Cosmic ray detection in space

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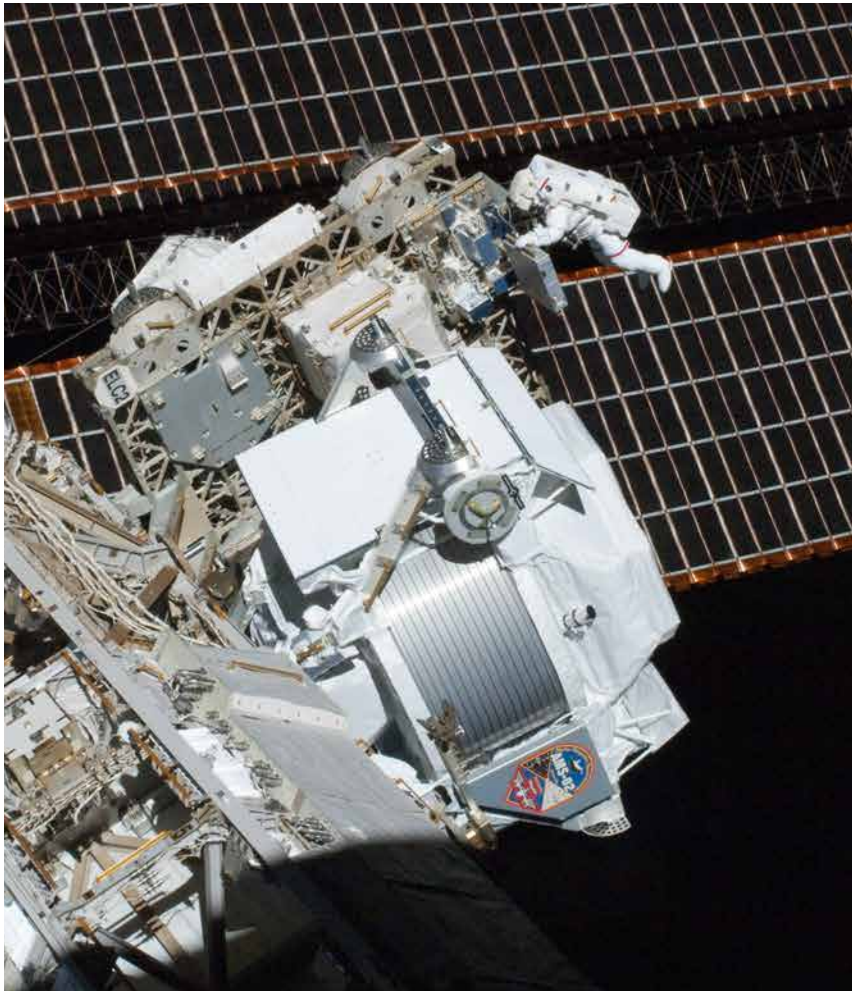
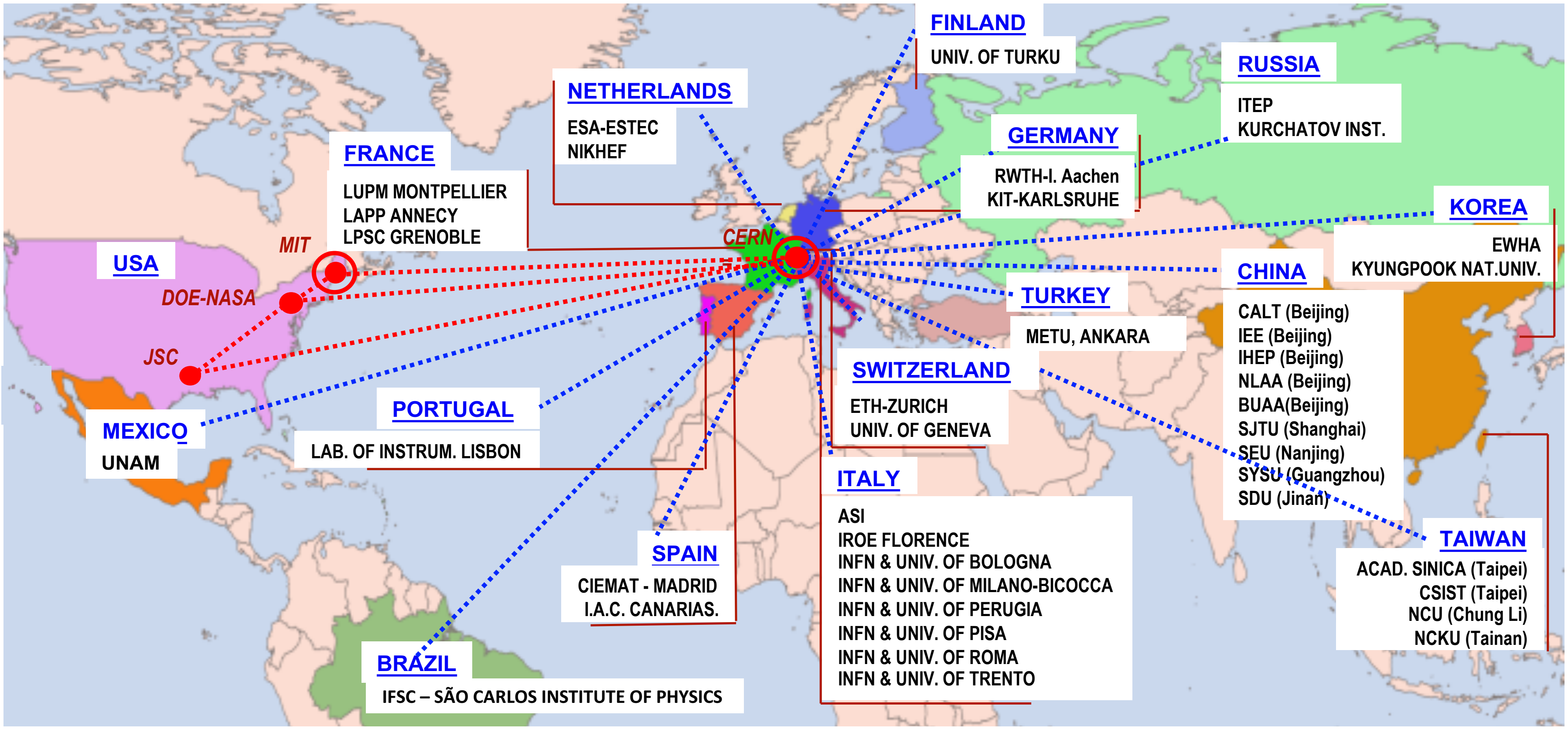
The AMS-02 detector

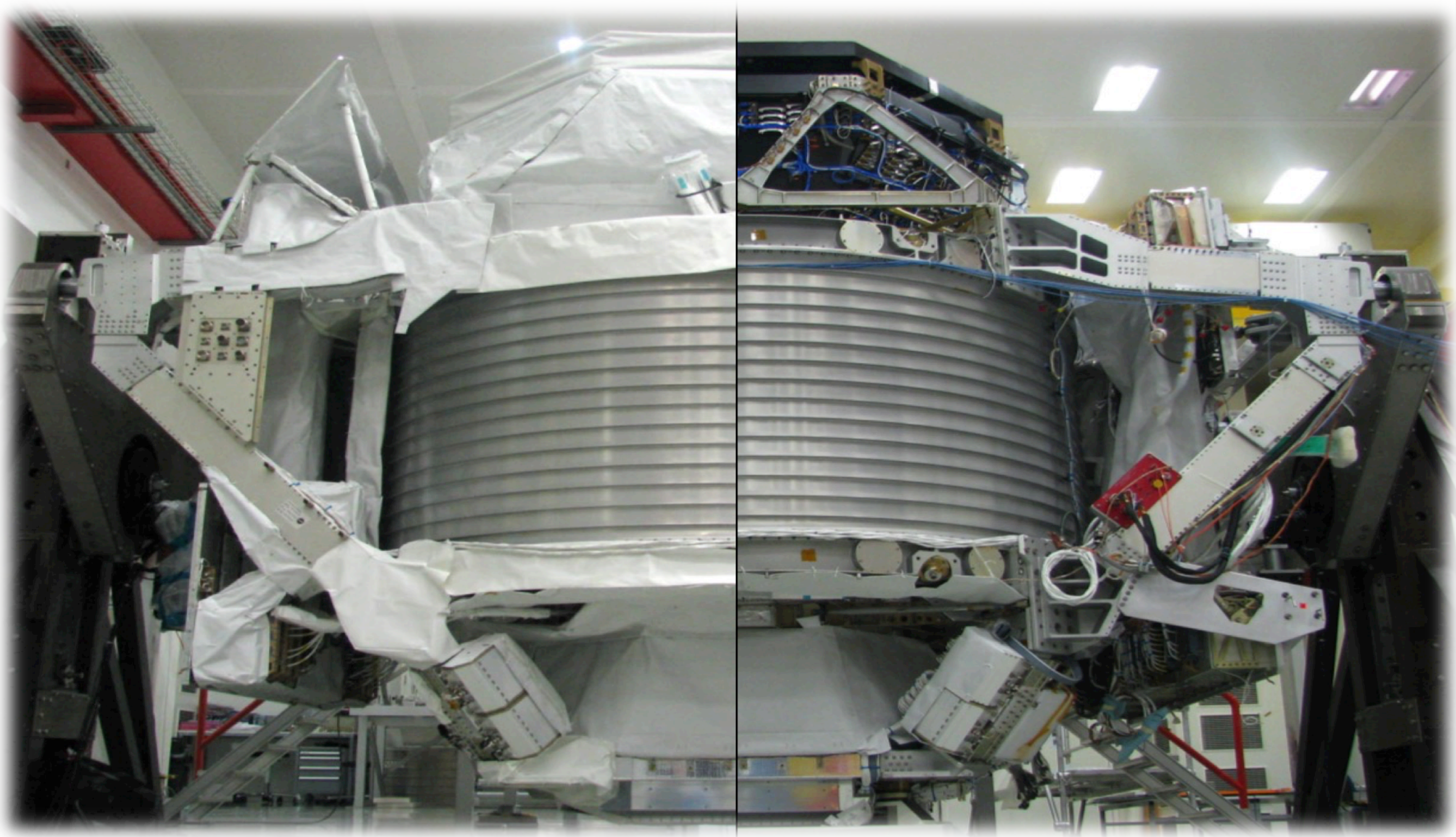


- **Size** 5 x 4 x 4 m, 7500 kg
- **Power** 2500 W
- **Data Readout** 300,000 channels
- **<Data Downlink>** ~ 12 Mbps
- **Magnetic Field** 0.14 T
- **Mission duration** until the end of the ISS operations (currently 2024)

