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DIPARTIMENTO
DI FISICA E GEOLOGIA
DIPARTIMENTO DI ECCELLENZA
MUR 2023/2027

INFN
PERUGIA
Istituto Nazionale di Fisica Nucleare
Sezione di Perugia

Silicon sensors for the AMS-L0 Upgrade: beam test setup and results

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Outline

1. AMS-02 experiment

    Upgrade: layer 0 (L0)

2. Beam Test & Results

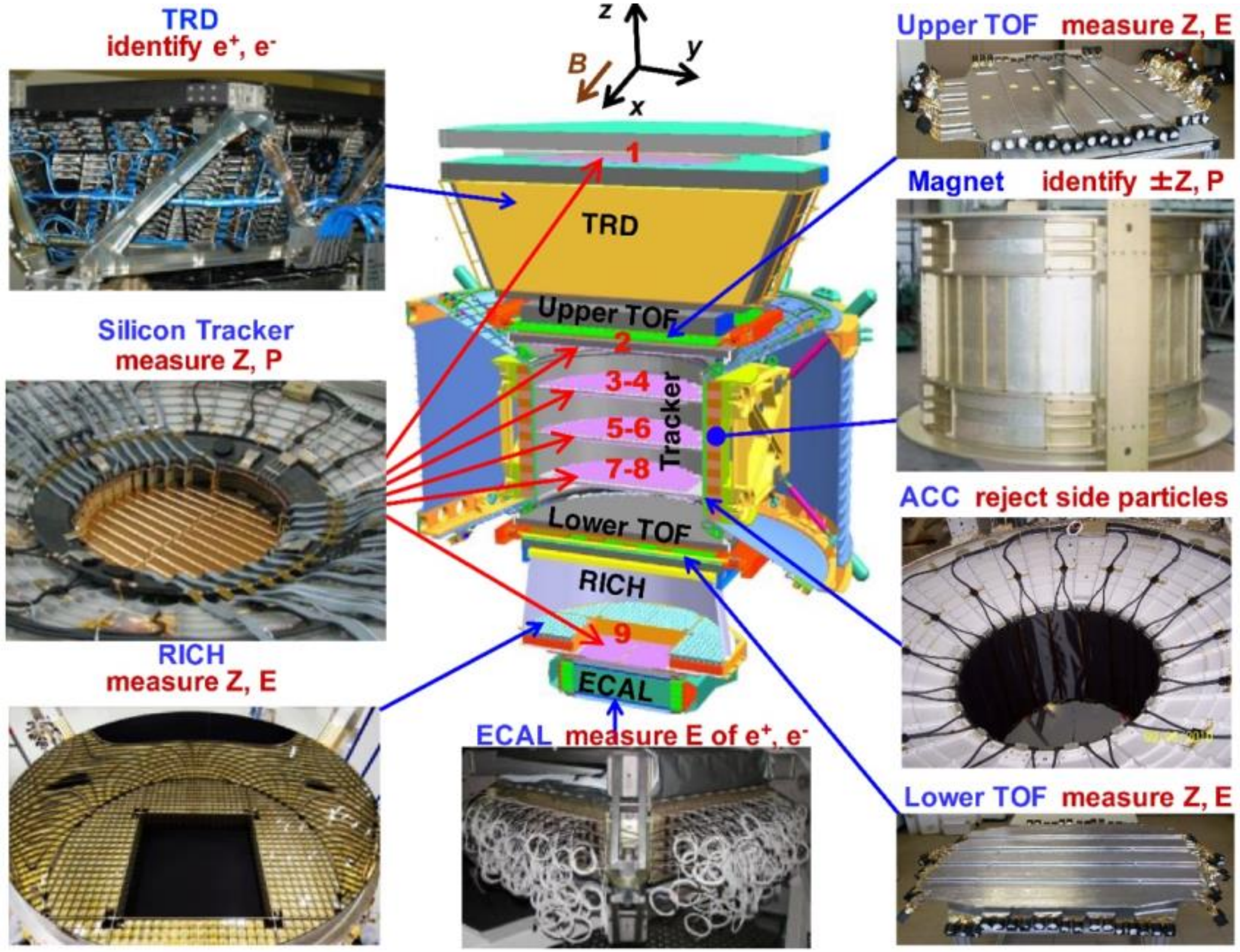
AMS 02: The Alpha Magnetic Spectrometer

Composed by:

• TRD (Transition Radiation Detector): distinguishes proton/antiproton from electron/positron
• TOF (Time of Flight): determines the particle time of flight and charge
• Tracker: measure the particle rigidity and charge
• RICH (Ring Imaging Cherenkov): measures the particle charge and velocity
• ECAL (Electromagnetic Calorimeter):distinguishes between proton/antiproton and electron/positron

Main objectives:

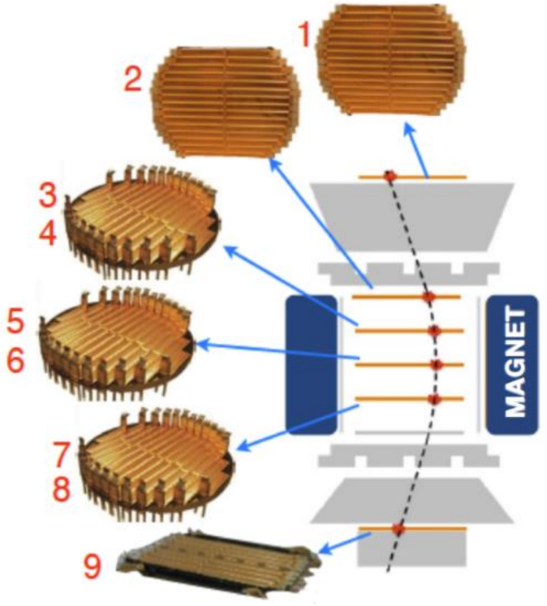
• search for Primordial Antimatter by direct detection of antinuclei
• search for indirect Dark Matter signals
• study of production, acceleration and propagation of Cosmic-Rays
• study of Solar Modulation

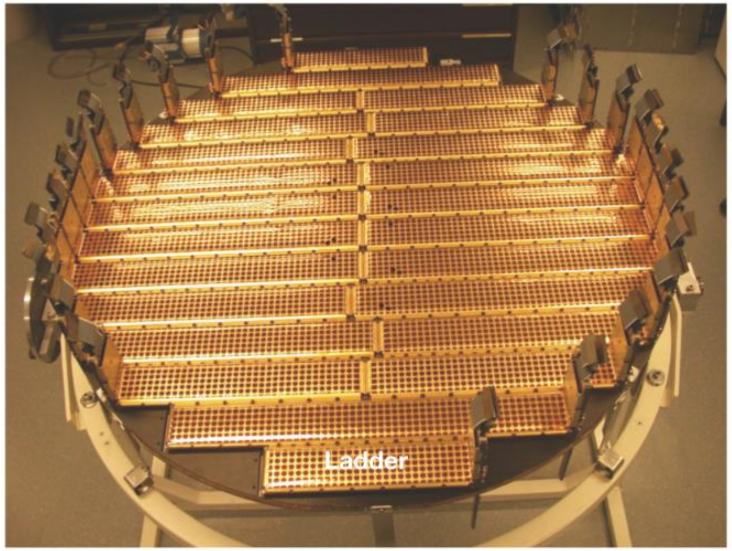


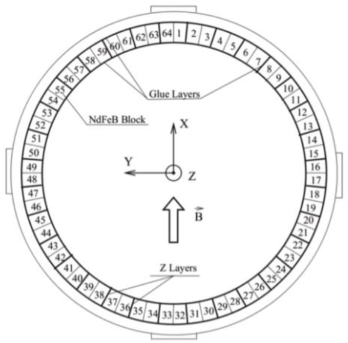
In orbit on the International Space Station since May 2011

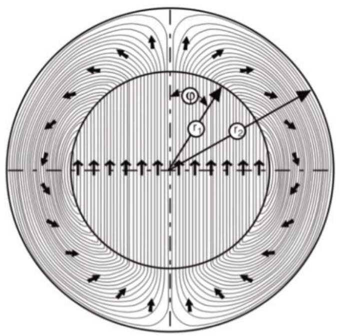
AMS 02: The magnetic spectrometer

- The magnetic field is generated by 64 sectors of Nd-Fe-B magnets in a Hallbach array configuration (1400 Gauss in the central region)
- Charged particle trajectories are influenced by the Lorentz force, leading to deflection
- The tracker consists of 9 layers of silicon microstrip detectors, each layer composed of 16-26 rectangular modules (*ladder*)
- Each ladder consists of 9 to 15 double-sided silicon sensors. The p-side (measuring *y*) strips with a readout pitch of 110 μm, while the n-side strips (measuring *x*) with a readout pitch of 208 μm

