Recent Results from the Alpha Magnetic Spectrometer (AMS) Experiment on the International Space Station

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University and INFN-TIFPA, Trento

INFN-Space 3, LNF, September 18th 2013

AMS in Italy

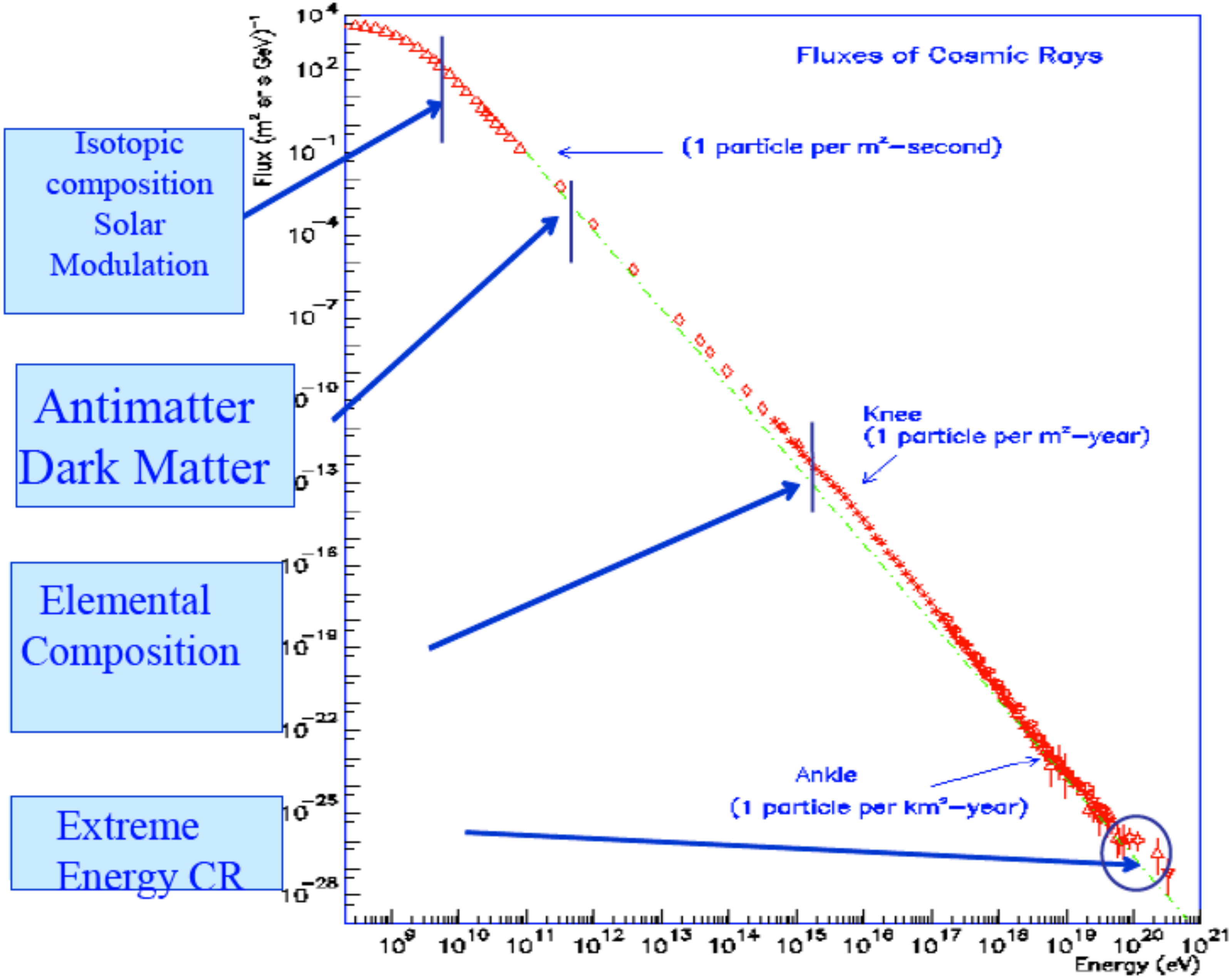
60 Scientists and Engineers

6 Universities / INFN Sections

2 INFN National Laboratories

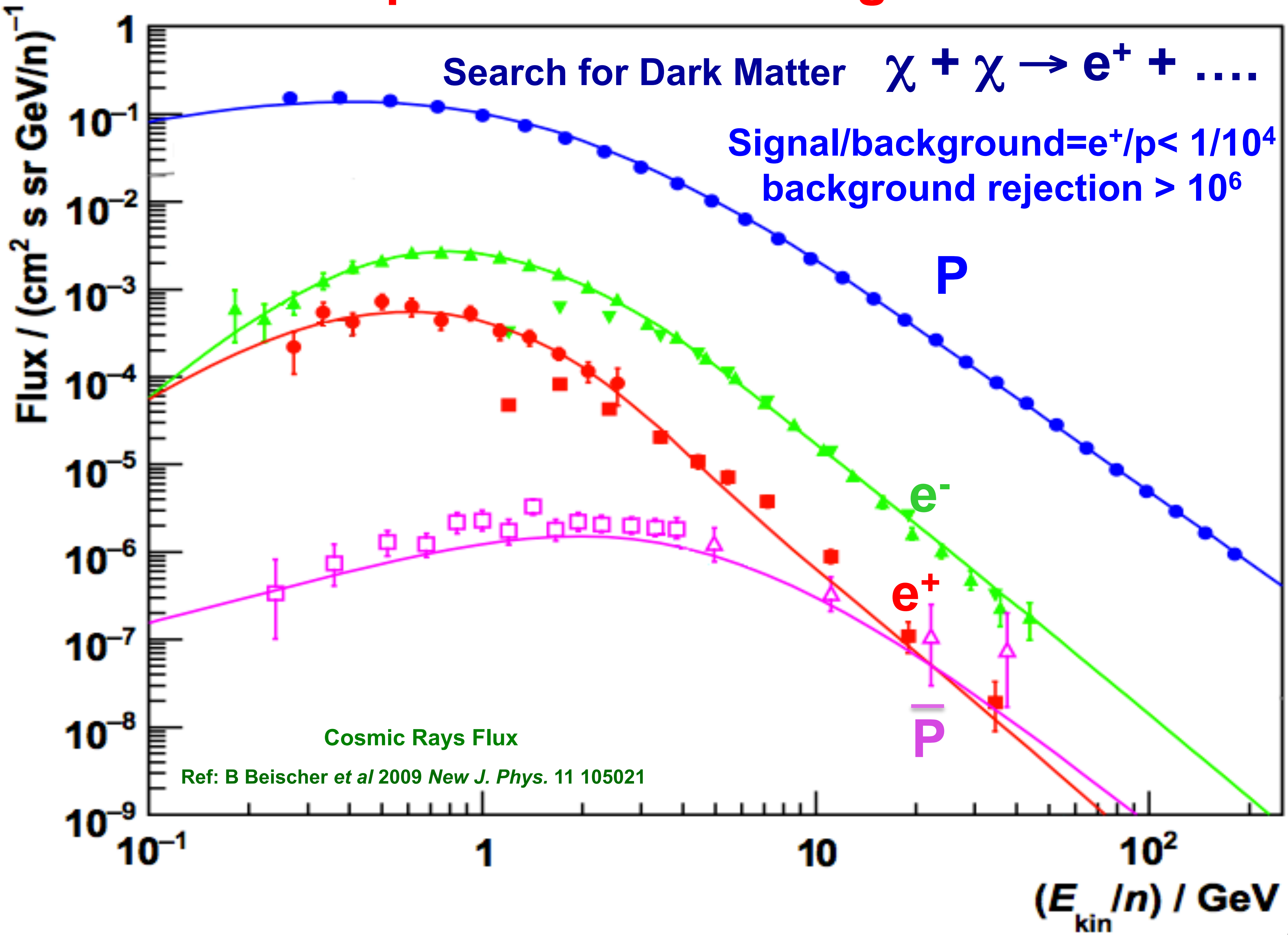
2 Data centers

18 years of collaboration among INFN and ASI

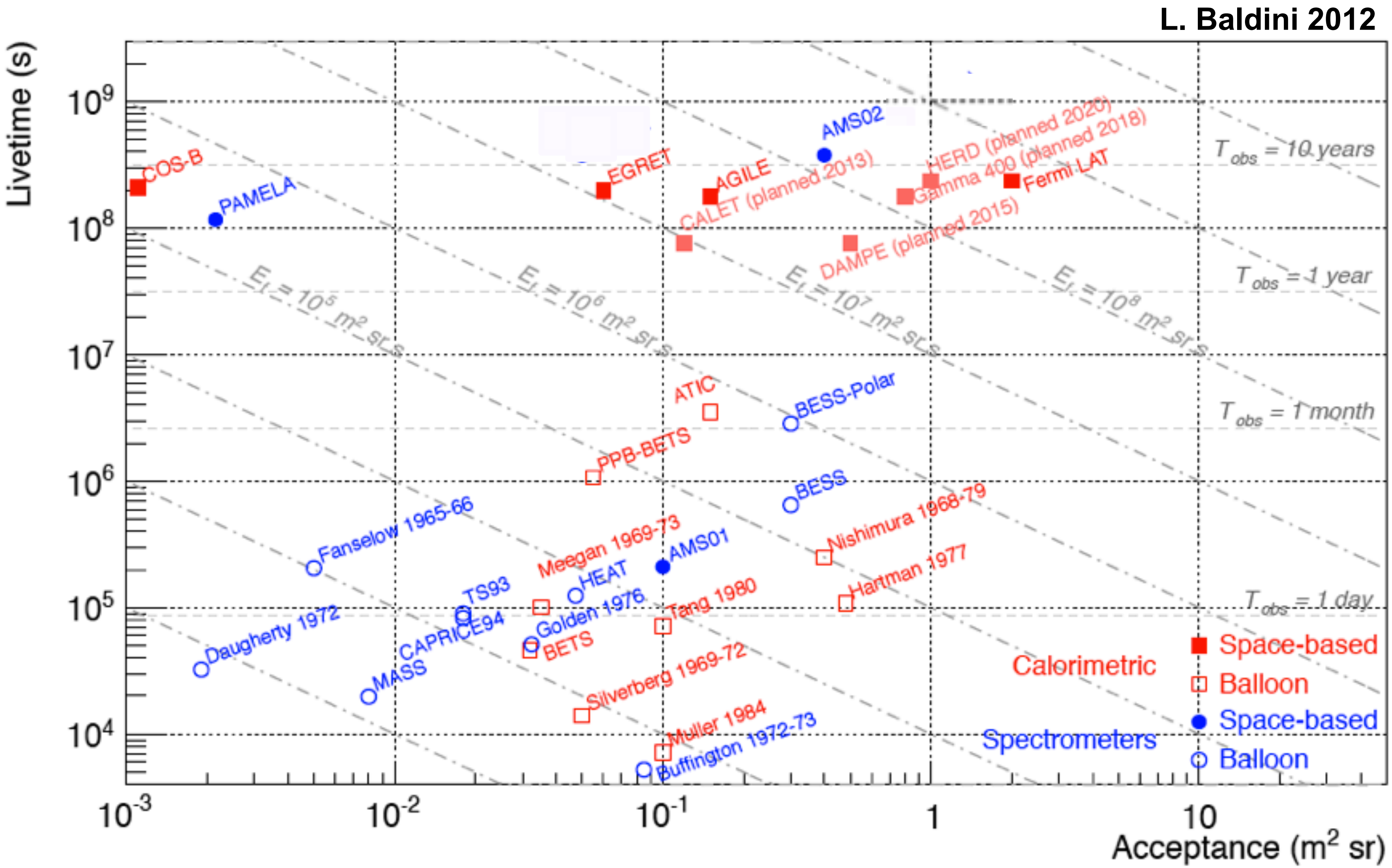


J. Cronin ,T.K. Gaisser & S.P. Swordy, Sci. Amer. 276 (1997) 44

Experimental Challenges



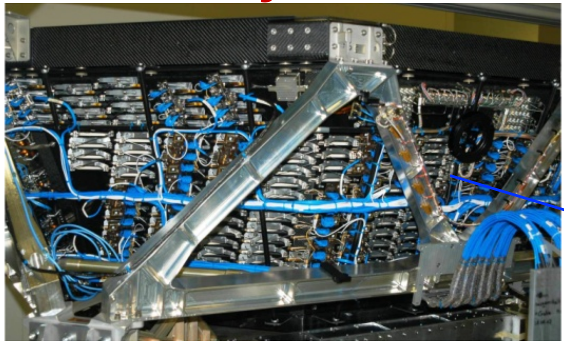
A Large Magnetic Spectrometer in Space :
a game changing for the study of Cosmic Ray



AMS: A TeV precision, multipurpose spectrometer

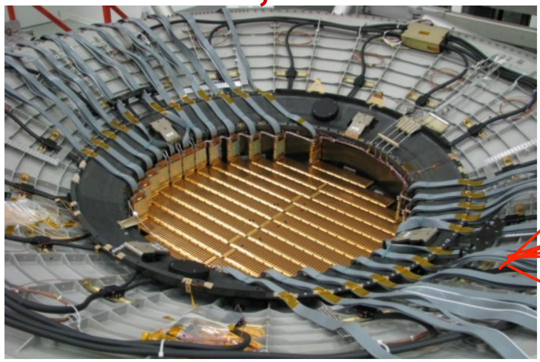
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)

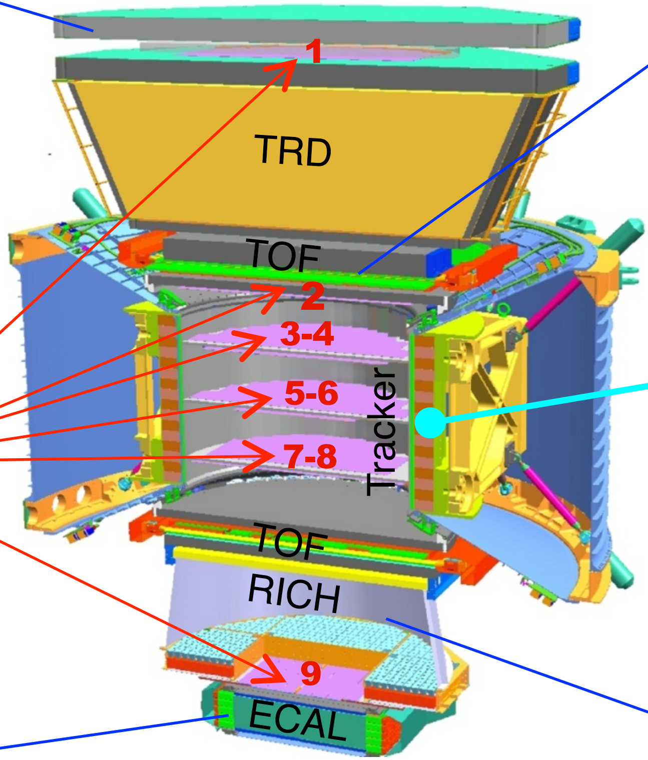
TRD
Identify e^+, e^-



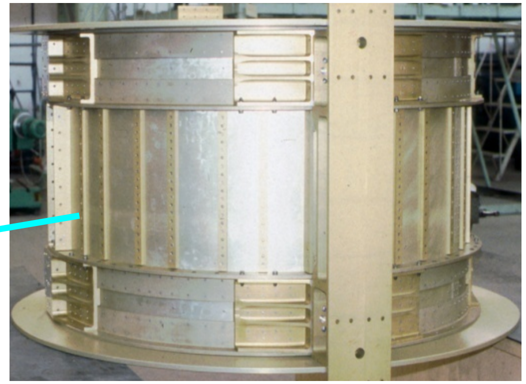
TOF
Z, E

Silicon Tracker
Z, P

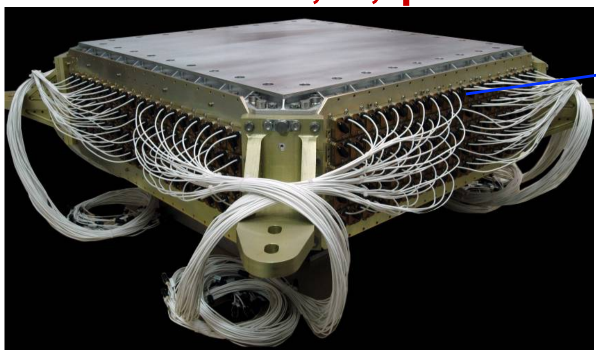




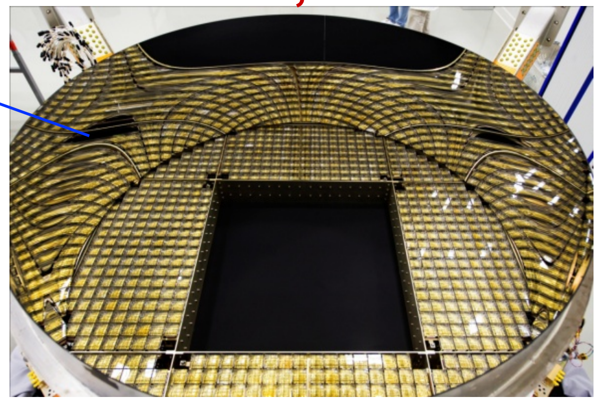
Magnet
±Z



ECAL
E of e^+, e^-, γ



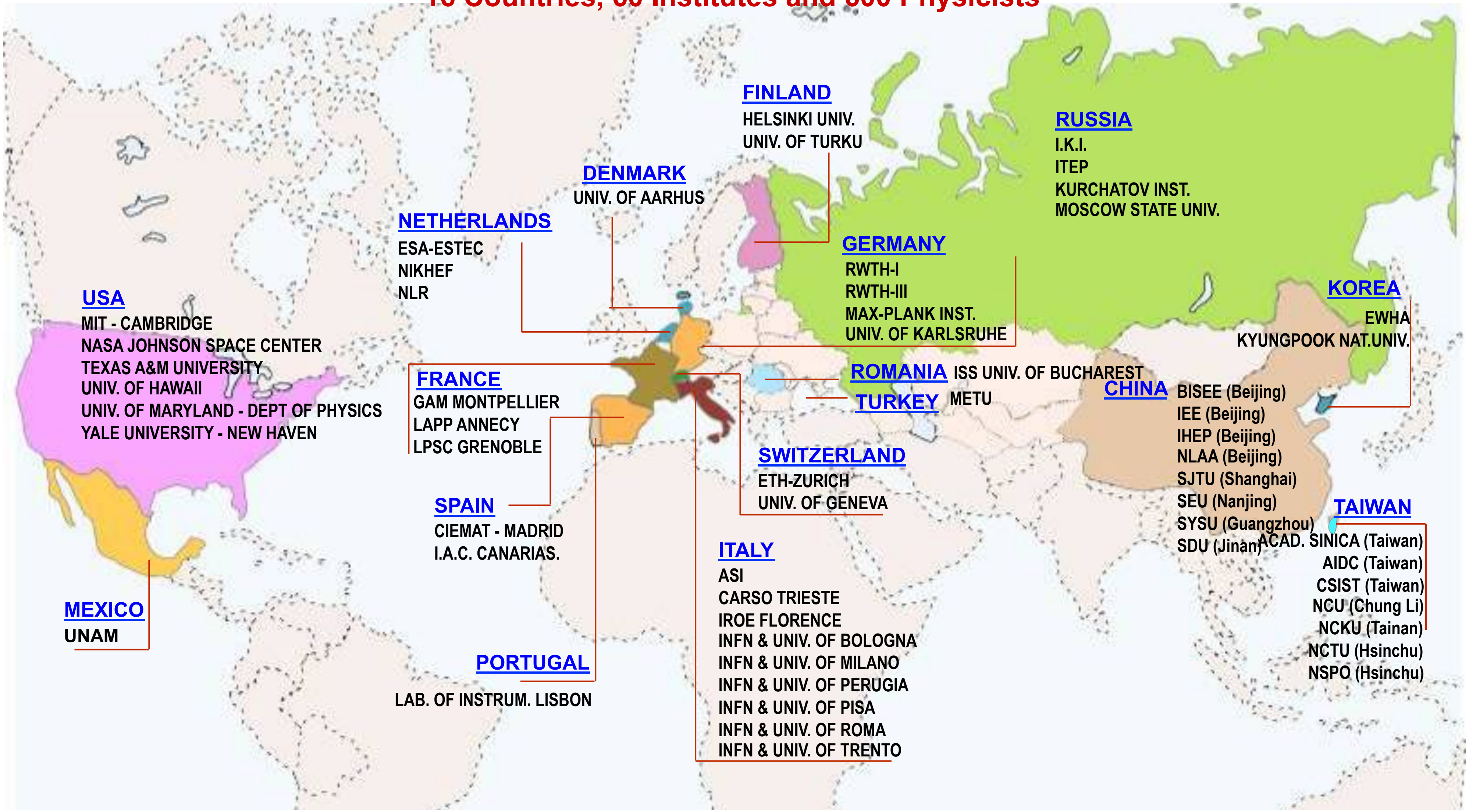
RICH
Z, E



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

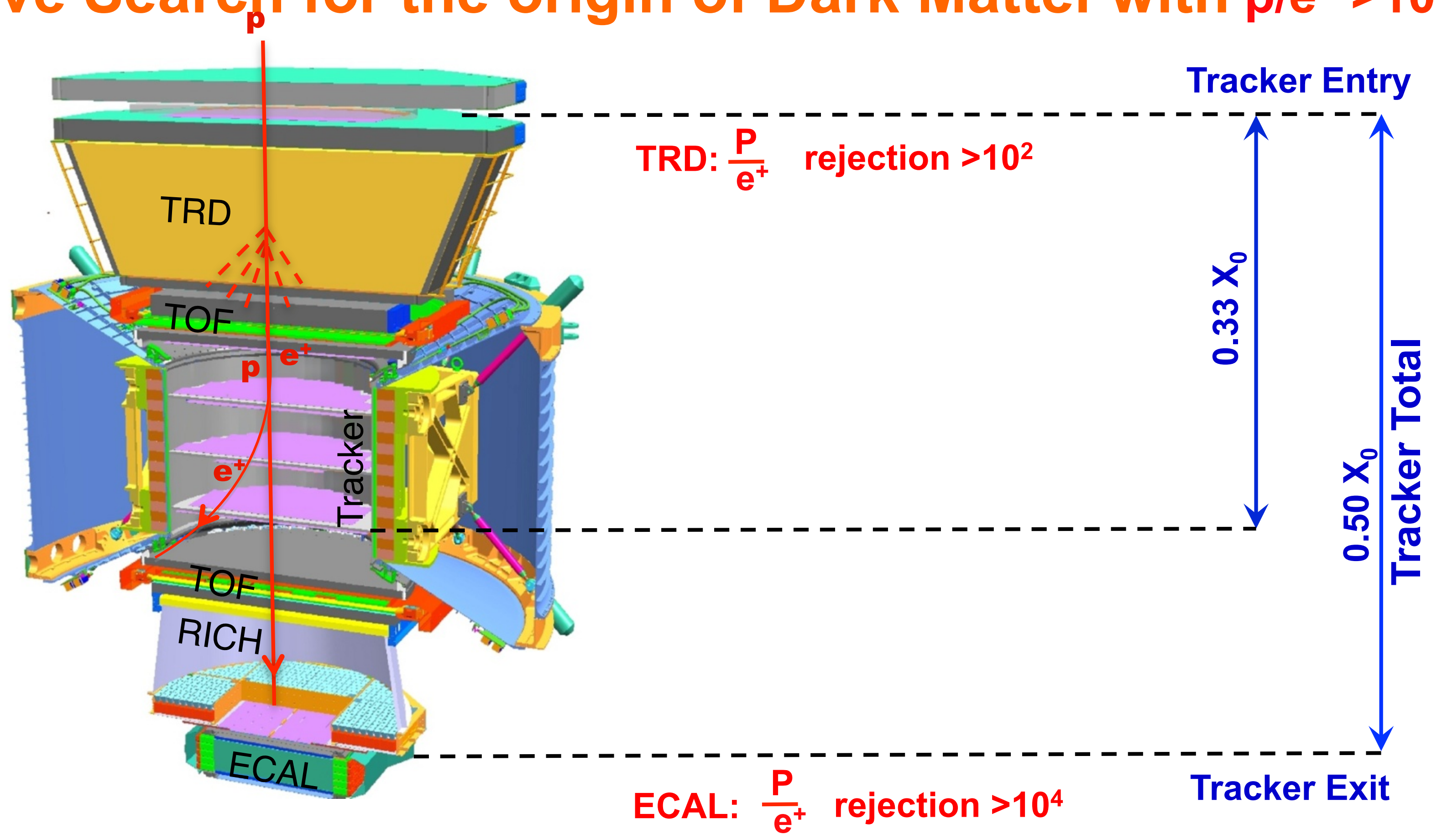
AMS International Collaboration

16 Countries, 60 Institutes and 600 Physicists



DOE sponsored experiment, NASA space operation
95% construction from Europe and Asia

Sensitive Search for the origin of Dark Matter with $p/e^+ > 10^6$



a) Minimal material in the TRD and TOF
So that the detector does not become a source of e^+.

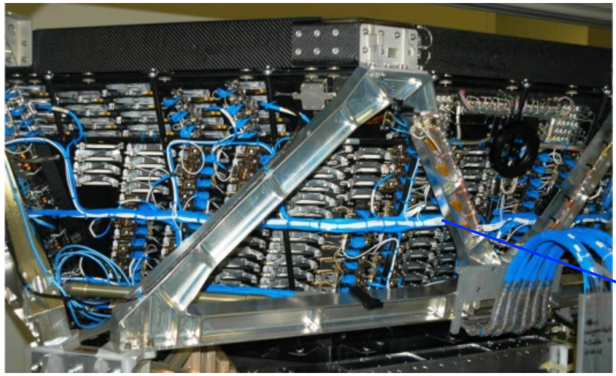
b) A magnet separates TRD and ECAL so that e^+ produced in TRD will be swept away and not enter ECAL
In this way the rejection power of TRD and ECAL are independent

c) Matching momentum of 9 tracker planes with ECAL energy measurements

AMS Flight Electronics for Data Acquisition (DAQ)

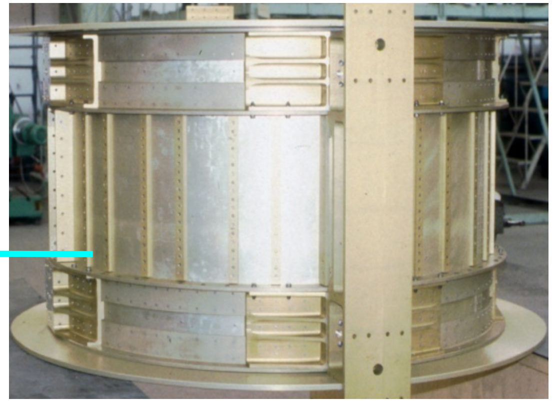
300,000 channels at 2 KHz,
650 computers
designed and built by AMS

TRD: 5248 Signals

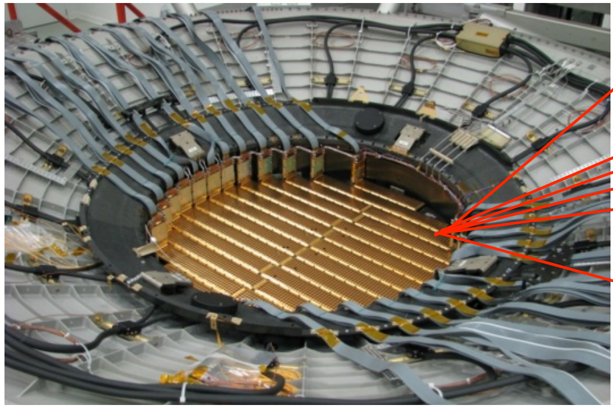


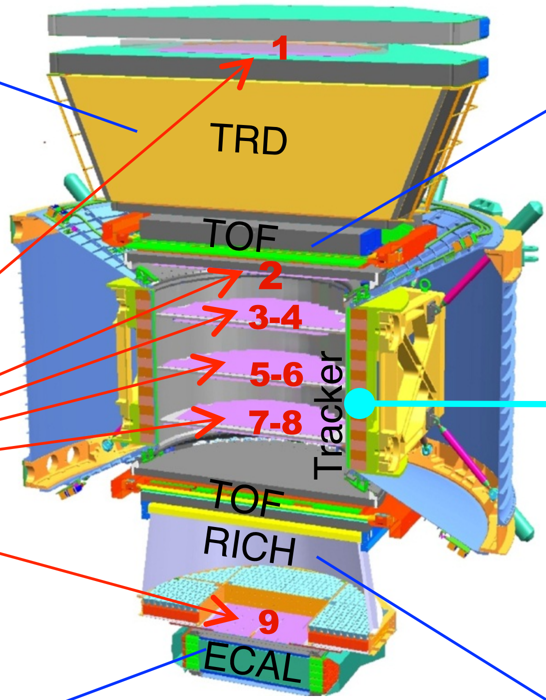
TOF & ACC: 88 Signals

Magnet

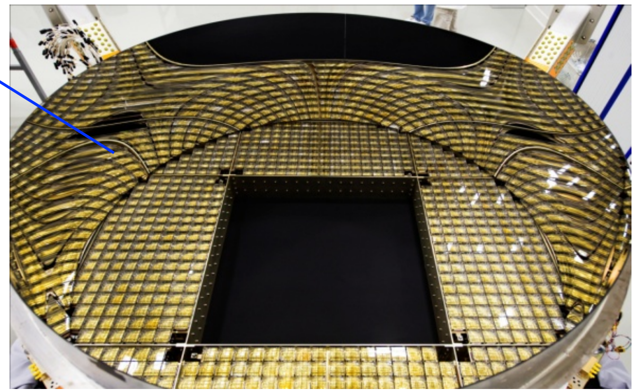


Silicon Tracker:
196,608 Signals





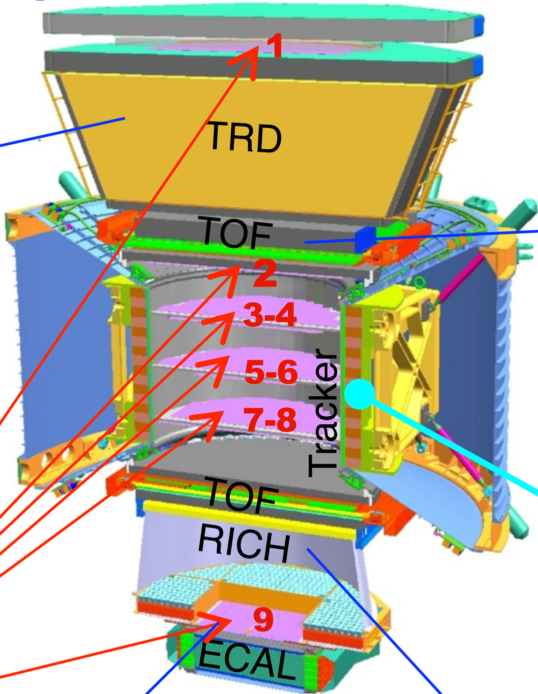
RICH: 10,800 * 2 Signals



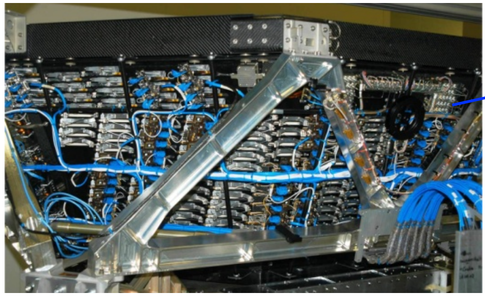
ECAL: 2,916 Signals

AMS Flight Electronics for Thermal Control

1118 temperature sensors, 298 heaters

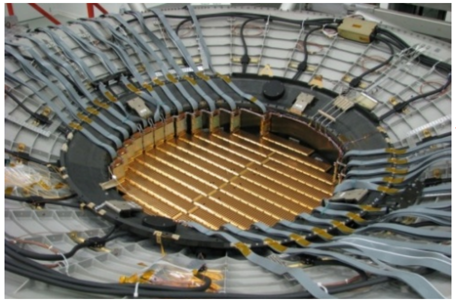


TRD
24 Heaters
8 Pressure Sensors
482 Temperature Sensors

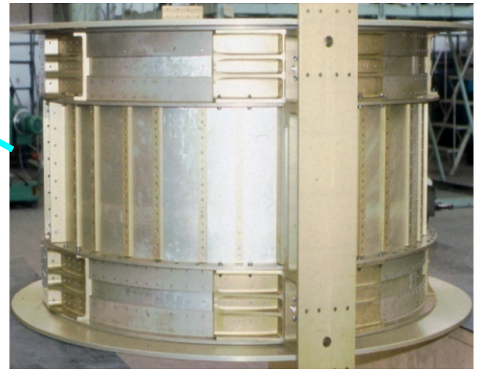


TOF & ACC
64 Temperature Sensors

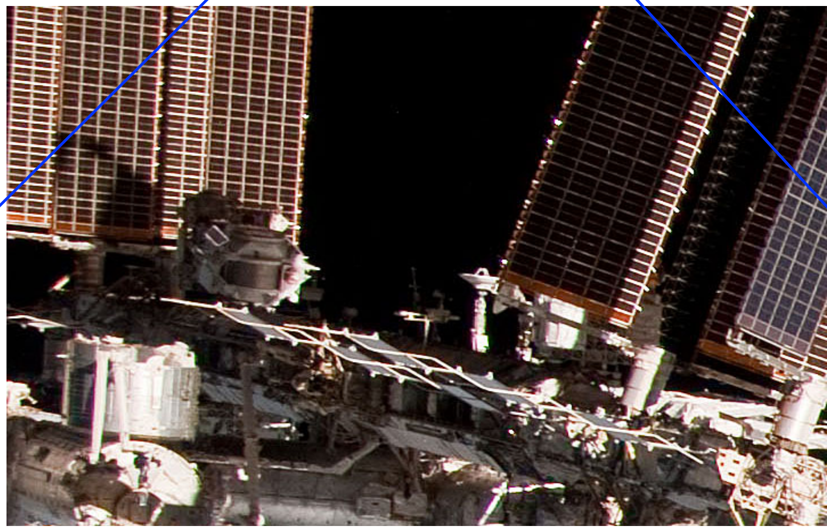
Silicon Tracker
4 -Pressure Sensors
32 Heaters
142 Temperature Sensors



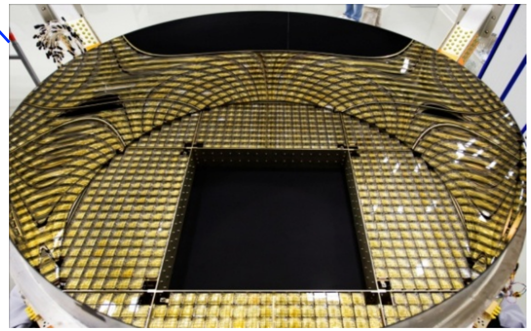
Magnet
68 Temperature Sensors



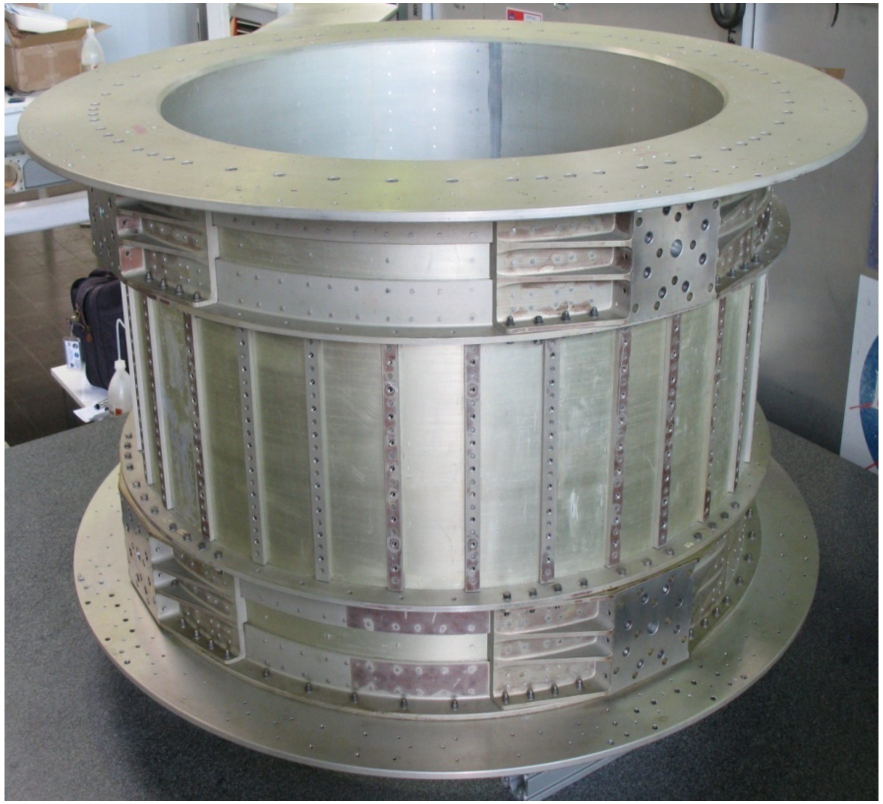
ECAL
80 Temperature Sensors

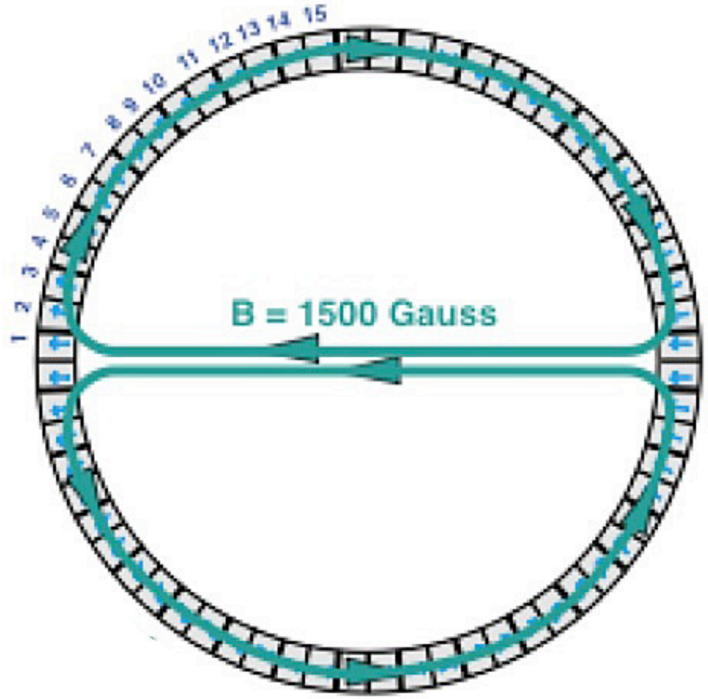


RICH
96 Temperature Sensors



The Magnet





1. Stable: no torque
2. Safety : no field leak out of the magnet
3 . Low weight: no iron

The detailed 3D field map (120k locations) was measured in May 2010

It was found that the deviation from the 1997 measurement had remained the same to <1%

For AMS, 10 Magnets were made:

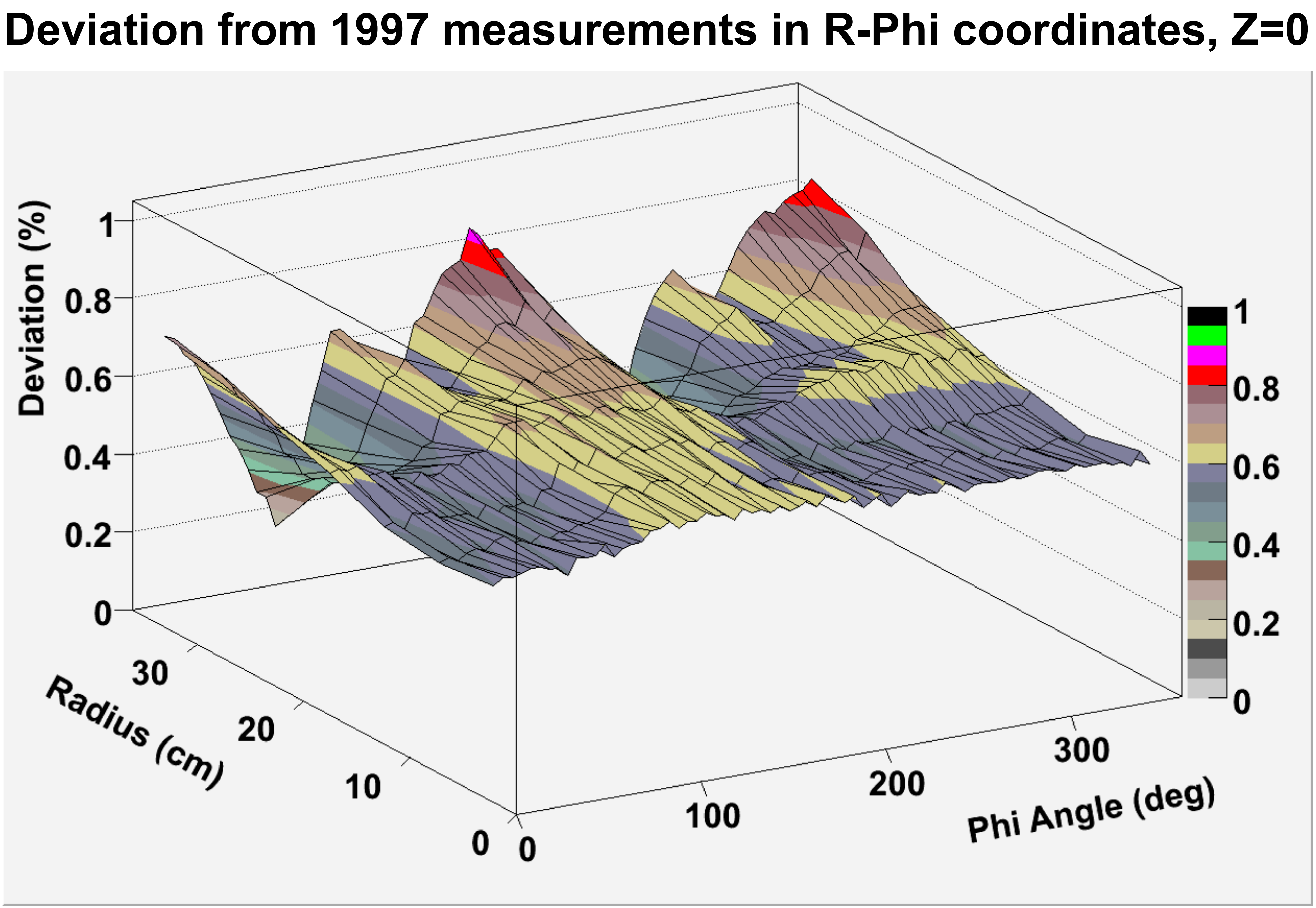
Seven magnets to understand the field calculation, leakage and dipole moment

