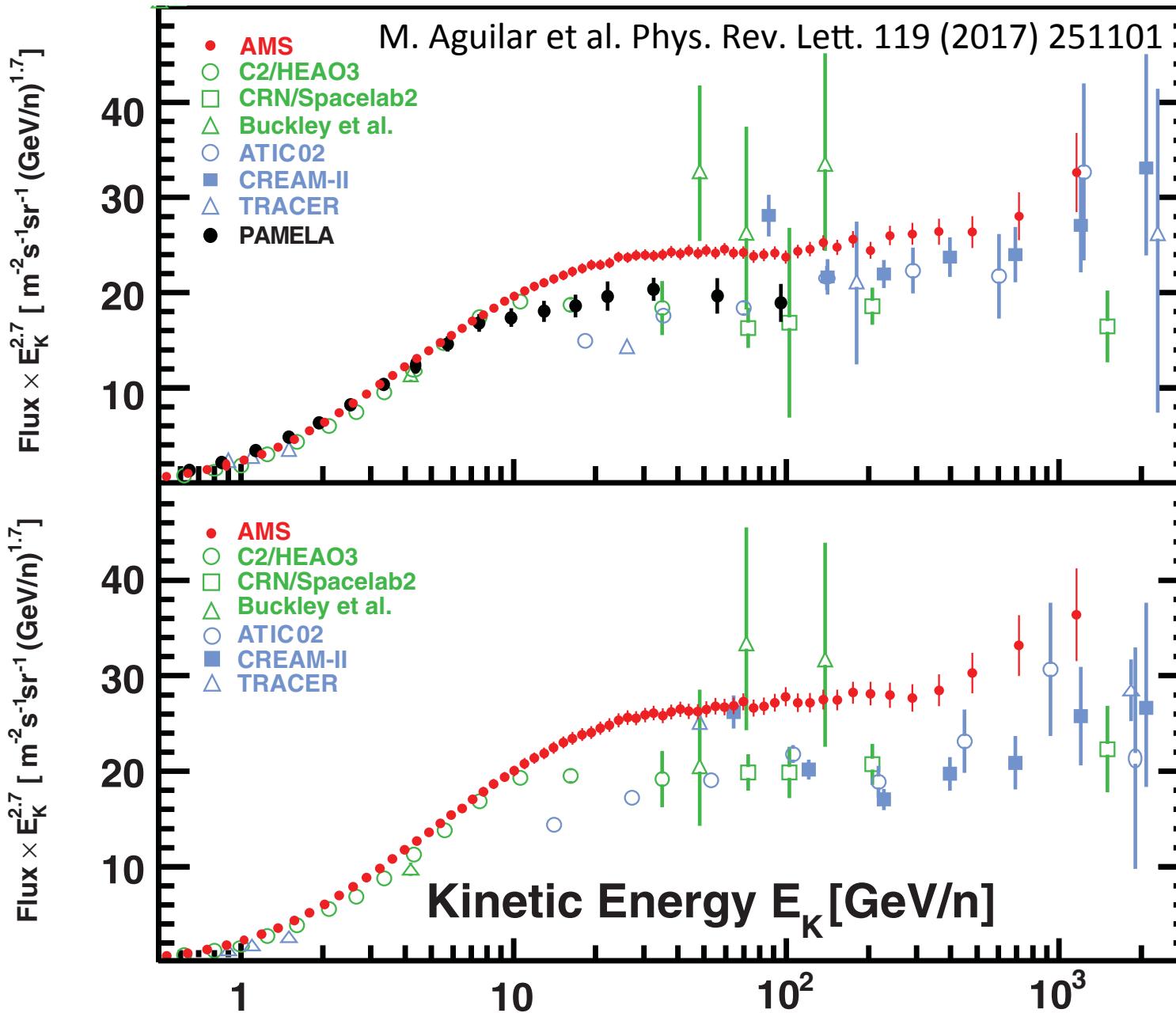


H and He exhibit a hardening at  $\sim 200$  GV,  
their ratio is a single power law above 45 GV.

