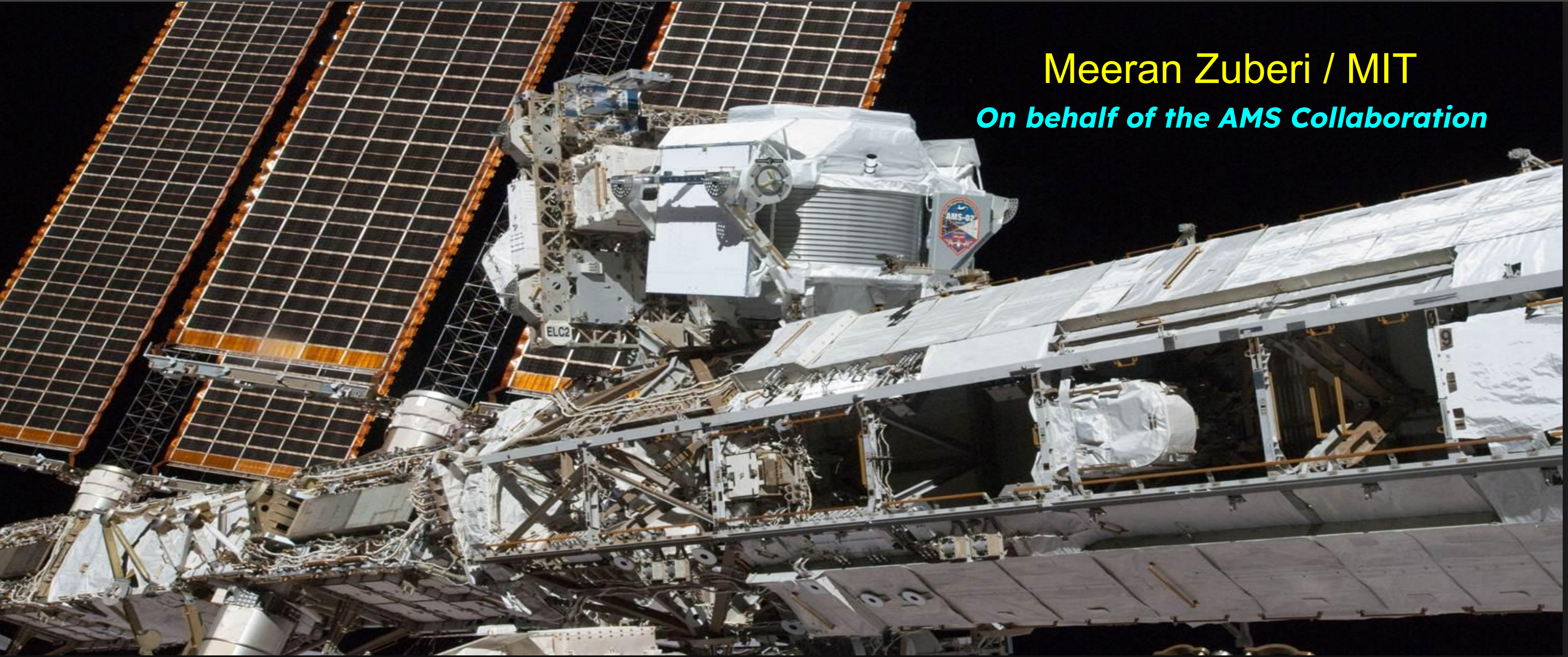
Unique Properties of Primary Cosmic Rays: Results from the AMS Experiment



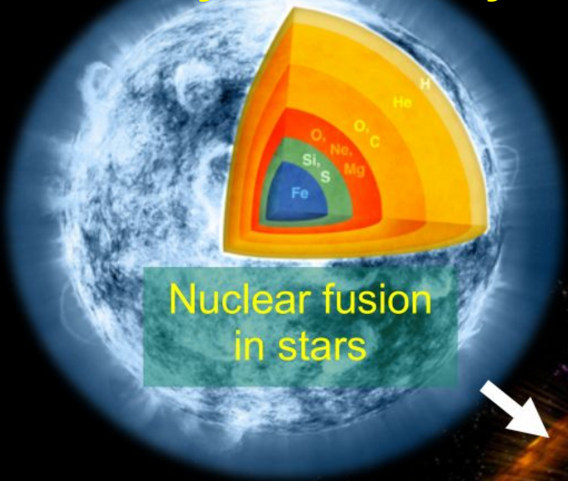
Meeran Zuberi / MIT

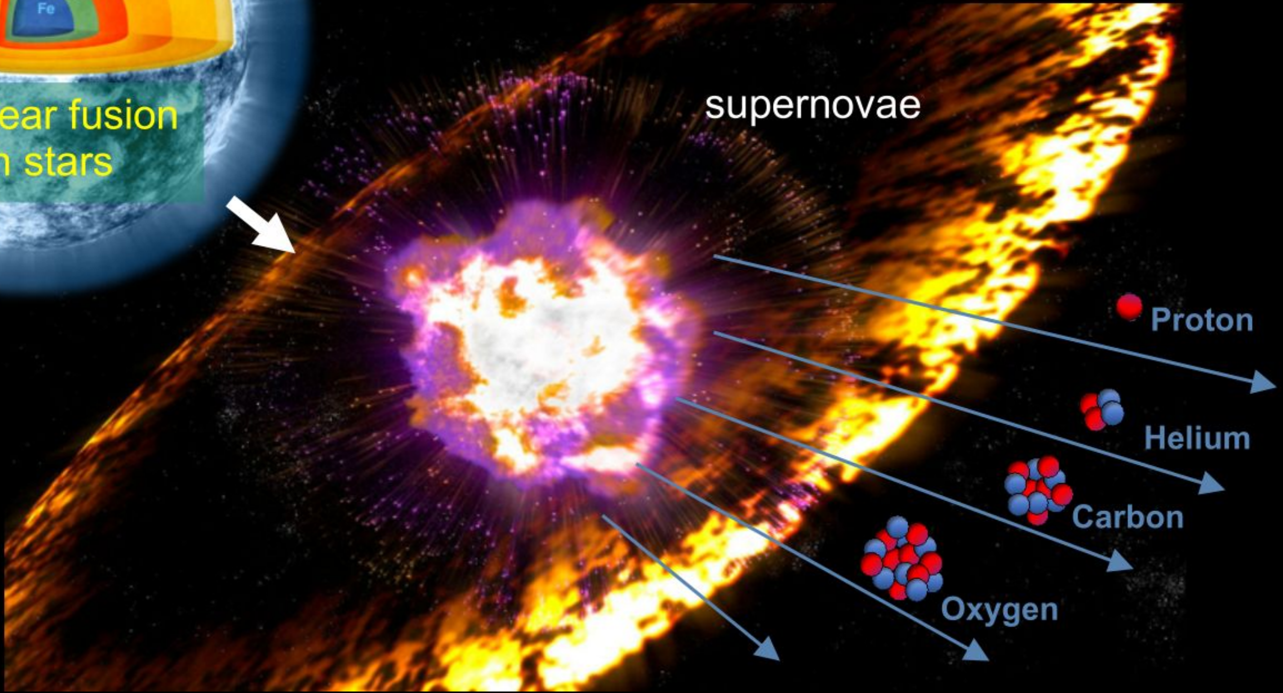
On behalf of the AMS Collaboration

Seventeenth Marcel Grossmann Meeting | 07-12 July, 2024

Primary Cosmic Rays

Primary cosmic rays (p, He, C, O, Ne, …, Fe) are mostly produced during the lifetime of stars and are accelerated in supernovae shocks, whose explosion rate is about 2-3 per century in our Galaxy.

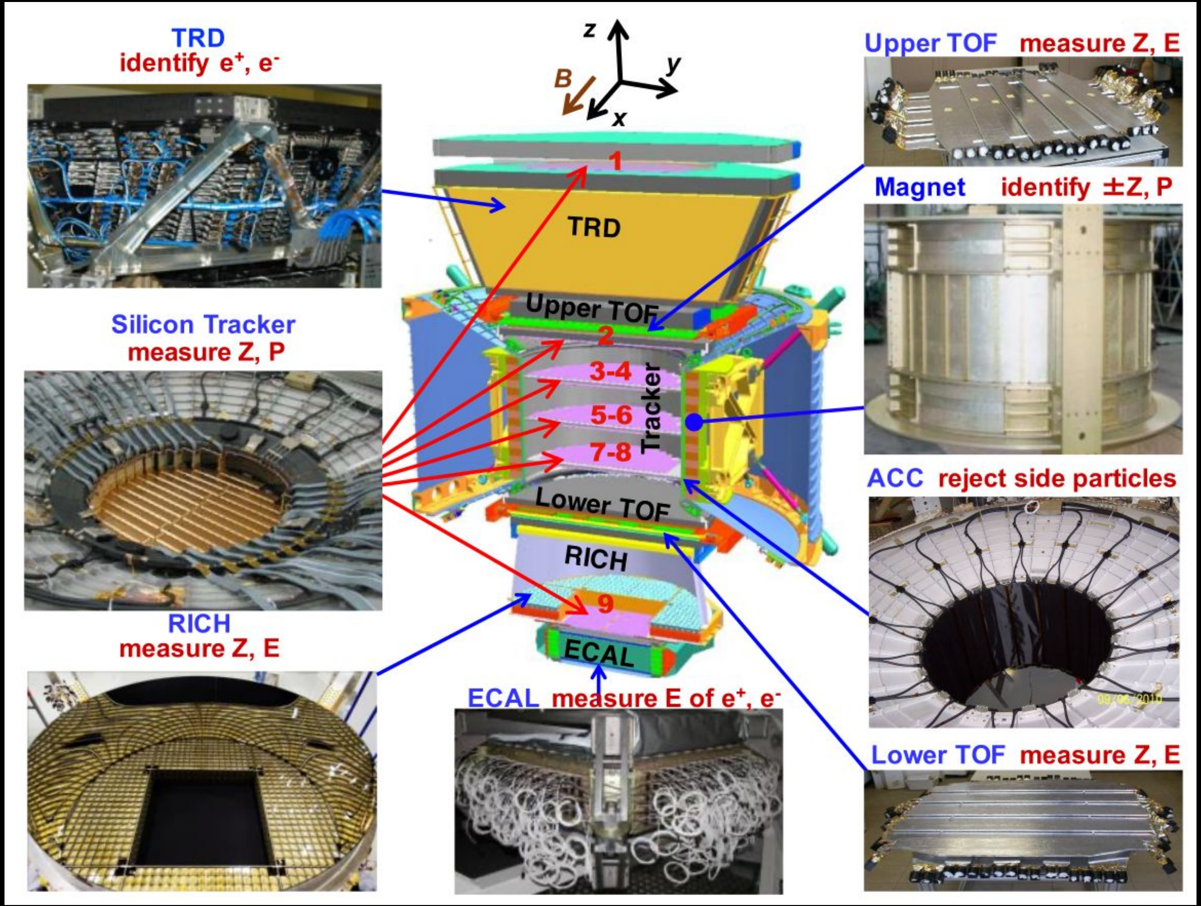




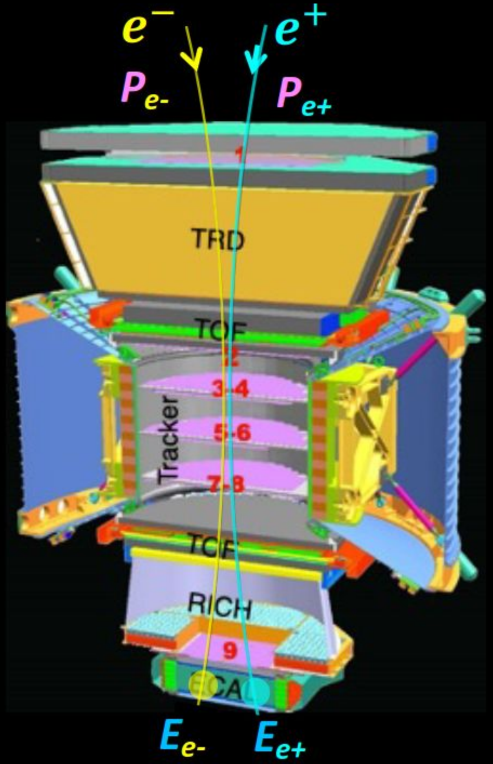
Measurements of the primary cosmic ray spectra carry information about the sources, acceleration, and propagation processes of cosmic rays in the Galaxy.

