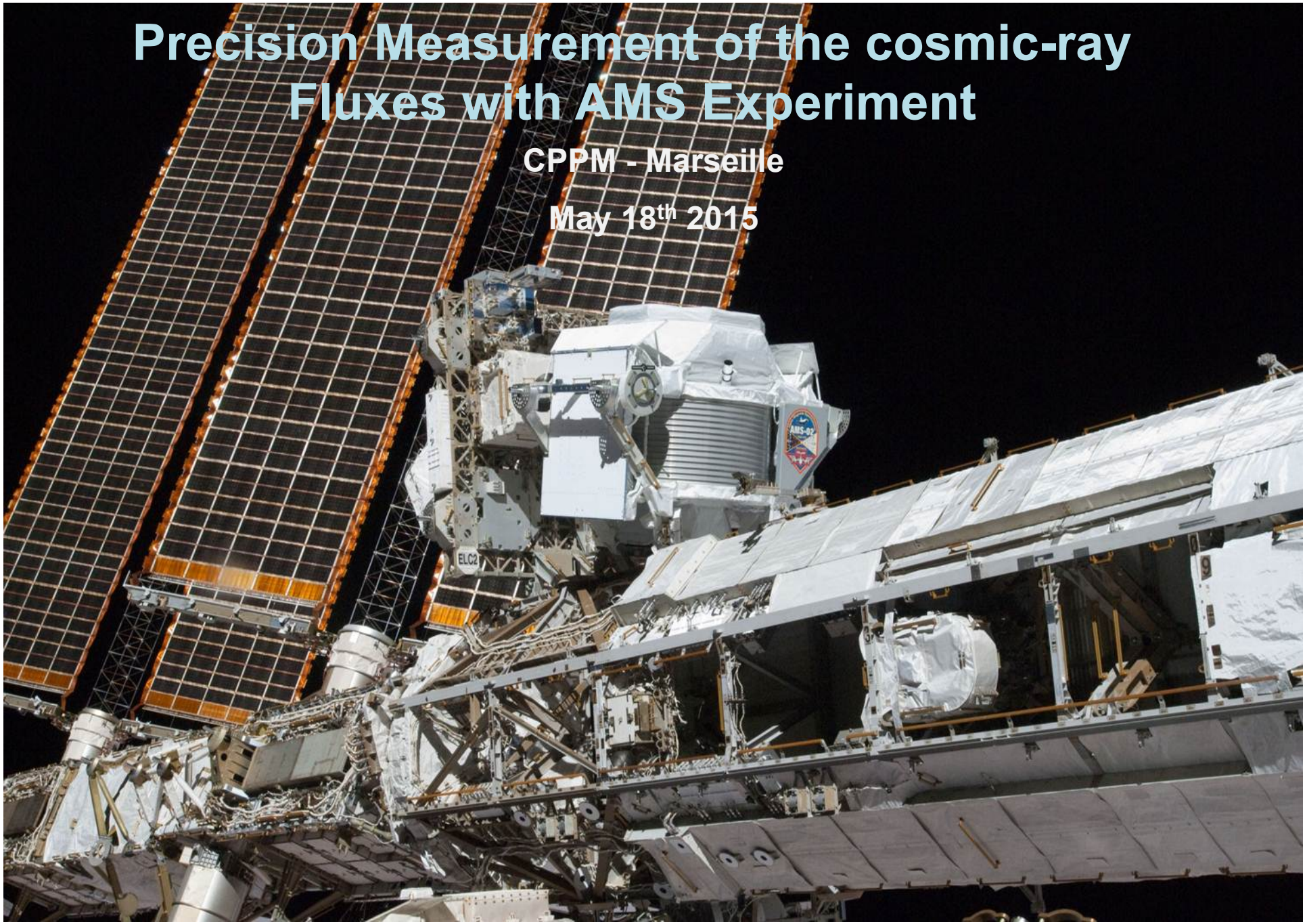
Precision Measurement of the cosmic-ray Fluxes with AMS Experiment

CPPM - Marseille

May 18th 2015



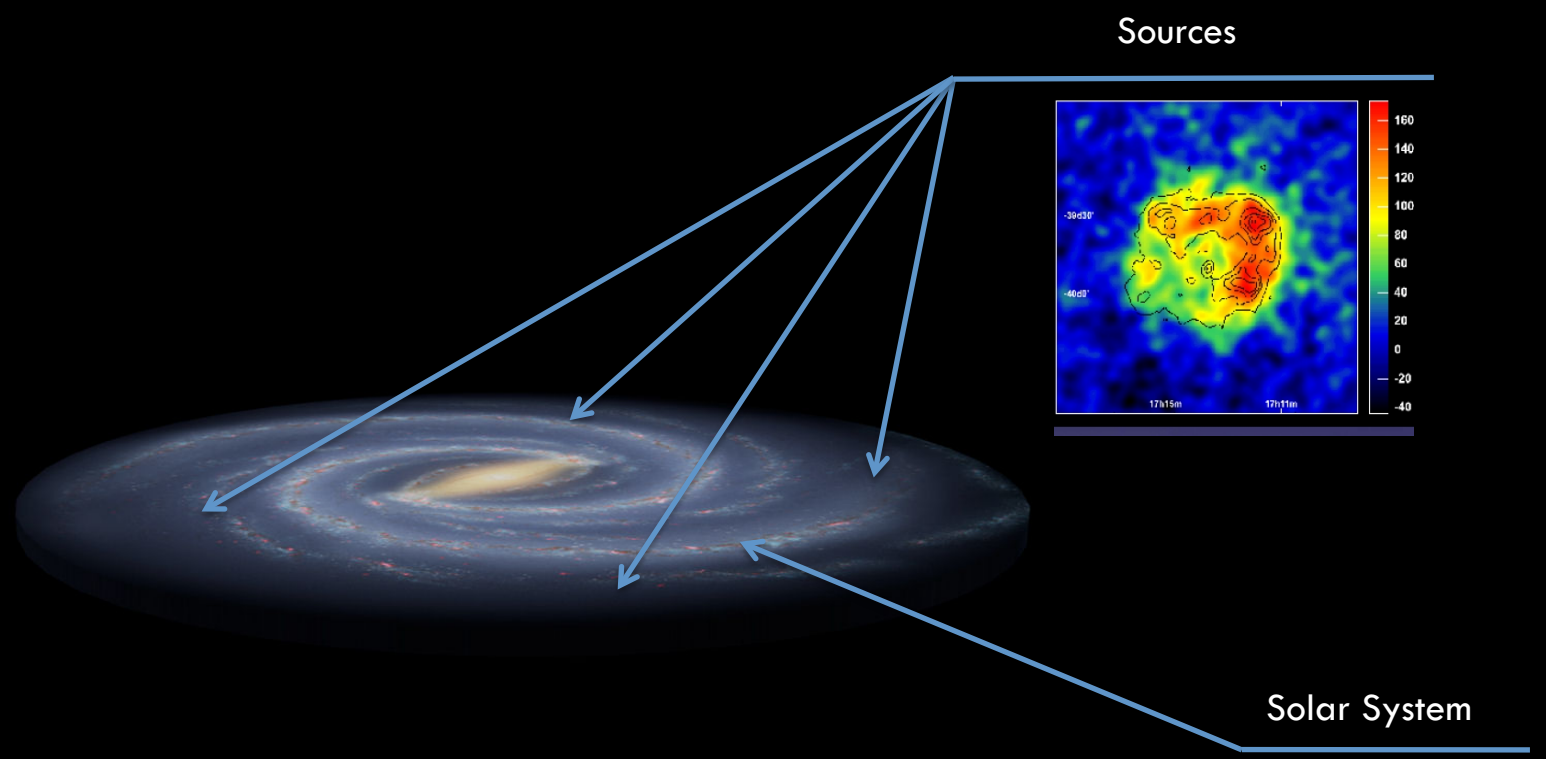
L. Derome/LPSC – Université de Grenoble-Alpes

Plan

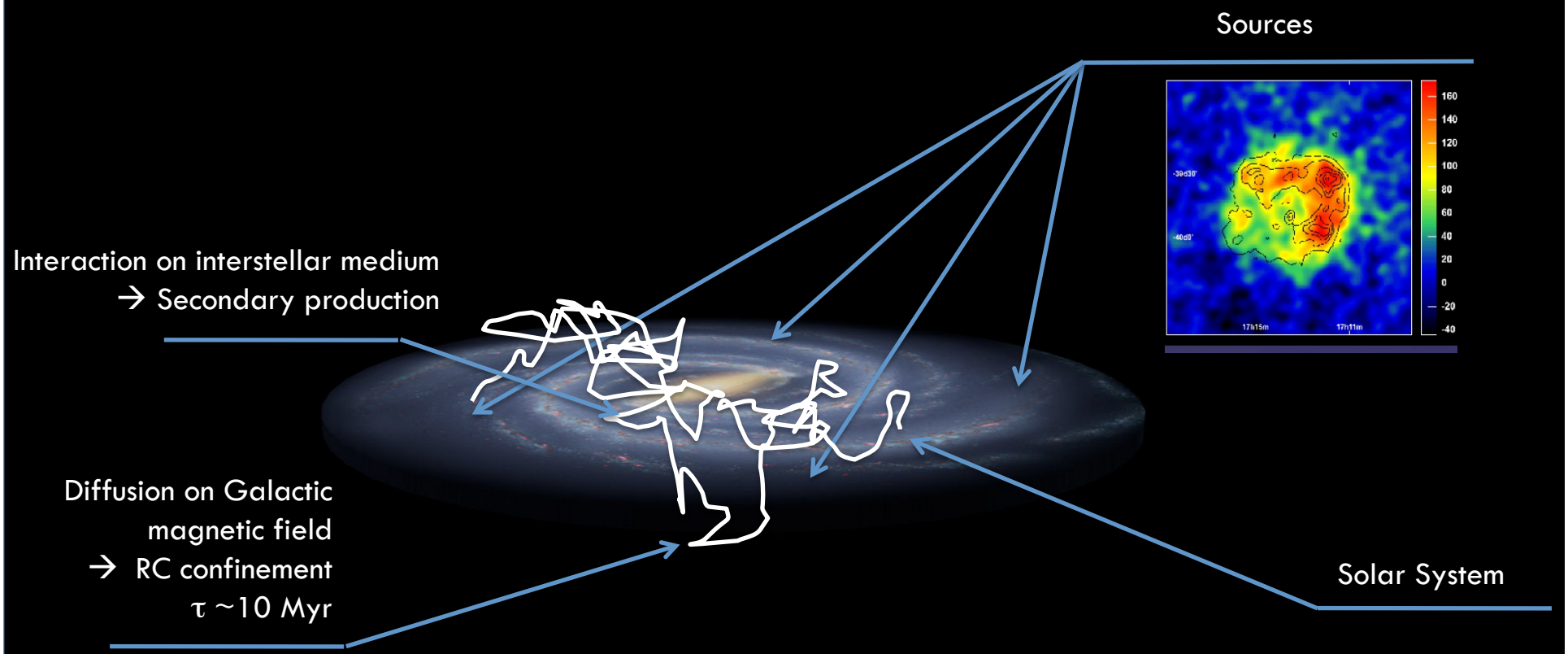
- Cosmic-ray Physics
- AMS experiment
- Proton flux measurement with AMS
- Latest Helium flux from AMS
- Progress report on Lithium Flux
- Progress report on B/C
- Progress report on pbar/p ratio.

→ *More details on AMS-days@CERN. Presentations available online*

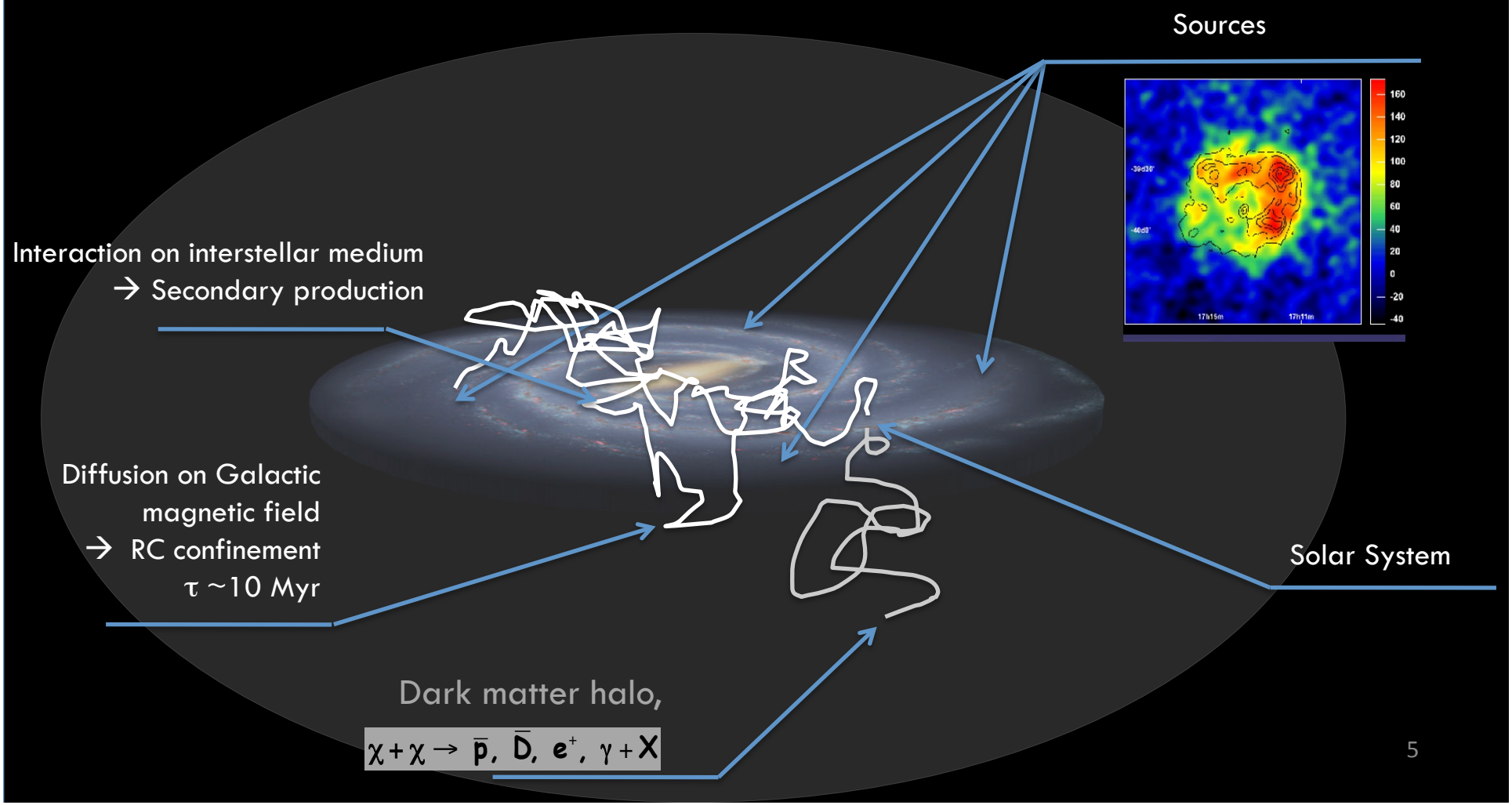
Cosmic rays



Cosmic rays


Sources
Interaction on interstellar medium
→ Secondary production
Diffusion on Galactic
magnetic field
→ RC confinement
τ ~10 Myr
Solar System

Cosmic rays


Sources
Interaction on interstellar medium
→ Secondary production
Diffusion on Galactic
magnetic field
→ RC confinement
τ ~10 Myr
Solar System
Dark matter halo,
$\chi + \chi \rightarrow \bar{p}, \bar{D}, e^+, \gamma + X$

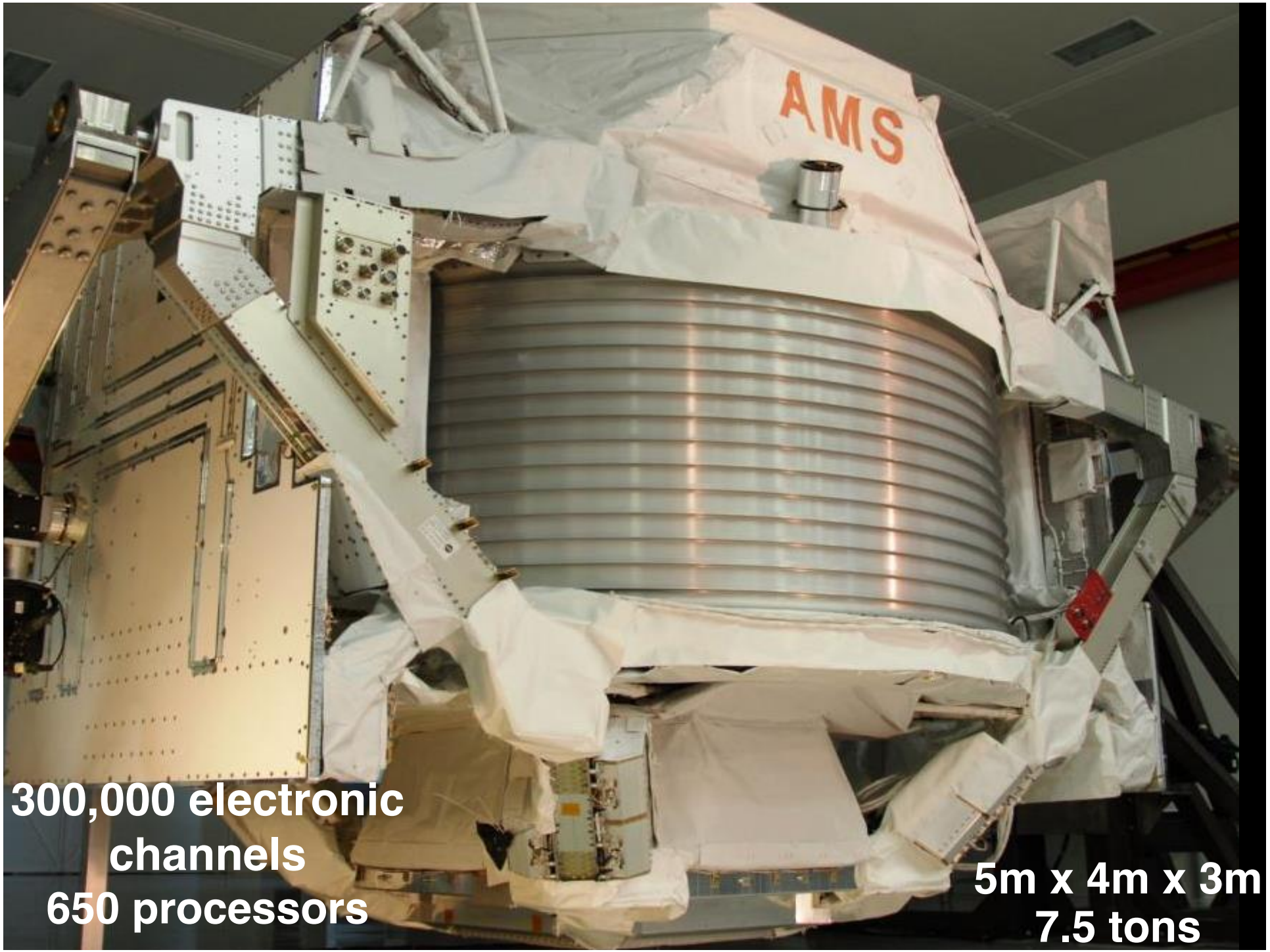
Cosmic rays

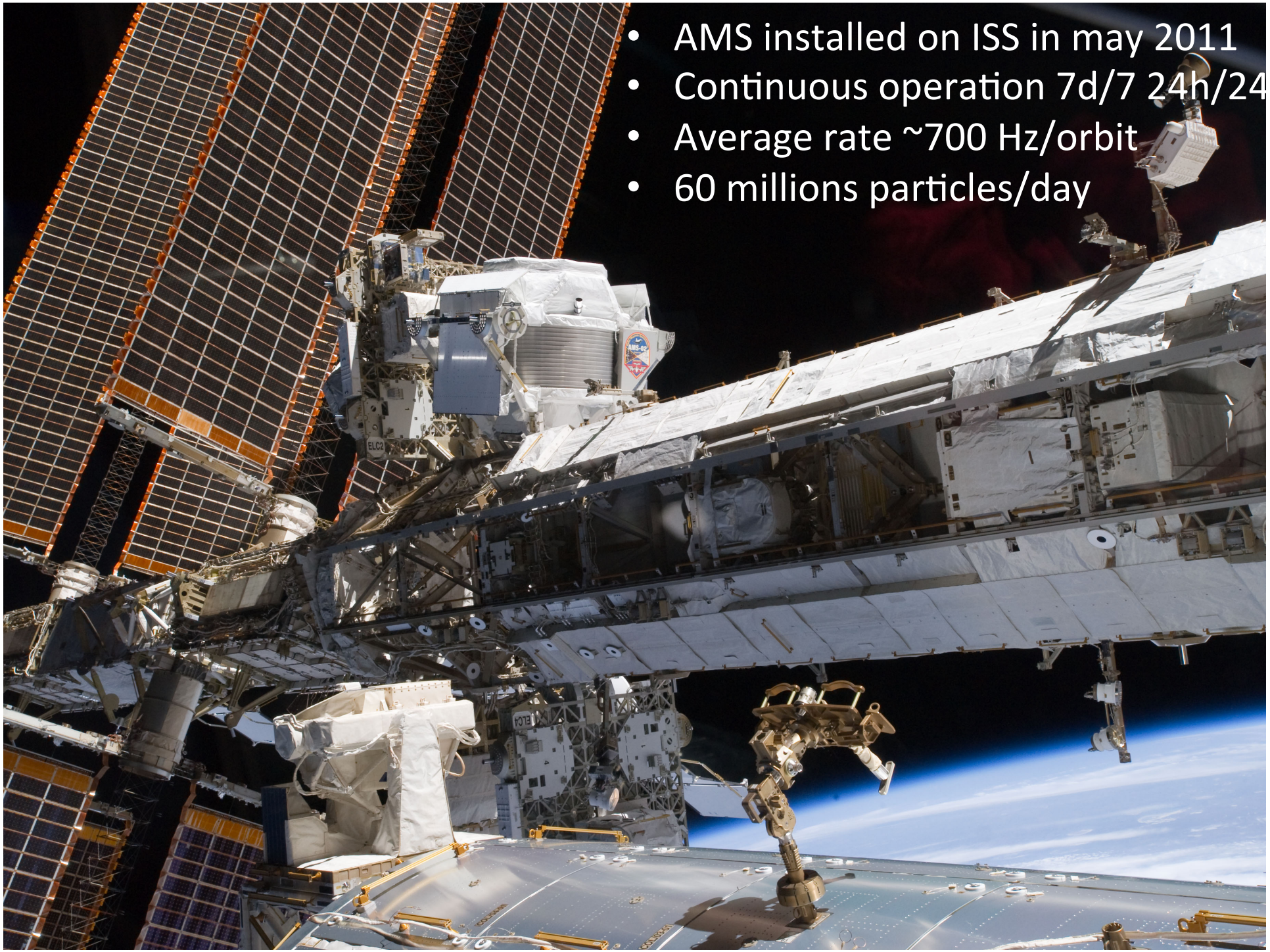
- Key measurements in cosmic-ray physics:
  1. p, He, C, N, O,… : Primary component (mainly produced and accelerated in the CR sources) :

     → CR origin: Understanding sources, acceleration mechanism
  2. Li, Be, B, … (+ $\bar{p}$, e^+) and ratios (B/C, …) : Secondary component

     → CR Propagation
  3. $\bar{p}$, $\bar{D}$, e^+: DM searches

     → Room for DM? *Do we need extra sources to reproduce $\bar{p}$ and e^+ signals or are they compatible with a pure secondary production? need for precise description of:*
     - *CR propagation mechanism*
     - *The dominant CR components (Primaries)*
- AMS as the capability to address these points with high precision data.


