Protons and helium in cosmic rays

AMS results and interpretations

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on behalf of the AMS Collaboration

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TeV Particle Astrophysics conference "TeVPA-2016"
12 – 16 September 2016 – CERN, Switzerland

The AMS Project

Particle physics detector for high precision CR measurements at TeV energy

[→ see presentation by S. Shael]

Physics goals

- ✓ Antimatter search (|Z|>1 anti-nuclei)
- ✓ Dark Matter (light anti-matter & γ-rays)
- ✓ Exotic signals?
- ✓ **Galactic CR 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]**

Flux Measurement

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

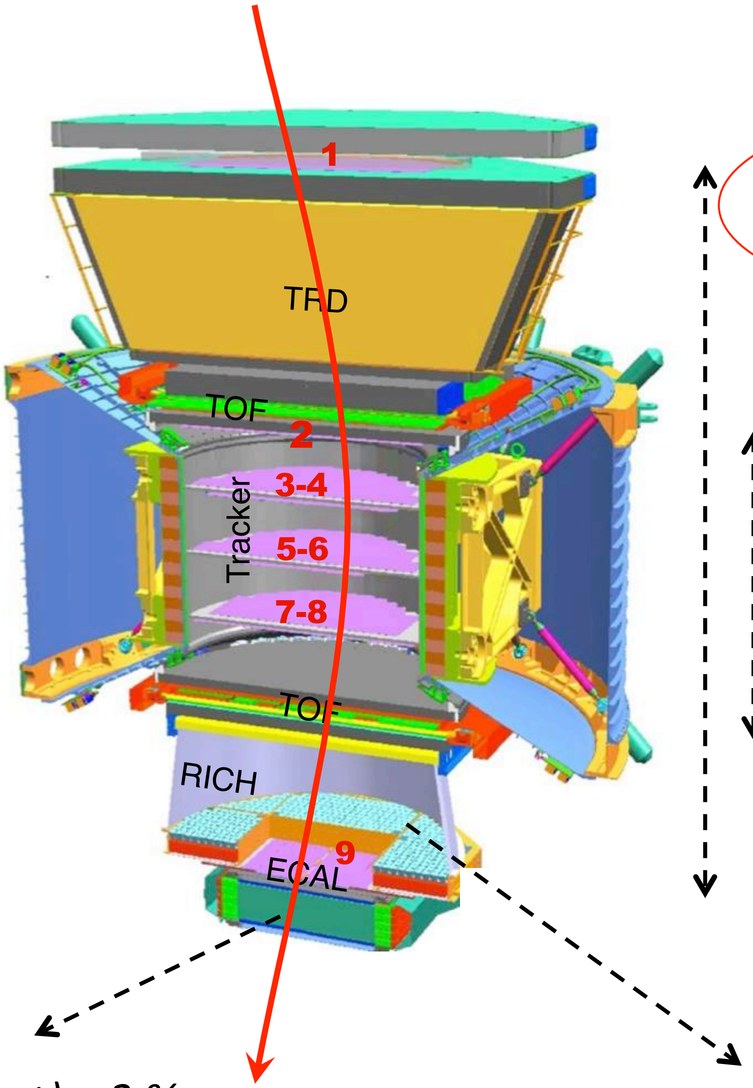
$$\Phi(R) = \frac{N(R, R+\Delta R)}{\varepsilon_{Trig}(R) \times A_{Tot}(R) \times T(R) \times \Delta R}$$

R = p/Z, rigidity; important in magnetic spectrometry & 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%

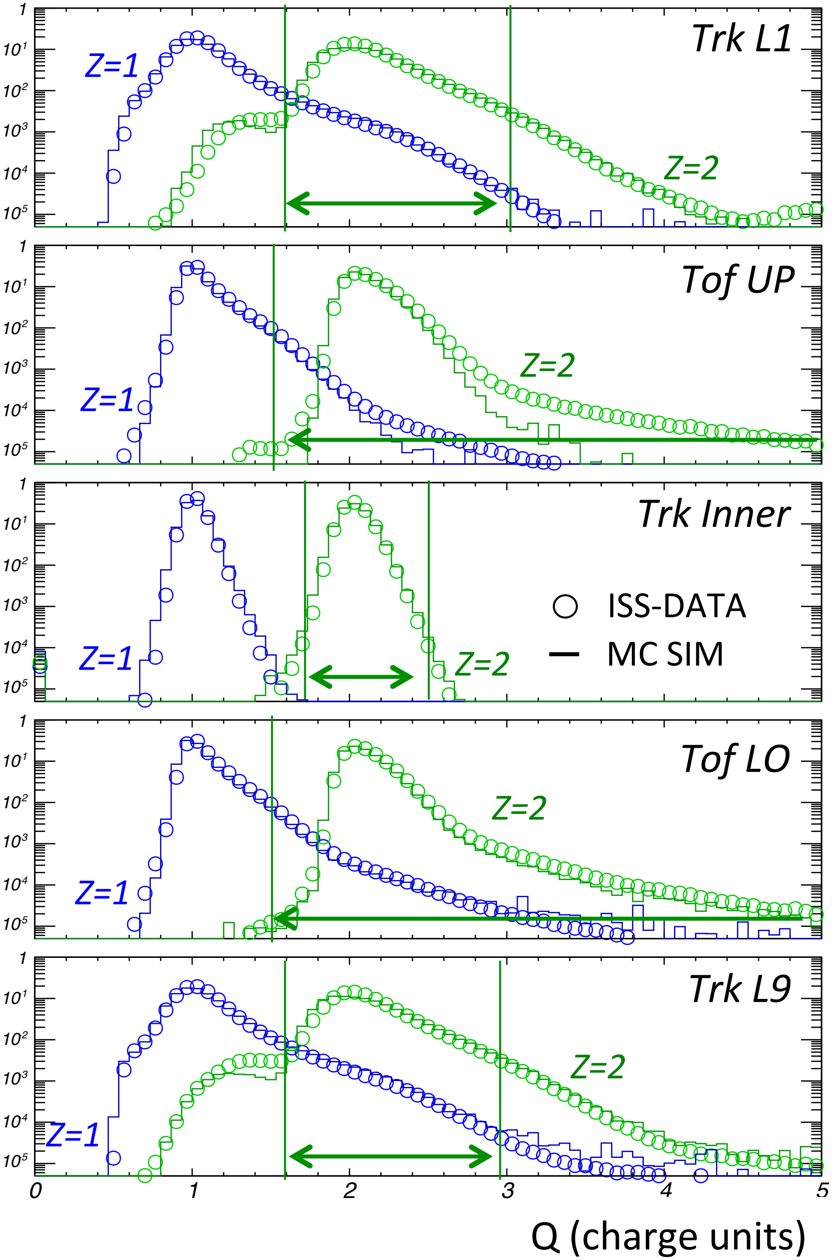
ECAL*, *E
ΔE/E (TeV e±) ~ 2 %
ΔE/E (TeV p) ~ 50 %

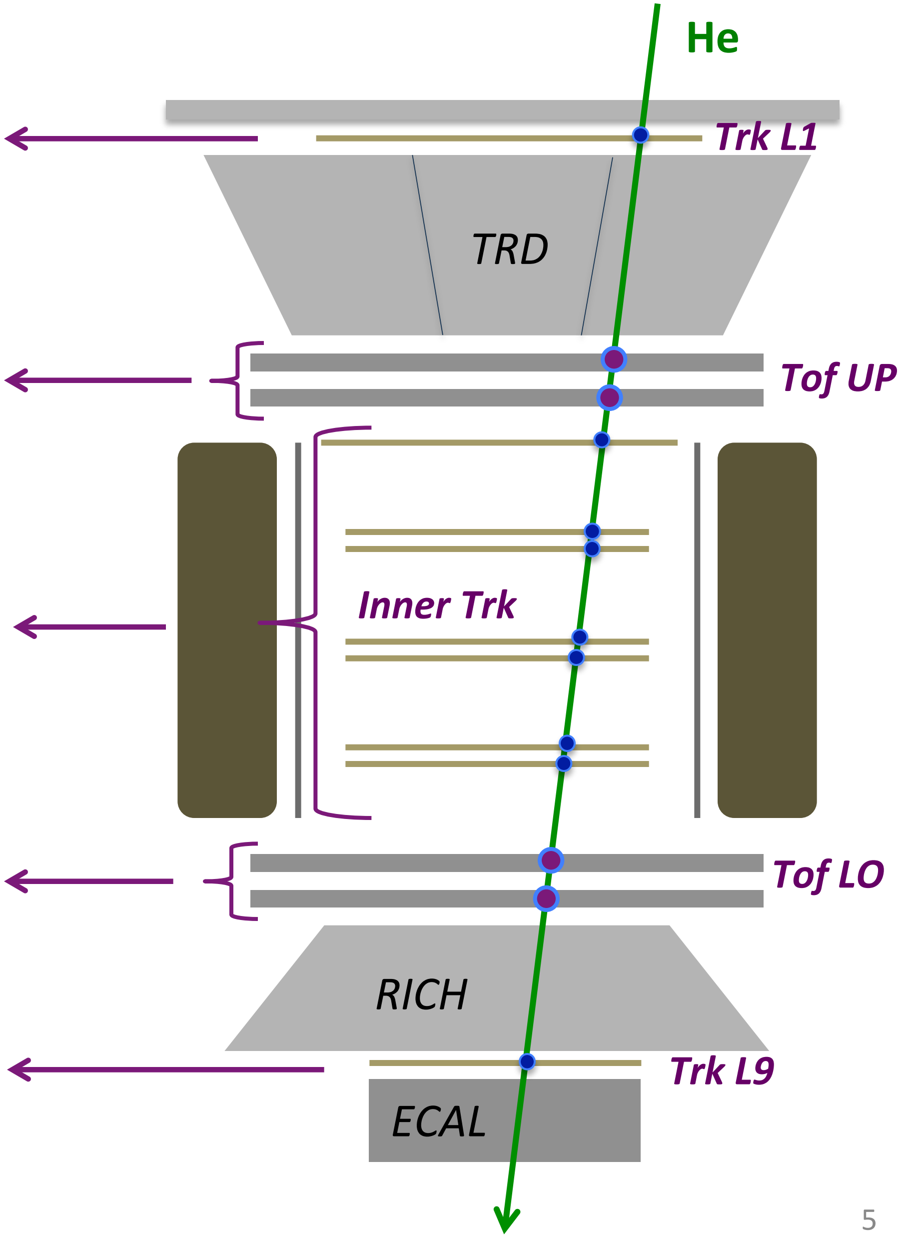
***RICH*, β**
Δβ/β ≈ 0.05%

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

Selection of Proton and Helium signals

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





Acceptance

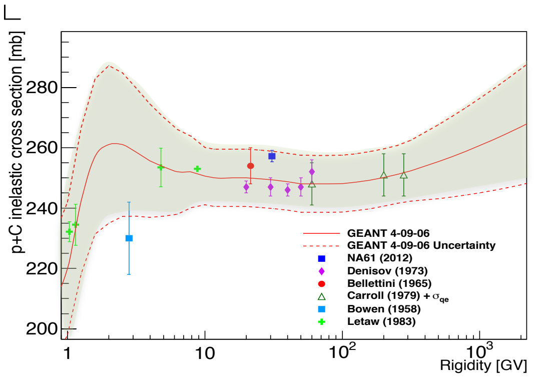
$$\Phi_i(R_i) = \frac{N_i}{T_i\,\varepsilon_i\,A_i\,\Delta R_i}$$

- ✓ 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)

[→ see presentation by Q. Yan]

Proton acceptance

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

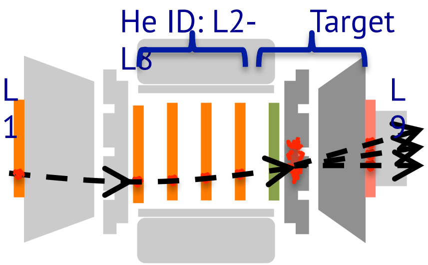


~0.6 – 1 % systematic errors at GV – 2 TV

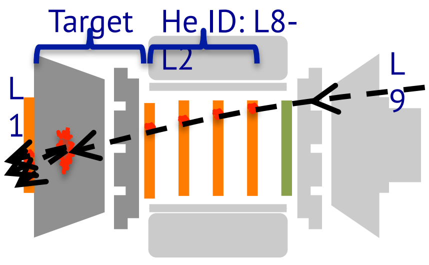
Helium acceptance

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

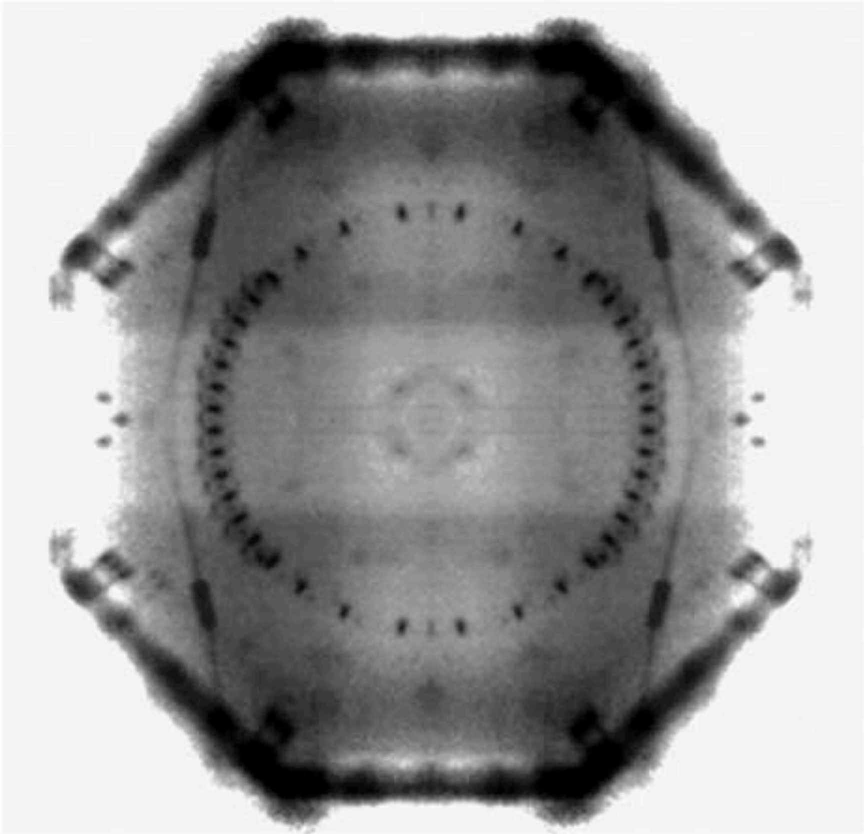
~1% < 200 GV increasing to ~2% at highest rigidities

p/He fragmentation studies: 3D CAT

AMS Hadronic Tomography

with the cosmic-ray p/He ratio

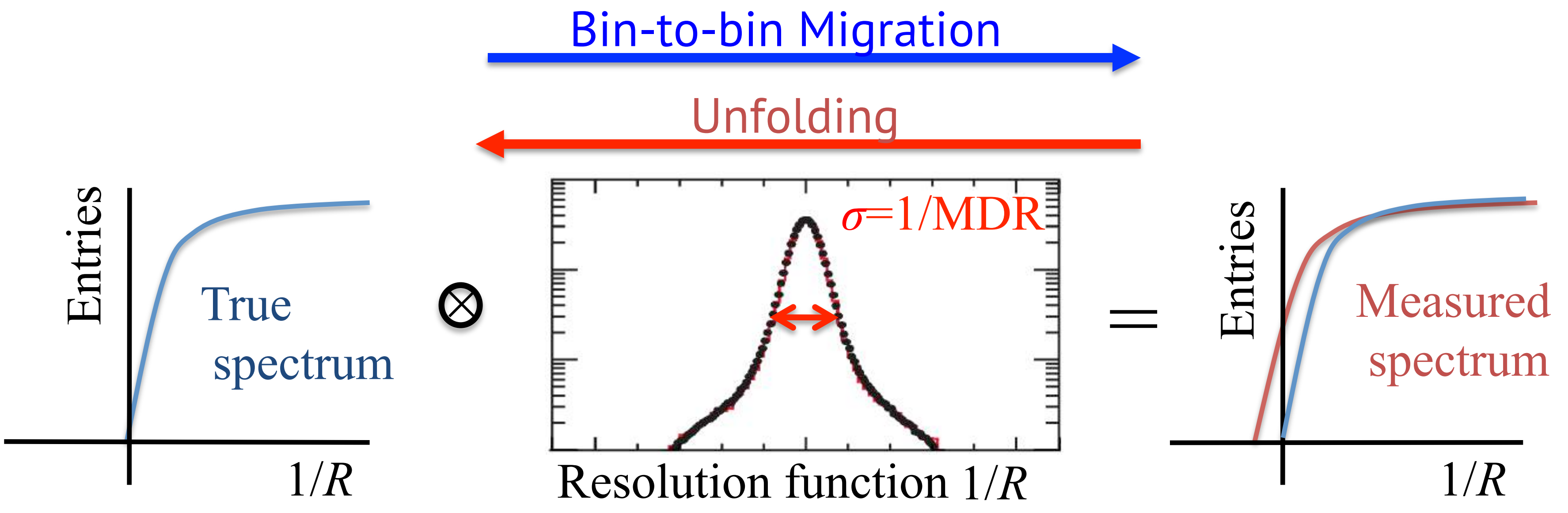
Exposure Time:	May 20 2011 - May 20 2012
Number of Protons:	3,676,863,217
Number of Helium nuclei:	620,303,906
Rigidity range:	2 GV - 2000 GV
Tomographic plane:	Z = +165 cm
XY pixel area:	1 cm^2



