The Alpha Magnetic Spectrometer (AMS) Experiment

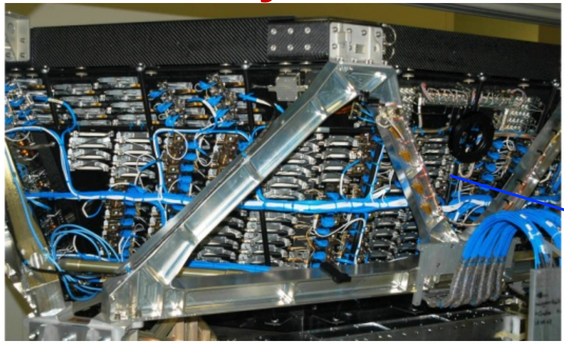
R. Battiston

XV Neutrino Telescopes

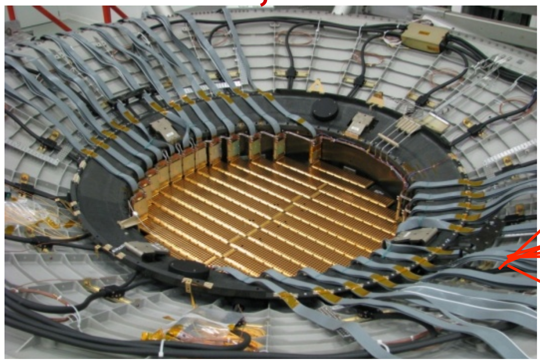
Venice 2013

AMS: A TeV precision, multipurpose spectrometer

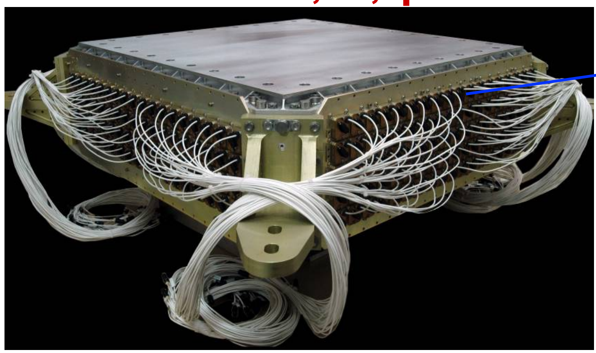
TRD
Identify e^+, e^-



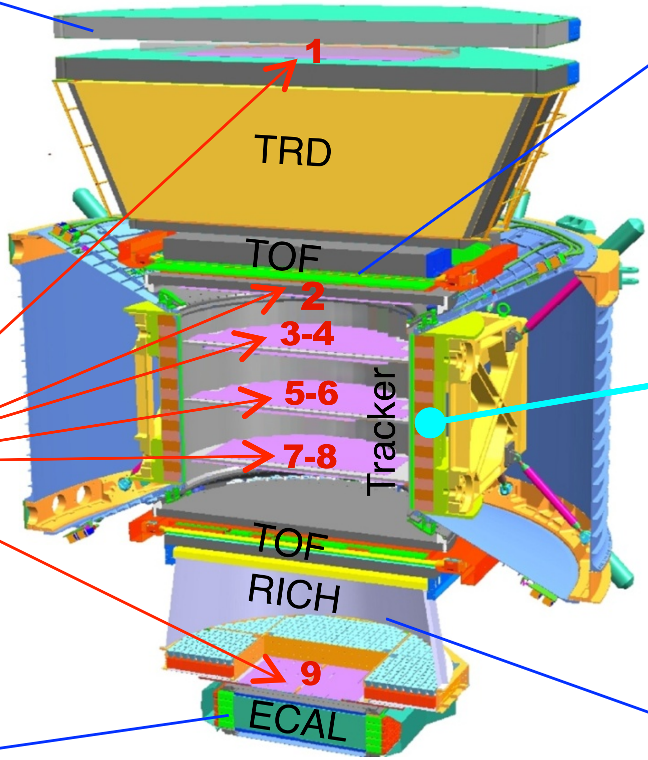
Silicon Tracker
Z, P



ECAL
E of e^+, e^-, γ



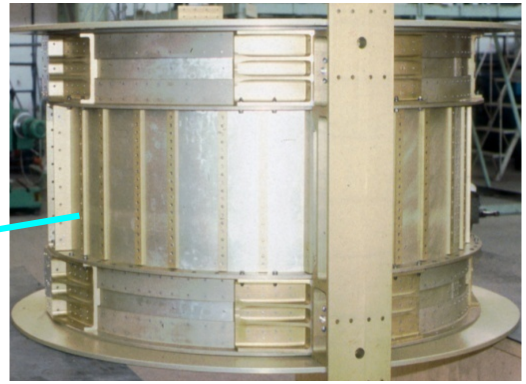
Particles and nuclei are defined by their charge (Z) and energy (E ~ P)



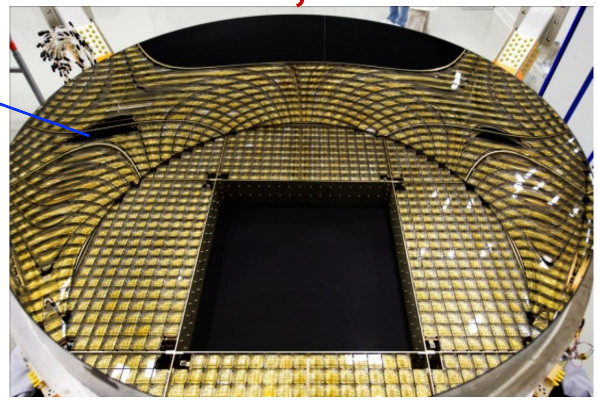
***Z, P* are measured independently by the Tracker, RICH, TOF and ECAL**

TOF
Z, E

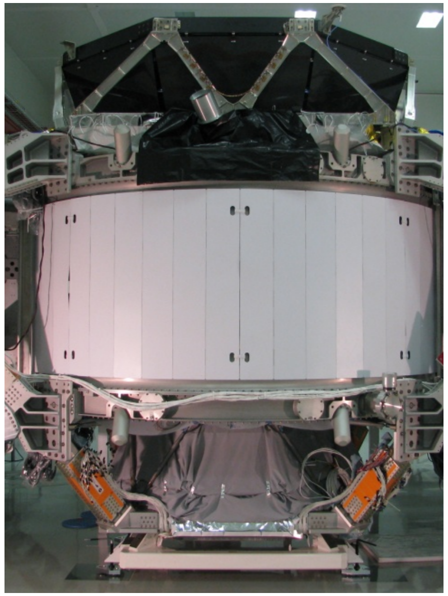
Magnet
±Z



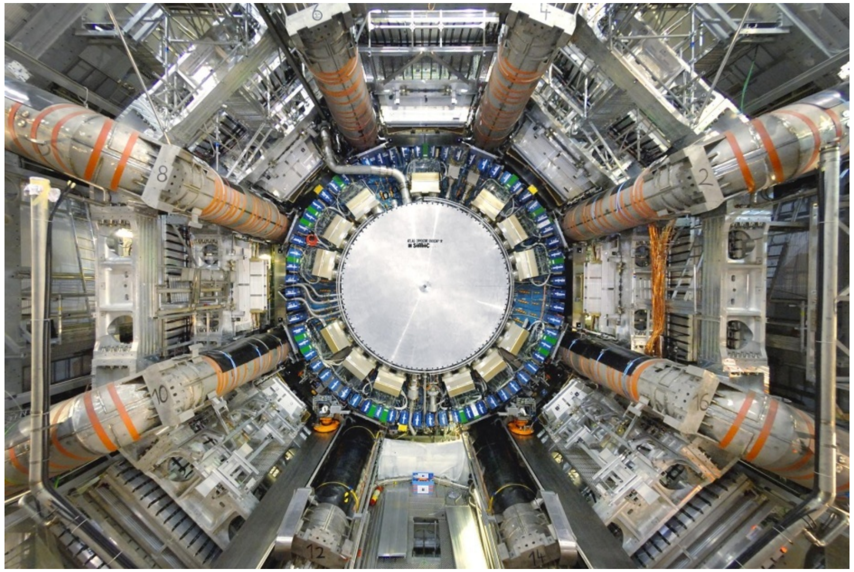
RICH
Z, E

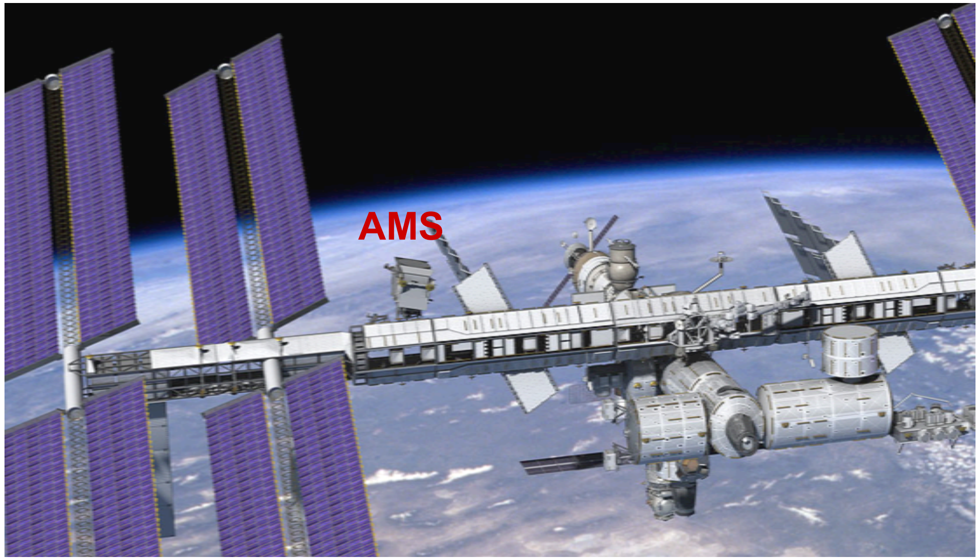


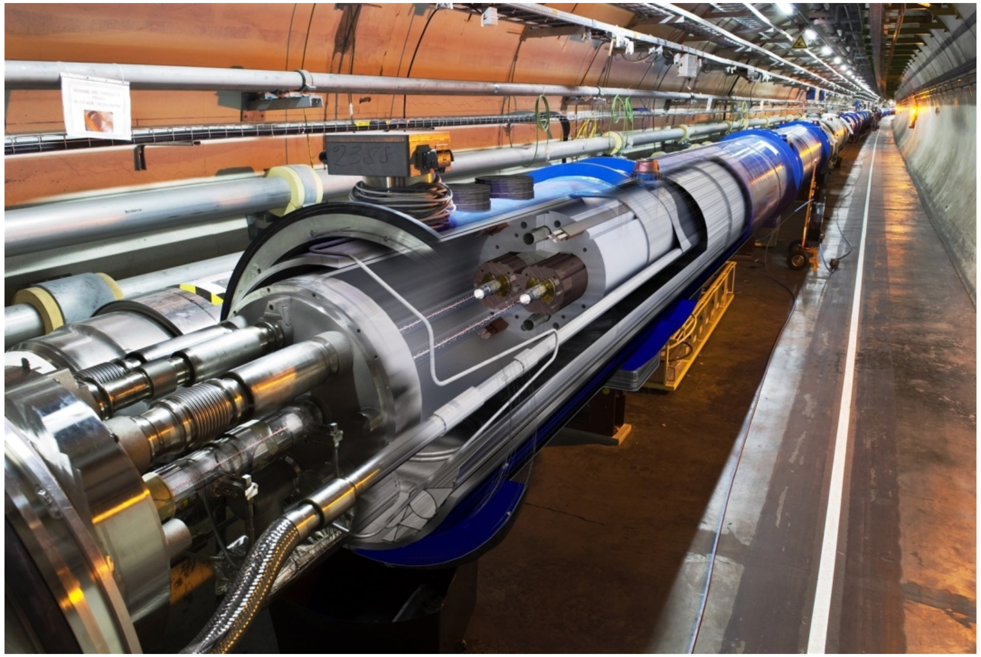
AMS



ATLAS, CMS, ALICE & LHCb

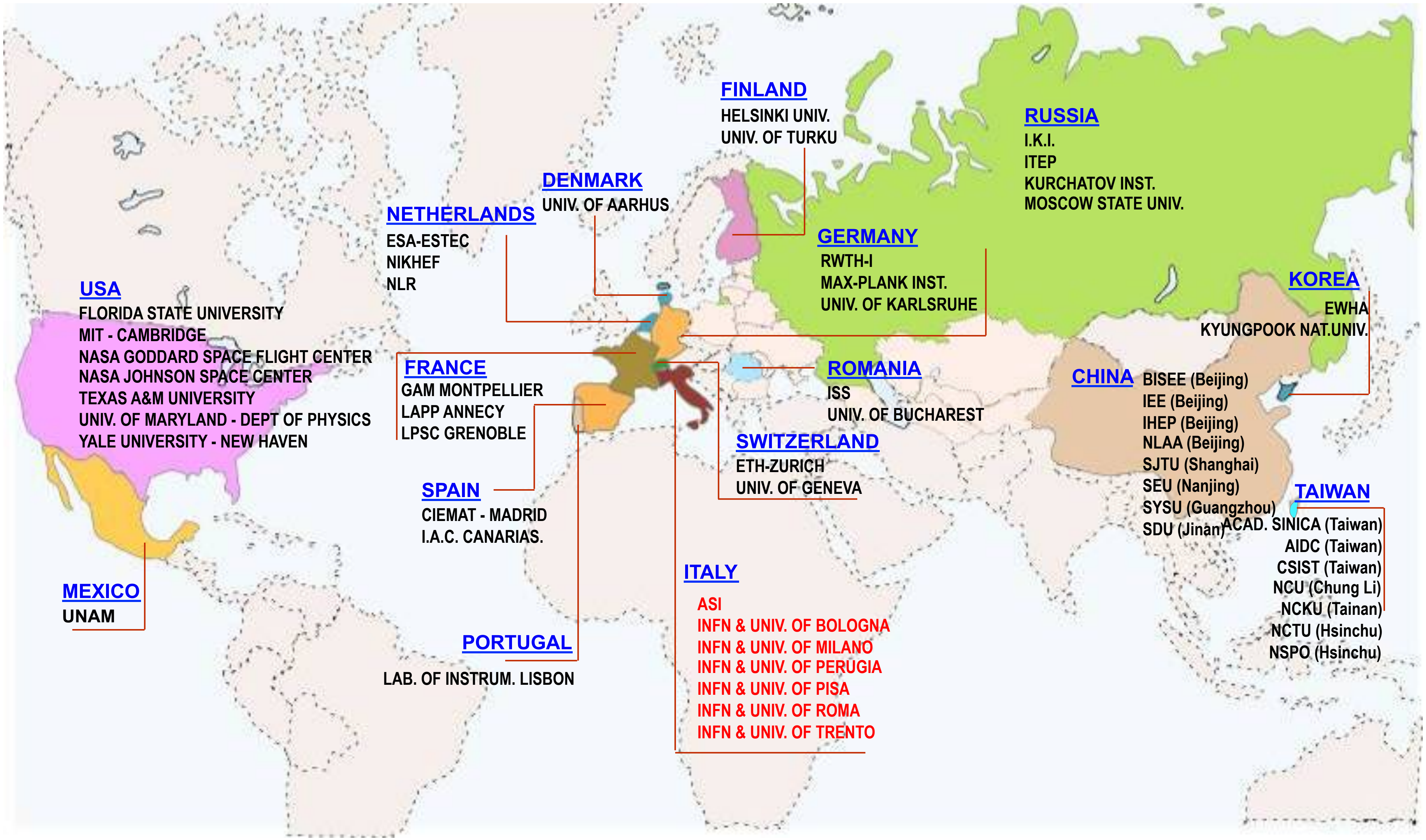






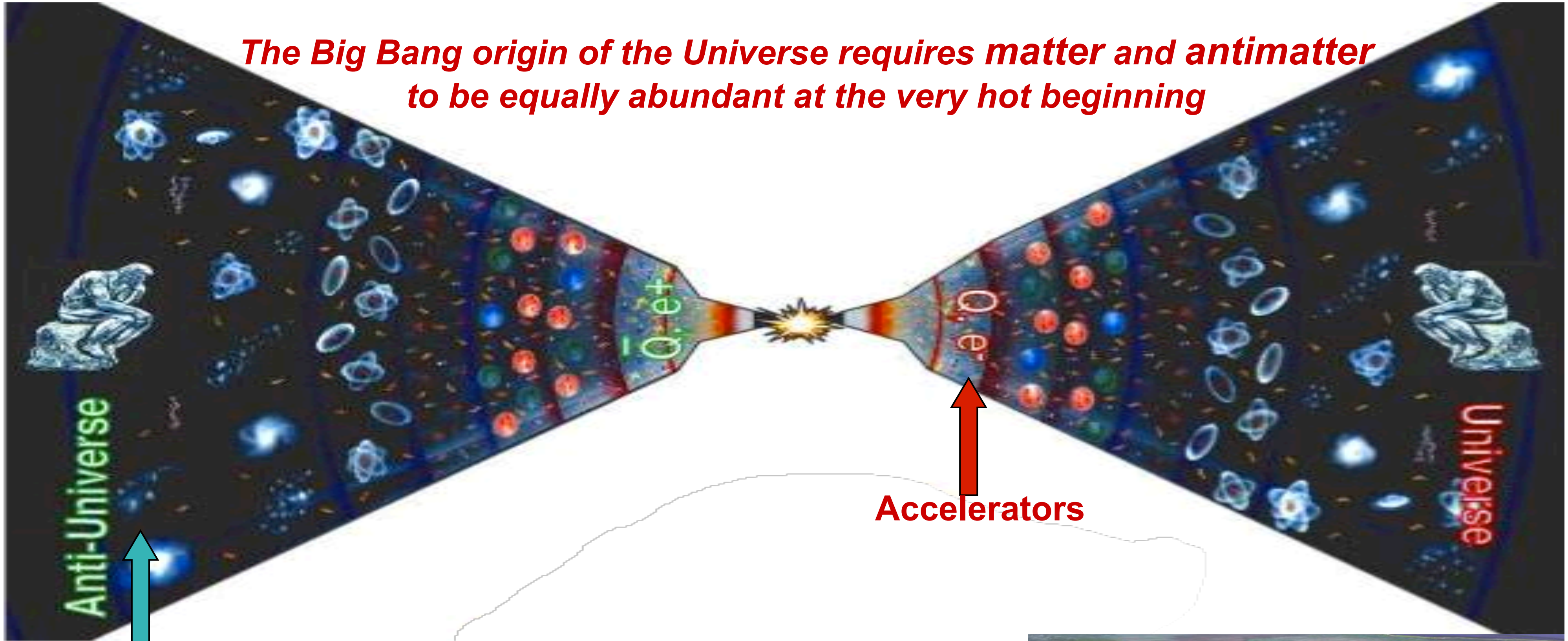
ISS cost = ~10 LHC.
LHC has 4 big experiments.
ISS only has AMS.

AMS is an International Collaboration

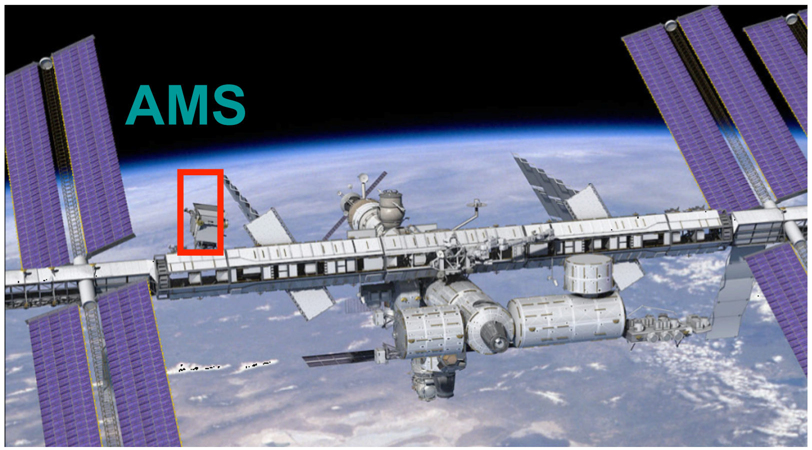


Physics examples

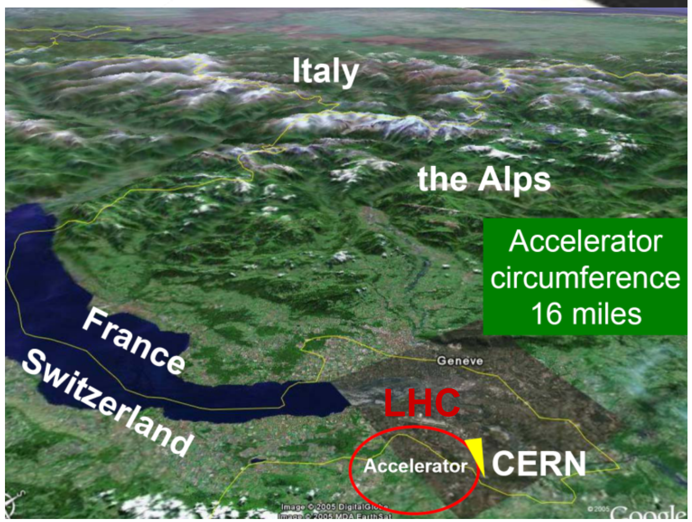
Search for the existence of Antimatter in the Universe



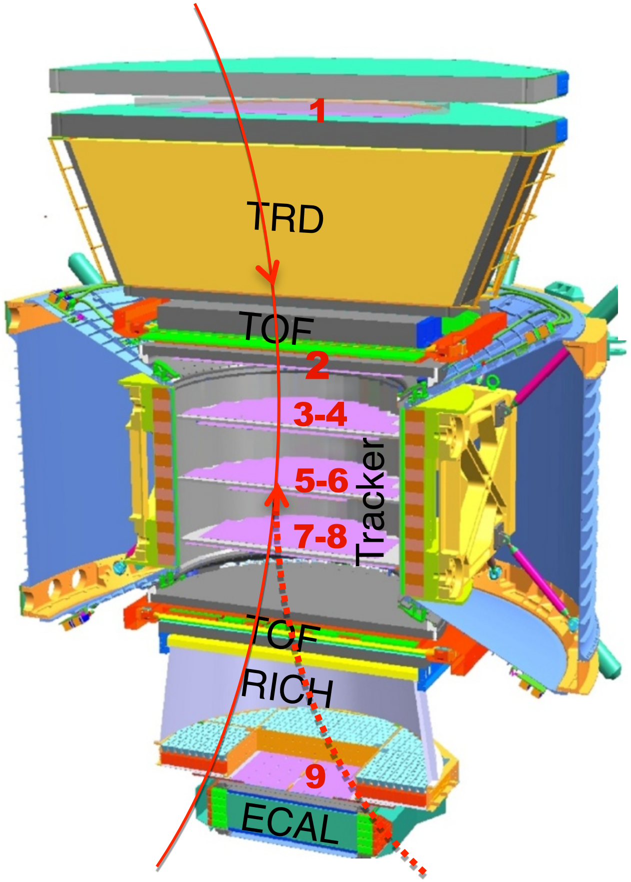
AMS in Space



AMS on the Space Station for 10-20 years will search for the existence of antimatter to the edge of the universe



Sensitive Search for Antimatter with He/$\overline{He}$ >10^{10}



a) Minimal material in the detector

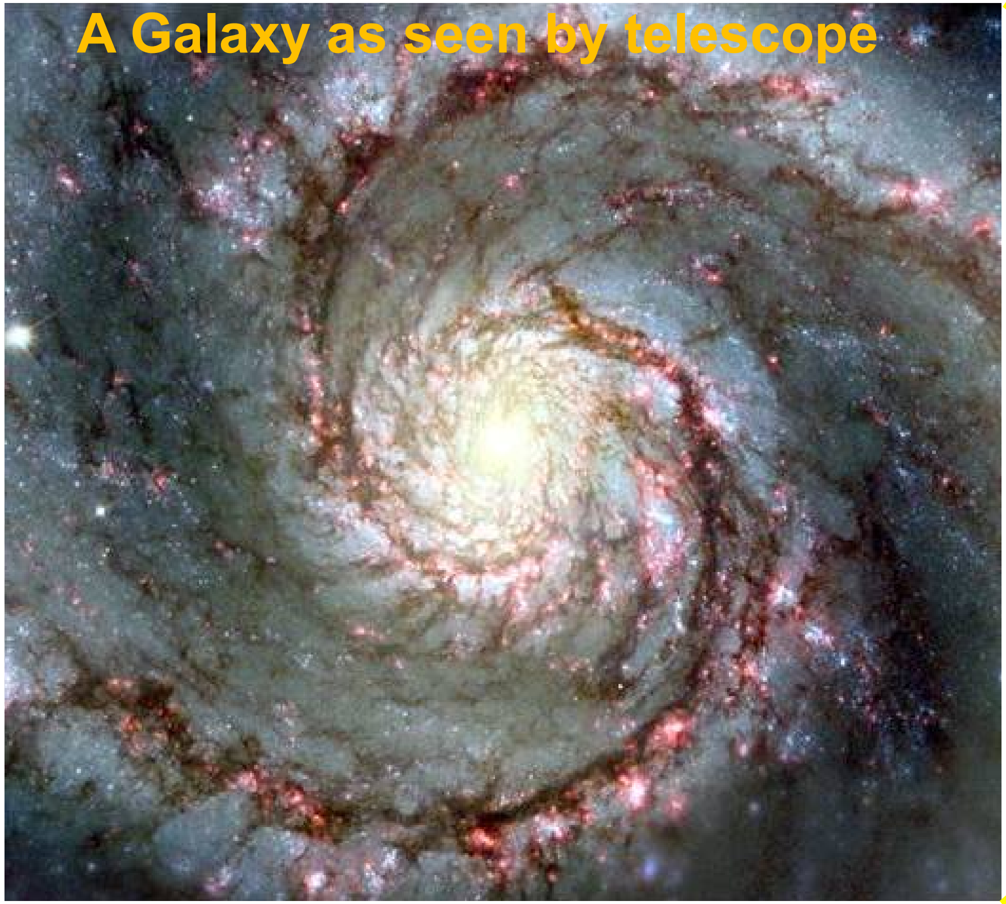
So that the detector does not become a source of large angle scattering

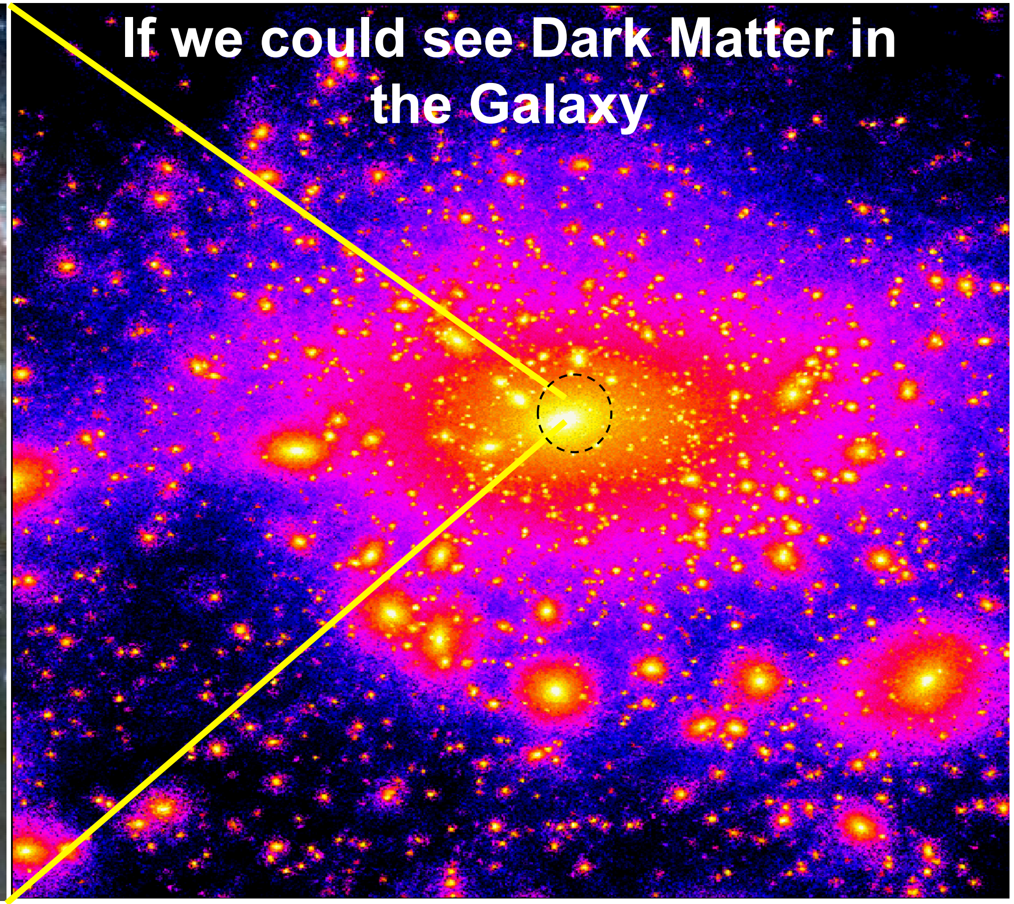
b) Repetitive measurements of momentum

To ensure that particles which had large angle scattering are not confused with the signal.

Another physics example:
Search for the Origin of Dark Matter

~ 90% of Matter in the Universe is not visible and is called Dark Matter



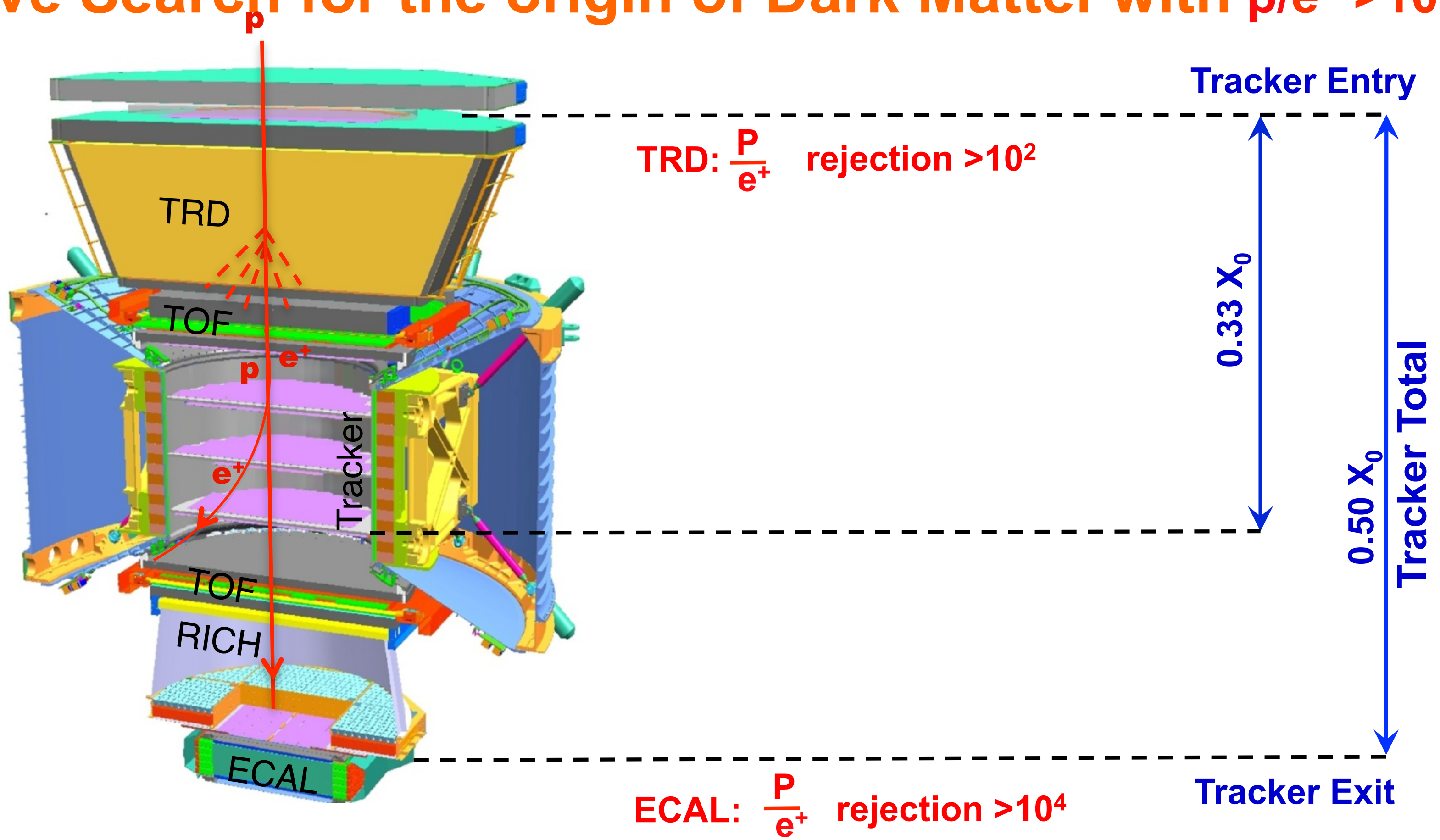


Collision of Cosmic Rays produce e+ …

Collisions of Dark Matter will produce an excess of e+

These characteristics of additional e+ can be measured accurately by AMS

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



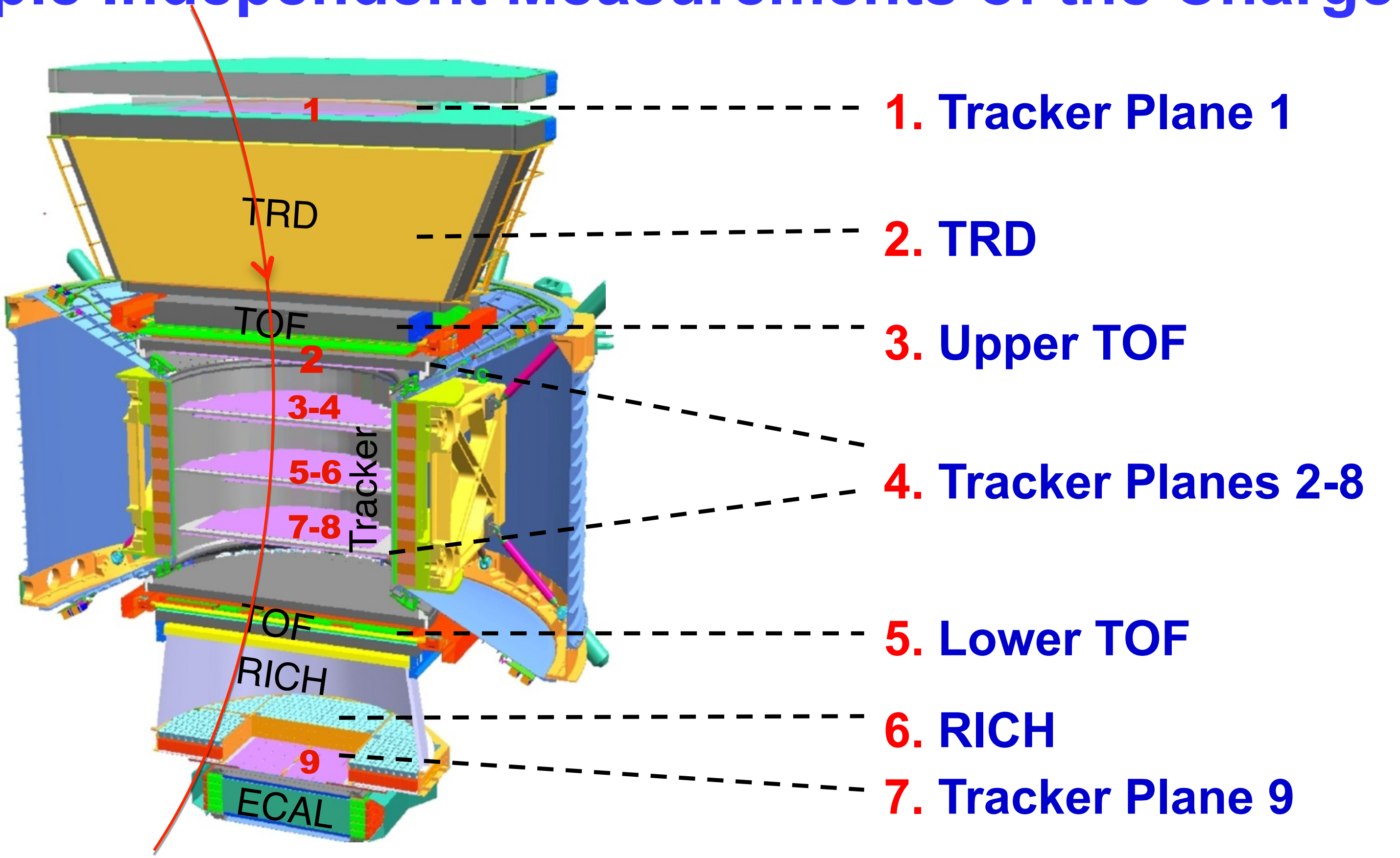
a) Minimal material in the TRD and TOF
So that the detector does not become a source of e^+.