Three full-size magnets for 1) space qualification, 2) destructive testing and 3) flight

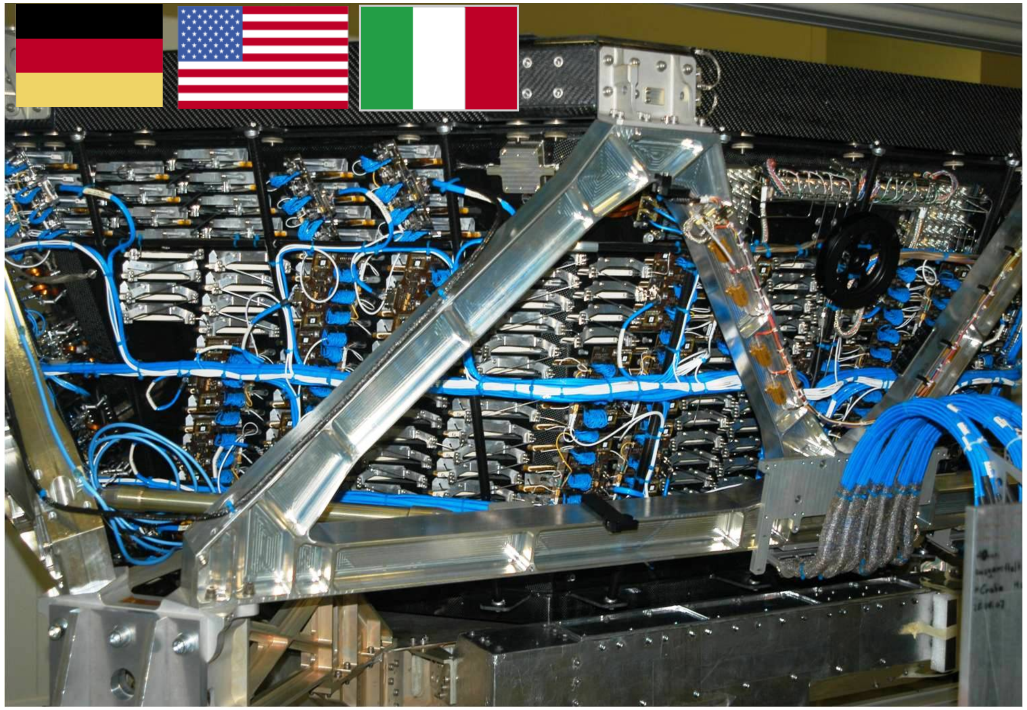
The magnetic field measured in May 2010 (120K location) is identical to the measurement in September 1997

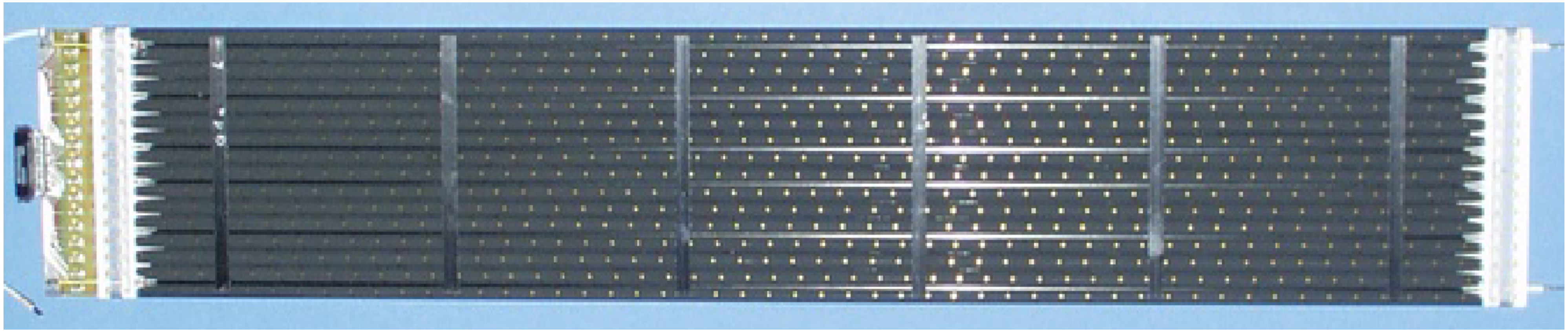
Acceleration test to 17.7 G in Beijing


Magnet vibration qualification at CALT, Beijing


Deviation from 1997 measurements in R-Phi coordinates, Z=0
Deviation (%)
0
0.2
0.4
0.6
0.8
1
Radius (cm)
0
10
20
30
Phi Angle (deg)
0
100
200
300
0
0.2
0.4
0.6
0.8
1

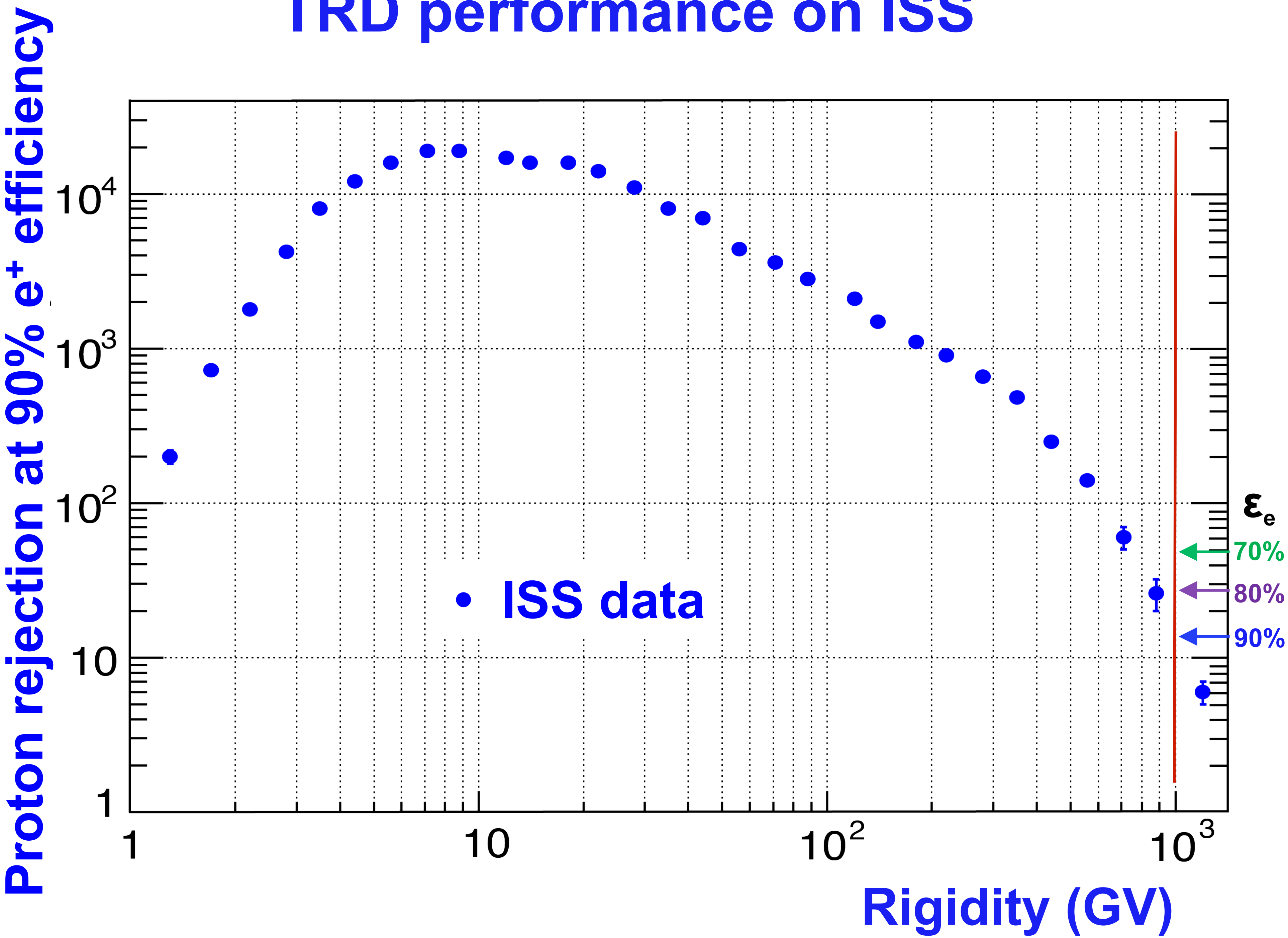
Transition Radiation Detector (TRD) Identifies Positrons, Electrons by transition radiation and Nuclei by dE/dX





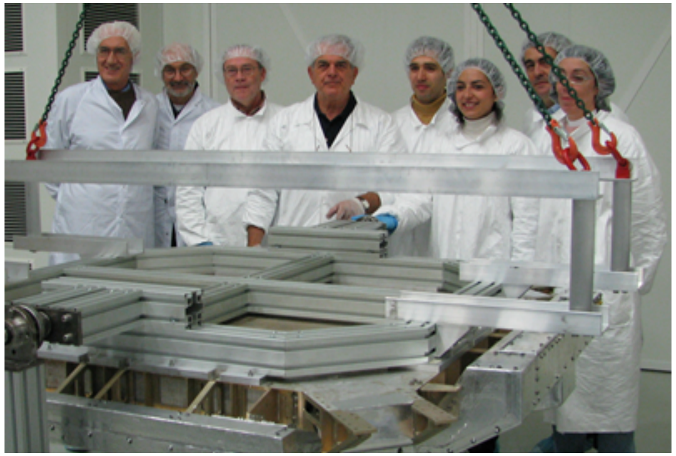
5,248 tubes selected from 9,000, 2 m length centered to 100μm, verified by CAT scanner

TRD performance on ISS



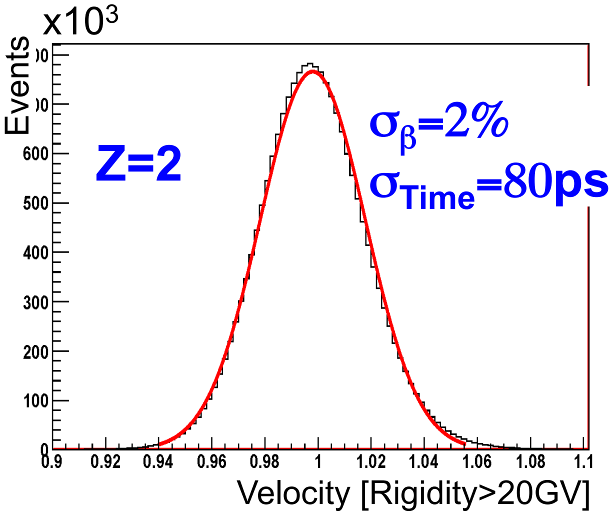
Data from ISS   Time of Flight System

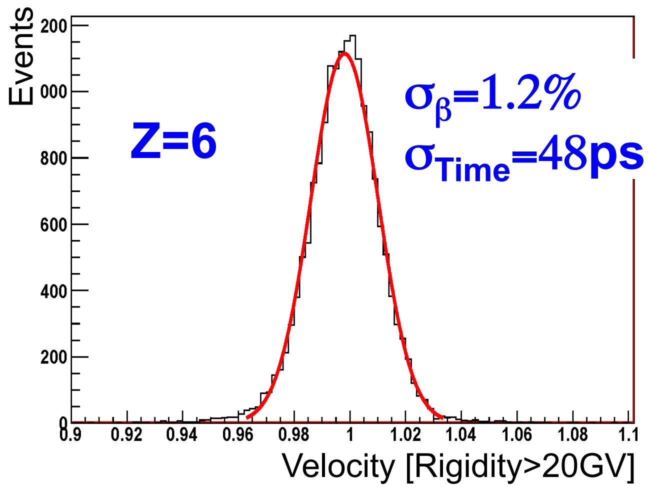
Measures Velocity and Charge of particles

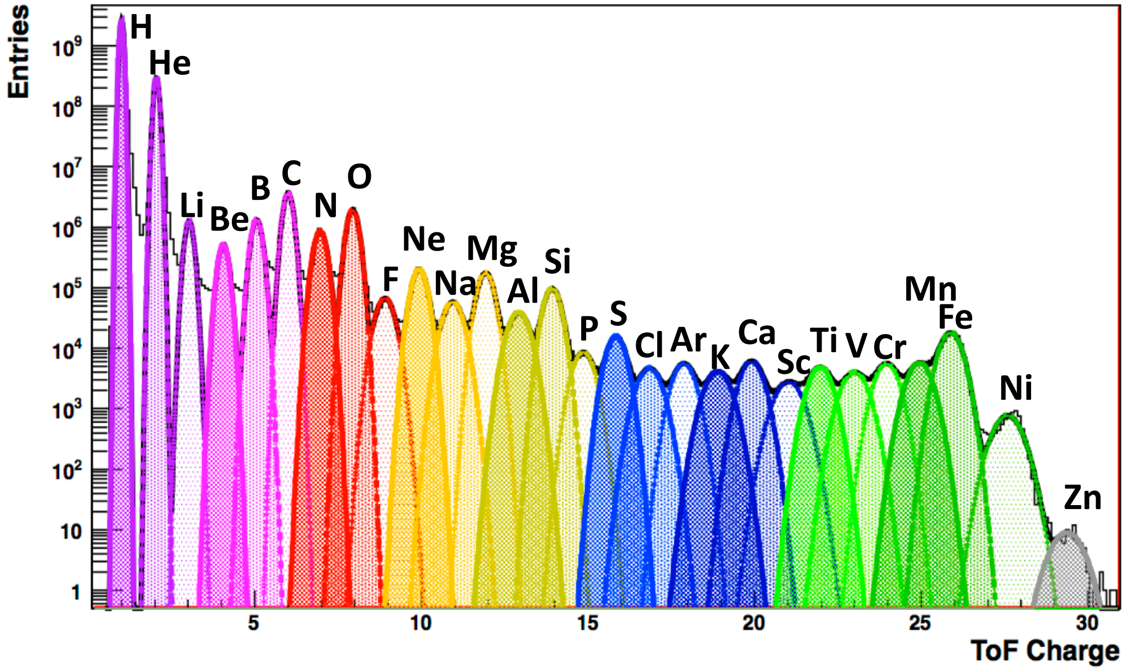


Bologna

Professors A. Contin, G. Laurenti, F. Palmonari



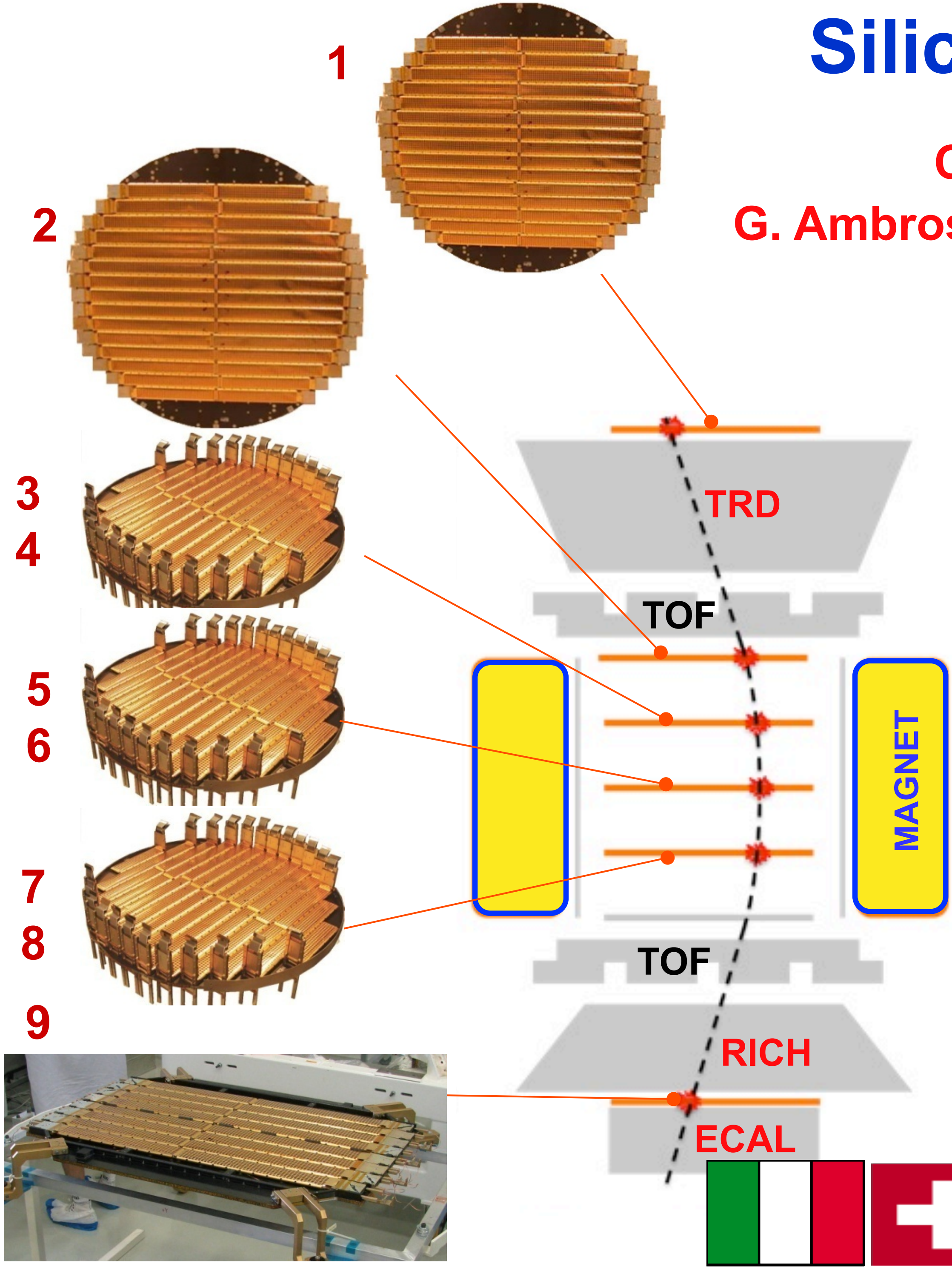


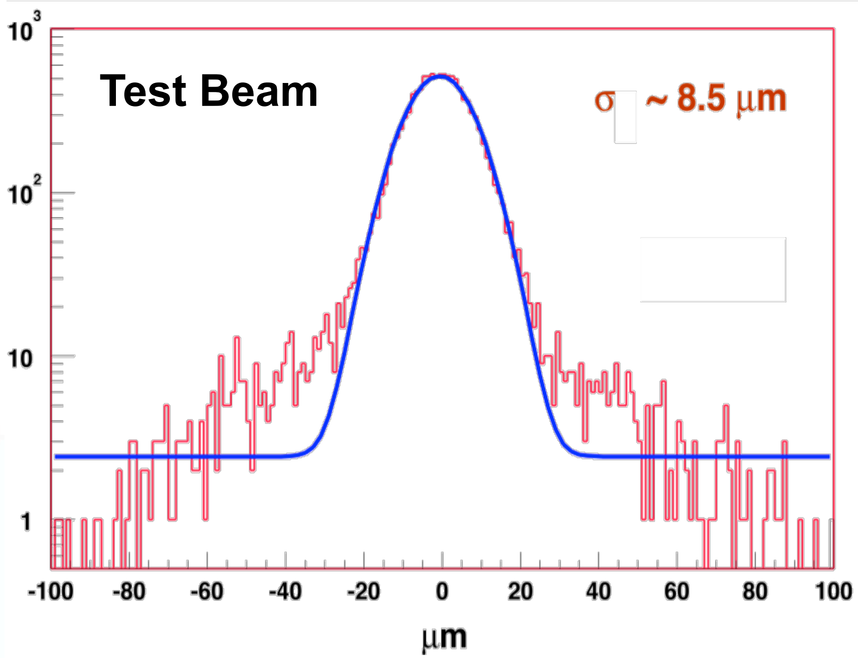


Silicon Tracker

Coordinator

G. Ambrosi INFN-Perugia

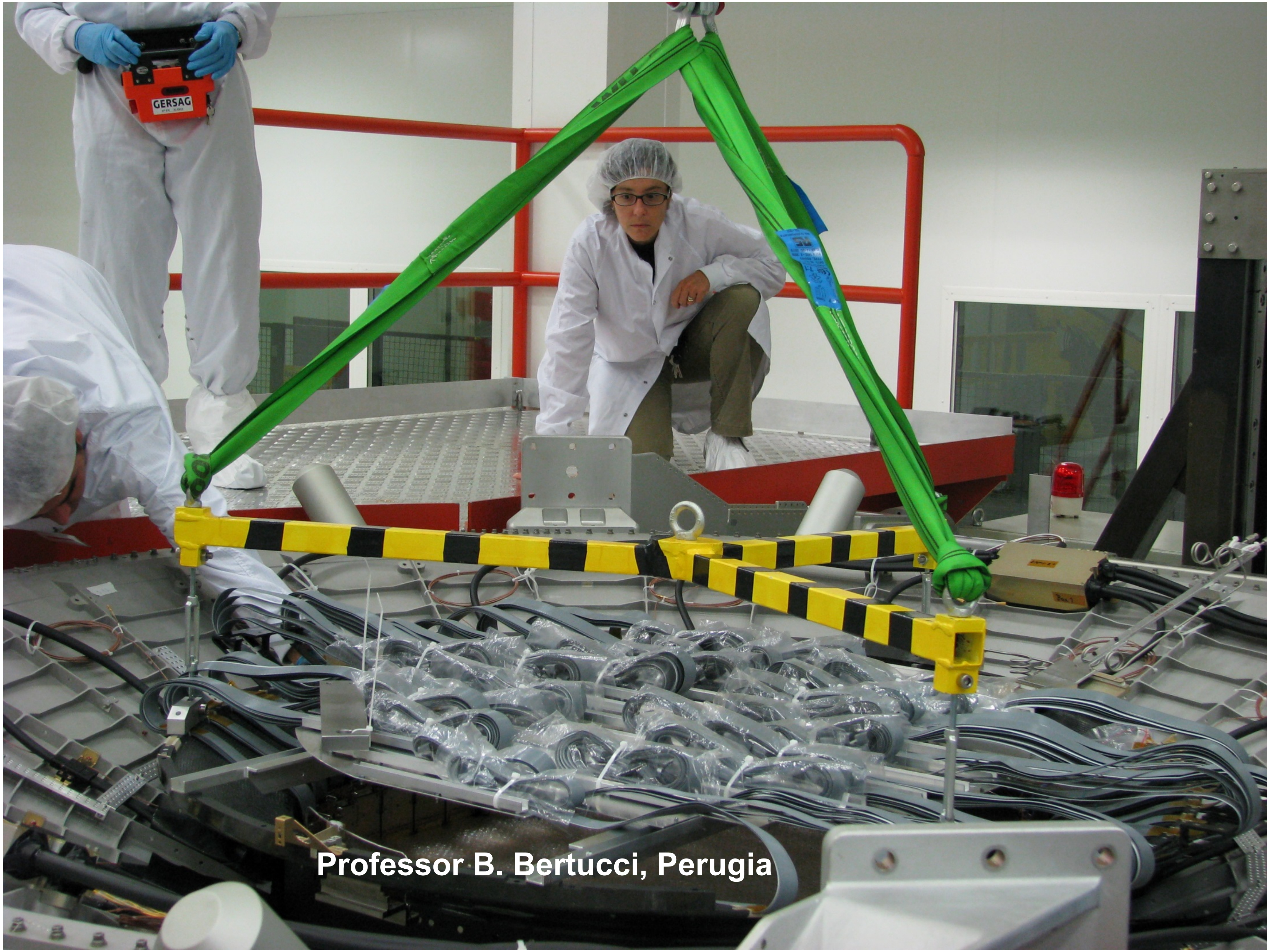




MDR ~2.0 TV

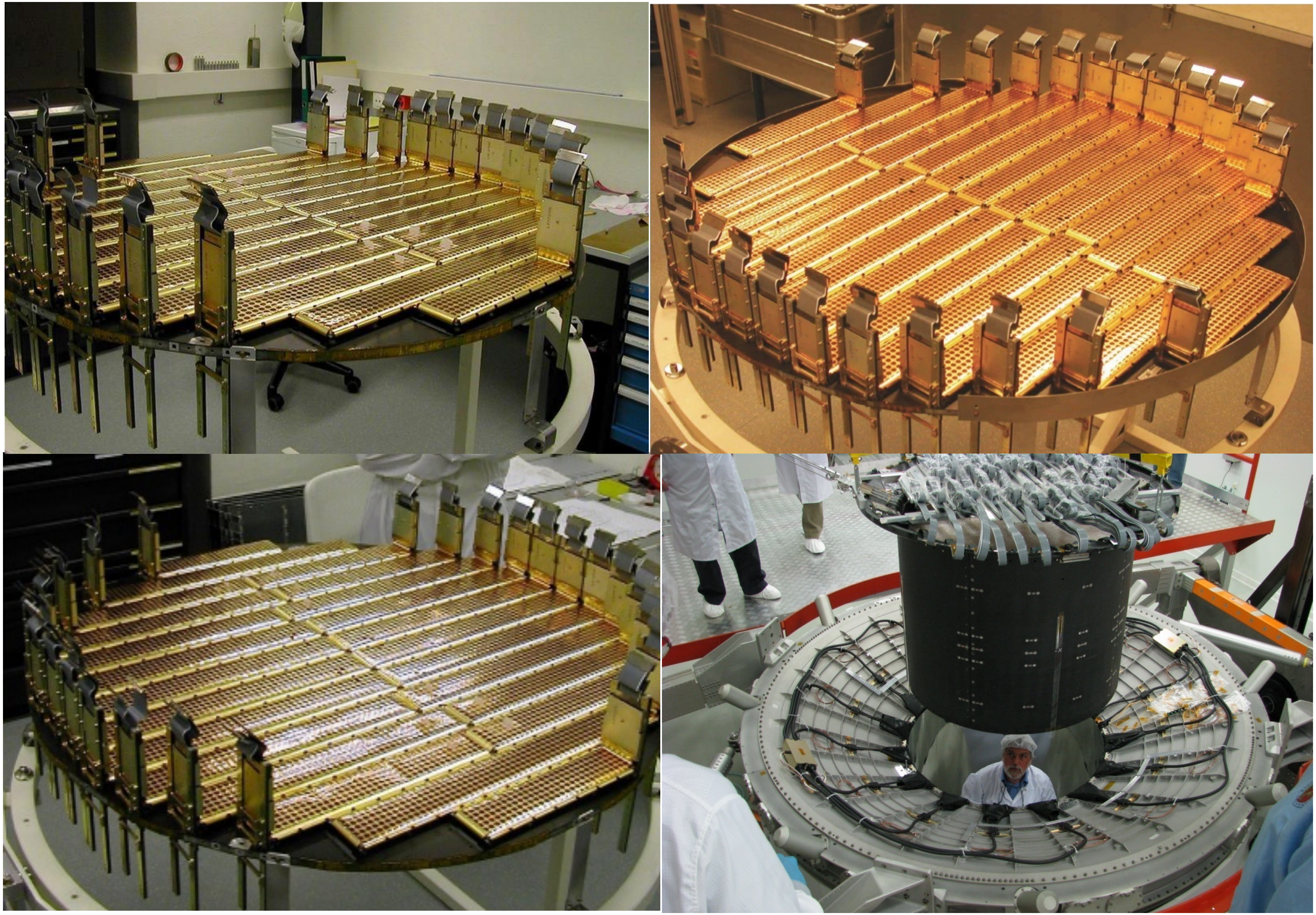
E / |p| matching

AMS Group at INFN and University of Perugia



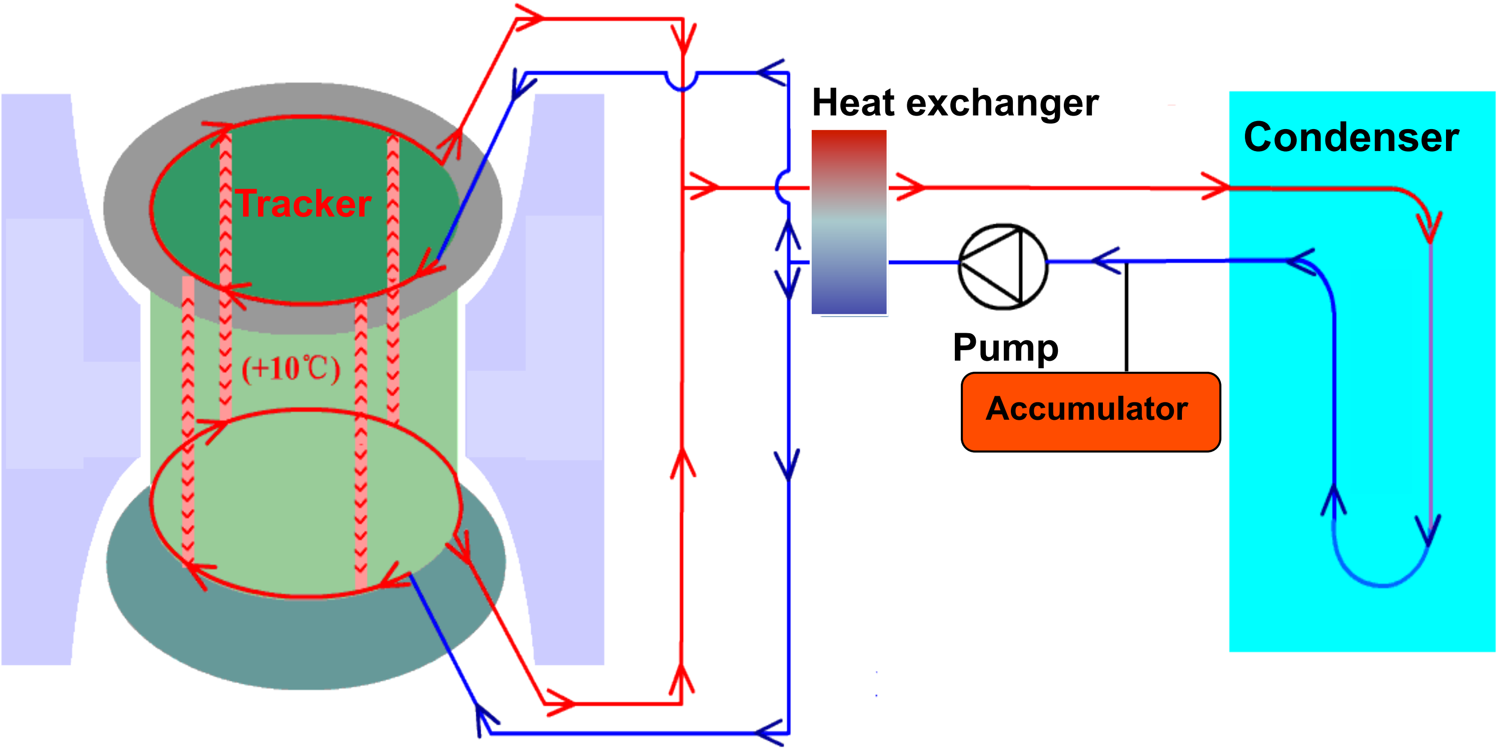
Professor B. Bertucci, Perugia

There are 9 planes with 200,000 channels aligned to 3 microns



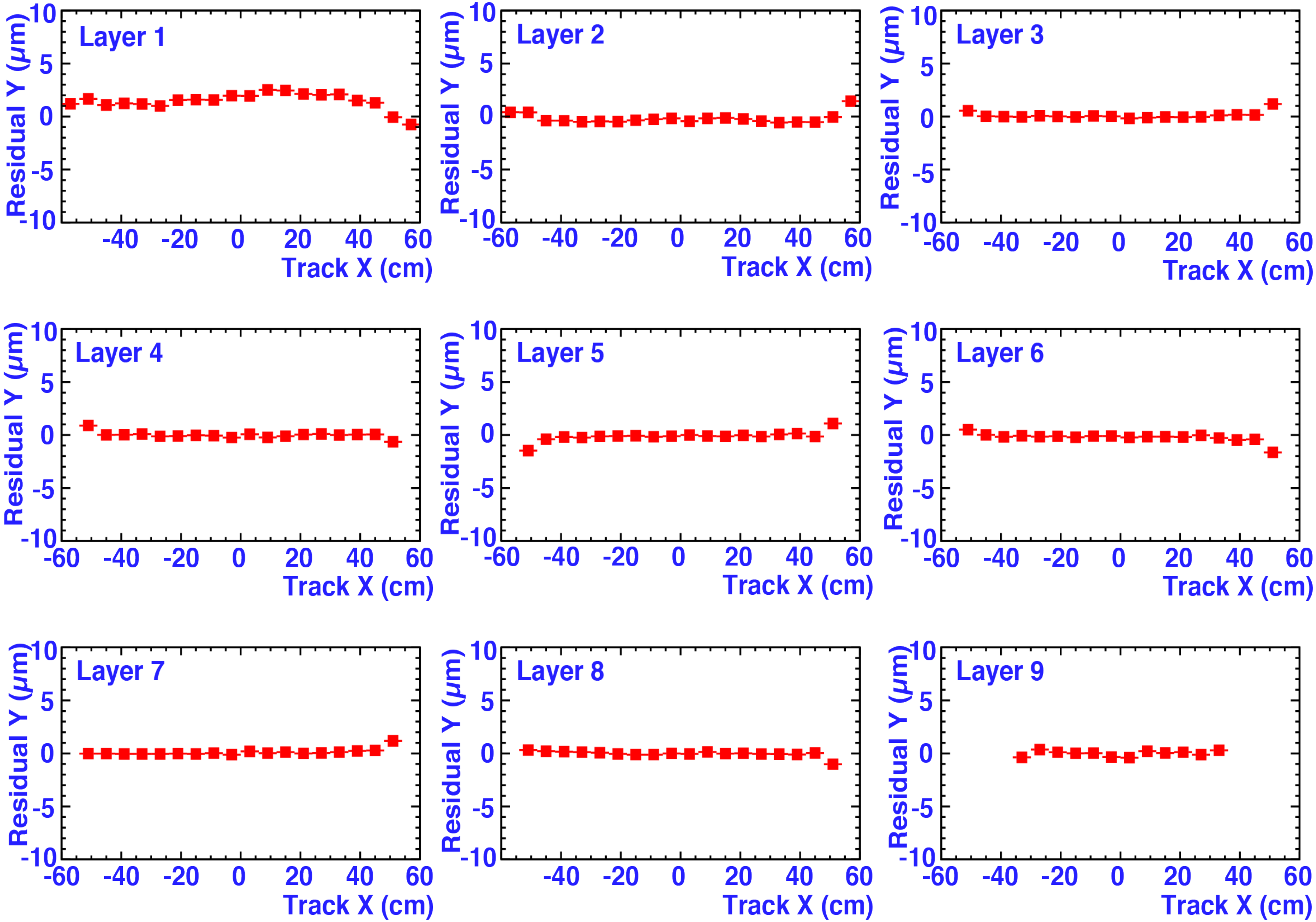
Tracker explained to US Senator B. Nelson, G. Bignami (ASI), J. Woerner (DLR)

Tracker Thermal Control System in Space

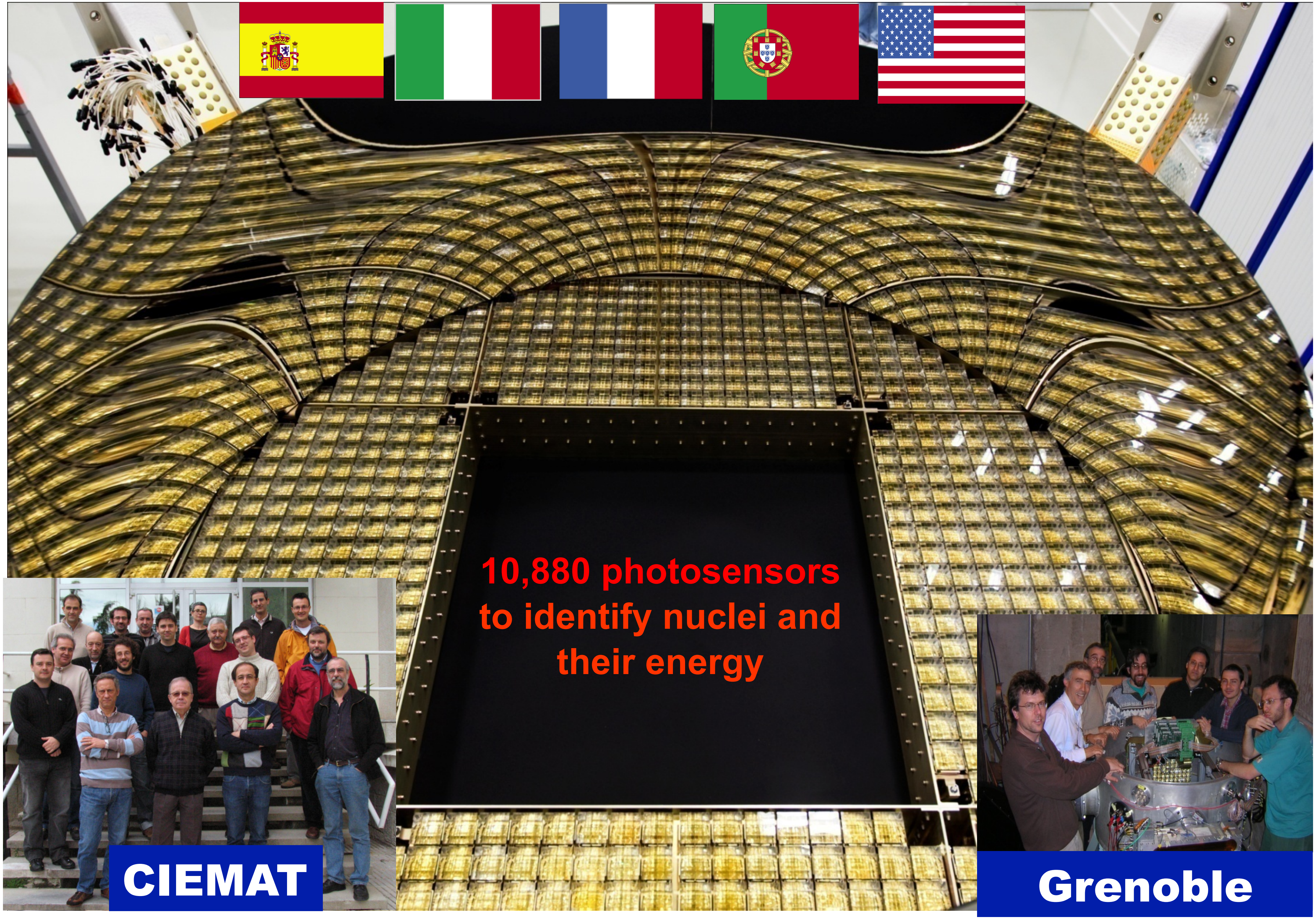


Red line: CO_2 gas/liquid two phase   Blue line: CO_2 liquid phase

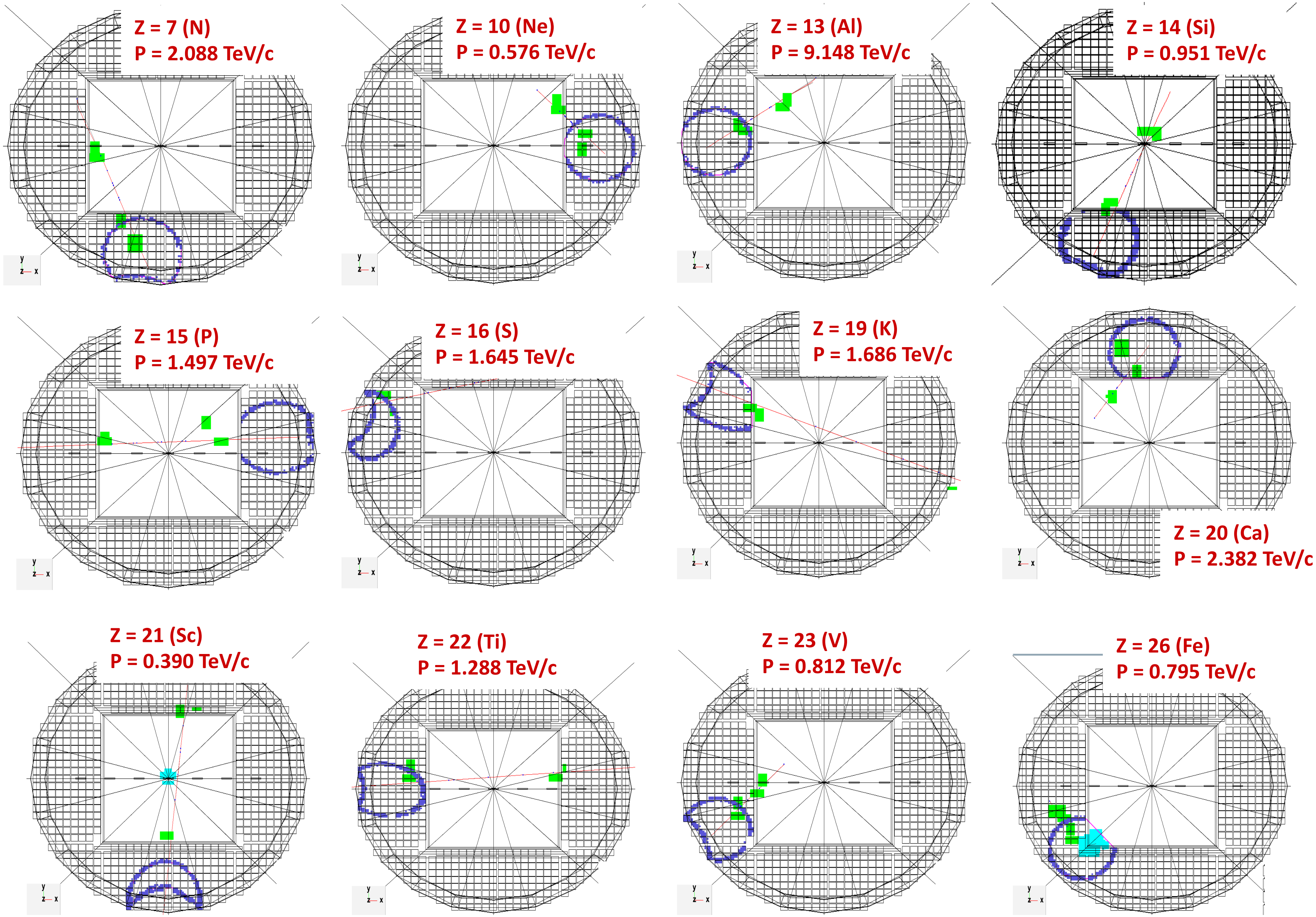
Alignment accuracy of the 9 Tracker layers over 18 months