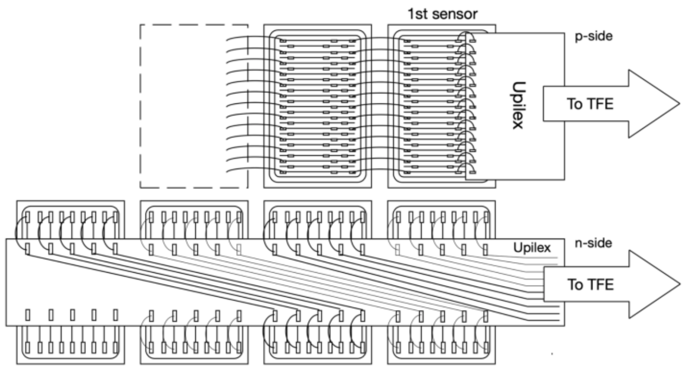


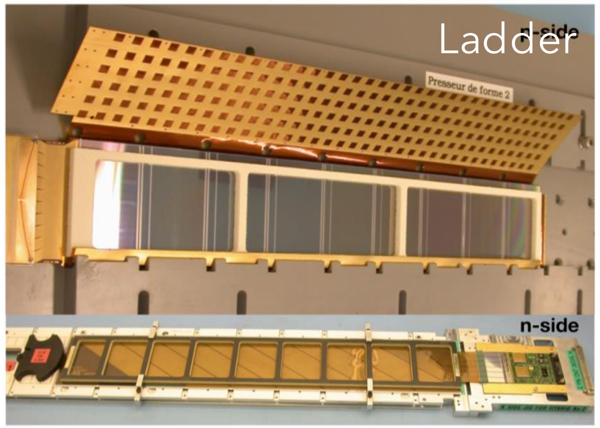


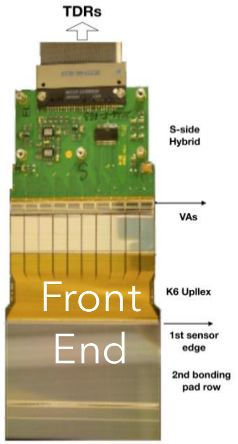




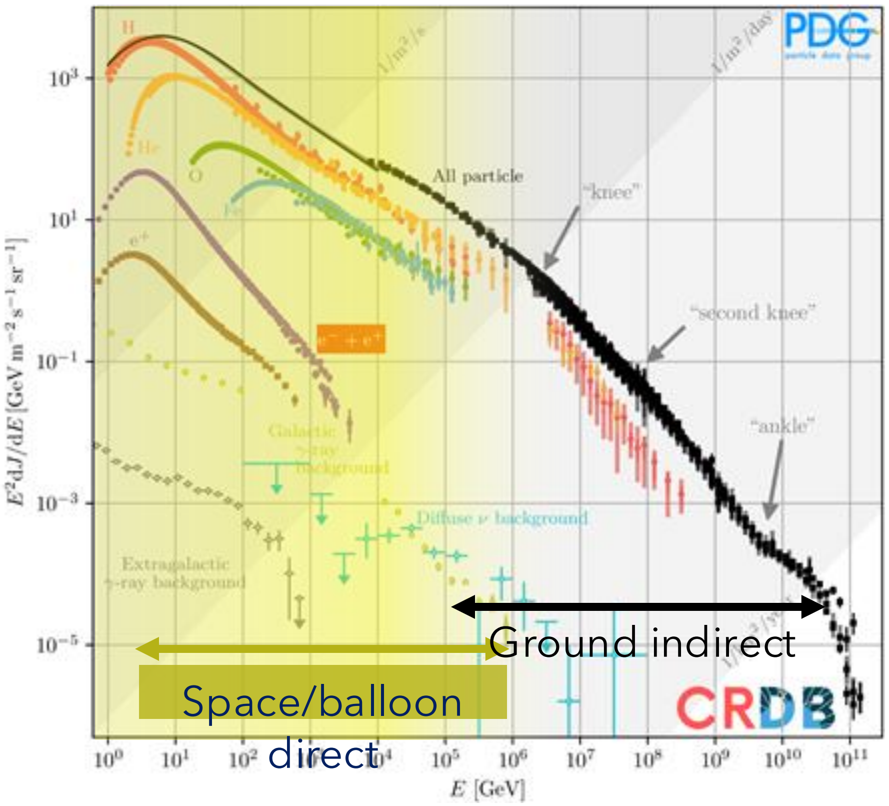
Magnet and Magnetic field

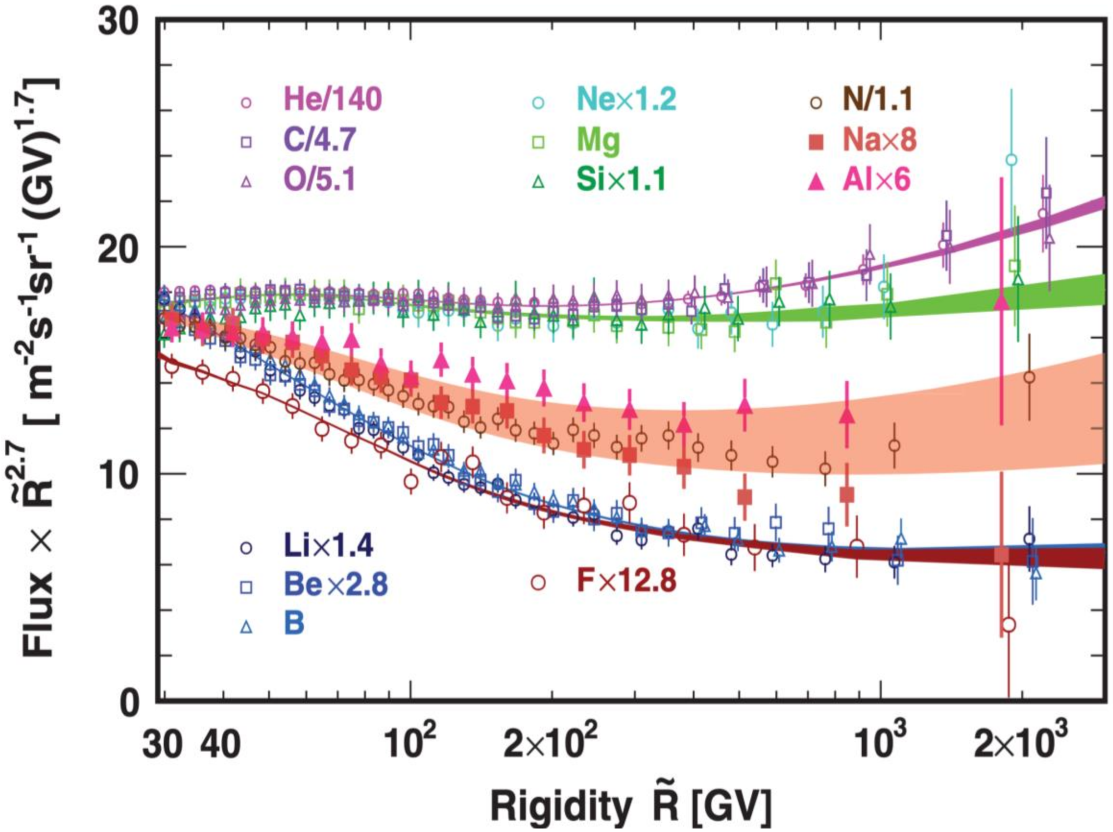






(Charged) Cosmic Rays





Spectrum:

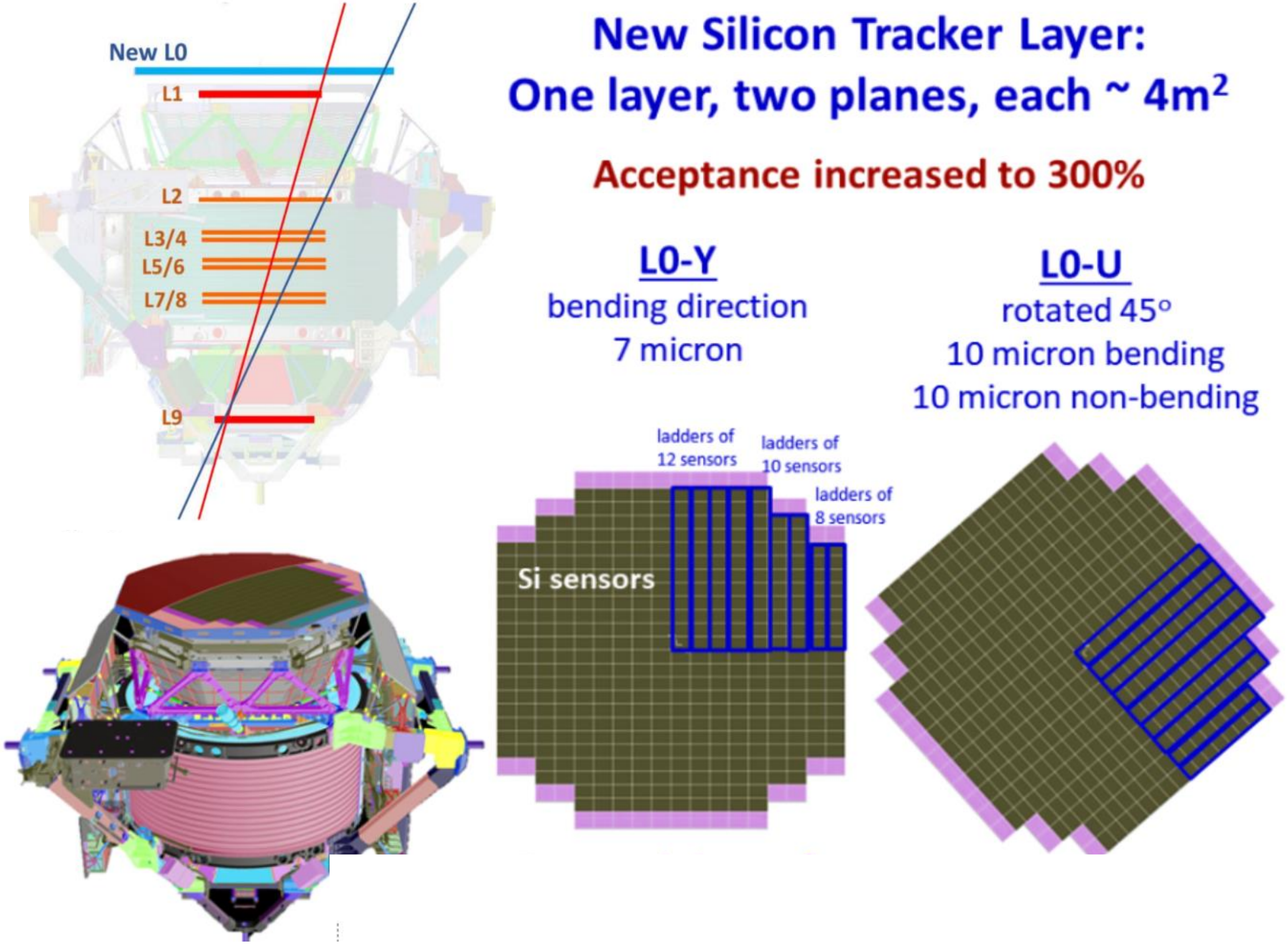
$$\Phi = \Phi_0 E^{-\gamma}$$

with γ ~ 3

- two classes of primaries:
  - light and very heavy (He, C, O, Fe, Ni)
  - heavy (Ne, Mg, Si, …)
- mixed (N, Na, Al): primary + secondary with different composition

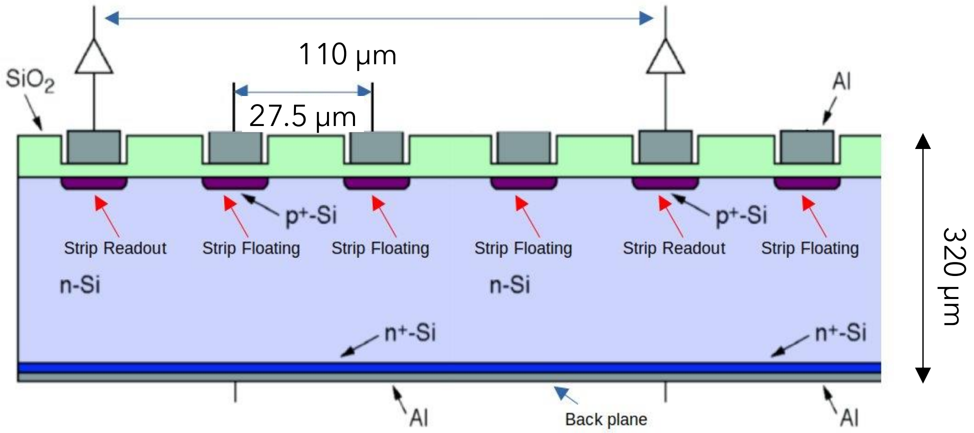
The AMS-02 Upgrade

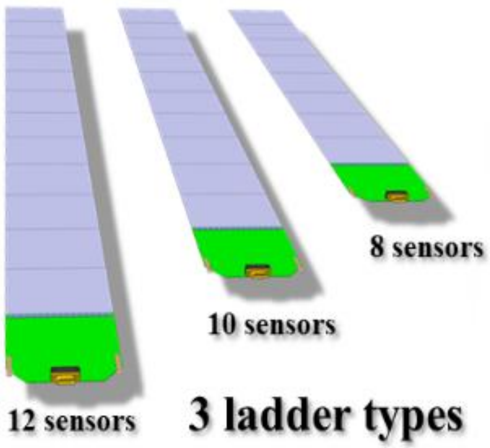
- AMS02-L0, an upgrade which involves adding a new silicon detection layer, called L0, above the existing L1 layer to increase the overall acceptance area
- The total area of the silicon sensors to be installed is ~ 8 m^2. Will increase by 300% the acceptance of the experiment
- Composed of two layers of silicon sensors, where one layer is measuring Y and the other is at 45°
- L0 will be installed in spring 2026

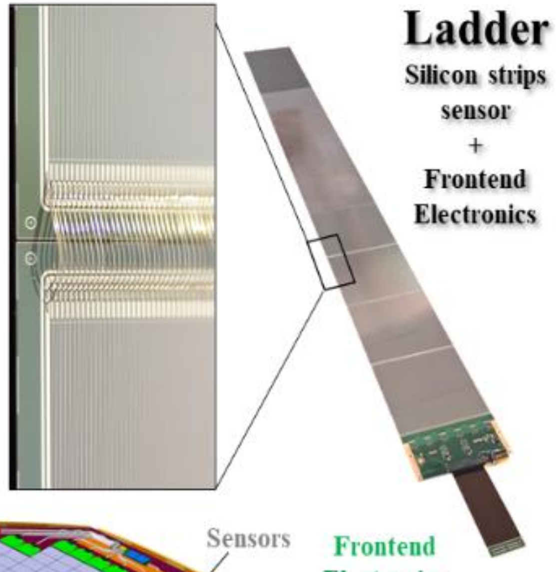


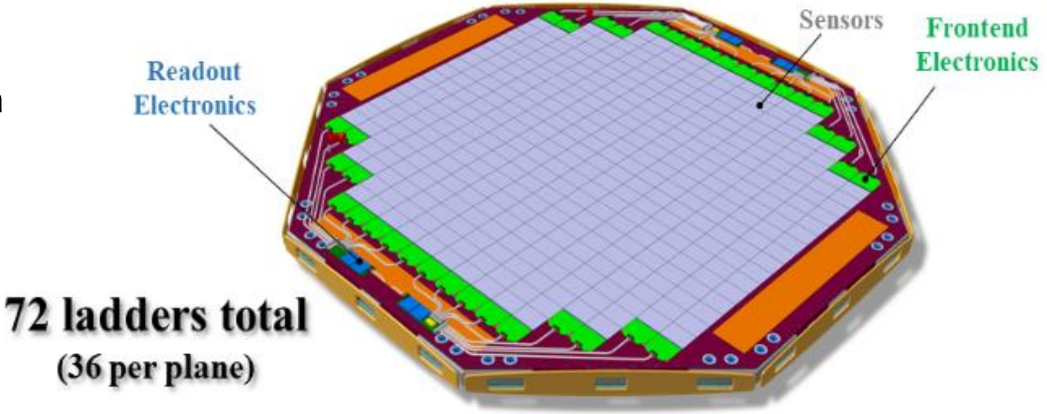
AMS-L0 Ladder

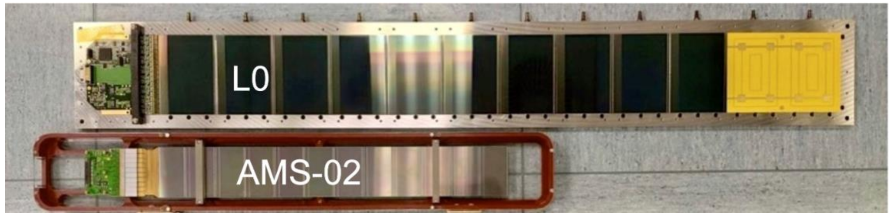
- Each silicon sensors has an area of 8x11 cm^2, 1024 readout channels (110 μm pitch)
- To cover large areas without increasing the number of channels. the design must be based on "long" silicon sensor modules (called *ladders*)
- All channels of adjacent silicon sensors are connected in daisy chain to form a single sensor with longer strips
- Each ladder is composed of 8, 10, or 12 silicon sensors plus a frontend electronics board and a long flexible printed circuit board for mounting