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

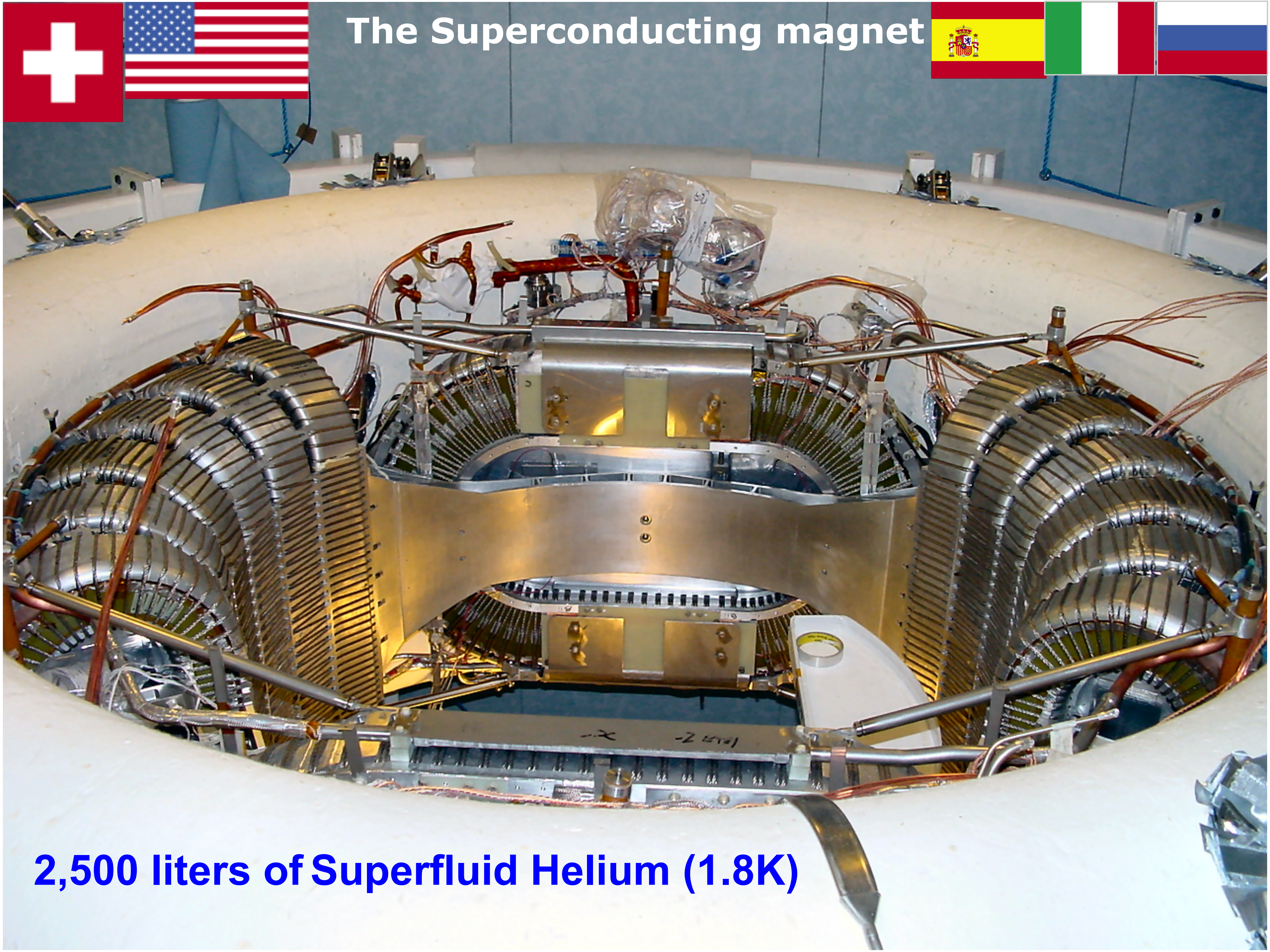
c) Matching momentum of 9 tracker planes with ECAL energy measurements

Accurate Study of the Origin of Cosmic Rays

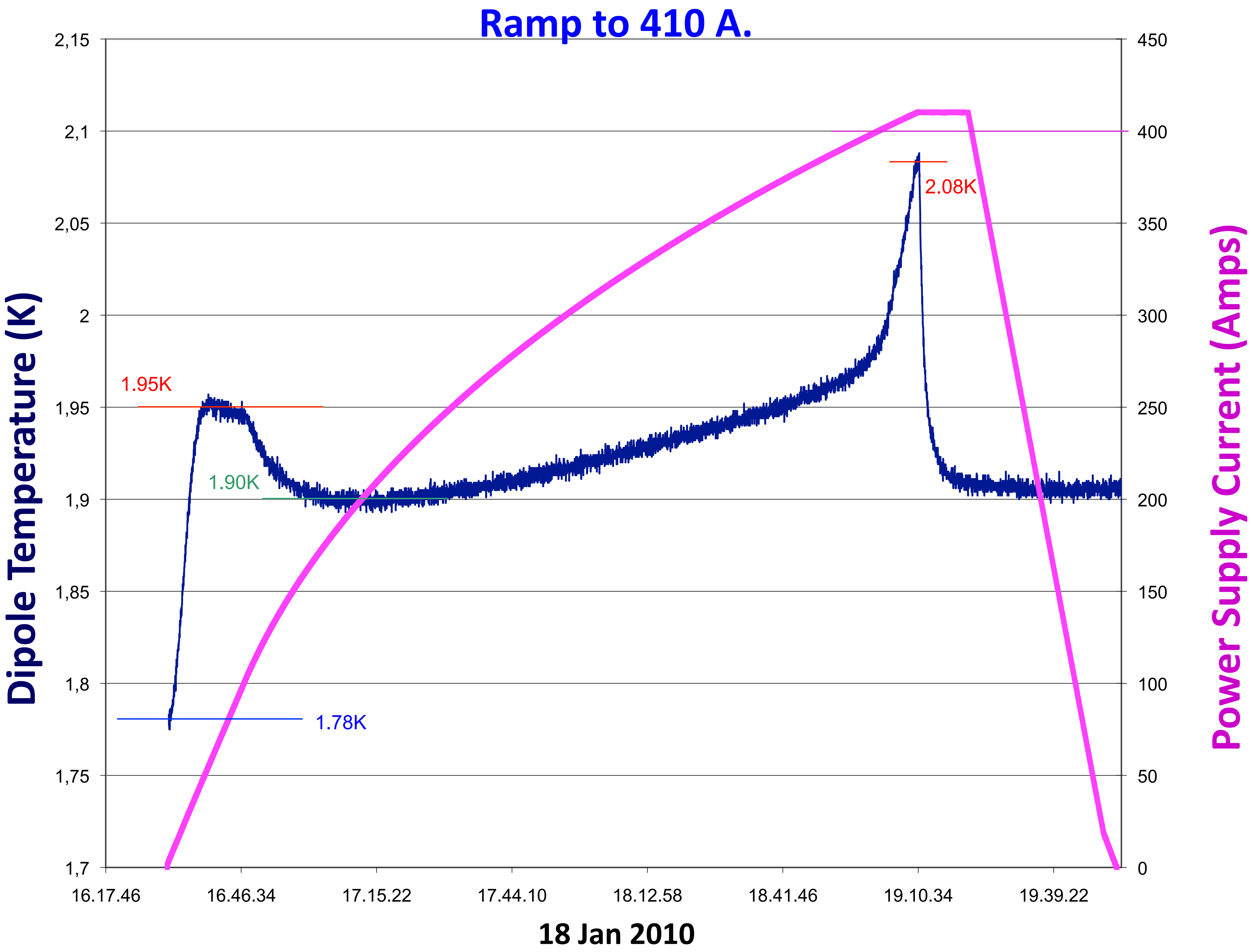
Multiple Independent Measurements of the Charge (|Z|)



The Superconducting magnet

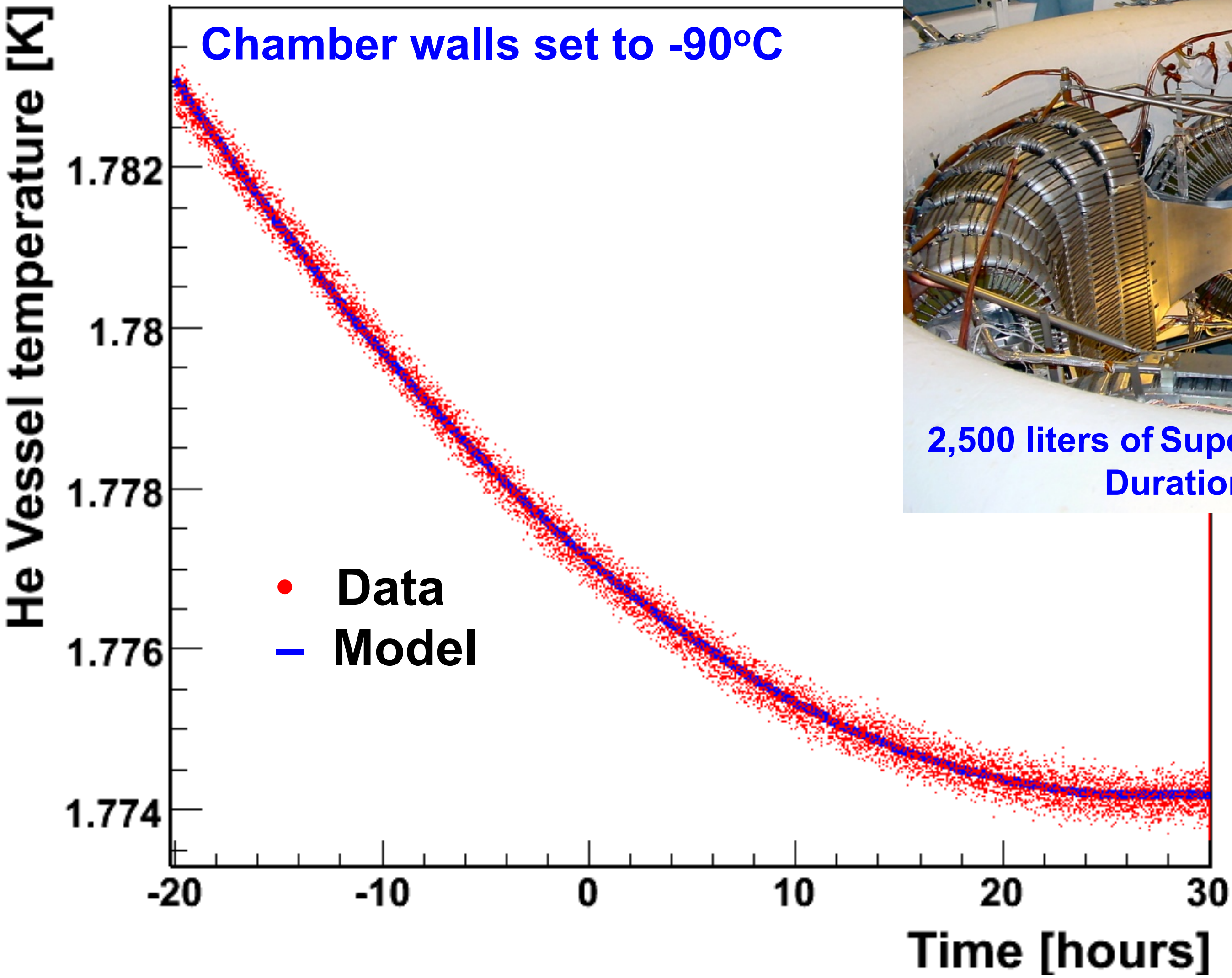


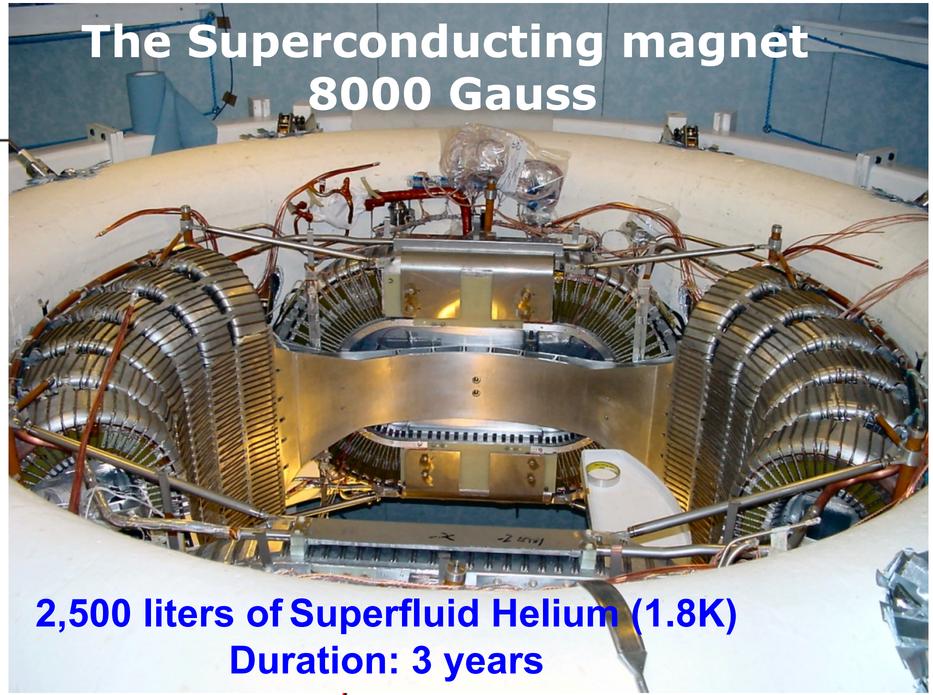
2,500 liters of Superfluid Helium (1.8K)



Ramp to 410 A.
Dipole Temperature (K)
Power Supply Current (Amps)
2,15
2,1
2,05
2
1,95
1,9
1,85
1,8
1,75
1,7
450
400
350
300
250
200
150
100
50
0
2.08K
1.95K
1.90K
1.78K
16.17.46
16.46.34
17.15.22
17.44.10
18.12.58
18.41.46
19.10.34
19.39.22
18 Jan 2010

Stabilization of the He Vessel





Stability criteria:
dT/dt < 0.0001K/h

Expected life time of the AMS Cryostat on ISS: 28±6 months

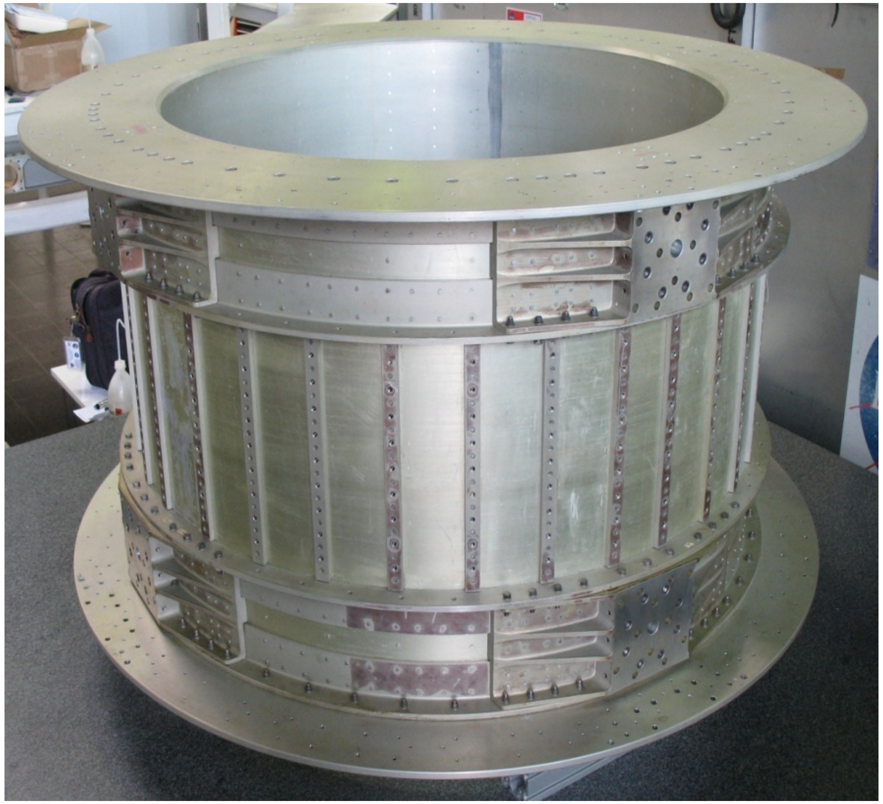
A superconducting magnet was ideal for a three year stay on ISS as originally approved for AMS.

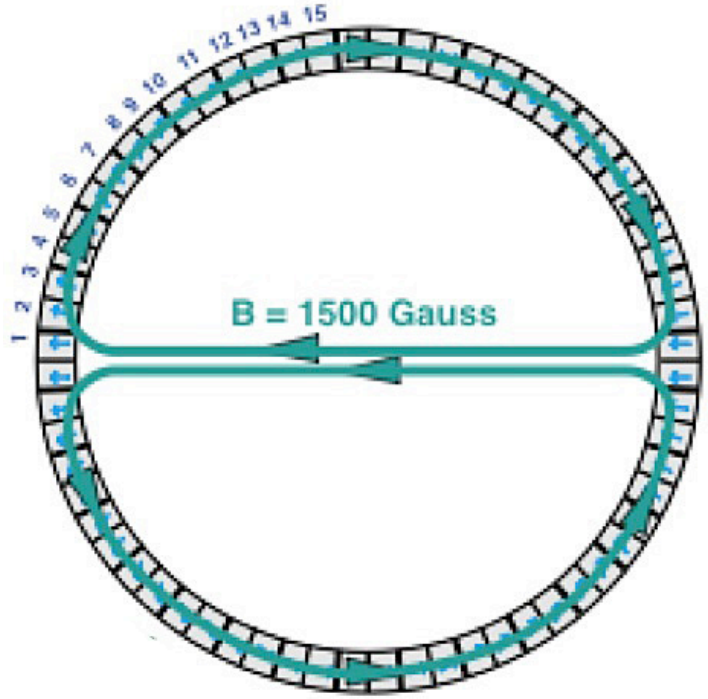
The ISS lifetime has been extended to 2020 (2028), the Shuttle program was terminated, thus eliminating any possibility of returning and refilling AMS.

A superconducting magnet is no longer the ideal choice.

To fully utilize the extended lifetime of the ISS, we upgraded the magnet system to a permanent magnet and added more detectors to maintain the same resolution. This provides a six fold increase in statistics.

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

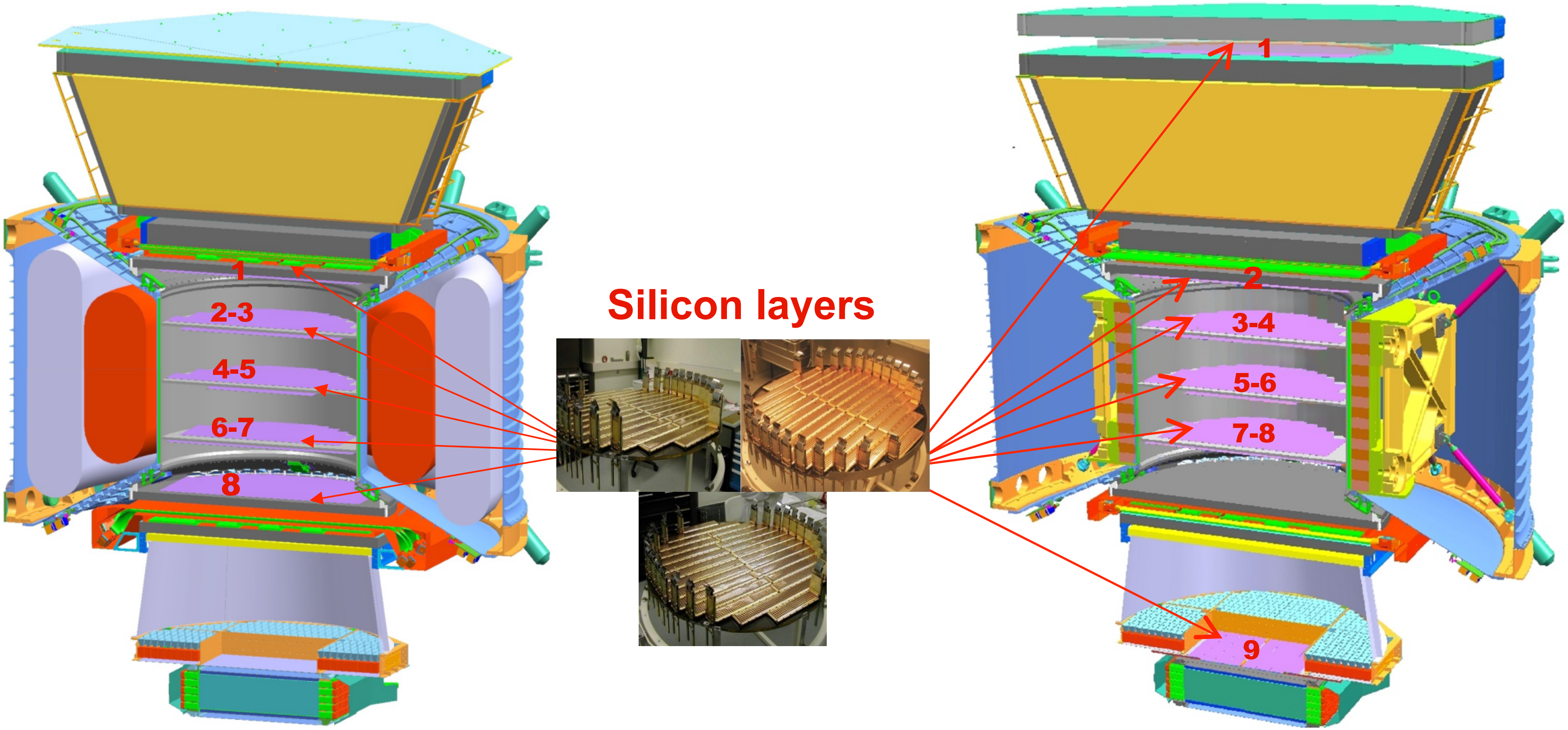
It was found that the deviation from the 1997 measurement had remained the same to <1%

AMS-02

(3 yrs)
with Superconducting Magnet
8 layers of Silicon

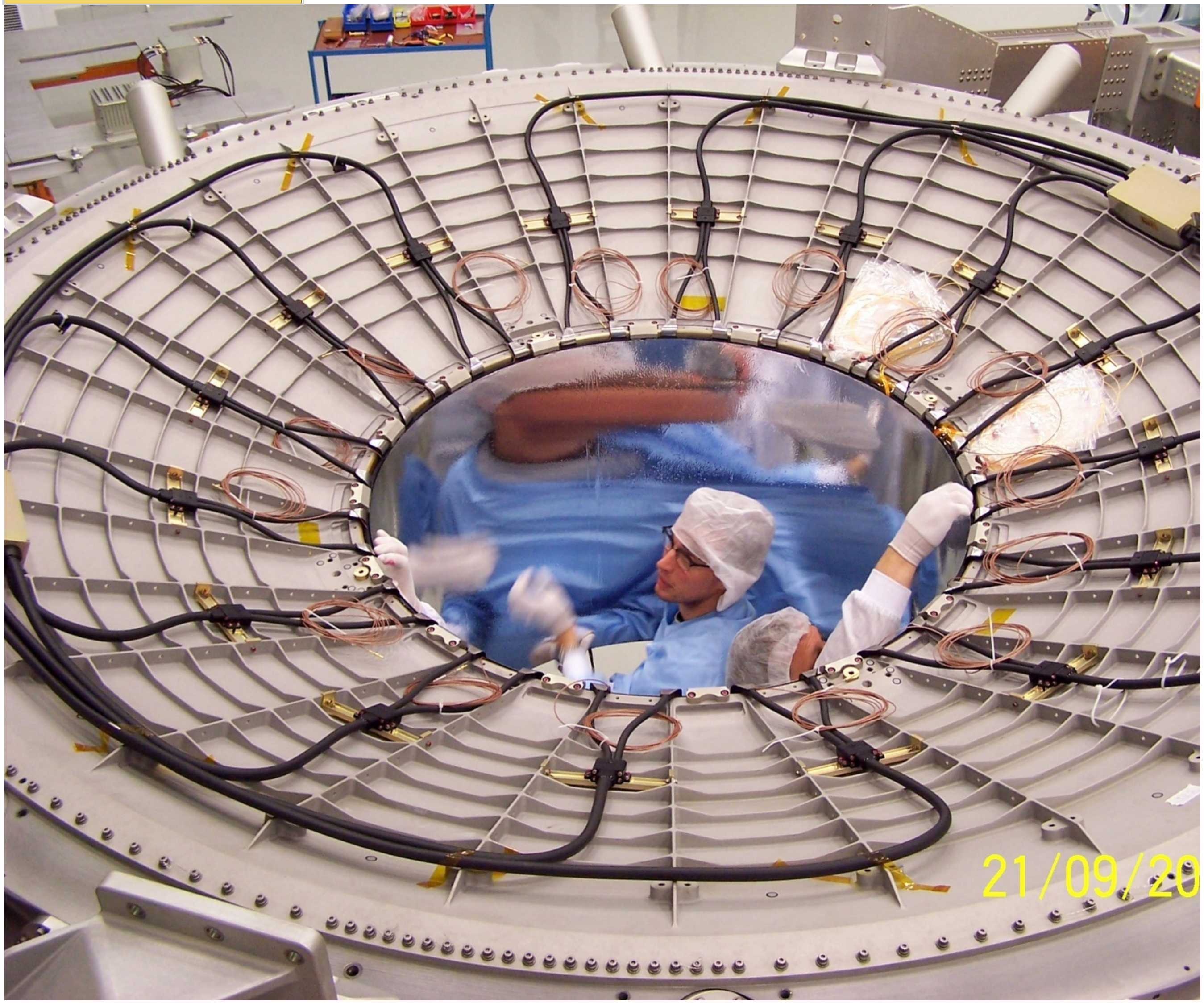
AMS-02

with Permanent Magnet
9 layers of Silicon



Layers 1 and 9 are far away from
the magnet to extend the lever arm.

Veto System rejects random cosmic rays

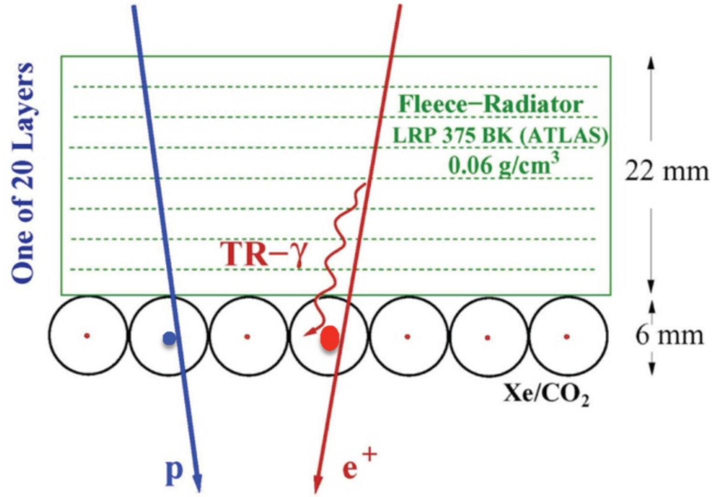


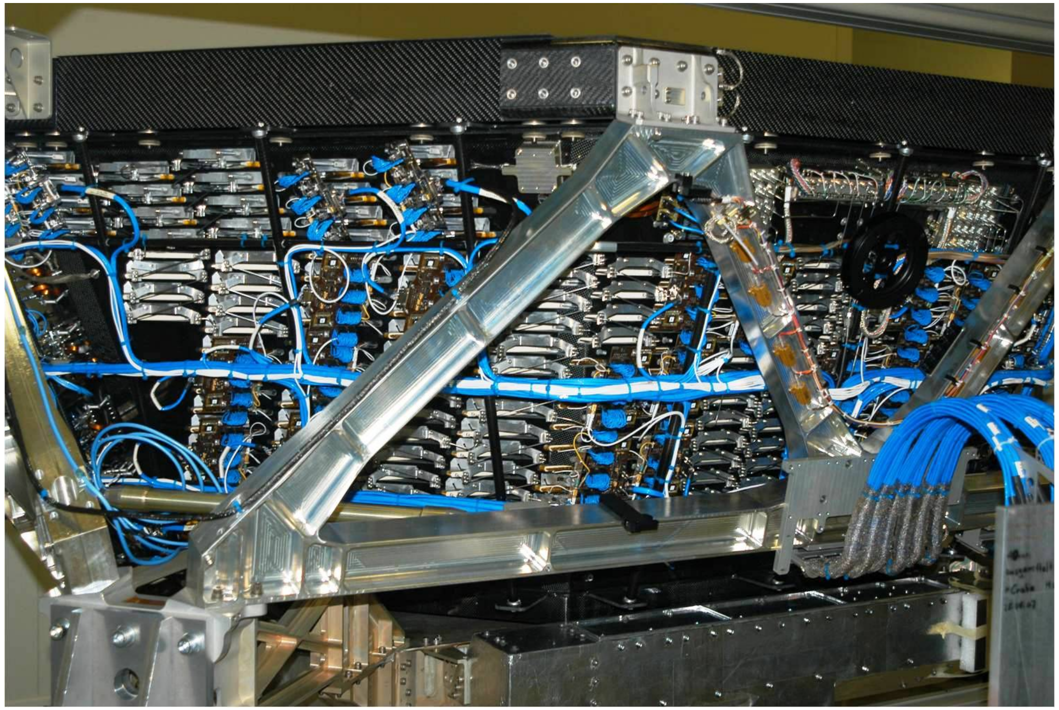
Measured veto(ACC) efficiency better than 0.99999

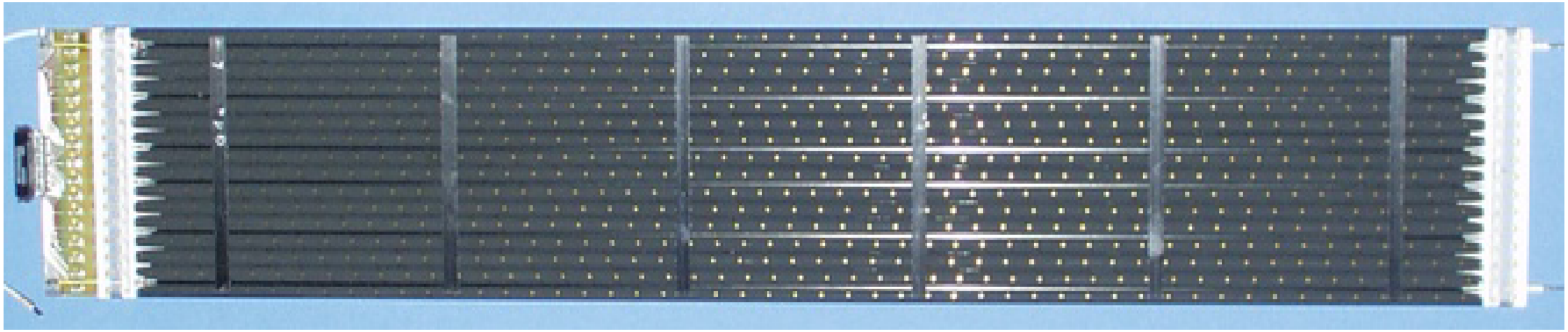
Transition Radiation Detector (TRD) Identifies Positrons, Electrons by transition radiation and Nuclei by dE/dX

20 Layers each consisting of:

- 22 mm fibre fleece
- Ø 6 mm straw tubes
  filled with Xe/CO_2 80%/20%

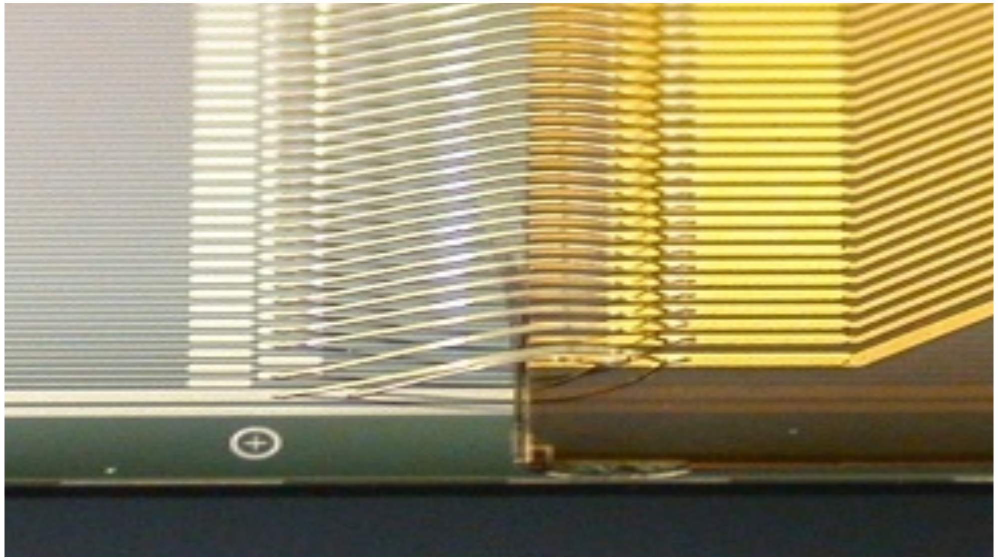






5,248 tubes selected from 9,000, 2 m length centered to 100μm, verified by CAT scanner