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%

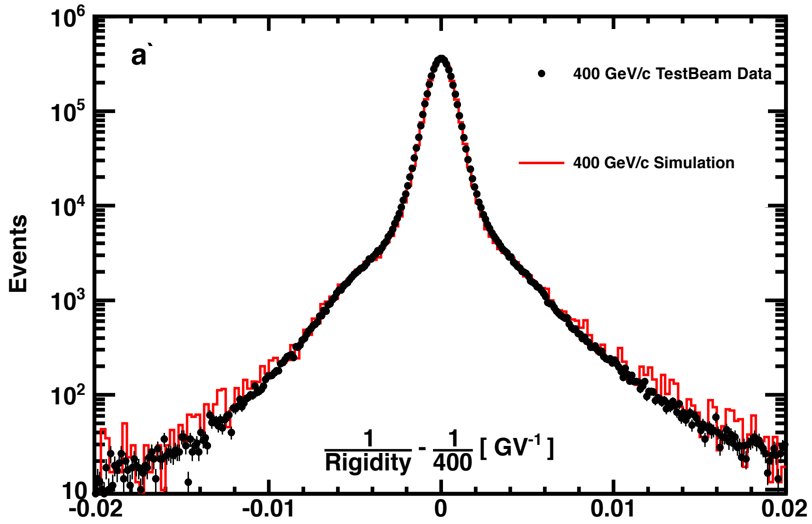
Tracker resolution

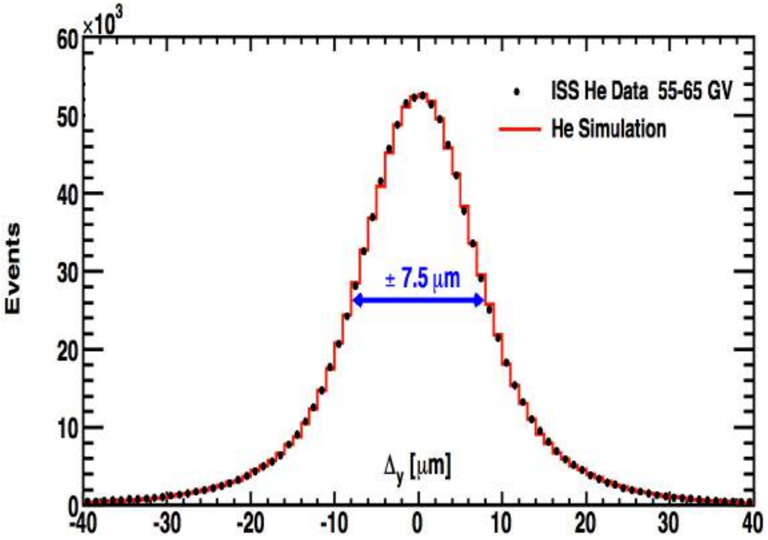
Protons:

- 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)



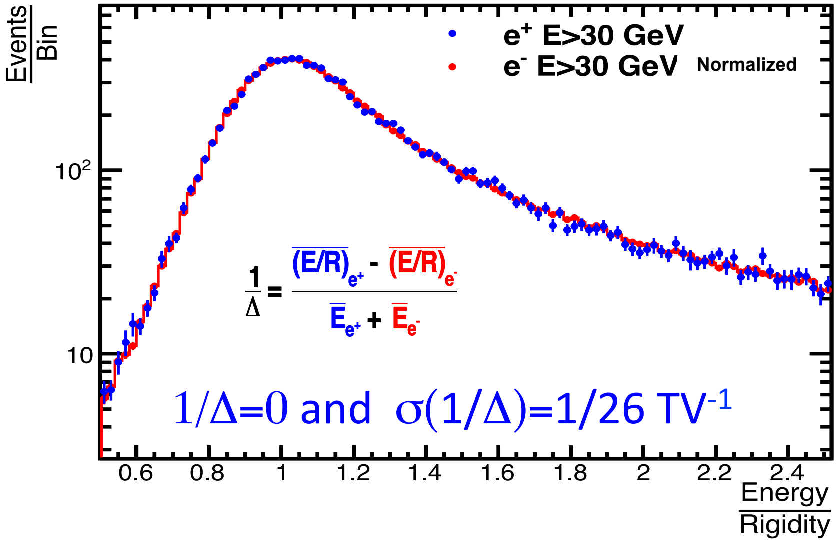


Uncertainty on the flux < 1% below 300 GV rising to 3% at 2 TV

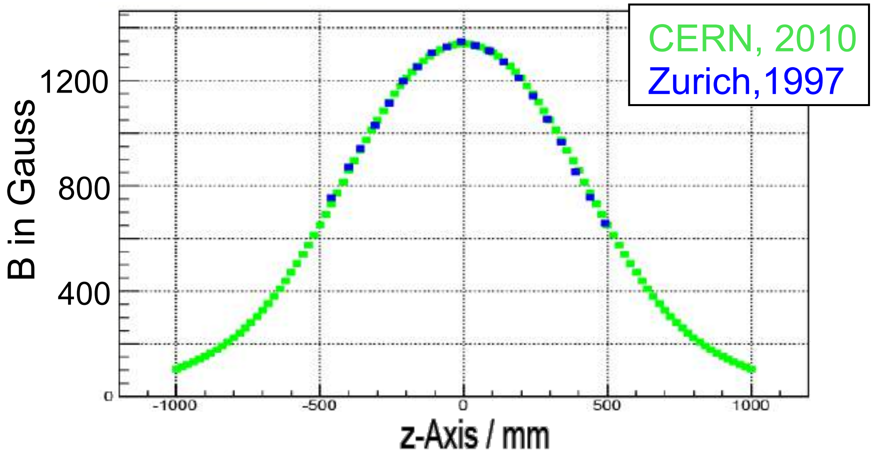
Absolute Rigidity Scale

Two contributions to the uncertainty:

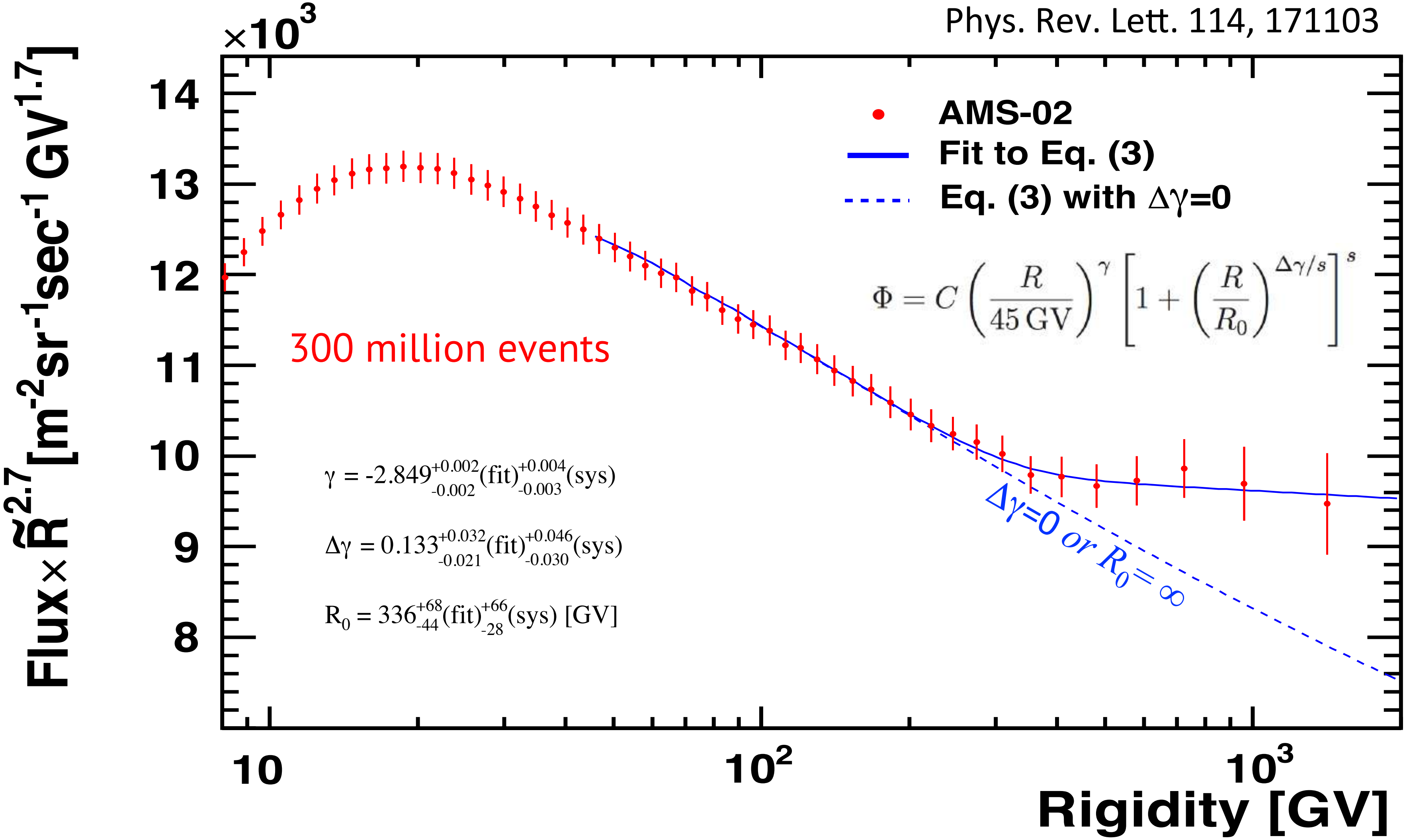
1. **Residual tracker misalignment** $(1/\Delta)$: checked with $E_{ECAL}/R_{Tracker}$ ratio for **electrons and positrons**, limited by the current high energy positron statistics. Corresponding flux error: 2.5% @1 TV.



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



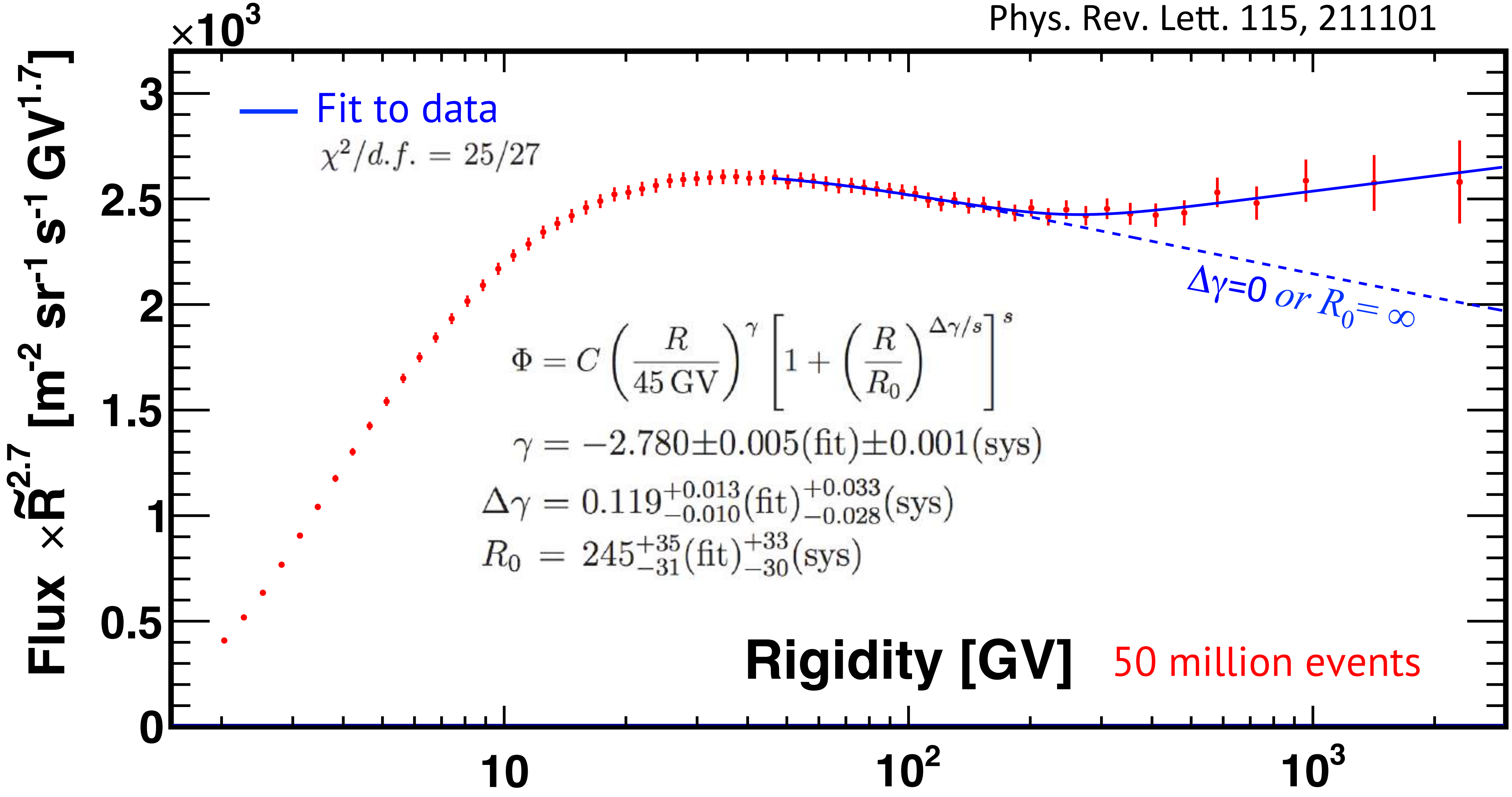
Proton Flux



Phys. Rev. Lett. 114, 171103

300 million events

Helium Flux



Phys. Rev. Lett. 115, 211101

$\chi^2/d.f. = 25/27$

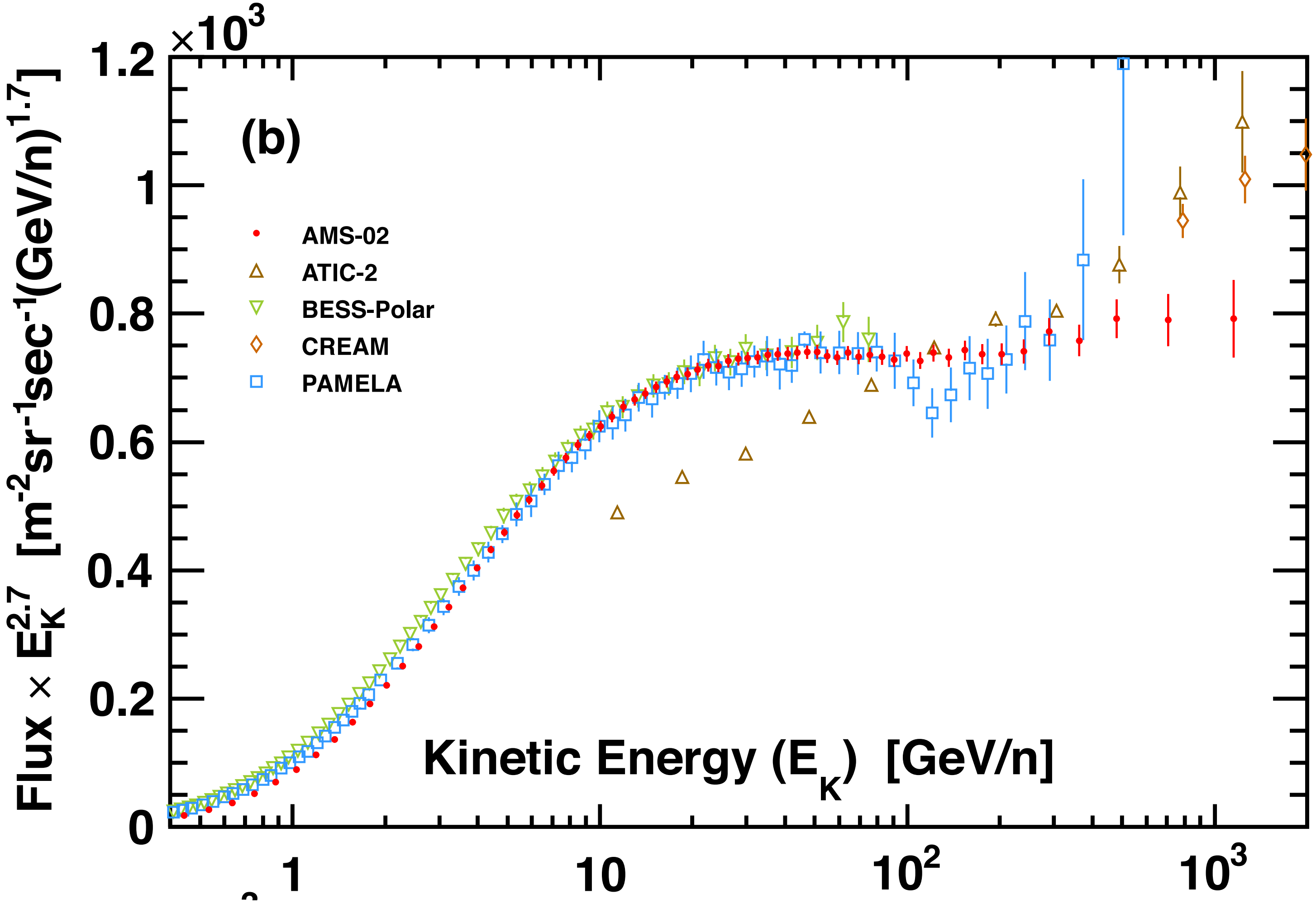
$$\Phi = C\left(\frac{R}{45\,\mathrm{GV}}\right)^{\gamma}\left[1+\left(\frac{R}{R_0}\right)^{\Delta\gamma/s}\right]^{s}$$