AMS-02: A TeV precision magnetic spectrometer in space

Layout of the AMS Detector



Continuous Momentum Scale Verification
(Unique Advantage of a Magnetic Spectrometer)



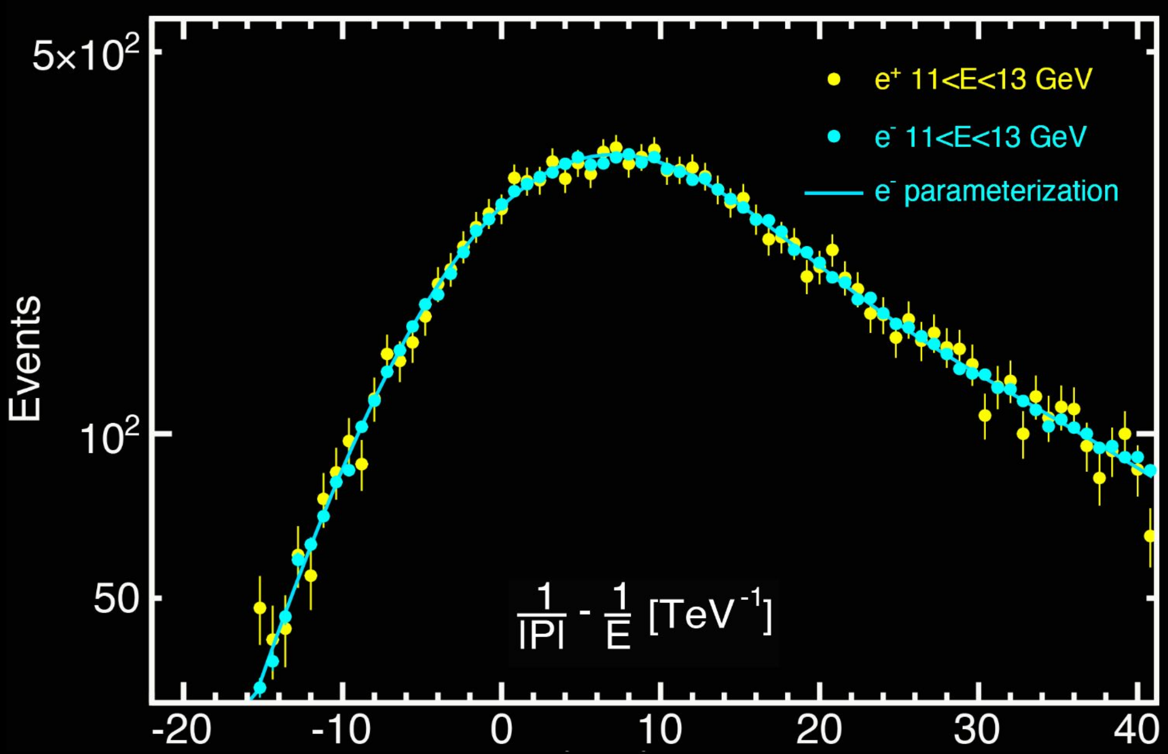
In AMS, the largest systematic error in the determination of the fluxes at the highest energies is due to the uncertainty in the absolute momentum scale.

In space continuous outgassing of the supporting structure can affect the position of the tracker sensors at the sub-micron level.

A shift in the central tracker planes
of 0.5 microns
is sufficient to create
a momentum shift of 10% at 1 TeV
and bias flux measurements.

Momentum Scale Verification

with 4 independent measurements of P_{e+}, E_{e+}, P_{e-}, E_{e-}



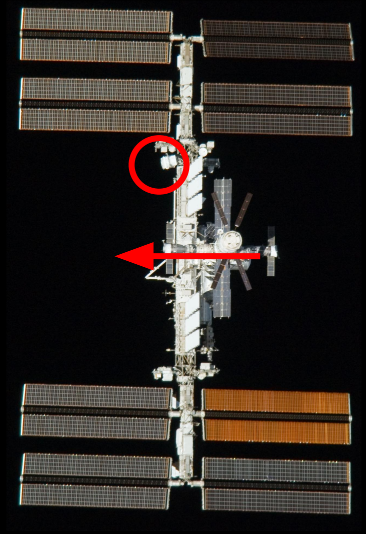
The accuracy of the momentum scale is determined to be 1/(34,000 GeV)

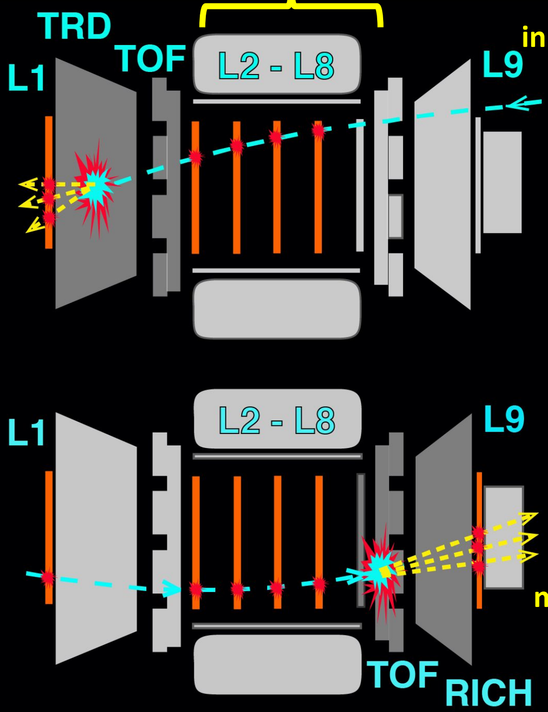
i.e., at 1 TeV the uncertainty is less than 3%

Precision measurement of cosmic-ray spectra requires an determination of nuclear interactions of each element in the detector material

Define (P, Z) of nuclei with the central spectrometer

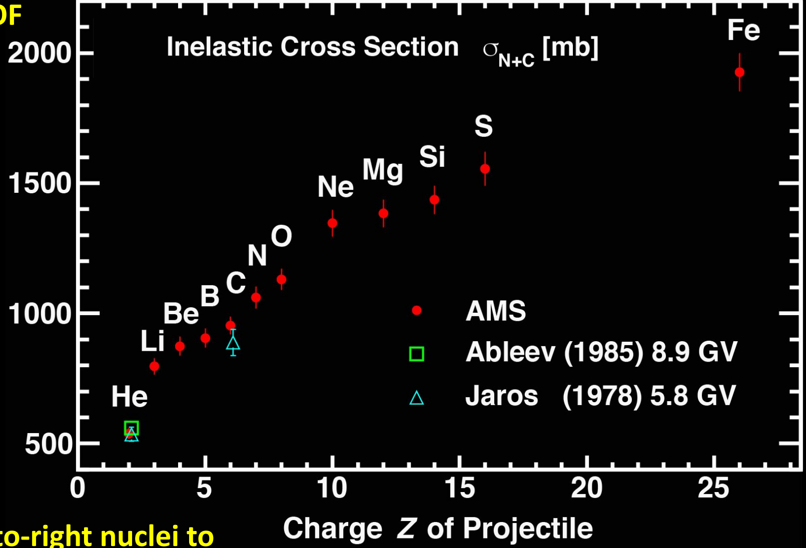
ISS horizontal





Use right-to-left nuclei to measure nuclear interactions in the TRD+TOF

Use left-to-right nuclei to measure the nuclear interactions in the TOF+RICH



AMS Nuclei Flux Measurements

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

Where,

N_i: Number of events with background subtracted and corrected for bin-to-bin migration.

A_i : Effective acceptance obtained by simulations.

ε_i : Trigger efficiency.

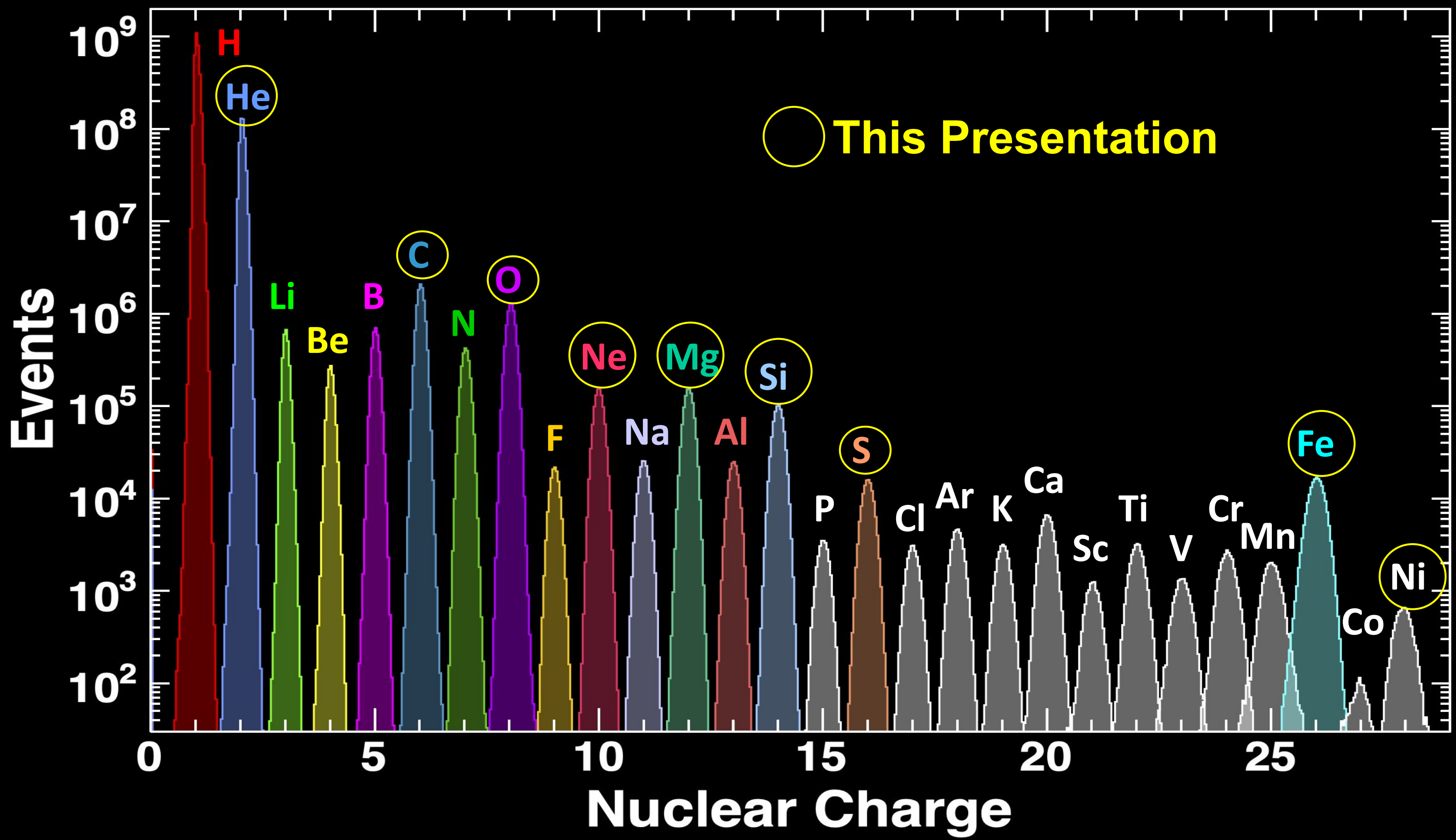
T_i : Collection time (2.45×10^8s above 30 GV).

ΔR_i : Bin Width

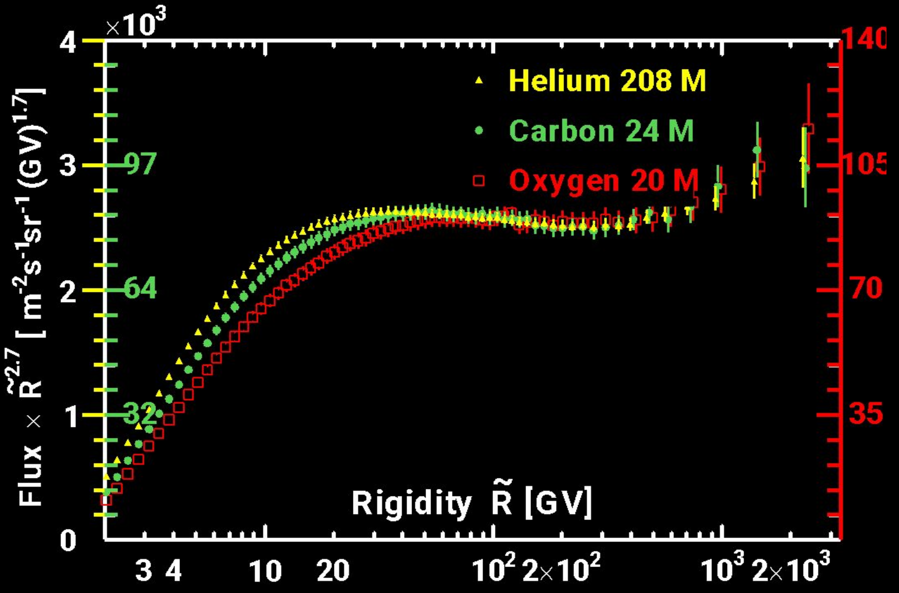
Fluxes statistical errors are often small so the final accuracy is defined mostly by systematic errors on trigger efficiency, acceptance, and rigidity resolution.