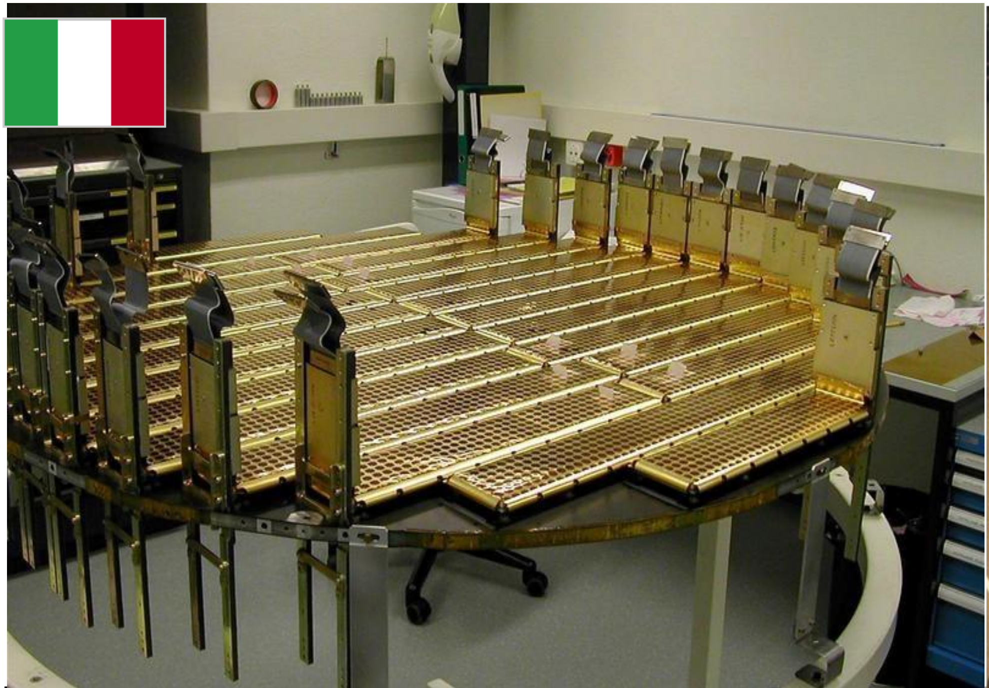
Silicon Tracker

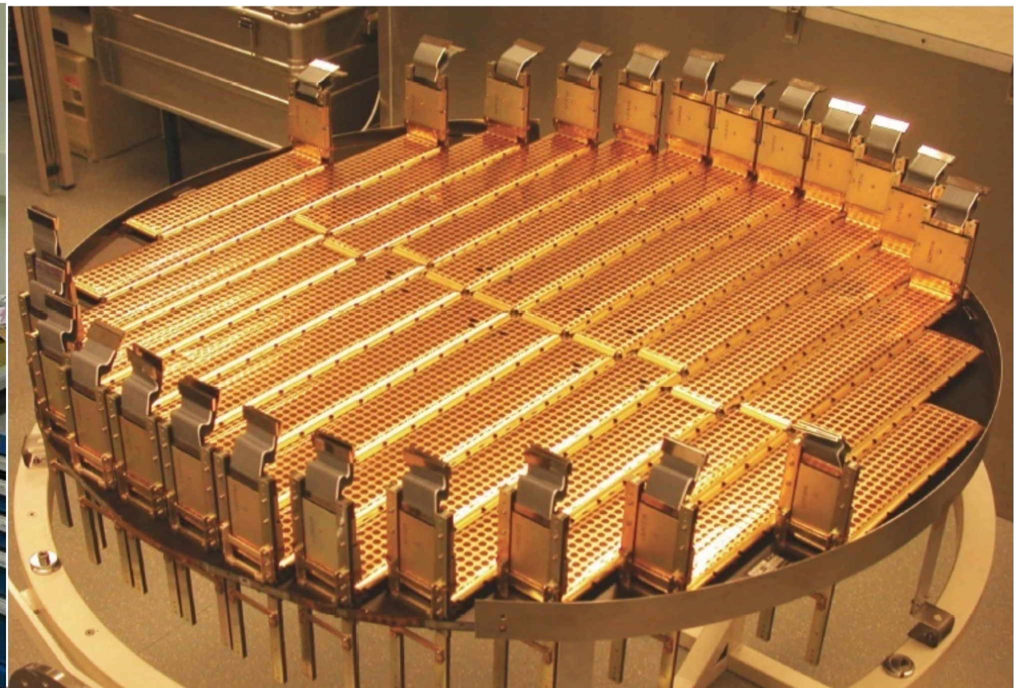


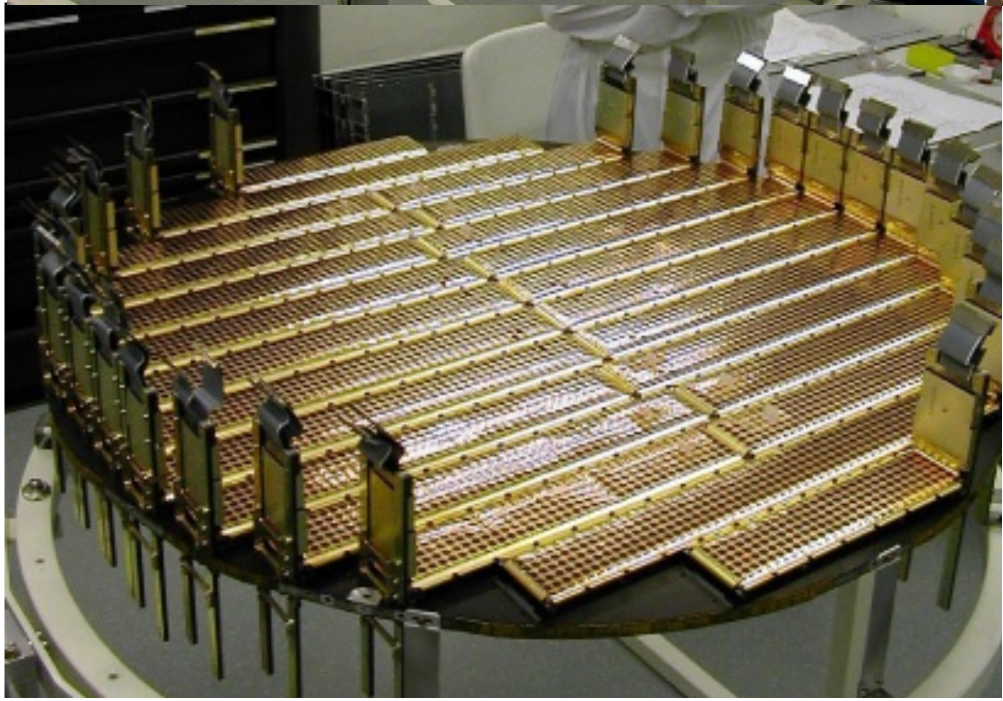
The coordinate resolution is 10 microns

It has taken
50 engineers
3 years
to complete
the silicon
tracker

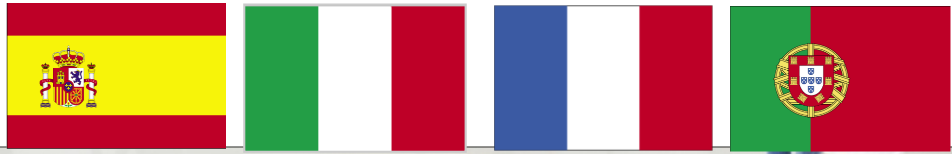
There are 9 planes with 200,000 channels aligned to 3 microns



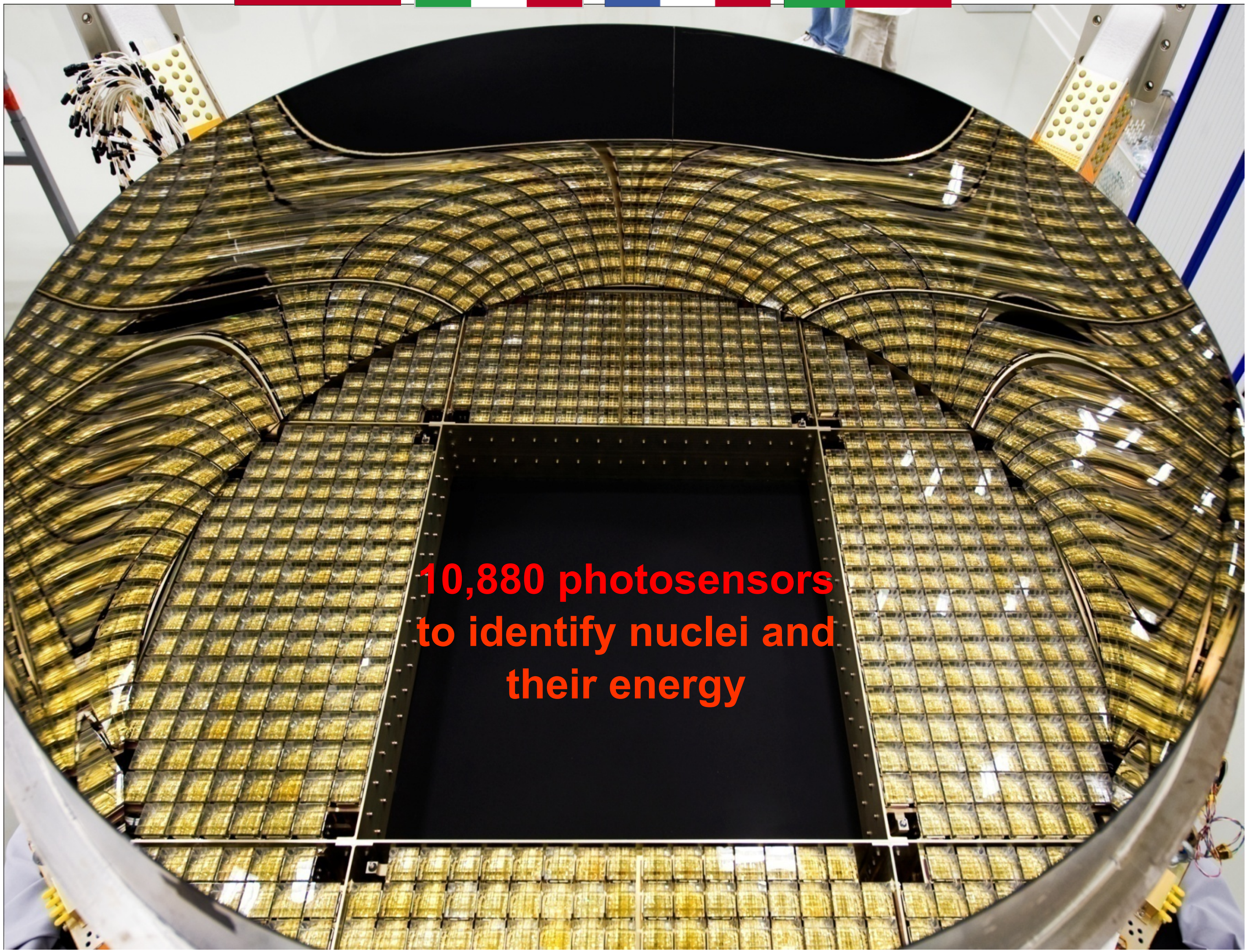


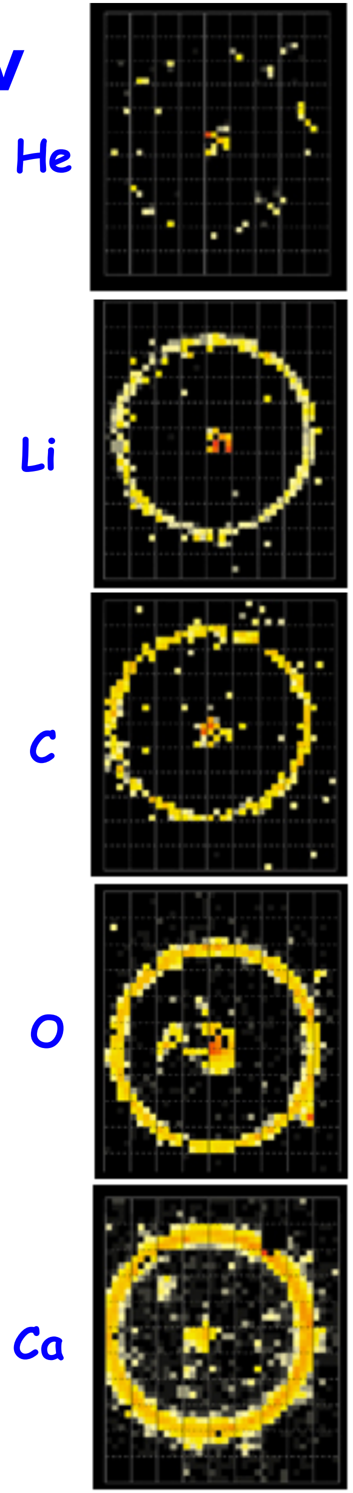


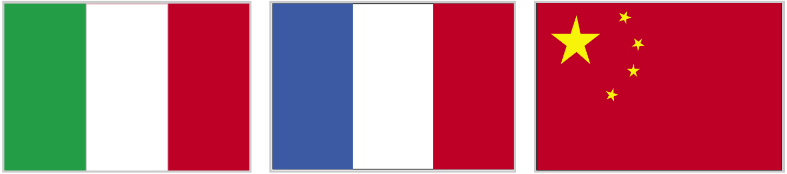
Ring Imaging CHerenkov (RICH)



160 Gv

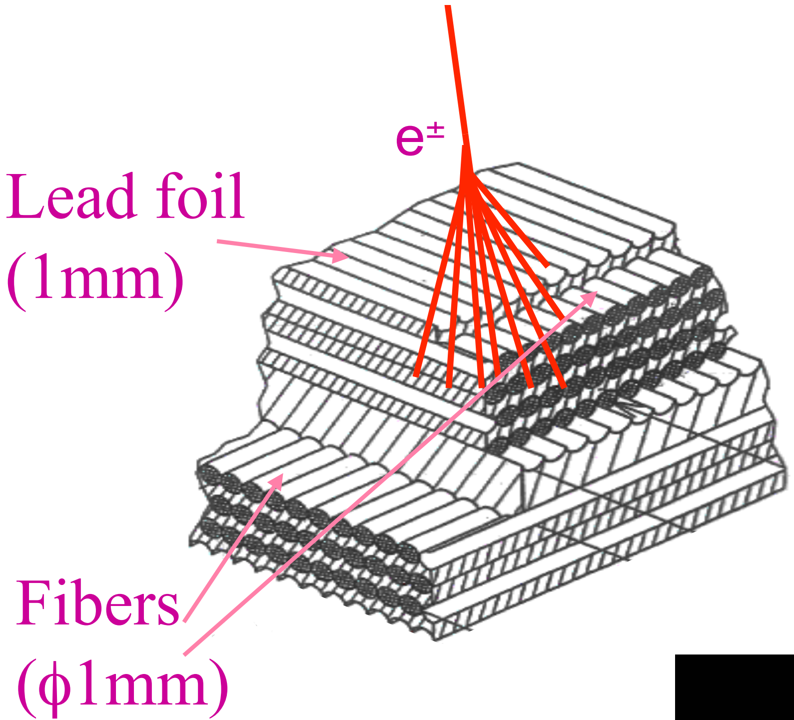


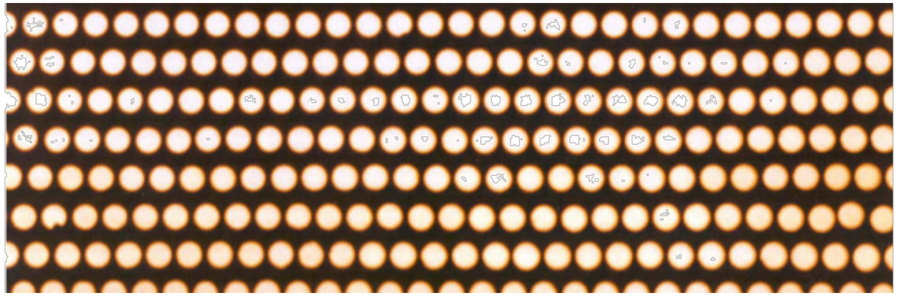




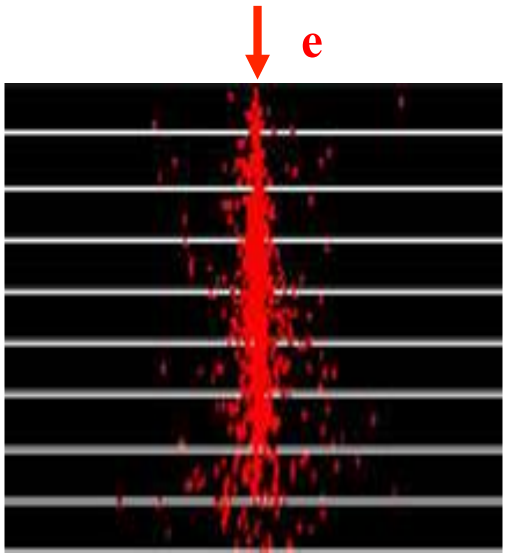
Calorimeter (ECAL)

A precision (3% resolution), 3-D measurement of the directions and energies of light rays and electrons up to 1 TeV





50,000 fibers, $\phi = 1$ mm
distributed uniformly Inside 1,200 lb of lead
Total 17 X_0



AMS electronics

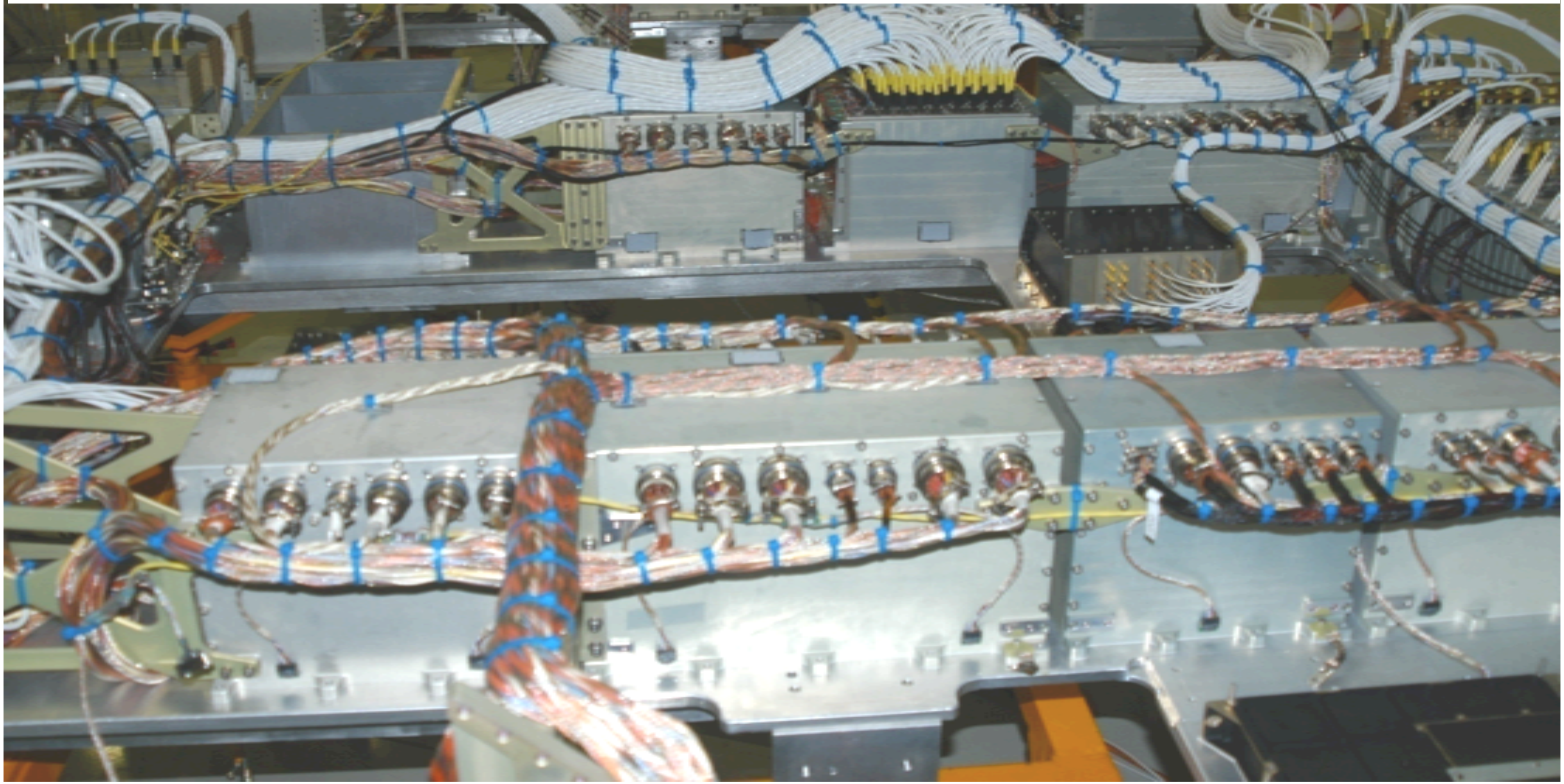
650 computers, 300,000 channels, up to 400% redundancy

Fast: 10 x the commercial space electronics

Accurate: measure coordinate to 10 microns

Linear: 1 in 10^5, 10 MeV to 1 TeV

Electronics fabricated in Taiwan, under NASA supervision



AMS Electronics

Reliability: operational for 20 years.

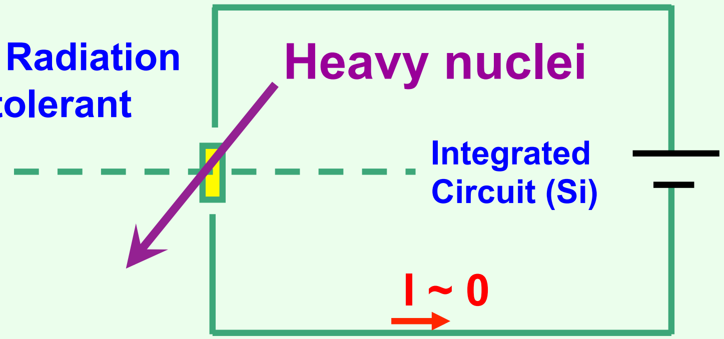
Fast: 10 x the commercial space electronics

Accurate: measure coordinate to 10 microns

Linear: 1 in 10^5, 10 MeV to 1 TeV

Radiation Effects on Components:

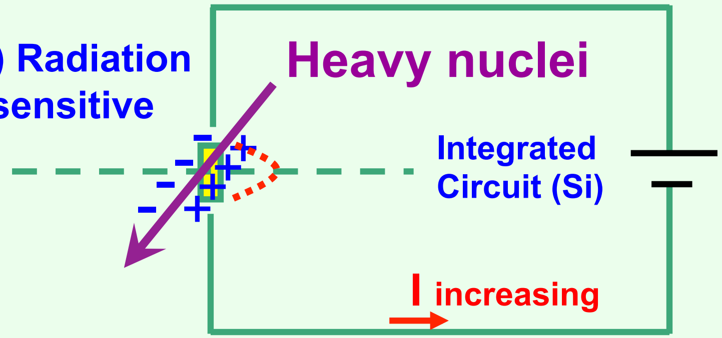
(A) Radiation tolerant



(A) For a radiation tolerant IC, the current induced by a heavy ion is ~ 0

Only radiation tolerant chips (A) are allowed in space.

(B) Radiation sensitive

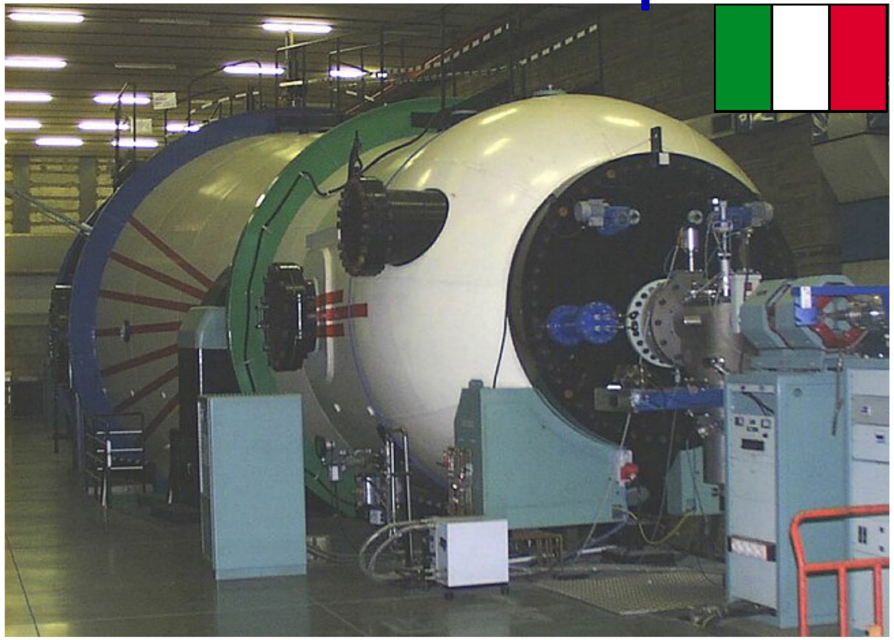


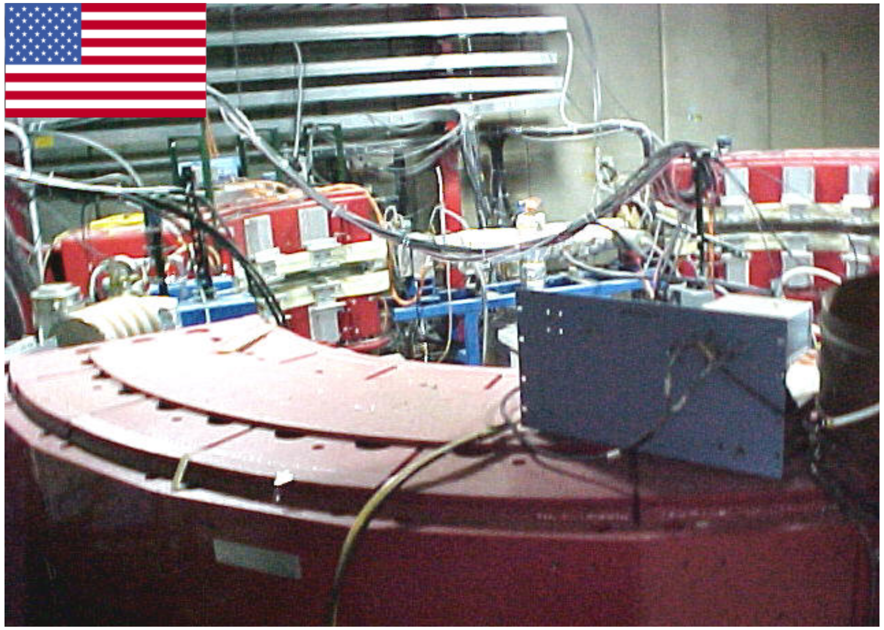
(B) For a radiation sensitive IC, the current induced by a heavy ion increases, leading to:

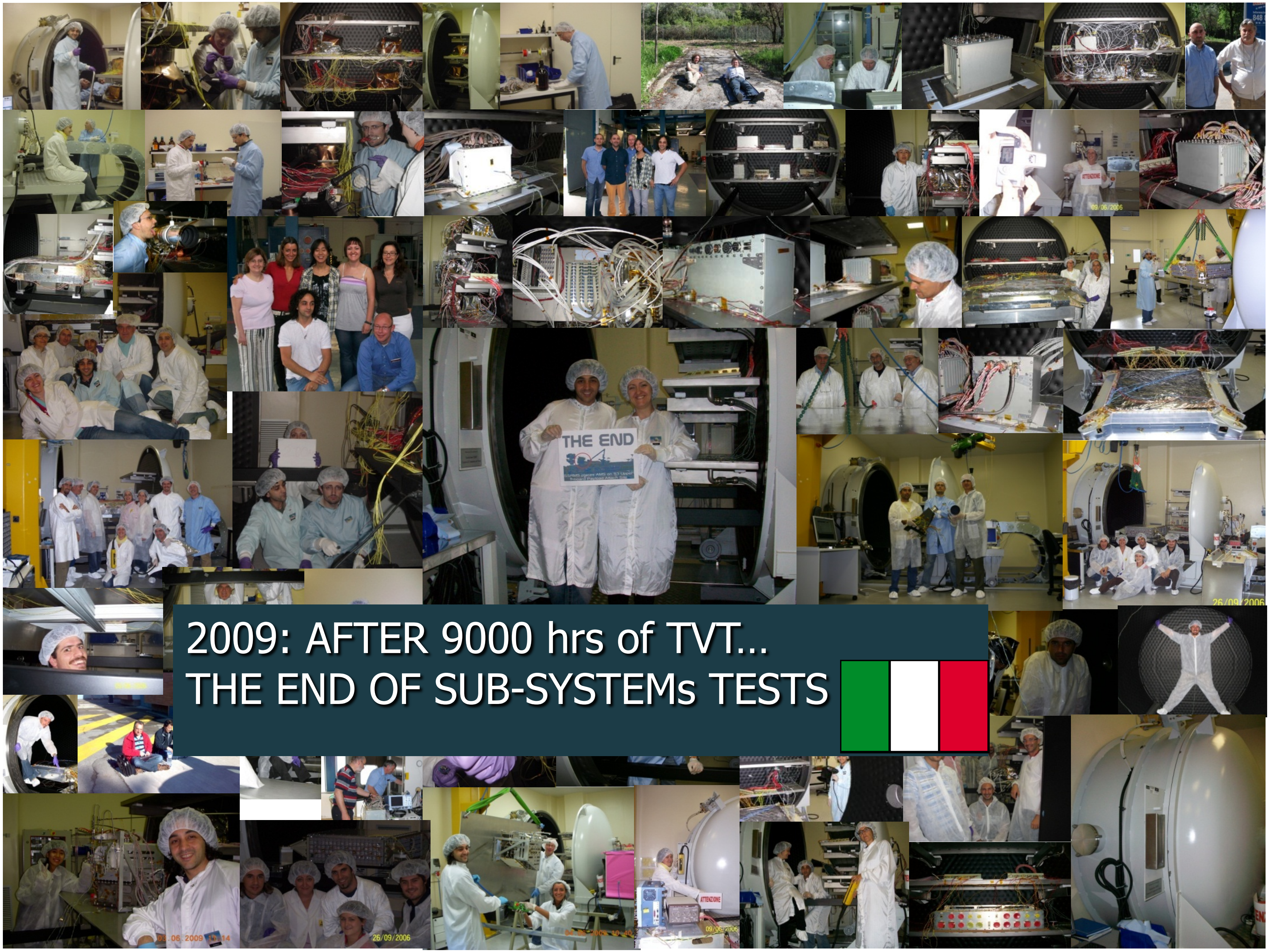
1) Bit-flips - a logic state is changed,
2) Latch-ups - the IC or circuit are damaged.

AMS Electronics

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



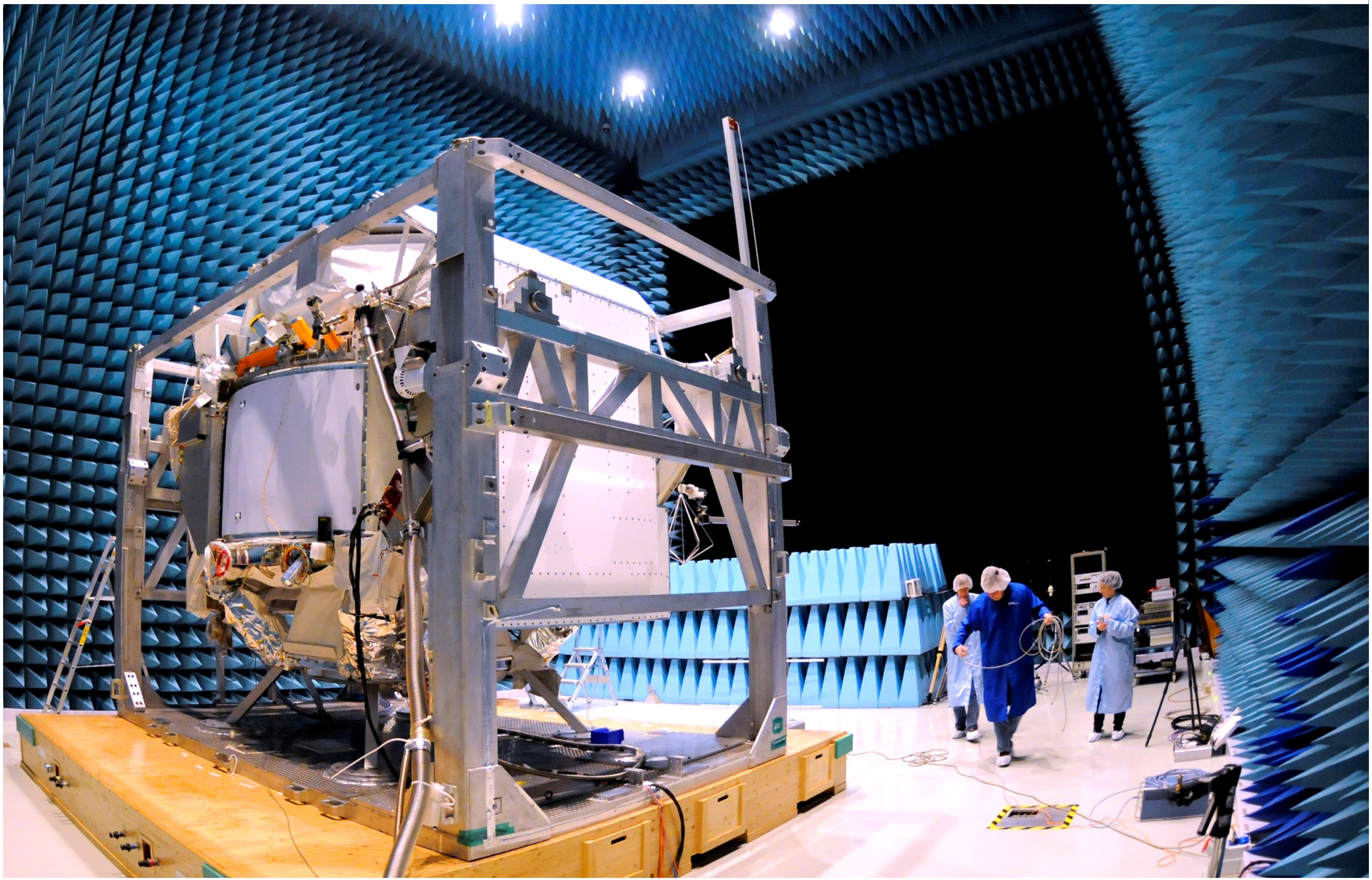




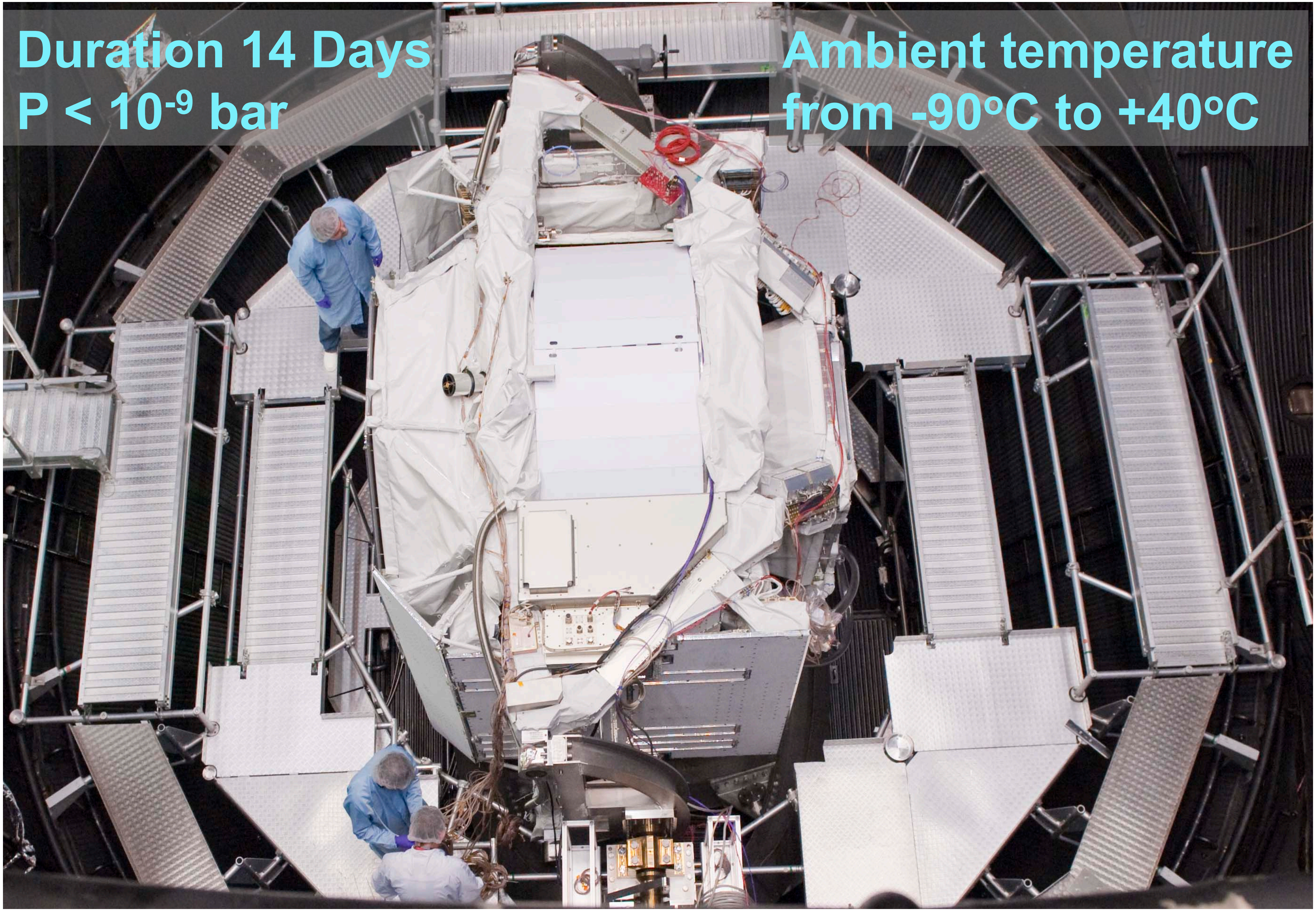
2009: AFTER 9000 hrs of TVT…

THE END OF SUB-SYSTEMs TESTS

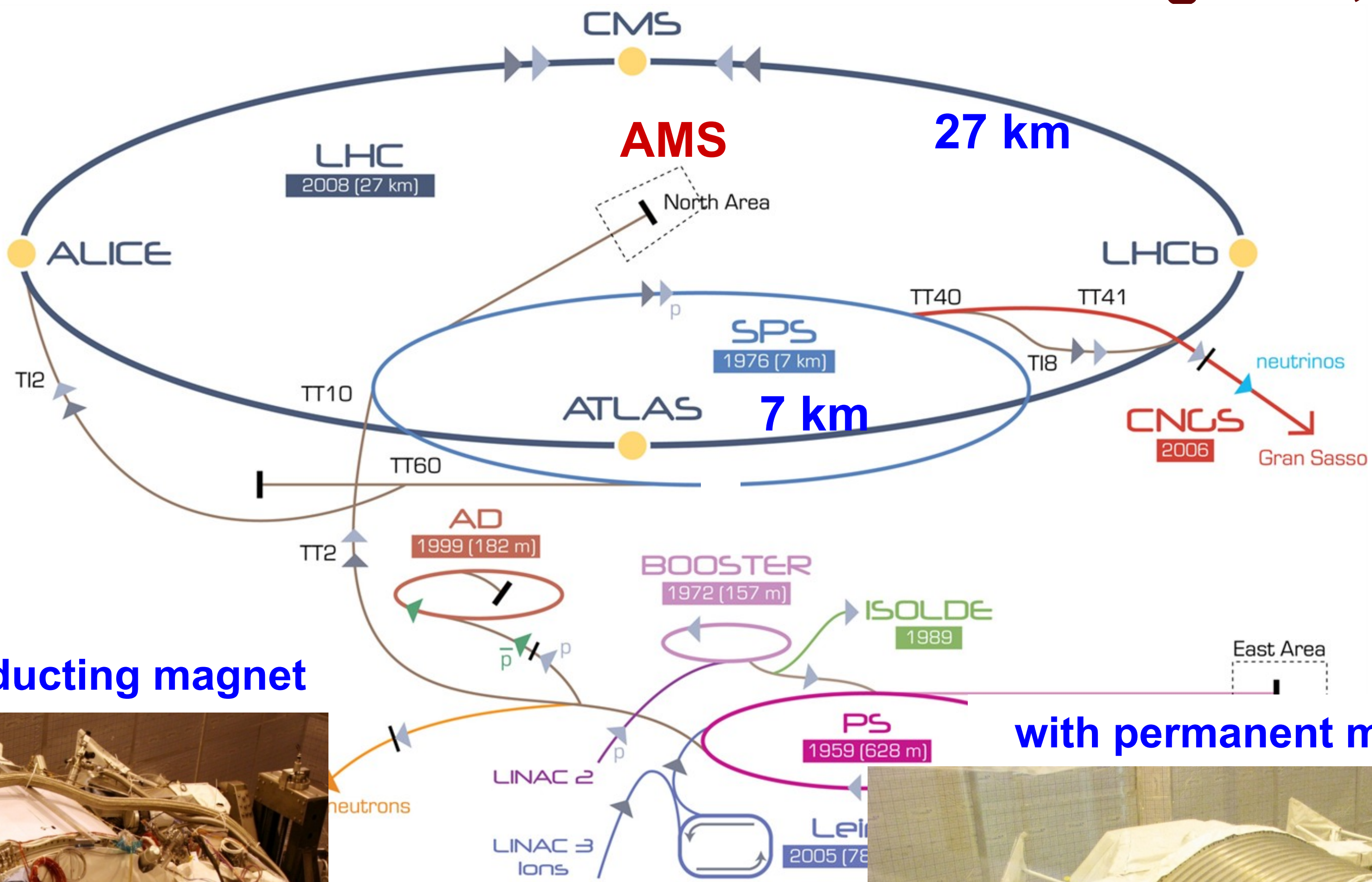
AMS in the ESA Electromagnetic Interference (EMI) Chamber, March 2010, Noordwijk, the Netherlands



