Nuclei Measurements with the Alpha Magnetic Spectrometer on the International Space Station

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On behalf of the AMS collaboration

RICAP'16, Frascati, 23rd June 2016

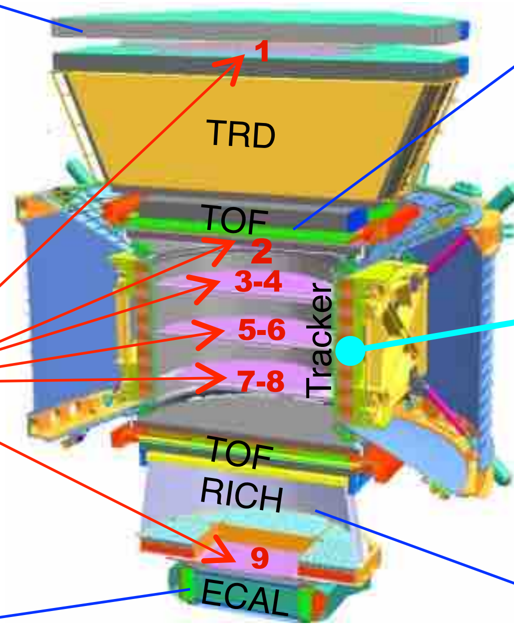
The Alpha Magnetic Spectrometer

TRD
Identify e^+, e^-

Silicon Tracker
Z, P

ECAL
E of e^+, e^-

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



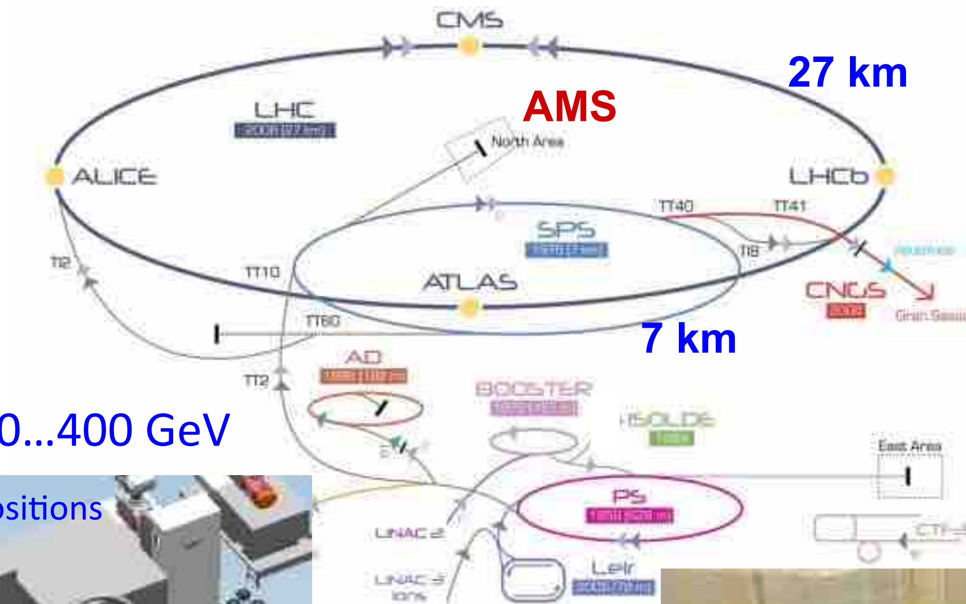
Z and P ~ E
are measured independently by Tracker, RICH, TOF and ECAL

TOF
Z, E

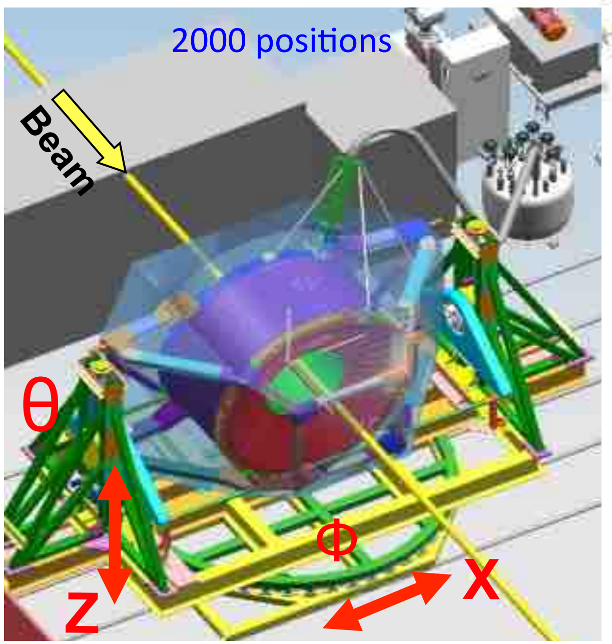
Magnet
±Z

RICH
Z, E

Beam Tests at CERN



p, e^+, e^-, π 20…400 GeV



AMS in Space

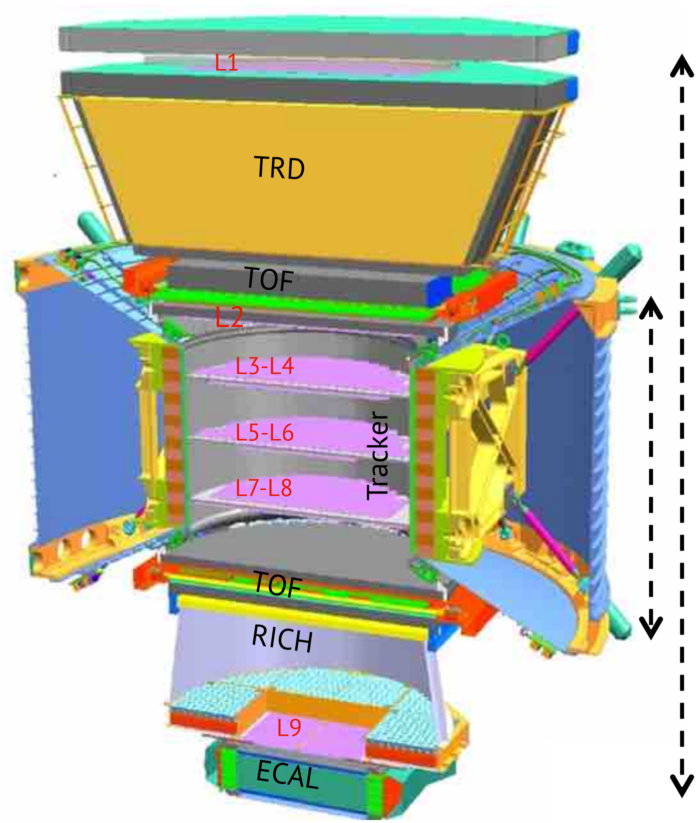
In 5 years on ISS,

AMS has collected >80 billion cosmic rays.

To match the statistics,

systematic error studies are important.

Nuclei Analysis



Tracker (L1 – L9) + Magnet

Rigidity (momentum/charge)

Bending Coordinate Resolution ≈ 10 μm / 7.5 μm

protons helium

MDR ≈ 2 TV / 3.2 TV

TOF

Velocity and Direction

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

TRD, Tracker, RICH ,TOF, ECAL

Charge Magnitude Along Particle Trajectory, e.g.

$\Delta Z_{\text{Tracker}} \approx 0.05 / 0.07$

Flux Measurement

PRL 114, 171103 (2015) PHYSICAL REVIEW LETTERS week ending 1 MAY 2015

Precision Measurement of the Proton Flux in Primary Cosmic Rays from Rigidity 1 GV to 1.8 TV with the Alpha Magnetic Spectrometer on the International Space Station

The isotropic proton flux Φ_i for the i^{th} rigidity bin (R_i, $R_i + \Delta R_i$) is:

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

To match the statistics of 300 million events, extensive systematic errors studies have been made.

1) $\sigma_{trig.}$:trigger efficiency

2) $\sigma_{acc.}$:
- **a. the acceptance and event selection**
- **b. background contamination**
- **c. geomagnetic cutoff**

3) $\sigma_{unf.}$
- **a. unfolding**
- **b. the rigidity resolution function**

4) $\sigma_{scale.}$: the absolute rigidity scale

TABLE I: The proton flux Φ as a function of rigidity

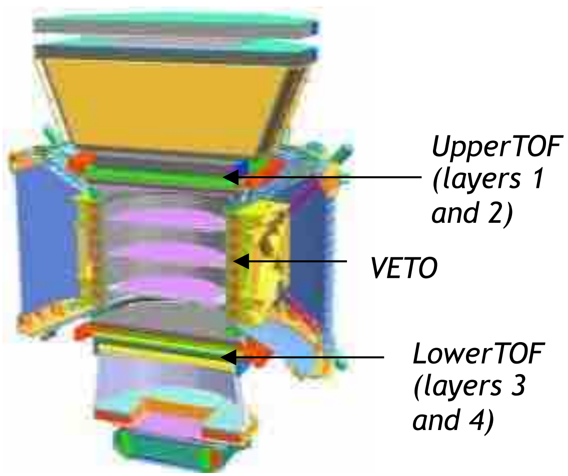
Rigidity [GV]	Φ	$\sigma_{stat.}$	$\sigma_{trig.}$	$\sigma_{acc.}$	$\sigma_{unf.}$	σ_{scale}	$\sigma_{syst.}$
100 – 108	(4.085	0.007	0.006	0.040	0.035	0.022	0.058) $\times 10^{-2}$
108 – 116	(3.294	0.007	0.005	0.033	0.028	0.018	0.047) $\times 10^{-2}$
116 – 125	(2.698	0.006	0.004	0.027	0.023	0.016	0.039) $\times 10^{-2}$
125 – 135	(2.174	0.005	0.004	0.022	0.019	0.013	0.032) $\times 10^{-2}$

Trigger Efficiency

Trigger efficiency [4/4 TOF (+ VETO)] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger:

ε_T= 90-95% for protons, 95-99% for helium, ~100% Z>2

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

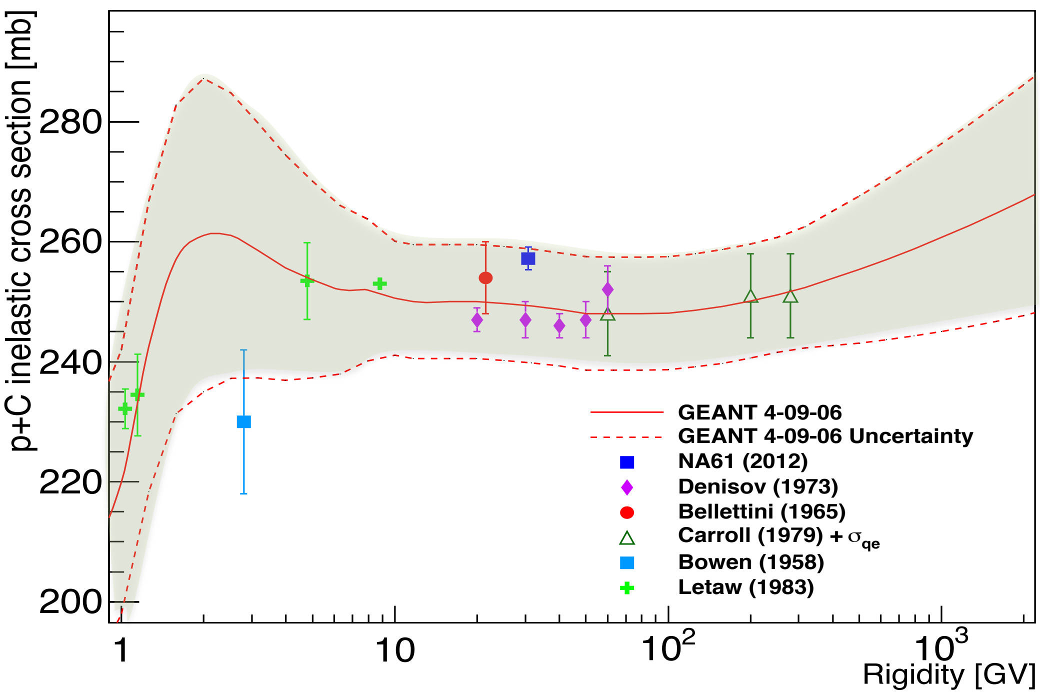


This systematic error is negligible (less than 0.1%) below 100GV and increasing ~1.5% at highest rigidities

Proton Acceptance

The detector is mostly made of C(73% by weight) and Al(17 %). The inelastic cross sections of *p* + C and *p* + Al are known to few percent between 1 GV and 1.8 TV.

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



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

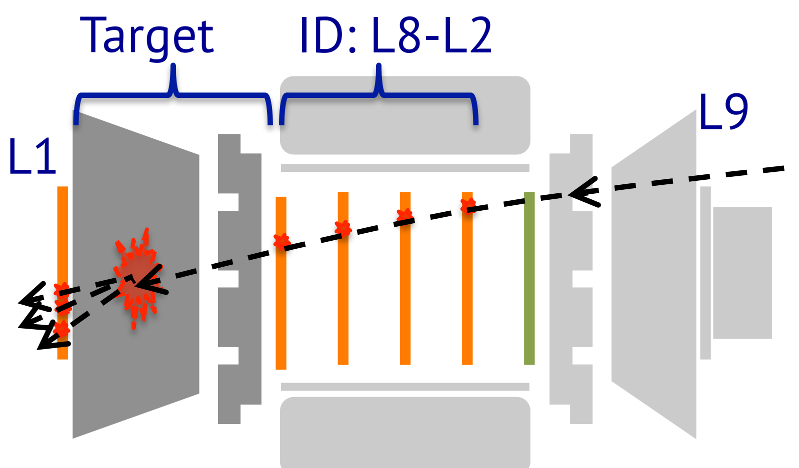
1% [1GV]
0.6% [10-300 GV]
0.8% [1.8 TV]

Nuclei Acceptance

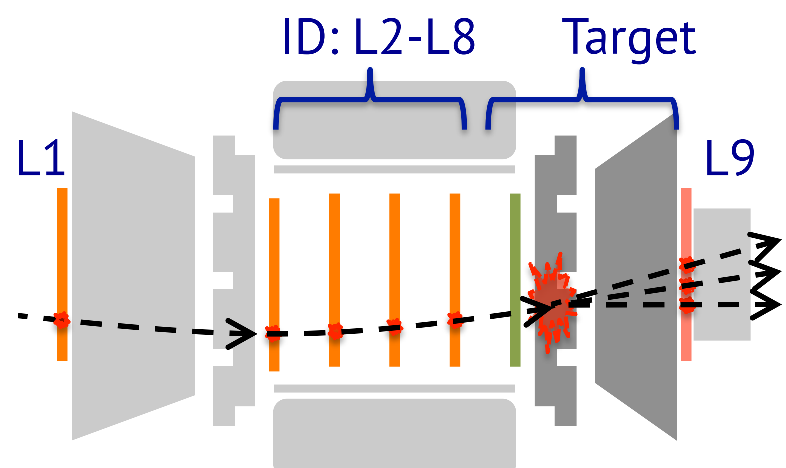
eg. He+C and He+Al are measured only below 10 GV

→ New method to determine interactions from ISS data with AMS pointing in horizontal direction: 2+ days in total