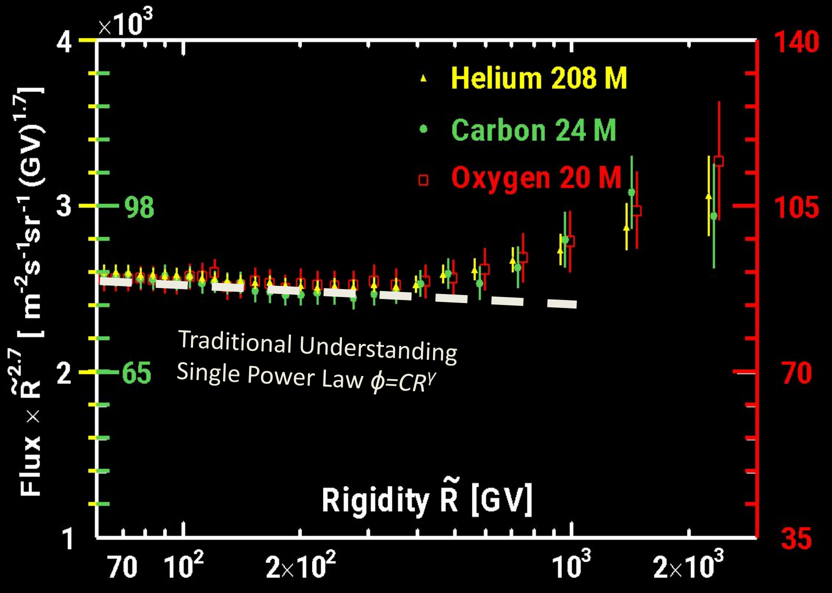
In AMS 2 to 4 independent analysis are done to compute N_i, A_i, ε_i, T_i for each flux

Results of AMS: Measurements of cosmic Nuclei



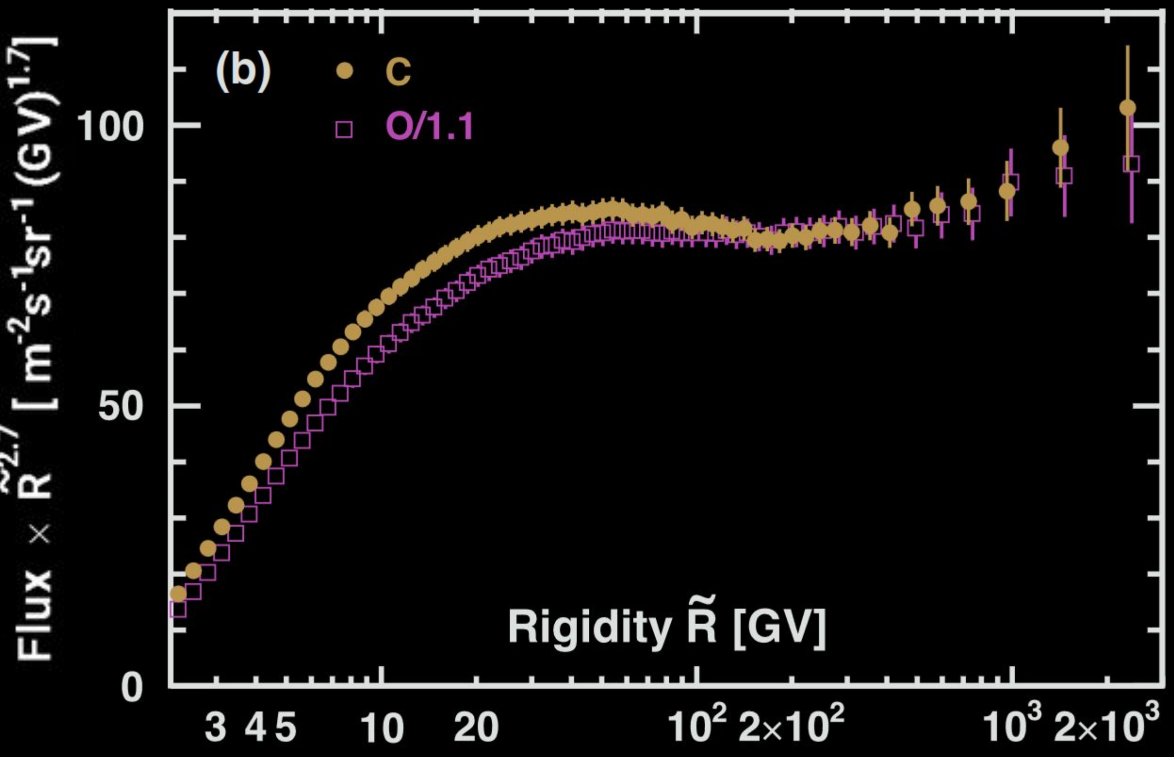
Latest AMS He, C and O Flux Measurements





AMS found that He, C, O have an identical rigidity dependence above ~60 GV and at higher rigidities they all deviate from a single power law in an identical way

Latest AMS Carbon and Oxygen Flux Measurements

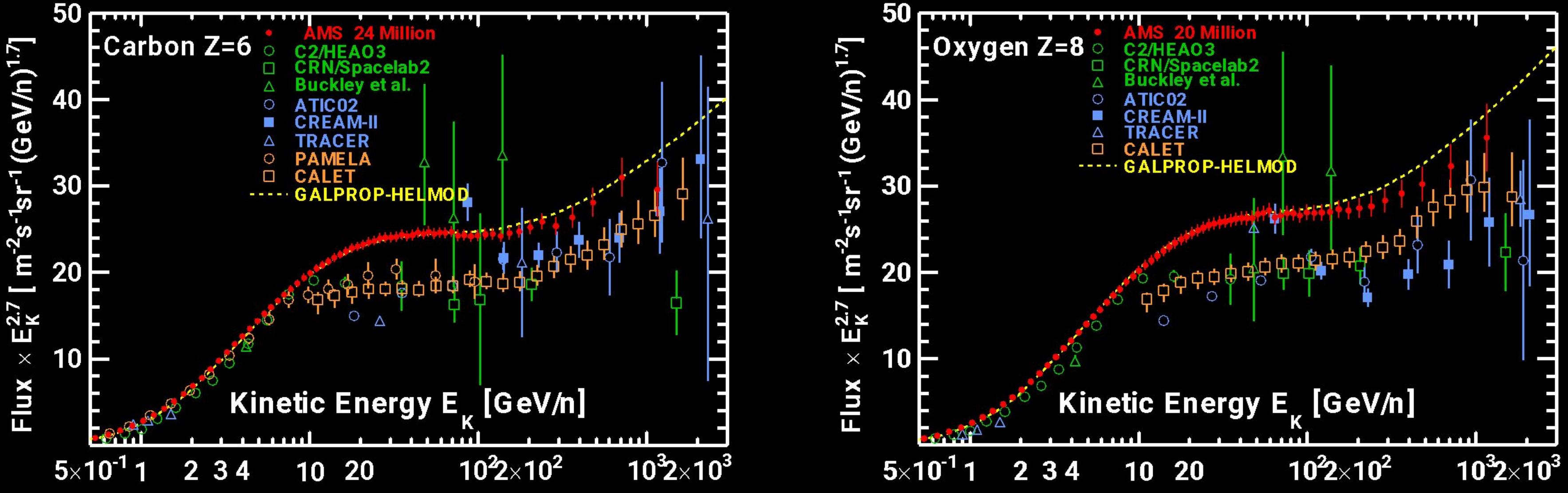


The Rigidity dependence of C and O are identical at high rigidities but different at low rigidities.

These observed differences indicate that at low rigidities, sizeable fractions of the C fluxes have a secondary origin.

Will be discussed in details by Dr. Nikita Belyaev

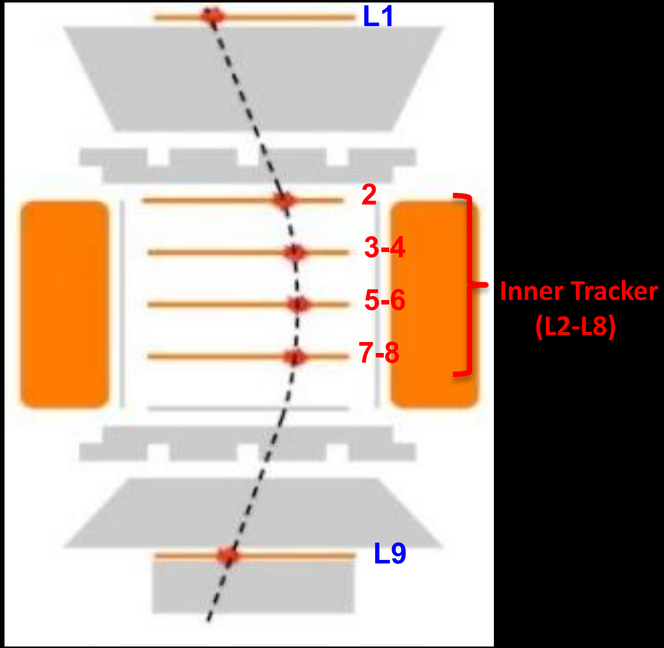
AMS C and O Flux Measurements together with other measurements

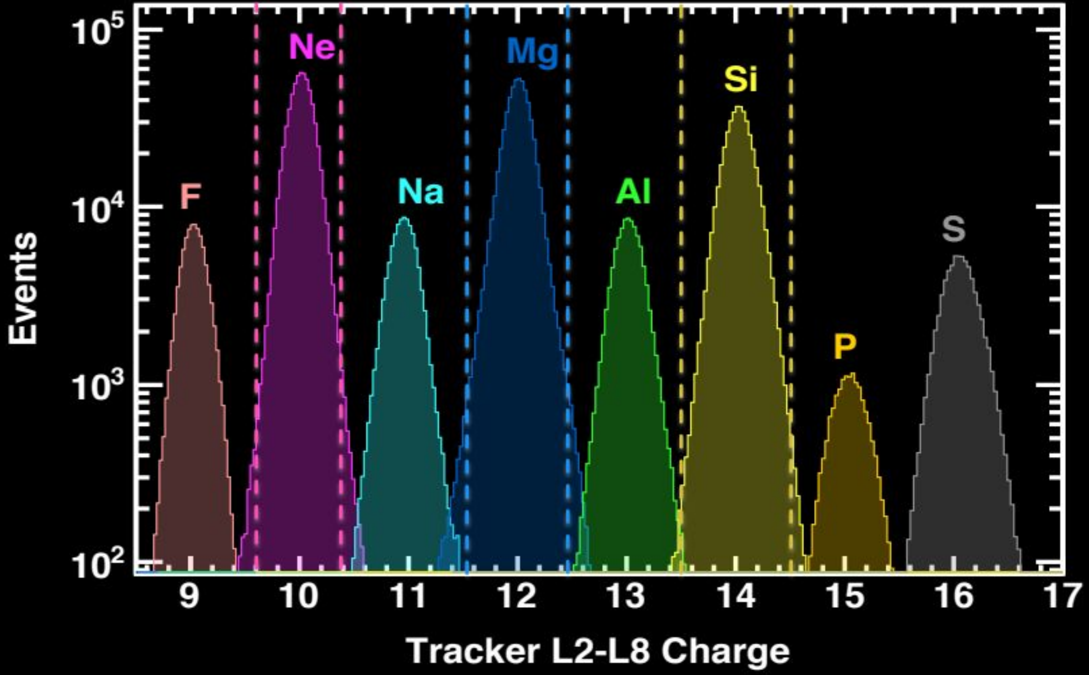


AMS results are different from other measurement in the energy dependence.
GALPROP Model is tuned based on AMS Data.

Ne, Mg, Si and S : Heavier Primary Cosmic Rays

Charge misidentification from non-interacting nuclei is negligible <0.1%

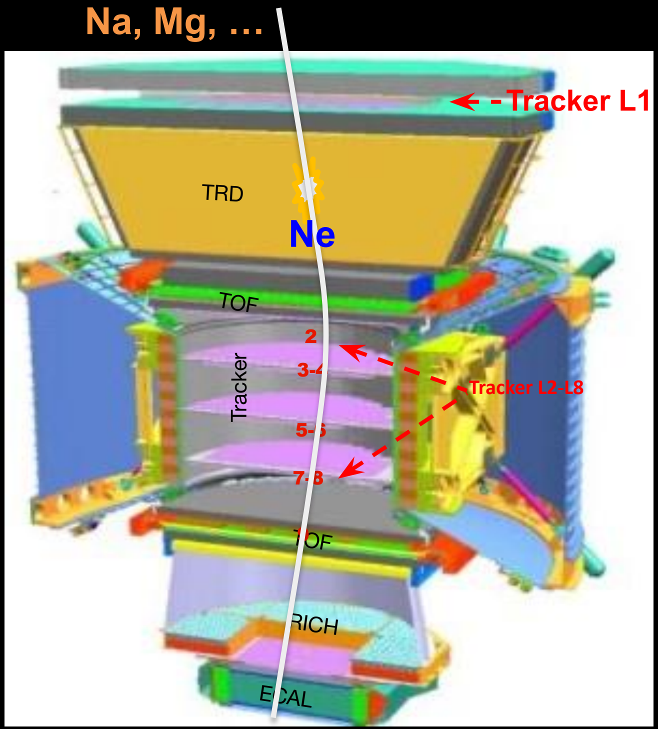


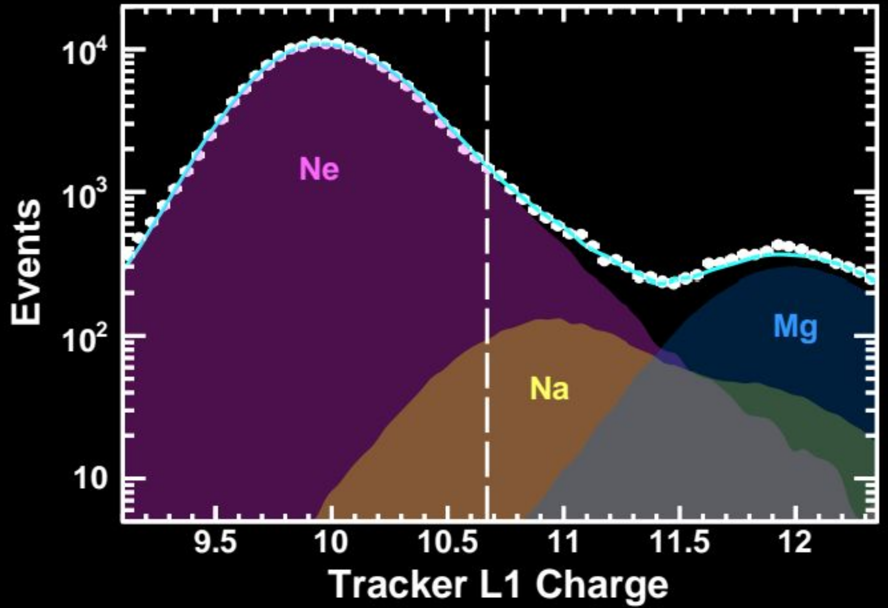


For the events R > 4 GV selected by Tracker L1, UpperTOF and LowerTOF.

