Performance of a simple 2-plane telescope (CHROMini) and a CMS 2S module in a 25 MeV proton beam: Comparison between data and Geant4 simulation

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The need for high-rate telescopes

- Probing of new physics requires the increase of the luminosity: from 300 fb^{-1} (2011-2023) to 3000 fb^{-1} (2026-2037)

- Silicon sensors for the CMS Tracker: Need for radiation-hard silicon sensors (fluence: ~2.5 x 10^{16} n_{eq}/cm^2 in the center of CMS).

- Right now we are in the prototyping phase of the new Tracker modules, so extensive beam tests of the silicon sensors and their readout electronics are necessary to examine the behavior of the sensors in realistic conditions. A new DUT can be tested for channel efficiency, cluster size, cross talk between adjacent channels etc.

- Comparison: Existing telescopes used by CMS use a Monolithic Active Pixel Sensor chip with an integration time of 115.2 μs or 8.68 kHz readout frequency. Integration time in Phase-2 Tracker modules (and other HL-LHC sensors) is 25 ns → 40 MHz (x4600 the today's CMS telescopes readout frequency).

- We cannot test Phase-2 modules at nominal rates with the old telescopes used by CMS → That's why new high-rate telescopes are being developed, e.g. CHROMIE (see N. Deelen's talk) and CHROMini.

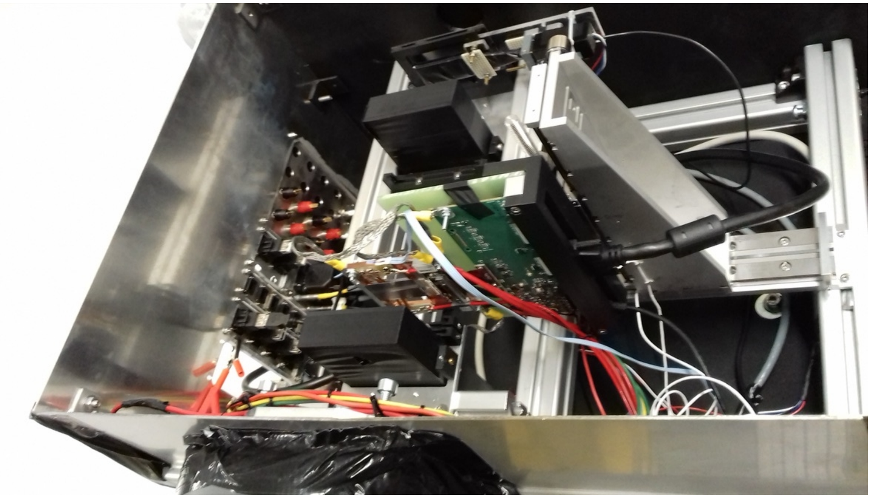
CYRCé cyclotron and CHROMini

- CYRCé (CYclotron pour la ReCherche et l'Enseignement), a low energy cyclotron for radionuclide production located at IPHC-Strasbourg with 25 MeV protons (large energy deposition), high intensities (up to 100 nA → 10^{12} protons/second), 85 MHz time structure (about twice the LHC frequency, can be made half with a kicker), Bρ = 0.72 Tm and Gaussian profile

- A new beam line dedicated to the tests of the CMS Tracker modules has been added and a mini-telescope called CHROMini is being designed and constructed for the new beam line at IPHC

- CHROMini will consist of two CMS pixel Phase-I module planes, each plane containing two modules sandwiching the DUT on shifting (on trail) planes to accommodate different sizes of DUT, 1-2 scintillators for triggering

- For more details see U. Goerlach's and C. Grimault's talks

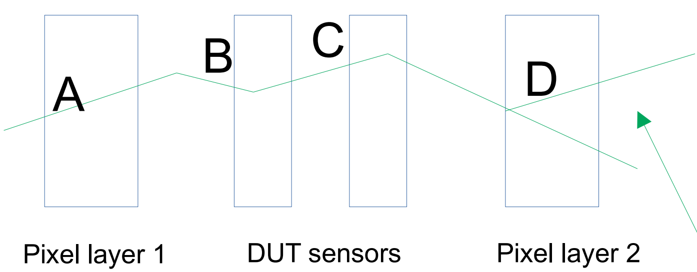


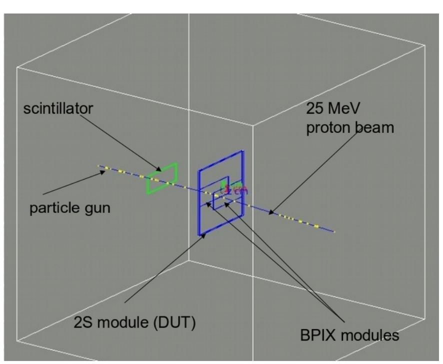
A Geant4 simulation of CHROMini

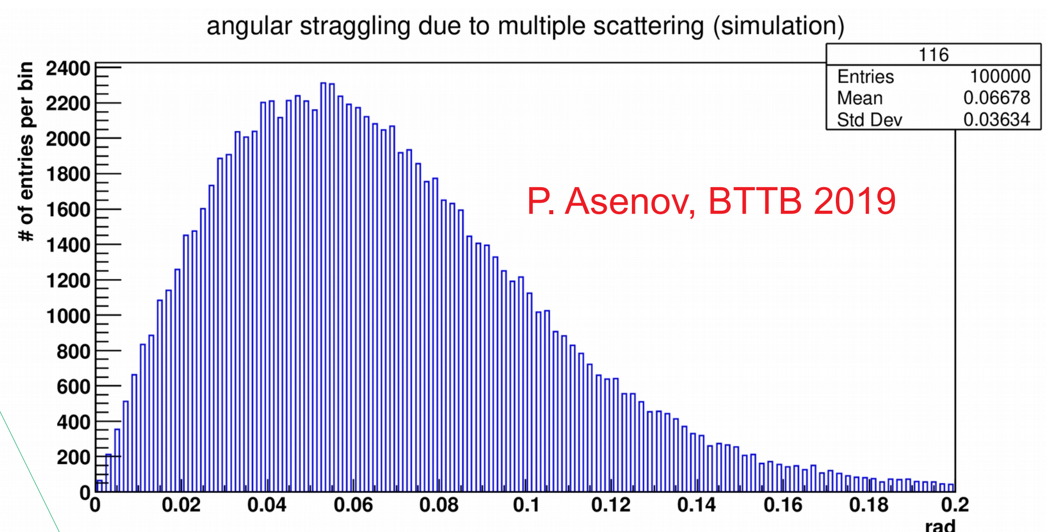
- The standalone simulation had showed that the CHROMini project is feasible and can be used for tracking

- In the simulation telescope modules with different materials, thicknesses and pixel sizes were tested, for various distances from the DUT

- DUT and telescope module residuals, as well as angular straggling were estimated







$$\mathit{deflection\ angle} = \mathrm{acos}\left(\vec{u}_A \cdot \vec{u}_D\right), \vec{u}: \mathit{momentum\ direction\ unit\ vector}$$

Motivation for further simulations

- Difficulties experienced when trying to make the readout electronics work in time

- Effective energy losses in materials of silicon detectors and scintillators had to be better estimated

- Increasing stopping power over the path and the thicknesses of several materials

- That’s why runs were performed with only one pixel layer → comparison with simulation

Simulation characteristics (1)

