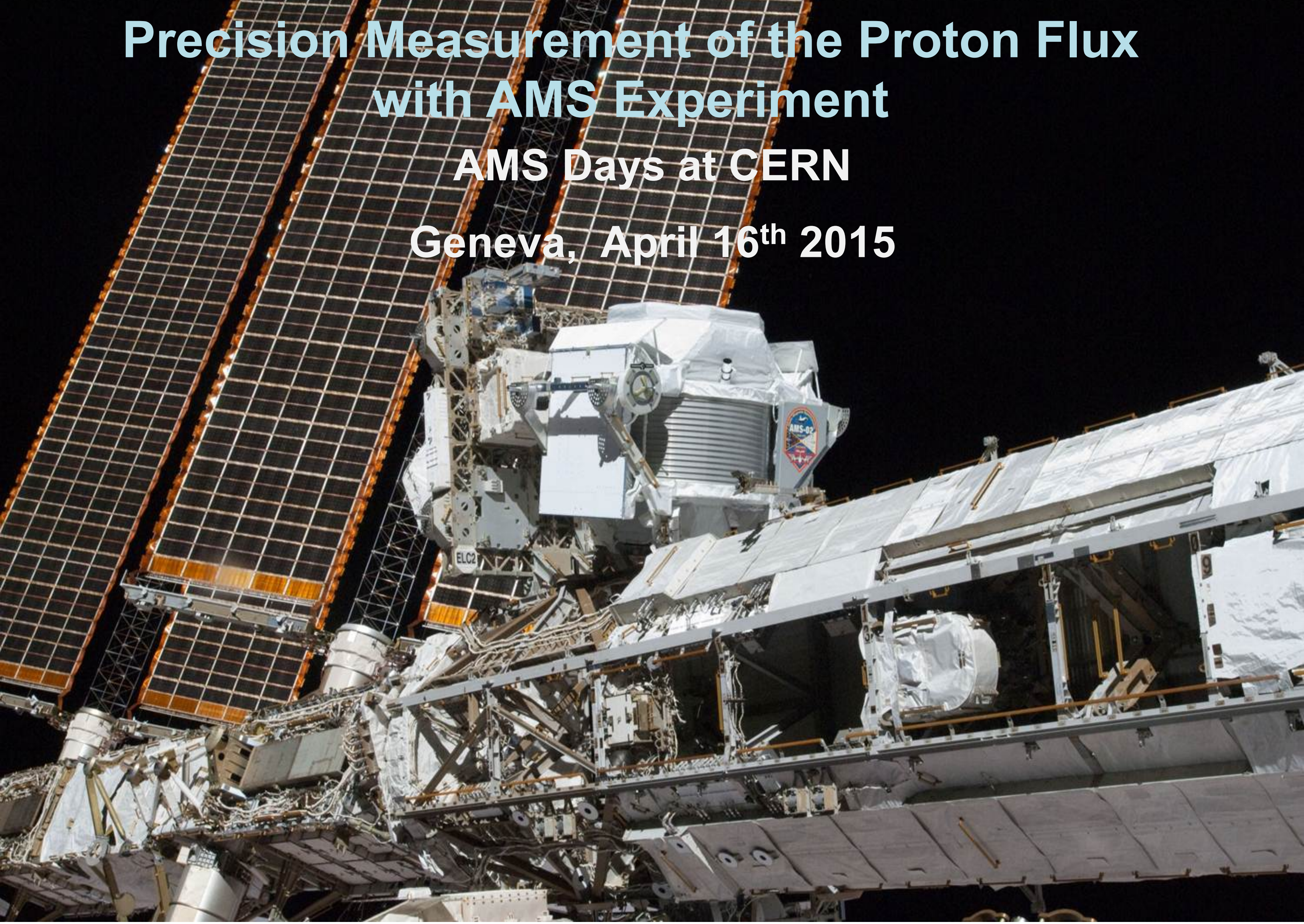
Precision Measurement of the Proton Flux with AMS Experiment

AMS Days at CERN

Geneva, April 16th 2015



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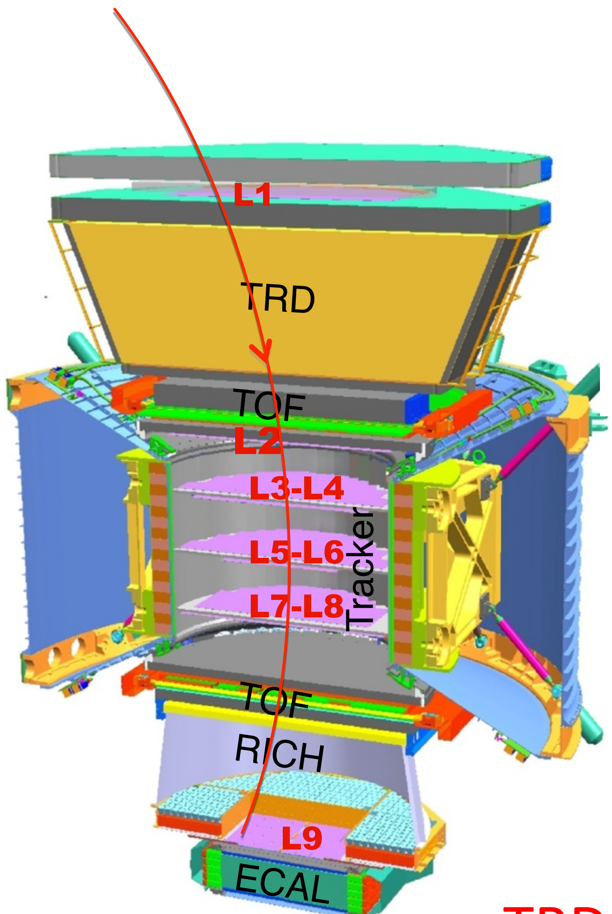
Introduction

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.

Here we report on the precise measurement of the proton flux in primary cosmic rays in the rigidity range from 1 GV to 1.8 TV based on 300 million events collected by the AMS.

AMS Cosmic Ray Protons Measurement



Tracker (9 Layers) + Magnet

Rigidity and Charge Sign

Bending Coordinate Resolution (Z=1) ≈ 10 μm

MDR (Z=1) ≈ 2 TV

ToF (4 Layers)

Velocity and Direction

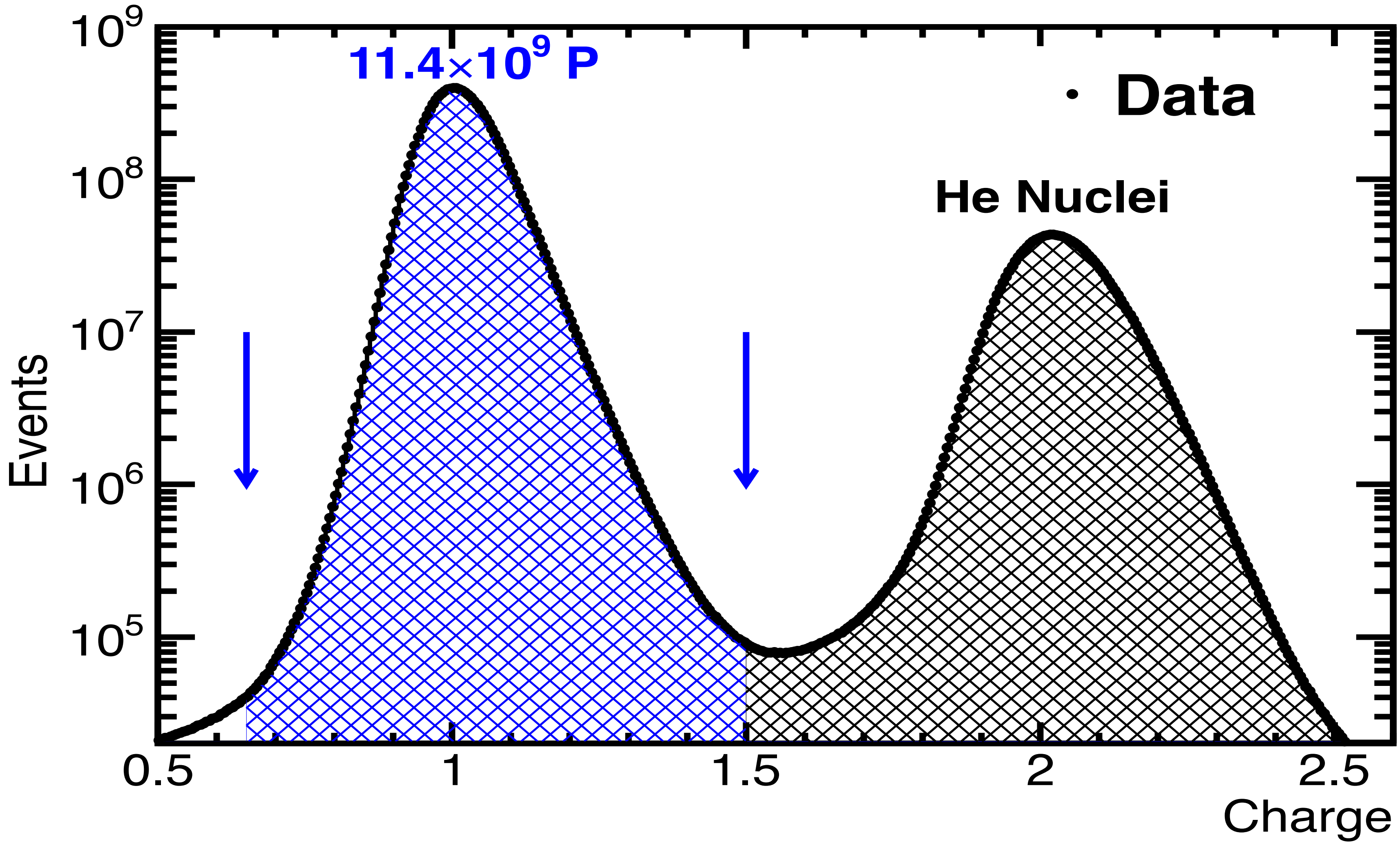
$\Delta\beta/\beta^2$ (Z=1) ≈ 4%

TRD, Tracker, RICH ,TOF, ECAL

Charge Magnitude Along Particle Trajectory

ΔZ (Z=1) ≈ 0.05-0.2

AMS Data Sample



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|~1 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

Residual Background

(I) Protons from He and other Nuclei interacted on very top of AMS:

0.5% @ 1GV and negligible (<0.1%) above 10 GV

(II) π' s from protons interacted on top of AMS:

Less than 0.1% in all rigidity range

(III) Positrons and Electrons:

Less than 0.1% in all rigidity range

Flux Measurement

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

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

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

i=1,72

Rigidity 1-1800 GV

Time ~63,000,000 sec , R>30 GV

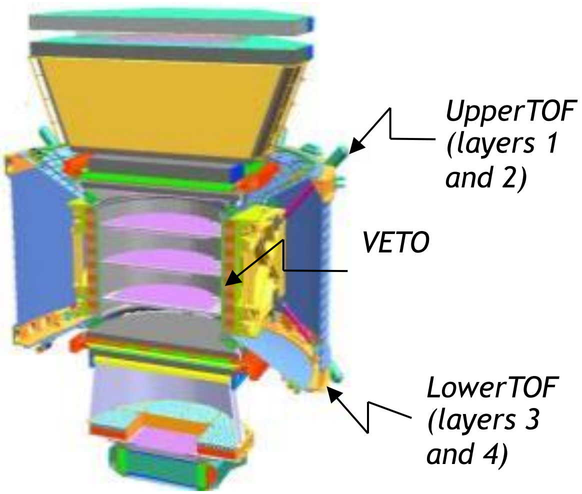
Bin width

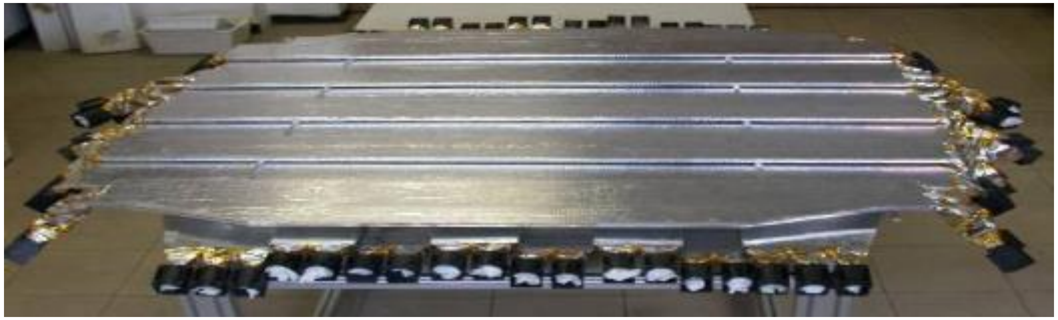
Trigger Efficiency from Data

Effective Acceptance from MC, Verified with Data

Proton flux: (i) systematic errors on trigger efficiency

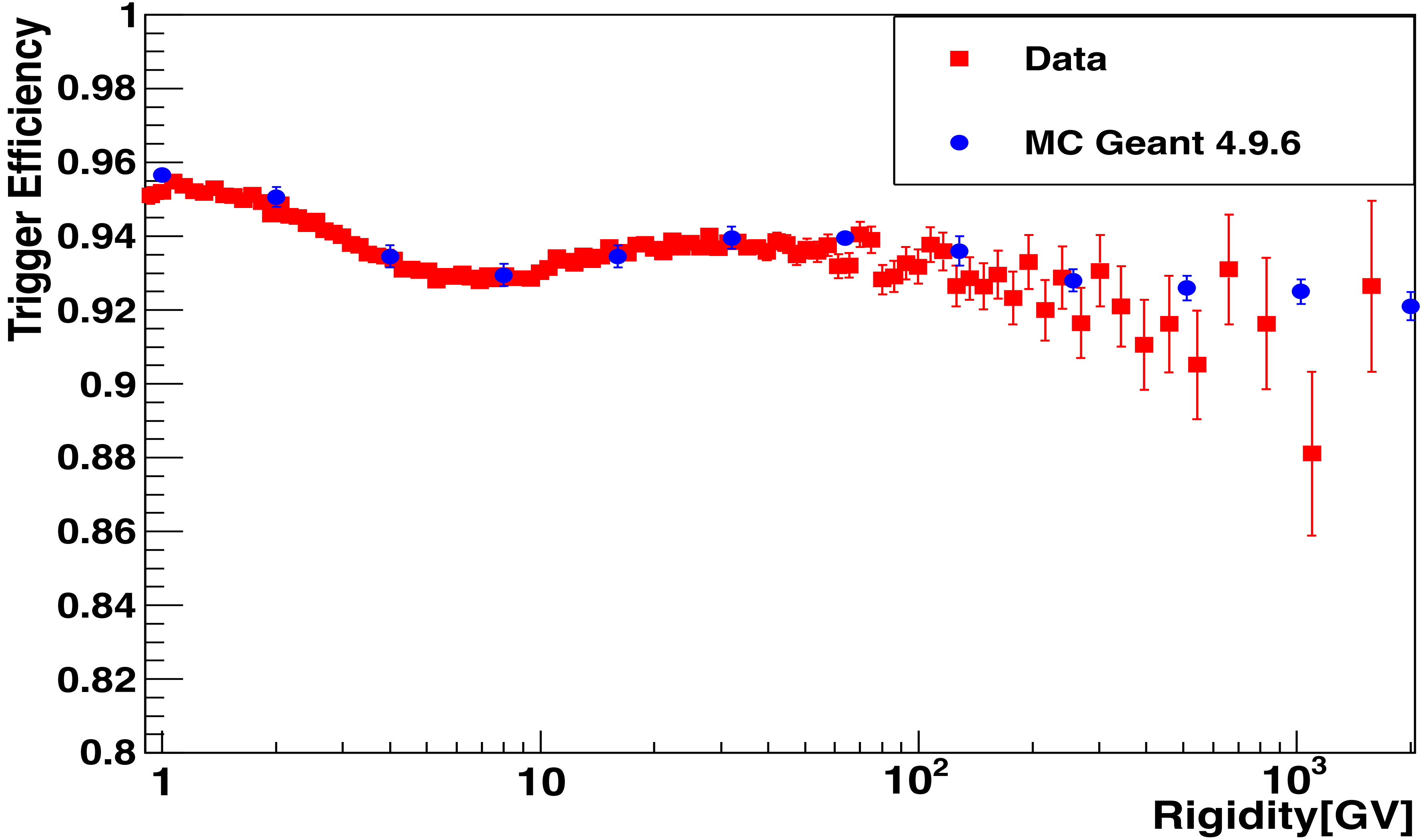
Trigger efficiency [4/4 TOF + VETO] was measured using 1% prescaled event sample obtained with unbiased 3 out of 4 ToF coincidence trigger. The error is dominated by the statistics available from the unbiased trigger.





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

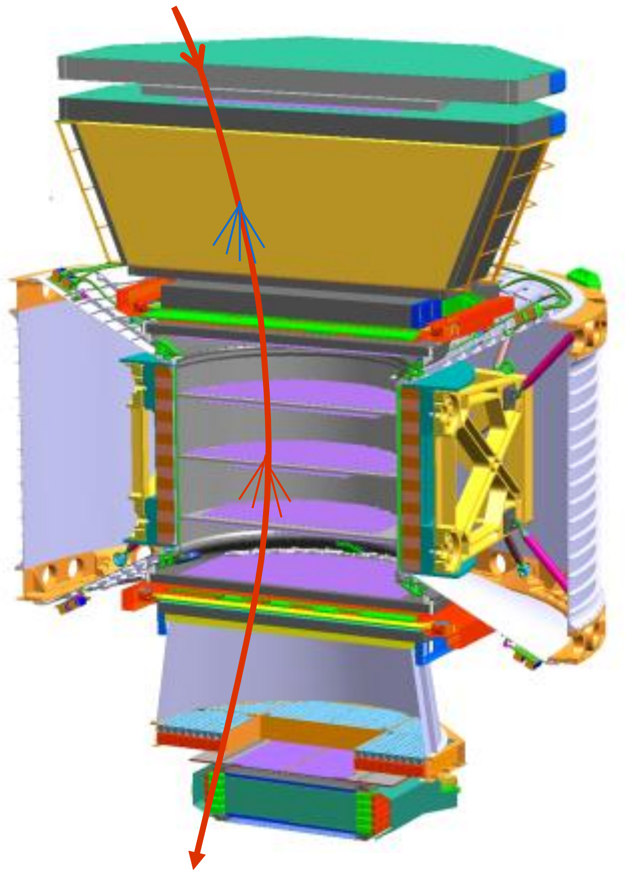
Trigger Efficiency Measured from Unbiased Trigger



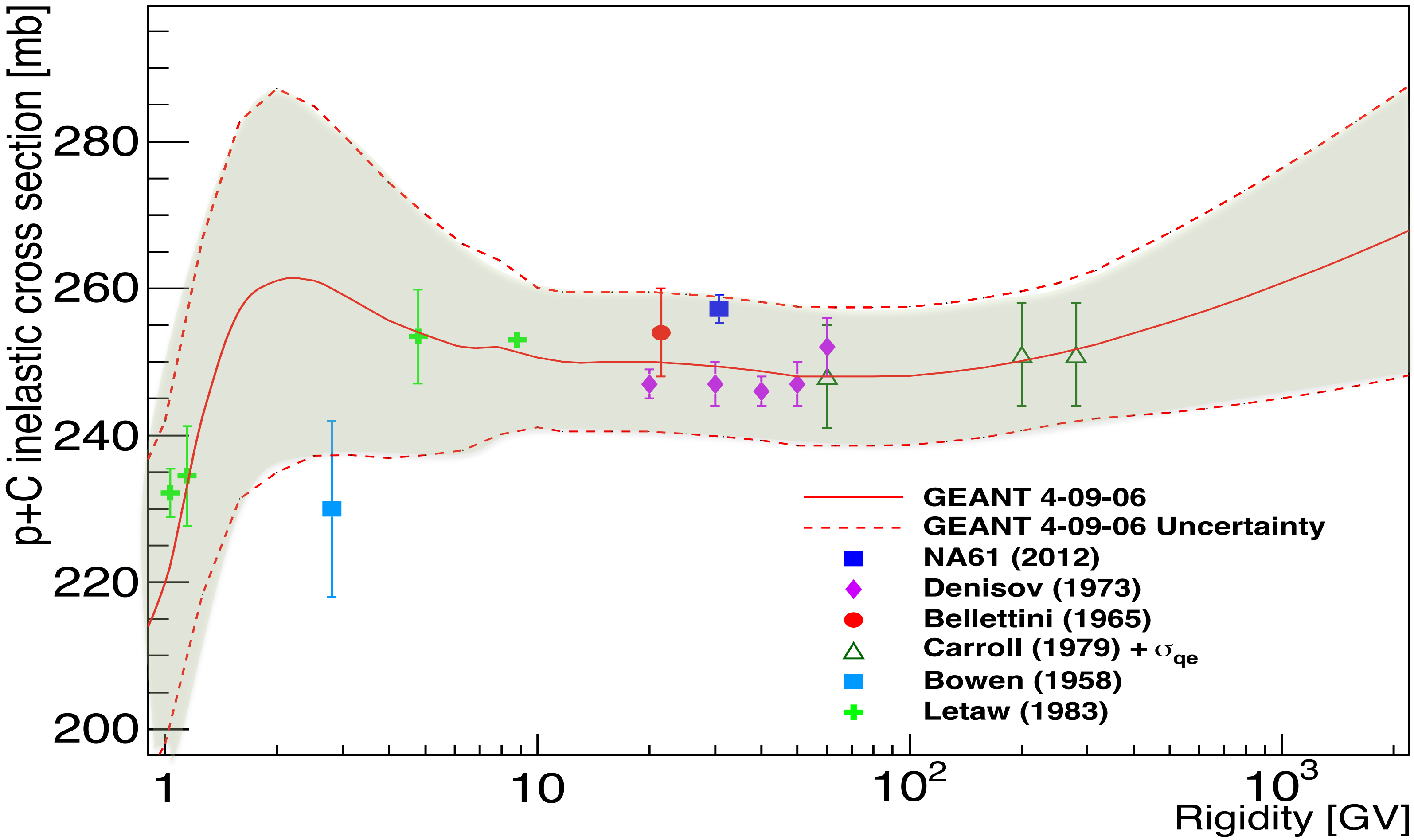
Proton flux: (ii) systematic errors on the acceptance and event selection

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.