Background from Nuclei Interactions

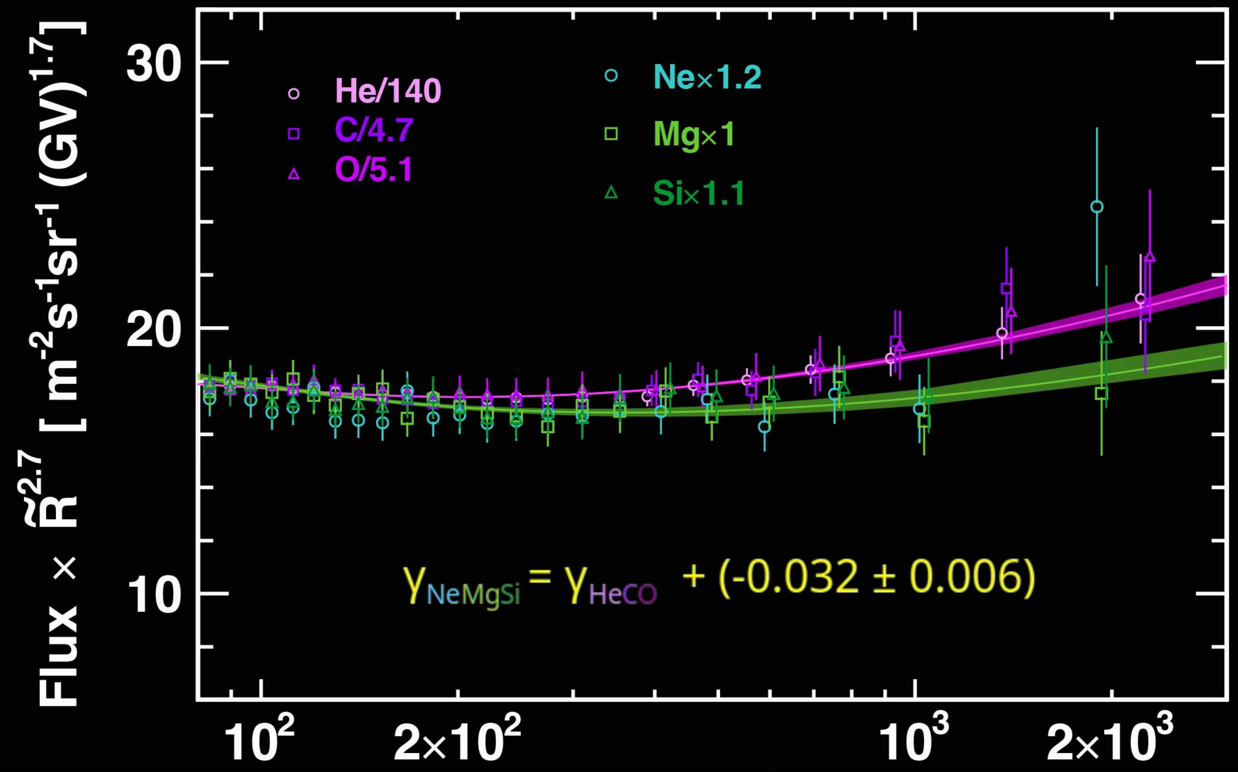
Residual background from heavy nuclei , interacting in AMS materials between L1 and L2 , was found to be 1-2% depending on rigidity, with systematic error on flux measurements <0.5%.





For the Ne events 18<R<22 GV selected by Tracker L2-L8.

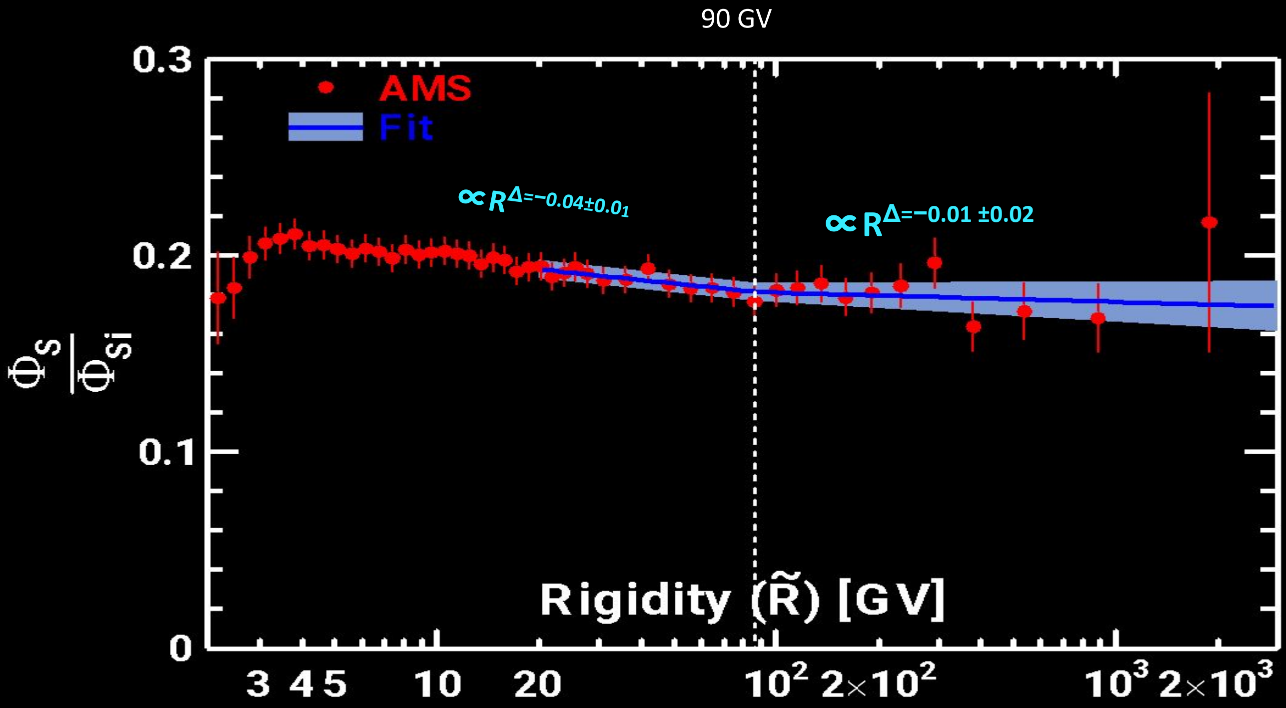
AMS Ne, Mg, and Si Flux Measurements



Surprisingly, heavy primary cosmic rays Ne, Mg, and Si also have identical rigidity dependence, but it is distinctly different from light primary cosmic rays He, C, O.

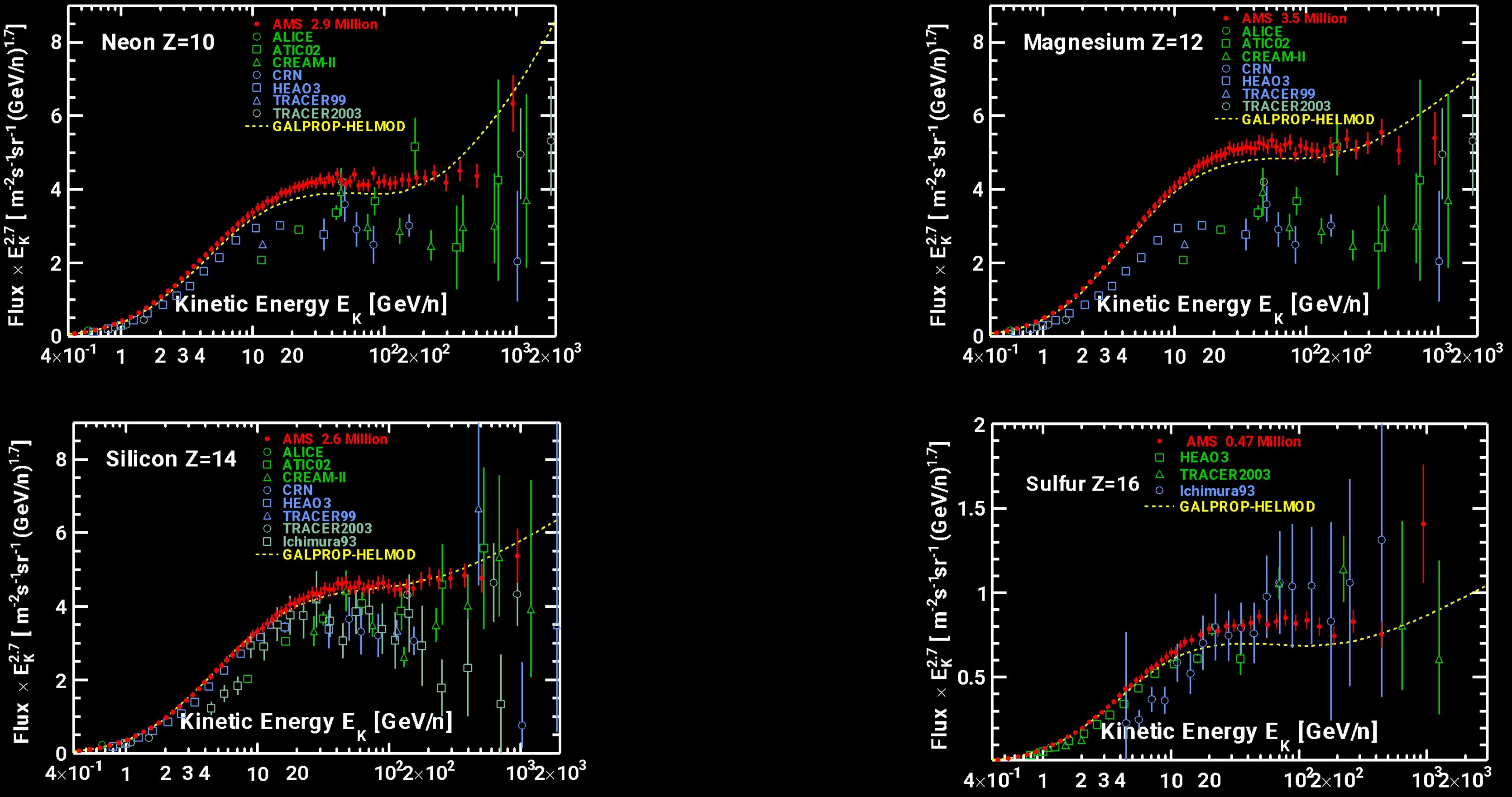
This shows that primary cosmic rays have at least two distinct classes.

AMS Sulfur Rigidity Dependence

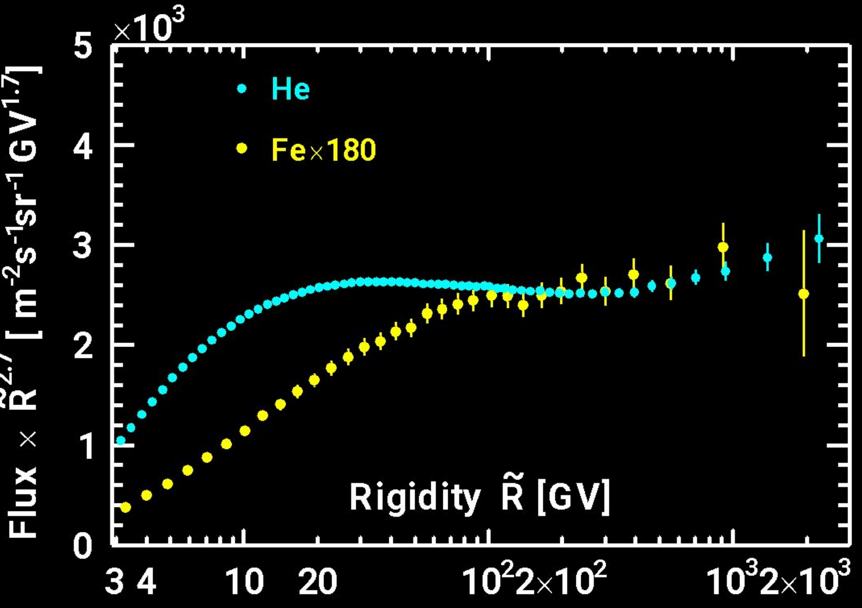


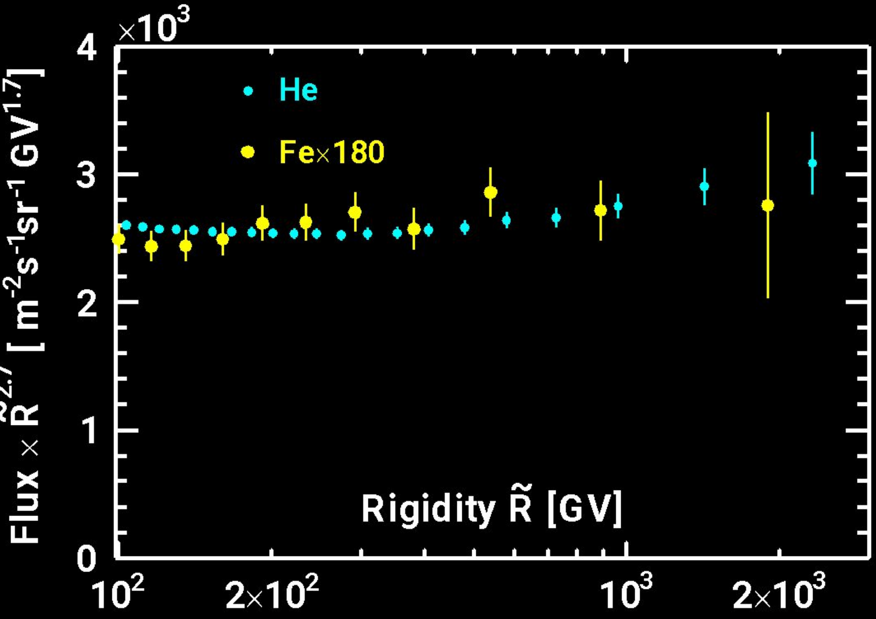
Sulfur belongs to the same class as Ne, Mg, and Si.