# More CRs Primaries: Carbon and Oxygen

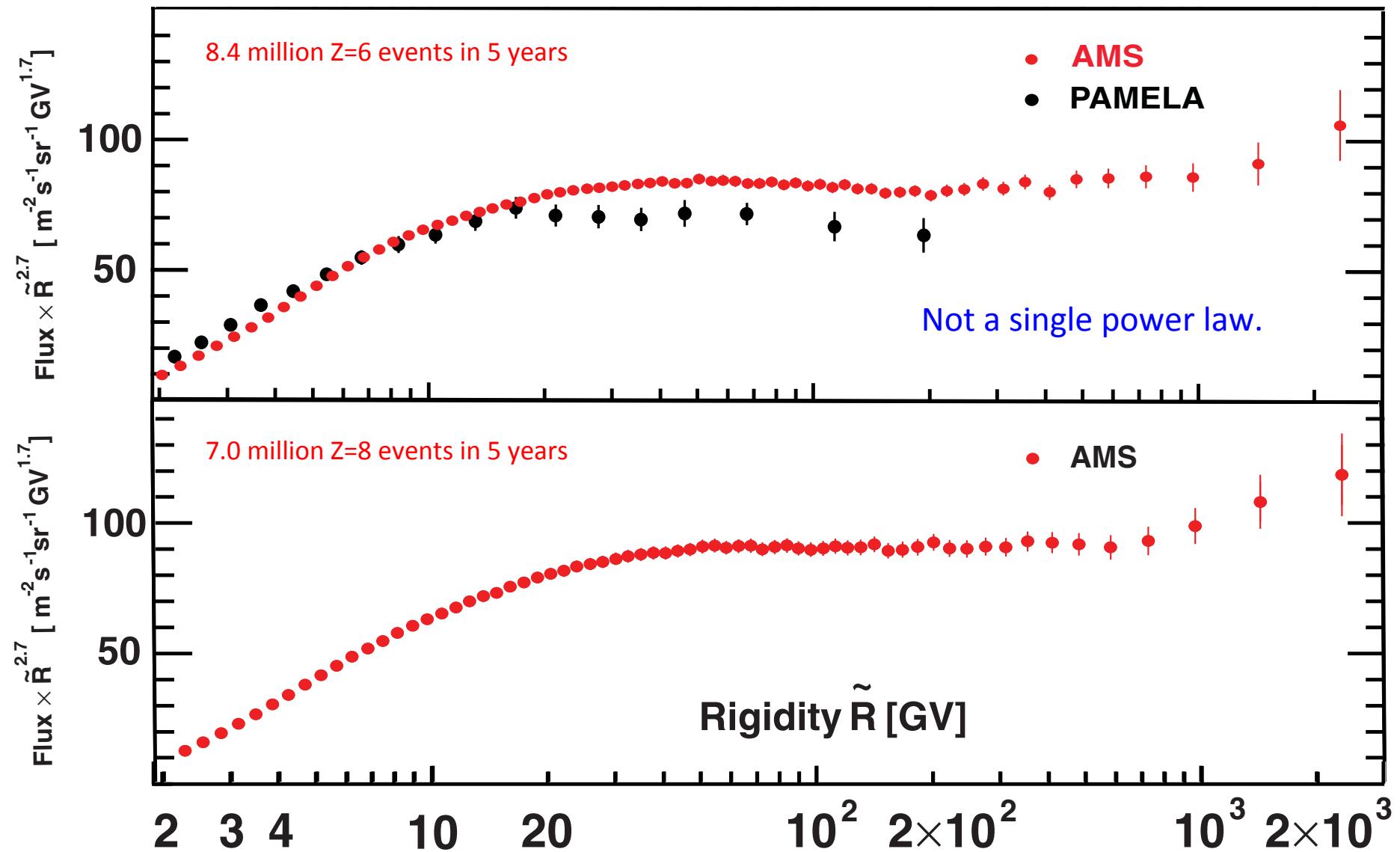


# Carbon and Oxygen Fluxes



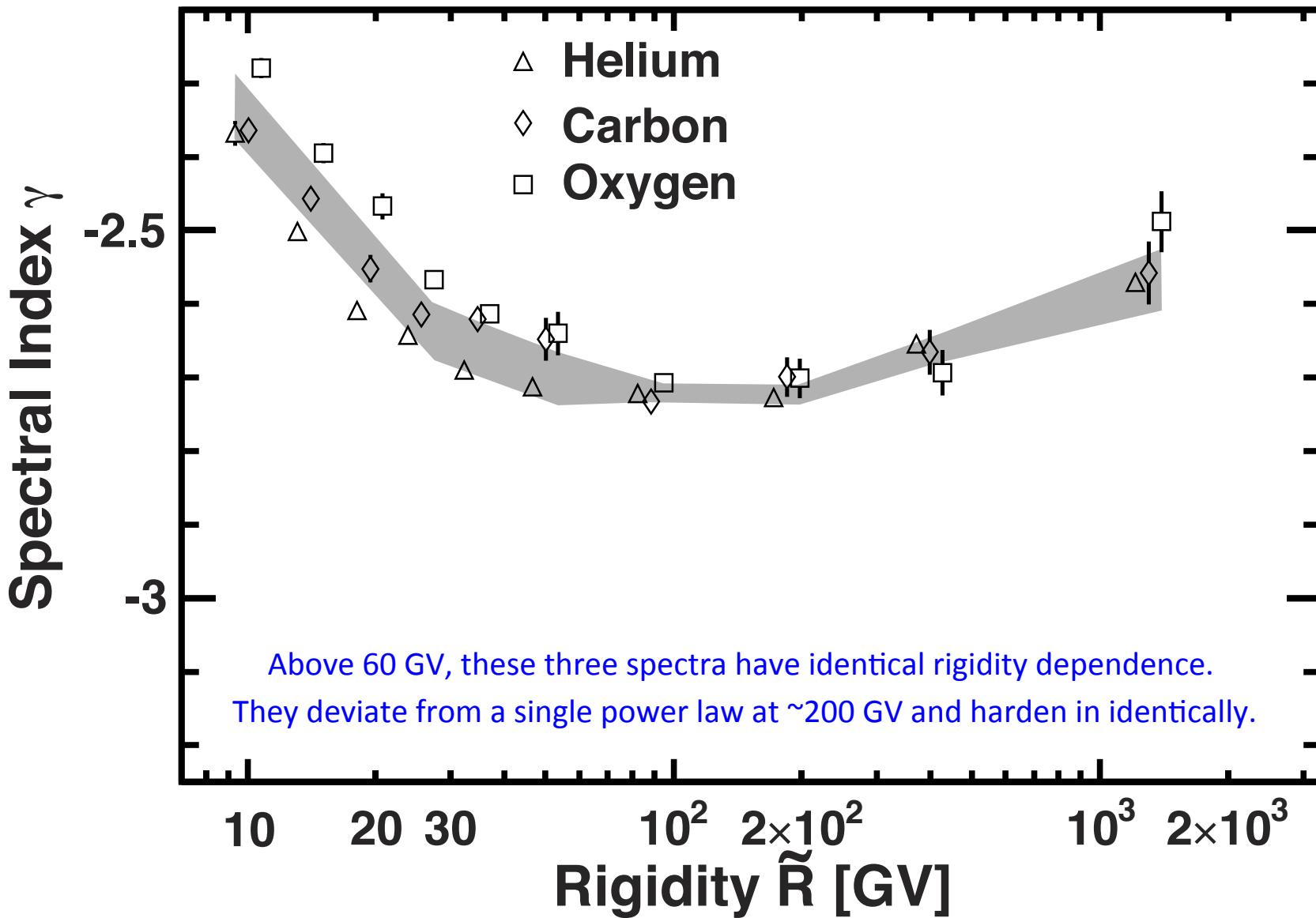
# Carbon and Oxygen Fluxes

M. Aguilar et al. Phys. Rev. Lett. 119 (2017) 251101



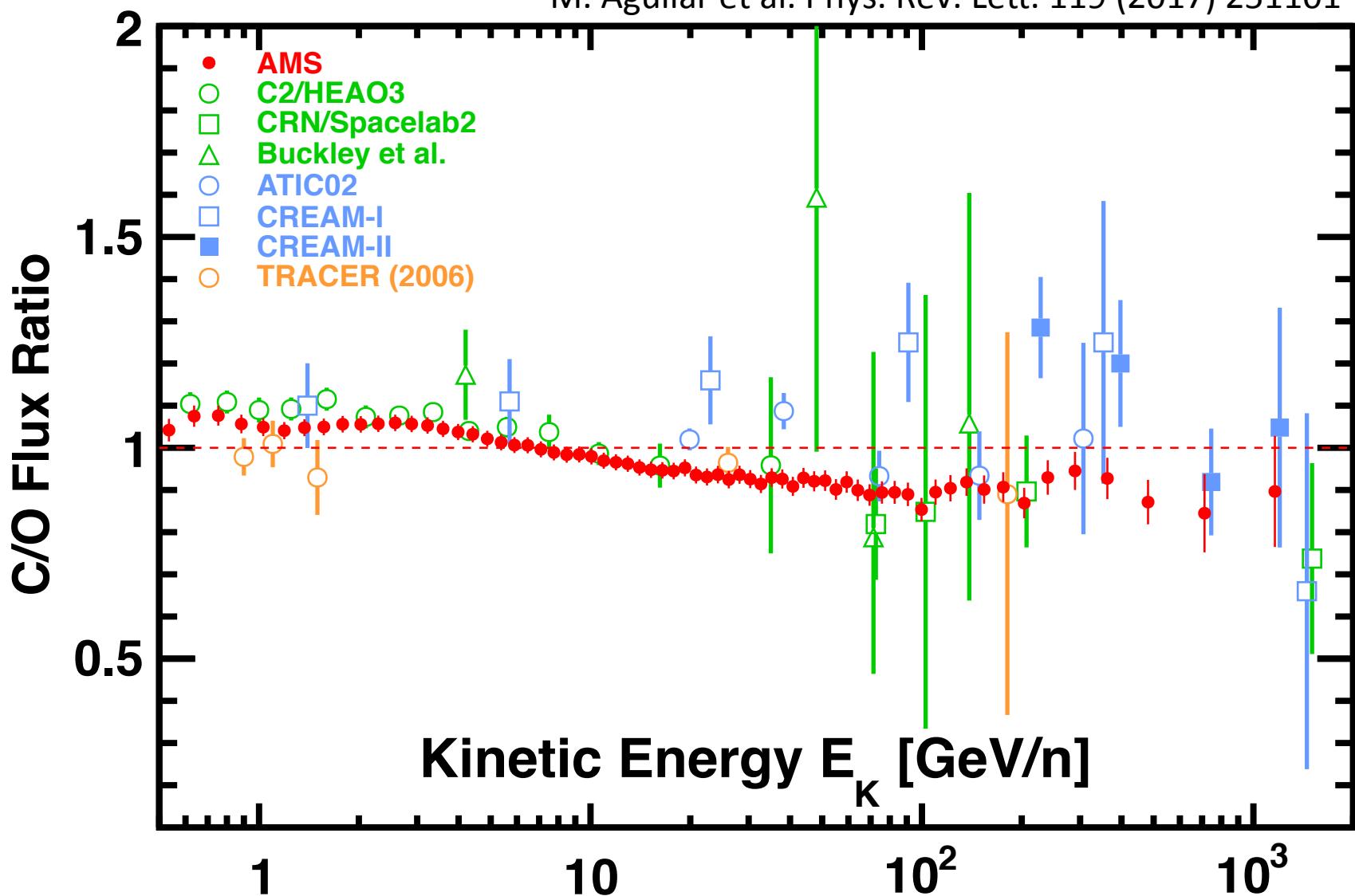
# Carbon and Oxygen Spectral Indexes

M. Aguilar et al. Phys. Rev. Lett. 119 (2017) 251101

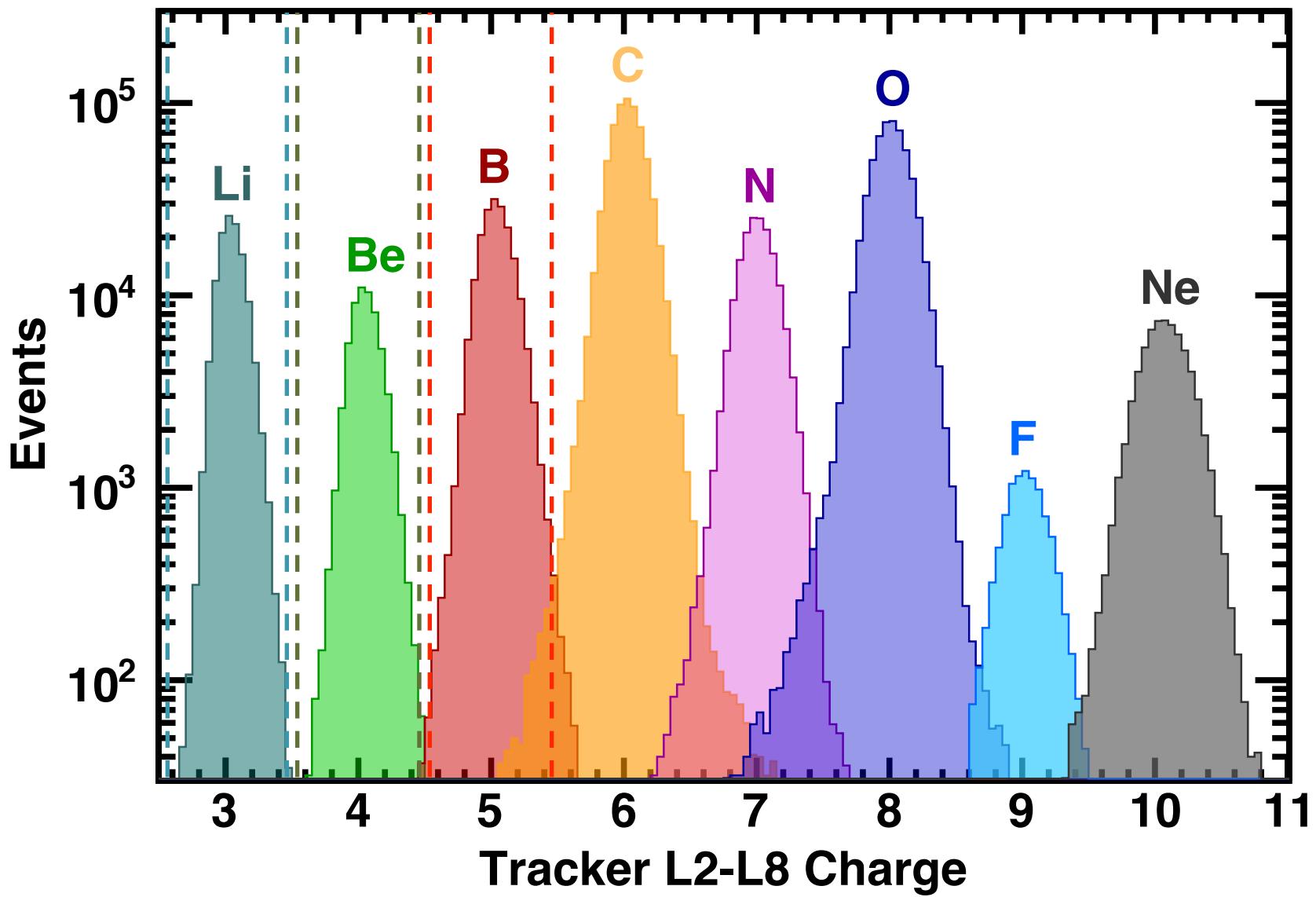


# C/O Flux Ratio

M. Aguilar et al. Phys. Rev. Lett. 119 (2017) 251101

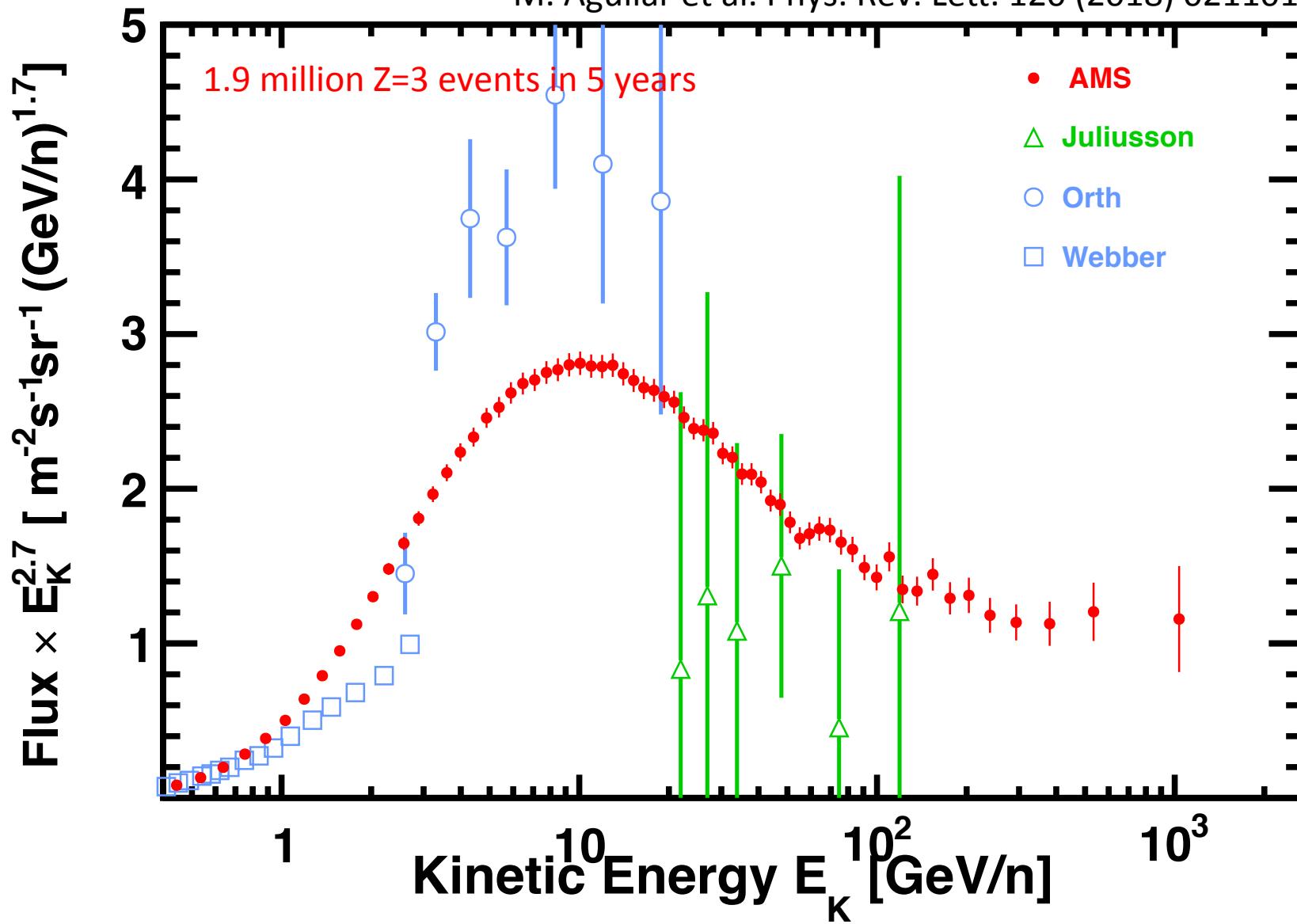


# Secondary CRs: Lithium, Beryllium and Boron



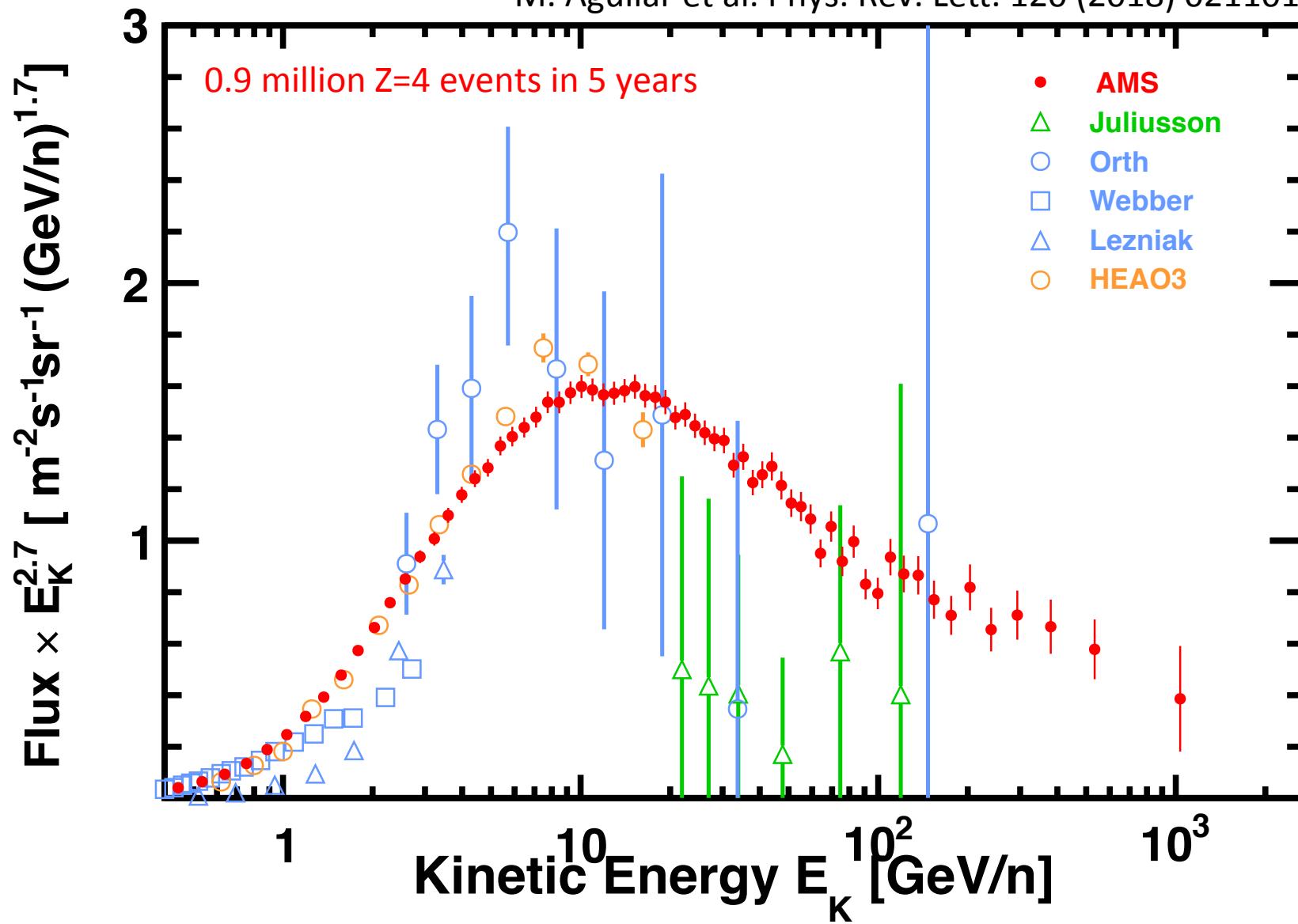
# Lithium Flux

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101



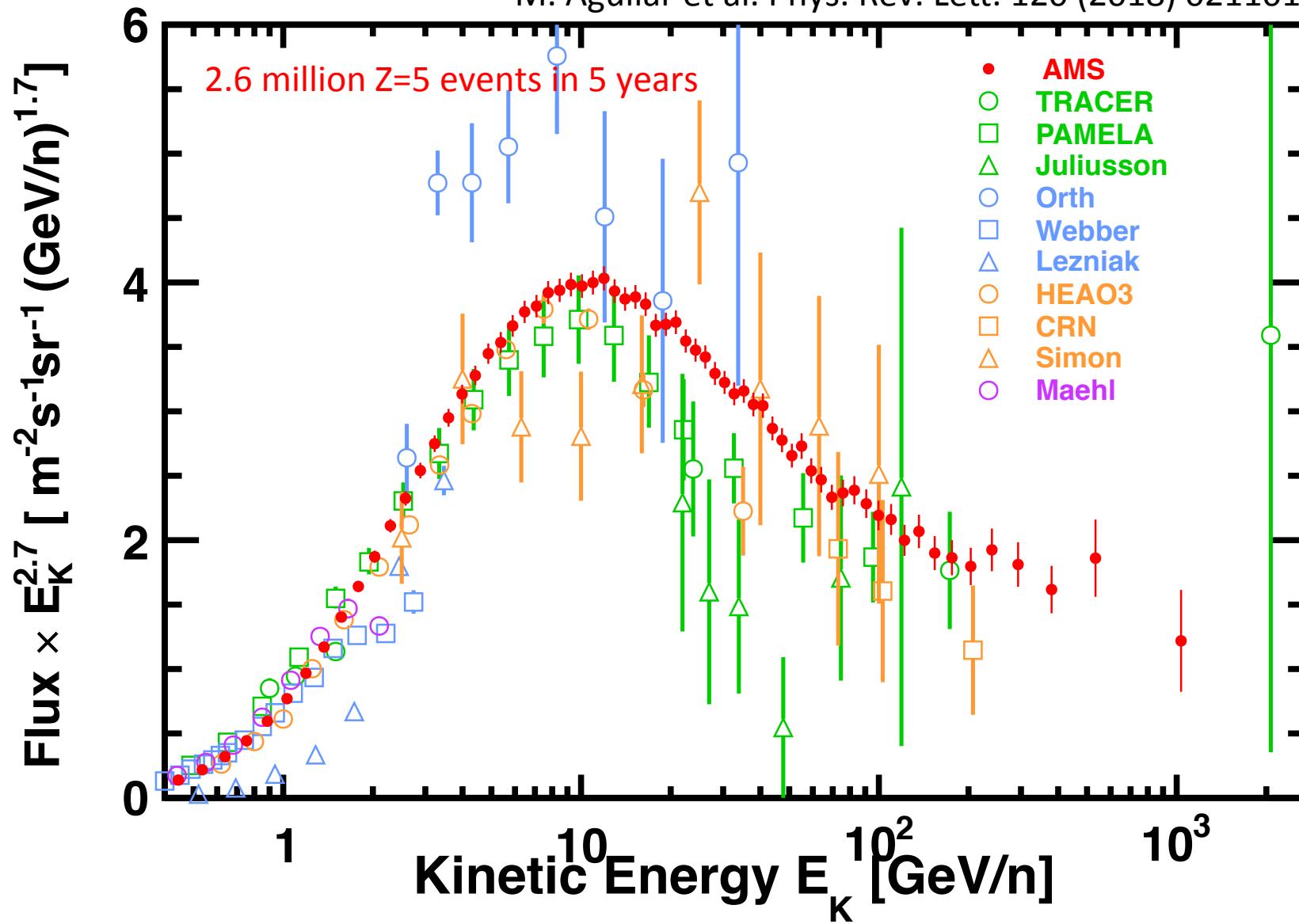
# Beryllium Flux

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101



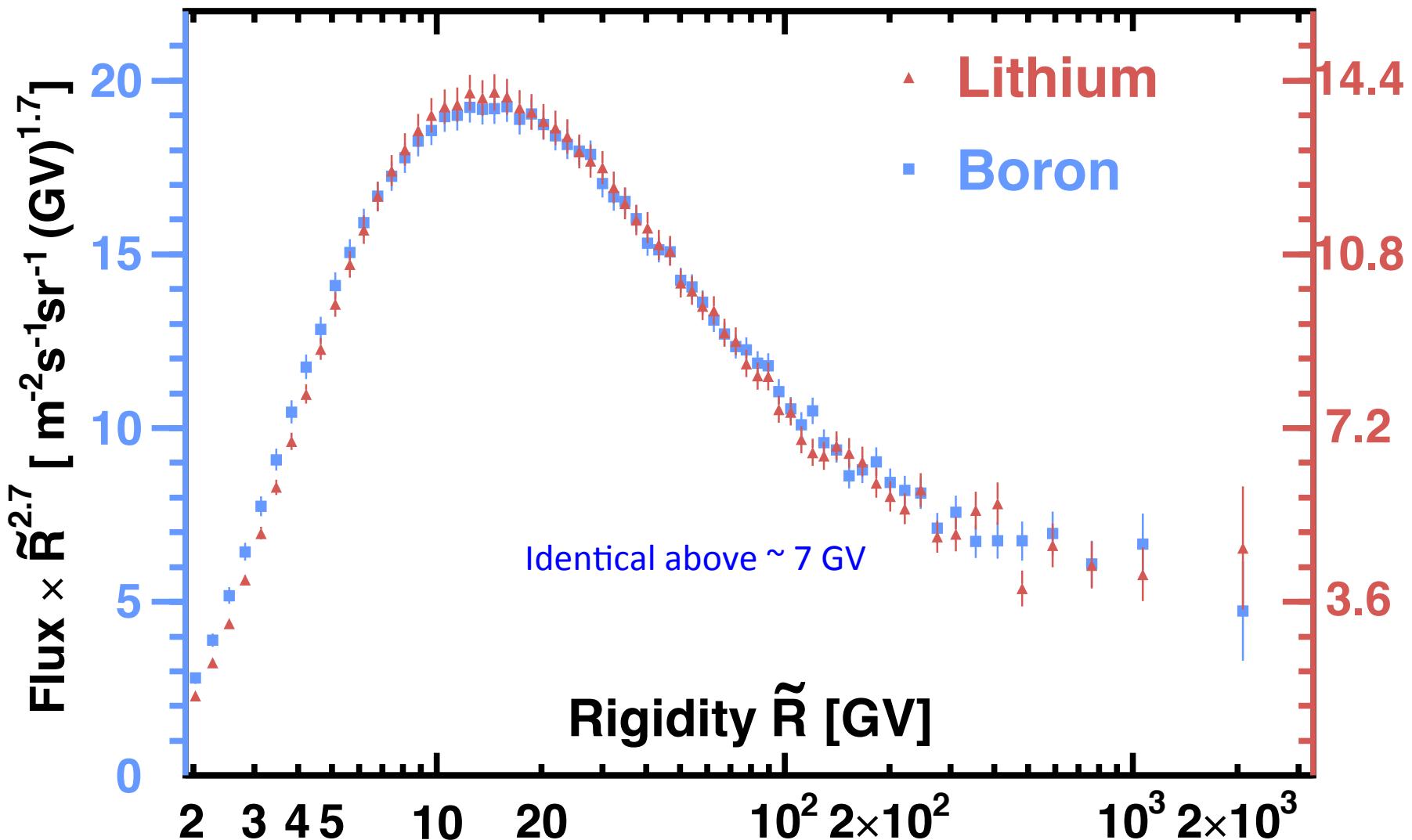
# Boron Flux

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101



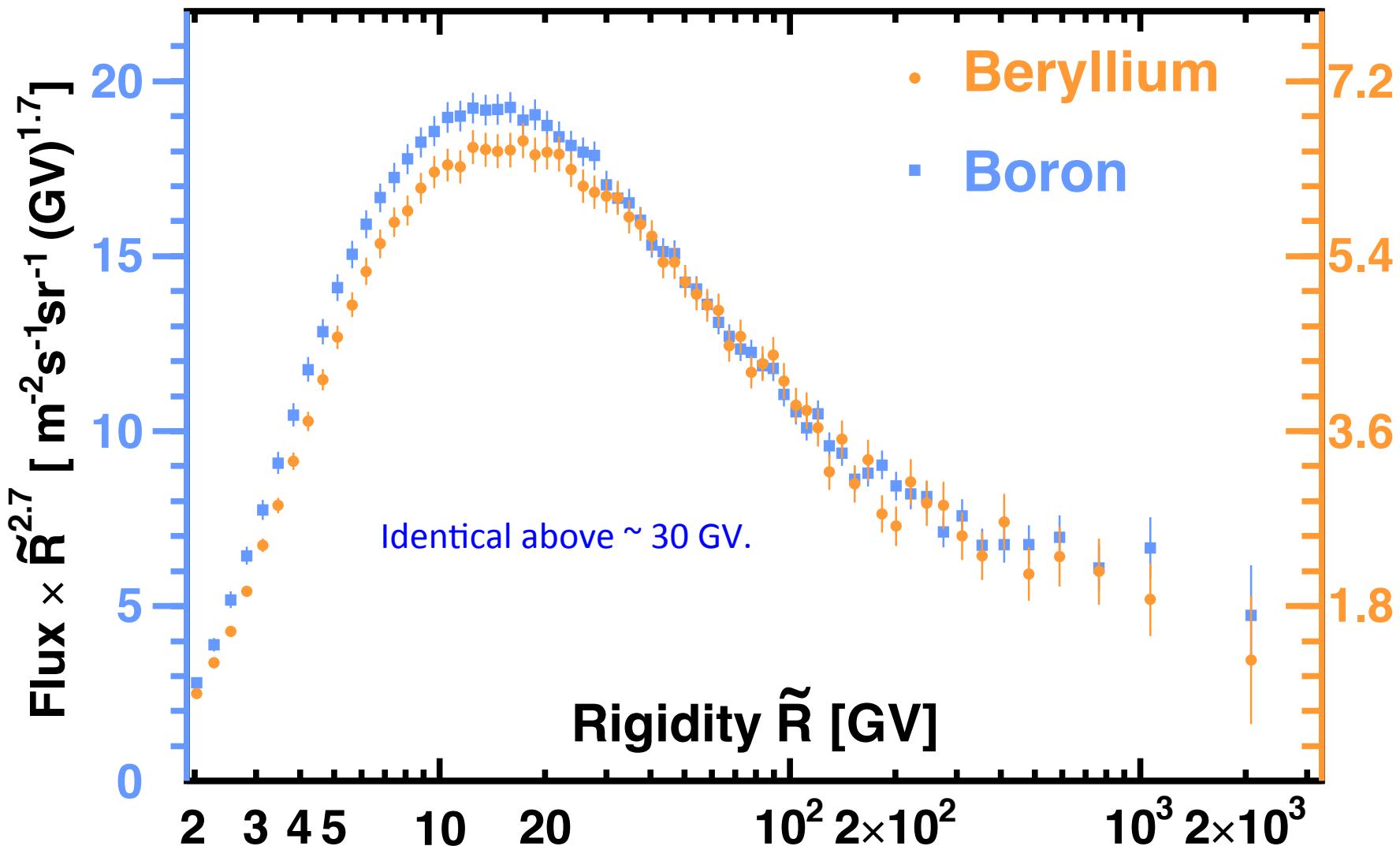
# Lithium and Boron Fluxes

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101