Ring Imaging CHerenkov (RICH)

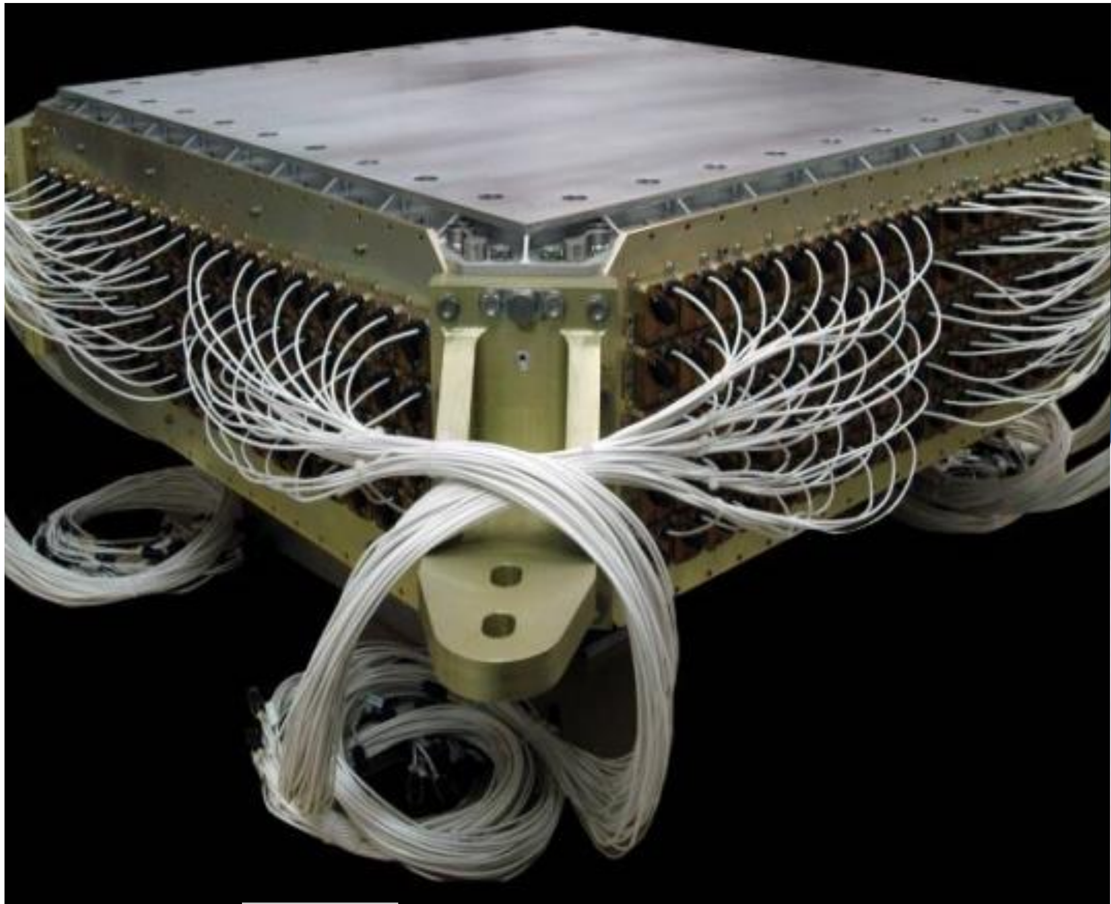


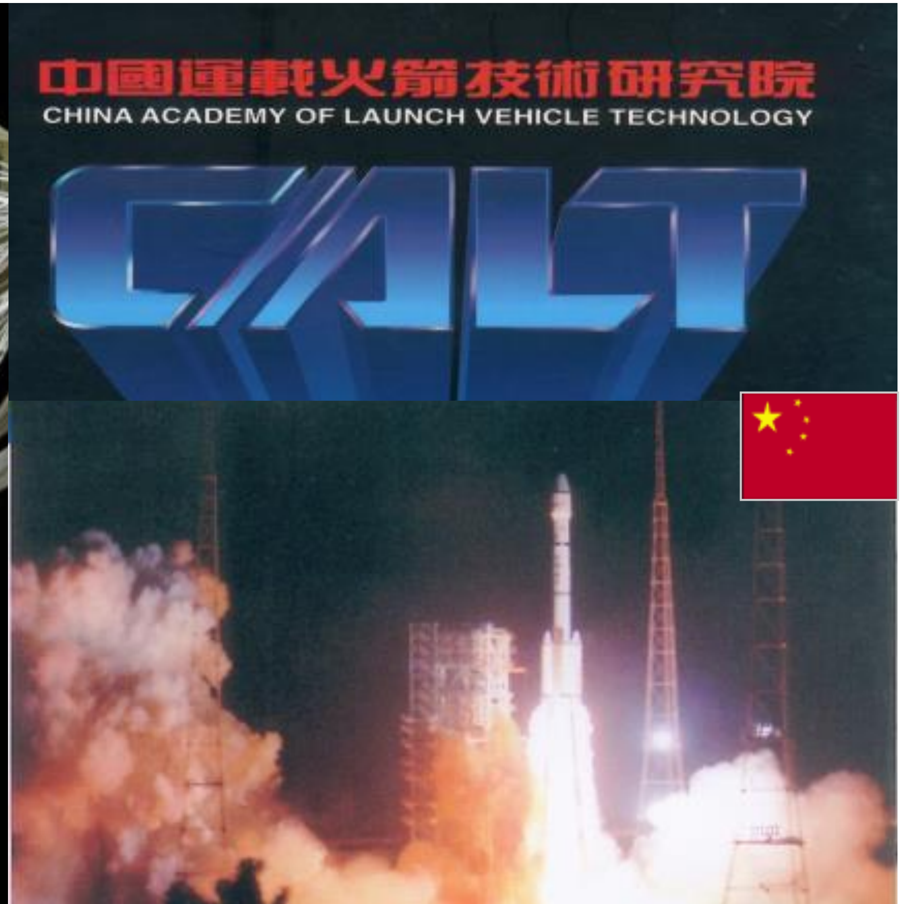
Detector performance on ISS RICH



Calorimeter (ECAL)

50,000 fibers, $\phi = 1$mm, distributed uniformly inside 600 kg of lead which provides a precision, 3-dimensional, $17X_0$ measurement of the directions and energies of light rays and electrons up to 1 TeV

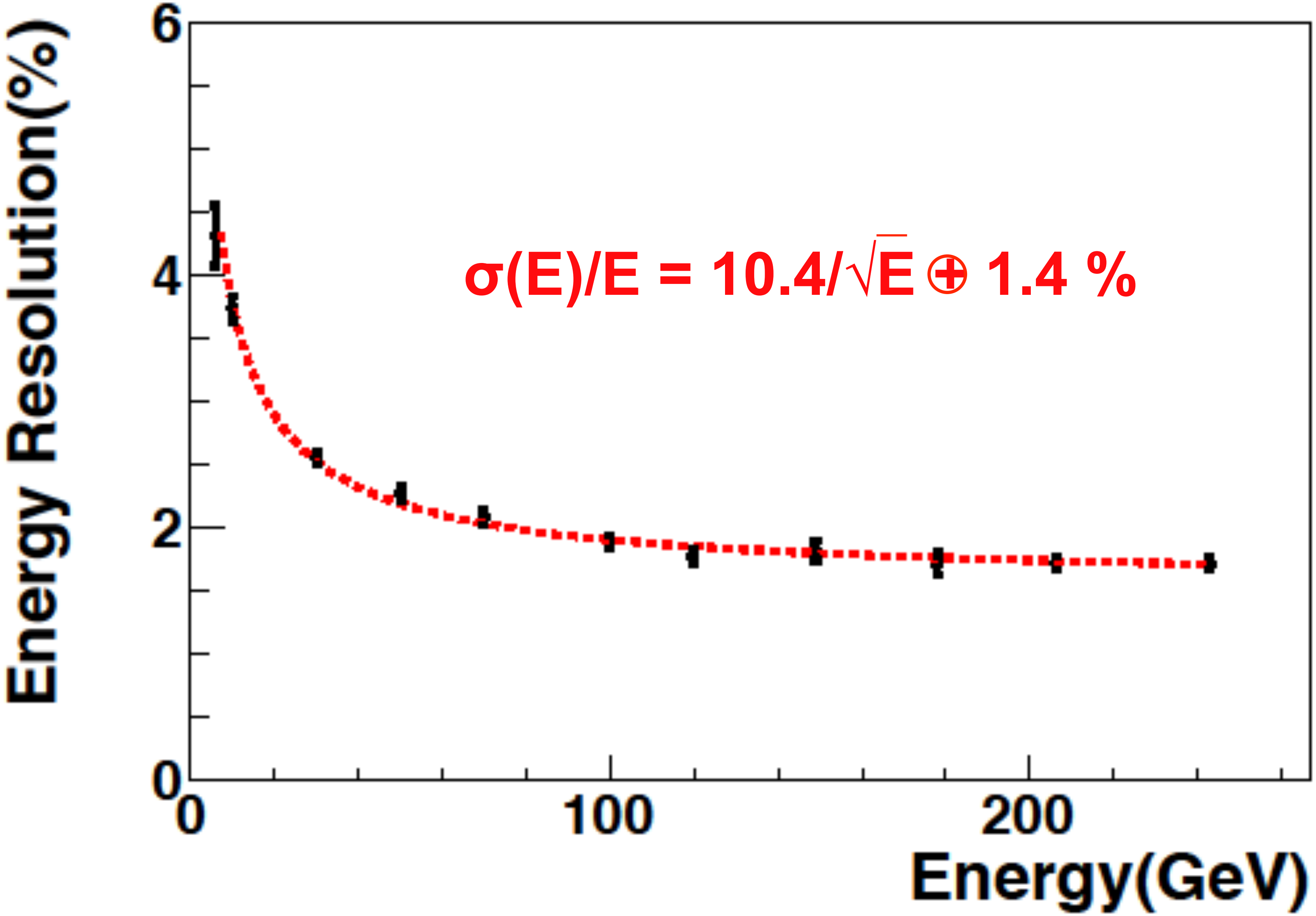



中国運載火箭技術研究院
CHINA ACADEMY OF LAUNCH VEHICLE TECHNOLOGY
CALT

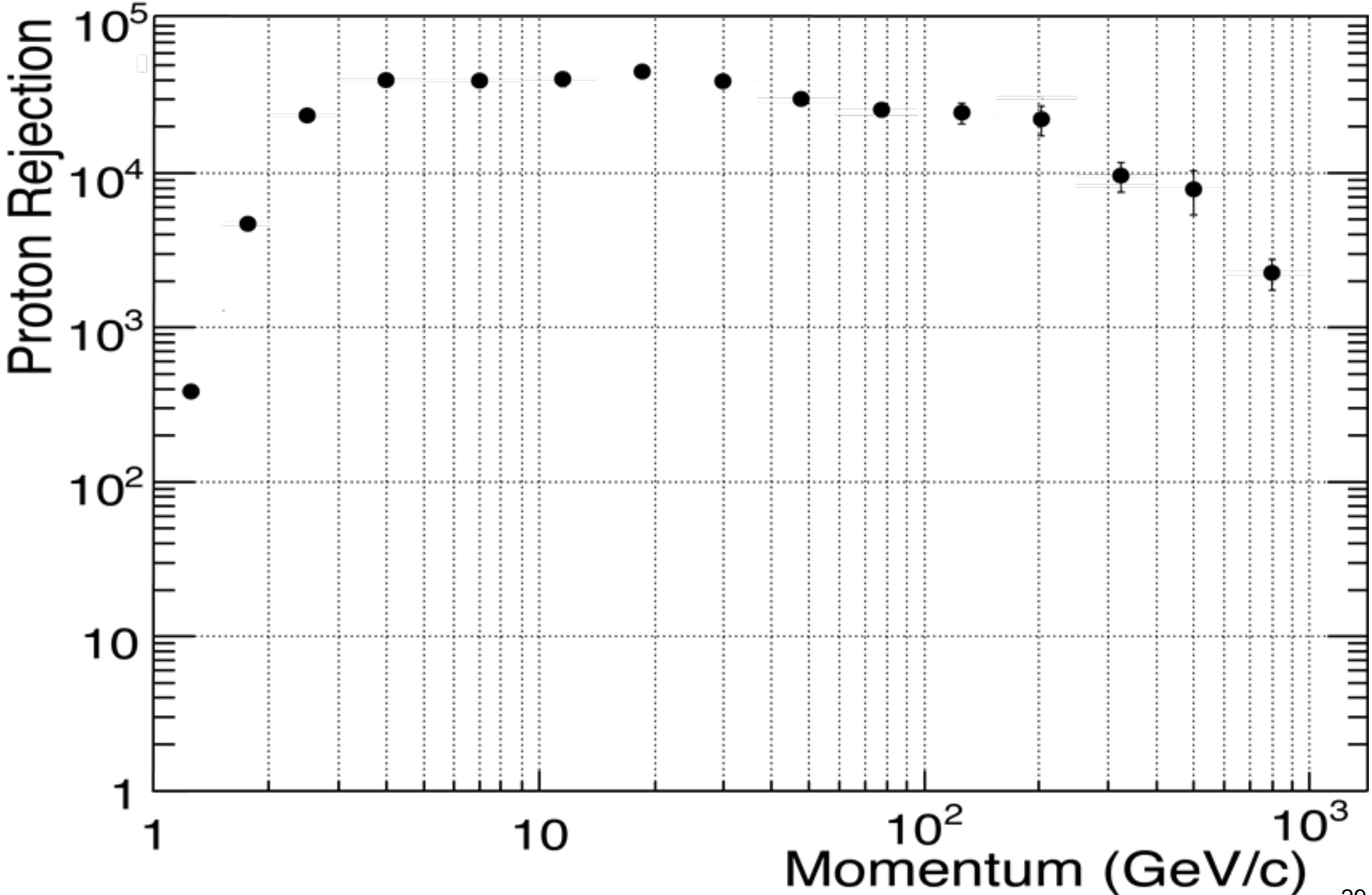
Pisa

LAPP

ECAL Performance

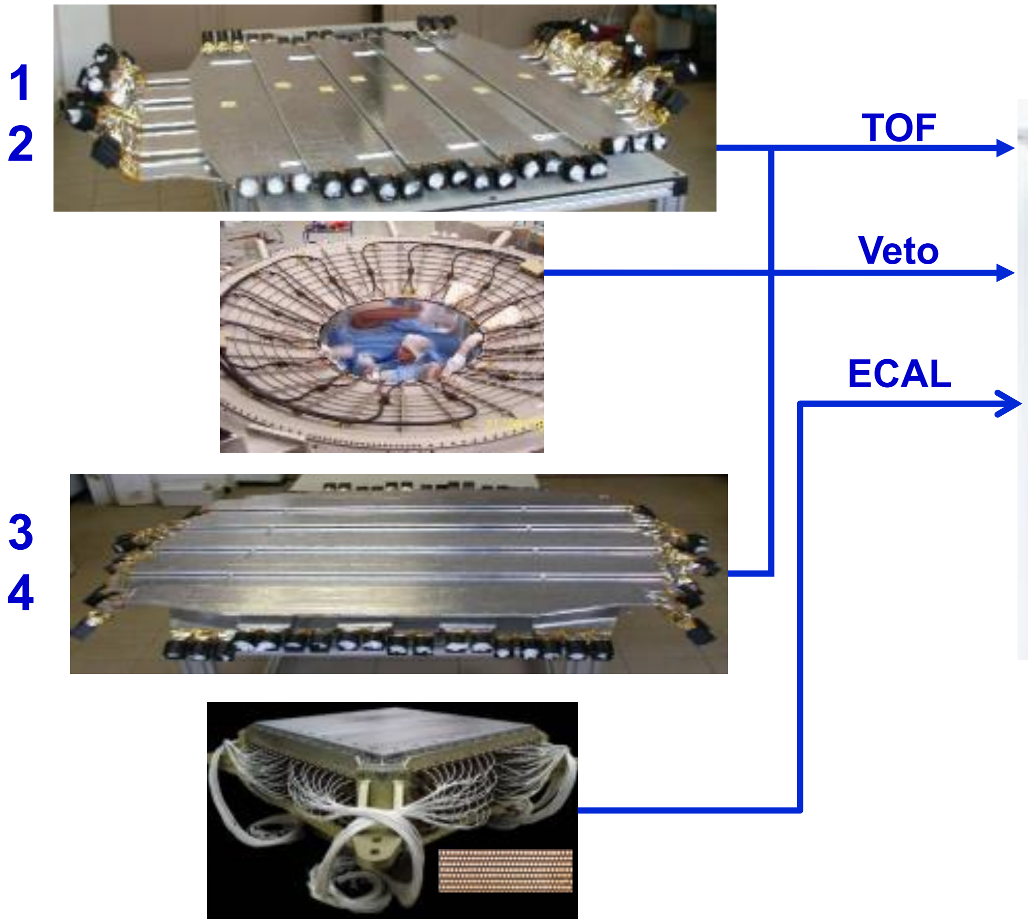


Data from ISS: Proton rejection using the ECAL

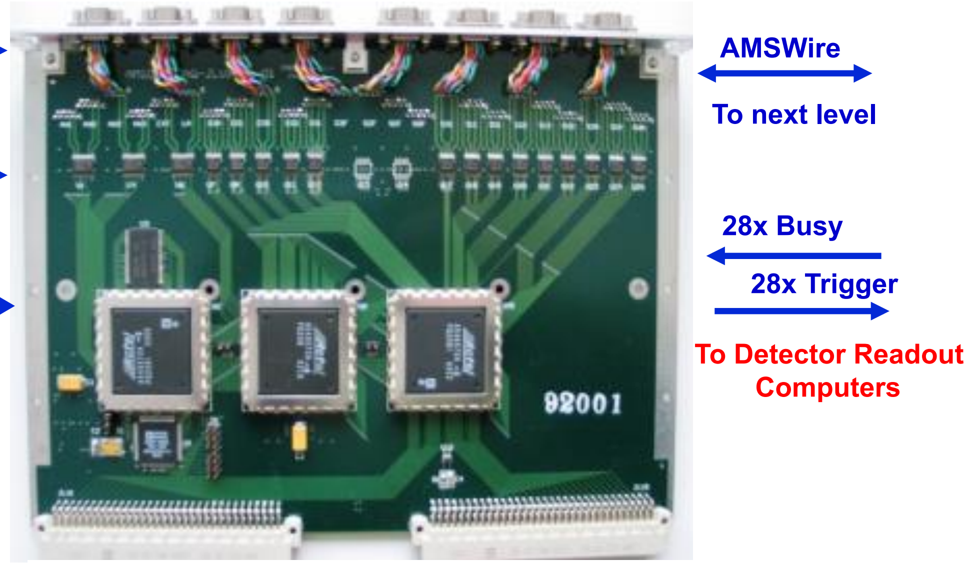


Flight Electronics for DAQ

Trigger Computers



2 Trigger Computers (JLV1)



Produce trigger in 1us for:

- Charged particles,
- Heavy Ions,
- Strangelets,
- Positrons, Electrons,
- Photons
- Efficiencies.

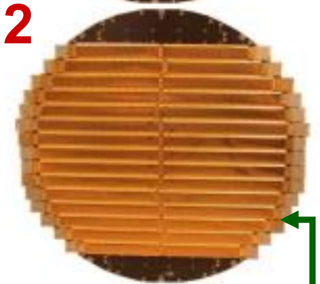
Flight Electronics for DAQ

196,608 Pulse Heights,
216 Low Voltages,

Tracker Data Reduction and Readout Computers

1

2



3
4

5
6

7
8

9

196,608
Pulse Heights

Low voltage

192 Tracker Data Reduction (TDR)

AMSWire

Busy

Trigger

16 Readout Computers (JINF-T)

AMSWire

To next level

Busy

Trigger

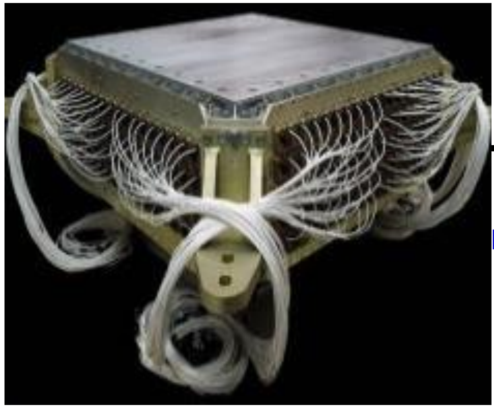
- Analog to digital conversion
  coordinate resolution of 10 um
- Data reduction:
  - Pedestal subtraction
  - Noise suppression
  - Cluster finding

- Collect data from TDR
- Control Low Voltages
- Combine Busy signals
- Distribute Trigger
- Distribute command to TDR

Flight Electronics for DAQ

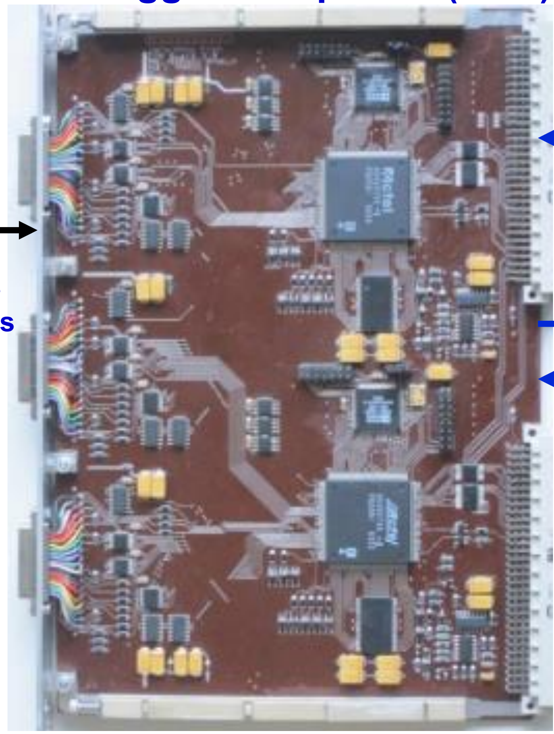
ECAL Data Reduction & Trigger, Readout Computers

2,916 Pulse Heights (high and low gain, dynodes), 346 Voltages



2,916 Pulse Heights

28 ECAL Data Reduction & Trigger Computers (EDR)

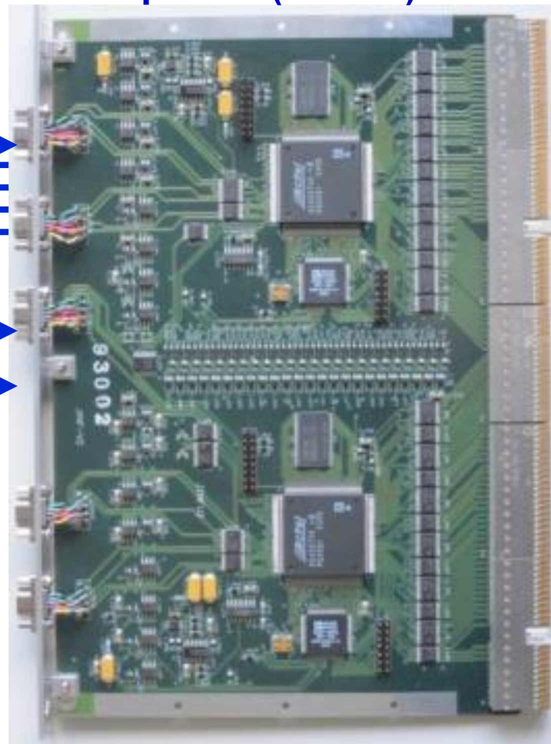


AMSWire

Busy

Trigger

4 Readout Computers (JINF-E)



AMSWire

To next level

Busy

Trigger

High & Low Voltage Control

- Analog to digital conversion
- Linear to 1 in 10^5
- Produce Trigger inputs

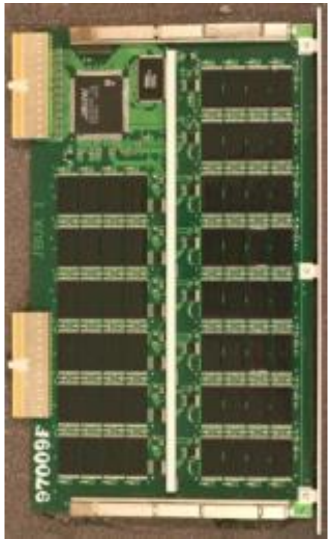
- Collect data from EDR
- Control High & Low Voltage
- Combine Busy signals
- Distribute Trigger

Flight Electronics for DAQ

4 Redundant AMS Main Data Computers, each with:

High Rate Interface

400 MHz Processor



112 GB Flash Memory

CAN bus interface

AMSWire & Low Rate Interfaces

- Collect data, compress reconstruct, send to POCC
- On-board buffer for ~1 day of data
- Interface to ISS Avionics
- Execute commands from the POCC
- Collect monitoring data, analyze, respond, send to POCC

DAQ Computers ⟷ AMSWire 100 MBit/s

HRDL 100 MBit/s ⟷ ISS Avionics

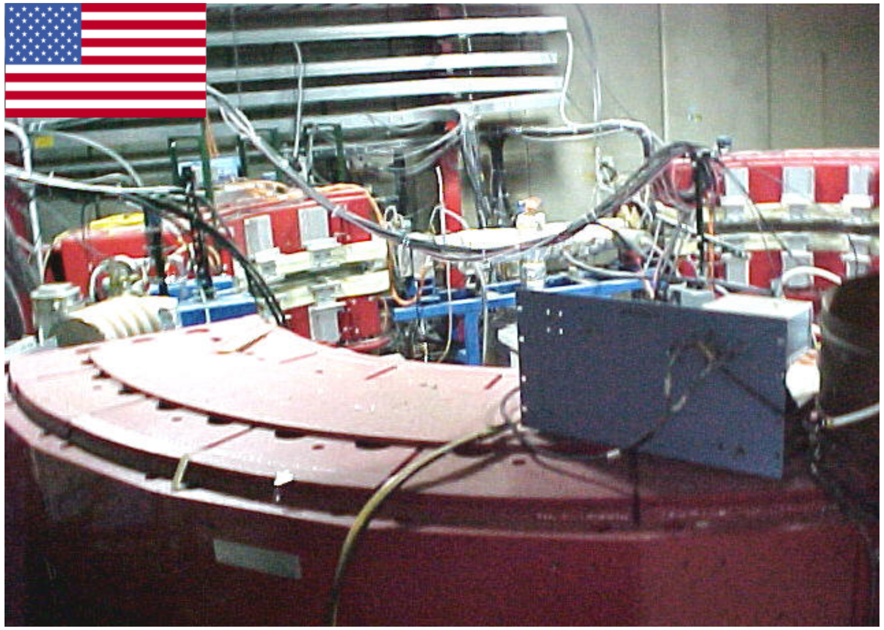
LRDL ⟷ ISS Avionics

AMS CAN Buses

Main Computer Power	Monitoring (TAS, GPS, Star Tracker)	TRD Gas, Temperature	Tracker Thermal Control	Power Distribution
USCM-J	USCM-M	UGSCM	TTCE	PDS

AMS Electronics

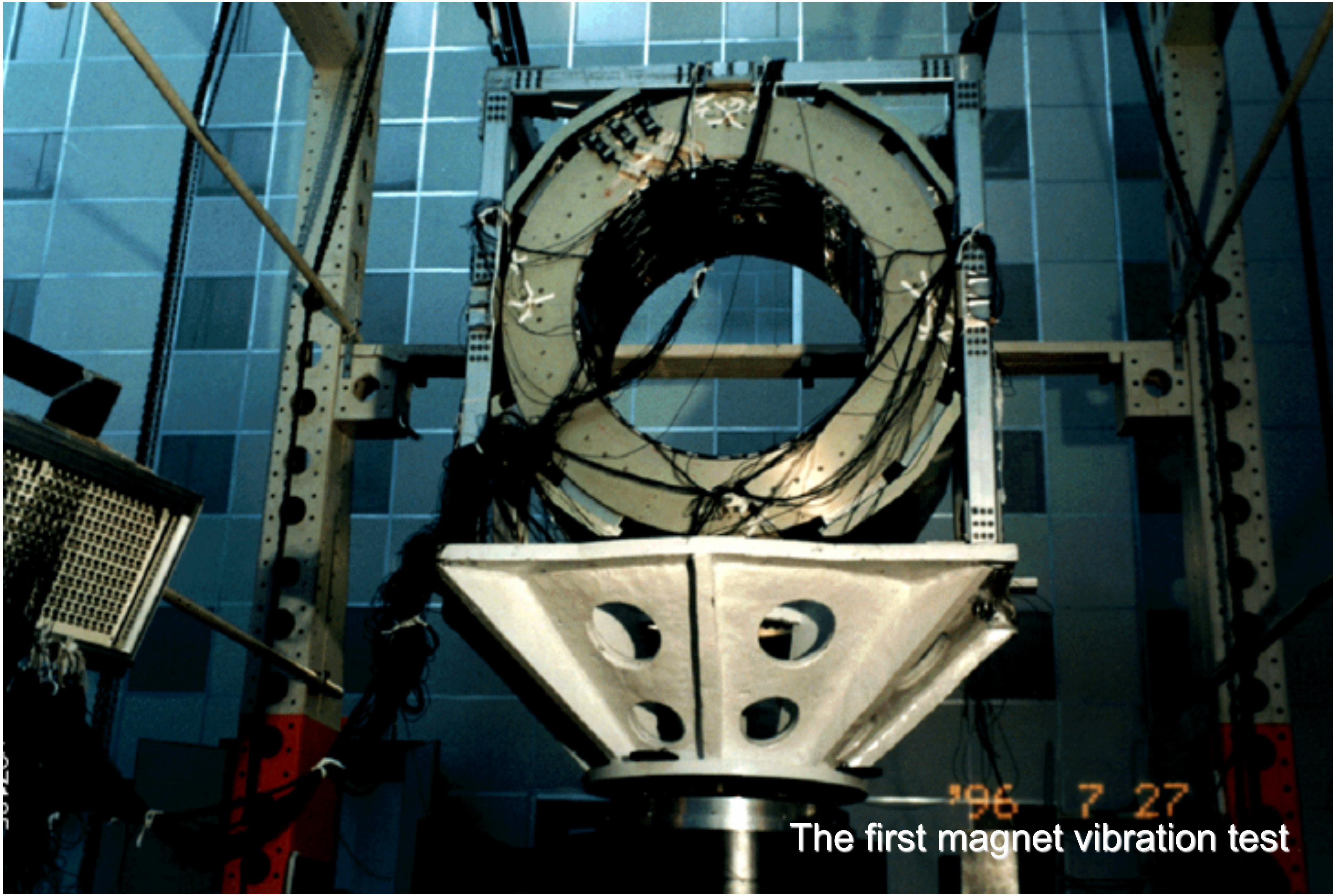
The AMS group performed extensive radiation tests
to select components that tolerate the radiation of space.



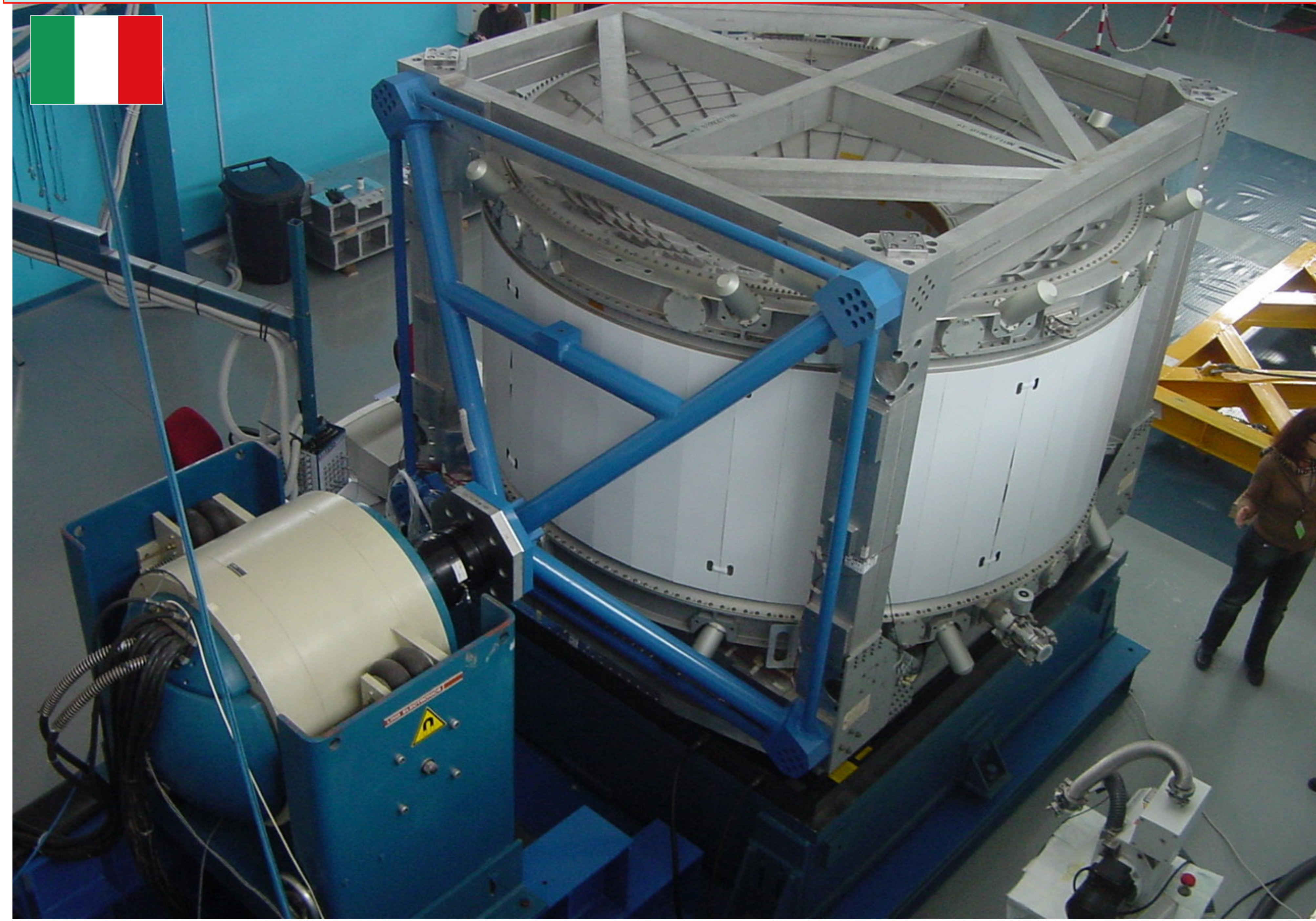
Extensive tests were made in Italy, France, Germany, Spain, Taiwan, China … for example:
in 2009: AFTER 9000 hrs of Thermal-Vacuum Tests
THE END OF SUB-SYSTEMs TESTS AT SERMS

RWTH Aachen, I. Physics Institute
Workshop

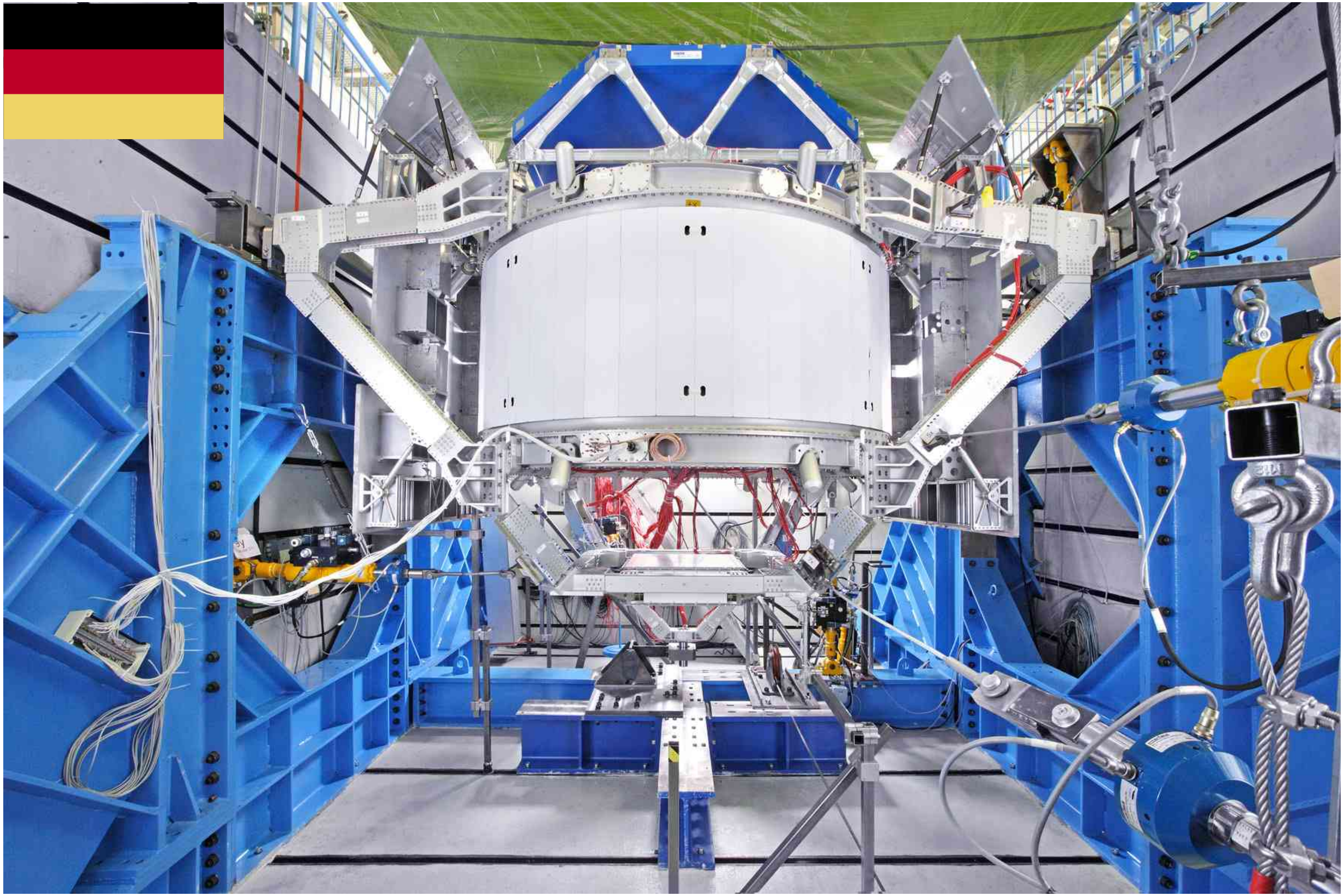
Space Qualification Tests of AMS in China