AMS
300,000 electronic
channels
650 processors
5m x 4m x 3m
7.5 tons



- AMS installed on ISS in may 2011
- Continuous operation 7d/7 24h/24
- Average rate ~700 Hz/orbit
- 60 millions particles/day

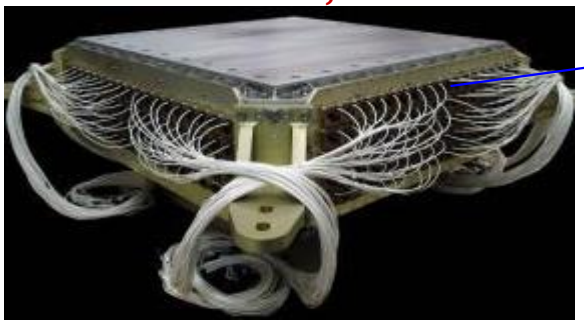
AMS: A TeV precision, multipurpose spectrometer

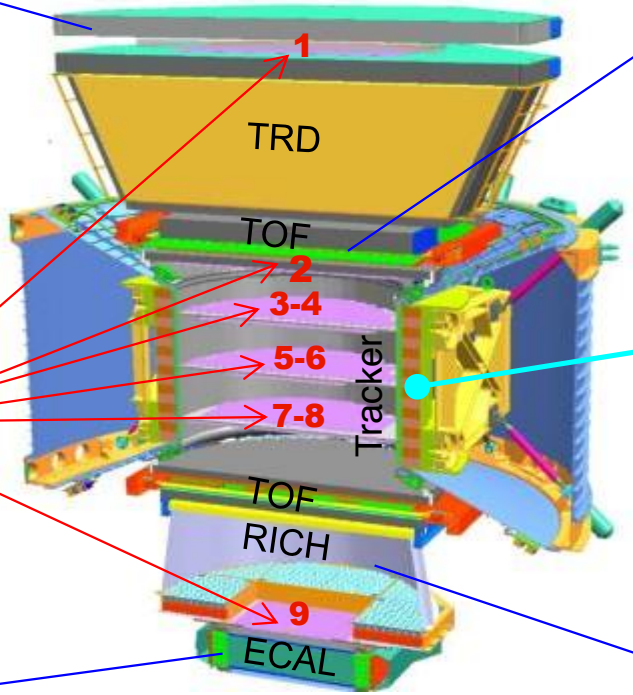
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

TRD
Identify e^+, e^-

Silicon Tracker
Z, P

ECAL
E of e^+, e^-



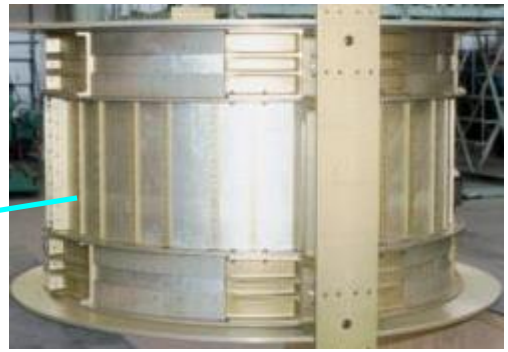


Z and P

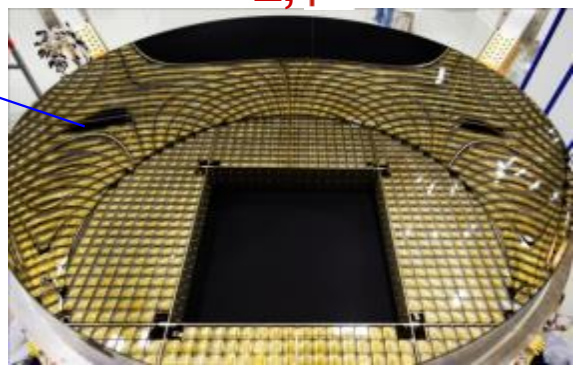
are measured independently by the Tracker, RICH, TOF and ECAL

TOF
Z, β

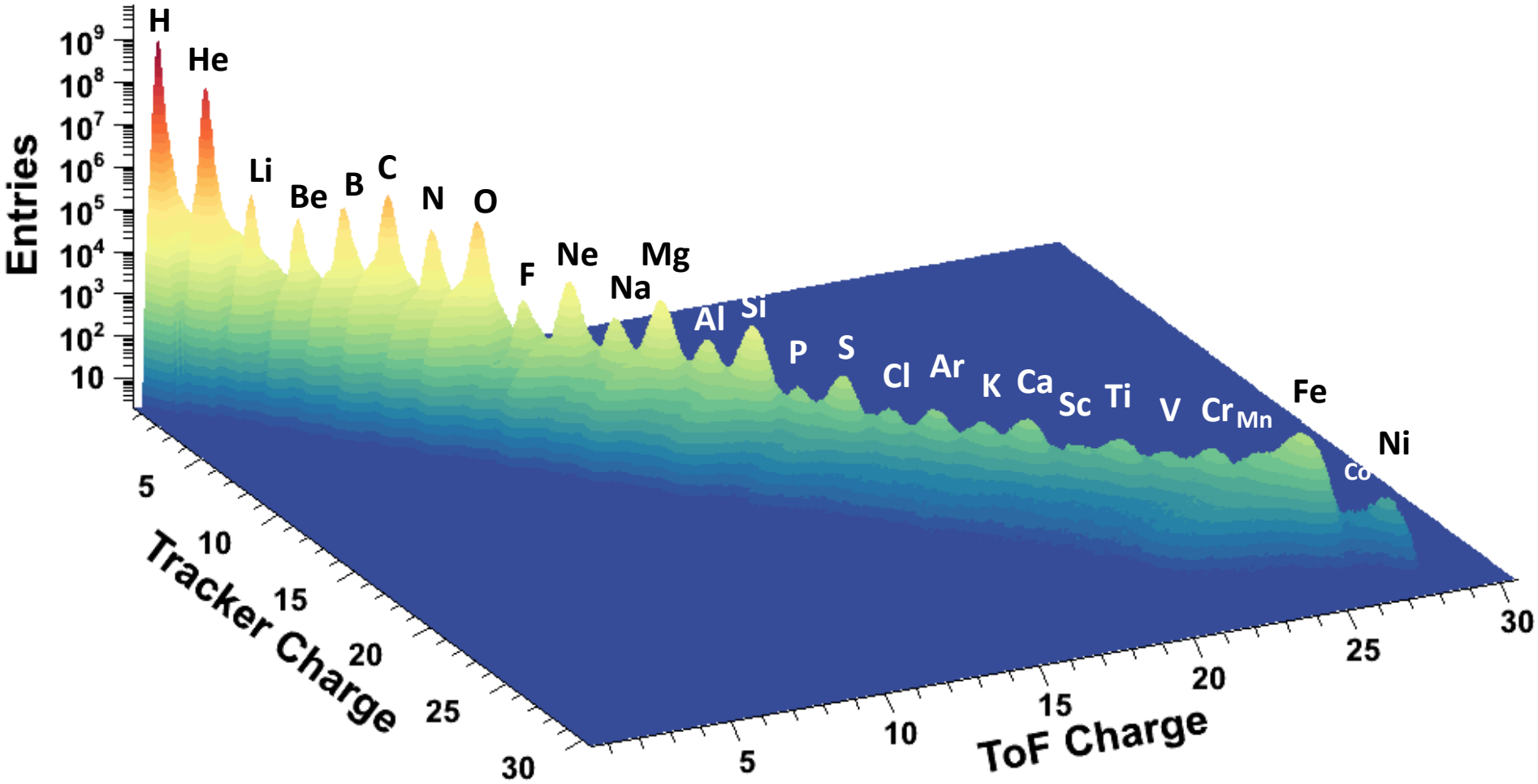
Magnet
±Z



RICH
Z, β



Nuclei Identification in AMS



Proton flux

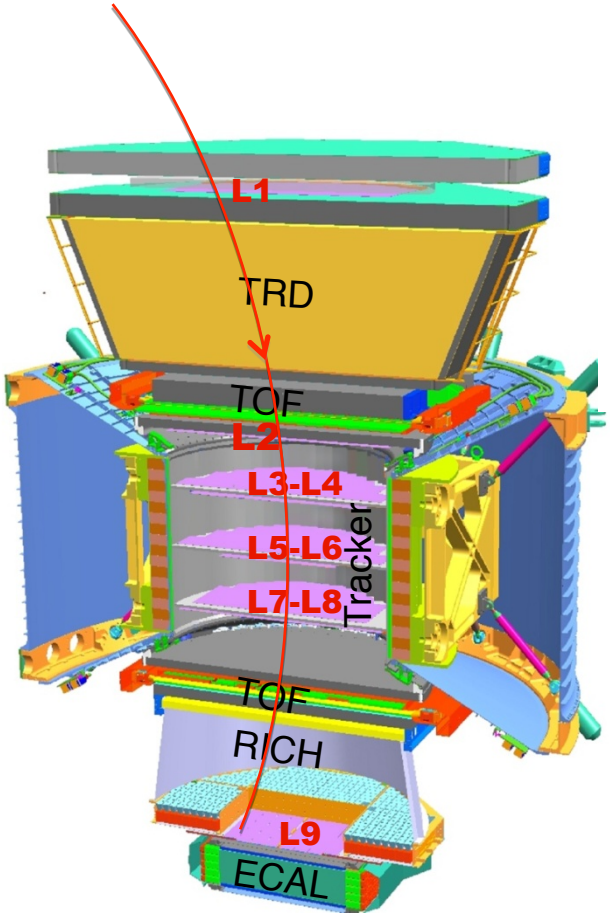
PRL **114,** 171103 (2015) PHYSICAL REVIEW LETTERS week ending 1 MAY 2015

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

Protons are the most abundant charged particles in cosmic rays. Knowledge of the precise behavior of the proton spectrum is important in understanding the origin, acceleration, and propagation of cosmic rays.

Recent important measurements of the proton flux in cosmic rays have reported different variations of the flux with energy.
In particular, the ATIC–2, CREAM, and PAMELA experiments showed deviations of the proton flux from a single power law..

AMS Cosmic Ray Protons Measurement



Tracker (9 Layers) + Magnet

Rigidity (P/Z) and Charge Sign

Bending Coordinate Resolution (Z=1) ≈ 10 μm

MDR (Z=1) ≈ 2 TV

ToF (4 Layers)

Velocity and Direction

$\Delta\beta/\beta^2$ (Z=1) ≈ 4%

TRD, Tracker, RICH ,TOF, ECAL

Charge Magnitude Along Particle Trajectory

ΔZ (Z=1) ≈ 0.05-0.2

Proton Selection

(I) Downgoing Particle $\beta > 0.3$

(II) Rigidity (R) above Geomagnetic Cutoff (R_C)

$R > 1.2R_C$ [IGRF Magnetic Field]

(III) Charge $|Z|\sim1$ along Particle Trajectory:

For instance, for Inner Tracker $0.7 < |Z| < 1.5$

(IV) Full Tracker Level arm (L1 to L9), Z>0

(V) χ^2/NDF of the Particle Trajectory Fit < 10

Efficiency 98-99 %, Removes Bulk of Events with Large Scattering and Wrongly Measured Rigidity

(VI) Reconstructed Mass > 0.5 GeV/c^2

Removes low rigidity π's

Flux Measurement

Assuming flux over geomagnetic cutoff is isotropic
the differential in rigidity flux can be defined as

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

Events Corrected for Bin to Bin Migration (iv) due to Tracker Rigidity Resolution (v)

Bin width

Time ~63,000,000 sec, R>30 GV (iii)

i=1,72

Rigidity 1-1800 GV (vi)

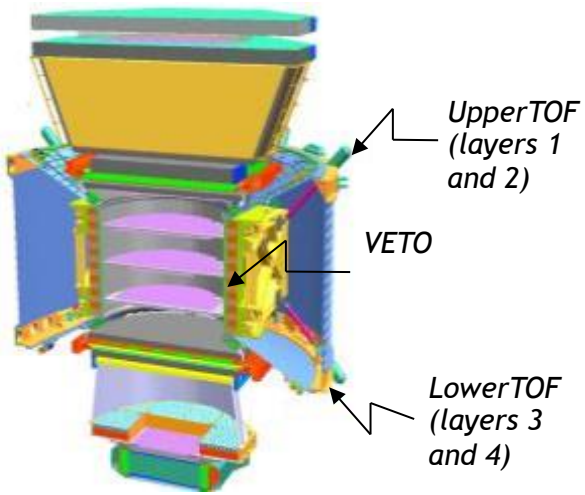
Trigger Efficiency from Data (i)

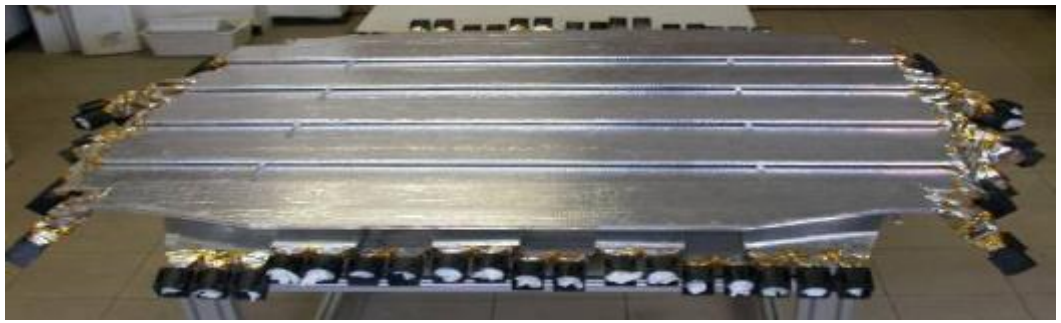
Effective Acceptance from MC in m^2sr, Verified with Data (ii)

Error on the flux dominated by systematics (i to vi) on the whole rigidity range.

Proton flux: (i) systematic errors on trigger efficiency

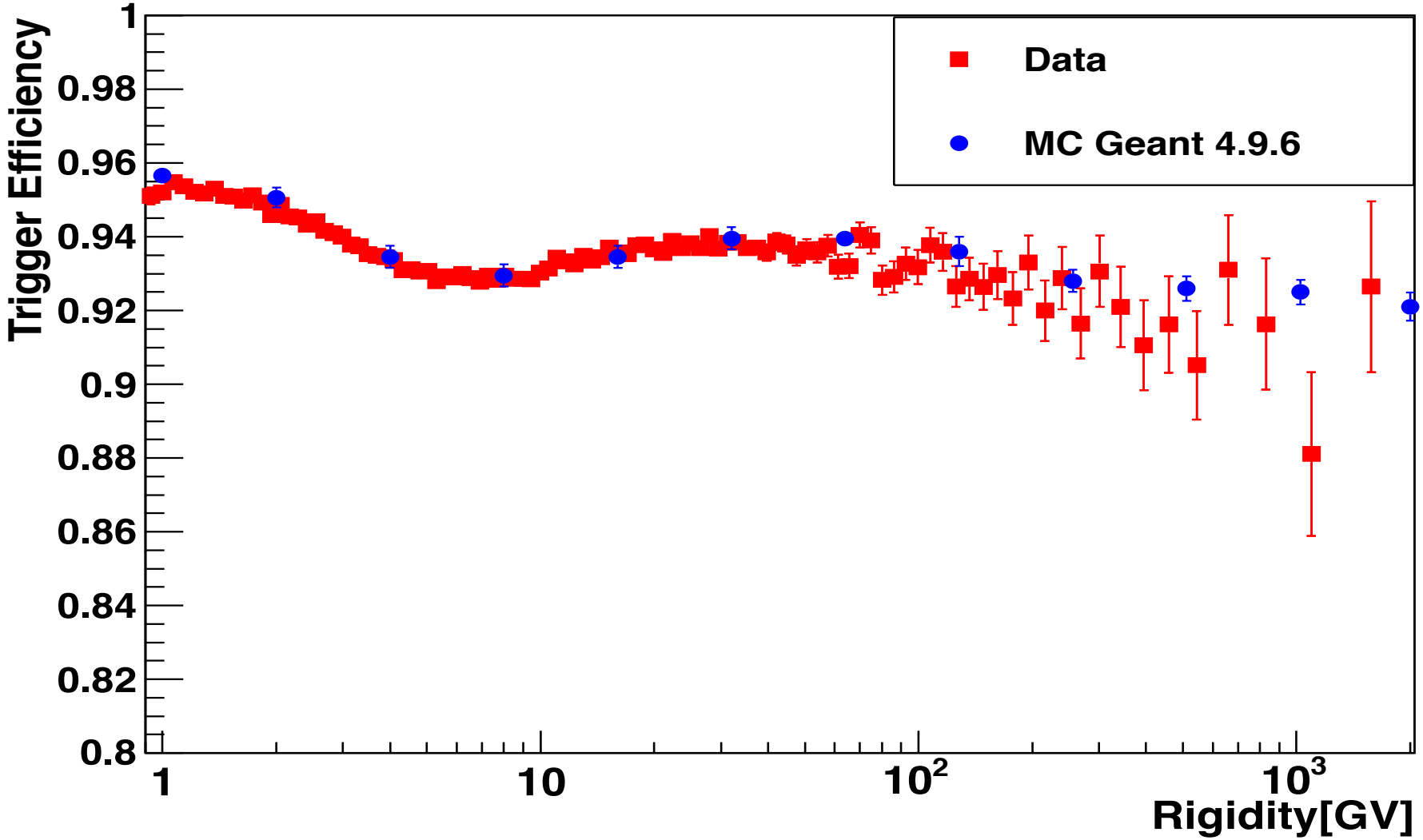
Trigger efficiency [4/4 TOF + VETO] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger. The error is dominated by the statistics available from the unbiased trigger.





This systematic error is negligible (less than 0.1%) below 100GV and reaches 1.5% at 1.8TV.

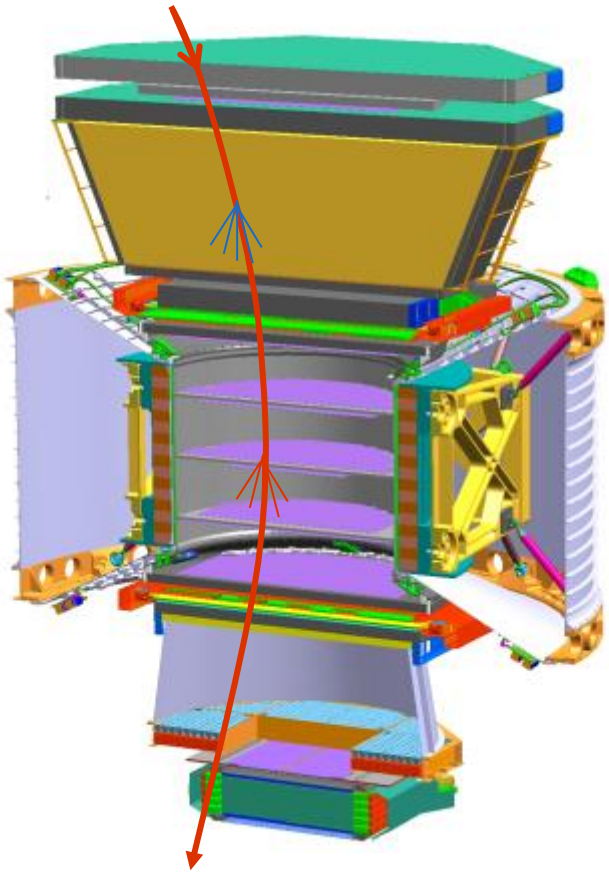
Trigger Efficiency Measured from Unbiased Trigger



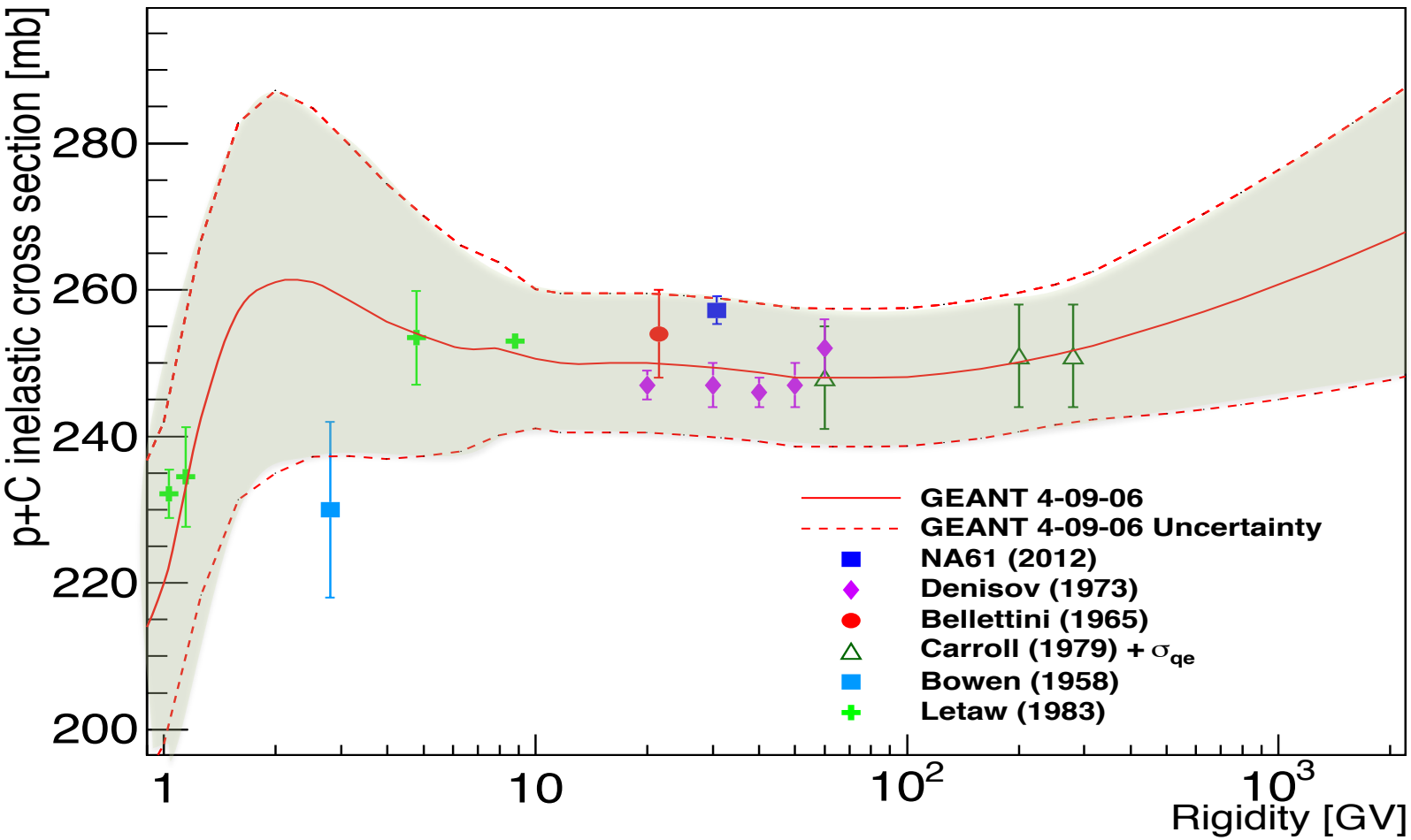
Proton flux: (ii) systematic errors on the acceptance and event selection

The effective acceptance obtained with Geant4.9.6 simulation was corrected for small differences between the data and the Monte Carlo samples related to the event reconstruction and selection. The typical systematic error on the flux is 0.8% at 200GV.