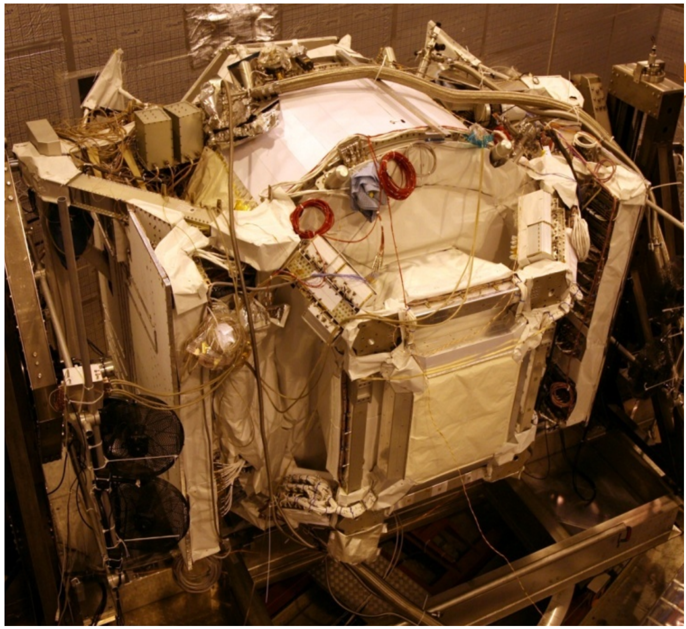
AMS in the ESA Thermal Vacuum Chamber, April 2010



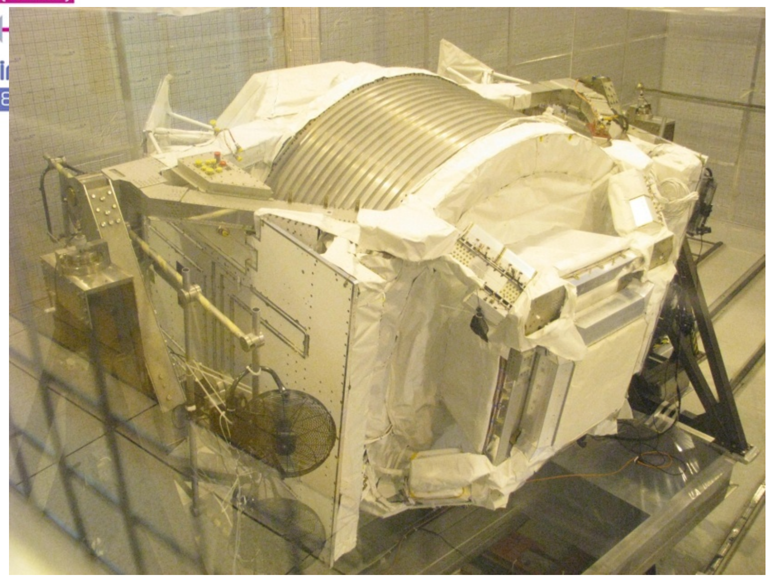
Tests at CERN
AMS in accelerator test beams Feb 4-8 and Aug 8-20, 2010



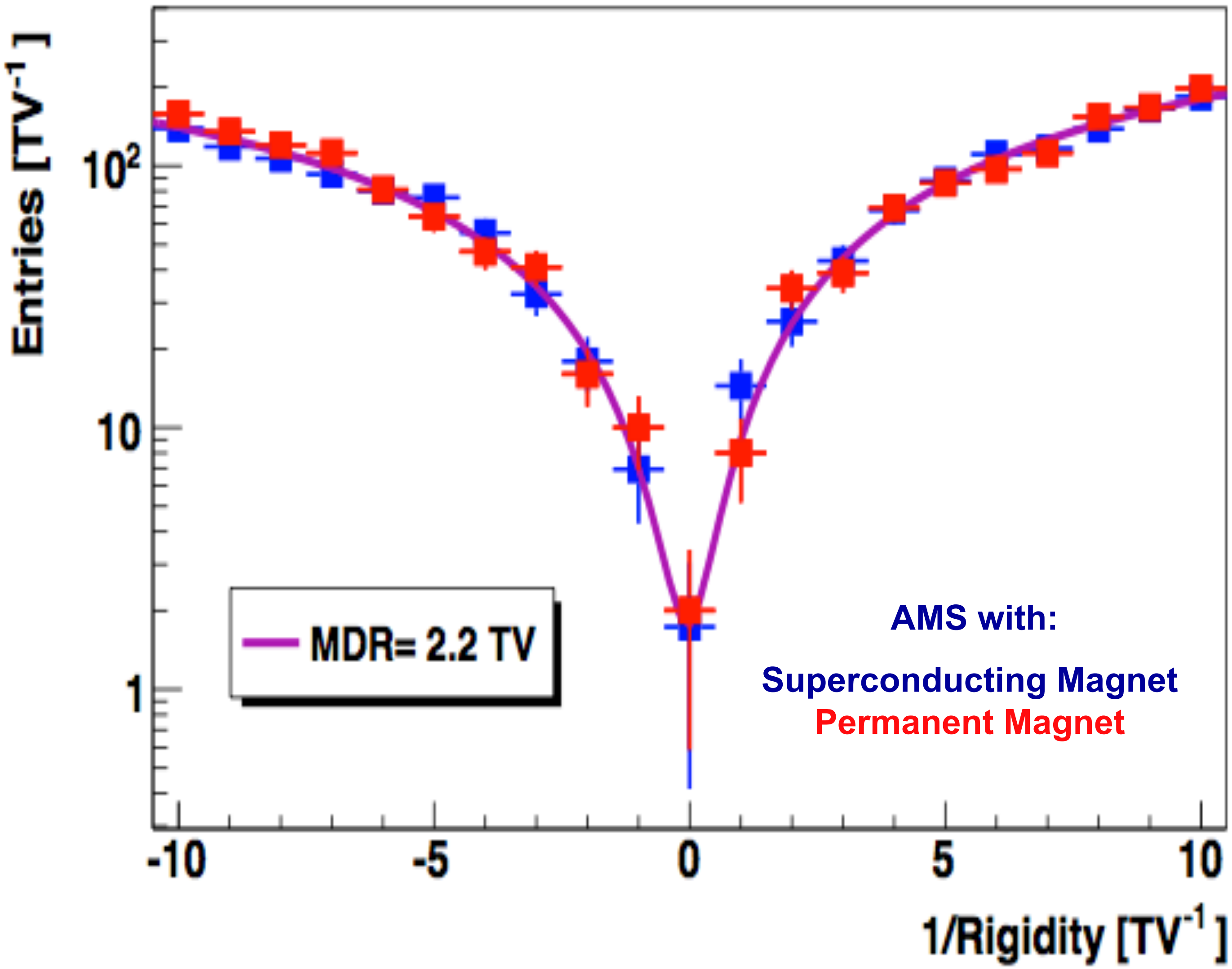
with superconducting magnet



with permanent magnet



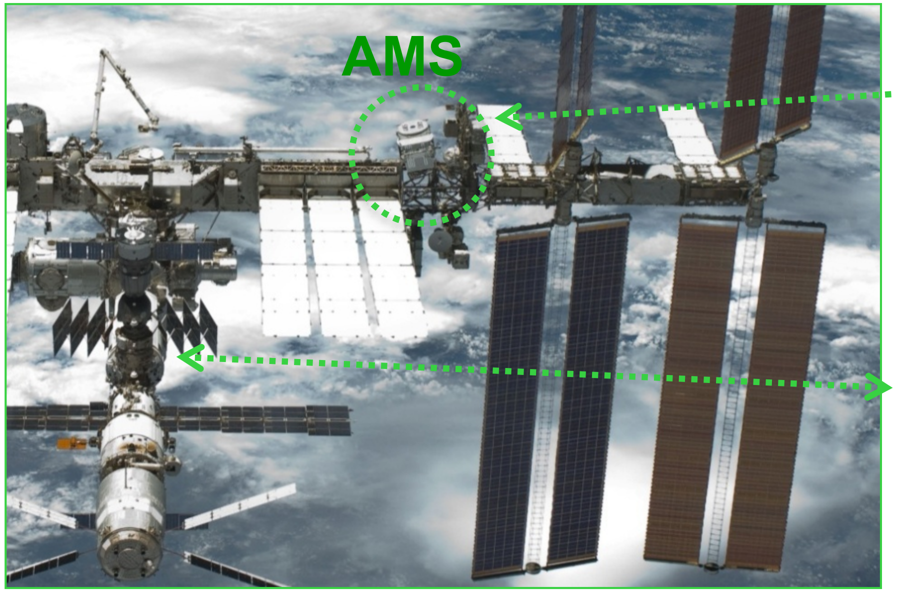
Rigidity resolution

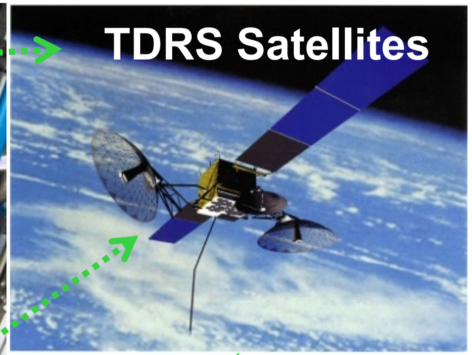



5m x 4m x 3m
7.5 tons
AMS
AMS is a unique Experiment on the ISS conducting particle physics research in space for the next two decades.

May 19, 2011: AMS installation completed at 5:15 AM.
Data taking started at 9:35 AM

AMS Operations





Flight Operations

Ku-Band
High Rate (down):
Events <10Mbit/s>

Ground Operations

S-Band
Low Rate (up & down):
Commanding: 1 Kbit/s
Monitoring: 30 Kbit/s

AMS Payload Operations Control and Science Operations Centers (POCC, SOC) at CERN

AMS Computers at MSFC, AL

White Sands Ground Terminal, NM

AMS Operations

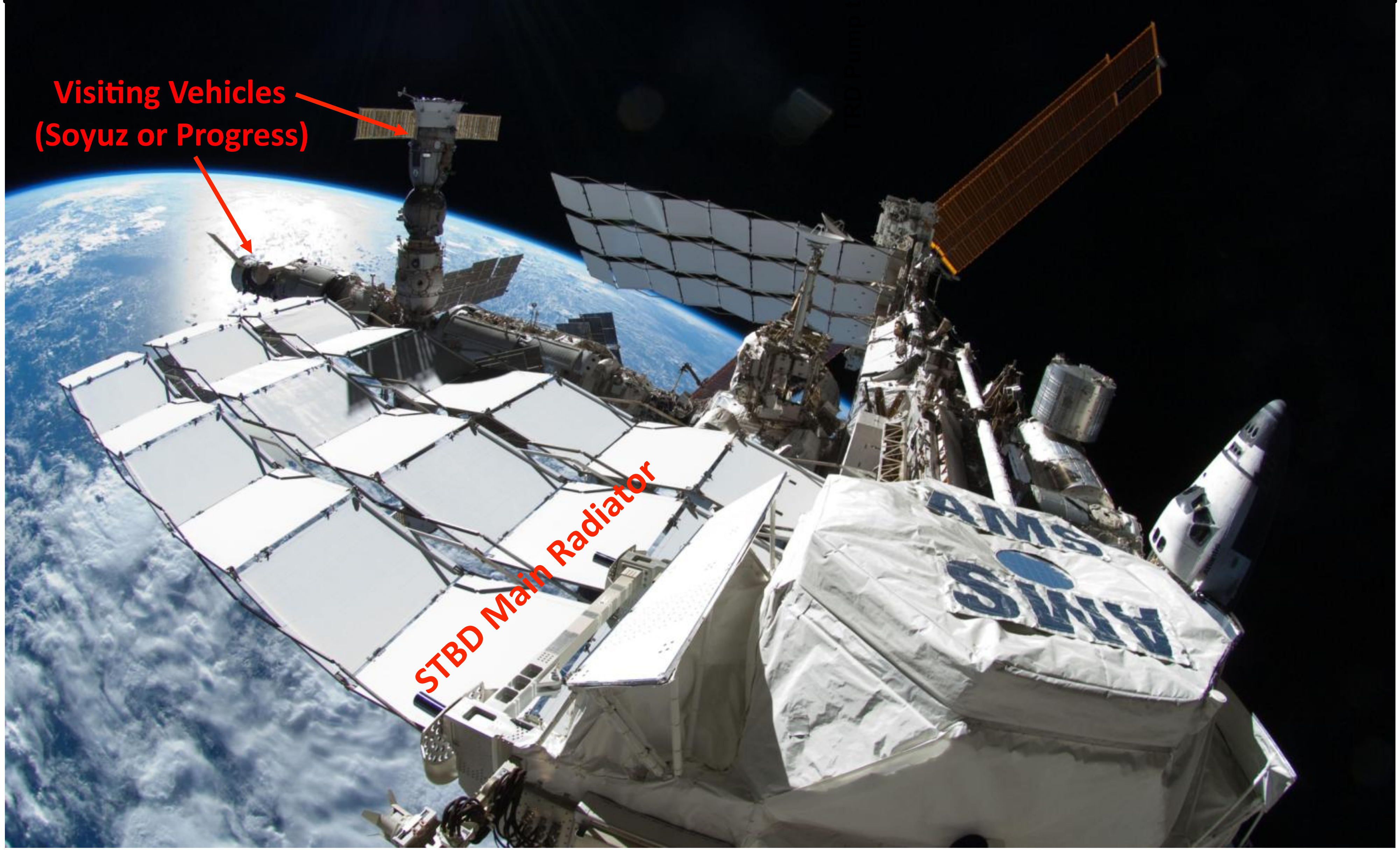
Thermal Control is the most challenging task in the operation of AMS

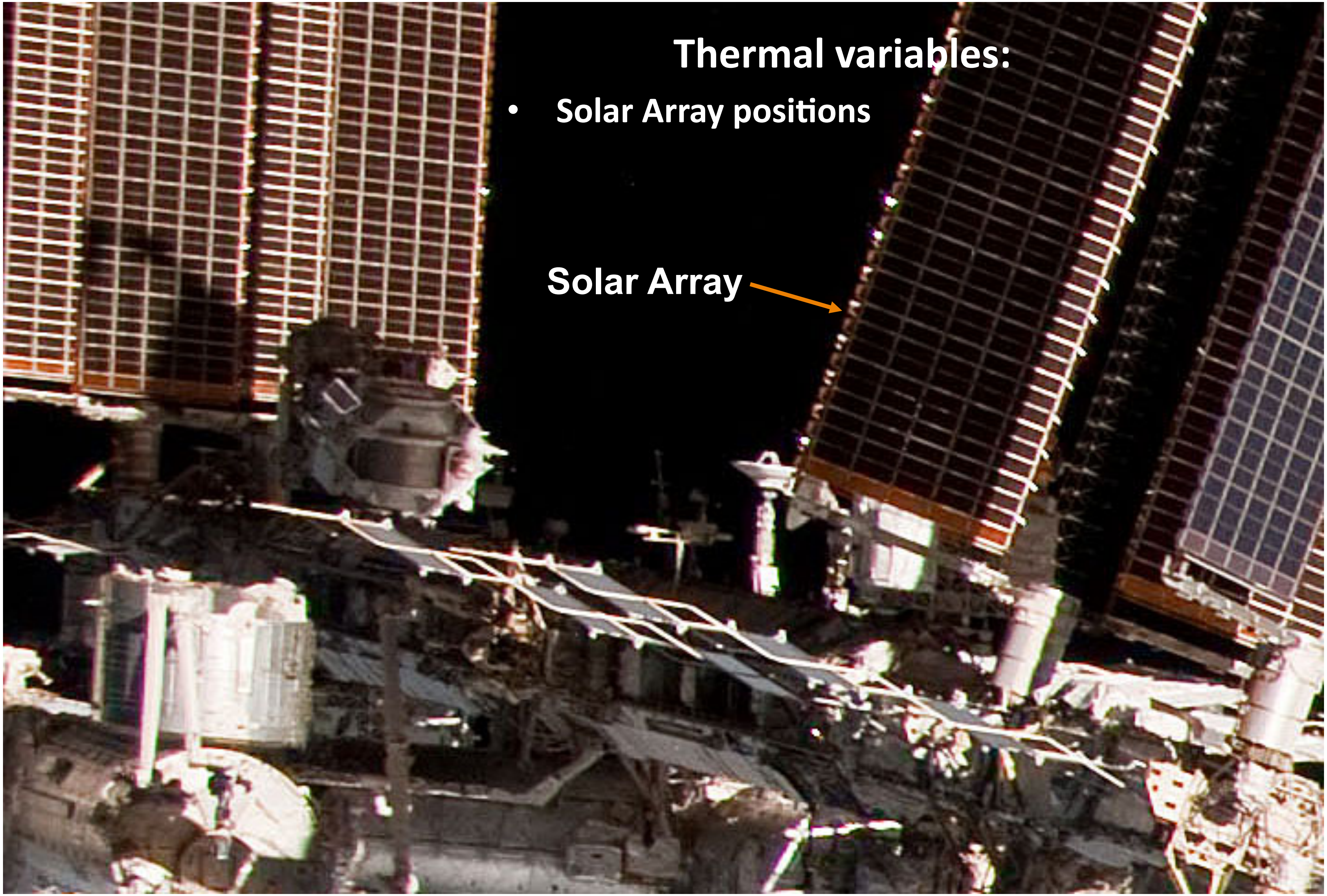
The thermal environment on ISS is constantly changing due to:

- Solar Beta Angle (β)
- Position of the ISS Radiators and Solar Arrays
- ISS Attitude

Thermal variables:

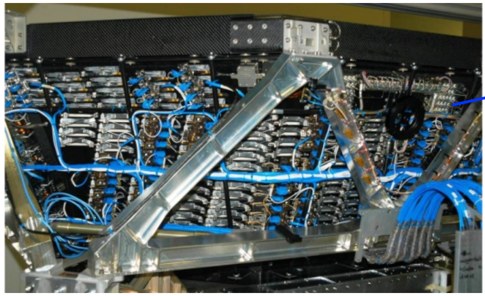
- ISS Radiator positions
- ISS attitude changes (primarily for visiting vehicles)

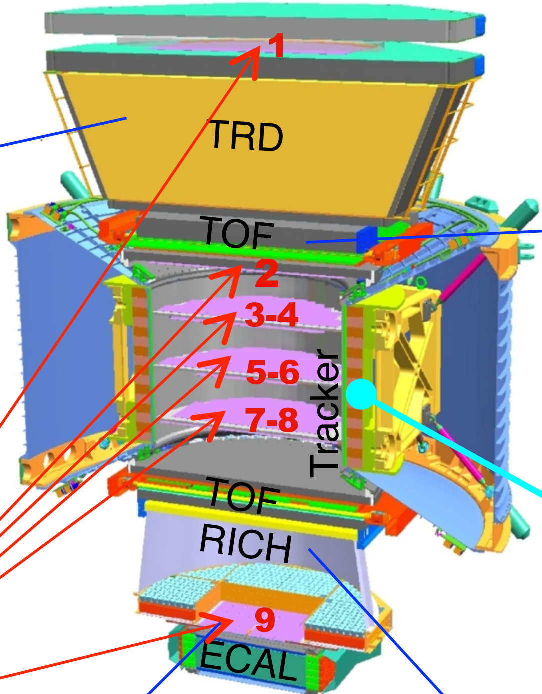



Thermal variables:
• Solar Array positions
Solar Array

AMS Flight Electronics for Thermal Control

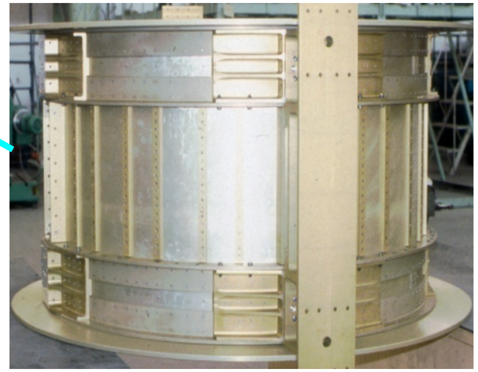
TRD
24 Heaters
8 Pressure Sensors
482 Temperature Sensors



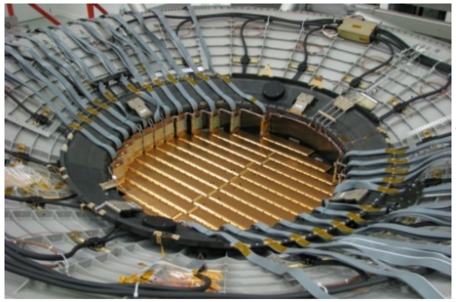


TOF & ACC
64 Temperature Sensors

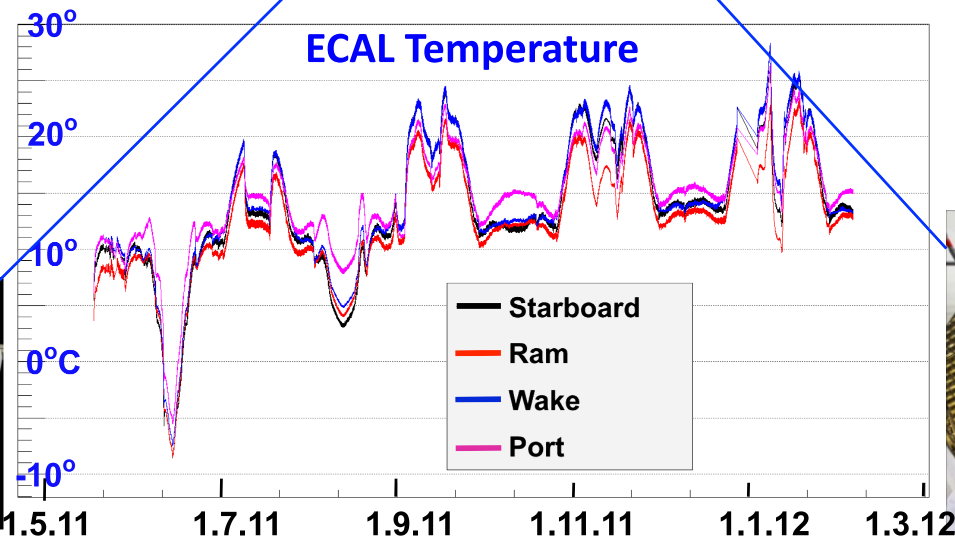
Magnet
68 Temperature Sensors



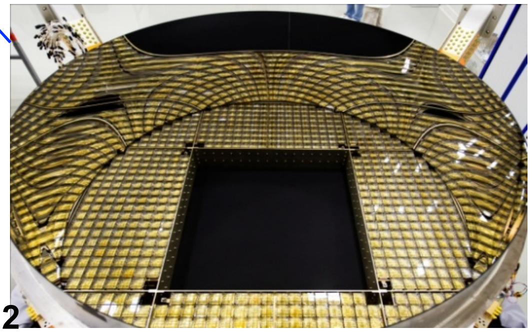
Silicon Tracker
4 -Pressure Sensors
32 Heaters
142 Temperature Sensors



ECAL
80 Temperature Sensors

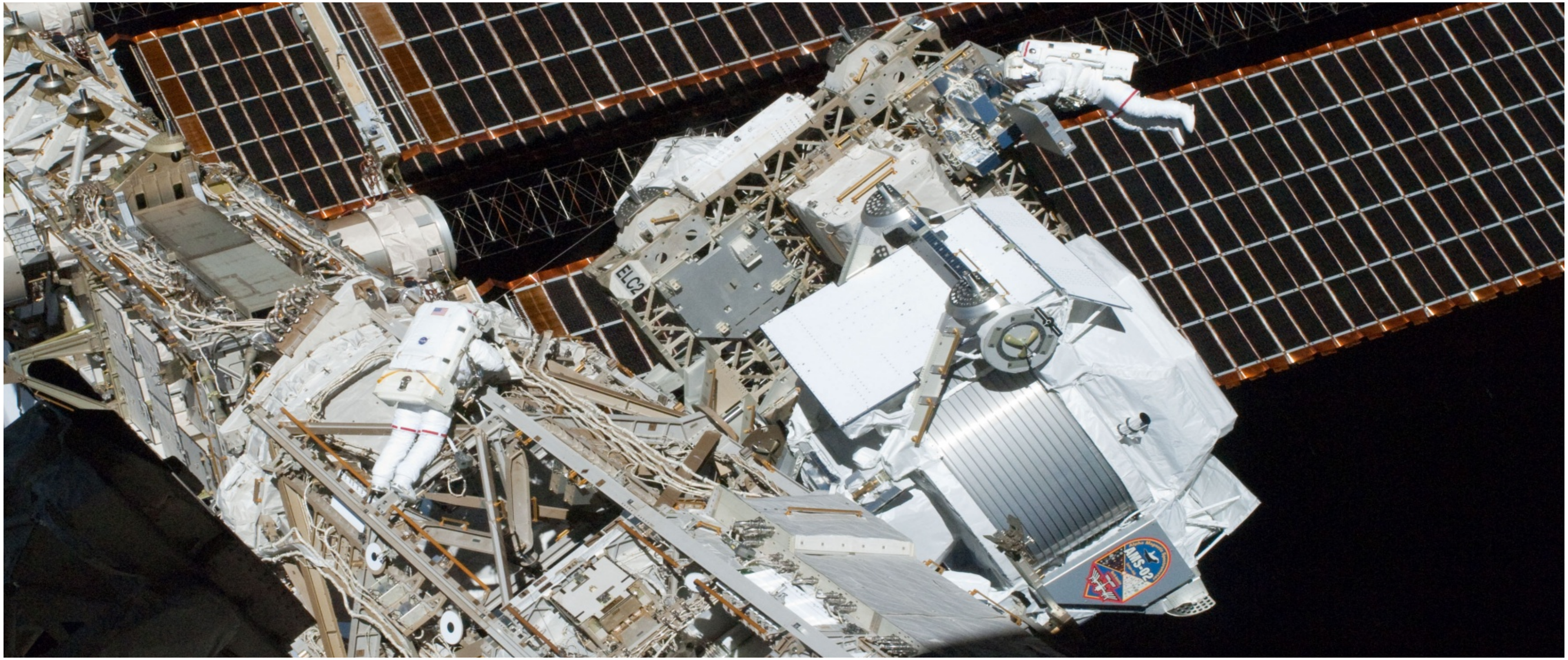


RICH
96 Temperature Sensors



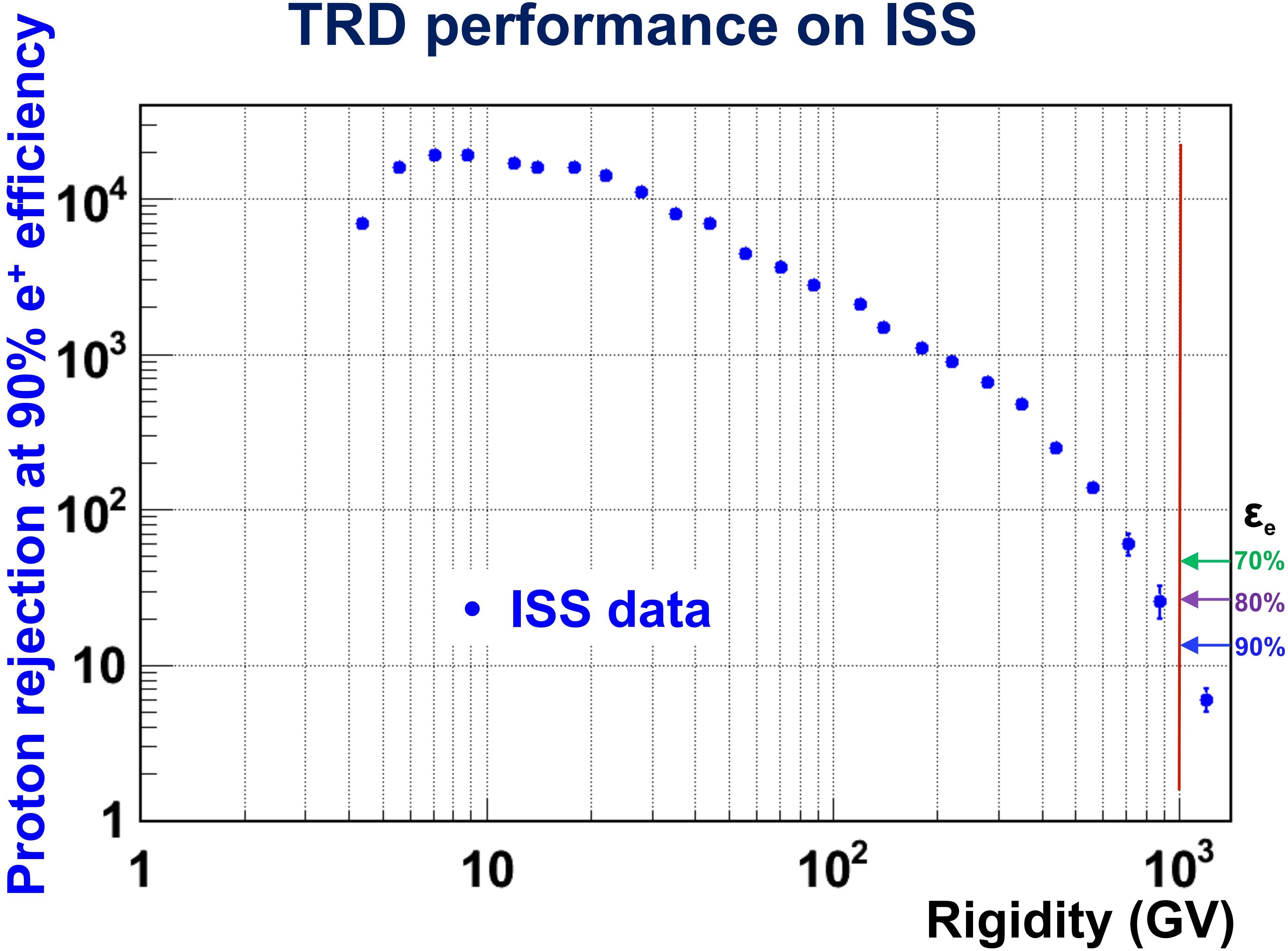
Flight Operations:

AMS Data Acquisition System



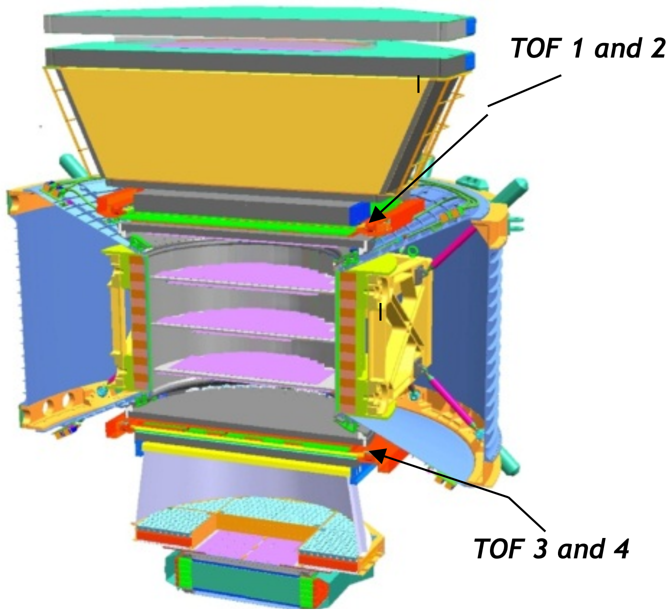
To read out 300,000 channels at up to 2 KHz, the AMS Team developed a large set of computers (650) which are programmable from the POCC and which readout all the different detectors with up to 400% redundancy. Hundreds of these computers are interconnected in a tree like structure with an 100 MBit/s serial link.

