protons and helium in cosmic rays
results from AMS

Nicola Tomassetti
LPSC/CNRS – Grenoble, France
on behalf of the AMS Collaboration

LPSC Grenoble
Laboratoire de Physique
Subatomique et de Cosmologie

Solar Energetic Particles, Solar Modulation and Space Radiation
New Opportunities in the AMS-02 Era
October 18 - 23, 2015 – Honolulu, Hawaii, USA

The AMS Project

Particle physics detector for high precision CR measurements at TeV energy

Physics goals

- ✓ Antimatter search (|Z|>1 anti-nuclei)
- ✓ Dark Matter (light anti-matter & γ-rays)
- ✓ Exotic signals?
- ✓ **GCR astrophysics** & γ-rays
- ✓ **Heliophysics (long-term modulation & SEP)**
- ✓ Magnetospheric physics & space radiation studies

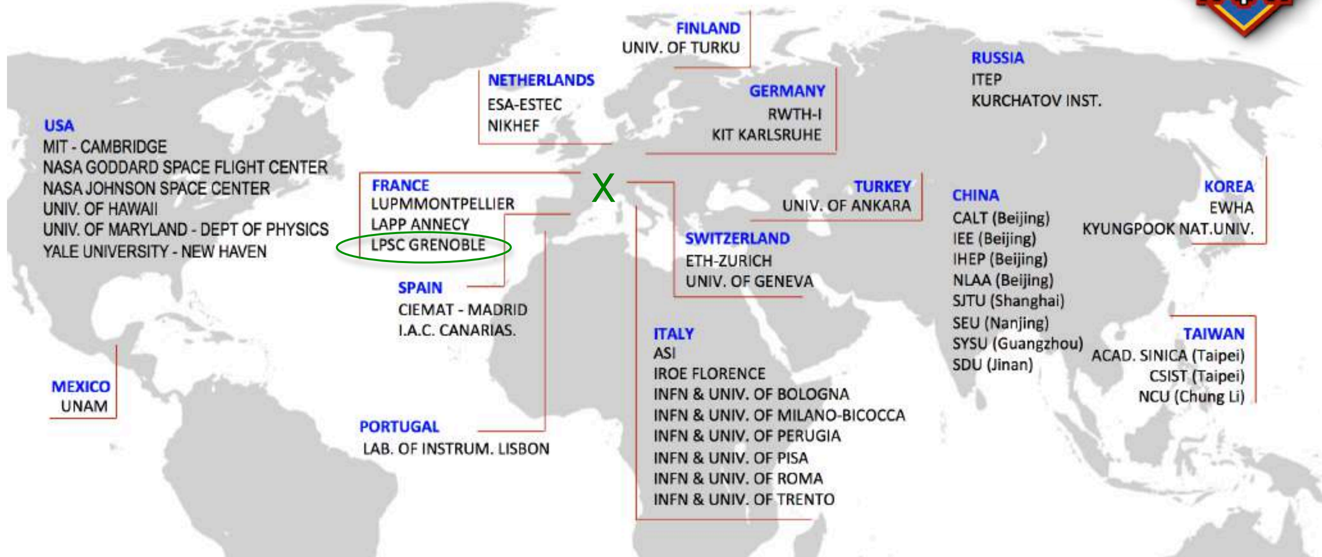
How it will fulfill these goals?

- **Large collaboration: 16 Countries, 60 Institutes and ~500+ Physicists**
- **Same concept (precision & capability) as the large state-of-the-art HEP detectors [but: fitting into the space shuttle & no human intervention after installation]**
- **Operation in space, ISS, at 400km, no backgrounds from atmospheric interactions [extensive multi-step space qualification tests]**
- **Collection power: geometrical factor (≈ 0.5 m2sr) X exposure time (= ISS lifetime) [extensive calibration campaigns on ground]**

The AMS Project

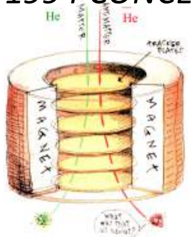
AMS Collaboration

- *16 countries*
- *60 institutes*
- *500+ physicists*
- *20 years*



Project timeline

1994 CONCEPT

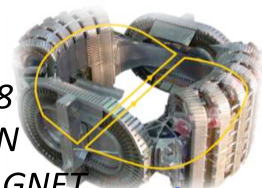


1997 AMS-01 PROTOTYPE

1998: STS-91

2000 @CERN AMS-02 CONSTRUCTION

2008 @CERN SC MAGNET BEAM TEST



2010 TVT @ ESA (NL)

2010 @CERN SC -> PM NEW BEAM TEST

2011 @KSC INTEGRATION & CR-μ RUN

MAY 2011 STS-134 FLIGHT

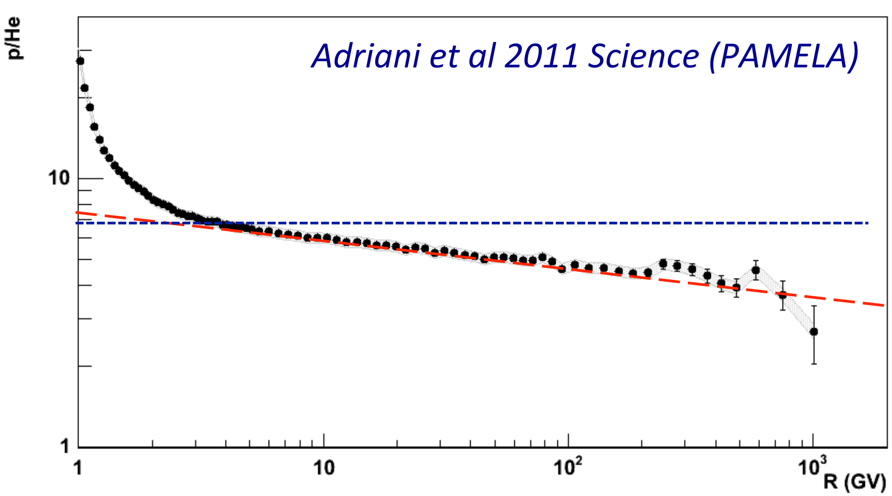
ON THE ISS

→ Steadily taking data on the ISS since May 19th 2011

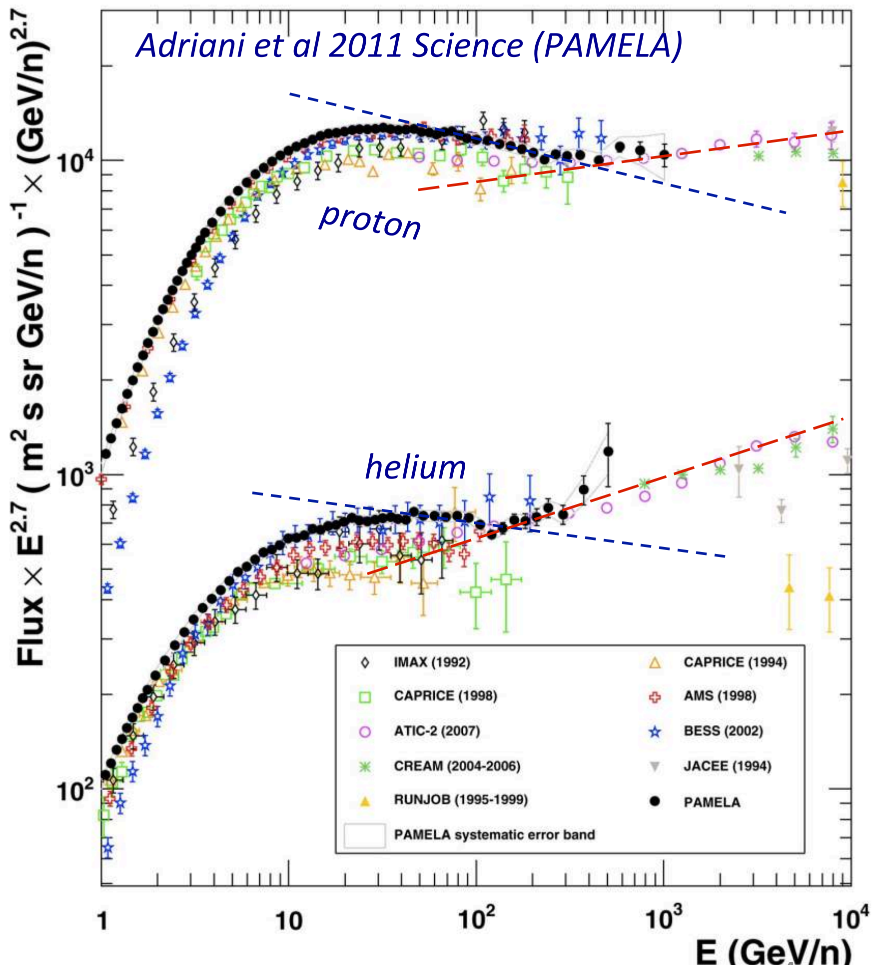
Cosmic-Ray Hadron Fluxes: a key science case

Proton and Helium spectra at high energies are revealing interesting spectral features that may offer a clue to the origin of the observed cosmic rays

- ***High-energy Hardening**: multi-TeV energy spectra are harder than those at GeV-TeV*
- ***p/He anomaly**: Helium energy spectrum seems harder than that of the Hydrogen.*
- **Sharp break? Sharp transition located at 300 GV, as reported by PAMELA in 2011.**



"These data challenge the current paradigm of cosmic-ray acceleration in supernova remnants followed by diffusive propagation in the Galaxy".



Spectral features in H and He

Basic predictions (E~ 10 GeV – 100 TeV)

Based on many simplifying (and unjustified) assumptions: homogenity, isotropy, stationarity, linearity…

- ***DSA@SNRs: power-law (α~ 2.0 – 2.2)*** $Q(E) \approx E^{-\nu}$
- ***QLT: power-law diffusivity (δ~ 0.3 - 0.6)*** $K(E) \approx E^{\delta}$
- ***Equilibrium spectra (E>>GeV)*** $\phi(E) \sim Q/K \approx E^{-(\nu+\delta)}$

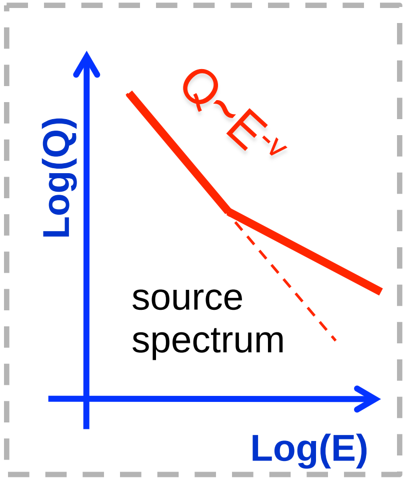
Deviations from power-law are unexplained by standard models of DSA acceleration and CR transport.

1) Intrinsic acceleration effects
- *Non-linear DSA*
- *Mach number time-evolution*

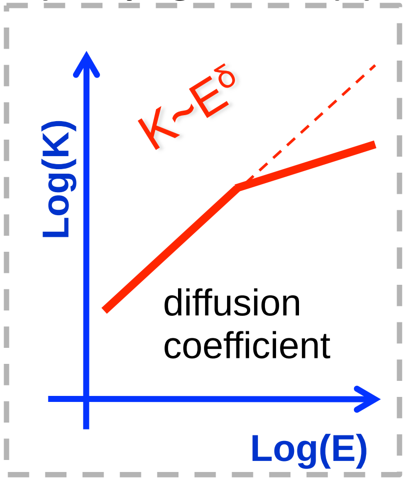
2) Propagation effects
- *Transport in CR-induced turbulence*
- *Inhomogeneus diffusion coefficient*

3) Multi-component nature of CR flux
- *Local SNR + Galactic ensemble*
- *Reaccelerated CRs in weak shocks*

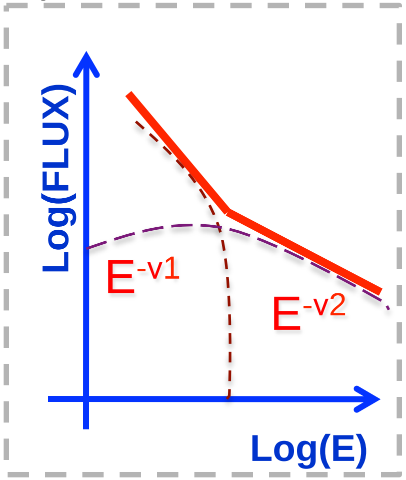
1) Acceleration, Q(E)



2) Propagation, K(E)



3) Multi-sources



p/He ratio: violation of universality in CR acceleration?

- *Particle-dependent injection*
- *Non-uniform He distribution*
- *Non-DSA acceleration in*
- *Strong unaccounted spallation*
- *….*

Flux Measurement

Differential flux (m^{-2} sr^{-1} s^{-1} GV^{-1})

$$\Phi(R) = \frac{N(R, R+\Delta R)}{\varepsilon_{Trig}(R) \times A_{Tot}(R) \times T(R) \times \Delta R}$$

R = p/Z, rigidity; important in magnetic spectrometers & CR astrophysics
N = *Number* of selected protons (helium) events in R,R+ΔR
T = Effective *exposure time* above geomagnetic cut-off (s)
A_{Tot} = Total *acceptance* (m^2 sr) including geom factor + efficiencies
ε_{Trig} = Trigger efficiency

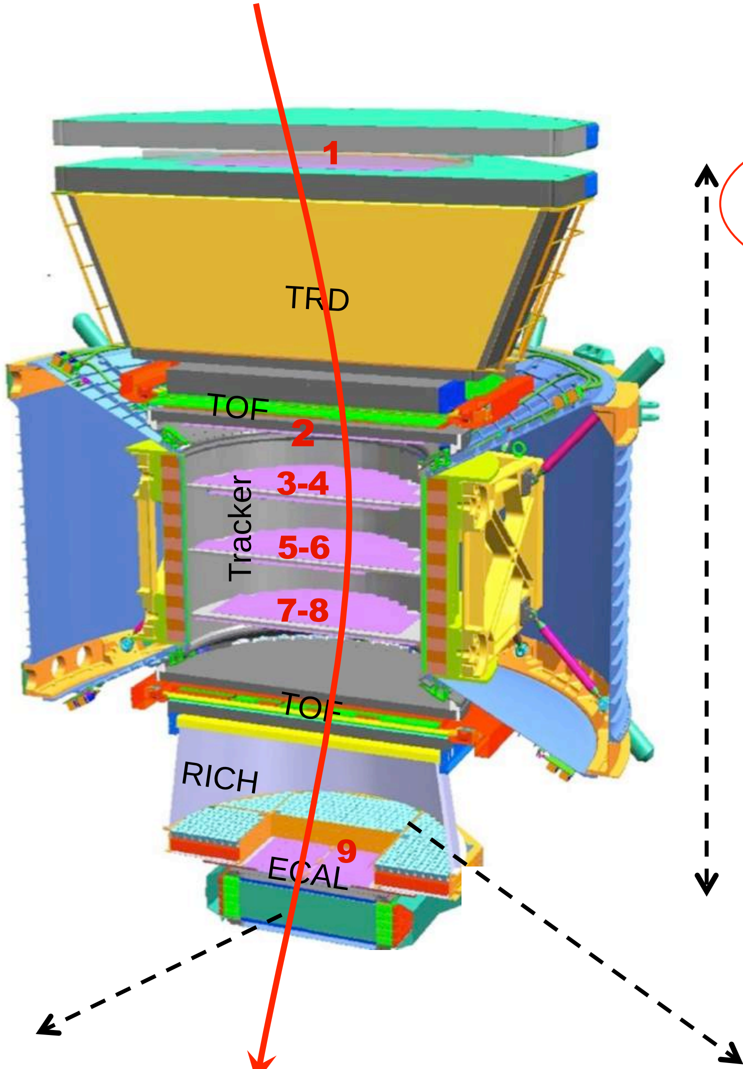
DATA/MC check

- Compute efficiencies
- Interaction studies

SPECTRAL UNFOLDING

- Resolution modeling
- Deconvolution algorithm

Multiple measurements of energy



Tracker, R = p/Z
MDR ≈ 2TV (p); 3TV (He)