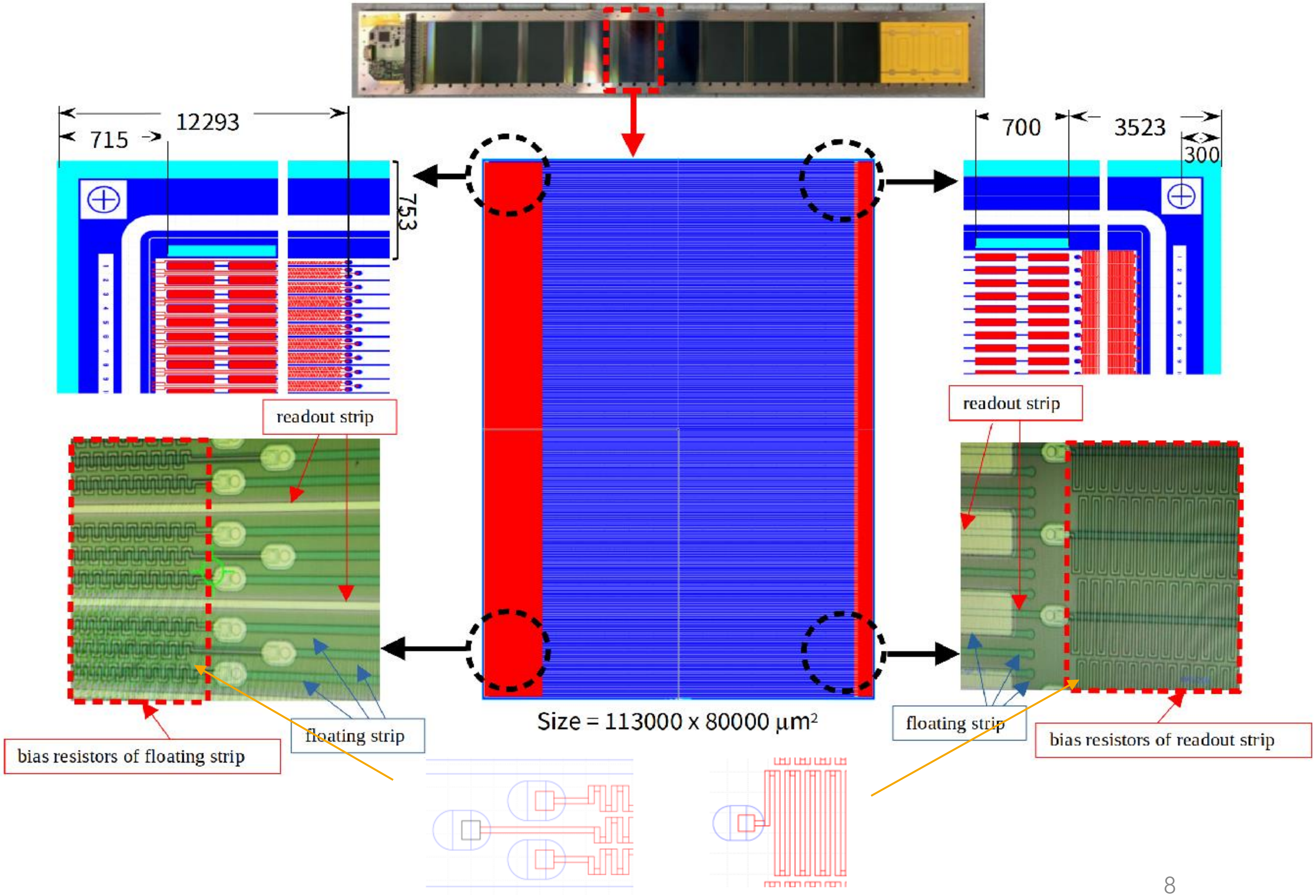


AMS-L0: resistor regions

- Bias resistors (polysilicon serpentines) to connect bias ring to each strip
  - needed for proper depletion voltage

- Bias resistors
  - readout strips: right end
  - intermediate (floating) strips: left end.

- Different sizes and structures for the two bias resistor regions
  - different efficiencies
  - different spatial resolutions



Beam tests:

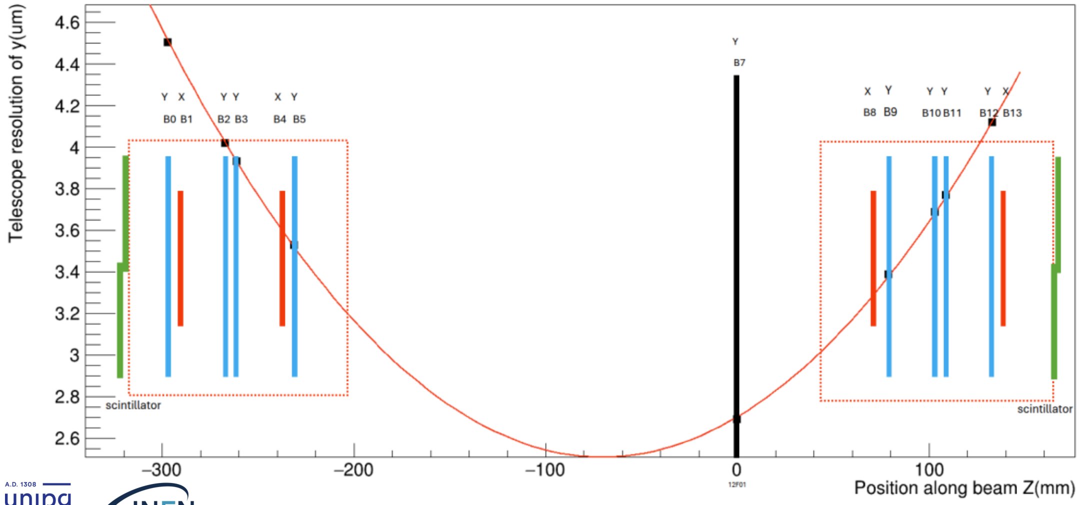
- S/N performance, spatial resolution, detection efficiency (*Z=1*)
    - muon (May 2024)
- Charge identification capability (*Z>>1*)
    - heavy ions (October 2023)
- The cross-section of the L0 structure on the incident particle
    - heavy ions (November 2024)

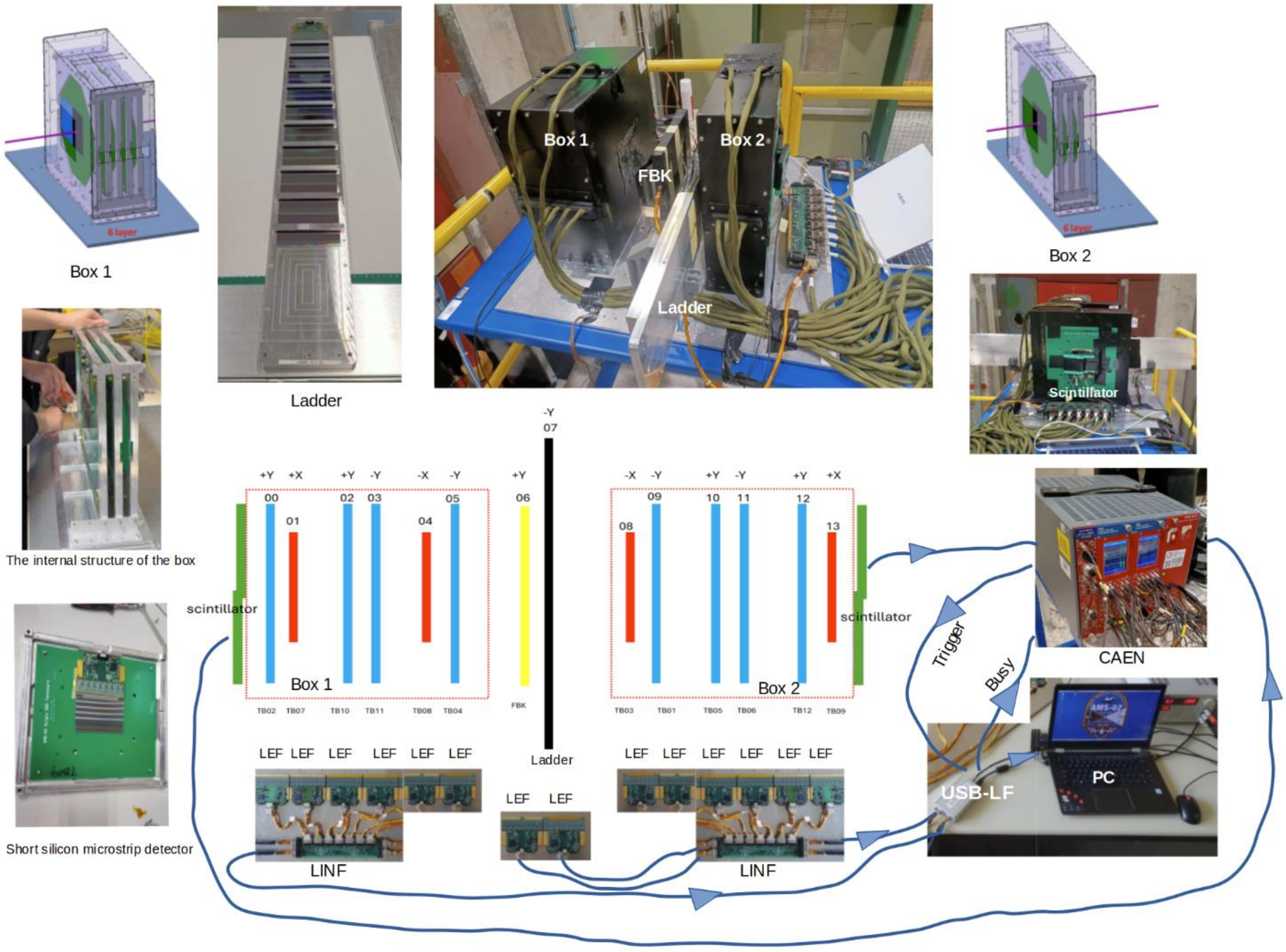
AMS-L0: single sensor detector (*Beam Monitor*) and Flight Ladder prototype

AMS-L0 muon beam test: setup

- Coincidence of two scintillators (green rectangles): trigger
- flight ladder (10 sensors) prototype under test
- short detectors (BM): ladders with 1 single silicon sensor, but functionally identical to flight ladder (same silicon sensors, same front-end)
- 12 short silicon microstrip detectors (red or blue rectangles) in two boxes: Beam Monitor and tracking system for spatial resolution of the flight ladder under test

assuming 7µm single sensor resolution





$$\sigma_{fit,i} = \sigma_s \sqrt{\left(\sum_j^n z_j^2/n + \cdot z_i^2 - 2z_i \cdot \sum_j^n z_j^2/n\right) \Big/ \left(\sum_j^n z_j^2 - \sum_j^n z_j \sum_k^n z_k\right)}$$

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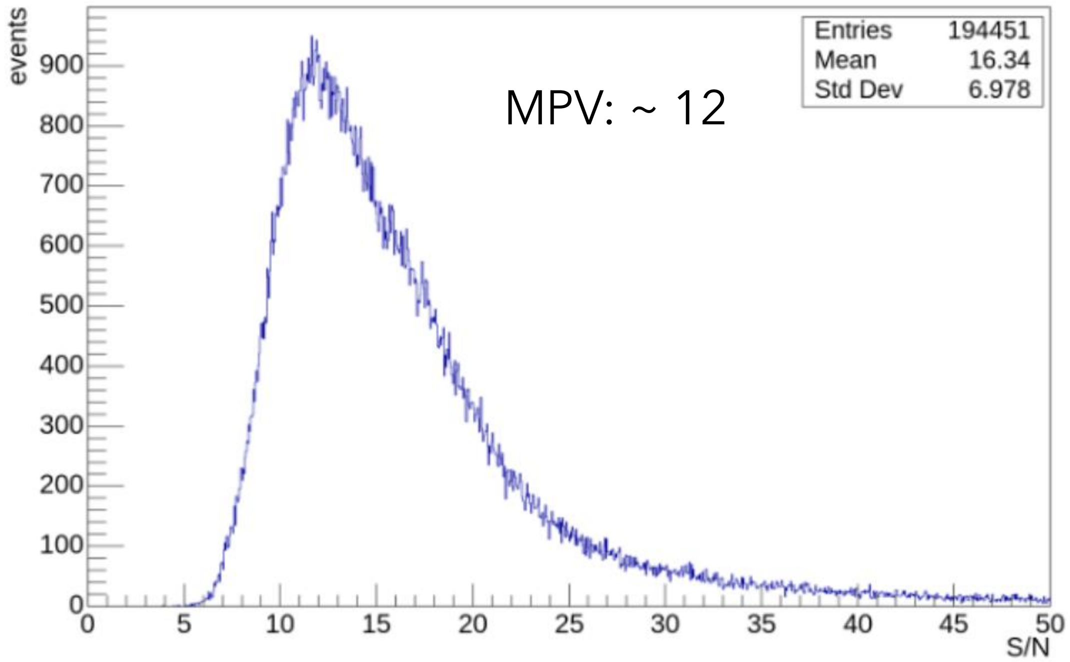
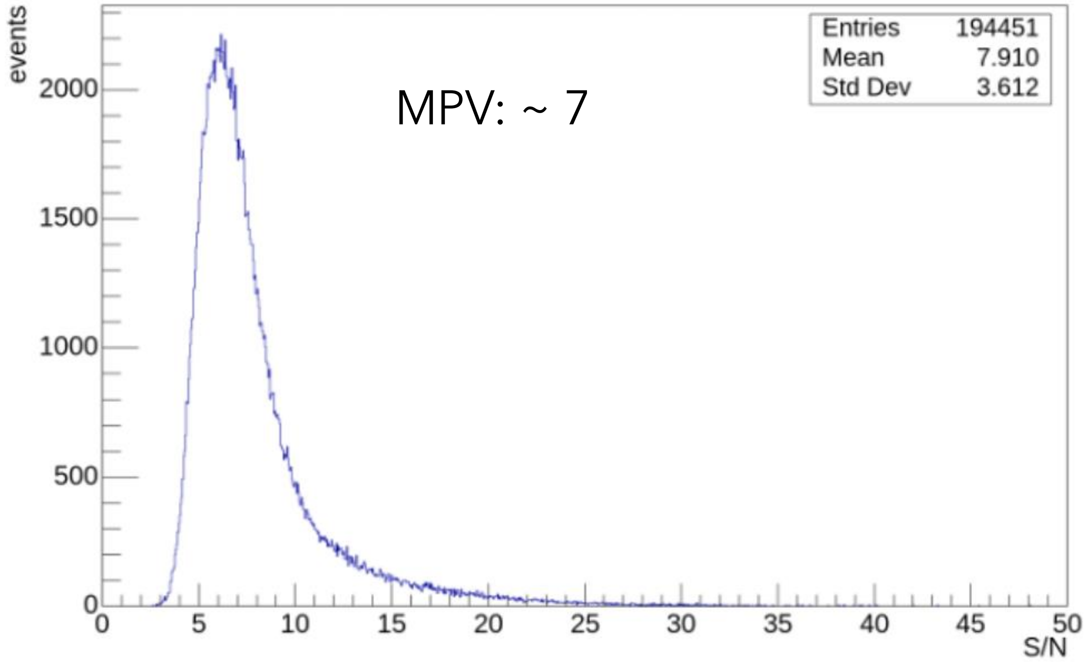
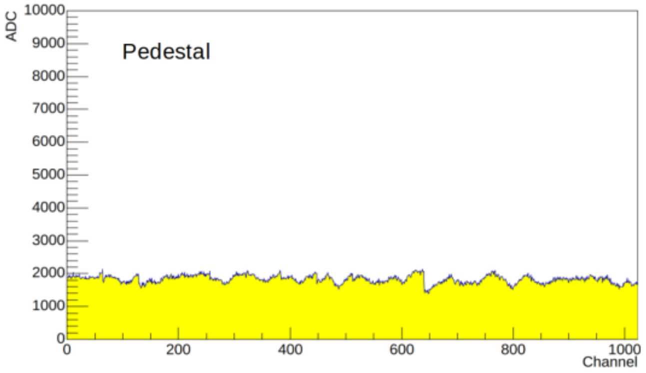
AMS-L0 muon beam test: calibration & S/N performance