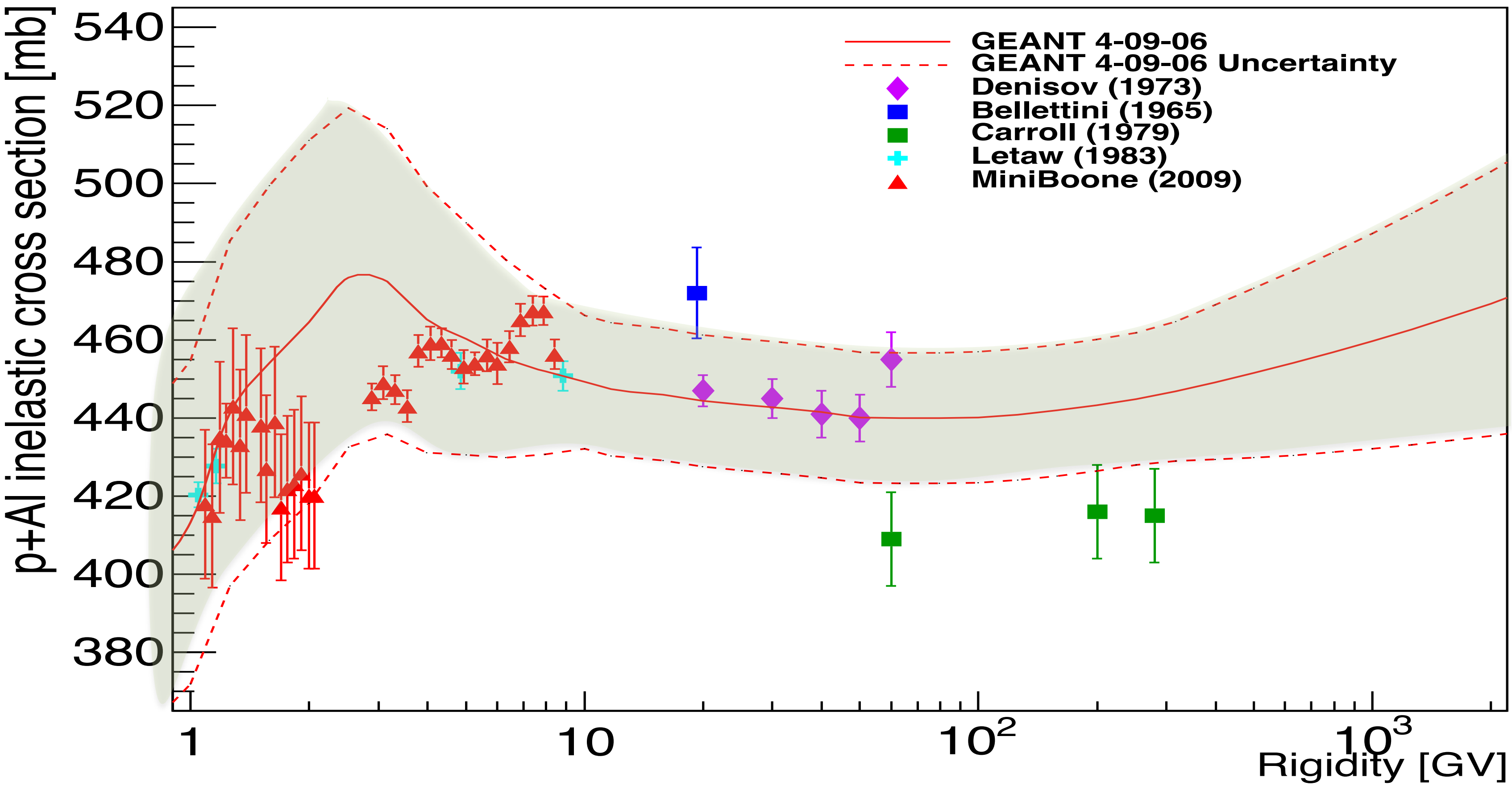


Acceptance Error due to Interactions



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.

Acceptance Error due to Interactions

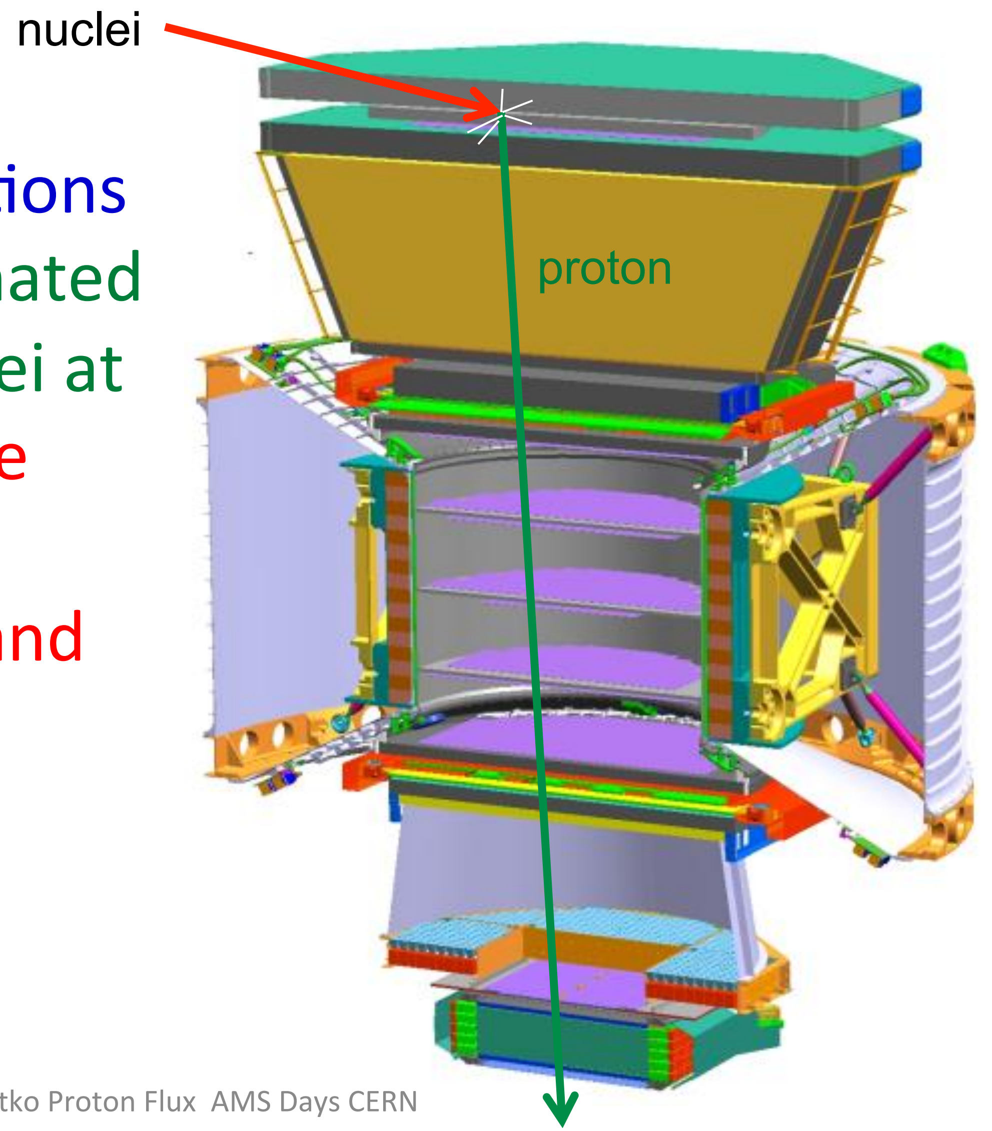


Using scaled by ±10% cross sections MC samples allowed to evaluate acceptance error.