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



Survival prob. L2 → L1



Survival prob. L8 → L9

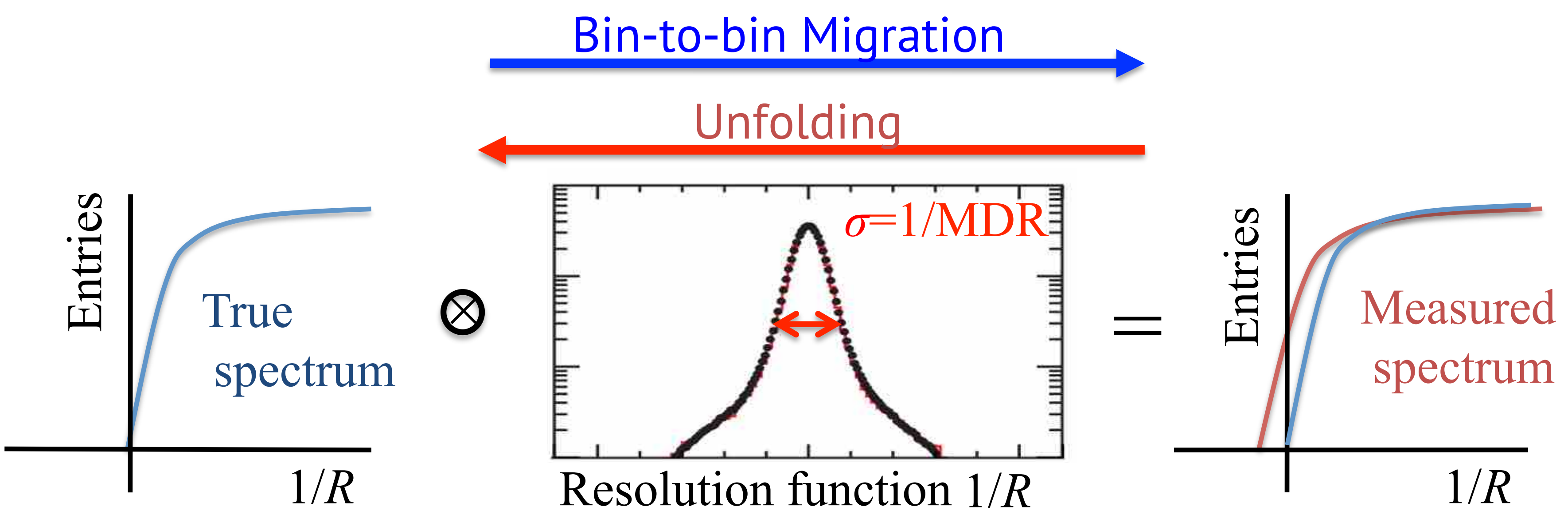
Method was verified by comparing this L8 → L9 survival probability to one obtained from data collected in nominal AMS orientation:

For Helium ~1% < 200 GV increasing to ~2% at highest rigidities

Unfolding

Correction of bin-to-bin migration is needed due to the finite tracker resolution

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



Difference between different unfolding algorithms gives a systematic error ~0.5%

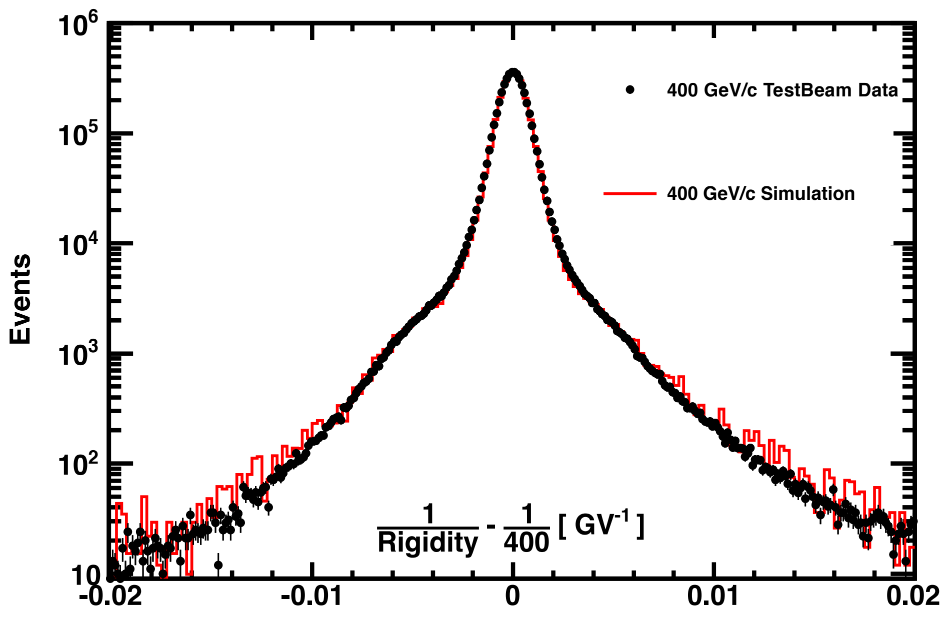
Tracker resolution

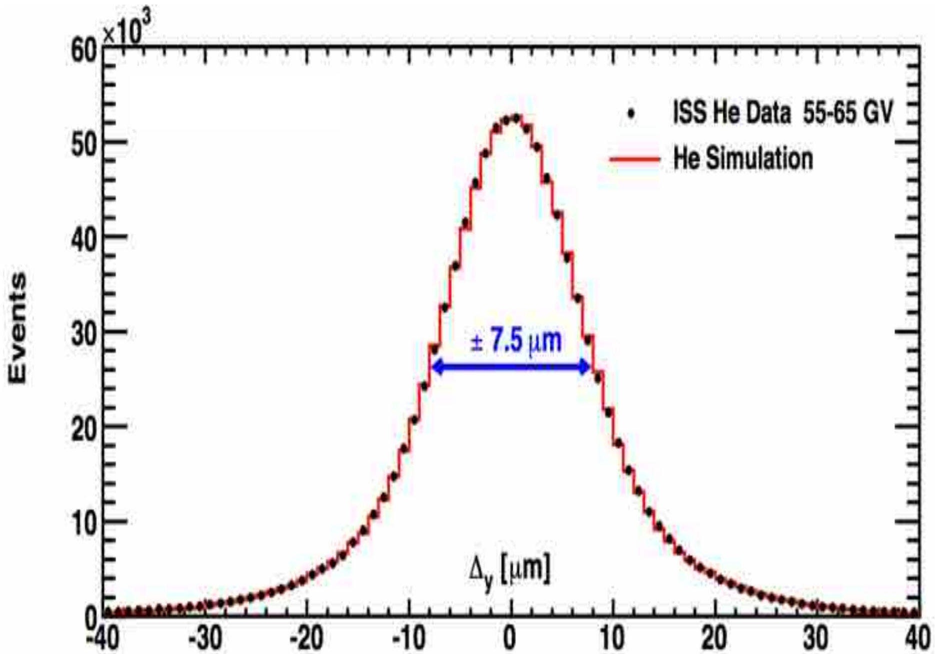
Protons:

- Resolution function from MC simulation
- Verified with:
  - 400 GeV/c Test Beams data
  - ISS data: tracker residuals, rigidity reconstruction (L1-L8) vs. (L2-L9)

Nuclei:

- Resolution function from MC simulation
- Verified with ISS data:
  - Tracker residuals
  - Rigidity reconstruction (L1-L8) vs. (L2-L9)



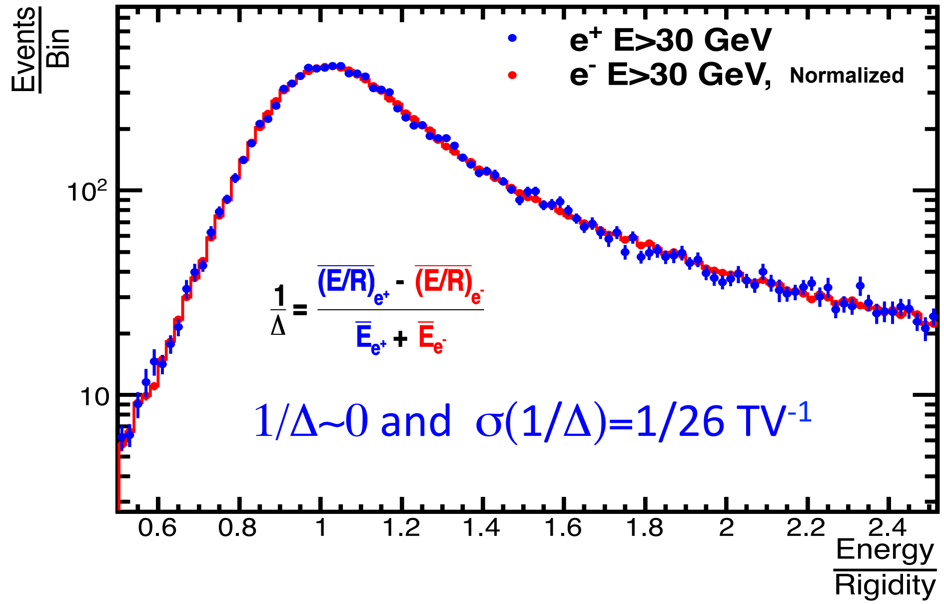


Uncertainty on the flux < 1% below 300 GV rising to 3% at 2 TV

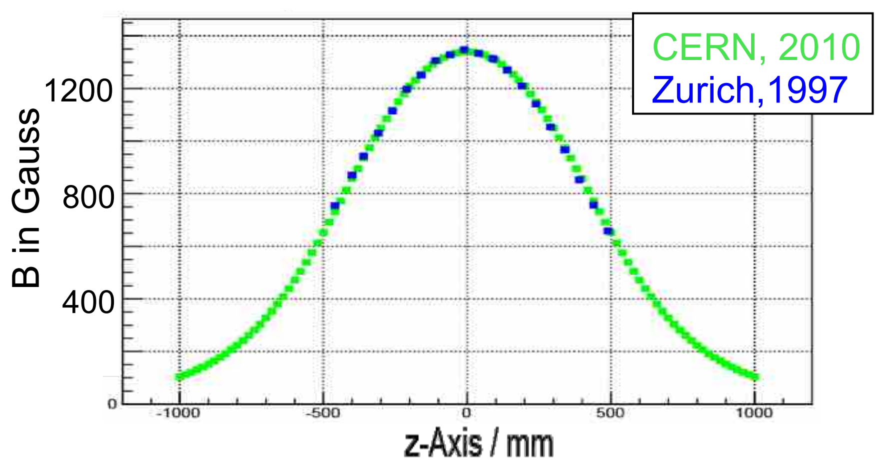
Rigidity Scale

Two contributions to the uncertainty:

1. **Residual tracker misalignment** $(1/\Delta)$:
   checked with $E_{ECAL}/R_{Tracker}$ ratio for electrons and positrons, limited by the current high energy positron statistics.
   The corresponding flux error is 2.5% @1 TV.

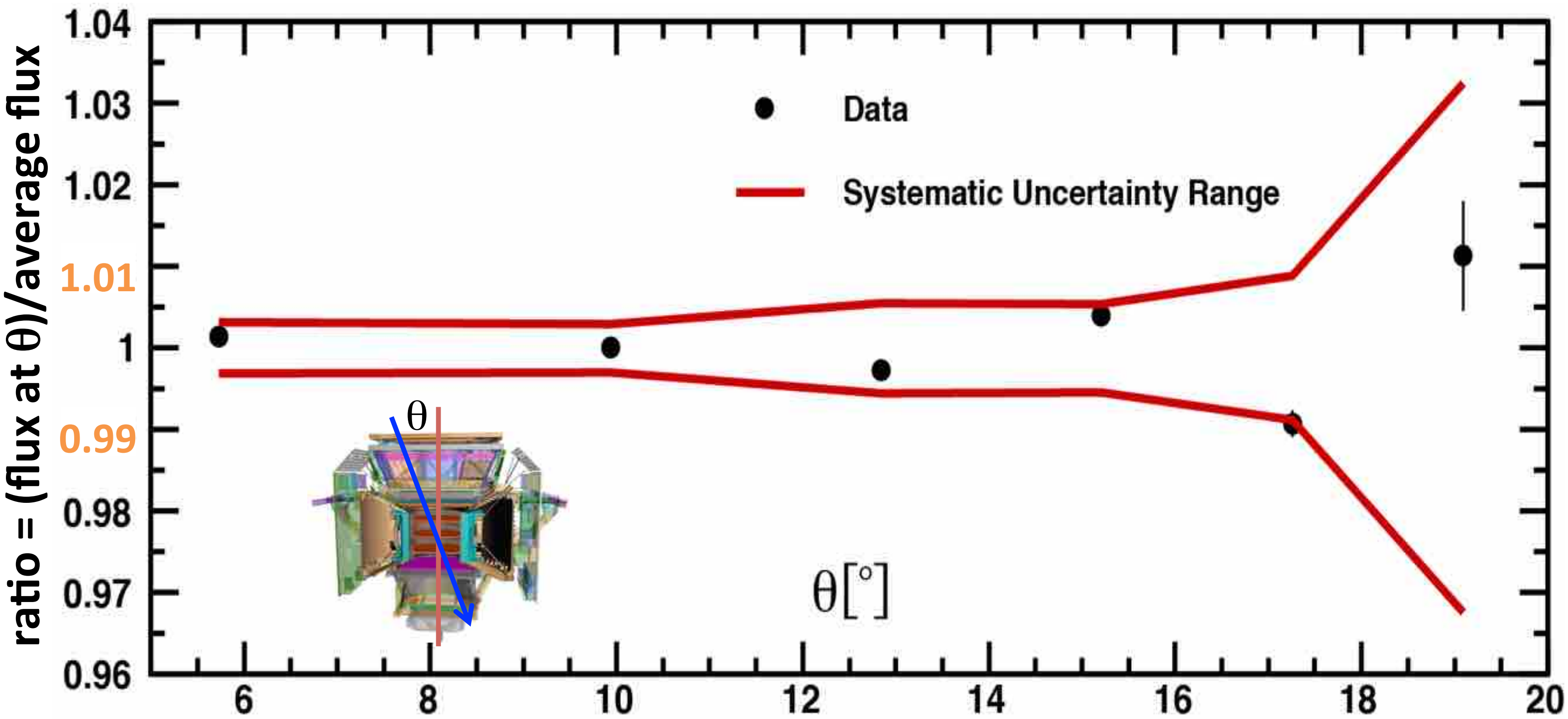


2. **Magnetic field:**
   Mapping measurement (0.25%) and temperature corrections (0.1%).
   Taken in quadrature and weighted by the measured flux rigidity dependence, this amounts to less than 0.5% systematic error on the flux.



Verification (I)

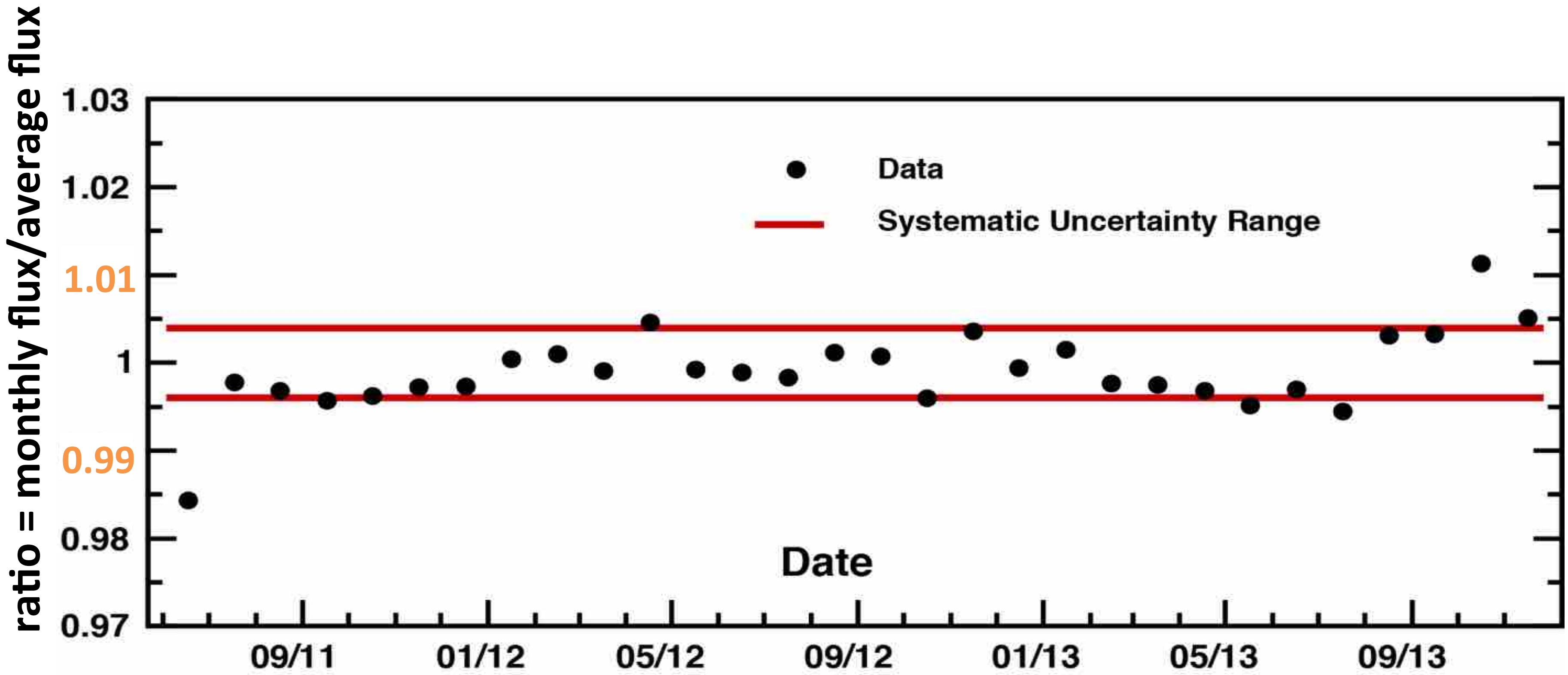
Study the dependence of the integral of the proton flux above 30 GV on the angle Θ between the incoming proton direction and the AMS zenith axis.