The AMS-02 Collaboration



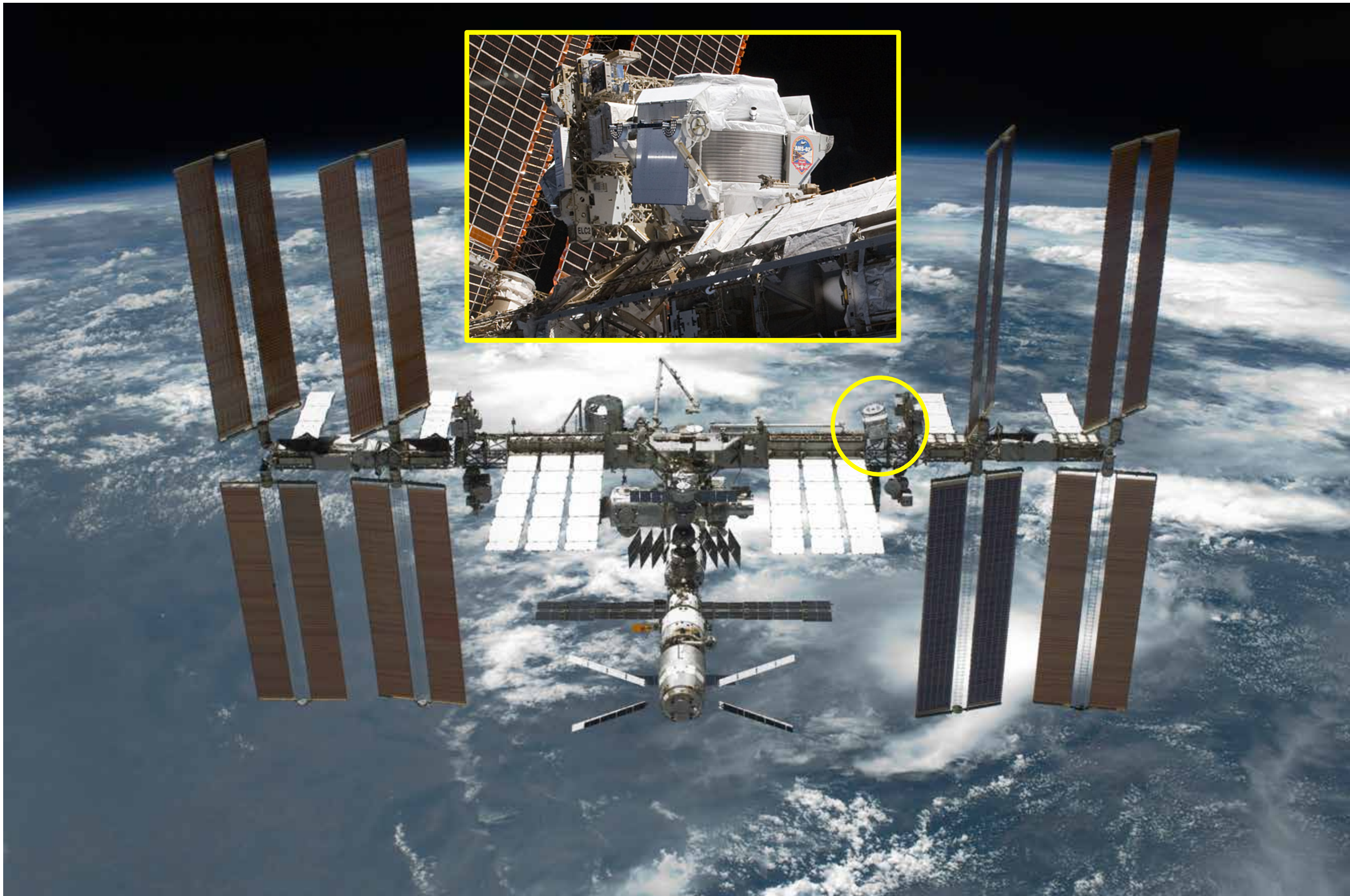
The AMS-02 detector



The AMS-02 detector

The AMS-02 detector

AMS-02 on the ISS



AMS-02 Physics

FUNDAMENTAL PHYSICS

- Indirect search for Dark Matter (e^+, anti-p,….)
- Search for primordial antimatter (anti-He)

COSMIC RAY COMPOSITION AND ENERGETICS

- Precise measurement of the energy spectra of H, He, Li, B, C

to provide information on CR interactions and propagation in the galactic environment

TO ACHIEVE THIS…..

Particle identification and Energy measurement up to TeVs

- Matter/antimatter separation using magnetic field
- e/p separation using independent subdetectors

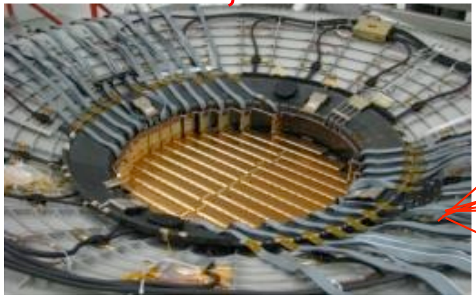
Maximize the data sample

- Detector size (acceptance)
- Exposure time: ISS in space

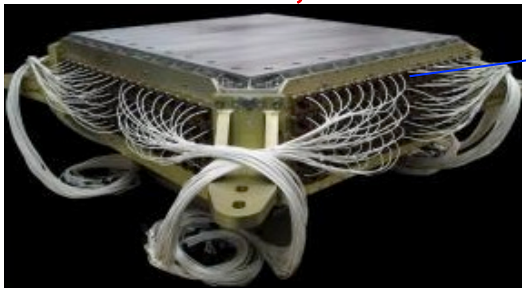
AMS: TeV precision spectrometer

TRD
Identifies e^+, e^-

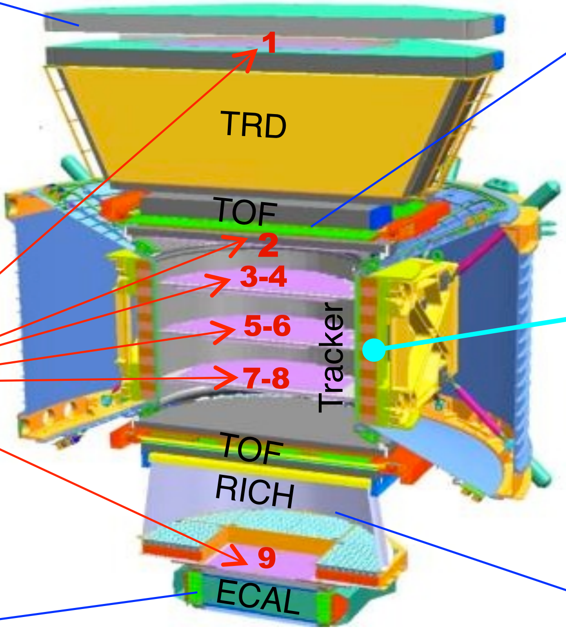
Silicon Tracker
Z, P



ECAL
E of e^+, e^-



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



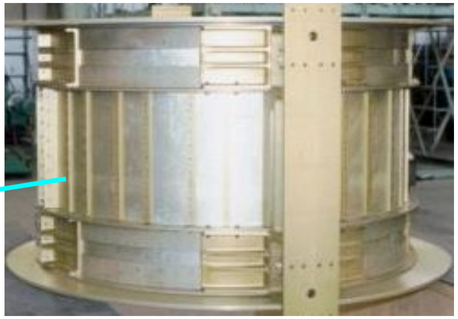
Z and P ~ E

are measured independently by the

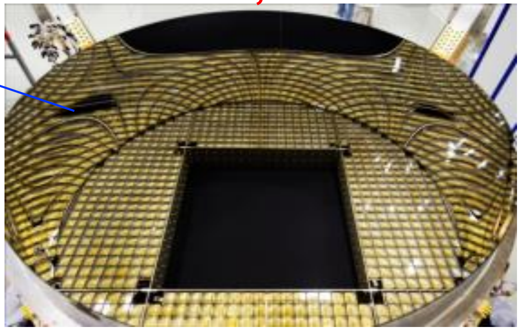
Tracker, RICH, TOF and ECAL

TOF
Z, E

Magnet
±Z



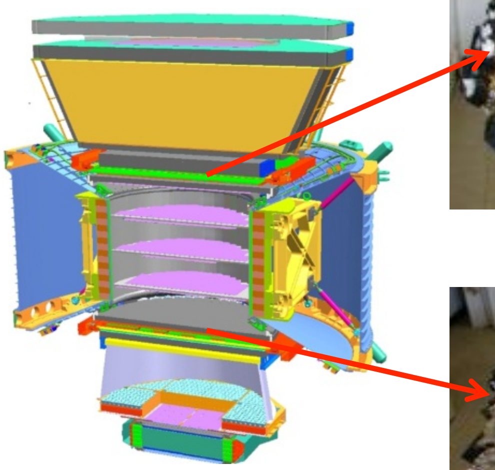
RICH
Z, E

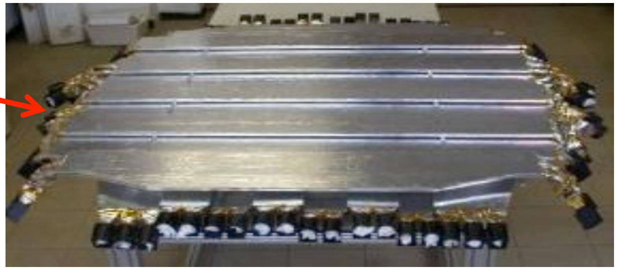


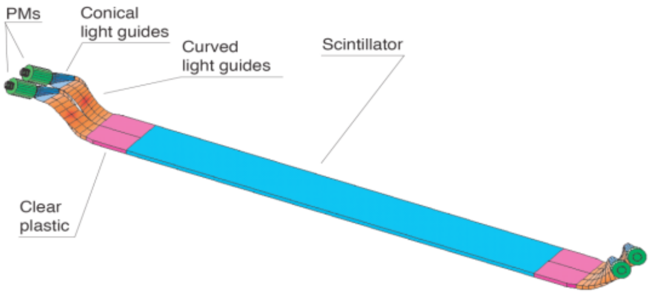
Time of Flight TOF

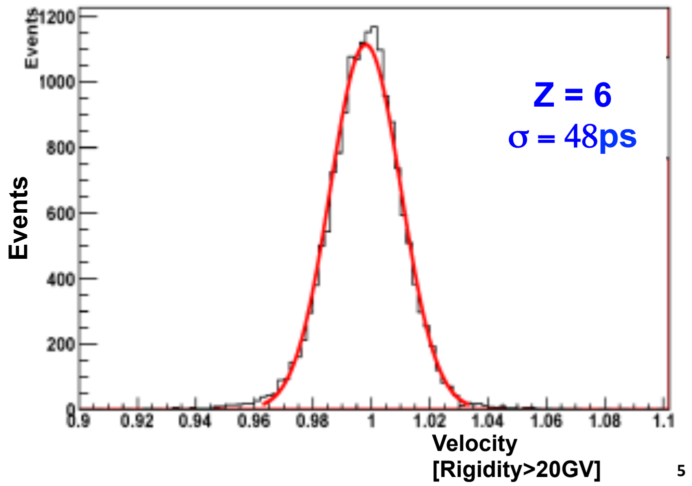
Fast scintillator planes coupled with PMTs for fast light readout

Time of flight resolutions ~ 160 ps → $d\beta/\beta^2$ ~ 4% for Z=1 particles, better for higher charges