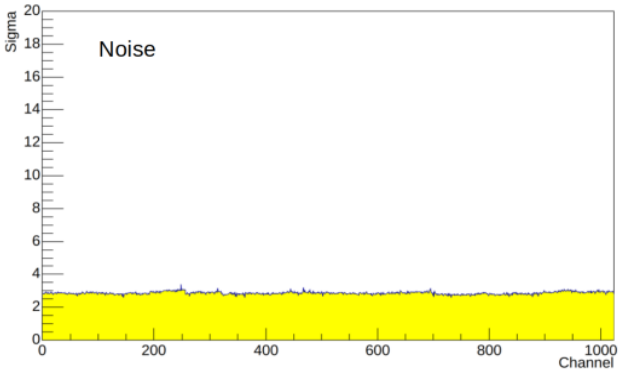


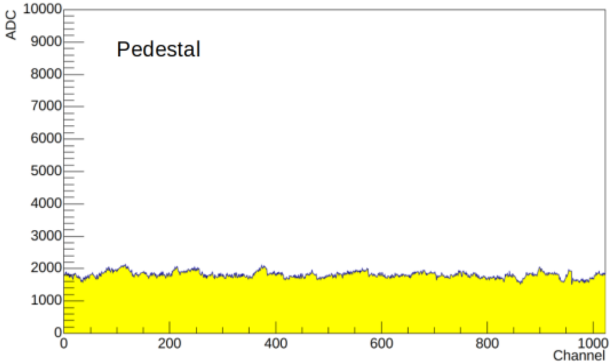
Beam Monitors

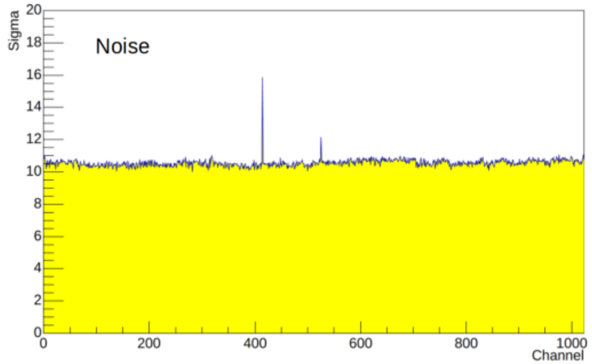


Flight ladder prototype

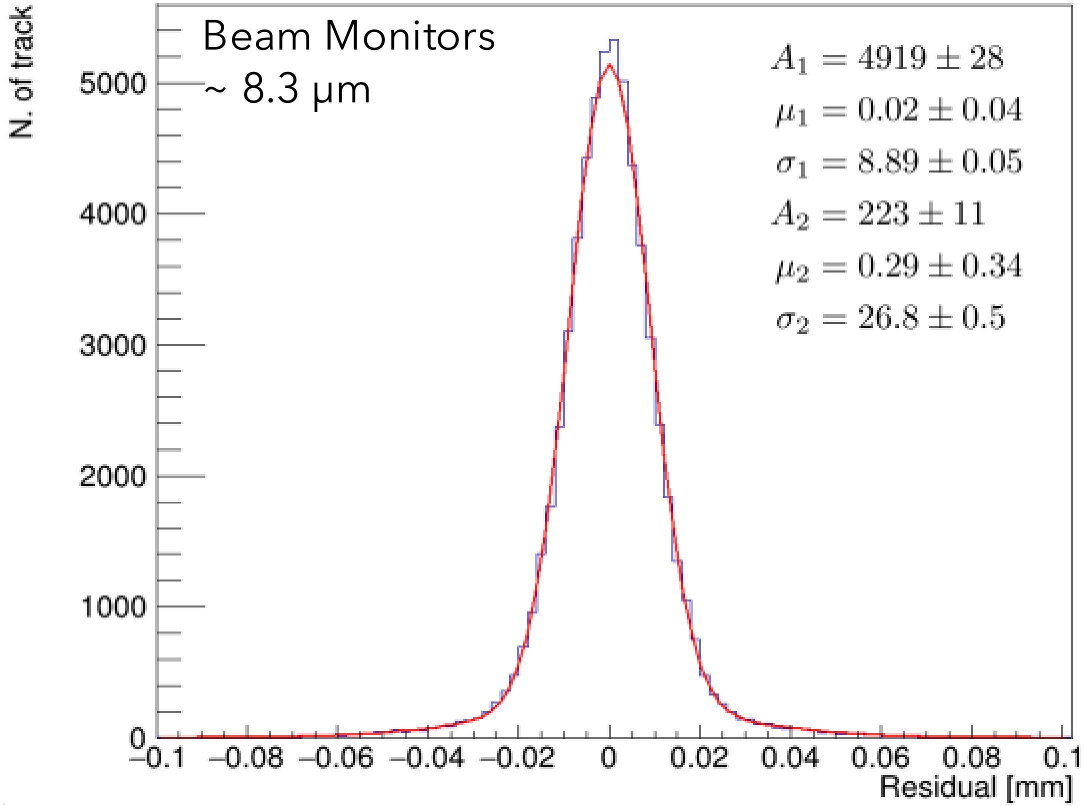


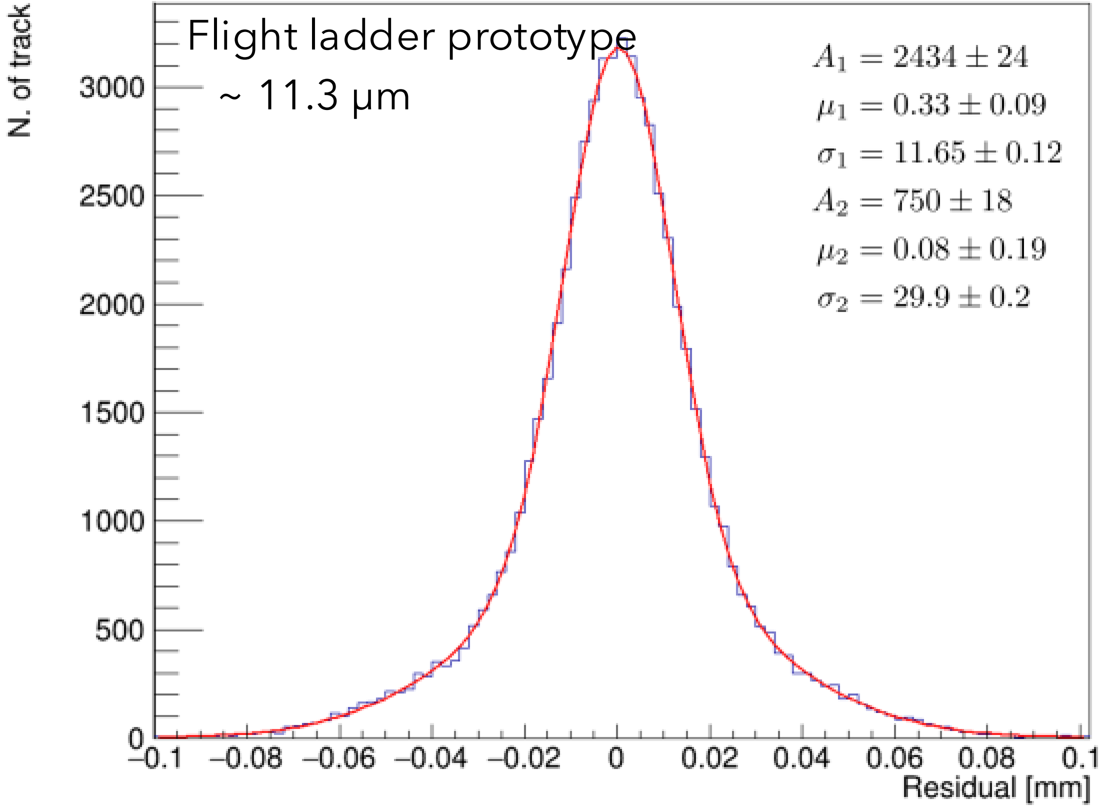






AMS-L0 muon beam test: spatial resolution





Unbiased residuals, fitted the sum of two Gaussian

Residual unbiased:

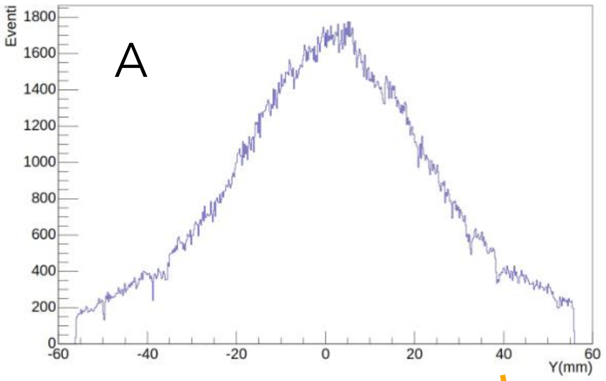
$$UR_i = X_{impact,i} - X_{predicted,i}$$

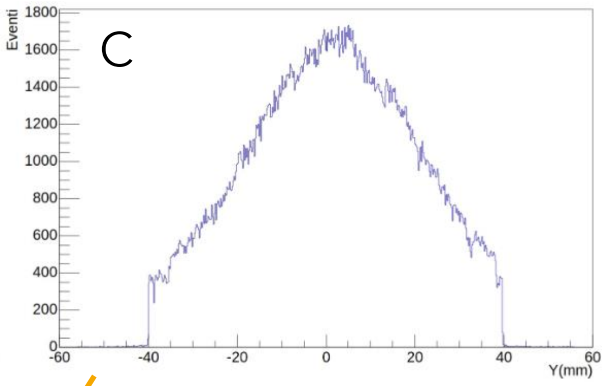
Standard deviation:

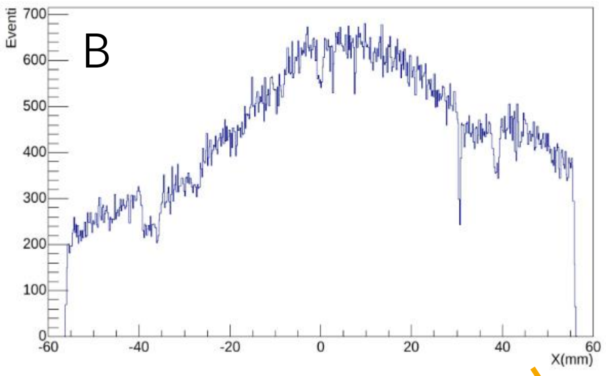
$$\sigma_{UR,i} = \sqrt{\sigma^2_{fit,i} + \sigma^2_{resolution,i}}$$

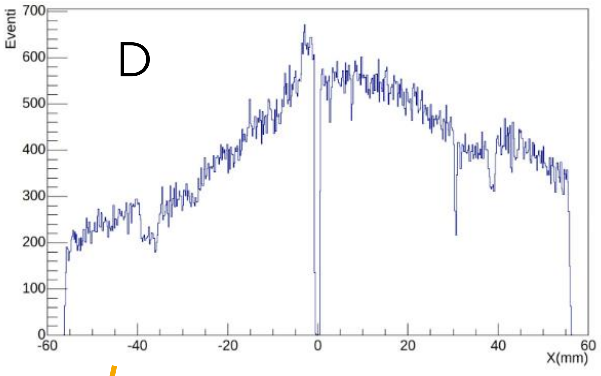
$$\sigma_{fit,i} = \sigma_s \sqrt{\left(\sum_j^n z_j^2/n + \cdot z_i^2 - 2z_i \cdot \sum_j^n z_j^2/n\right) / \left(\sum_j^n z_j^2 - \sum_j^n z_j \sum_k^n z_k\right)}$$