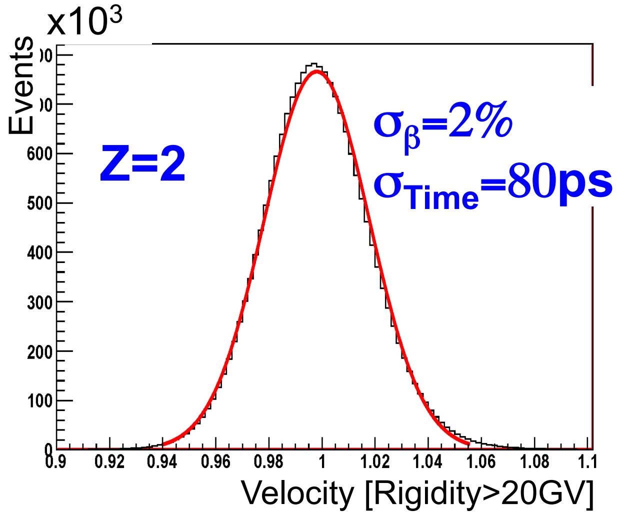
TRD performance on ISS

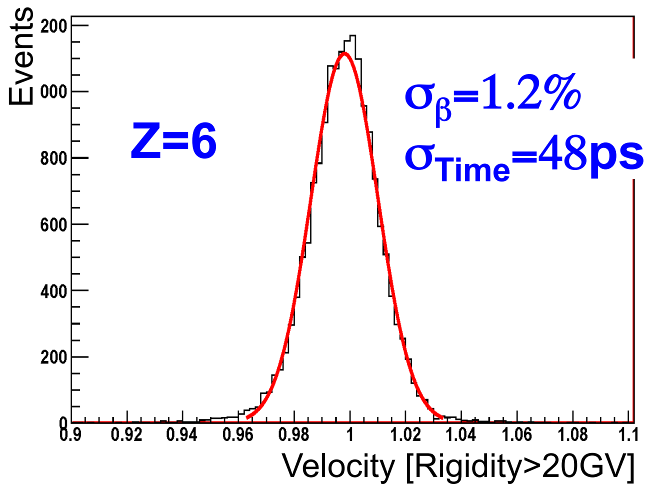


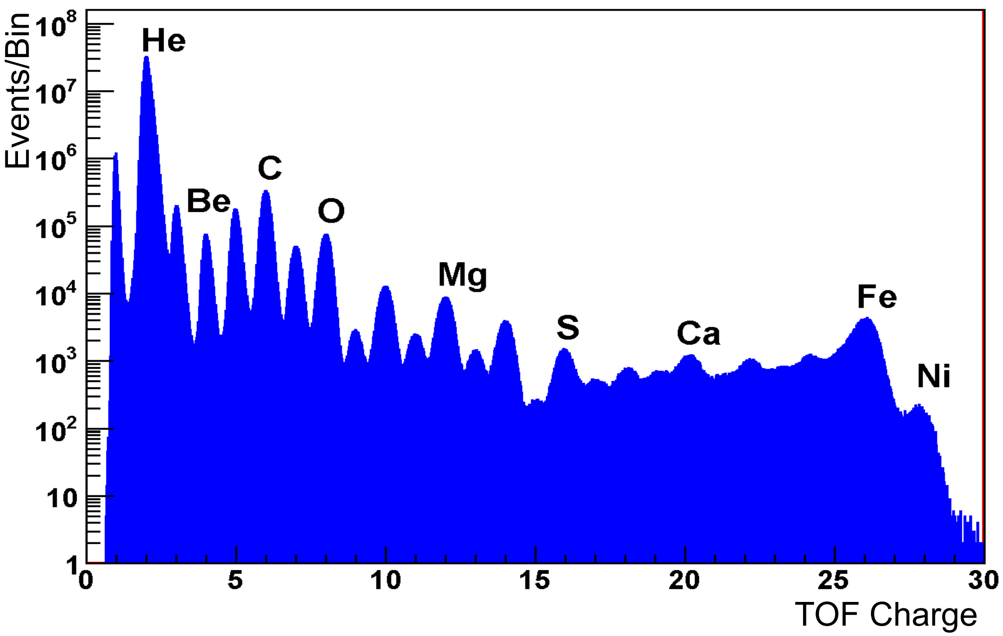
Data from ISS Time of Flight System

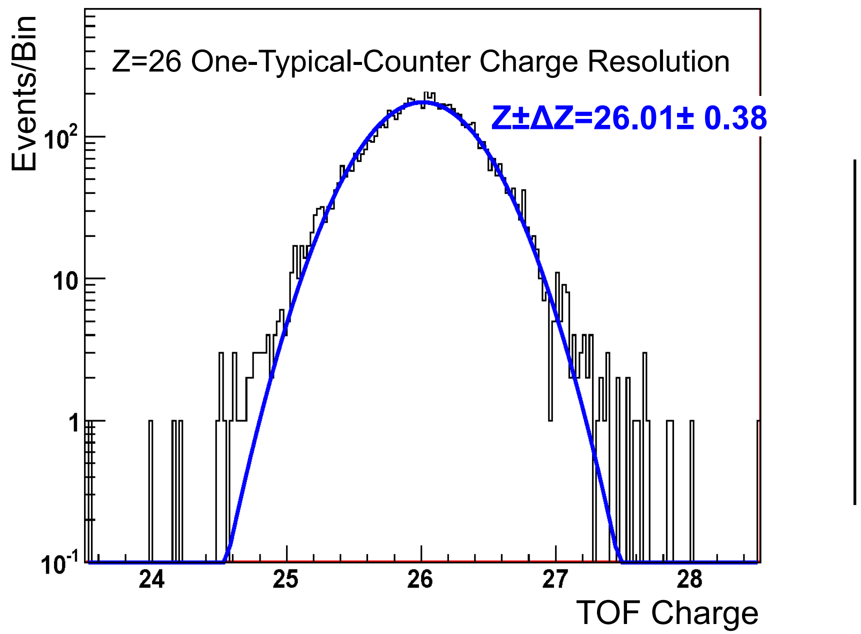
Measures Velocity and Charge of particles









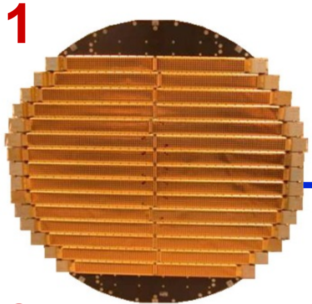


Tracker Readout Computers

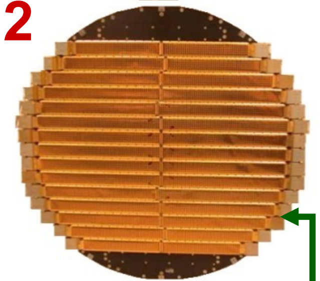
196,608 Pulse Heights,
216 Low Voltages,

192 Tracker Data Reduction (TDR) **16** Readout Computers (JINF-T)

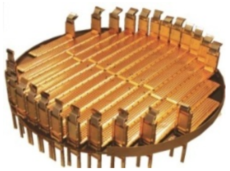
1



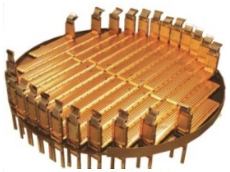
2



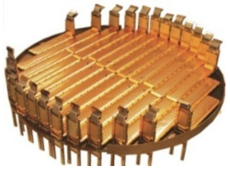
3
4



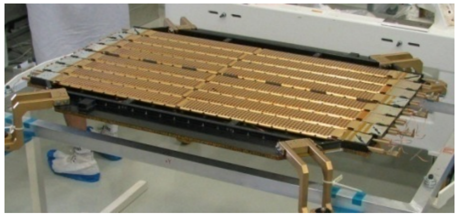
5
6



7
8

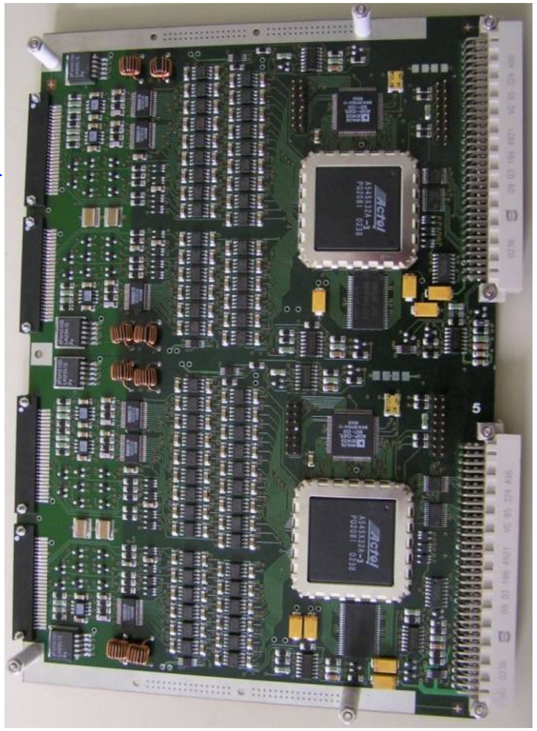


9



196,608
Pulse Heights

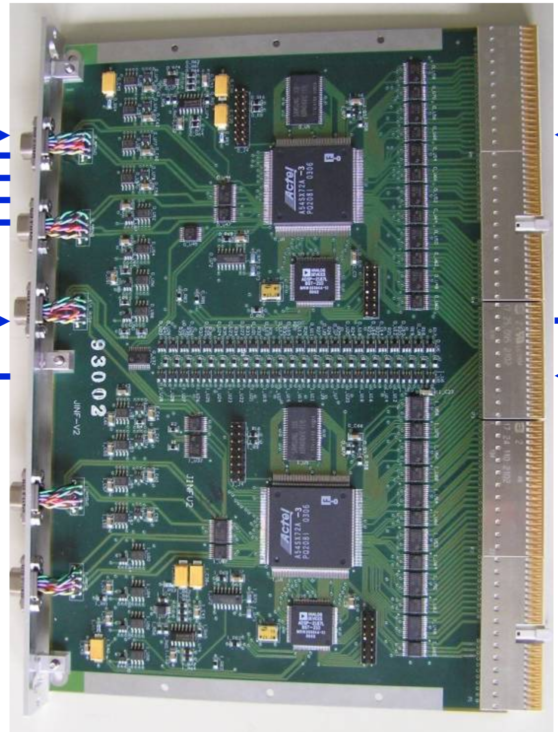
Low voltage



AMSWire

Busy

Trigger



AMSWire

To next level

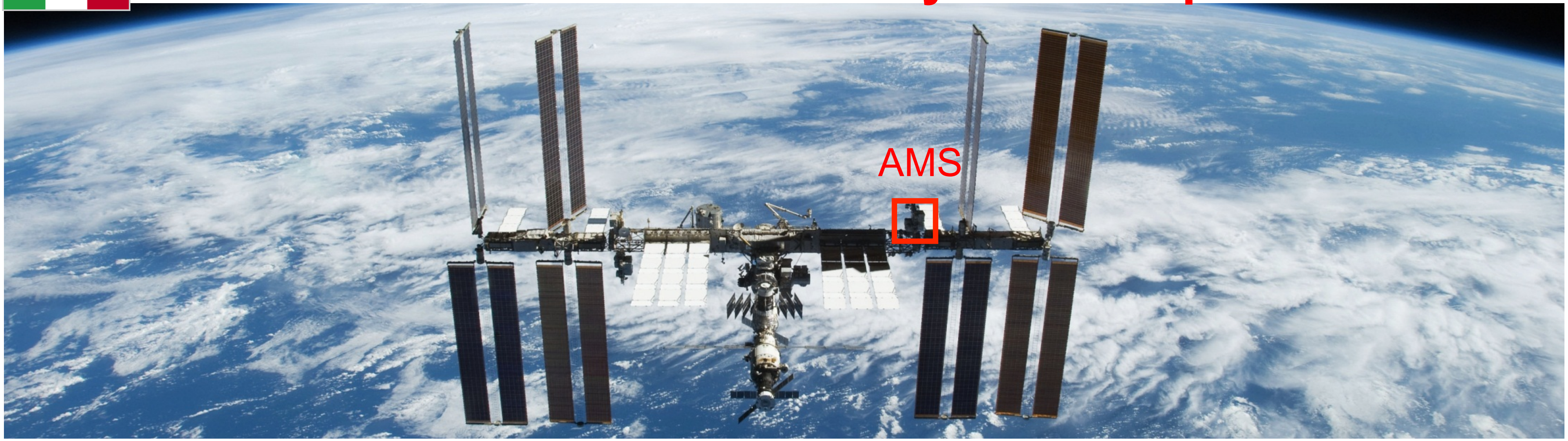
Busy

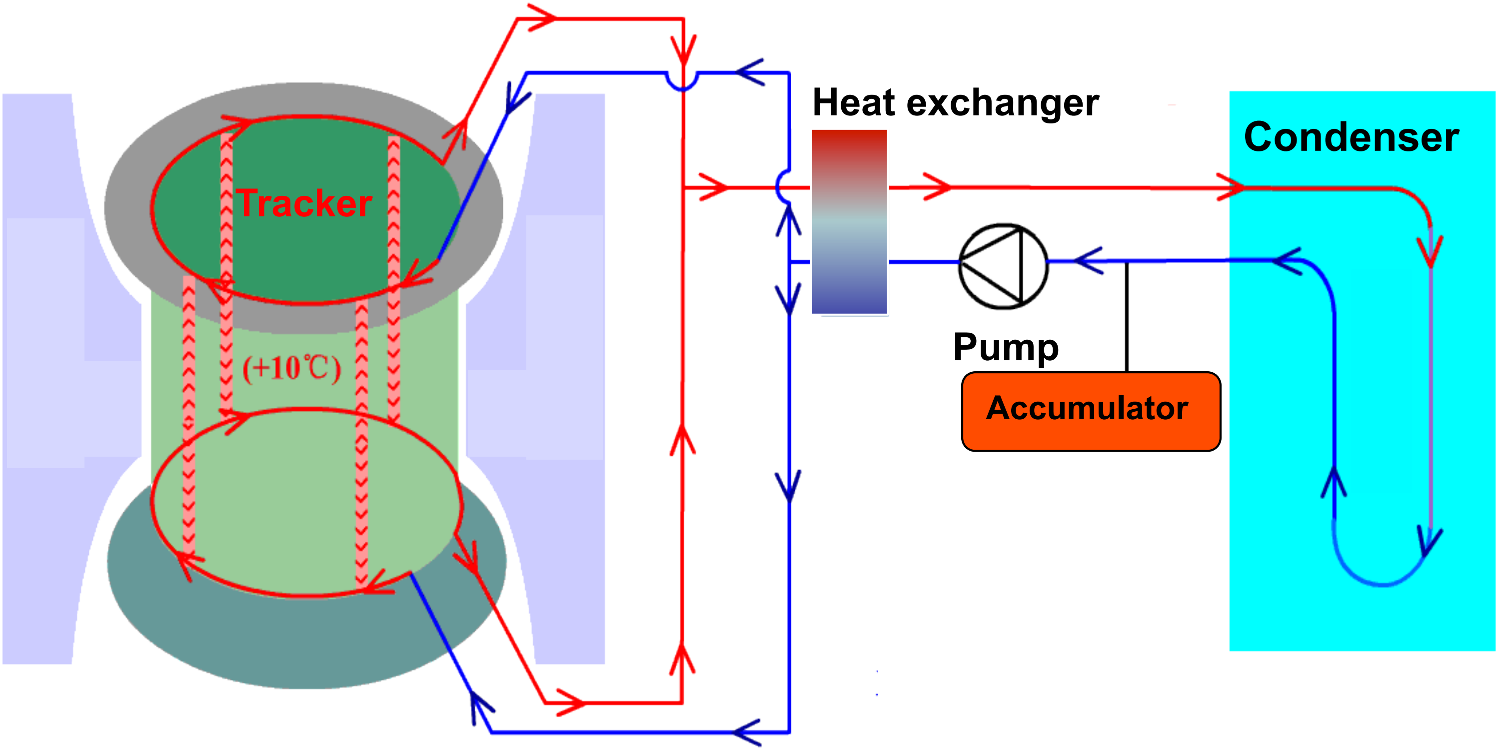
Trigger

- Analog to digital conversion
  coordinate resolution of 10 um
- Data reduction:
  - Pedestal subtraction
  - Noise suppression
  - Cluster finding
- Format, send to next level

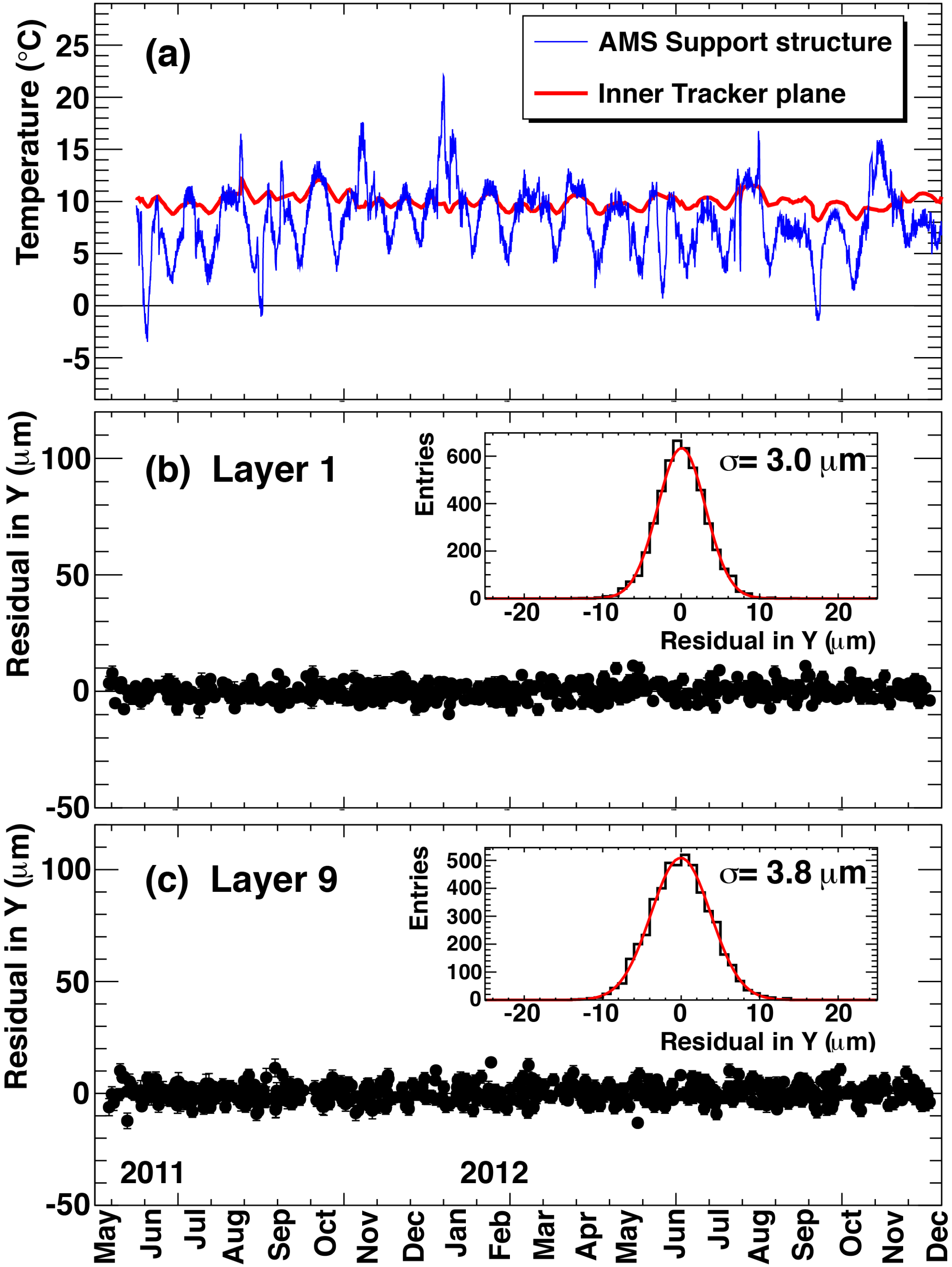
- Collect data from TDR
- Format, send to next level
- Control Low Voltages
- Combine Busy signals
- Distribute Trigger
- Distribute command to TDR

Tracker Thermal Control System in Space





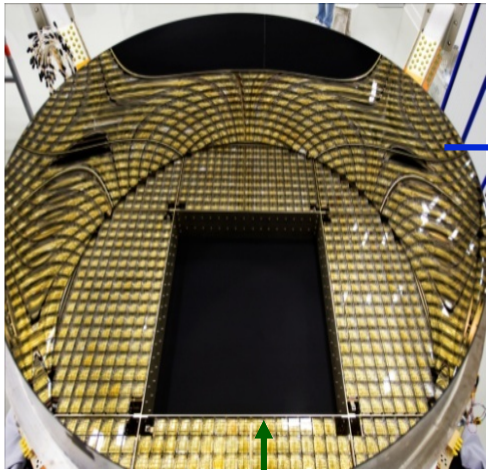
Red line: CO_2 gas/liquid two phase   **Blue line: CO_2 liquid phase**



(a)
AMS Support structure
Inner Tracker plane
Temperature (°C)
(b) Layer 1
σ= 3.0 μm
Entries
Residual in Y (μm)
(c) Layer 9
σ= 3.8 μm
Entries
Residual in Y (μm)
2011
2012
May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

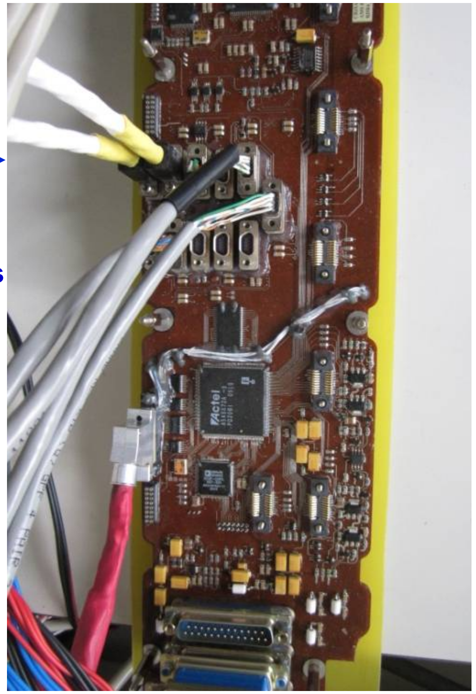
RICH Readout Electronics

21,760 Pulse Heights (high and low gain), 176 Voltages



21,760 Pulse Heights

24 RICH Data Reduction Computers (RDR)

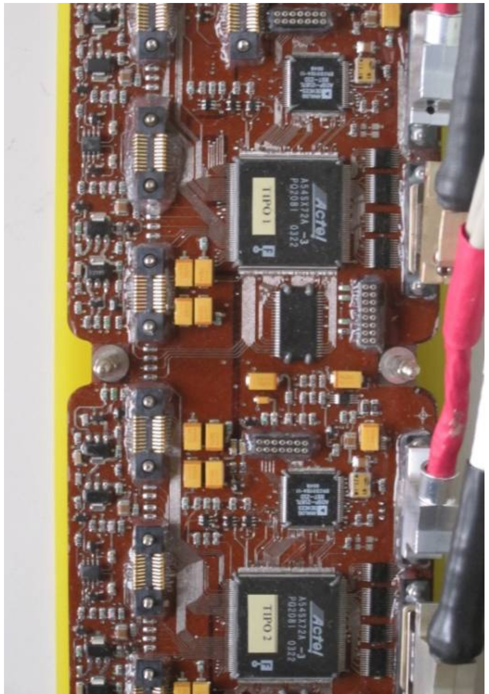


AMSWire

Busy

Trigger

4 Readout Computers (JINF-R)



AMSWire

To next level

Busy

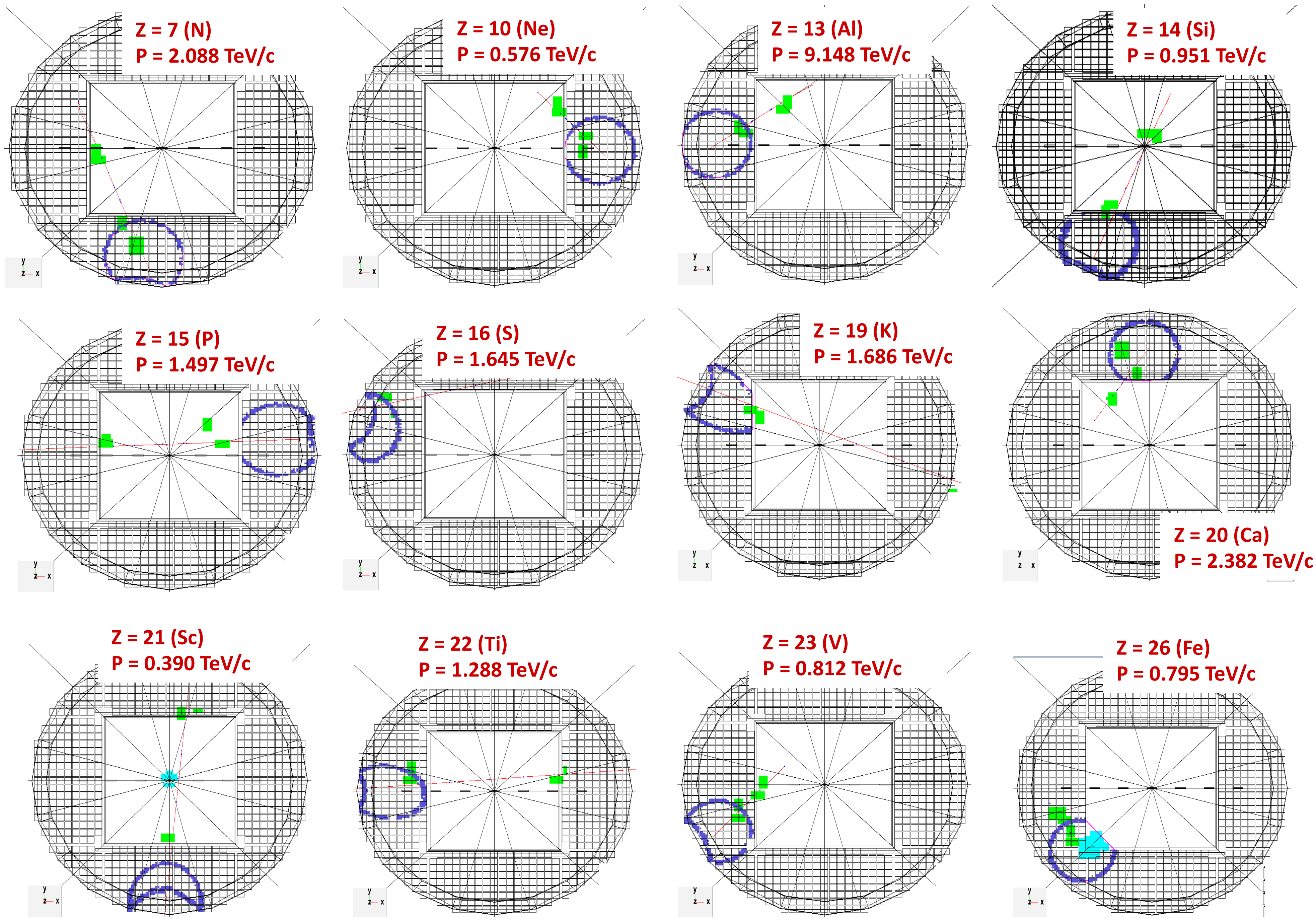
Trigger

High & Low Voltage Control

- Analog to digital conversion
- Velocity resolution of 1:1000
- Data reduction
- Format, send to next level

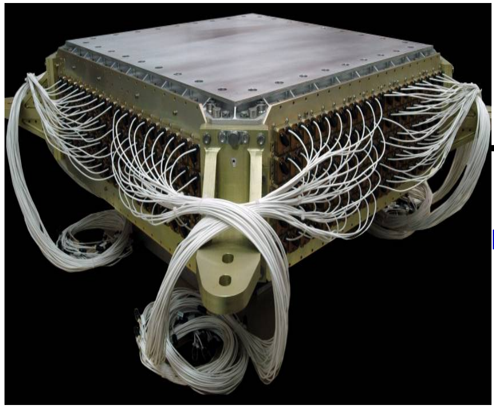
- Collect data from RDR
- Format, send to next level
- Control High & Low Voltage
- Combine Busy signals
- Distribute Trigger
- Distribute command to RDR

Data from ISS Nuclei in the TeV range



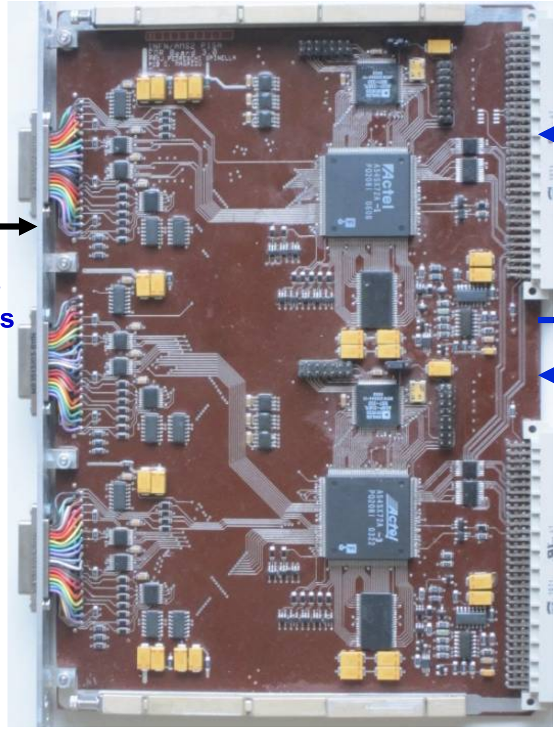
ECAL Computers

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



2,916 Pulse Heights

28 ECAL Data Reduction
& Trigger Computers (EDR)

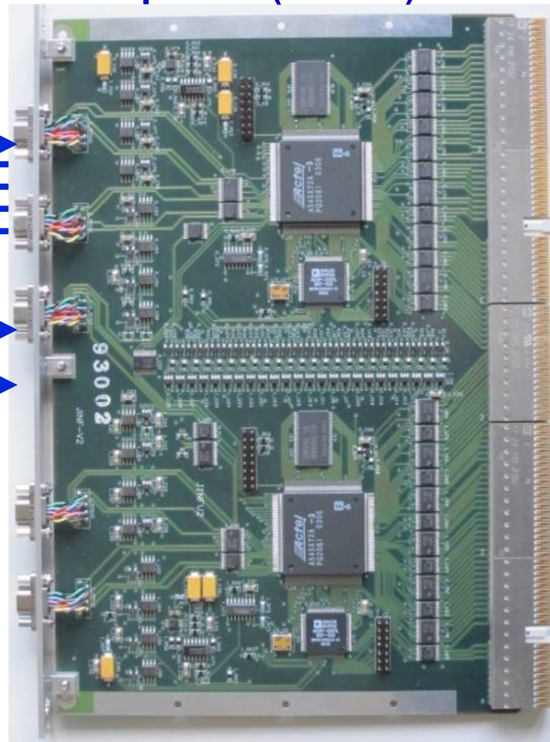


AMSWire

Busy

Trigger

4 Readout
Computers (JINF-E)



AMSWire

To next level

Busy

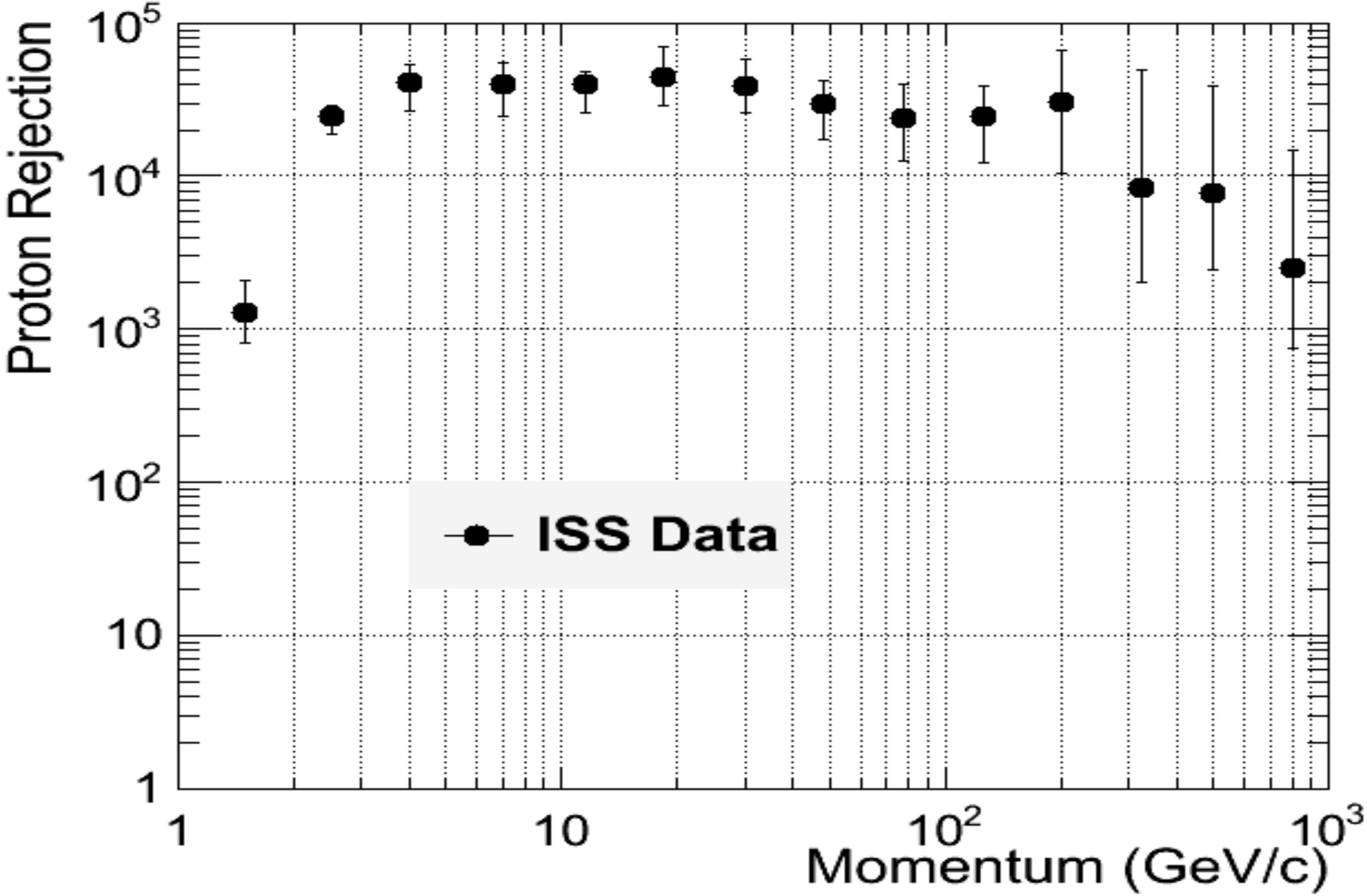
Trigger

High & Low Voltage Control

- Analog to digital conversion
- Linear to 1 in 10^5
- Standard data reduction
- Format, send to next level
- Produce Trigger inputs

- Collect data from EDR
- Format, send to next level
- Control High & Low Voltage
- Combine Busy signals
- Distribute Trigger
- Distribute command to EDR

Data from ISS

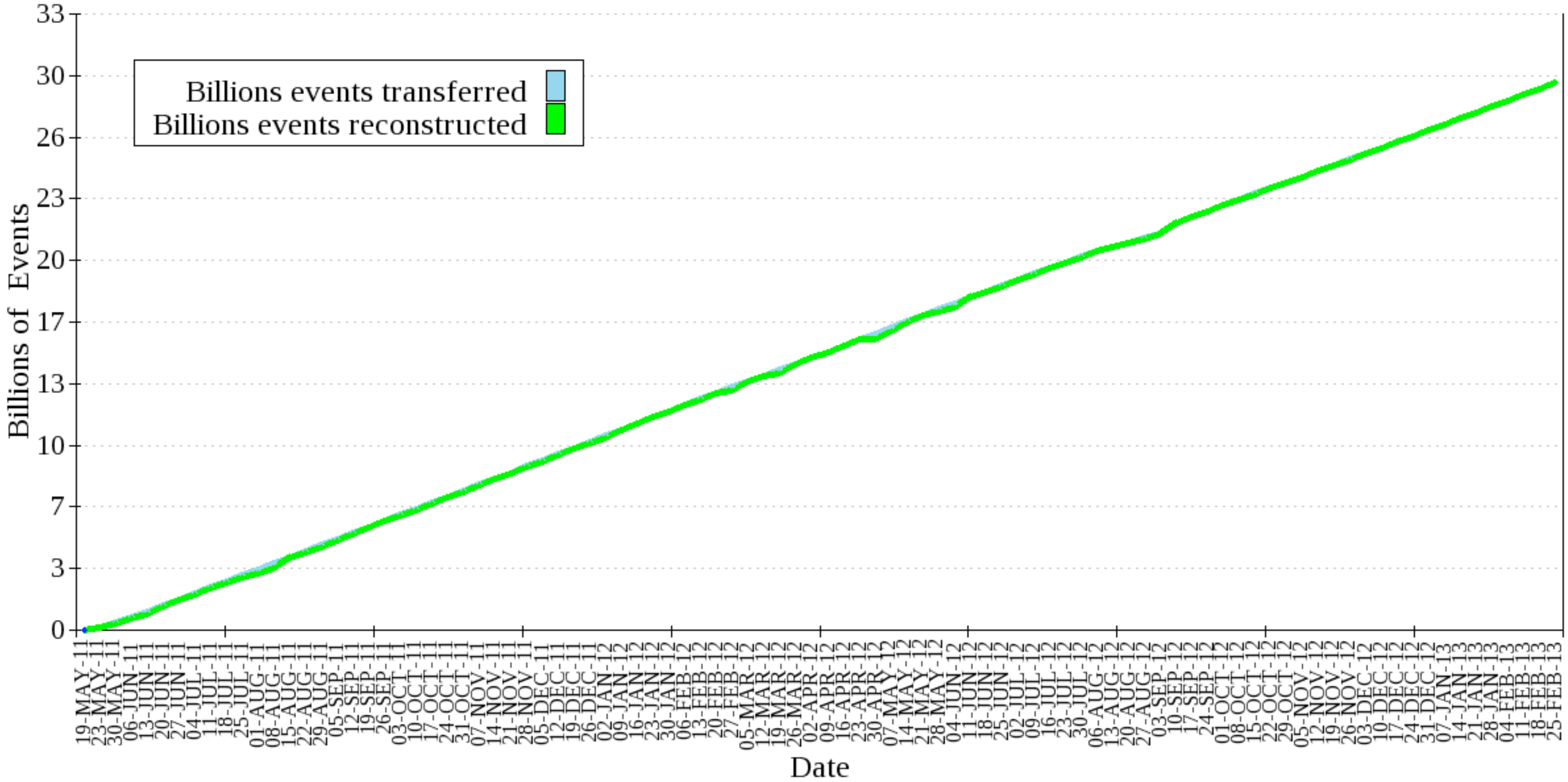


POCC at CERN in control of AMS since 19 June 2011

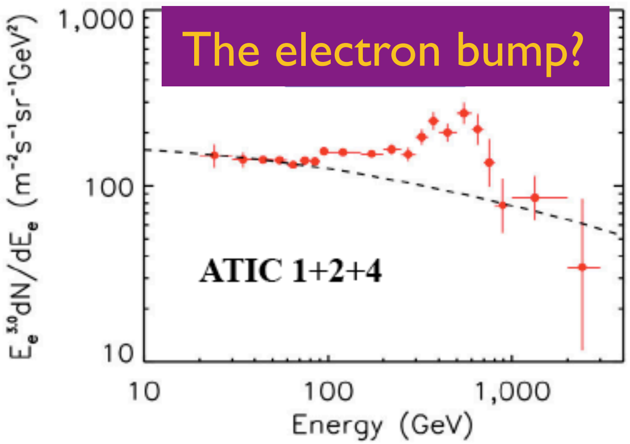

AMS Astronauts visit the POCC, July 25, 2012

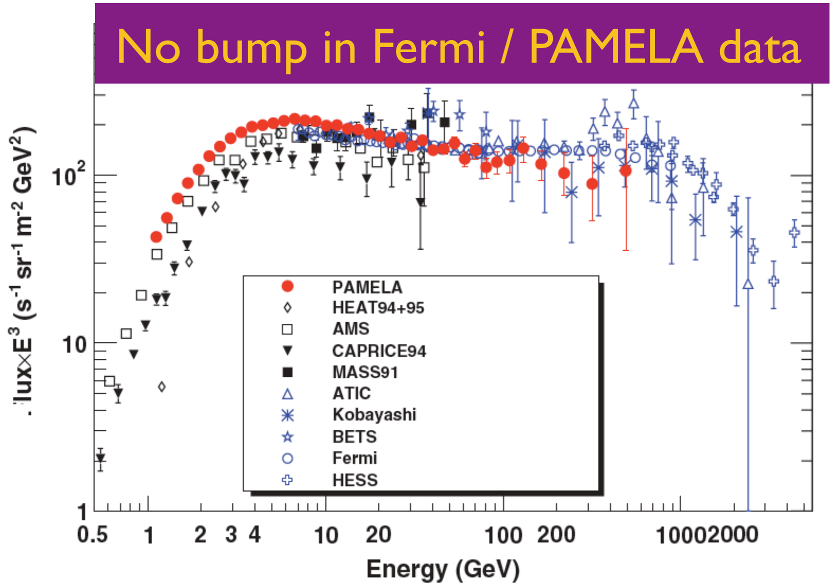
Non-stop collection of ≈30 Billion triggers