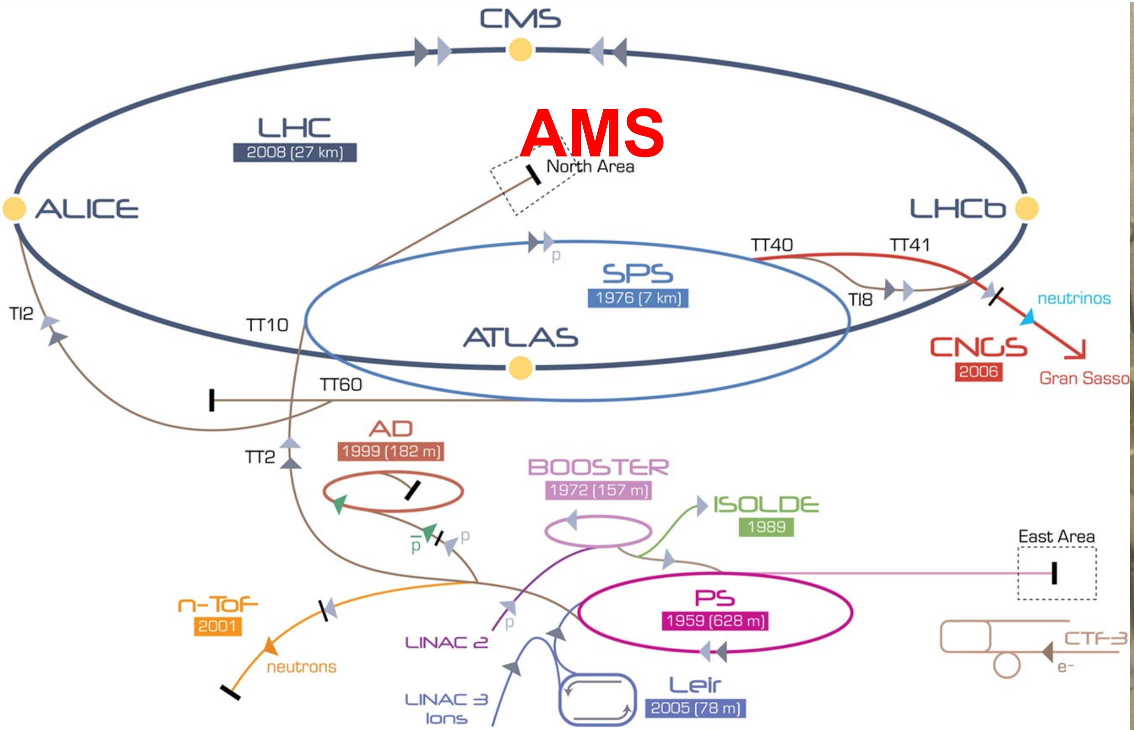
Space Qualification Tests of AMS in Italy (INFN)

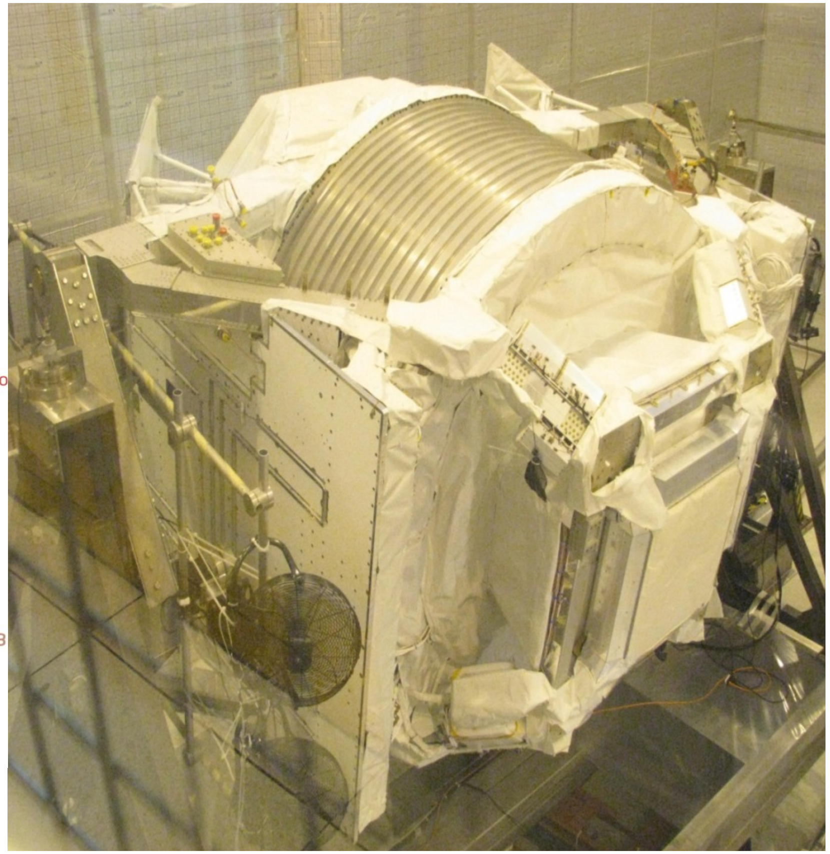


Space Qualification Tests of AMS in Germany



Intensive Beam Tests at CERN



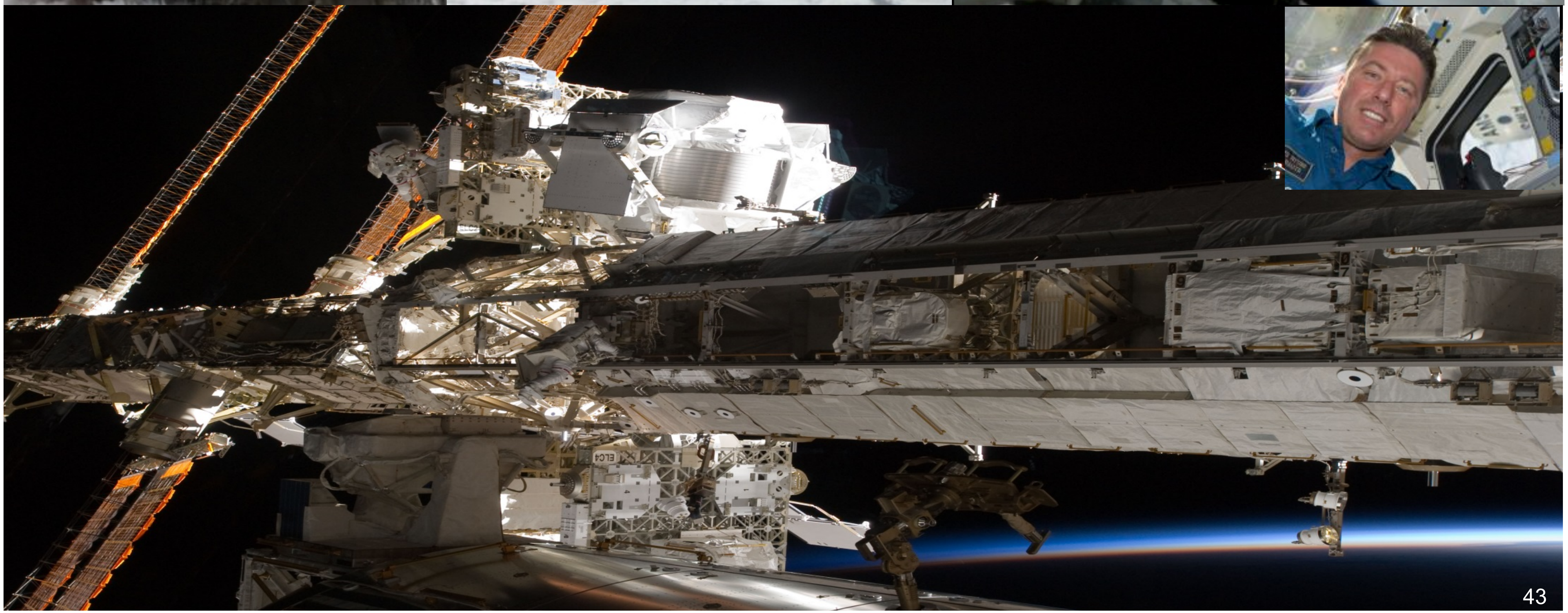


AMS in SPS Test Beam, 2010

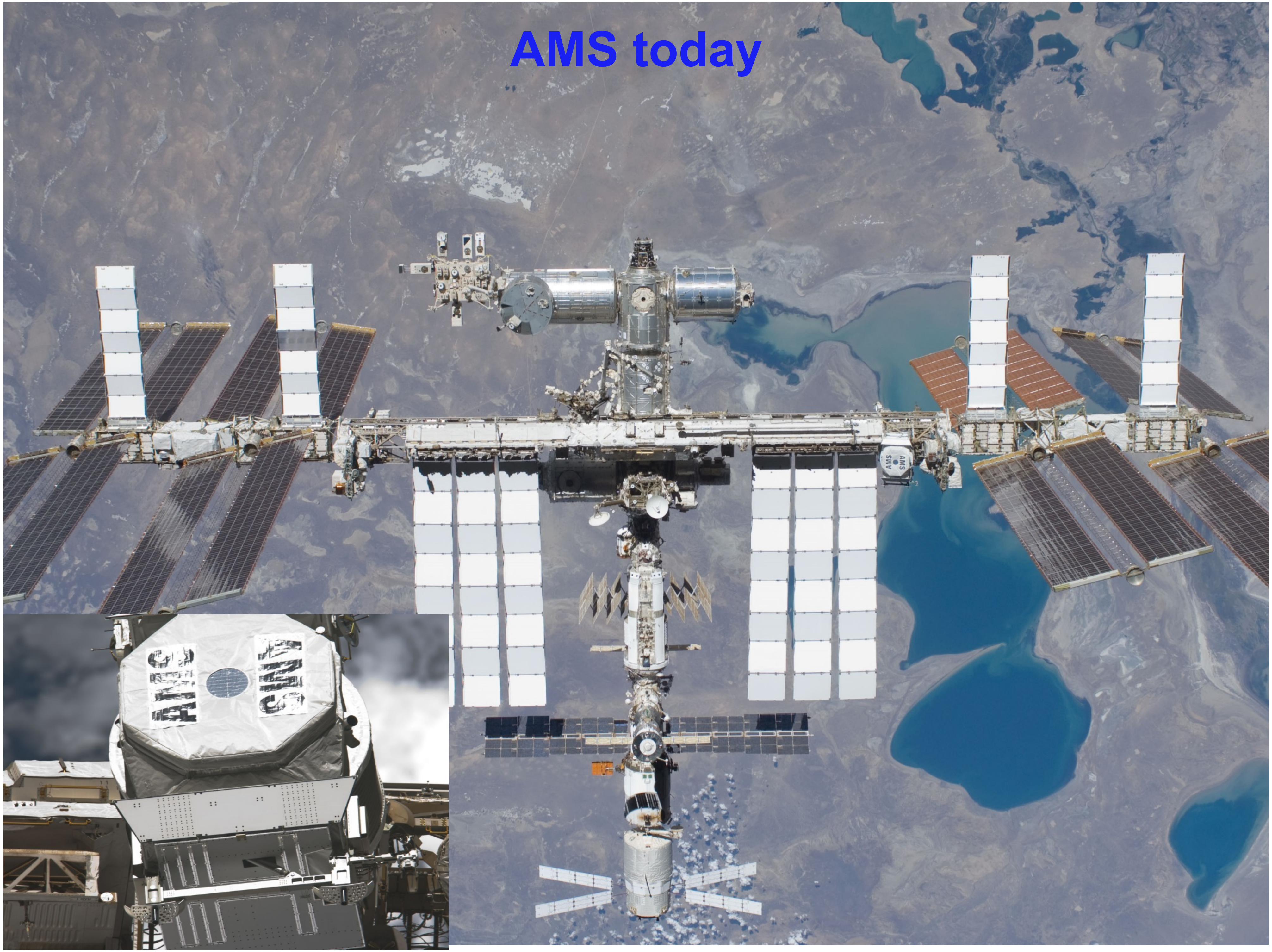
Particle	Momentum (GeV/c)	Positions	Purpose
Protons	400 + 180	1,650	Full Tracker alignment, TOF calibration, ECAL uniformity
Electrons	100, 120, 180, 290	7 each	TRD, ECAL performance study
Positrons	10, 20, 60, 80, 120, 180	7 each	TRD, ECAL performance study
Pions	20, 60, 80, 100, 120, 180	7 each	TRD performance to 1.2 TeV


May 16, 2011

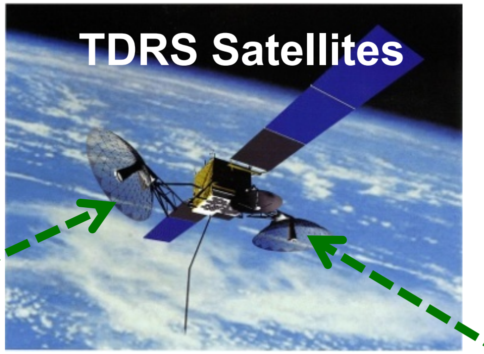

May 16th, 2011



AMS today



AMS Operations



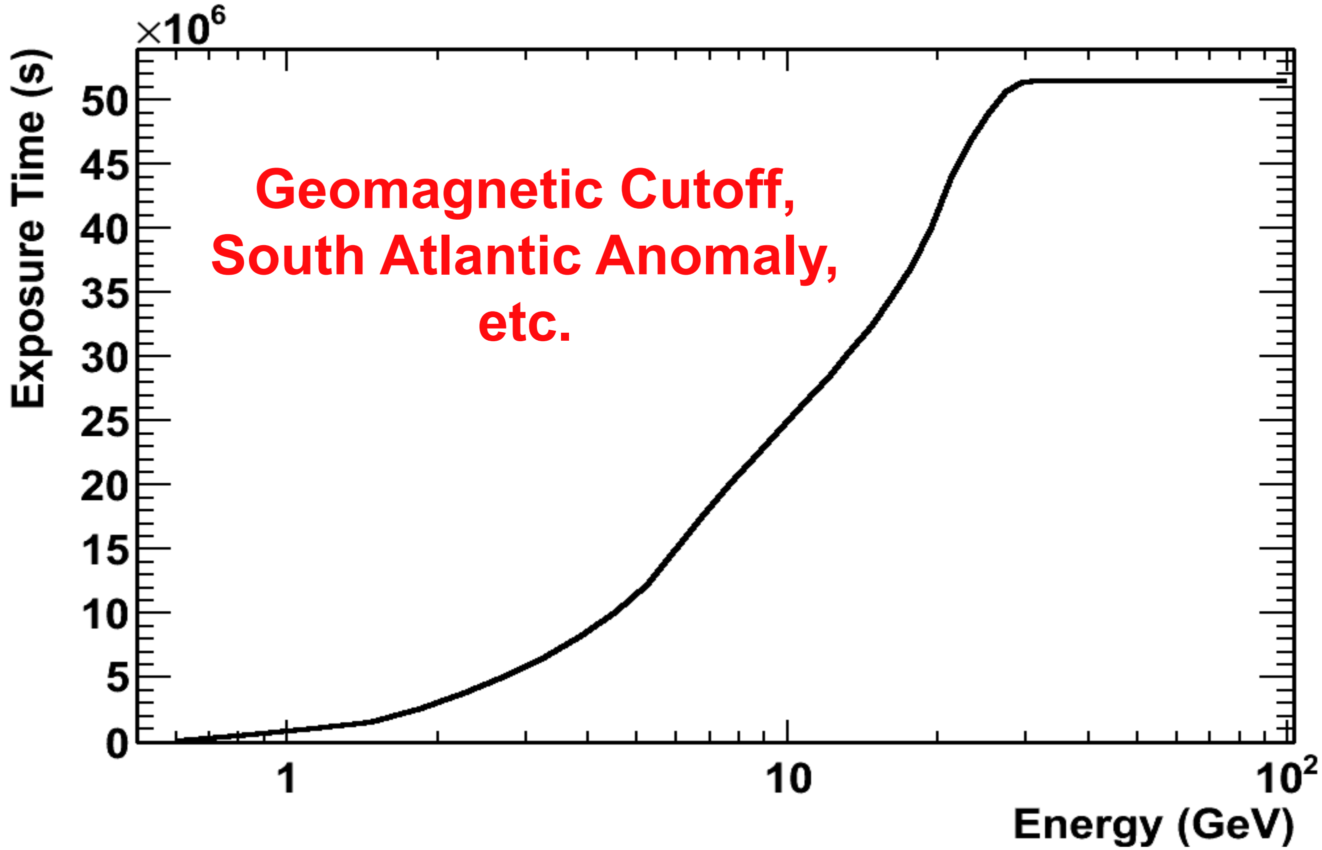
24 hours
x 365 days
x 10-20 years

White Sands, NM

AMS

Physics results

Results from the first 2 years of AMS



Average live time = 82 %

Data analysis in AMS (2 years of data)

AMS is a very precise particle physics detector.

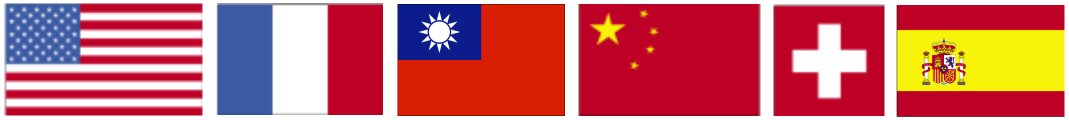
Precision physics results require attention to detail and a large analysis effort.

The data are analysed by two independent AMS international teams.

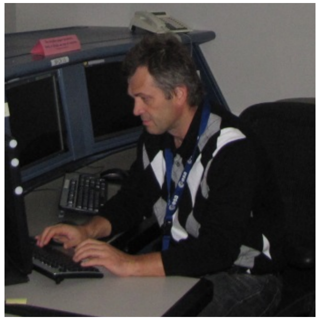
Example: the positron fraction paper

Group A

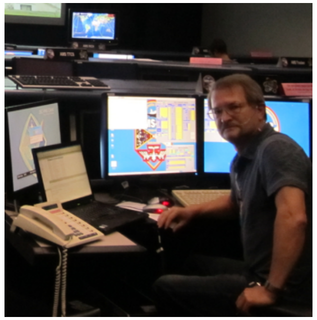
Group α



B. Bertucci



V. Choutko



A. Kounine

J. Berdugo

S. Schael

M. Incagli

S. Rosier-Lees

S. Haino, A. Oliva

J. Casaus, P. Zuccon

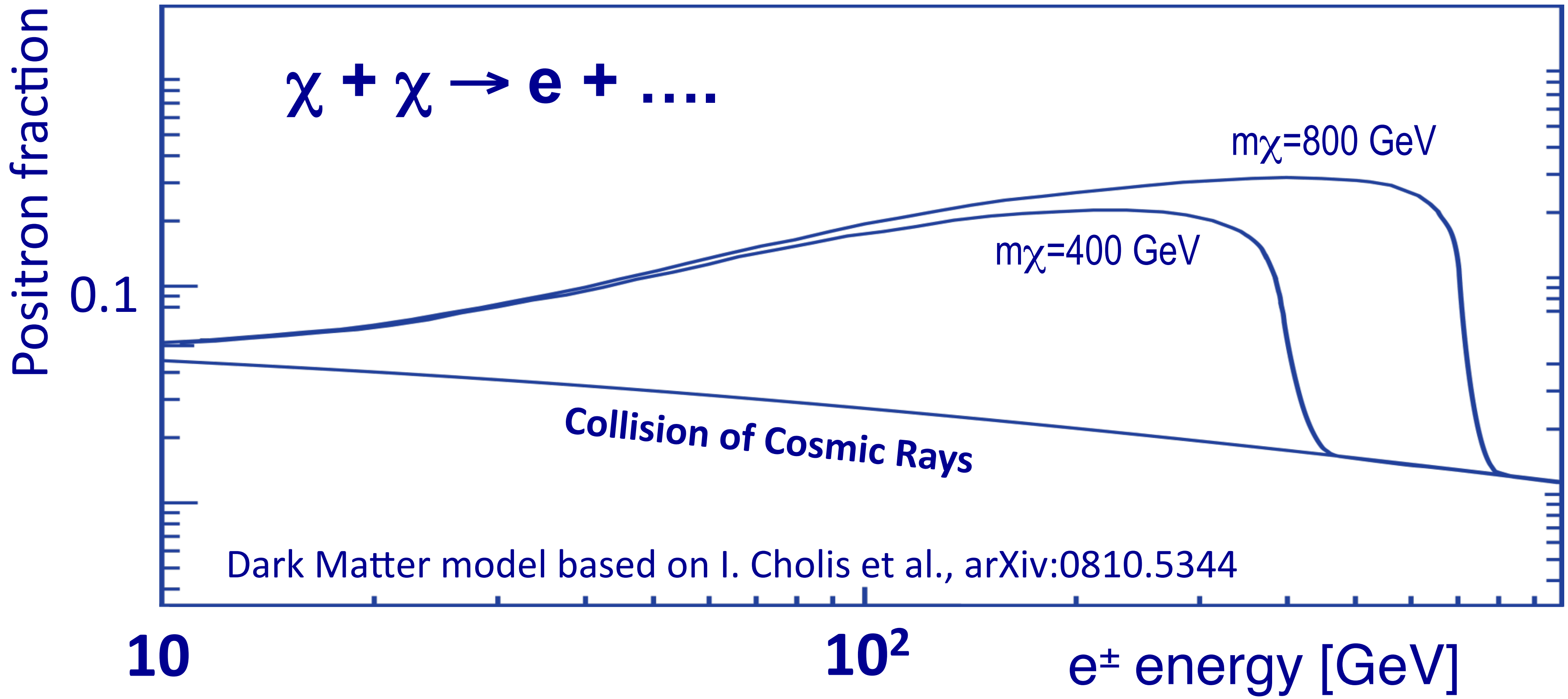
A. Contin

Physics results (ICRC 2013)

1. $e^+/(e^+ + e^-)$ ratio and anysotropy
2. Proton spectrum
3. Helium spectrum
4. Electron Spectrum
5. Positron Spectrum
6. All electron spectrum
7. Boron-to-Carbon ratio

Physics of Positron Fraction: $e^+/(e^+ + e^-)$

M. Turner and F. Wilczek, Phys. Rev. D42 (1990) 1001;
J. Ellis, 26th ICRC Salt Lake City (1999) astro-ph/9911440;
H. Cheng, J. Feng and K. Matchev, Phys. Rev. Lett. 89 (2002) 211301;
S. Profumo and P. Ullio, J. Cosmology Astroparticle Phys. JCAP07 (2004) 006;
D. Hooper and J. Silk, Phys. Rev. D 71 (2005) 083503;
E. Ponton and L. Randall, JHEP 0904 (2009) 080;
G. Kane, R. Lu and S. Watson, Phys. Lett. B681 (2009) 151;
D. Hooper, P. Blasi and P. D. Serpico, JCAP 0901 025 (2009) 0810.1527; B2
Y–Z. Fan et al., Int. J. Mod. Phys. D19 (2010) 2011;
M. Pato, M. Lattanzi and G. Bertone, JCAP 1012 (2010) 020.

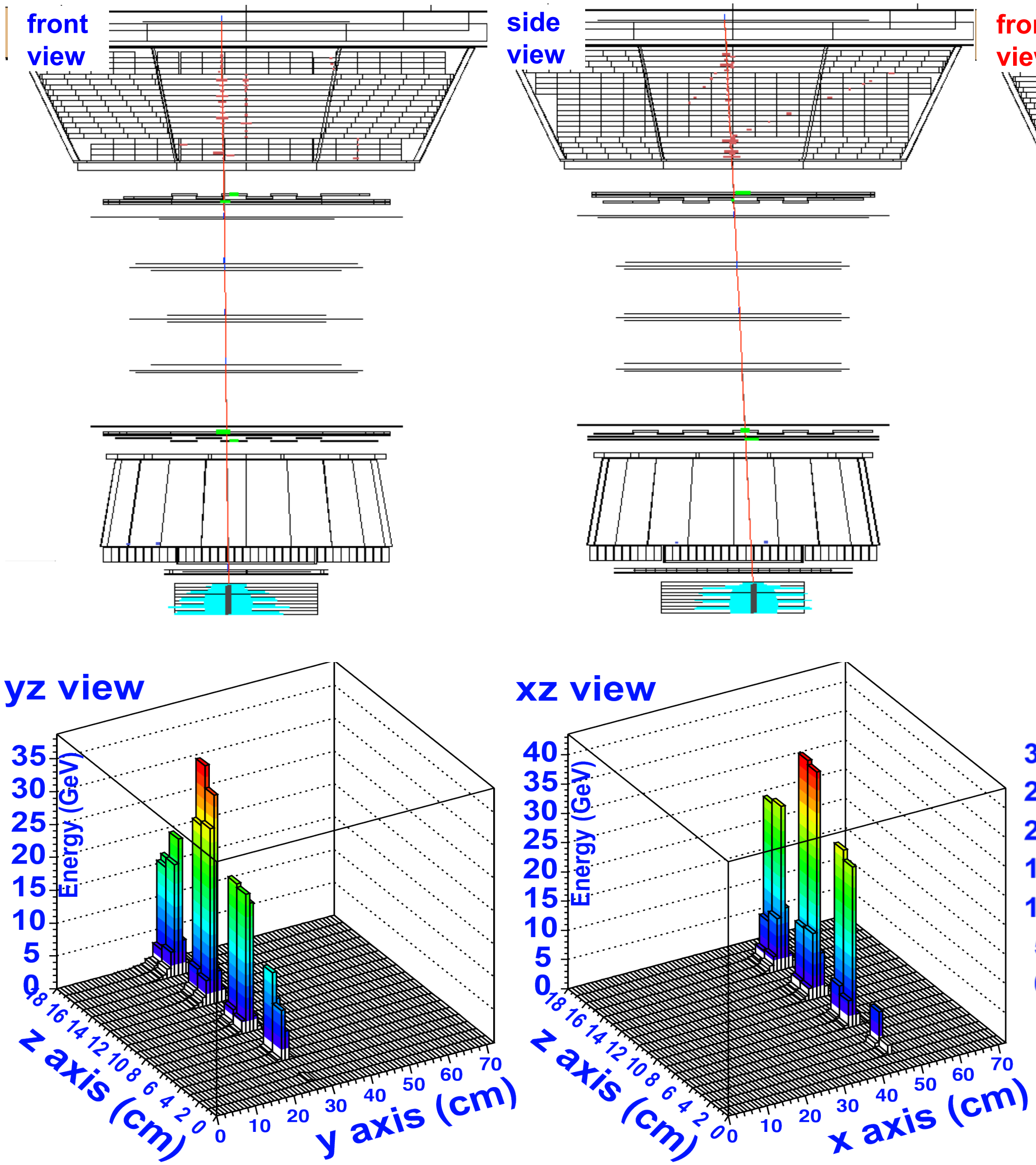


In the first 1.5 years in space, AMS has collected over 25 billion events.

6.8 million are electrons or positrons.

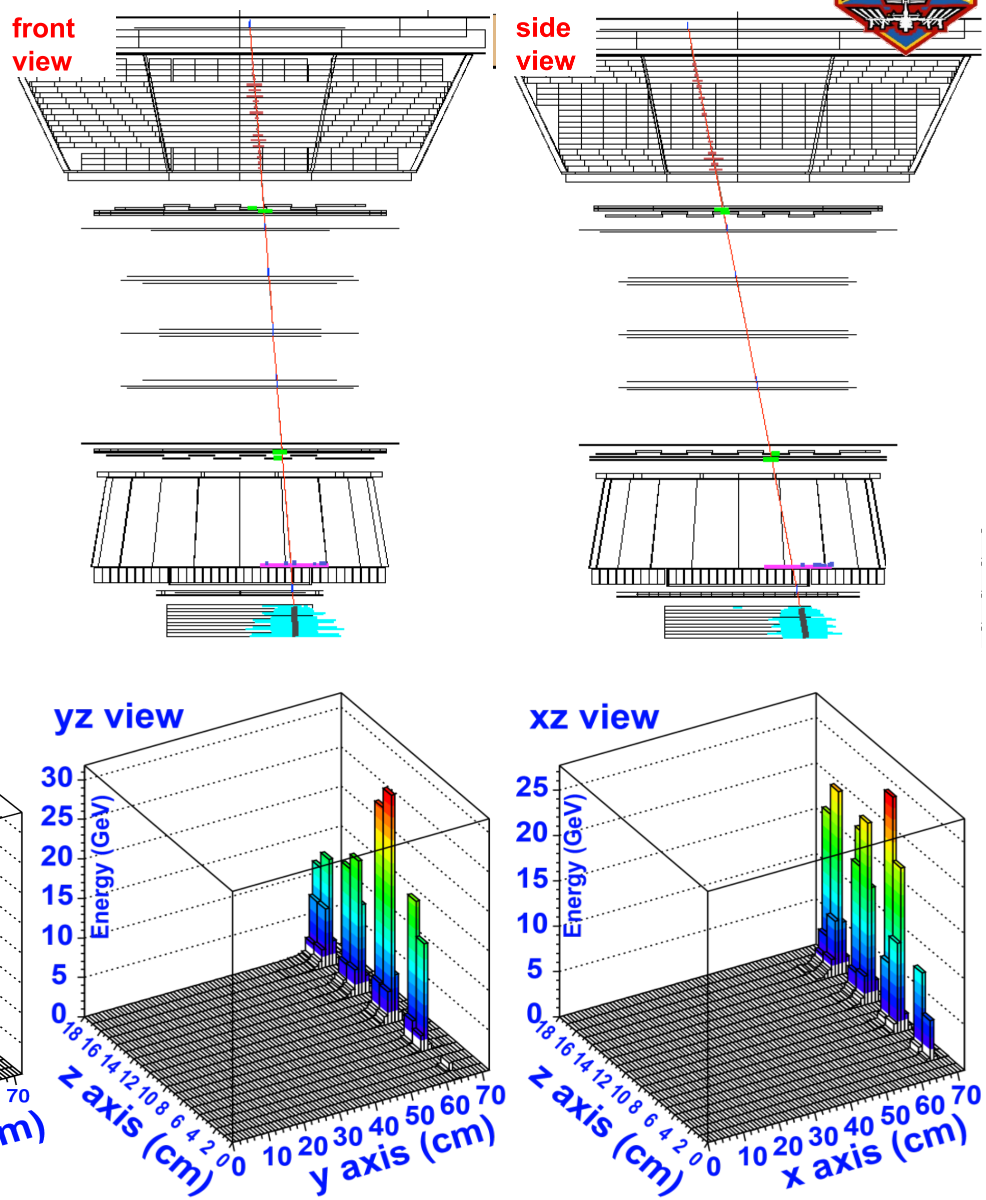
Electron E=982 GeV

Run/Event 1329775818/ 60709



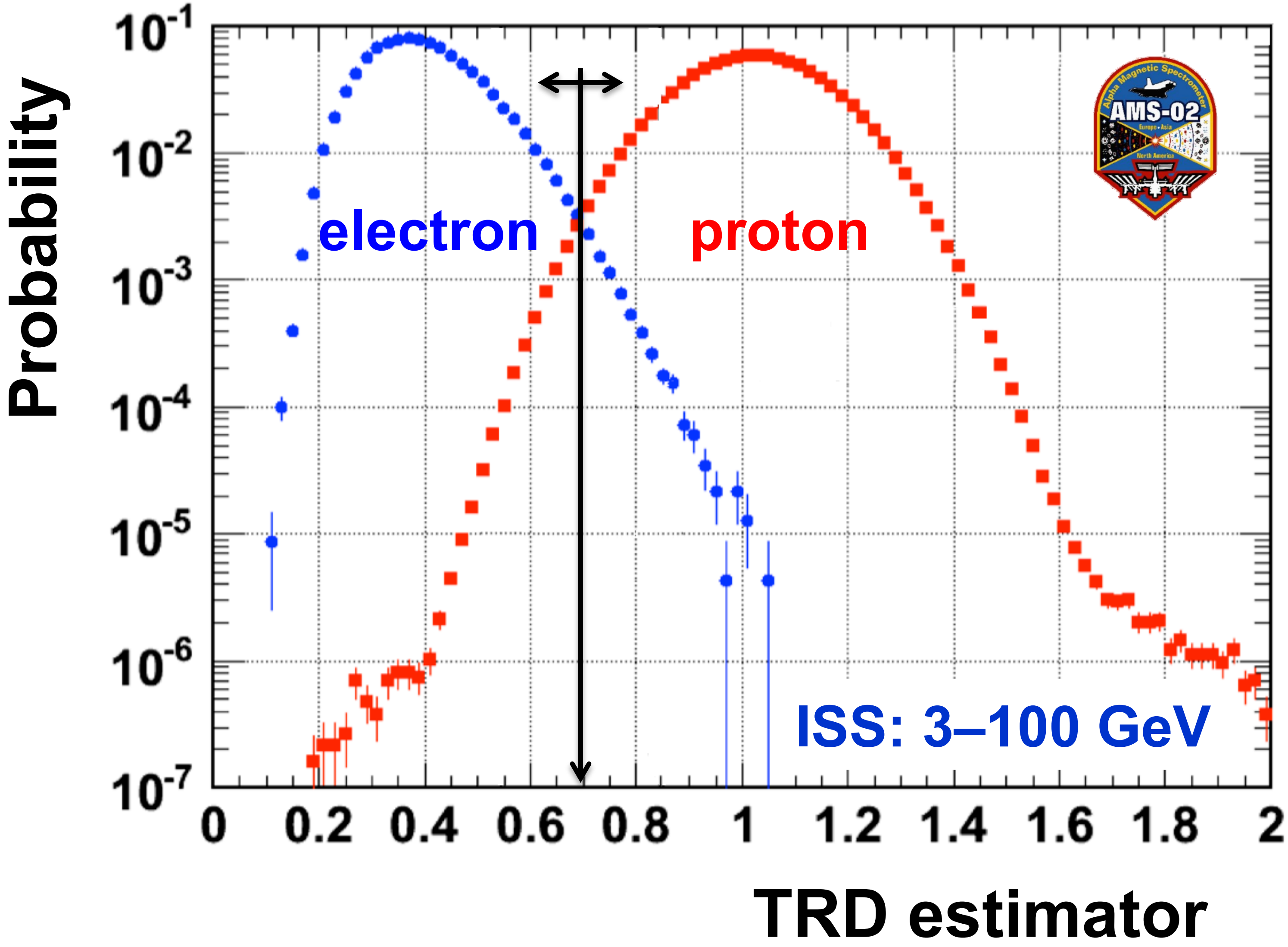
Positron E=636 GeV

Run/Event 133119-743/ 56950



TRD performance on ISS

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

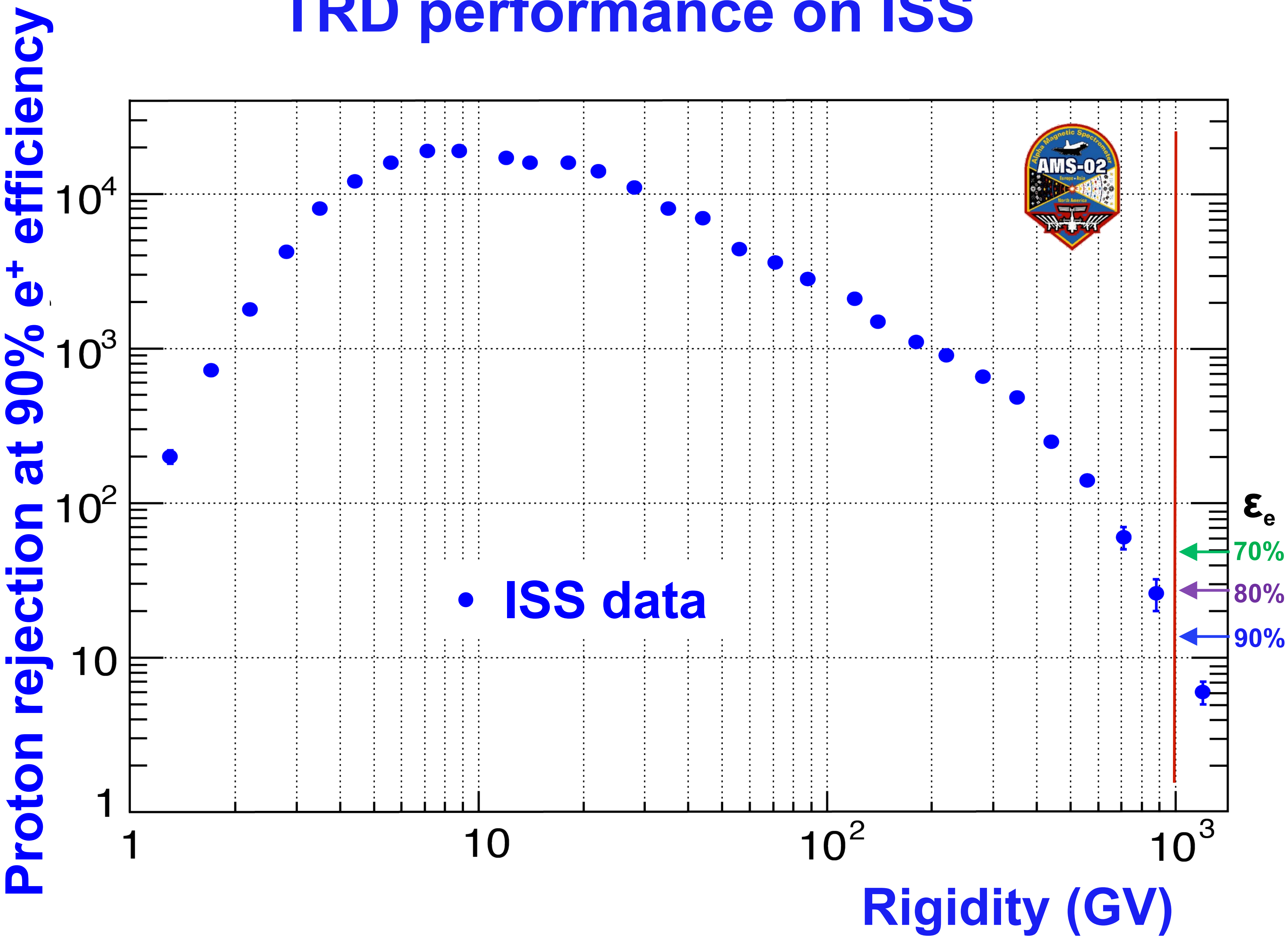


Normalized probabilities P_e and P_p

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

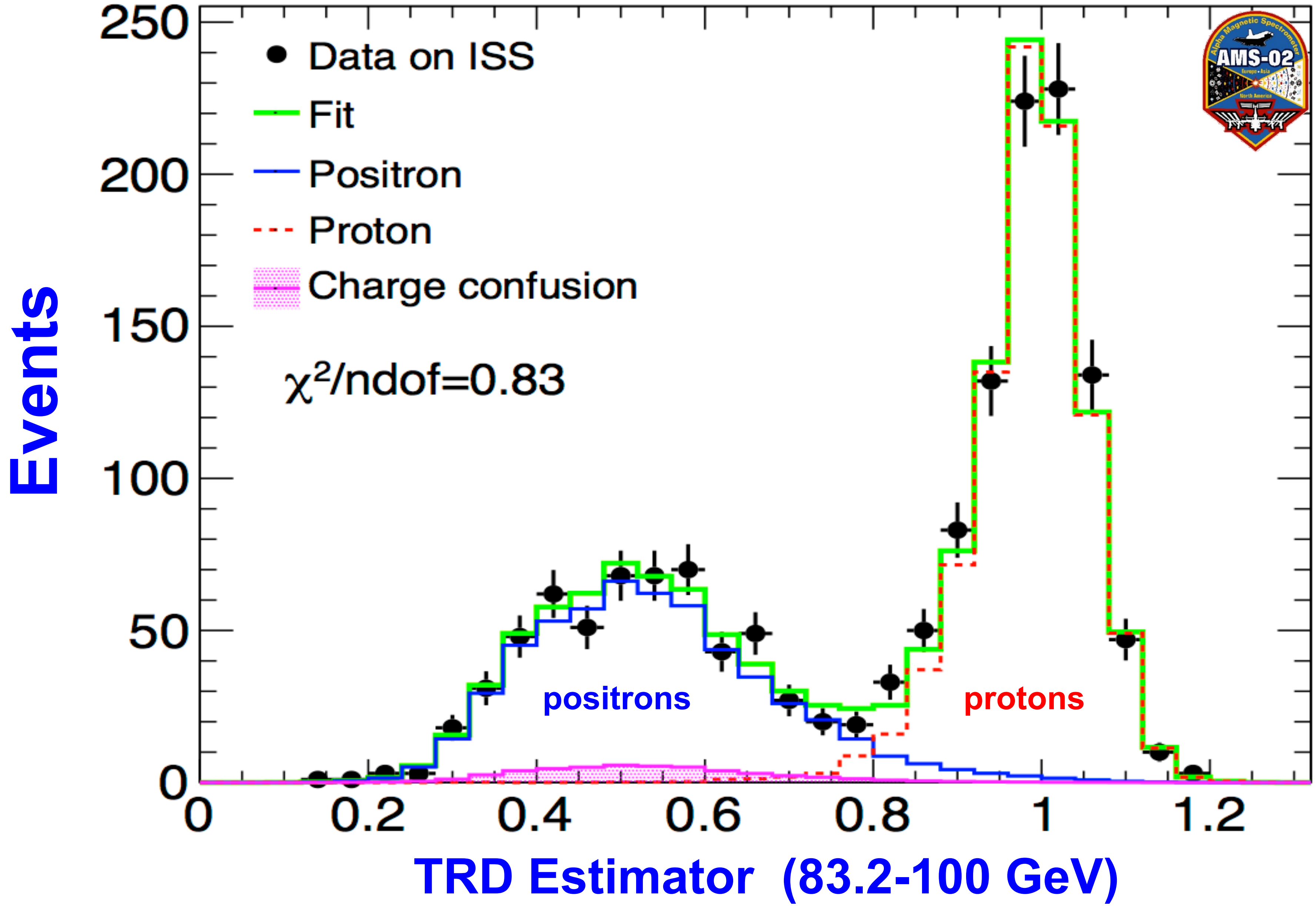
$$P_p = \sqrt[n]{\prod_i^n P_p^{(i)}(A)}$$