This verifies the systematic error assigned to the **acceptance.**

Verification (II)

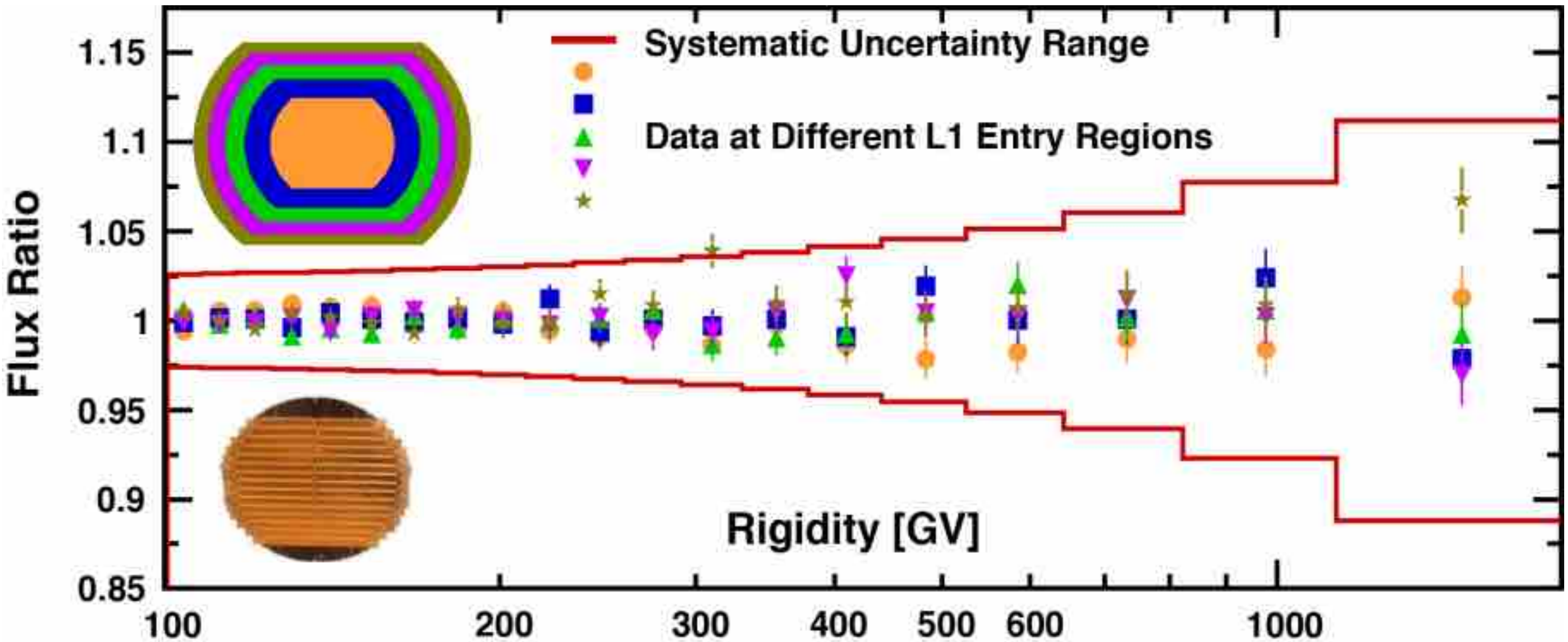
The monthly integral flux above 45GV is within the systematic error of 0.4%.



This verifies that the flux above 45GV shows no observable effect from solar modulation fluctuations and that the **detector performance is stable**.

Verification (III)

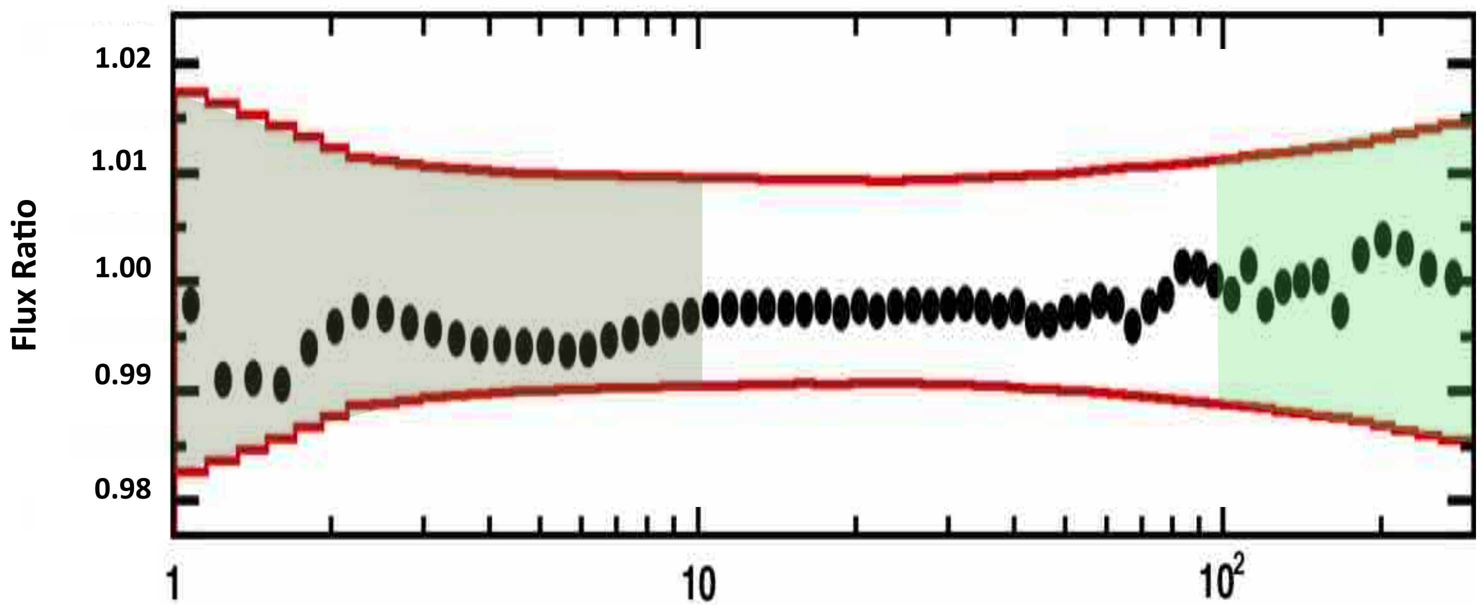
The ratios of fluxes obtained using events which pass through different sections of L1 to the average flux is in good agreement and within the assigned systematic errors.



This verifies the errors assigned to the tracker alignment.

Verification (IV)

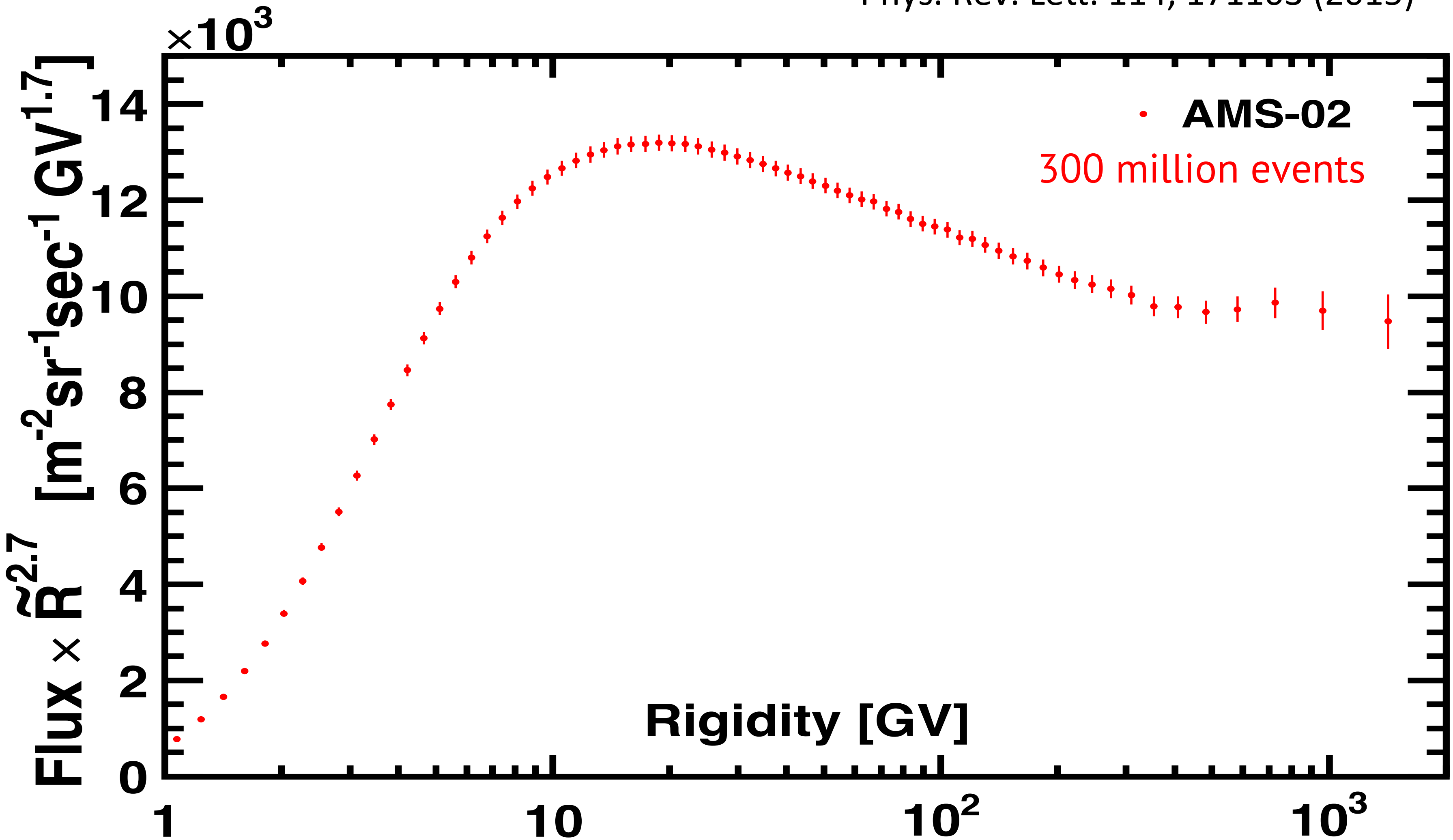
The flux obtained with only the inner Tracker (L2-L8) is in good agreement to the one obtained with the full span Tracker (L1-L9)



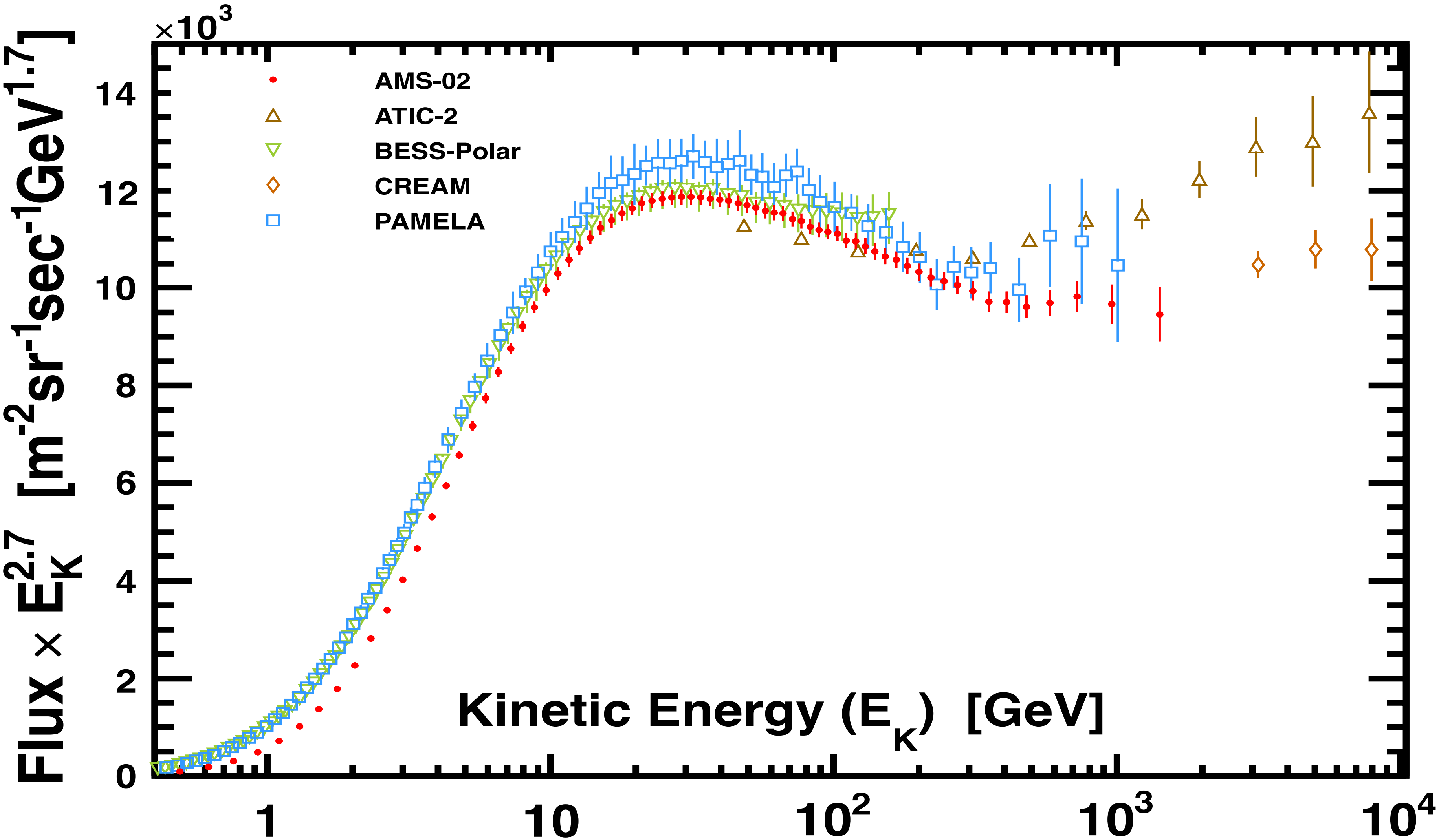
This verifies the error on the **rigidity resolution function and the unfolding**

Proton Flux

Phys. Rev. Lett. 114, 171103 (2015)