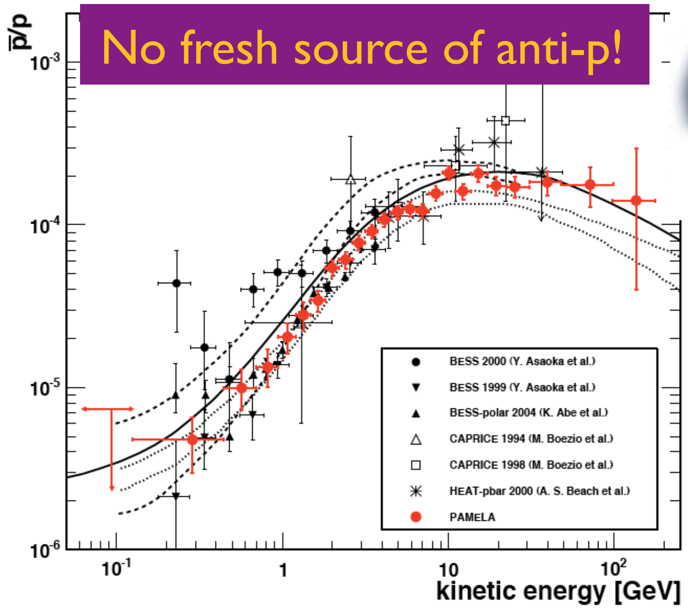
→ 70 TB of raw data on ground
→ 300 TB of reconstructed data for analysis

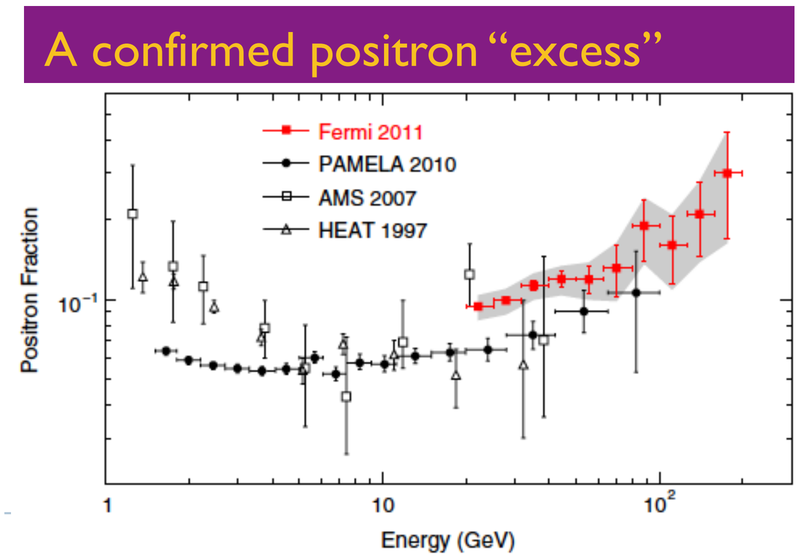


Anti-matter & Exotic sources (DM ?)





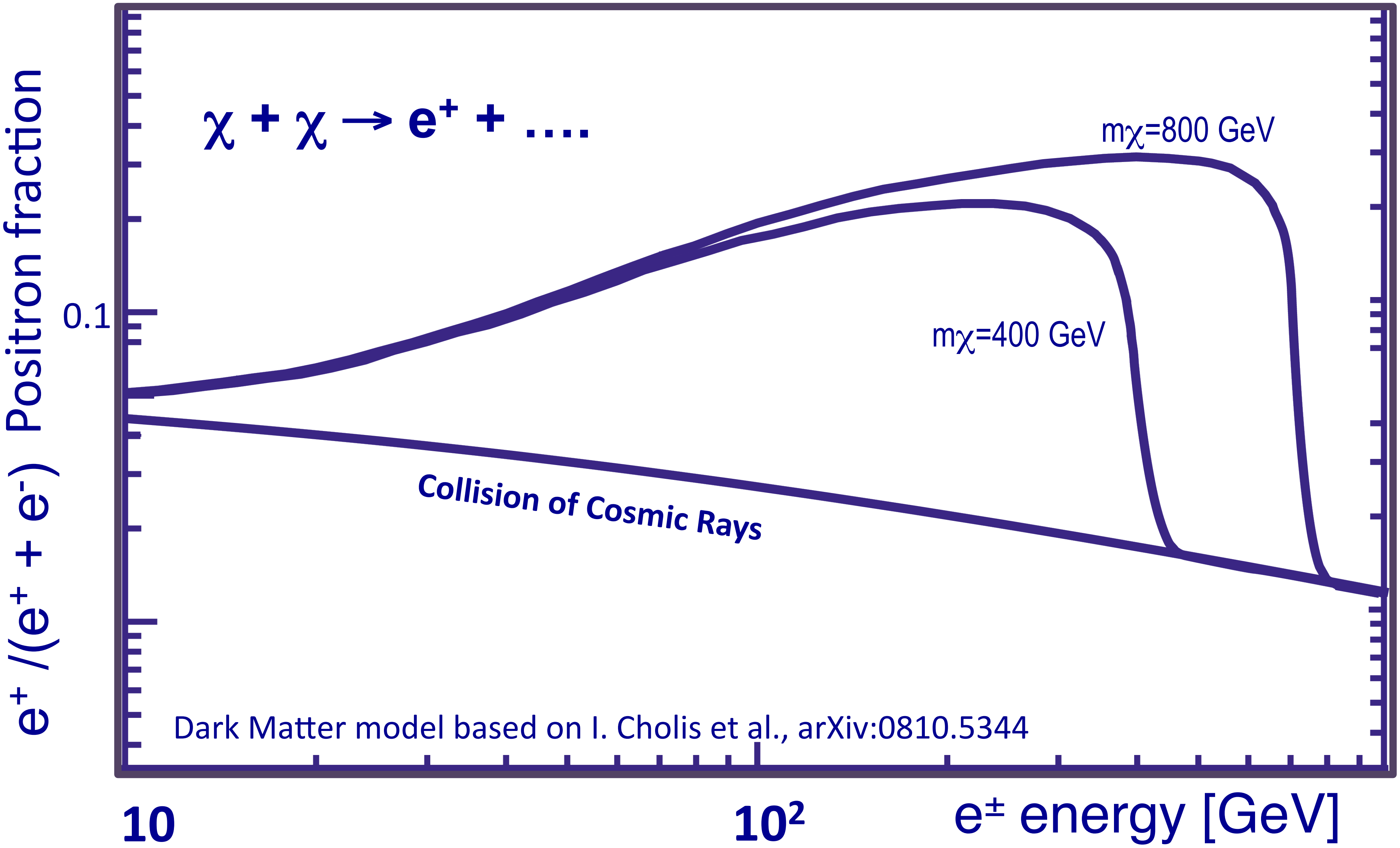


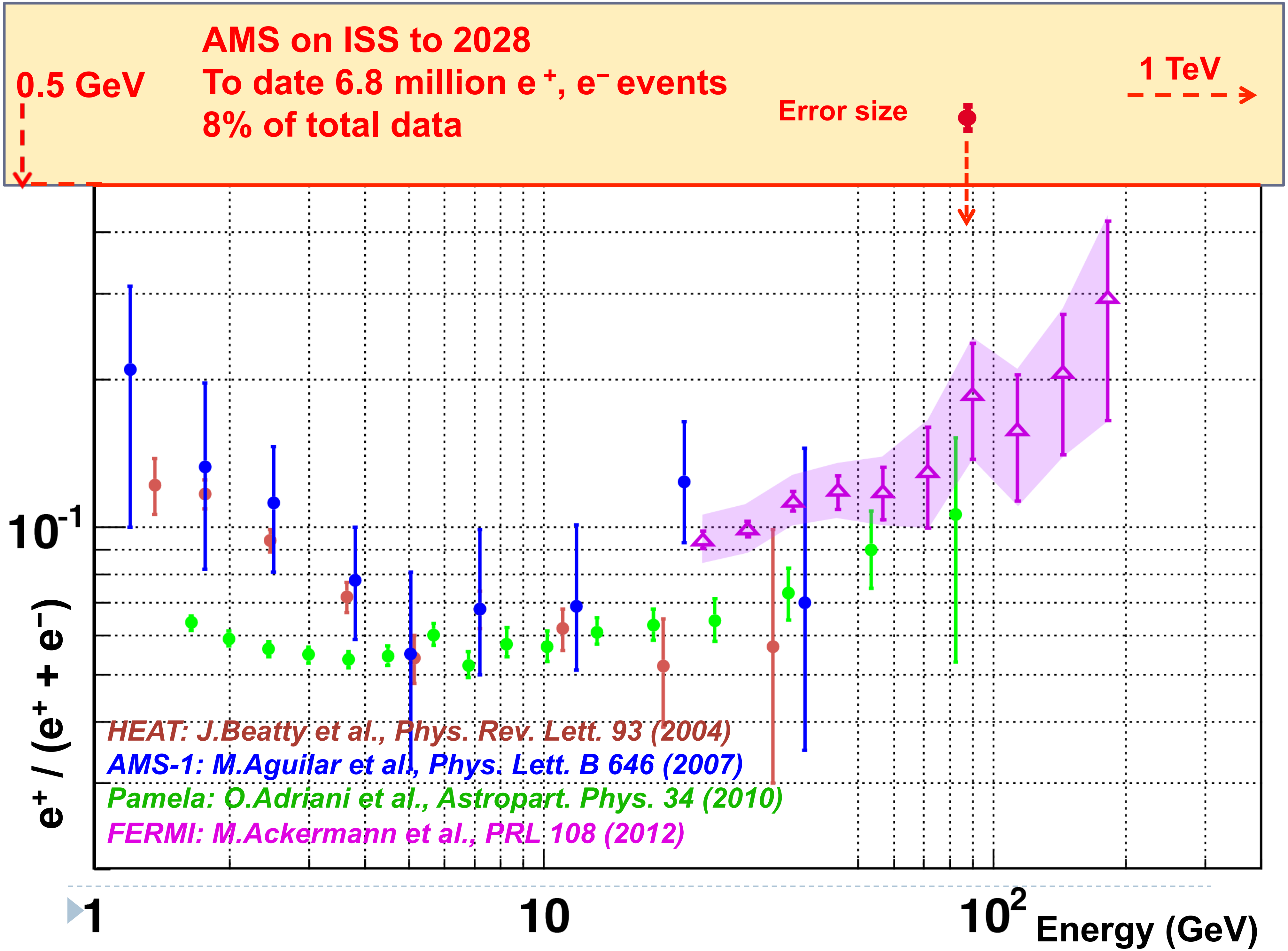


First Publication of AMS:

“A Precision Measurement of the Positron Fraction from AMS”

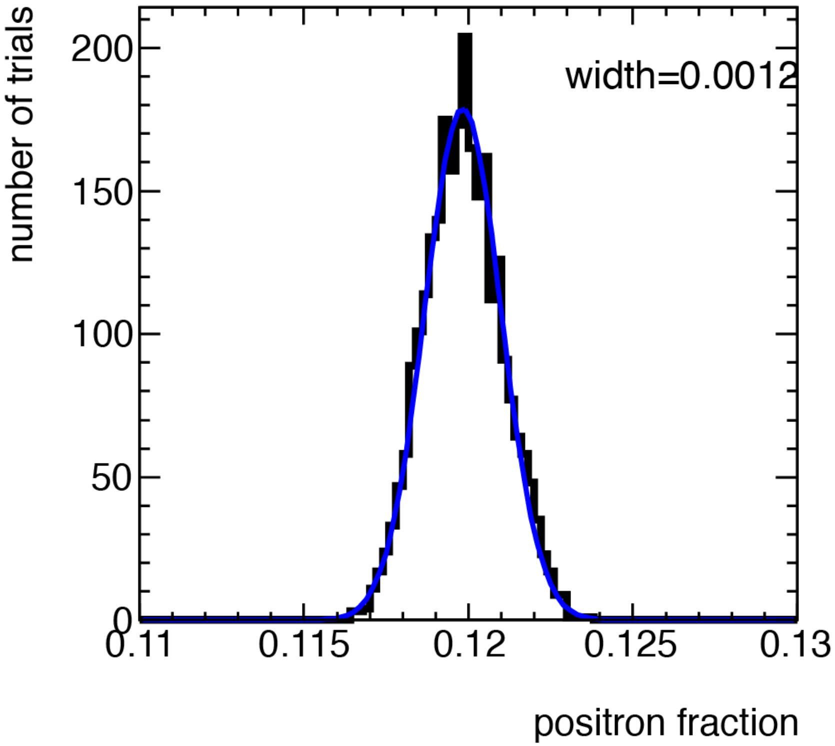
Energy range: 0.5 to 350 GeV, study of the e+ fraction anisotropy

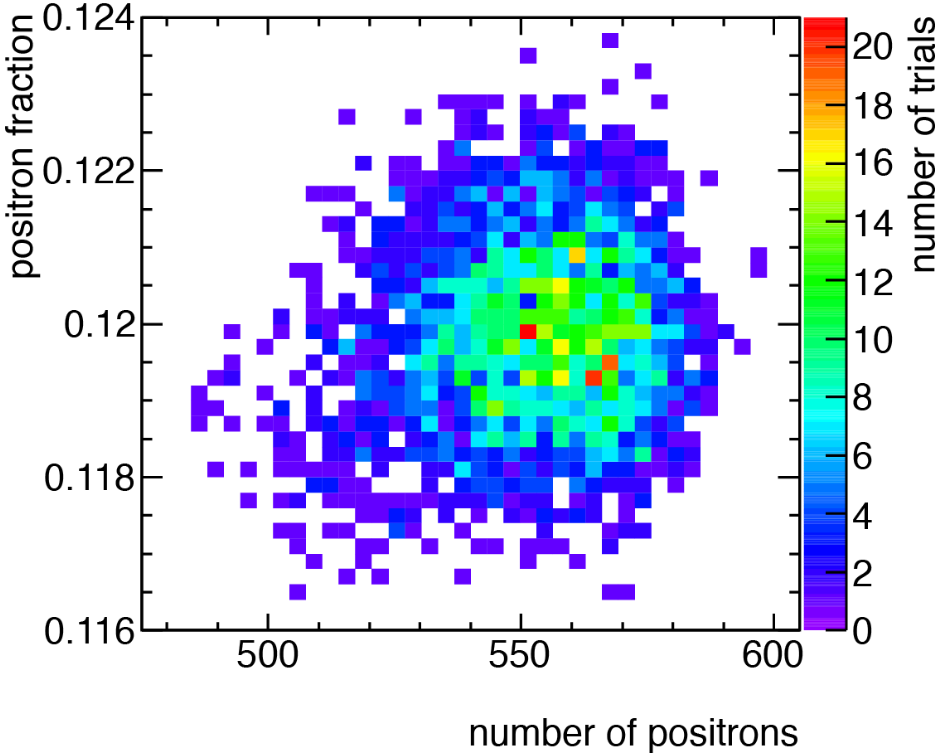




AMS on ISS to 2028
To date 6.8 million e⁺, e⁻ events
8% of total data
0.5 GeV
1 TeV
Error size
10^{-1}
$e^+ / (e^+ + e^-)$
HEAT: J.Beatty et al., Phys. Rev. Lett. 93 (2004)
AMS-1: M.Aguilar et al., Phys. Lett. B 646 (2007)
Pamela: O.Adriani et al., Astropart. Phys. 34 (2010)
FERMI: M.Ackermann et al., PRL 108 (2012)
1
10
10^2
Energy (GeV)

The measurement is stable over wide variations of the cuts in the TRD identification, ECAL Shower Shape, E (from ECAL) matched to |P| (from the Tracker), ...
For each energy bin, over 1,000 sets of cuts were analyzed.

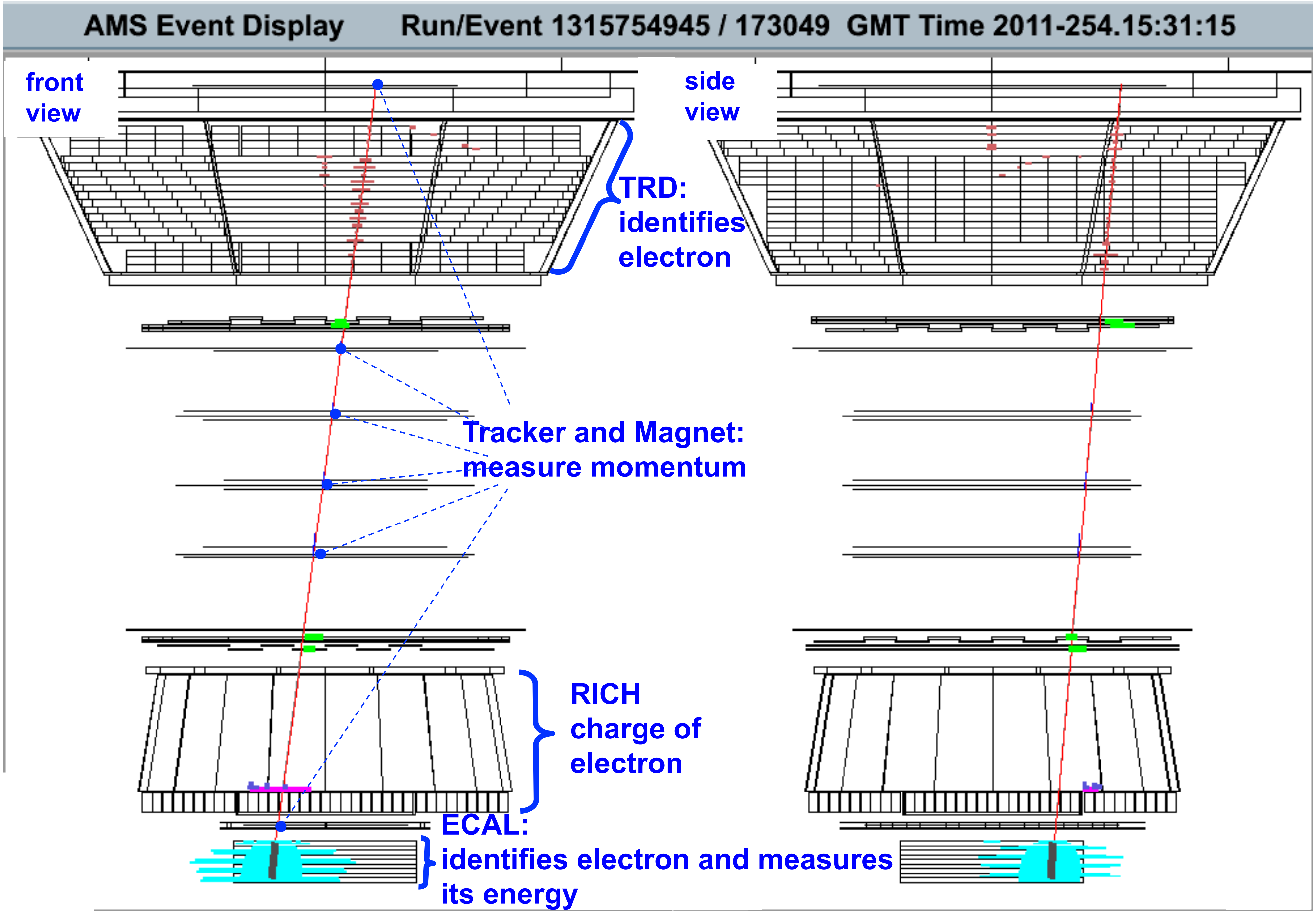




Typical result for the energy bin 83.2-100GeV.

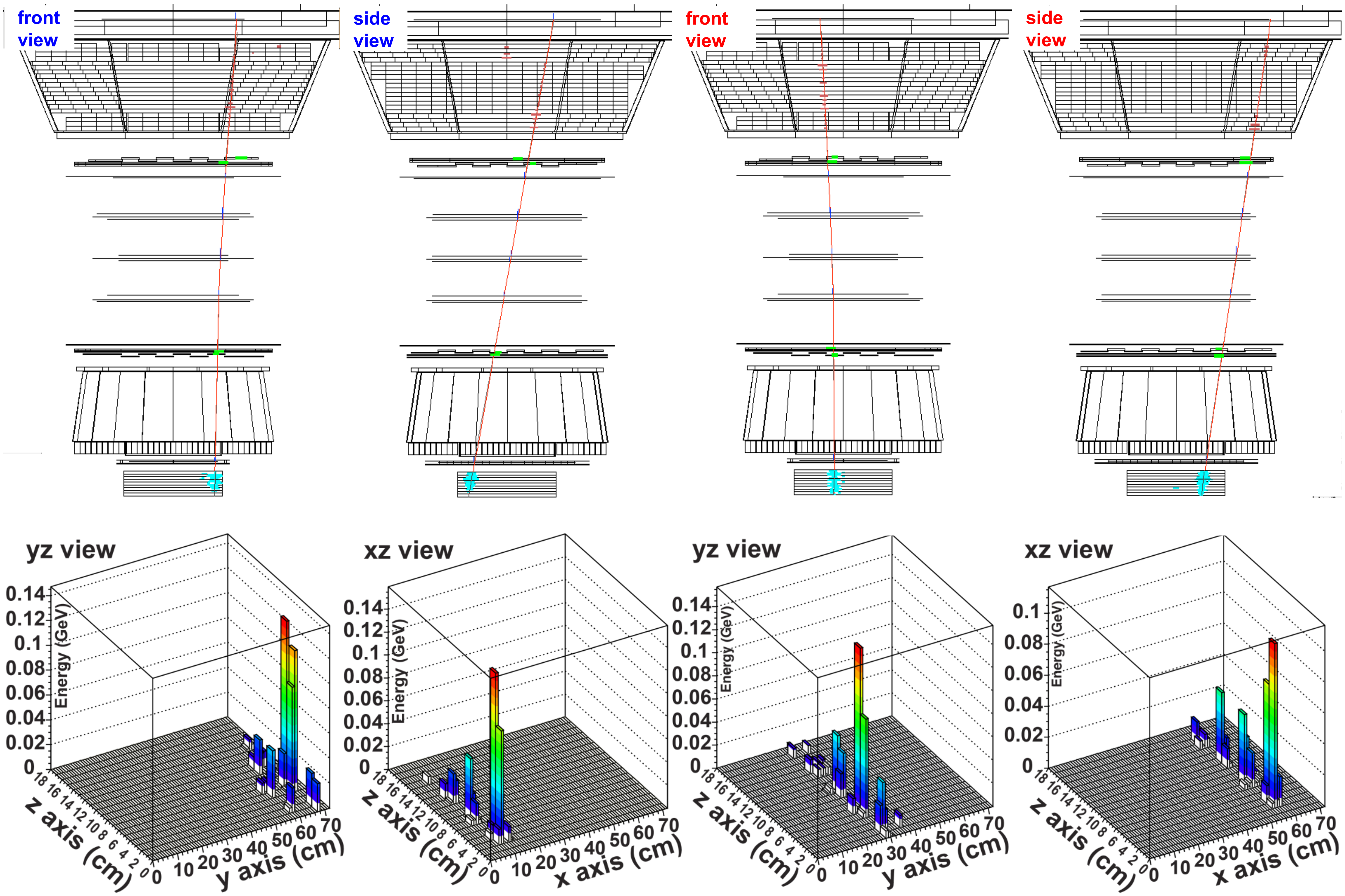
AMS data on ISS

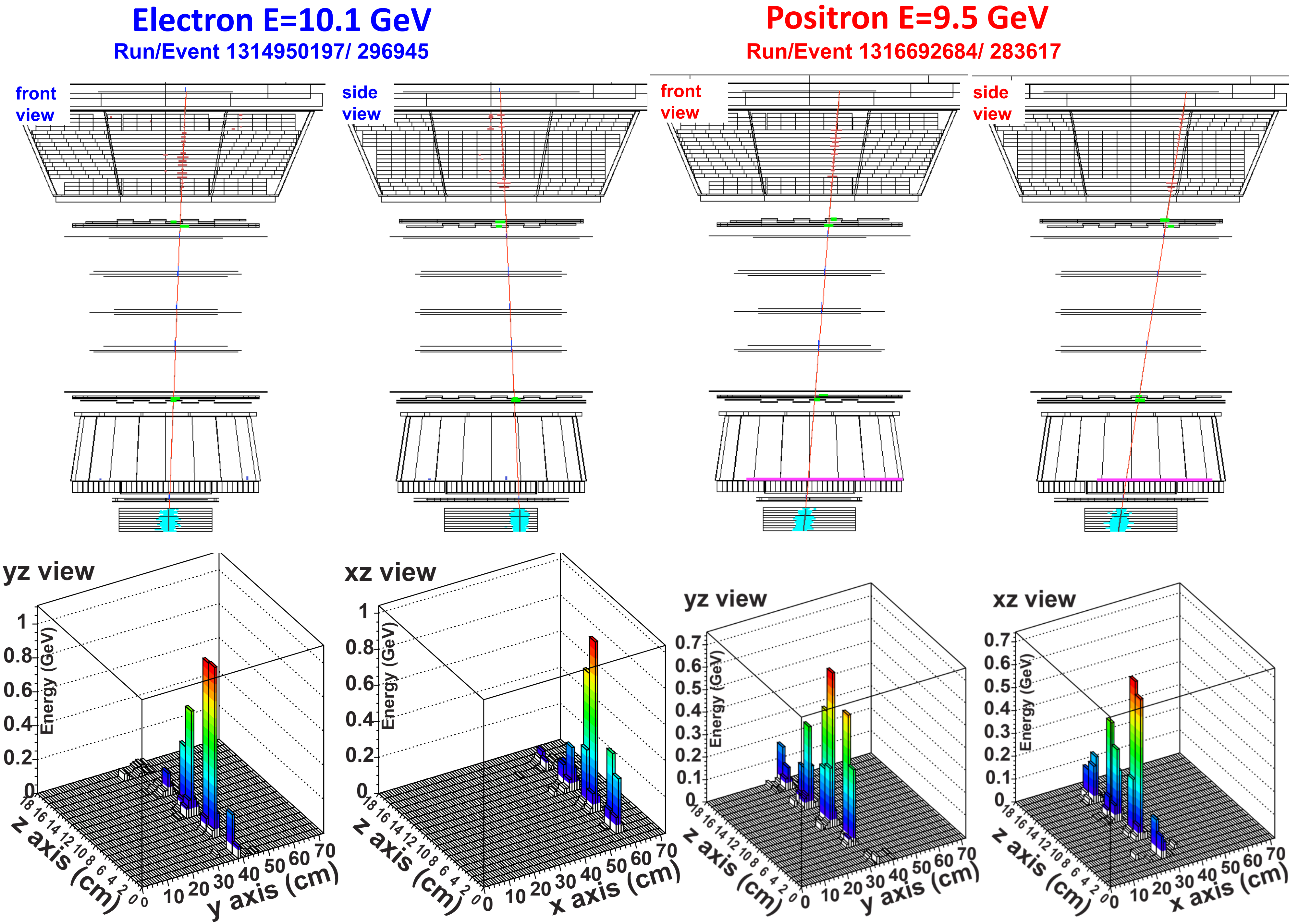
1.03 TeV electron

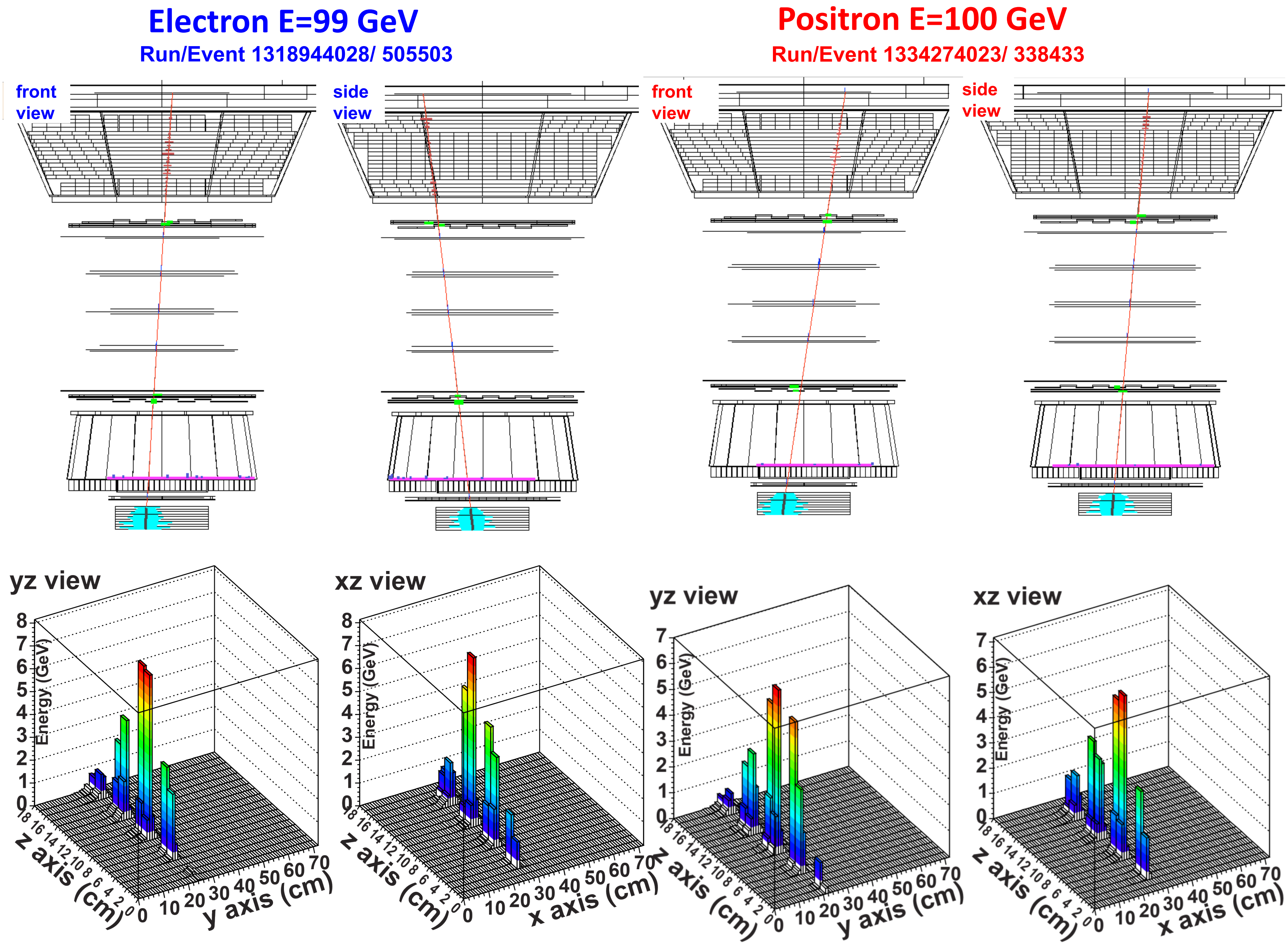


Electron E=1.1 GeV | **Positron E=1.1 GeV**

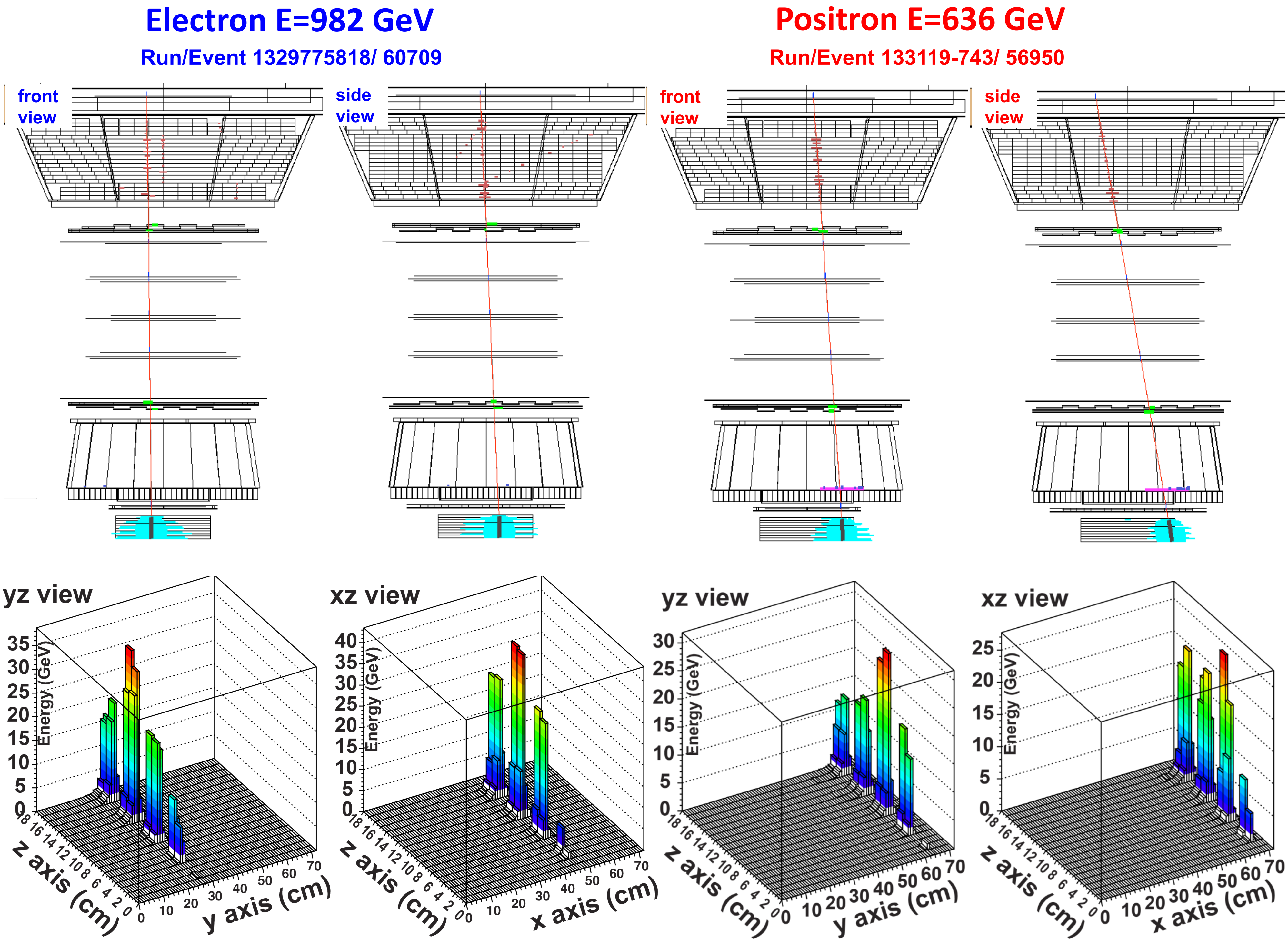
Run/Event 1315150703/ 667540 | Run/Event 1316182344/ 919896