Latest AMS Ne, Mg, Si and S Flux Measurements together with earlier measurements



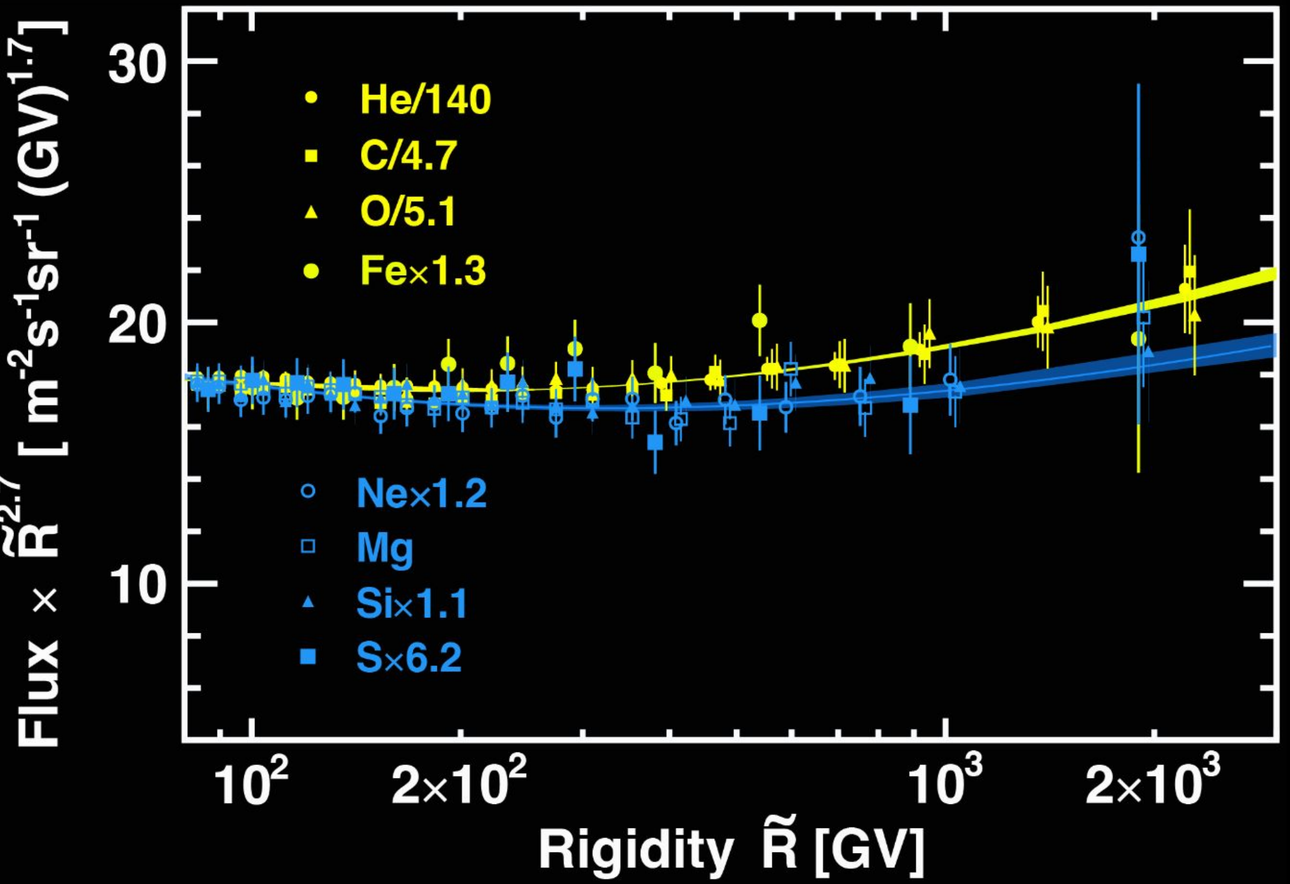
AMS Iron Flux Measurements



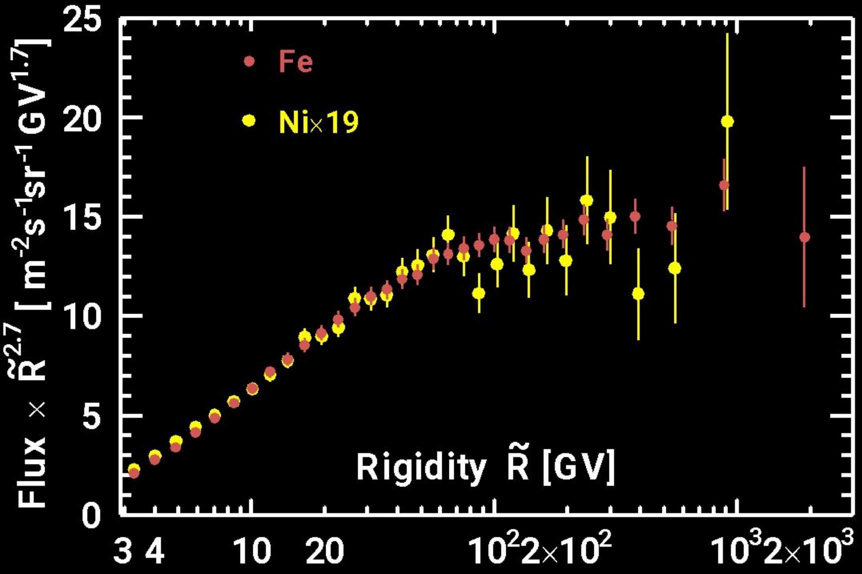


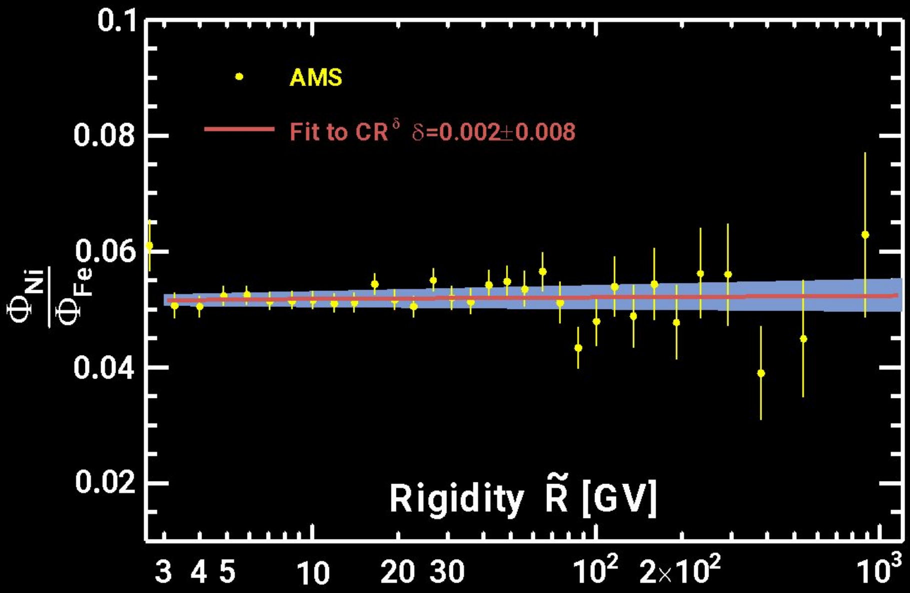
Iron and Helium have identical rigidity dependence at high rigidities