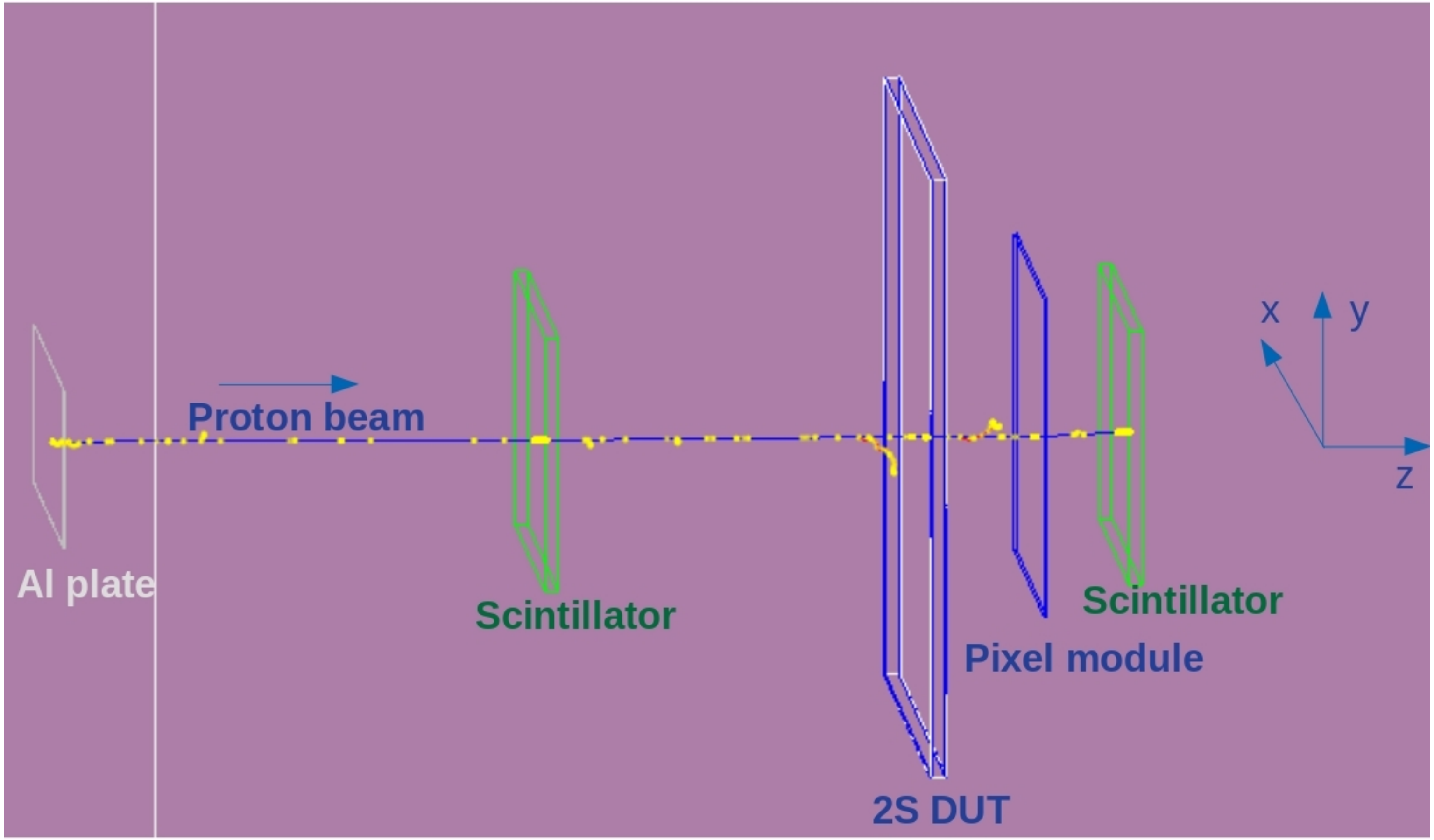
- 2S module DUT: 2 Si sensors (102700 µm X 94108 µm X 320 µm), with spacing between the sensors: 2 mm; strip pitch: 90 µm; active depth: 290 µm
- 1 pixel layer consisting of two Phase-1 BPIX modules behind the DUT
- BPIX module: 66.6 mm X 25 mm X 460 µm, 2 rows X 8 ROCs; pixel size: 150 µm X 100 µm
- A 50 µm-thick Al foil at the beam line exit to separate the vacuum from the air
- A PVT (C_9H_{10}) scintillator of 2 mm thickness in front of the DUT and one similar scintillator behind the pixel layer, for triggering
- 25 MeV proton beam in z-direction
- Scintillator 1: z = 7.6 cm; DUT: z = 13.5 cm; Pixel layer: z = 15.3 cm; Scintillator 2: z = 16.7 cm
- 20000 events for all plots presented below, except where mentioned otherwise

Simulation characteristics (2)

- Physics processes:
  - Ionizations
  - Bremsstrahlung
  - Pair production
  - Annihilation
  - Photoelectric effect
  - γ production
  - Compton scattering
  - Rayleigh scattering
  - Klein-Nishina model for the differential cross section

- General Particle Source (GPS) used instead of a particle gun (since it allows the specifications of the spectral, spatial and angular distribution of the primary source particles):
  - Energy = 25 MeV
  - Direction = (0, 0, 1)
  - Position adjusted to the center of the beam from the data of a real run; only one pixel module hit
  - type: beam
  - shape: circle
  - σ_r = 2.123 mm