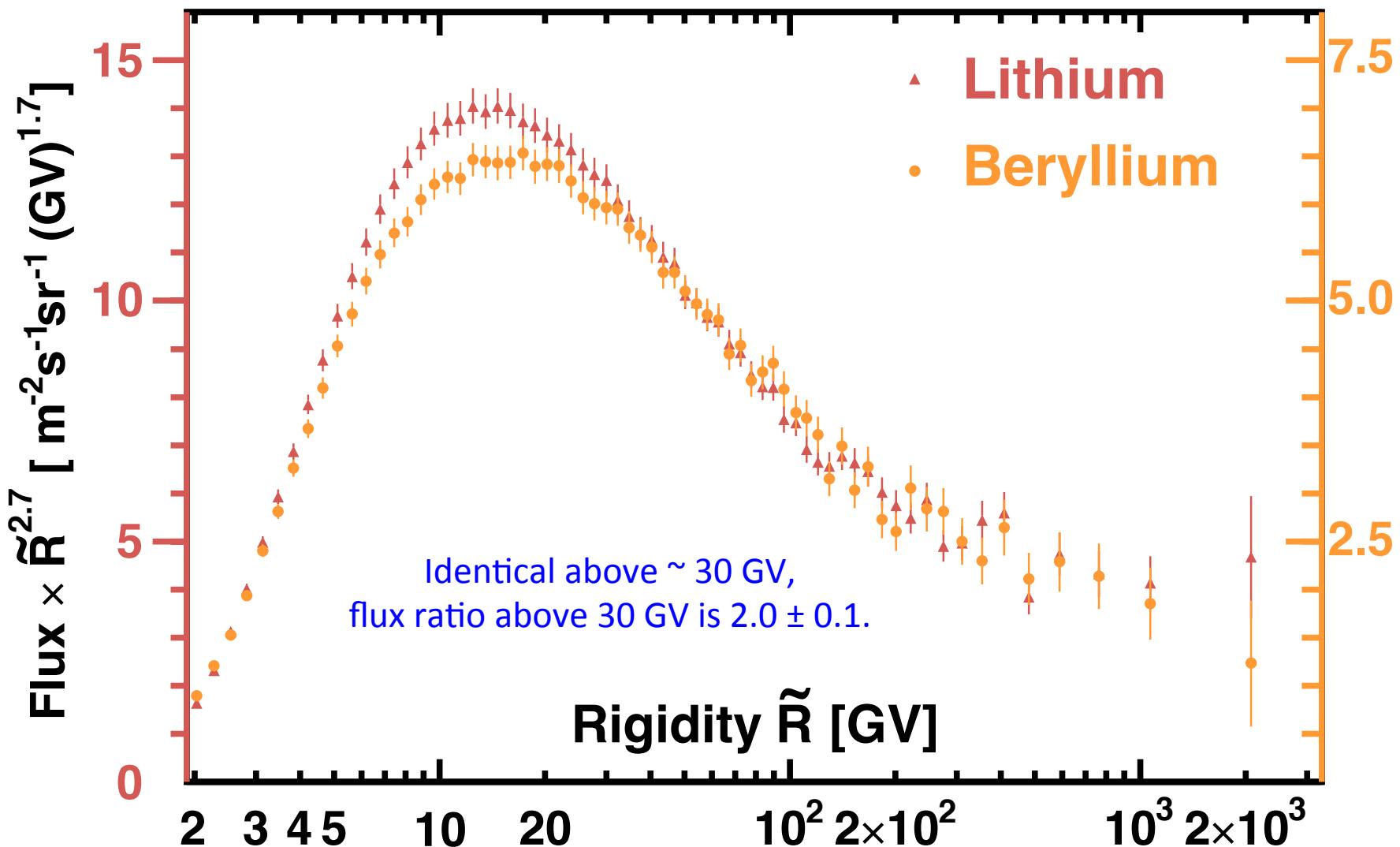
# Beryllium and Boron Fluxes

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101

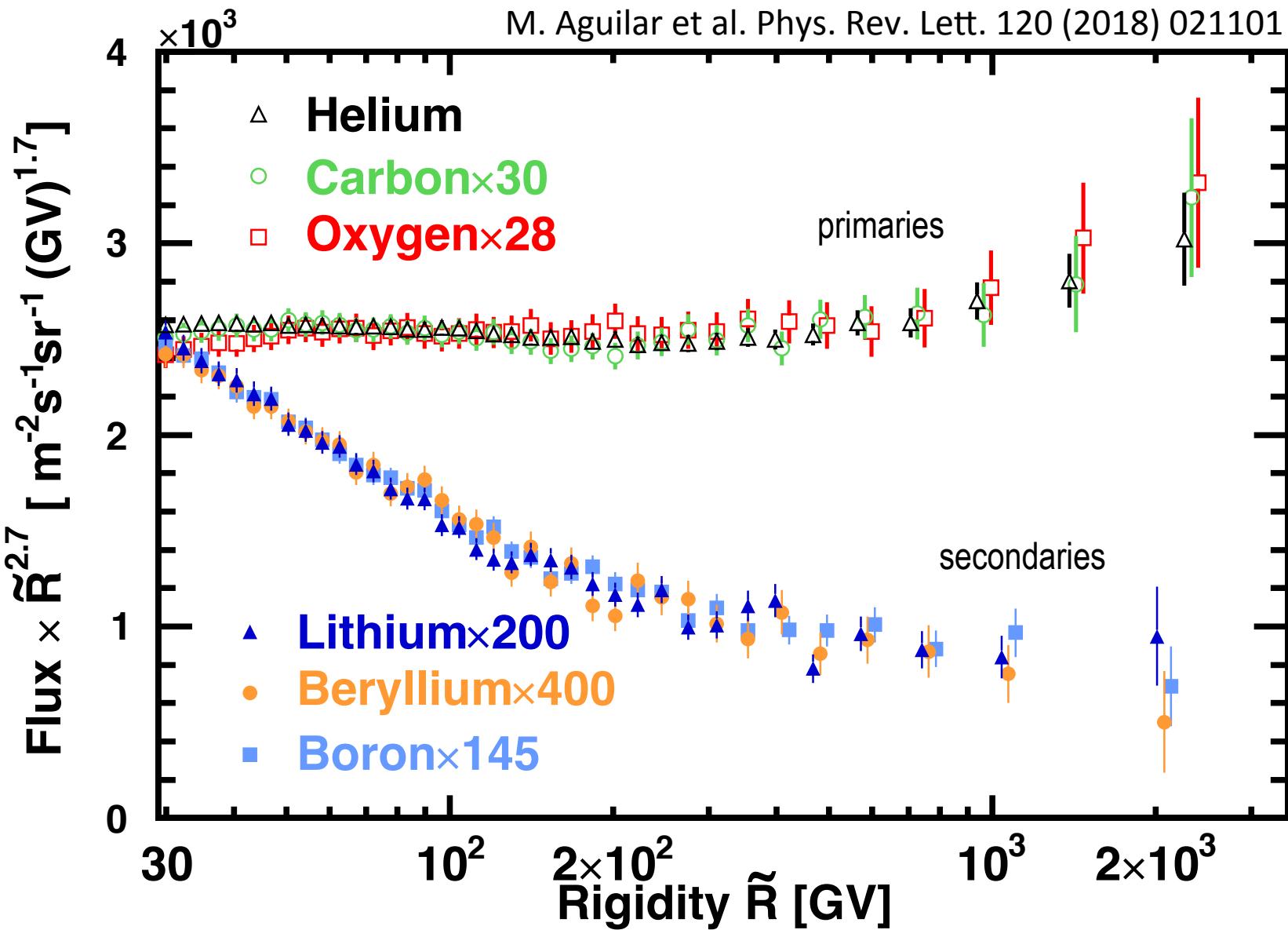


# Lithium and Beryllium Fluxes

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101

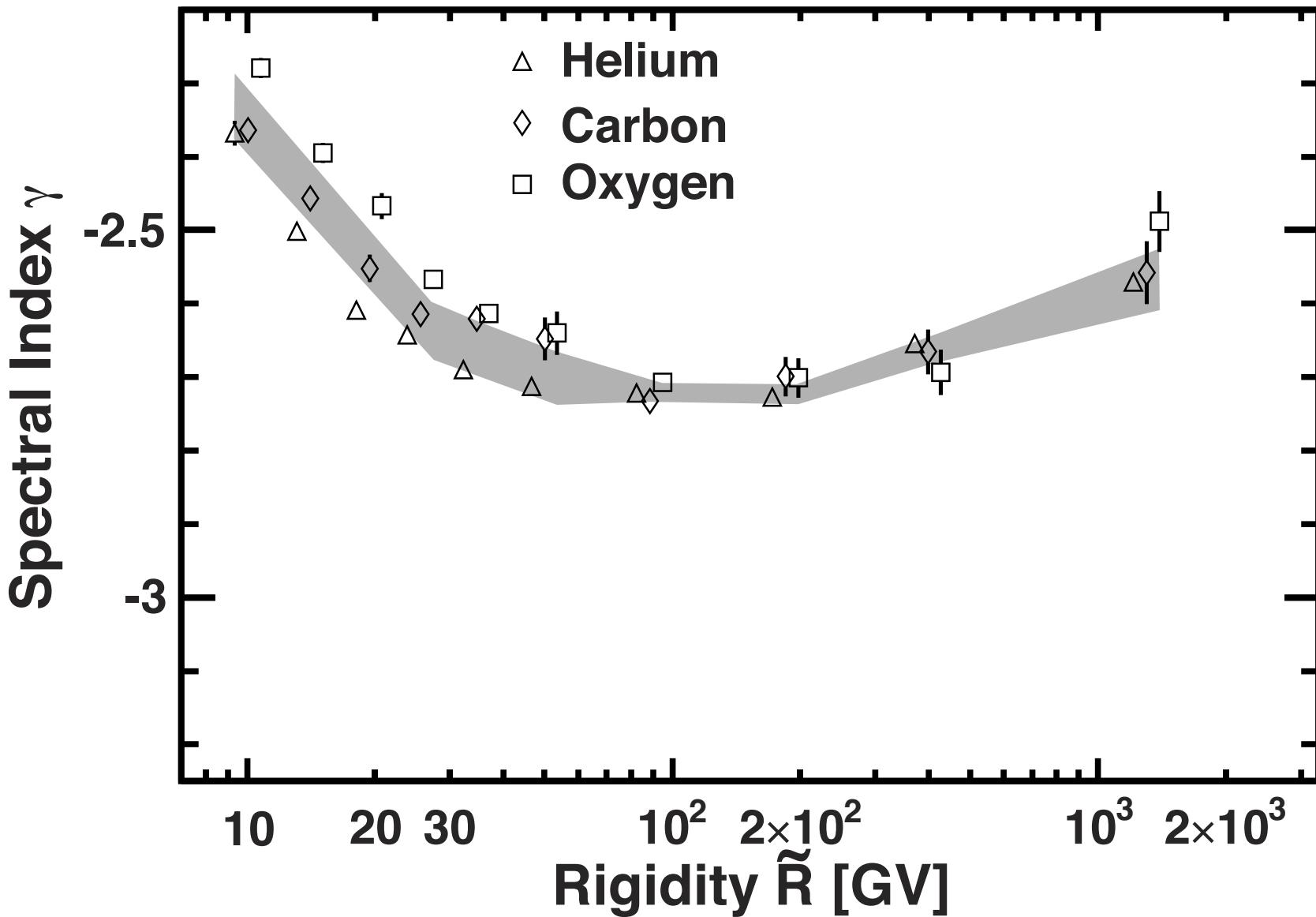


# Primary and Secondary Cosmic Ray Fluxes



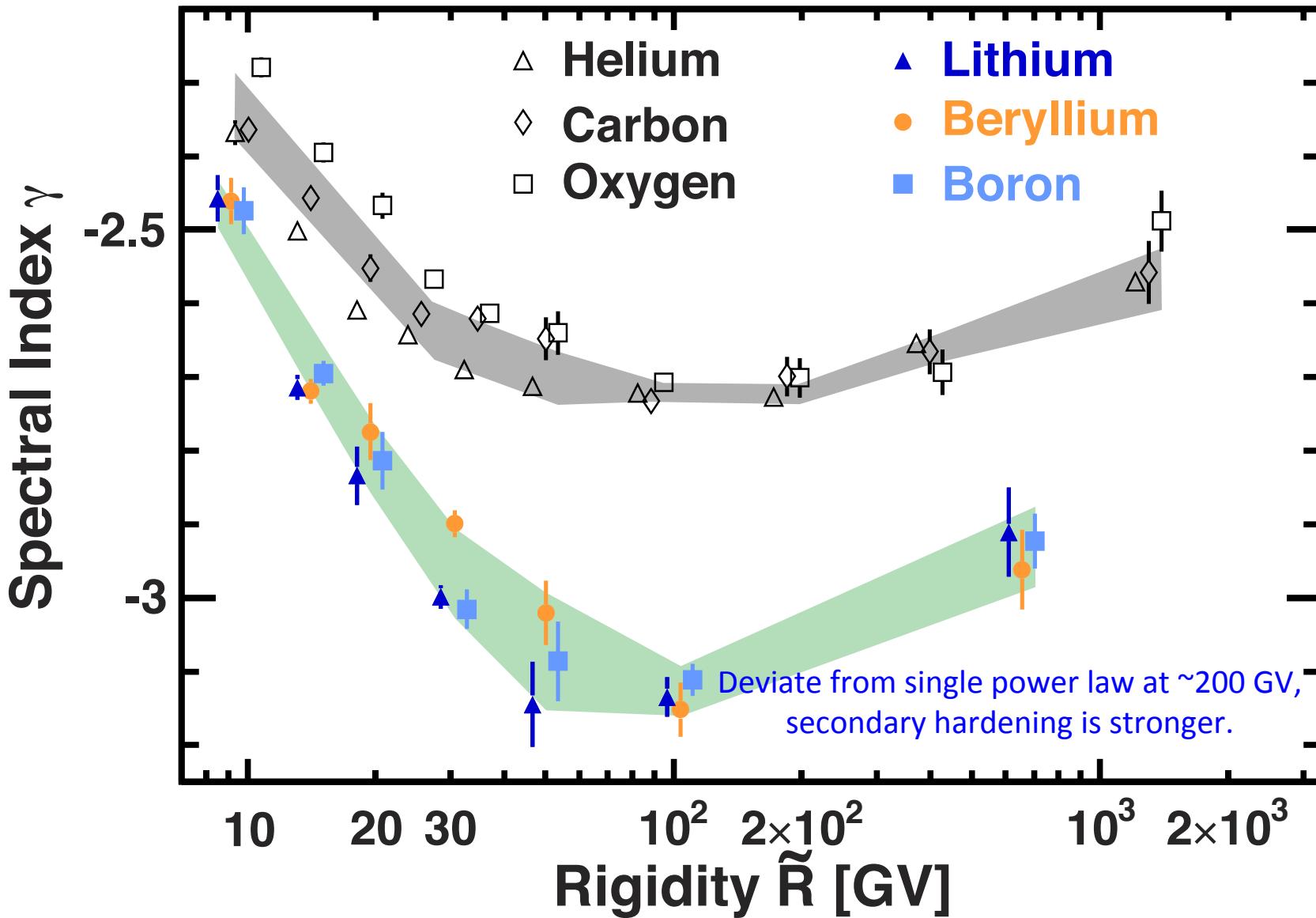
# Primary Spectral Indices

M. Aguilar et al. Phys. Rev. Lett. 119 (2017) 251101



# Primary and Secondary Spectral Indices

M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101



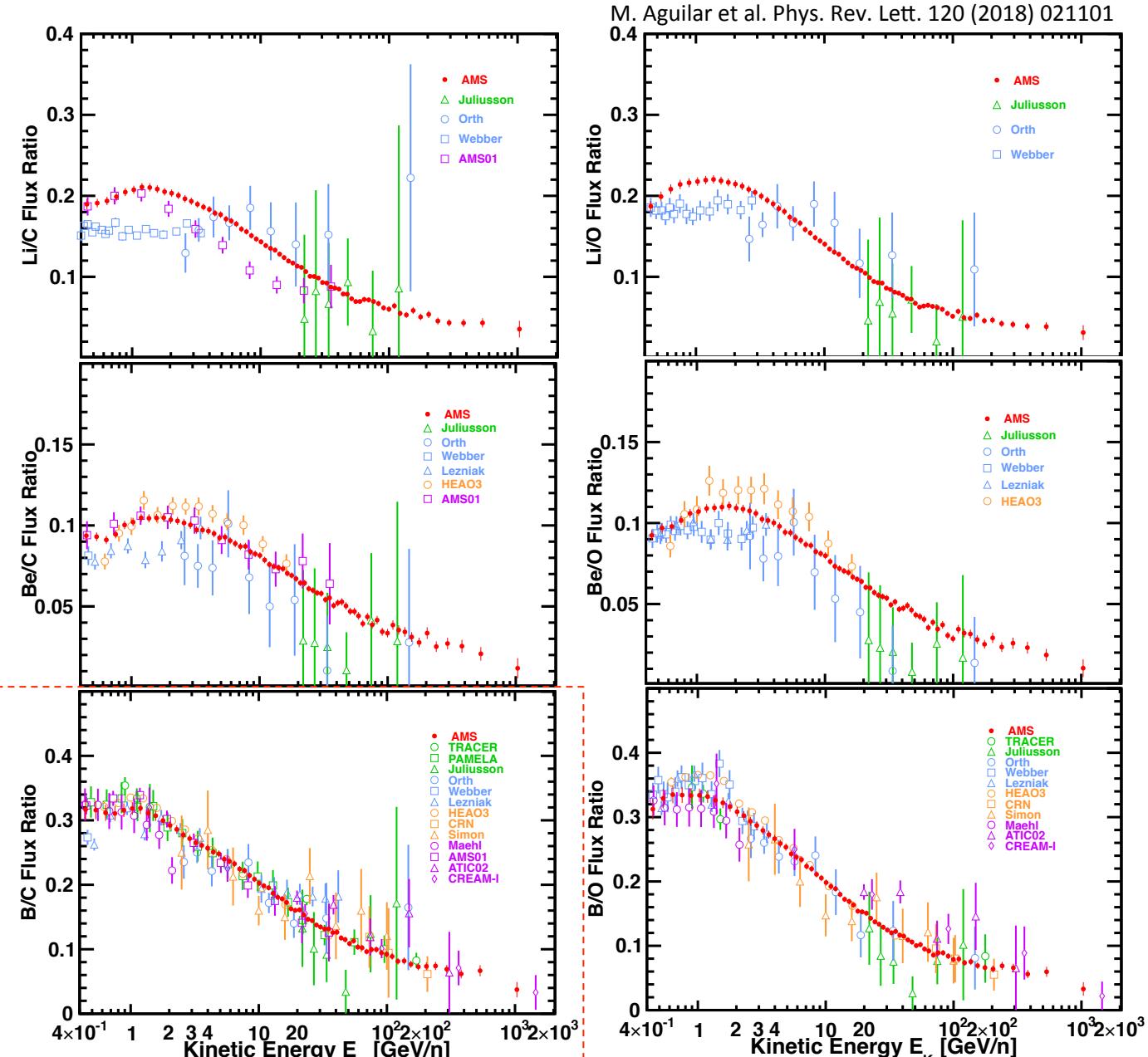
# Secondary/Primary Flux Ratios

Before AMS the propagation models were essentially tuned with B/C ratio (in the ratio many systematics on measurement and models cancel out).

AMS published high precision data of:  
Li/C, Be/C, B/C and  
Li/O, Be/O, B/O.

This allows extensive study of propagation. Few remarks:

- oxygen is “more primary” than carbon