Unexpectedly, Iron is in the He, C, O primary cosmic ray class



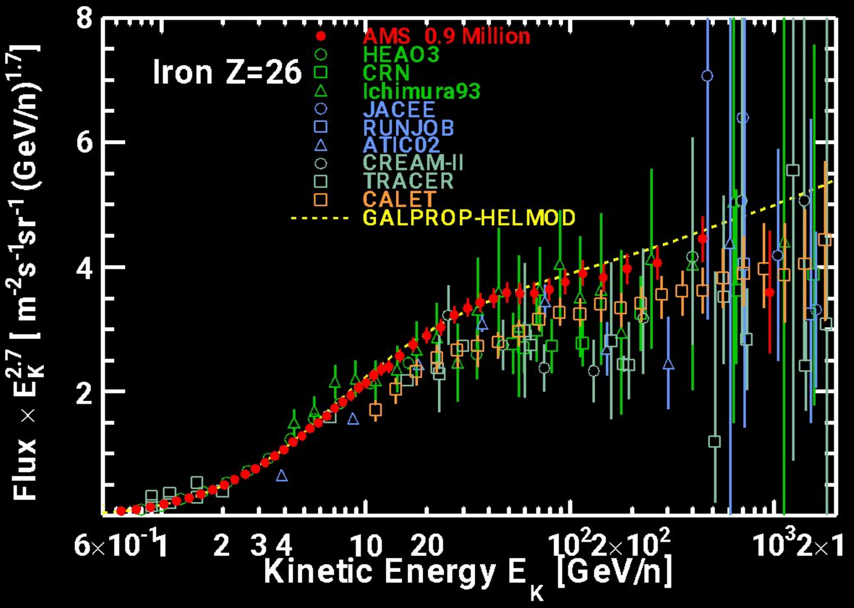
Latest AMS Nickel Flux Measurements

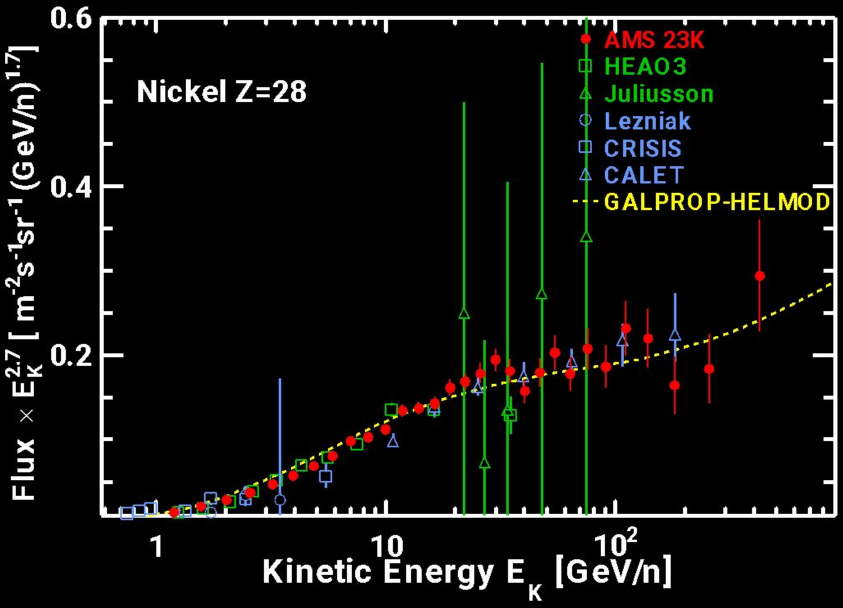




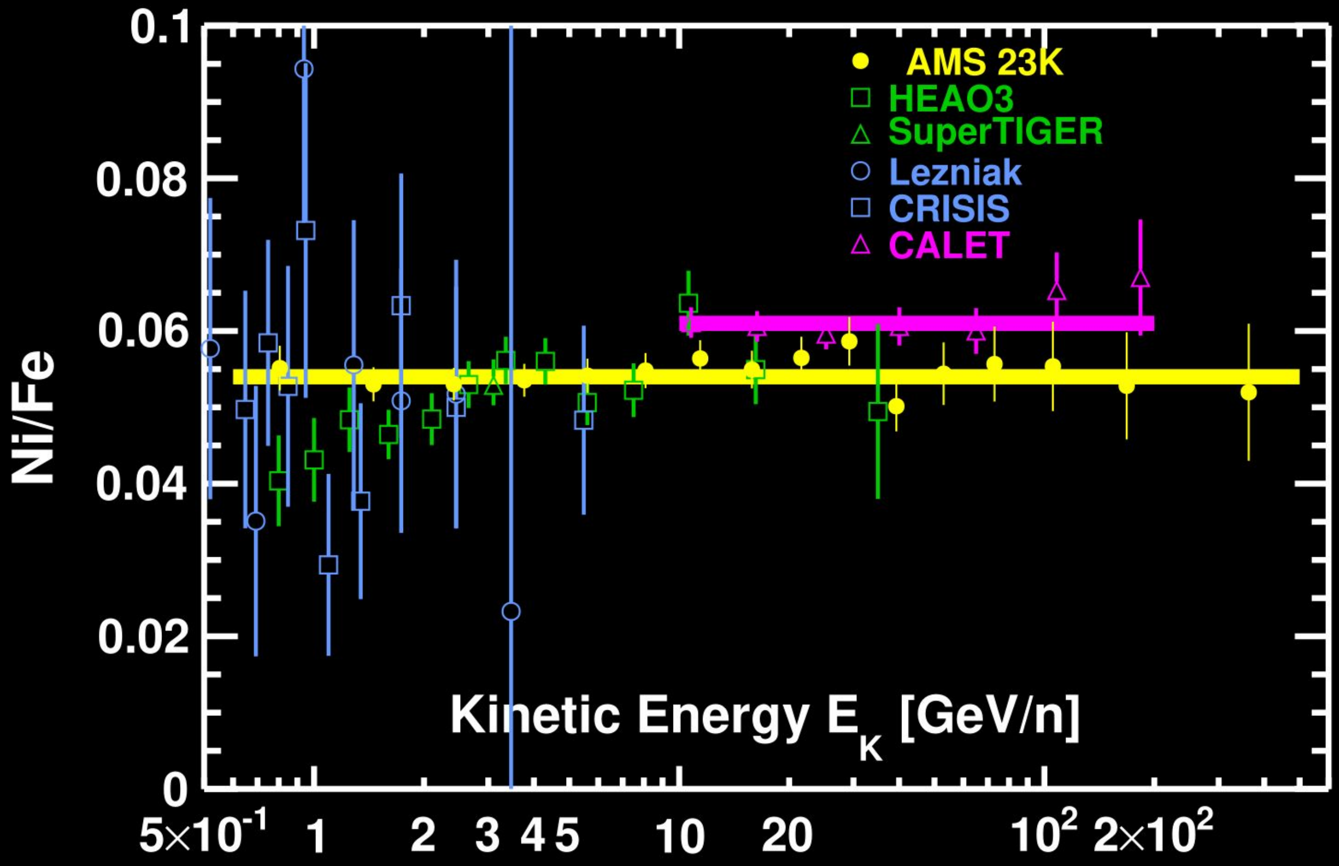
AMS Nickel flux rigidity dependence is identical to Iron

Heavy Primary cosmic rays: Iron and Nickel Fluxes together with other measurements





AMS Ni/Fe Ratio Compared with Other Measurements



Summary

- We have presented precise measurements of the primary cosmic ray fluxes for Helium, Carbon, Oxygen, Magnesium, Silicon, Sulfur, Iron, and Nickel.

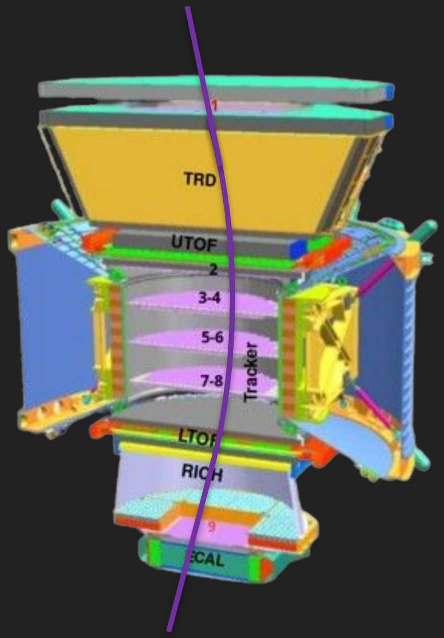
- AMS reveals that primary cosmic rays exhibit two distinct classes of rigidity dependence: He, C and O fluxes shows identical rigidity dependence above 60 GV and deviates from a single power law above 200 GV, while Ne, Mg, Si, and S fluxes shows identical rigidity dependence above 86 GV with a distinctly different spectrum from He, C, and O fluxes.

- Unexpectedly, we found that Fe and Ni fluxes exhibit identical rigidity dependence and above ~100 GV, their rigidity dependence is identical to the He, C and O fluxes.

- AMS is the only magnetic spectrometer in space, and it will continue to take data for the ISS life time, exploring properties of cosmic ray up to Zn and beyond.

Backup

AMS Nuclei Flux Measurements



Tracker (9 layers) + Magnet:
Rigidity (Momentum/Charge) with multi-TV maximal detectable rigidity (MDR)

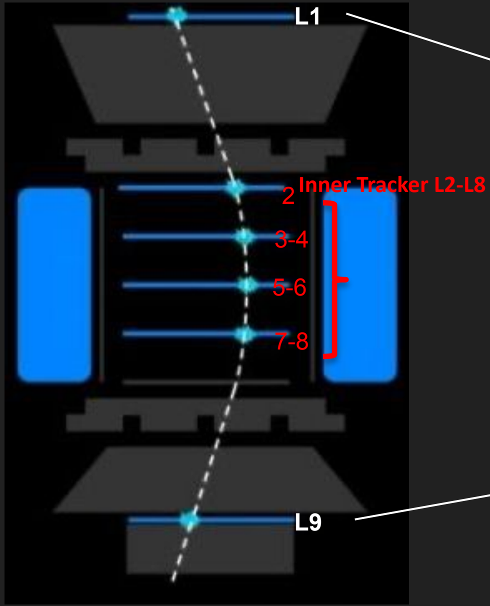
TOF (4 layers):
Velocity and Direction

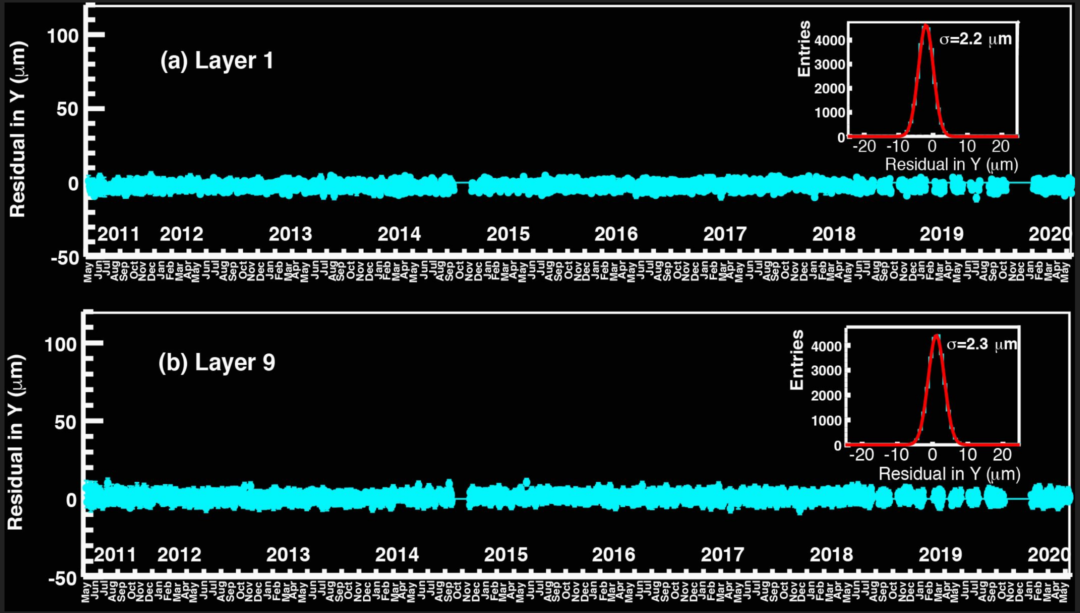
Charge (Z)	Coordinate Resolution (μm)	MDR (TV)	$\Delta\beta/\beta^2$ (%)
1	10	2.0	4
>=2	5-8	3.0-3.7	1-2

L1, UTOF, Inner Tracker (L2-L8), LTOF and L9:
Consistent Charge Along Particle Trajectory

Inner Tracker (L2-L8) Charge Resolution:
$\Delta Z = 0.05 - 0.35$ $(1 \le Z \le 28)$