$$\gamma = -2.780 \pm 0.005(\mathrm{fit}) \pm 0.001(\mathrm{sys})$$

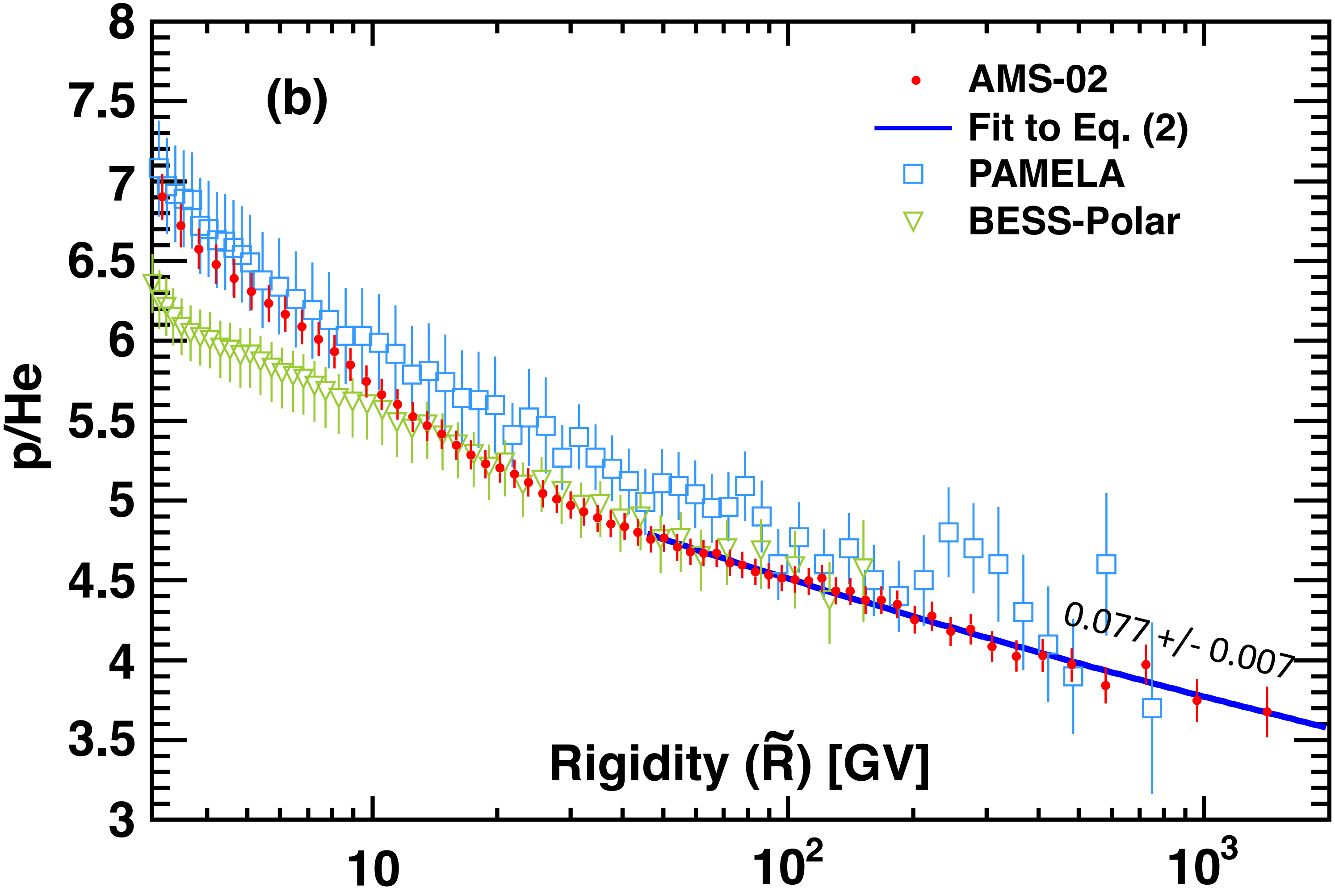
$$\Delta\gamma = 0.119^{+0.013}_{-0.010}(\mathrm{fit})^{+0.033}_{-0.028}(\mathrm{sys})$$

$$R_0 = 245^{+35}_{-31}(\mathrm{fit})^{+33}_{-30}(\mathrm{sys})$$

Helium Flux VS Kinetic energy per nucleon



p/He ratio as function of rigidity



0.077 +/- 0.007

Physics behind p-HE anomalies…?

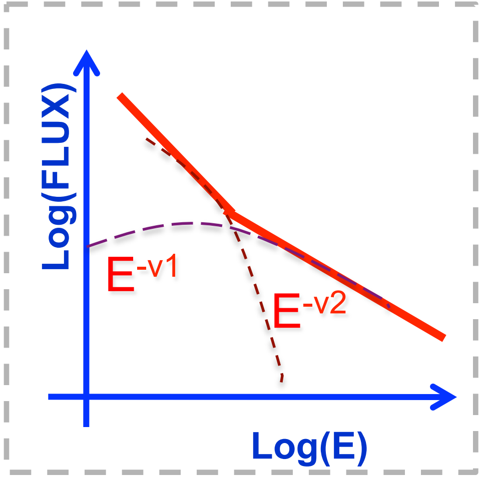
Basic predictions

- *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)* $\phi(E) \sim Q/K \approx E^{-(\nu+\delta)}$

homogenity
isotropy
stationarity
linearity

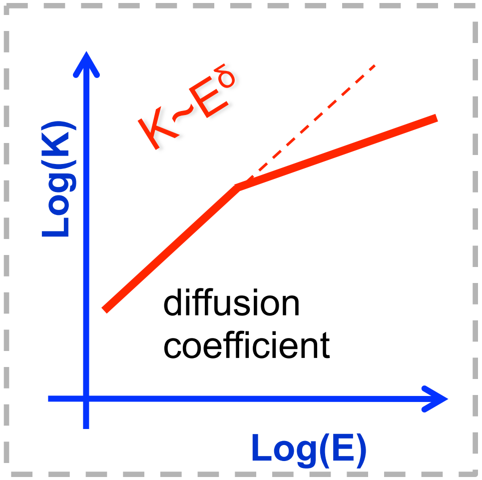
Proton and He data cannot be explained by standard models of DSA acceleration and CR transport.

Multi-component flux



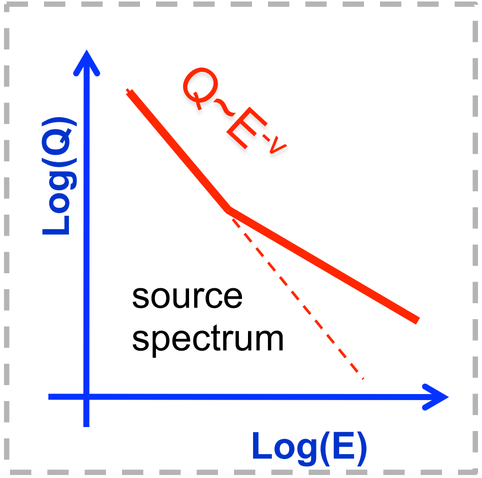
- *Non-linear DSA*
- *Mach number time-evolution*

Propagation, K(E)



- *Transport in CR-induced turbulence*
- *Spatial dependent diffusion K(z,E)*

Acceleration, Q(E)



- *Local SNR + Galactic ensemble*
- *Reaccelerated CRs in weak shocks*

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

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

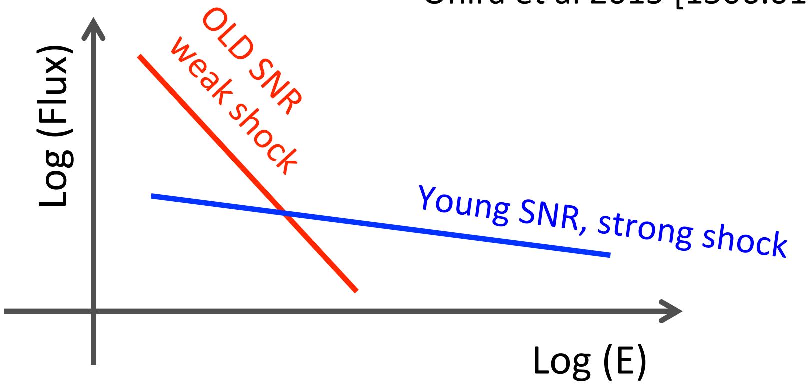
Q(E): Revisited CR acceleration

- Non-linear DSA: concavity from backreaction of CRs to the shock structure. Ptuskin 2013 [*1212.0381]*

- Time-dependent DSA with decreasing speed of the shock and decreasing Emax-> low-energy steepening.

→ Decreasing p/He ratio from inhomogeneus H/He background density around the SN

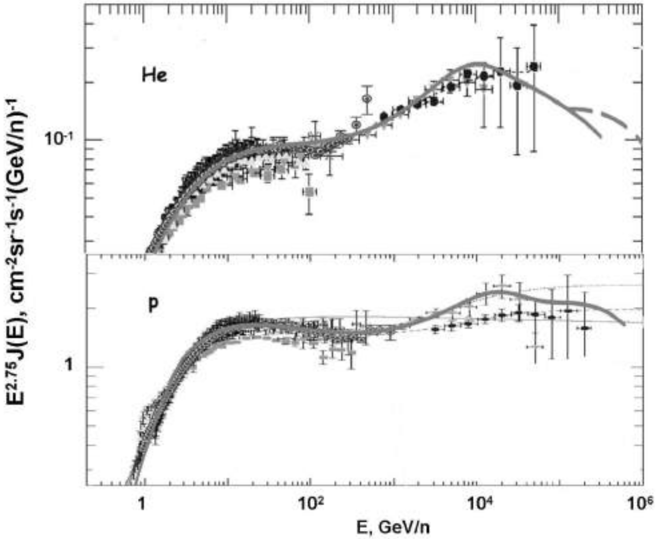
Ohira et al 2015 [1506.01196]



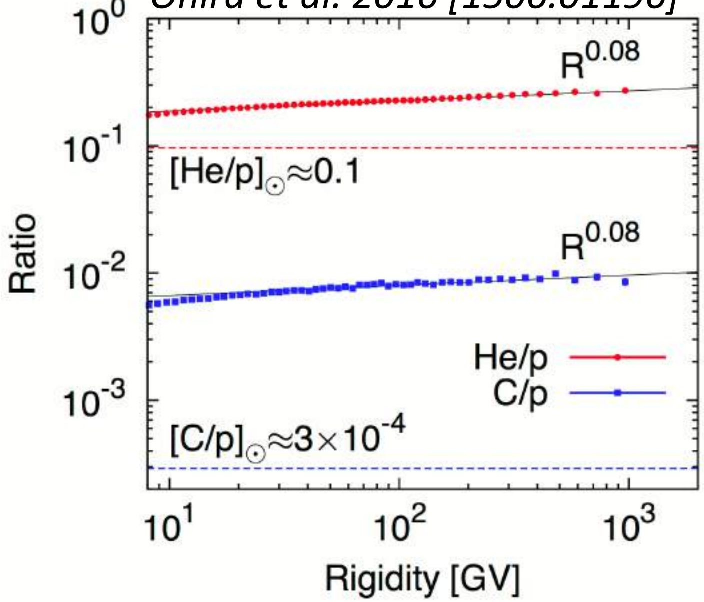
- Re-acceleration of pre-existing CRs from (weak) expandig shockwaves. → steep LE flux contribution

Thoudam & Horandel 2013 [1308.1357]
Ptuskin et al 2013 [1212.0381]

Ptuskin et al. 2013 [1212.0381]



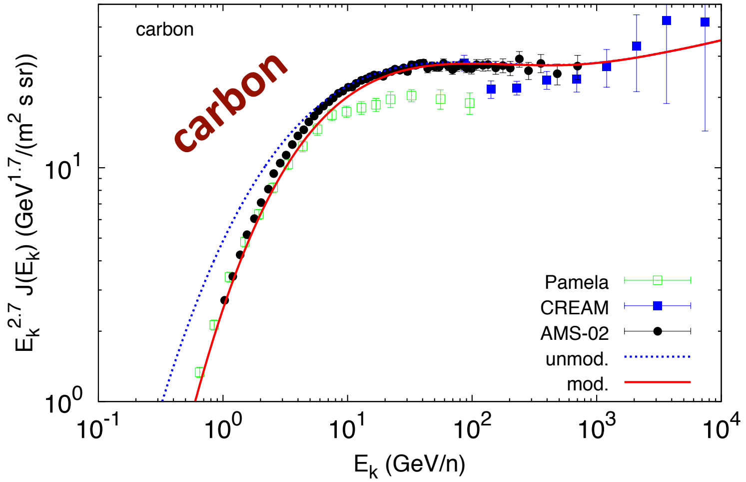
Ohira et al. 2016 [1506.01196]



K(E): Revisited CR propagation

CR propagation under self-generated (+ pre-existing) turbulence

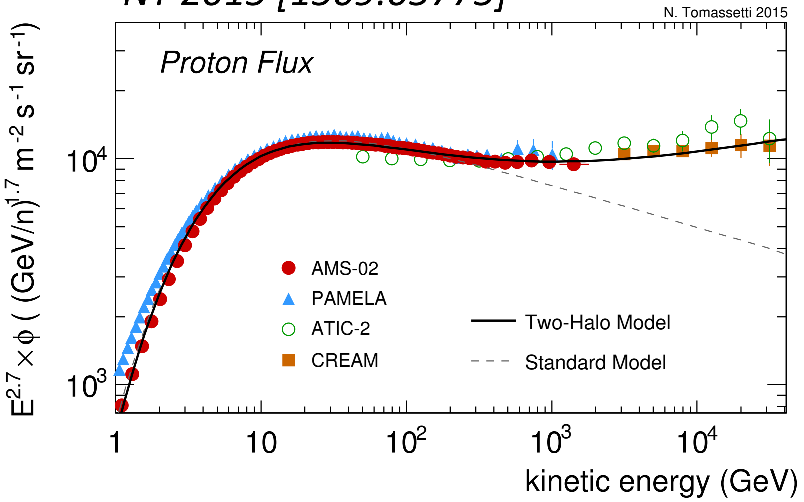
Aloisio et al 2015 [1507.00594]



The transition betwen CR propagation in their own generated turbulence and pre-existing is seen as a feature at E~300 GeV.