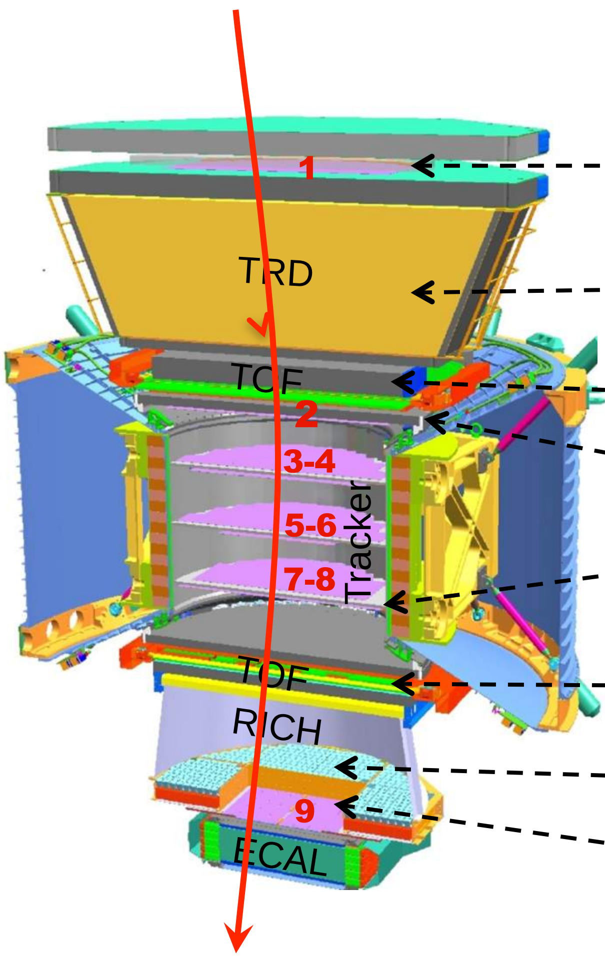
***TOF**, β*
Δβ/β ≈ 1%

ECAL, E
ΔE/E (TeV e±) ~ 2 %
ΔE/E (TeV p) ~ 50 %

***RICH**, β*
Δβ/β ≈ 0.05%

Geomagnetic cutoff, R
ΔR/R ≈ 10% up ~25 GV

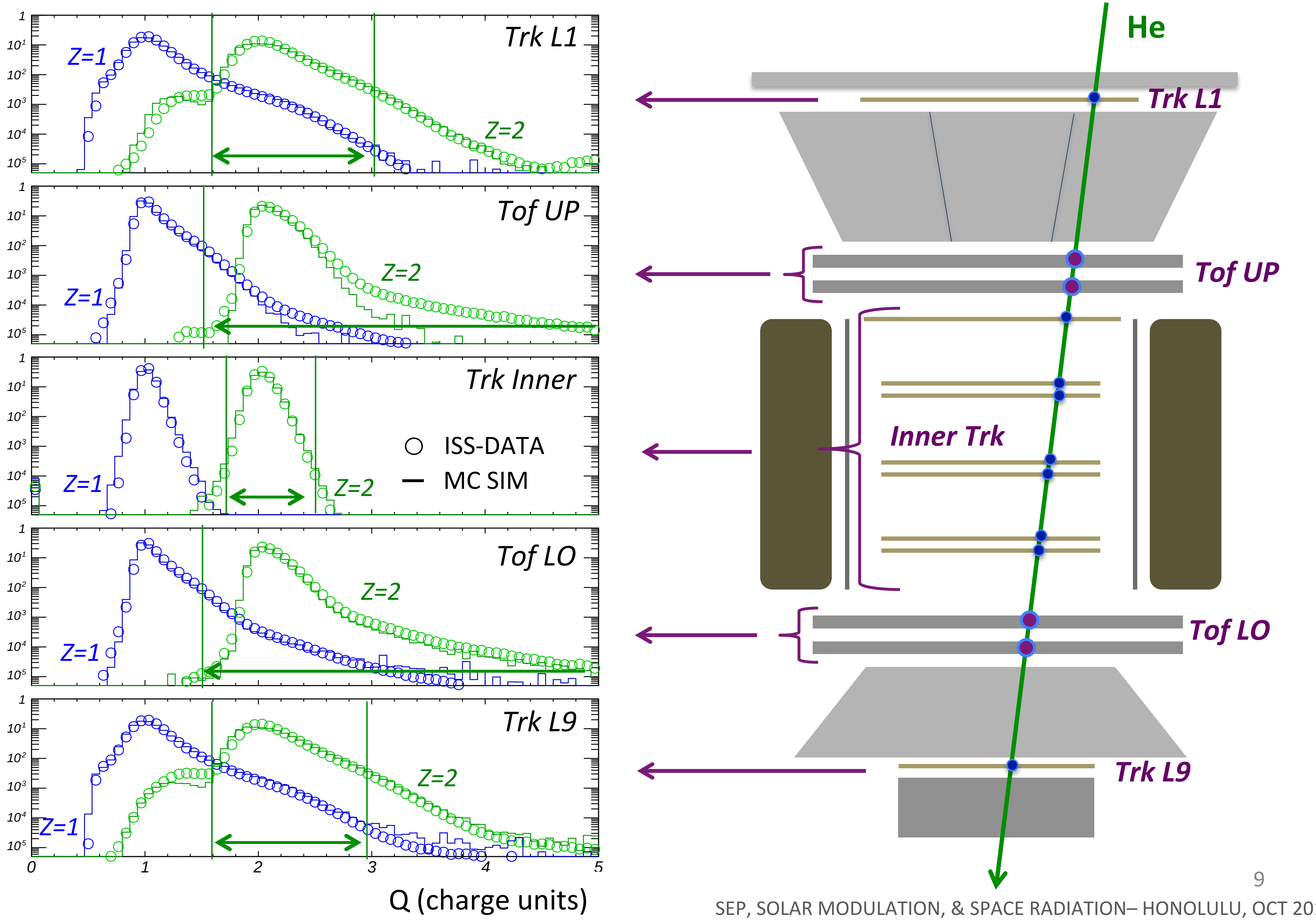
Multiple measurements of charge



	ΔZ
Tracker Plane 1 (L1)	*0.25*
TRD	*0.30*
Upper TOF (1 counter)	*0.15*
Inner Tracker (L2-L8)	*0.10*
Lower TOF (1 counter)	*0.15*
RICH	*0.30*
Tracker Plane 9 (L9)	*0.25*

Selection of Proton and Helium signals

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



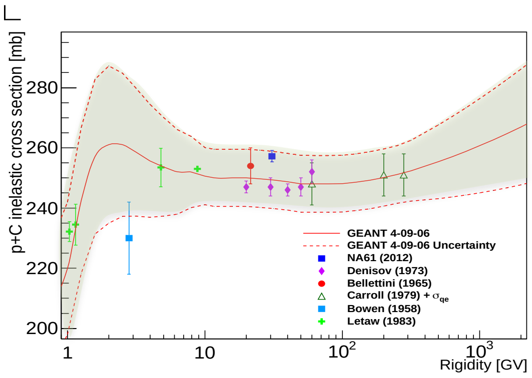
Acceptance

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

- ✓ Based on our MC simulation program.
- ✓ Detector response, signal digitization, and full analysis chain simulated.
- ✓ Data/MC corrections and several data-driven crosschecks performed.
- ✓ Role of interactions: flux attenuation in the detector material (C, Al)

Proton acceptance

Cross-sections for proton interactions off detector material (C, Al) known to few percent at 1 GV and 1.8 TV.

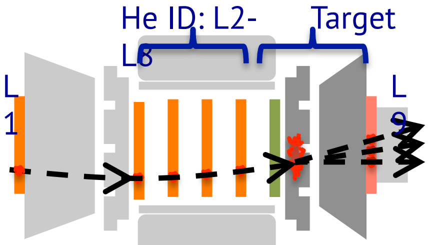


~0.6 – 1 % systematic errors at GV – 2 TV

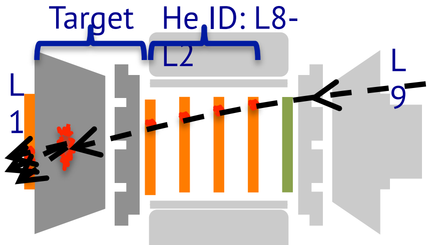
Helium acceptance

Helium collisions off C and Al: cross section data exist only below 10 GV

New method to determine interactions from ISS data with AMS pointing in horizontal direction



Survival prob. L8 → L9

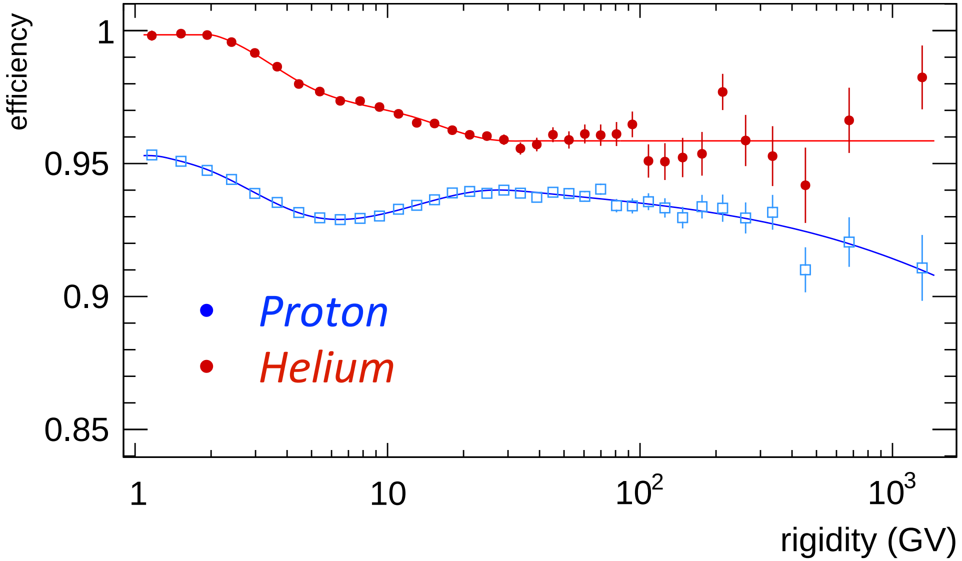


Survival prob. L2 → L1

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

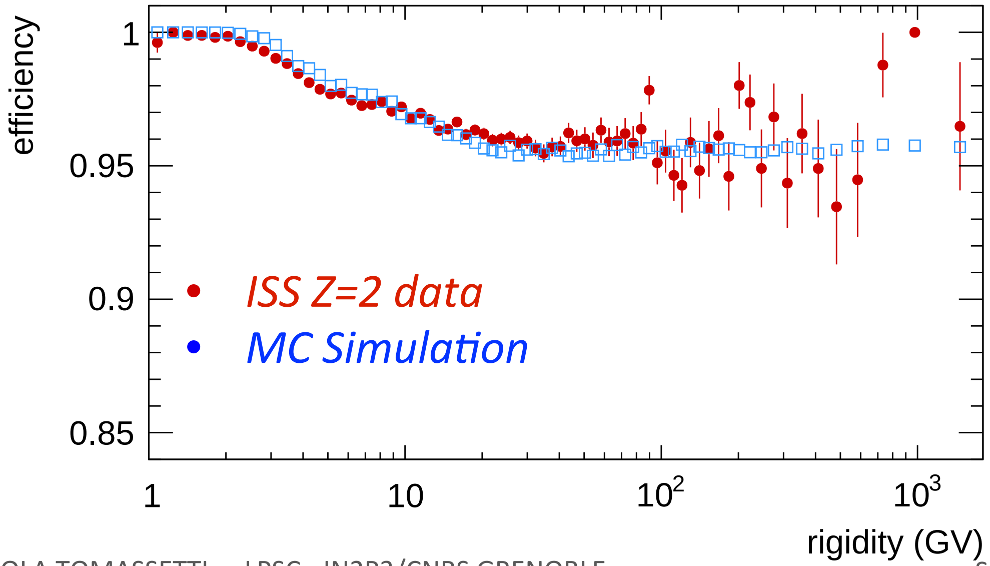
Trigger Efficiency

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



Trigger efficiency estimation can be done using flight data, thanks to a event sample collected with a dedicated minimum-bias trigger.

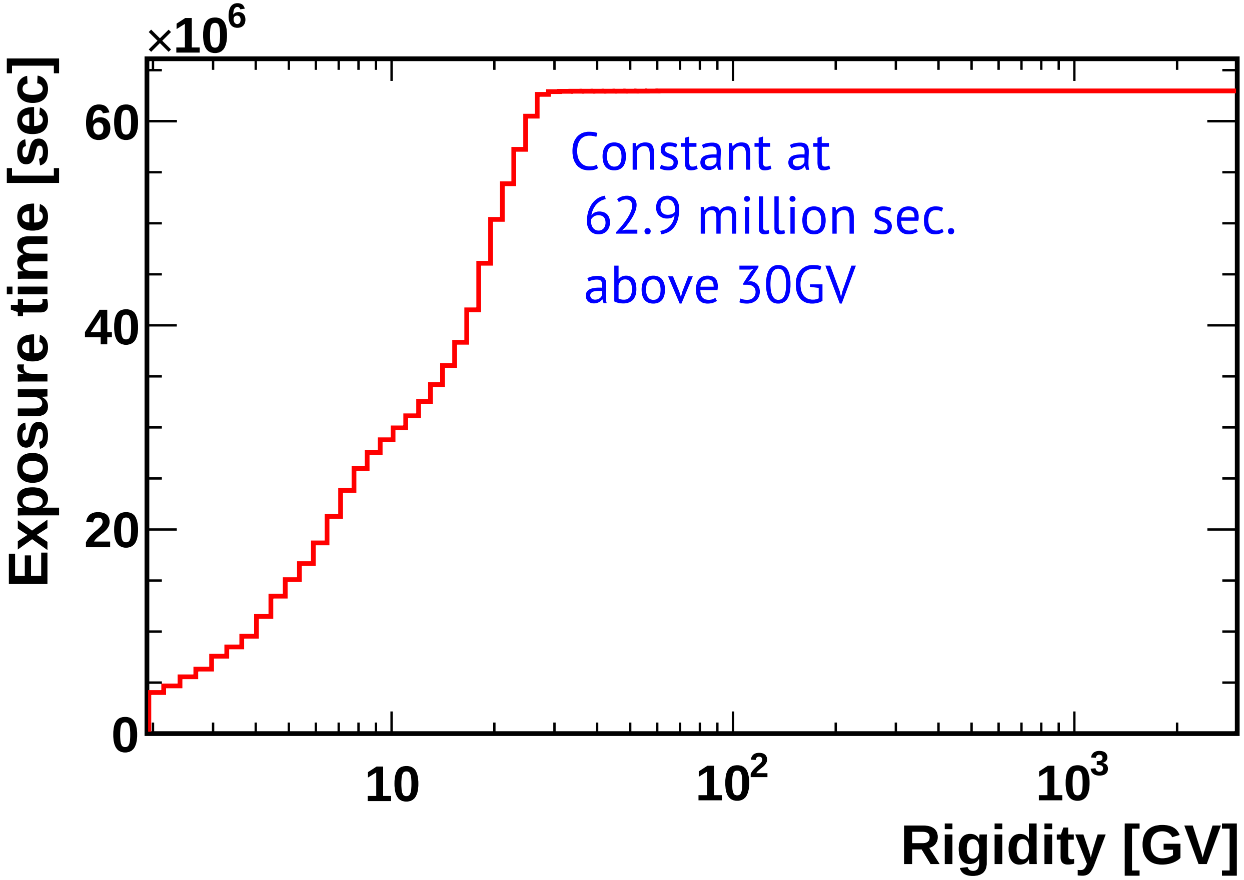
$$\varepsilon_{Trig} = \frac{N_{Phys}}{N_{Phys} + 100 \cdot N_{MinBias}}$$

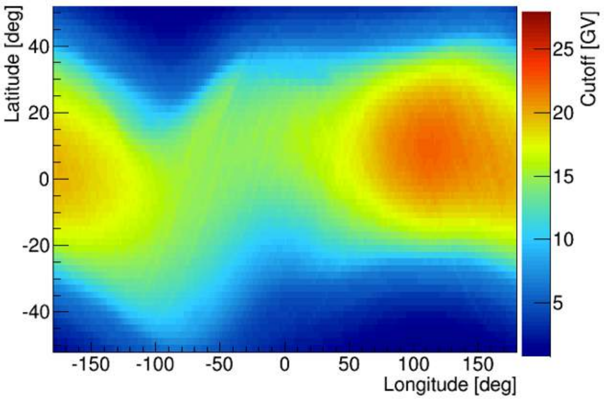


Exposure Time

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

Exposure time "above cutoff" is function of rigidity
It depends on the ISS orbit along the geomagnetic field