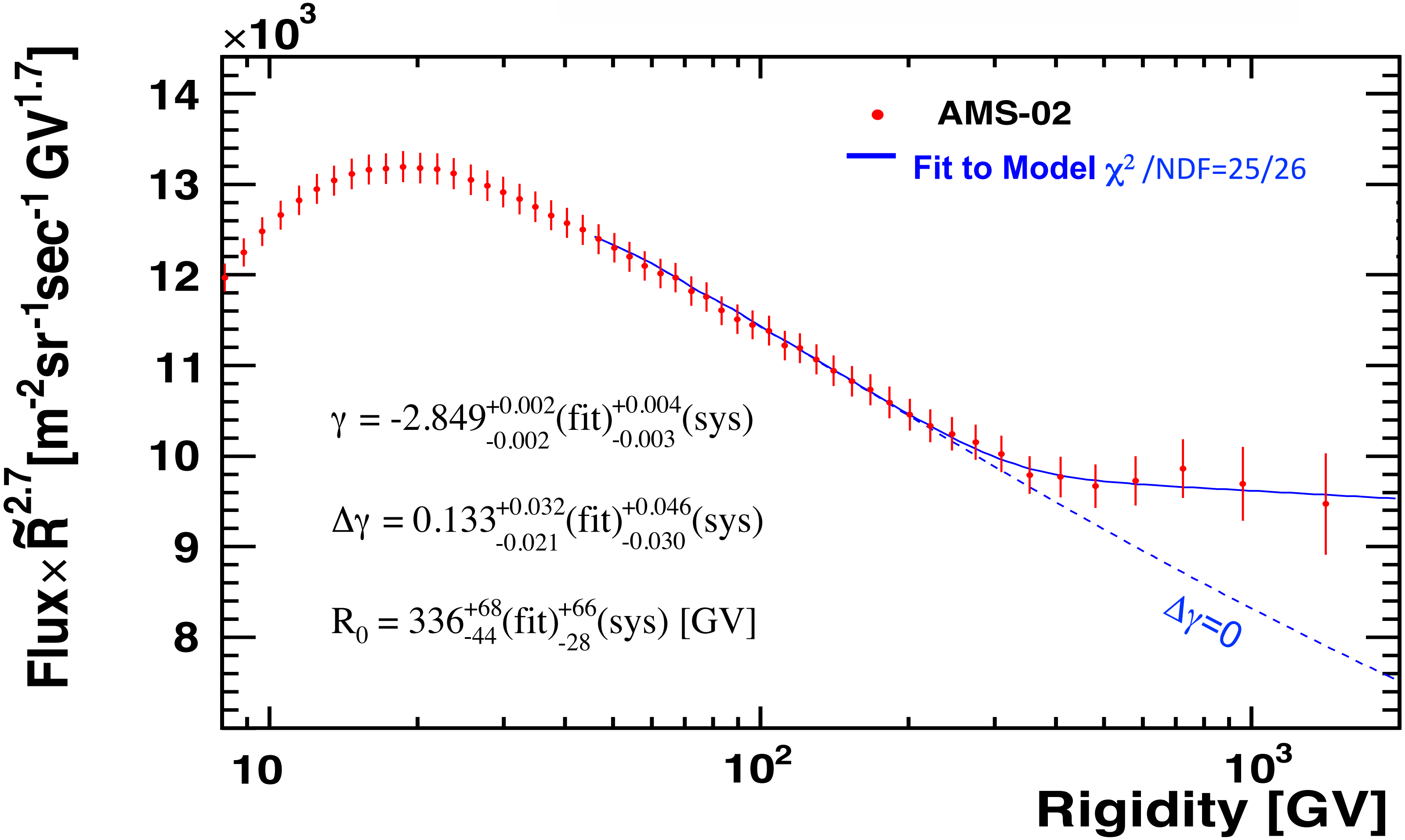


Proton Flux

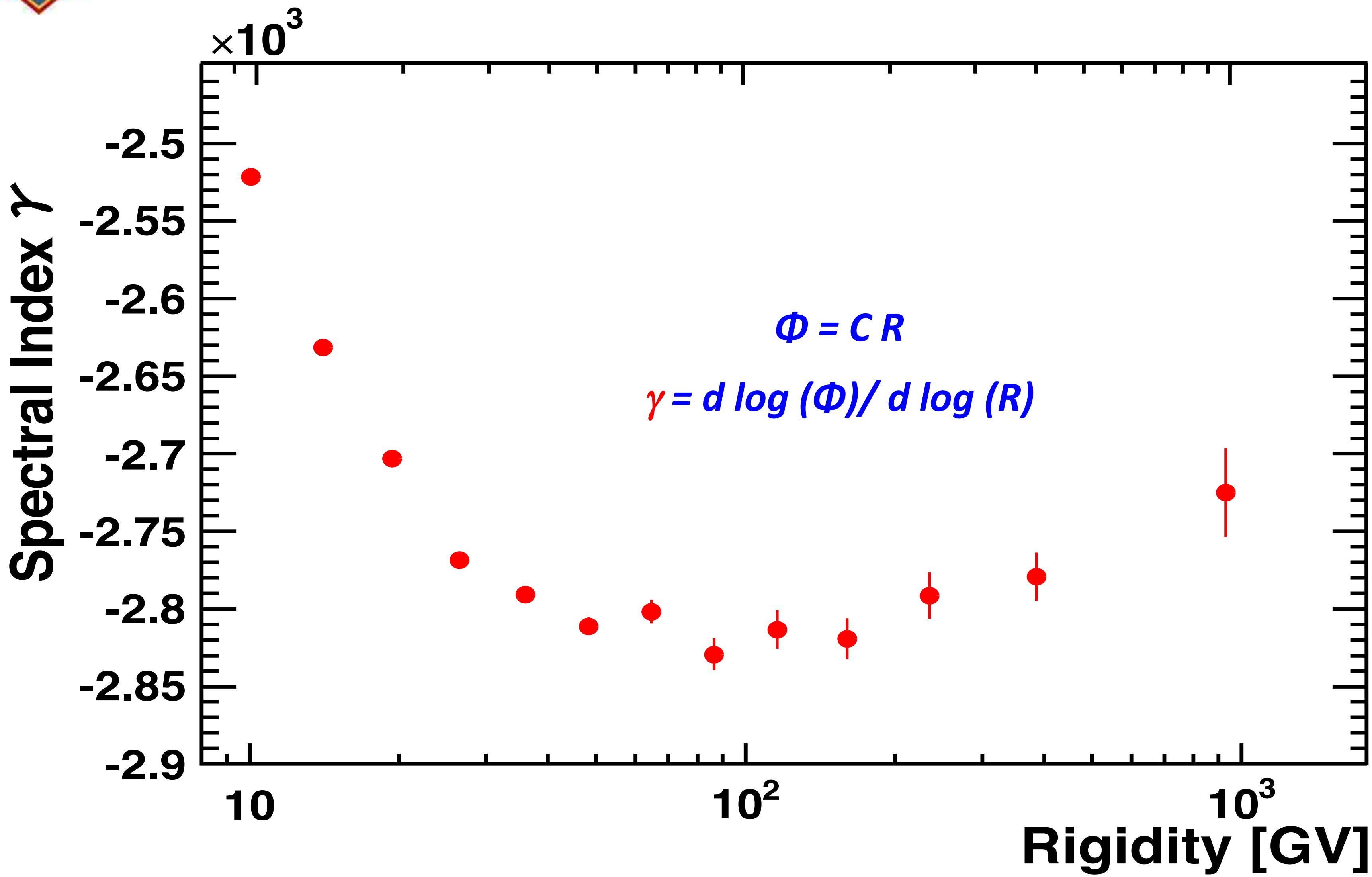

×10^3
14
12
10
8
6
4
2
0
Flux × E_K^2.7 [m^-2 sr^-1 sec^-1 GeV^1.7]
AMS-02
ATIC-2
BESS-Polar
CREAM
PAMELA
Kinetic Energy (E_K) [GeV]
1
10
10^2
10^3
10^4

Proton Flux

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

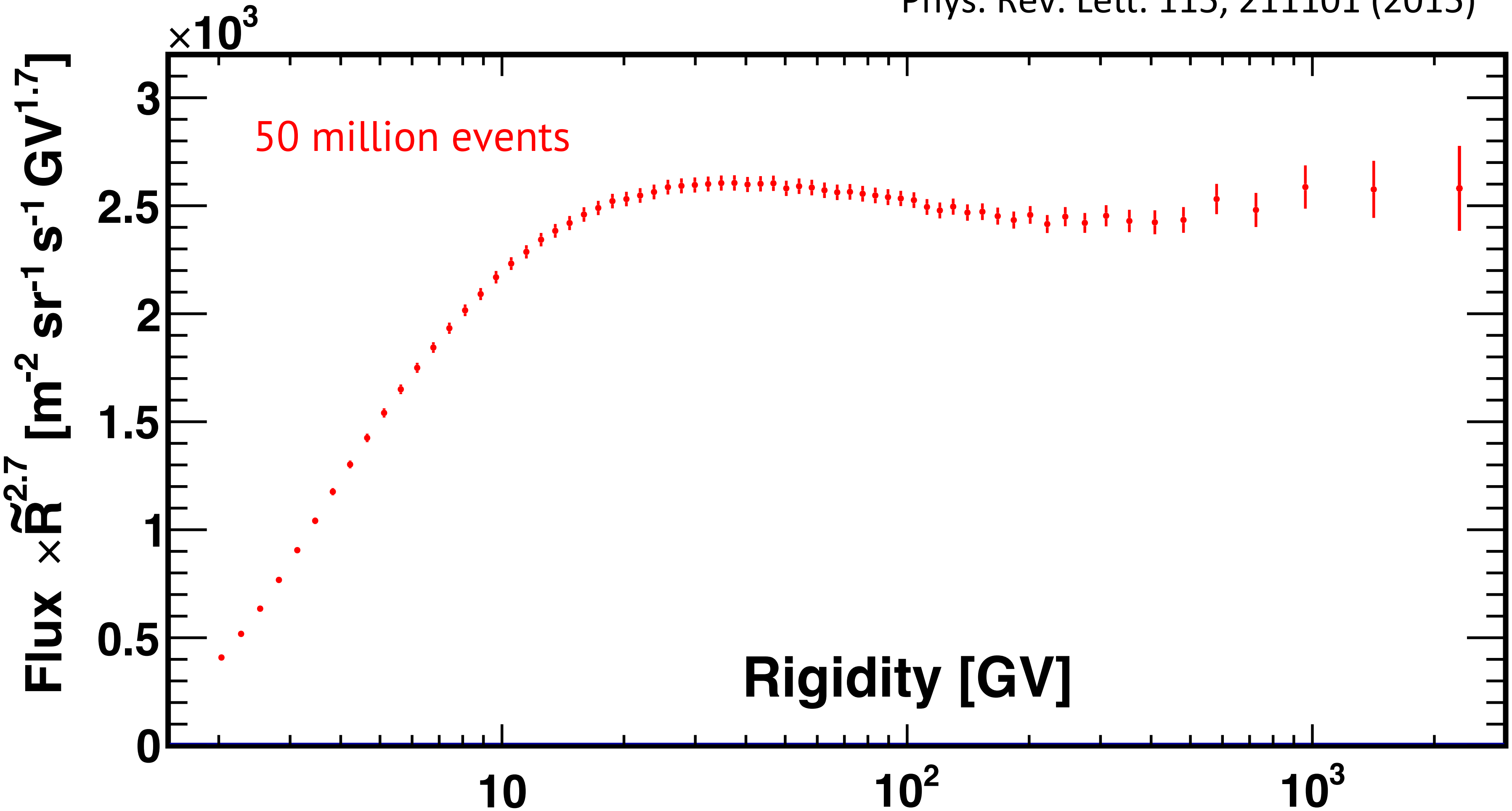


Proton Spectral Index

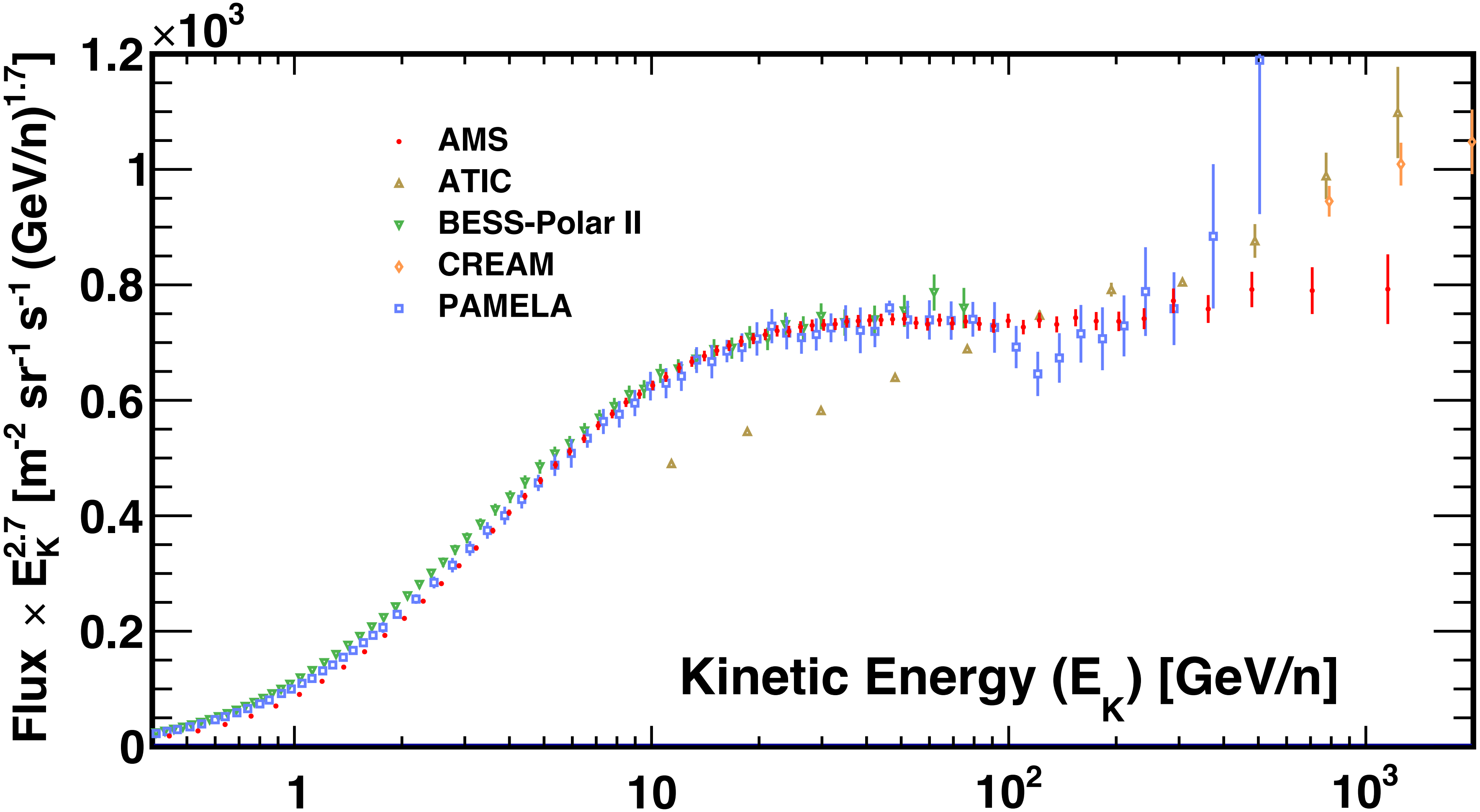


Helium Flux

Phys. Rev. Lett. 115, 211101 (2015)