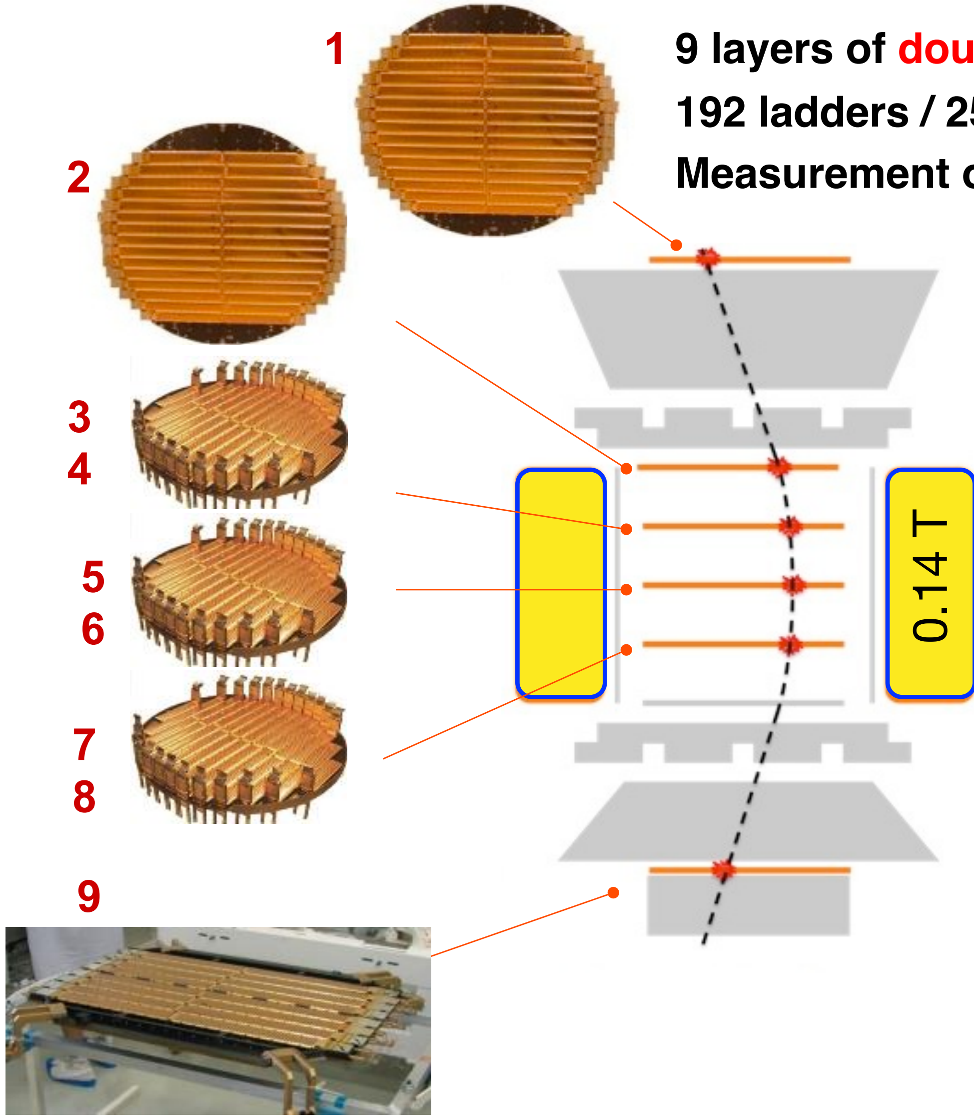
Fast signal used to provide the experiment trigger to charged particles

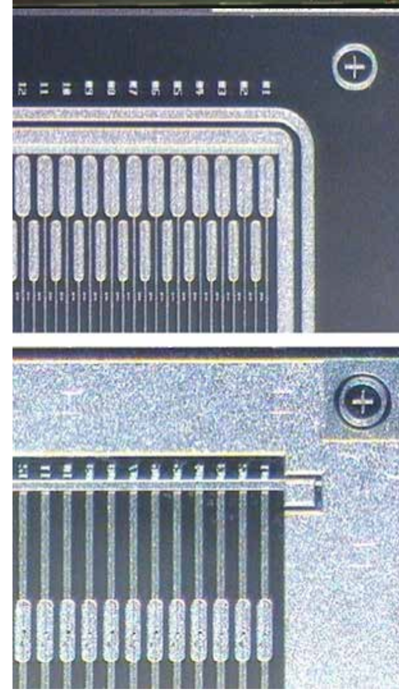
Magnetic Spectrometer

9 layers of **double sided silicon microstrip detectors**

192 ladders / 2598 sensors/ 200k readout channels

Measurement of the coordinate with 10μm accuracy



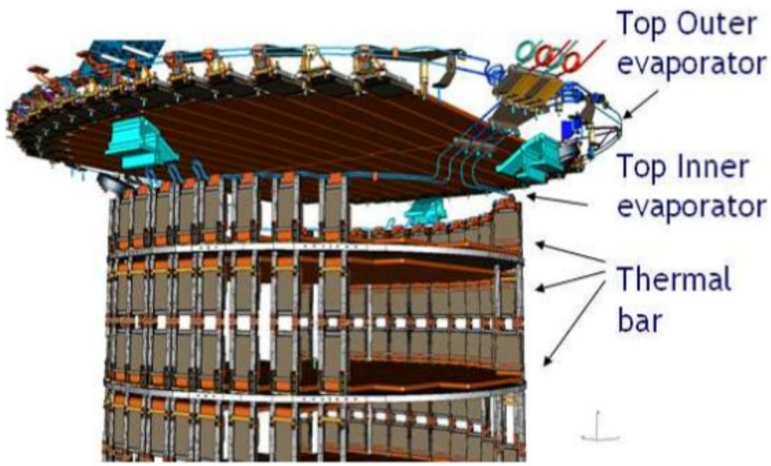


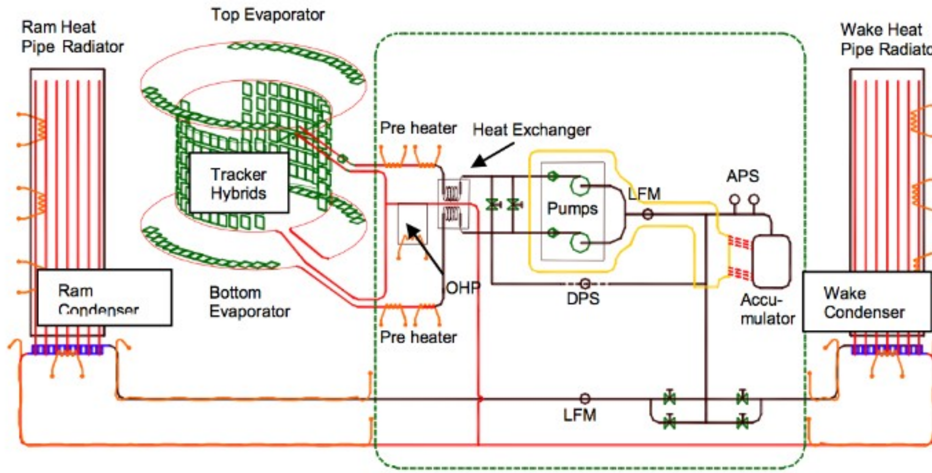
P-side (bending dir)
27.5 µm pitch
104 µm readout

N-side
104 µm pitch
208 µm readout

Tracker Thermal Control System

150 W to be dissipated from Inner Tracker



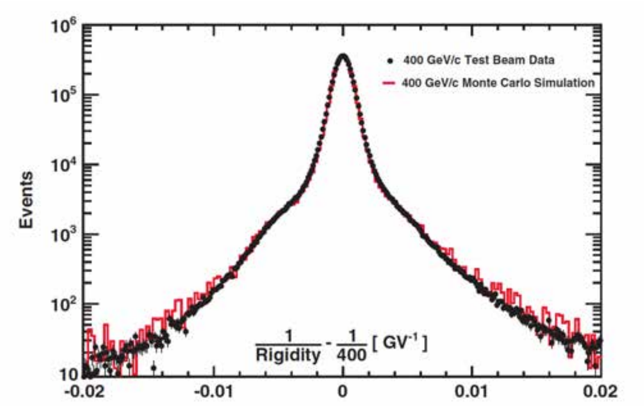


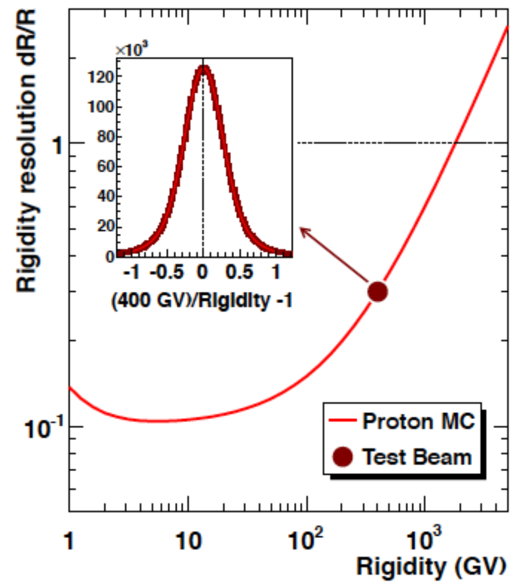
2-phases CO_2 cooling system (4x redundant)

CO_2 pumped through an evaporator and boils due to the heat produced by electronics.
Exiting/Entering CO_2 thermally connected (CO_2 is entering at the boiling point).
CO_2 dissipates heat through dedicated radiators (condenser)

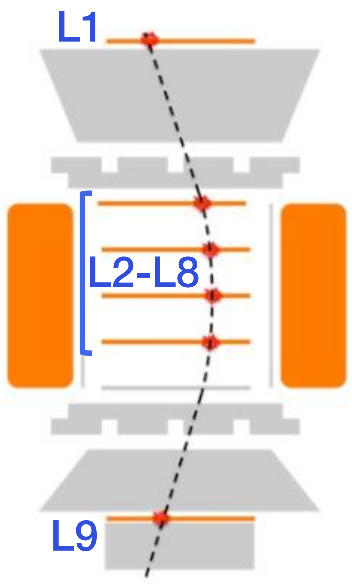
Magnetic Spectrometer

The spectrometer resolution is studied using test beam particles and MC simulations





Magnetic Spectrometer



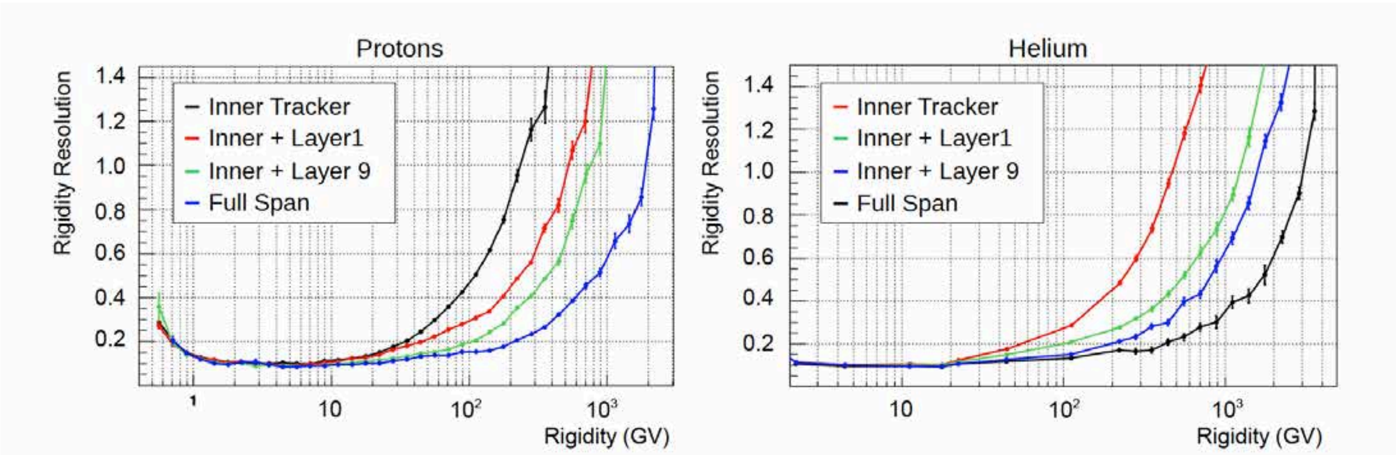


Figure 2.12: Rigidity measurement resolution for protons (**Left**) and Helium (**Right**) estimated from MC. Different colors identify different Tracker spans. The presence of the external layers used to increase the trajectory lever of arm allows to measure the rigidity of particles crossing the Tracker layers up to the TeV range