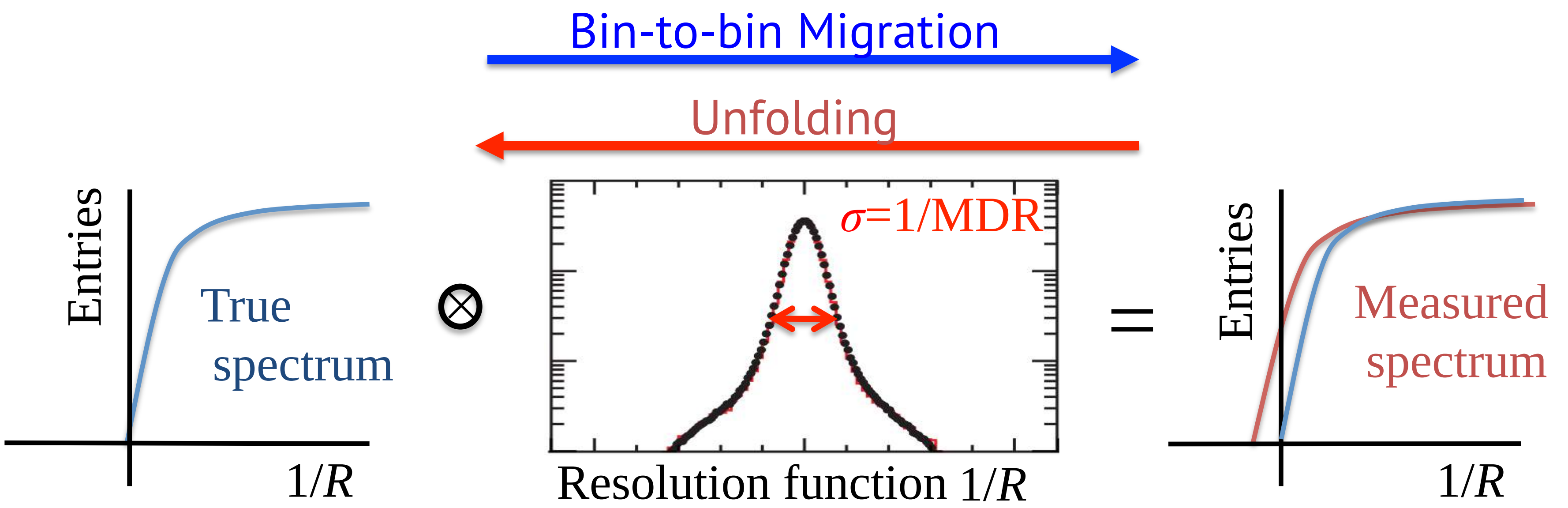




Unfolding

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

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

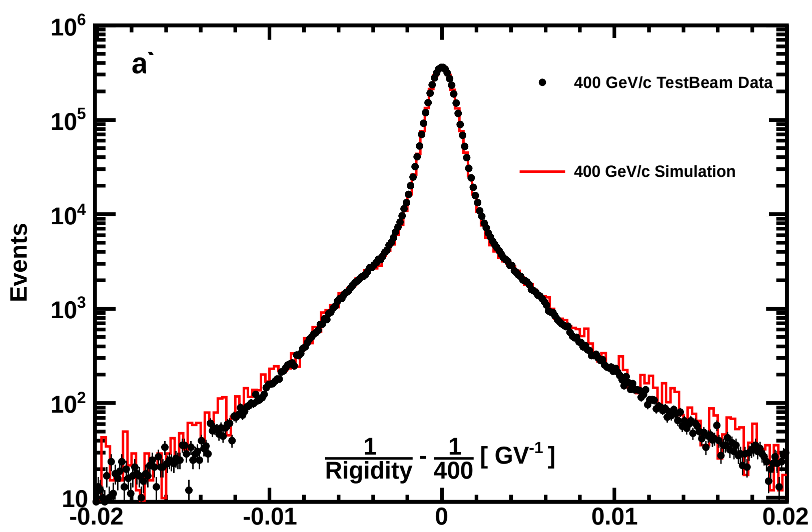


Difference between different unfolding algorithms gives a systematic error ~0.5%

Tracker resolution

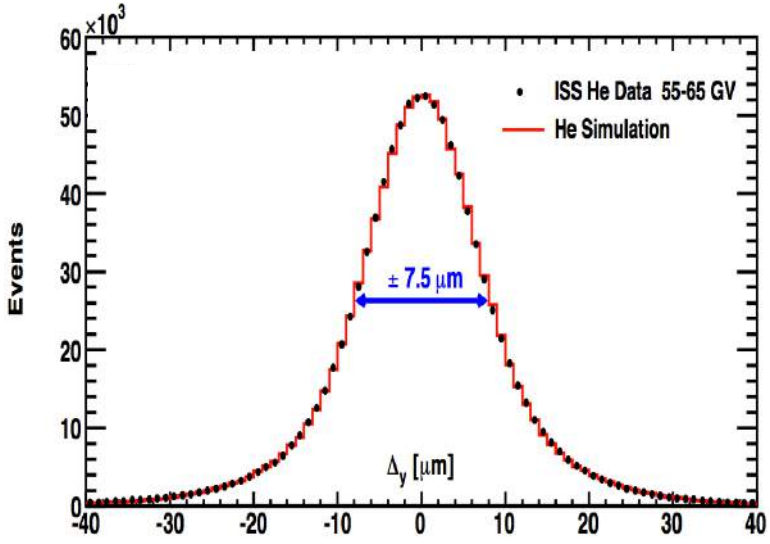
Protons:

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



Helium:

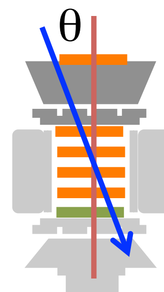
- Resolution function from MC simulation
- Verified with ISS data:
  - Tracker residuals
  - Rigidity reconstruction (L1-L8) vs. (L2-L9)

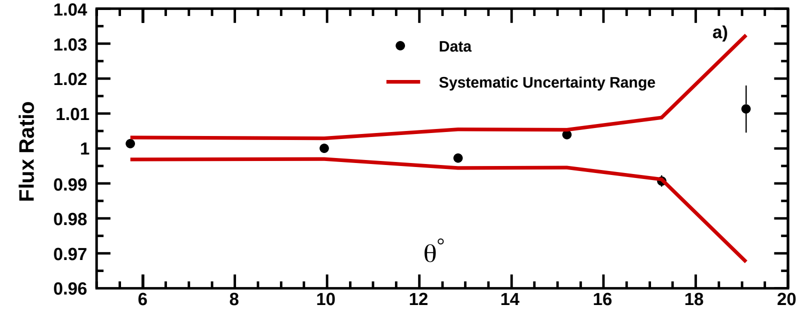


Uncertainty on the flux < 1% below 300 GV rising to 3% at 2 TV

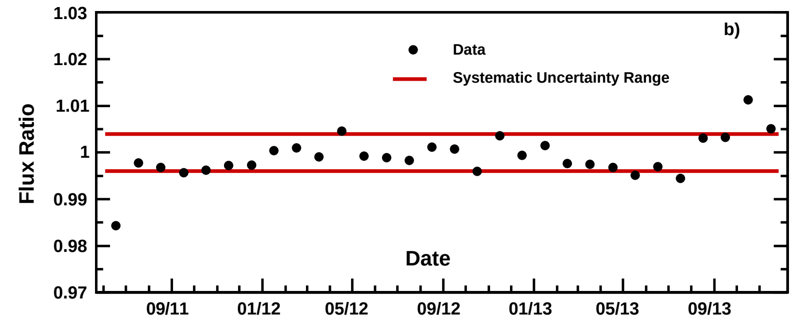
Verifications: Protons

Angular dependence of measured flux at R>45 GV: to verify the systematic error assigned to the **acceptance.**

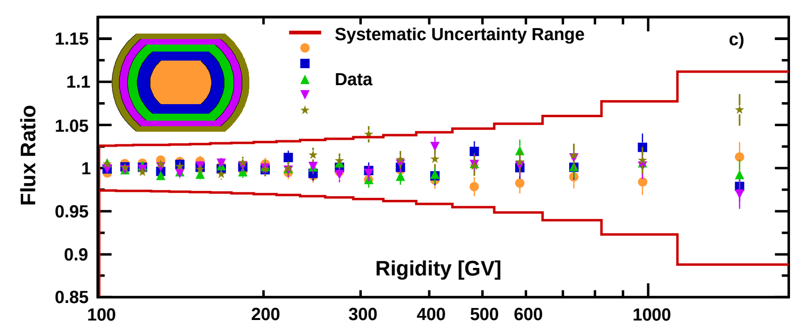




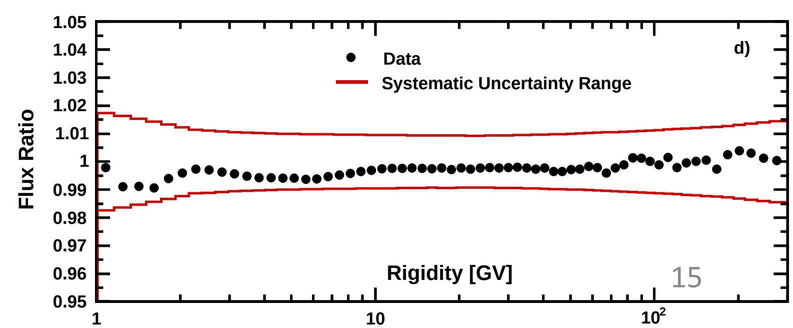
Time dependence of the high-energy flux: at R>45 GV no observable effects from solar modulation. This verifies that the **detector performance is stable**.



Flux reconstruction in different TOI entry regions of the acceptance. Verification of errors assigned to the tracker alignment.

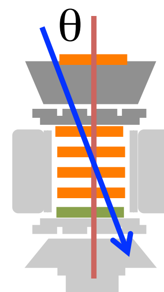


Measured flux using **inner tracker**, i.e., with a different resolution and MDR. This verifies the errors on **rigidity resolution function and unfolding procedure**



Verifications: Helium

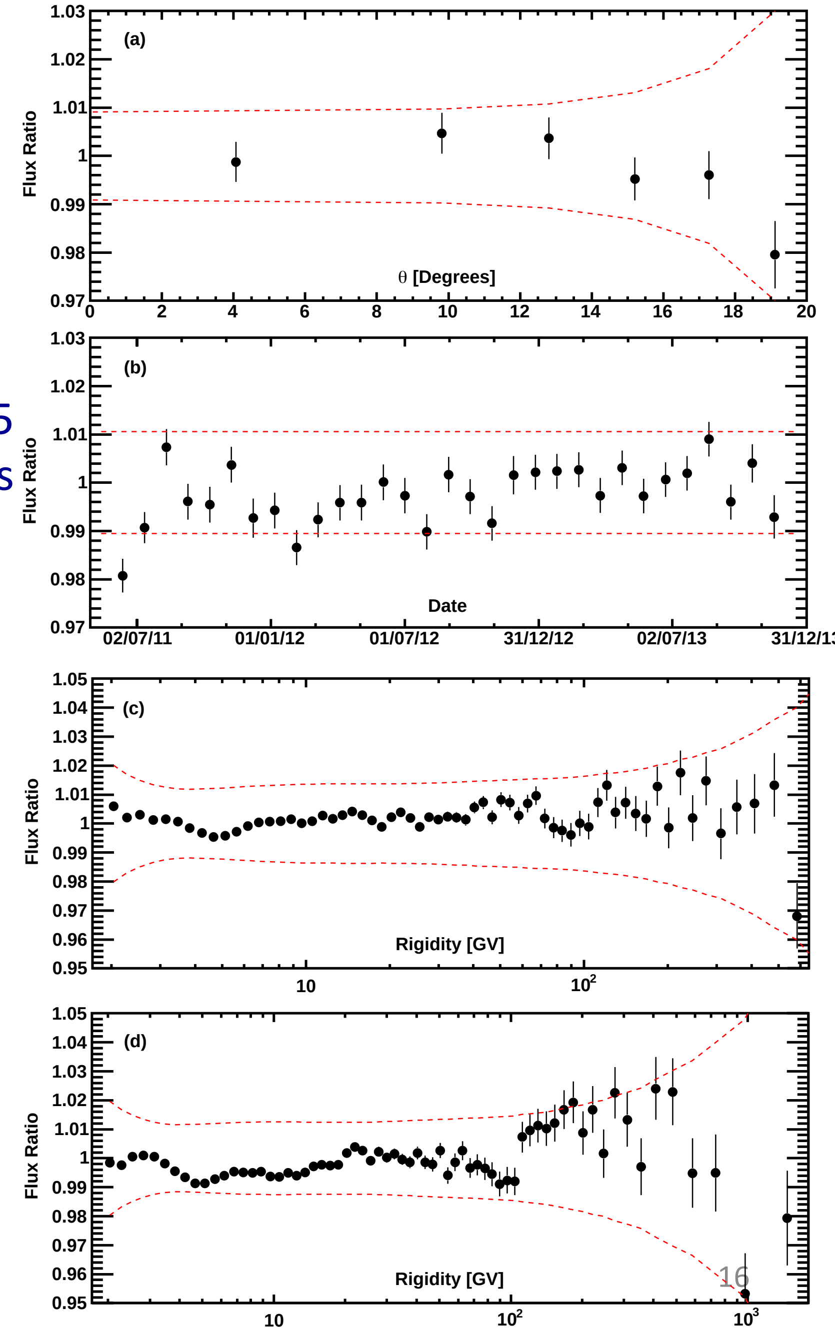
Angular dependence of measured flux at R>45 GV: to verify the systematic error assigned to the **acceptance.**



Time dependence of the high-energy flux: at R>45 GV no observable effects from solar modulation. This verifies that the **detector performance is stable**.

Measured flux using different tracker patterns (**inner-tracker+L1**) with a different resolution and MDR. This verifies the errors on **rigidity resolution function and unfolding procedure**

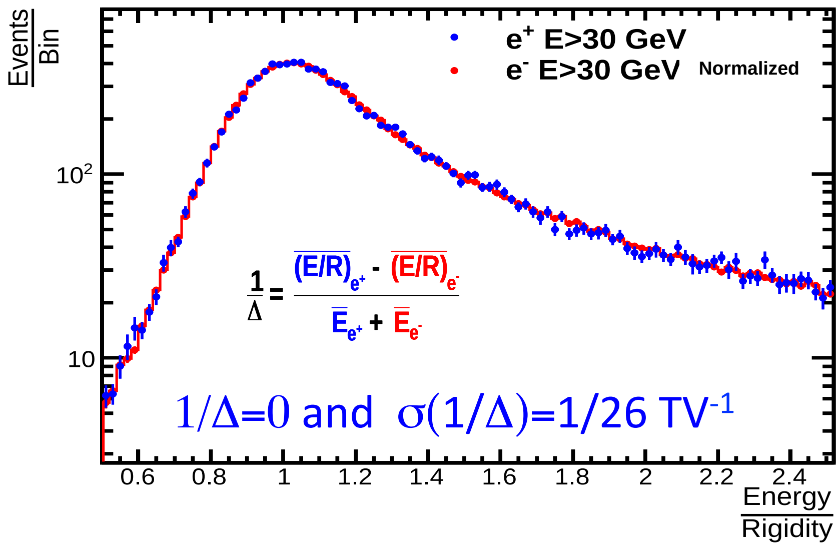
Measured flux using **inner tracker**, i.e., with a tracker pattern of different rigidity resolution and MDR. This verifies the errors on **rigidity resolution function and unfolding procedure**



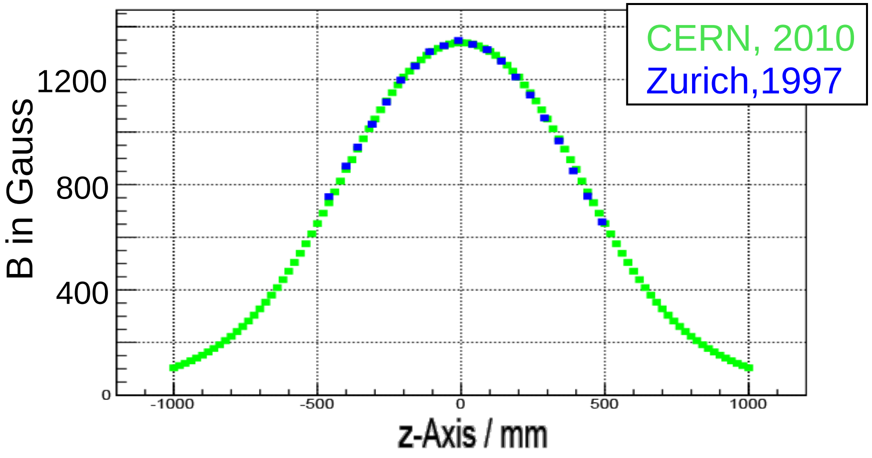
Absolute Rigidity Scale

<u>Two contributions to the uncertainty:</u>

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.
   Corresponding flux error: 2.5% @1 TV.