Spatial dependent propagation:
Non-separable K(Z,E) -> two halos

NT 2015 [1509.05775]



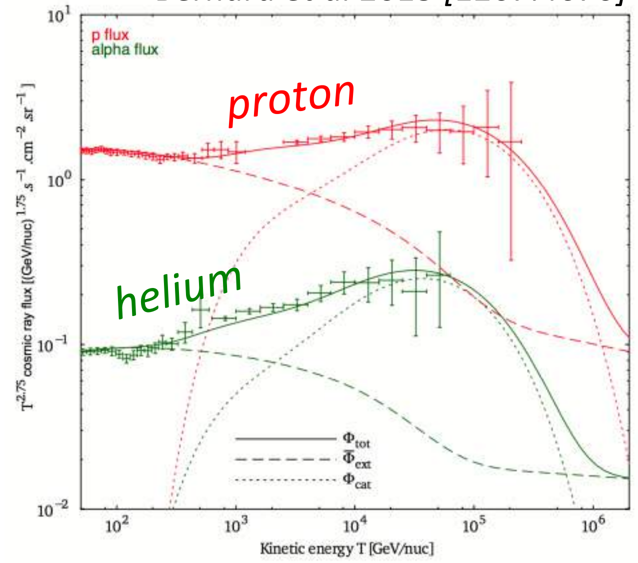
Shallower CR propagation in proximity of the Galactic plane. Two diffusive propagation zones characterized by different diffusion properties.

- ✓ *Univeral features in all primary and in S/P ratios (pbar/p & B/C, Li/C ratios)*
- ✓ *Smaller anisotropy amplitude. Connections w/ γ-ray gradient [Gaggero et al 1411.7623]*
- X *p/He ratio anomaly not addresed. [→ ascribed to acceleration]*
- X *No solution for the positron excess [→nearby source of HE e+e-]*

Nearby sources, but where?

GeV-TeV: Steep flux of Galactic <SNRs>
TeV-PeV: Hard flux from local young SNR

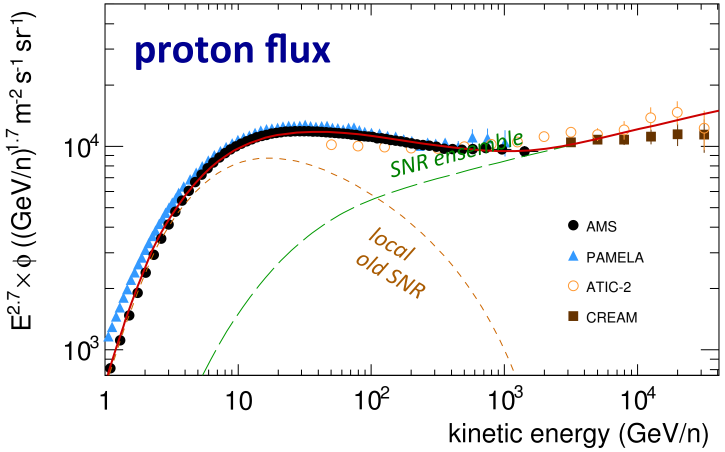
Bernard et al 2013 [1207.4670]



Bernard et al 2013 [1207.4670]
Thoudam & Horandel 2013[1304.1400]
Erlikin & Wolfendale 2012 [.]

GeV-TeV Steep spectrum from local SNRs
TeV-PeV: Hard flux of Galactic <SNR> ensemble

NT & Donato 2015 [1502.06150]



Connection w/ e+ excess — *Kachelriess et al 1504.06472*
Explanation for p/He — *NT 2015, 1511.04460*
Implications for O/Fe — *NT 2015, 1509.05774*
TeV anisotropy signatures — *Kachelriess et al 1505.02720*

With extra sources, all anomalies in charged CR spectra can be explained.
No clear predictions for secondary/primary ratios. Implications for DGE emissions.

Many unknowns --- Fine tuning --- Loose predictivity

Conclusions

AMS-02 has measured proton and Helium at 0.5 GeV - 2 TeV/nucleon of kinetic energy

High statistics, extensive studies of the systematics, cross-checks, independent analyses.

- ✓ A smooth spectral change in both fluxes has been reported ("happy ending")
- ✓ The p/He ratio above ~40 GV of rigidity decreases steadily as power-law

Explanations may require a revisitation of CR acceleration, diffusive propagation, or the inclusion of multiple sources contributing to the observed flux.

Secondary/primary data from AMS-02: *[→ talks by S. Shael, Q. Yan, A. Bachlechner]*

- B/C ratio does *not* harden
- Li/C ratio *seems* to harden
- Pbar/p ratio *flattens*

:-/
It is not clear if a consistent picture is emerging. Multi-TeV nuclear data may be crucial

Protons and helium fluxes in cosmic rays

AMS-02 results and interpretations

Nicola Tomassetti

on behalf of the AMS Collaboration

Perugia University & INFN Perugia, Italy
LPSC & CNRS/IN2P3 Grenoble, France

thank you

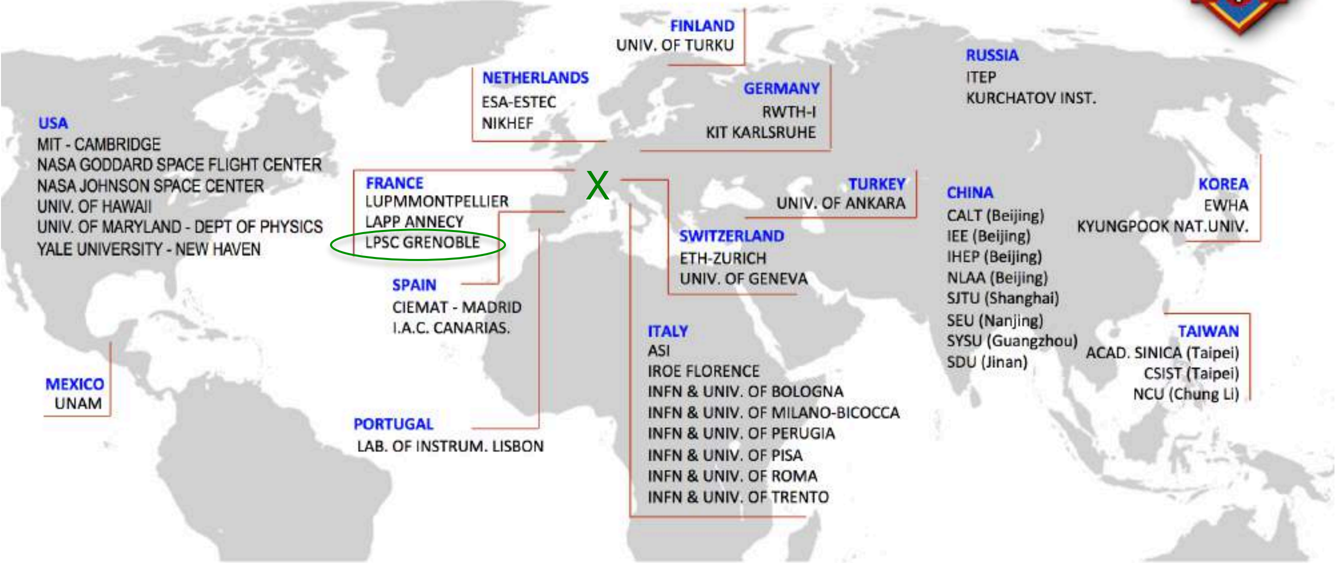
This work is supported by all organizations and individuals acknowledged in PRL 115(2015)211101

backup slides

The AMS Project

AMS Collaboration

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


USA
MIT - CAMBRIDGE
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TURKEY
UNIV. OF ANKARA

RUSSIA
ITEP
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CHINA
CALT (Beijing)
IEE (Beijing)
IHEP (Beijing)
NLAA (Beijing)
SJTU (Shanghai)
SEU (Nanjing)
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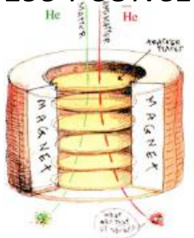
KOREA
EWHA
KYUNGPOOK NAT.UNIV.

TAIWAN
ACAD. SINICA (Taipei)
CSIST (Taipei)
NCU (Chung Li)

Project timeline

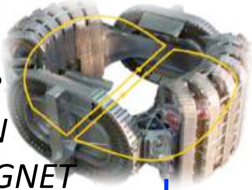
1994 CONCEPT



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

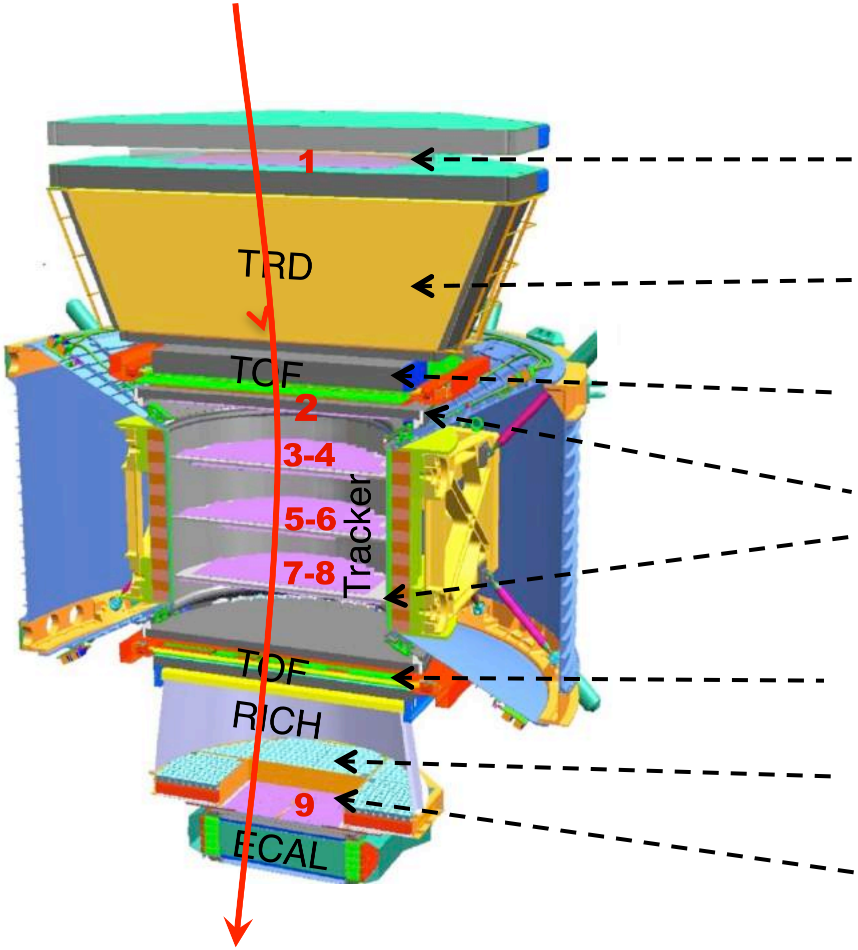
2011
@KSC
INTEGRATION & CR-μ RUN

MAY 2011
STS-134
FLIGHT

ON THE ISS

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

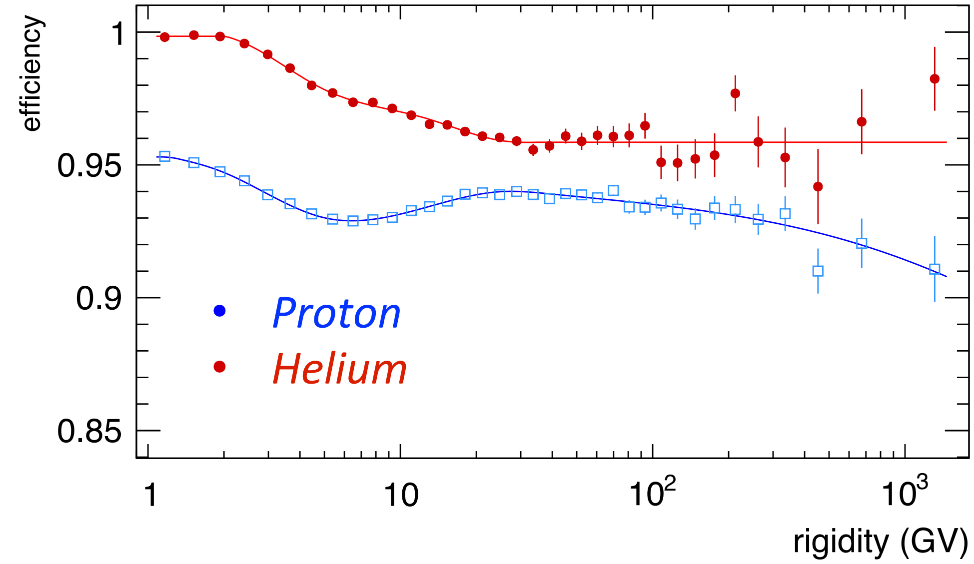
Multiple measurements of charge



	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

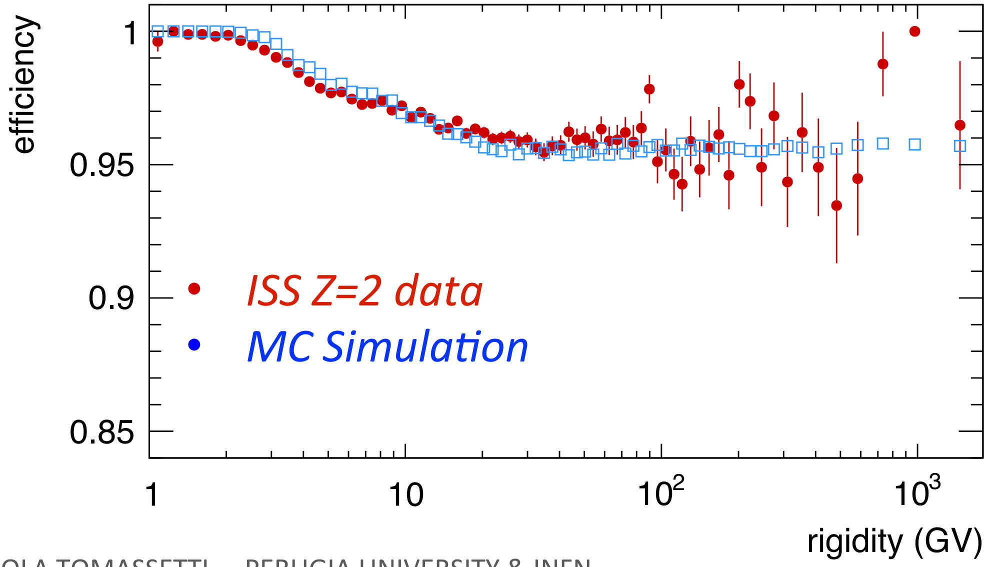
Trigger Efficiency

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



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

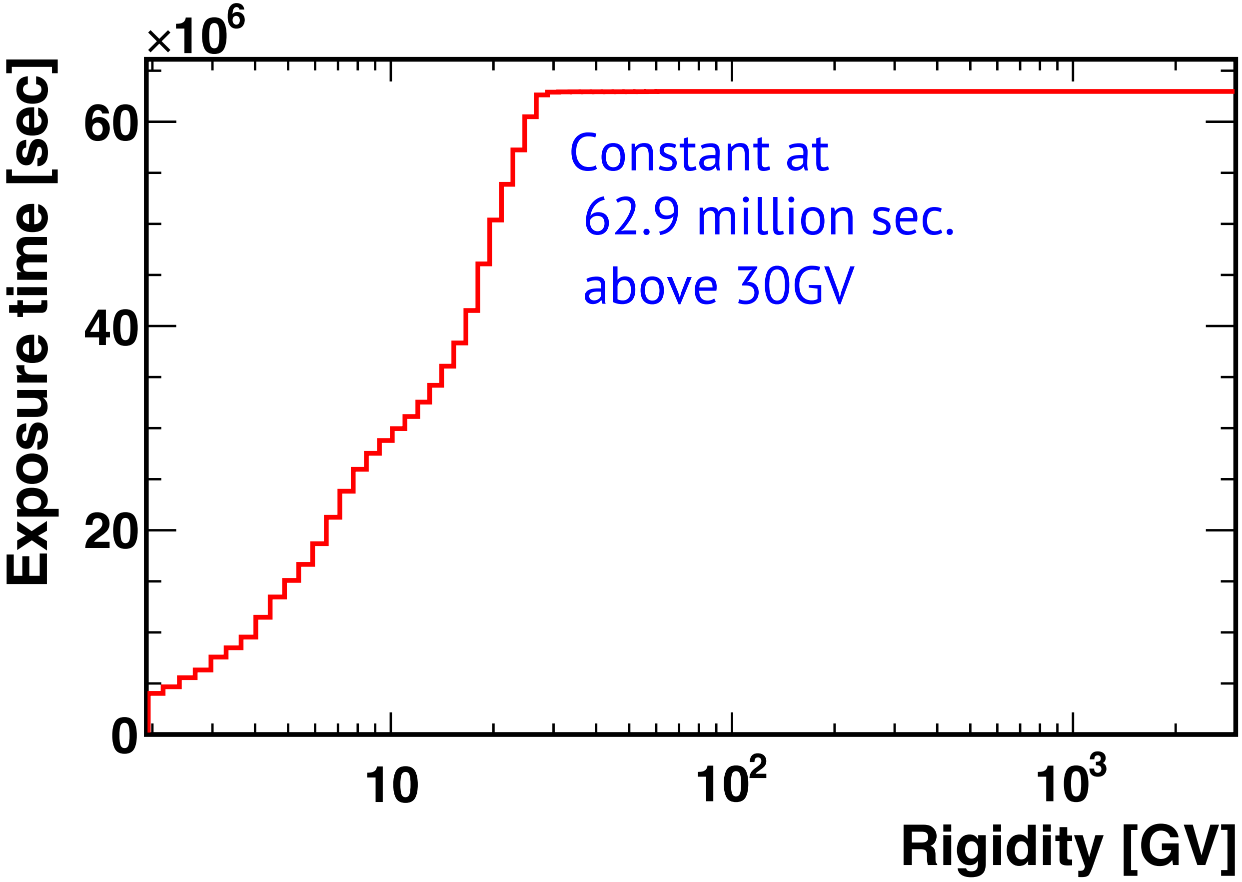
$$\varepsilon_{Trig} = \frac{N_{Phys}}{N_{Phys} + 100 \cdot N_{MinBias}}$$