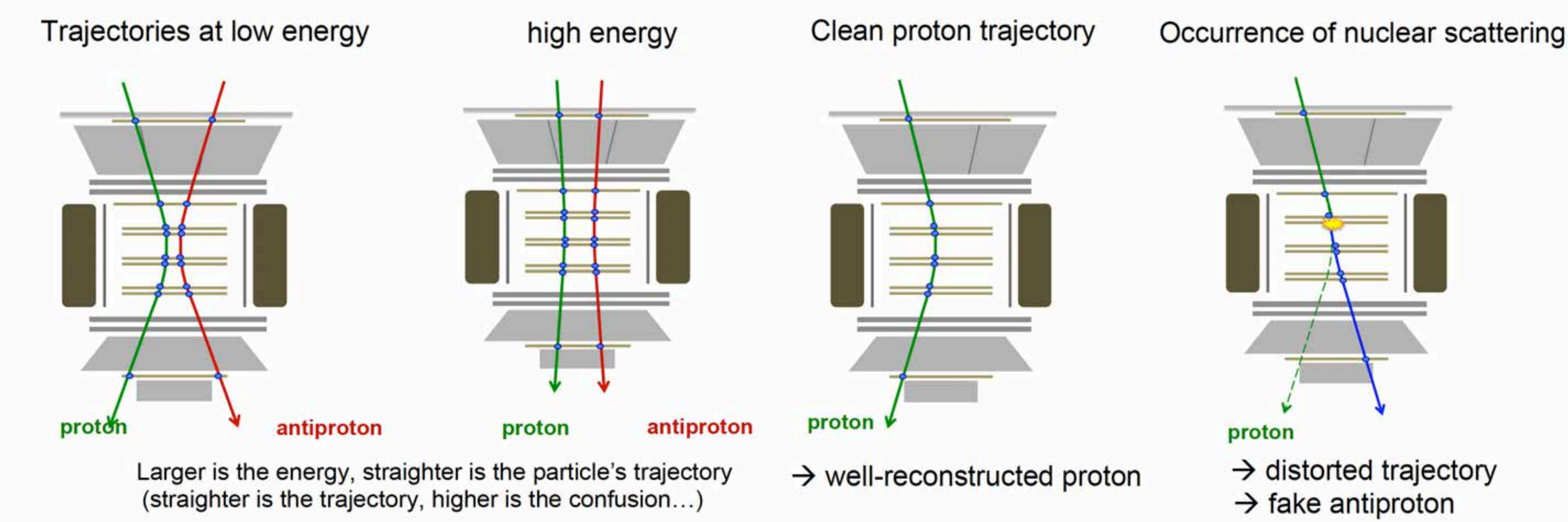
At low energies, the rigidity measurement resolution is dominated by the multiple scattering in the tracker material (dR/R ~ cost).
At high energies, the resolution is defined by the curvature measurement (dR/R ~ R).

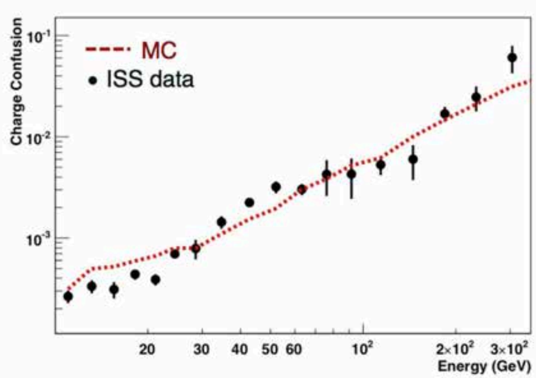
The maximum detectable rigidity is defined as the rigidity when the resolution is 100% (Cannot distinguish between negative and positive curvatures)

Magnetic Spectrometer

Charge Confusion (or Flip)

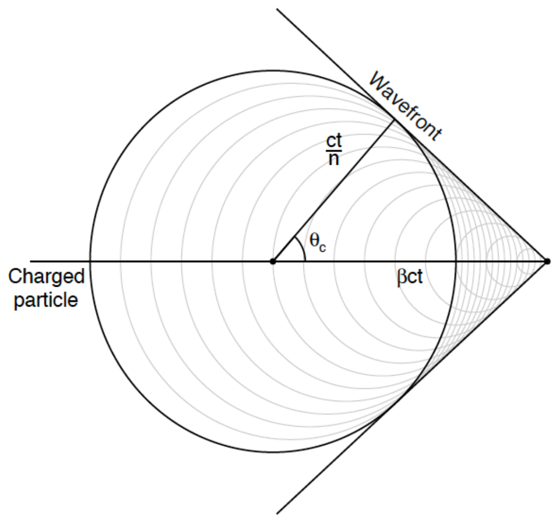
Tracker Resolution (statistical) | **Interactions with the material**





The amount of charge confusion increases with energy, limiting the capabilities to correctly measure the fraction of antimatter in cosmic rays

Ring Imaging Cherenkov RICH



Cherenkov radiation is emitted when a charged particle moves in a medium at a speed greater than the speed of light *in that medium*

$$\beta > \frac{1}{n}. \qquad (52)$$

$$\cos\theta_c = \frac{1}{n\beta}$$

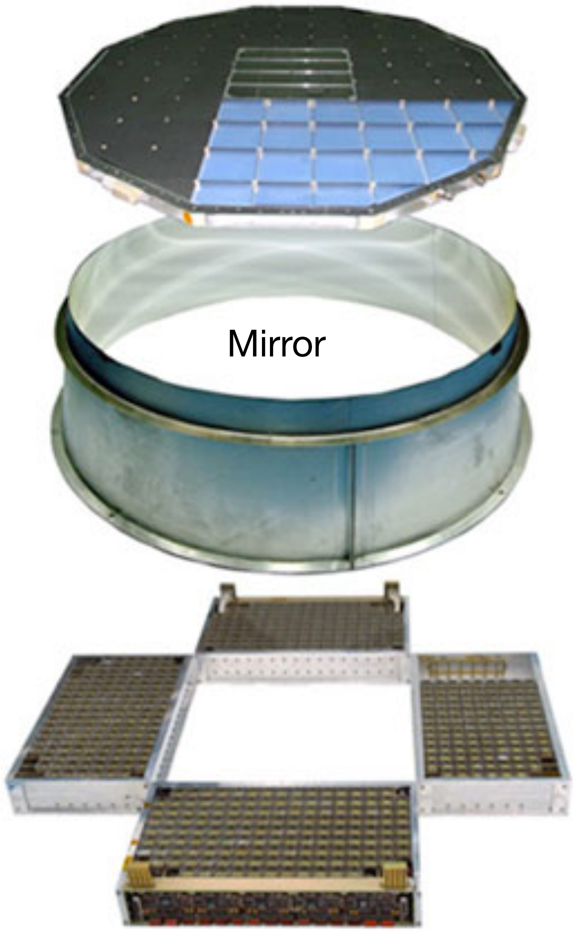
Geometry: Cherenkov ring aperture used to measure the particle velocity

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

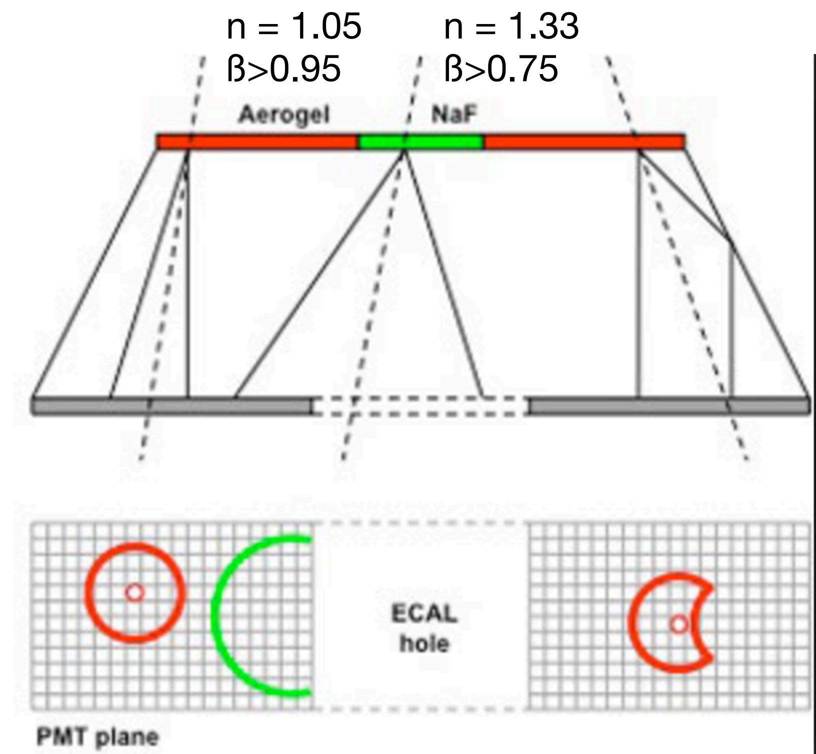
Intensity: number of UV photons proportional to particle charge

Ring Imaging Cherenkov RICH

Radiator

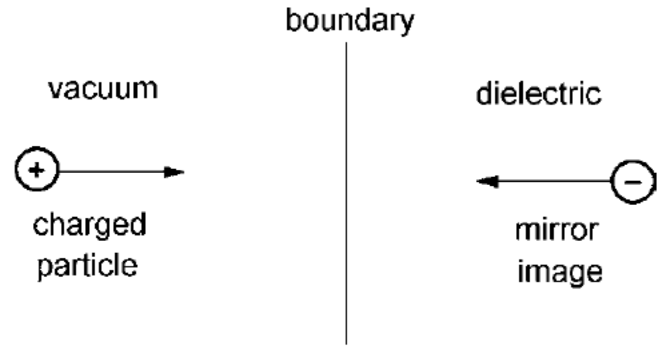


10,880 photosensor plane



Measurement of velocity with dß/ß~0.1%

Transition Radiation



Radiation emitted when charged particles cross boundaries between media.

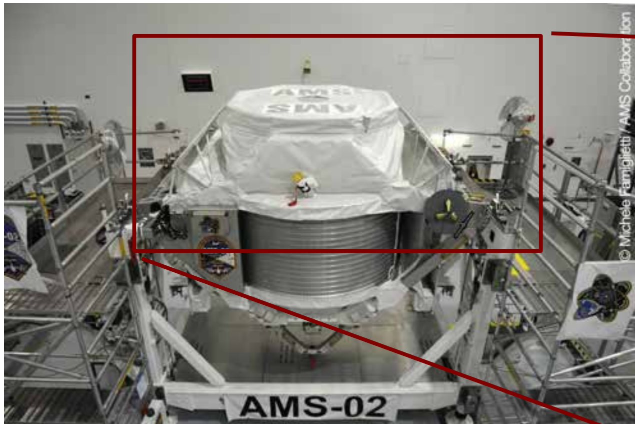
For each crossing, the probability of emission is very small (prop. to α) → T.R. gives a small contribution to the total energy losses.

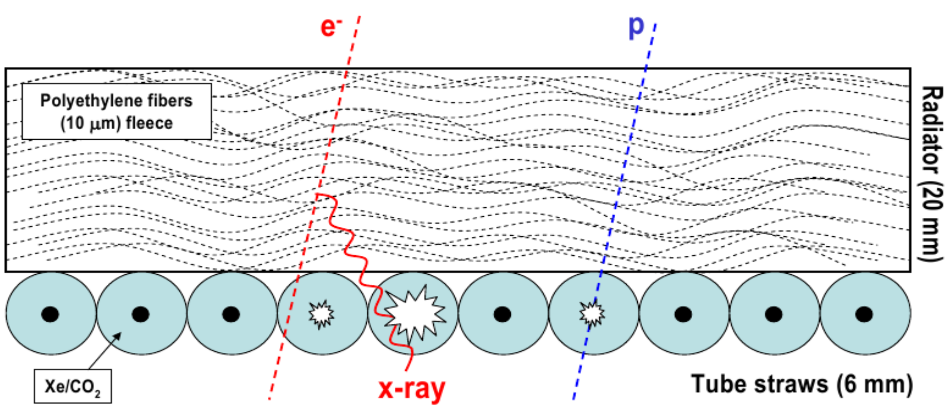
BUT is has a very peculiar dependence on the particle energy. $\mathcal{P}_{TR} \propto \gamma = E/m$

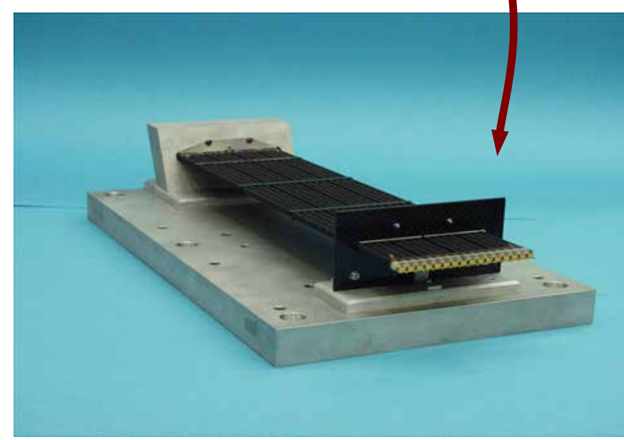
Since it depends on γ (and not on β) it is fundamental to identify high energy particles.