- different species have different measurement and model uncertainties



# Secondary/Primary Flux Ratios

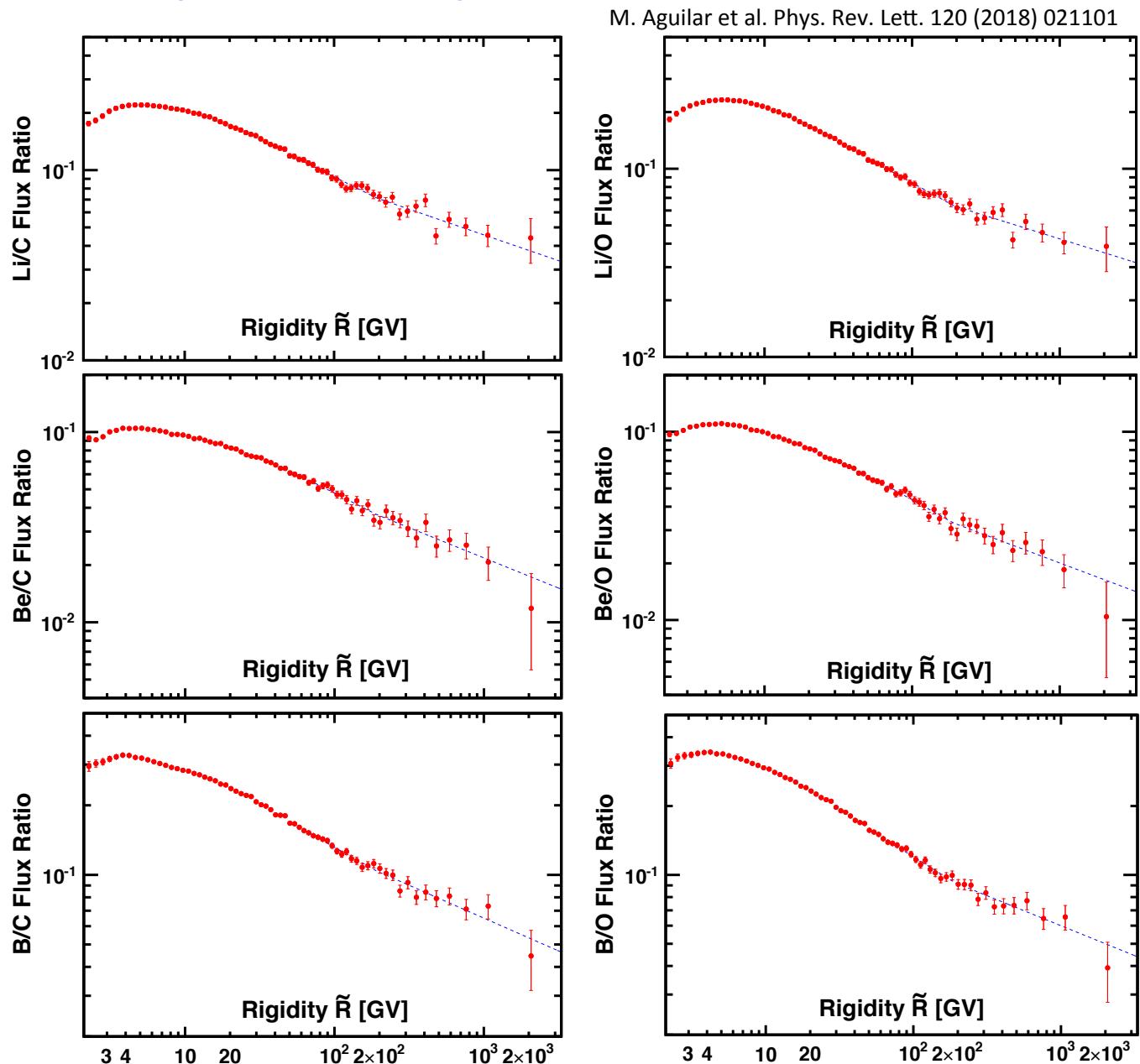
Data were fit with a broken power law with break at 192 GV.

All ratio show a hardening (at the level of  $2\sigma$ ), consequence of the fact that secondary show a hardening stronger than primaries.

Globally an average hardening of  $0.13 \pm 0.03$  is observed.

**Similar to the break in the primaries.**

→ this has strong implication for propagation models (break in propagation, ...)



M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101

# Secondary/Primary Ratio Spectral Indices

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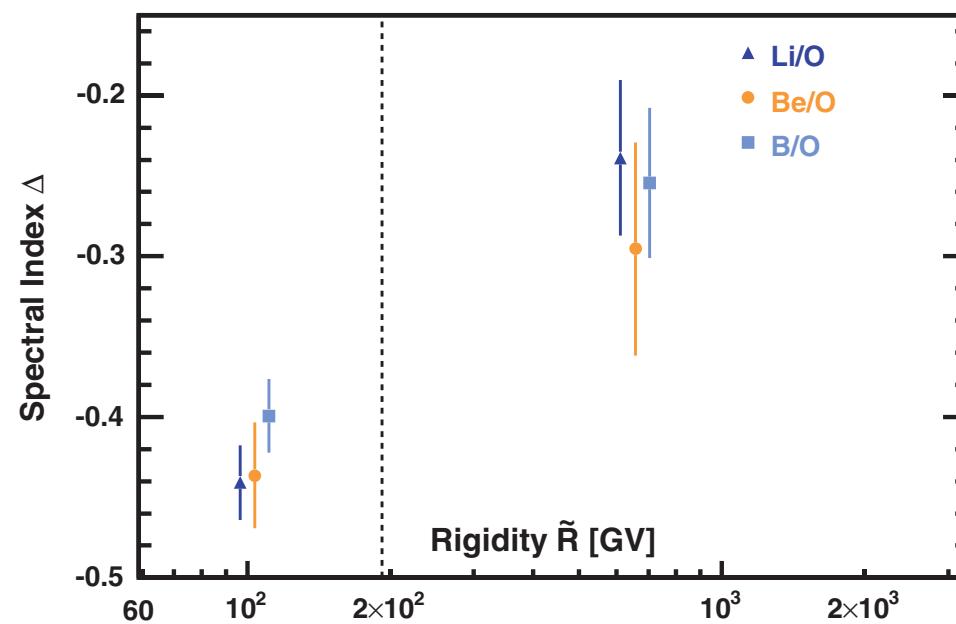
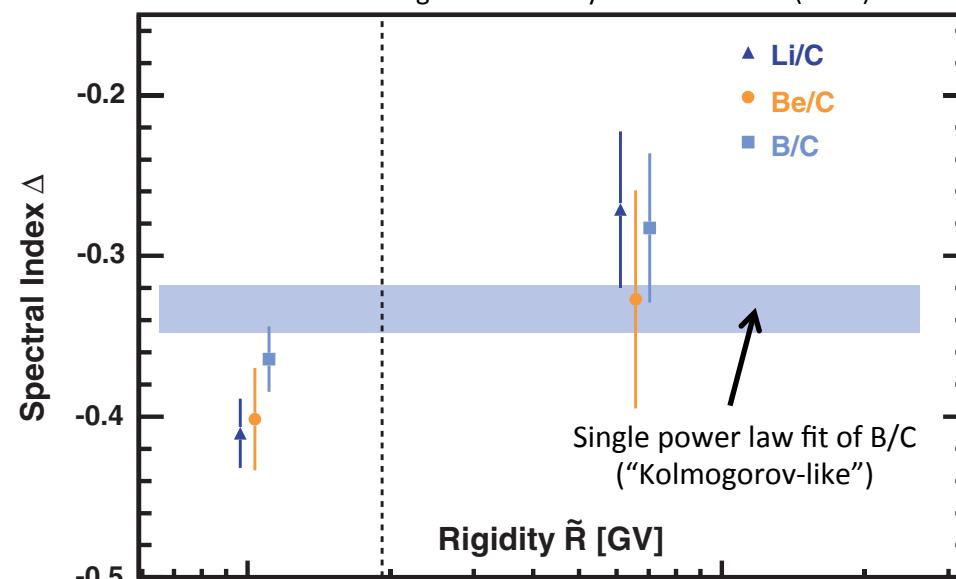
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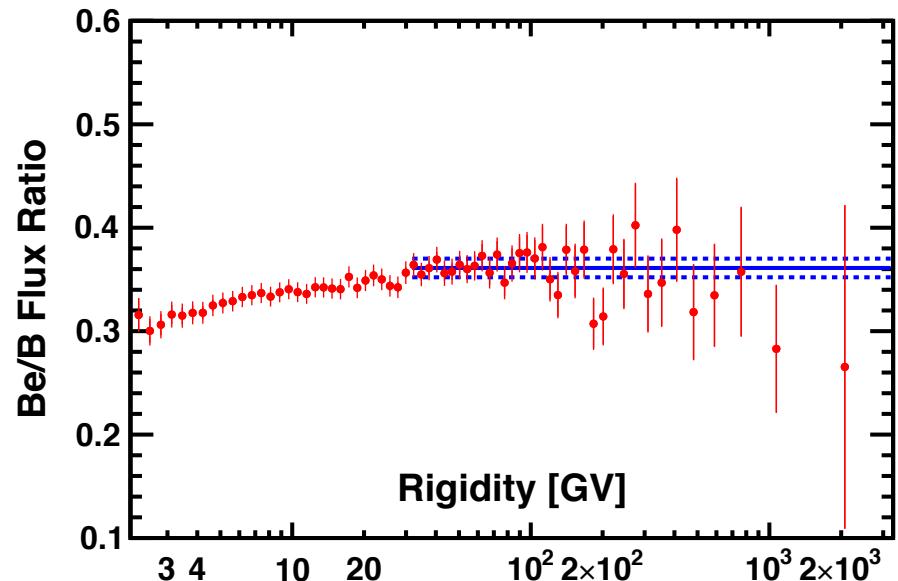
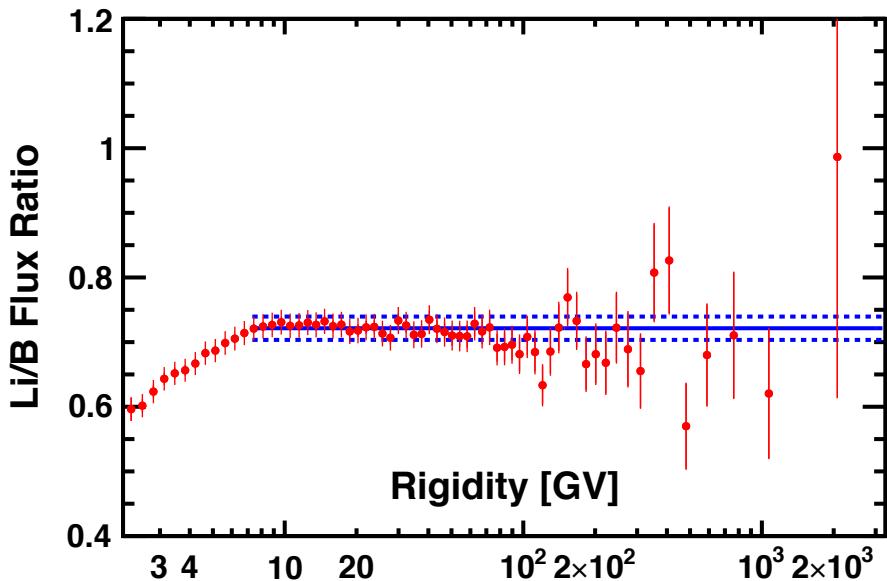
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M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101