AMS-L0 muon beam test: detection efficiency in bias resistor regions







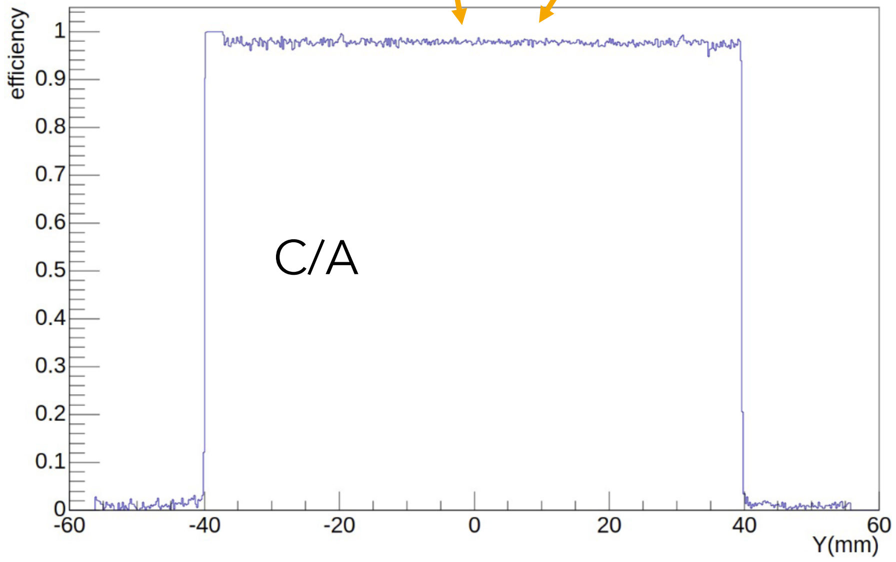


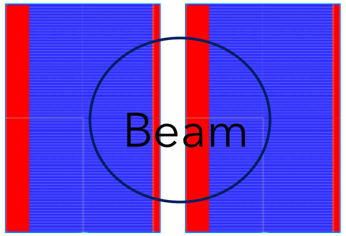
Beam position @ BM sensor location

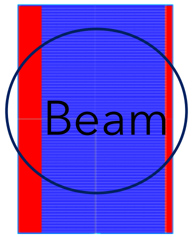
Beam position @ BM sensor & cluster in BM

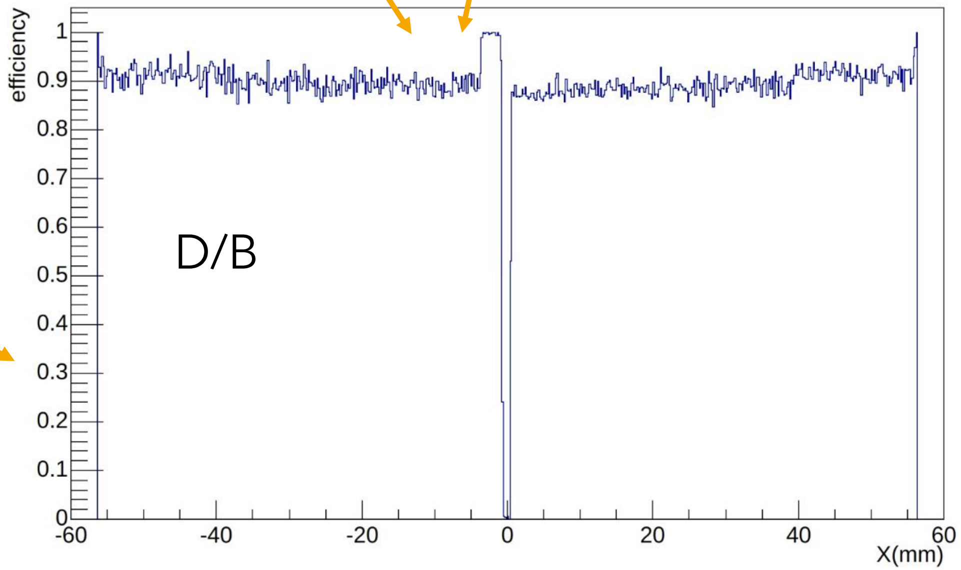
Beam position @ ladder location

Beam position @ ladder & cluster in ladder





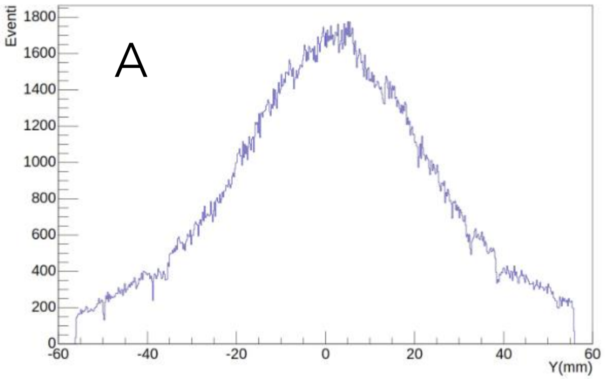




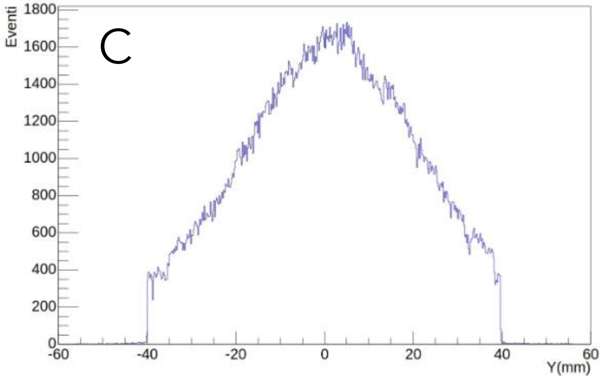
BM: detection efficiency as a function of the coordinate along the strip

Flight ladder: detection efficiency as a function of the coordinate along the strips

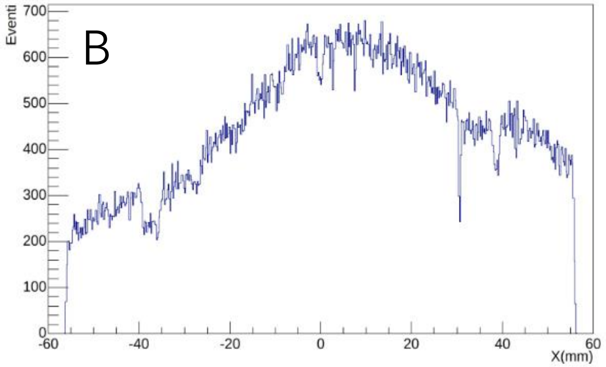
AMS-L0 muon beam test: detection efficiency in bias resistor regions



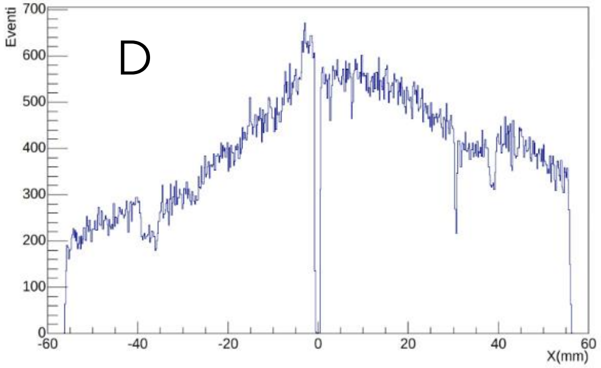
Beam position @ BM sensor location



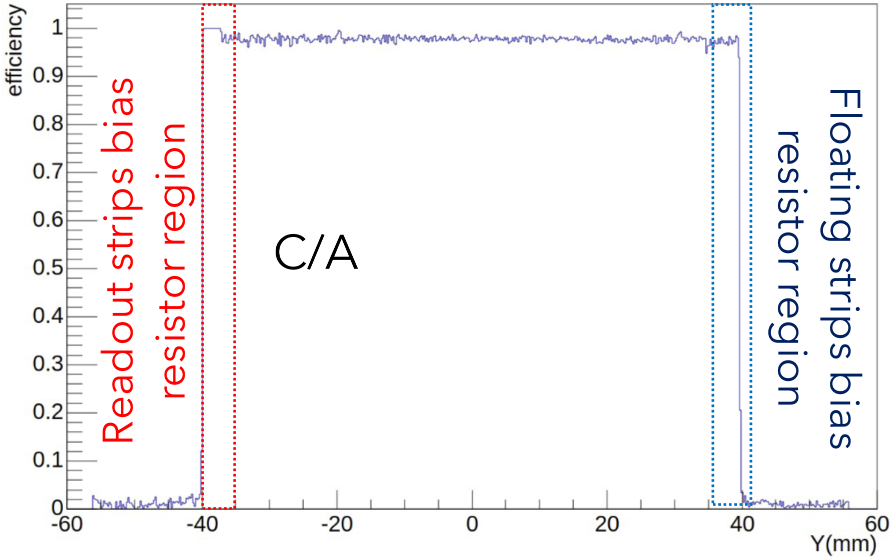
Beam position @ BM sensor & cluster in BM



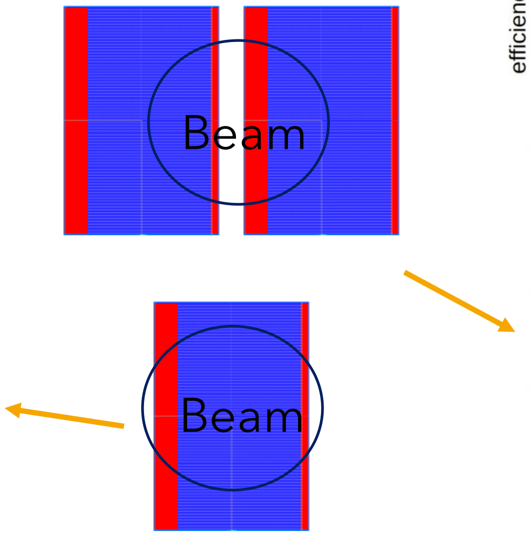
Beam position @ ladder location

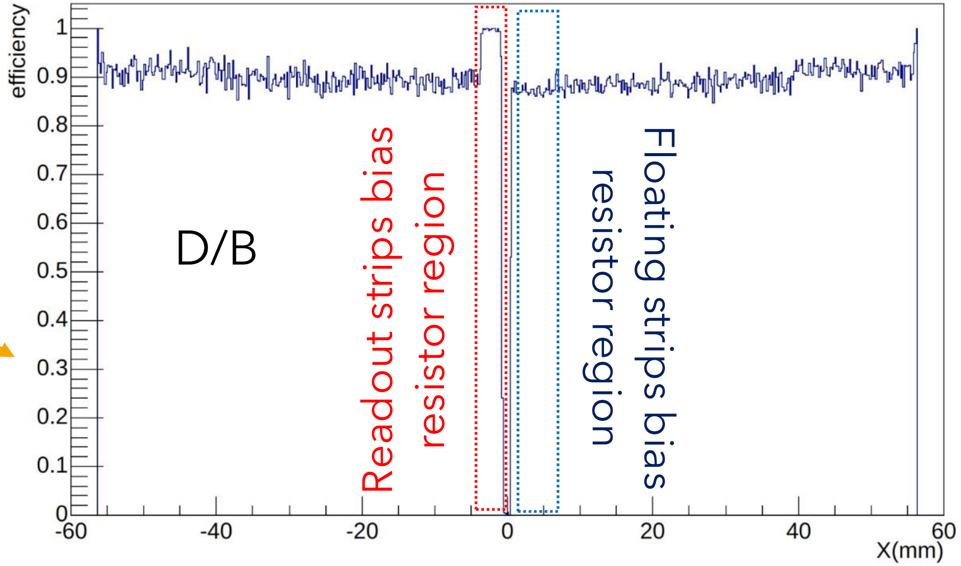


Beam position @ ladder & cluster in ladder



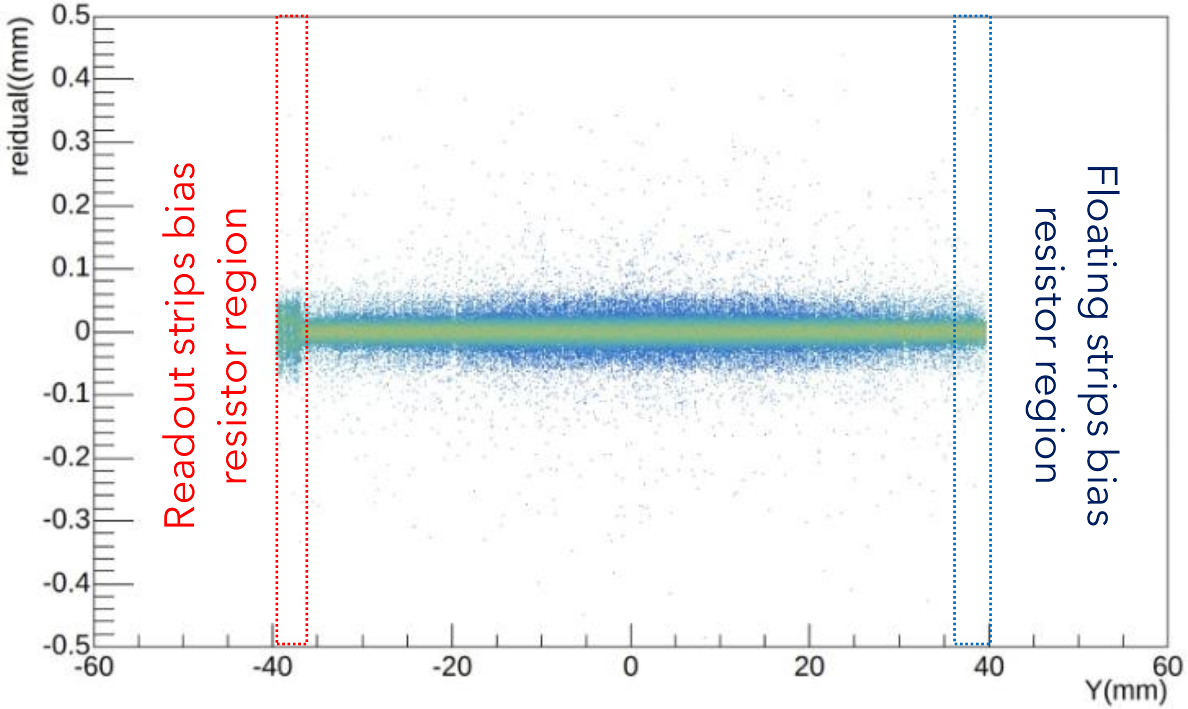
BM: detection efficiency as a function of the coordinate along the strip