The T.R. emission is dominated by X-rays, that can be detected by gaseous detectors

Transition Radiation Detector TRD



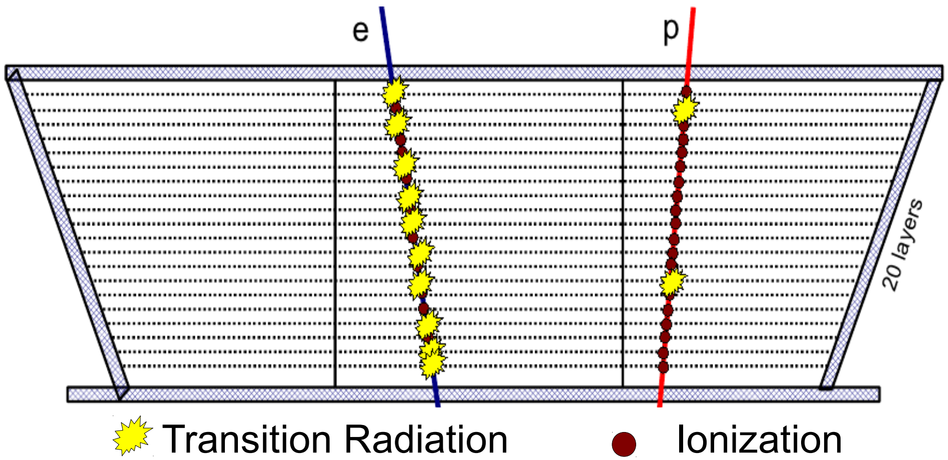




$$\mathcal{P}_{TR} \propto \gamma = E/m$$

20 Layers of radiator (fleece) to induce X ray radiation
Straw tubes for ~KeV xray detection (Xe/C02 gas)

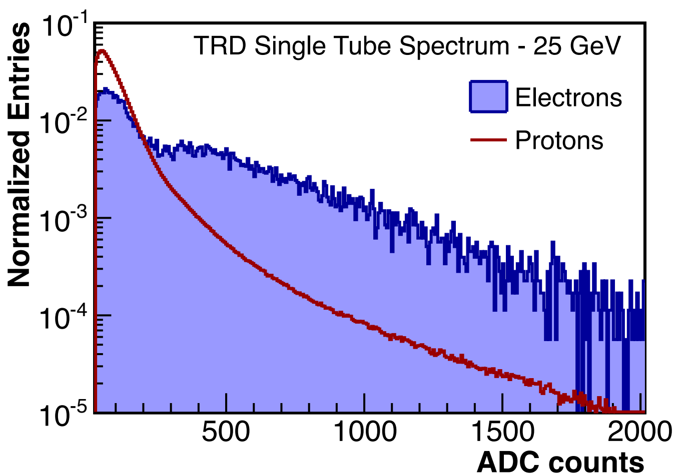
Transition Radiation Detector TRD



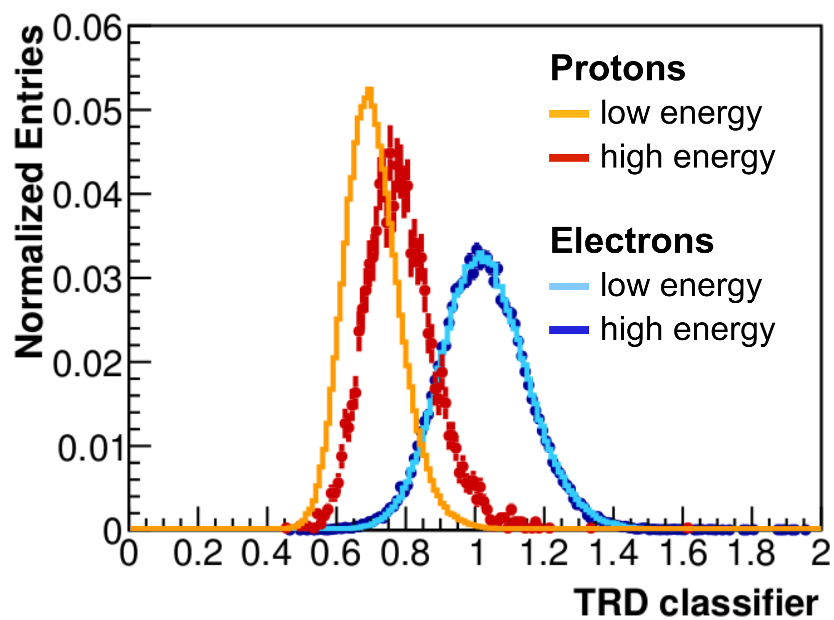
$$\mathcal{P}_{TR} \propto \gamma = E/m$$

For same Rigidity or Energy particles

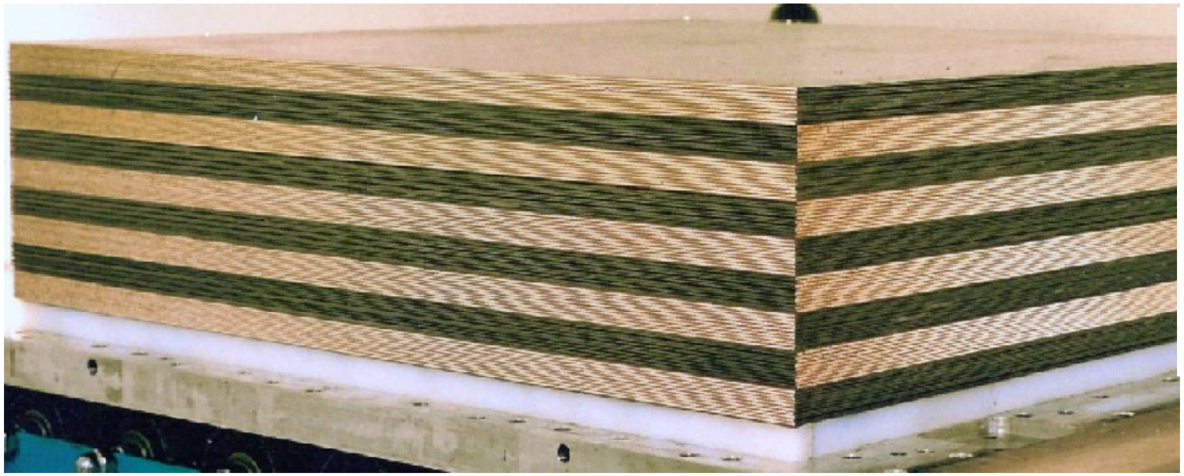
$$\mathcal{P}_{TR}(e^{\pm}) \gg \mathcal{P}_{TR}(p)$$



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

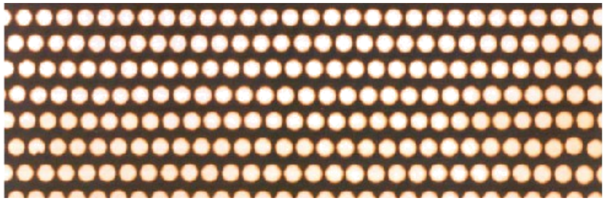


Electromagnetic Calorimeter ECAL



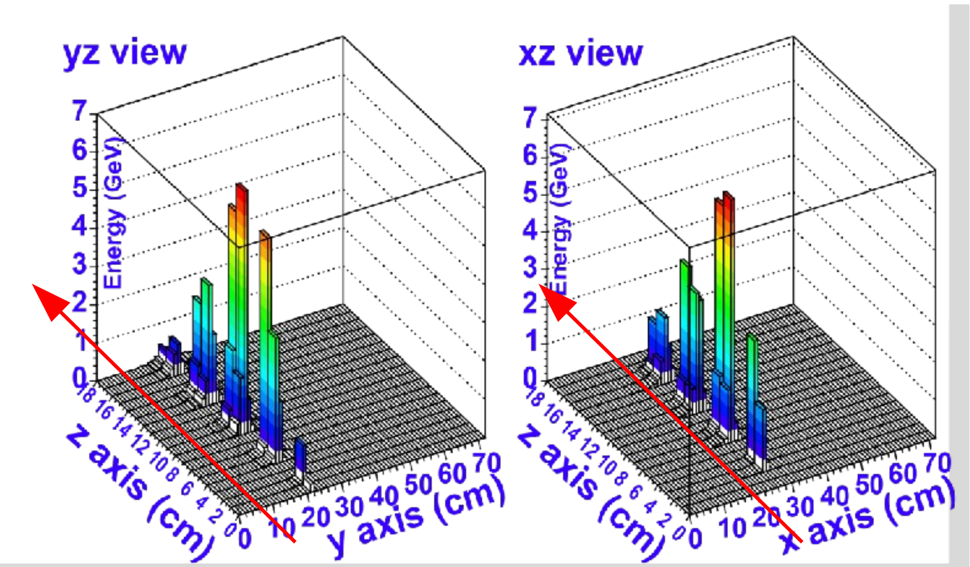
SAMPLING CALORIMETER
Lead + Scintillating fibers
66 x 66 x 17 cm^3
1296 readout cells
17 X_0, 0.6 λ_{nucl}