# Secondary/Secondary Flux Ratios

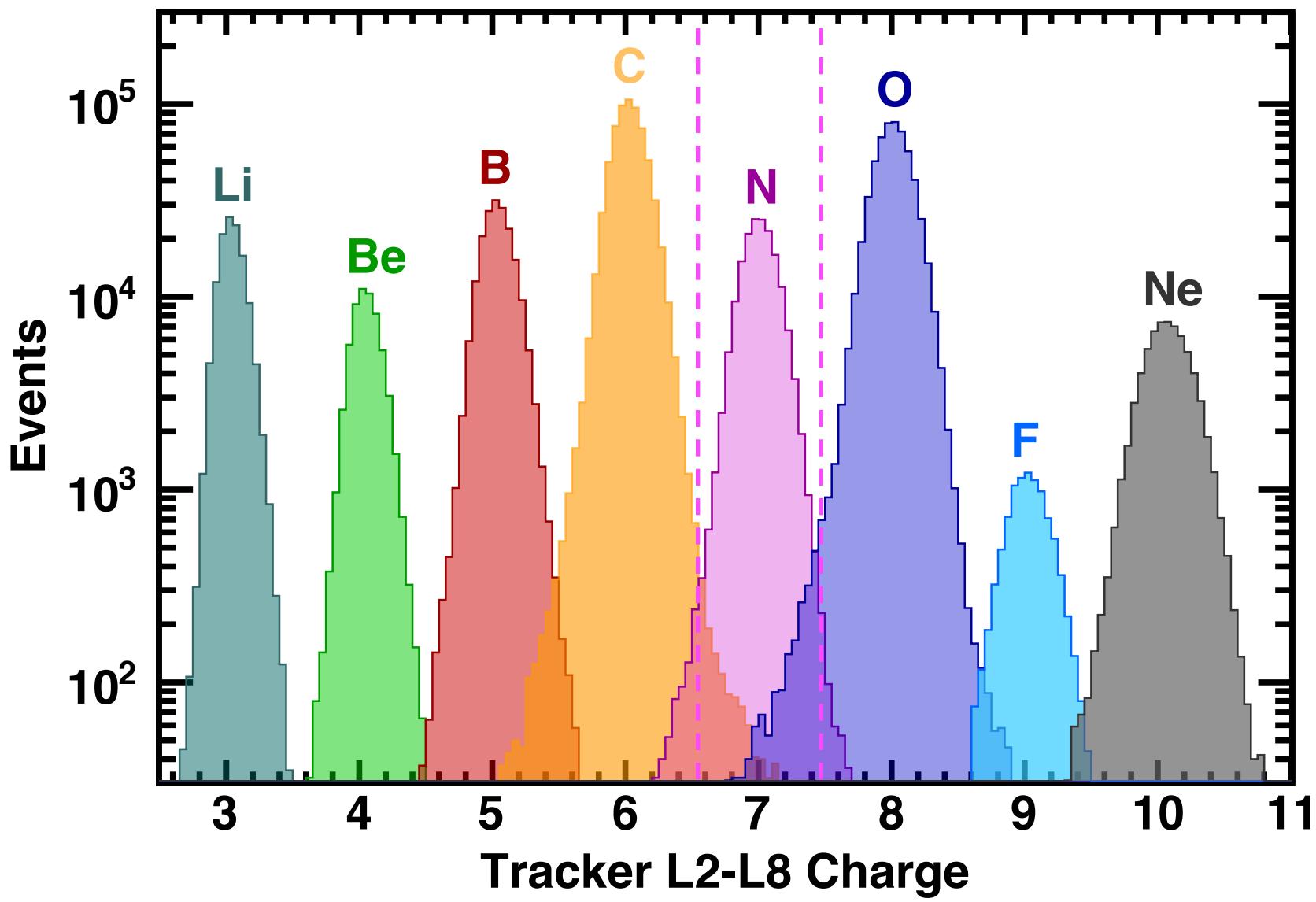


They have the same behavior above 30 GV (all secondary).

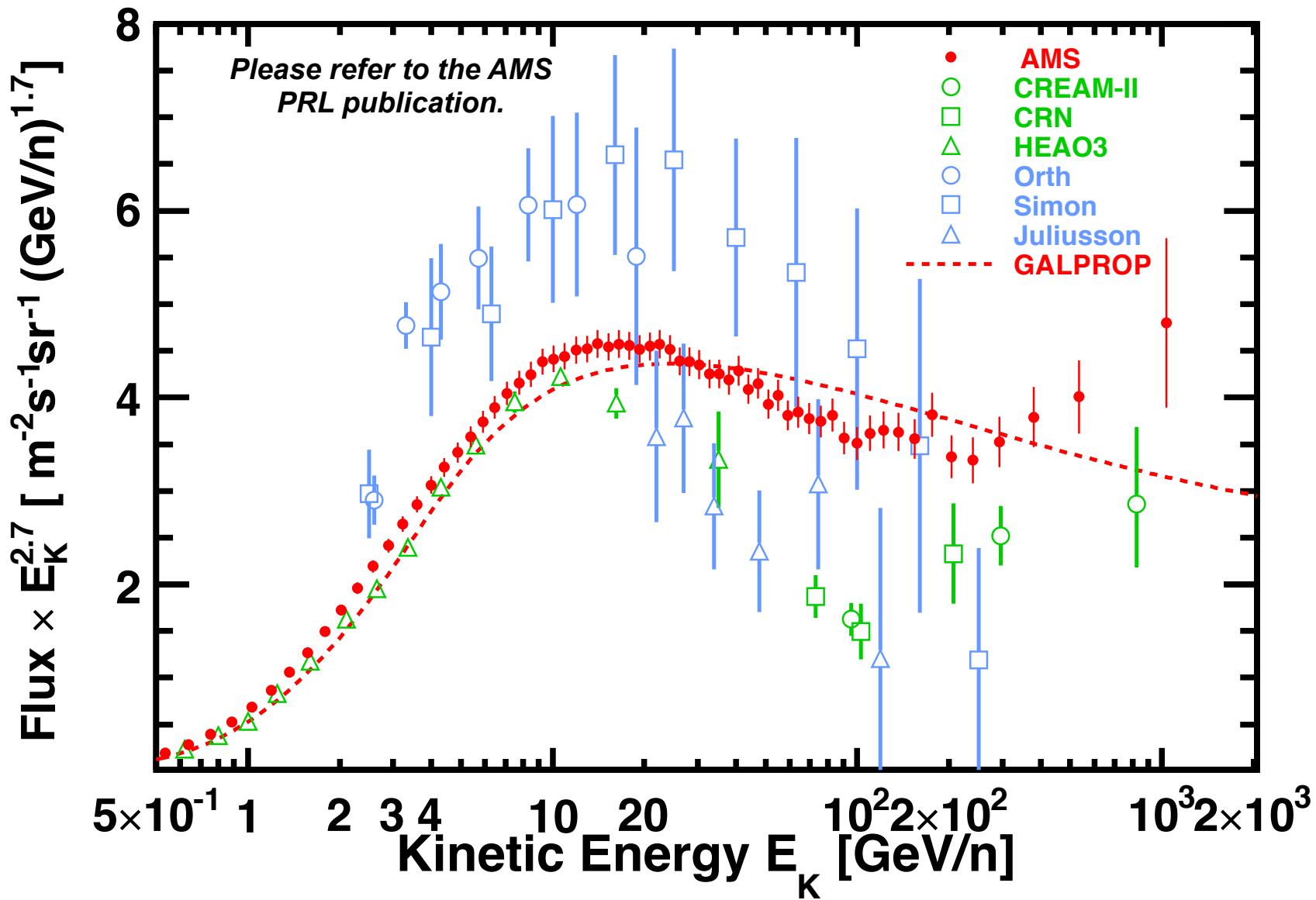
Differences at low energy can be due to:

1. a tertiary component
2. differences in inelastic cross section between elements
3. differences in fragmentation cross section between elements
4.  $^{10}\text{Be}$  decays with  $t_{1/2} = 1.4$  My through  $^{10}\text{Be} \rightarrow ^{10}\text{B} + e^- + \bar{\nu}$