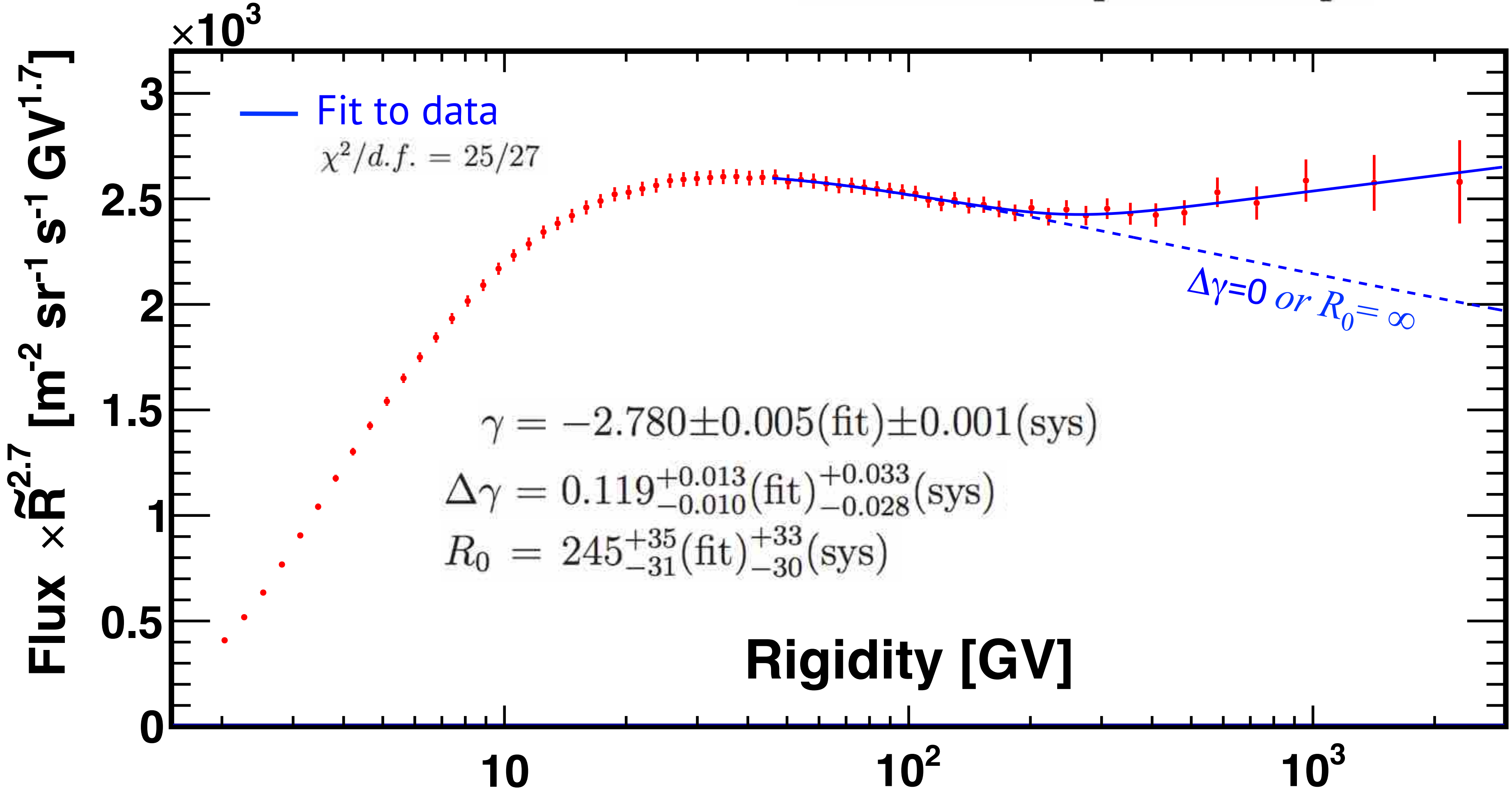
Helium Flux



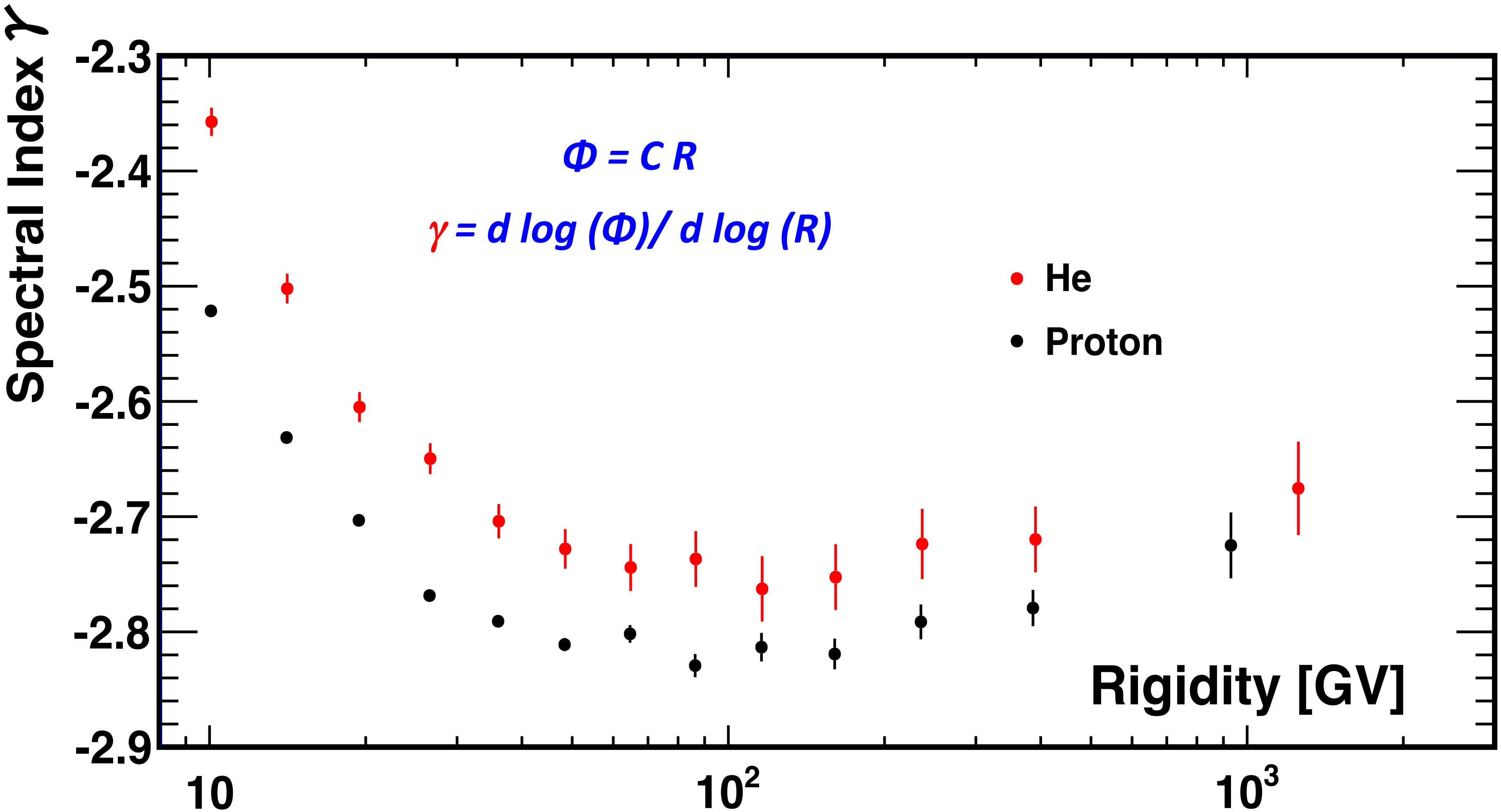
$\times 10^3$
1.2
1
0.8
0.6
0.4
0.2
0
Flux × $E_K^{2.7}$ [m^{-2} sr^{-1} s^{-1} $(GeV/n)^{1.7}$]
AMS
ATIC
BESS-Polar II
CREAM
PAMELA
Kinetic Energy (E_K) [GeV/n]
1
10
10^2
10^3

Helium Flux

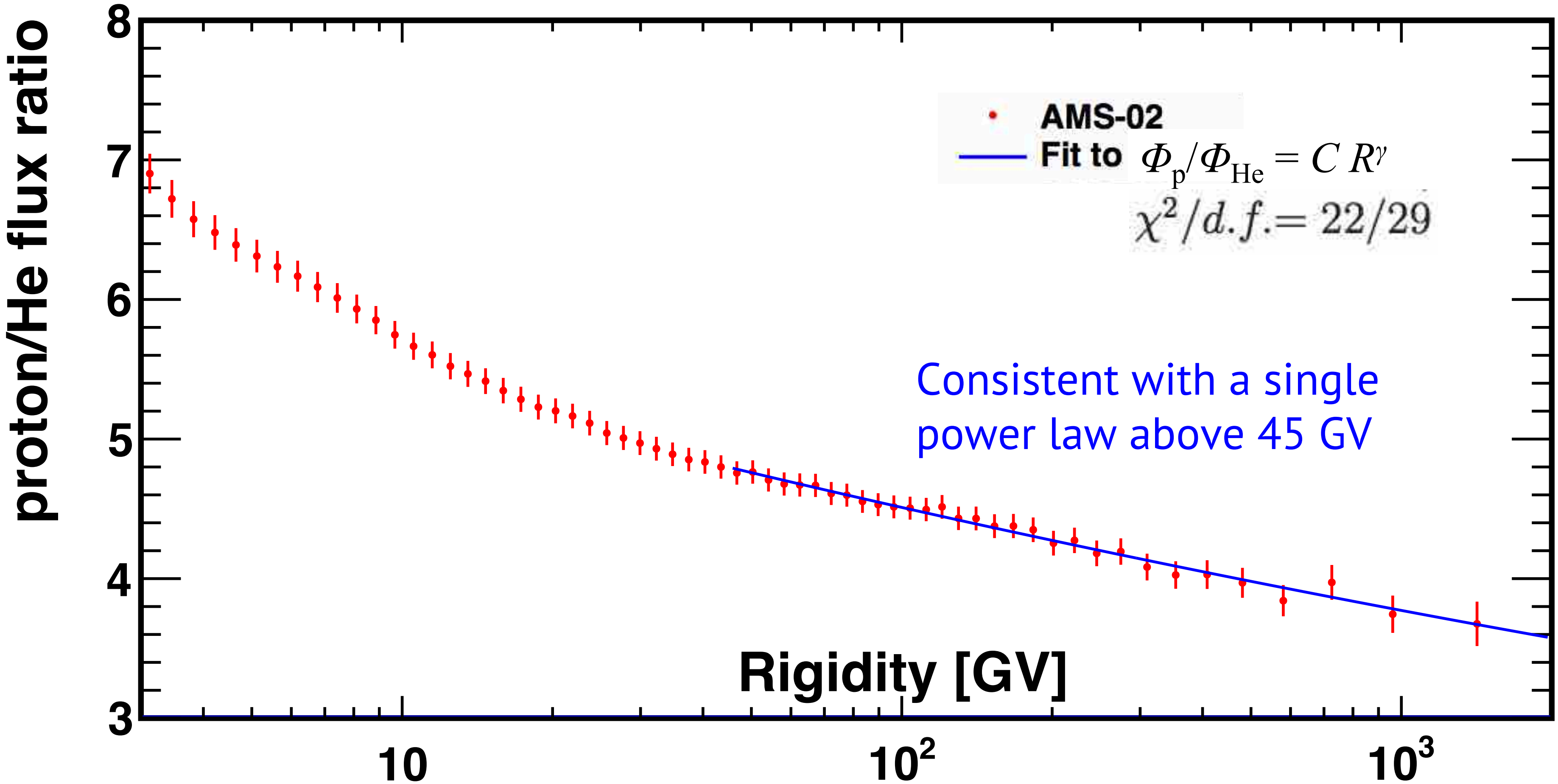
Double Power Law: $\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$



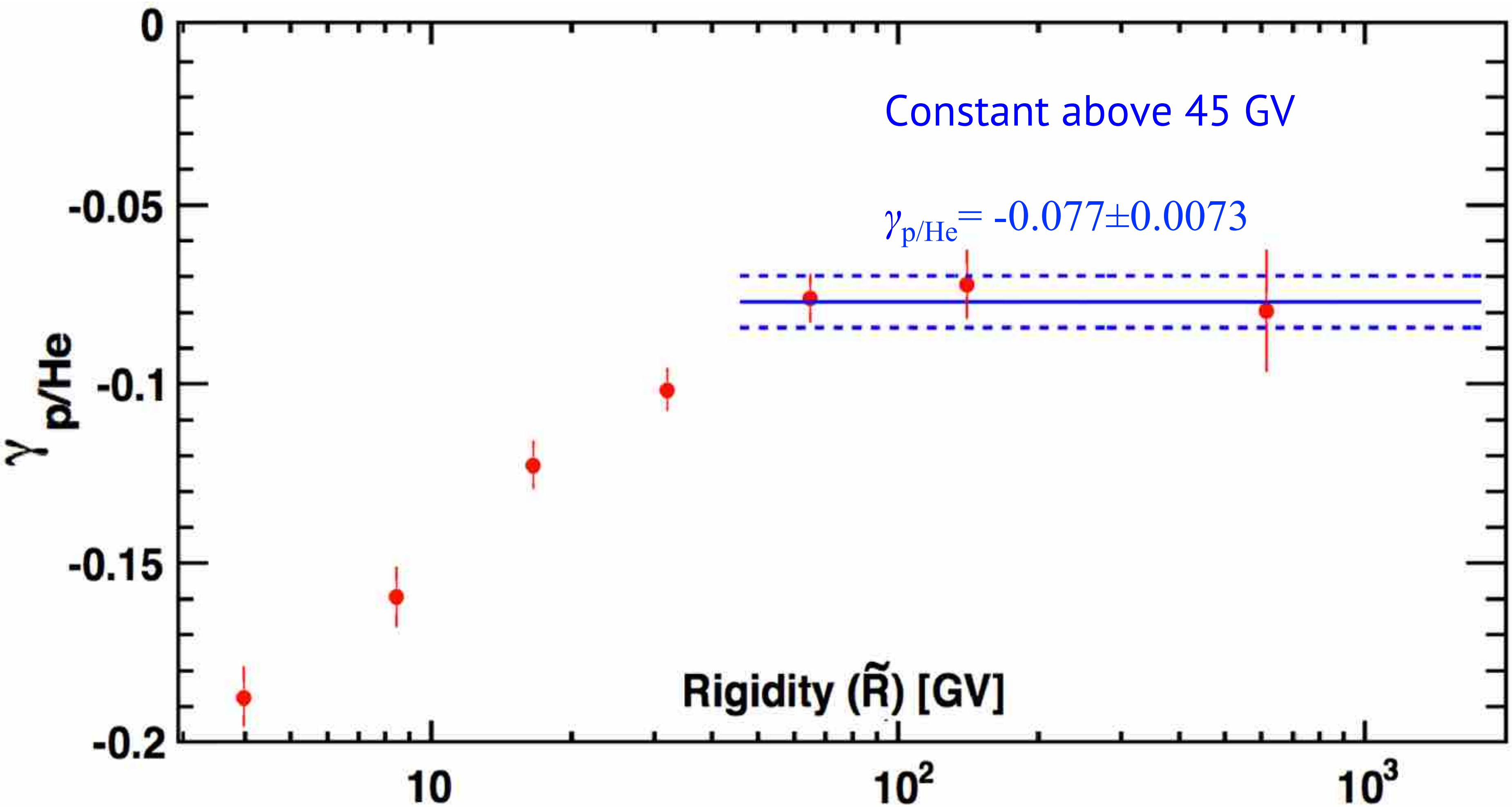
Helium Spectral Index



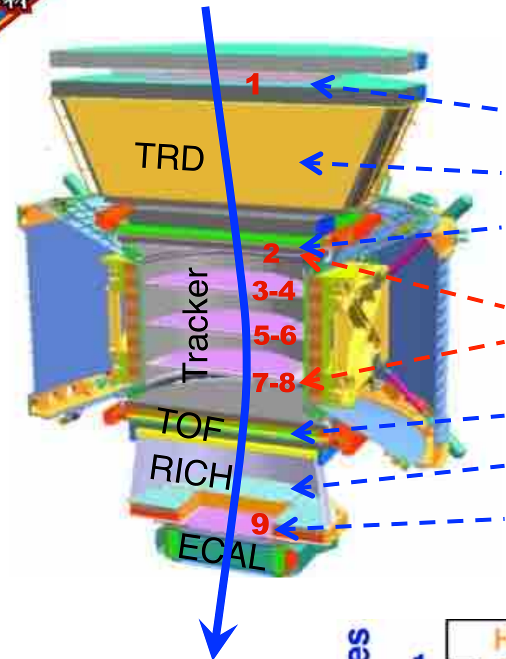
Proton/Helium Flux Ratio



Proton/Helium Ratio Spectral Index

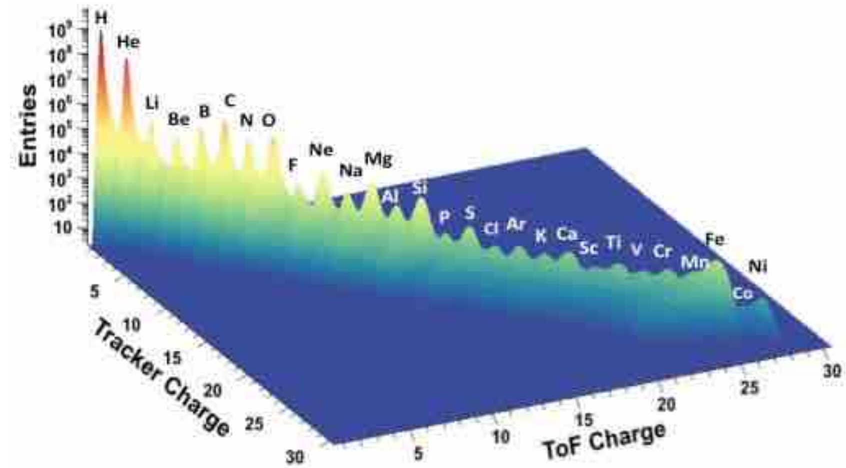


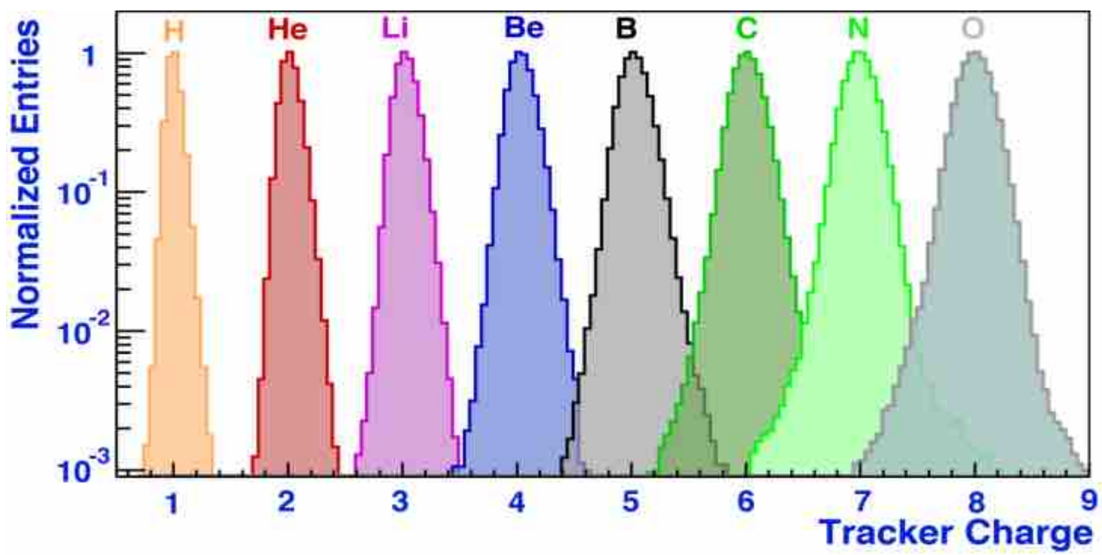
Light Nuclei Analysis



Charge Resolution (Z=6)