TRD performance on ISS

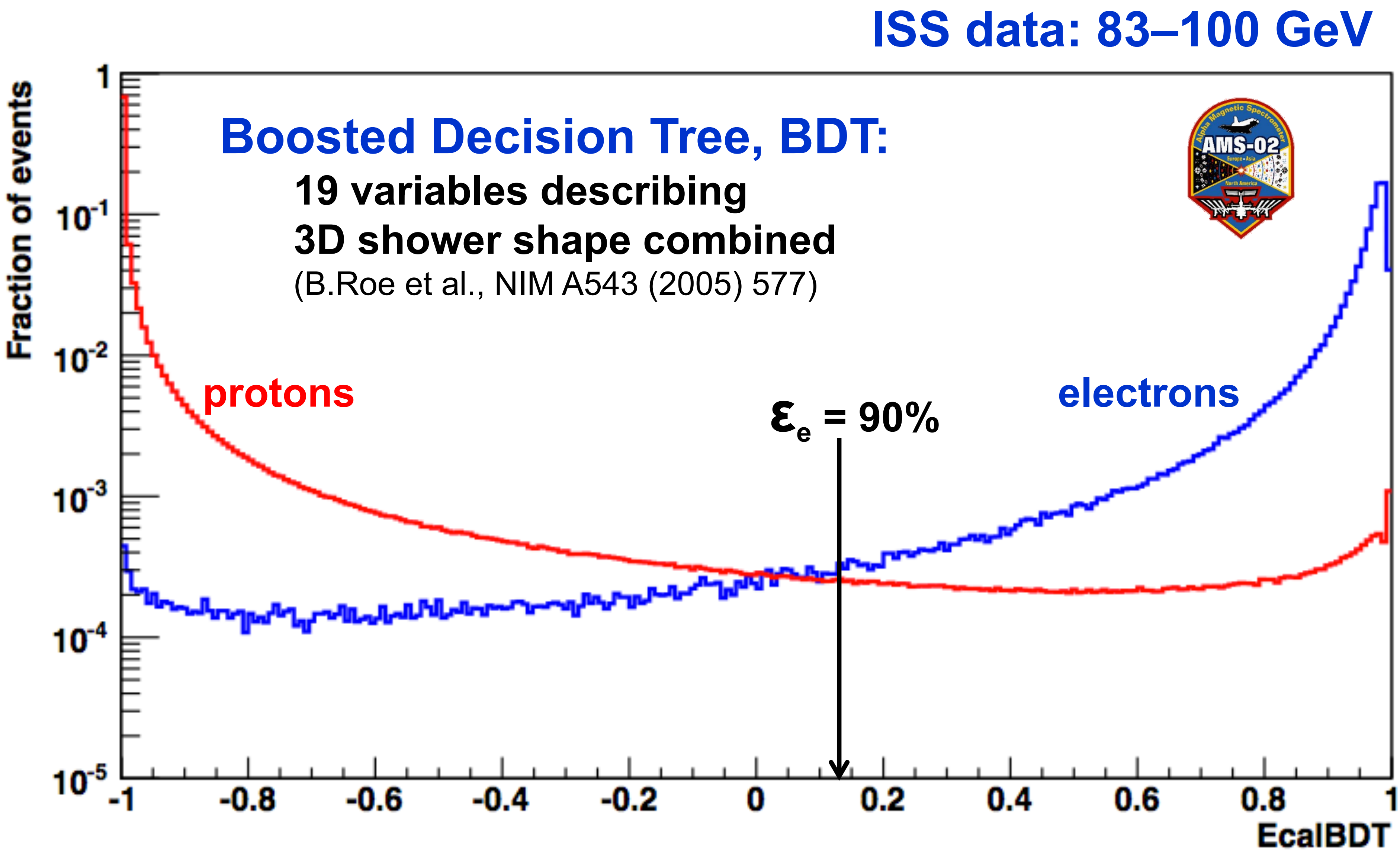


Results of the fit:

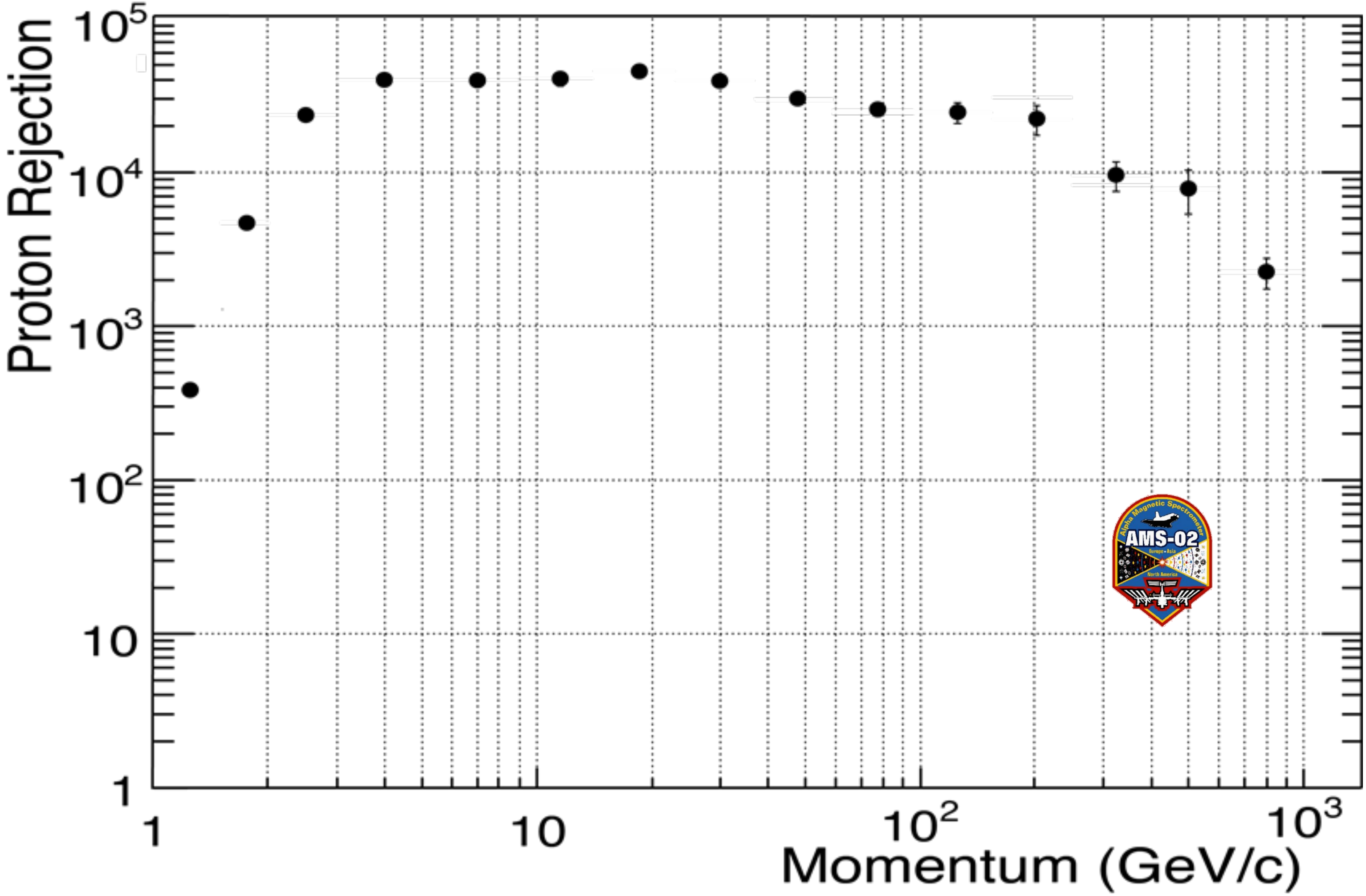
The TRD Estimator shows clear separation between protons and positrons with a small charge confusion background



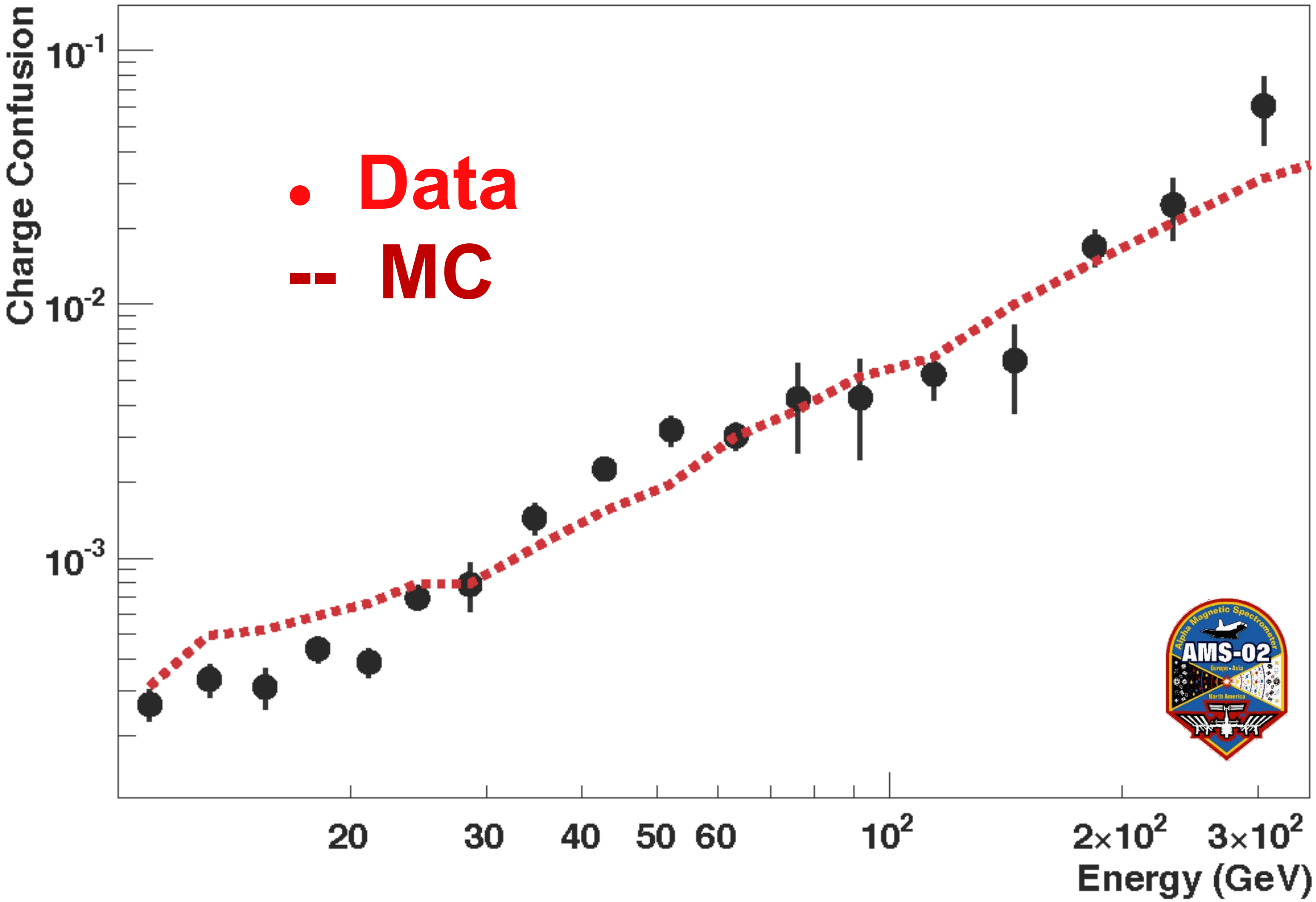
Separation of protons and electrons with ECAL



Data from ISS: Proton rejection using the ECAL



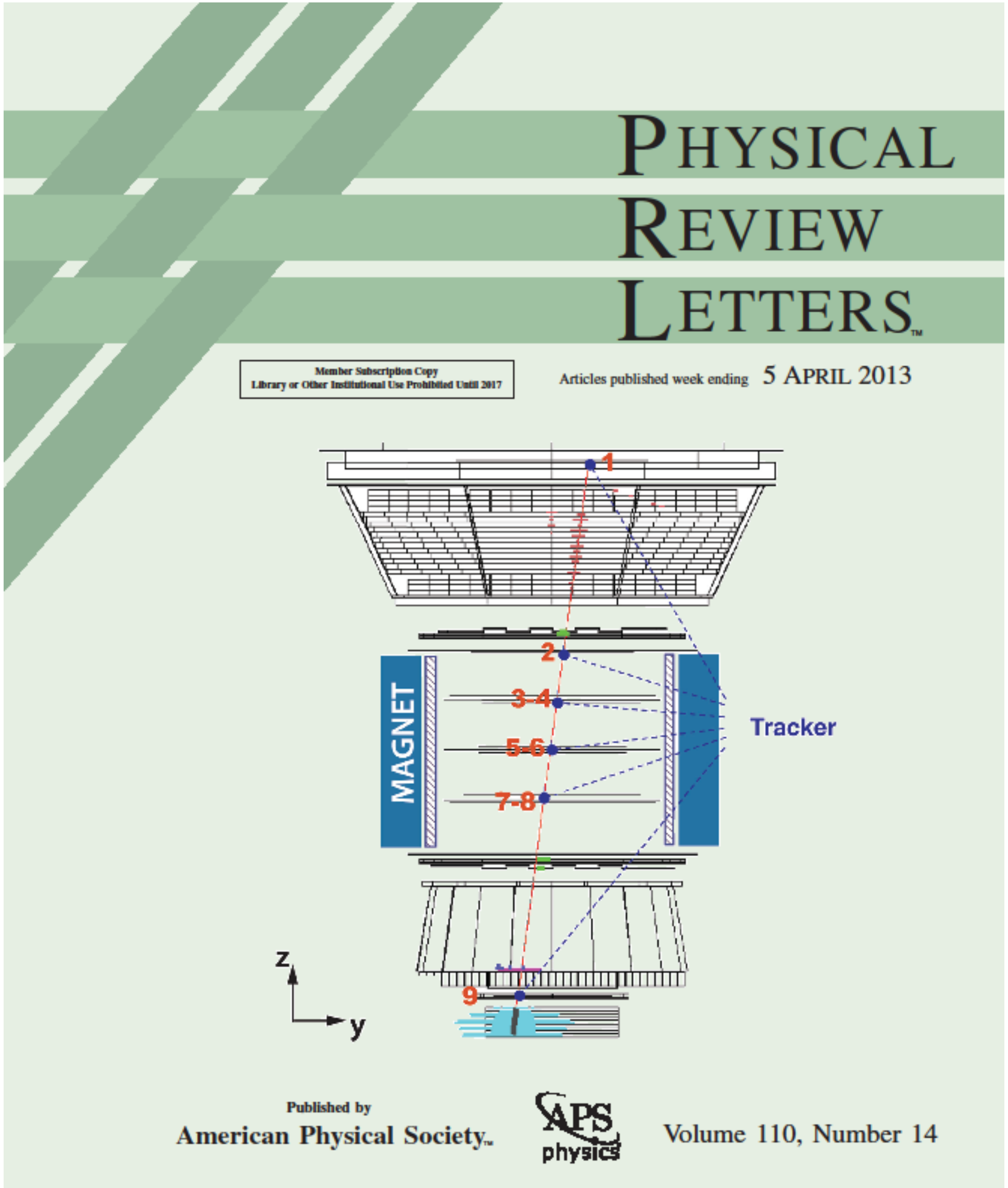
Systematic error on the positron fraction: e+/- Charge confusion



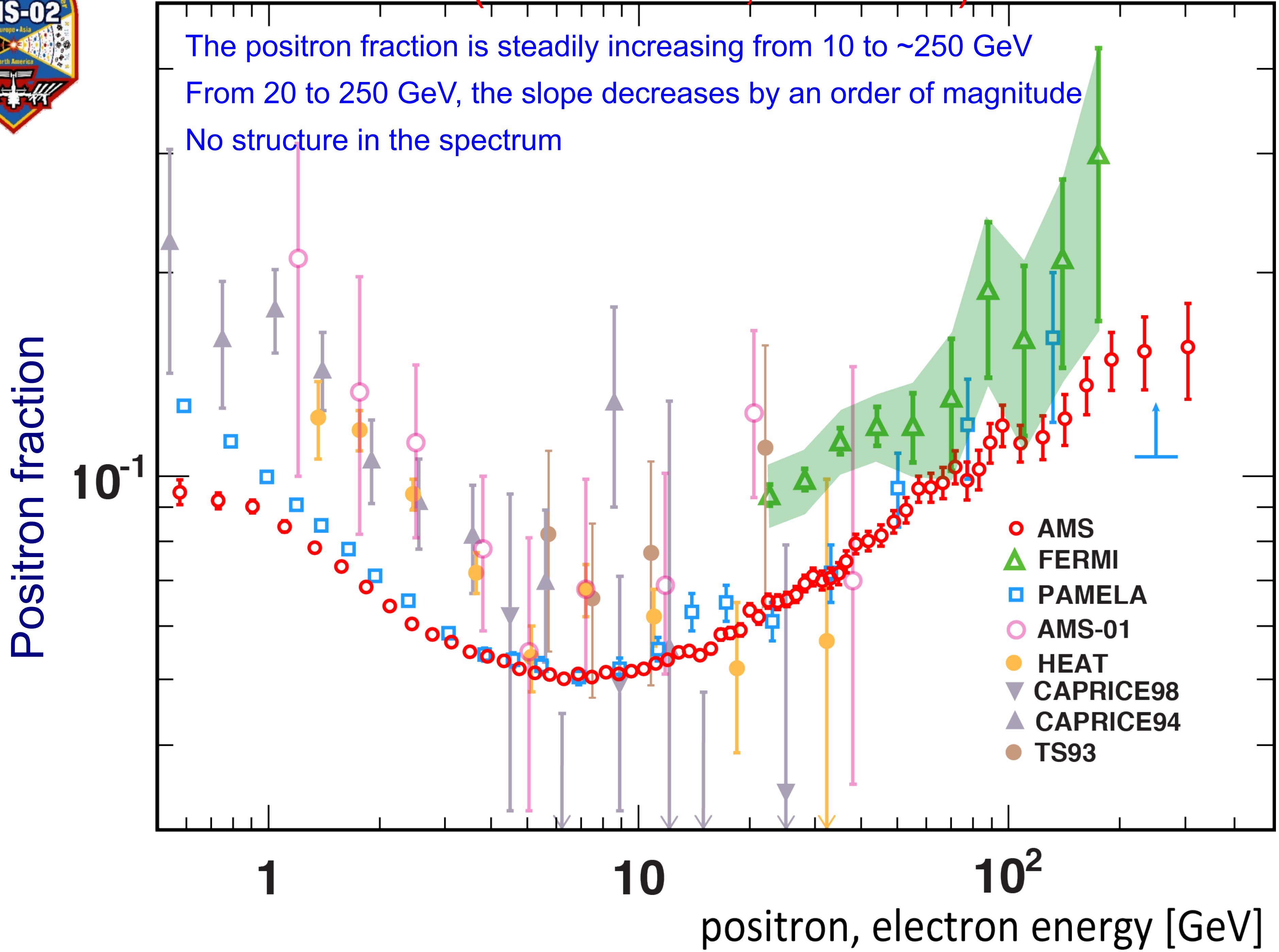
Two sources: large angle scattering and production of secondary tracks along the path of the primary track. Both are well reproduced by MC. Systematic errors correspond to variations of these effects within their statistical limits.

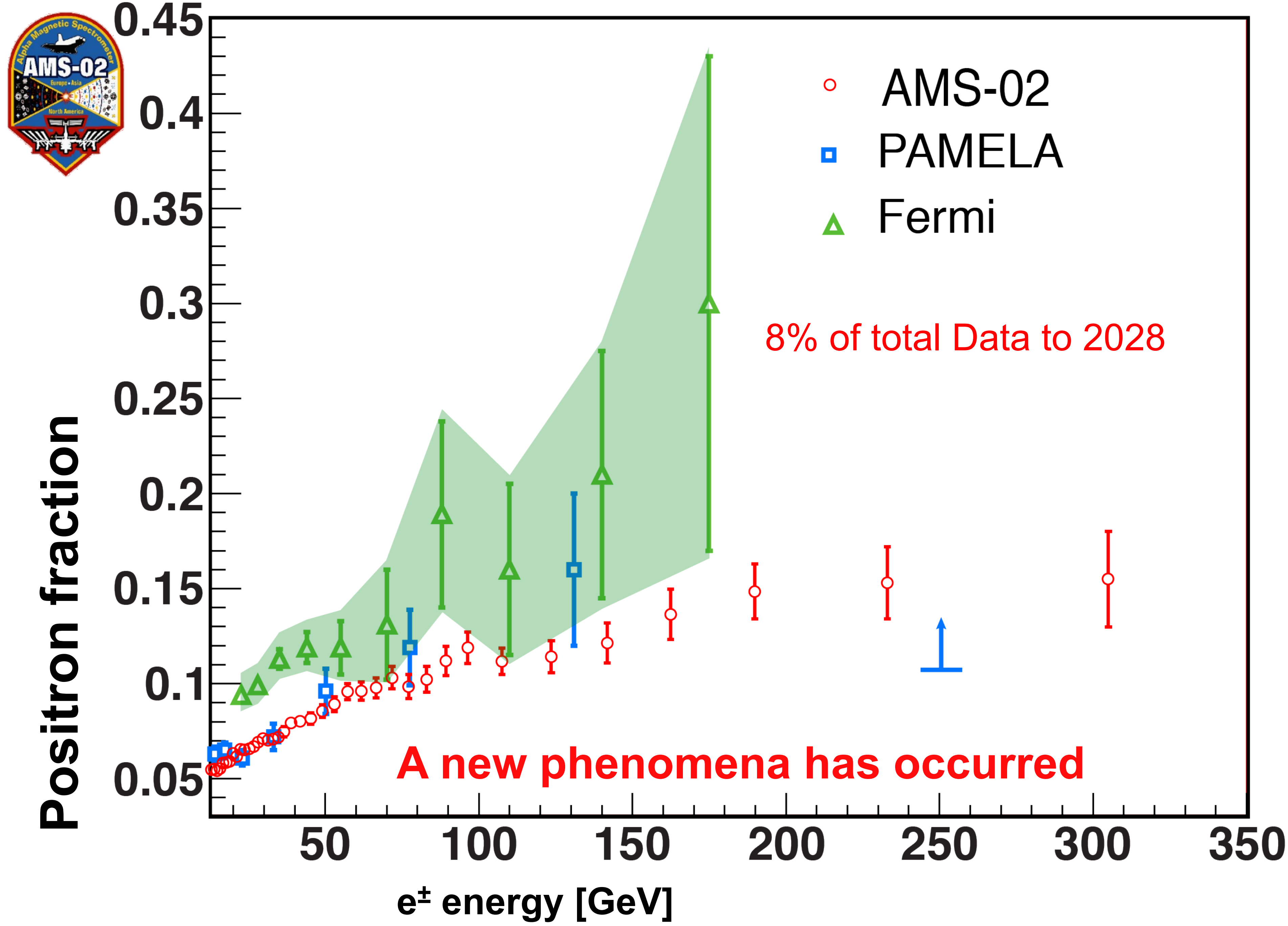
"First Result from the AMS on the ISS: Precision Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5-350 GeV"

Selected for a Viewpoint in Physics and an Editors' Suggestion [Aguilar,M. et al (AMS Collaboration) Phys. Rev. Lett. 110, 1411xx (2013)]

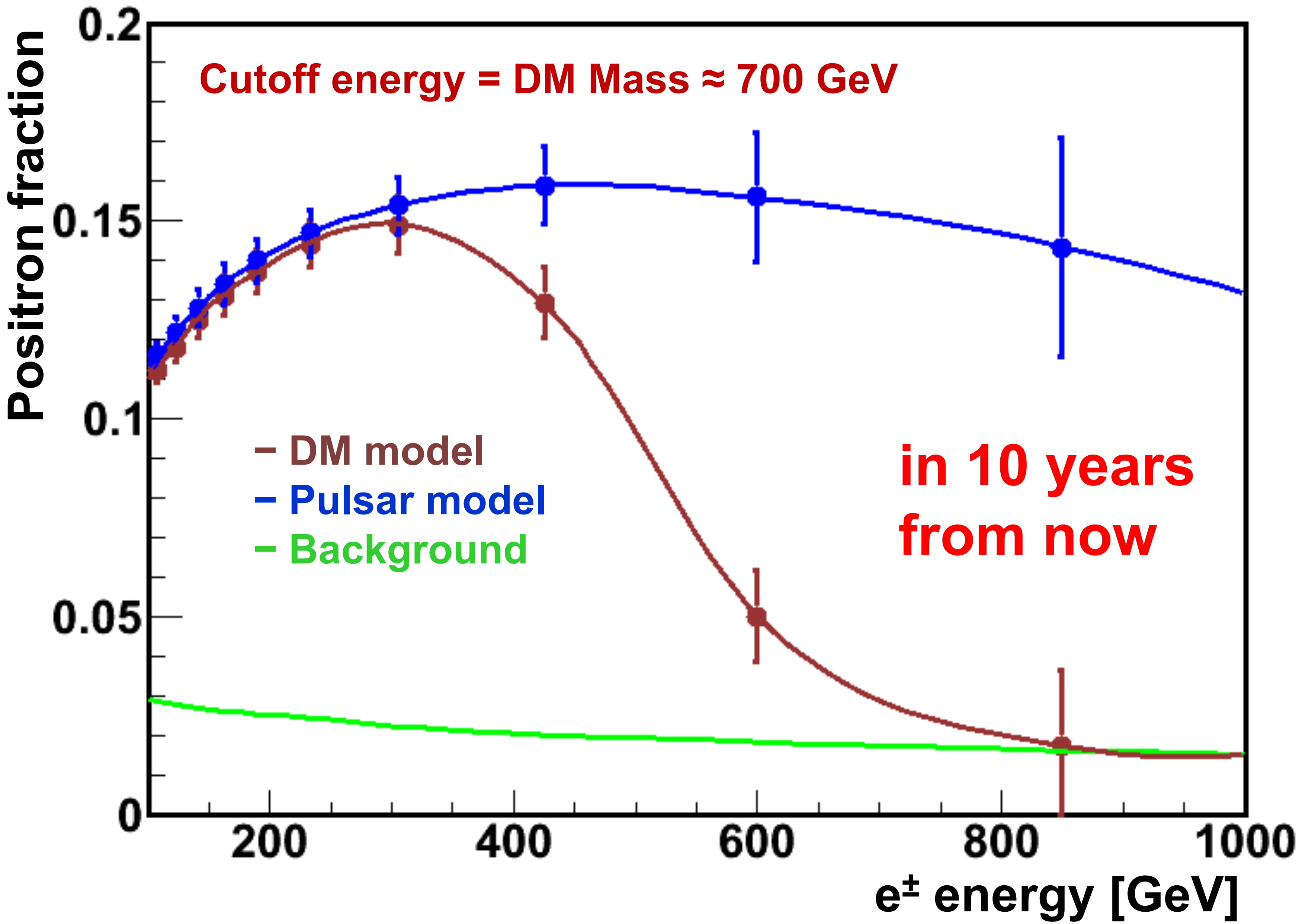


AMS-02 (6.8 million e^+, e^- events)



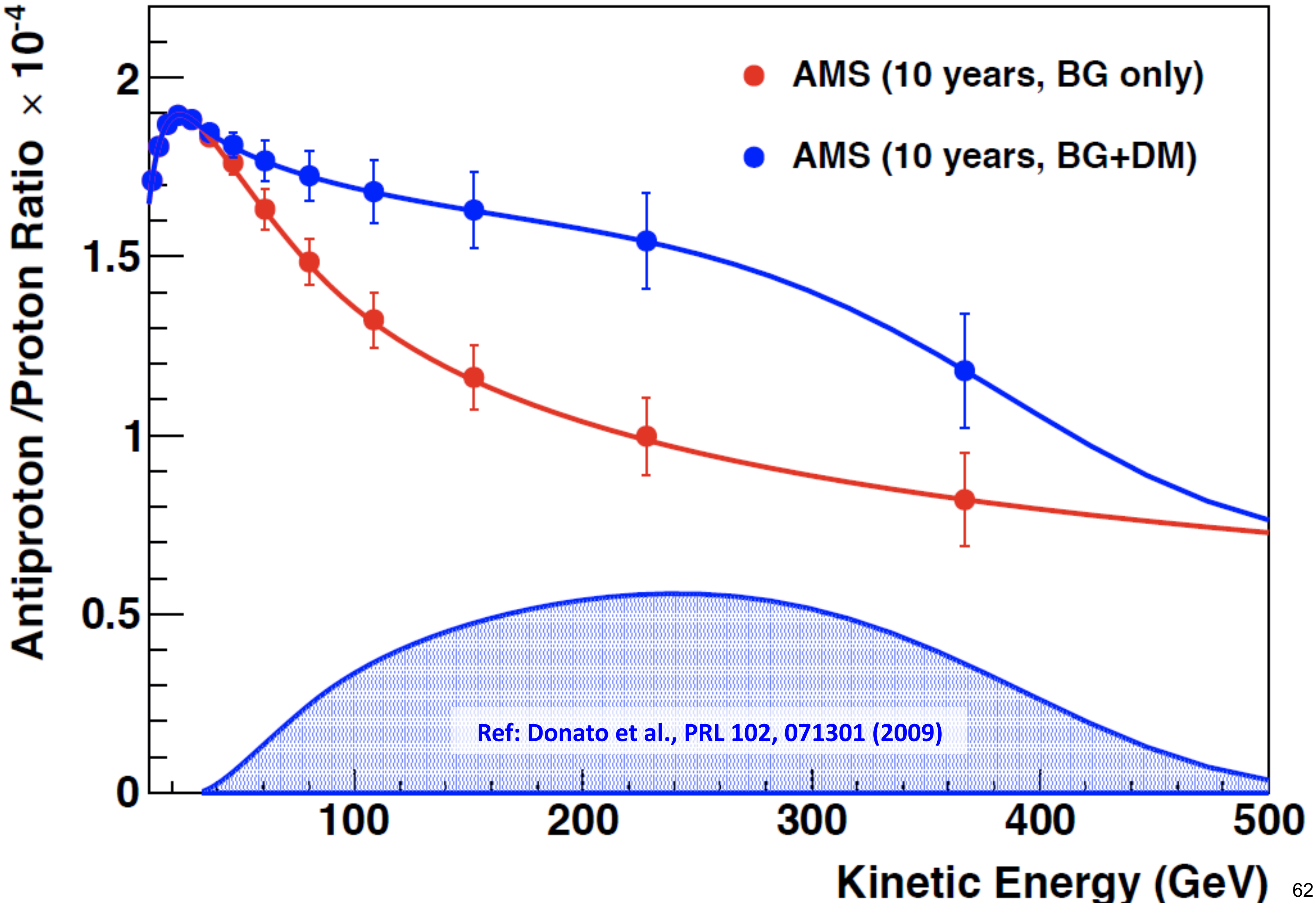


To be presented by A. Kounine (8 July 14:30, ICRC-1264)



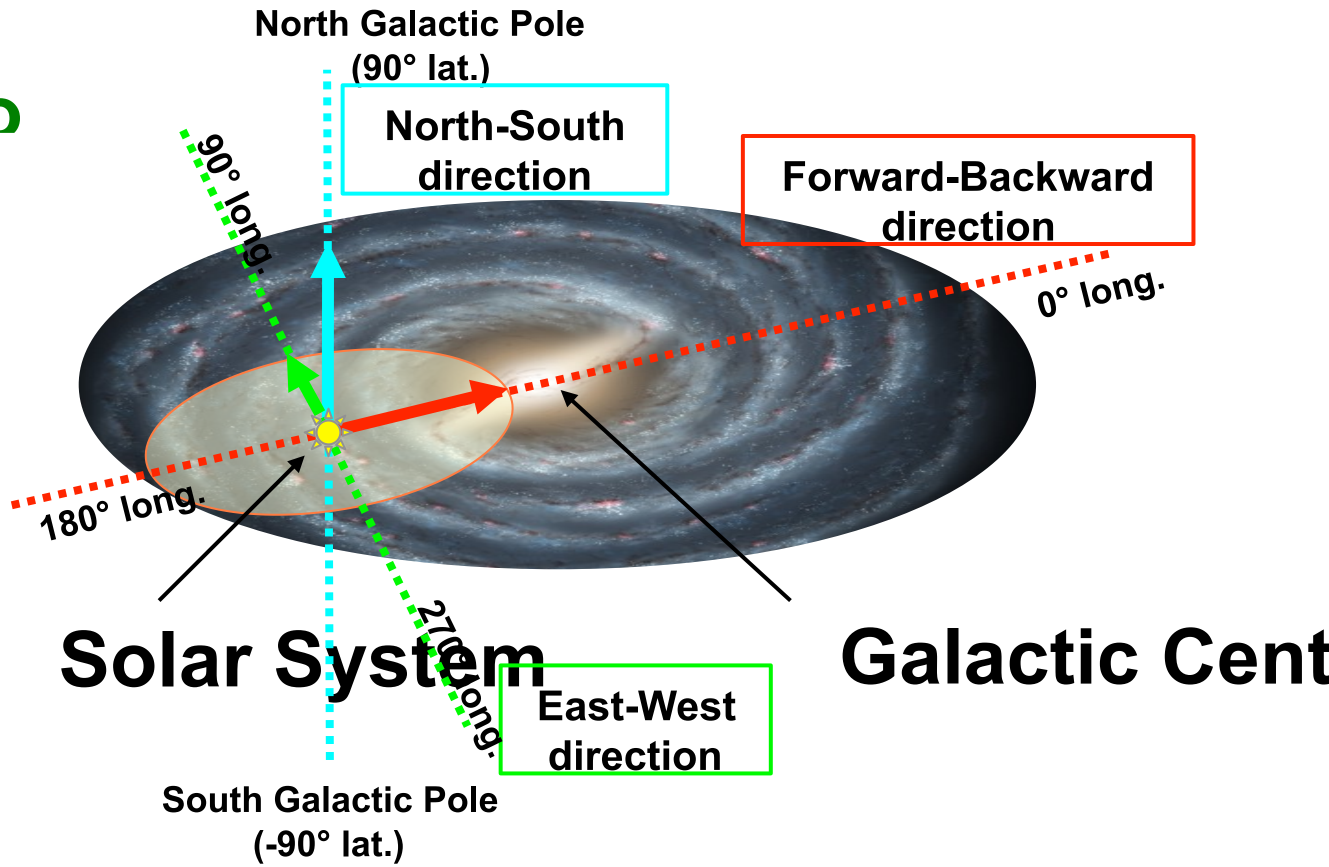
What will the Positron Fraction look like at high energy?

Comparison of $\bar{p}/p$ Results with Models in 10 more years

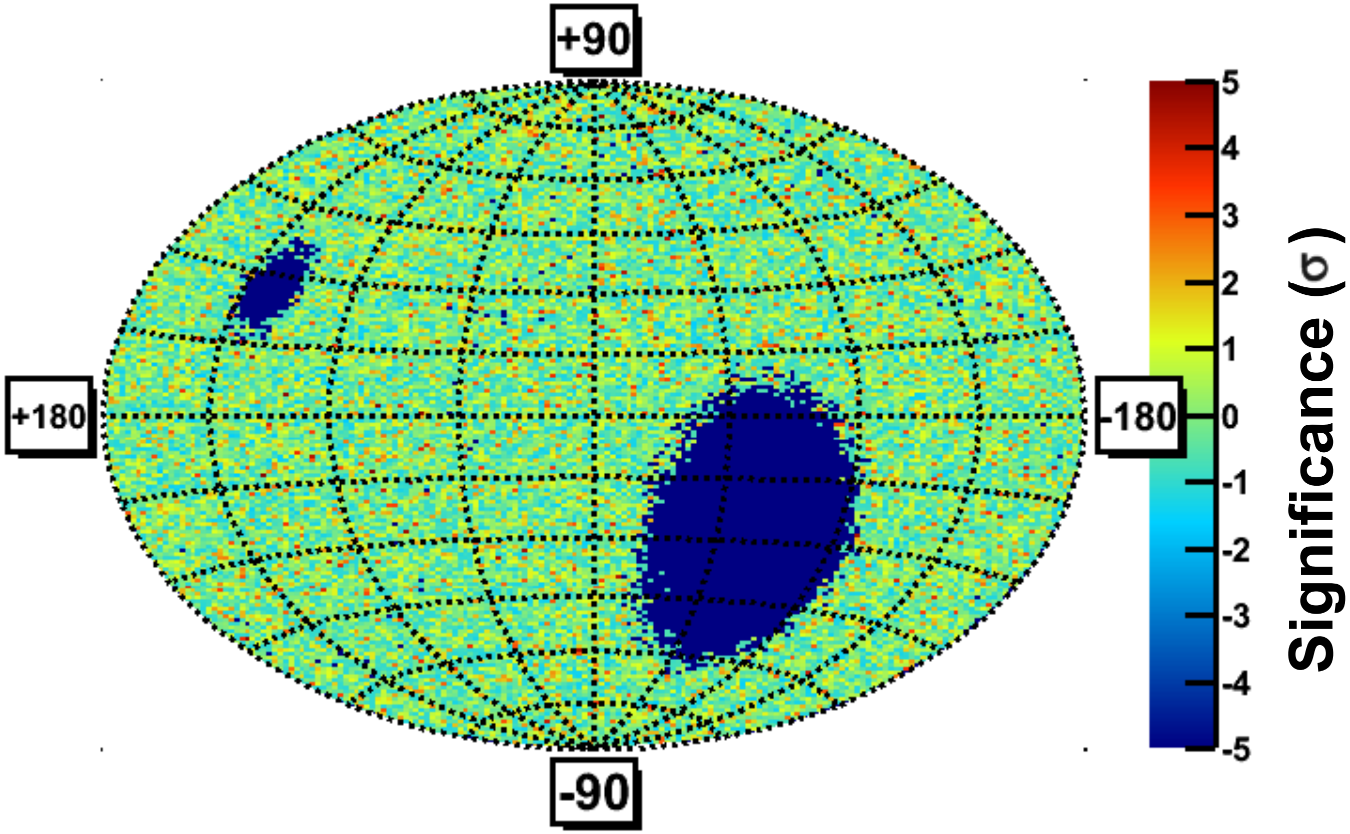


Selected events are grouped into 5 cumulative energy bins: 16-350, 25-350, 40-350, 65-350 and 100-350 GeV.