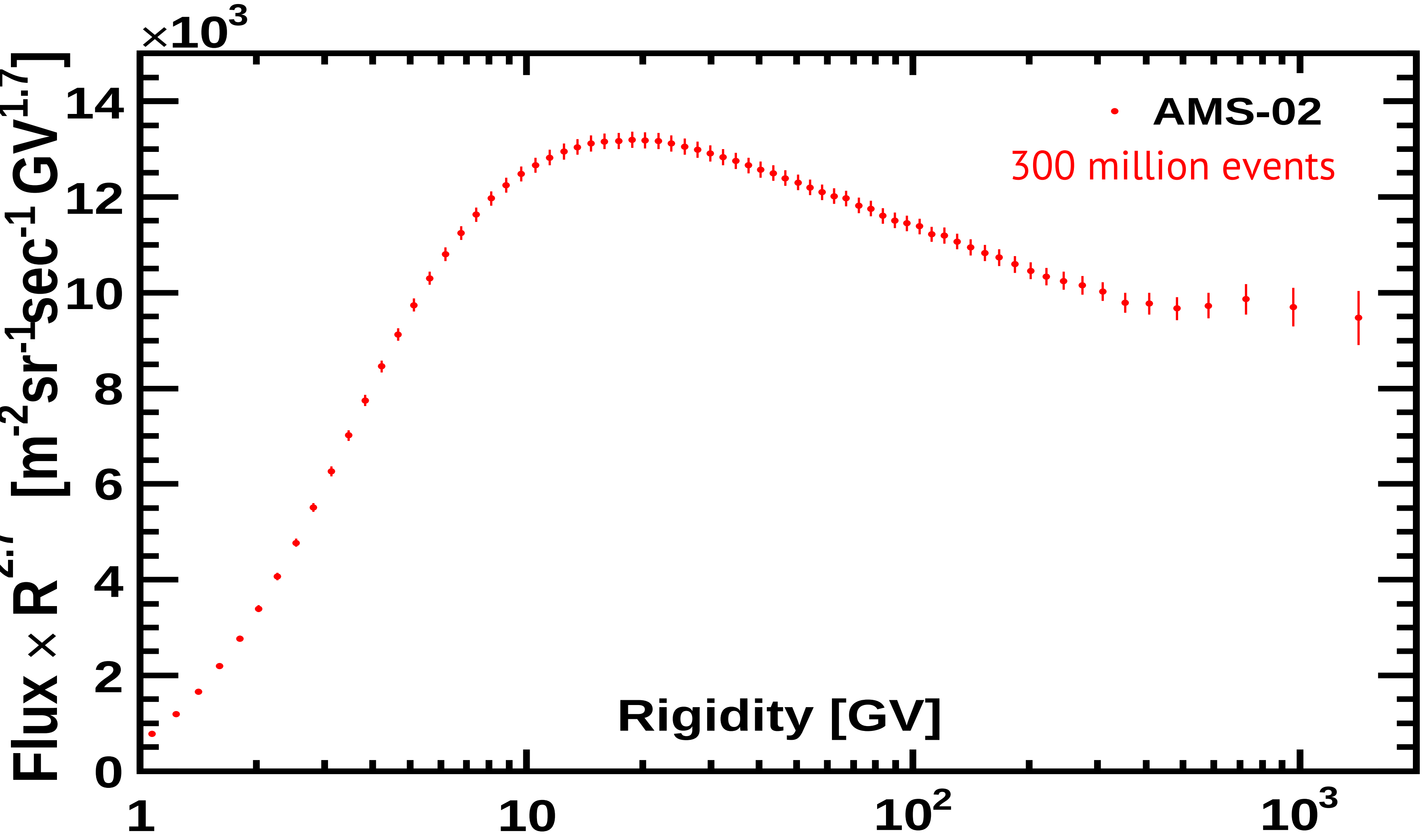


2. **Magnetic field:**
   Mapping measurement (0.25%) and temperature corrections (0.1%).
   Flux error: less than 0.5% at all rigidity

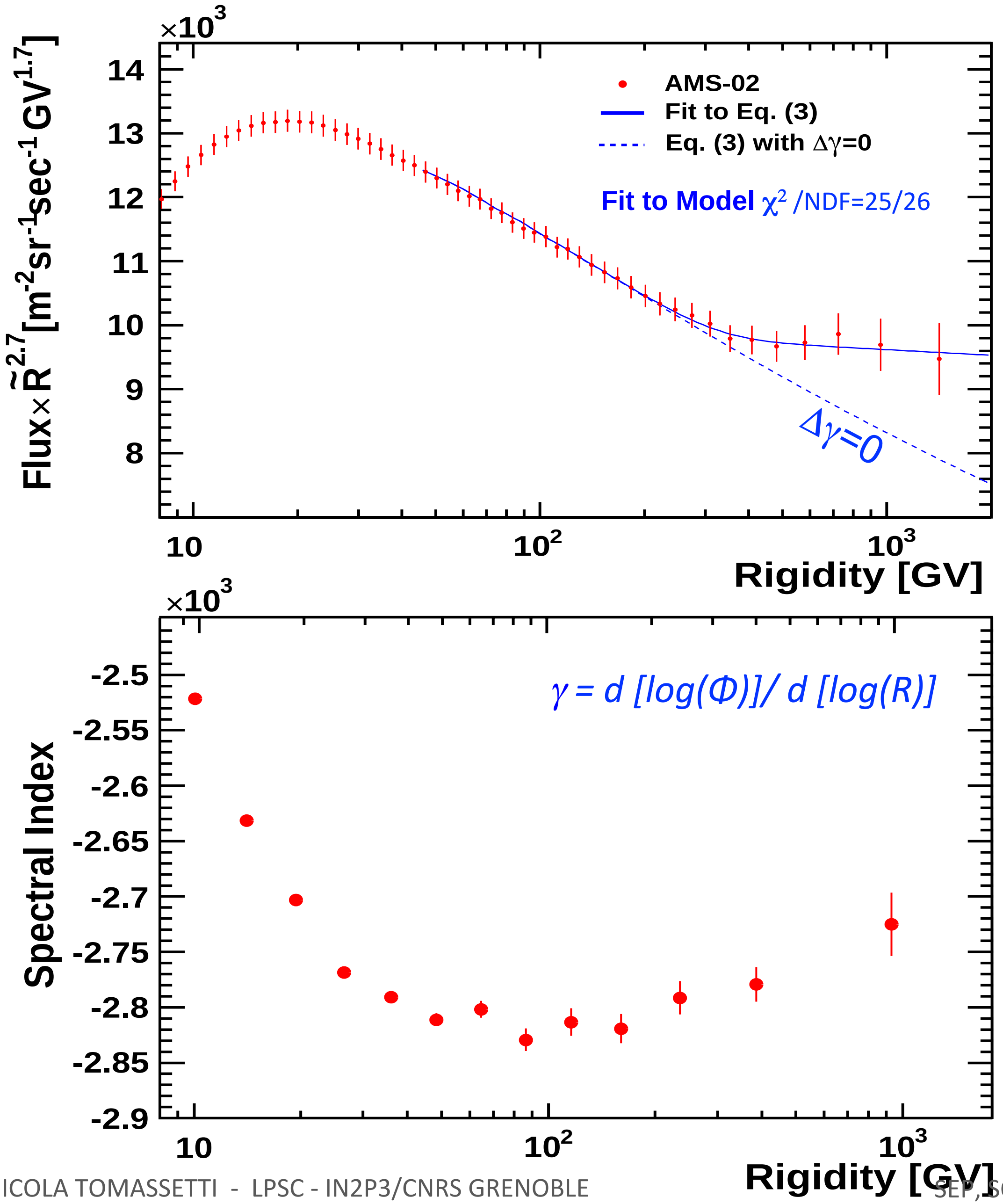


Proton Flux

Phys. Rev. Lett. 114, 171103



Proton Flux



The spectrum cannot be described by a single power-law function. We obtain a good description using a double power-law:

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

$\gamma = -2.849^{+0.002}_{-0.002}(\mathrm{fit})^{+0.004}_{-0.003}(\mathrm{sys})$ low-rigidity slope

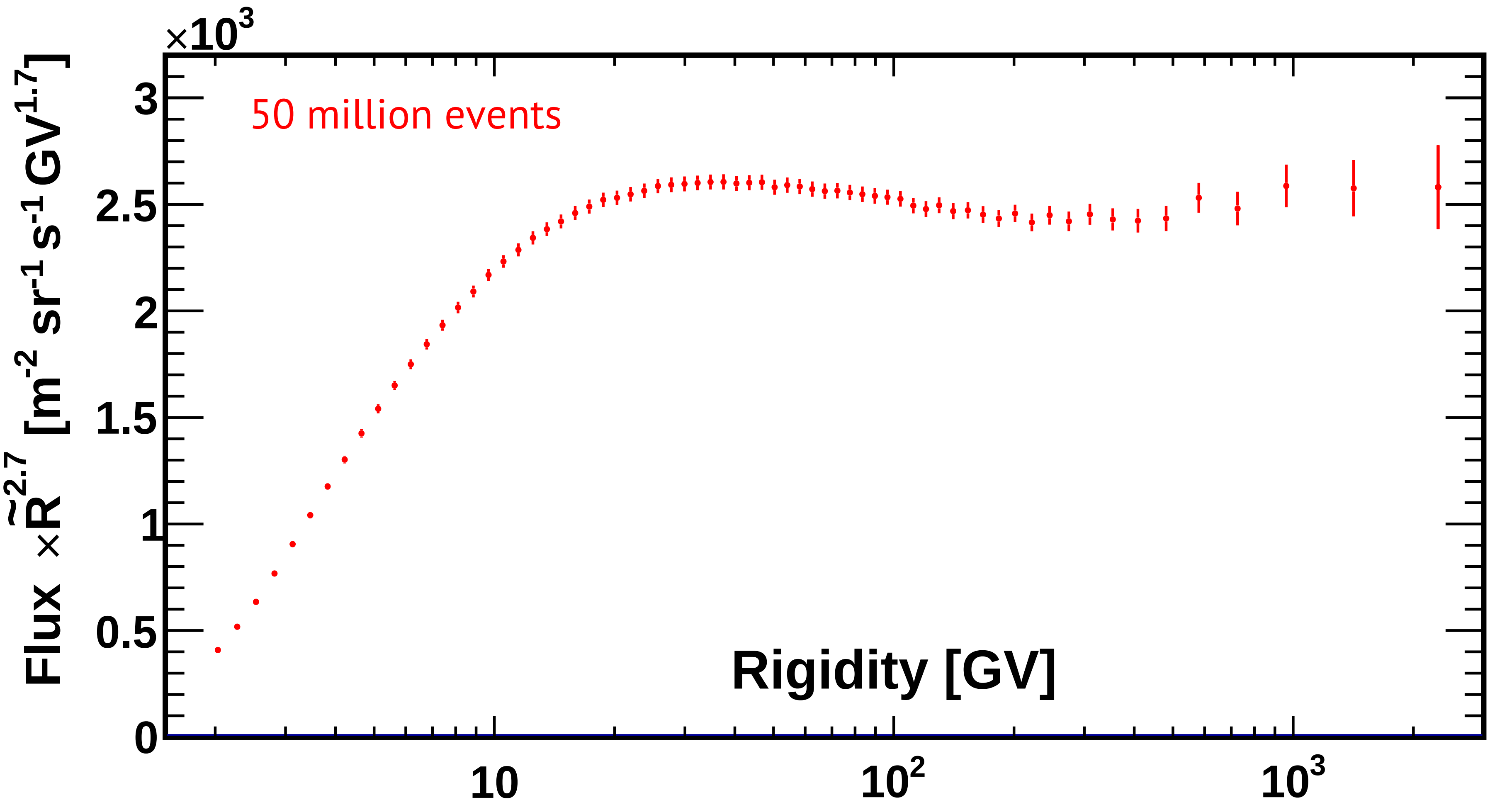
$\Delta\gamma = 0.133^{+0.032}_{-0.021}(\mathrm{fit})^{+0.046}_{-0.030}(\mathrm{sys})$ delta-slope

$R_0 = 336^{+68}_{-44}(\mathrm{fit})^{+66}_{-28}(\mathrm{sys})$ [GV] critical rigidity

The detailed variation of the high-energy flux can be characterized by measuring the log-slope. As shown, the proton flux experiences a progressive hardening above ~100 GV of rigidity.