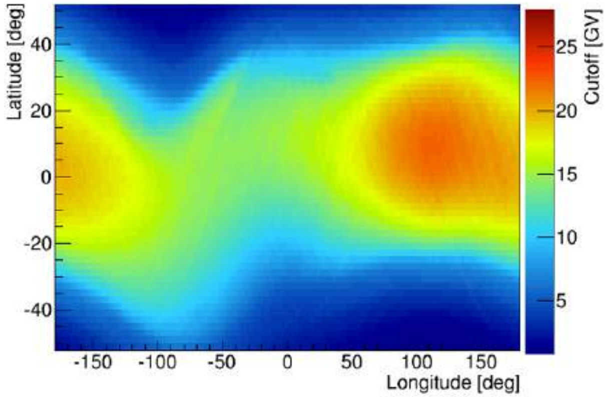
Exposure Time

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

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

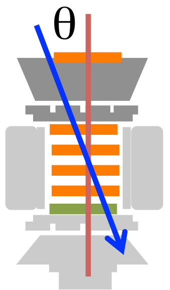


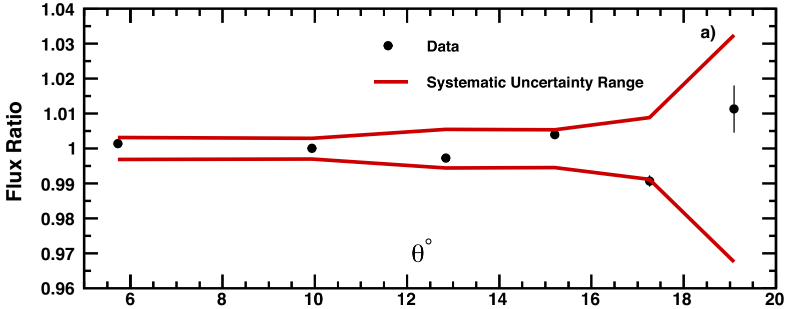
Constant at 62.9 million sec. above 30GV



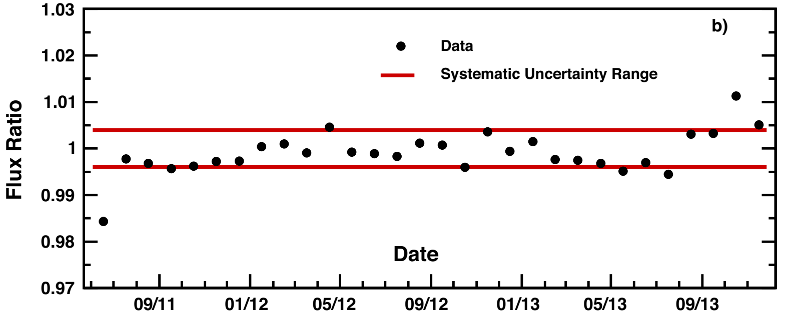
Verifications: Protons

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

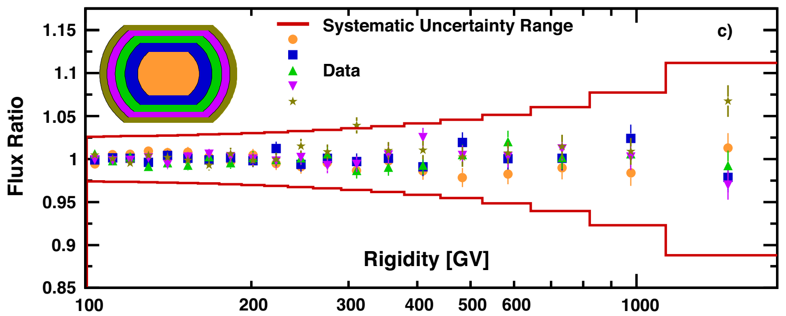




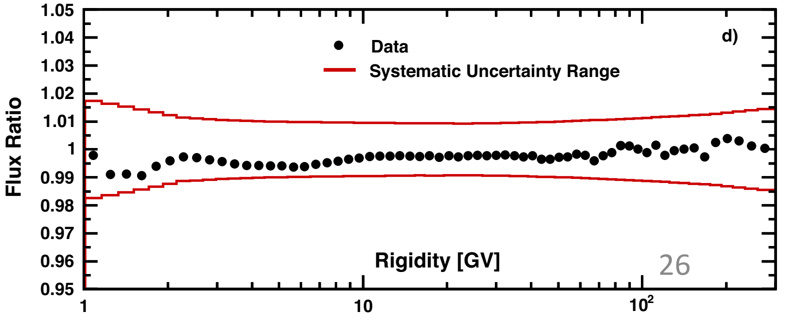
Time dependence of the high-energy flux: at R>45 GV no observable effects from solar modulation. This verifies that the **detector performance is stable**.



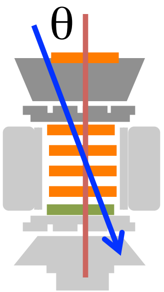
Flux reconstruction in different TOI entry regions of the acceptance. Verification of errors assigned to the tracker alignment.



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

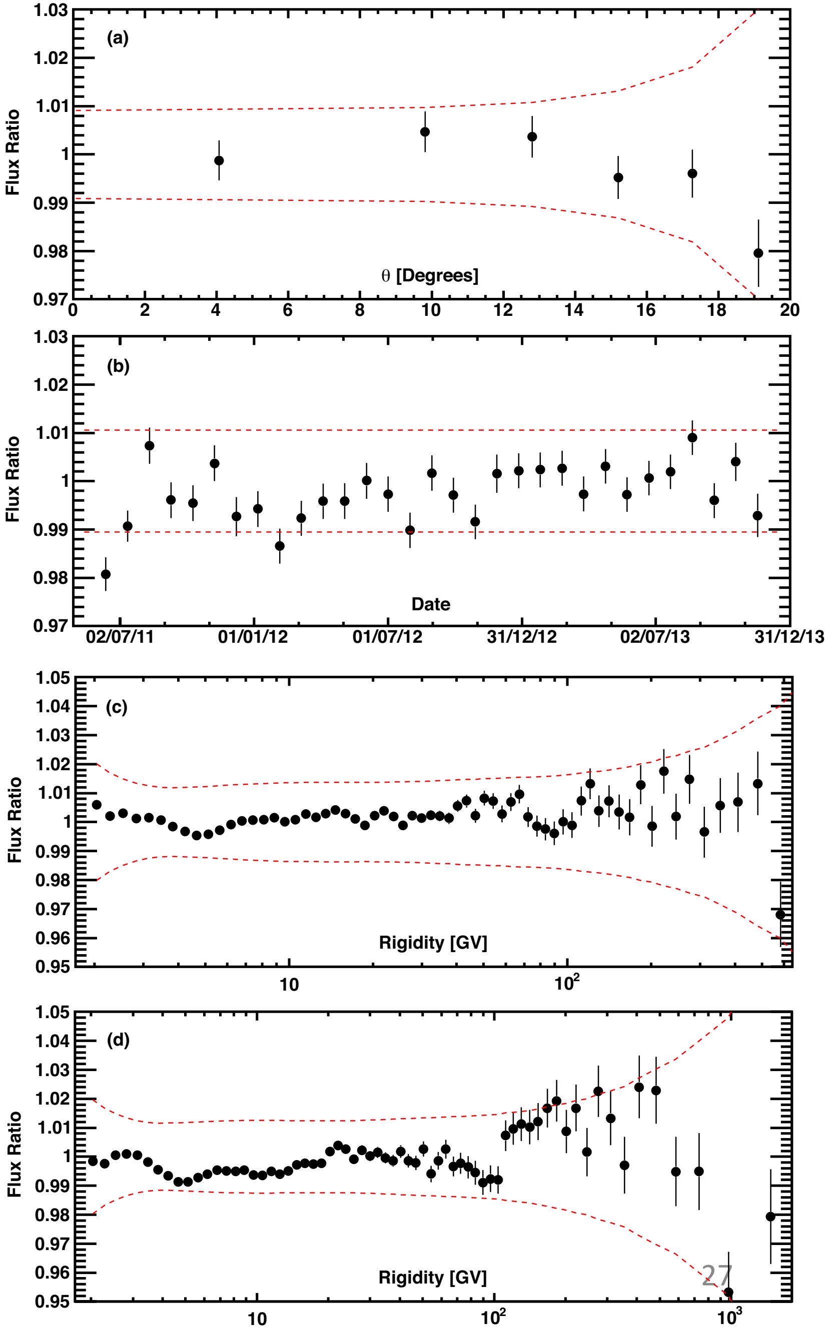


Angular dependence of measured flux at R>45 GV: to verify the systematic error assigned to the **acceptance.**

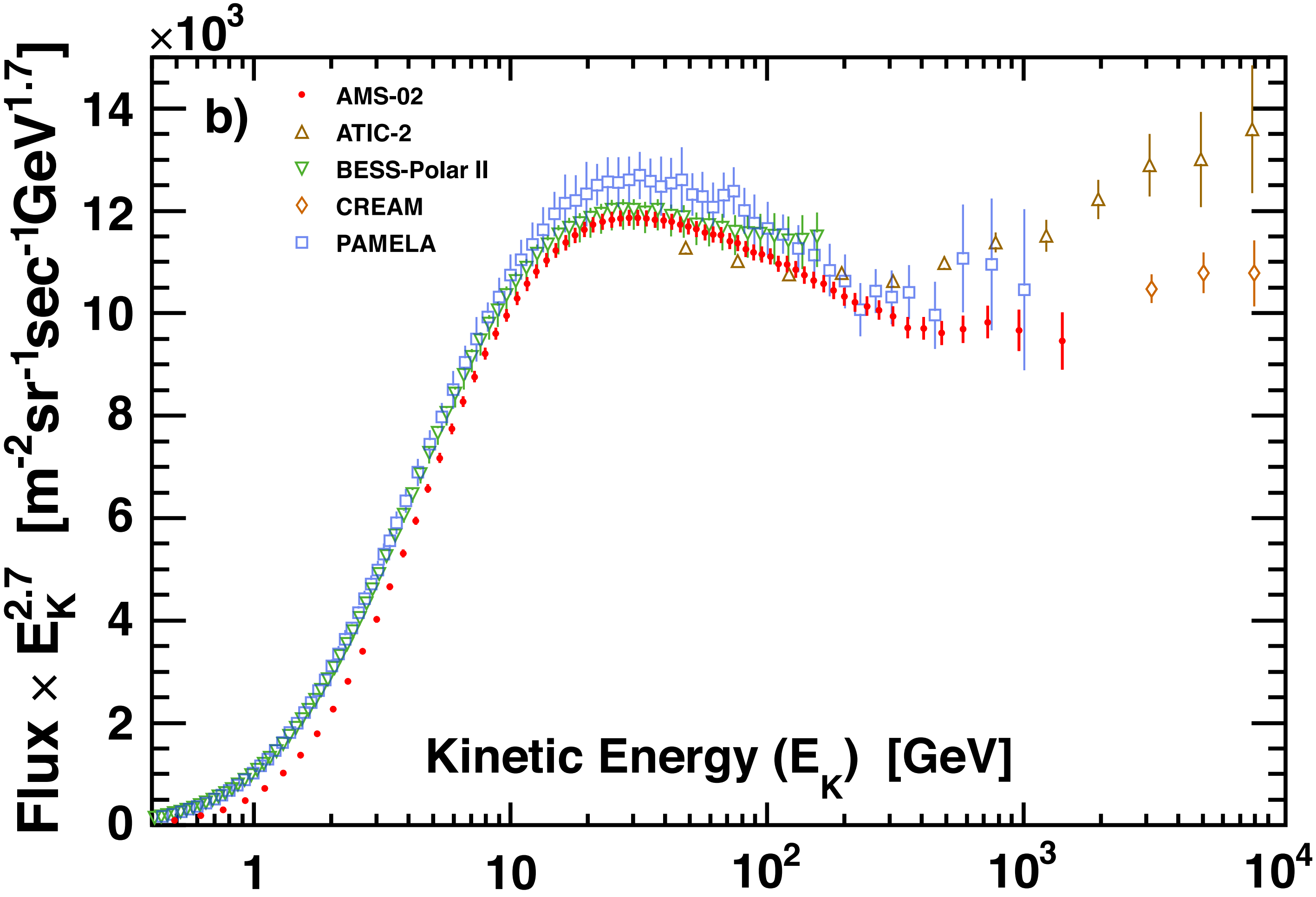
Time dependence of the high-energy flux: at R>45 GV no observable effects from solar modulation. This verifies that the **detector performance is stable**.

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**

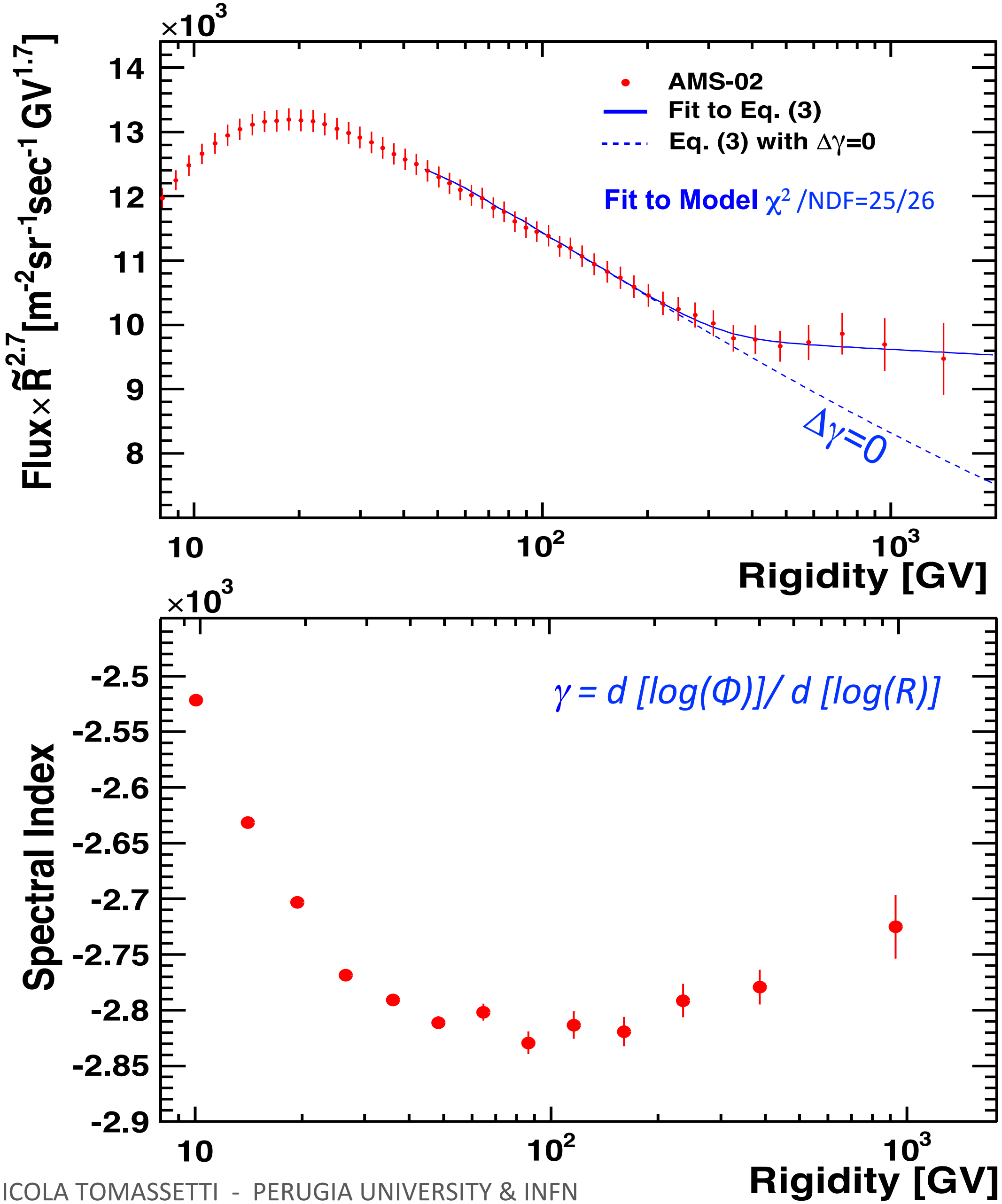
Measured flux using **inner tracker**, i.e., with a tracker pattern of different rigidity resolution and MDR. This verifies the errors on **rigidity resolution function and unfolding procedure**



Proton Flux VS Kinetic energy



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.