Tracker Alignment

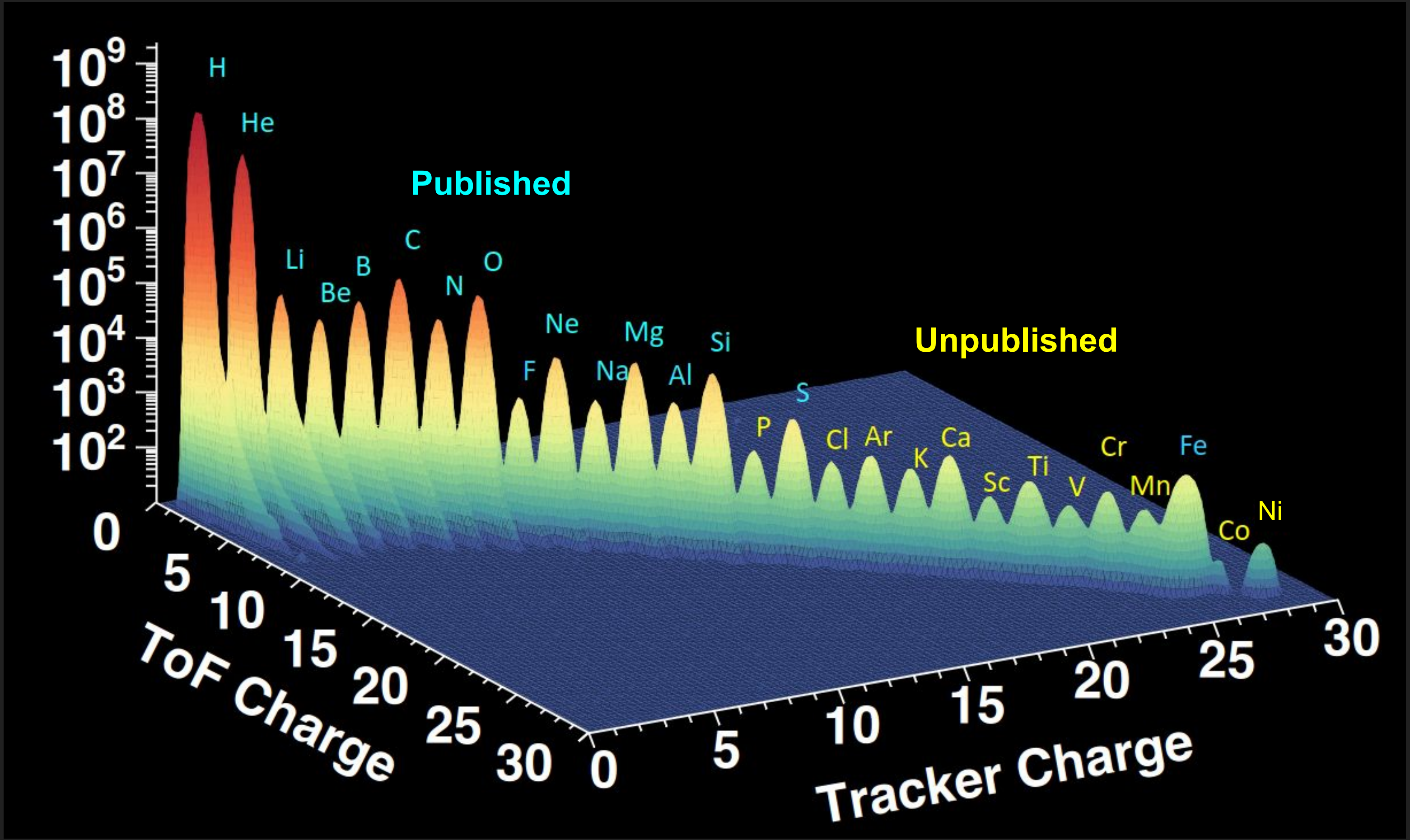




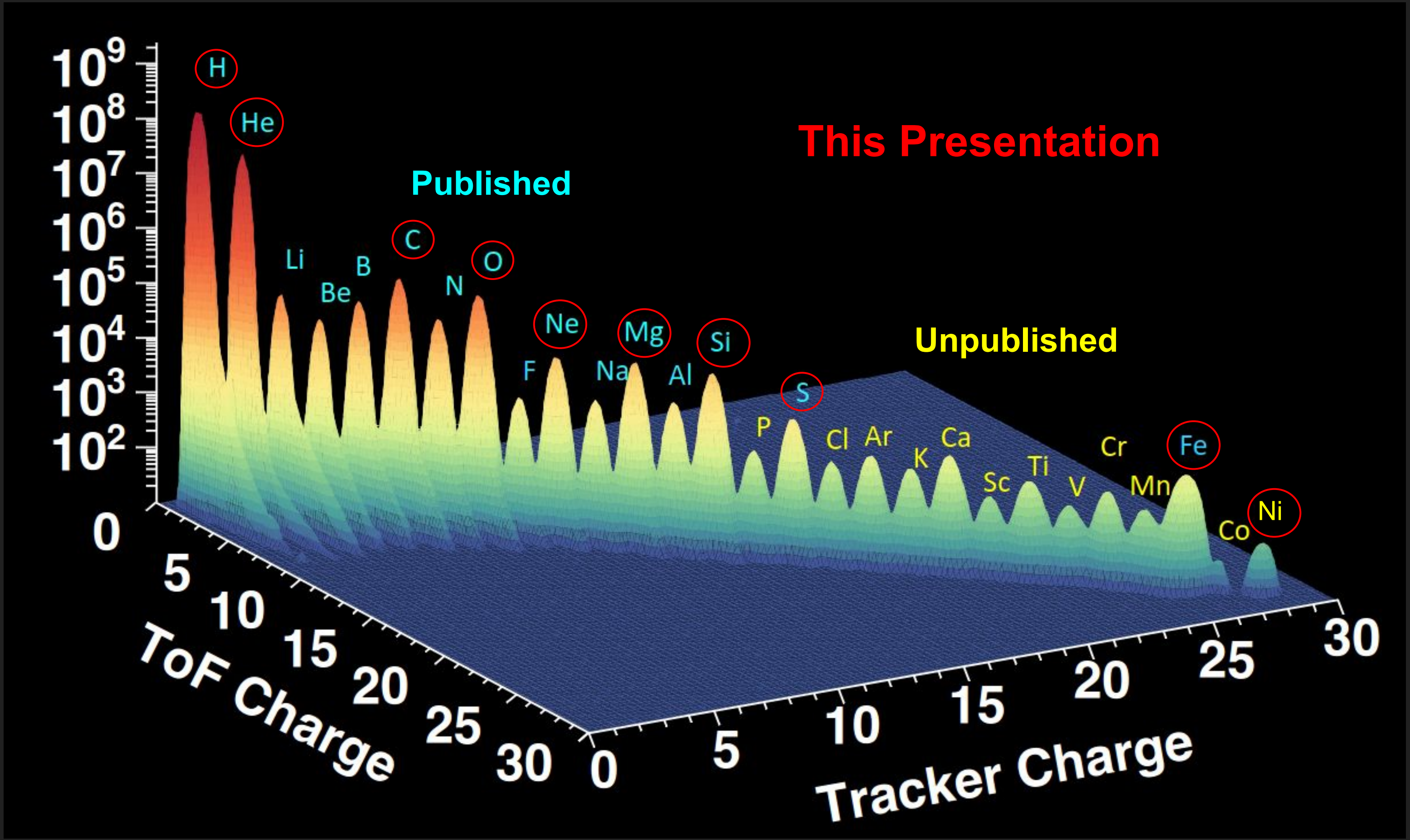
The position of the outer layers L1 and L9 are precisely aligned by using cosmic rays events to a stability of ~2 μm.

Inner tracker layers (L2-L8) monitored with IR lasers and have the stability of a tenth of micron.

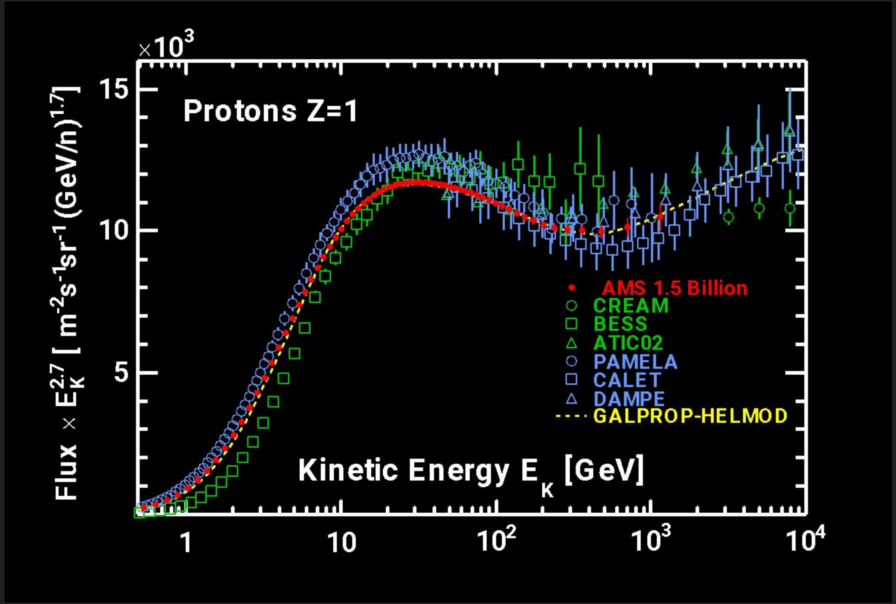
AMS Nuclei Flux Measurements in 11.5 Years (2011-2021)

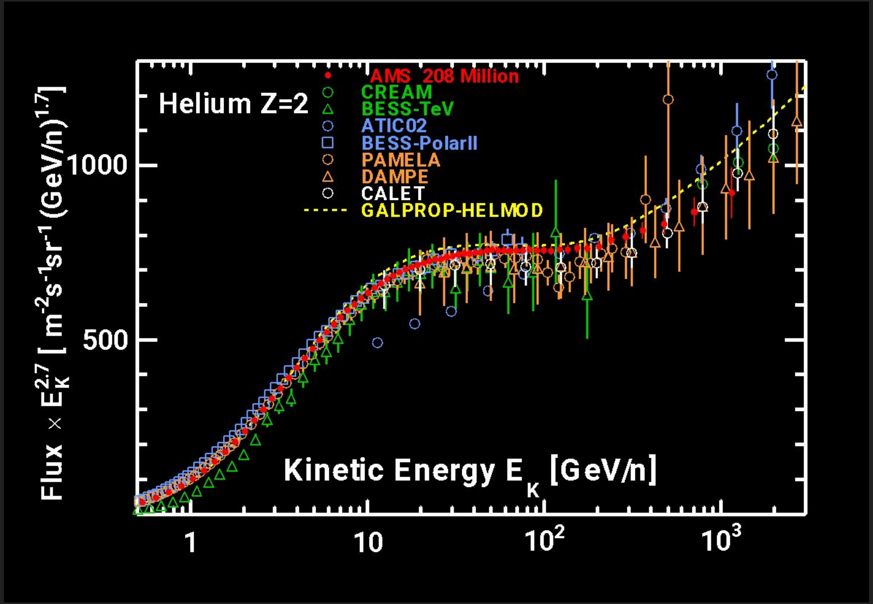


AMS Nuclei Flux Measurements in 11.5 Years (2011-2021)



AMS Proton and Helium Flux Measurements together with other measurements

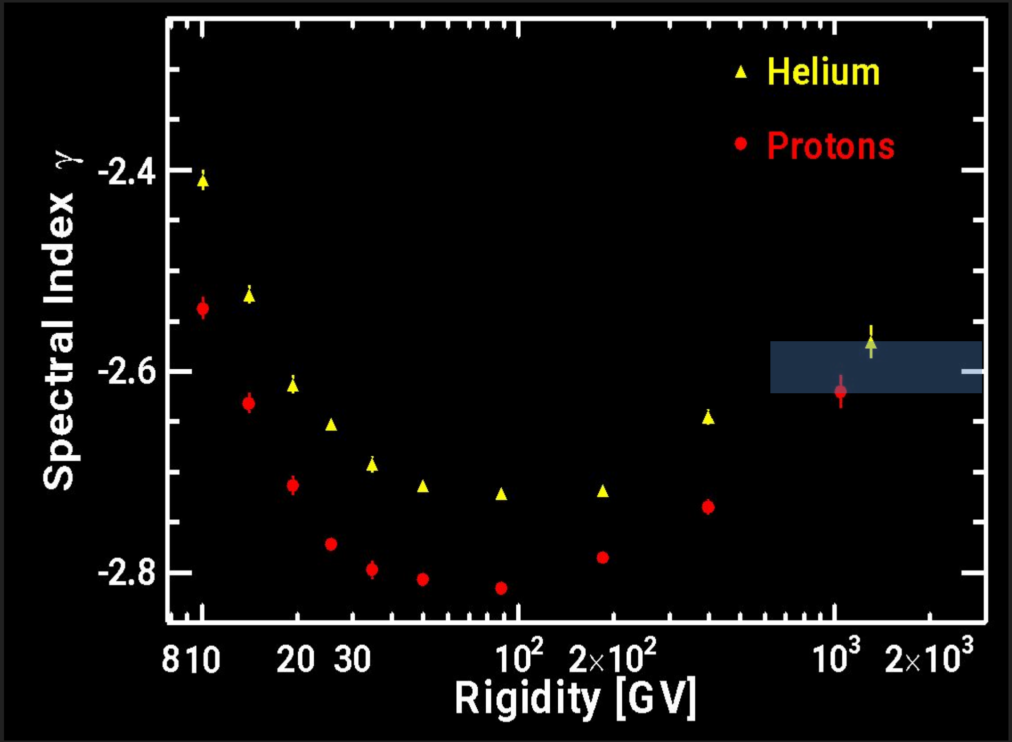




AMS provides the most accurate proton and Helium measurement in the energy range 1 GeV to 1.8 TeV for proton and 1 GeV to 6 TeV for Helium.

AMS Proton and Helium Spectral Index

$\gamma = d\log\Phi / d\log R$

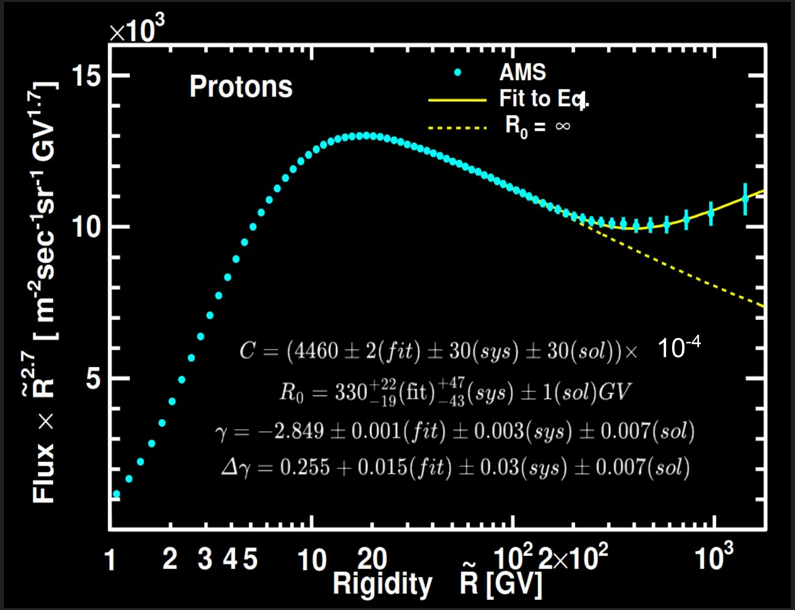


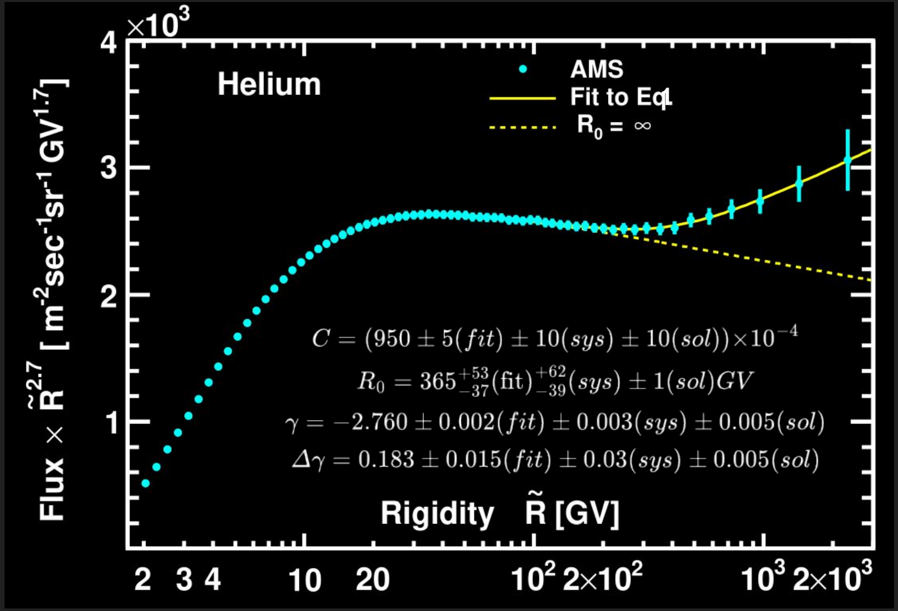
Proton and Helium may have same spectral index at highest rigidities

AMS Proton and Helium Flux Measurements

The **Proton** and **Helium** fluxes are fitted by using double power law equation in the presence of the solar modulation.

$$\Phi = C\frac{R^2}{\hat{R}^2}\left(\frac{\hat{R}}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{\hat{R}}{R_0}\right)^{\Delta\gamma/s}\right]^{s} \quad (1)$$