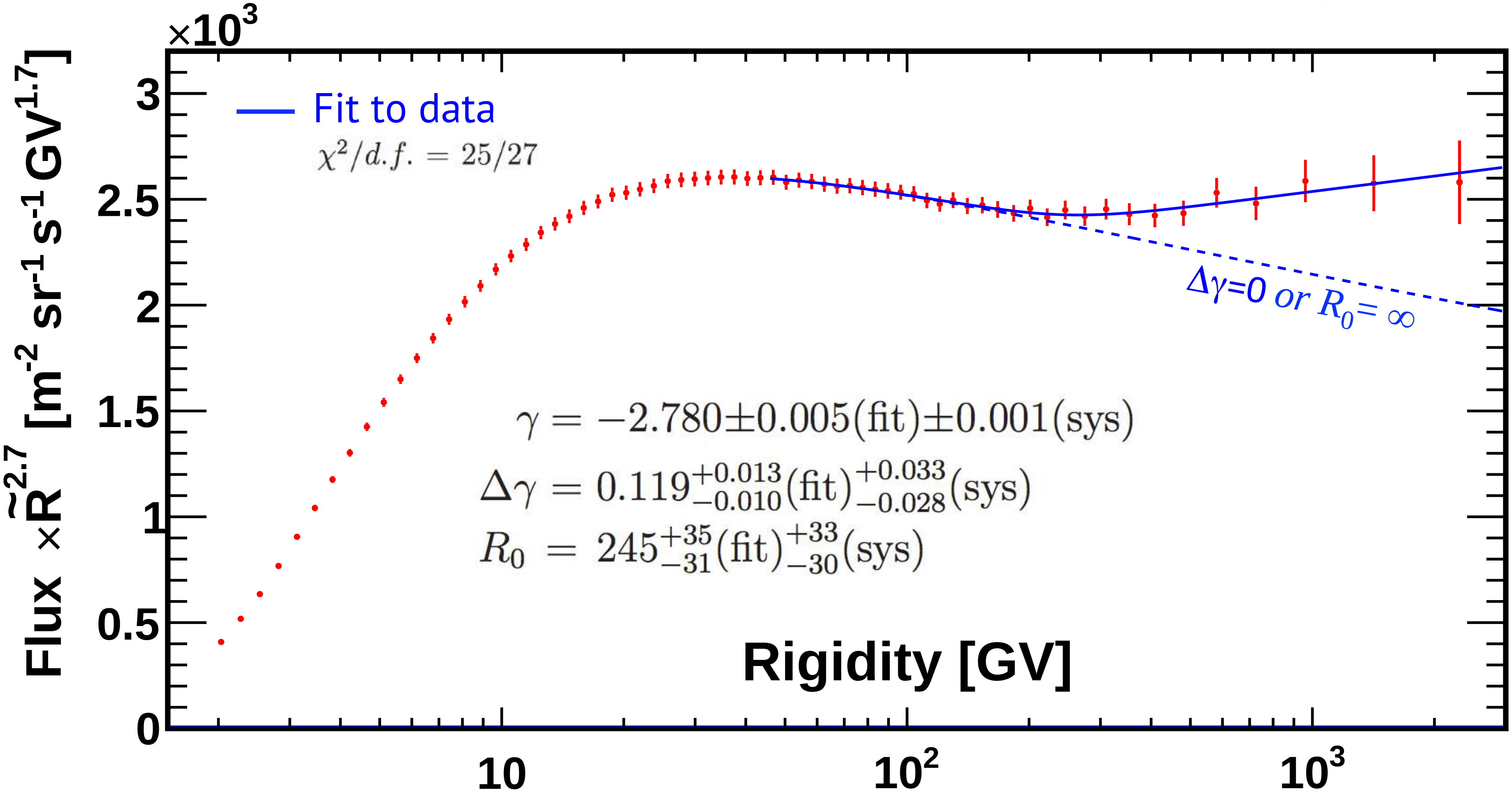
Helium Flux

to appear in PRL - November 2016 issue – Editors' suggestion

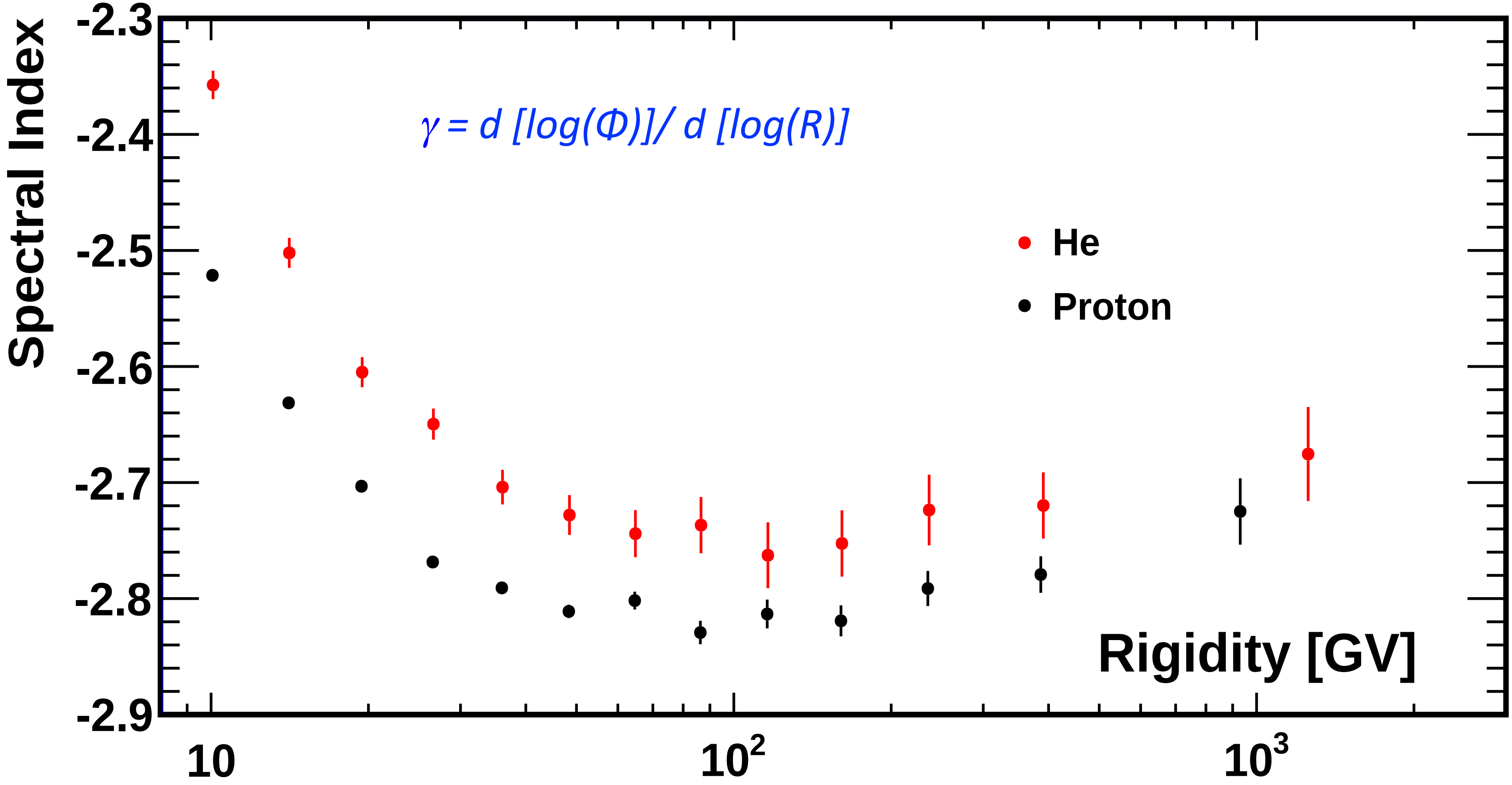


Helium Flux

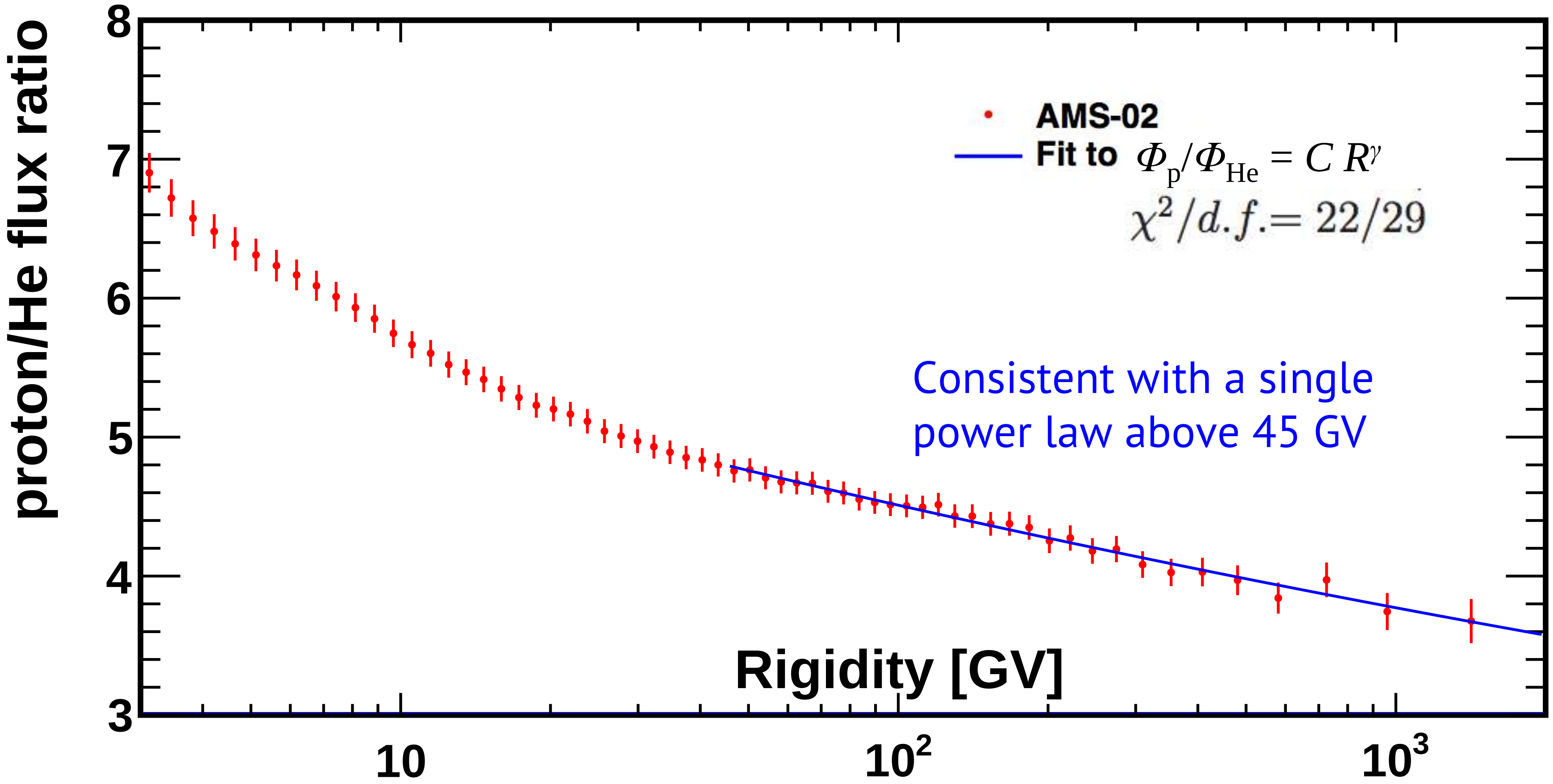
Double Power Law: $\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$