The detector is mostly made of carbon and aluminum. The corresponding inelastic cross sections of *p* + C and *p* + Al are known to within 10% at 1GV and 4% at 300GV, and 7% at 1.8TV from model estimations.



Acceptance Error due to Interactions

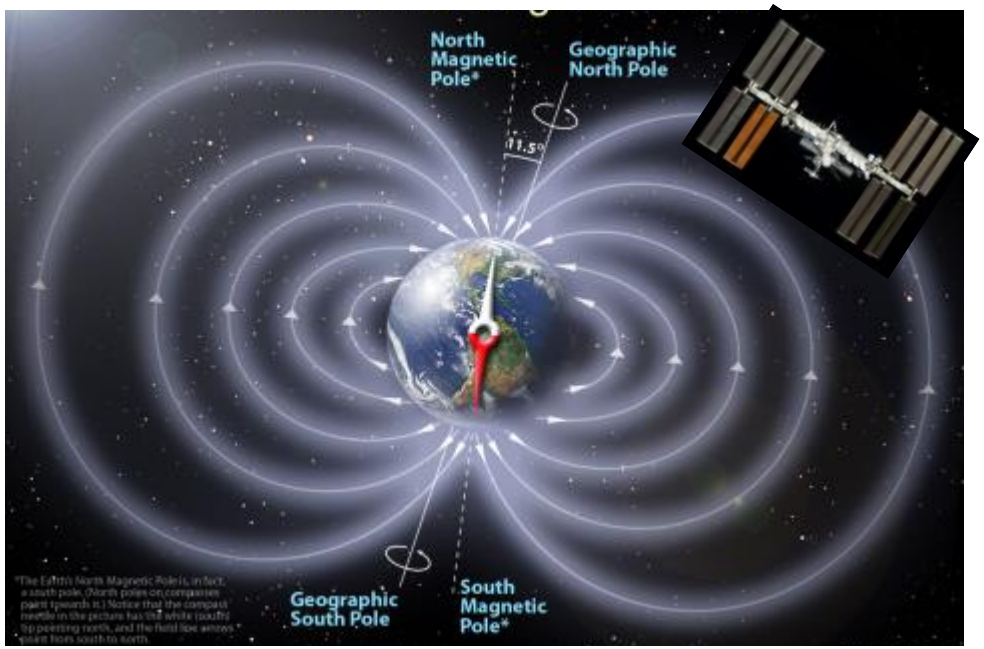


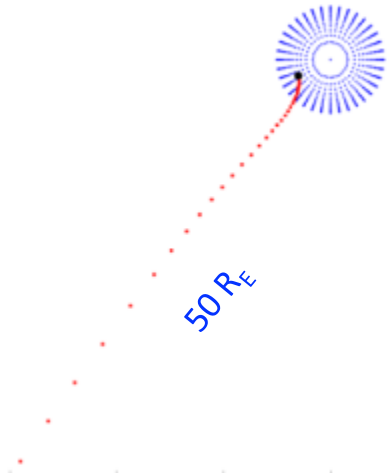
Knowledge of p+C(Al) inelastic σ is important to assess error on acceptance due to proton interactions. p+C(Al) inelastic σ is known 4 to 10 % accuracy.

The corresponding systematic error is 1% at 1GV, 0.6% from 10 to 300GV, and 0.8% at 1.8TV.

Proton flux: (iii) systematic errors on geomagnetic cutoff

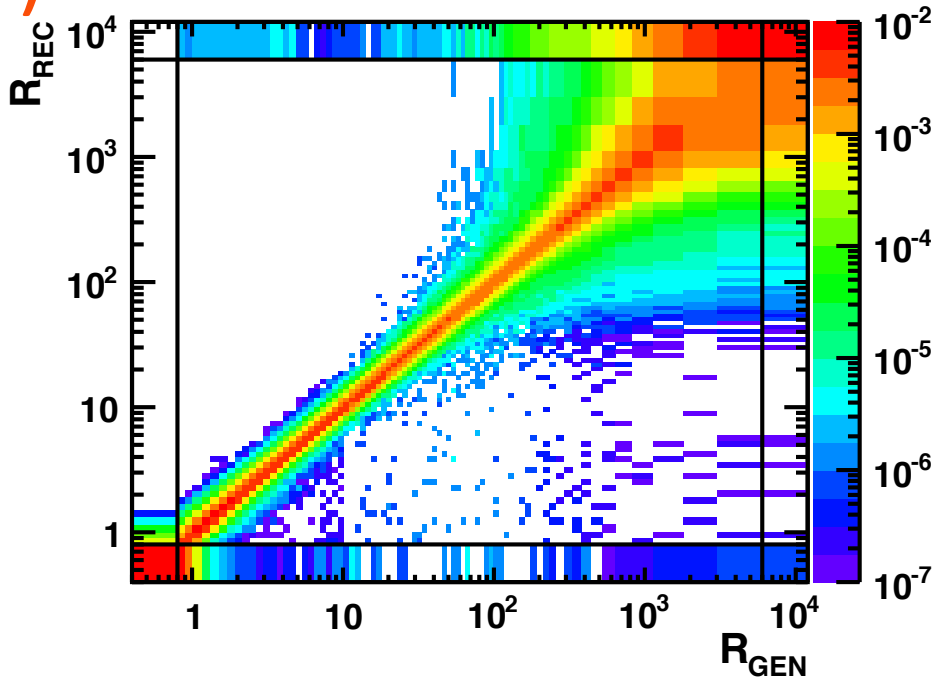
The cutoff was calculated by backtracing particles from the top of AMS out to 50 Earth's radii. A safety factor of 1.2 is then applied. It was varied from 1.0 to 1.4 and the resulting proton fluxes showed a systematic uncertainty of 2% at 1GV and negligible above 2GV.





Proton flux: Unfolding (iv)

Migration matrix:



- Iterative method:
  - M: migration matrix.
  - F_{mes}: measured rate
  - $F^{(i)}$: folded rate iteration i
  - $U^{(i)}$: unfolded rate iteration i
  - $\omega^{(i)}$: weight factors.
- We have checked the sensitivity of the results to the binning by:
  1. increasing the bin width by factors of 2 and 4
  2. reducing the bin width by factors of 2 and 4.

→ The resulting uncertainty is well within the assigned systematic errors

$$F^{(i)} = M \otimes U^{(i)}$$

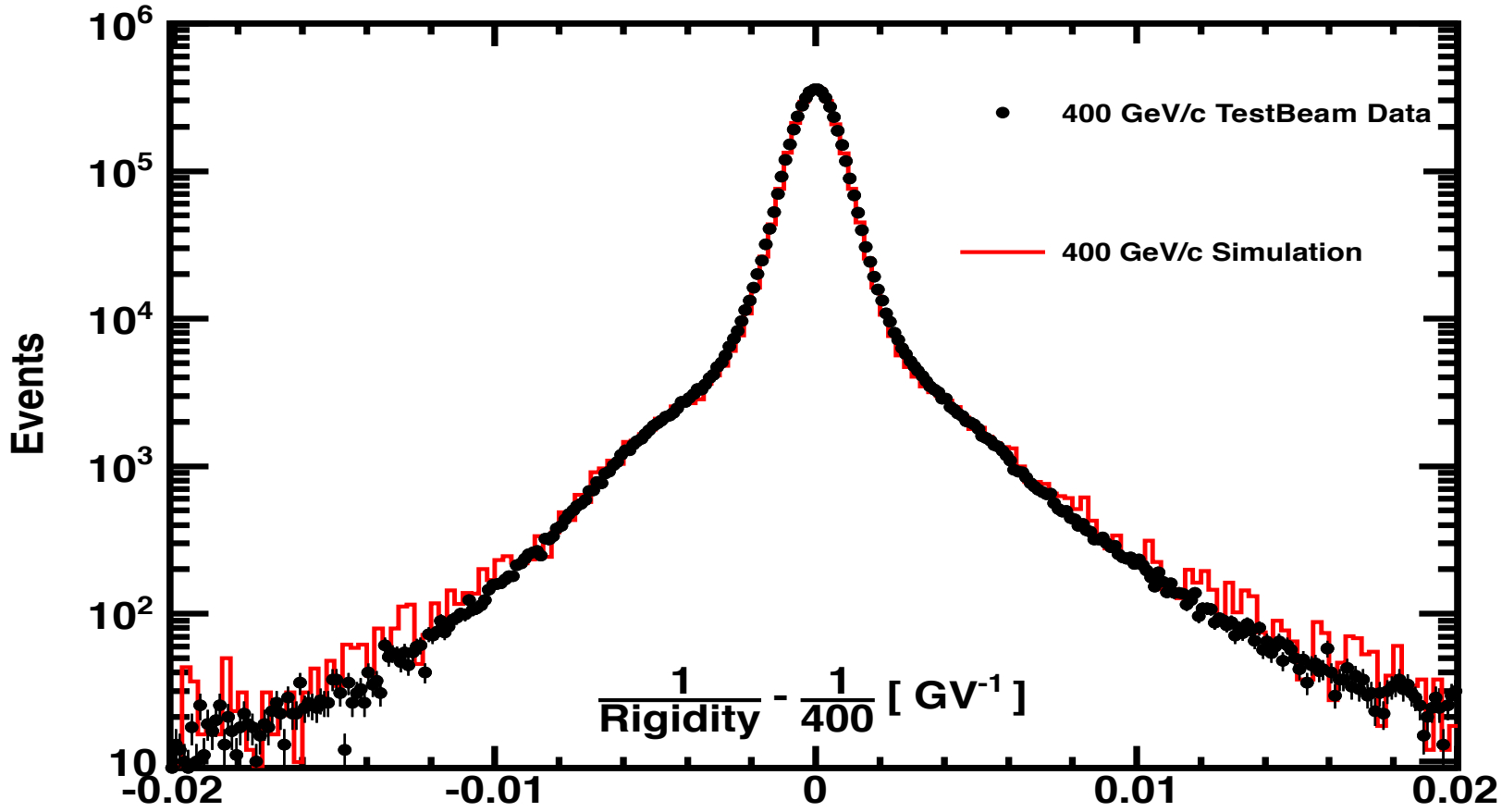
$$\omega^{(i)} = \frac{F^{(i)}}{U^{(i)}}$$

$$\omega^{(i)} \xrightarrow{\text{Reg}} \tilde{\omega}^{(i)}$$

$$U^{(i+1)} = \frac{F_{mes}}{\tilde{\omega}^{(i)}}$$

Proton flux: (v) systematic errors on the rigidity resolution function

The corresponding unfolding errors were obtained by varying the width of the Gaussian core of the resolution function by 5% and the amplitude of the non-Gaussian tails by ~20% and found to be 1% below 200GV and 3% at 1.8TV.

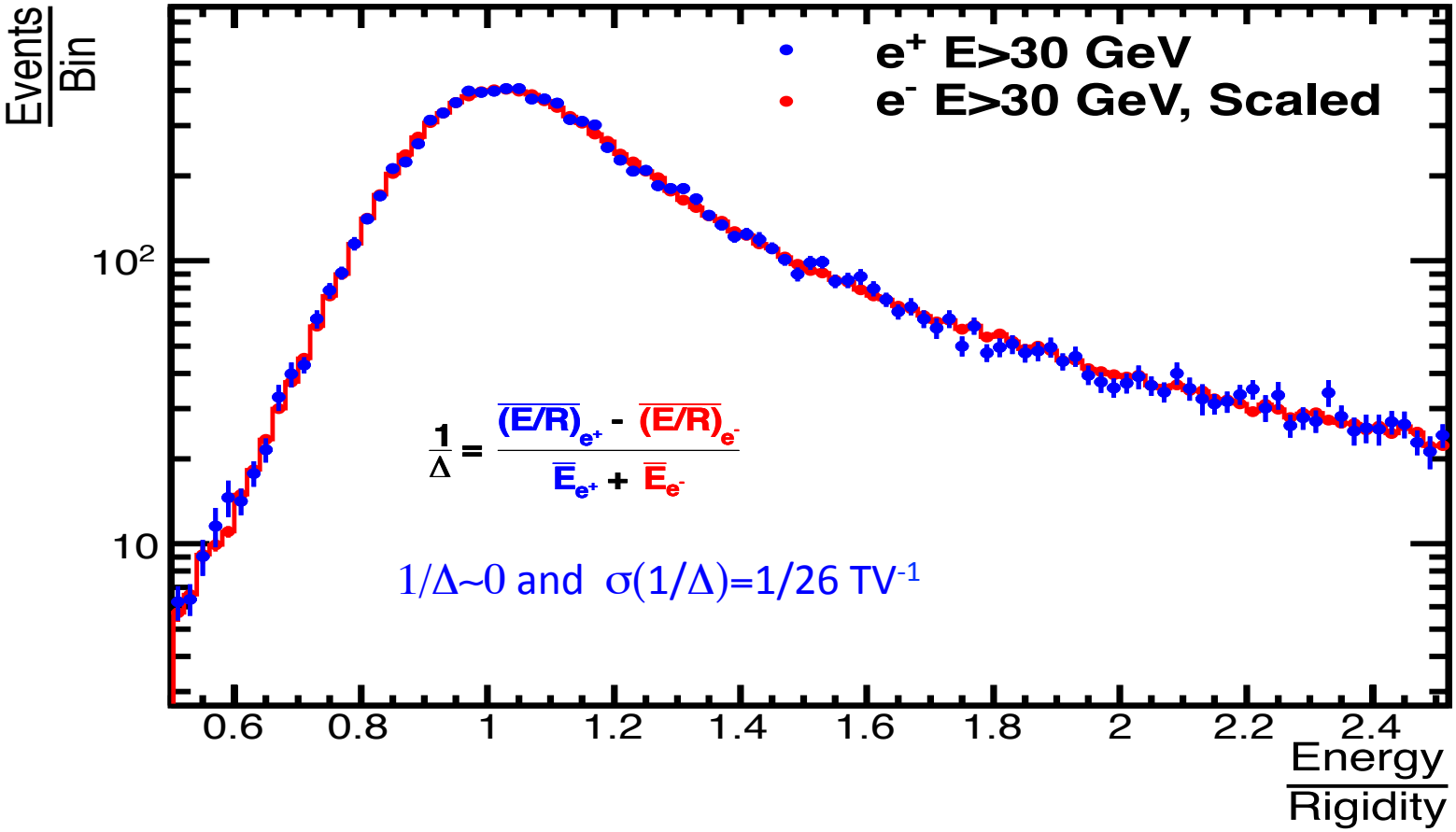


The resolution function for 400 GeV/*c* protons measured in the test beam compared with Monte Carlo simulated events.

Proton flux: (vi) systematic errors on the absolute rigidity scale (1/Δ)

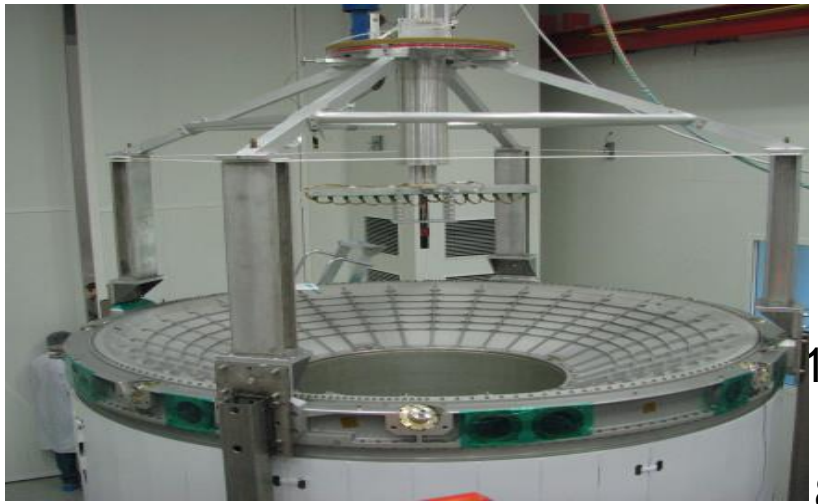
1) Residual tracker misalignment:

This error was estimated by comparing the *E/R* ratio for electron and positron events, where *E* is the energy measured with the ECAL and *R* is the rigidity measured with the tracker. It was found to be 1/(26TV), limited by the current high energy positron statistics and corresponds to flux error 2.5% @1 TV.



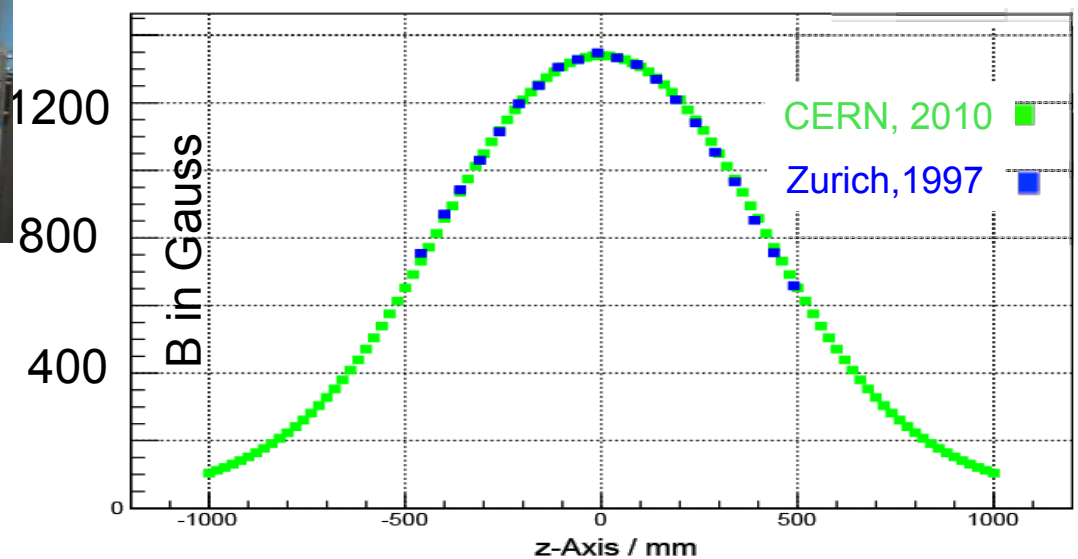
Proton flux: (vi) systematic errors on the absolute rigidity scale

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.