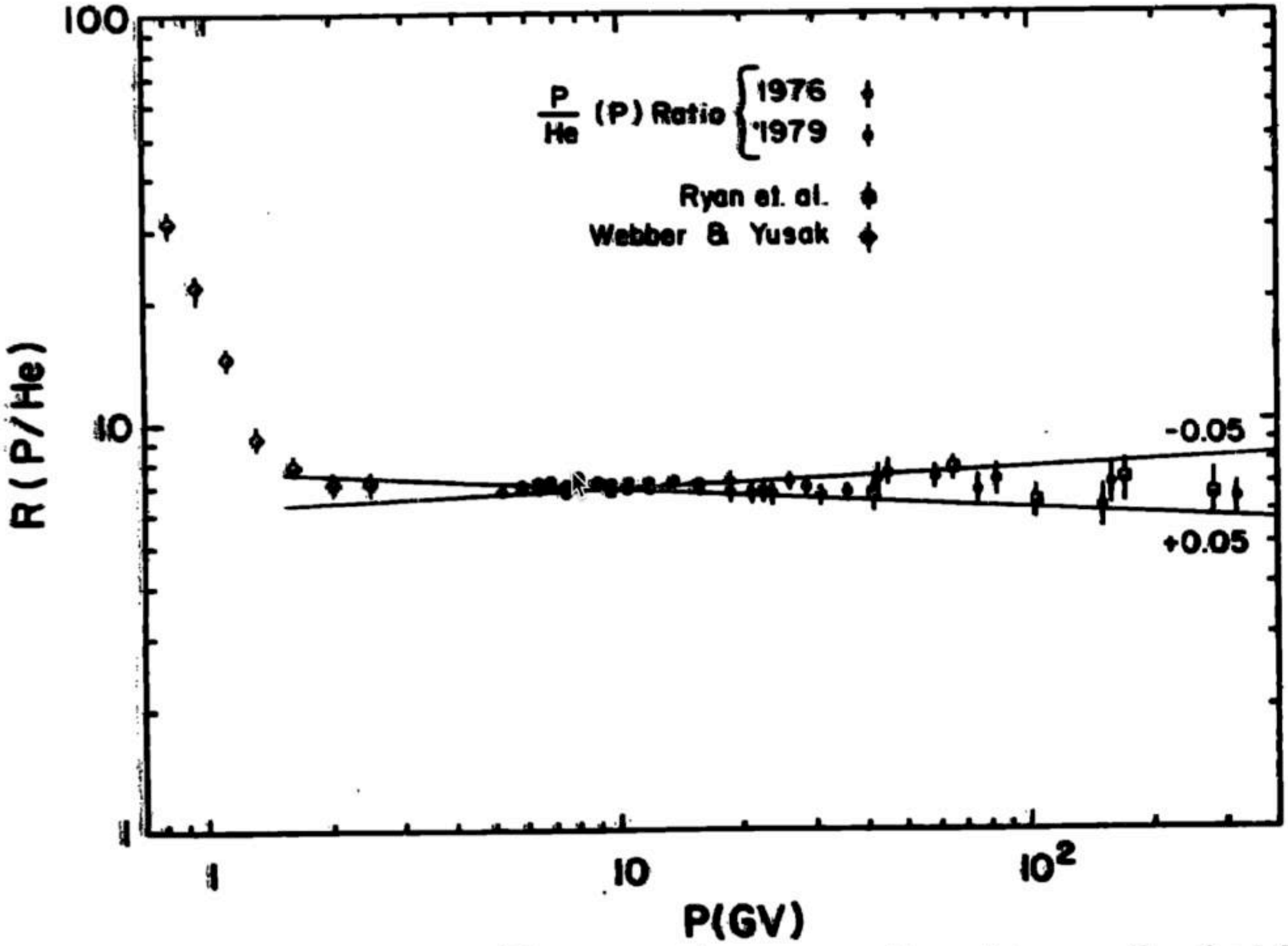
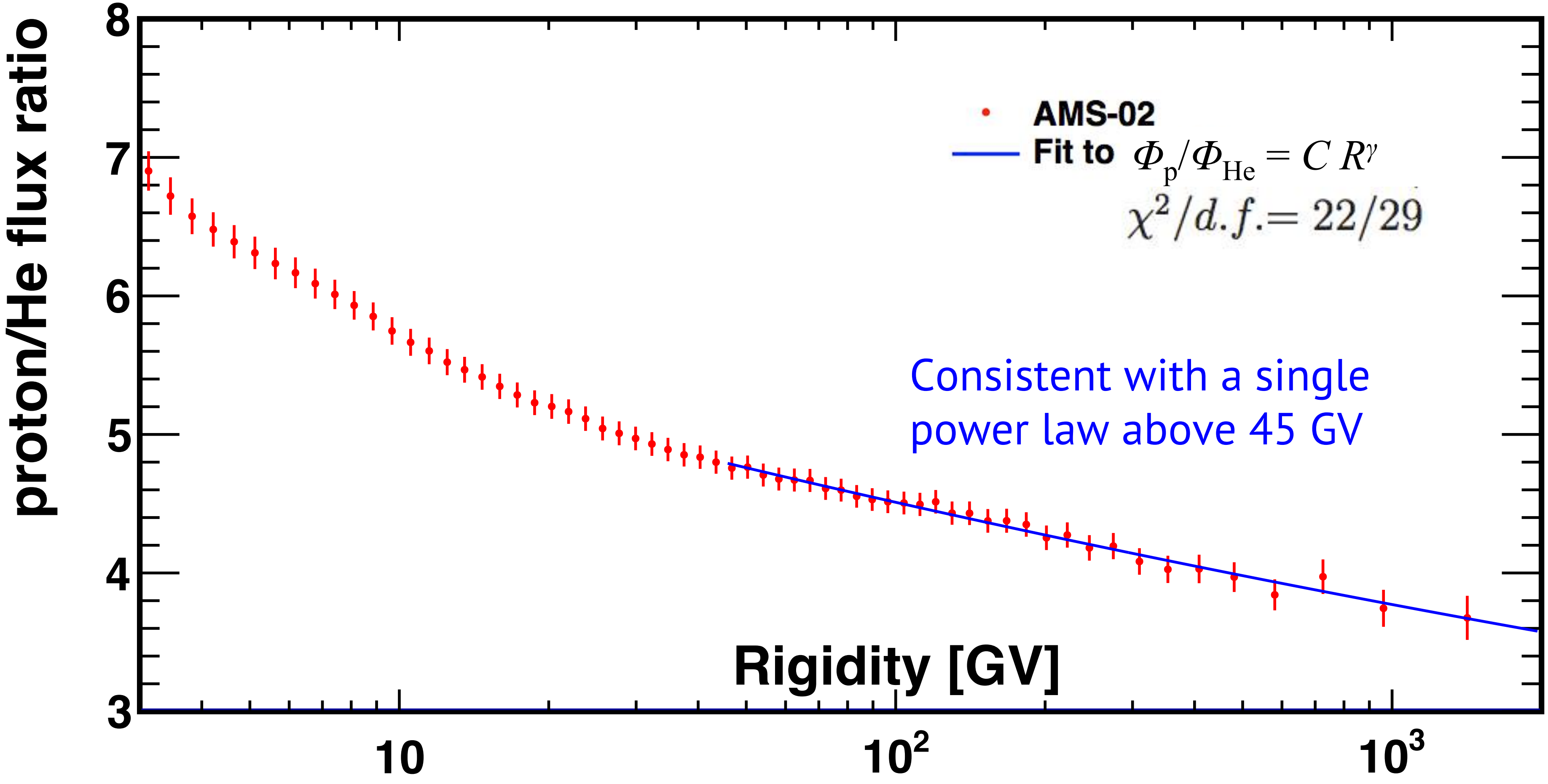


Figure 3. Protom to Helium ratio as a function of rigidity.