1 superlayer

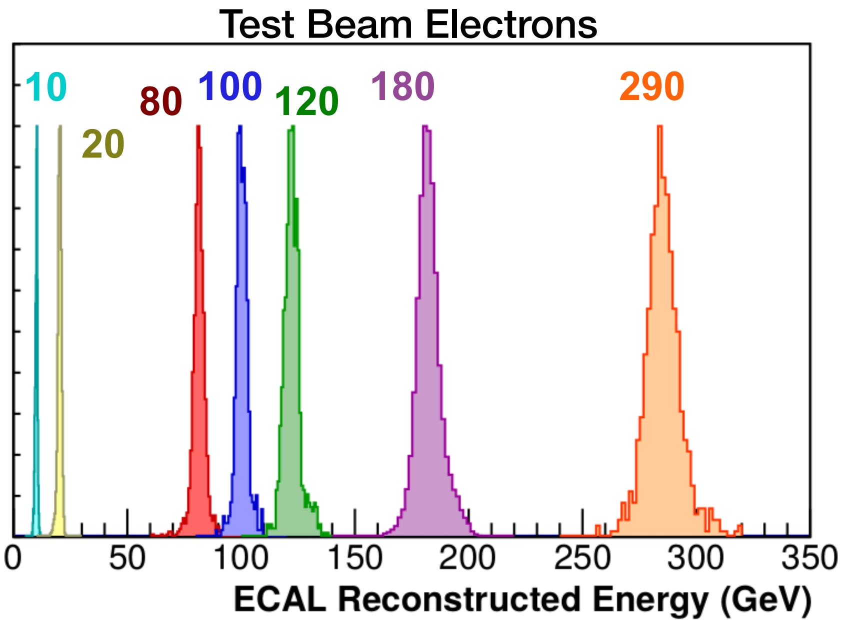


50,000 fibers, Φ=1mm
Uniformly distributed in 600 kg of lead

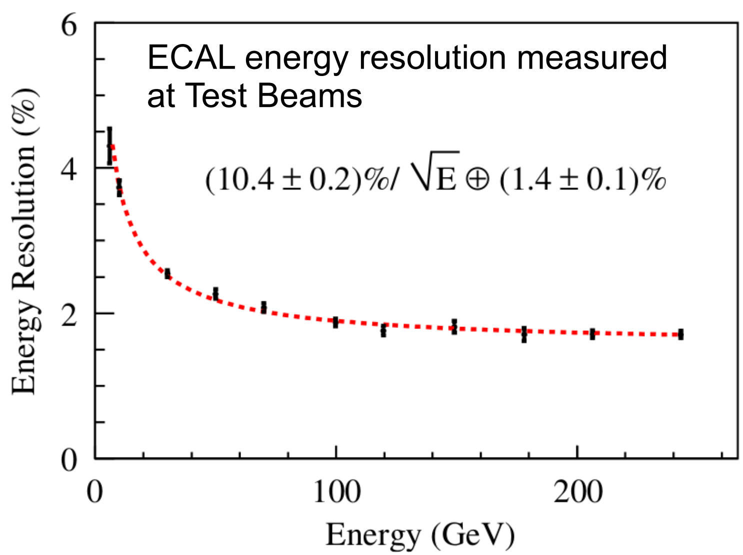
Energy and **arrival direction** measurement of electrons and photons up to 1 TeV

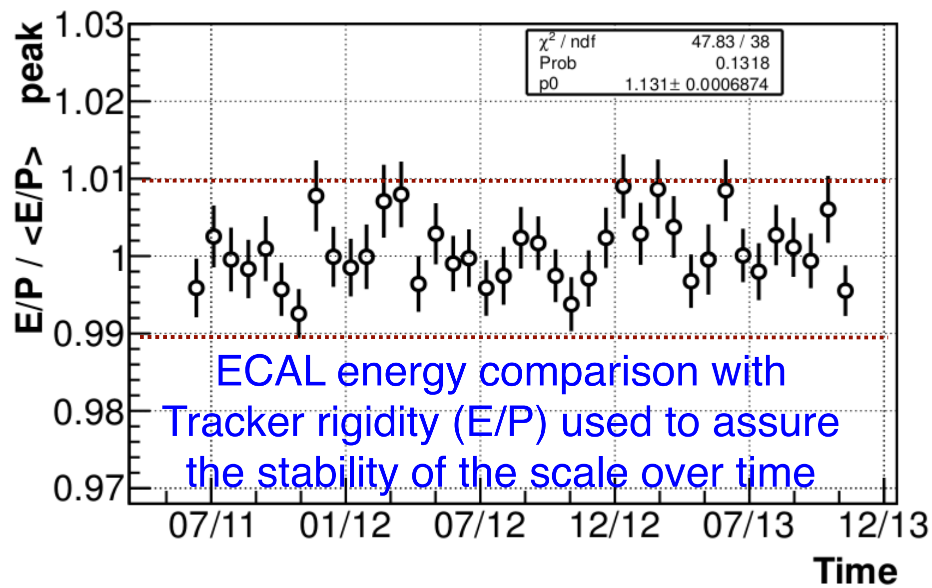


Energy Measurement



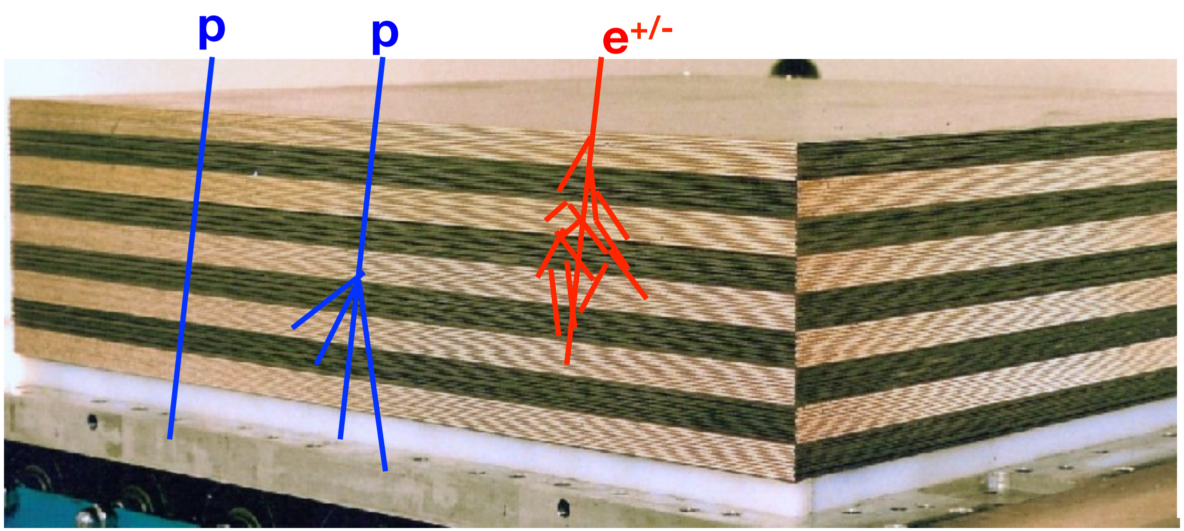
- ECAL energy resolution ~2%
- ECAL energy absolute scale tested during test beams on ground
- We have no line in space (as in collider exp.) to calibrate the energy scale in orbit!
    - MIP ionization used to cross-calibrate the energy scale in orbit





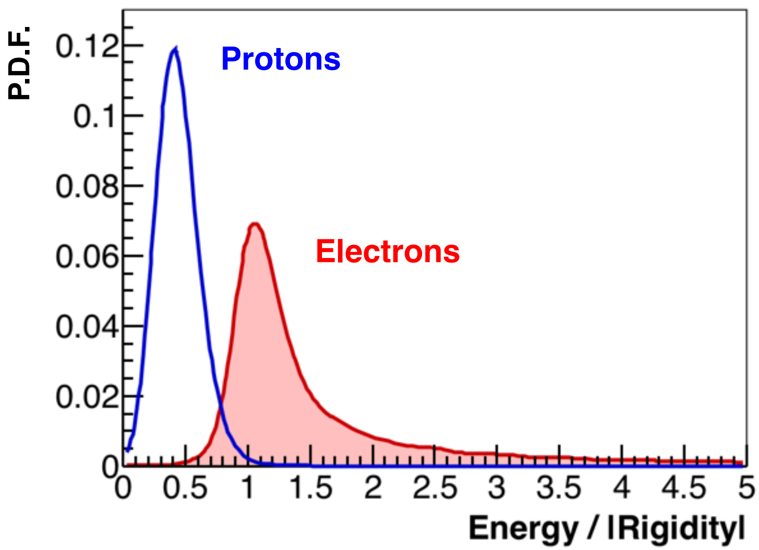
Calorimeter resolution impreves at high energy (compare with spectrometer)

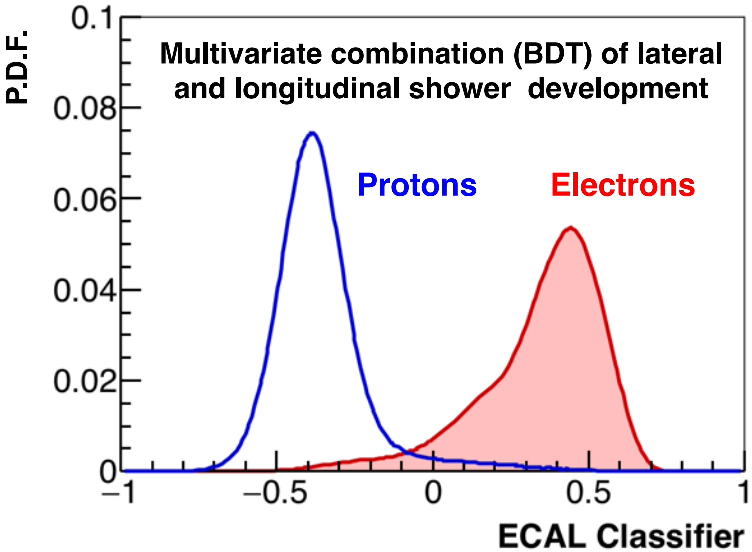
Electromagnetic Calorimeter ECAL



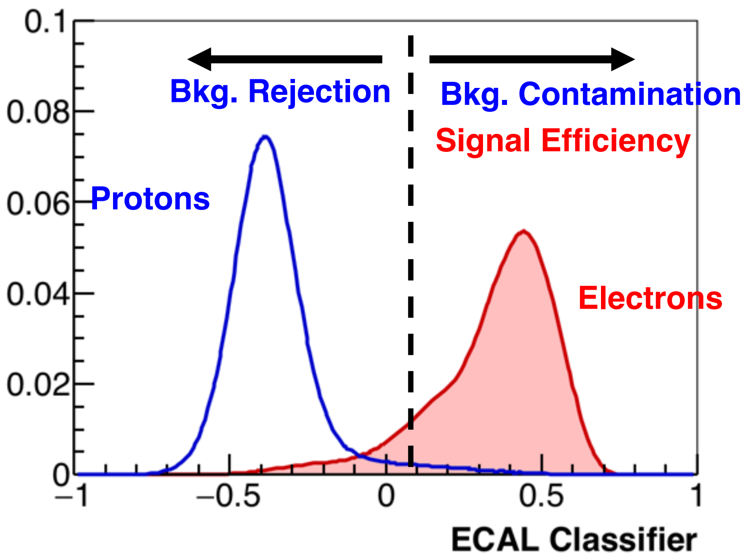
Electrons
Electromagnetic Shower
Energy contained
$E_{ECAL} \sim P_{TRACKER}$

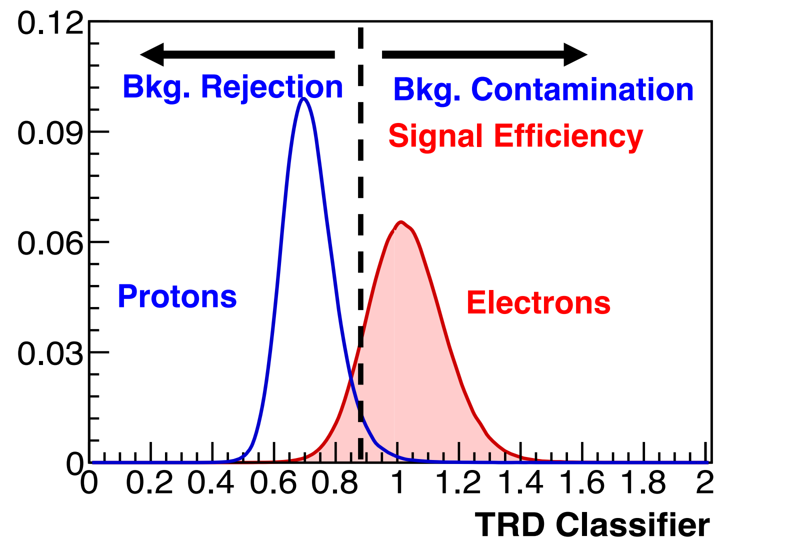
Protons
MIP or Hadronic Shower
Irregular shower
$E_{ECAL} << P_{TRACKER}$