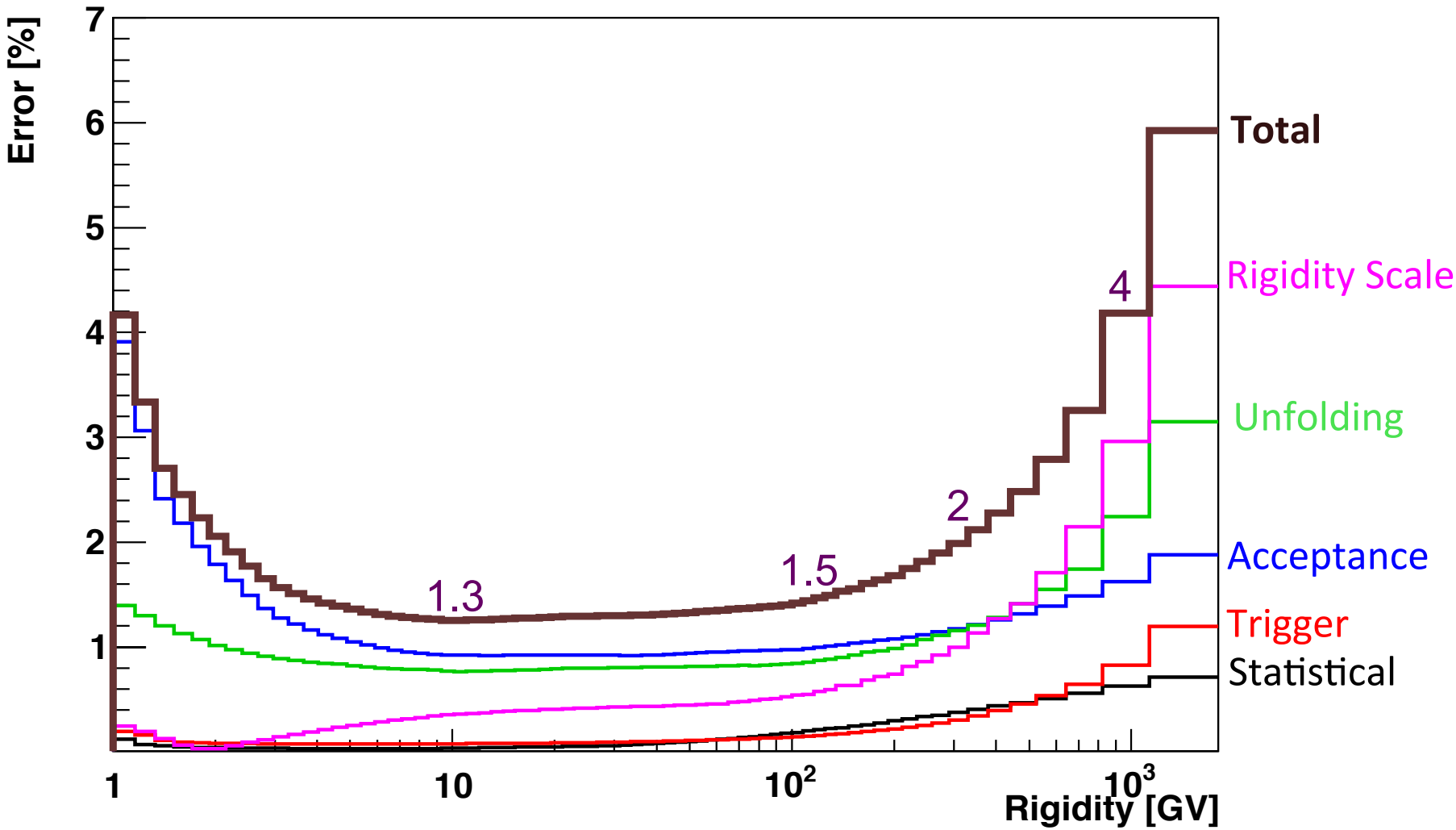


3D field map
(120,000 locations)
Measured at CERN
in May 2010

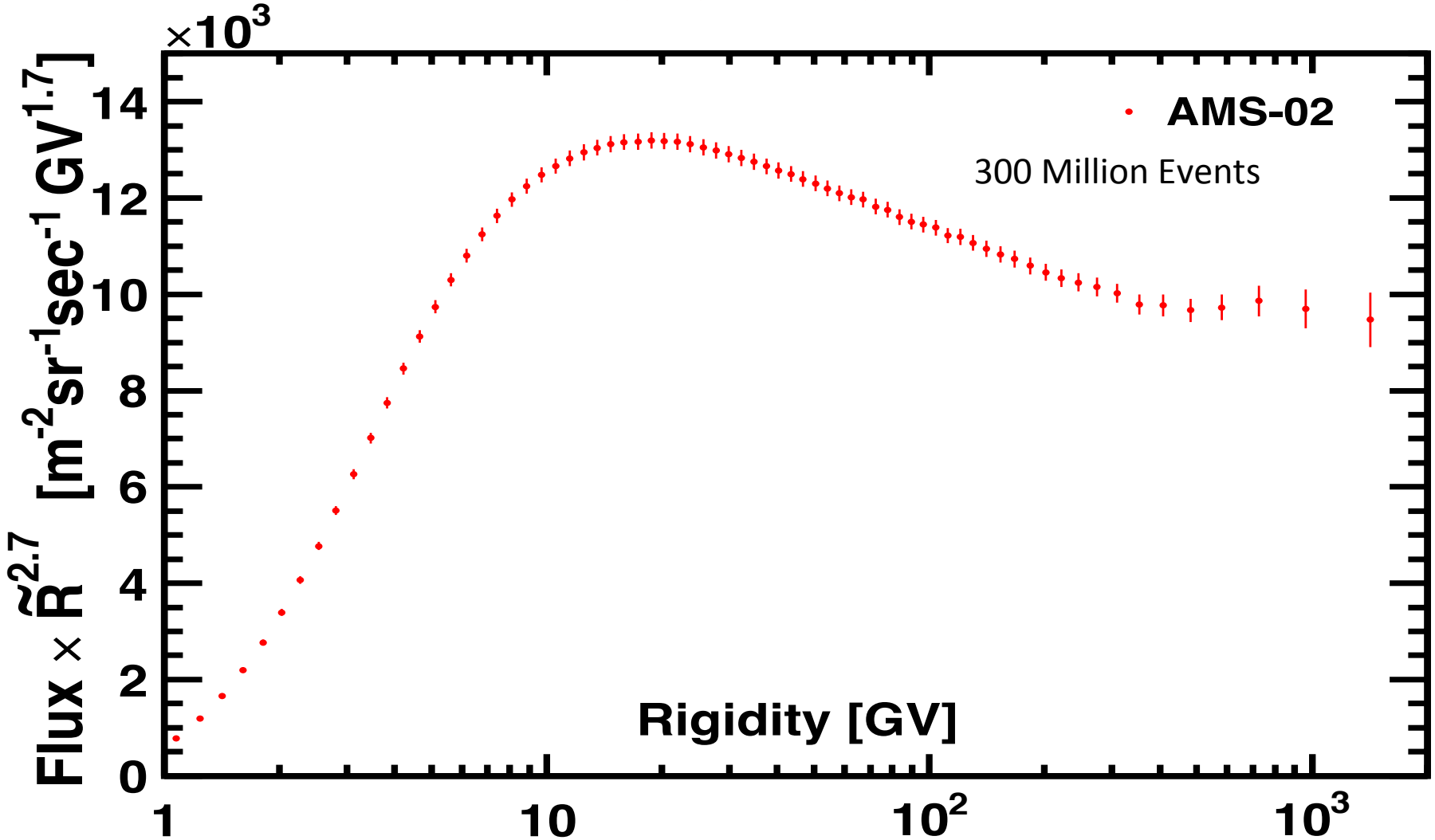
In 12 years the field has
remained the same to <1%



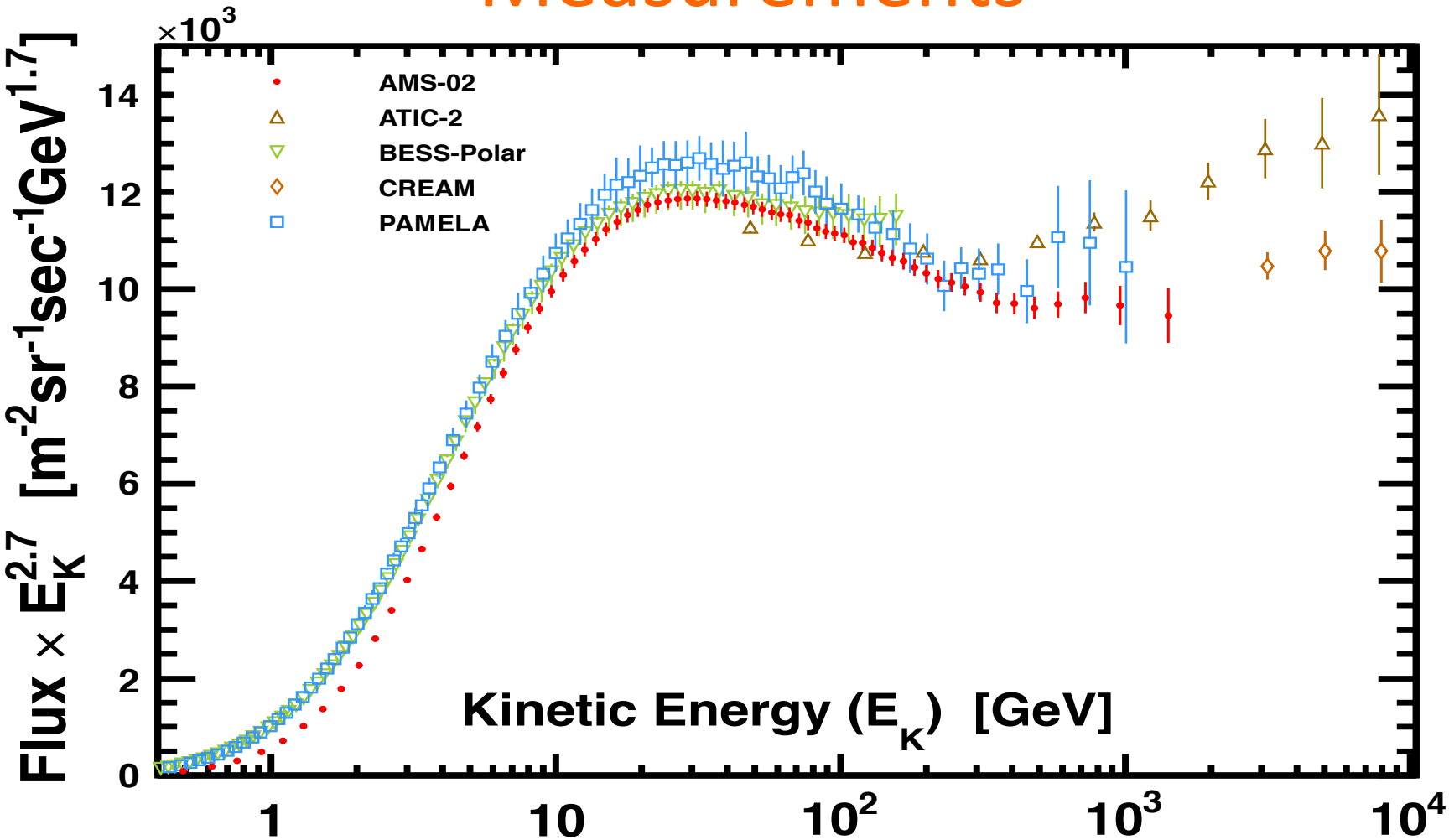
Flux Errors Breakdown



Proton Flux

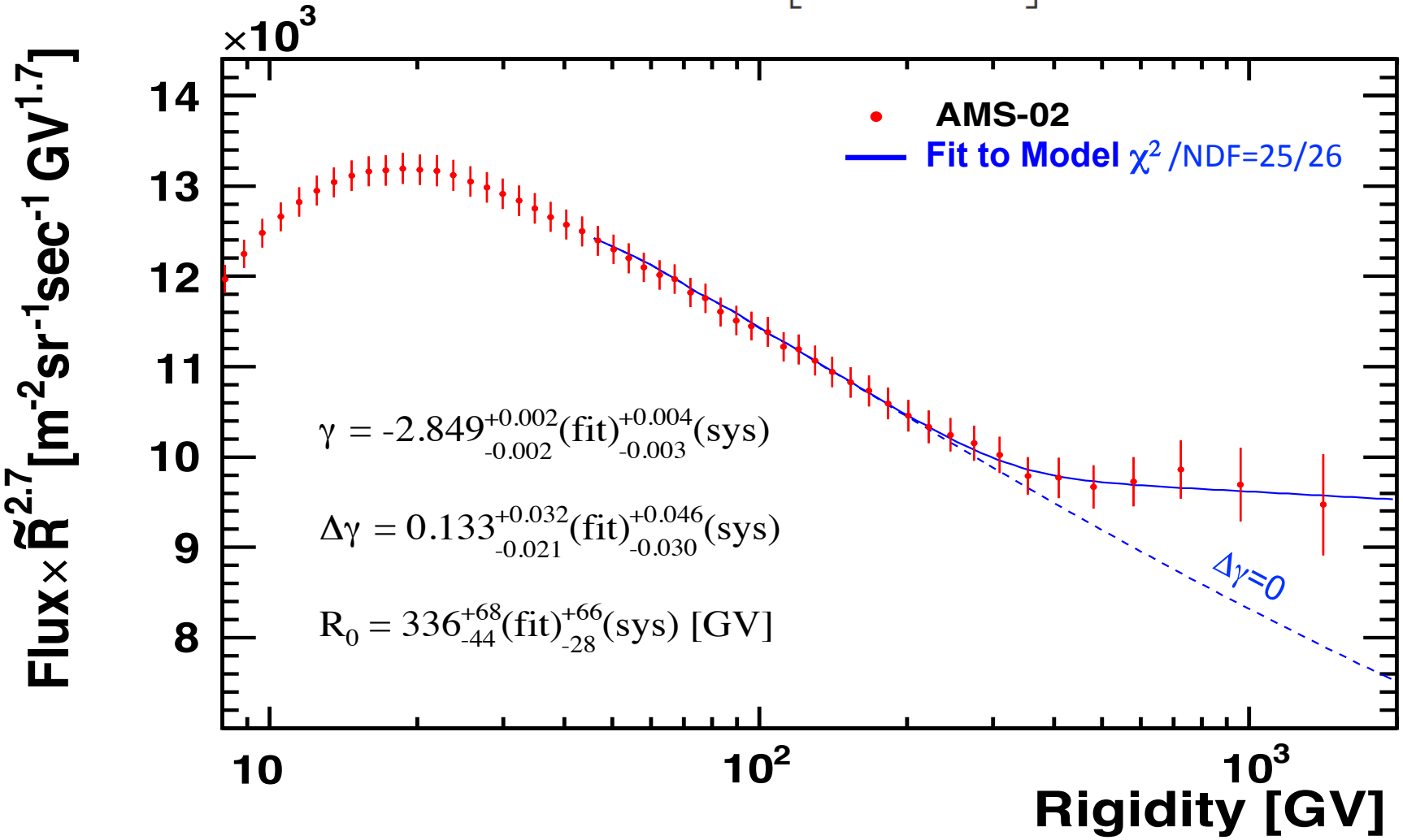

×10^3
Flux × R̃^2.7 [m^-2sr^-1sec^-1 GV^1.7]
14
12
10
8
6
4
2
0
AMS-02
300 Million Events
Rigidity [GV]
1
10
10^2
10^3

Proton Flux Comparison with Earlier Measurements

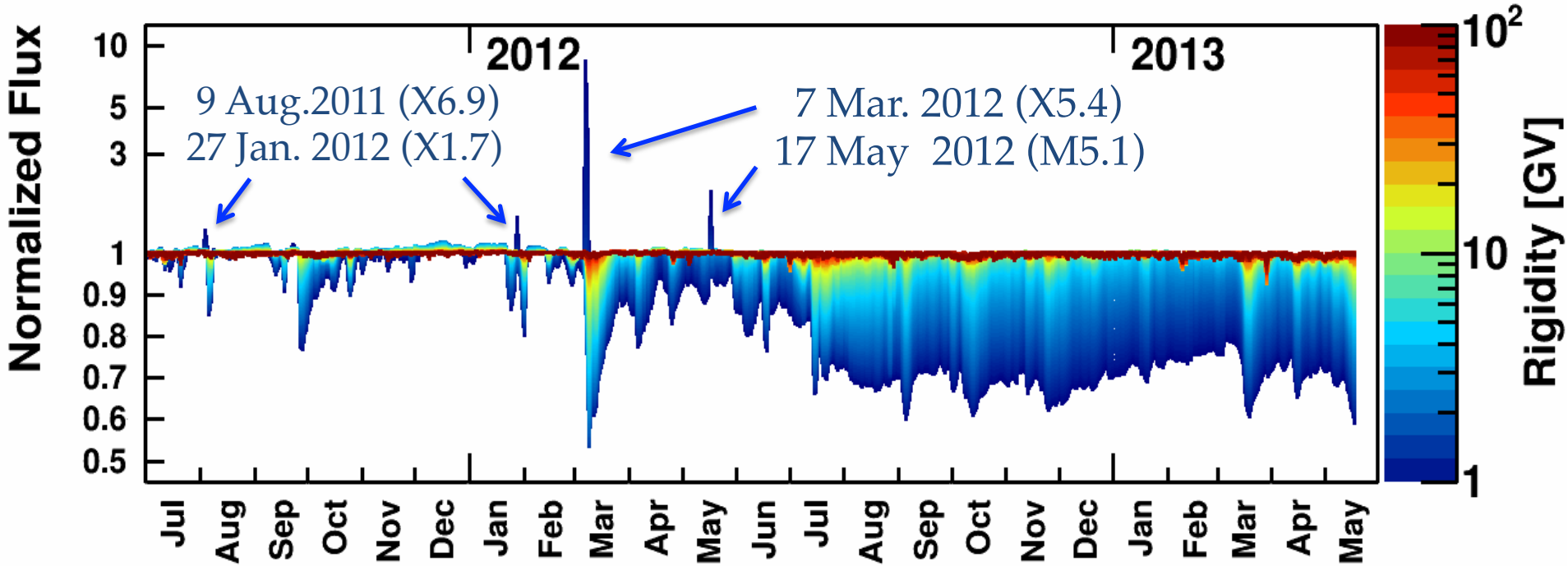


Proton Flux Fit with the Model

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



Proton Flux: Time dependence



AMS02: Long time exposure, large acceptance → precise measurement of the time dependence of the fluxes. Full Solar cycle and different polarity periods available in the future with AMS02

By-product of the current analyses, important data for the solar physics community, radiation dose studies.

He event selection

Data sample : May/2011 – Nov/2013 (30 months)

1. Downgoing particle ($\beta > 0.3$)
2. Rigidity (R) above Geomagnetic cutoff :

   $R > 1.2\ R_{\text{IGRF-cutoff}}$
3. Track has top (L1) and bottom (L9) layers
   to ensure the best resolution ($\text{MDR}_{\text{L19}} \approx 3.2$ TV)

4. Charge compatible with Z=2 along the trajectory
   e.g. Inner Tracker : $1.7 < Q_{\text{inner}} < 2.5$
5. Quality of the track fitting : $\chi^2/\text{NDF} < 10$

Data/MC comparison examples

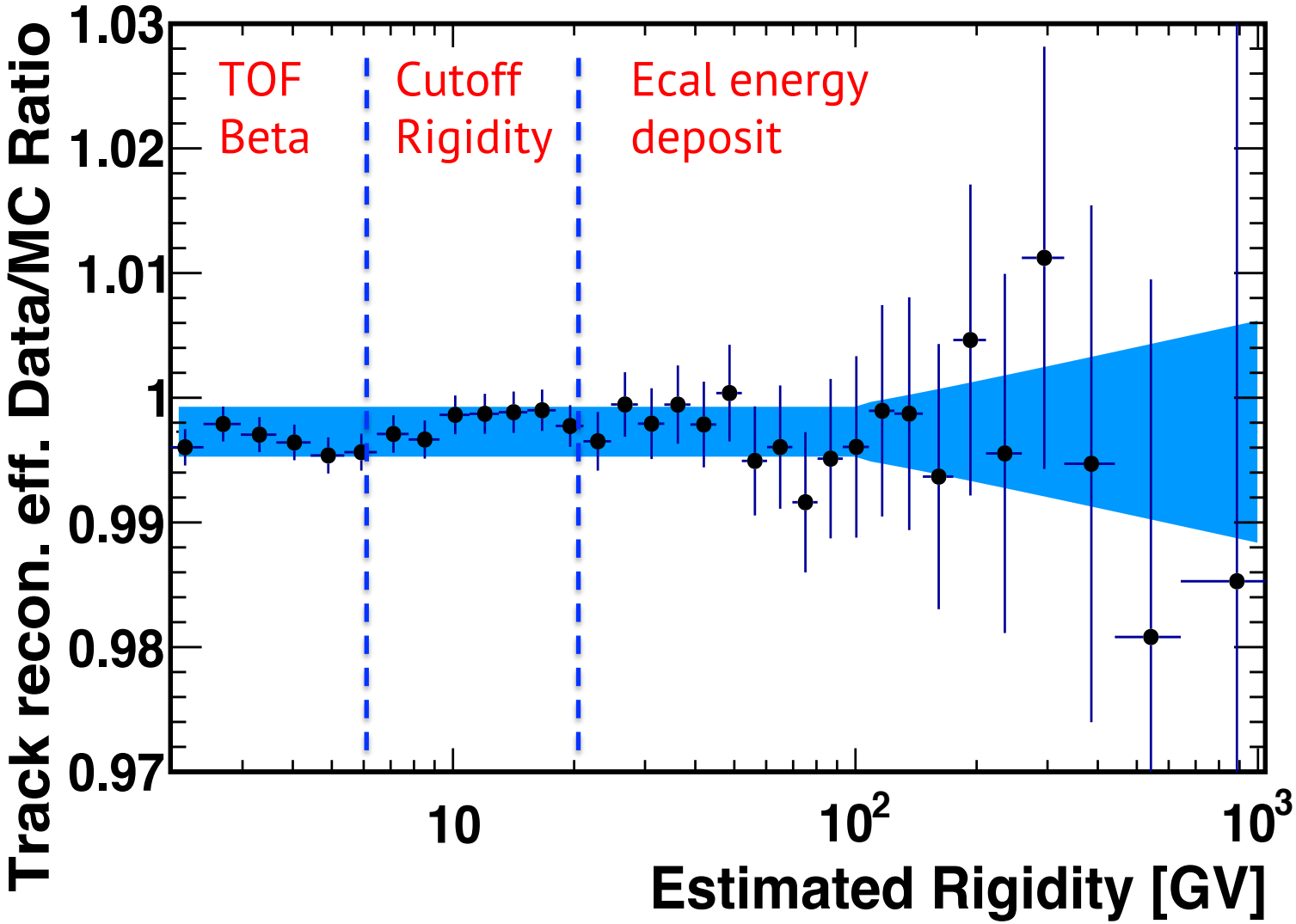
1. Track reconstruction efficiency
   - Validation of the description of the detector performance in MC simulation