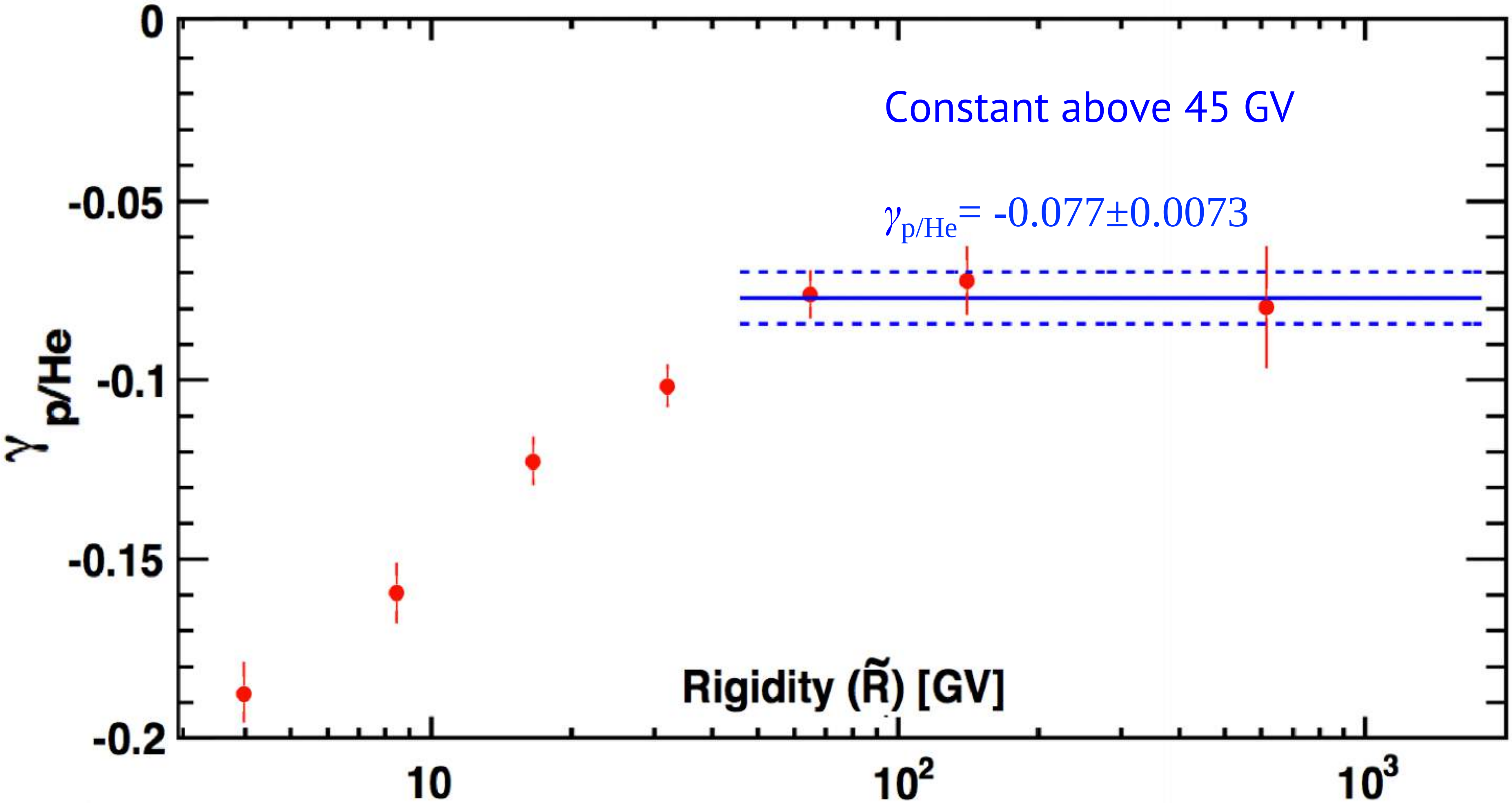
Helium Spectral Index



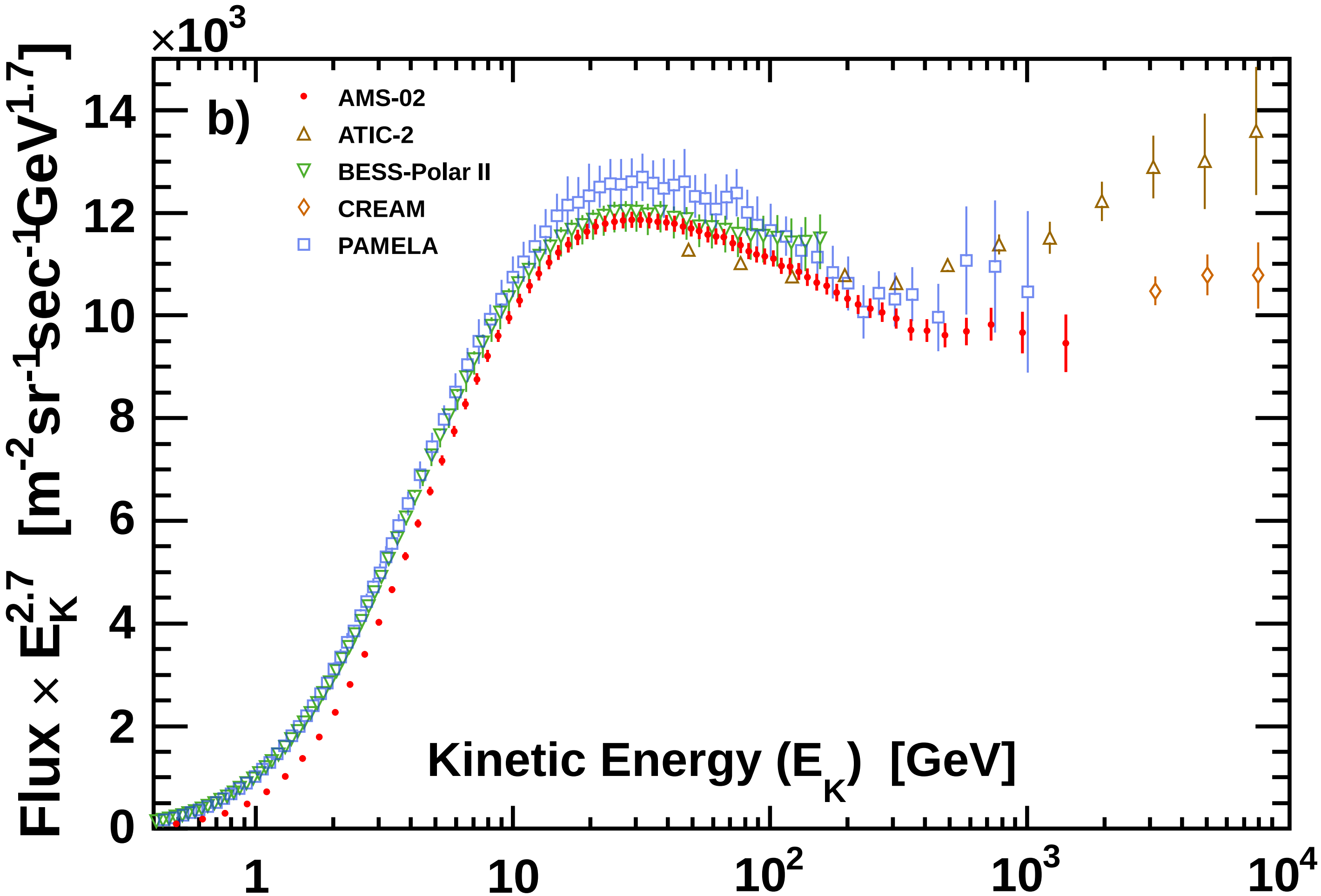
Proton/Helium Flux Ratio



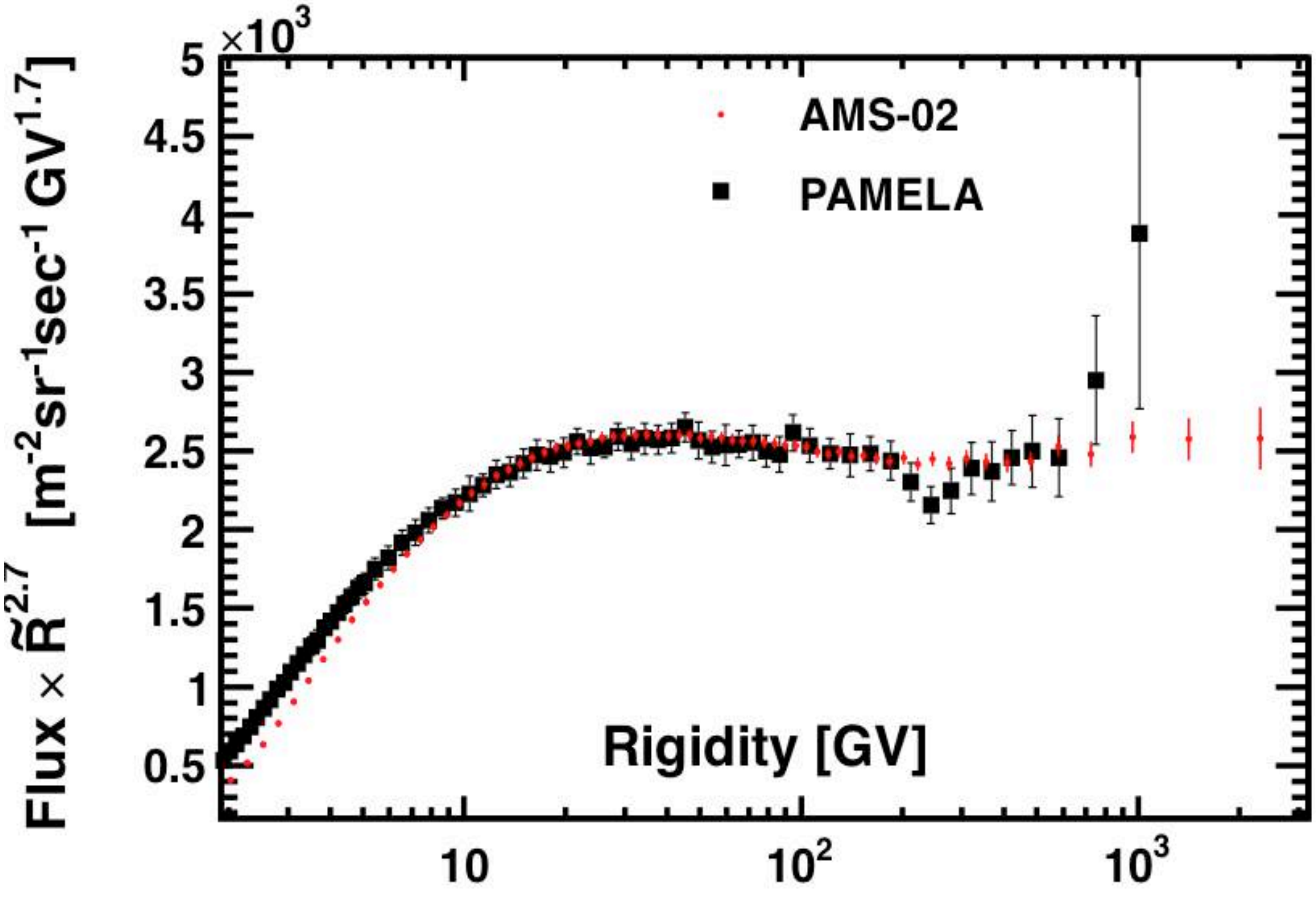
Proton/Helium Ratio Spectral Index



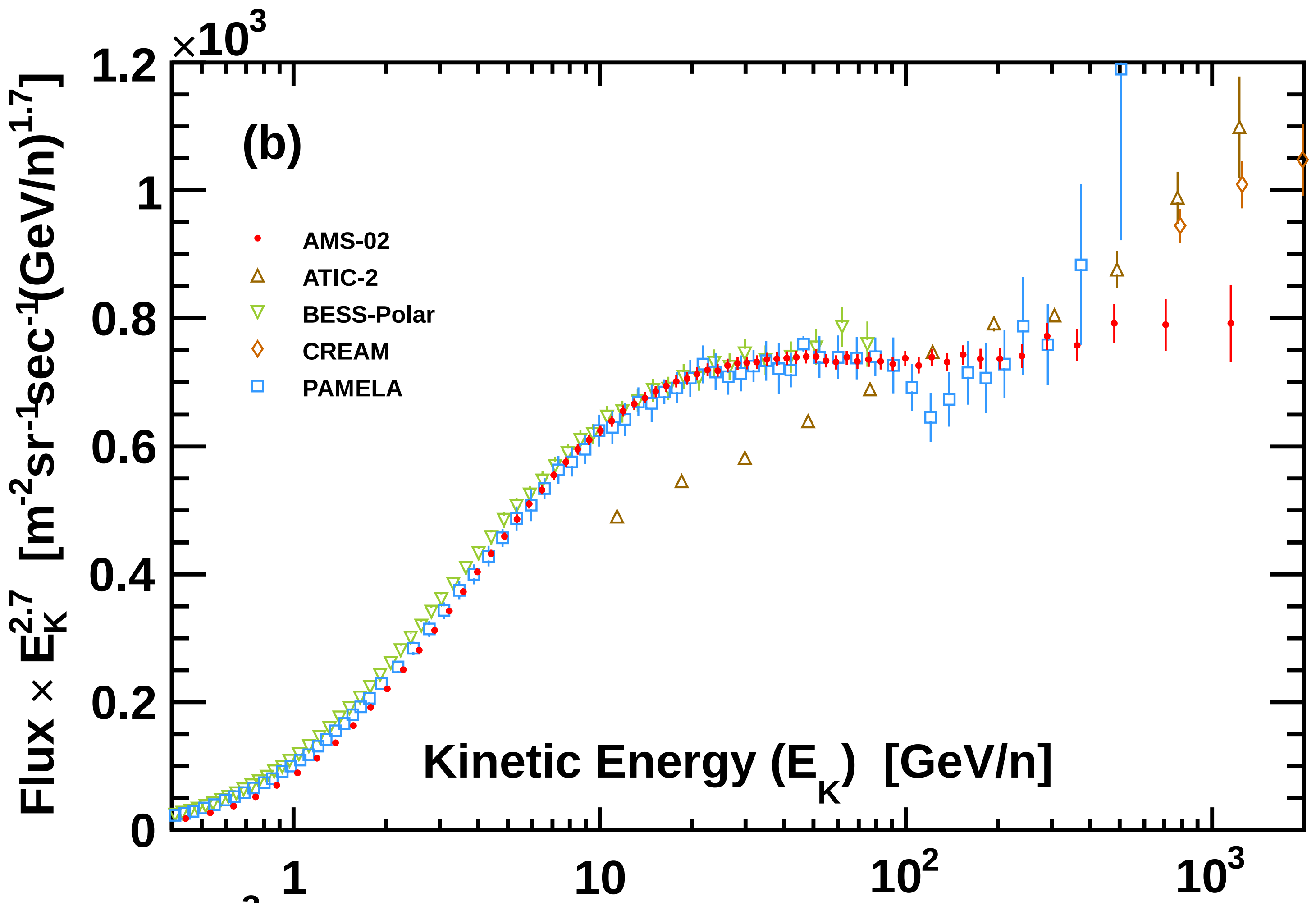
Proton Flux VS Kinetic energy



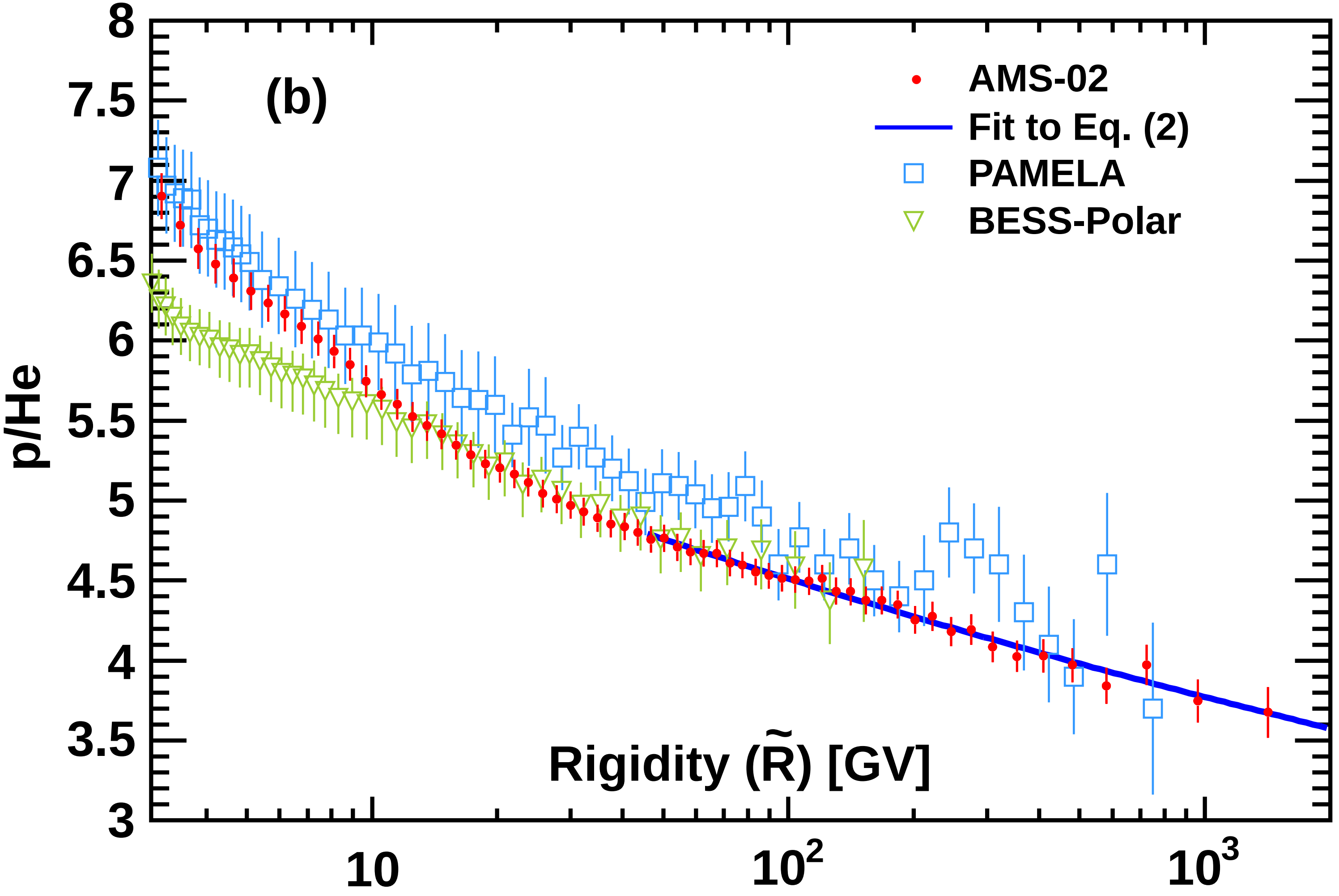
Helium Flux VS rigidity



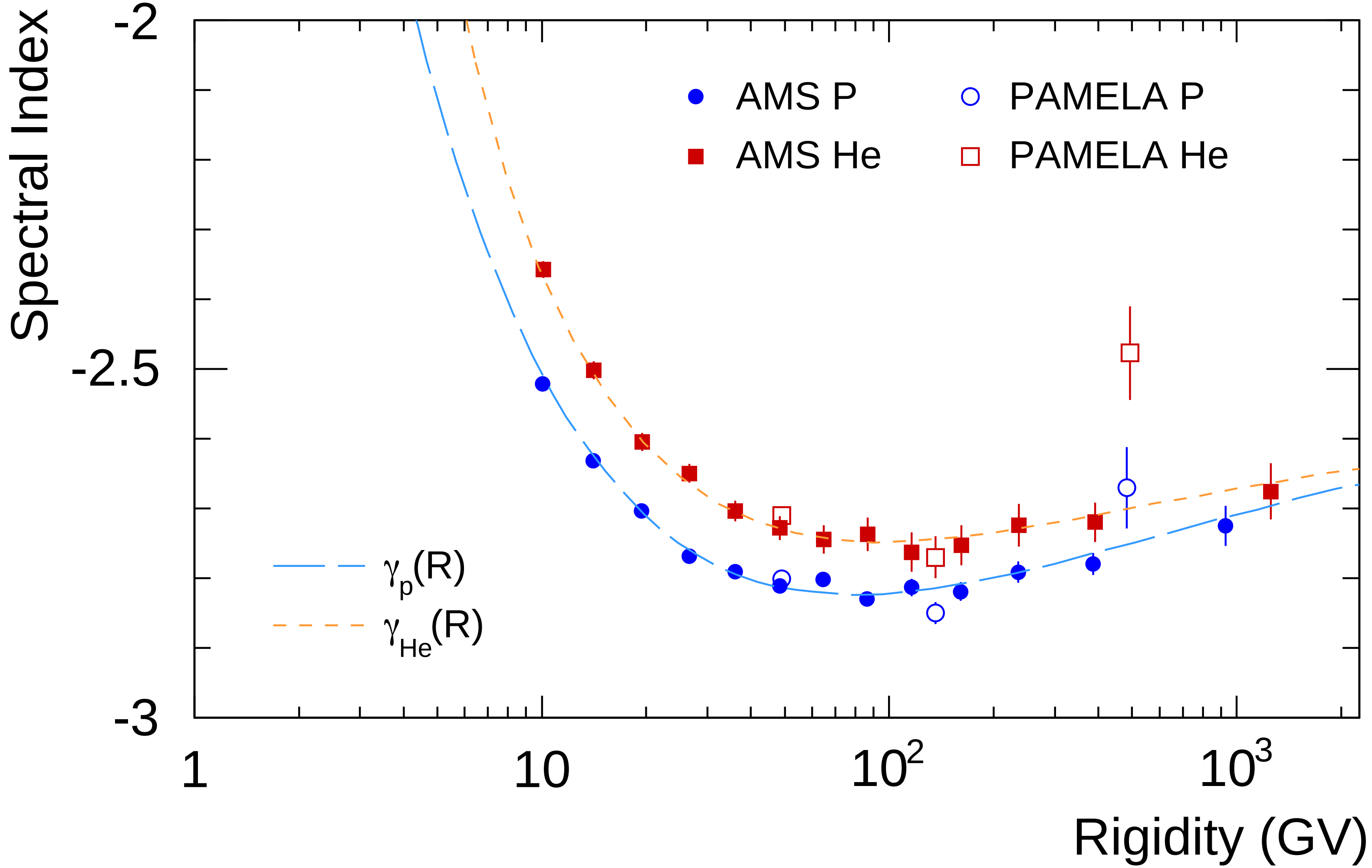
Helium Flux VS Kinetic energy per nucleon