Their arrival directions are used to build sky maps in galactic coordinates, (*b*,*l*), containing the number of observed positrons and electrons



The relative fluctuations of the positron ratio, e^+/e^-, across the observed sky map show no evident pattern



The relative fluctuations of the positron ratio, e^+/e^-, are described by means of a spherical harmonic expansion

$$\frac{\mathrm{r_e}(\mathrm{b},\mathrm{l}) - \langle \mathrm{r_e} \rangle}{\langle \mathrm{r_e} \rangle} = \sum_{\ell=0}^{\infty} \sum_{\mathrm{m}=-\ell}^{\ell} \mathrm{a}_{\ell\mathrm{m}} \, \mathrm{Y}_{\ell\mathrm{m}}(\pi/2 - \mathrm{b}, \mathrm{l})$$

Where

$\mathrm{r_e}(\mathrm{b},\mathrm{l})$ **: denotes the positron ratio at *(b,l)*,**

$\langle \mathrm{r_e} \rangle$ ***:* is the average ratio over the sky map,**

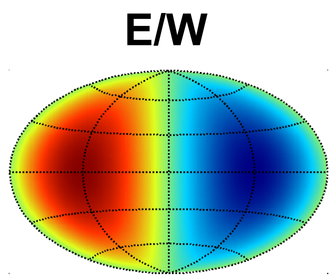
$\mathrm{Y}_{\ell\mathrm{m}}$ **: are the real spherical harmonic functions,**

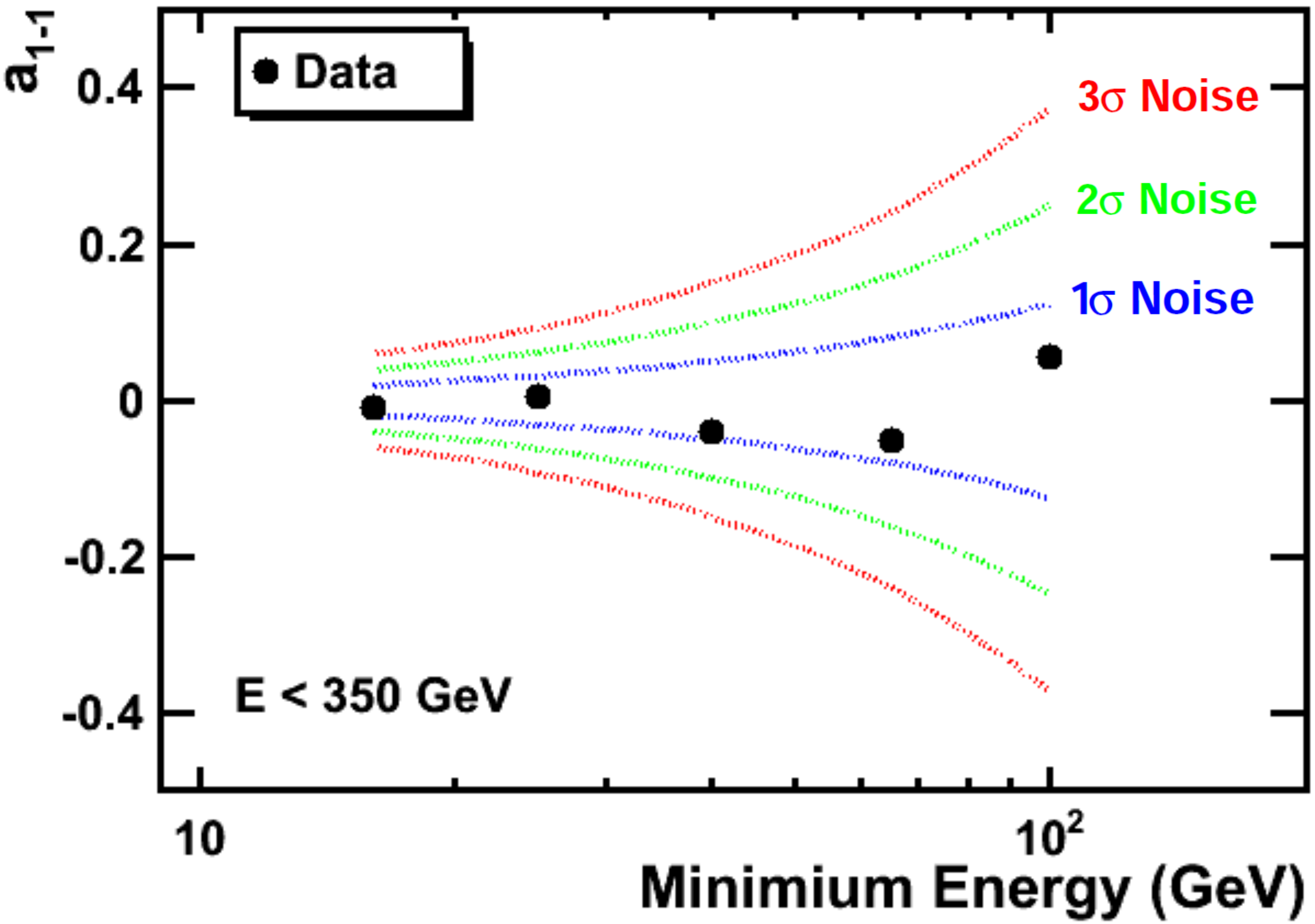
$\mathrm{a}_{\ell\mathrm{m}}$ **: are their corresponding amplitudes**

The amplitudes of spherical harmonic contributions at fixed angular scale, ℓ are fit to data for dipole (ℓ =*1*), quadrupole (ℓ=*2*) and octopole (ℓ=*3*)

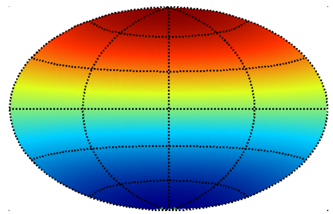
The fit amplitudes, $a_{\ell m}$, are found to be consistent with the hypothesis of isotropy at all energies and angular scales

Dipole amplitude a_{1-1}

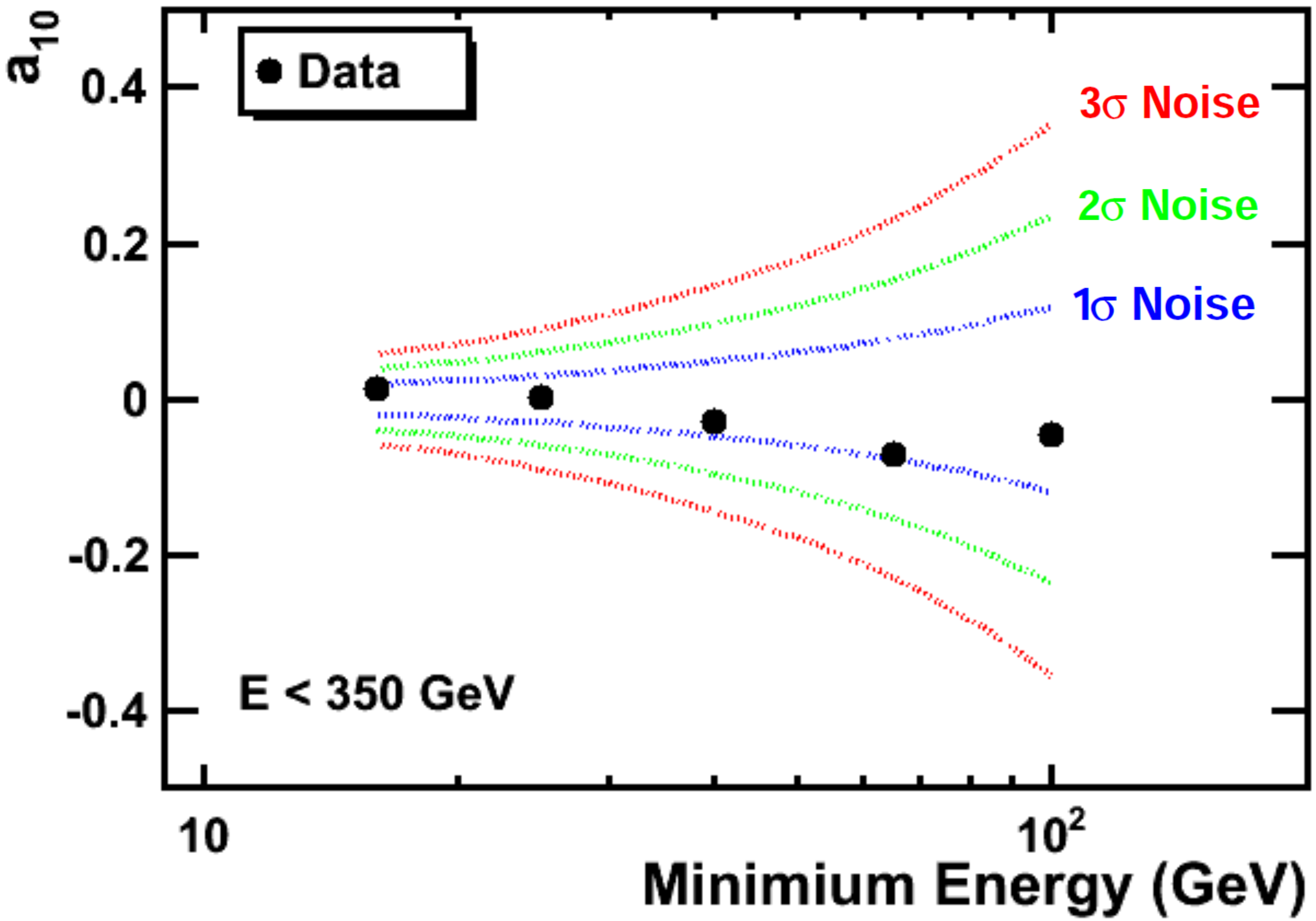




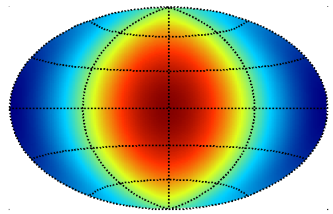
N/S



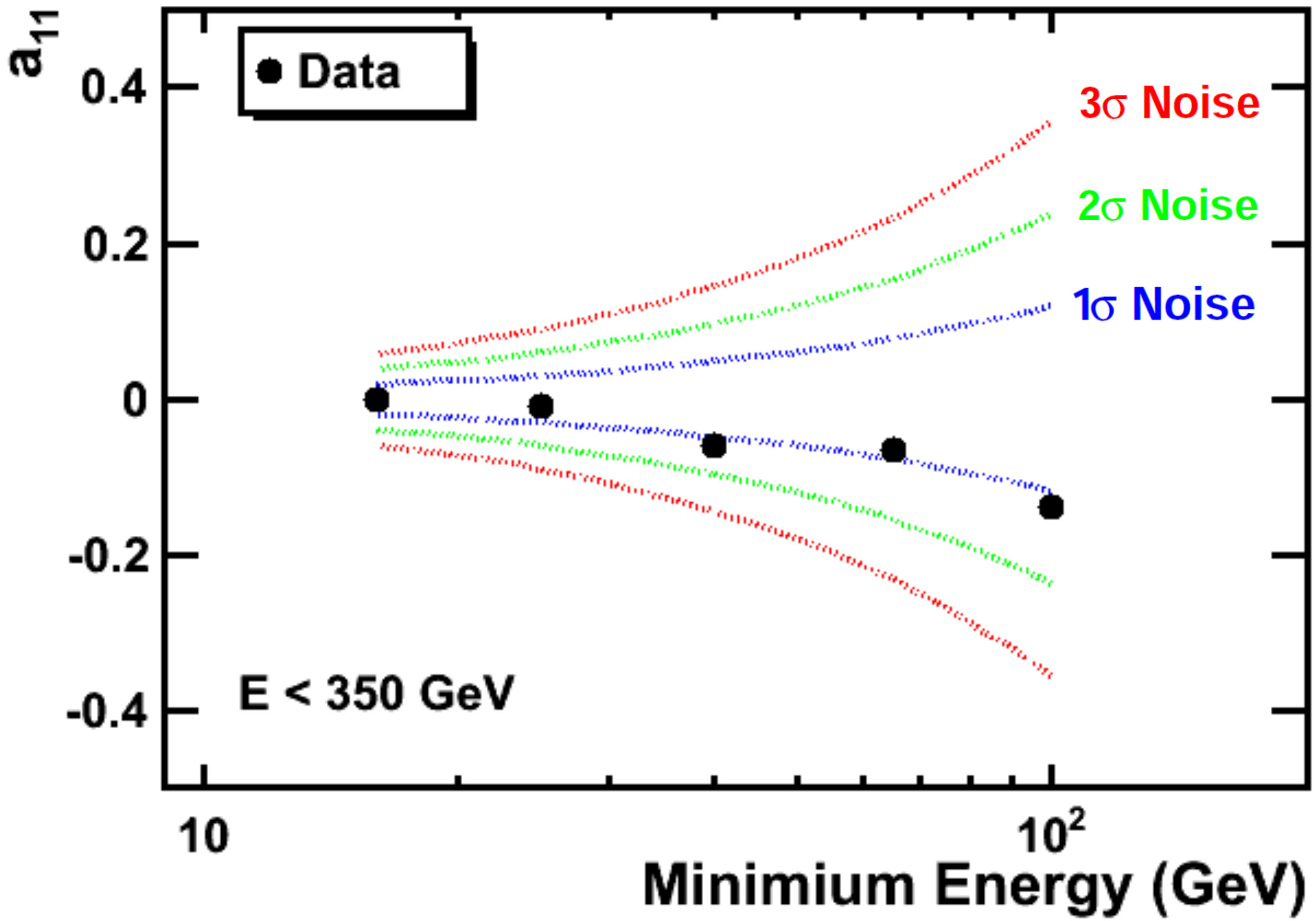
Dipole amplitude a_{10}



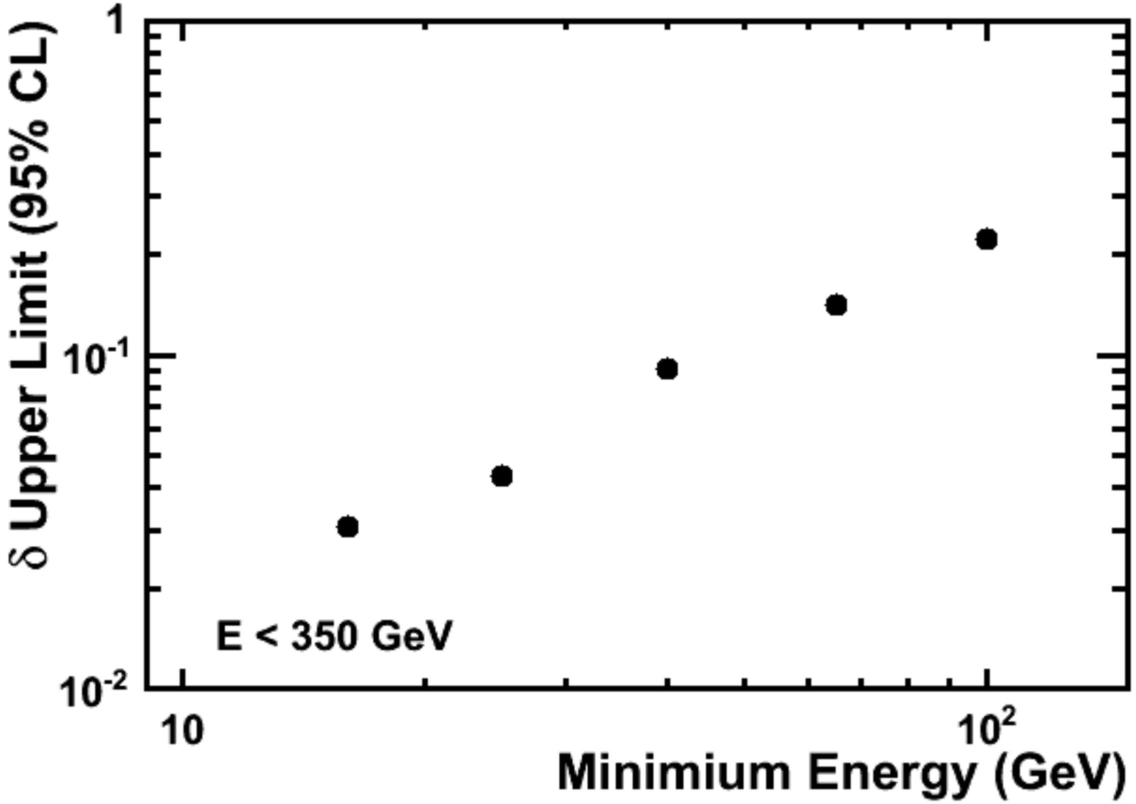
F/B



Dipole amplitude a_{11}



AMS upper limits on δ at the 95% CL

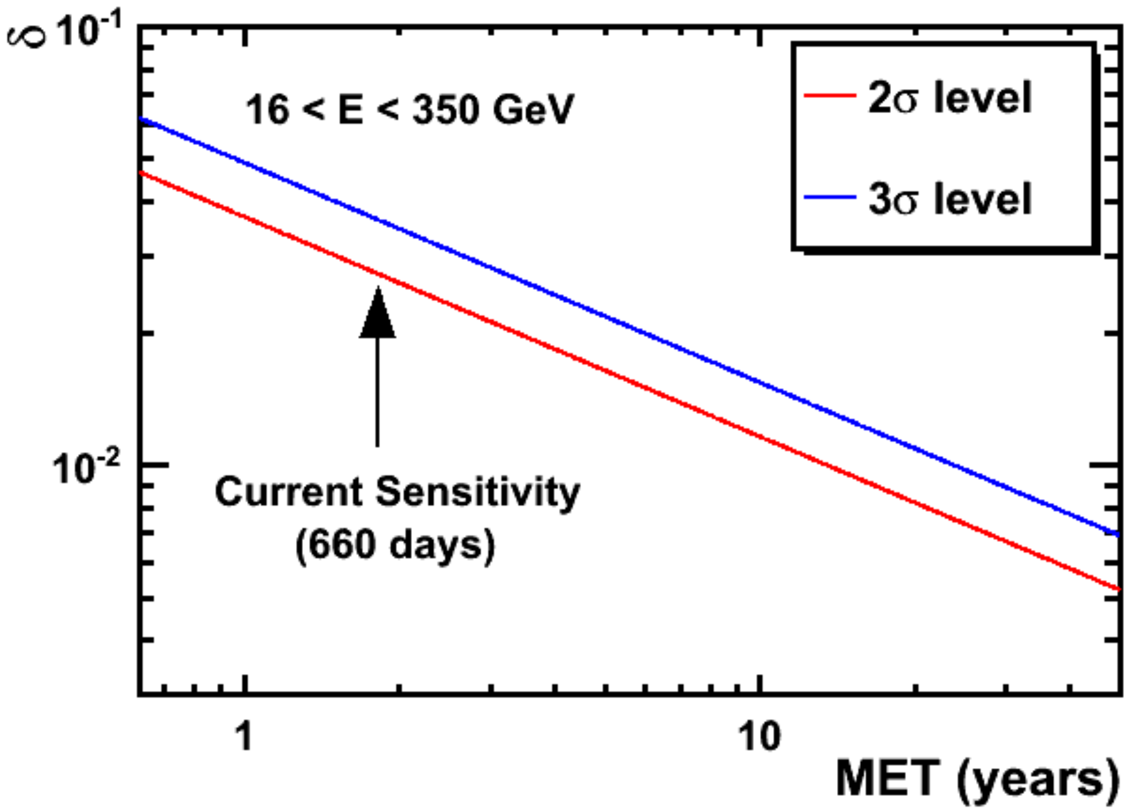


δ <0.030 for 16<E<350GeV

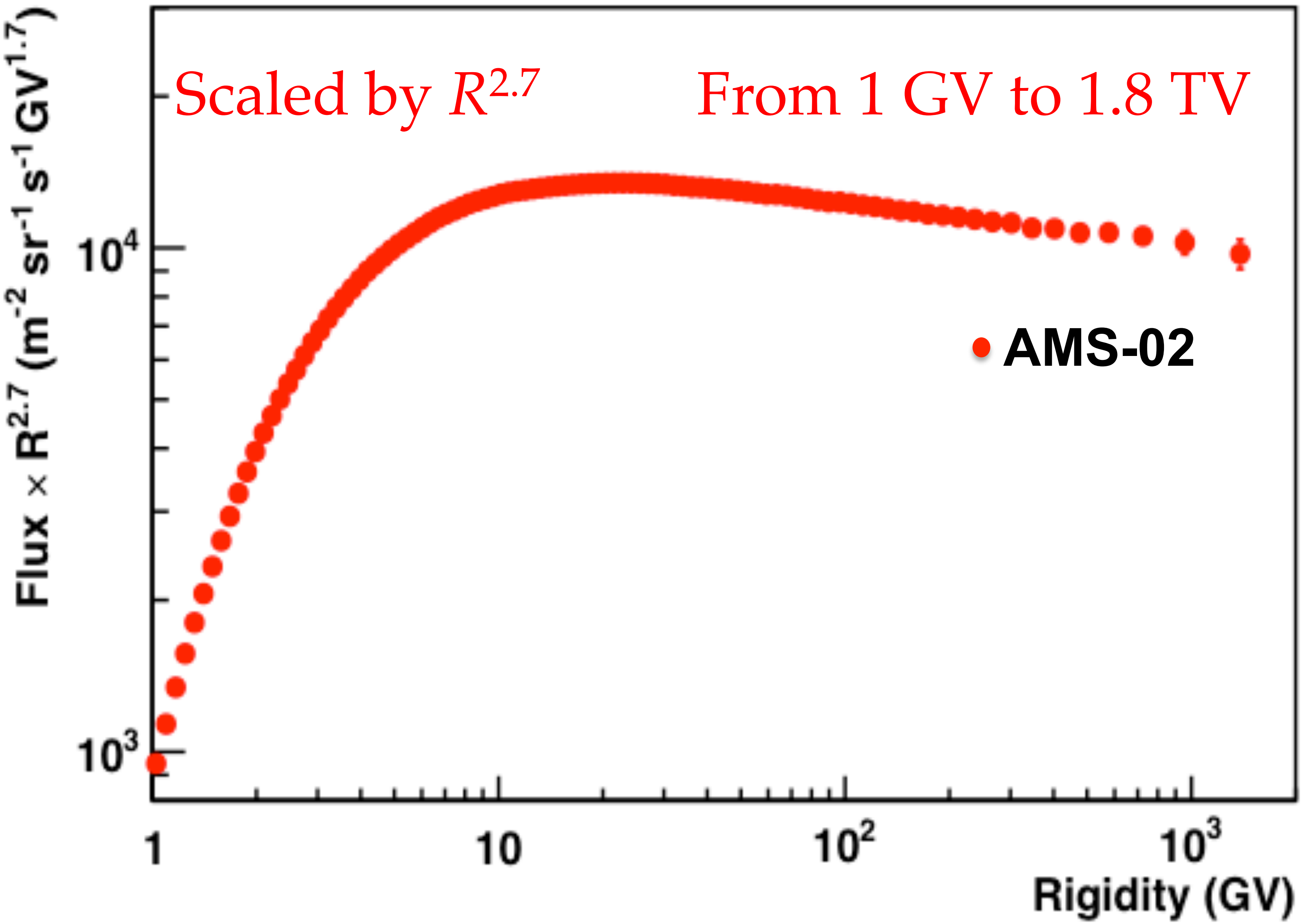
No seasonal excess is observed and same results are obtained using solar ecliptic coordinates

Anisotropy Discovery Potential

In 10 years, the projected sensitivity of AMS to a dipole anisotropy is 2σ for δ=0.010 and 3σ for δ=0.014

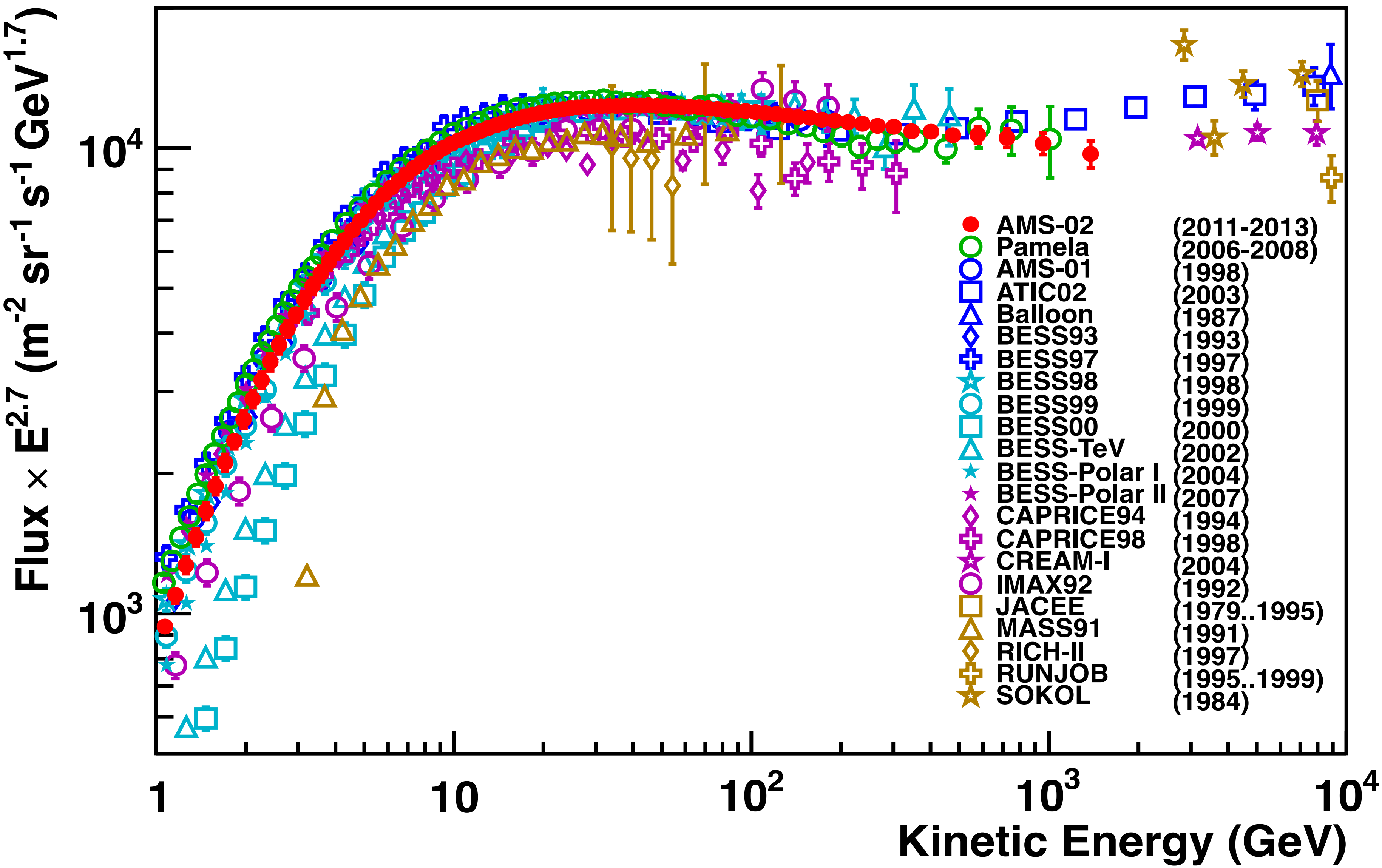


New results from AMS
2) Proton flux

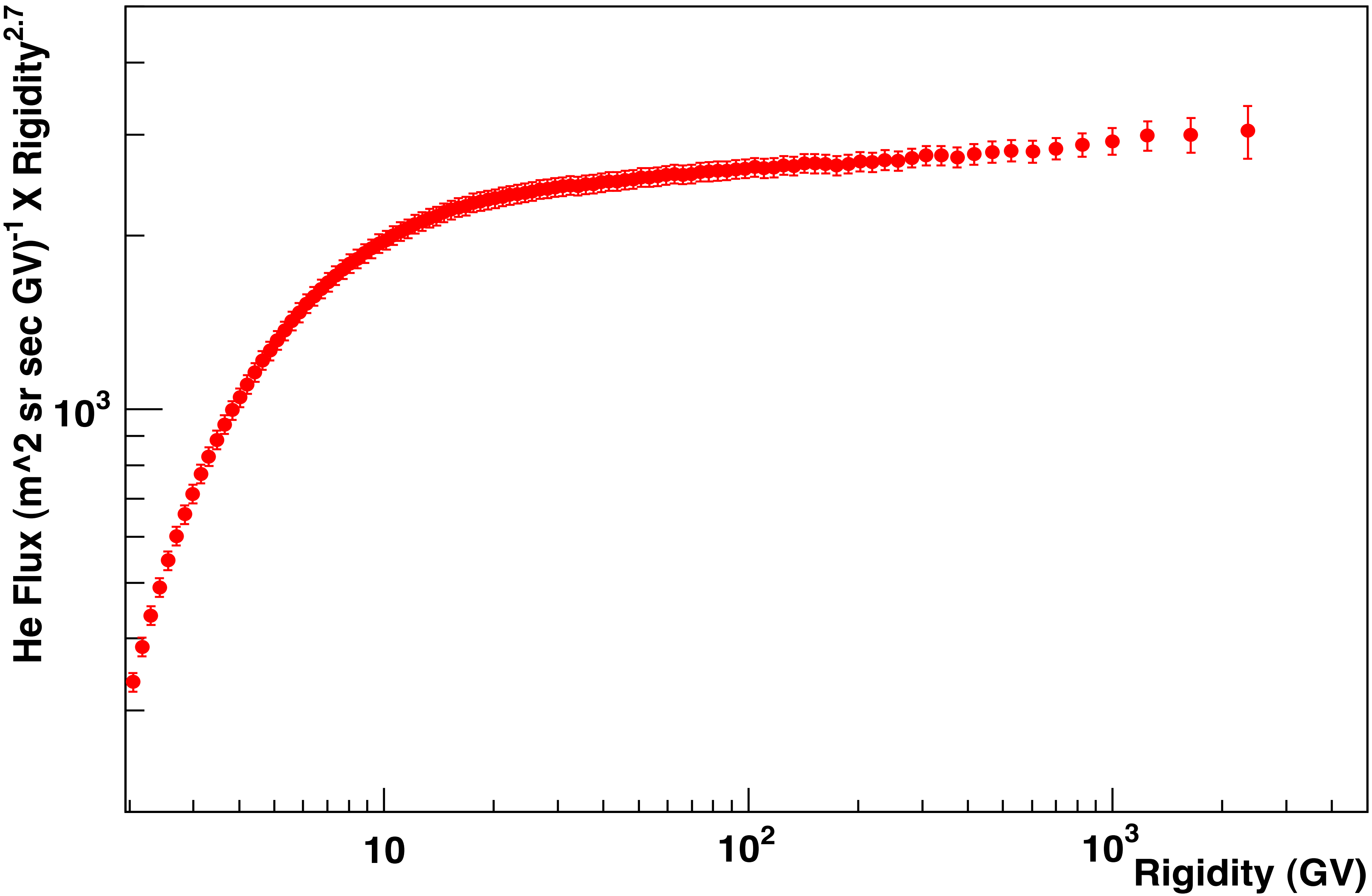


Proton flux

Comparison with past measurements

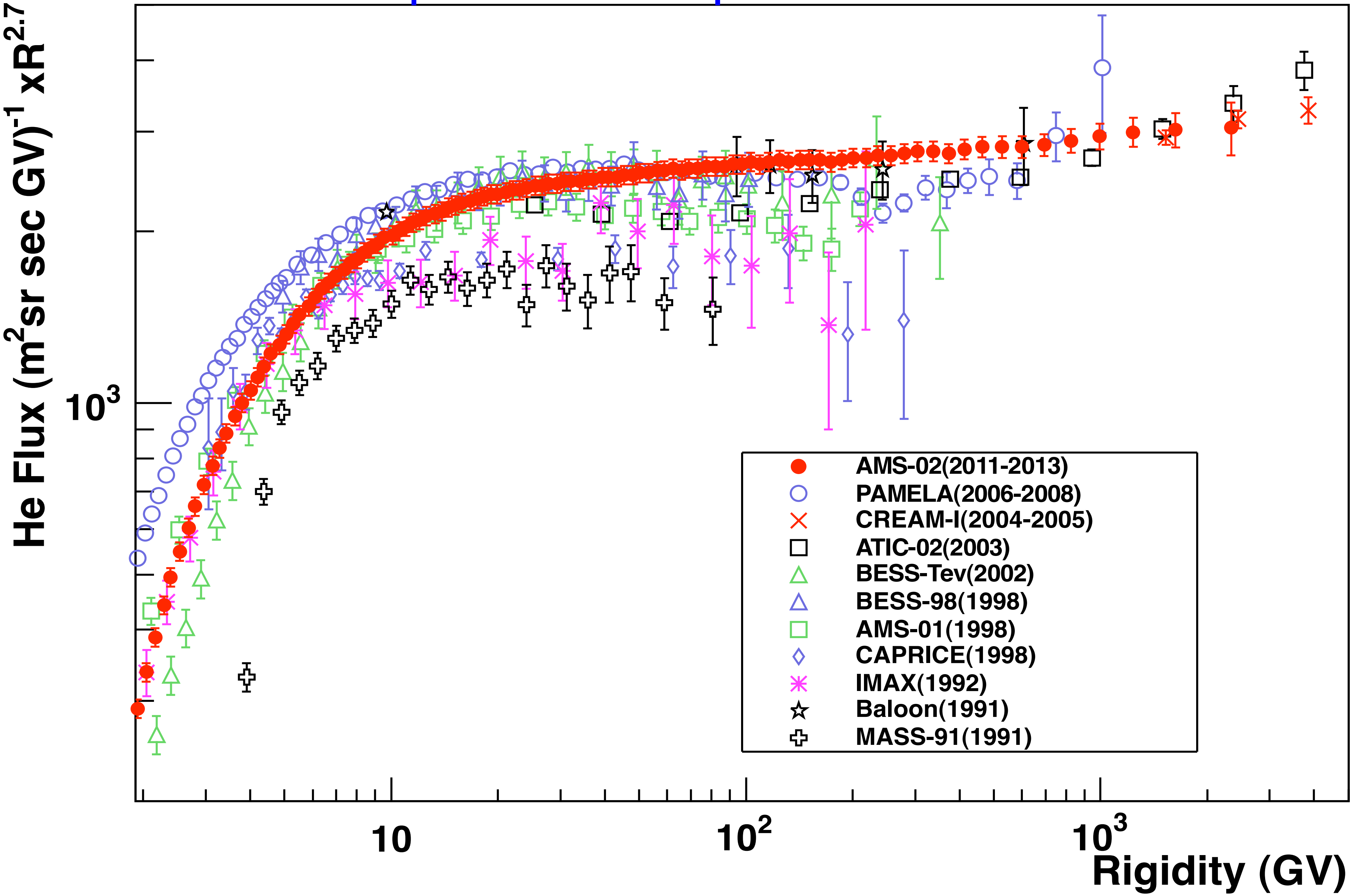


New Results from AMS
3) Helium flux



Helium flux

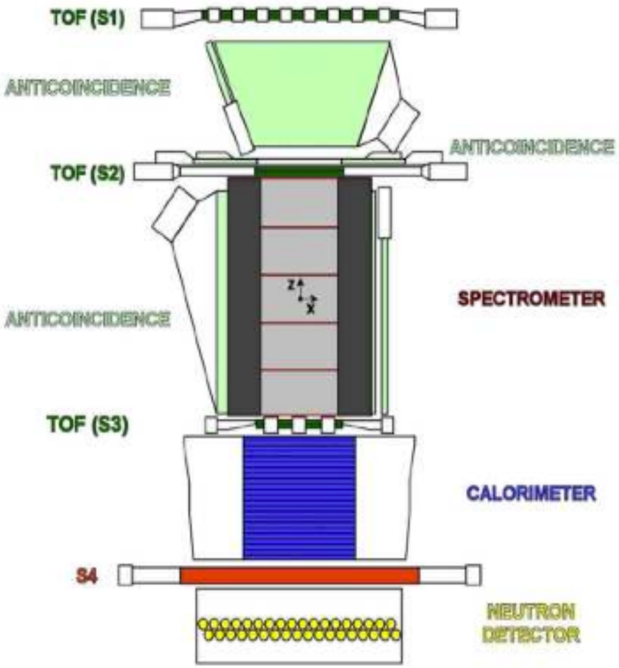
Comparison with past measurements



PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra
O. Adriani *et al.*
Science **332**, 69 (2011);
DOI: 10.1126/science.1199172

PAMELA Measurements of Cosmic-Ray Proton and Helium Spectra

O. Adriani,[1,2] G. C. Barbarino,[3,4] G. A. Bazilevskaya,[5] R. Bellotti,[6,7] M. Boezio,[8] E. A. Bogomolov,[9] L. Bonechi,[1,2] M. Bongi,[2] V. Bonvicini,[8] S. Borisov,[10,11,12] S. Bottai,[2] A. Bruno,[6,7] F. Cafagna,[7] D. Campana,[4] R. Carbone,[4,11] P. Carlson,[13] M. Casolino,[10] G. Castellini,[14] L. Consiglio,[4] M. P. De Pascale,[10,11] C. De Santis,[10,11] N. De Simone,[10,11] V. Di Felice,[10] A. M. Galper,[12] W. Gillard,[13] L. Grishantseva,[12] G. Jerse,[8,15] A. V. Karelin,[12] S. V. Koldashov,[12] S. Y. Krutkov,[9] A. N. Kvashnin,[5] A. Leonov,[12] V. Malakhov,[12] V. Malvezzi,[10] L. Marcelli,[10] A. G. Mayorov,[12] W. Menn,[16] V. V. Mikhailov,[12] E. Mocchiutti,[8] A. Monaco,[6,7] N. Mori,[1,2] N. Nikonov,[9,10,11] G. Osteria,[4] F. Palma,[10,11] P. Papini,[2] M. Pearce,[13] P. Picozza,[10,11]* C. Pizzolotto,[8] M. Ricci,[17] S. B. Ricciarini,[2] L. Rossetto,[13] R. Sarkar,[8] M. Simon,[16] R. Sparvoli,[10,11] P. Spillantini,[1,2] Y. I. Stozhkov,[5] A. Vacchi,[8] E. Vannuccini,[2] G. Vasilyev,[9] S. A. Voronov,[12] Y. T. Yurkin,[12] J. Wu,[13]† G. Zampa,[8] N. Zampa,[8] V. G. Zverev[12]