2. L1 hit association efficiency
   - Validation of the He elastic scattering

3. Survival probability between L8 and L9
   - Validation of the He inelastic cross section

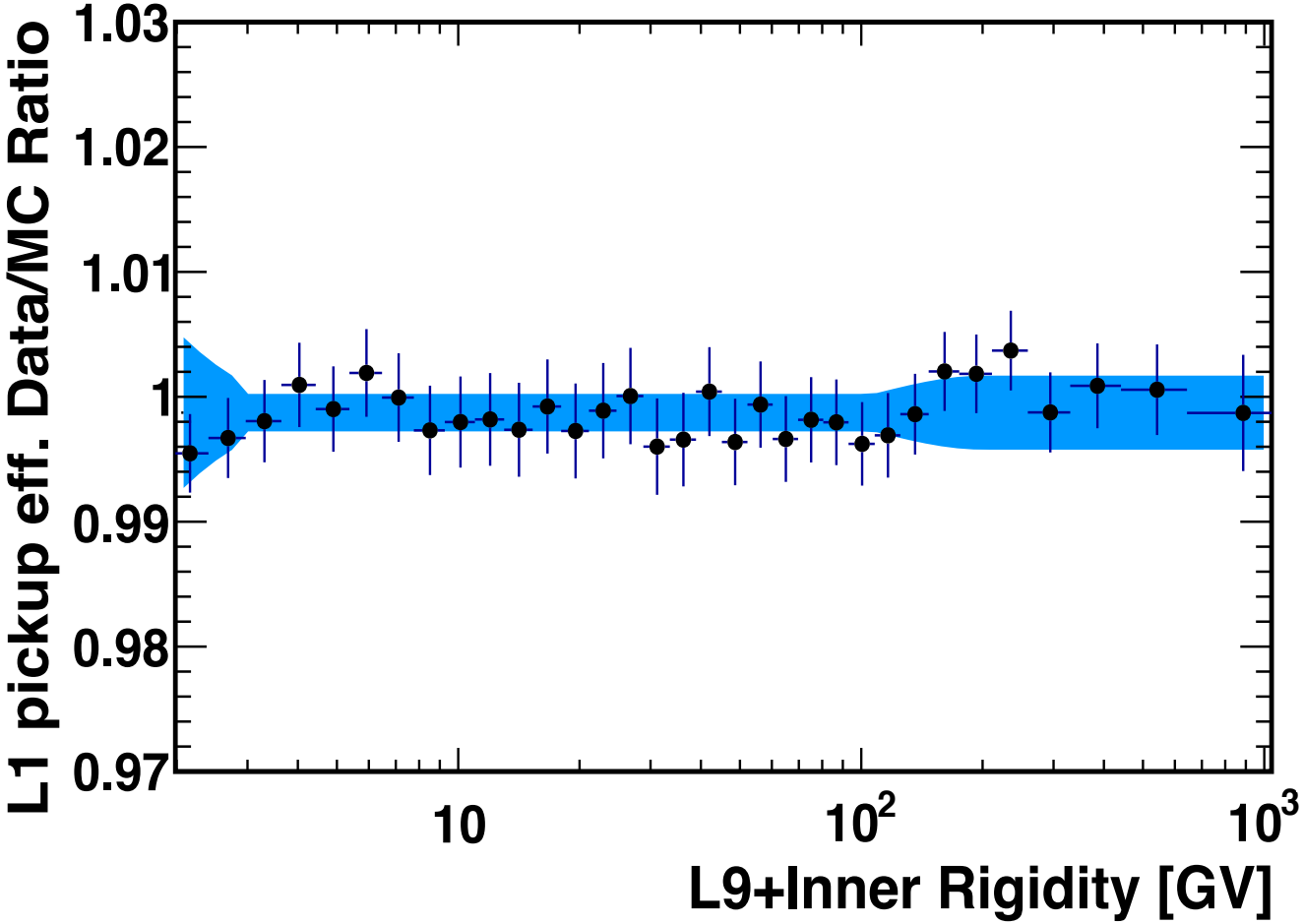
Data/MC comparison (1)

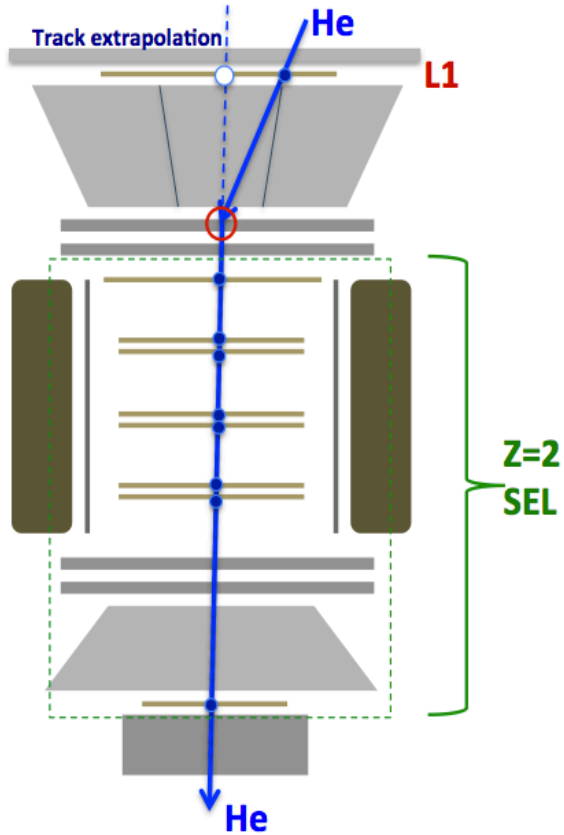
Comparison of Track reconstruction efficiency



Data/MC comparison (2)

L1 hit association : Validation of elastic scattering

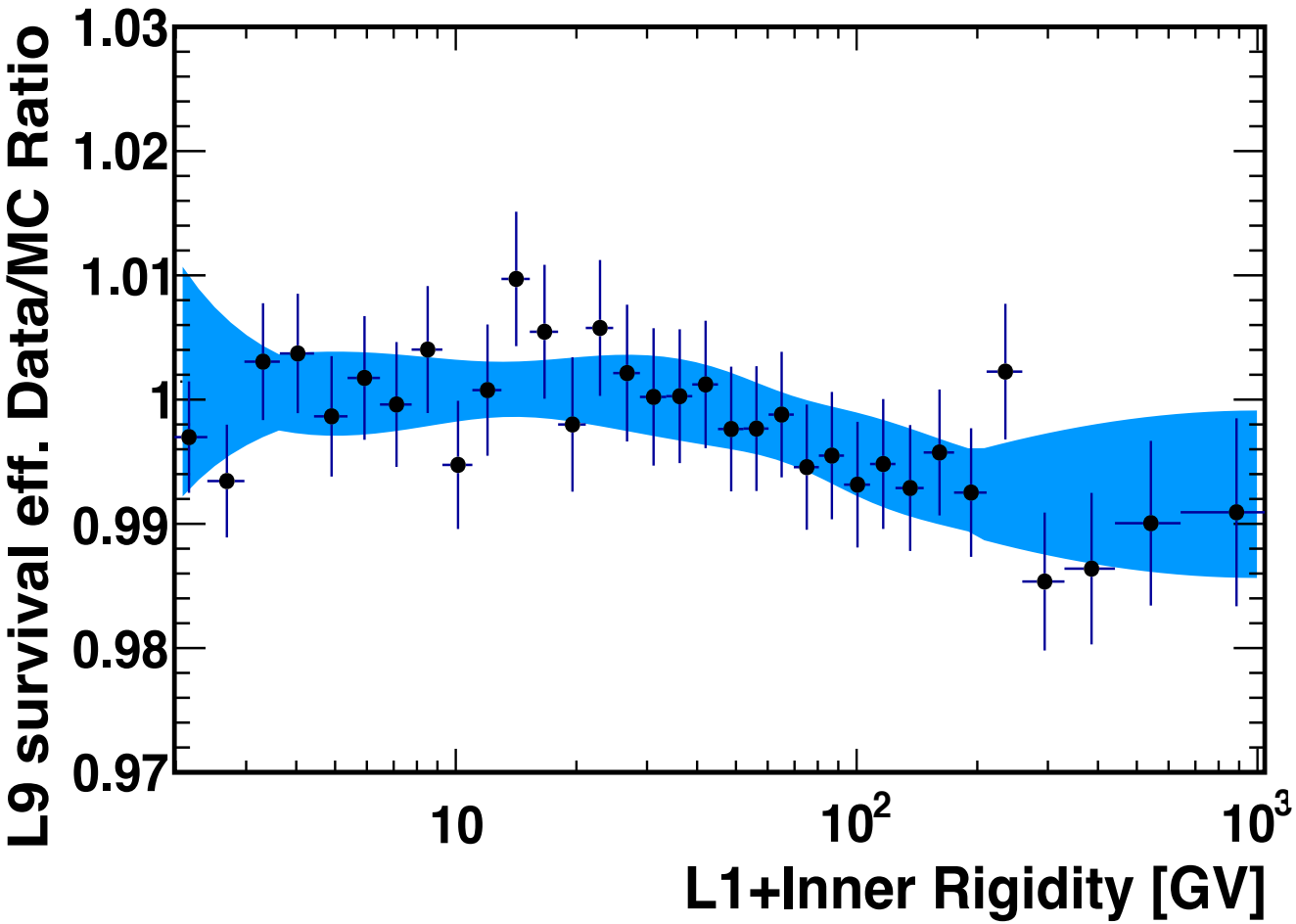


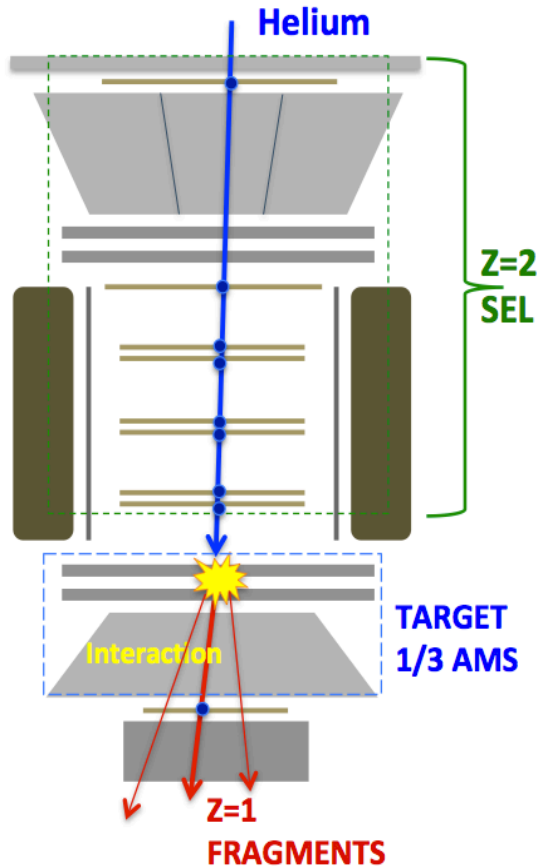


Data/MC comparison (3)

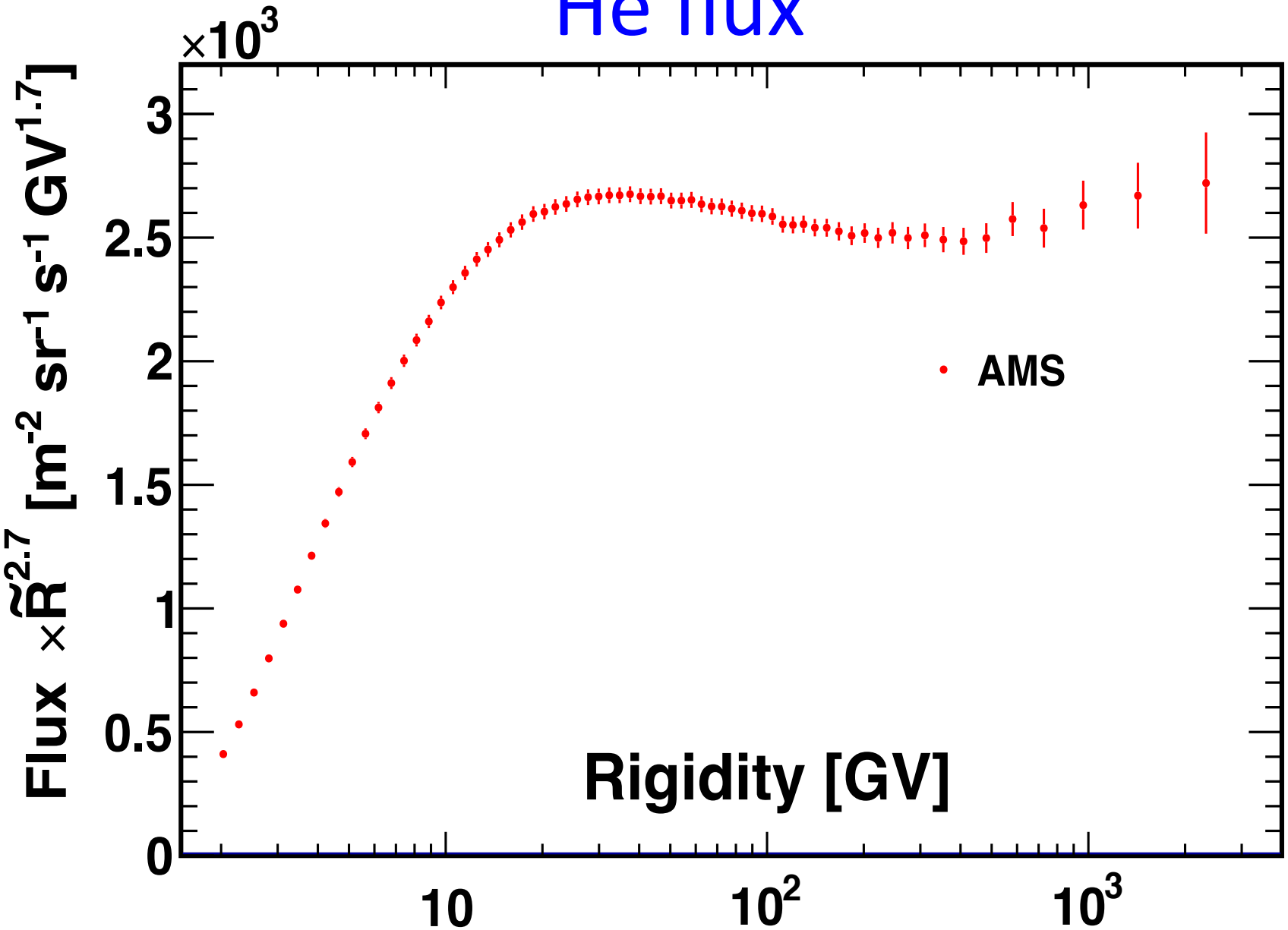
Survival probability between L8 and L9 :

Validation of He inelastic cross section

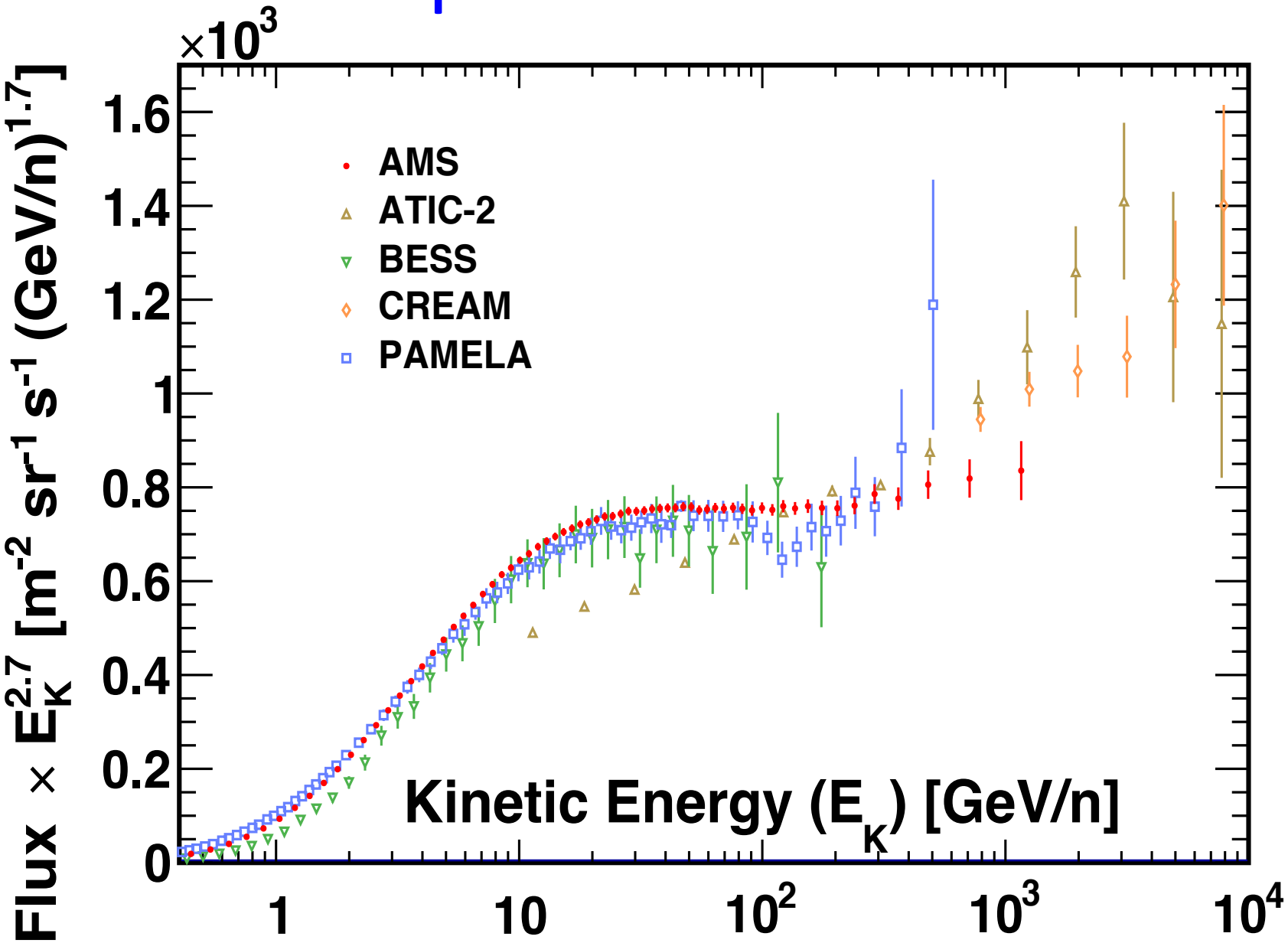




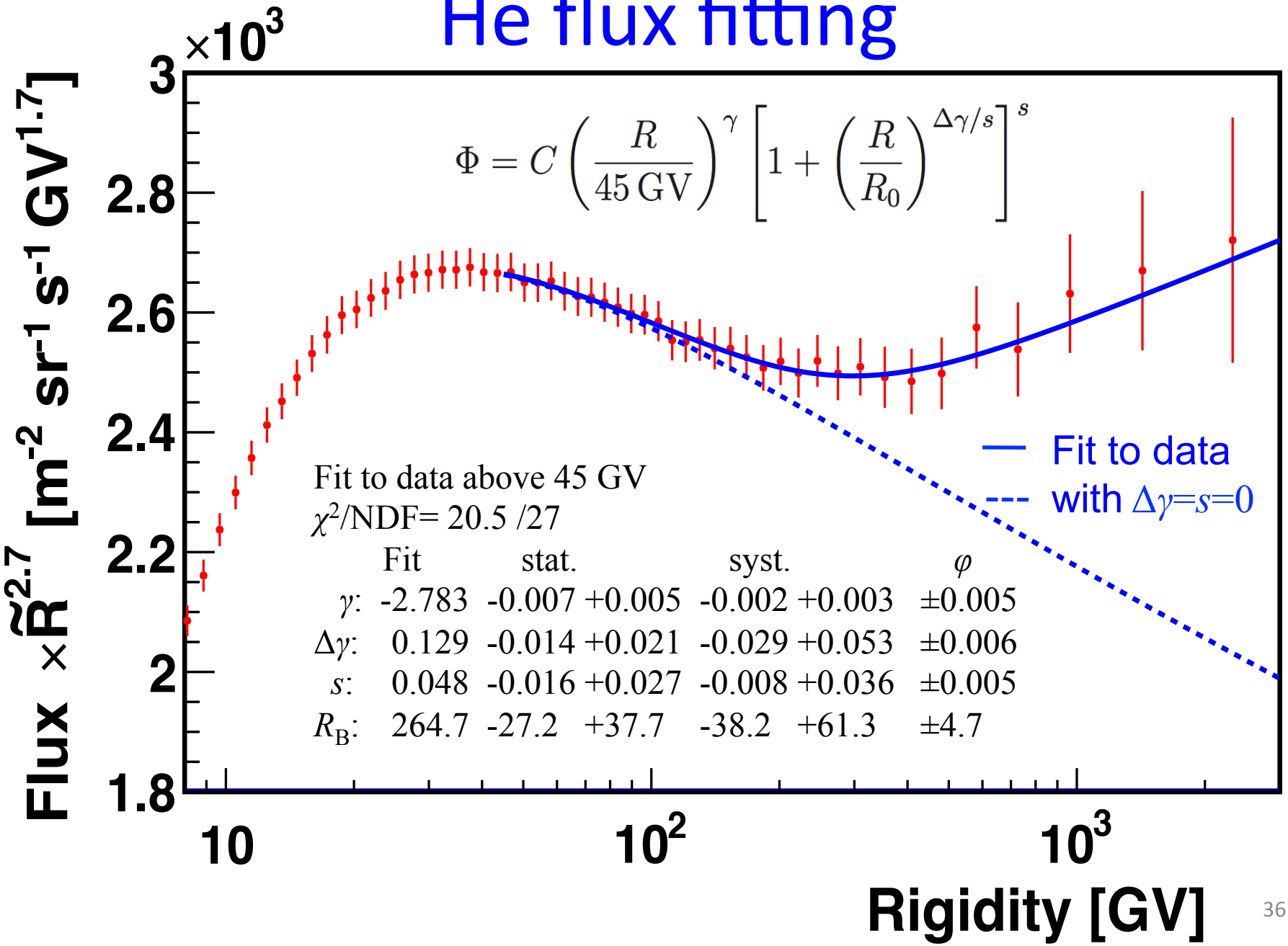
He flux


×10^3
Flux ×R̃^2.7 [m^-2 sr^-1 s^-1 GV^1.7]
3
2.5
2
1.5
1
0.5
0
AMS
Rigidity [GV]
10
10^2
10^3