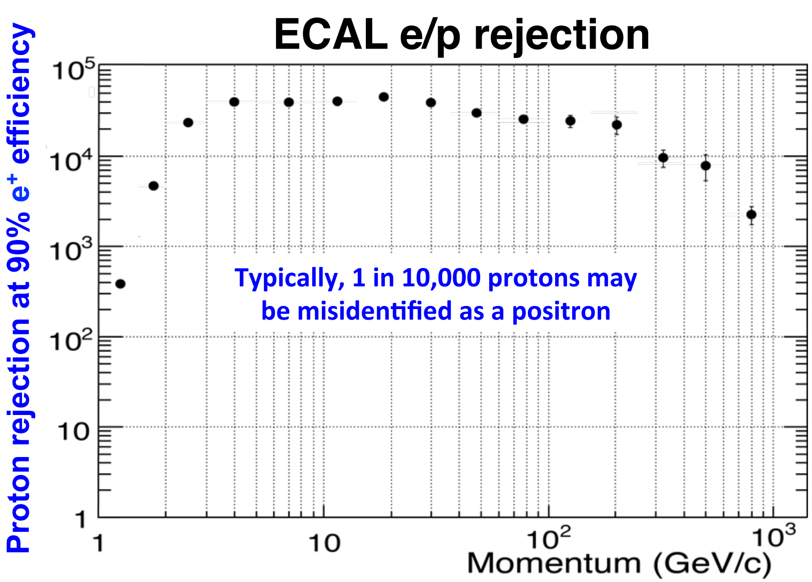


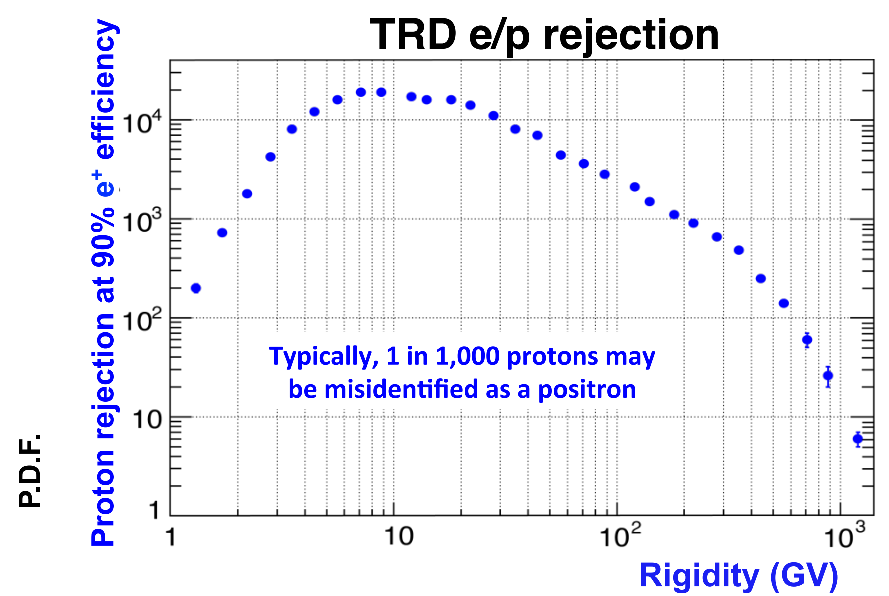


ECAL and TRD e/p separation



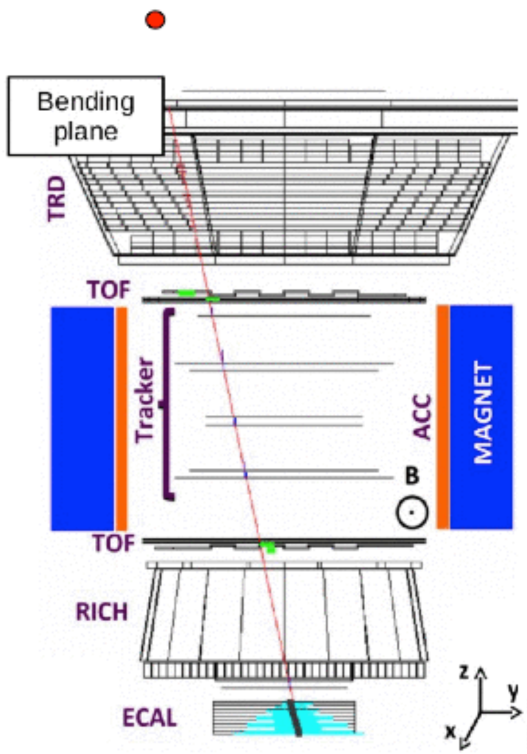


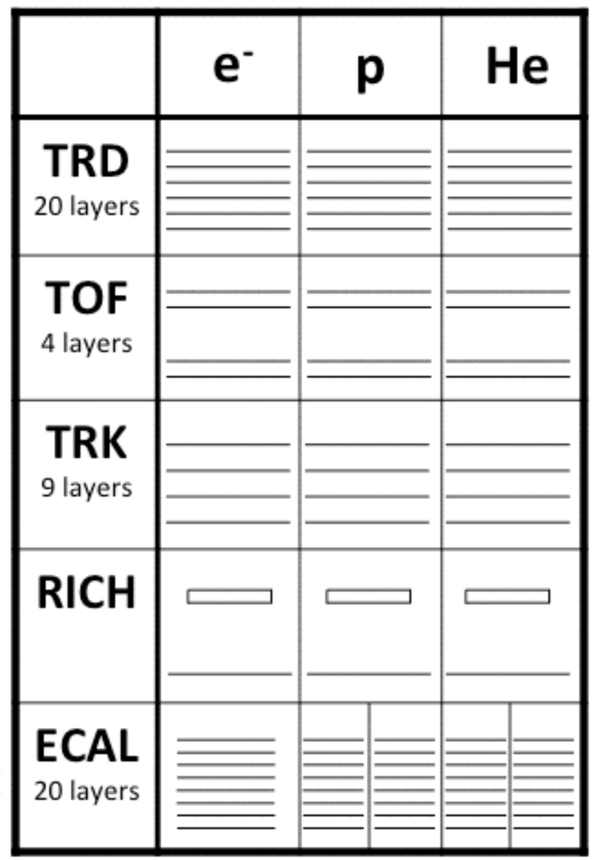




AMS: TeV precision spectrometer

Full coverage of anti-matter and CR physics





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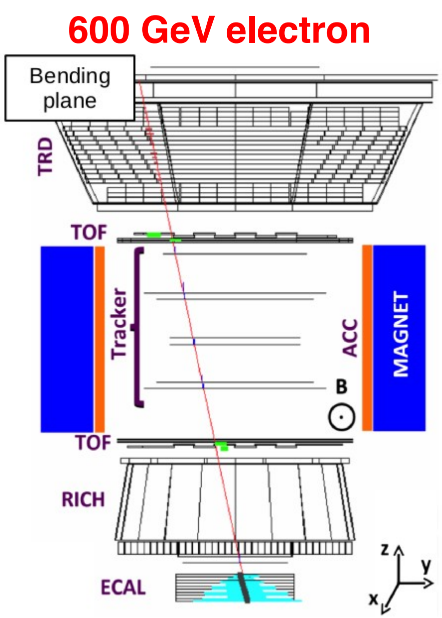
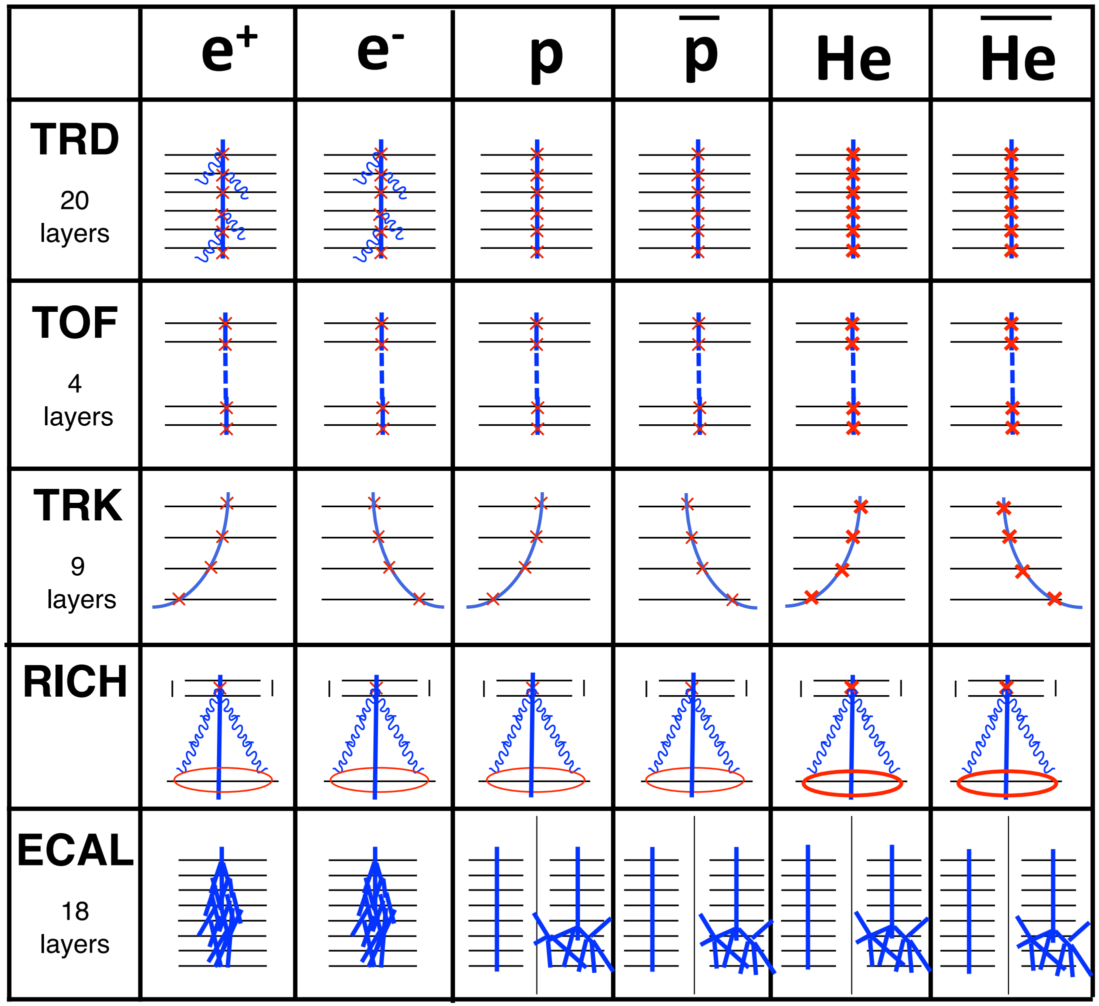
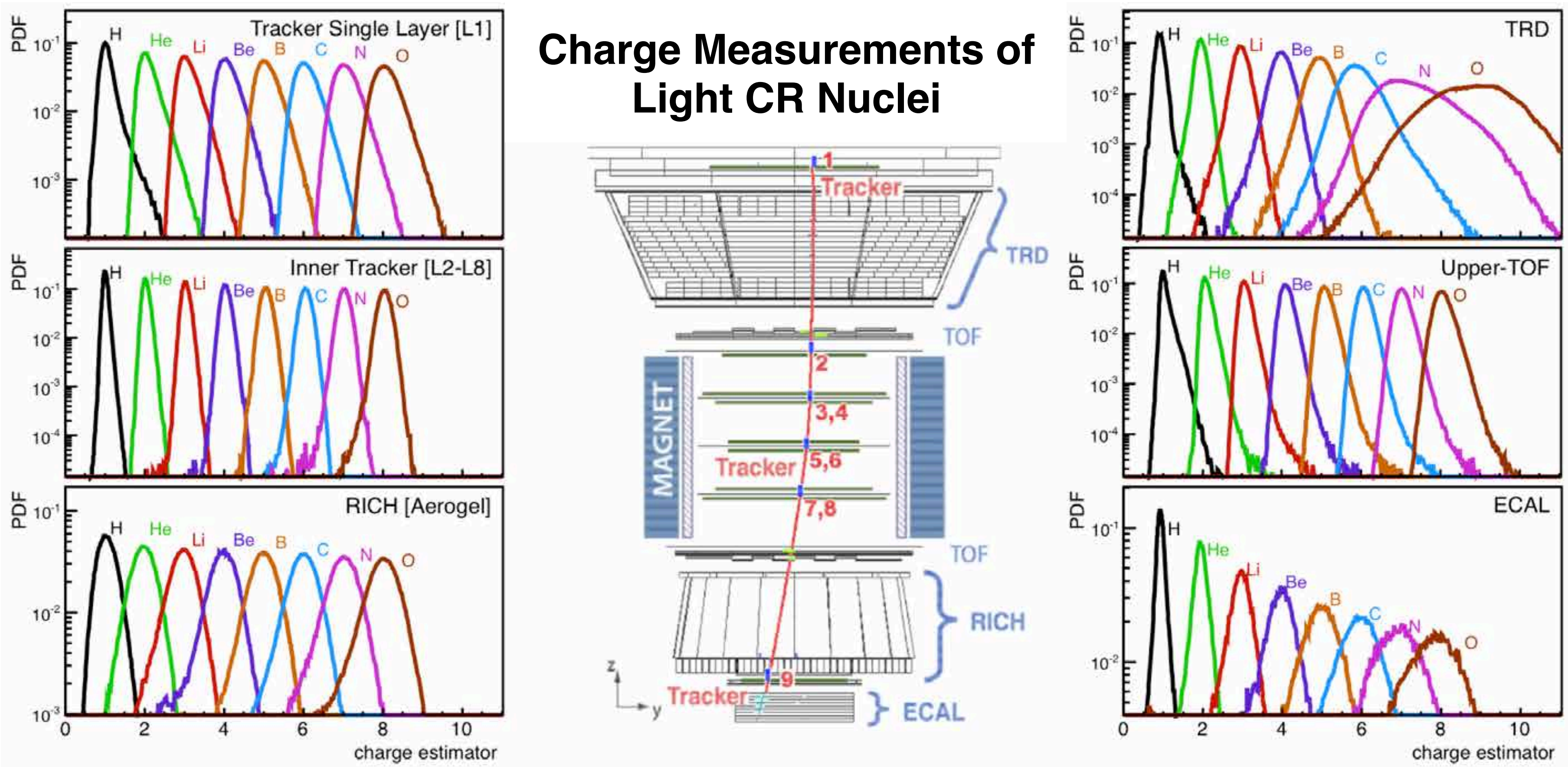