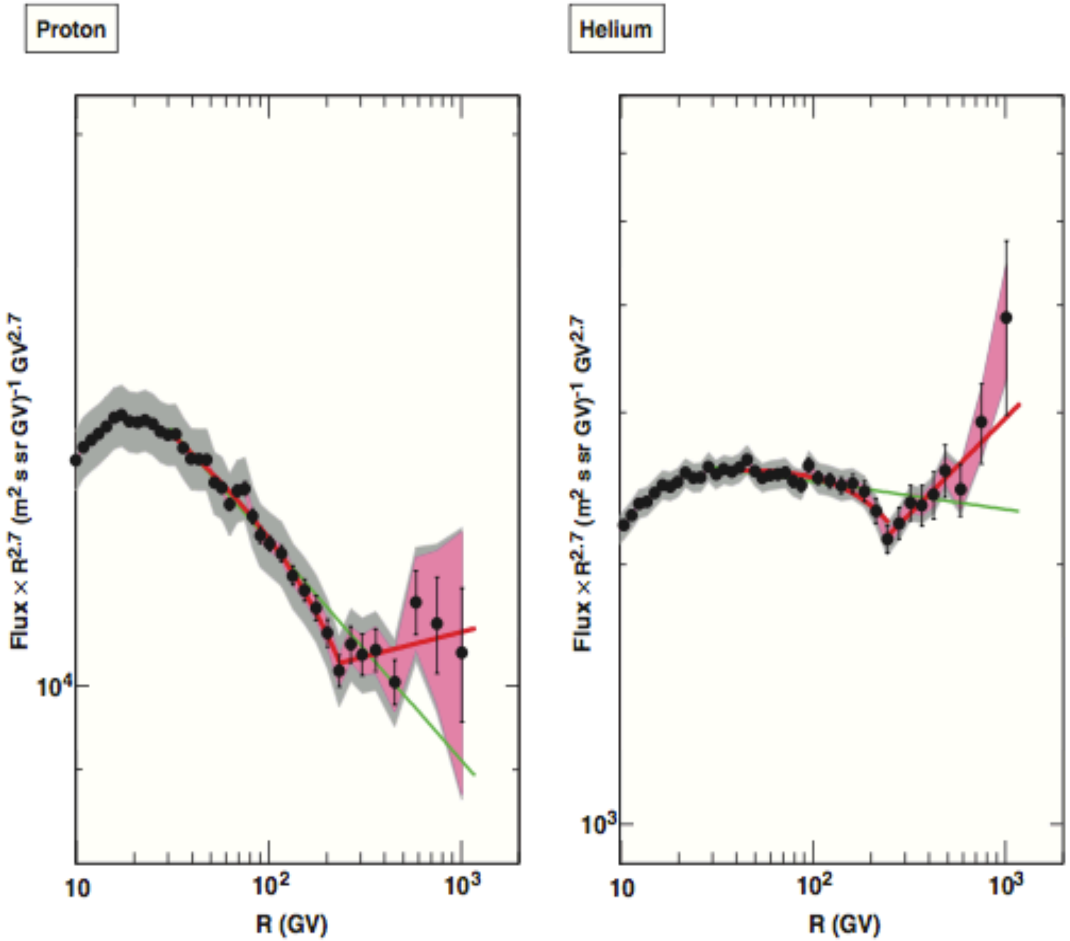
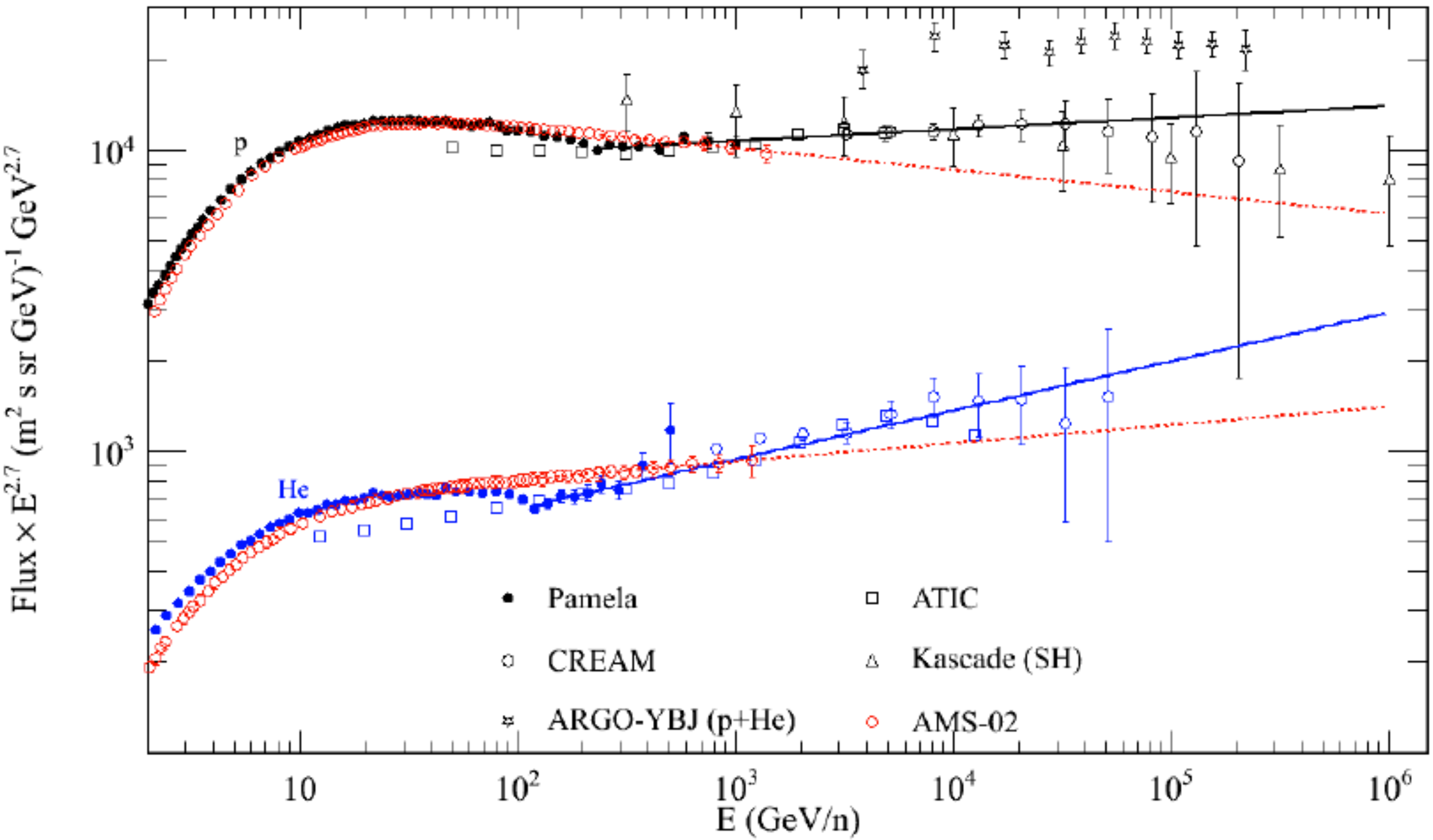
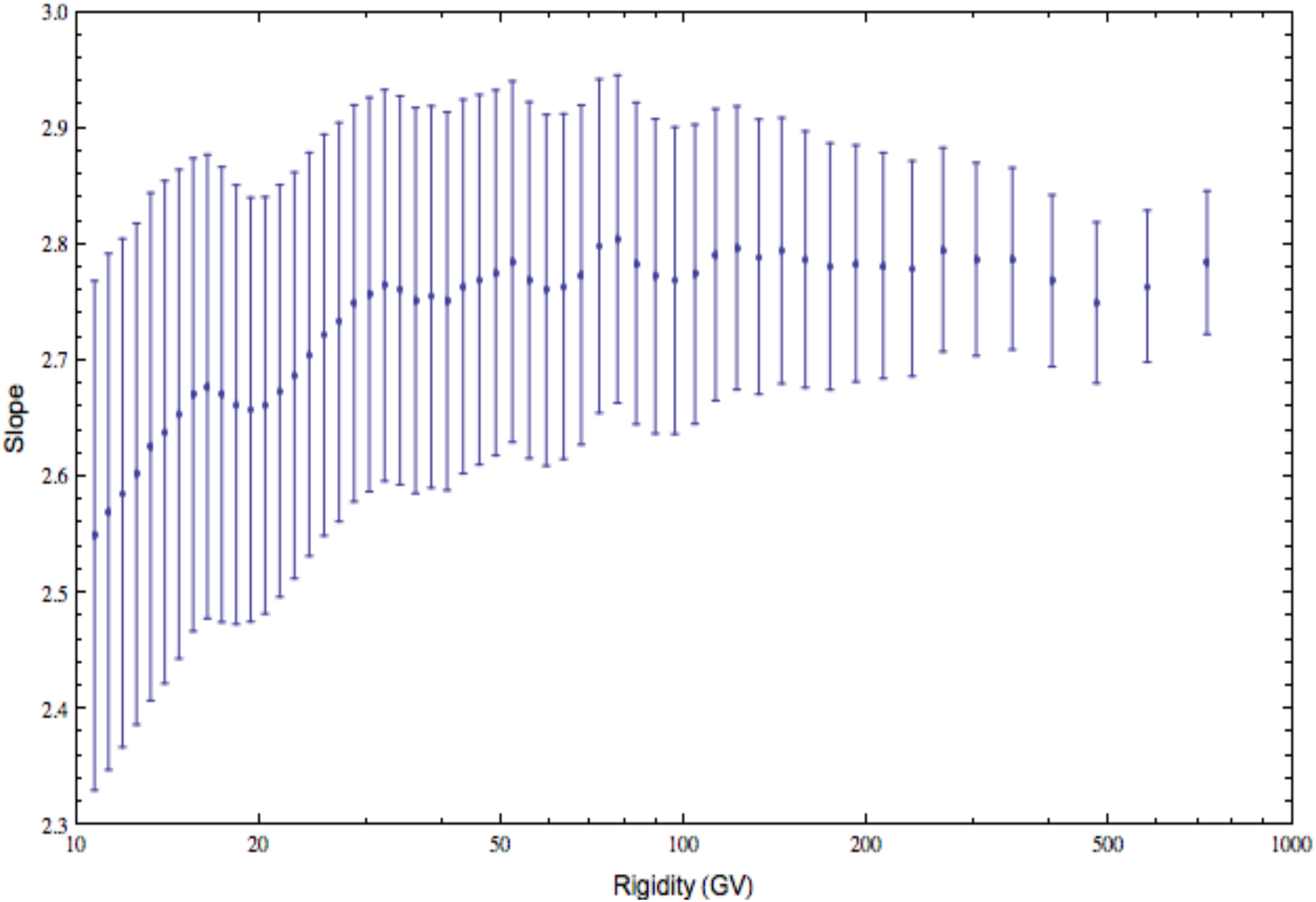


Fig. 4. Proton (**left**) and helium (**right**) spectra in the range 10 GV to 1.2 TV. The gray shaded area represents the estimated systematic uncertainty, and the pink shaded area represents the contribution due to tracker alignment. The green lines represent fits with a single power law in the rigidity range 30 to 240 GV. The red curves represent the fit with a rigidity-dependent power law (30 to 240 GV) and with a single power law above 240 GV.

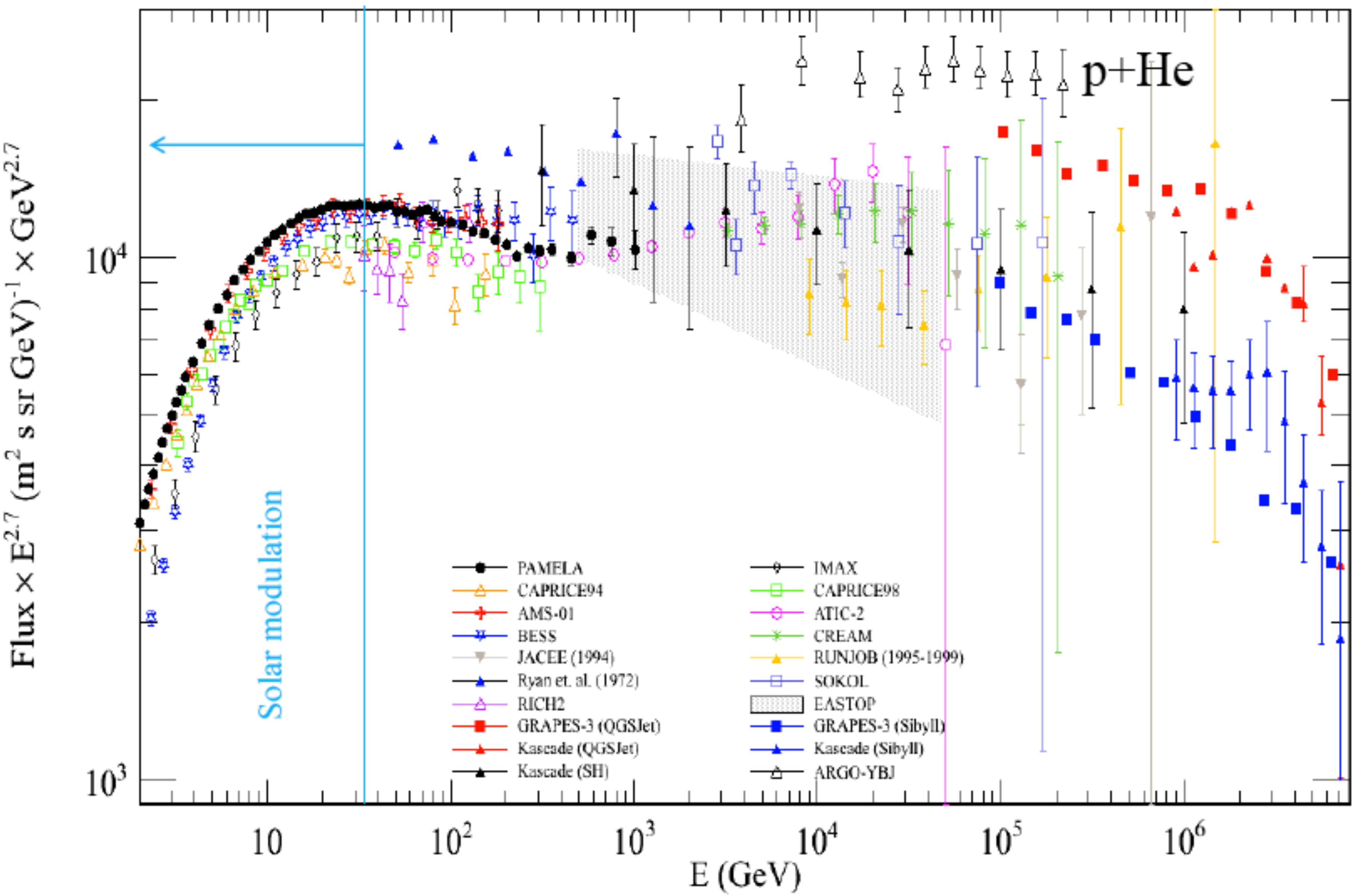
Proton and Helium Nuclei Spectra



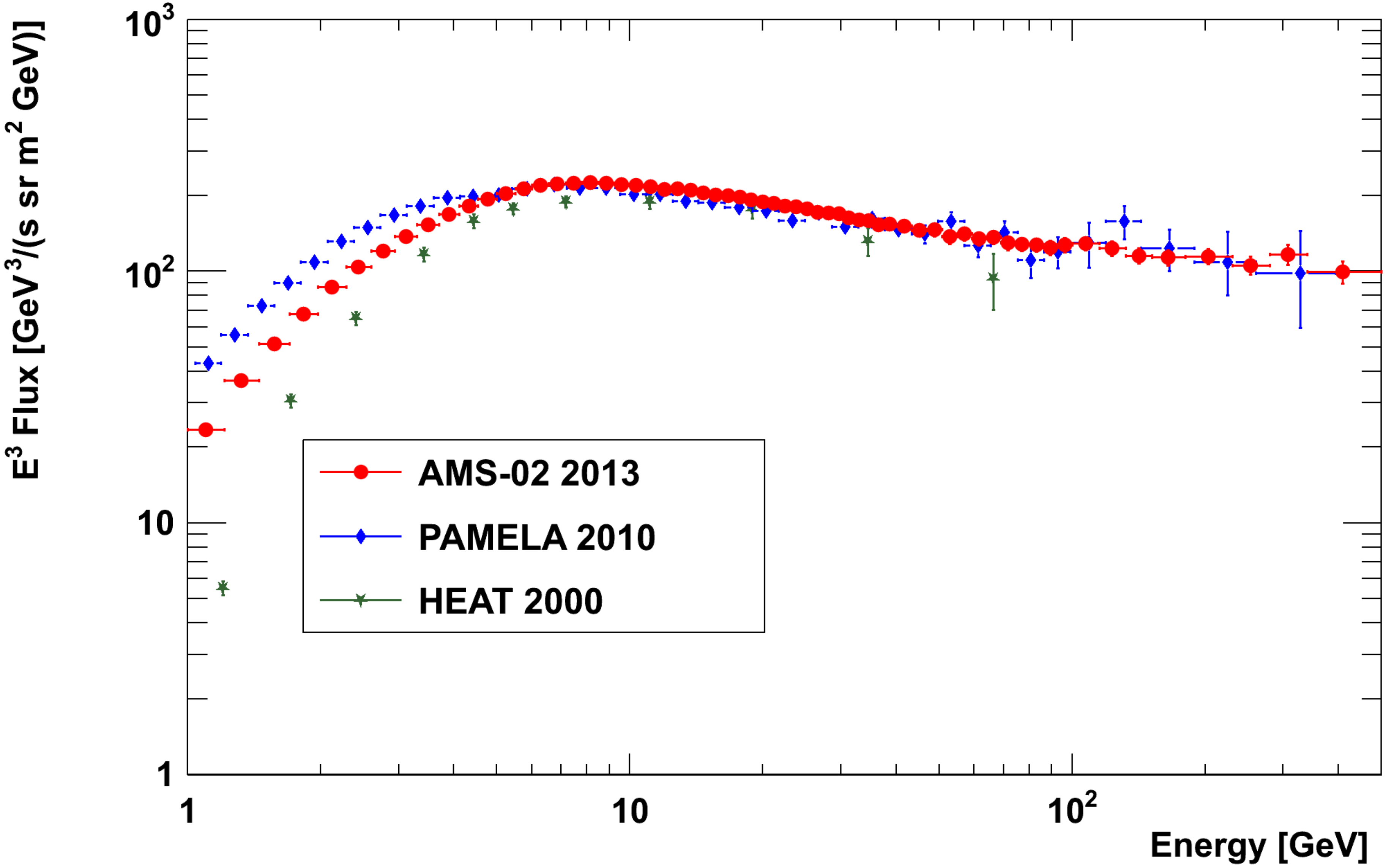
Slope of p flux versus R



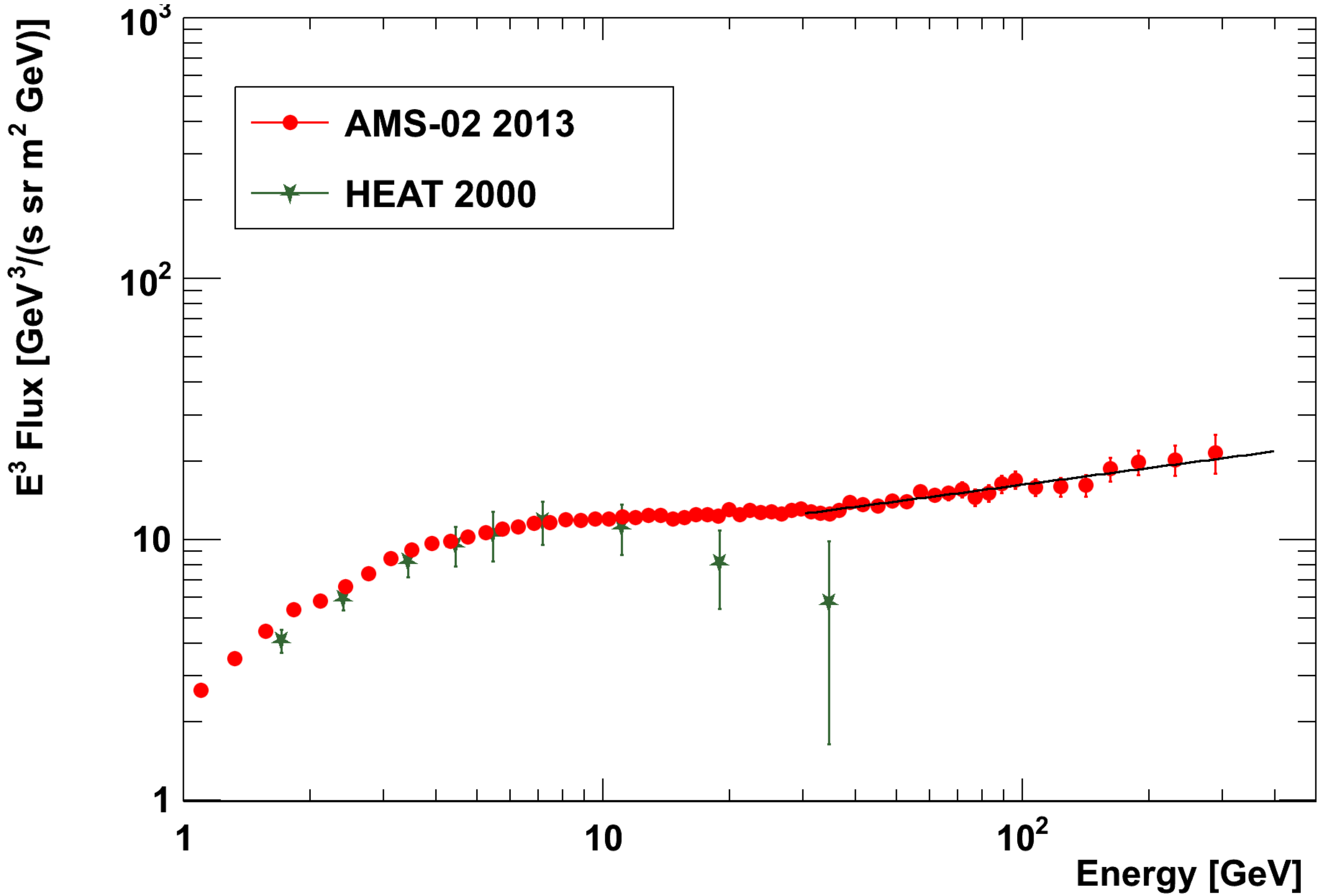
Proton (Hydrogen) Spectrum



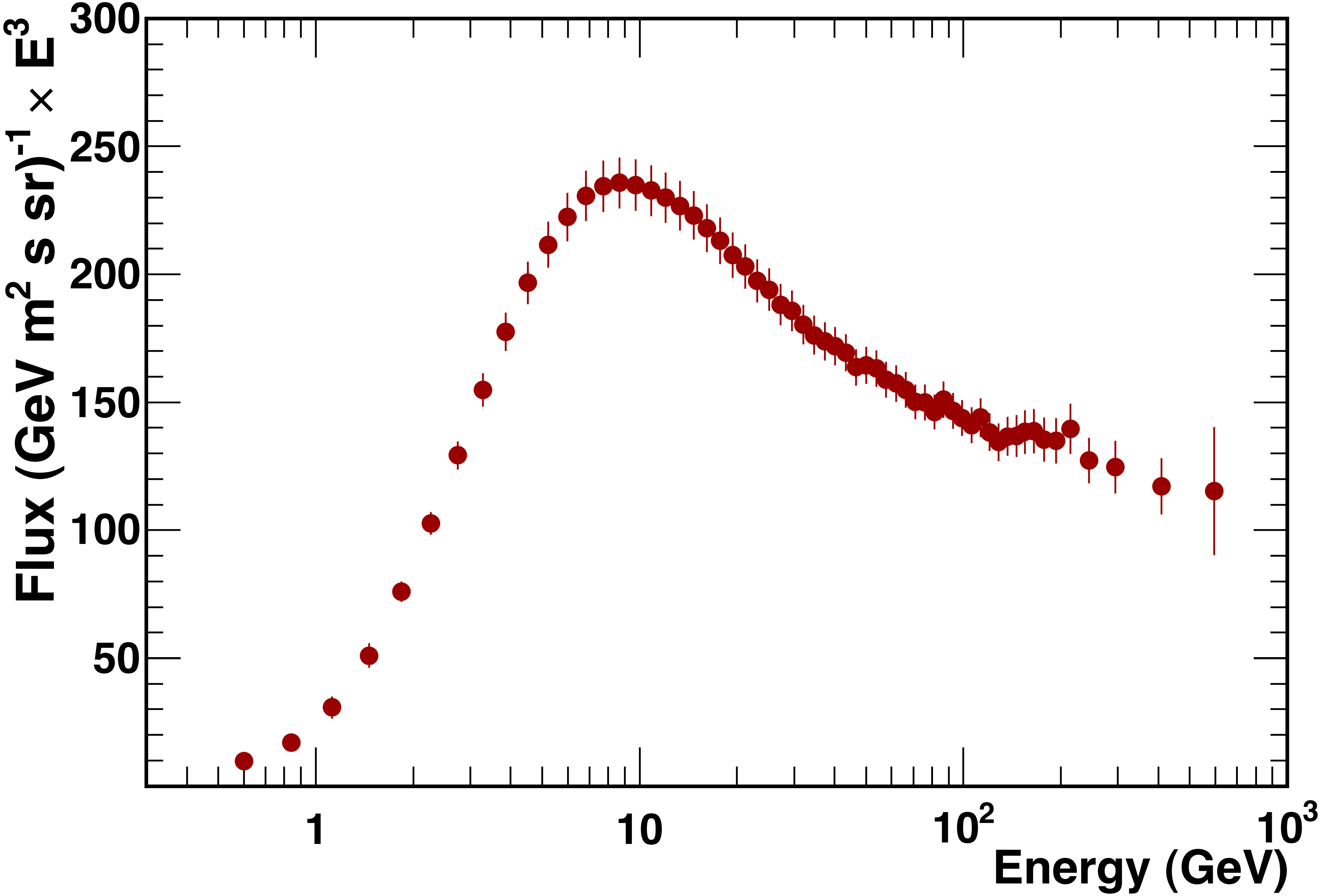
New results from AMS
4) Electron Spectrum



New results from AMS
5) Positron Spectrum

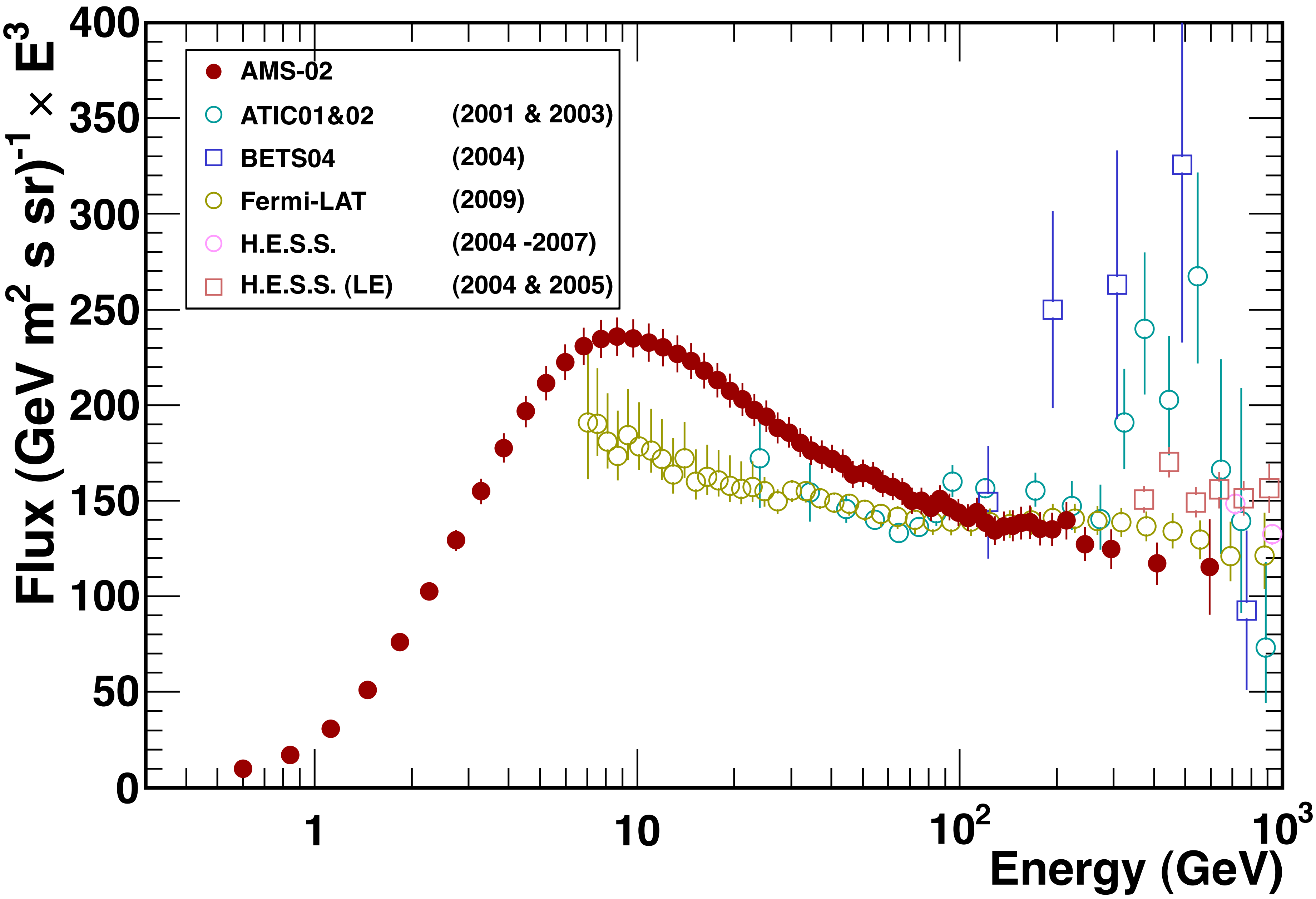


New results from AMS
6) (Electron plus Positron) Spectrum



(Electron plus Positron) Spectrum

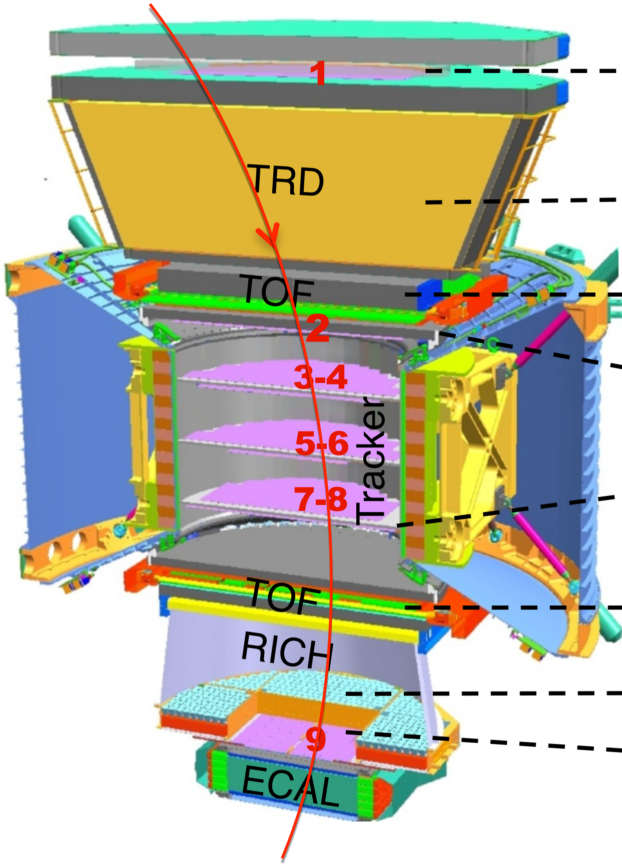
comparison with recent measurements



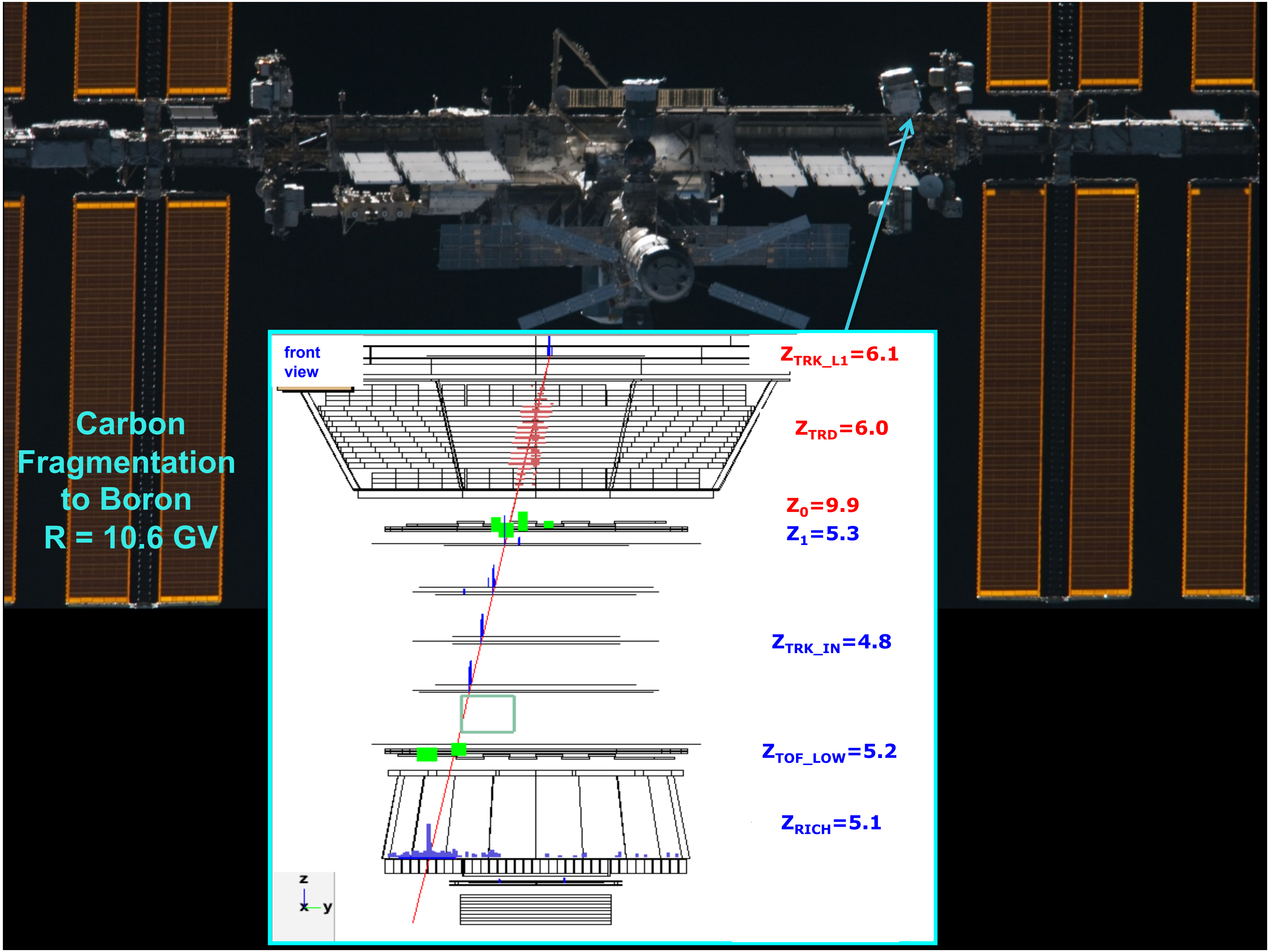
New results from AMS
7) Boron-to-Carbon ratio

Precise measurement of the energy spectra of B/C provides information on Cosmic Ray Interactions and Propagation

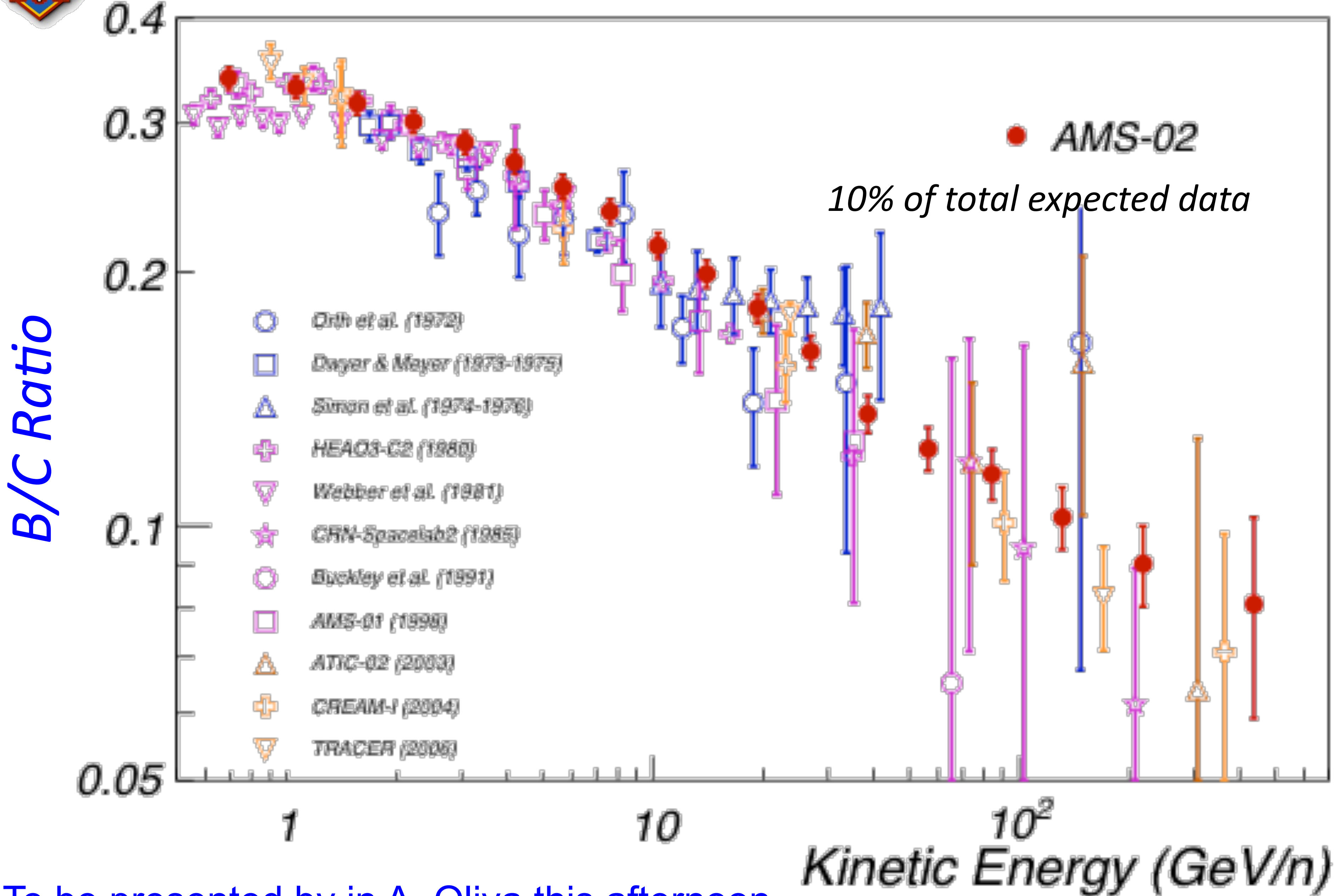
AMS: Multiple Independent Measurements of the Charge (|Z|)



	Carbon (Z=6) ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF (1 counter)	0.16
4. Tracker Planes 2-8	0.12
5. Lower TOF (1 counter)	0.16
6. RICH	0.32
7. Tracker Plane 9	0.30


Carbon
Fragmentation
to Boron
R = 10.6 GV
front
view
$Z_{TRK\_L1}=6.1$
$Z_{TRD}=6.0$
$Z_0=9.9$
$Z_1=5.3$
$Z_{TRK\_IN}=4.8$
$Z_{TOF\_LOW}=5.2$
$Z_{RICH}=5.1$
z
x
y

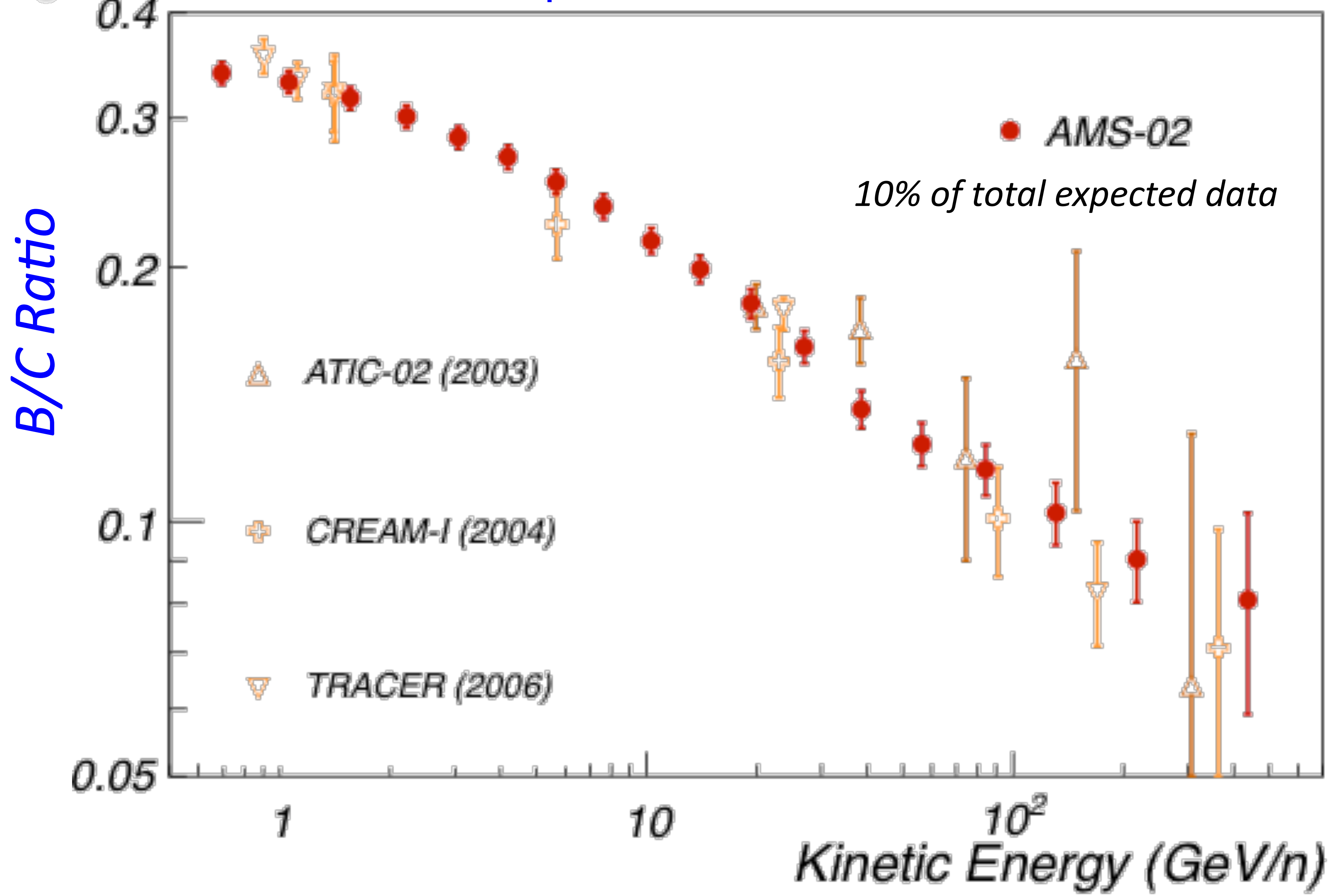
Boron-to-Carbon ratio



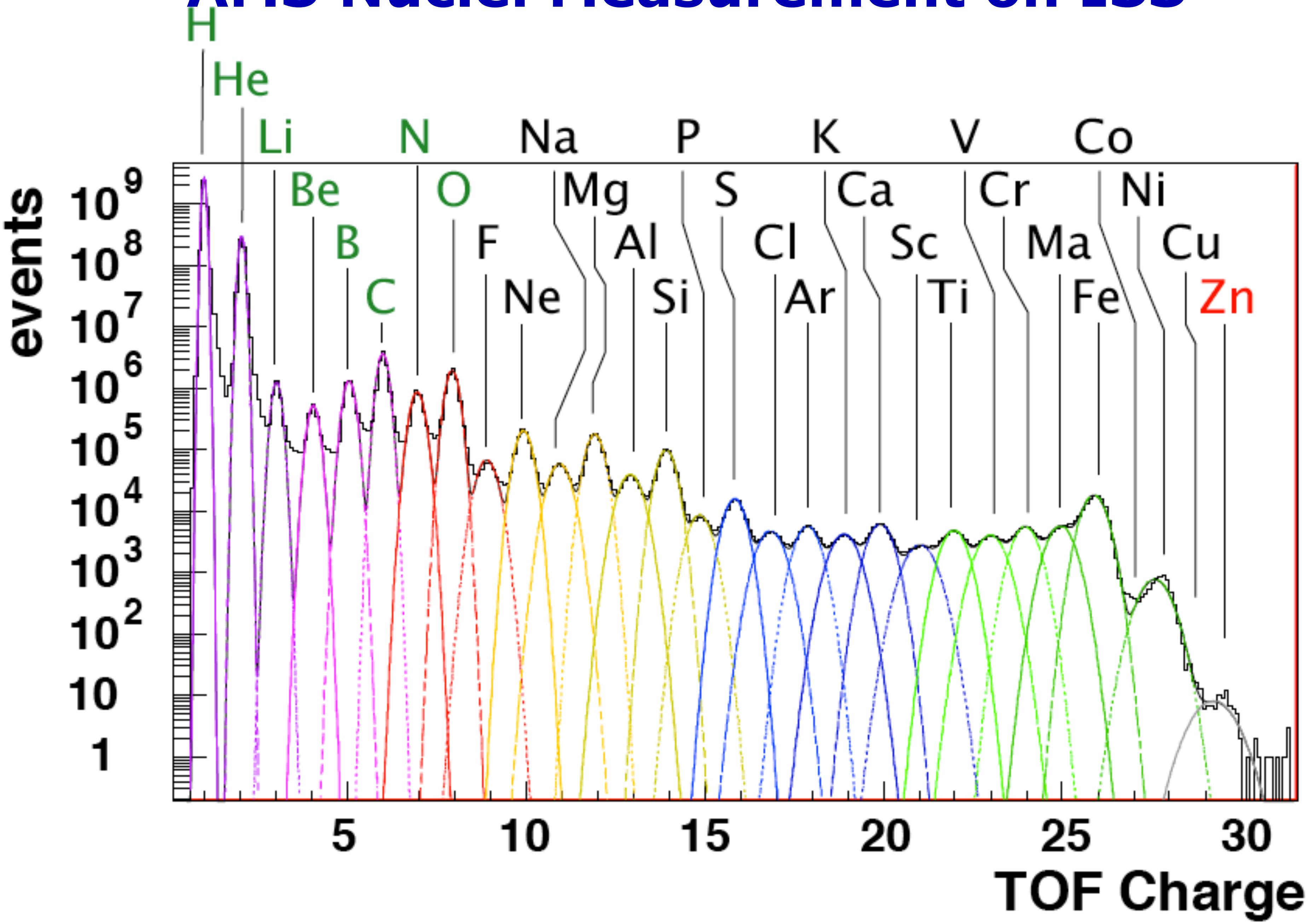
To be presented by in A. Oliva this afternoon

Boron-to-Carbon ratio

comparison with recent data



AMS Nuclei Measurement on ISS



We now understand
the systematic errors to ~1%.