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

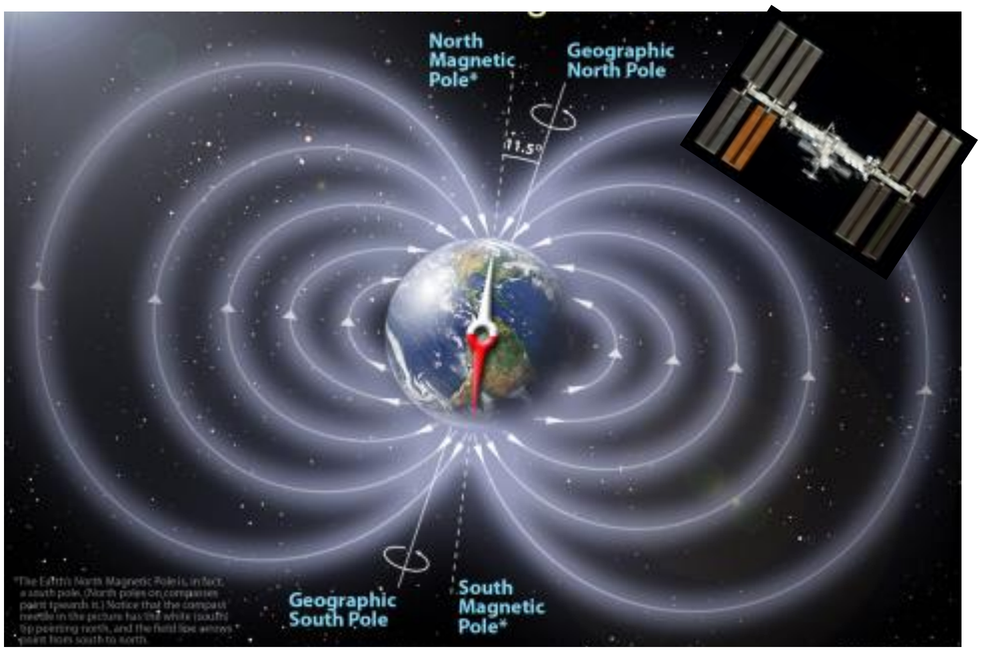
Proton Flux: (iii) systematic errors on background contamination

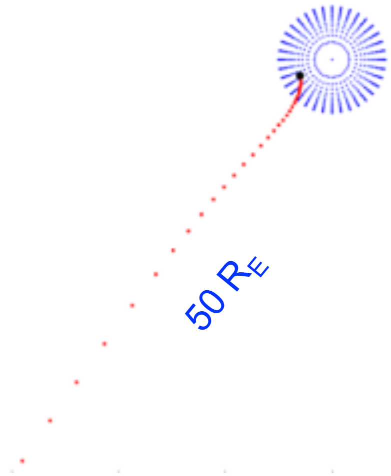
The background contributions from protons which originated in the interactions of nuclei at the top of AMS, noticeable only below 2GV, are subtracted from the flux and the uncertainties are accounted for in the systematic errors.



Proton flux: (iv) 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.





We have also verified that using the most recent IGRF model and the IGRF model with external non-symmetric magnetic fields does not introduce observable changes in the flux values nor in the systematic errors.

Proton flux: (v) systematic errors on unfolding

Among many unfolding procedures, we selected two. The small differences between the two procedures (< 0.5%) are accounted as a systematic error.

We have checked the sensitivity of the results to the binning by:

1. increasing the bin width by factors of 2 and 4

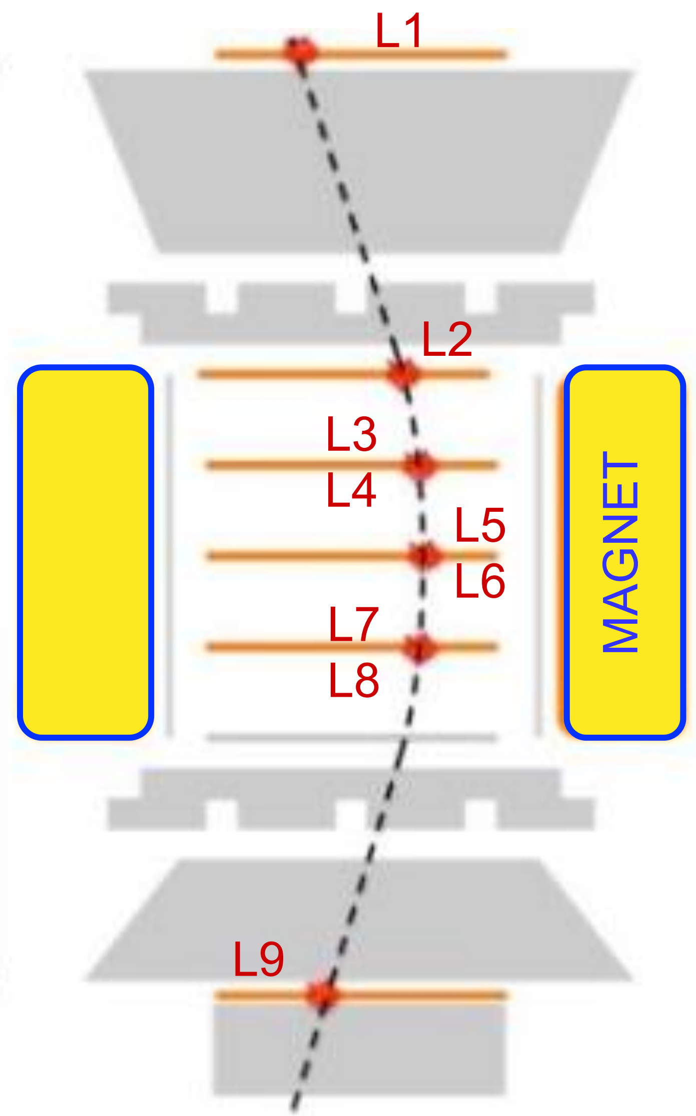
2. reducing the bin width by factors of 2 and 4.

The resulting uncertainty is well within the assigned systematic errors.

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

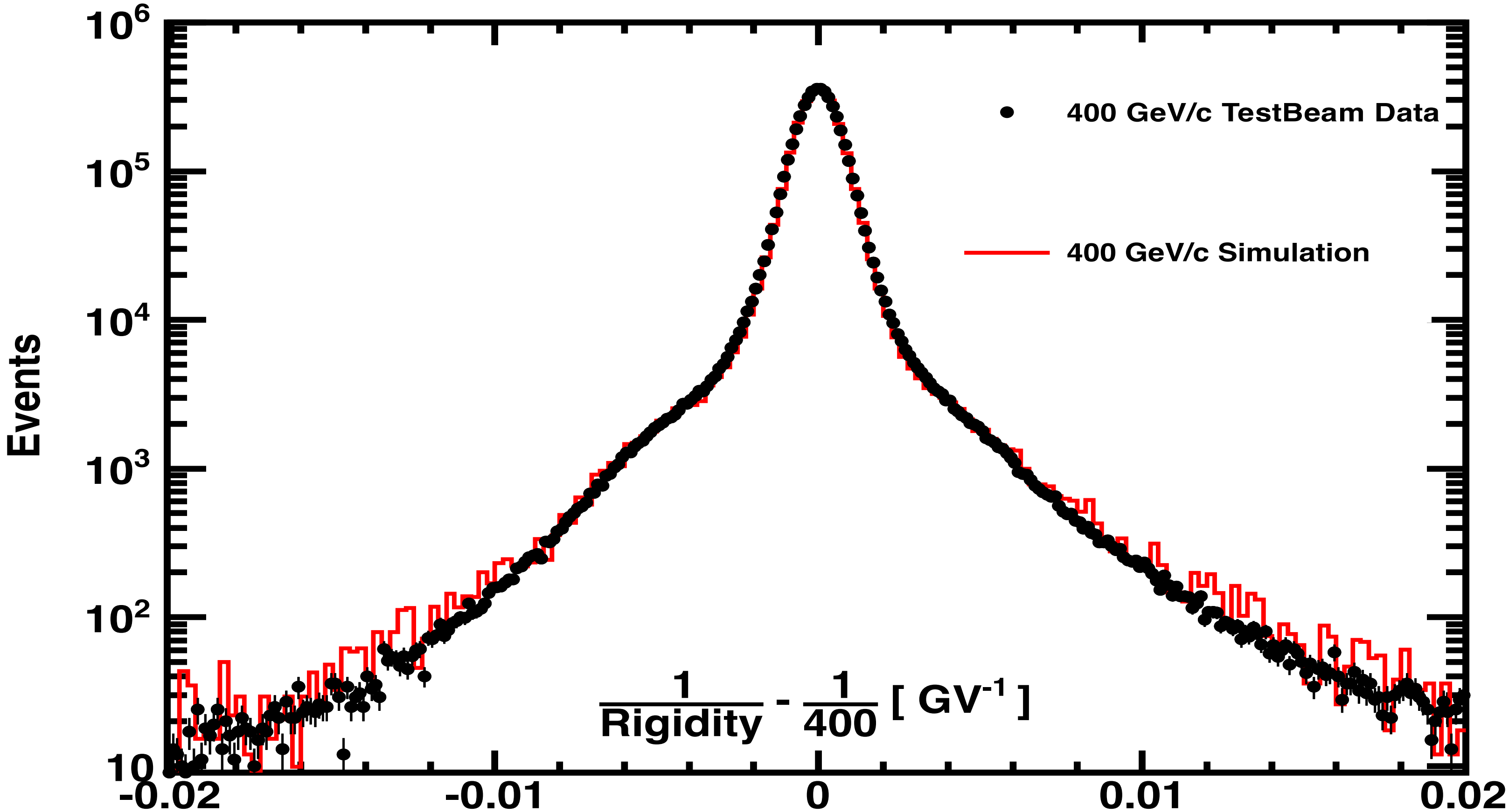
The rigidity resolution function was verified with data from both the ISS and the 400 GeV proton beam. For this the residuals between the hit coordinates measured in tracker layers L1 and L9 and those obtained from the track fit from only the inner tracker L2 to L8 were compared between data and simulation.

In order to additionally validate the alignment of the external layers the difference between the rigidity measured using the information from L1 to L8 and from L2 to L9 was compared between data and the simulation.



Proton flux: (vi) systematic errors on the rigidity resolution function (cont'd)

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.