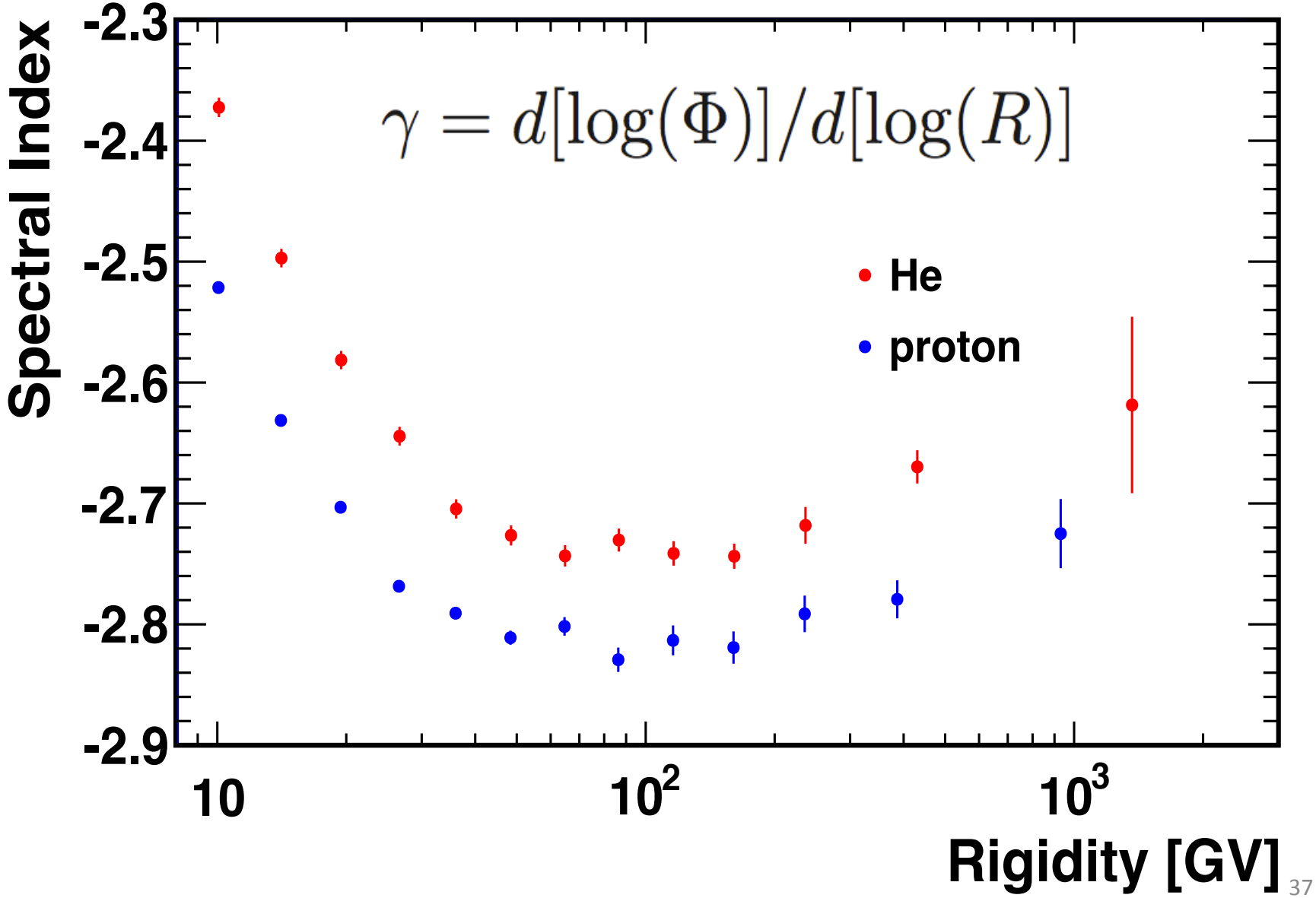
AMS compared with recent data



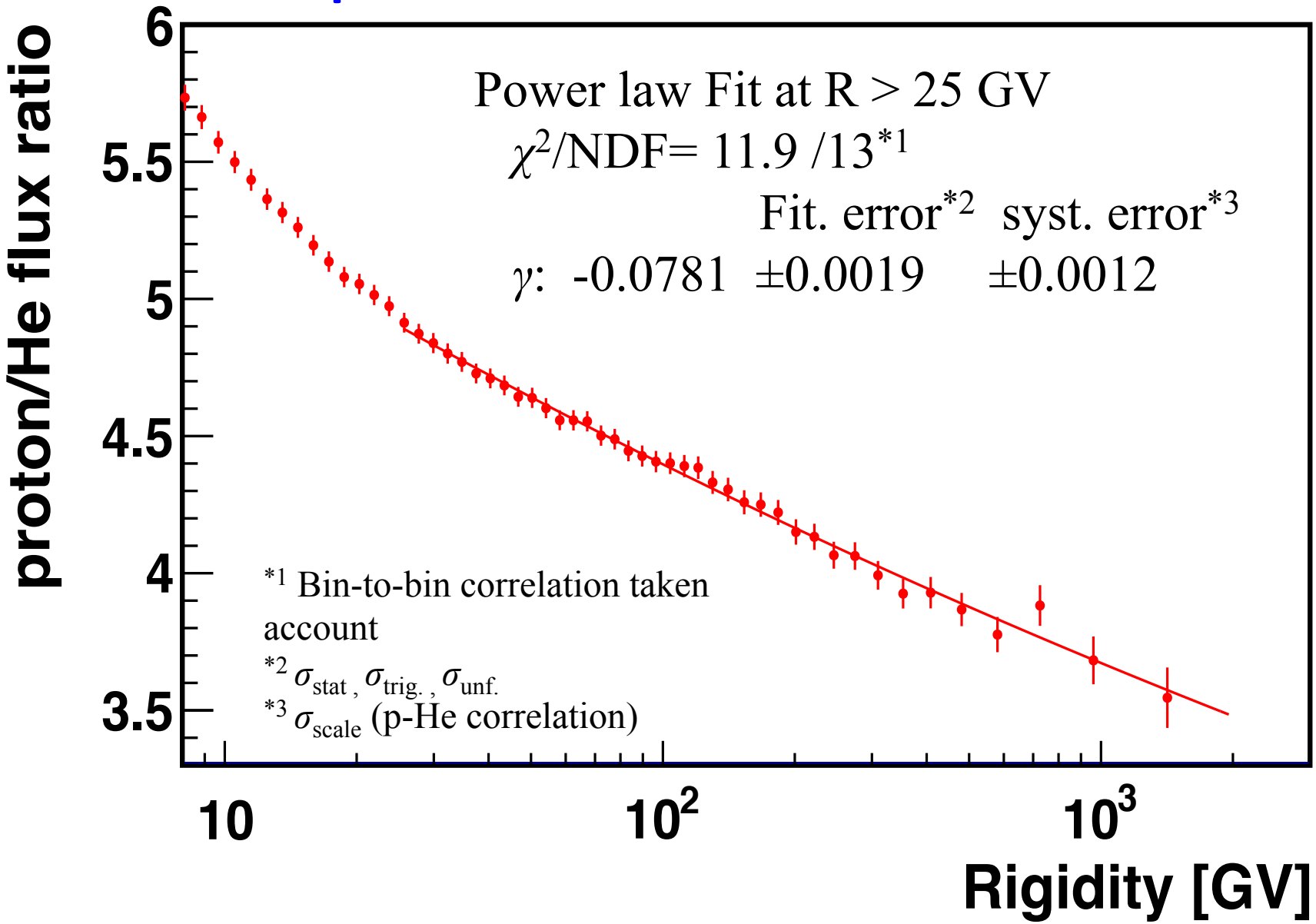
He flux fitting



Spectral indices p/He comparison



proton/He flux ratio

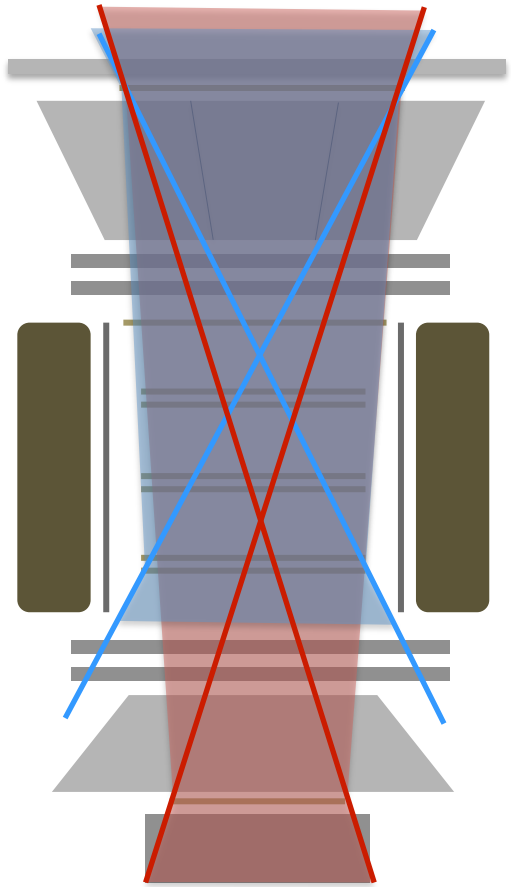


Lithium in Cosmic Rays

- Like B and Be, Li is produced by spallation processes.
- Sensitive to CR propagation parameters (diffusion, convection, reacceleration…).

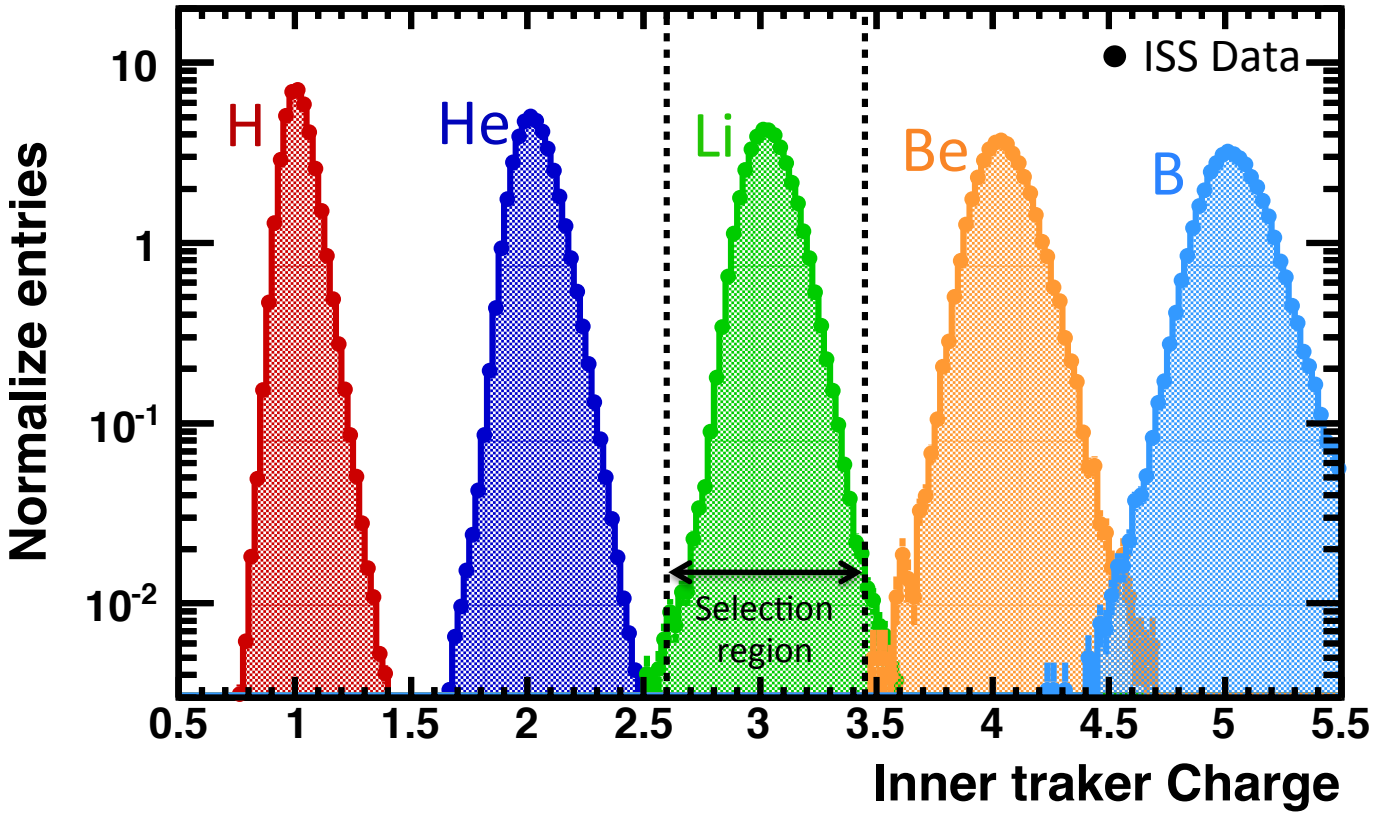
CNO…Fe + ISM → Li
→ B, Be + ISM → Li

- Lithium abundance ~1 per mil in cosmic ray. Use 2 different tracker patterns to optimize the measurement:
  1. Inner+L1&L9 (Full Span) with largest lever arm to maximize the MDR (3.2TV)
  2. Inner+L1 with 5 times larger the acceptance to maximize the statistic.



Lithium : Selection

Main identification capability provided by the Inner tracker:



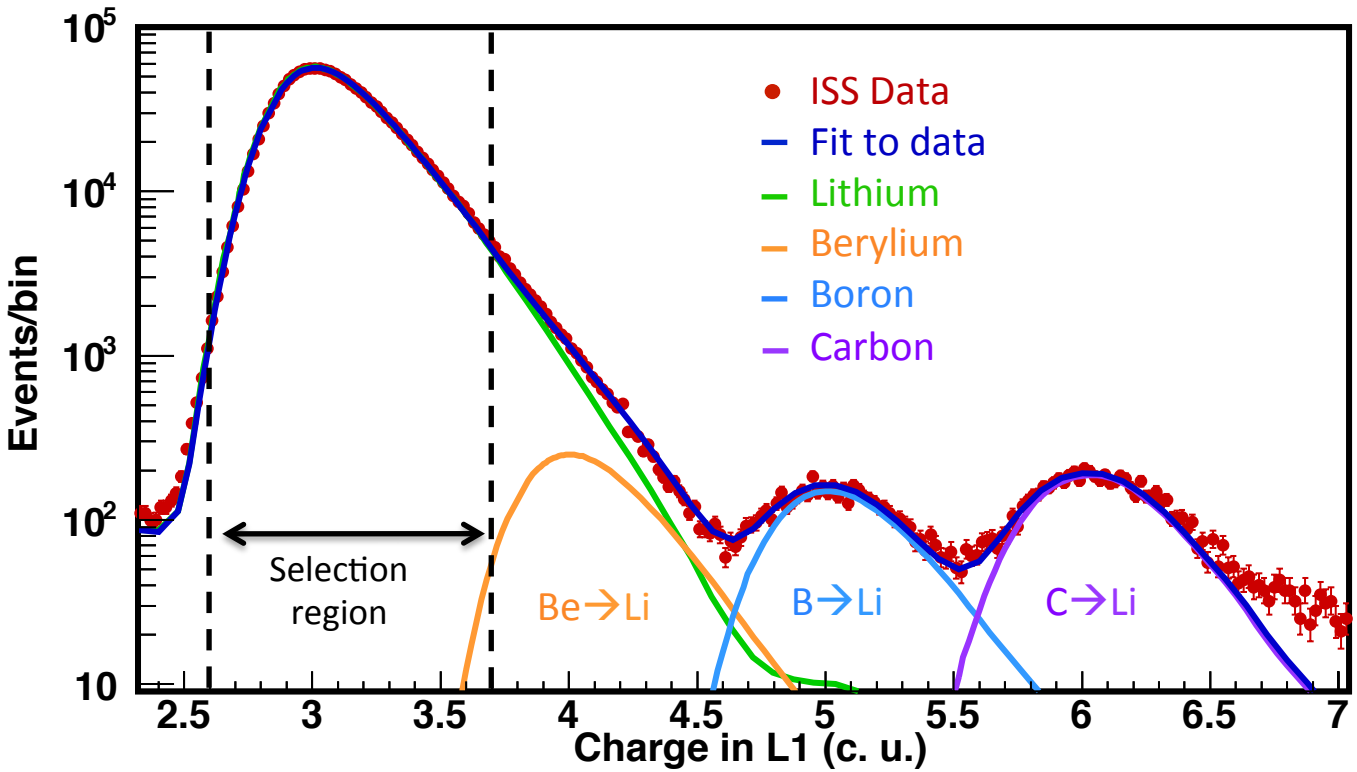
Combined with charge from TOF:

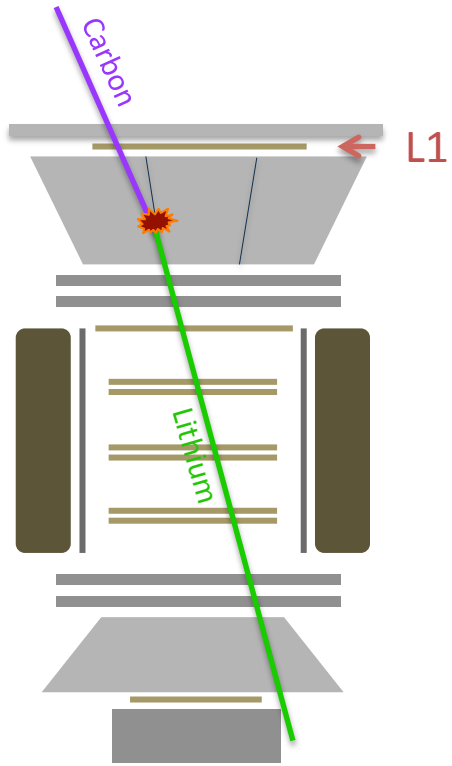
→ contamination from Proton and He < 0.02% on the whole rigidity range.

→ For heavier nuclei, negligible charge confusion. Contamination from Lithium production in the upper part of the detector

Charge Selection in L1

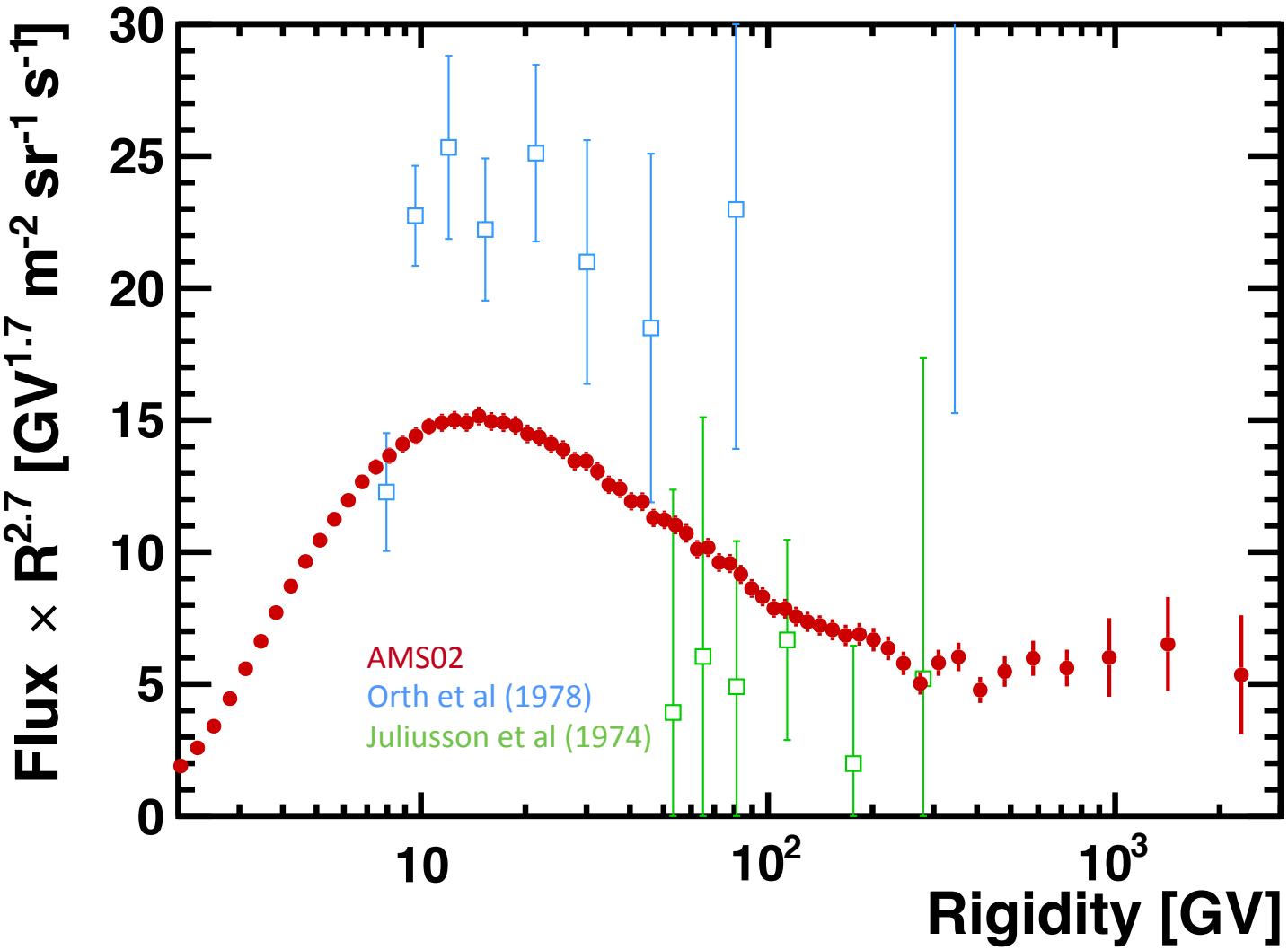
Charge distribution in L1 for events selected as Lithium in the inner tracker:





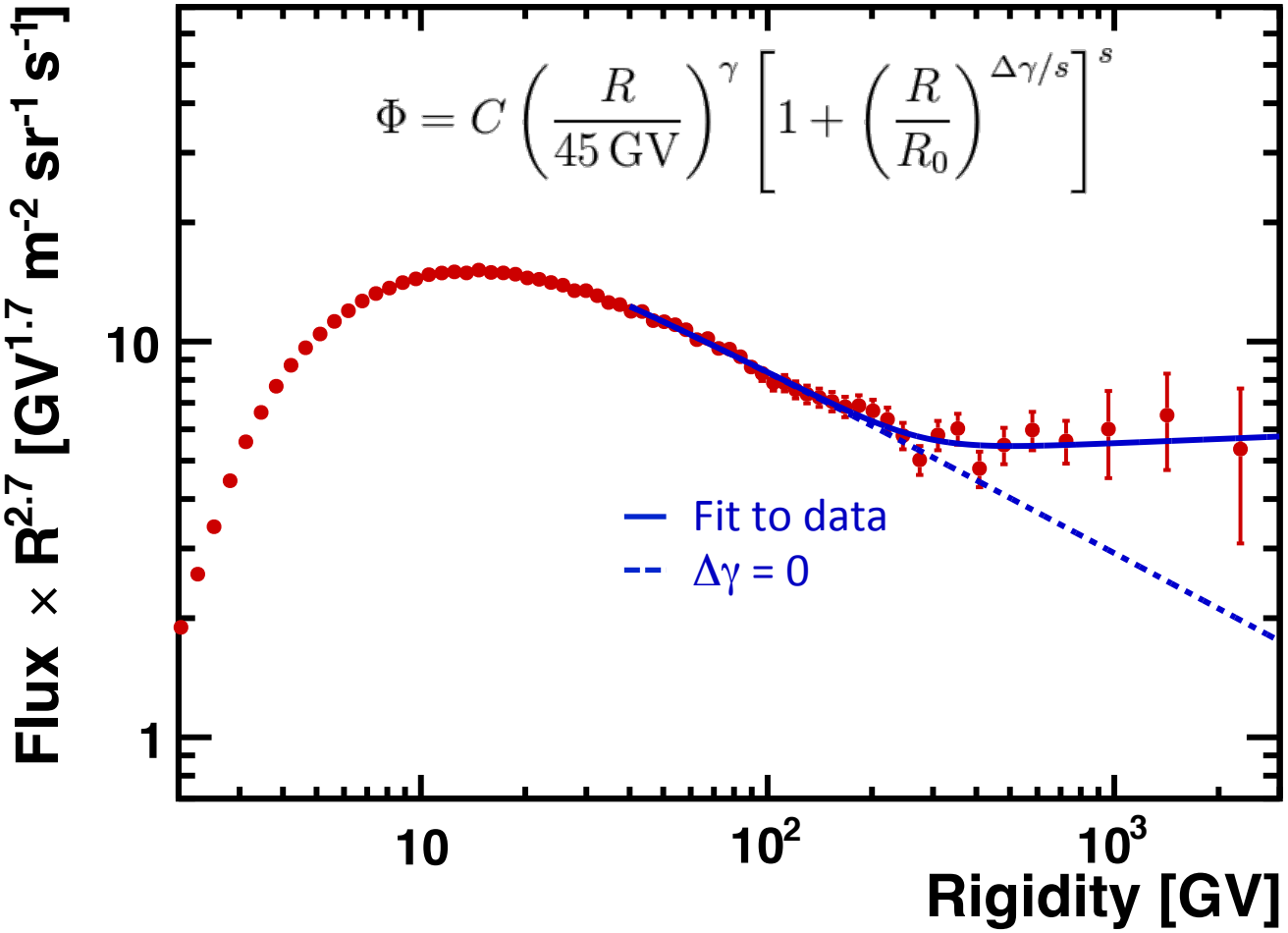
→ Layer 1 is used to reject Lithium produced in the upper part of the detector

Lithium flux



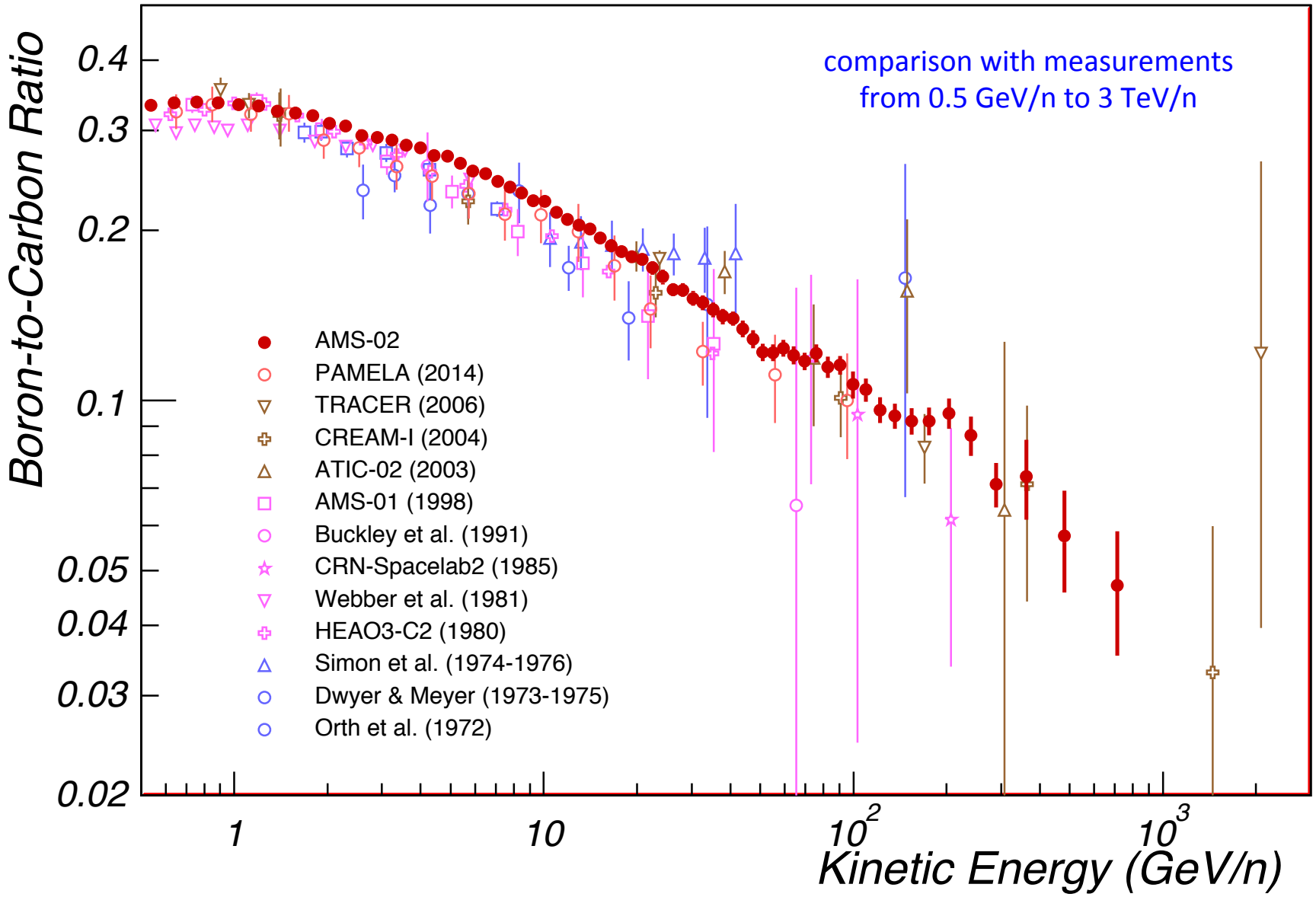
Fit of Lithium flux

Same model as the one used for proton and helium (double power law with smooth transition) between 45 GV and 3 TV:



→ Change of slope in the same rigidity range than for Proton and Helium.

B/C Ratio converted in Kinetic Energy

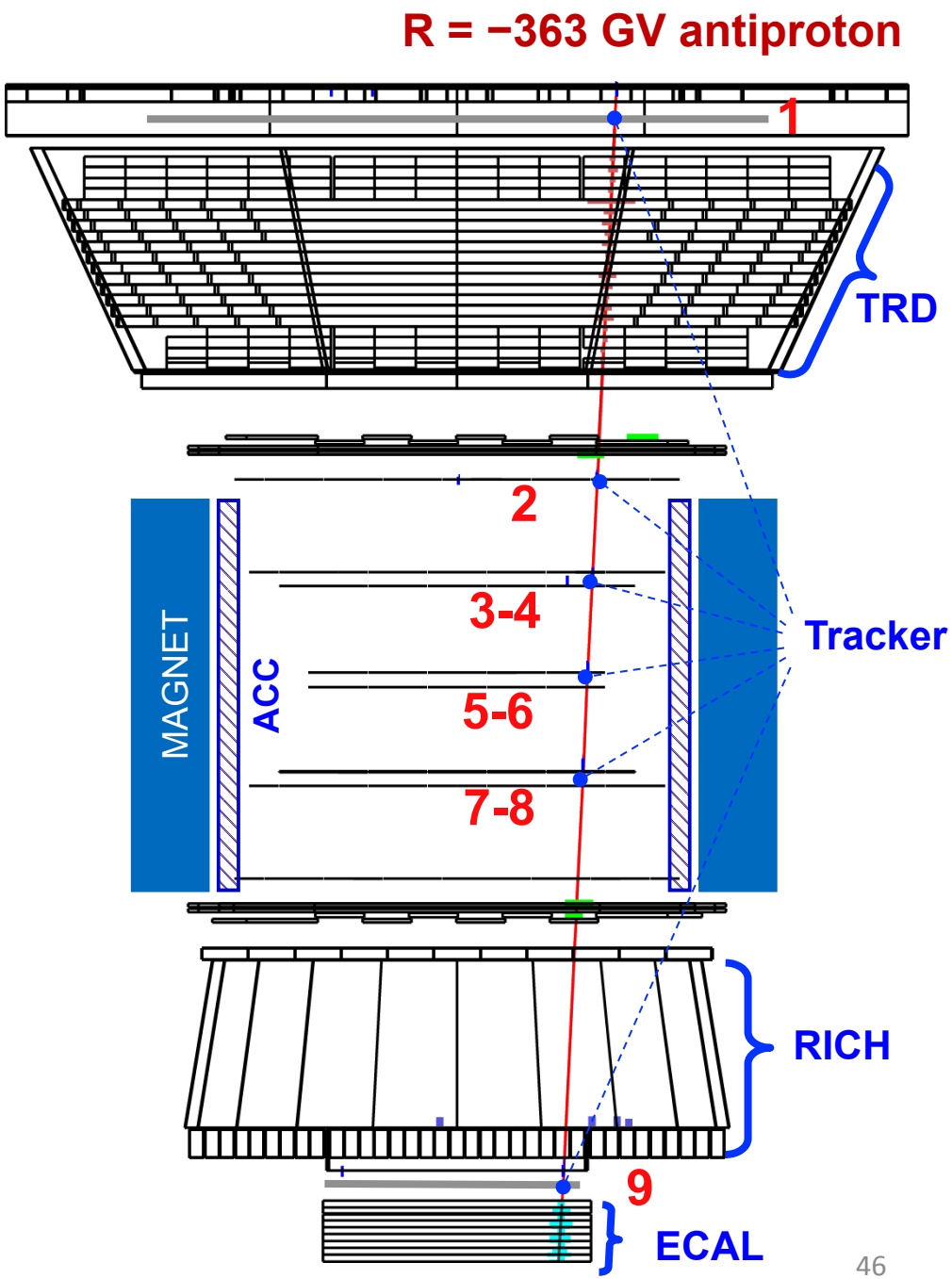


New results on the $\bar{p}/p$ ratio
Status Report

Rigidity range from 1 to 450 GV is studied using 290,000 antiprotons selected from the data sample of 54 billion events.

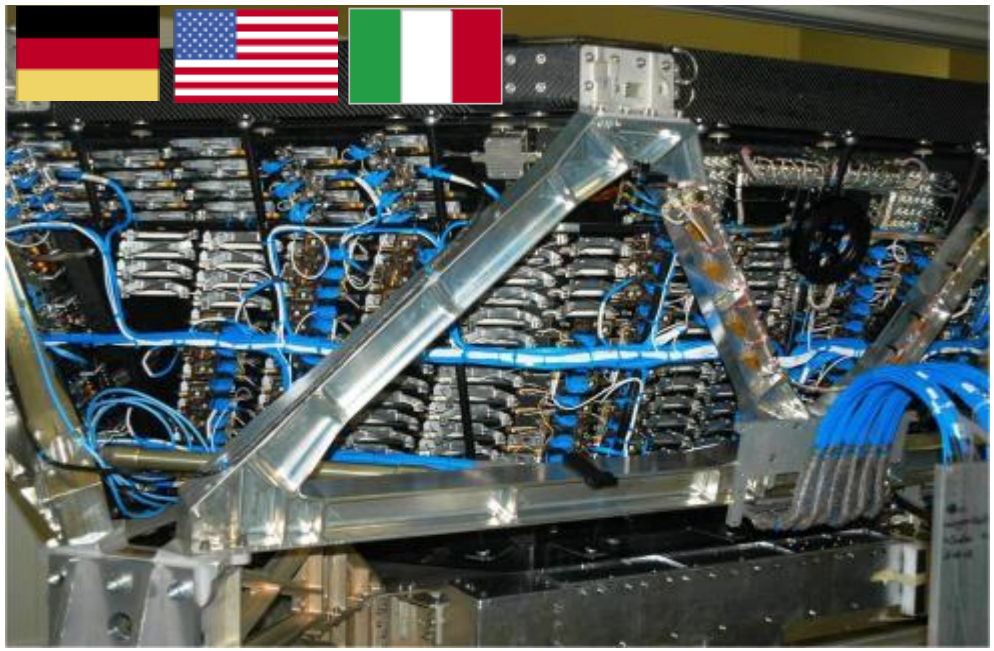
Event selection.

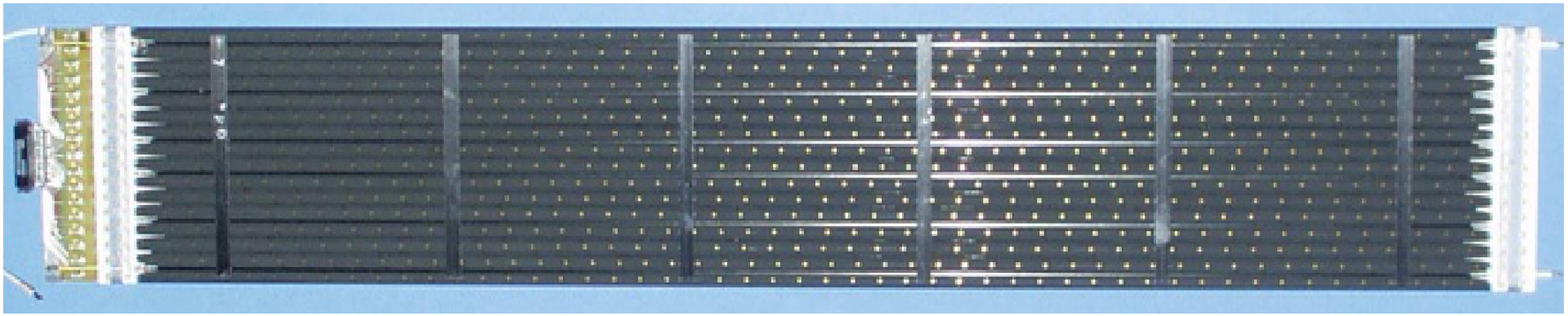
- DAQ:
  - livetime > 50% (no SAA)
- Geomagnetic cutoff:
  - |R| > 1.2·max cutoff
- TOF:
  - downgoing particle
  - β>0.3
- TRD:
  - at least 12 hits
- TRACKER:
  - Track quality
  - 0.8 < |Q| < 1.2
- ECAL:
  - Hadron shower shape



Transition Radiation Detector (TRD)

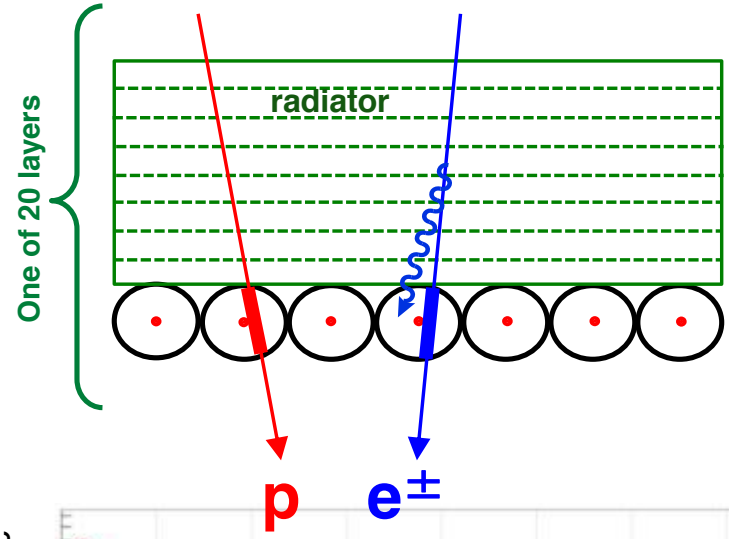
Identifies Positrons, Electrons by transition radiation and Nuclei by dE/dx

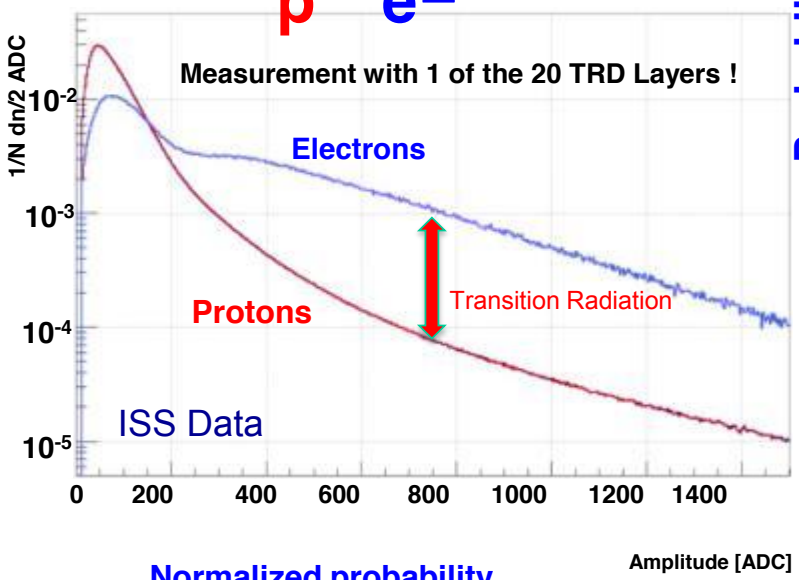


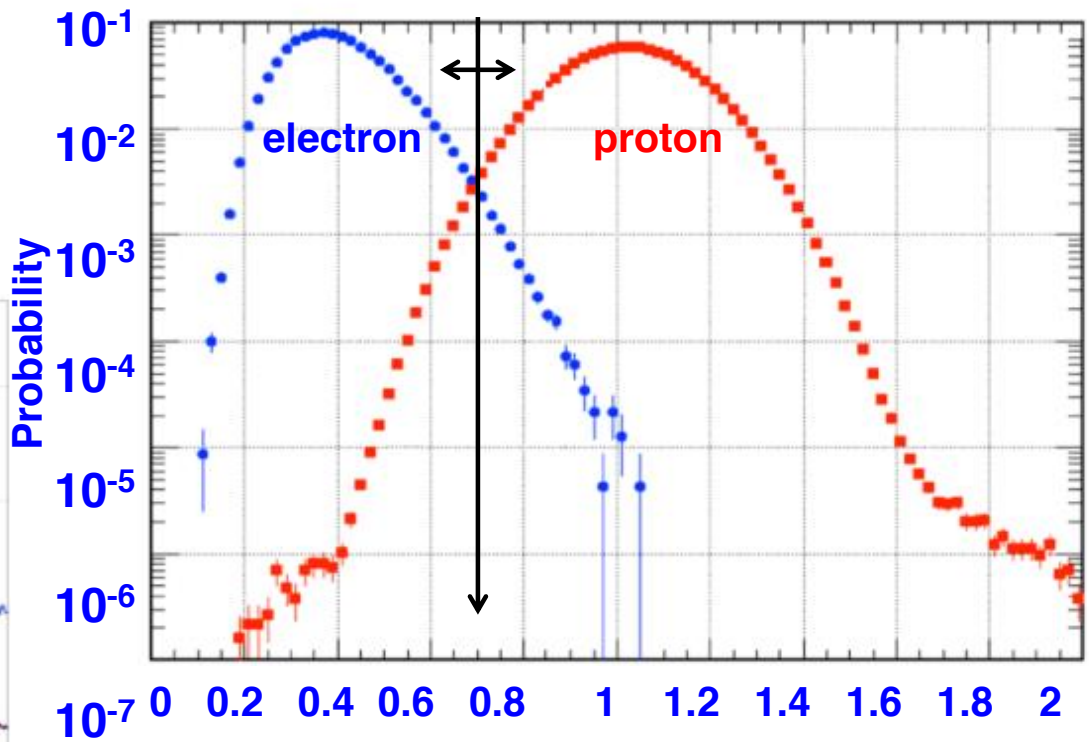


5,248 straw tubes selected from 9,000, 2 m length centered to 100μm.
K. Luebelsmeyer, S. Schael