p/He ratio as function of rigidity



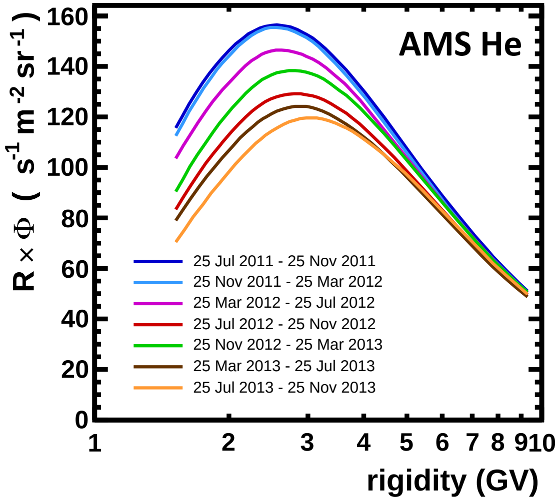
Proton & He Spectral Index



Conclusions

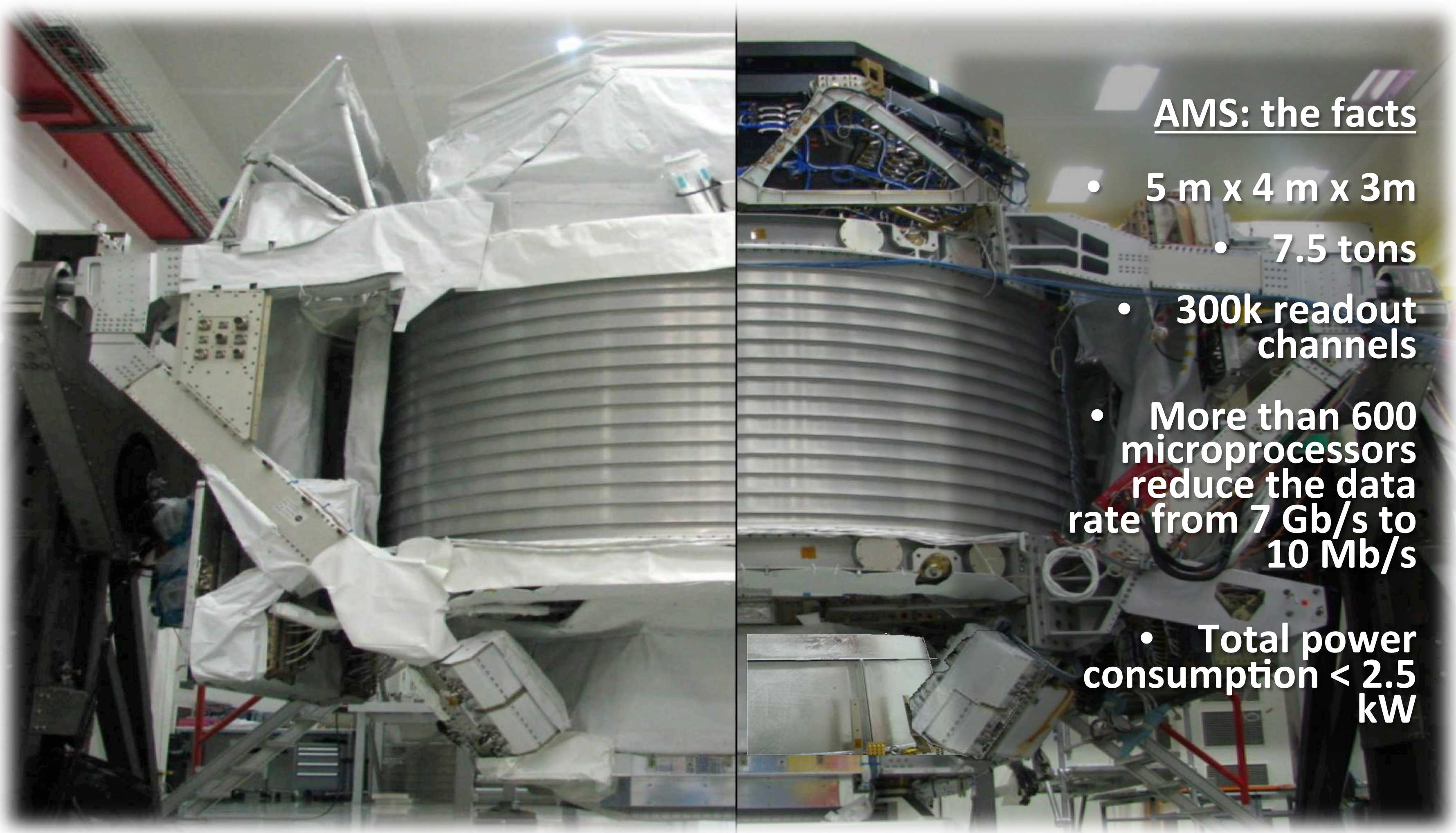
The high statistics of AMS required extensive studies of the systematic errors. Many cross-checks, several independent analyses.

This measurement provides the baseline for time variation studies: long-term solar modulation effects and SEP studies.



- **The high precision of the measurements allow a detailed study of the variation of the fluxes spectral indices with rigidity**
- **The spectral index of both the proton and the helium flux increases at high rigidities, i.e. the fluxes cannot be described by a single power law**
- **The magnitude of the helium spectral index is different from that of the protons, but the rigidity dependence is similar.**
- **The spectral index of the p/He ratio above ~45 GV becomes constant: the high-rigidity p/He ratio is well described by a single power law**

The Instrument – Pre-launch Integration



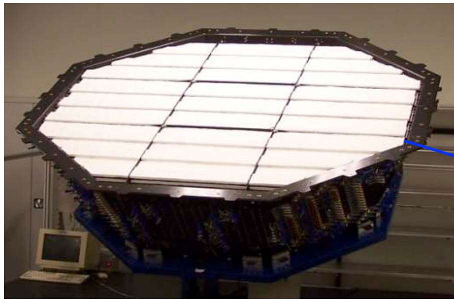
AMS: the facts

- 5 m x 4 m x 3m
- 7.5 tons
- 300k readout channels
- More than 600 microprocessors reduce the data rate from 7 Gb/s to 10 Mb/s
- Total power consumption < 2.5 kW

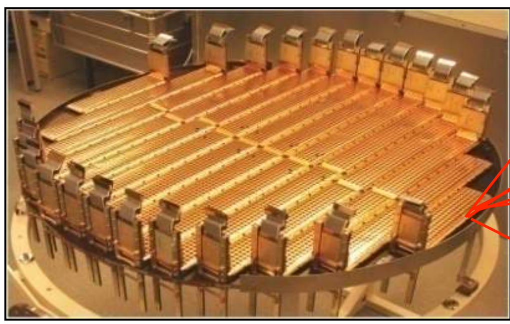
The AMS-02 instrument

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

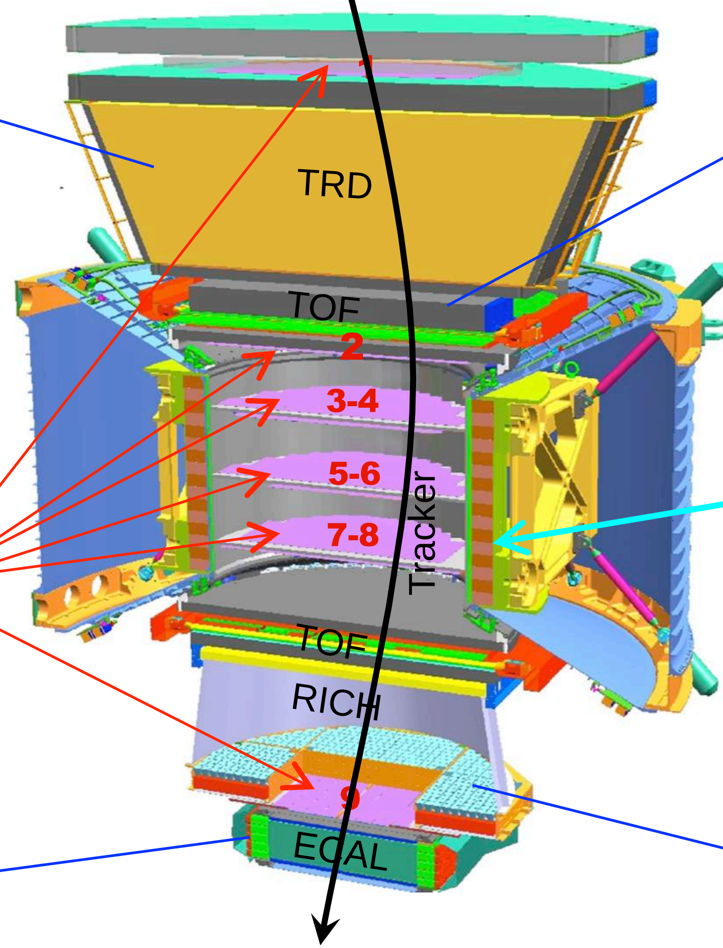
TRD
Identify e+, e-



Silicon Tracker
Z, P

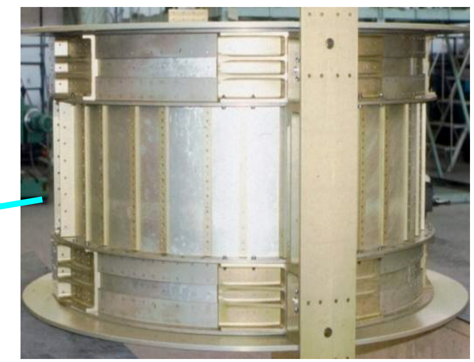


ECAL
E of e+, e-, γ



TOF
Z, E

Magnet
±Z



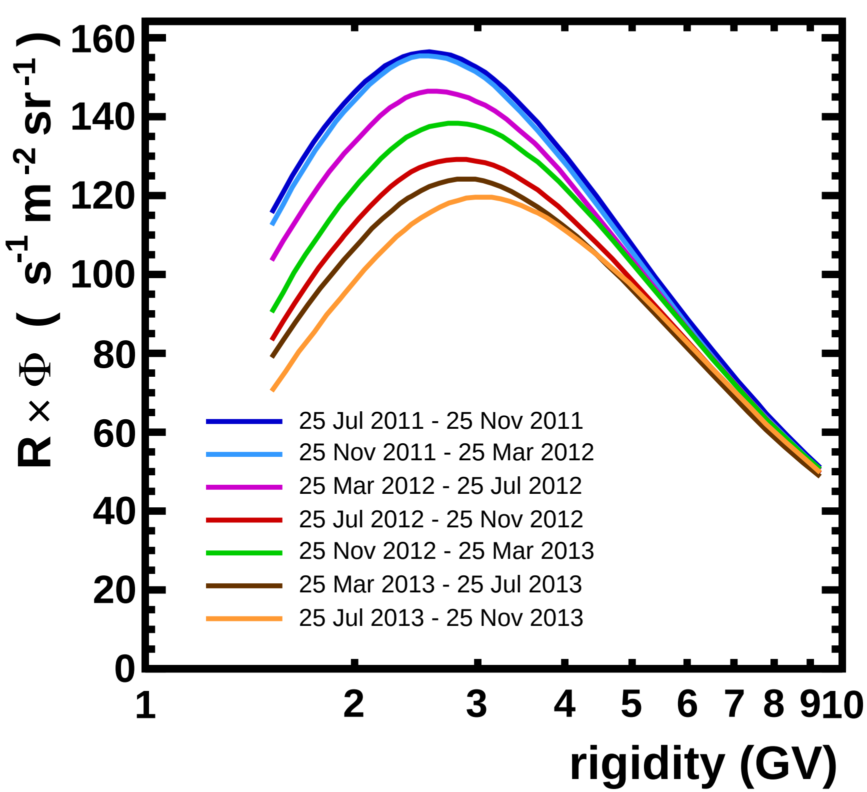
RICH
Z, E

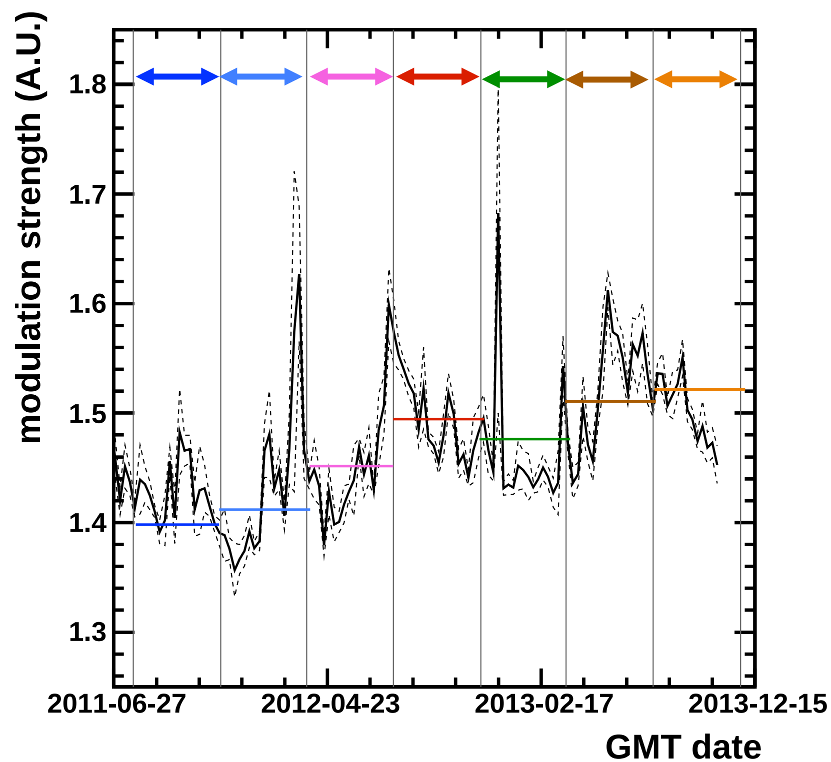
Z, P are measured independently from Tracker, RICH, TOF and ECAL

Low-Energy He spectrum and solar modulation

Helium spectrum from AMS data

Modulation strength from neutron monitor data (OULU station)





NICOLA TOMASSETTI - LPSC - IN2P3/CNRS GRENOBLE

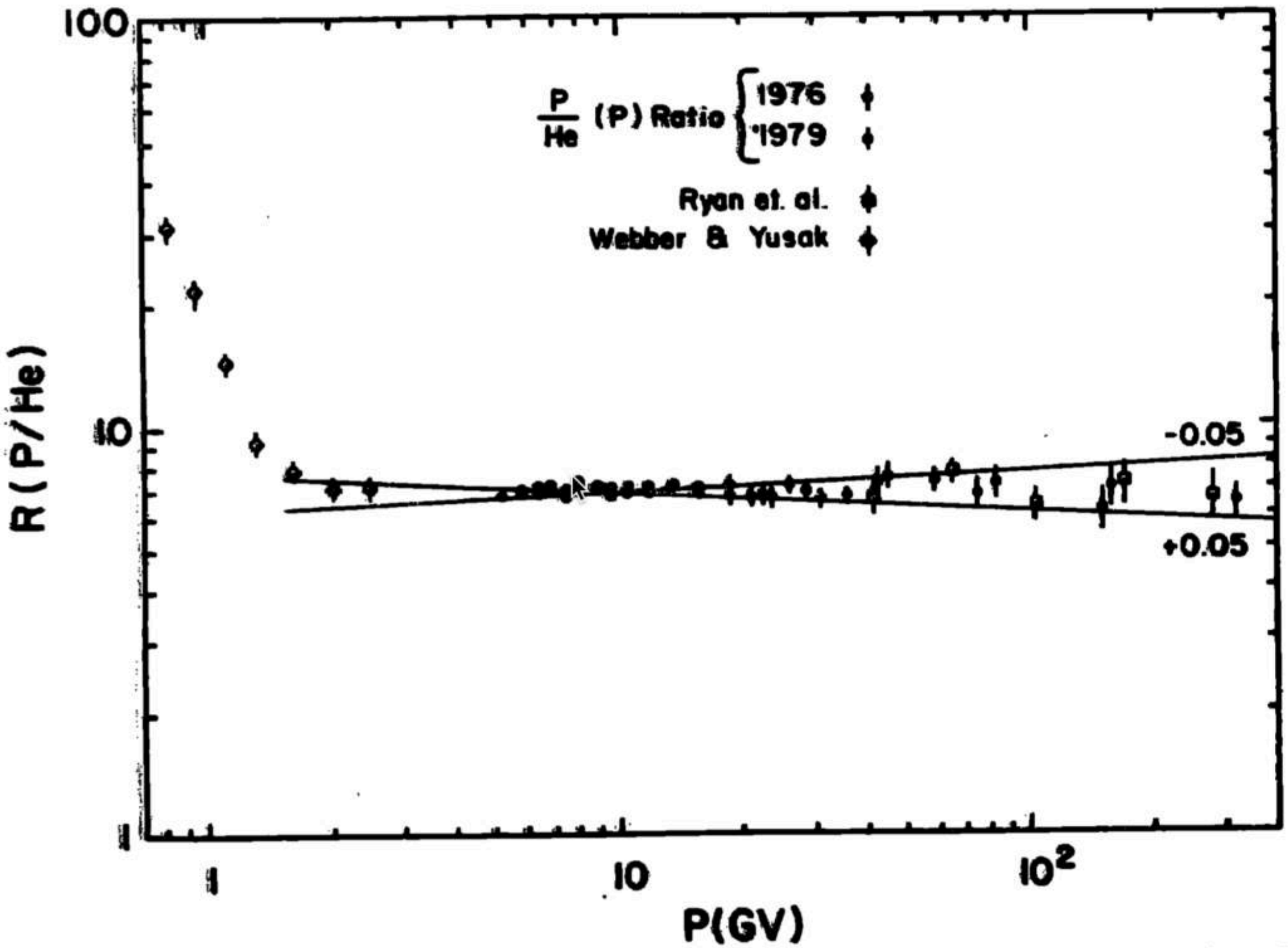
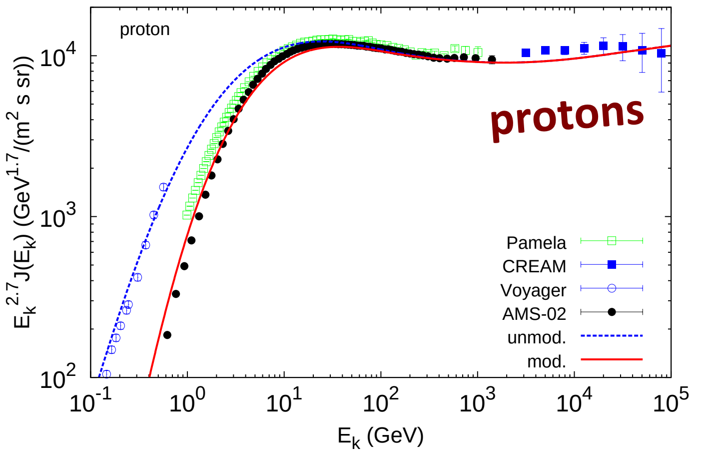


Figure 3. Proton to Helium ratio as a function of rigidity.