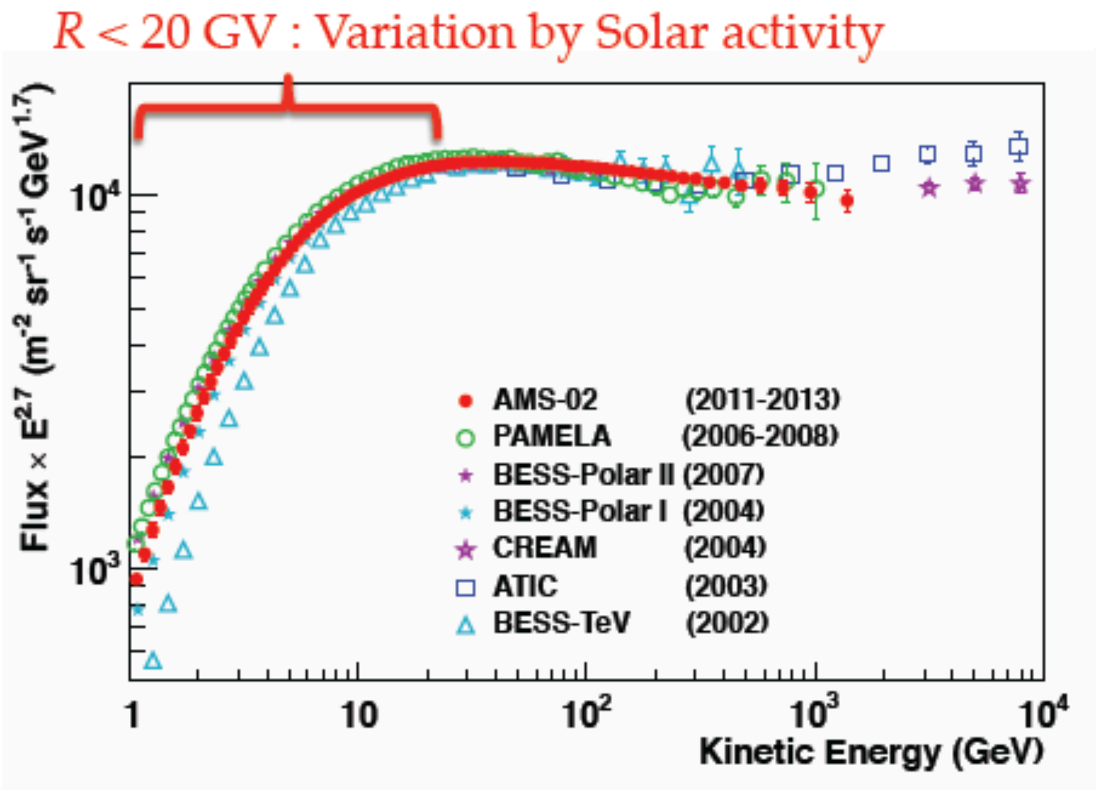
Studies with 1% statistical error
will take time to collect the data.

Physics analysis nearing completion

1. Antiprotons (0.5-300 GeV)
2. Anti-He (@ few 10^8 events)
3. Ion fluxes
4. Solar physics
5. ....

Low-energy CRs

- AMS02 Proton Flux (2 years):



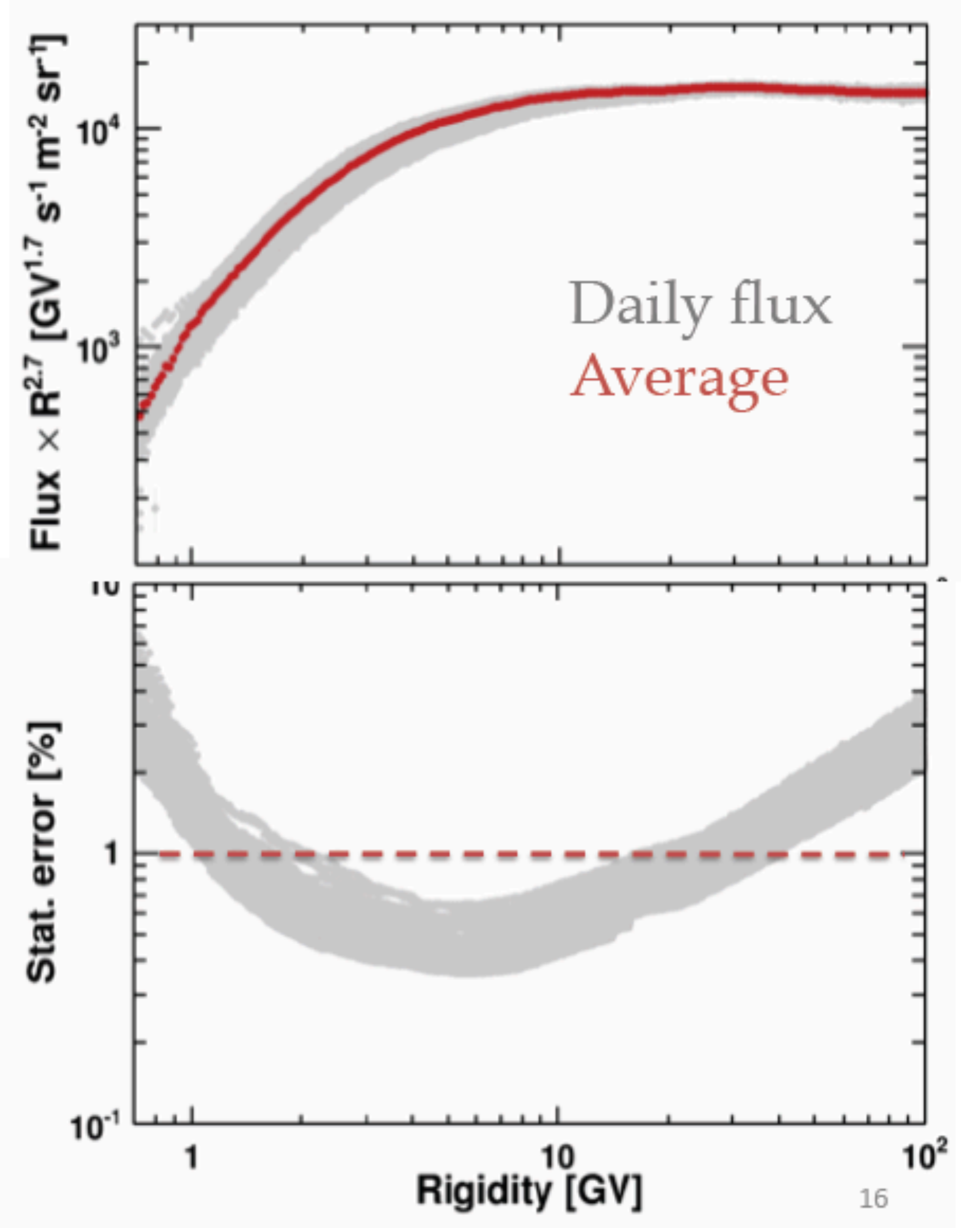
AMS02: unique detector to study Solar activity:

- Long duration → more than one full Solar cycle
- High statistics → daily fluxes
- Ability to measure all the CR components → charge sign dependence study (e-/e+, pbar/p)

Proton Daily flux

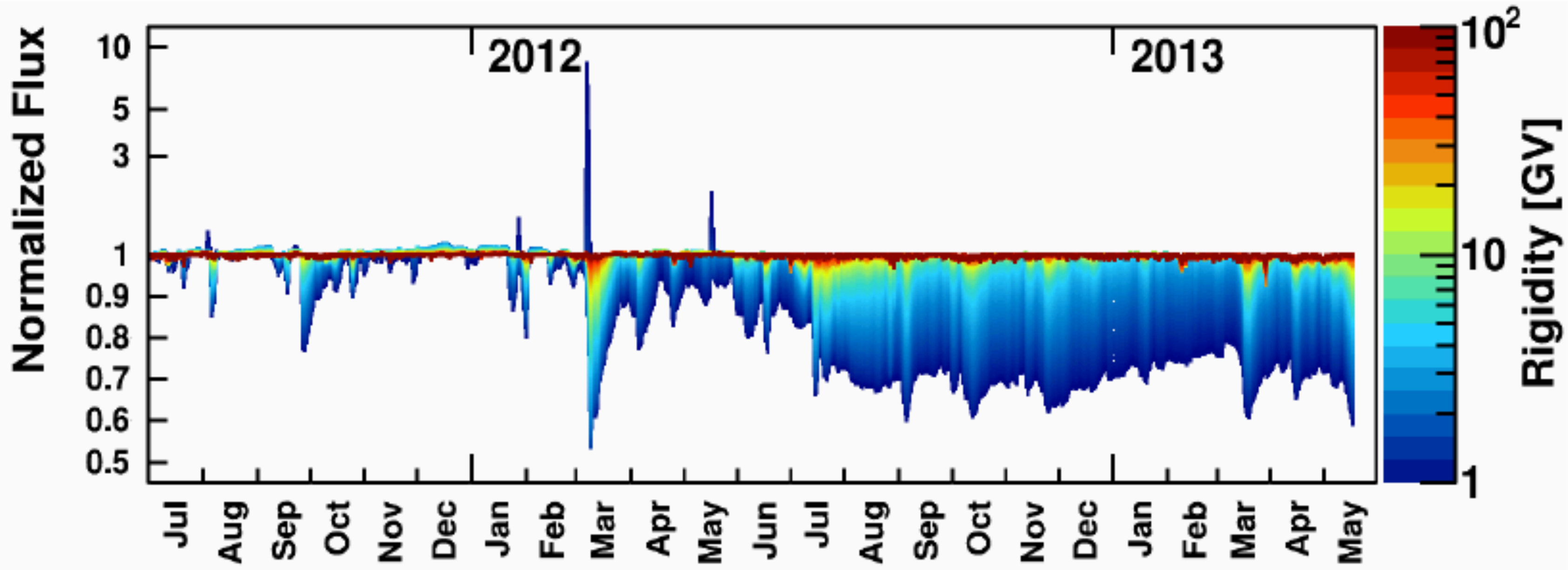
Use of the full acceptance (Inner Tracker):

- ~7 10^6 protons per day
- Stat. Error < ~1%
  (1 < R < ~20 GV)
- Large fluctuation (~30%) due to Solar activity.



Daily normalized flux

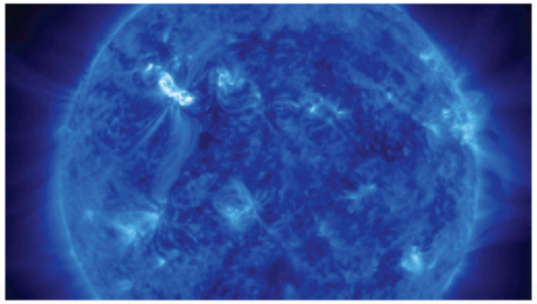
Time fluctuation of proton rate for different rigidities from AMS02 data:

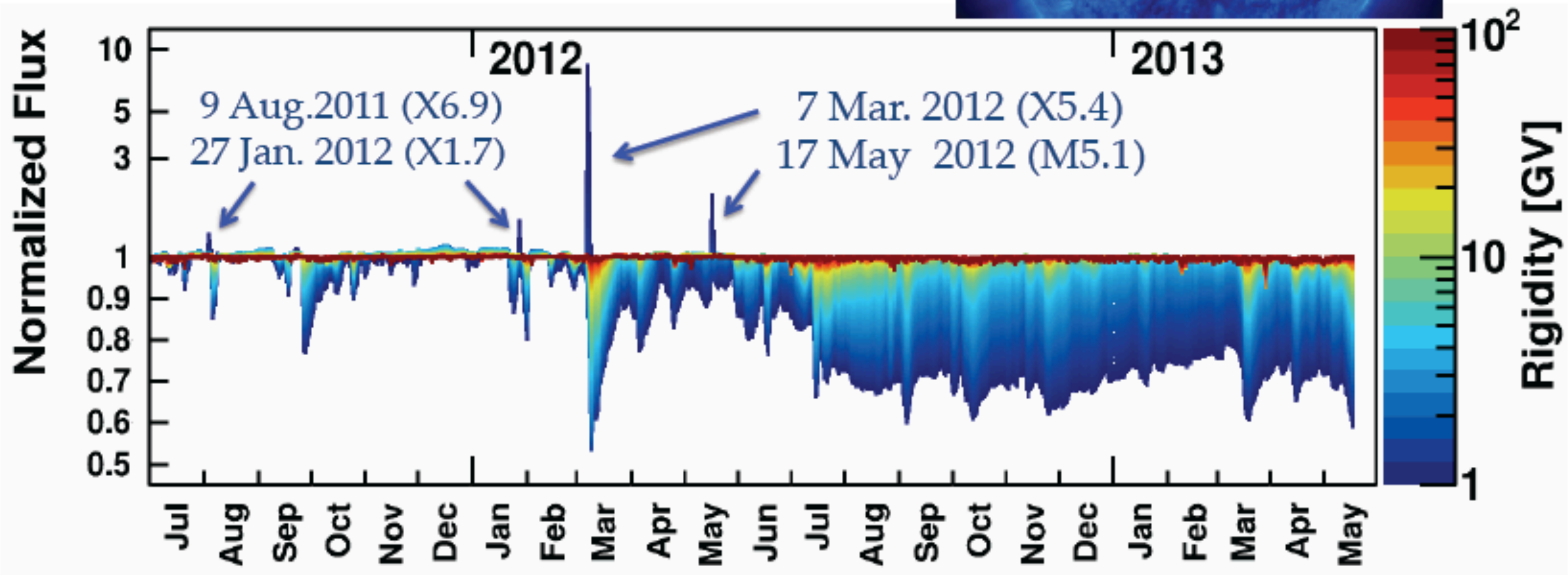


→ AMS proton daily fluxes represent a unique set of data for the Solar physics community, and to understand Solar modulation

Daily normalized flux

R < ~3 GV : Peaks associated with Solar flares (SEP)





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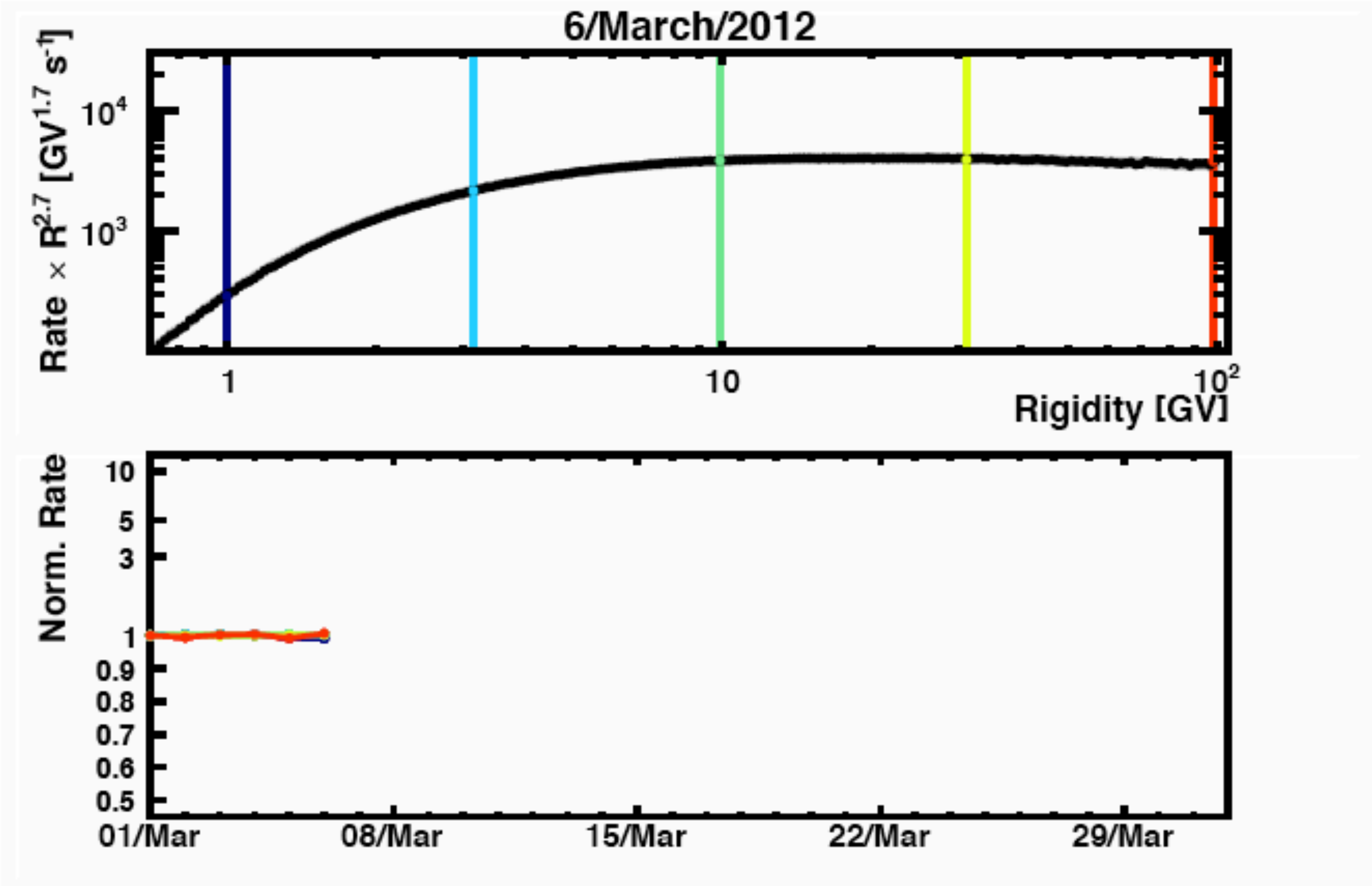
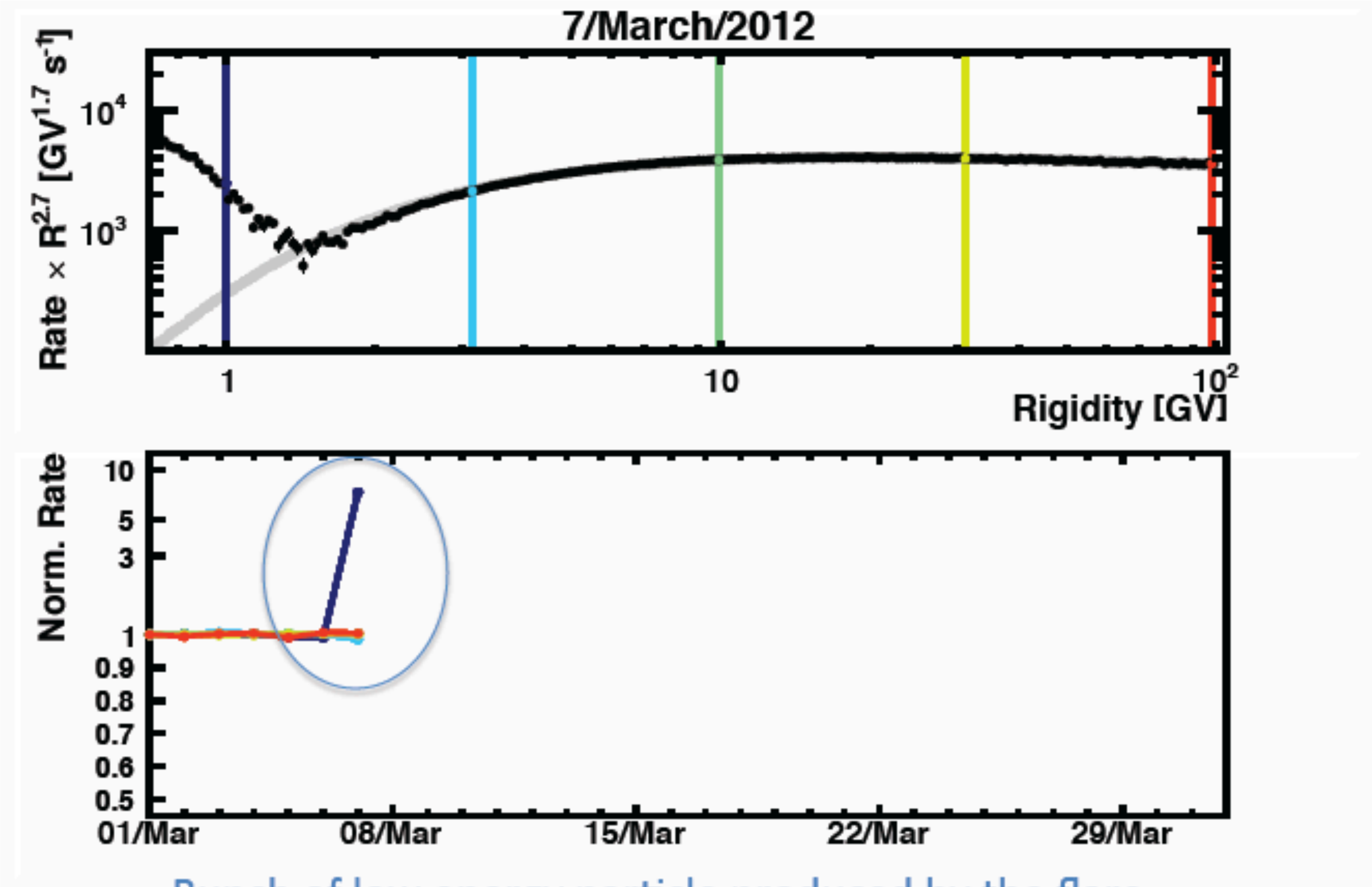
March 2012 solar event

Daily proton rate reconstructed from AMS02 data:



March 2012 solar event

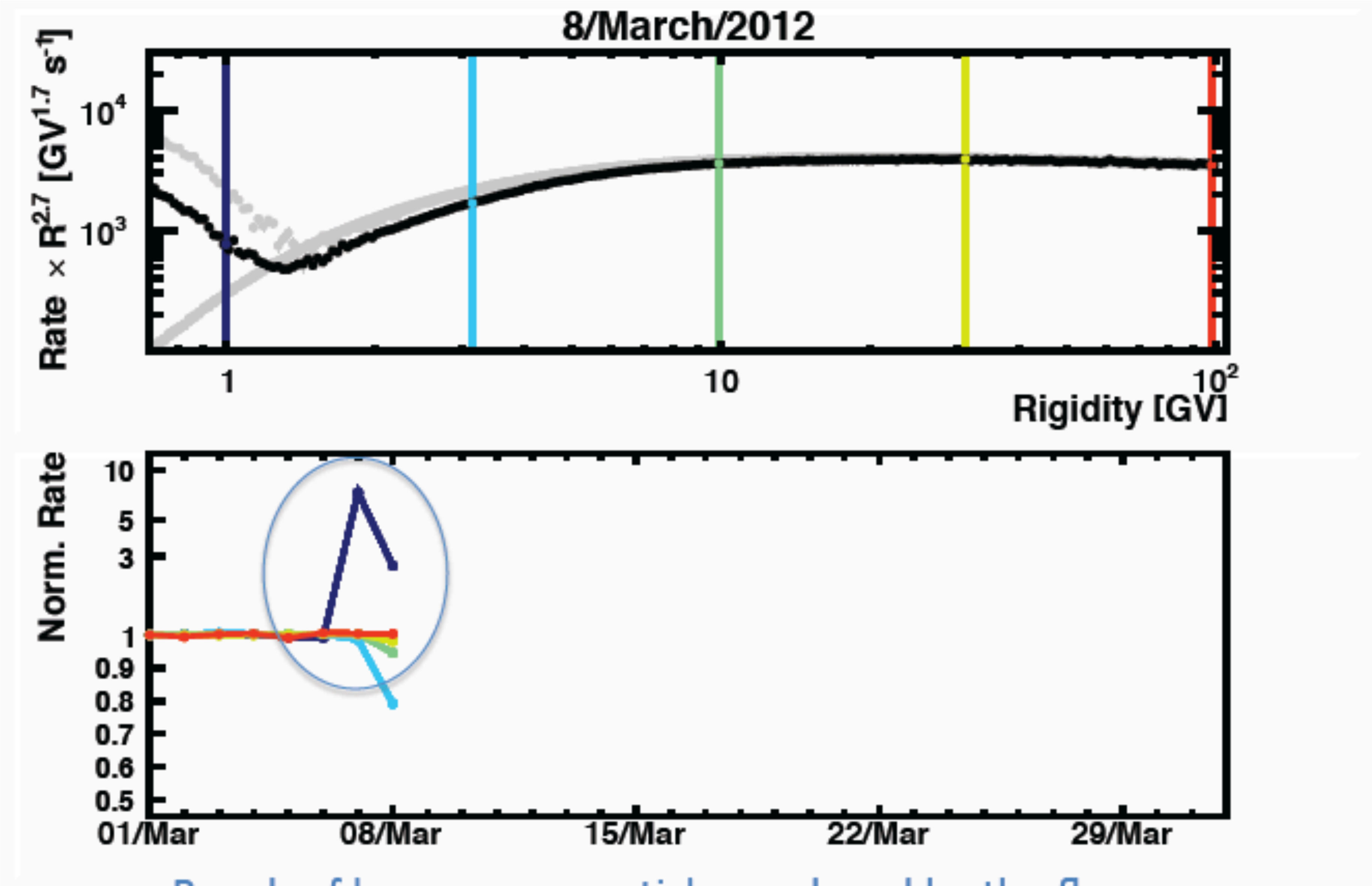
Daily proton rate reconstructed from AMS02 data:



Bunch of low energy particle produced by the flare

March 2012 solar event

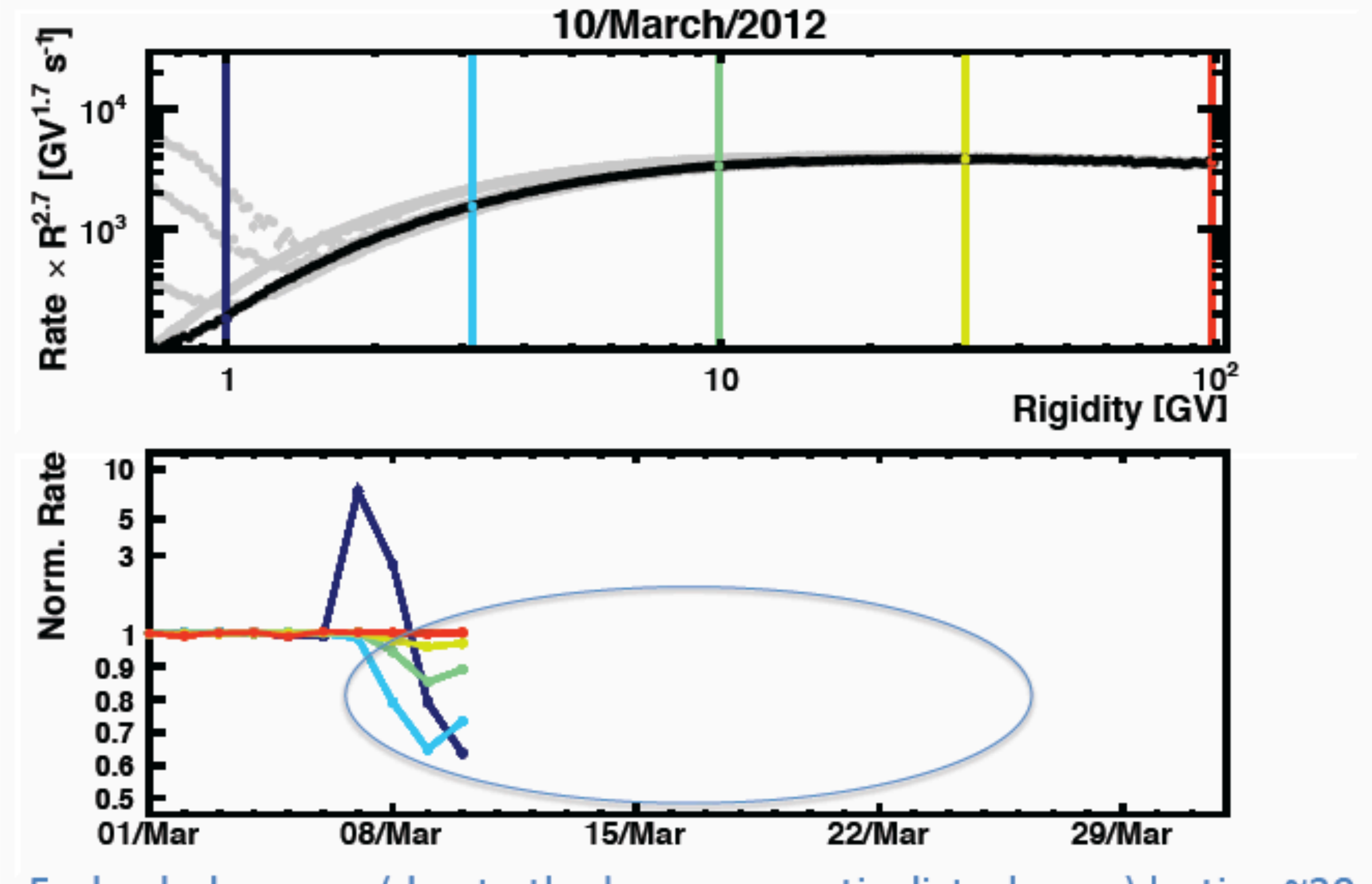
Daily proton rate reconstructed from AMS02 data:



Bunch of low energy particle produced by the flare

March 2012 solar event

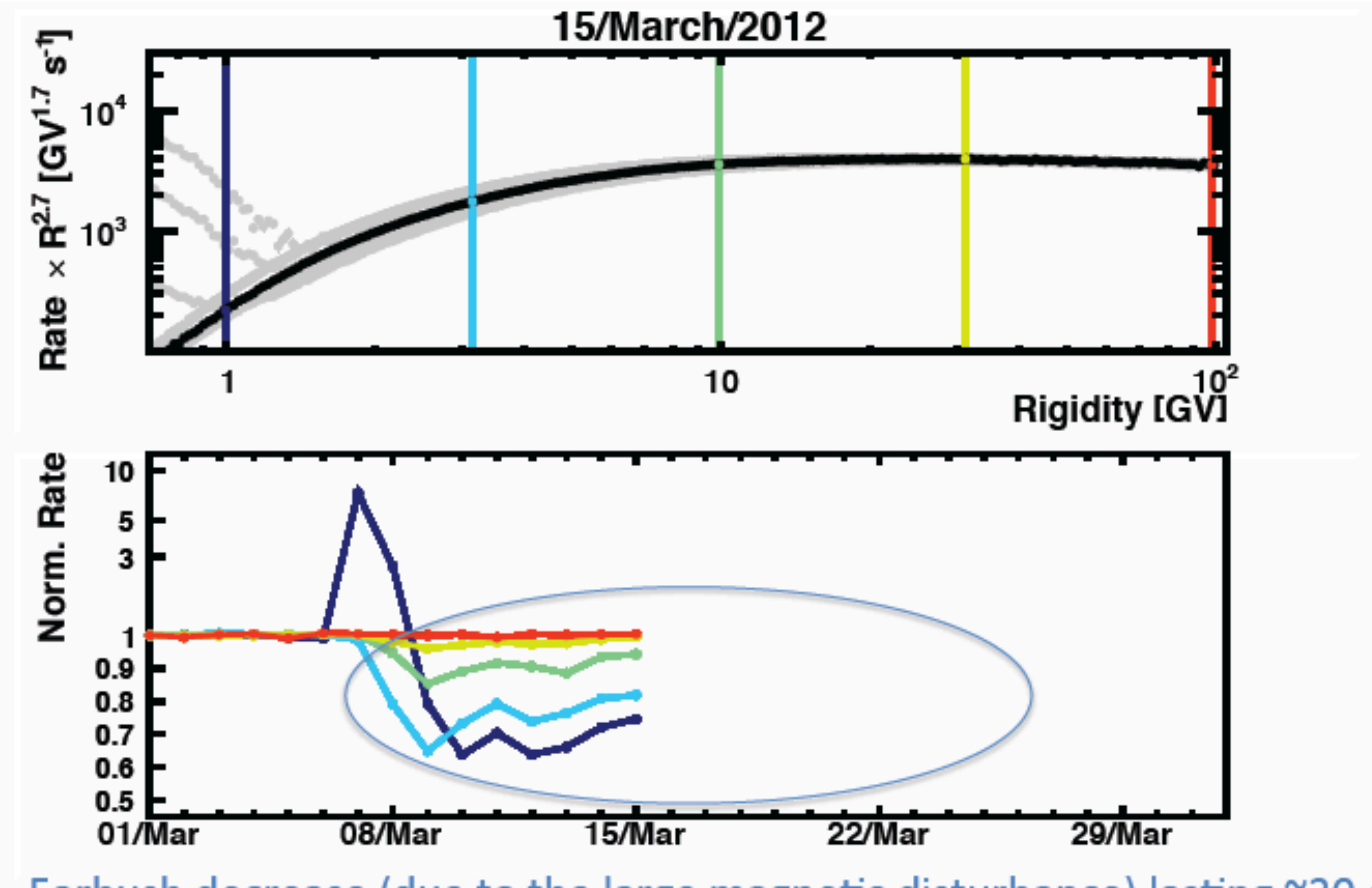
Daily proton rate reconstructed from AMS02 data:



Forbush decrease (due to the large magnetic disturbance) lasting ~20 days

March 2012 solar event

Daily proton rate reconstructed from AMS02 data:



Forbush decrease (due to the large magnetic disturbance) lasting ~20 days

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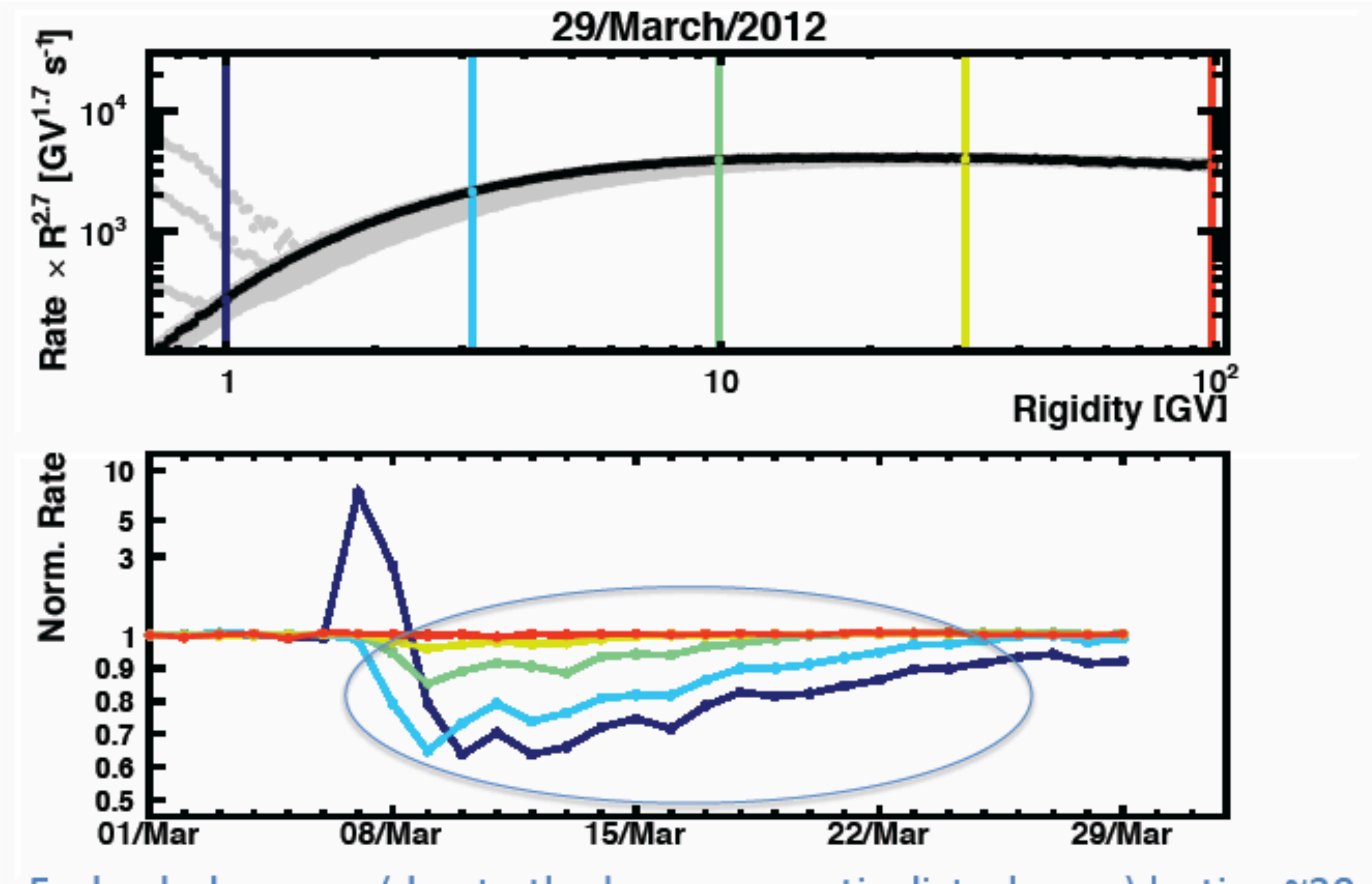

Forbush decrease (due to the large magnetic disturbance) lasting ~20 days

The Cosmos is the Ultimate Laboratory.

Cosmic rays can be observed at energies higher than any accelerator.

With AMS-02 on the ISS we have entered the era of precision Cosmic Ray physics to search for phenomena which exist in nature but we have not yet imagined nor had the tools to discover.