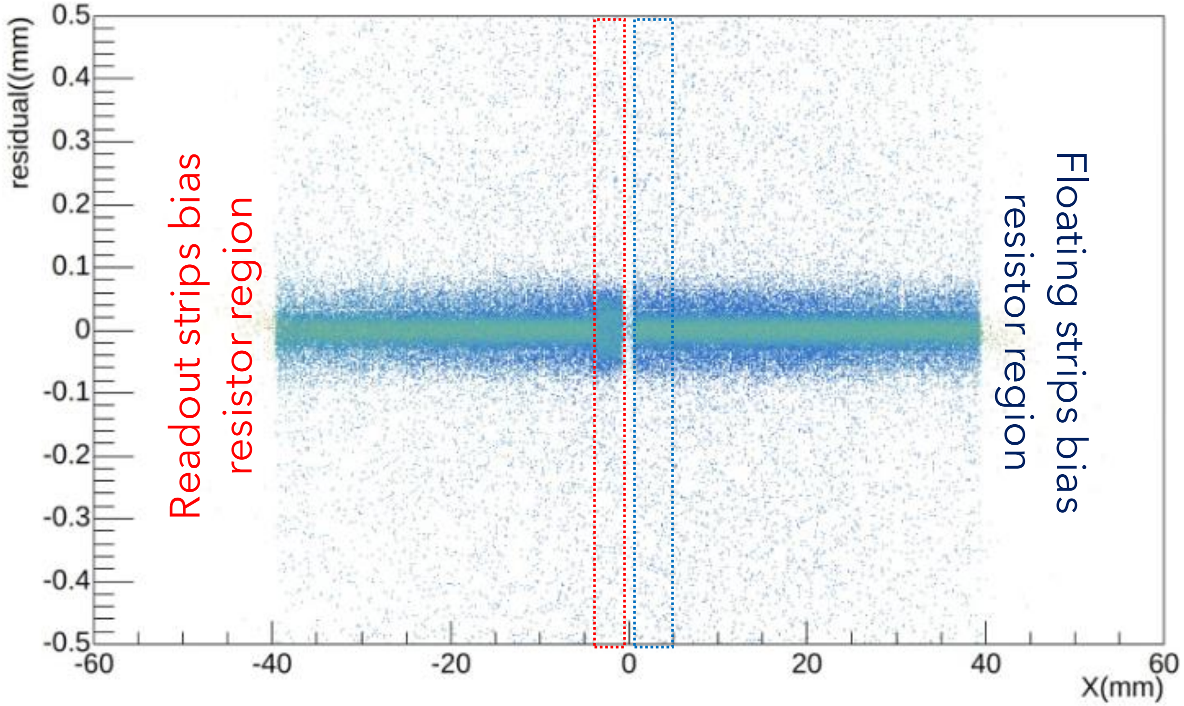




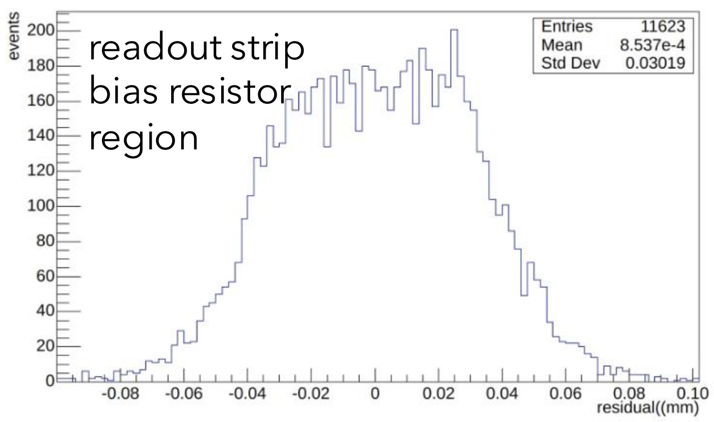
Flight ladder: detection efficiency as a function of the coordinate along the strips

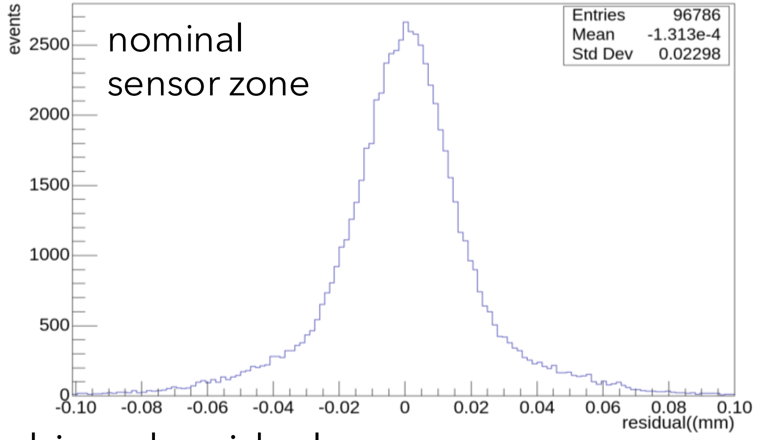
AMS-L0 muon beam test: spatial resolutions in bias resistor regions





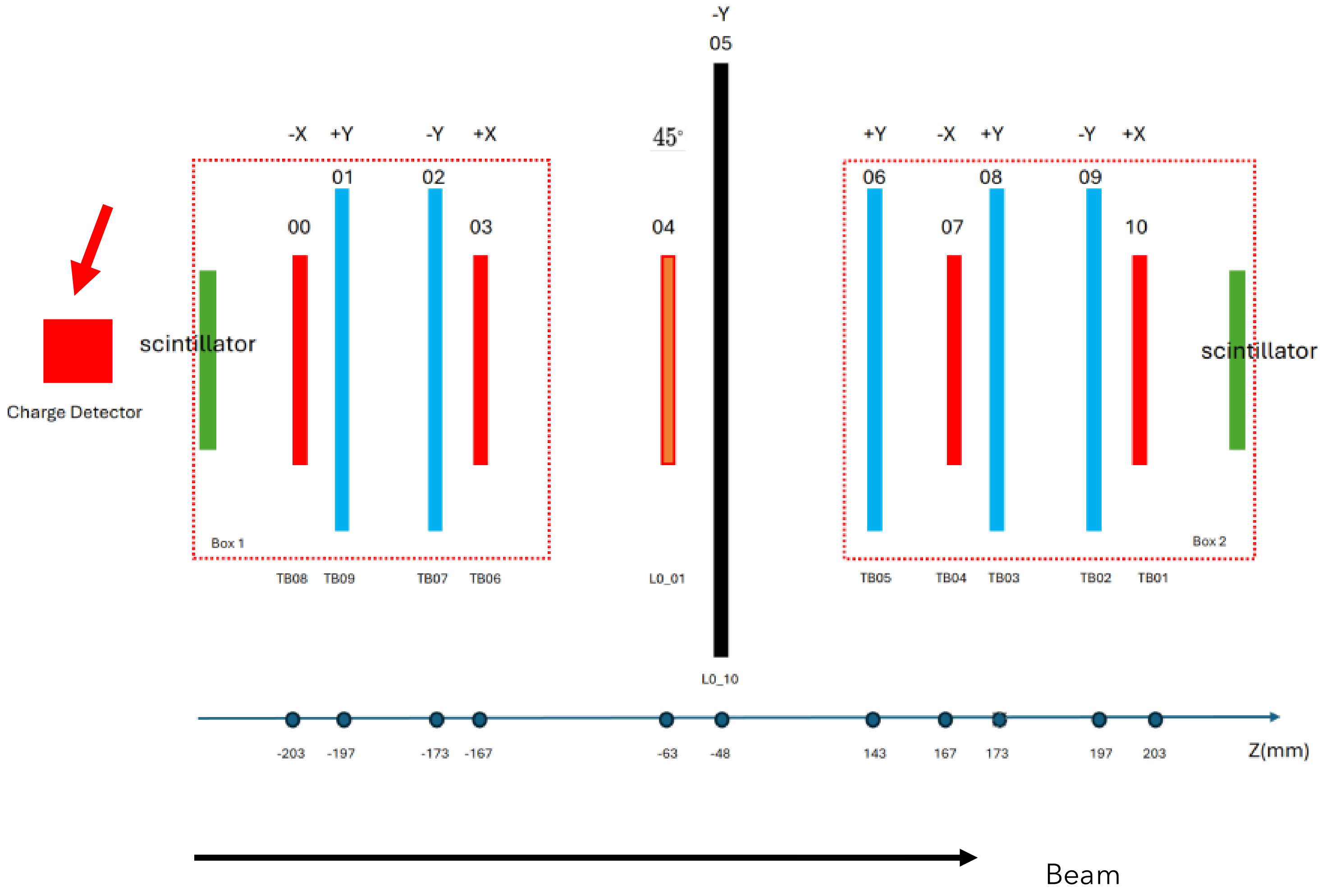
- spatial resolution in readout strip bias resistor region is relatively poor
- spatial resolution in intermediate strip bias resistor region has no significant change