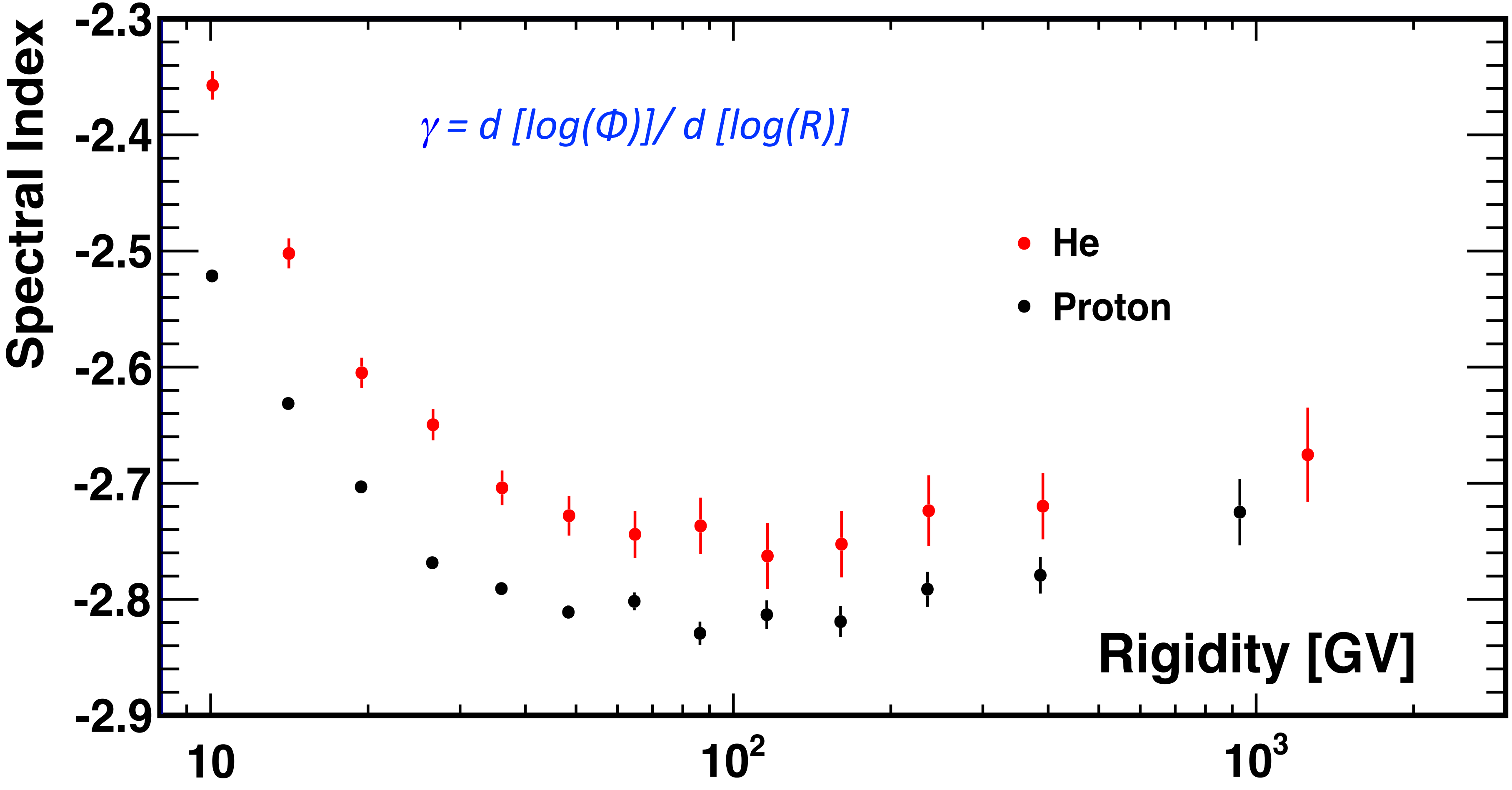
R. Webber et al. 1979

Proton/Helium Flux Ratio

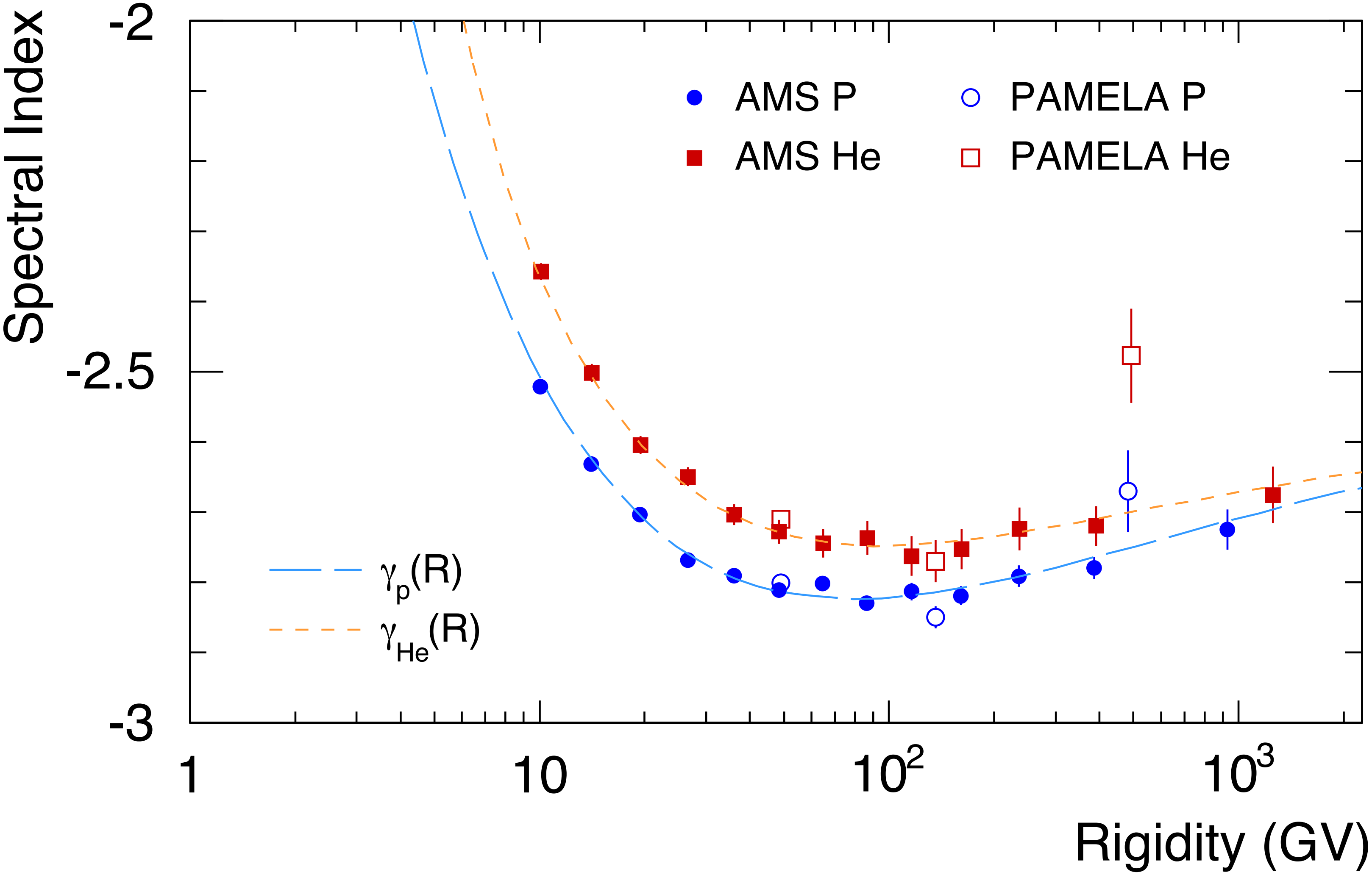


Consistent with a single power law above 45 GV

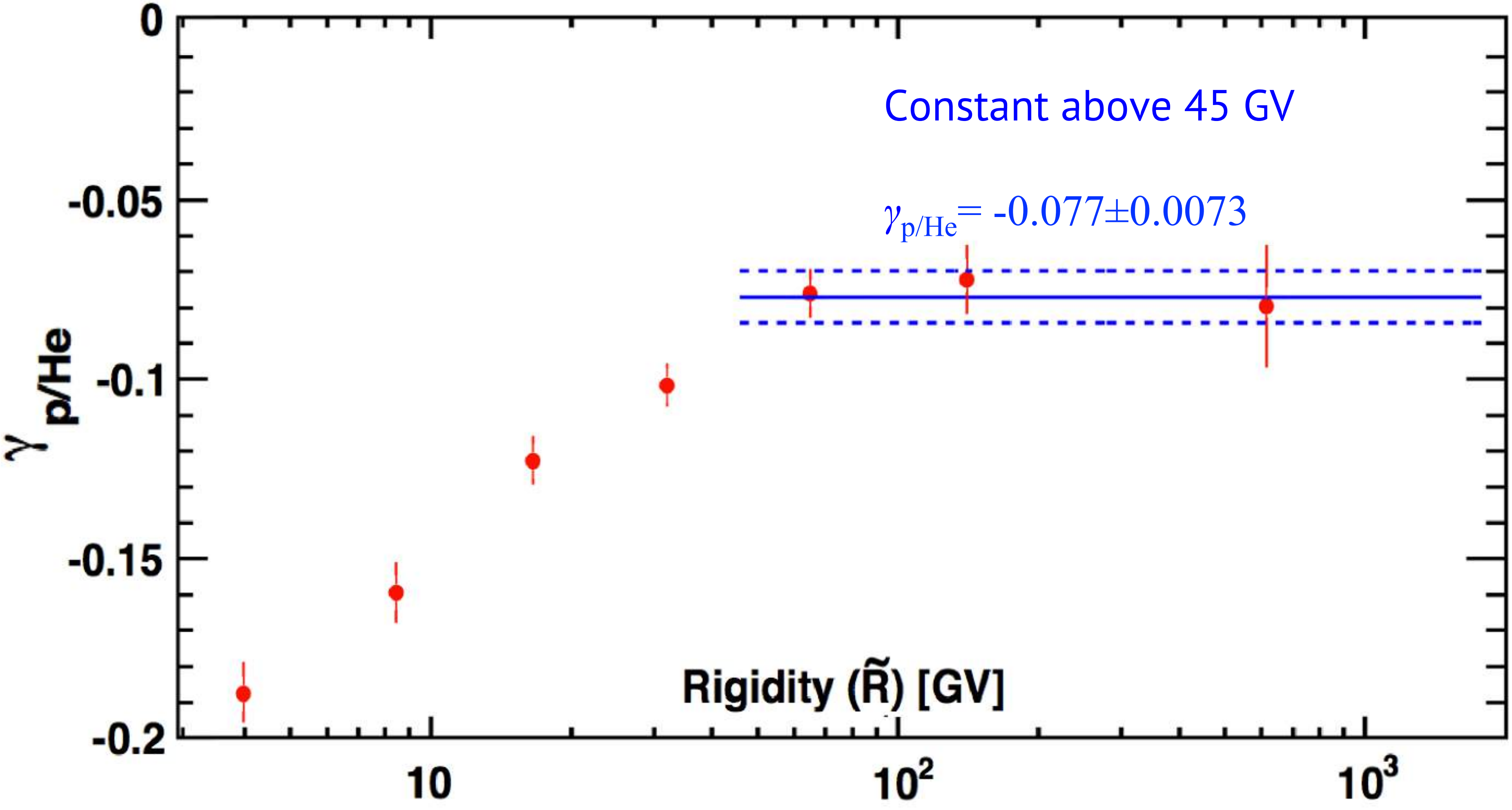
Helium Spectral Index



Proton & Helium Spectral Indices



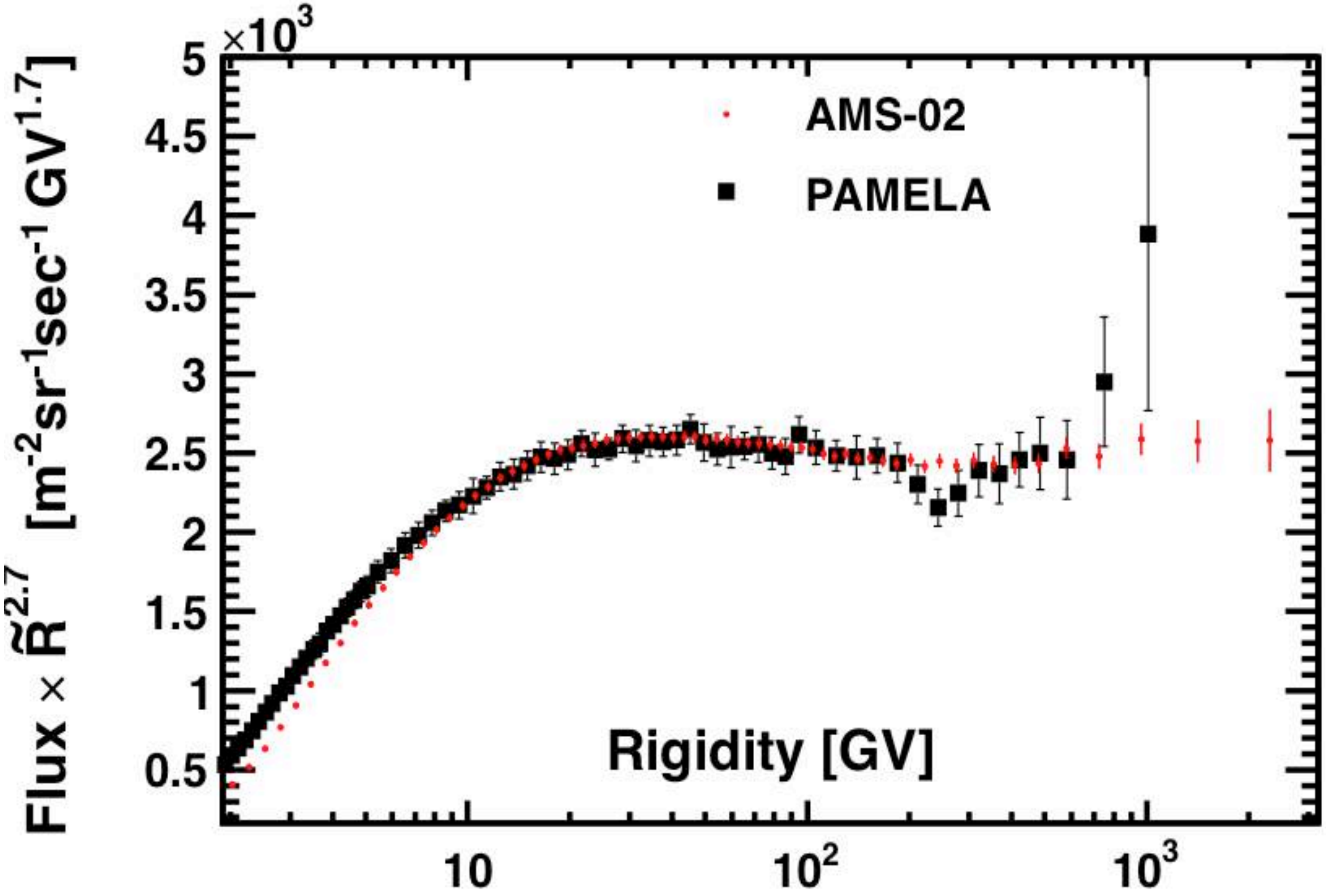
Proton/Helium Ratio Spectral Index



Constant above 45 GV

$\gamma_{p/He}$= -0.077±0.0073

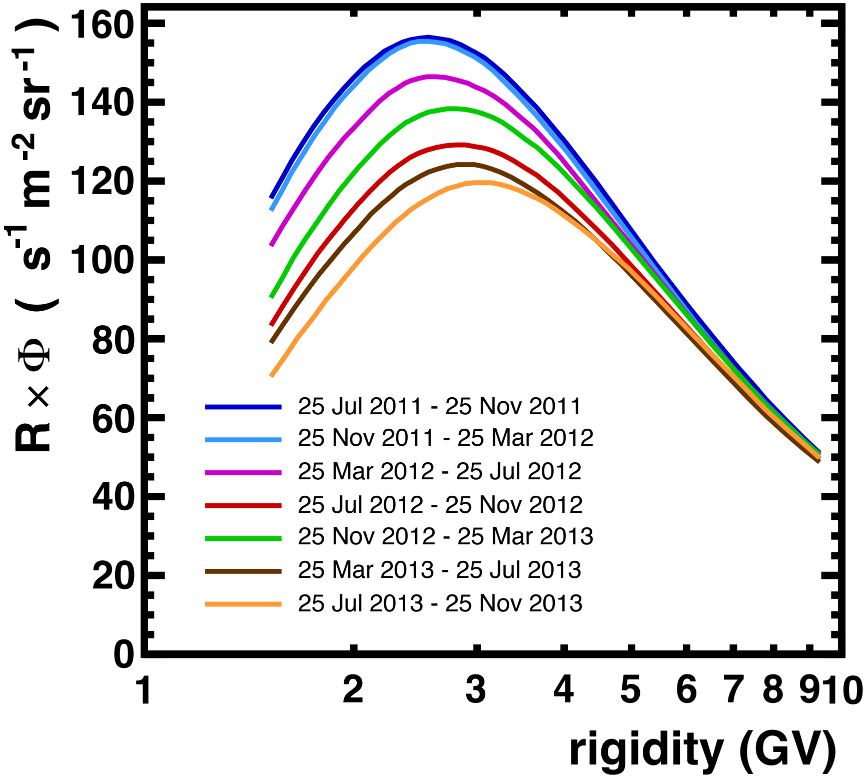
Helium Flux VS rigidity

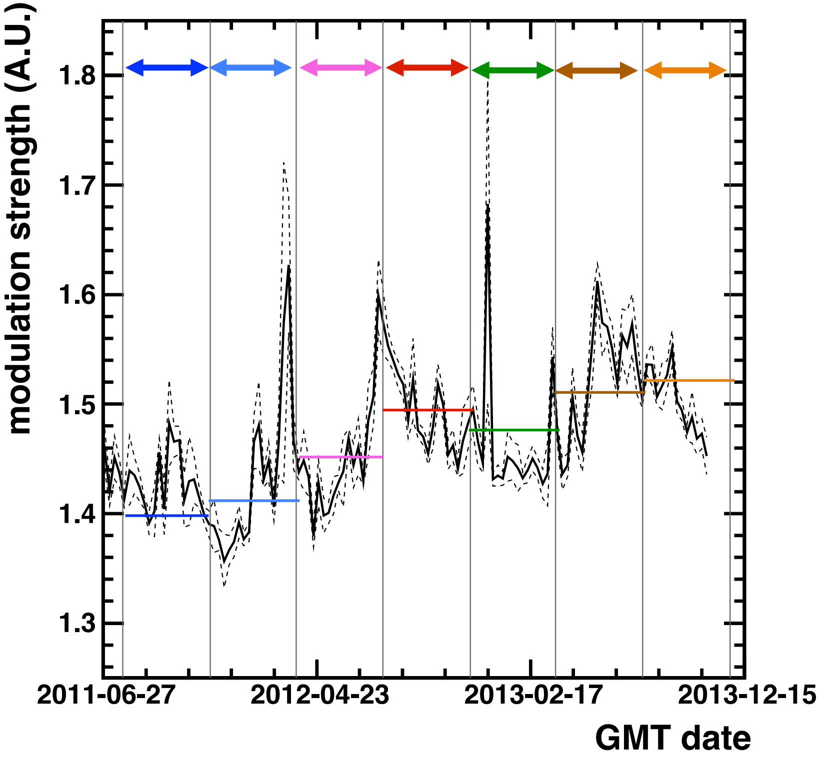


Low-Energy He spectrum and solar modulation

Helium spectrum from AMS data

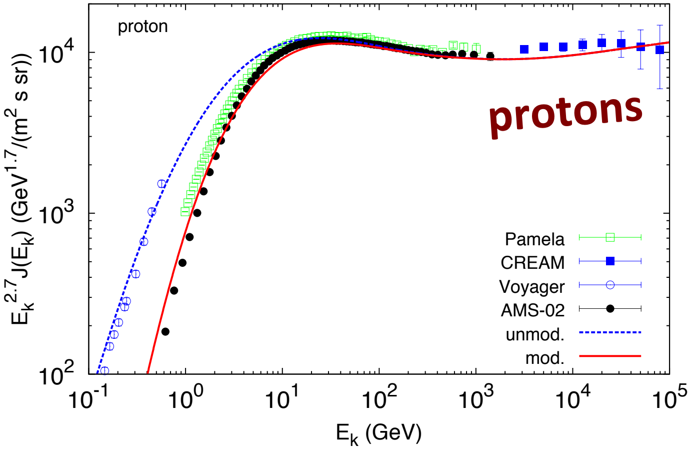
Modulation strength from neutron monitor data (OULU station)





Non-linear CR transport in self-induced turbulence

Self-induced (CR-driven) and pre-existing (SNR-generated) turbulence

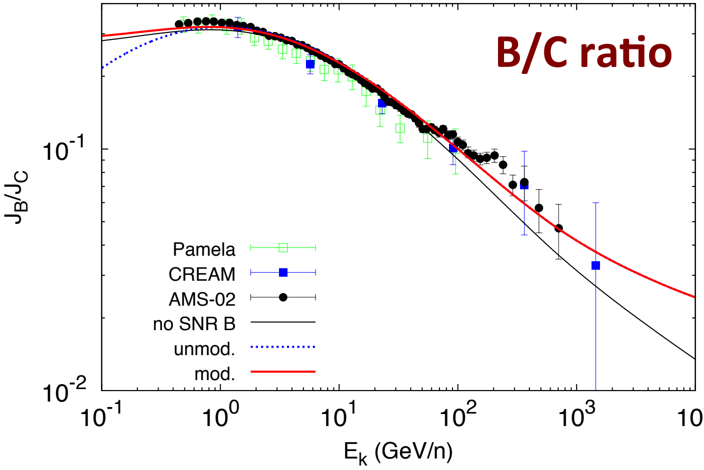


protons

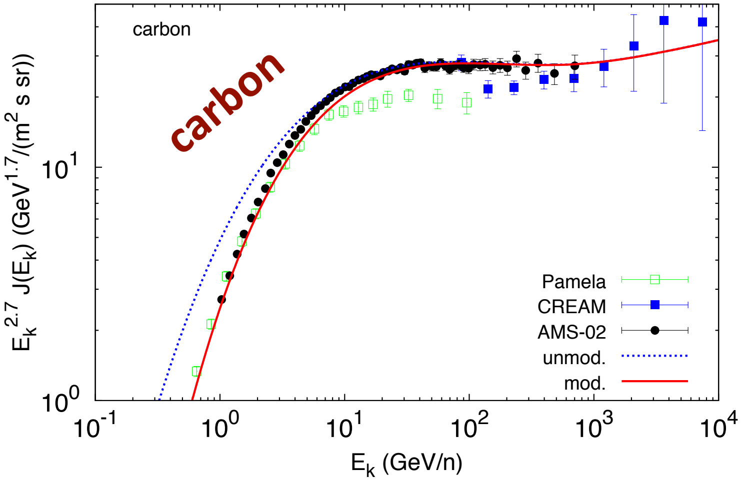
R. Aloisio et al. 1507.00594; P. Blasi et al. 1207.3706

- → **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**



B/C ratio



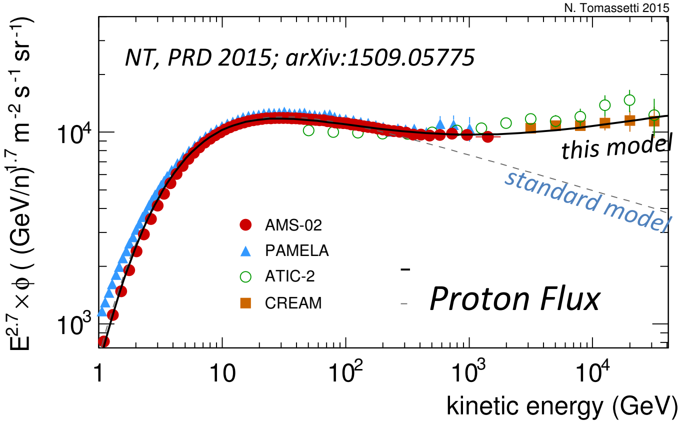
carbon

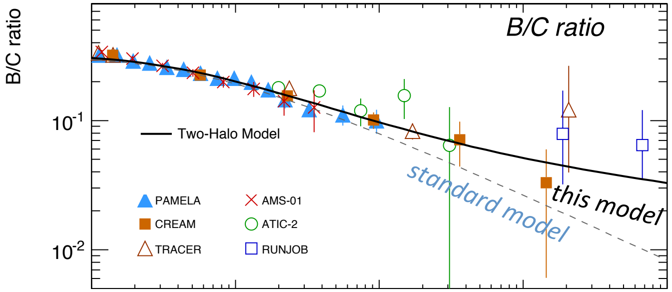
New phenomena in cosmic-ray propagation?