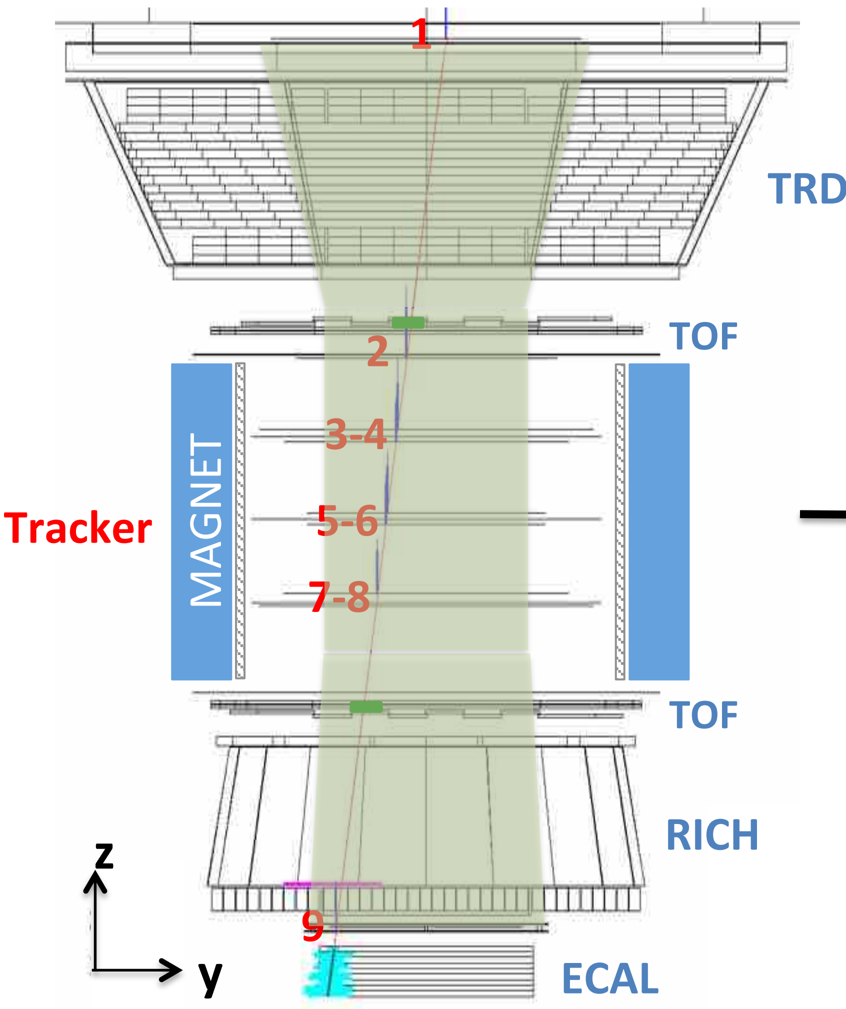
Tracker Plane 1	0.30
TRD	0.33
Upper TOF	0.16
Inner Tracker 2-8	0.12
Lower TOF	0.16
RICH	0.32
Tracker Plane 9	0.30



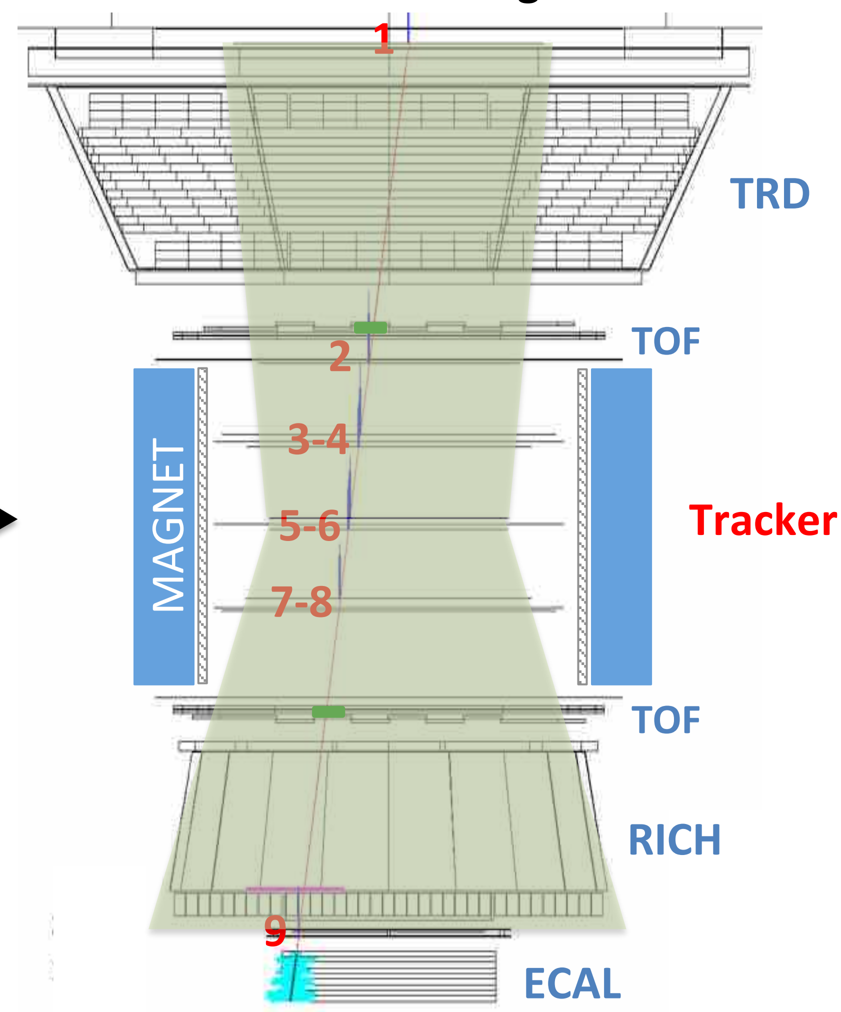


Acceptance for Light Nuclei Analyses

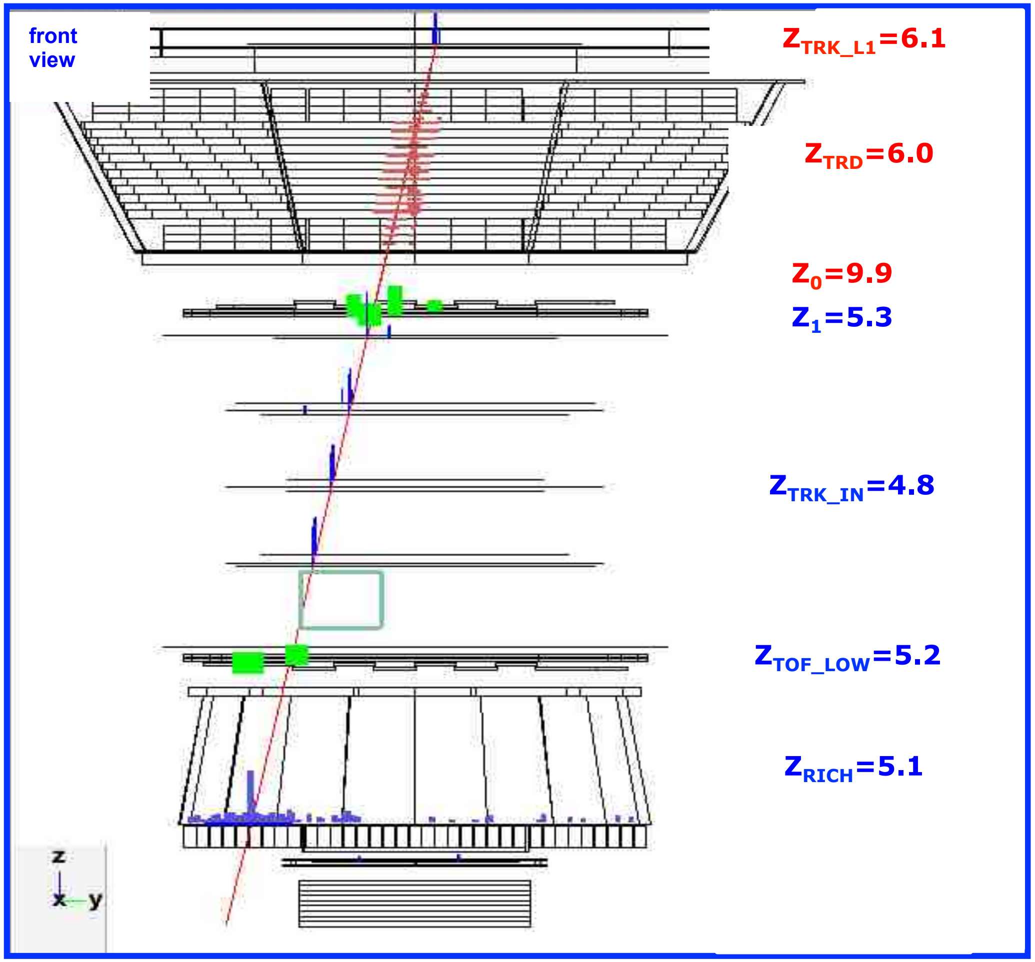
Protons, Helium: Tracker L1-L9



Z>2: Tracker L1-L8 for Rigidities <1TV

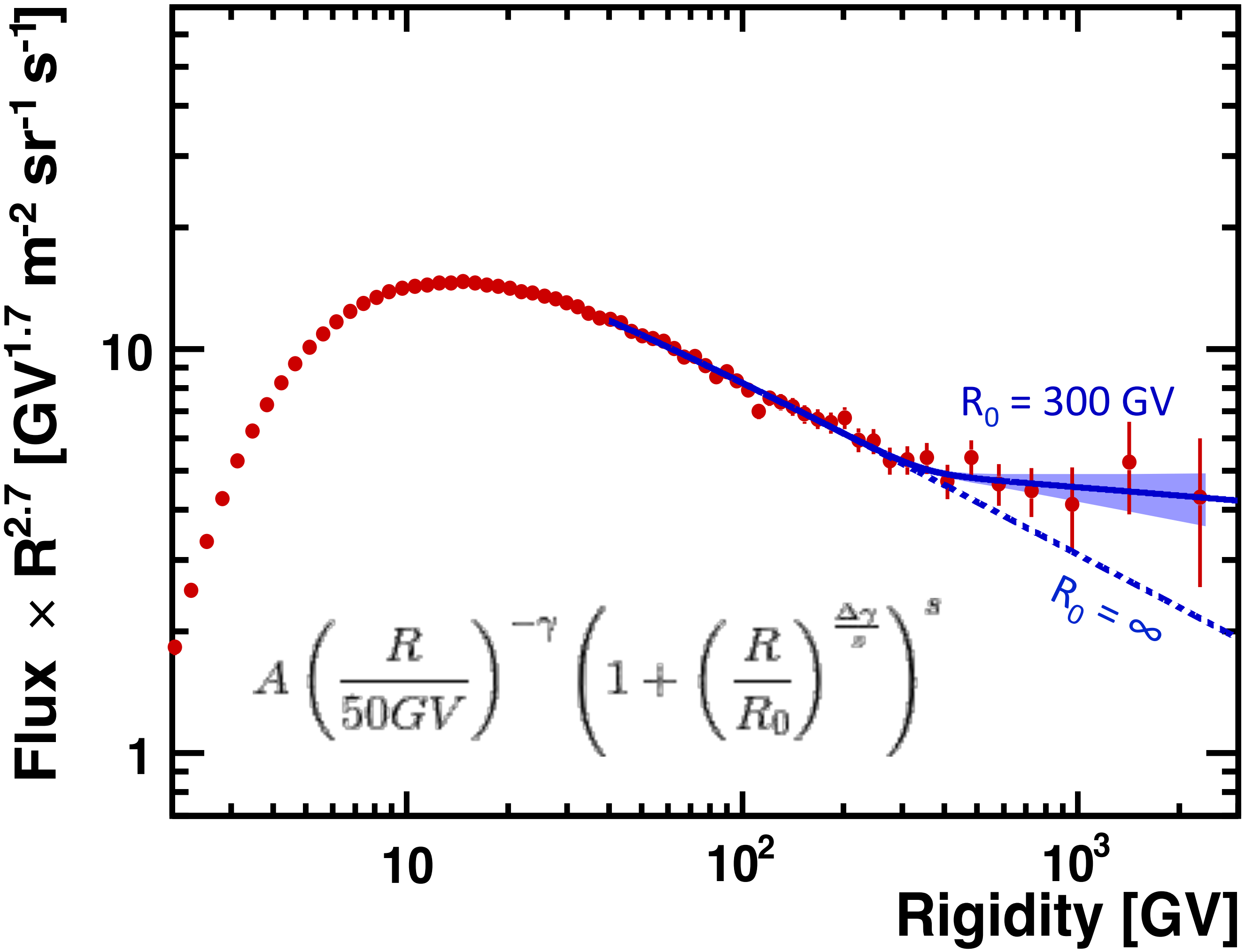


Background from Interactions

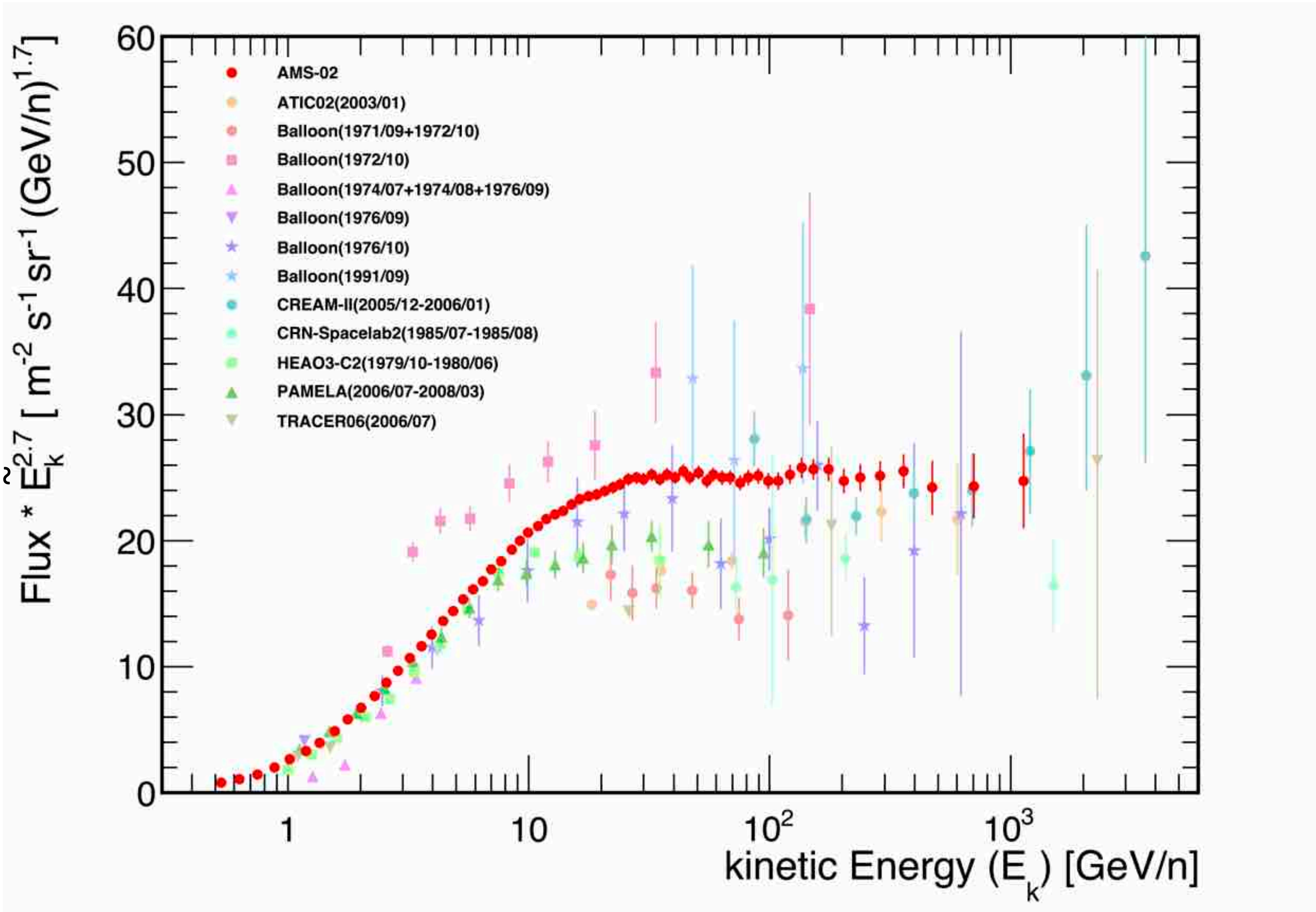


- There is a small background from higher charge nuclei interactions inside AMS, such as
  Carbon -> Lithium
  Carbon -> Boron or
  Oxygen -> Carbon or
- Due to their abundance in cosmic rays only nuclei up to Oxygen play a significant role
- Background is determined by charge measurement at the top of AMS (Tracker L1) and MC