Electron E=10.1 GeV
Run/Event 1314950197/ 296945
Positron E=9.5 GeV
Run/Event 1316692684/ 283617
front view
side view
front view
side view
yz view
xz view
yz view
xz view
Energy (GeV)
z axis (cm)
y axis (cm)
x axis (cm)



Electron E=99 GeV
Run/Event 1318944028/ 505503
Positron E=100 GeV
Run/Event 1334274023/ 338433
front view
side view
front view
side view
yz view
xz view
yz view
xz view
Energy (GeV)
z axis (cm)
y axis (cm)
x axis (cm)


Electron E=982 GeV
Run/Event 1329775818/ 60709
Positron E=636 GeV
Run/Event 133119-743/ 56950
front view
side view
front view
side view
yz view
xz view
yz view
xz view
Energy (GeV)
z axis (cm)
y axis (cm)
x axis (cm)

Physics analysis nearing completion

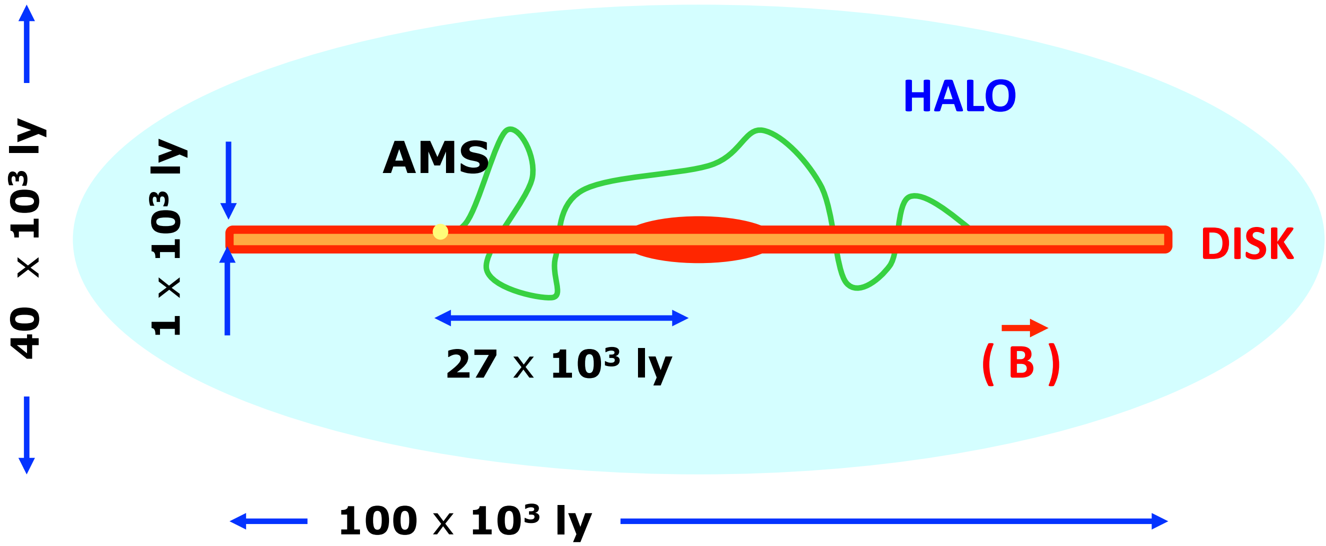
1. Electron Spectrum
2. Positron Spectrum
3. Boron-to-Carbon ratio

B/C ratio up to TeV

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

Interactions with the Interstellar Medium:

$$C + (p,He) \rightarrow B + \ldots$$

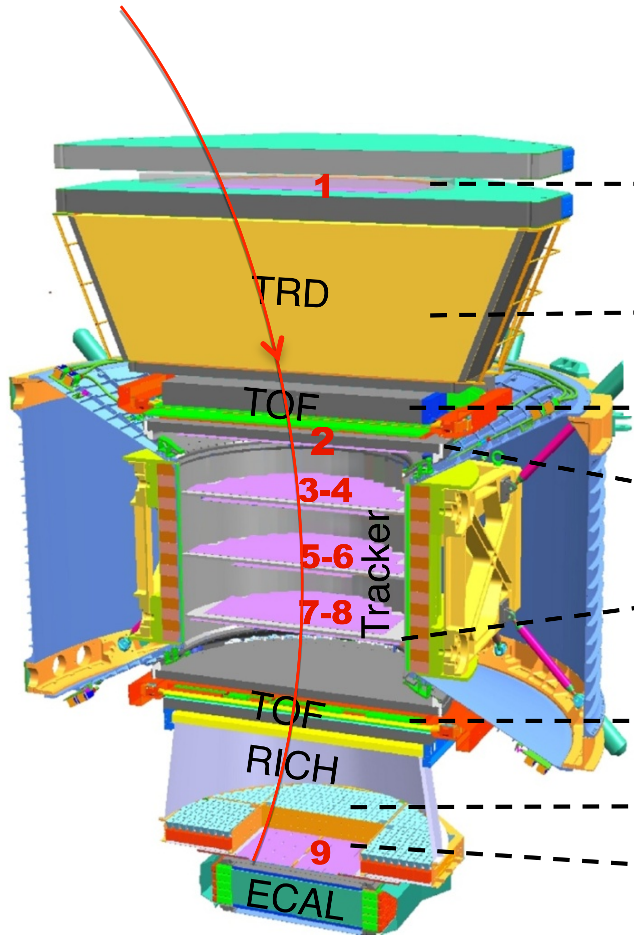


Diffusion
Convection
Reacceleration

Interactions with the Interstellar Medium (ISM):

- Fragmentation
- Secondaries
- Energy loss

Multiple Independent Measurements of the Charge (|Z|)



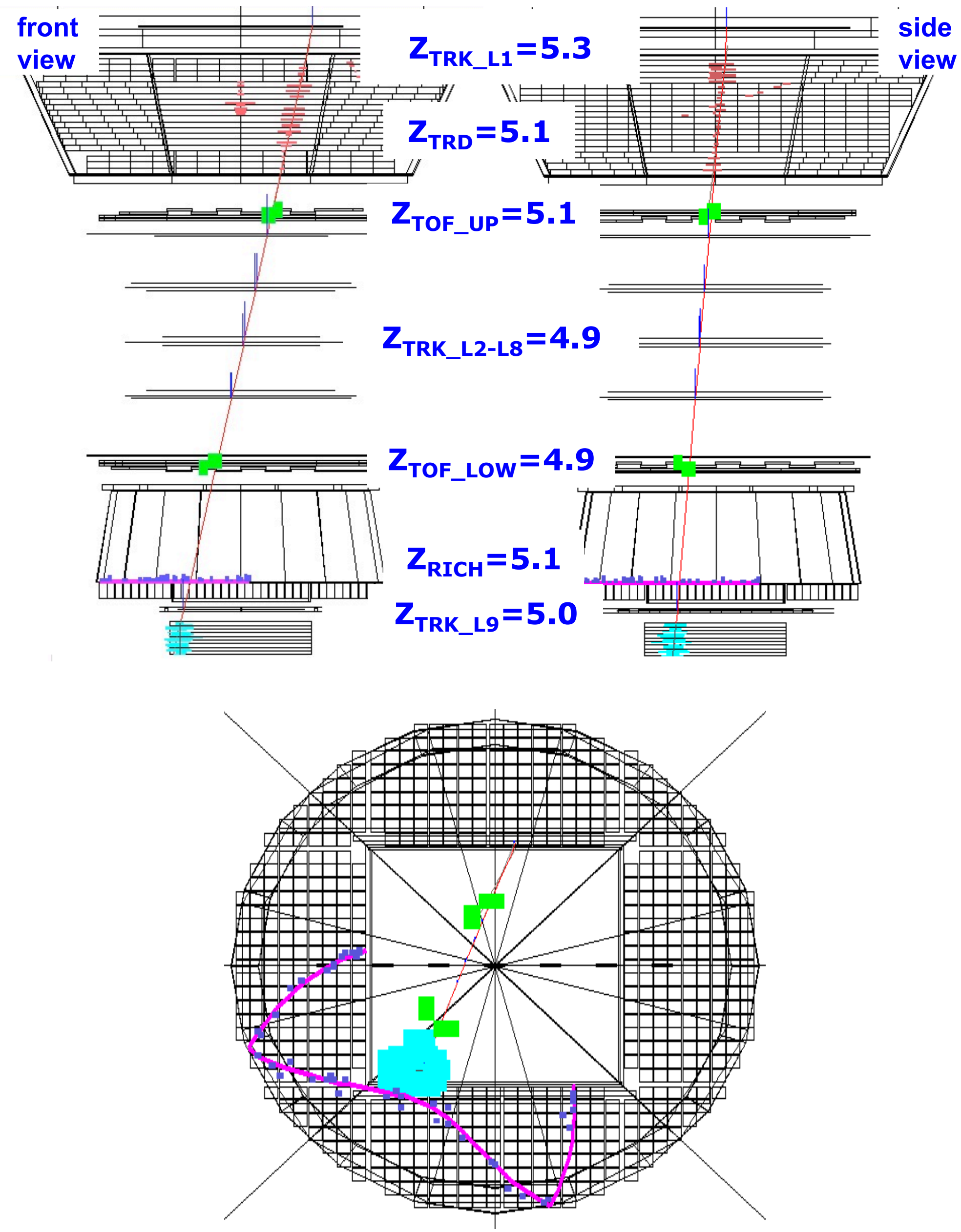
	Carbon (Z=6) ΔZ (cu)
1. Tracker Plane 1	0.30
2. TRD	0.33
3. Upper TOF	0.17
4. Tracker Planes 2-8	0.15
5. Lower TOF	0.20
6. RICH	0.32
7. Tracker Plane 9	0.30