Visualization of the Geant4-simulated geometry of the system under beam

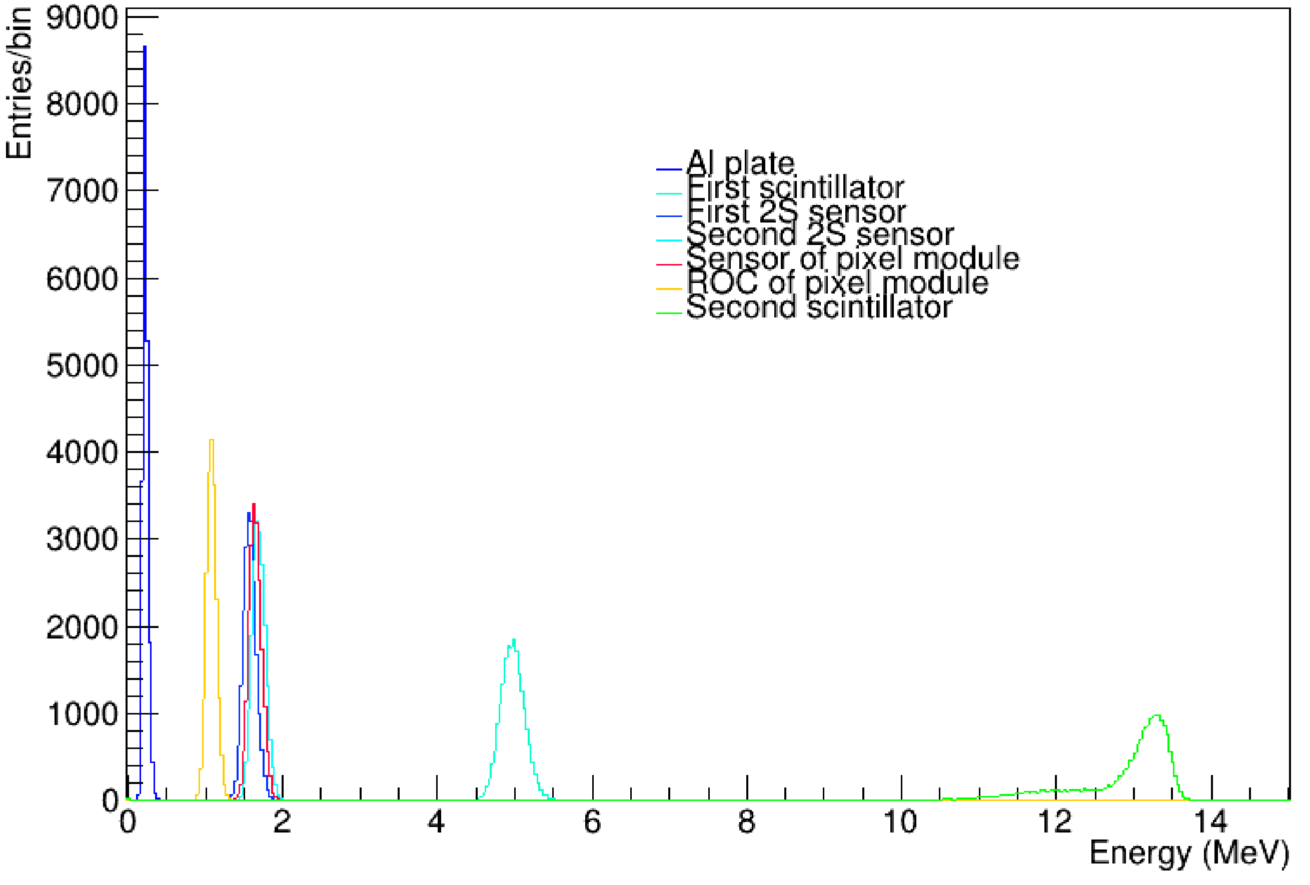


All results presented here are for a run of 20000 events except where stated elsewhere.

Energy deposition per volume (setup with only one pixel layer)

Mean value of energy deposition in 2S sensor 1: 1.574 MeV

Mean value of energy deposition in 2S sensor 2: 1.690 MeV

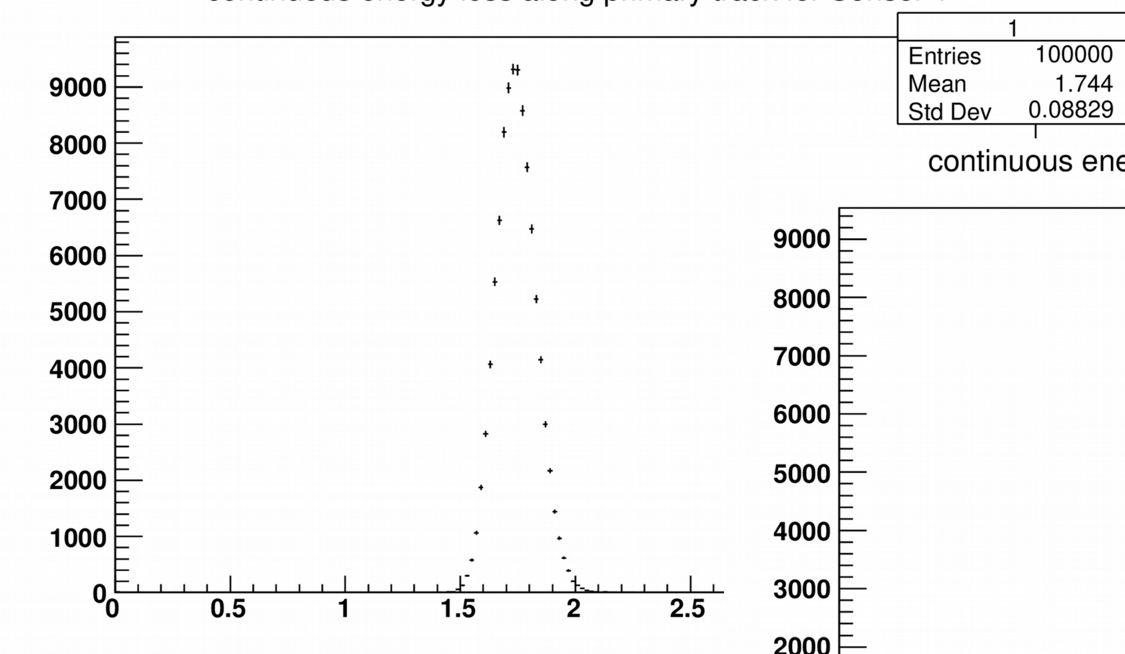


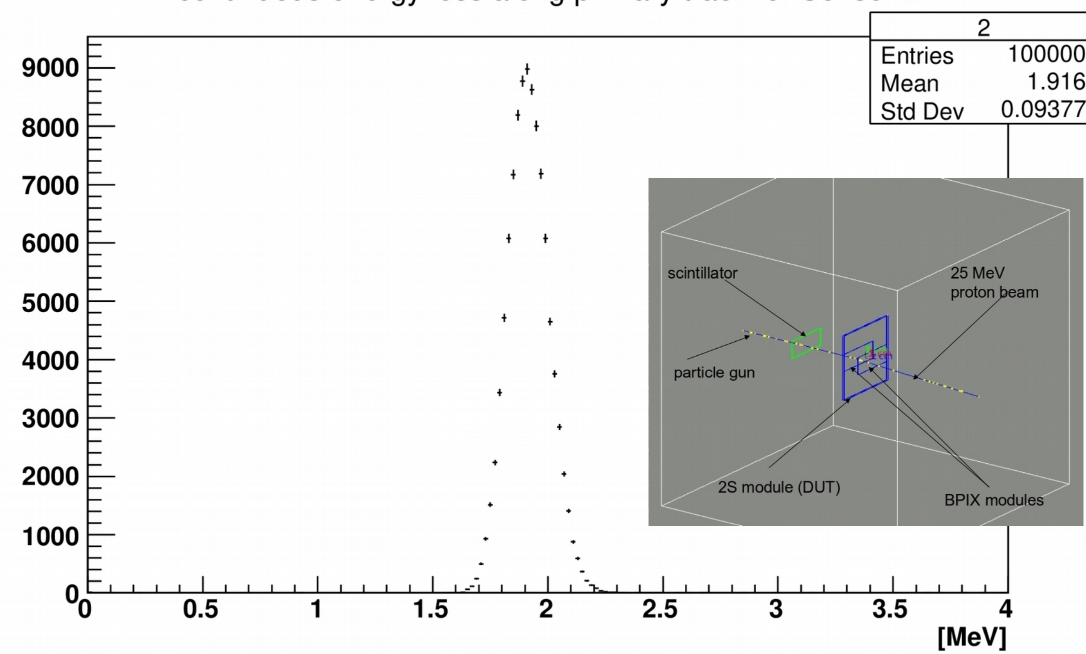
Energy deposited from primary particles (25 MeV protons) in each volume (simulation).