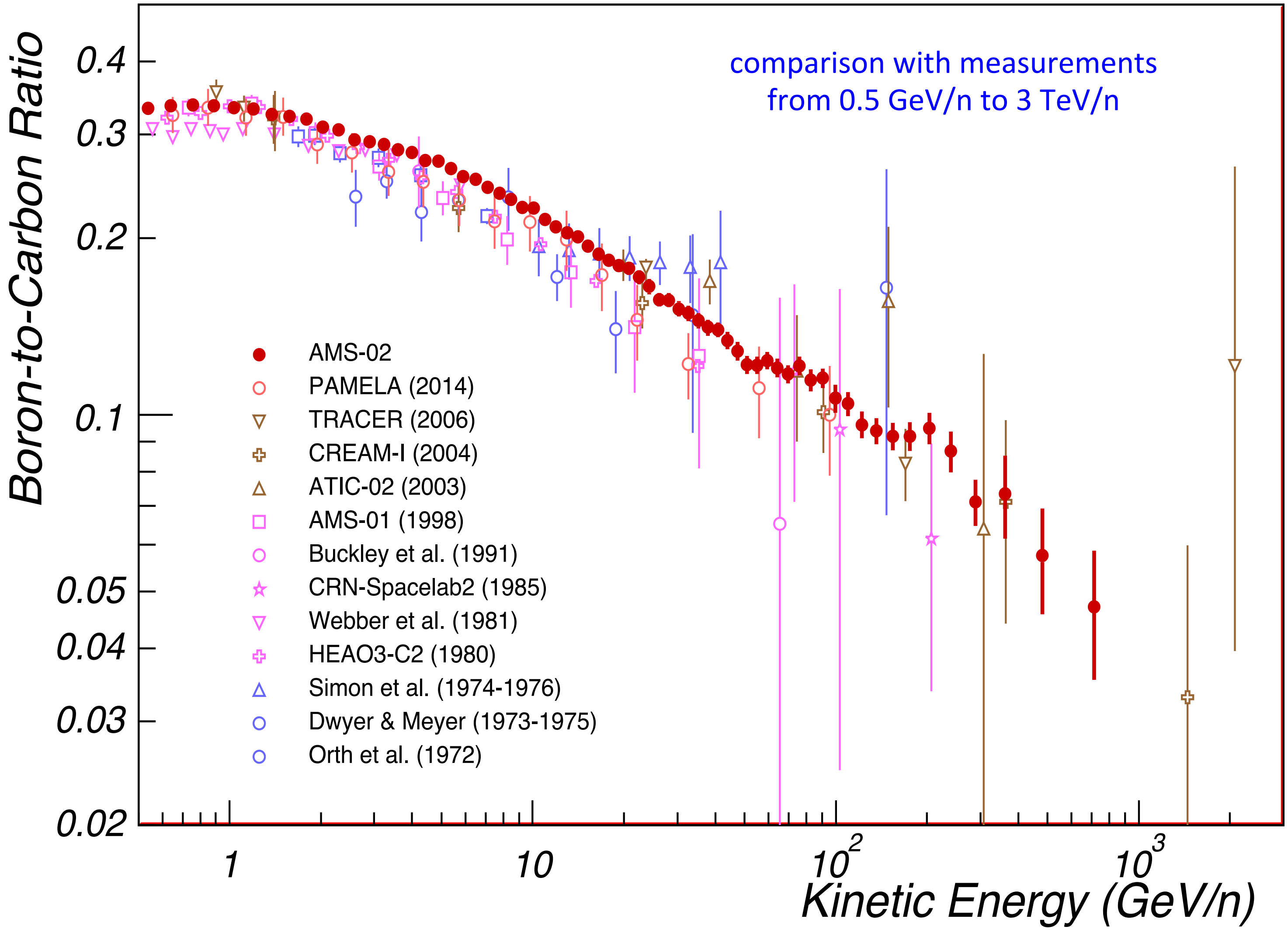
Lithium Flux – current status



Carbon Flux – current status



Boron/Carbon ratio– current status

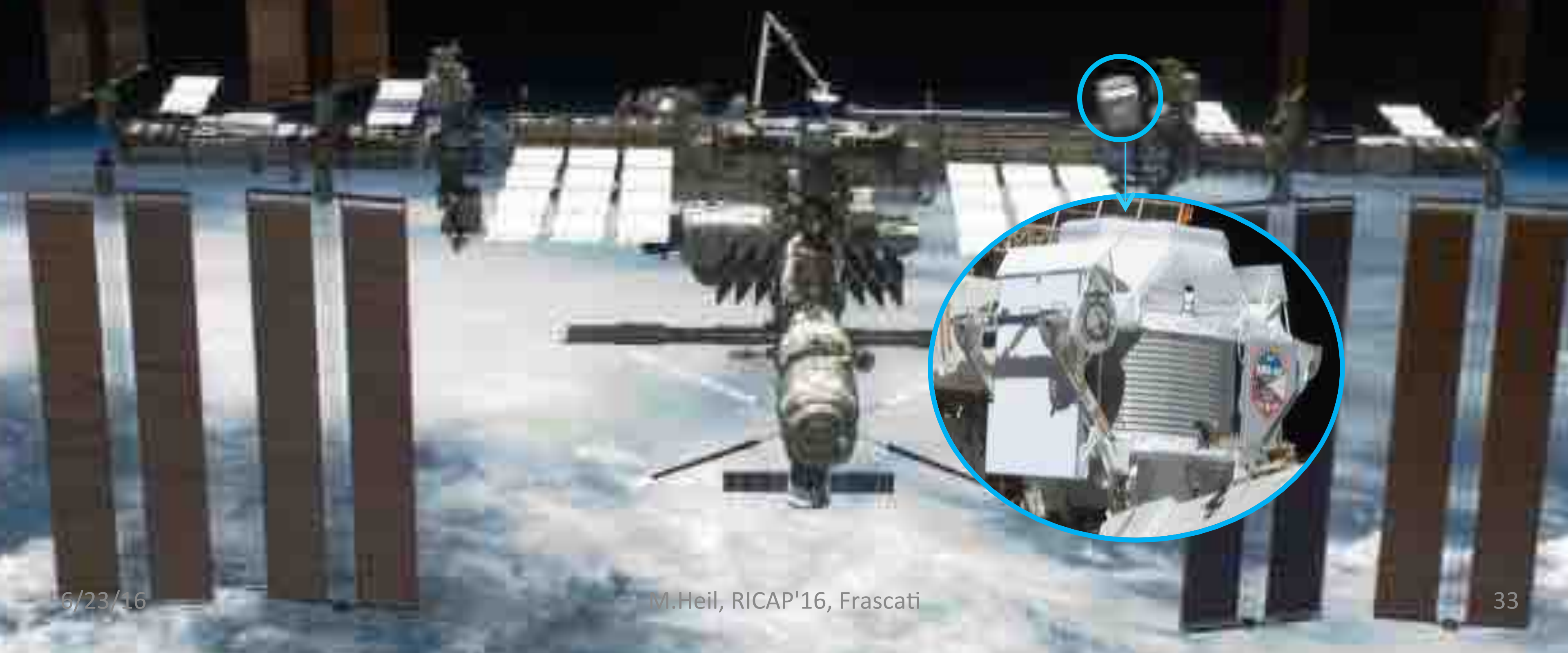


In the past hundred years, measurements of charged cosmic rays by balloons and satellites have typically contained ~30% accuracy.

AMS is providing cosmic ray information with ~1% accuracy.

The improvement in accuracy will provide new insights into the source of cosmic rays and their propagation through the galaxy.

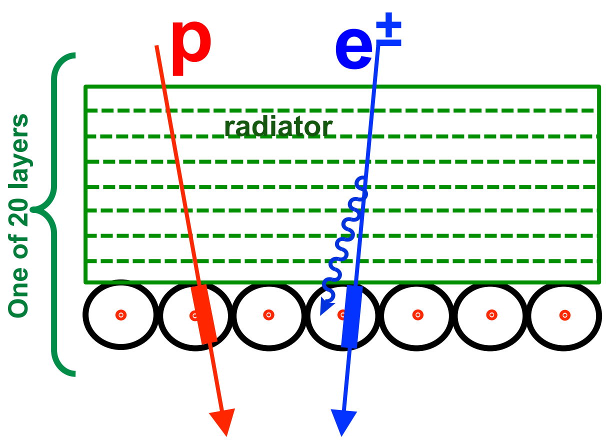
The Space Station is now a unique platform for fundamental physics research.



Back up

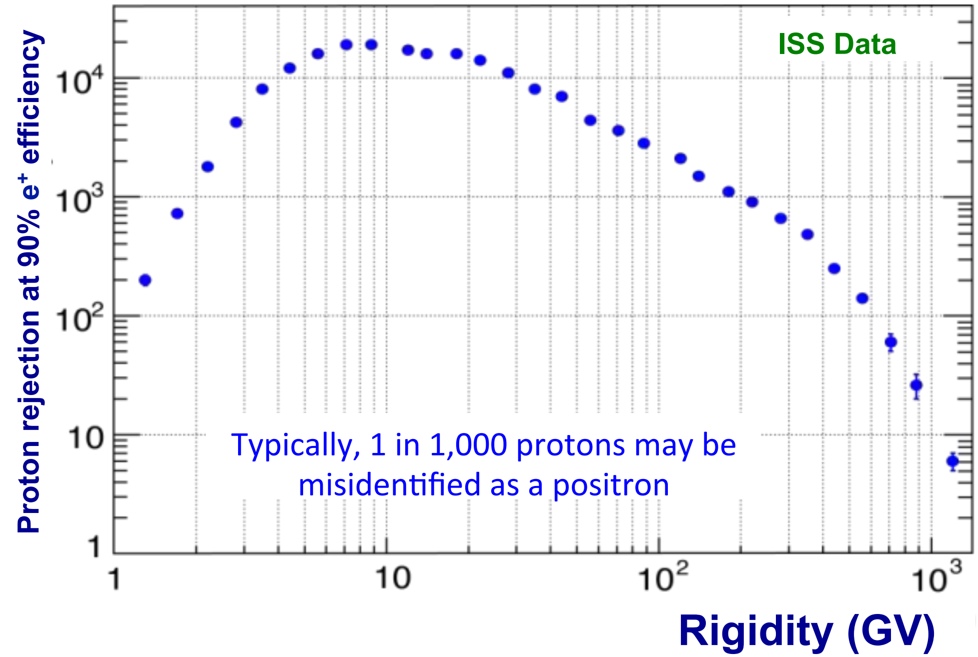
Transition Radiation Detector

20 layers: fleece radiator and proportional tubes



$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

$$P_e = \sqrt[n]{\prod_i^n P_e^{(i)}(A)}$$



Normalized Probabilities

TRD estimator = $-\ln(P_e/(P_e+P_p))$

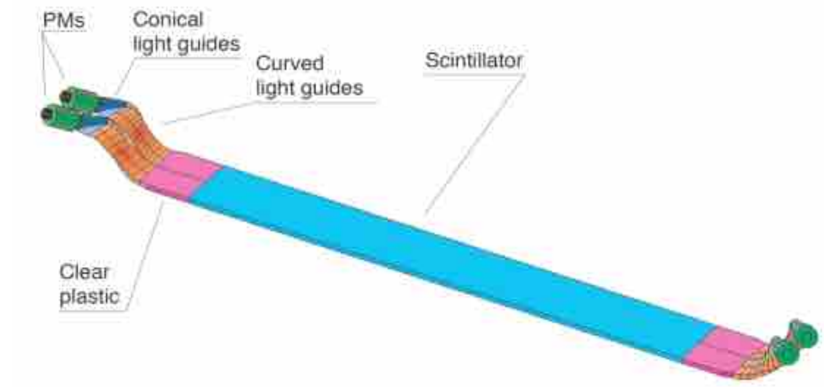
TRD likelihood = $-\mathrm{Log}_{10}(P_e)$

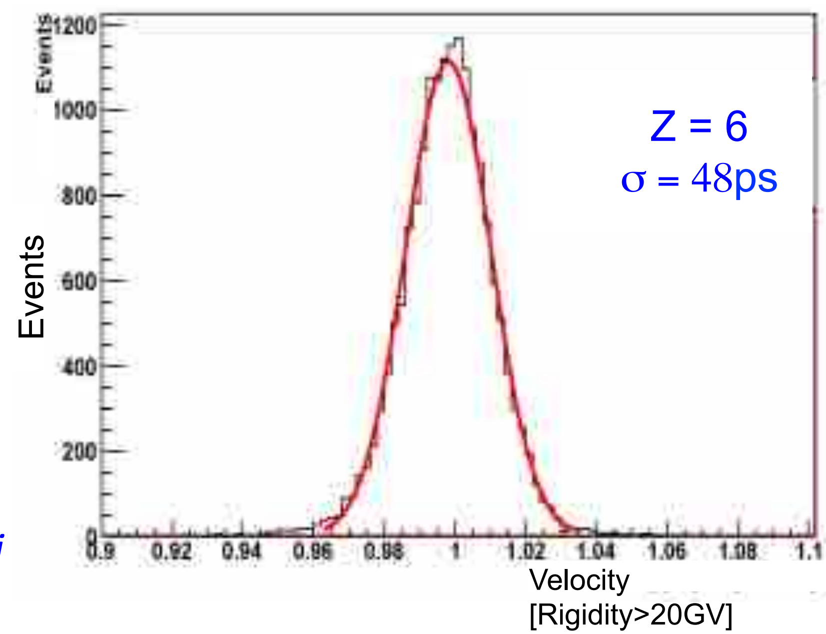
TRD classifier = $-\mathrm{Log}_{10}(P_e)-2$