Rigidity ~ 3 GV

Boron

Rigidity=3.7 GV

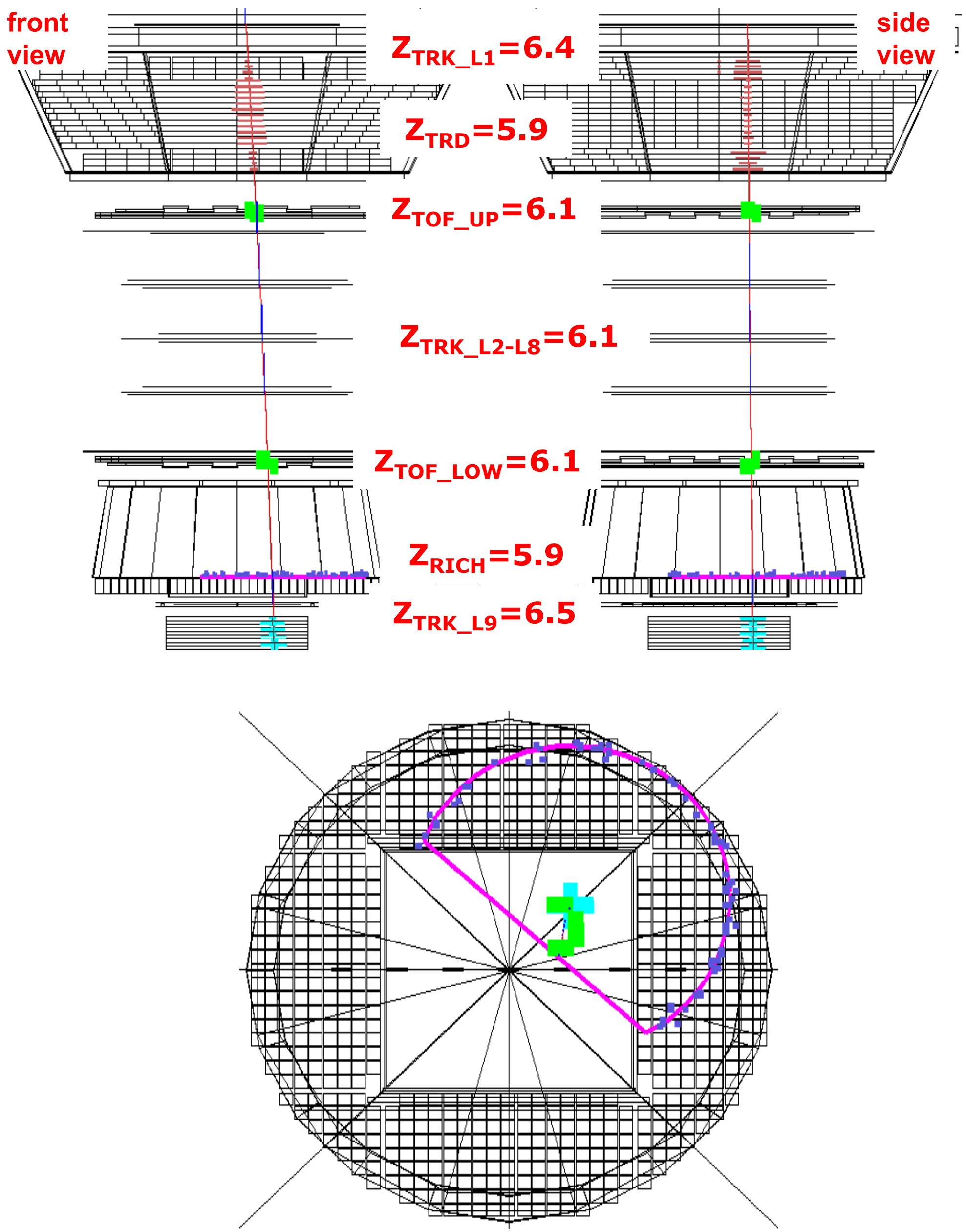
Run/Event 1333501084/ 42231



Carbon

Rigidity=3.3 GV

Run/Event 1327519853/ 487070

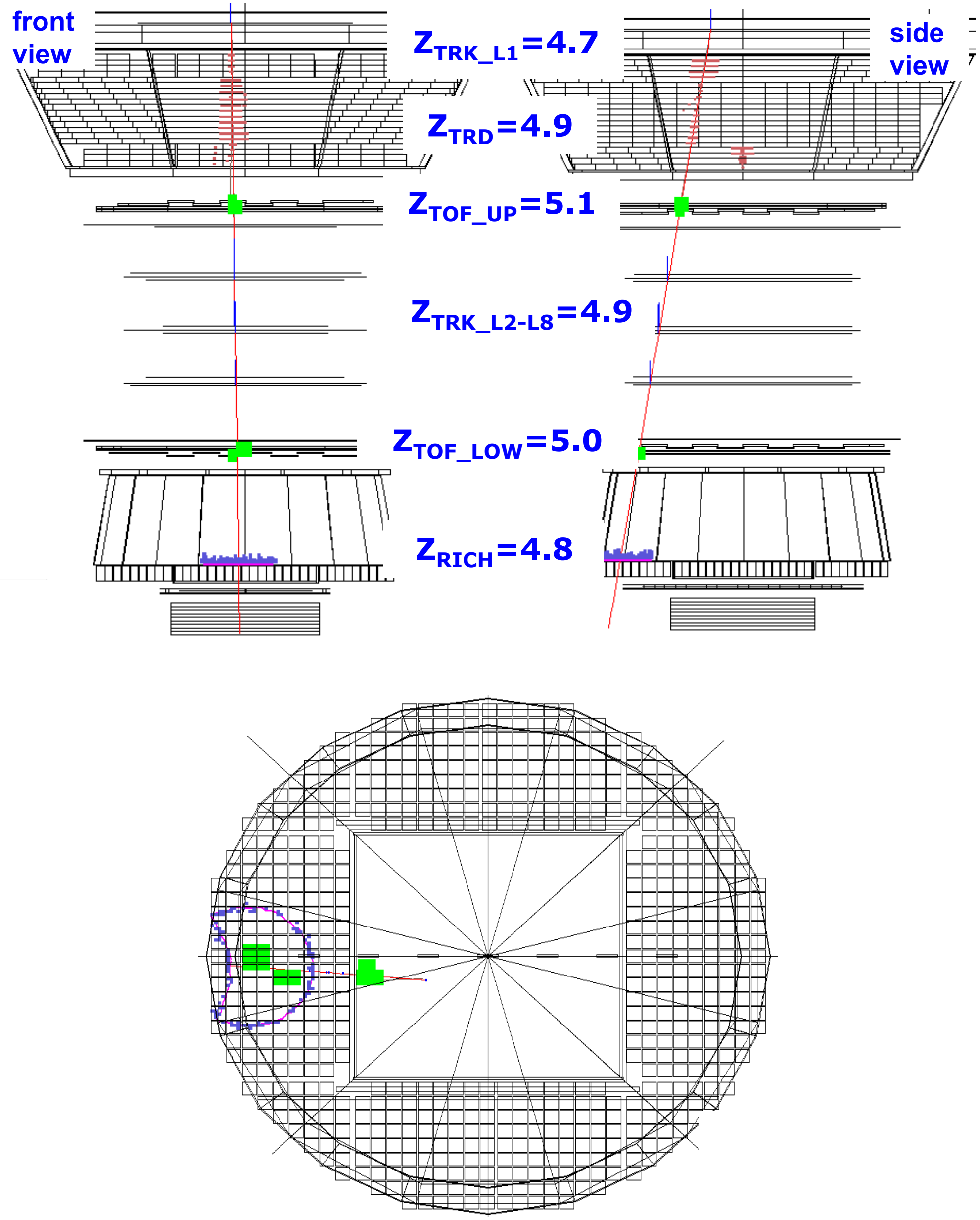


Rigidity ~ 20 GV

Boron

Rigidity=24 GV

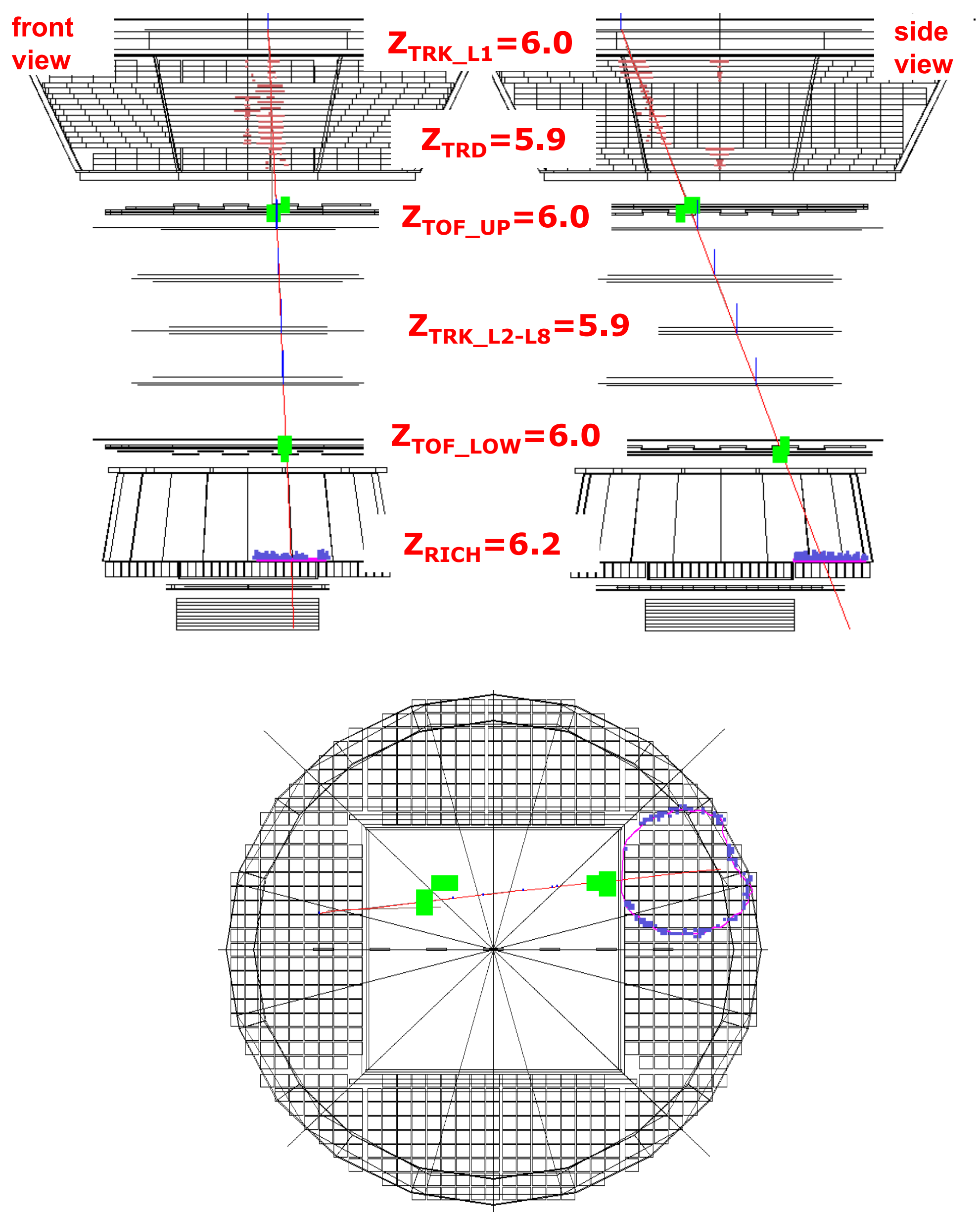
Run/Event 1326201809/ 798775



Carbon

Rigidity=24 GV

Run/Event 1329490720/ 473181

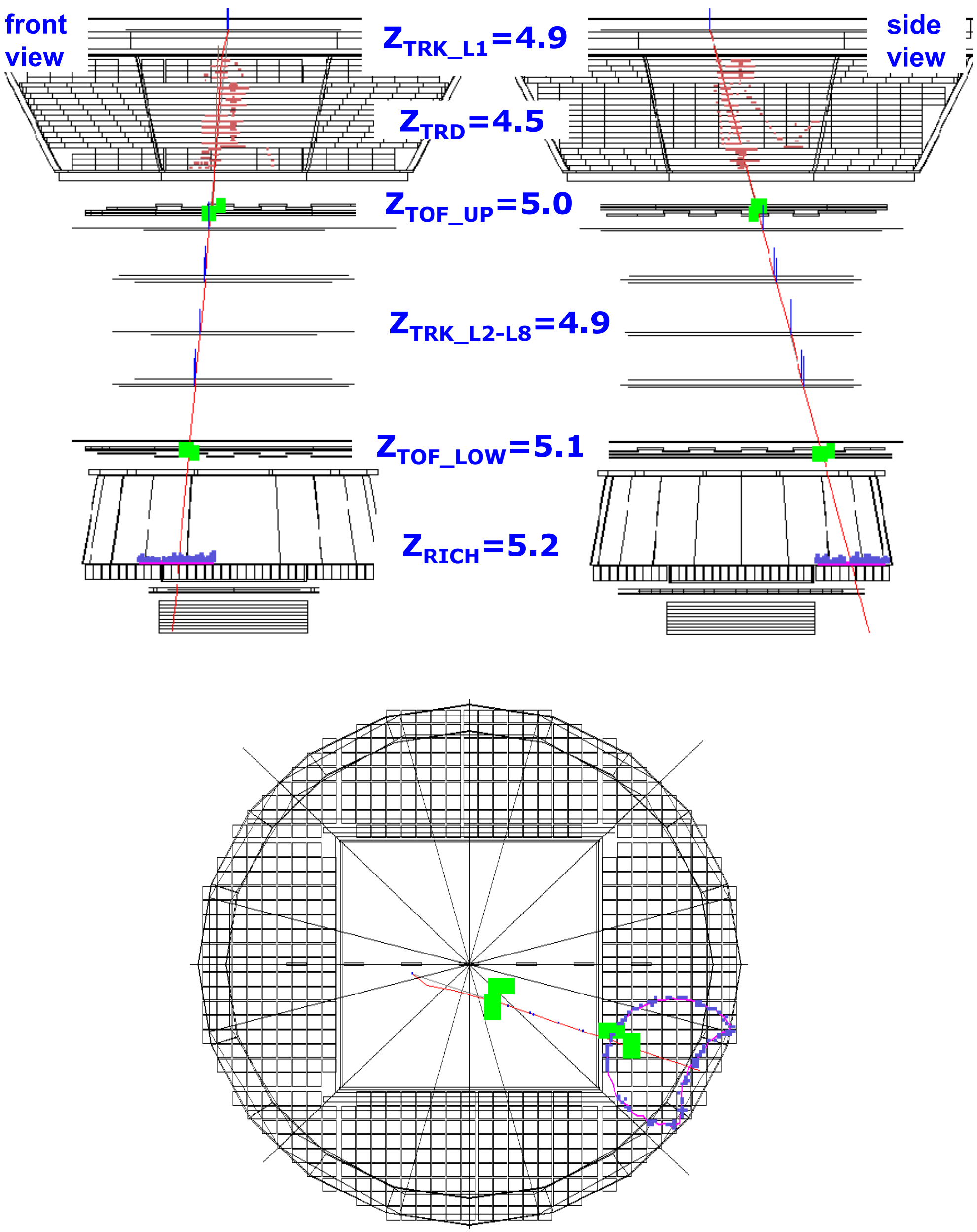


Rigidity ~ 200 GV

Boron

Rigidity=187 GV

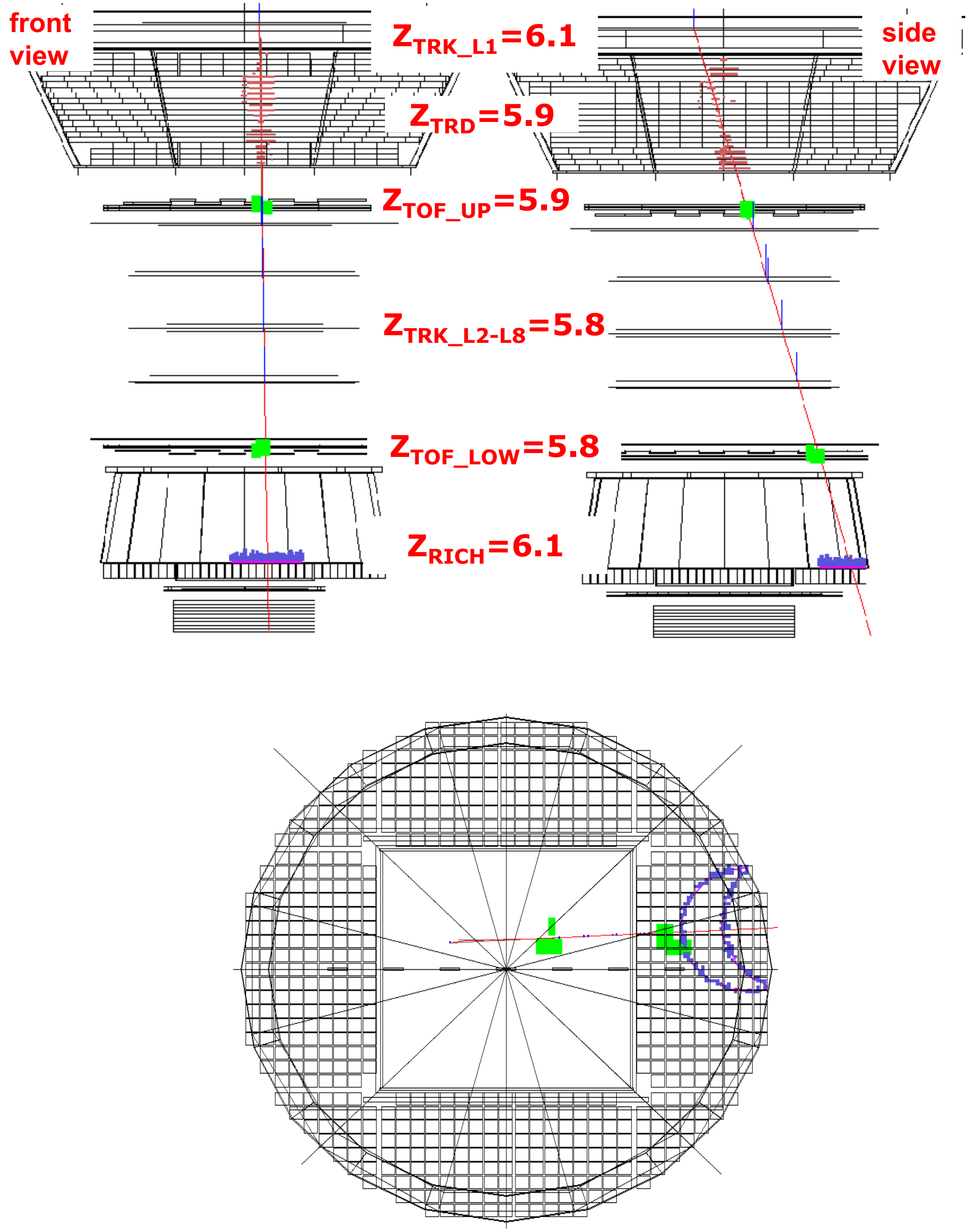
Run/Event 1329086299/ 747549



Carbon

Rigidity=215 GV

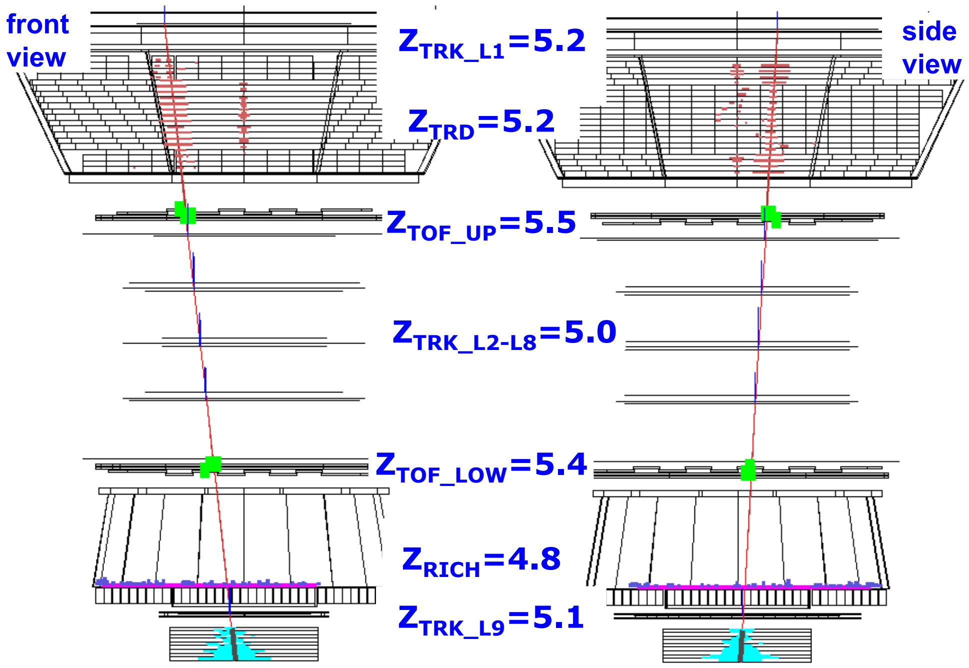
Run/Event 132643580/ 132197



Rigidity ~ 700 GV

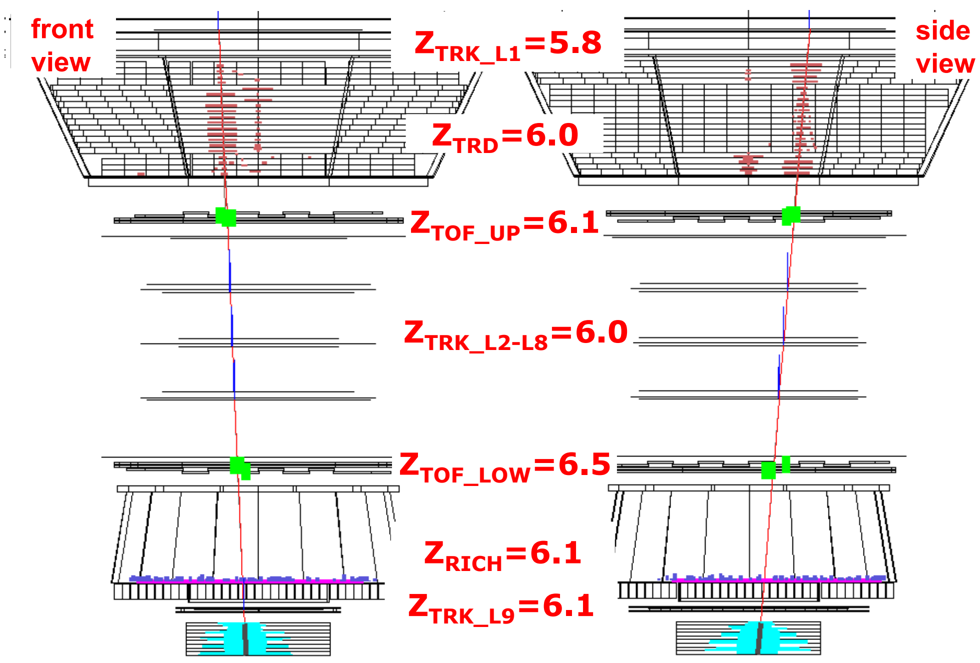
Boron
Rigidity=680 GV

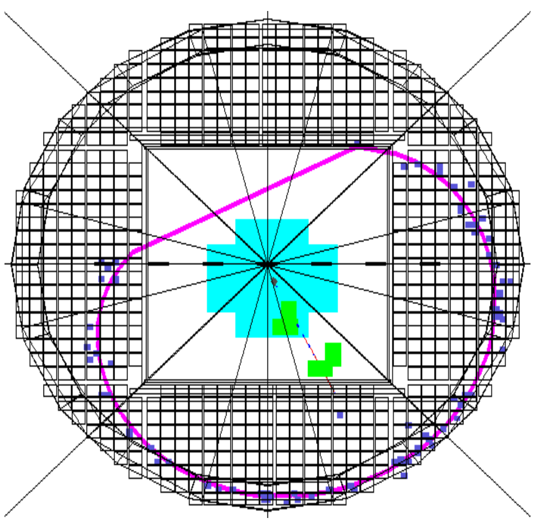
Run/Event 1319990213/ 235892

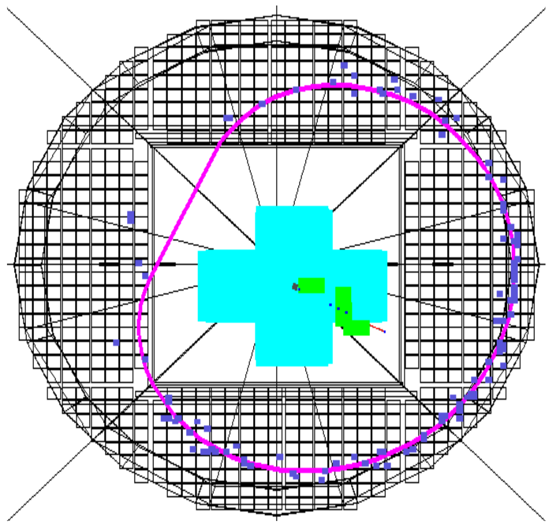


Carbon
Rigidity=666 GV

Run/Event 1327184805/ 266043

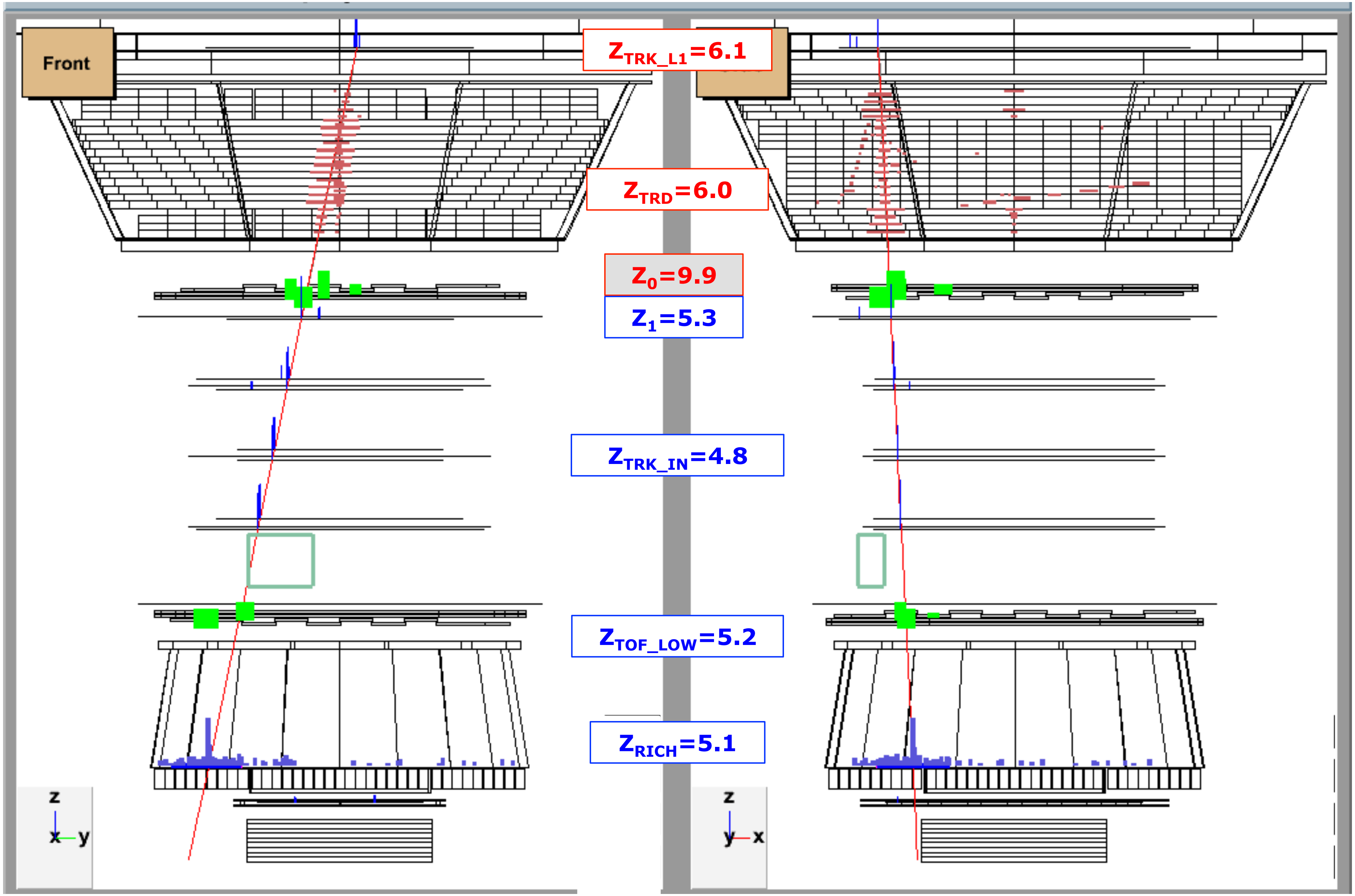




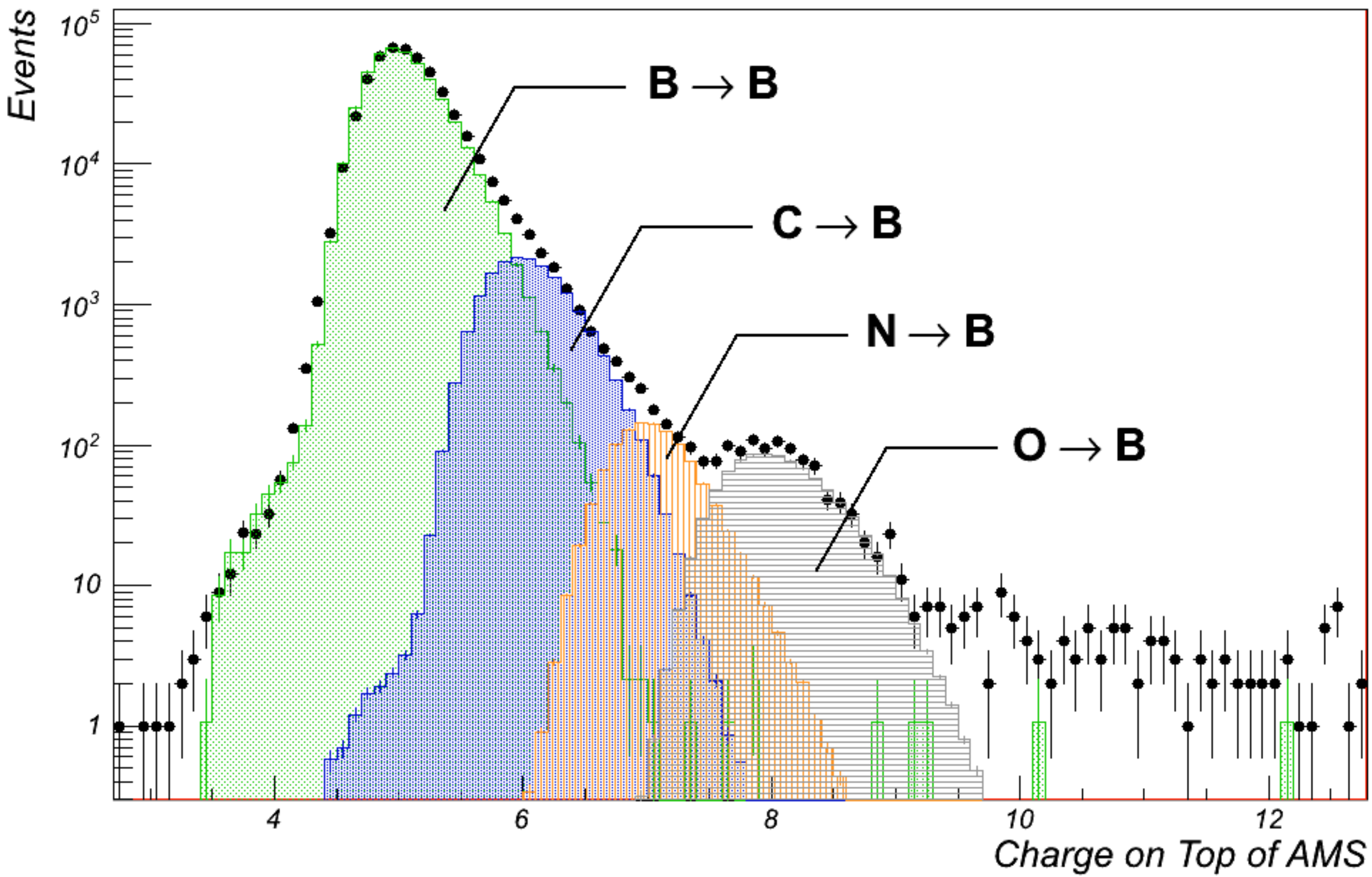


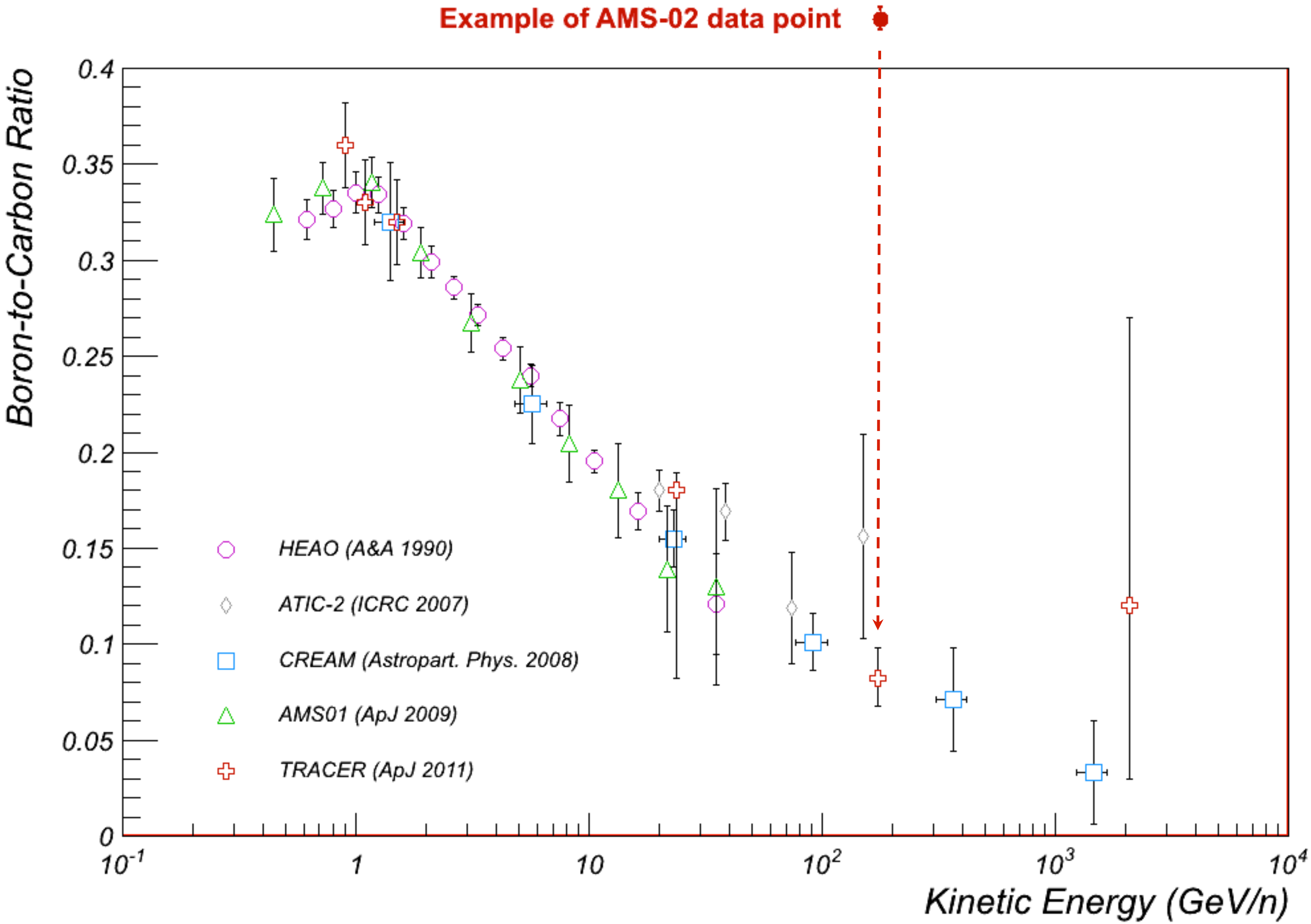
Carbon Fragmentation to Boron in Upper TOF

Rigidity 10.6 GV



Boron measured by AMS





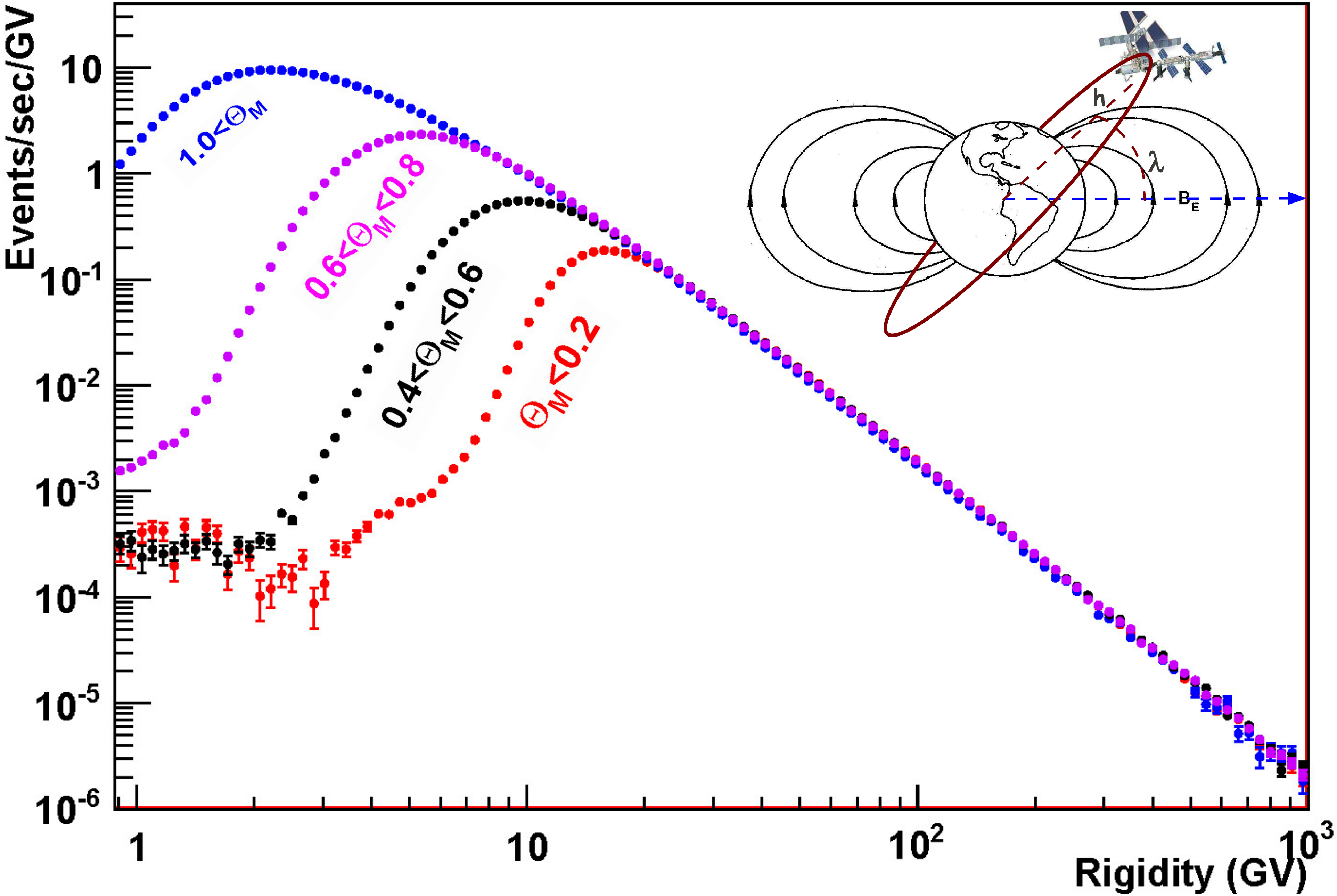
Example of AMS-02 data point
Boron-to-Carbon Ratio
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
HEAO (A&A 1990)
ATIC-2 (ICRC 2007)
CREAM (Astropart. Phys. 2008)
AMS01 (ApJ 2009)
TRACER (ApJ 2011)
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
Kinetic Energy (GeV/n)

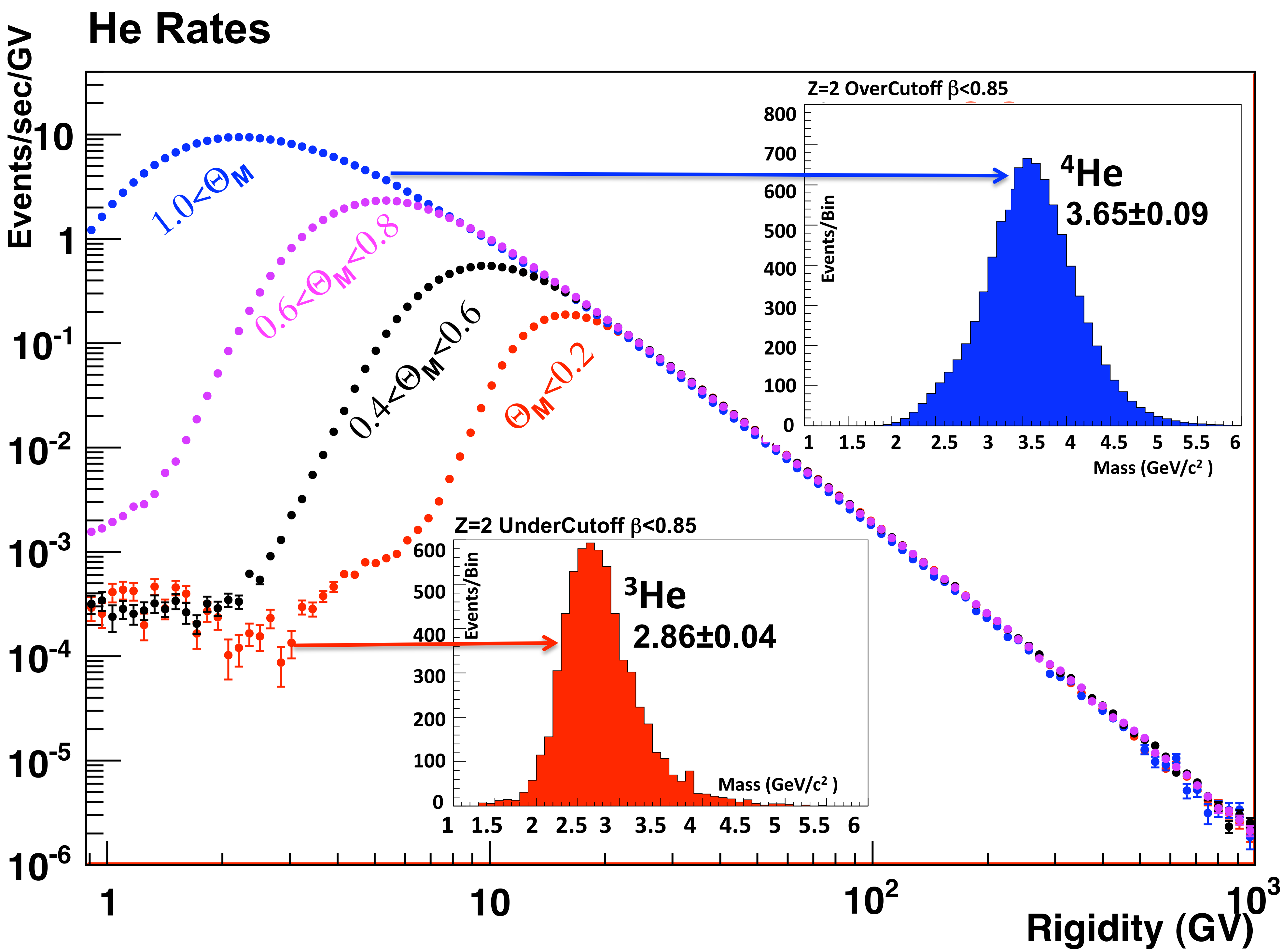
Physics analysis nearing completion

4. Helium spectrum

Study the Origin of Cosmic Rays

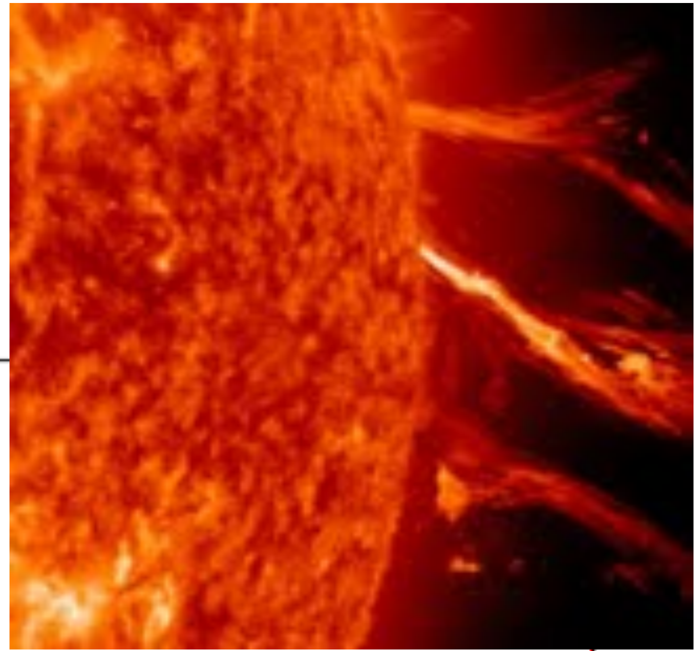
AMS data on ISS: He rate

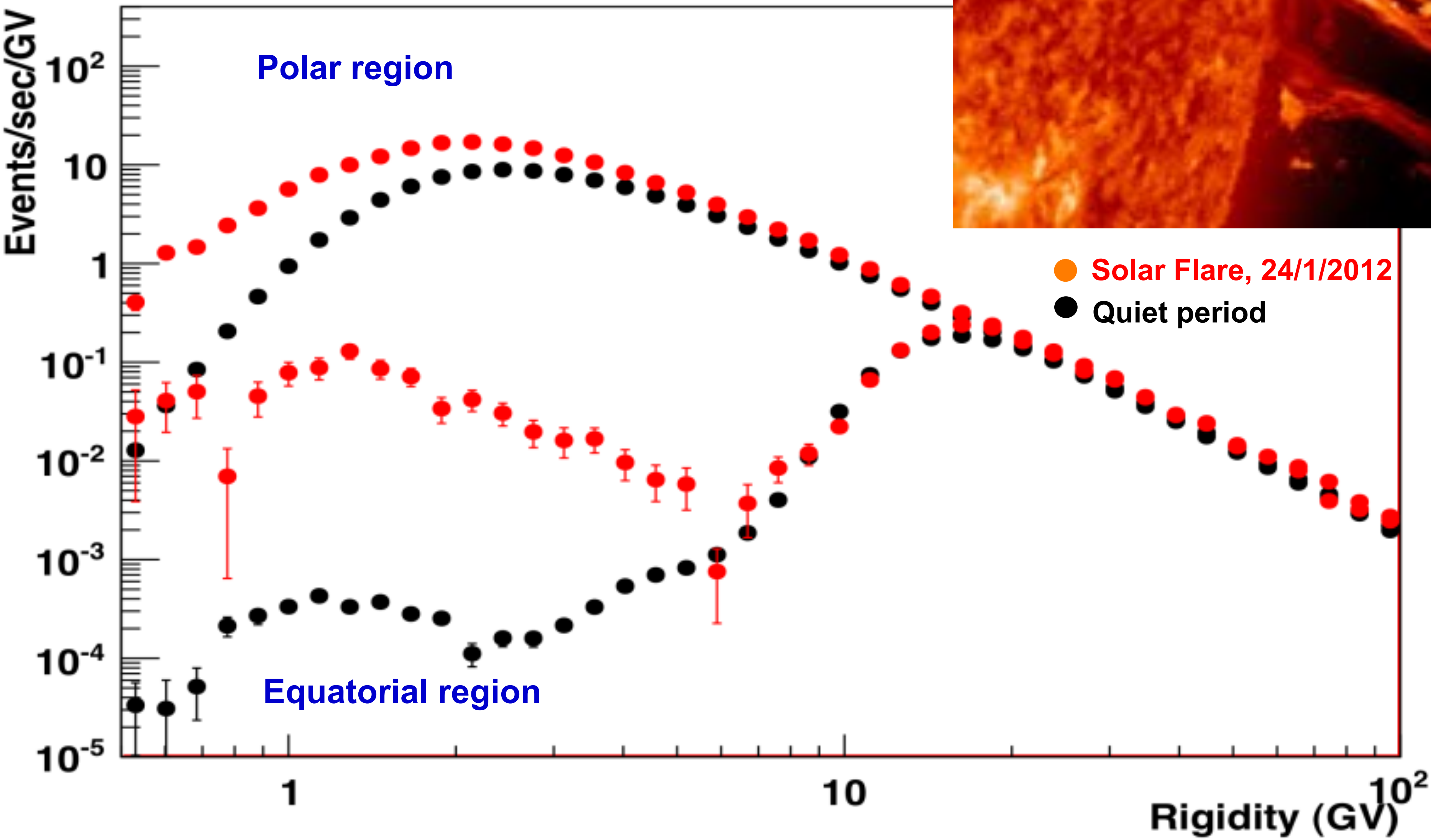




He Rates
Events/sec/GV
Rigidity (GV)
1.0<Θ_M
0.6<Θ_M<0.8
0.4<Θ_M<0.6
Θ_M<0.2
Z=2 OverCutoff β<0.85
Events/Bin
Mass (GeV/c²)
4He
3.65±0.09
Z=2 UnderCutoff β<0.85
Events/Bin
Mass (GeV/c²)
3He
2.86±0.04

AMS data: He rate and Solar Flare



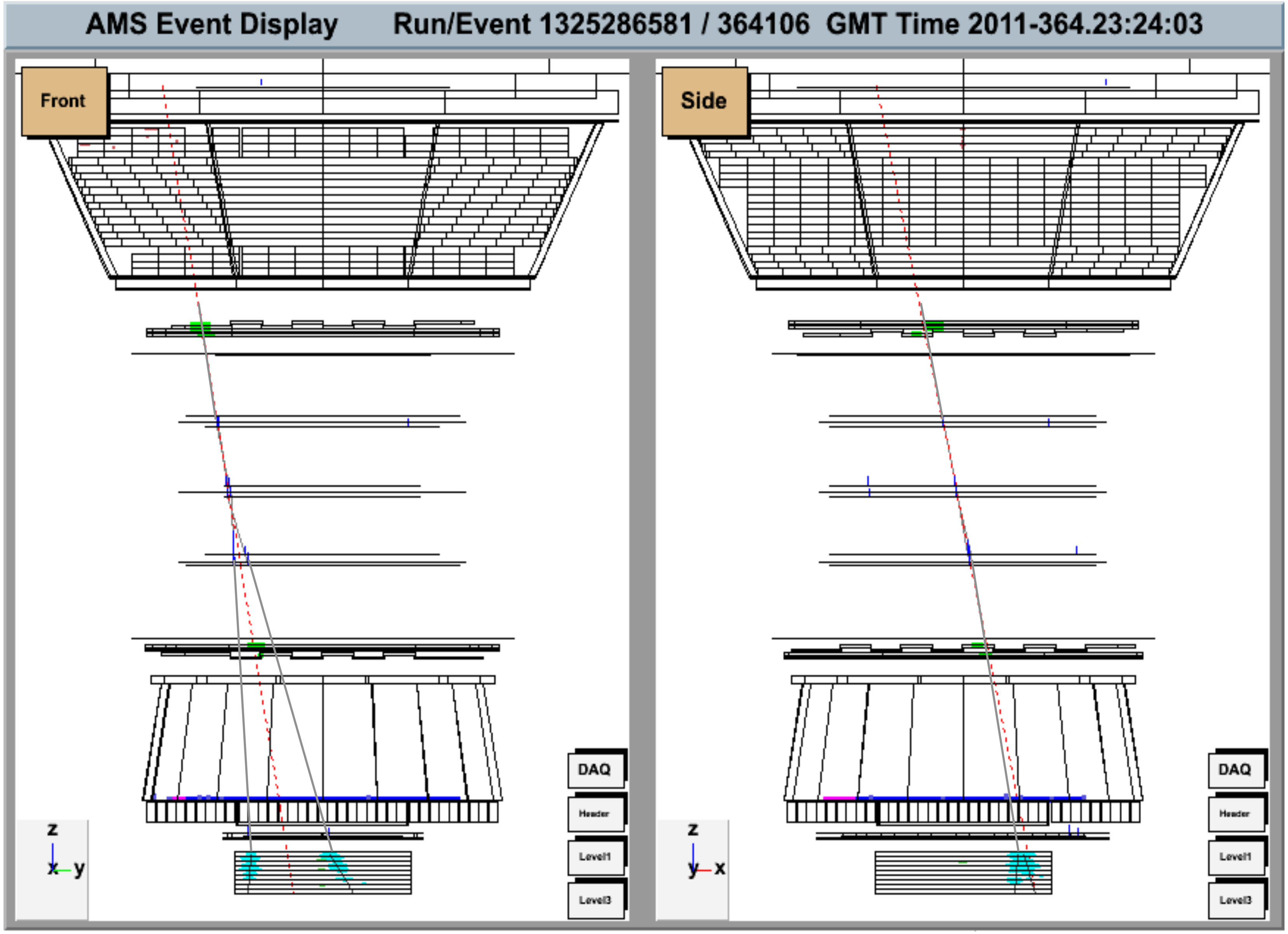


Examples of on-going physics analyses

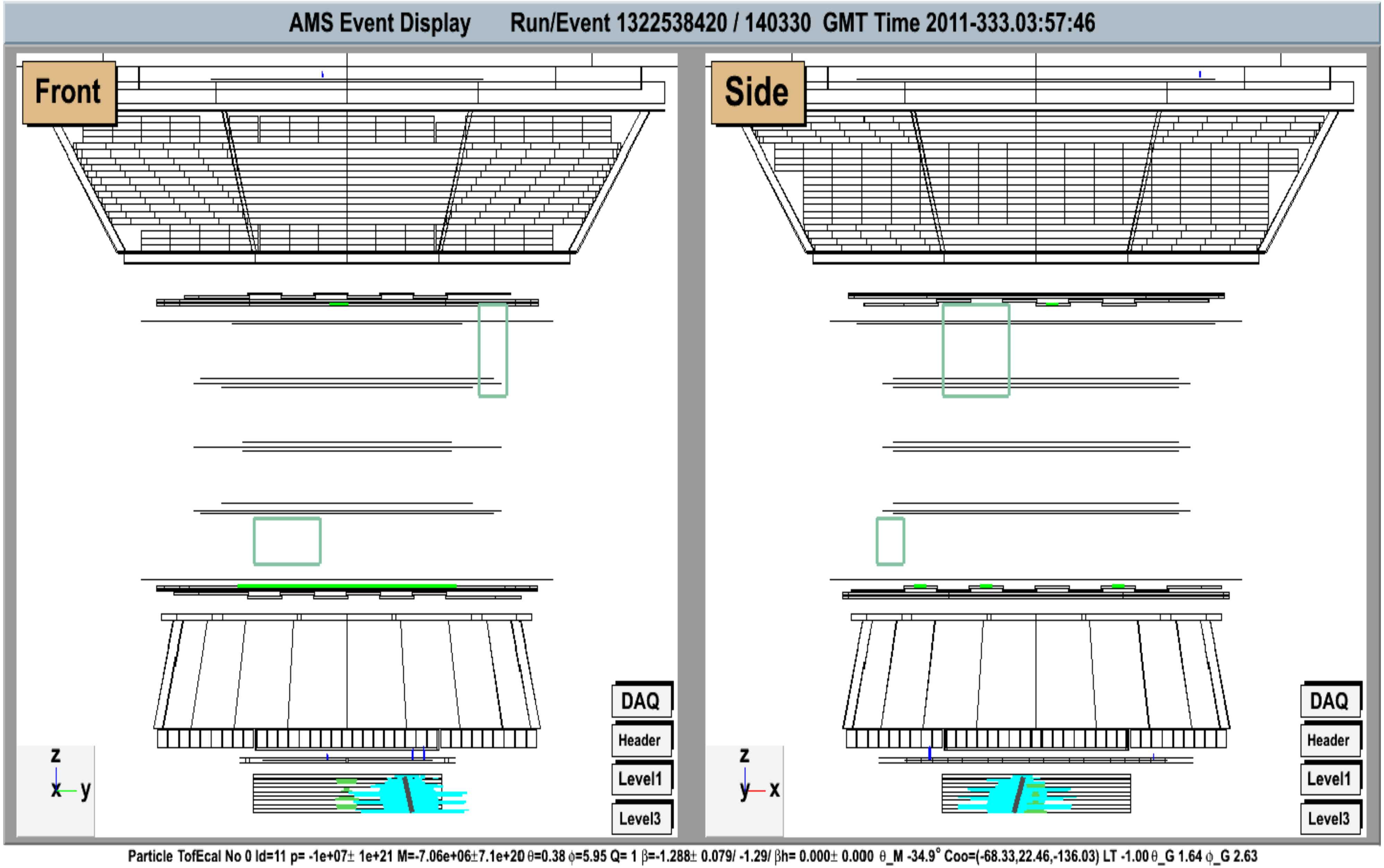
5. Low energy photons

6. High energy photons

Photon event - ISS data



257 GeV

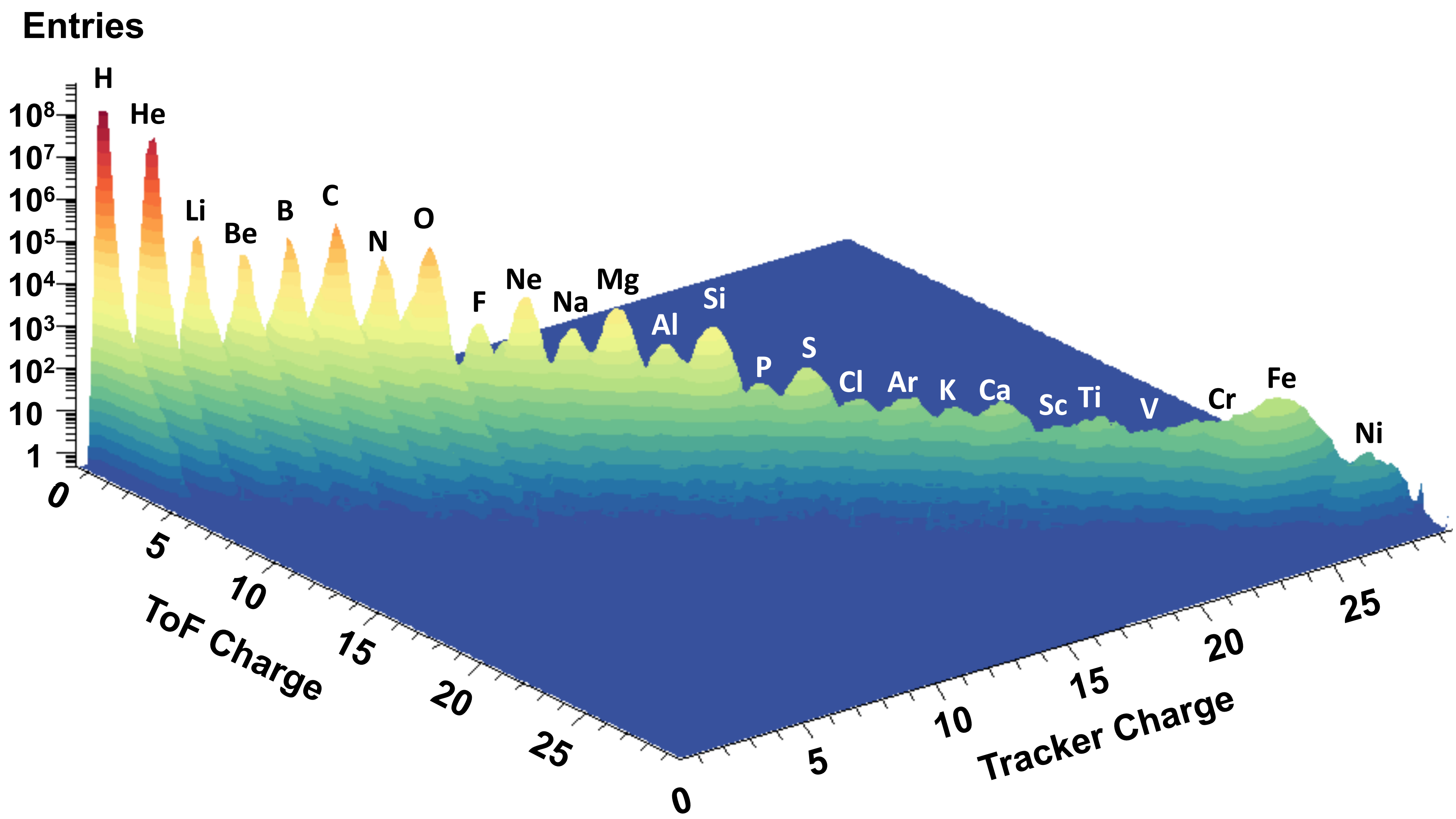


AMS Event Display
Run/Event 1322538420 / 140330 GMT Time 2011-333.03:57:46
Front
Side
DAQ
Header
Level1
Level3
z
x
y
z
y
x
DAQ
Header
Level1
Level3
Particle TofEcal No 0 Id=11 p= -1e+07± 1e+21 M=-7.06e+06±7.1e+20 θ=0.38 ϕ=5.95 Q= 1 β=-1.288± 0.079/ -1.29/ βh= 0.000± 0.000 θ_M -34.9° Coo=(-68.33,22.46,-136.03) LT -1.00 θ_G 1.64 ϕ_G 2.63

Examples of on-going physics analyses

7. Search for Antimatter
8. Search for Strangelets
9. Measurement of all nuclei

AMS Nuclei Measurement on ISS



The Cosmos is the Ultimate Laboratory.

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

The most exciting objective of AMS is to probe the unknown; to search for phenomena which exist in nature that we have not yet imagined nor had the tools to discover.

Discoveries in Physics

Facility	Original purpose, Expert Opinion	Discovery with Precision Instrument
P.S. CERN	π N interactions	Neutral Currents -> Z, W
Brookhaven	π N interactions	ν_e, ν_μ CP violation, J
FNAL	Neutrino physics	*b, t quarks*
SLAC Spear	ep, QED	Scaling, Ψ, τ
PETRA	t quark	*Gluon*
Super Kamiokande	Proton decay	Neutrino oscillations
Hubble Space Telescope	Galactic survey	*Curvature of the universe, dark energy*
AMS on ISS	Dark Matter, Antimatter Strangelets,…	*?*

Exploring a new territory with a precision instrument is the key to discovery.