Energy deposition in 2S sensors with CHROMini setup

One less scintillator, one more pixel layer in front of the DUT

Presented by P. Asenov, BTTB 2019

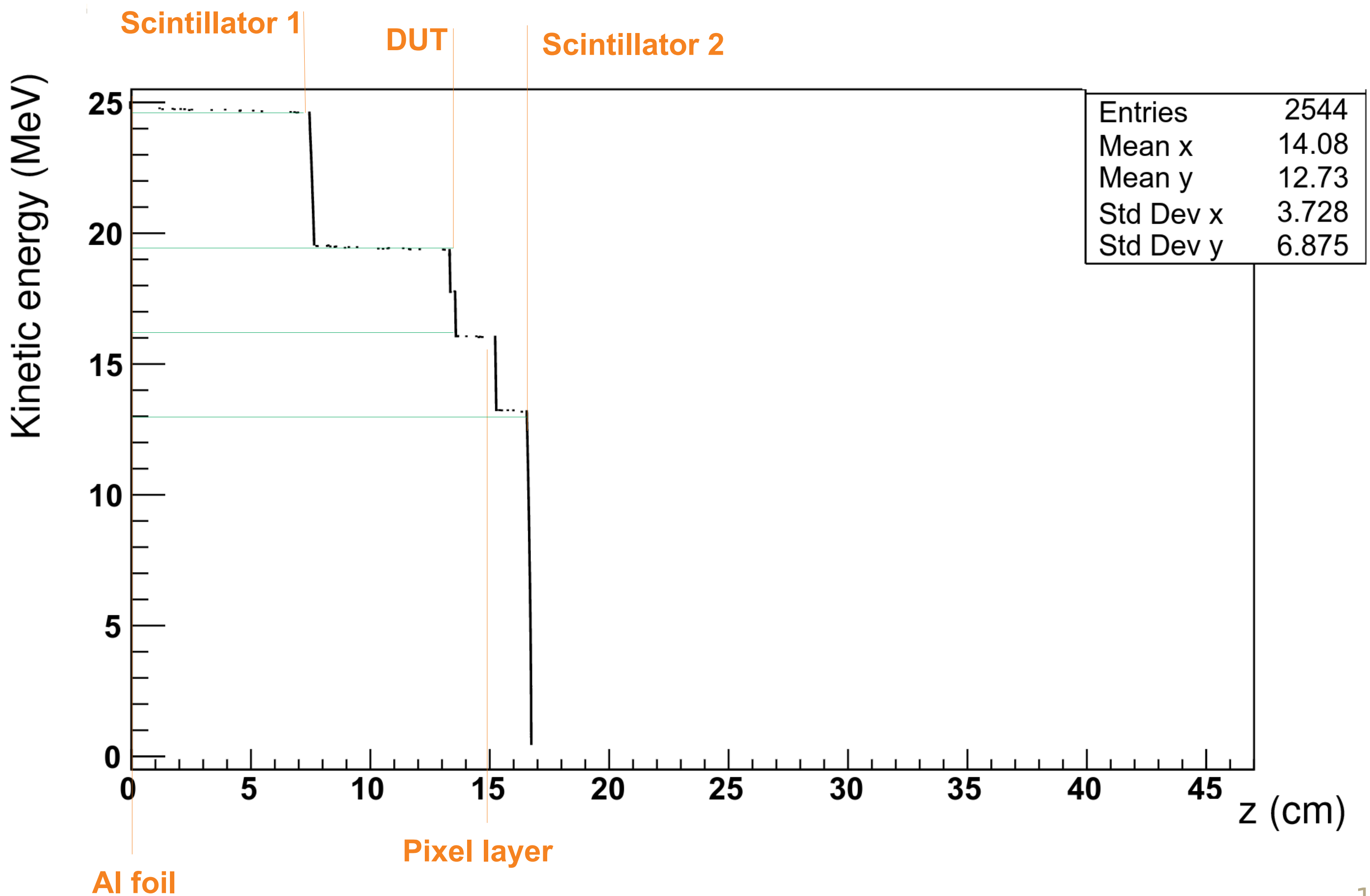




Mean value of energy deposition in 2S sensor 1: 1.744 MeV

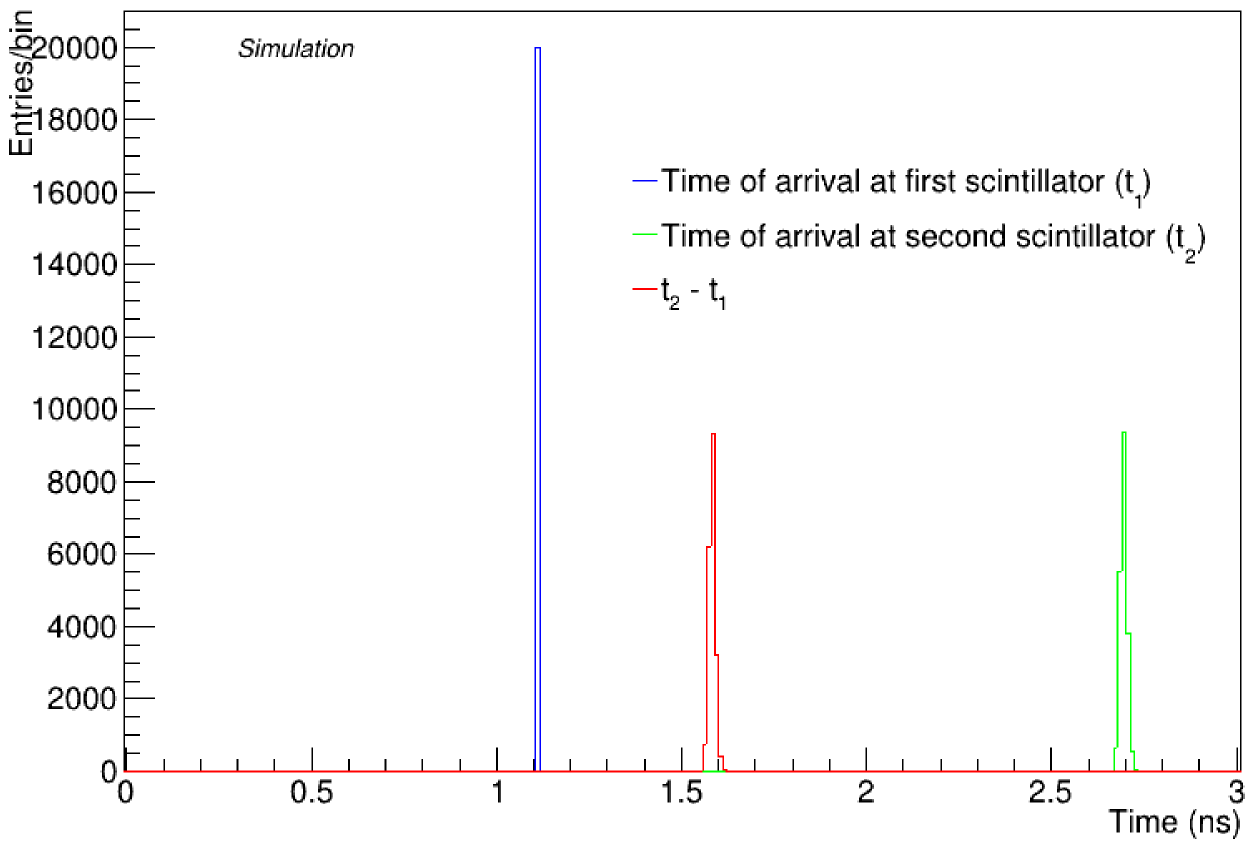
Mean value of energy deposition in 2S sensor 2: 1.916 MeV

Kinetic energy of beam protons along the z-direction (single event)