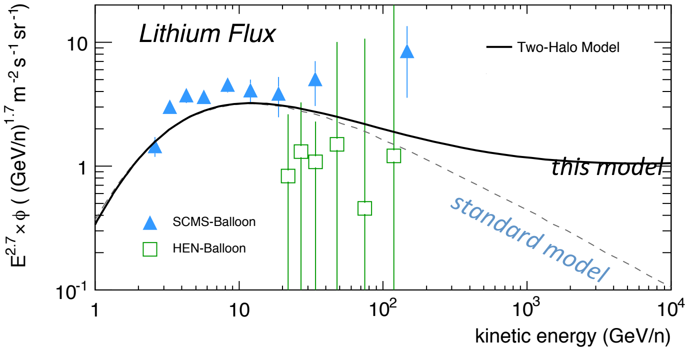
Diffusion coefficient is not separable into energy and space coordinates → no power-law
Shallower diffusivity in the region close to the Galactic disk → high-energy flattening

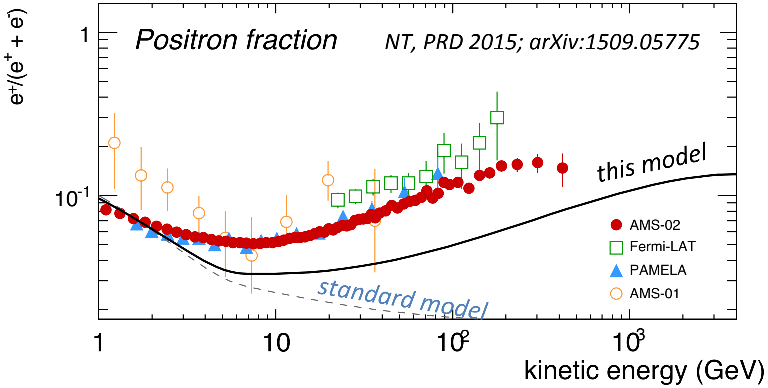
NT, 1204.4492 (2012); NT, 1509.05775 (2015)

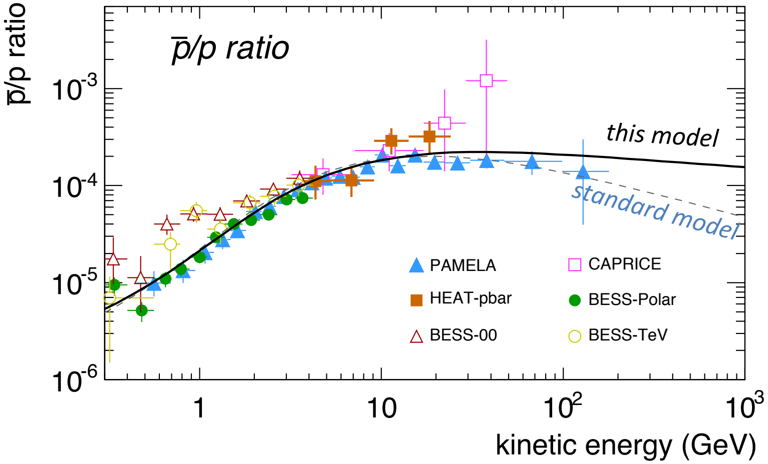
- ✓ **Predicted flattening in all nuclei and sec/pri ratios**
- ✓ **Enhanced antimatter production at high energy**
- ✓ **Connection with gamma-rays and anisotropy**











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

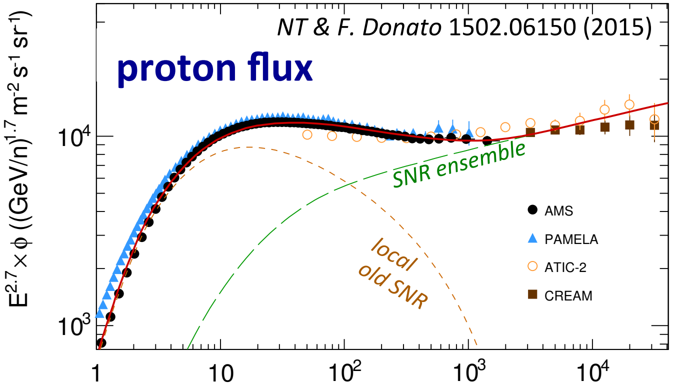
two SNR components in the CR flux

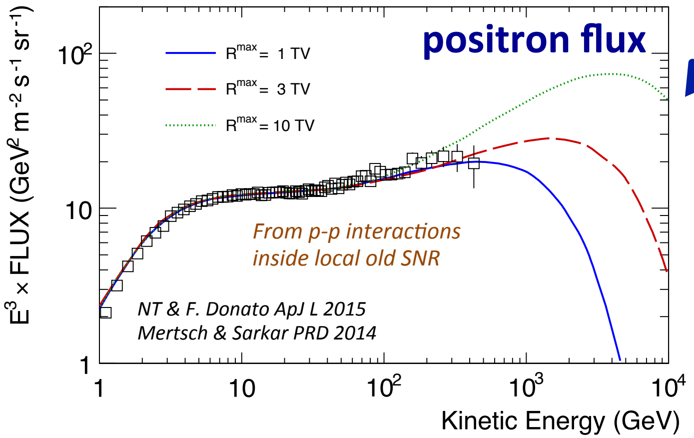
- *Nearby source component for the GeV-TeV flux (and e+ excess)*
  *Must have Rmax~TeV and secondary production (B~1uG, n>n_ISM, v~10^7 cm/s → **OLD SNR***
- *Galactic SNR ensemble*
  *Must have Rmax~PeV: B~500uG, v~10^9 m/s → **YOUNG SNRs***

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

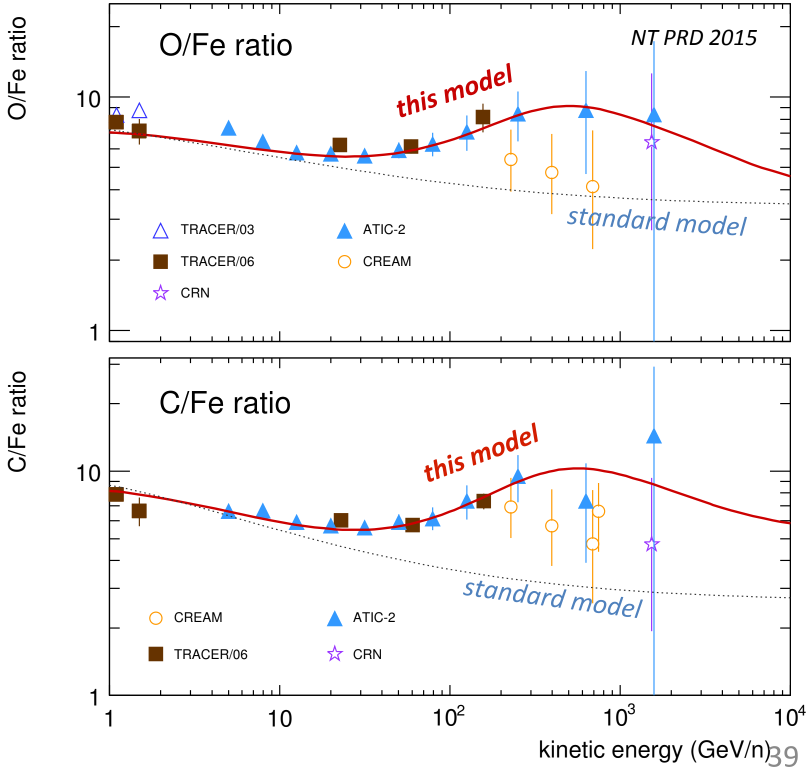
✓ **Predicted features in heavy nuclei: explanation of C/Fe and O/Fe** [NT, 1509.05774 (2015)]

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





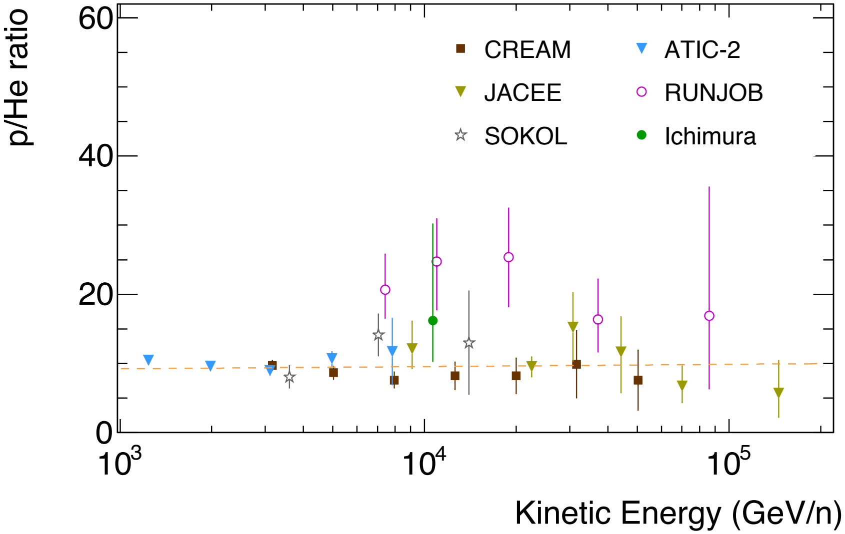
Unexplained rise in ATIC2 data of C/Fe and O/Fe



p/He ratio: two general considerations on the CR spectrum

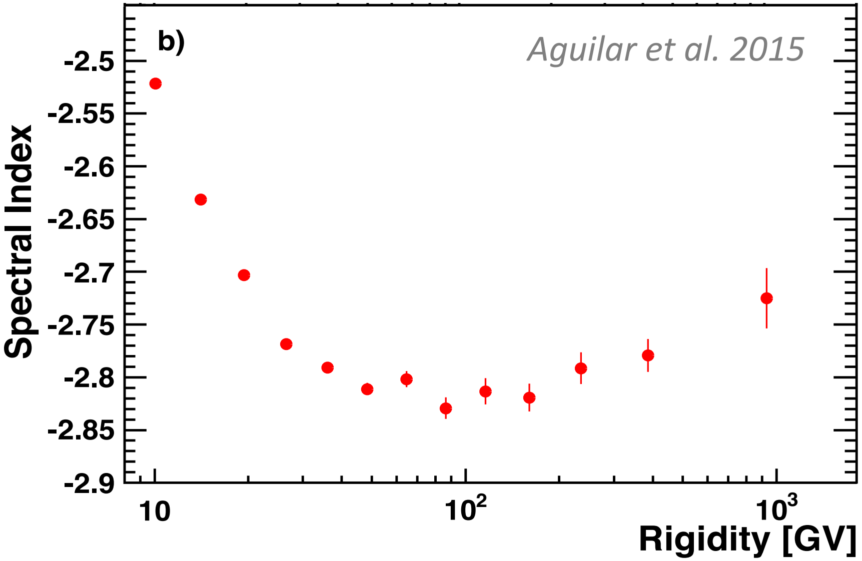
1. The data at multi-TeV energy do *not* show evidence of p/He decreasing. The p/He ratio at high-energy is essentially constant.

   This trend, if confirmed, will invalidate the existing explanations based on intrinsic properties of the DSA mechanism



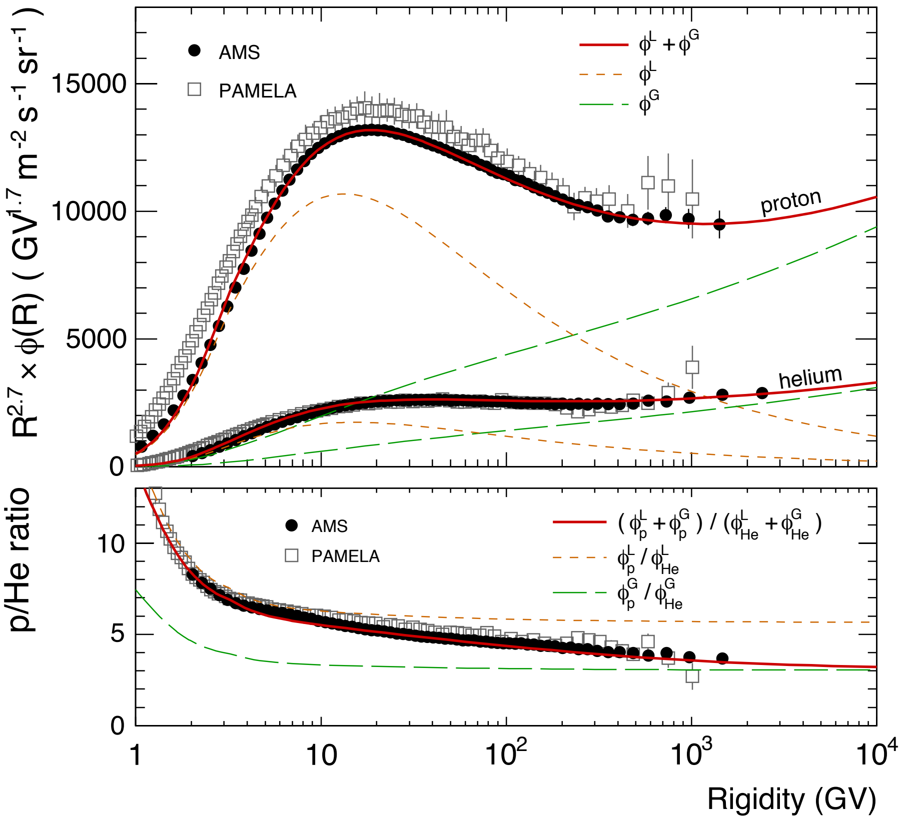
2. The AMS data indicate that the proton spectral change is much *smoother* than that reported by PAMELA. The differential slope hardens progressively at E>100 GV, without any spectral kink.

   This invalidates the usual considerations that the p/He ratio "cancels out" the features of the single p and He spectra.



The p/He ratio seems rather a ~10-1000 GV feature, vanishing at higher energies

p/He ratio anomaly as signature of a nearby source



The idea. Two different classes of sources contribute to the CR flux. Each class has different spectra and composition.

Low-energy flux (GeV-TeV energies)

Nearby old SNRs. The shock is weaker, the B-field are damping, the DSA is not efficient

→ **The injection spectra may be steeper**

Higher background density for p+p interactions (to explain the e+ excess), e.g. due a molecular cloud

→ **It may be well a hydrogen-rich source**

High-energy flux (TeV-PeV energies)

Galactic SNR ensemble. Younger SNRs, with stronger shock and B-field amplification

→ Efficient DSA woring up to PV rigidities.

→ Hard acceleration spectra: slope ~2-2.1.

Composition = average Galactic SNRs properties

- ✓ **Single p & He spectral hardening -> signature of transition to different DSA spectra**
- ✓ **pHe ratio -> signature of transition to different composition of H & He in the medium**

Each class of source has elemental-independent spectra → the DSA universality is preserved

p/He ratio: two general considerations on the CR spectrum