- TRD: e/p separation, charge (|Z|)
- TOF: trigger, velocity (β), charge (|Z|)
- TRK: momentum (p), sign (±Q), charge (|Z|)
- RICH: velocity (β), charge (|Z|)
- ECAL: $e^{\pm}$ energy, e/h separation, γ trigger

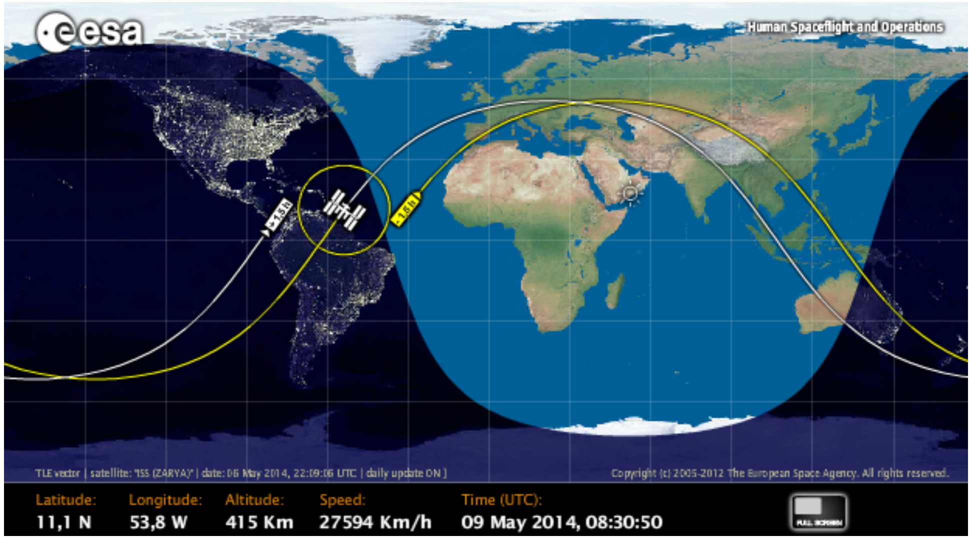
AMS-02 Charge Measurement



Redundant measurements of the nuclear charge at different depths of the detector.

Precise understanding of nuclear fragmentation in the materials.

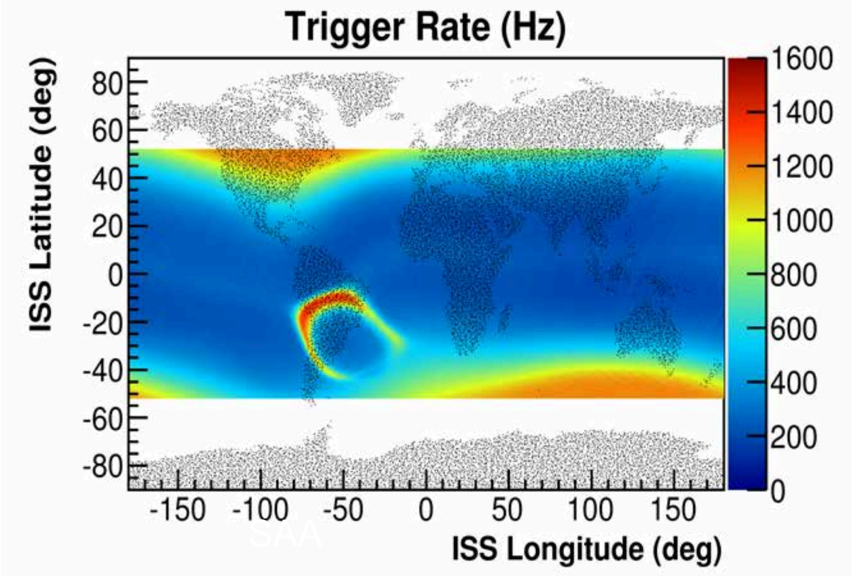
AMS orbit



ISS orbit period ~ 90min
+/- 50 deg latitude covered

DAQ operations depend on orbit position

Increase of trigger rate in polar region (low magnetic field and trapped particles) and in the South Atlantic Anomaly



Detector operated continuously around the clock since May 2011 with no major interruptions

Trigger

Each time a detector decides to save the information of a particle crossing, the electronics freezes the analog information on all the sensors (~300,000 for AMS), digitizes them and package them to send to ground. This procedure lasts O(100 μs – 1 ms).

The flux of cosmic rays through the detector volumes is typically higher than the digitization capabilities. Only a fraction of the total cosmic rays crossing the detector volumes has to be recorded (typically, particles crossing the interesting detector fiducial volume and above a certain energy threshold)

The **trigger** is a system that decides whether the instrument should freeze the analog information and save the **event**. It is based using information from fast detectors and combining it in a simple AND-OR logic.

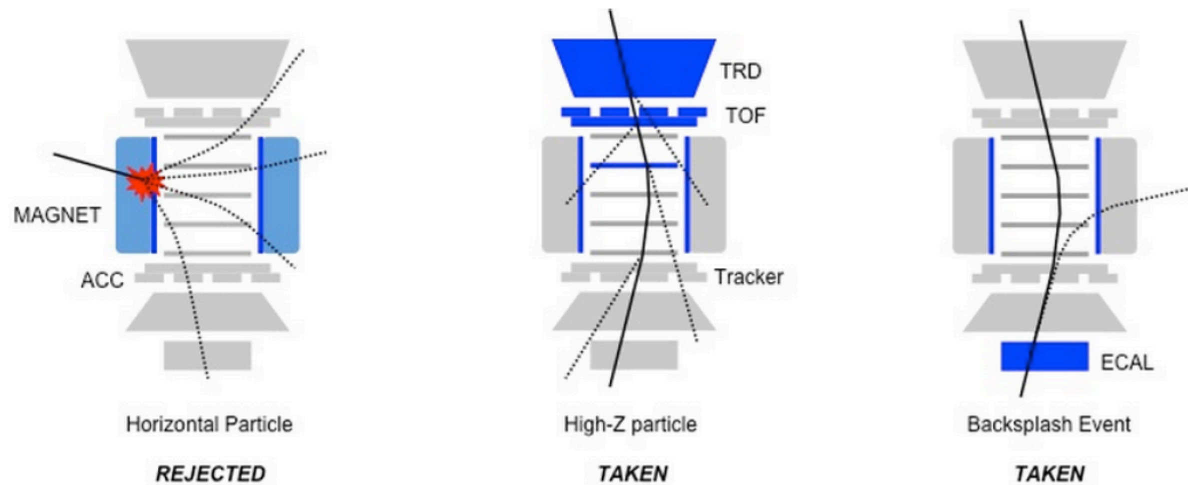
The trigger represent a very delicate system. If an interesting event is not triggered, it will be lost forever. Typically, the trigger selection it is a compromise between the maximum number of events stored with respect to the capabilities of data storage and transfer and event pileup.

Trigger

AMS uses the fast information of the **TOF** the trigger charged particles, the external **anticoincidence** to veto cosmic rays outside the acceptance, and the fast **ECAL** information to trigger photons (that do not leave energy in the TOF)

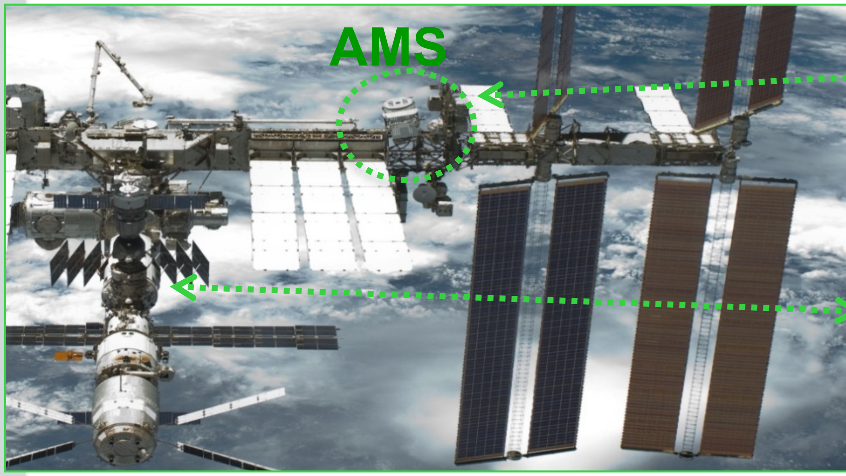
AMS-02 Triggers:

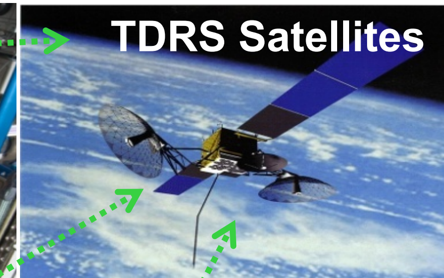
- Unbiased 3/4
- Charged Z=1
- Charged Ions
- "Slow" ions
- Electrons
- Photons
- Unbiased em



If any of these conditions is satisfied, the event is triggered

Data transfer





Ku-Band
High Rate (down):
Events <10Mbit/s>
≈30 billion triggers
70 TB of raw data

Flight Operations

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