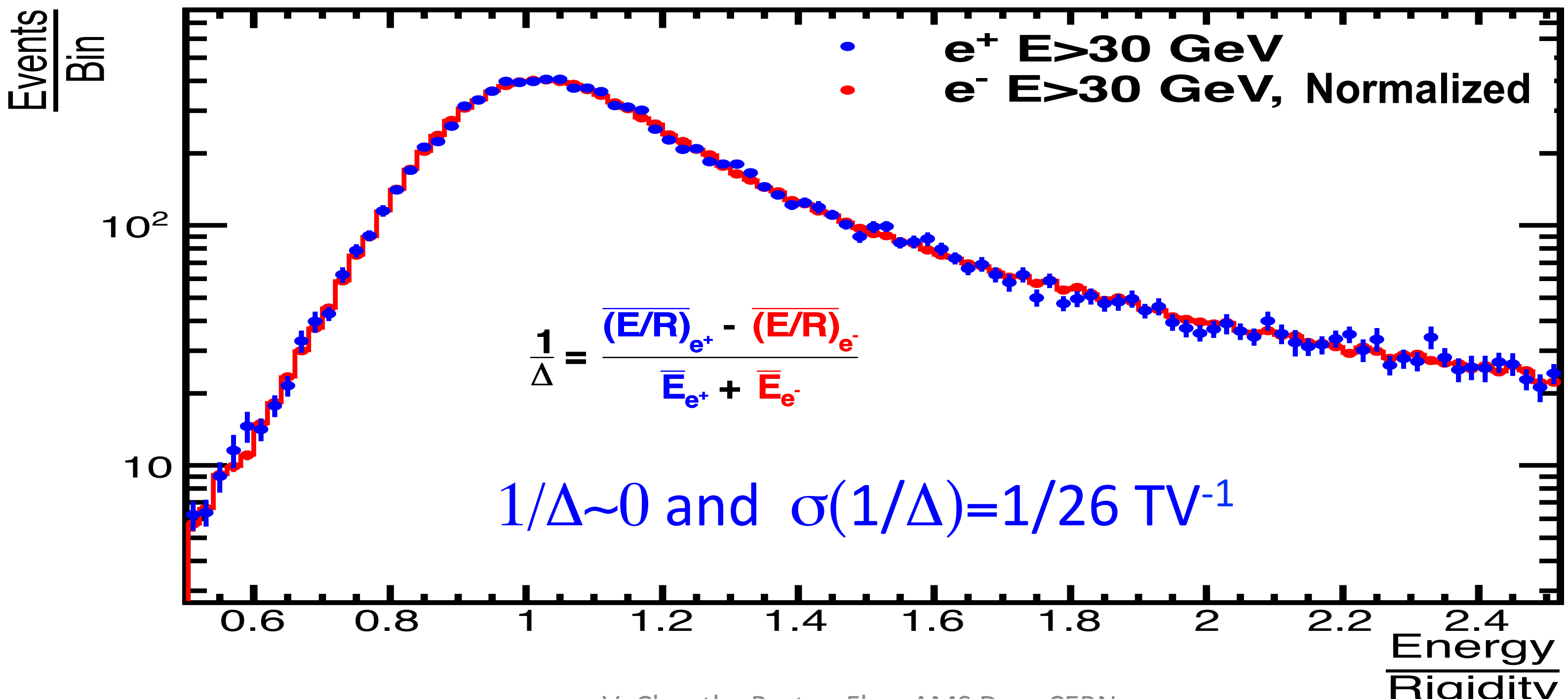


The resolution function for 400 GeV/*c* protons measured in the test beam compared with Monte Carlo simulated events.

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

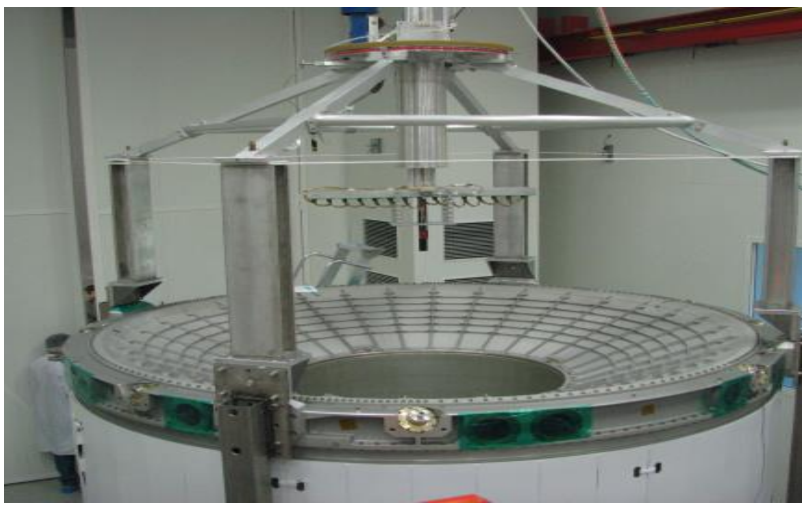
1) Residual tracker misalignment:

From the 400GeV/c test beam data it was measured to be less then 1/(300TV). For the ISS data 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.



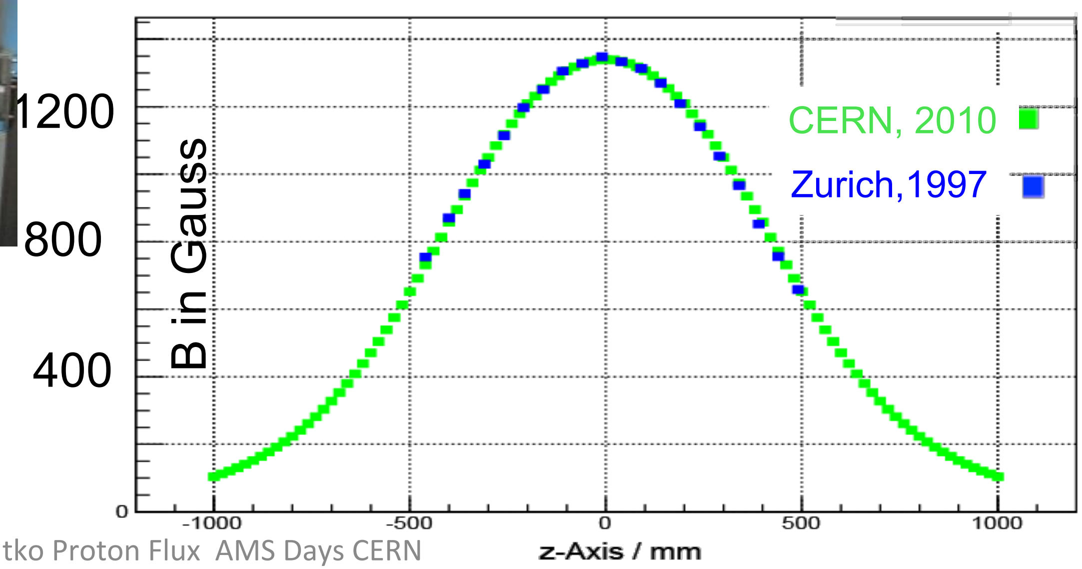
Proton flux: (vii) systematic errors on the absolute rigidity scale

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%



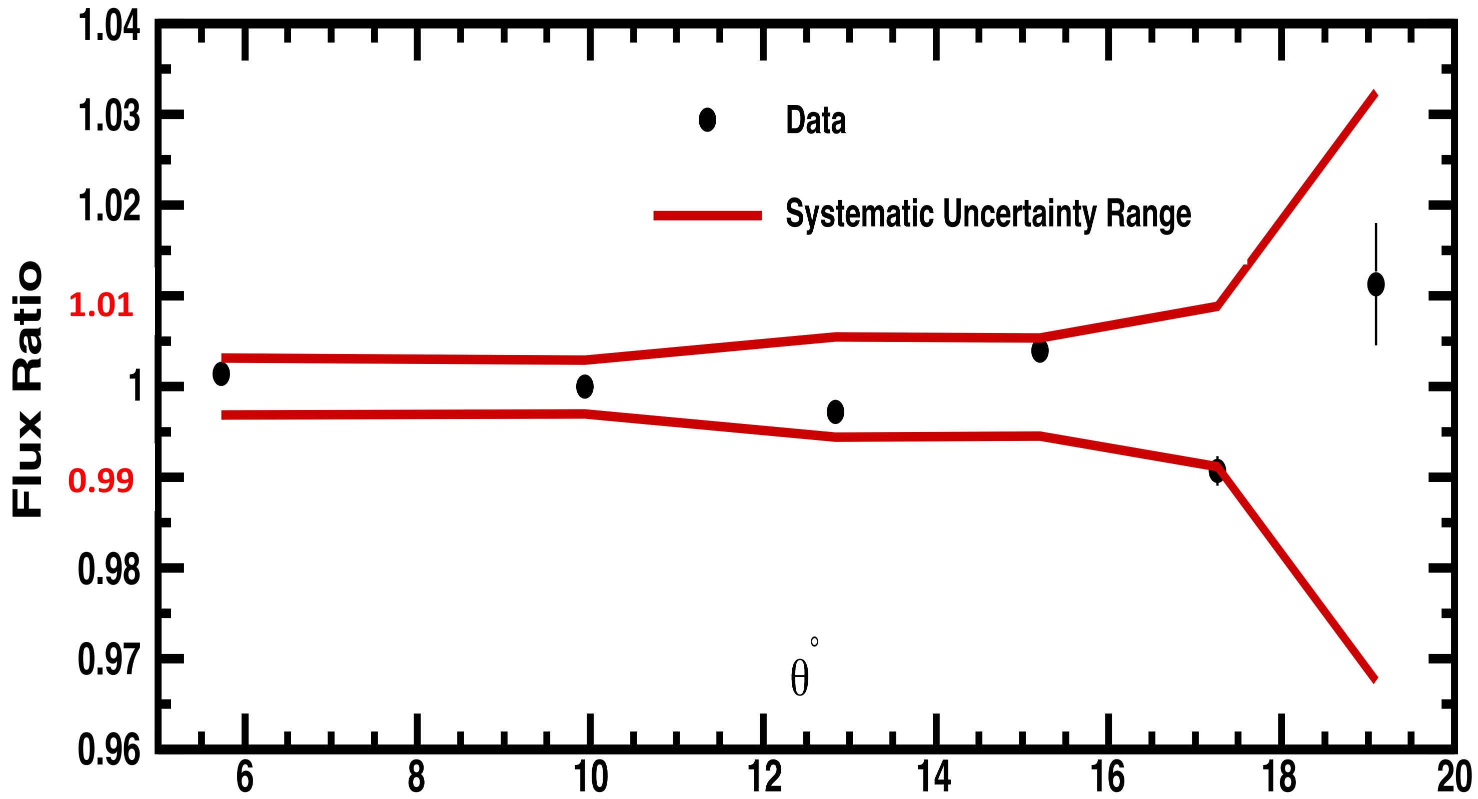
Break Down of Systematic Errors @ 200GV

Source	**Error (%)**
Trigger	0.2
Acceptance	1.1
- Selection	0.85
- Interactions	0.6
- Geomagnetic Cutoff [<2 GeV]	0
Unfolding & Rigidity Resolution	0.95
Rigidity Scale	0.7
- Residual tracker misalignment	0.55
- Magnetic field accuracy	0.45