TRD performance on the Space Station





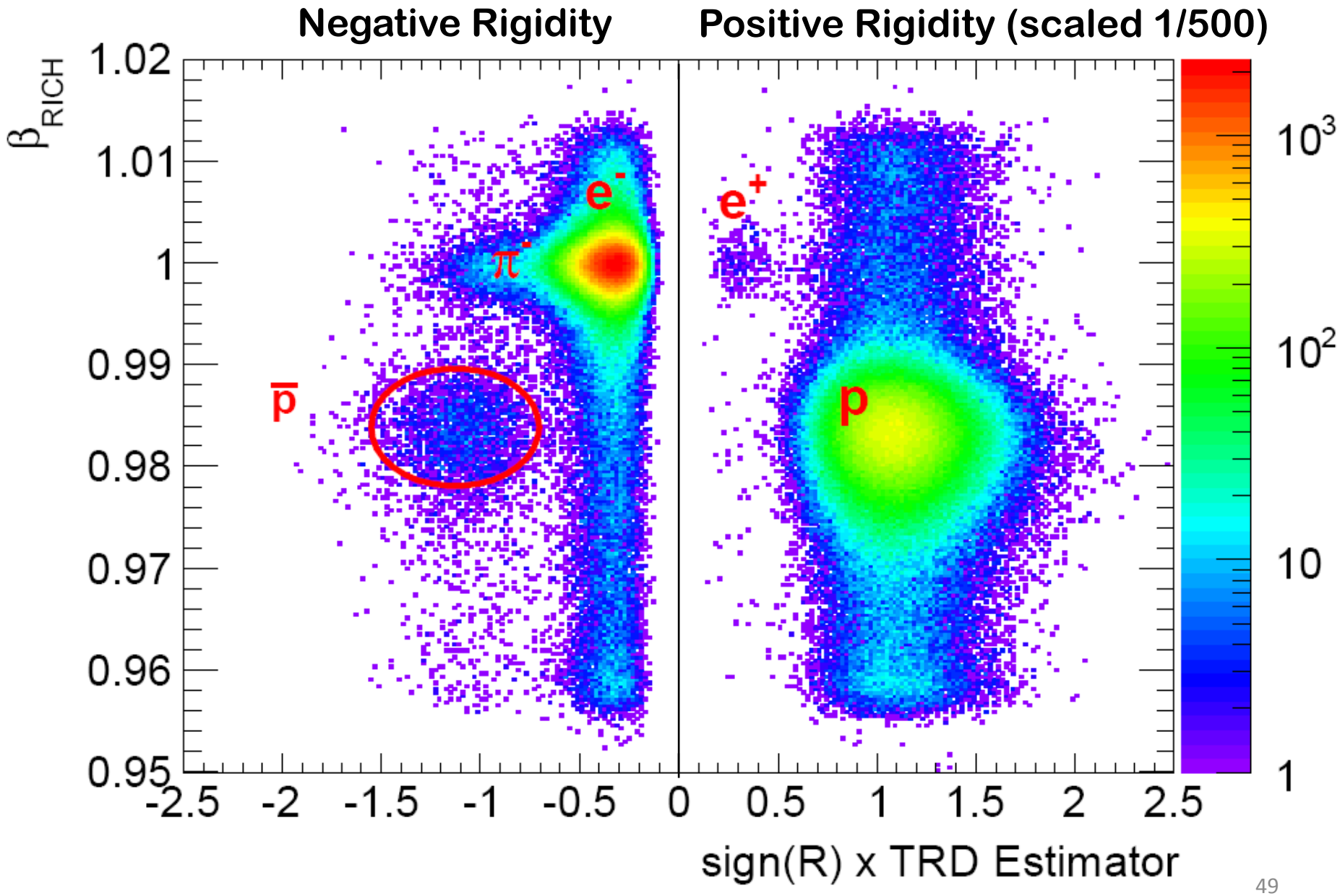


TRD estimator = $-\ln(P_e/(P_e+P_p))$

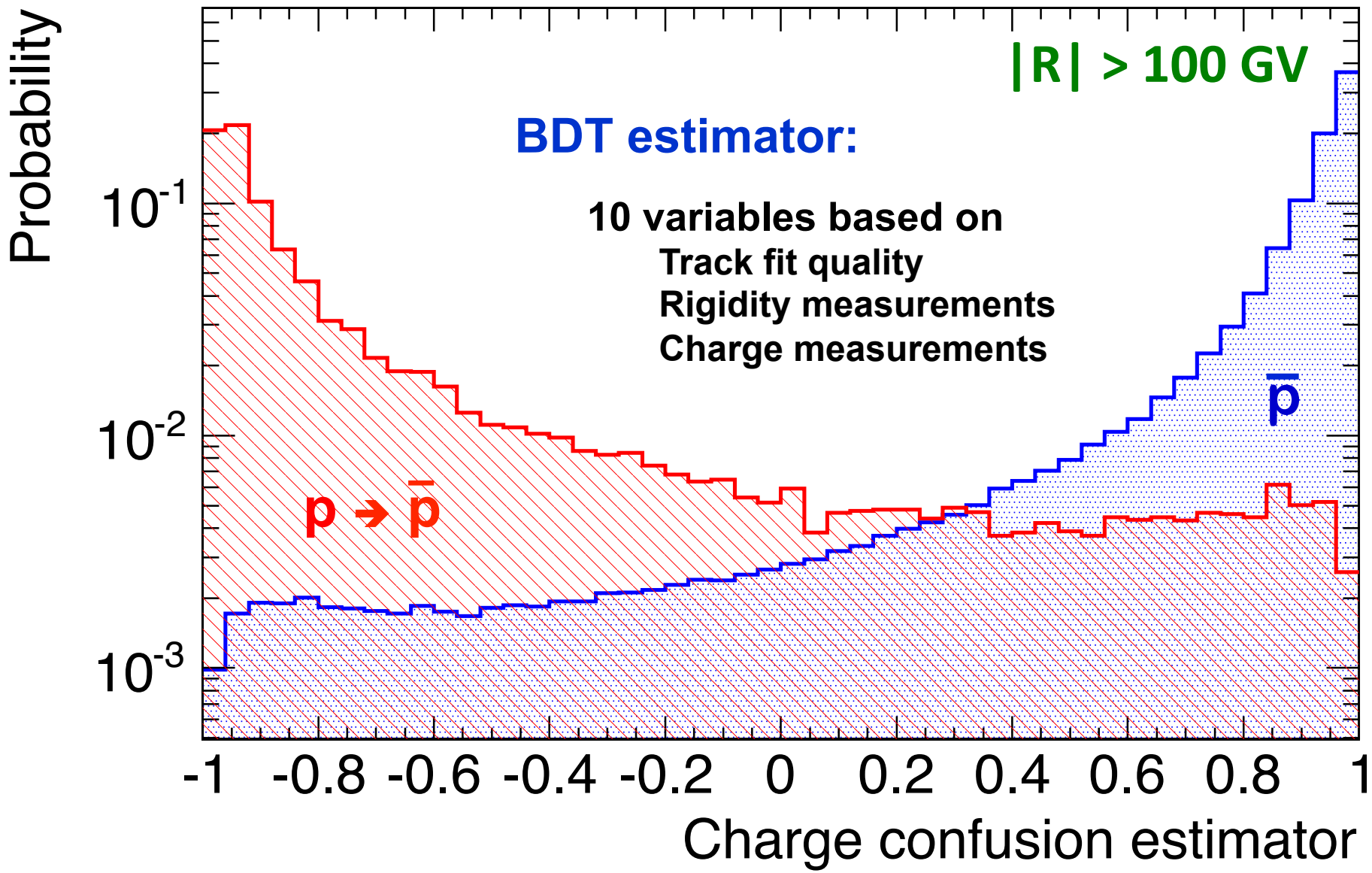
Normalized probability

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

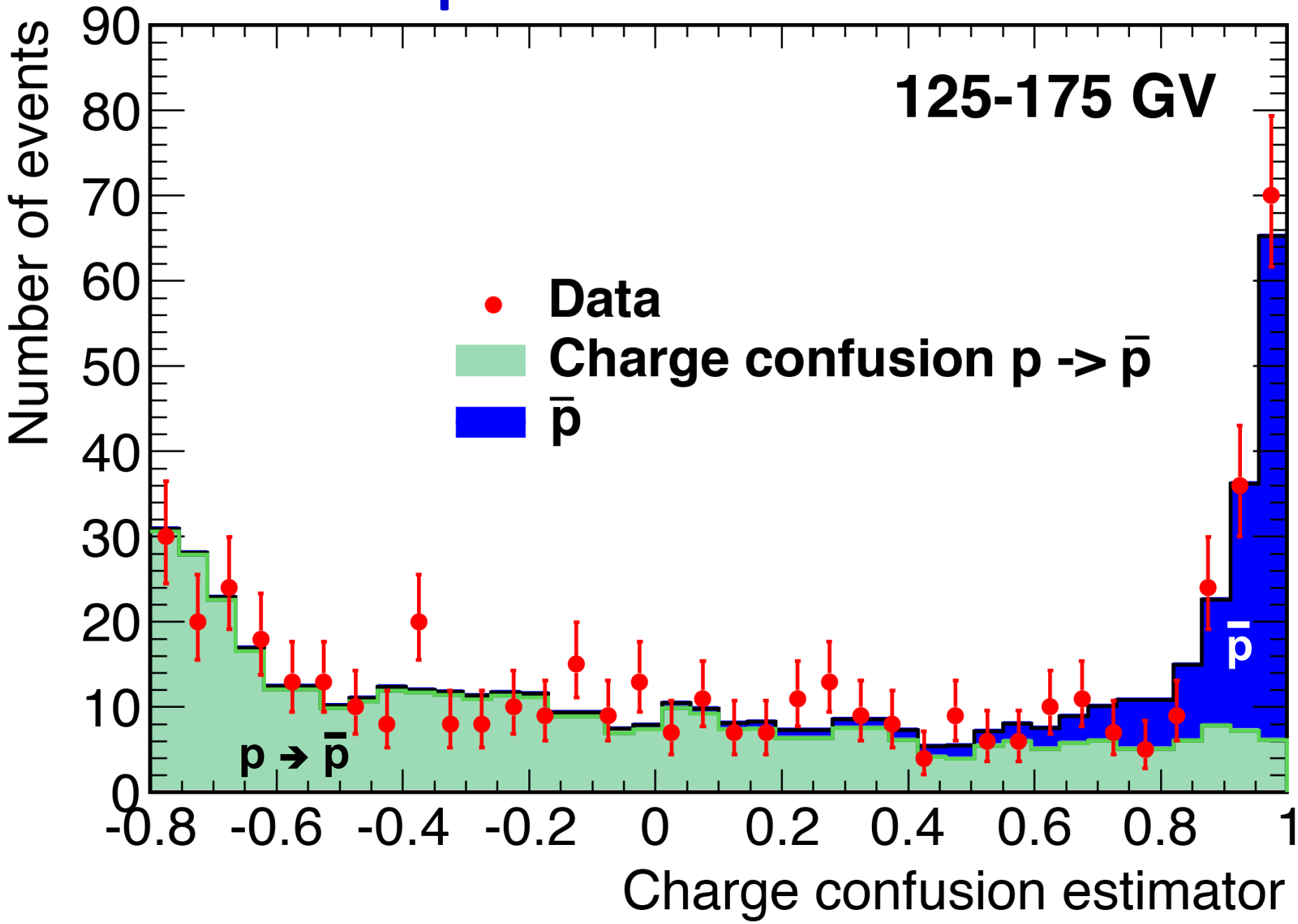
$\bar{p}$ identification below 10 GV



Charge confusion estimator at high rigidities



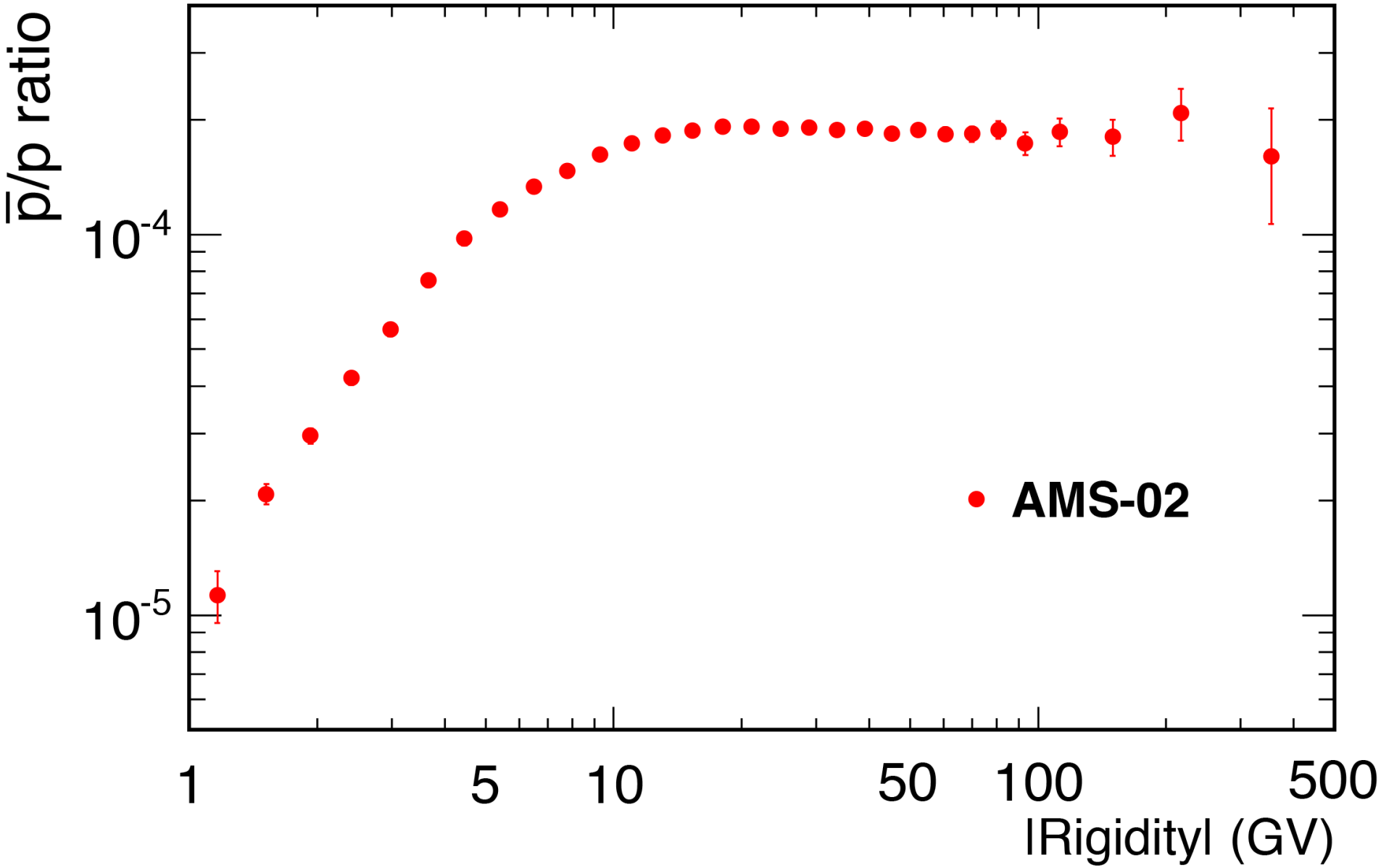
Anti-proton identification



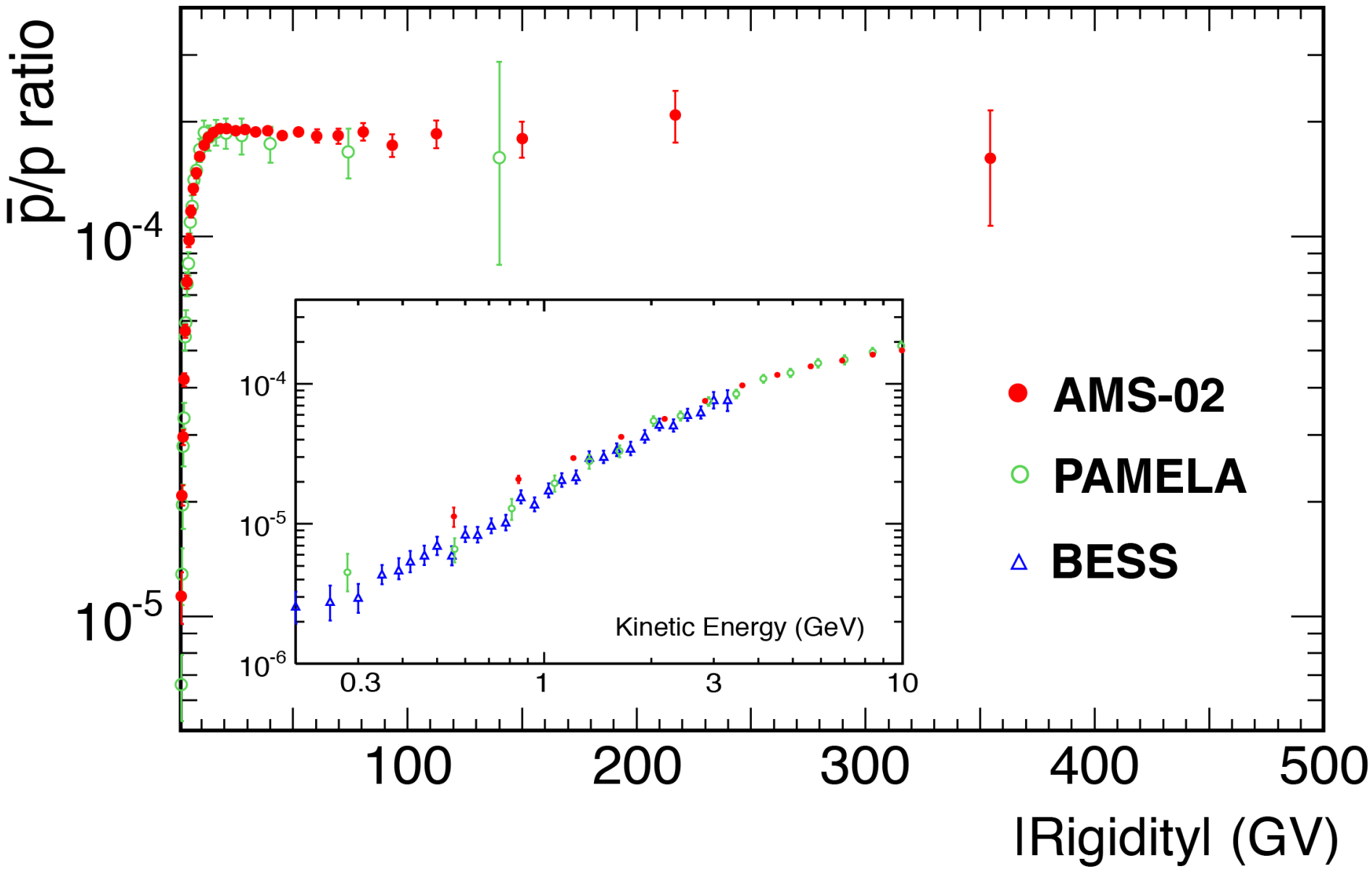
Statistical and systematic uncertainties in the rigidity bin 175-259 GV

$\bar{p}/p$ ratio	2.00 ($\times 10^{-4}$)	
Statistical error	0.29	14.4%
Systematic error	0.15	7.3%
Acceptance	0.03	1.4%
Selection	0.04	2.1%
Ref. spectra	0.14	6.9%
Total error	0.32	15.5%

AMS $\bar{p}/p$ results



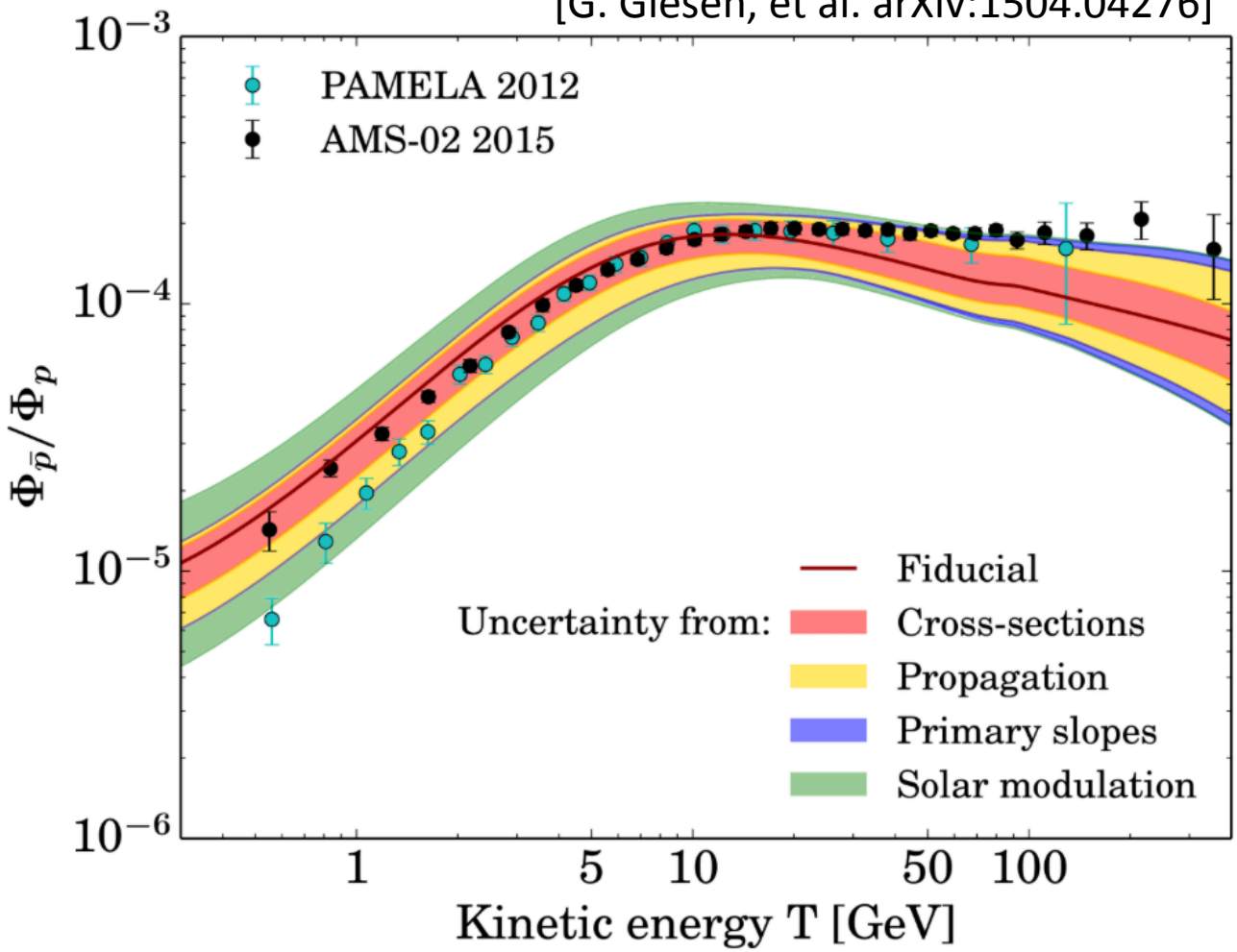
AMS $\bar{p}/p$ results



AMS $\bar{p}/p$ results

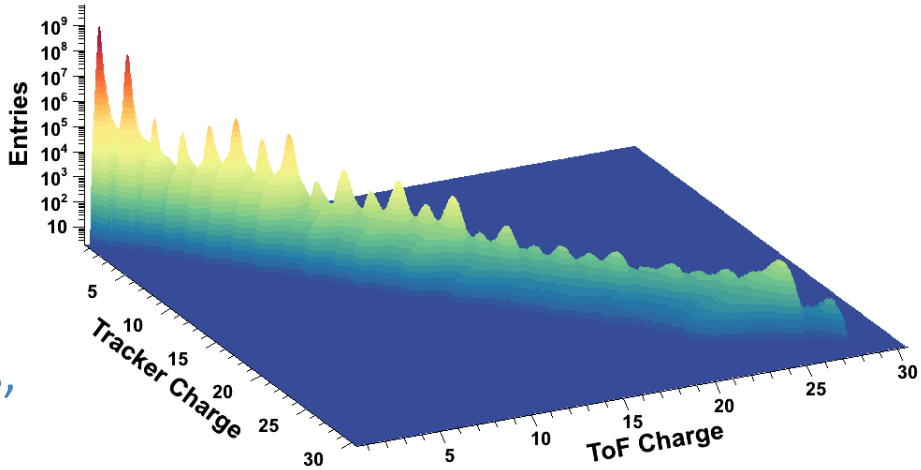
Latest AMS results used to estimate secondary production:

[G. Giesen, et al. arXiv:1504.04276]



Summary

- The AMS-02 experiment operates onboard the ISS since May 2011. All the detectors are working as expected.
- More than 60 billions events were recorded so far.
- The latest AMS measurements of protons, helium, and other nuclei provide precise and unexpected information.



- The $\bar{p}/p$ ratio, seems to remain flat at high energy. Not clear if extra sources are needed to reproduce this feature. More work needed on models.
- In the coming months and years, AMS will provide precision measurement of all the CR components from p to Oxygen: this will allows to considerably improved the comprehension of CR physics.