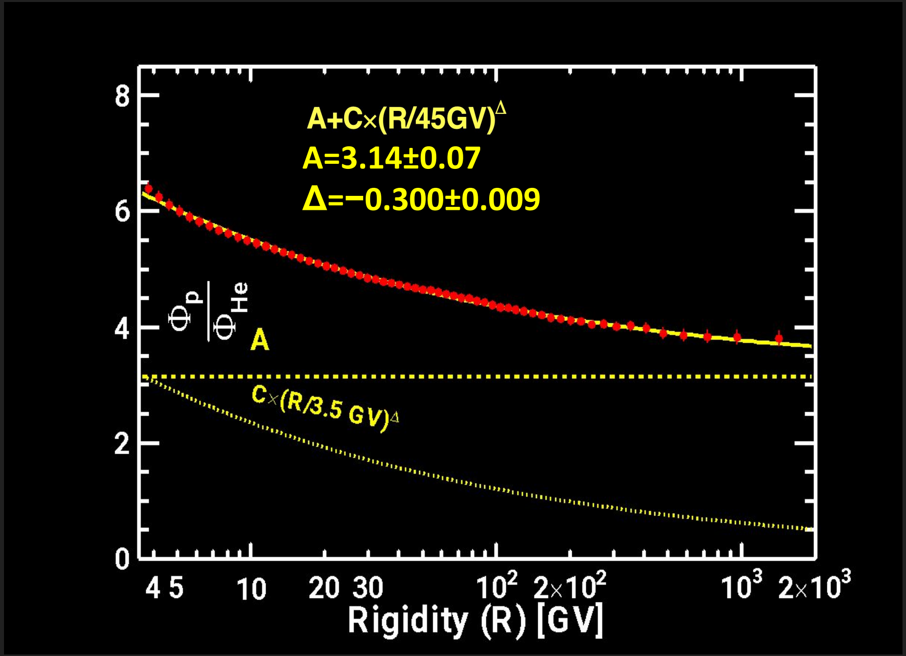


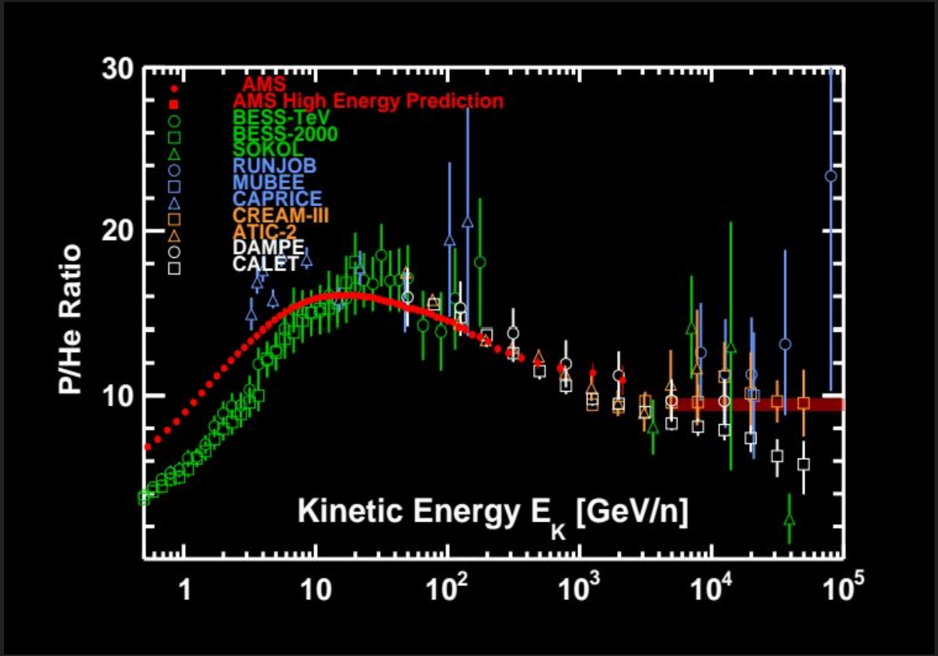


Proton and Helium spectrum measured by AMS shows a deviation from a single power law above few hundred GV.

The Proton $\gamma_P+\Delta\gamma_P$ = -2.59±0.02 is compatible with Helium $\gamma_{He}+\Delta\gamma_{He}$ = -2.58±0.02

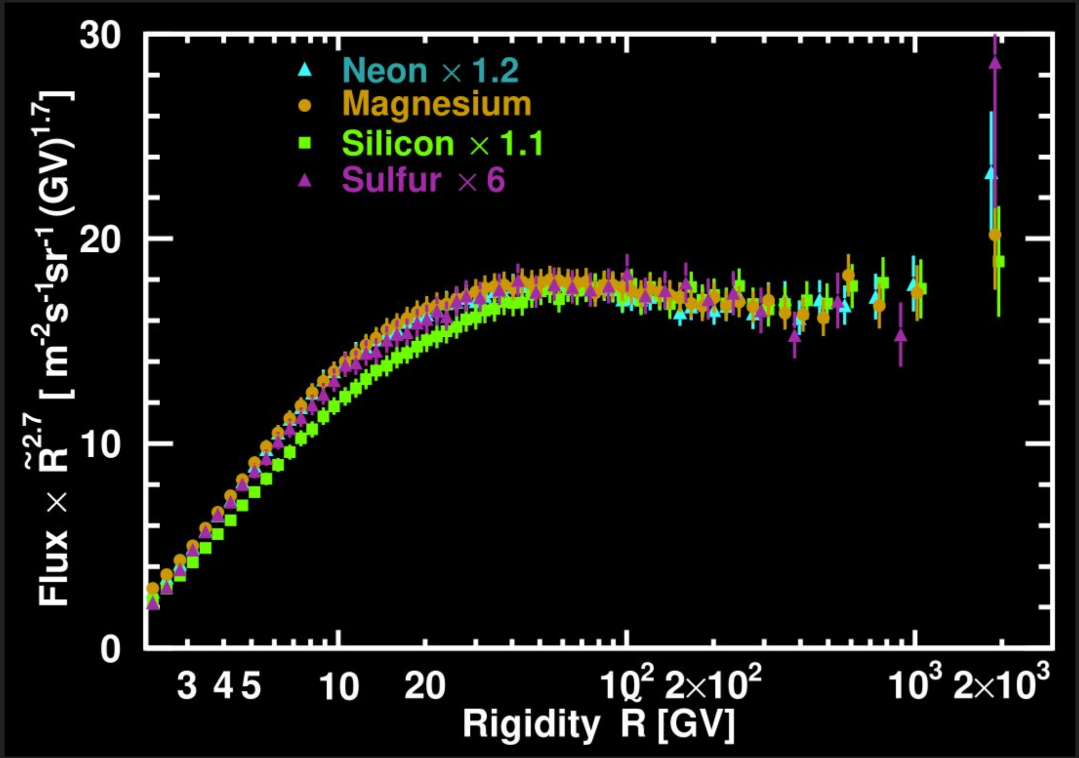
AMS P/He Ratio





AMS found that proton flux have two components, one is like Helium and another is unique to proton flux

AMS Ne, Mg, Si and S Flux Measurements

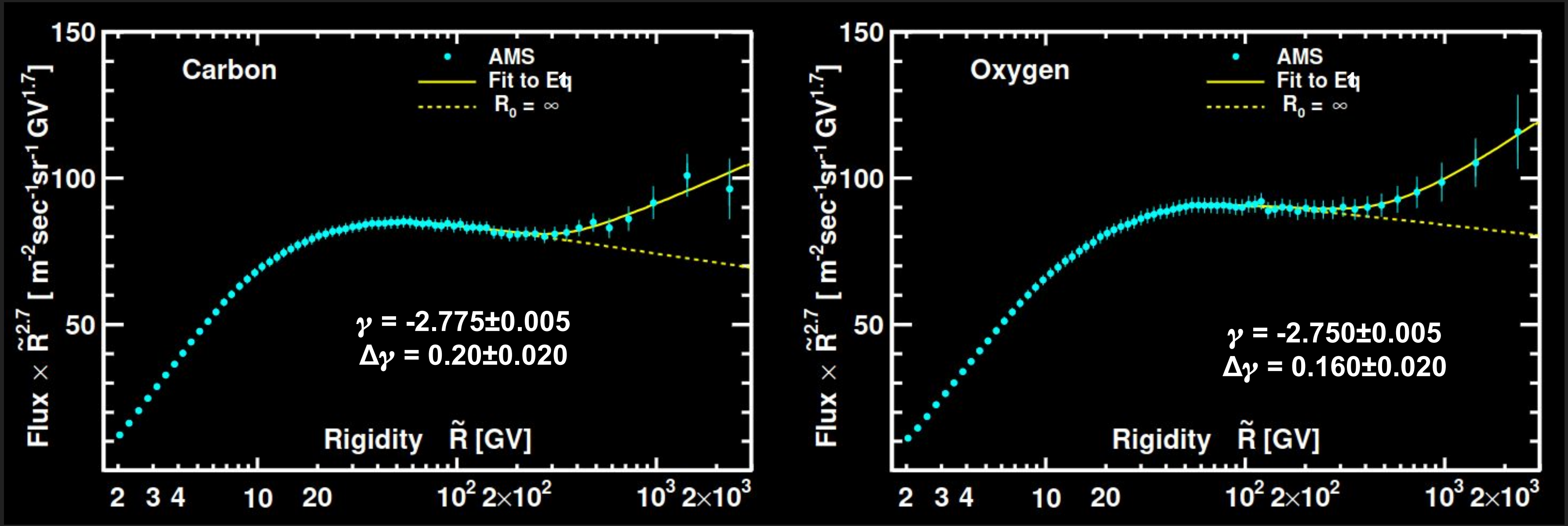


Heavy primary cosmic rays Ne, Mg, Si and S have identical rigidity dependence above ~86 GV and at higher rigidities they all deviate from a single power in an identical way

Latest AMS Carbon and Oxygen Flux Measurements

The **Carbon** and **Oxygen** fluxes are fitted by using double power law equation in the presence of the solar modulation.

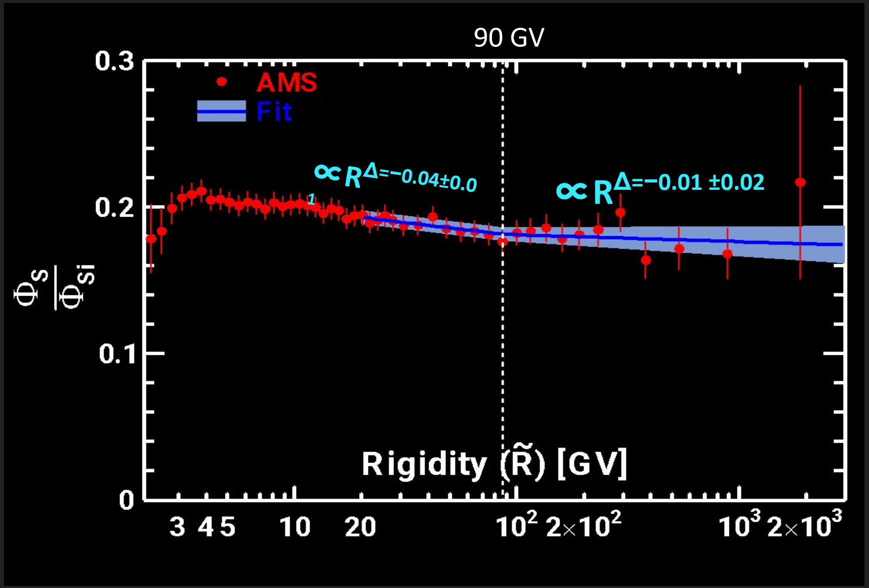
$$\Phi = C \frac{R^2}{\hat{R}^2} \left(\frac{\hat{R}}{45\ \mathrm{GV}} \right)^{\gamma} \left[1 + \left(\frac{\hat{R}}{R_0} \right)^{\Delta\gamma/s} \right]^{s} \quad (1)$$

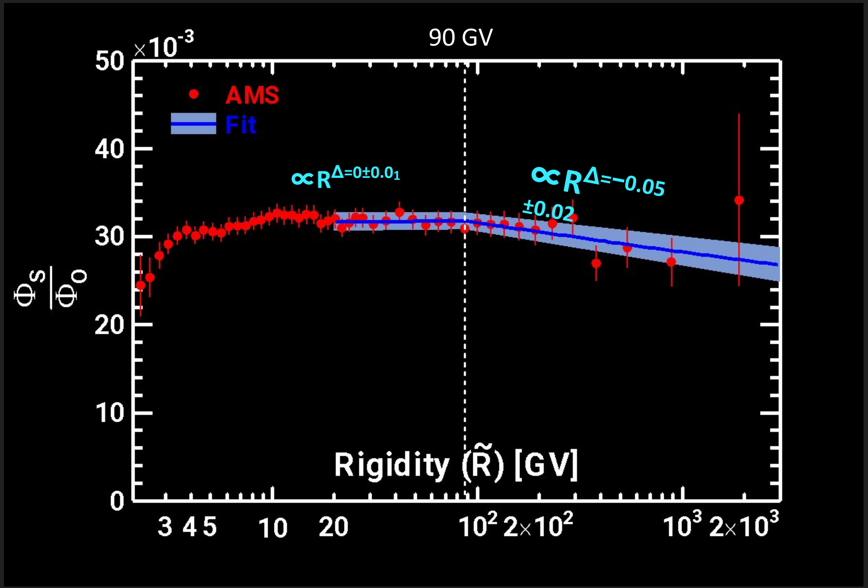


Carbon and Oxygen spectrum measured by AMS shows a deviation from a single power law above few hundred GV.

The Carbon $\gamma_C + \Delta\gamma_C$ = -2.58±0.02 and Oxygen $\gamma_O + \Delta\gamma_O$ = -2.59±0.02 are compatible with Helium $\gamma_{He} + \Delta\gamma_{He}$ = -2.58±0.02

AMS Sulphur Rigidity Dependence





Phys. Rev. Lett. 130, 211002 (2023): Sulfur belongs to the same class as Ne, Mg, and Si.