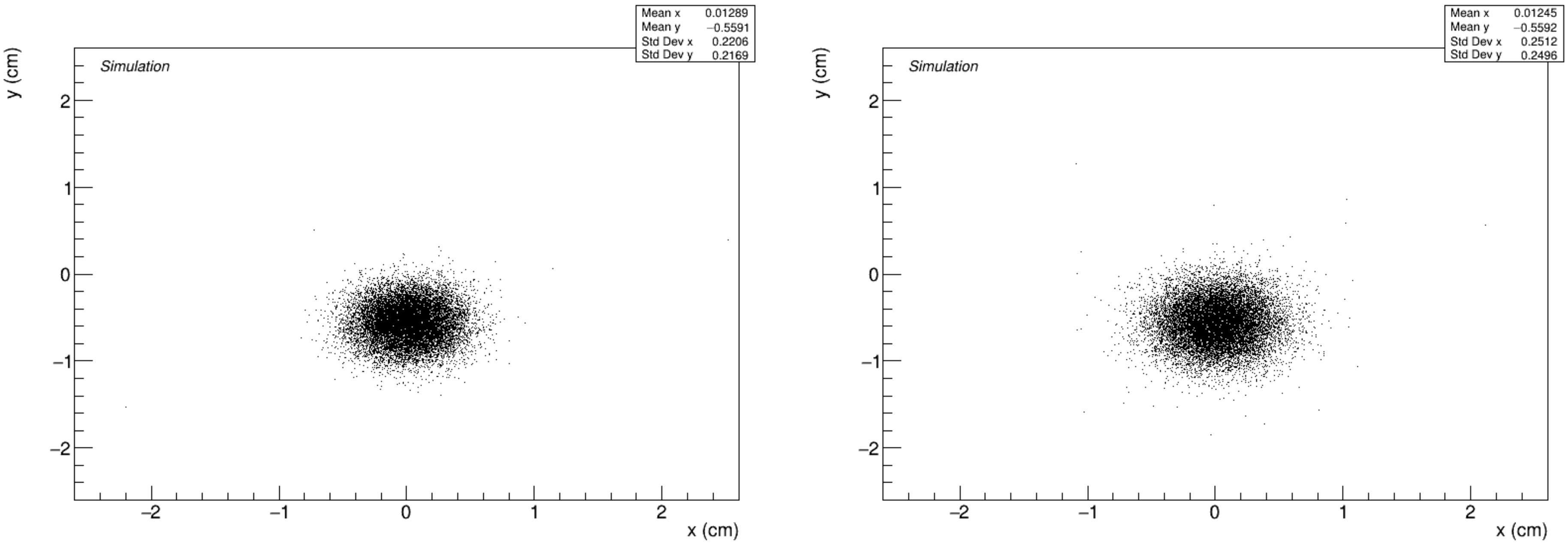
Kinetic energy of beam particles (25 MeV protons) along z-direction (simulation).

Time of flight between the two scintillators



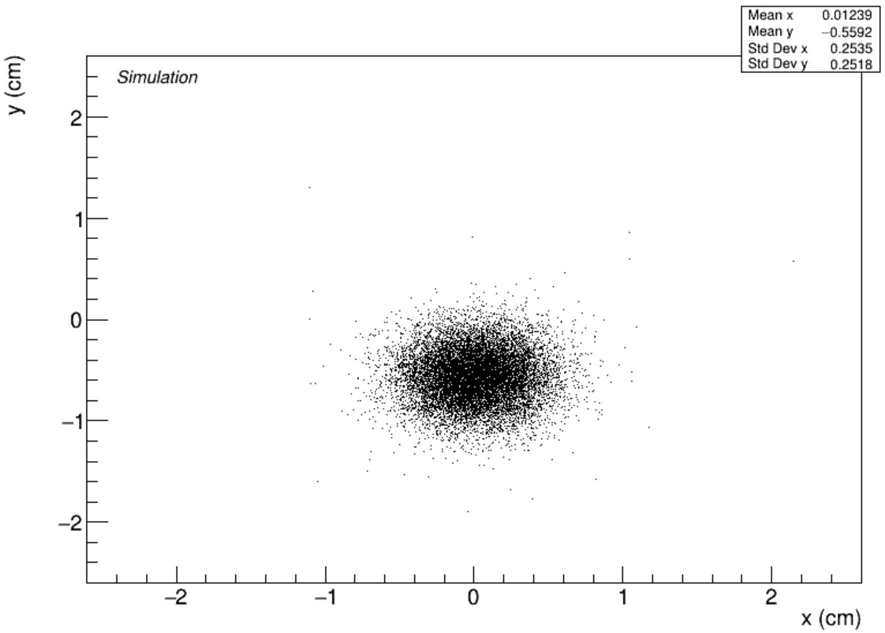
Time of flight beam particles (25 MeV protons) along z-direction (simulation). It is smaller than the scintillator coincidence width of 7 ns.

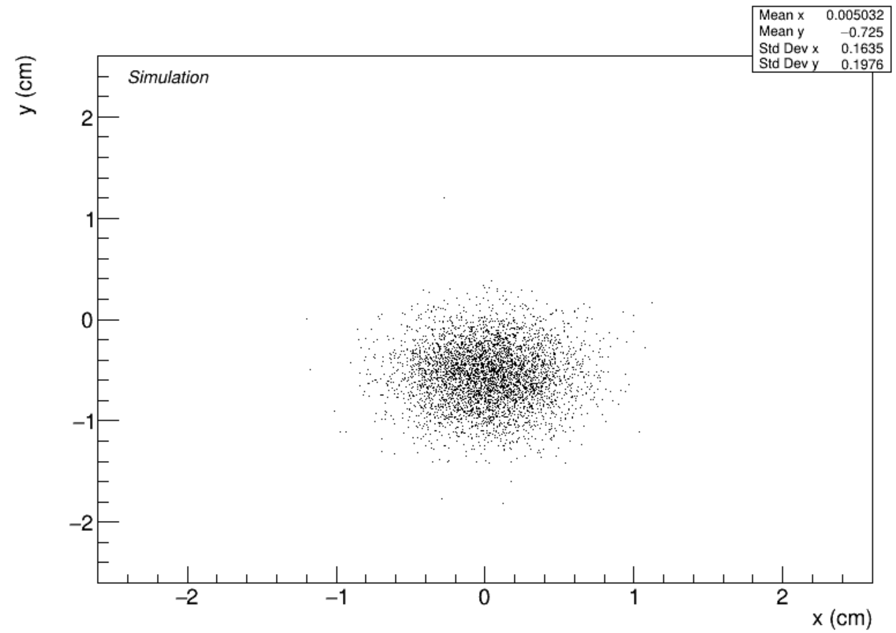
Beam profile at exit of different volumes (1)



Beam profile at the exit of the first scintillator (left) and the DUT (right) (simulation).

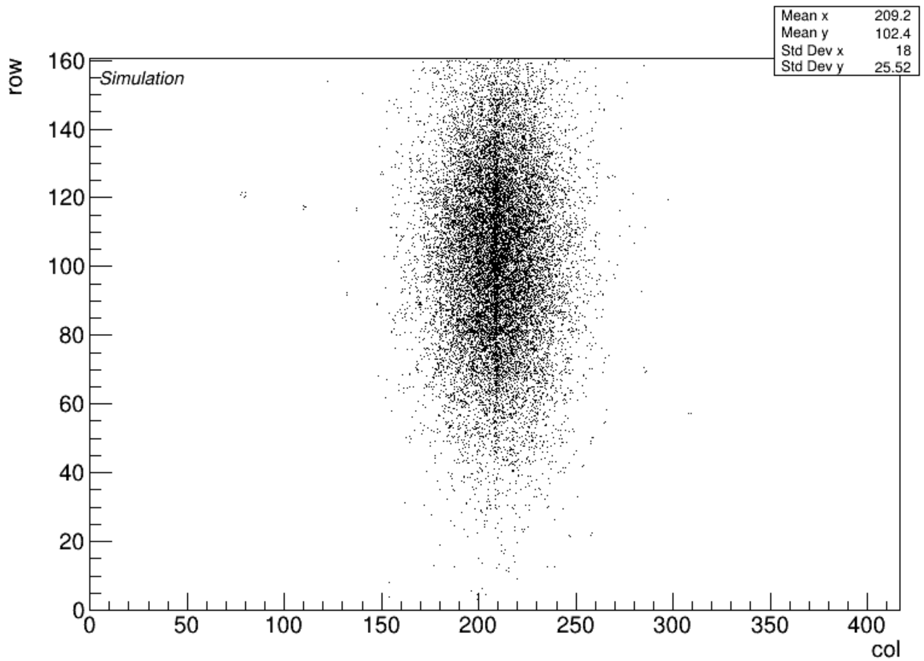
Beam profile at exit of different volumes (2)