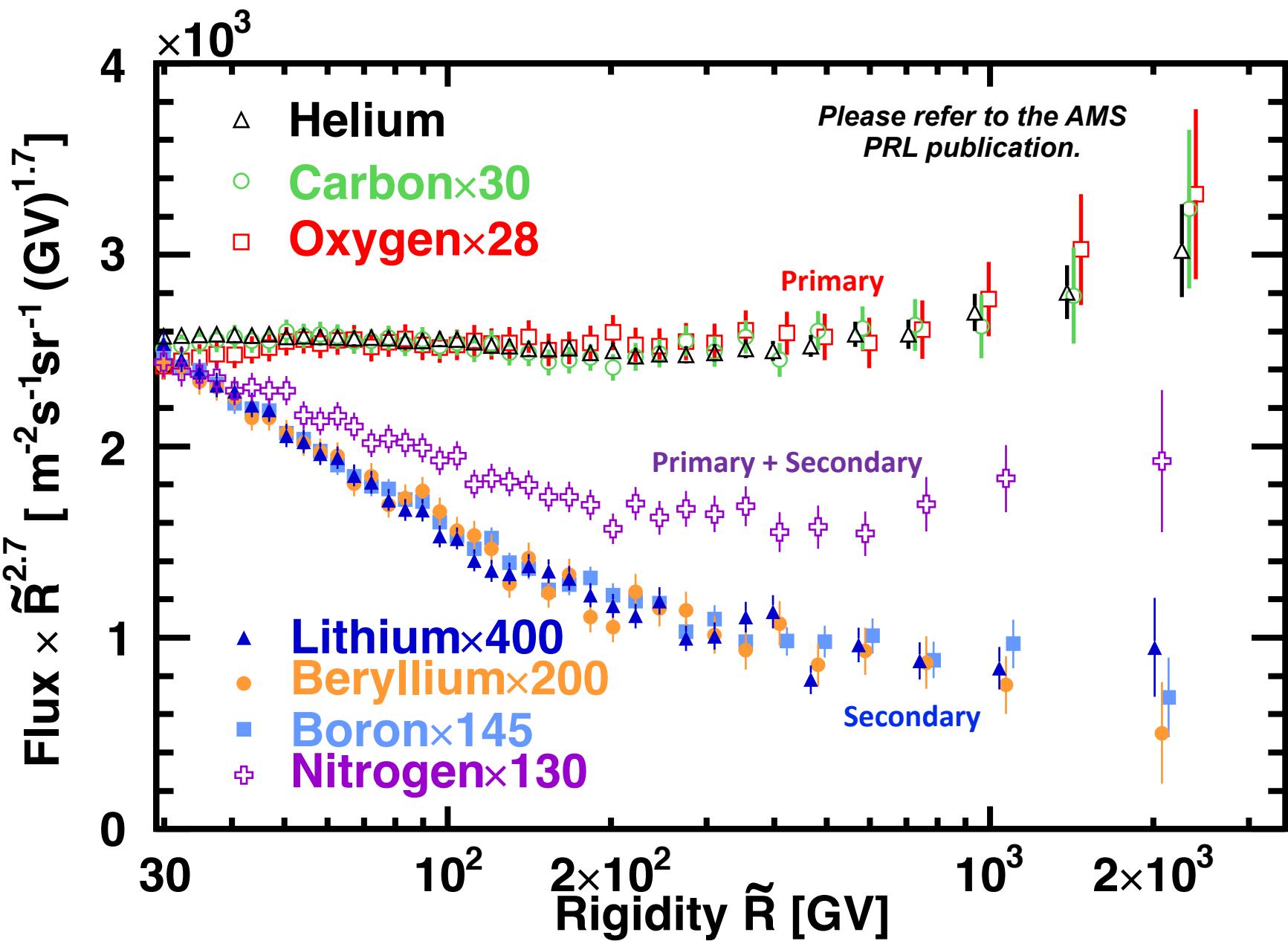
# Nitrogen



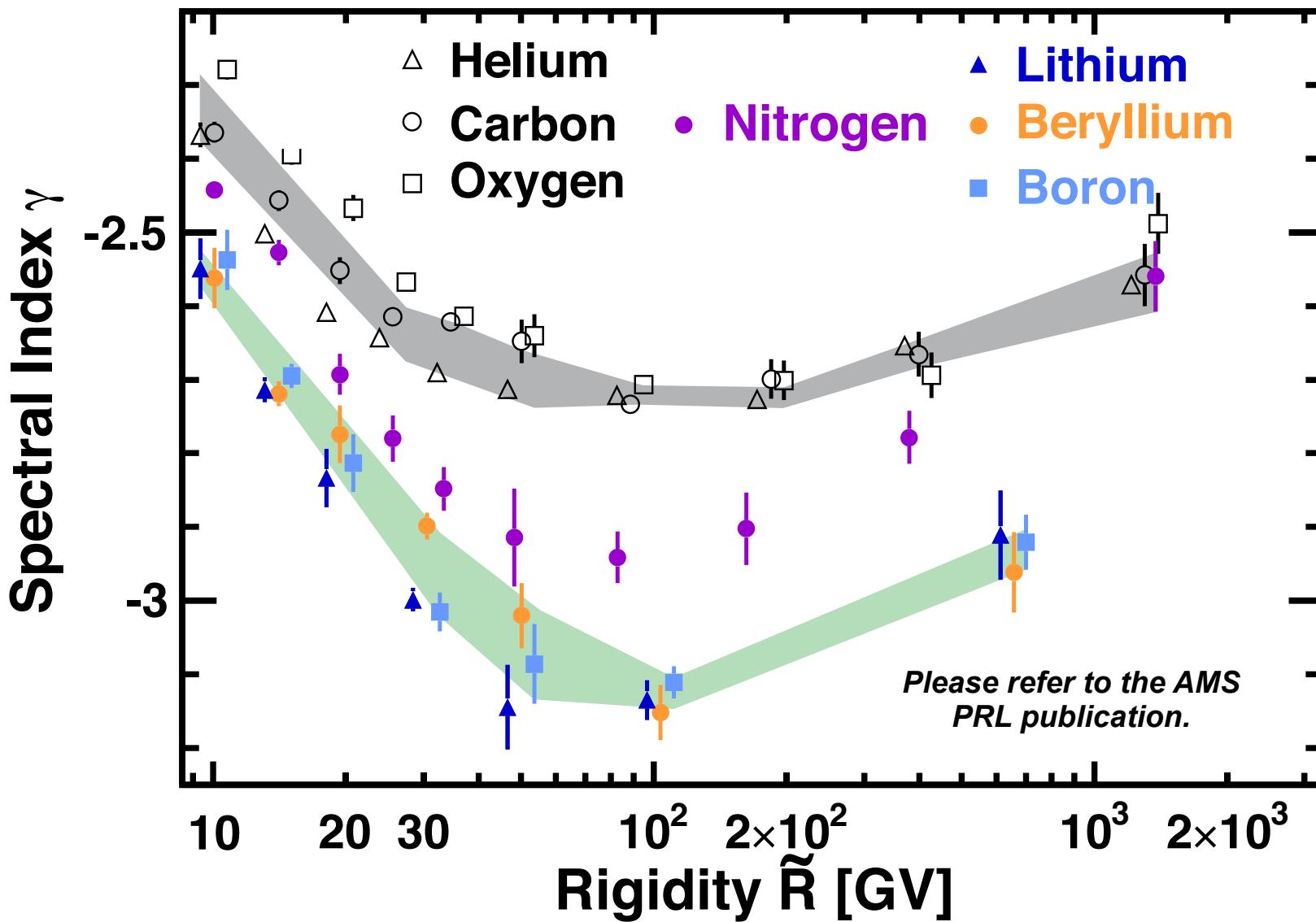
# Nitrogen Flux



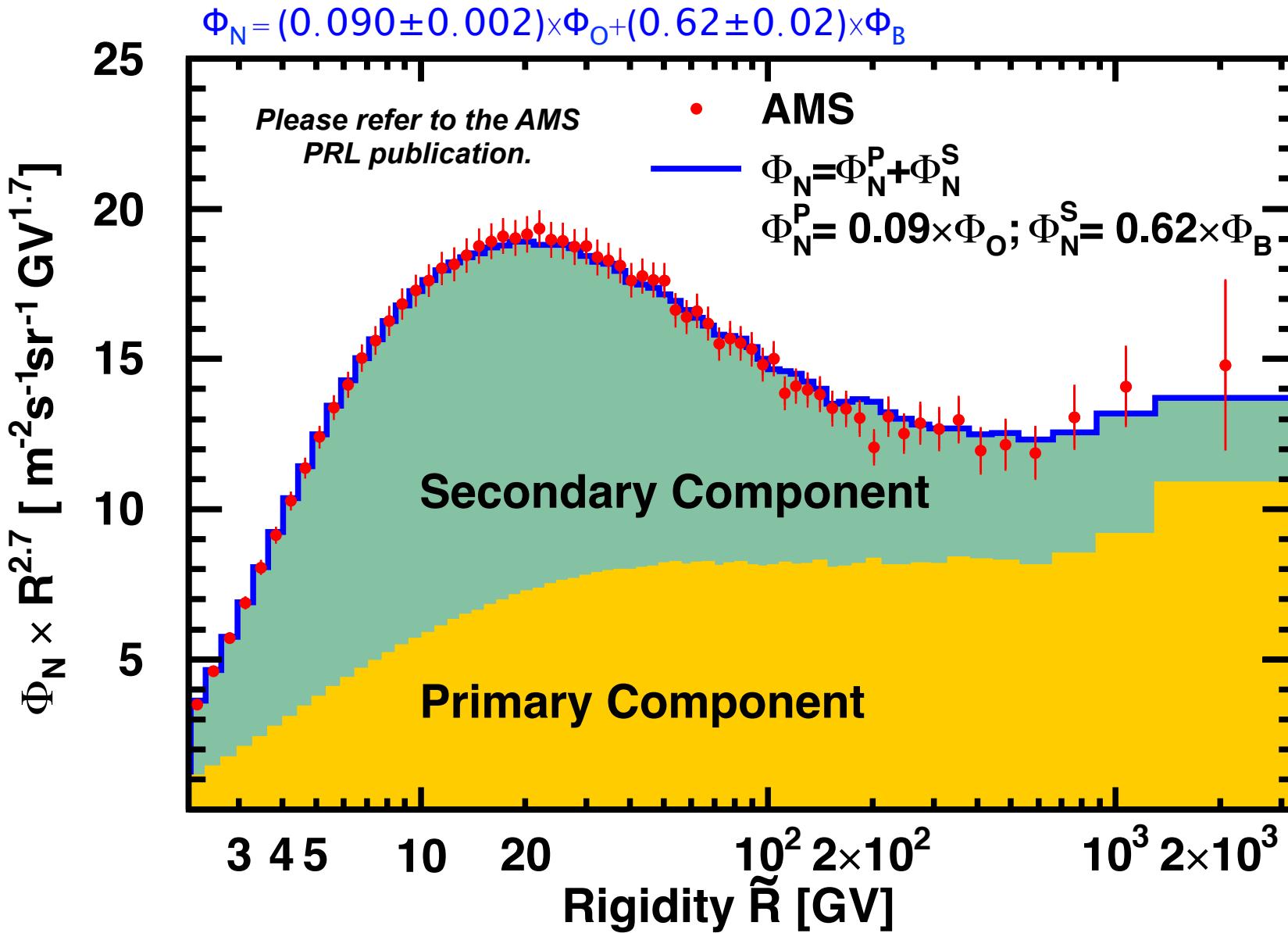
# Fluxes



# Spectral Indices

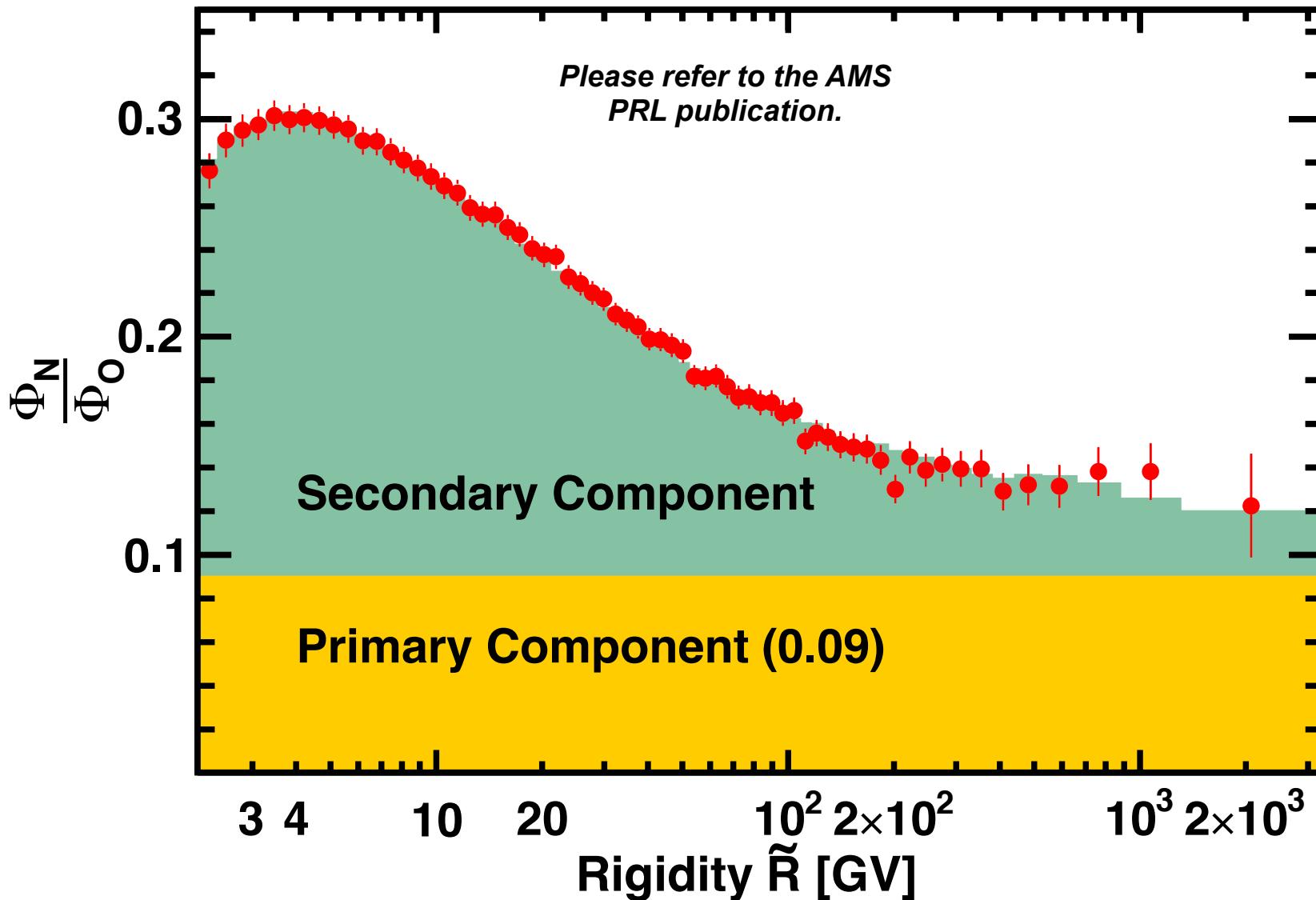


# Nitrogen Components

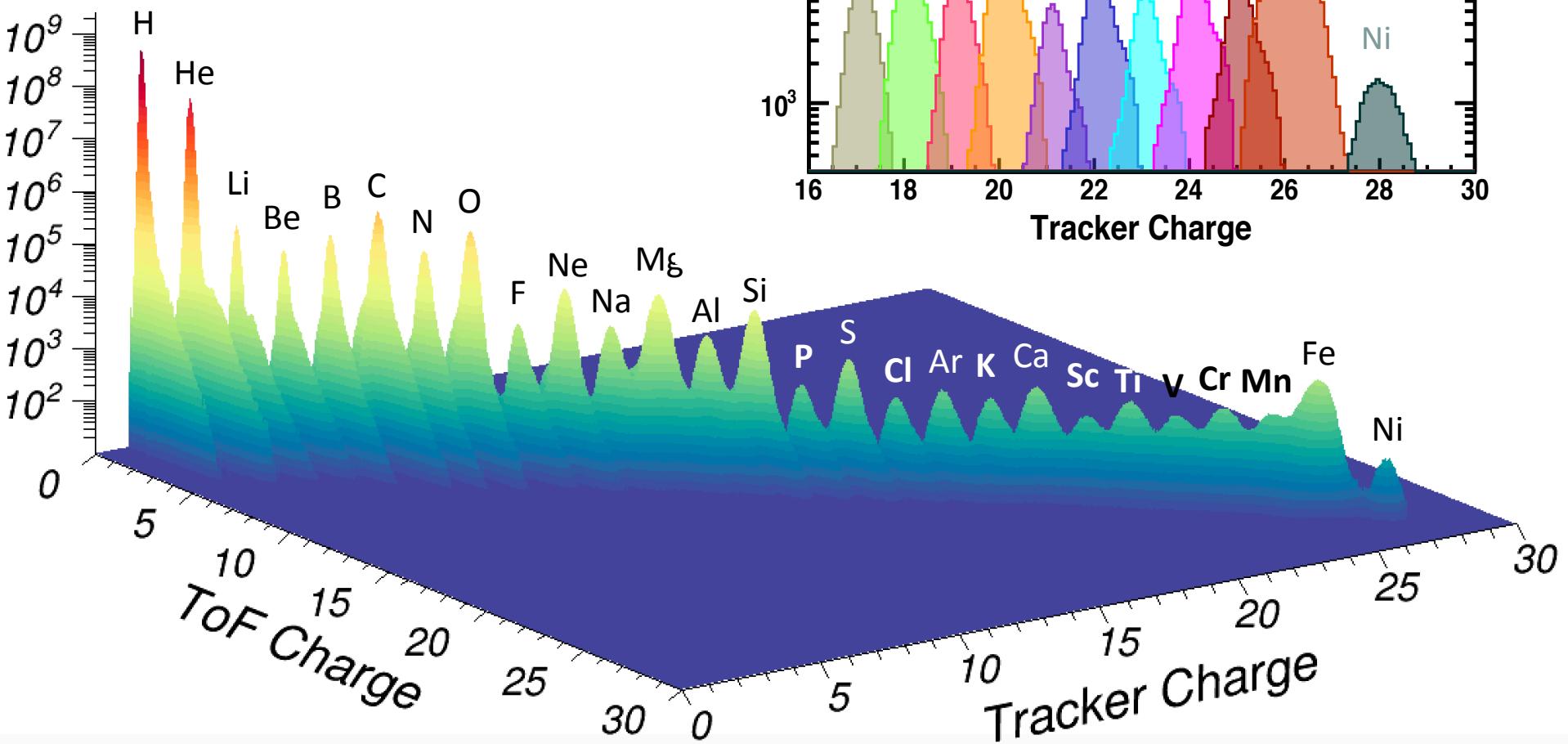


# Nitrogen Components in N/O

Secondary component in the Nitrogen: 70% at few GV, <30% above 1TV



# In Future



# Conclusions

For all nuclei species considered ( $1 \leq Z \leq 8$ ) the spectral index progressively hardens at rigidities larger than 100 GV.

The spectral index hardens identically for primaries nuclei H, He, C and O. The hardening is about of  $0.12 \pm 0.04$ .

Even if H and He have similar rigidity dependence, the H/He ratio is a well described by single power law above 45 GV of index  $-0.077 \pm 0.007$ .

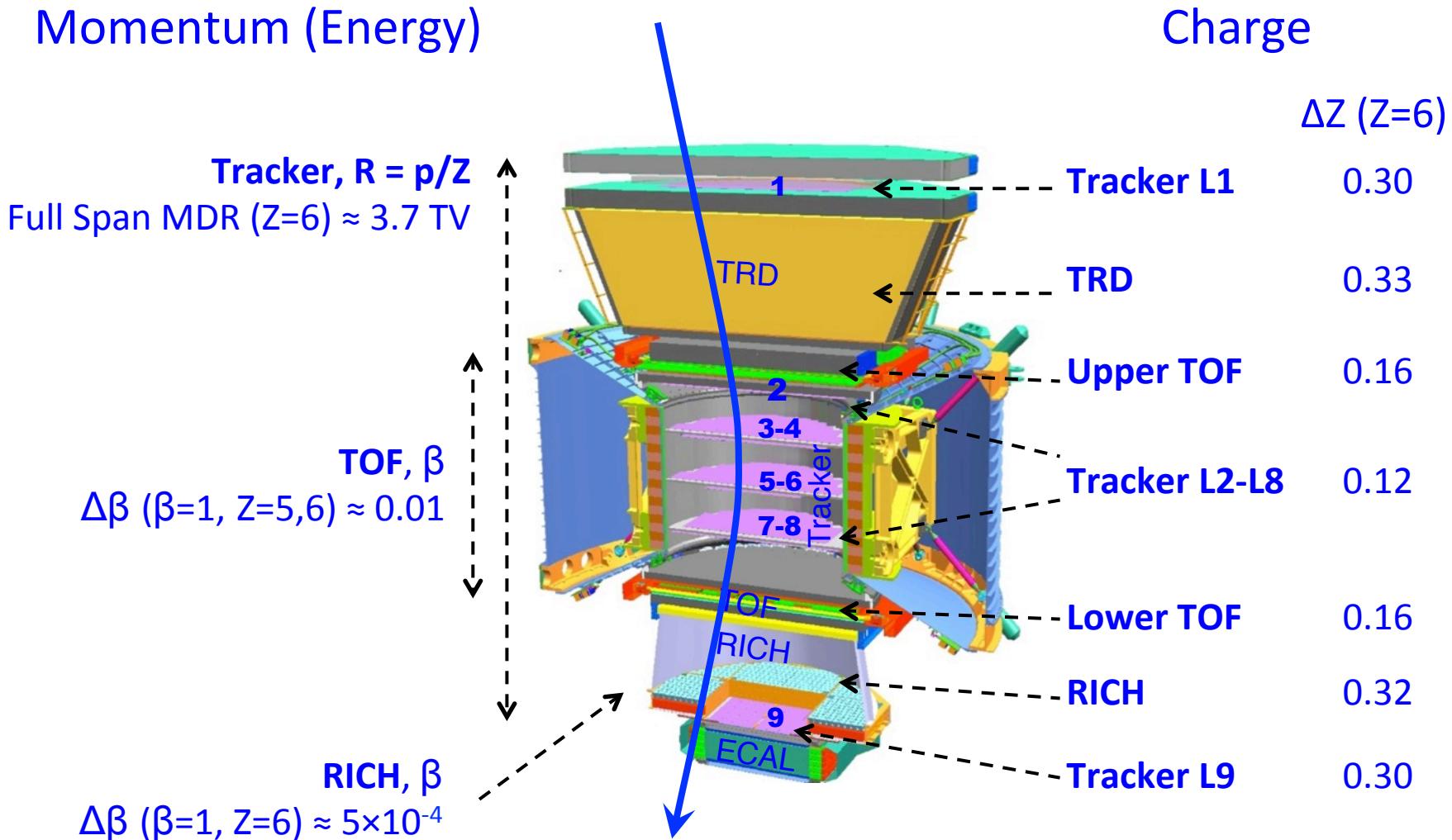
Secondary species, Li, Be and B have identical behavior above 30 GV. They all harden more than primary species. Together all secondary-to-primary ratio show a hardening difference of  $0.13 \pm 0.03$ .

Secondary-to-secondary ratio, in particular Be/B, has a structure at low energy that can be due to the decay of  $^{10}\text{Be}$ .

Nitrogen flux can be described as a superposition of a primary specie (Oxygen), and a secondary one (Boron).