R. Webber et al. 1972

New phenomena in cosmic-ray propagation?

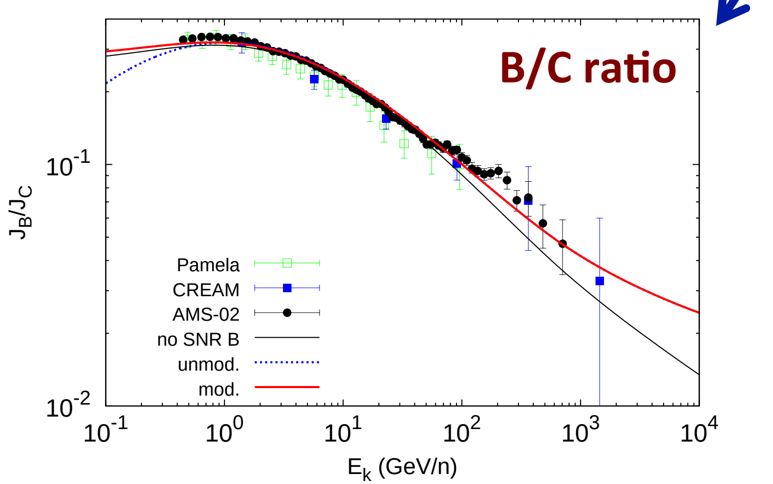
Non-linear CR transport due to self-induced turbulence

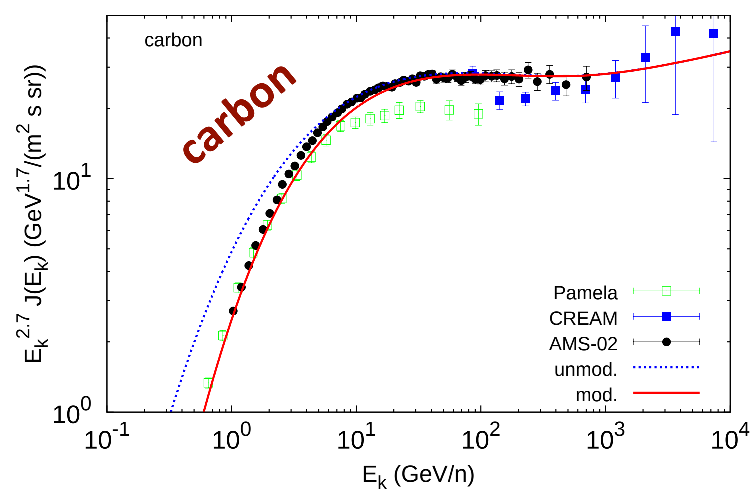


R. Aloisio et al. 1507.00594; P. Blasi et al. 1207.3706

→ **Diffusion to CR-induced turbulence at E ~1-300 GeV**
→ **Advection to CR-generated Alfvèn waves at E <1 GeV**
→ **Diffusion to pre-existing turbulence at >300 GeV**

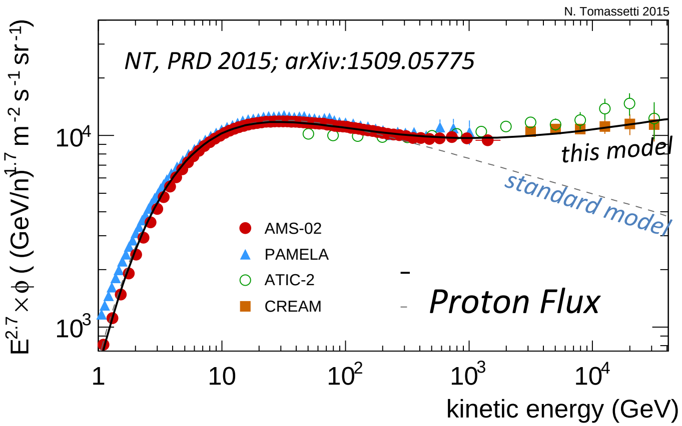
✓ **Flattening in all nuclei and sec/pri ratios**
✓ **Low energy Voyager-1 data.**
✓ **B/C seems to require an additional primary component**





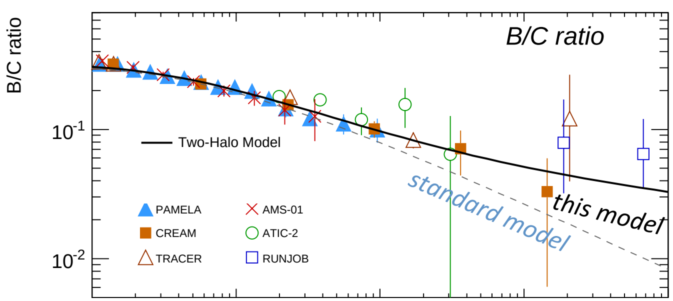
New phenomena in cosmic-ray propagation?

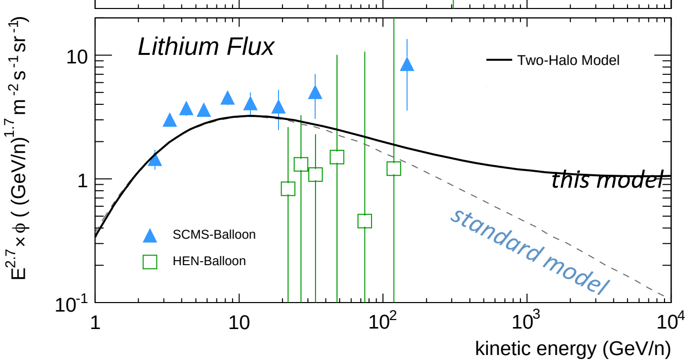
Diffusion coefficient is not separable into energy and space coordinates → no power-law
Shallower diffusivity in the region close to the Galactic disk → high-energy flattening

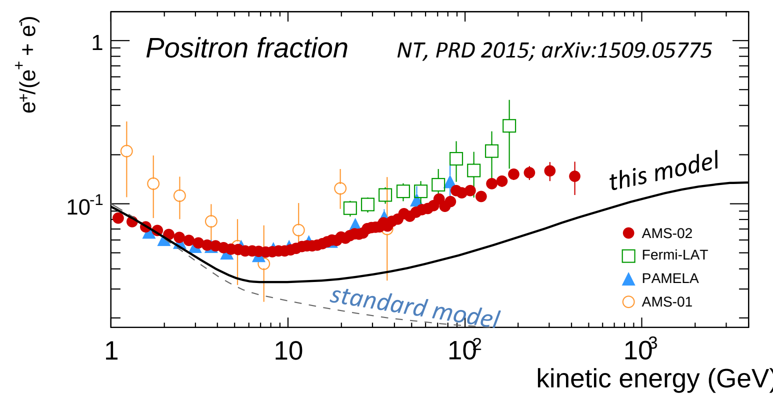


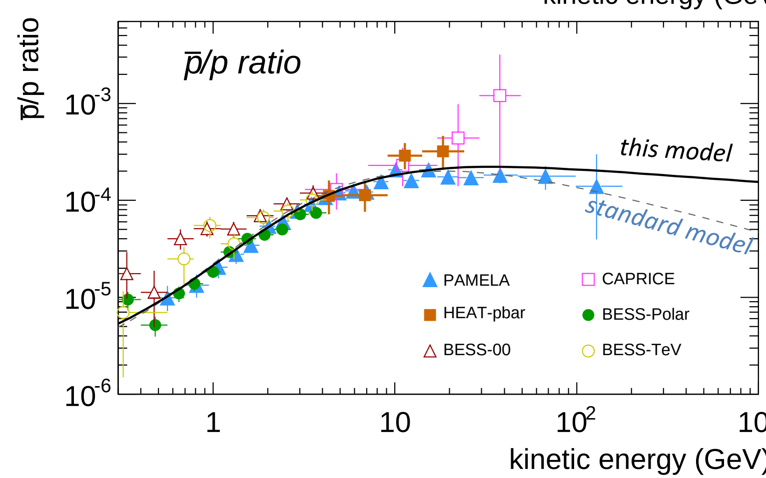
NT, 1204.4492 (2012); NT, 1509.05775 (2015)

- ✓ **Predicted flattening in all nuclei and sec/pri ratios**
- ✓ **Enhanced antimatter production at high energy**
- ✓ **Connection with gamma-rays and anisotropy**









New [nearby-SNR] components in the CR spectrum?

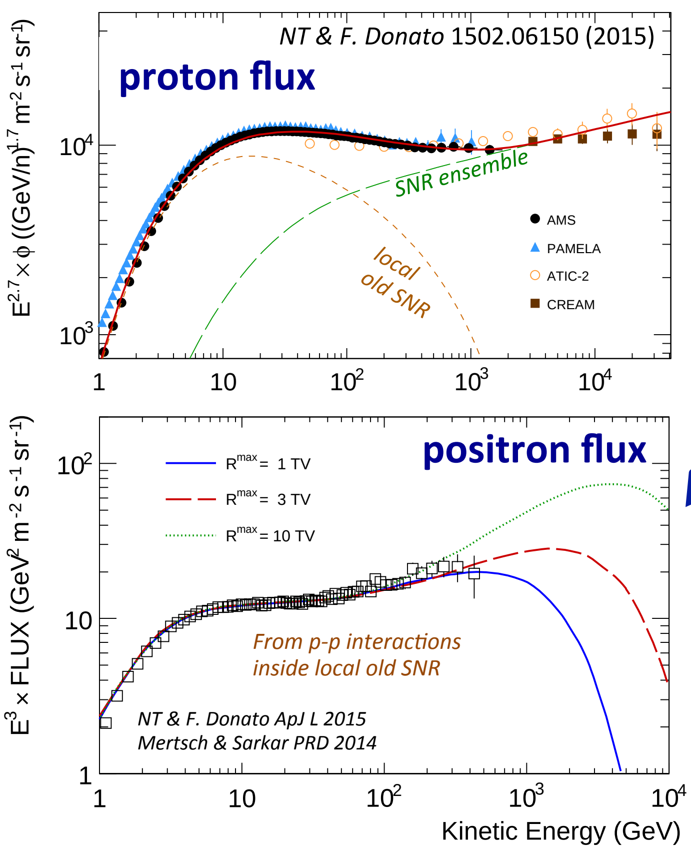
two SNR components in the CR flux

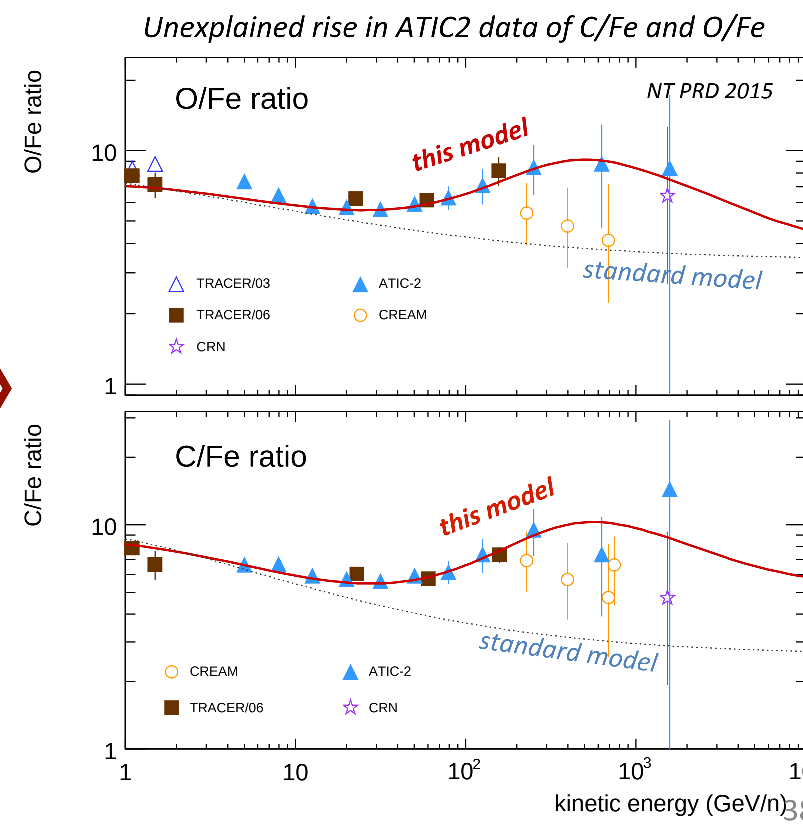
- *Nearby source component for the GeV-TeV flux (and e+ excess)*
  *Must have Rmax~TeV and secondary production (B~1uG, n>n_ISM, v~10^7 cm/s → **OLD SNR***
- *Galactic SNR ensemble*
  *Must have Rmax~PeV: B~500uG, v~10^9 m/s → **YOUNG SNRs***

✓ **Connection between hadron spectra and positron excess** [NT & F.Donato, 1502.06150 (2015)]

✓ **Predicted features in heavy nuclei: explanation of C/Fe and O/Fe** [NT, 1509.05774 (2015)]

✓ **Connection with p/He ratio anomaly?** [NT in preparation] [Kachelriess et al. 1504.06472 (2015)]





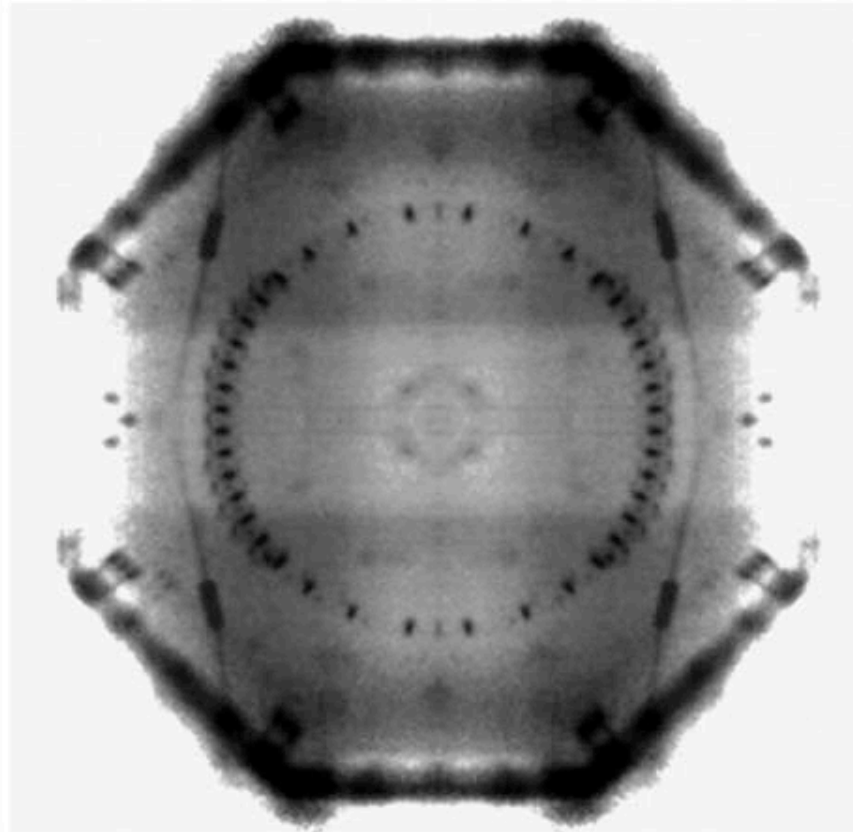
Fragmentation studies: 3D CAT

He absorption in TOI

AMS Hadronic Tomography

with the cosmic-ray p/He ratio

Exposure Time:	May 20 2011 – May 20 2012
Number of Protons:	3,676,863,217
Number of Helium nuclei:	620,303,906
Rigidity range:	2 GV – 2000 GV
Tomographic plane:	Z = +165 cm
XY pixel area:	1 cm^2



Tomographic reconstruction of the AMS top-of-instrument material obtained using the Proton-to-Helium flux ratio. Tiny differences in the interaction cross-section of proton and He are used to trace the material inhomogenities. Several detector elements such as screws, electronics boards, and mechanical interfaces are clearly recognizable.