Four Examples of Independent Verification of Systematic Errors on

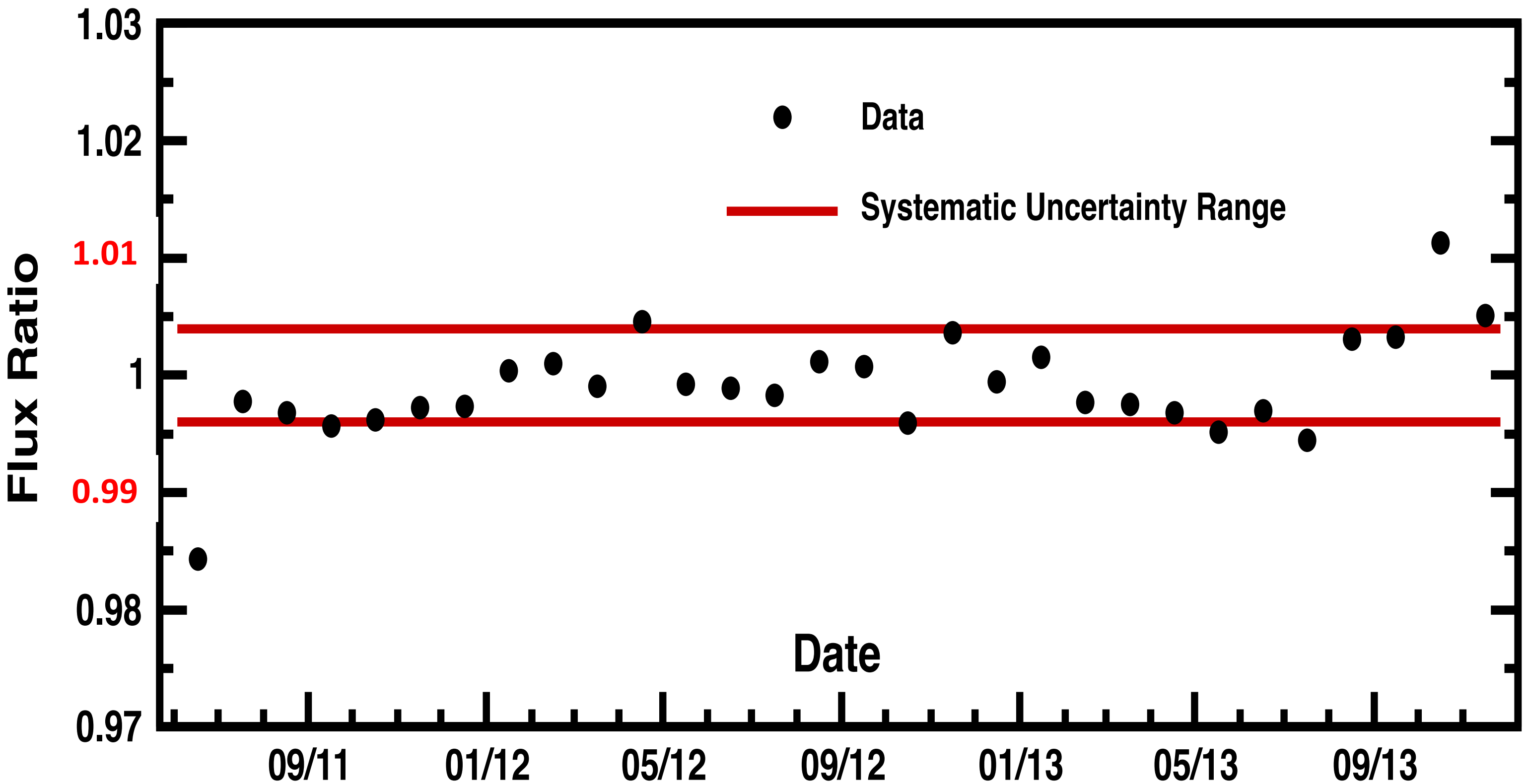
- Acceptance
- Time Stability
- Rigidity Scale
- Unfolding

Verification of the Systematic Error Assigned to Acceptance



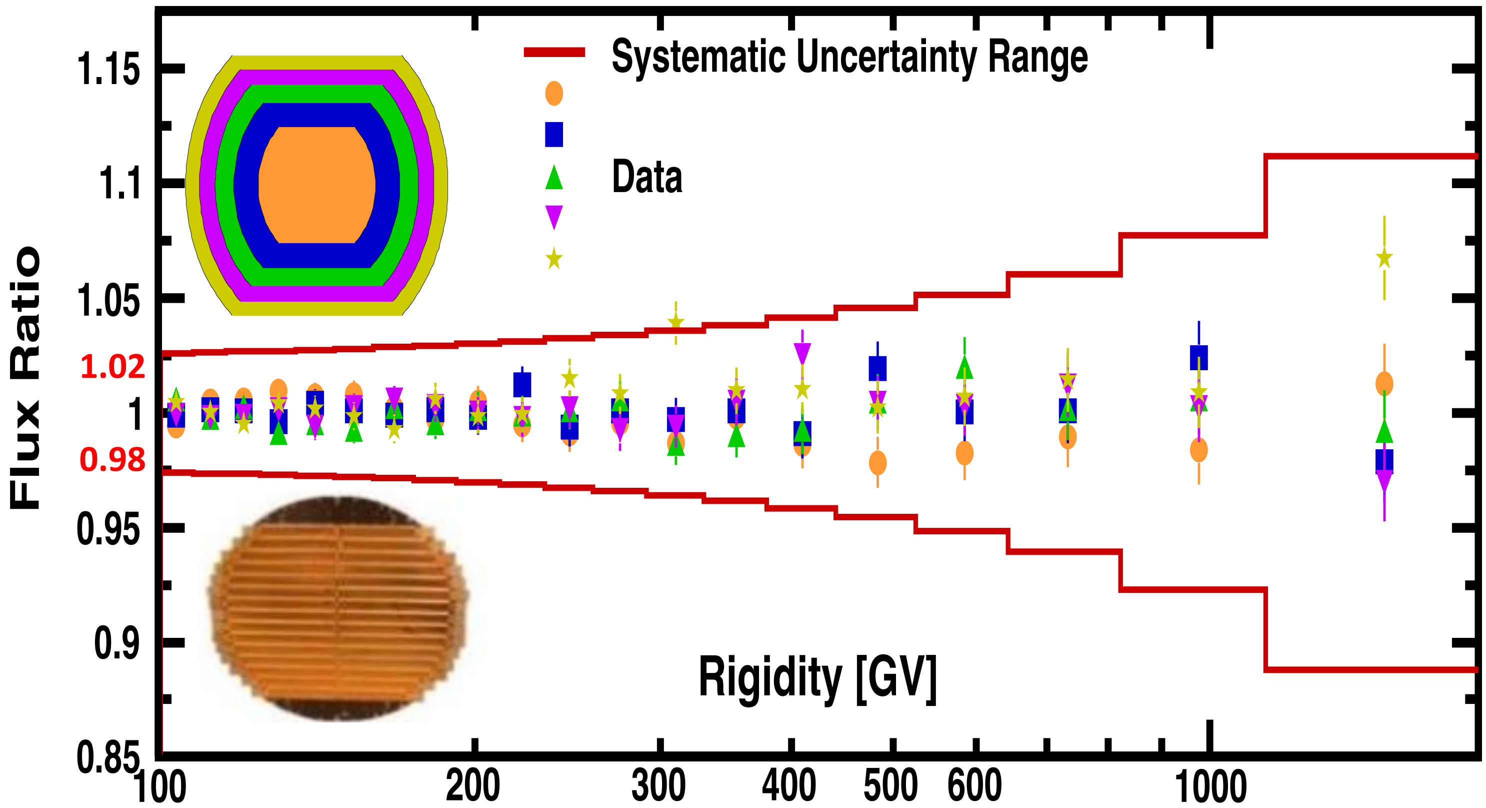
The variation of the flux ratio above 30 GV [Max GeoMag Cutoff] versus the angle θ to the AMS Z axis.

Verification of the Stability of Detector Performance



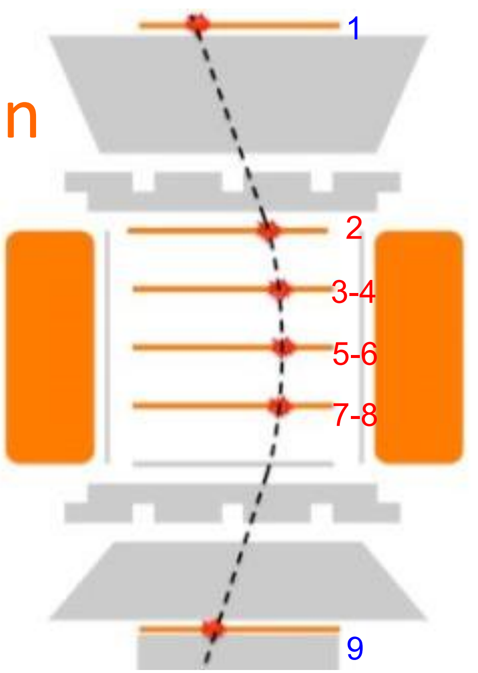
The variation of the (monthly) flux ratio above 45GV [Above Solar modulation Time Dependent Effects] vs time.

Verification of the Systematic Error Assigned to the Rigidity Scale



The variation of the flux ratio vs the rigidity for different Tracker Layer 1 (L1) entry regions

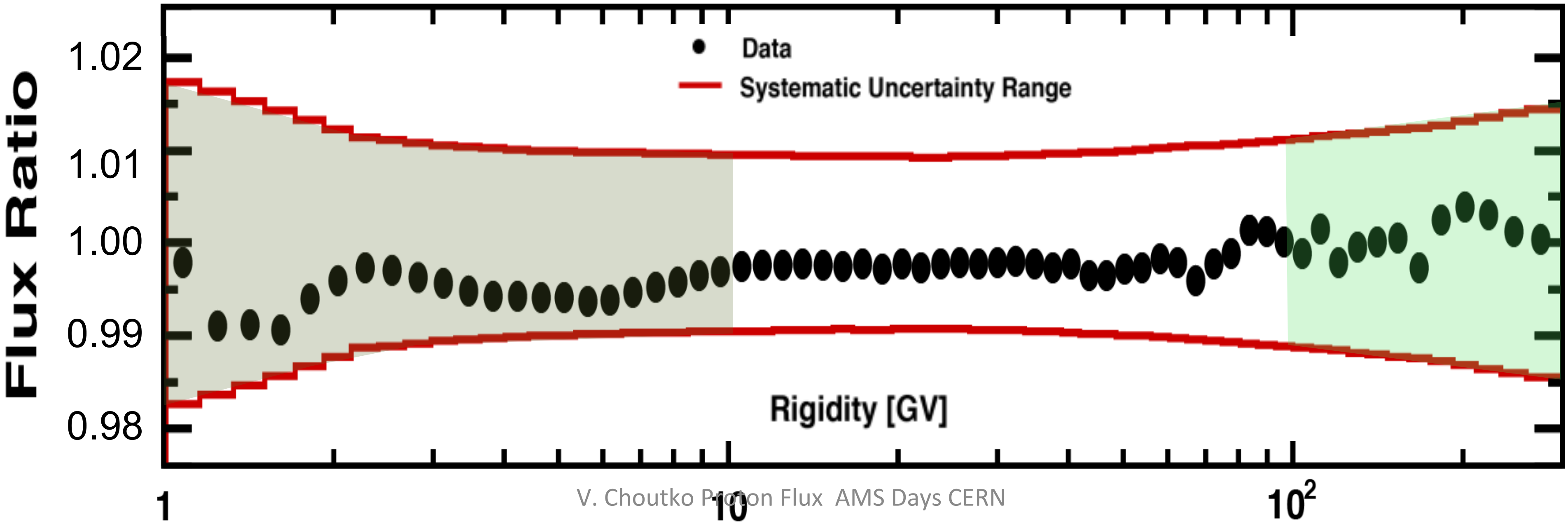
Verification of the Systematic Error of Unfolding, Acceptance and Rigidity Resolution