# Backup Slides About Analysis

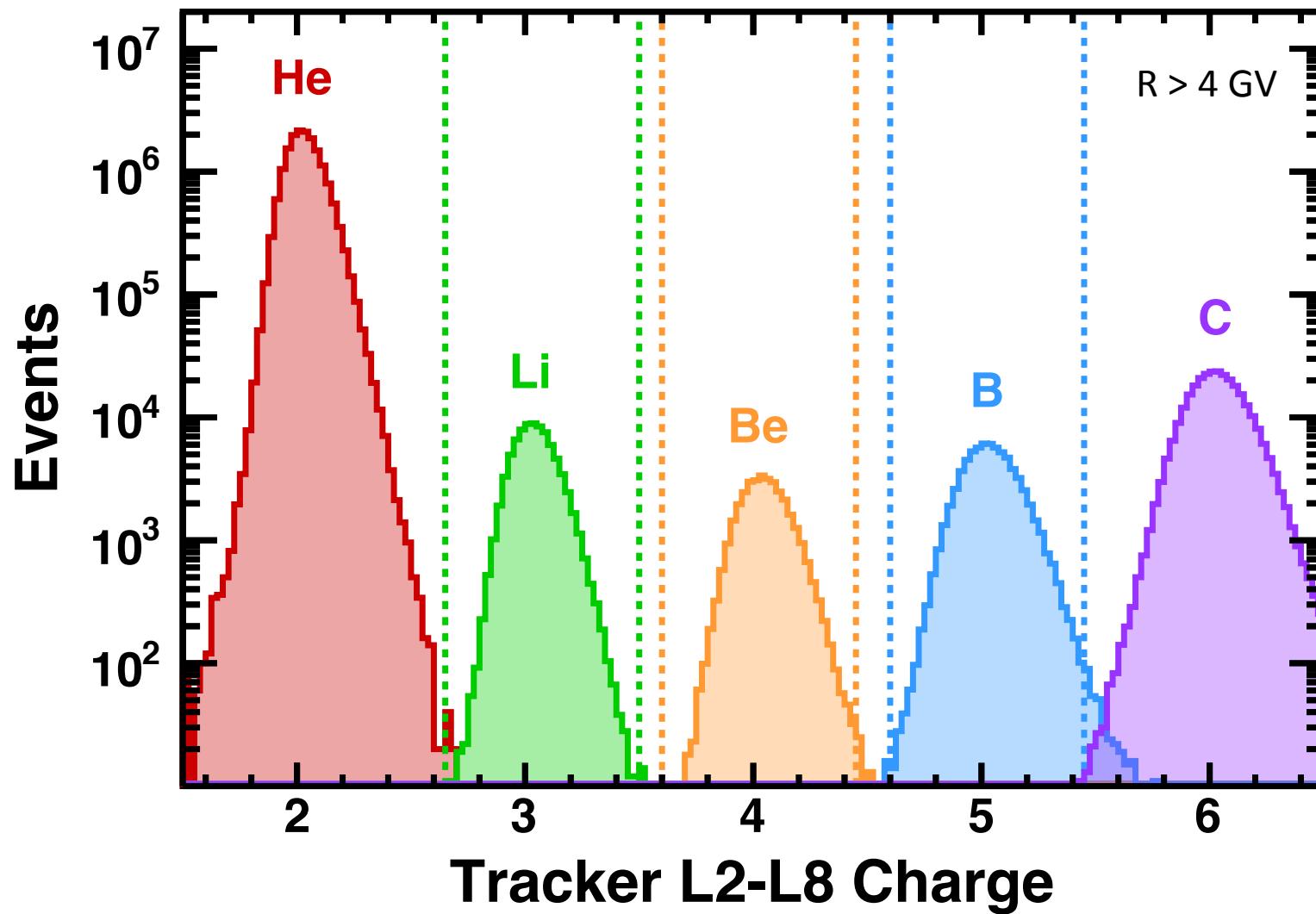
# Nuclei Measurement



# Event Selection

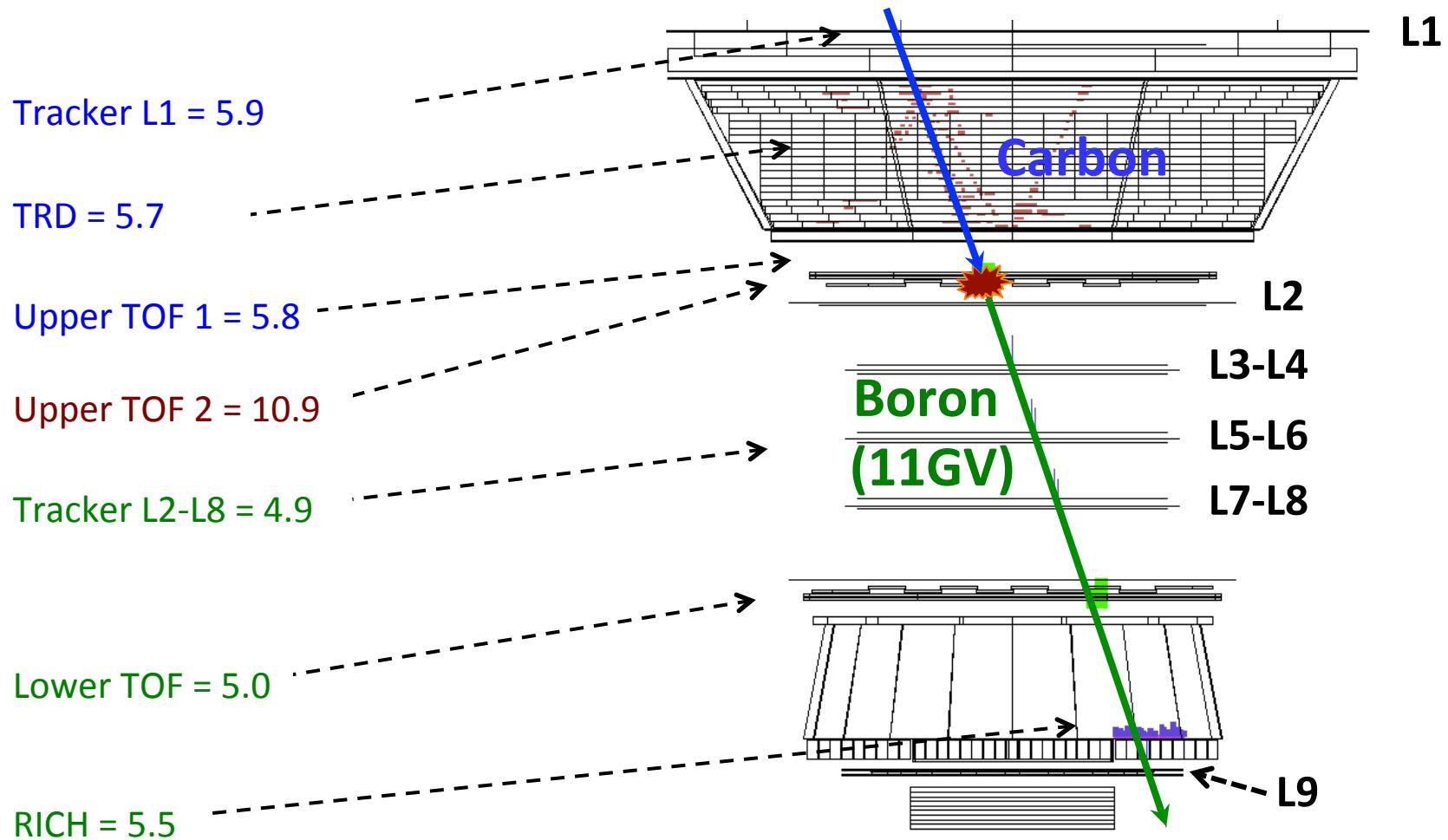
Tracker and TOF Charges compatible with Z=3,4,5 with negligible misidentification.

In 5 years we collected **1.9M Lithium**, **0.9M Beryllium** and **2.6M Boron nuclei**.



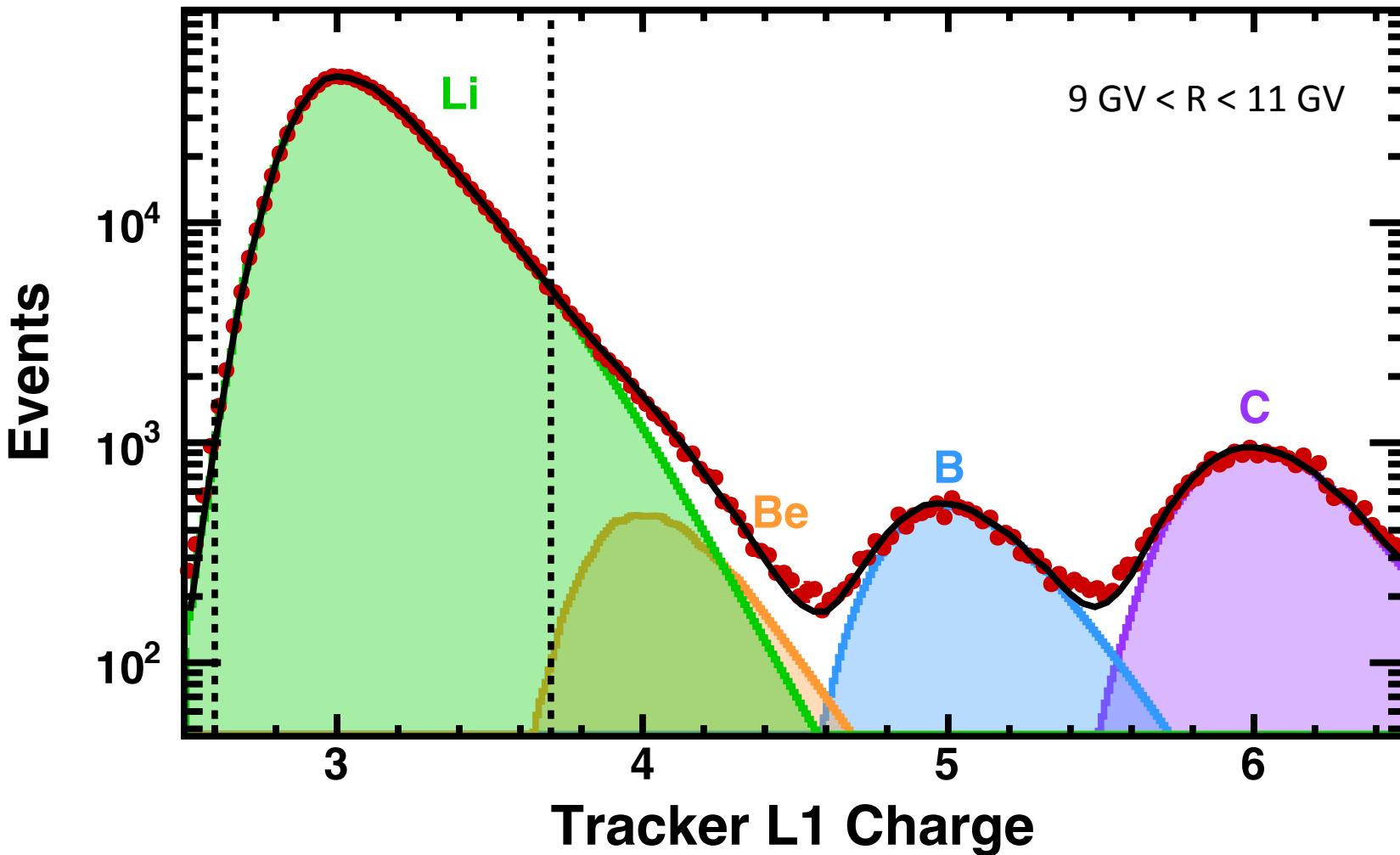
# Background Subtraction

The main backgrounds of these analysis consist of heavy nuclei interacting with AMS materials  
 $O, N, C + \text{AMS} \rightarrow B + X$ ;  $O, N, C, B + \text{AMS} \rightarrow \text{Be} + X$ ; and  $O, N, C, \text{Be} + \text{AMS} \rightarrow \text{Li} + X$ .



# Background from Interactions Below L1

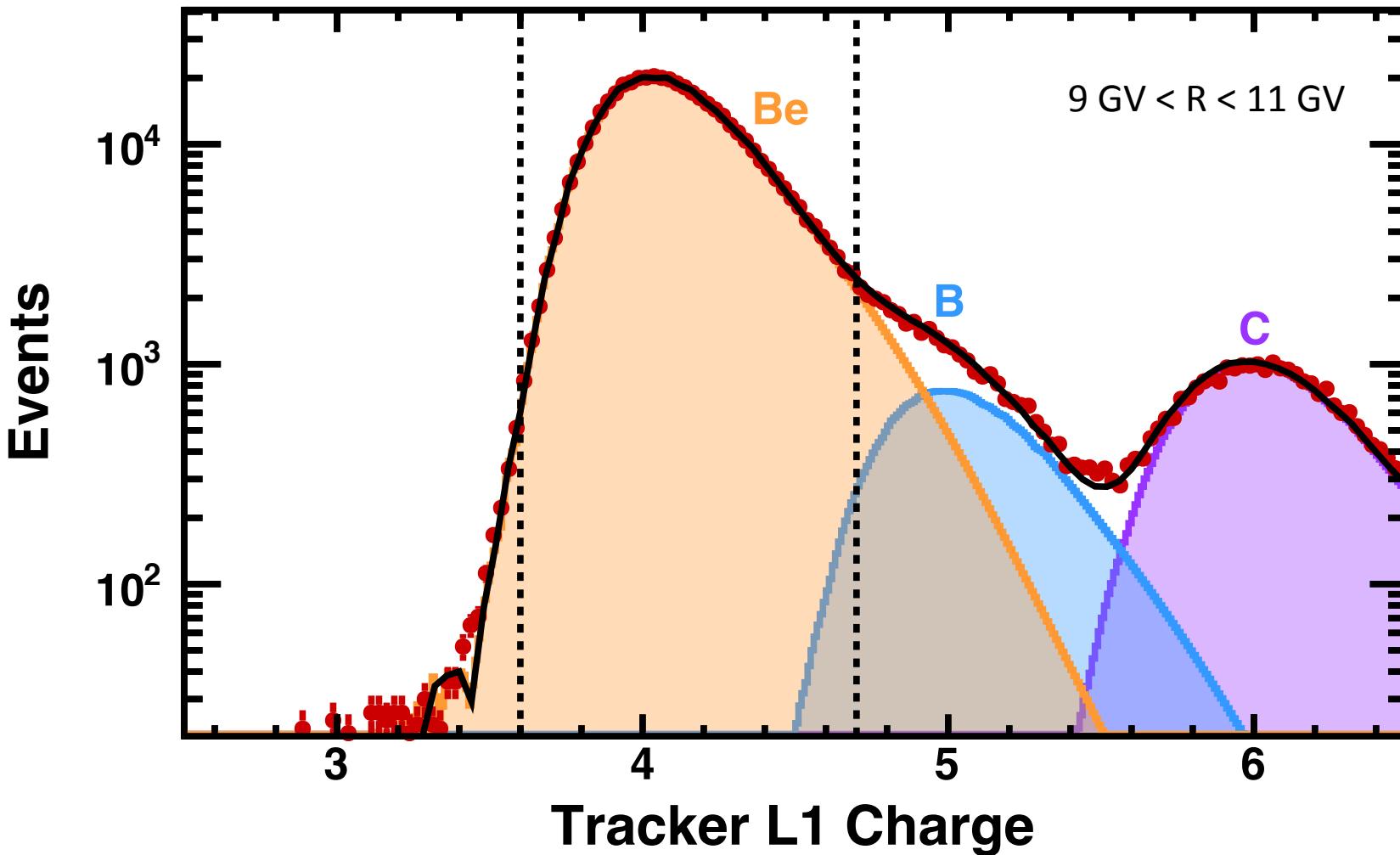
Events selected with inner tracker (L2-L8). Estimated background < 0.5%.



Systematic error is negligible.

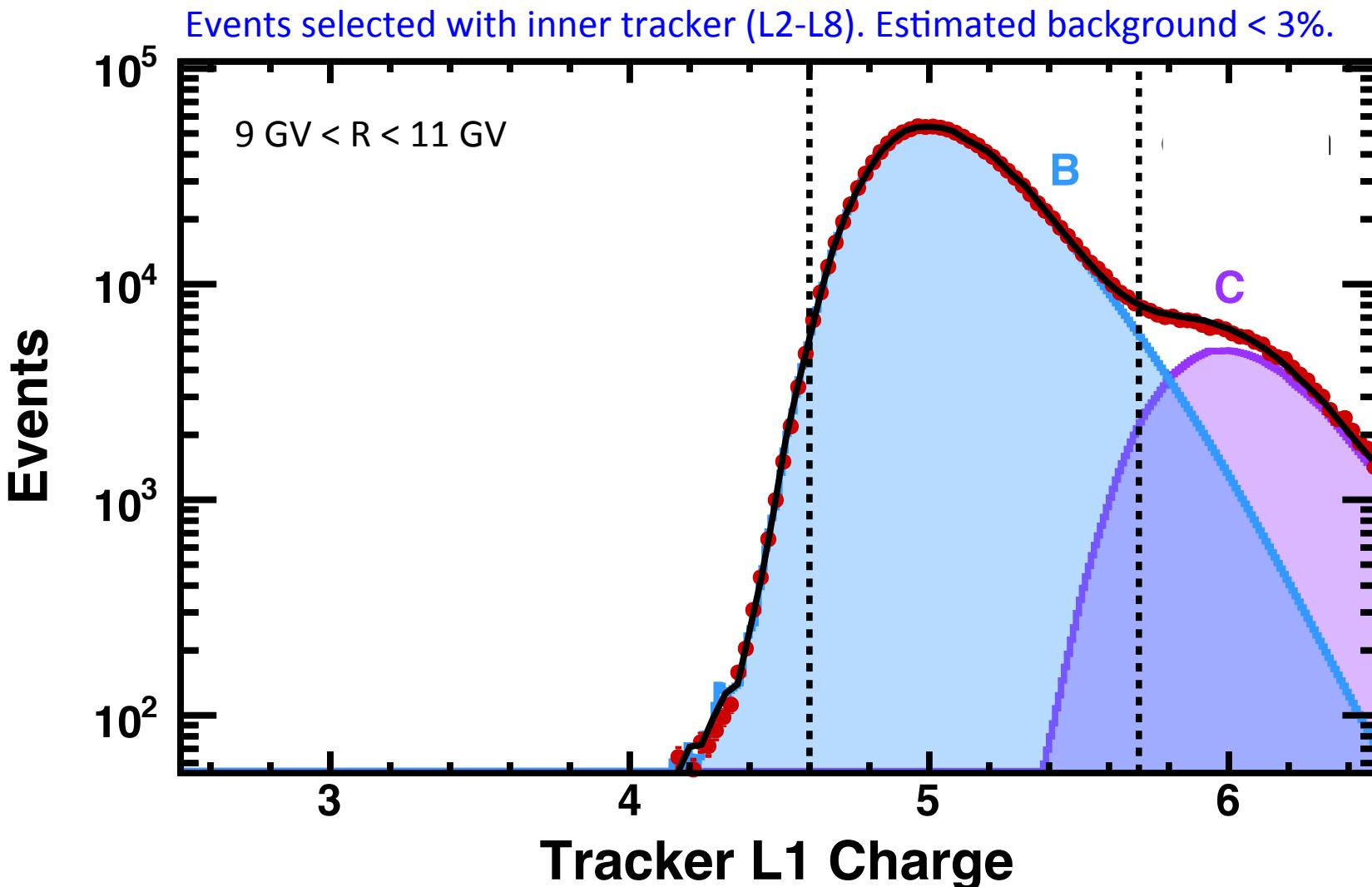
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# Background from Interactions Below L1

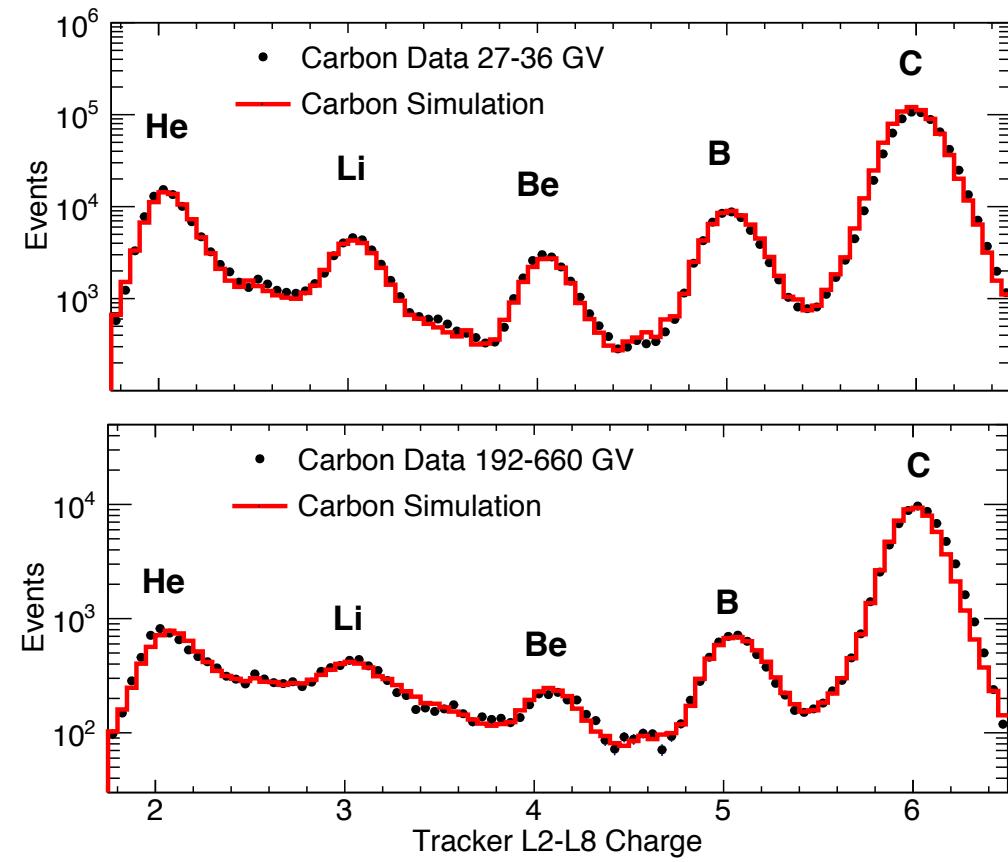
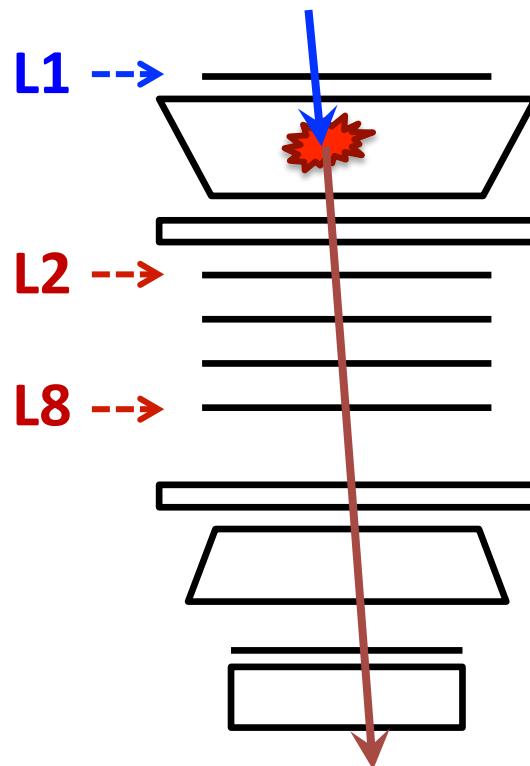


# Background from Interactions Above L1

Bkg. generated above L1 is calculated using MC and nuclei fluxes measured by AMS.