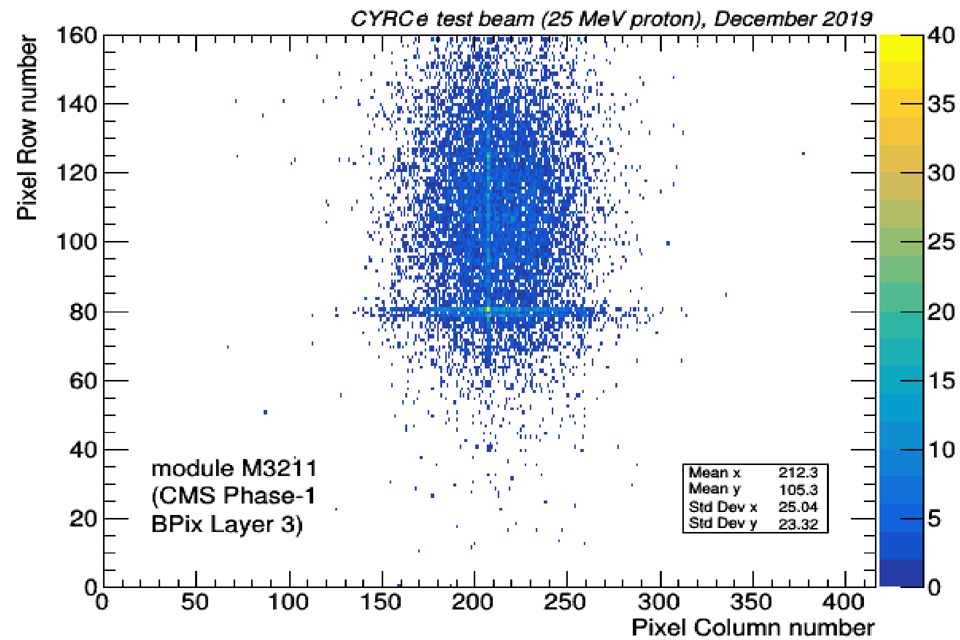




Beam profile at the exit of the pixel layer (left) and the second scintillator (right) (simulation).

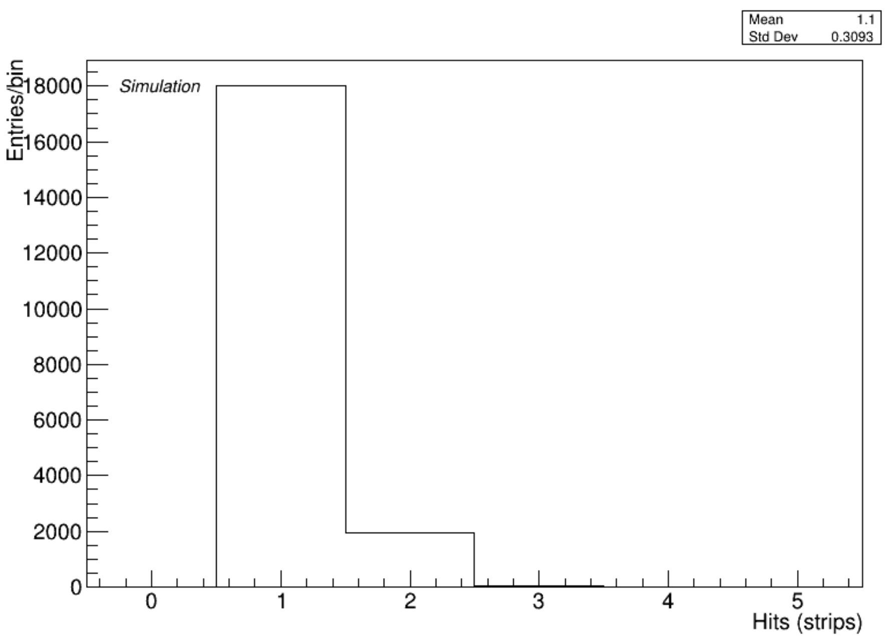
Cluster occupancy in a pixel module

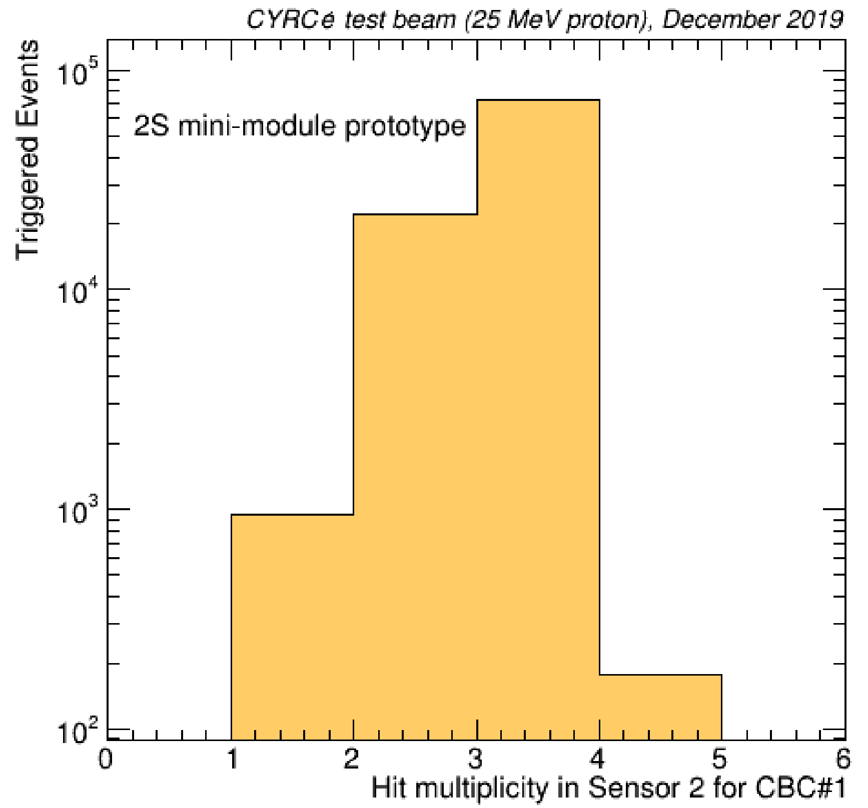




Cluster occupancy per column per row for the bottom module of the pixel layer for a 25 MeV proton beam (left: simulation with a circular beam of $\sigma_r = 2.123$ mm; right: test beam data); the beam size was measured from the beam spot on the cluster occupancy map for the same module, obtained from the analysis of the real run, and thus the above parameters were selected for the simulation run). FE electronics behavior not yet included in the model.

Hit multiplicity in the 2S sensors





Left: Hit multiplicity of the second 2S sensor (along the way of the beam) from a simulated run with a 25 MeV proton beam. The hit multiplicity is obtained by measuring the deposited energy in the volume of each strip and dividing it by the energy required for the creation of an electron-hole pair (3.67 eV). FE electronics behavior not yet included in the model. Right: The experimental value of the hit multiplicity for the same sensor and with the same configuration.