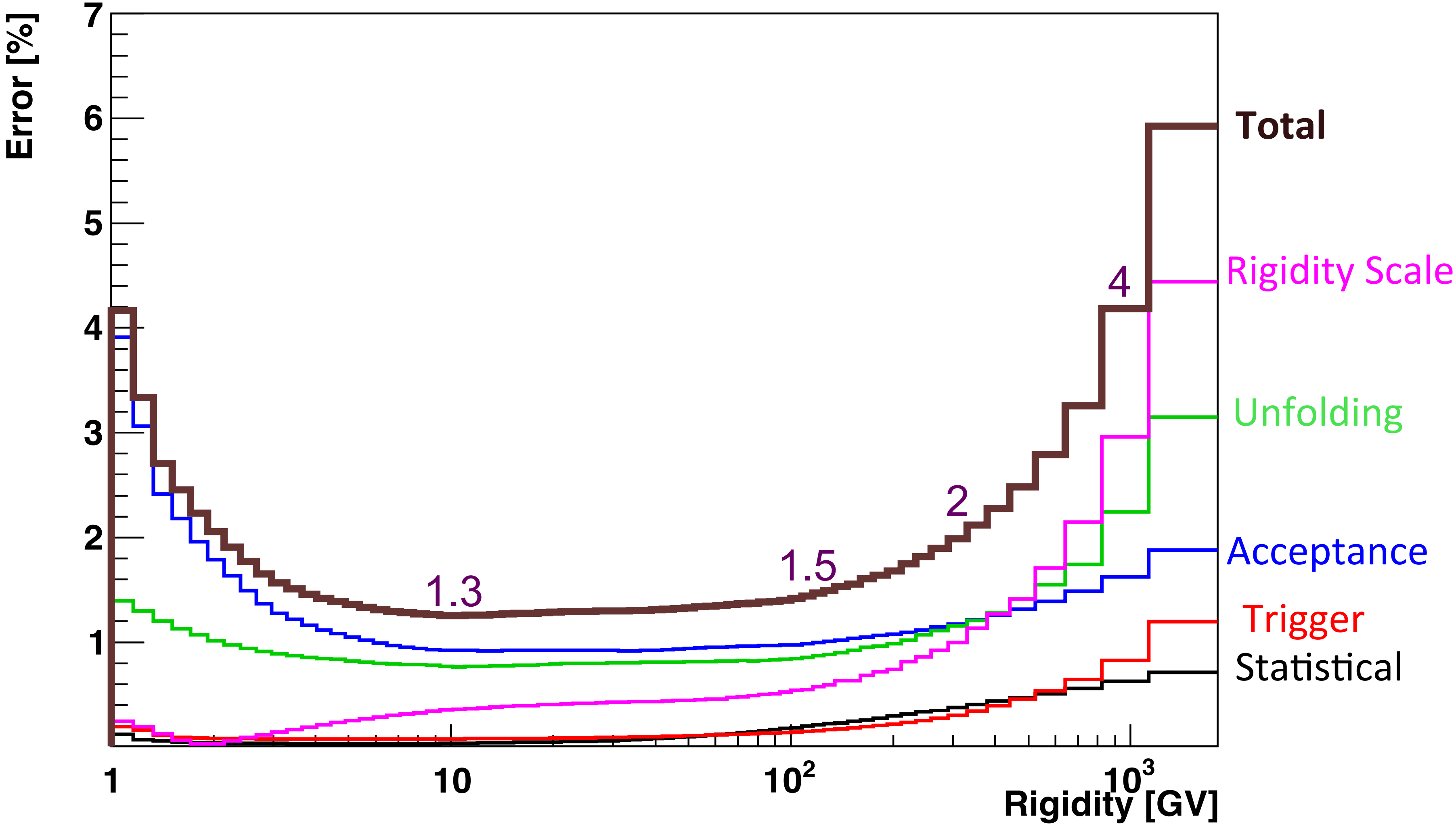
Flux obtained using the rigidity measured by only the inner tracker (2-8) is in good agreement with the flux measured using the full lever arm (1-9), specifically at

-High rigidities (100 to 300GV) where the unfolding effects and resolution functions of the inner tracker (300 GV MDR) and the full lever arm one (2 TV MDR) are very different.

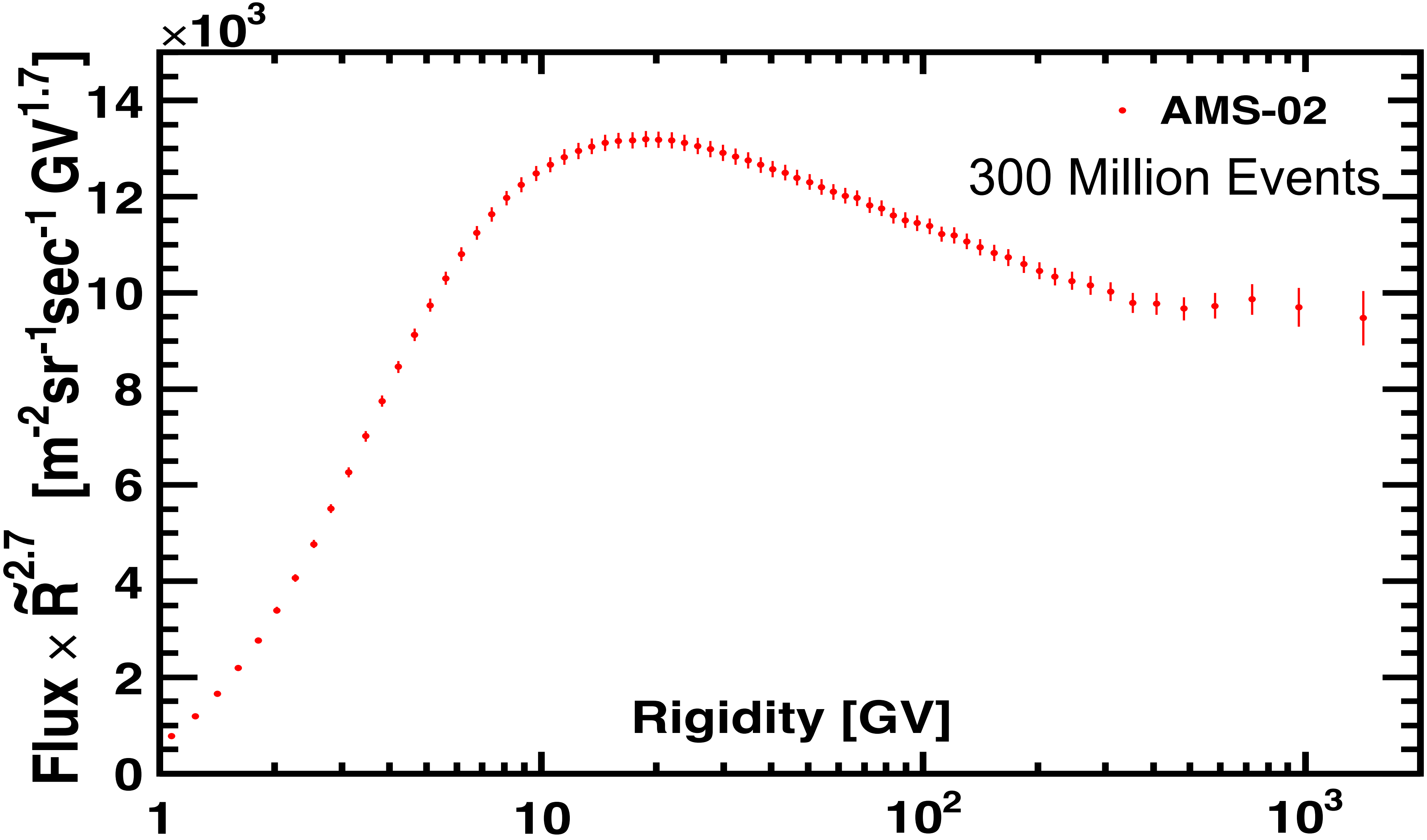
-Low rigidities (1 to 10GV) where the unfolding effects and the tails in the resolution functions of the inner tracker and full lever arm are also very different due to multiple and nuclear scattering.