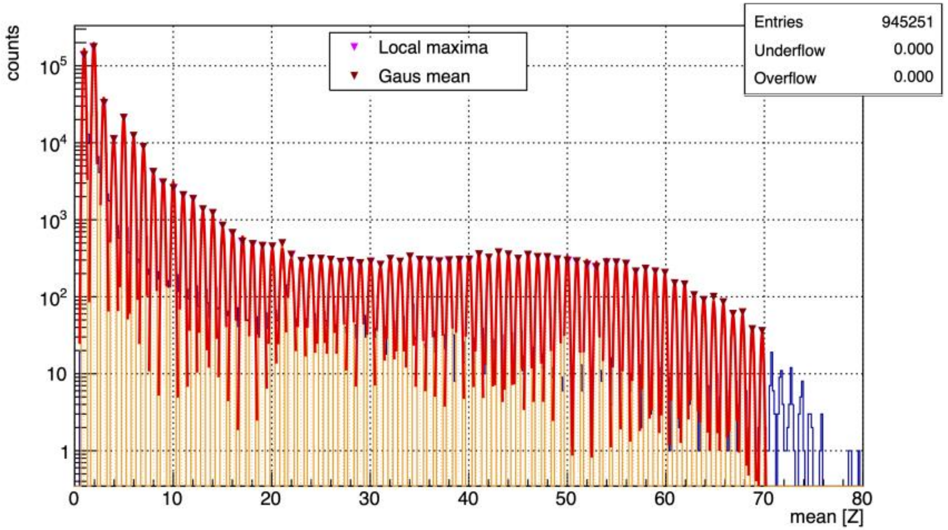




Flight ladder unbiased residuals

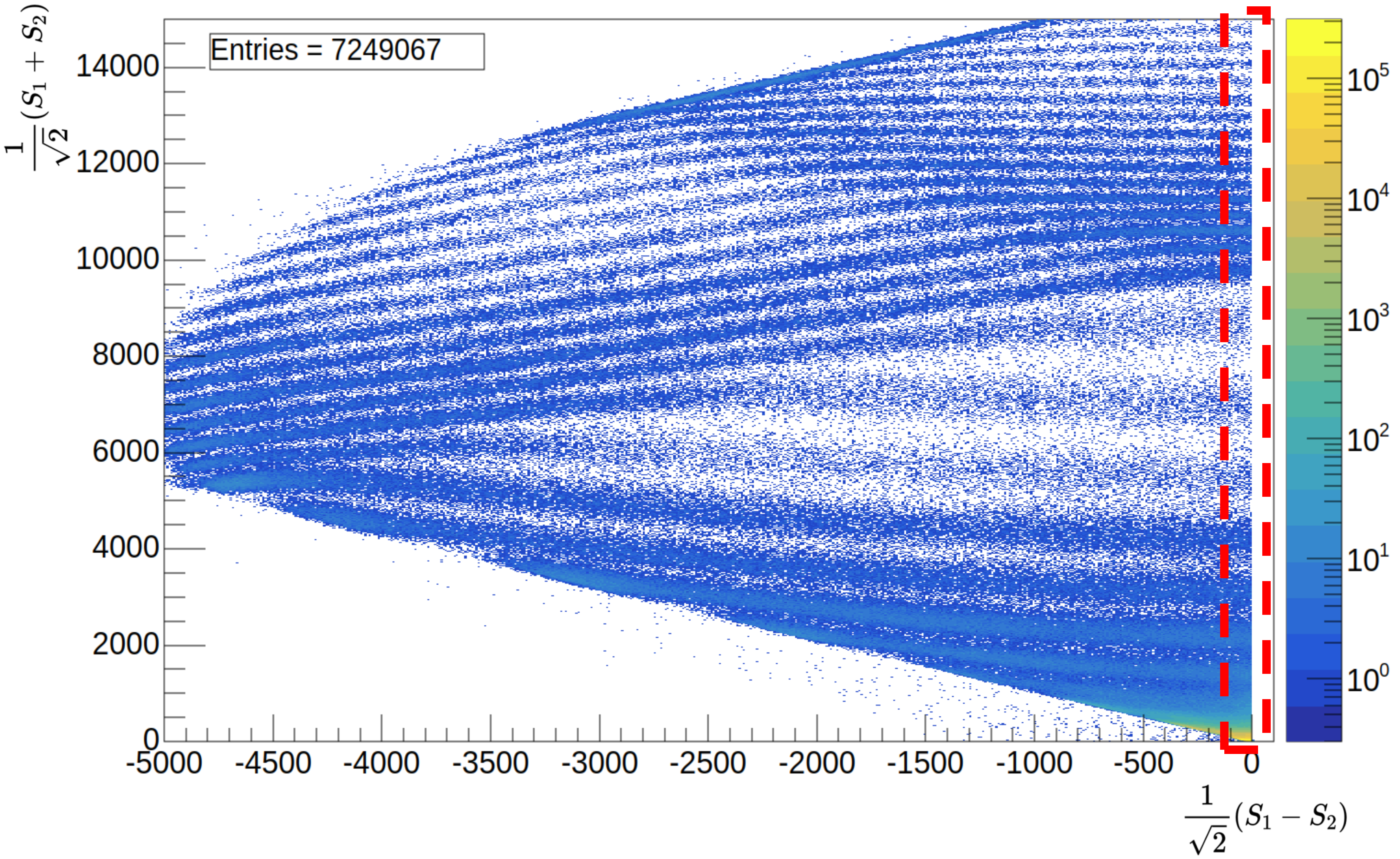
AMS-L0 heavy ions beam test(October 2023): setup



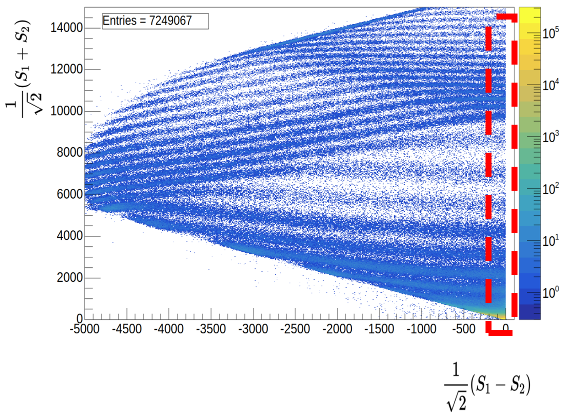


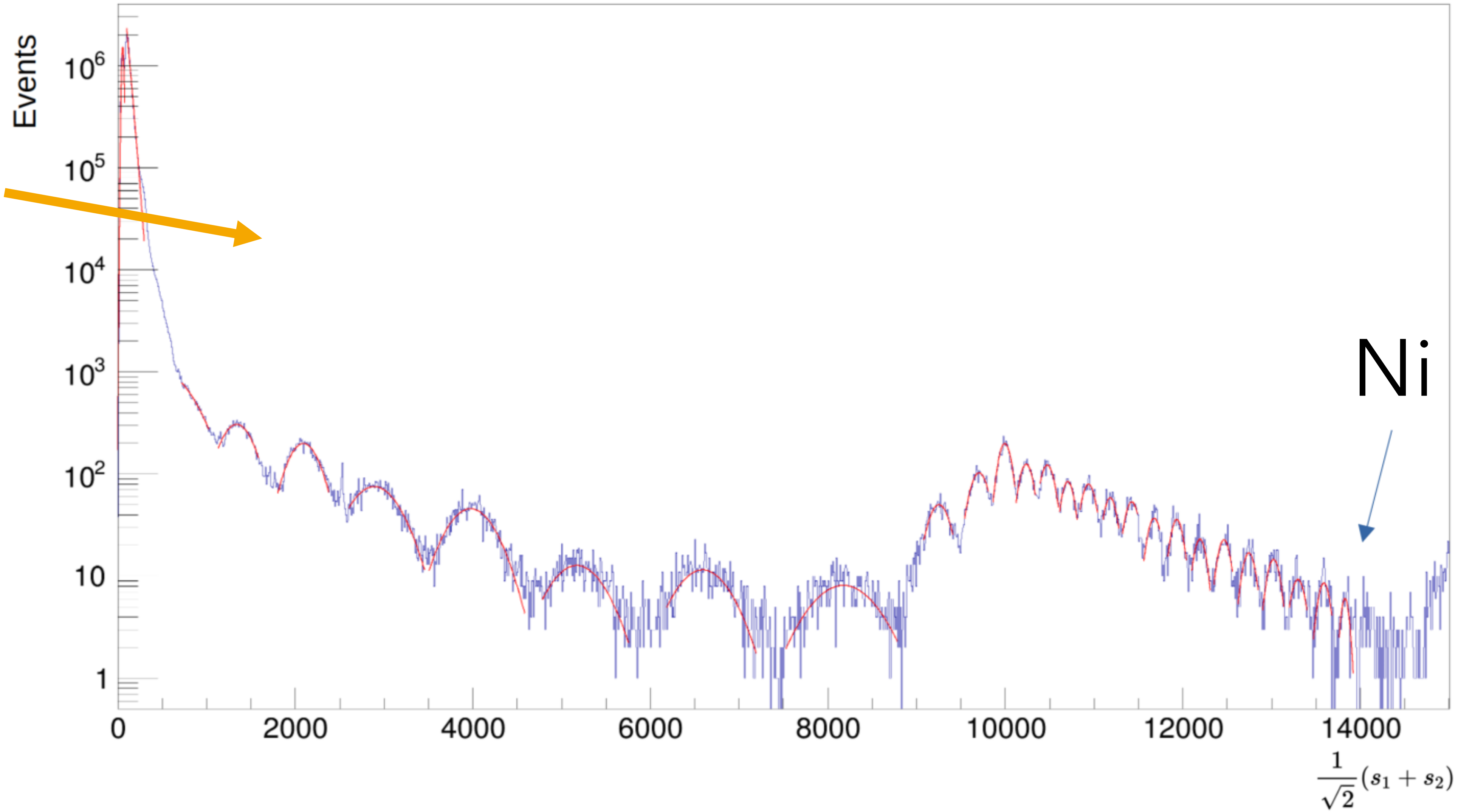
Charge distribution by the Charge Tagger detector

Study of reconstructed charge through *S1* and *S2*

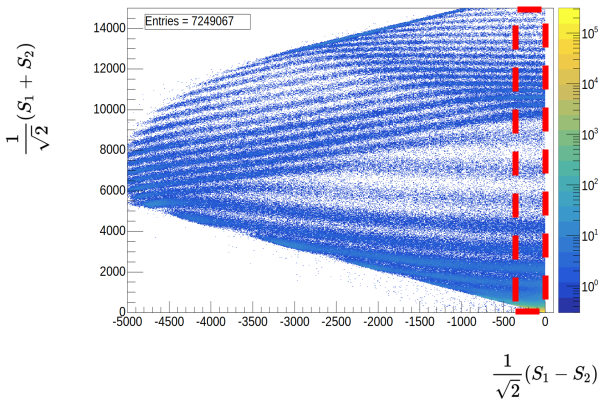


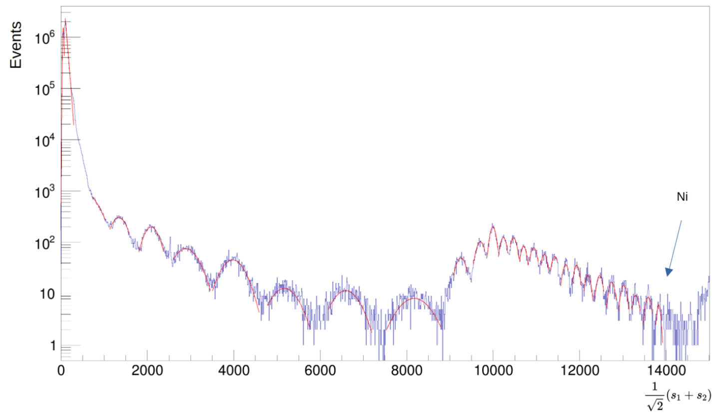
Study of reconstructed charge through *S1* and *S2*