Lead by: K. Luebelsmeyer, S. Schael

Time-of-Flight Detector

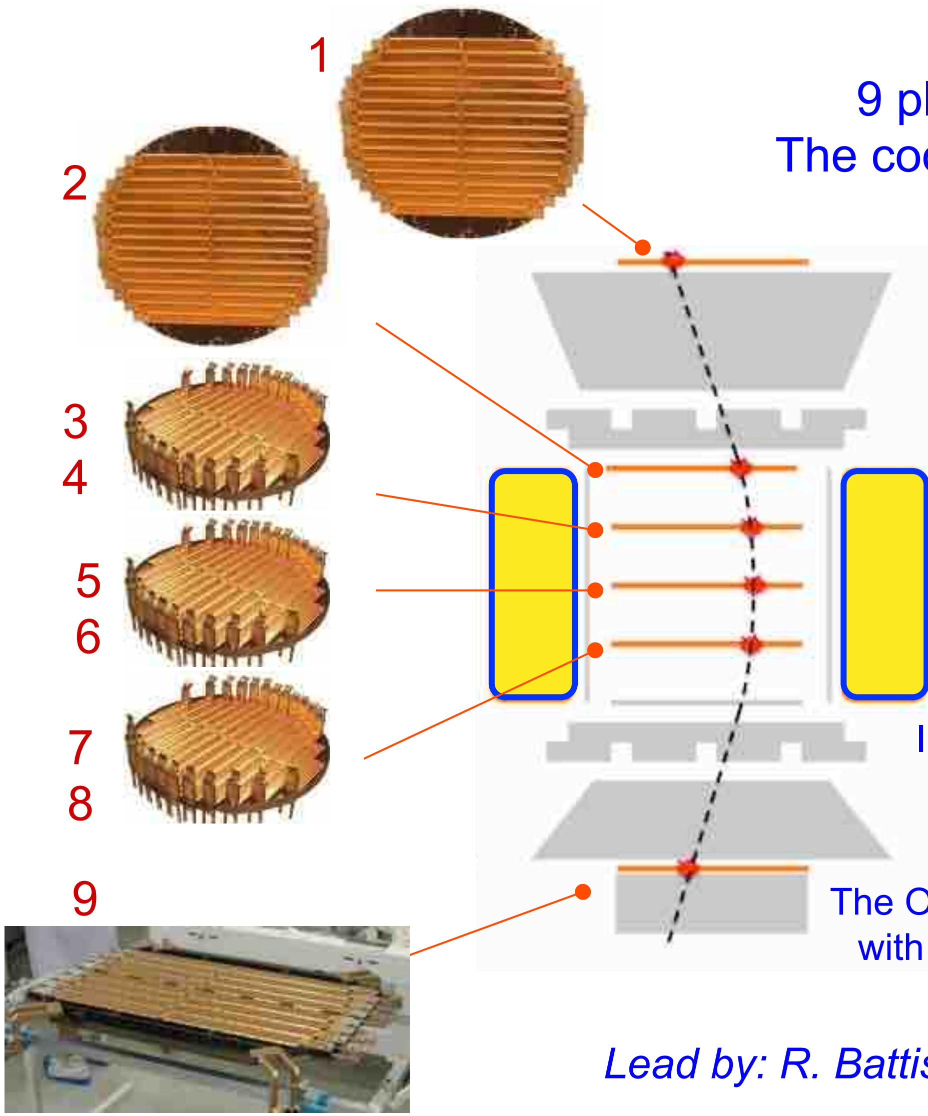
Measures Velocity and Charge of particles



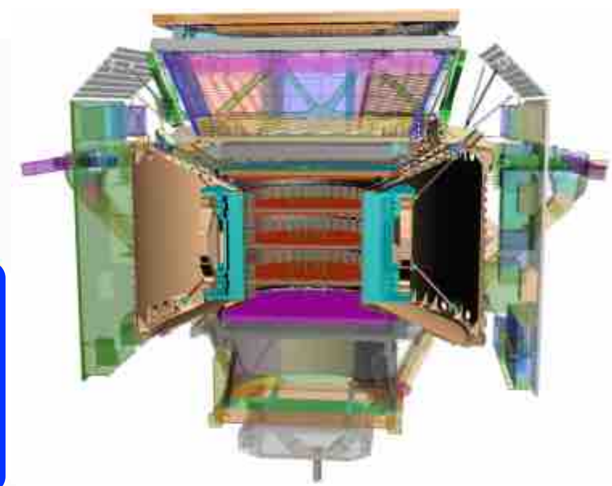


Lead by: A. Contin, G. Laurenti, F. Palmonari

Tracker



9 planes, 200,000 channels
The coordinate resolution is 10 μm.



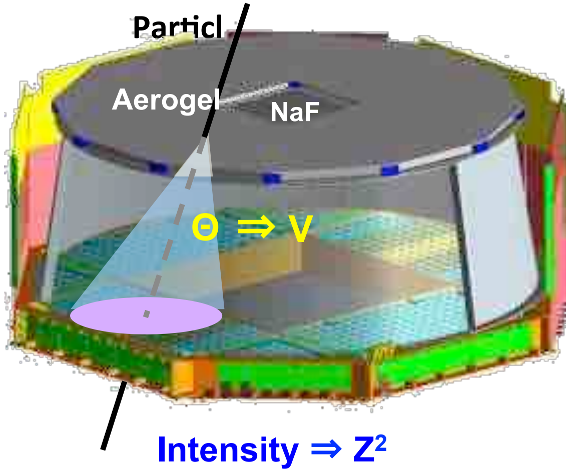
Inner tracker alignment stability monitored with IR Lasers.

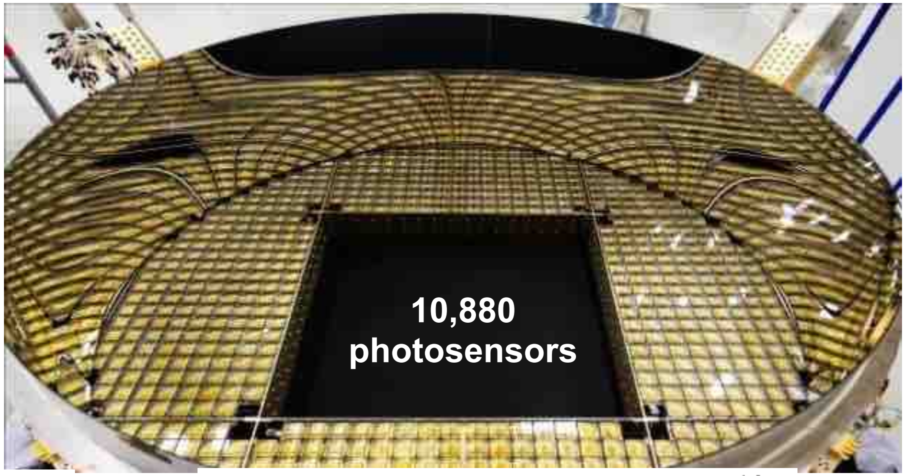
The Outer Tracker is continuously aligned with cosmic rays in a 2 minute window

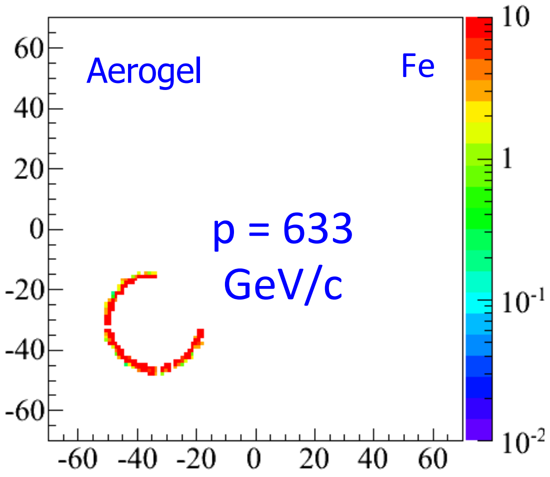
Lead by: R. Battiston, G. Ambrosi, B. Bertucci

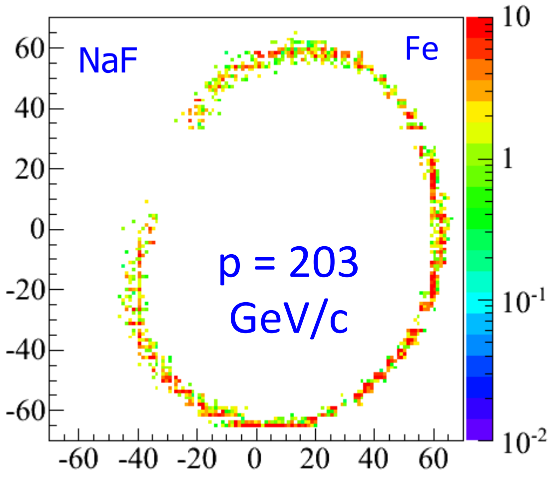
Ring Imaging Cherenkov

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





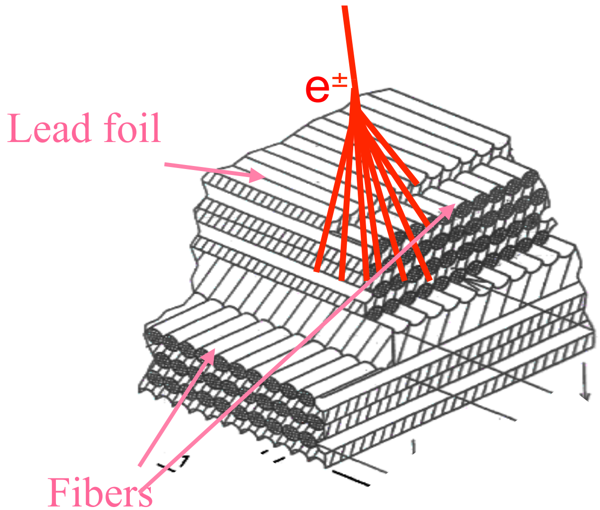


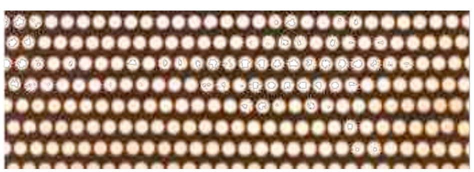


Lead by: J. Berdugo, G. Laurenti

Electromagnetic Calorimeter

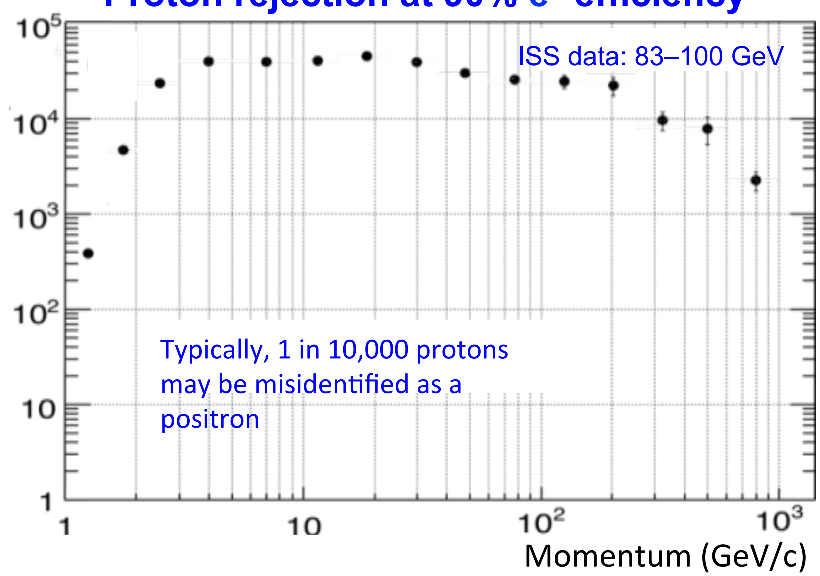
provides a precision, 17 X_0, TeV, 3-dimensional measurement of the directions and energies of electrons and positrons





50 000 fibers, $\phi = 1$ mm distributed uniformly inside 600 Kg of lead

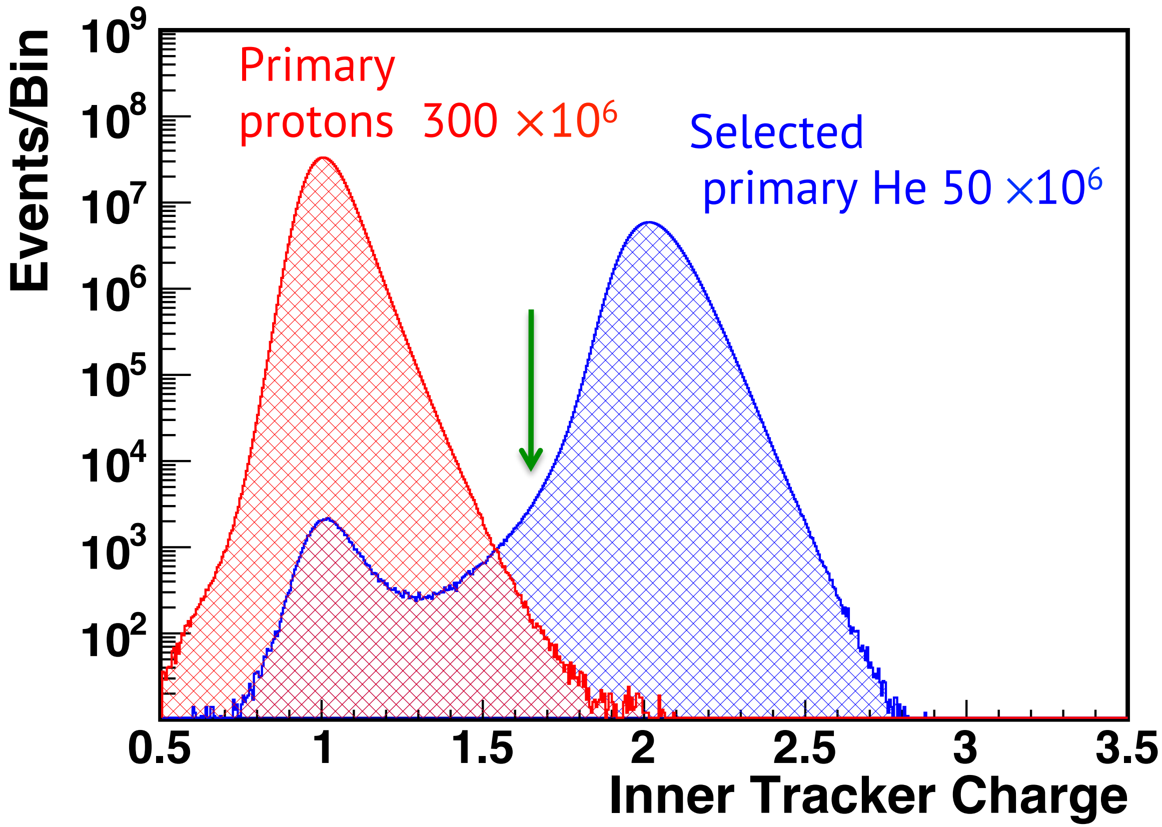
Proton rejection at 90% e^+ efficiency

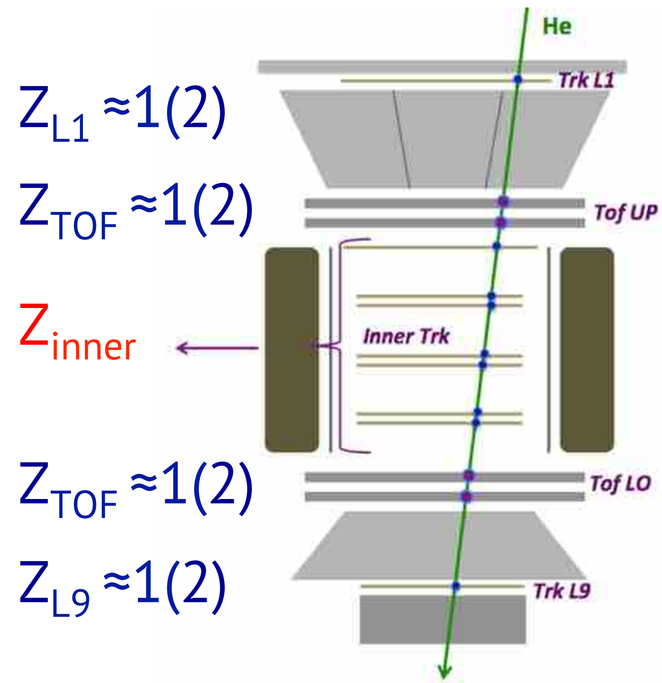


Lead by: F. Cervelli, S. Rosier-Lees, H.S. Chen

Proton / Helium selection

Tracker hits from L1 to L9 with $Z_{L1\text{-}L9} \approx 1(2)$, and $Z_{TOF} \approx 1(2)$





Flux Measurement

Assuming that the flux is isotropic,
the differential flux is defined as :

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

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

Rigidity:
1-1800 GV
2-3000 GV

Exposure Time:
$63 \cdot 10^6$ sec >30GV

ε_i: Trigger Efficiency

A_i: Effective Acceptance

ΔR_i: Bin width

Systematic Errors

Due to the high statistics of AMS, studies of the systematic errors are important:

- Background contributions — very small in AMS
- Trigger efficiency uncertainty — typically ≤ 1%
- Acceptance uncertainties — 1-2 % for all rigidities
  - Interaction cross-sections
  - Data/MC correction
- Unfolding uncertainties — at high rigidities ~3%
  - Unfolding method
  - Rigidity resolution function
- Rigidity scale uncertainty — at high rigidities 2-3%

Exposure Time

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