Conclusions

- A new high-rate telescope is being commissioned mostly based on technology developed for CMS (compatible with CMS-standard hardware and software)

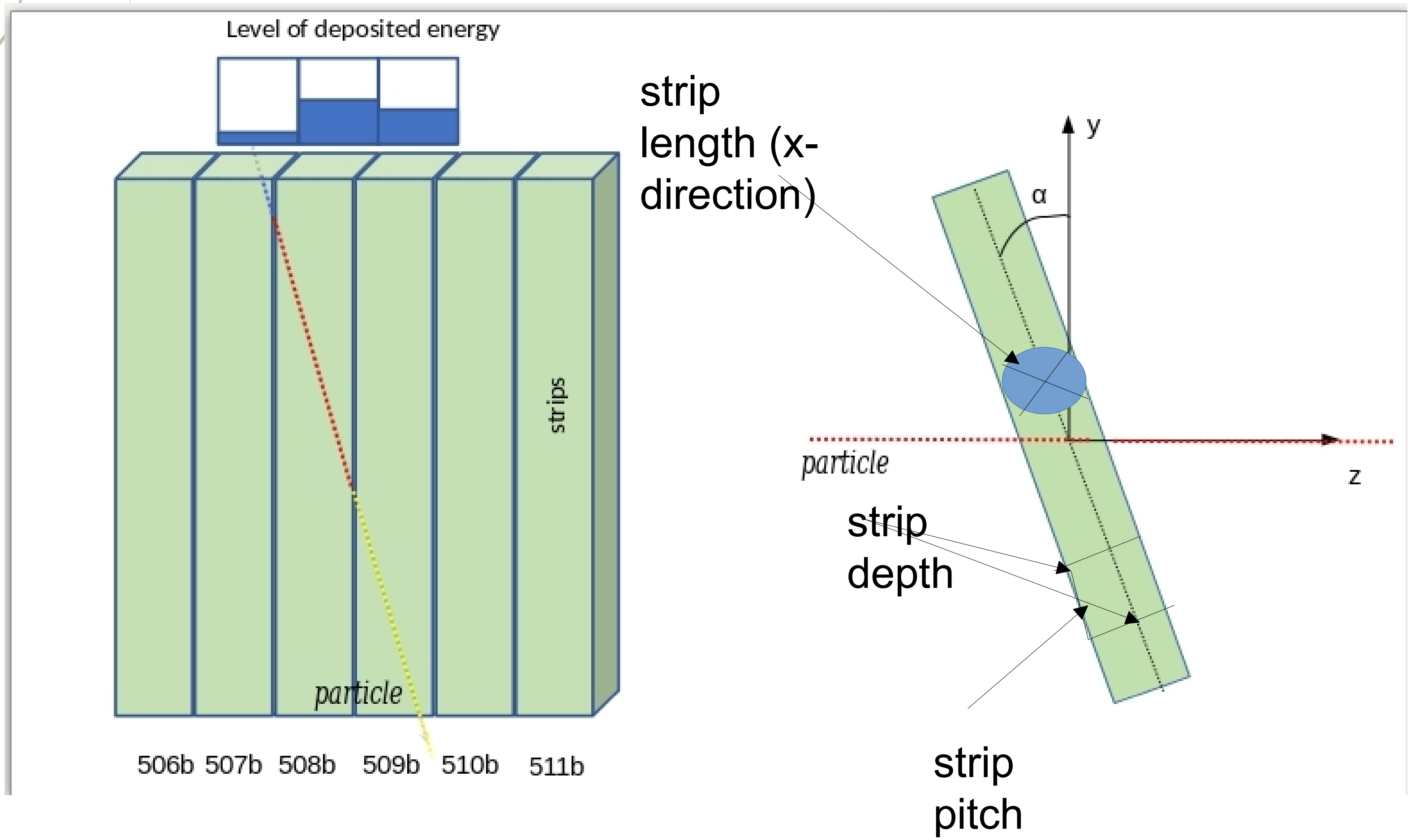
- A standalone simulation program → estimation of proton energy loss per volume, angular straggling (multiple scattering), proton time of flight and changes in beam spatial profile after each volume

- The mismatch in the hit multiplicity due to FE electronics behavior not included in the simulation

Backup

Sensitive 2S sensors

Level of deposited energy

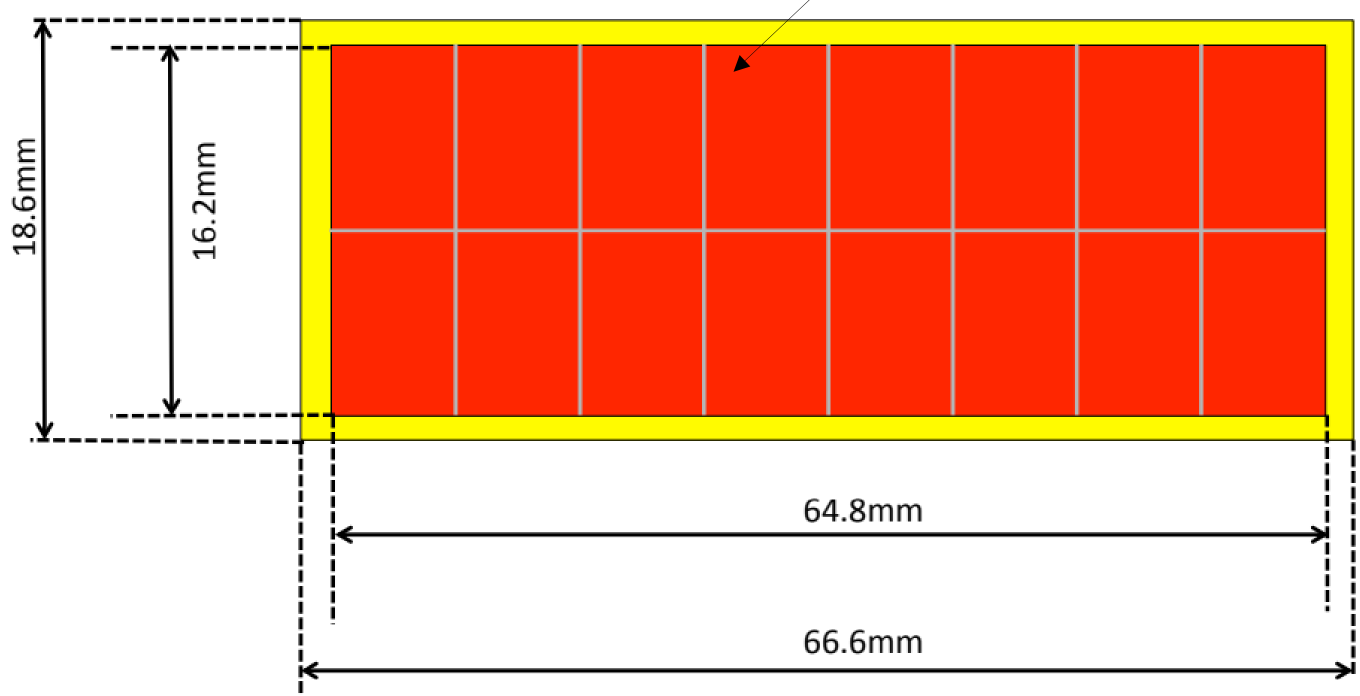


- 2 X 1016 strips in the active region (with active depth = 290 µm). Each strip is associated with an active volume below it with y-width = pitch = 90 µm.