Flux Errors Breakdown

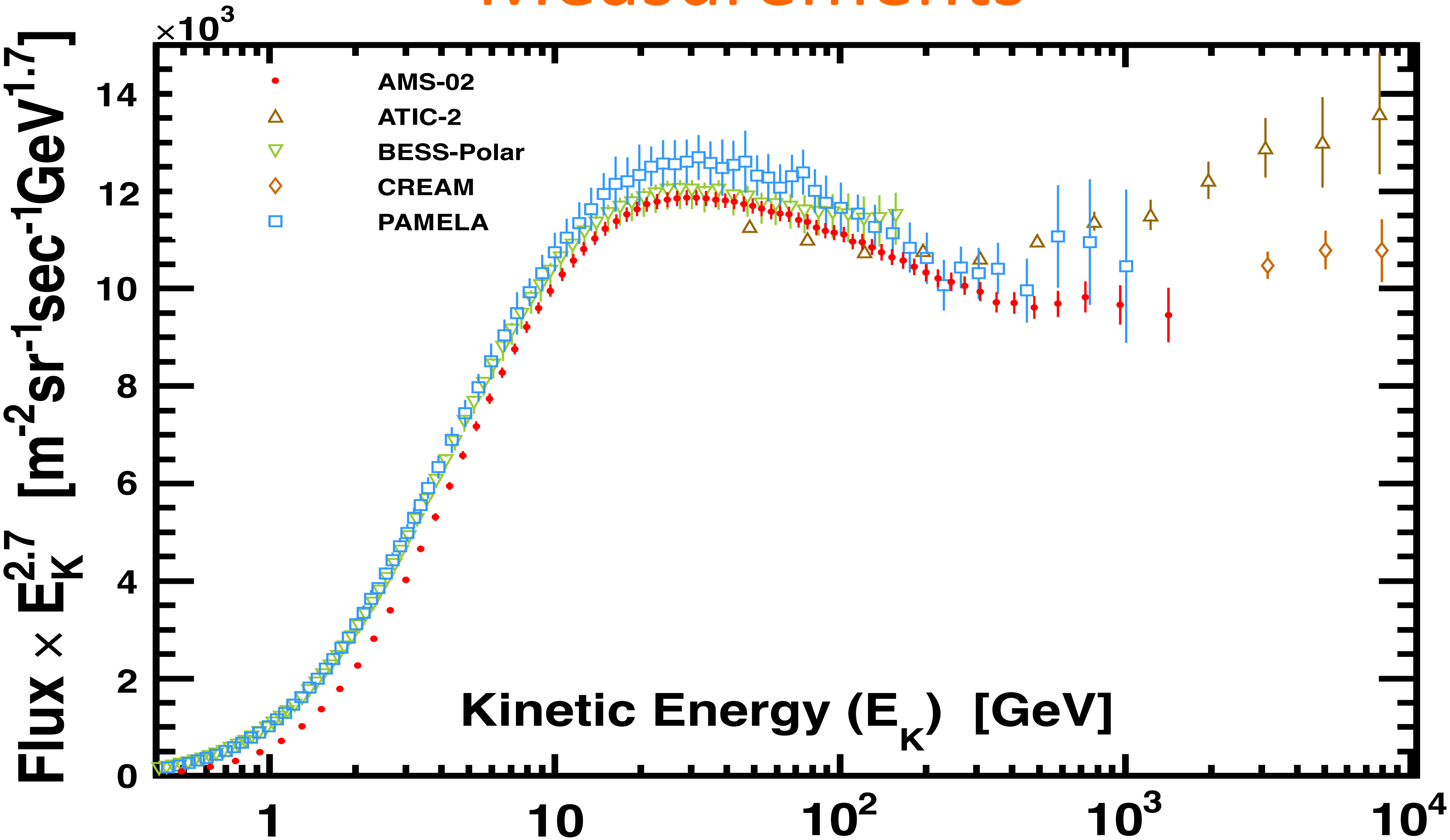


Proton Flux



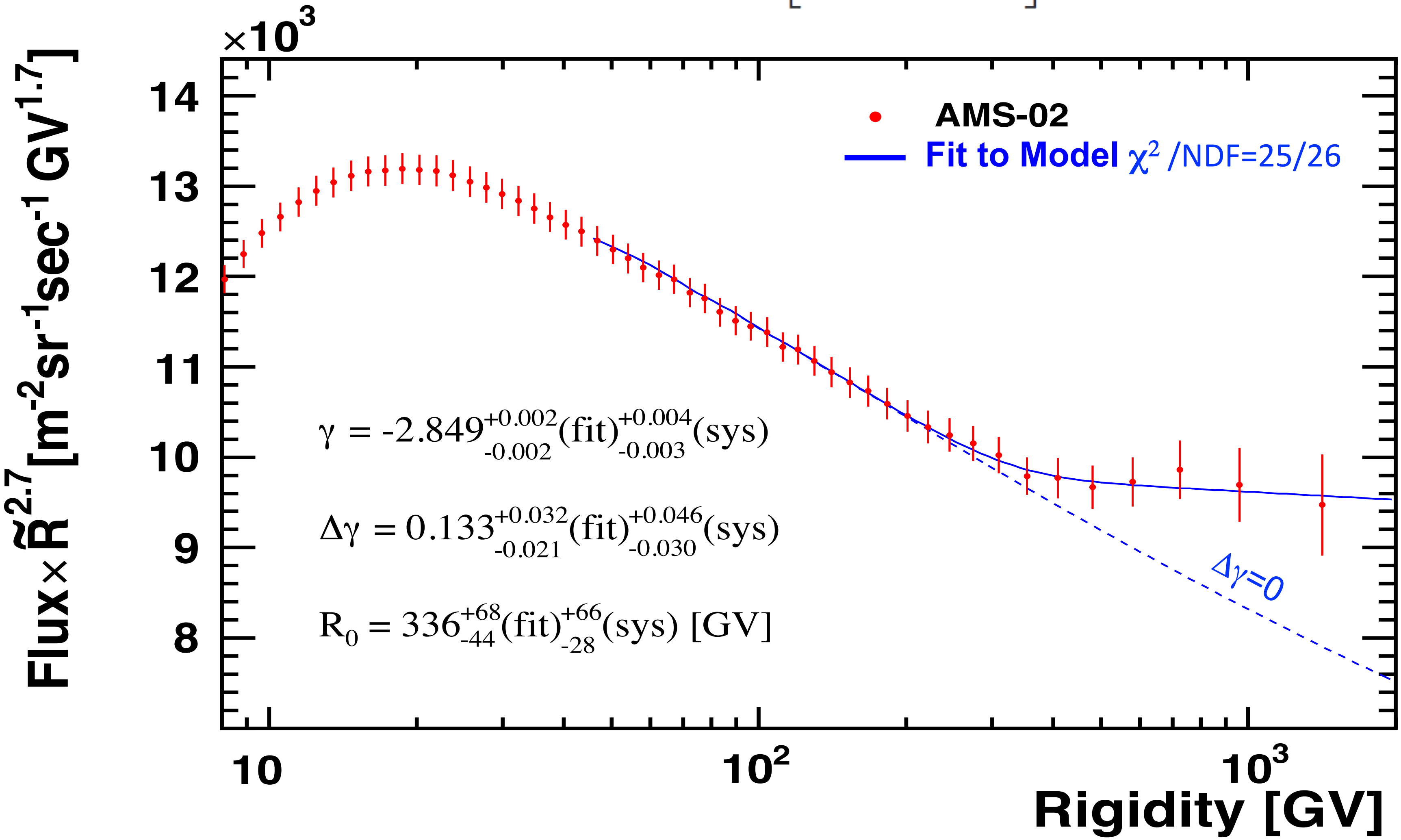
×10³
Flux × R̃^2.7 [m⁻²sr⁻¹sec⁻¹GV^1.7]
14
12
10
8
6
4
2
0
AMS-02
300 Million Events
Rigidity [GV]
1
10
10²
10³

Proton Flux Comparison with Earlier Measurements

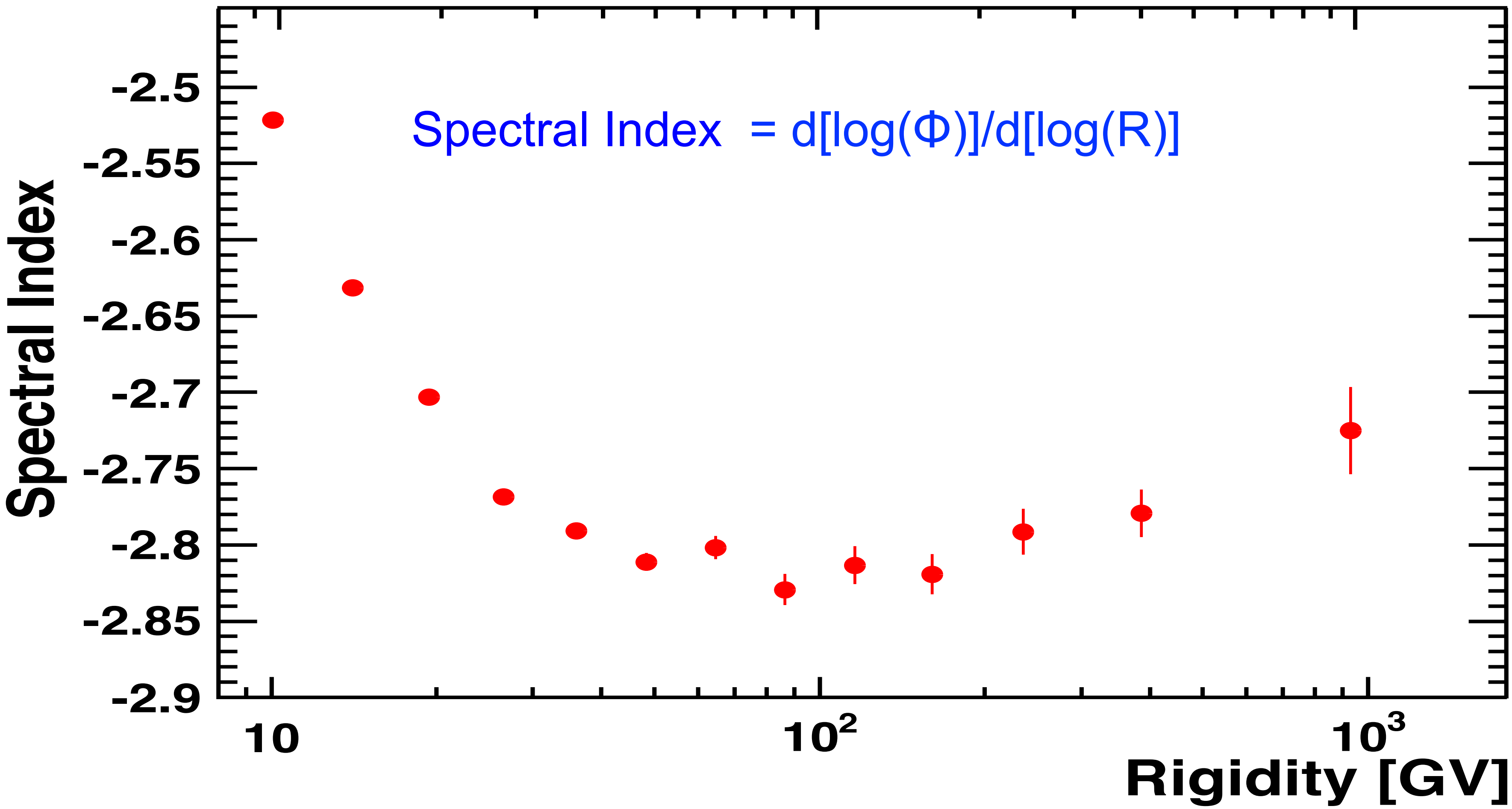


Proton Flux Fit with the Model

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



Model Independent Spectral Index Rigidity Dependence



The spectral index varies with rigidity. In particular, the spectral index is progressively hardening with rigidity above ~100 GV.

Conclusion

- Precision measurement of proton flux with AMS is done from 1 GV to 1.8 TV based on 300 million events
- The detailed variation of the flux spectral index is presented
- The spectral index is progressively hardening at high rigidities