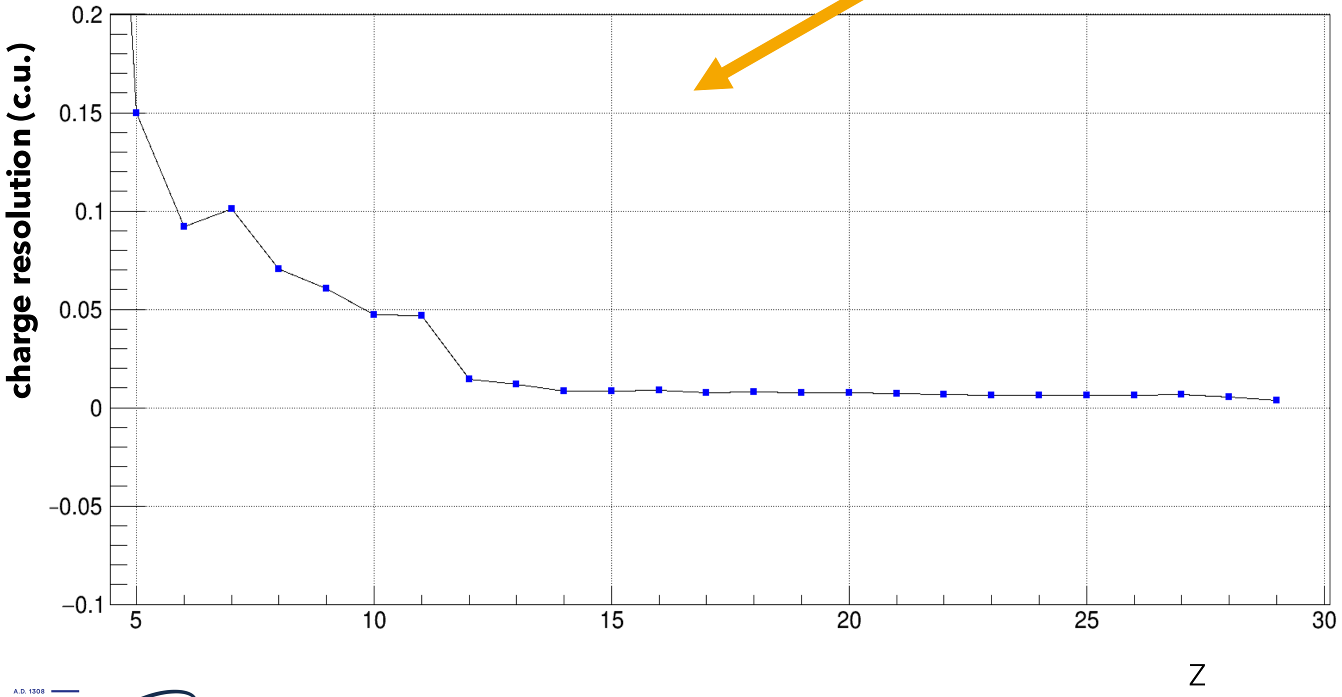


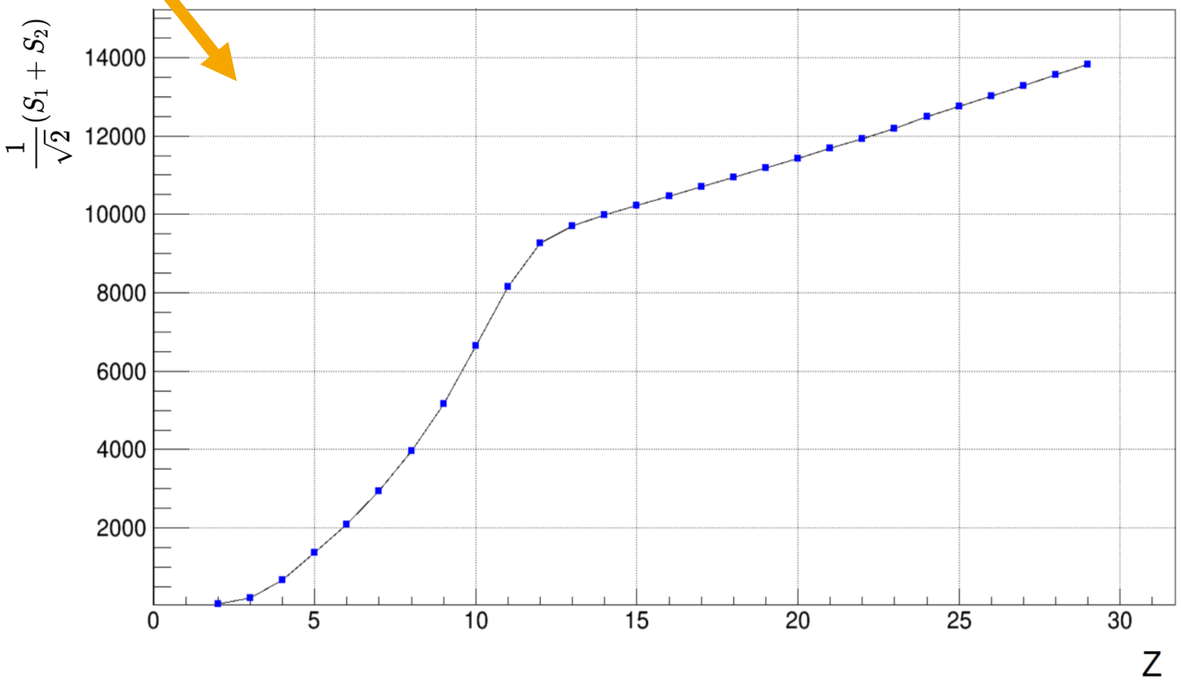


Study of reconstructed charge through *S1* and *S2*

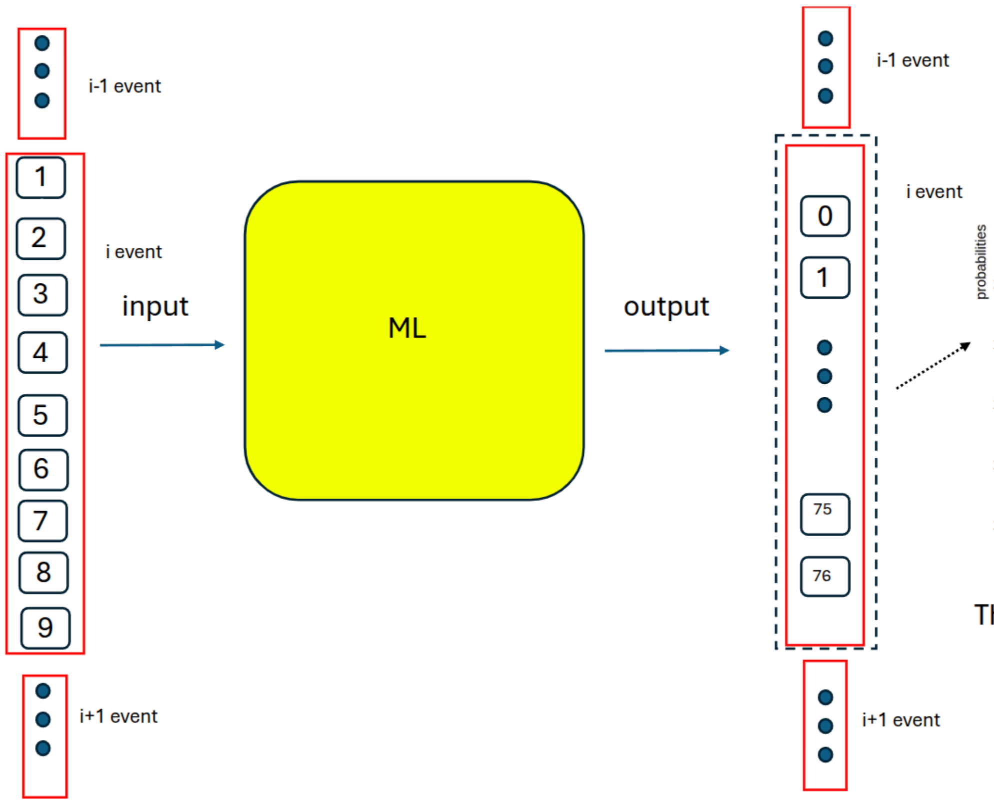


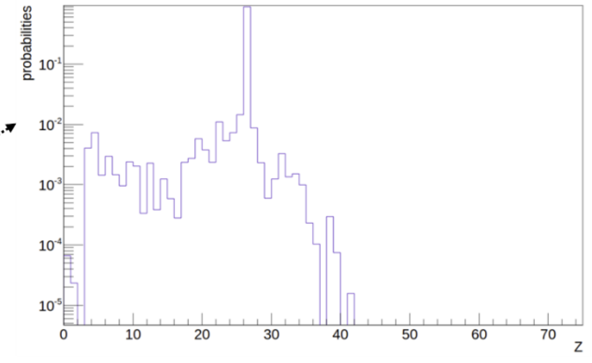




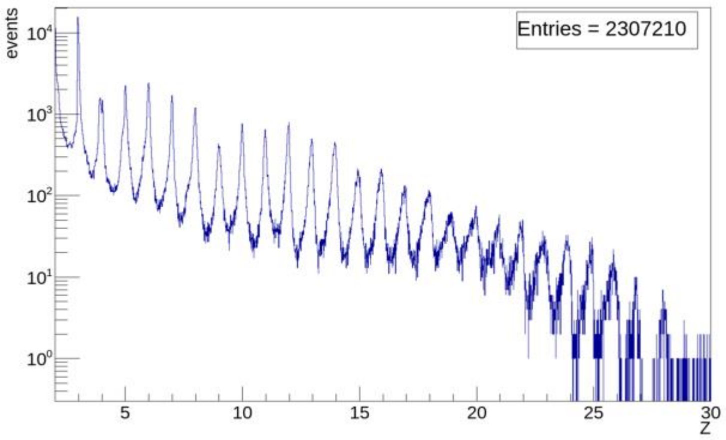


Multivariate approach for charge measurement

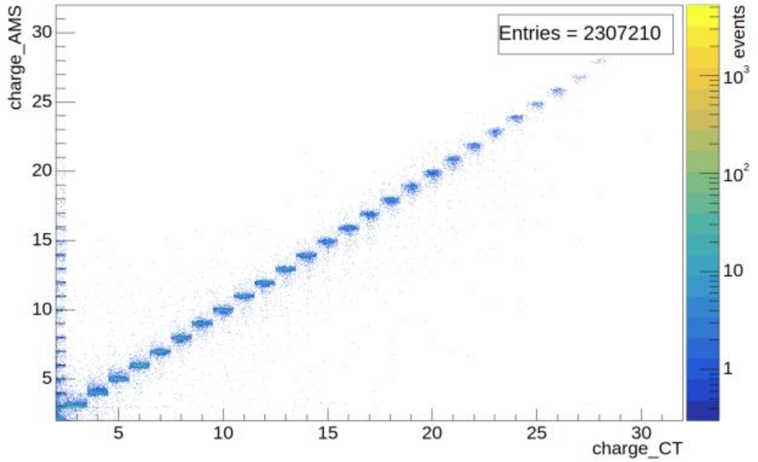




The predicted probabilities for each charge.



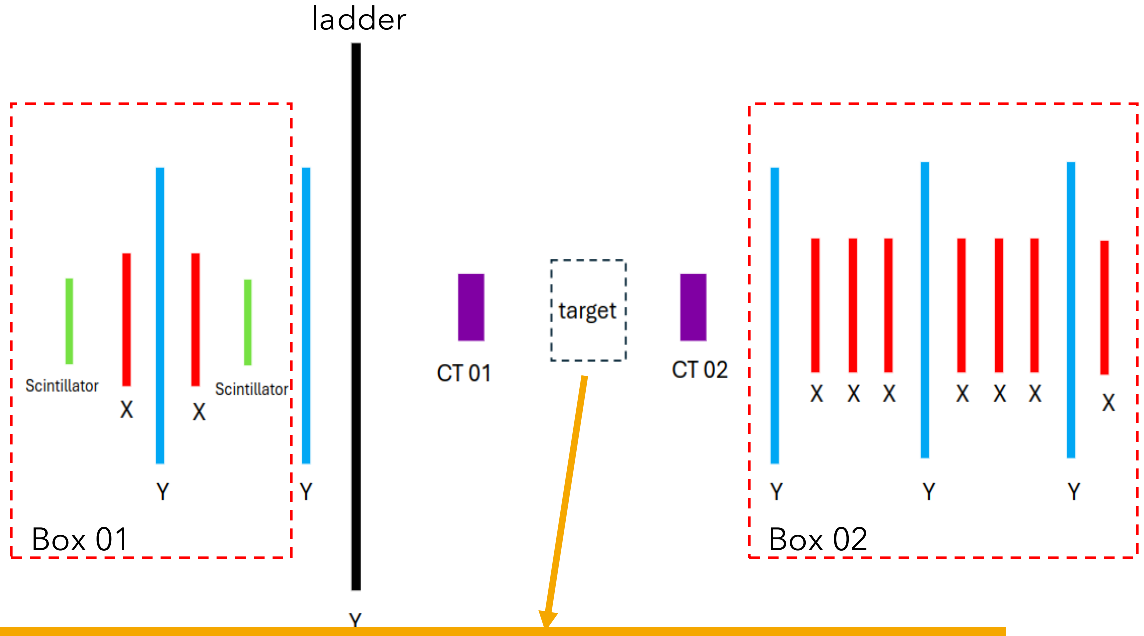
Distribution of the charge measured by the AMS-L0 sensors using a ML approach

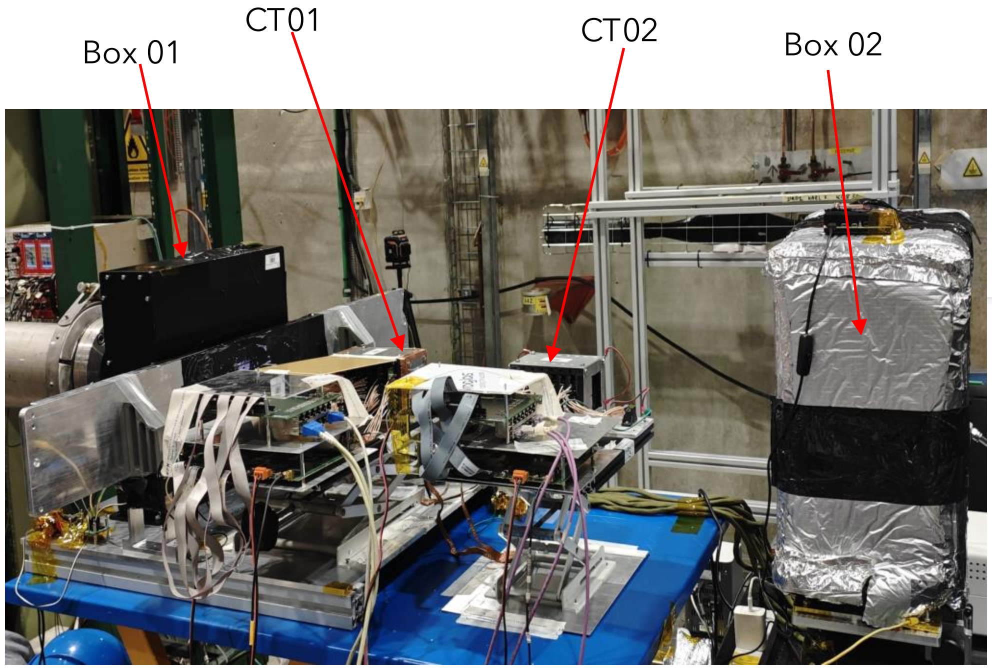


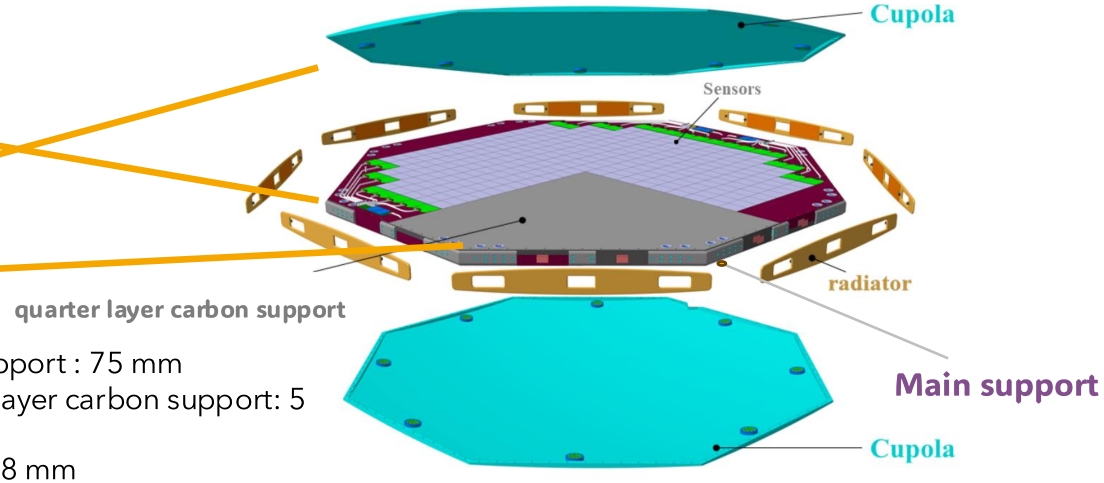
Charge measured by the AMS-L0 sensor using a ML approach as a function of the one measured by the CT

- The 9 initial characteristics (*features*) input are: the total signal of the cluster, the signals and positions of the three strongest strips in the cluster, the width and eta of the cluster. The nine feature values come from the cluster with the largest signal in each event
- The 76 output values represent the predicted probabilities for each of the 76 classes (charge)

AMS-L0 heavy ions beam test (November 2024): setup







- Main support : 75 mm
- quarter layer carbon support: 5 mm
- Cupola: 8 mm

Summary

A study was carried out on a 10-sensor ladder, focusing on signal-to-noise ratio, detection efficiency, spatial resolution, and charge measurement performances:

- ✓ performances at the single sensor level validate the new sensor design, with no limitations arising from the long bias resistors used;

- ✓ limited deterioration in efficiency and spatial resolution have been measured at the ladder level, despite the strip length being twice that of ladders currently used in AMS-02;