MC interaction channels (ex. C + C, Al  $\rightarrow$  Li, Be, B + X) have been verified with data.

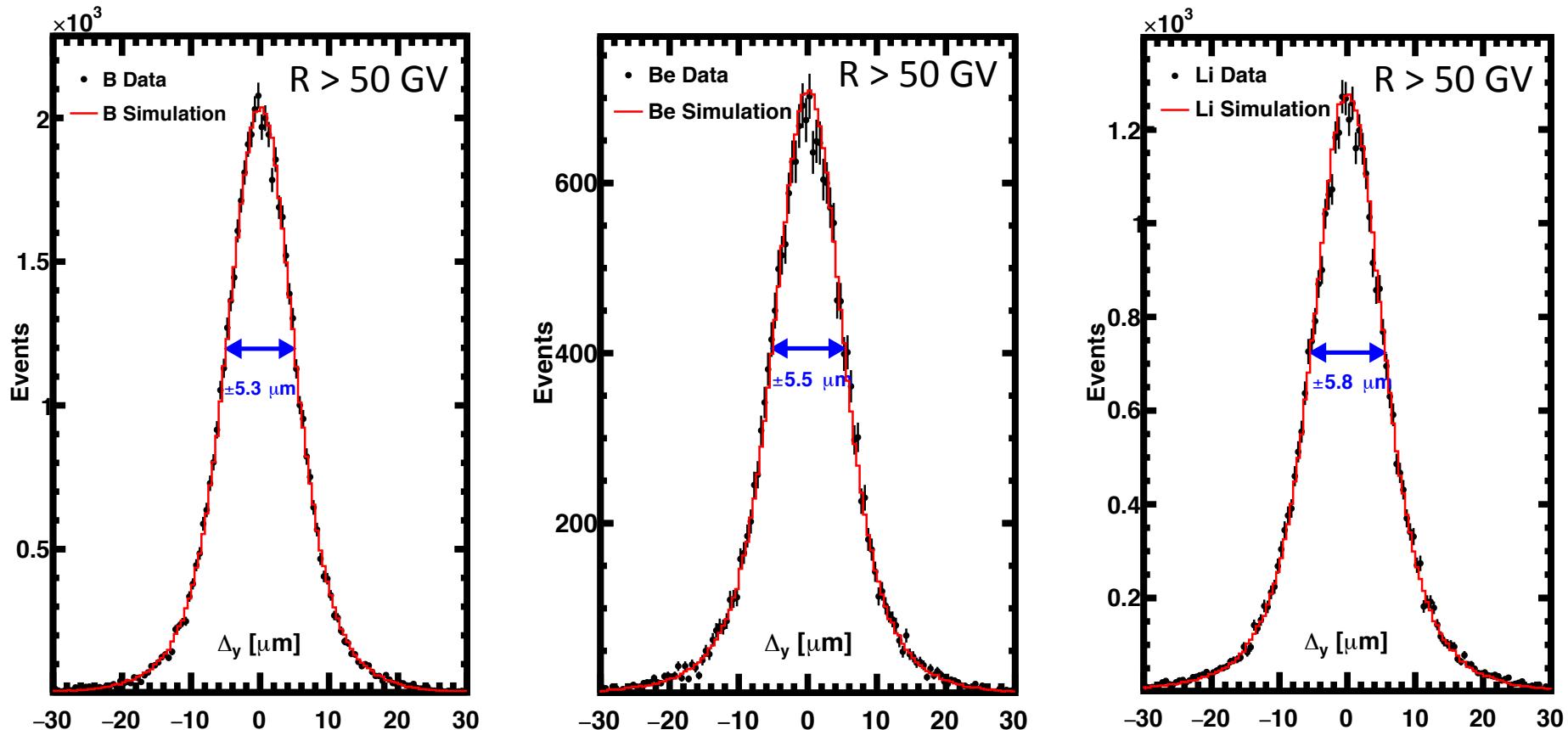
Background for Li, Be and B are 2%, 13% and 8% at 3.3 TV respectively.



Uncertainties on interactions above L1 by cross-section validation give < 1.5% systematic error.

# Rigidity Migration

The bin-to-bin migration of events was corrected using the unfolding procedure using the MC rigidity resolution functions. One of the many performed verification of the accuracy of this function is given by the comparison of the tracker spatial resolution.



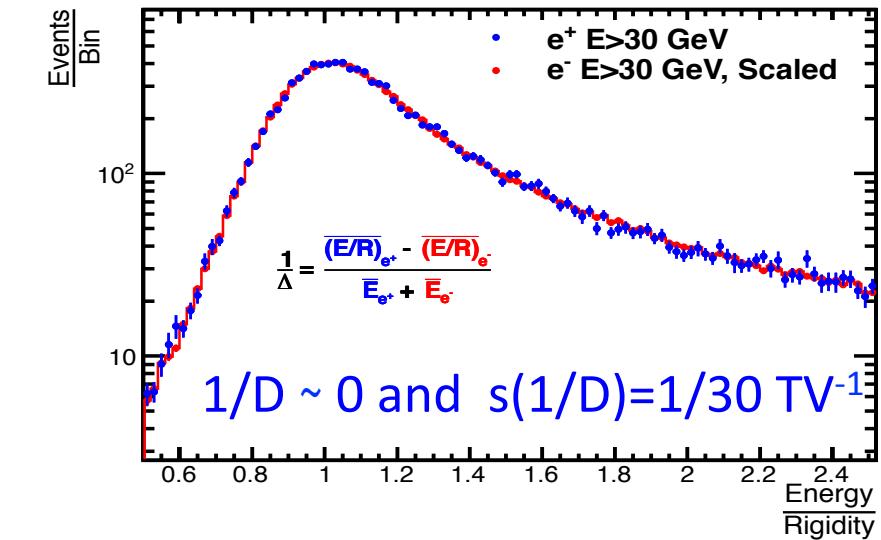
Systematic errors arising from the understanding of the resolution matrix and the bin-to-bin migration unfolding procedures account for 1.5% below 200GV and 8-10% at 3.3 TV.

# Rigidity Scale

Two contributions to the uncertainty:

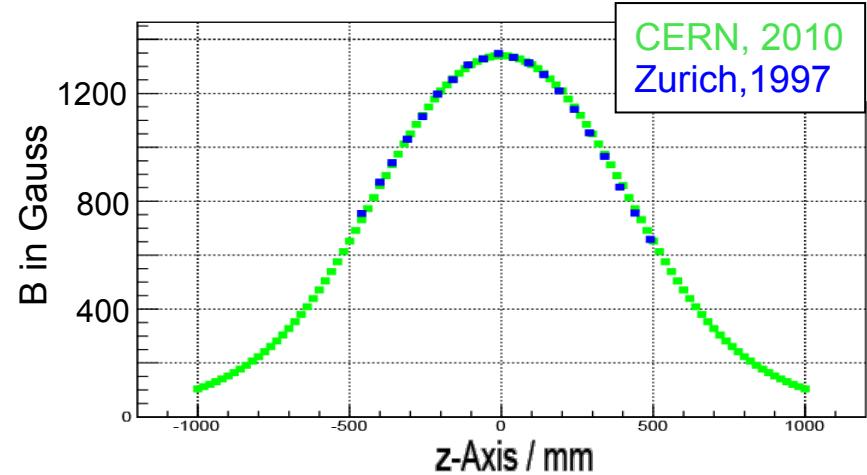
## Residual tracker misalignment

checked with  $E_{ECAL}/R_{Tracker}$  ratio for electrons and positrons, limited by the current high energy positron statistics.



## Magnetic field

mapping measurement (0.25%) and temperature corrections (0.1%). Taken in quadrature and weighted by the measured flux rigidity dependence.



Systematic errors on the migration due to rigidity scale is <1% below 200 GV and 5-7% at 3.3 TV.

# Effective Acceptance

Effective acceptance is determined with MC and corrected for small data/MC in (a) event reconstruction and selection, and (b) the inelastic interactions of nuclei in the AMS materials.

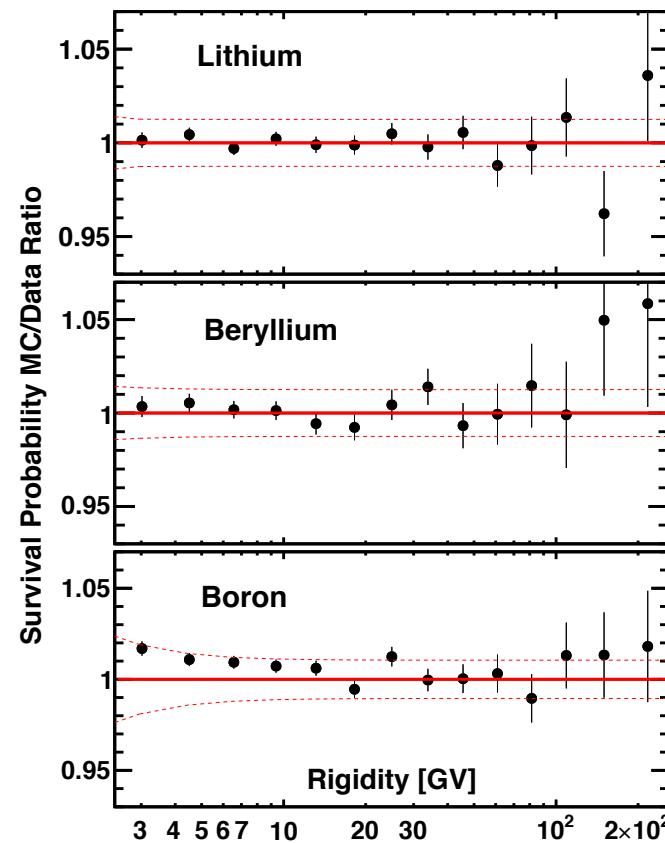
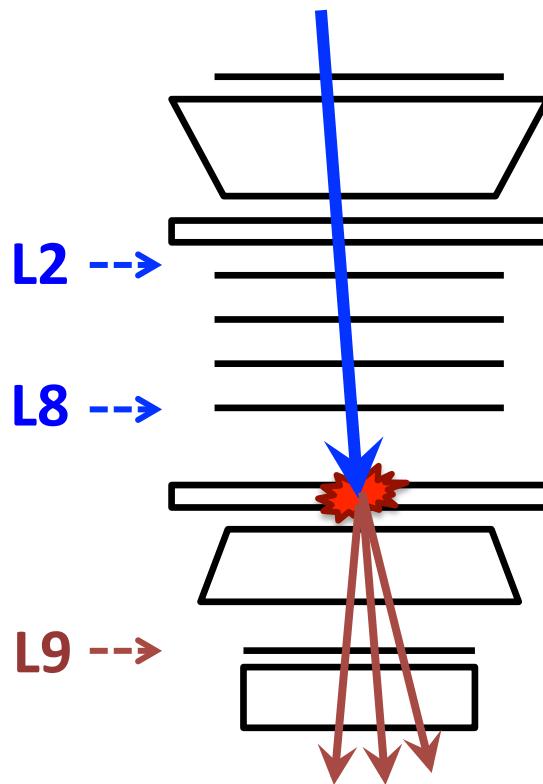
$$\Phi_i^Z = \frac{N_i^Z}{A_i^Z \epsilon_i^Z T_i \Delta R_i}$$

**Effective acceptance [m<sup>2</sup> sr]**  
(from MC, verified with data)

Systematic error for reconstruction and selection are < 2%

# Inelastic Interactions

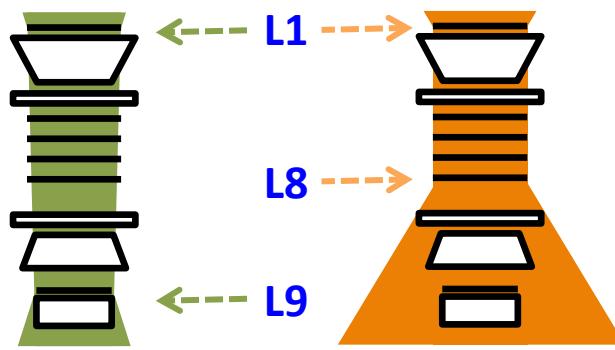
Probability of detecting a hit on L9 depends on the **inelastic interactions** in the materials between L8 and L9 (“1/3” of the AMS material). Direct measurement of this “survival probability” allows the control of flux normalization.



Systematic errors associated to inelastic interaction is < 2% up to 100 GV and 3-4% up to 3.3 TV.

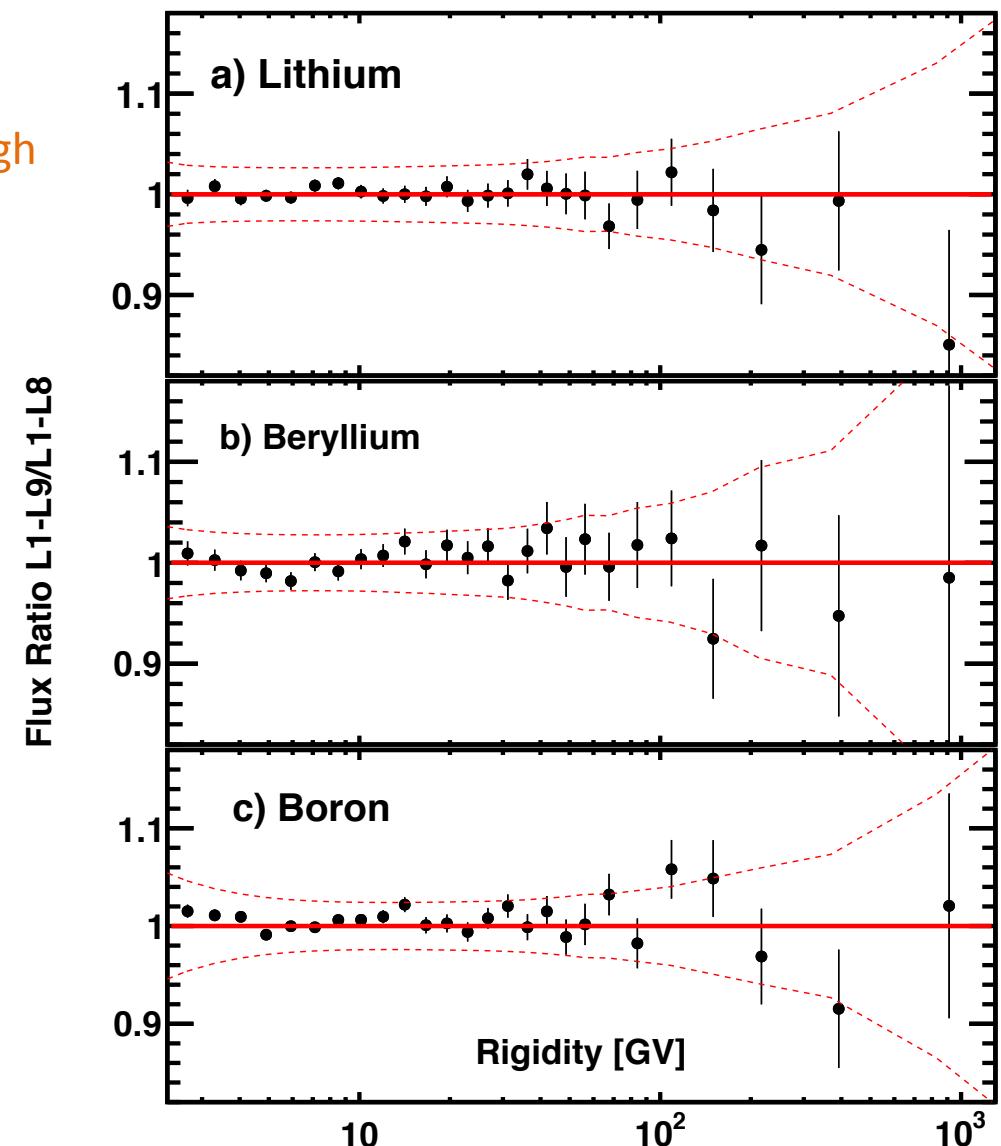
# Measurement Verification

Ratio of flux measured using events passing through L1-L9 over the one measured using events passing through L1-L8



The observed agreement verifies:

- (i) **acceptance**: the amount of material traversed is different
- (ii) **unfolding**: bin-to-bin migration is different due to different resolution



# Flux Errors (Boron)