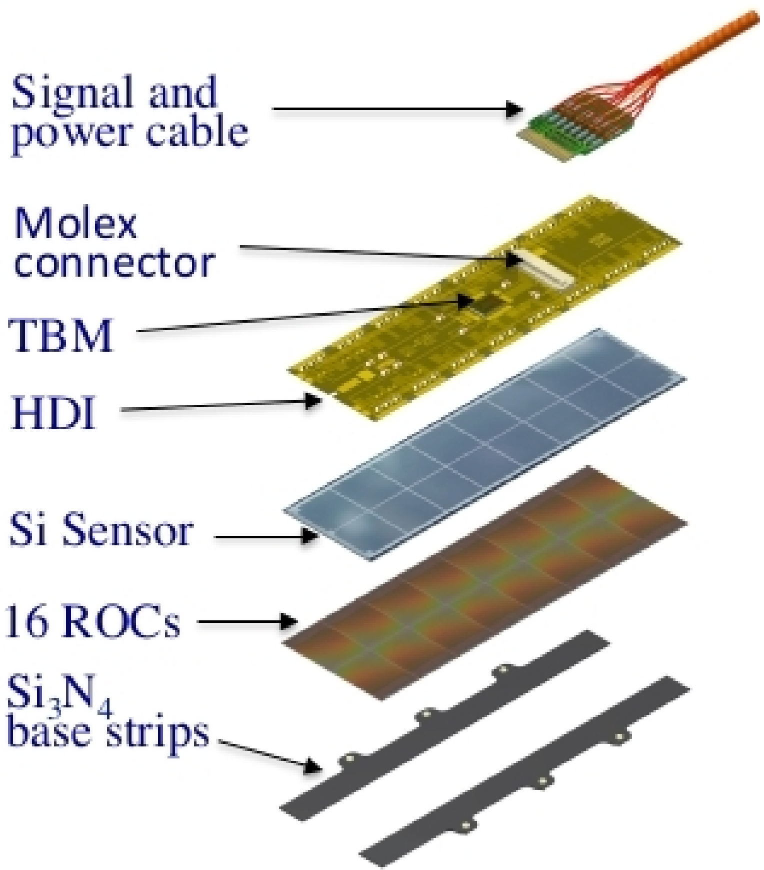
BPIX (barrel pixel) modules

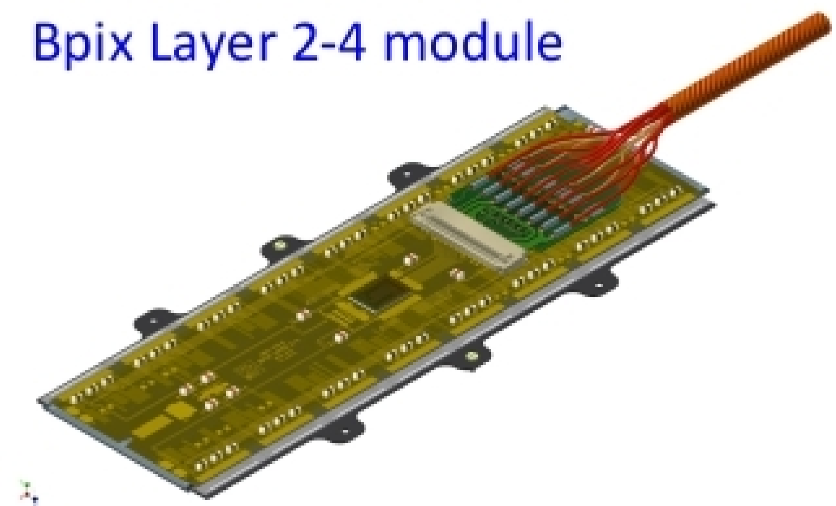
Sensor silicon area 18.6x66.6mm^2
Number of ROCs=2x8
Pixel size 100x150um^2 (size twice as wide at chip boarders)
Number of pixels 80x52
Sensor active area 16.2x64.8mm^2 since
2*(80*0.1mm+0.1mm)=16.2mm
8*(52*0.15mm+2*0.15mm)=64.8mm

Deposited energy calculated for each pixel



The structure of a Phase-1 BPIX module





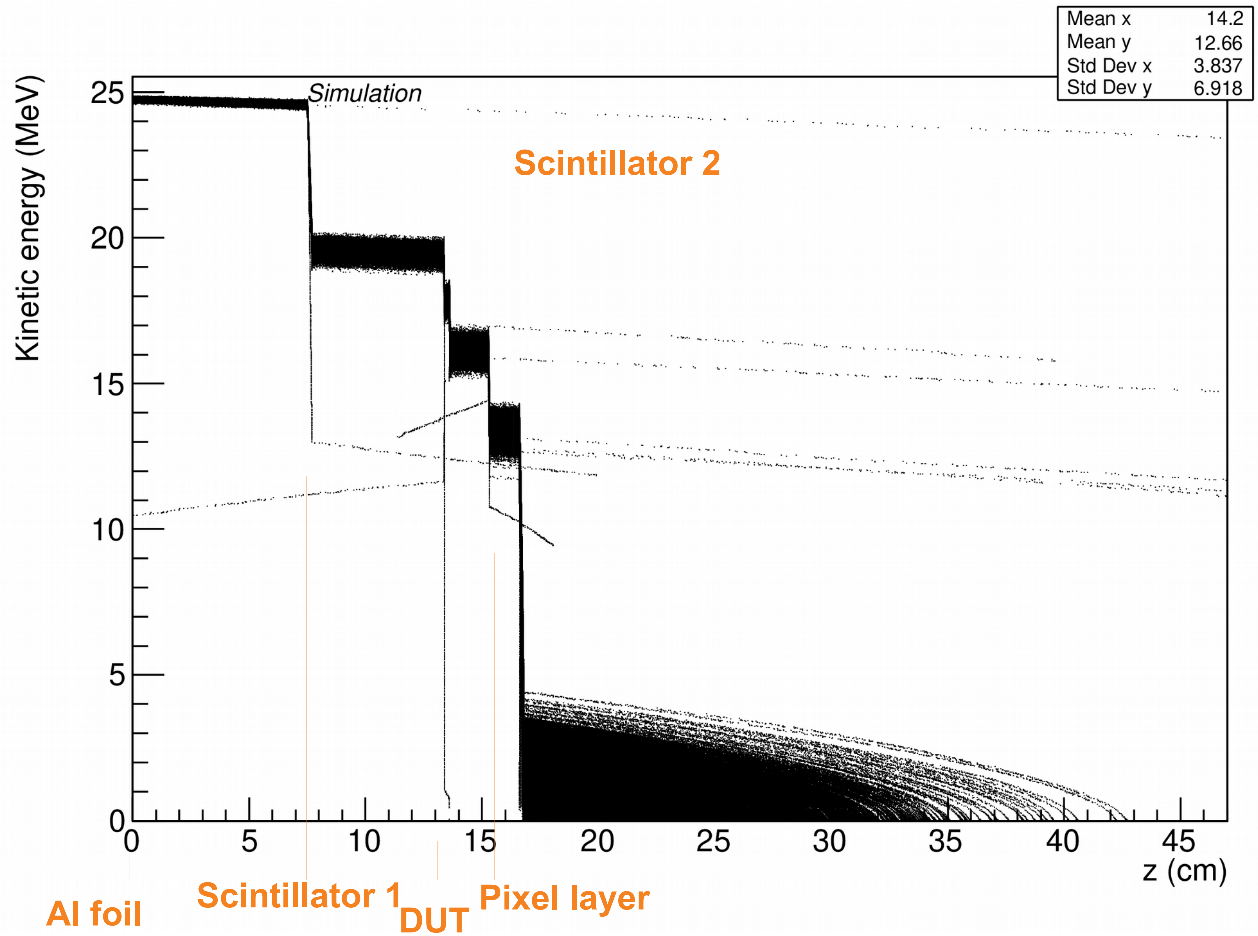
Definition of hits in strips and pixels

- 2S → strips: 5σ noise threshold → set at 10000 electrons

- BPIX → pixels: threshold → set at 1700 electrons

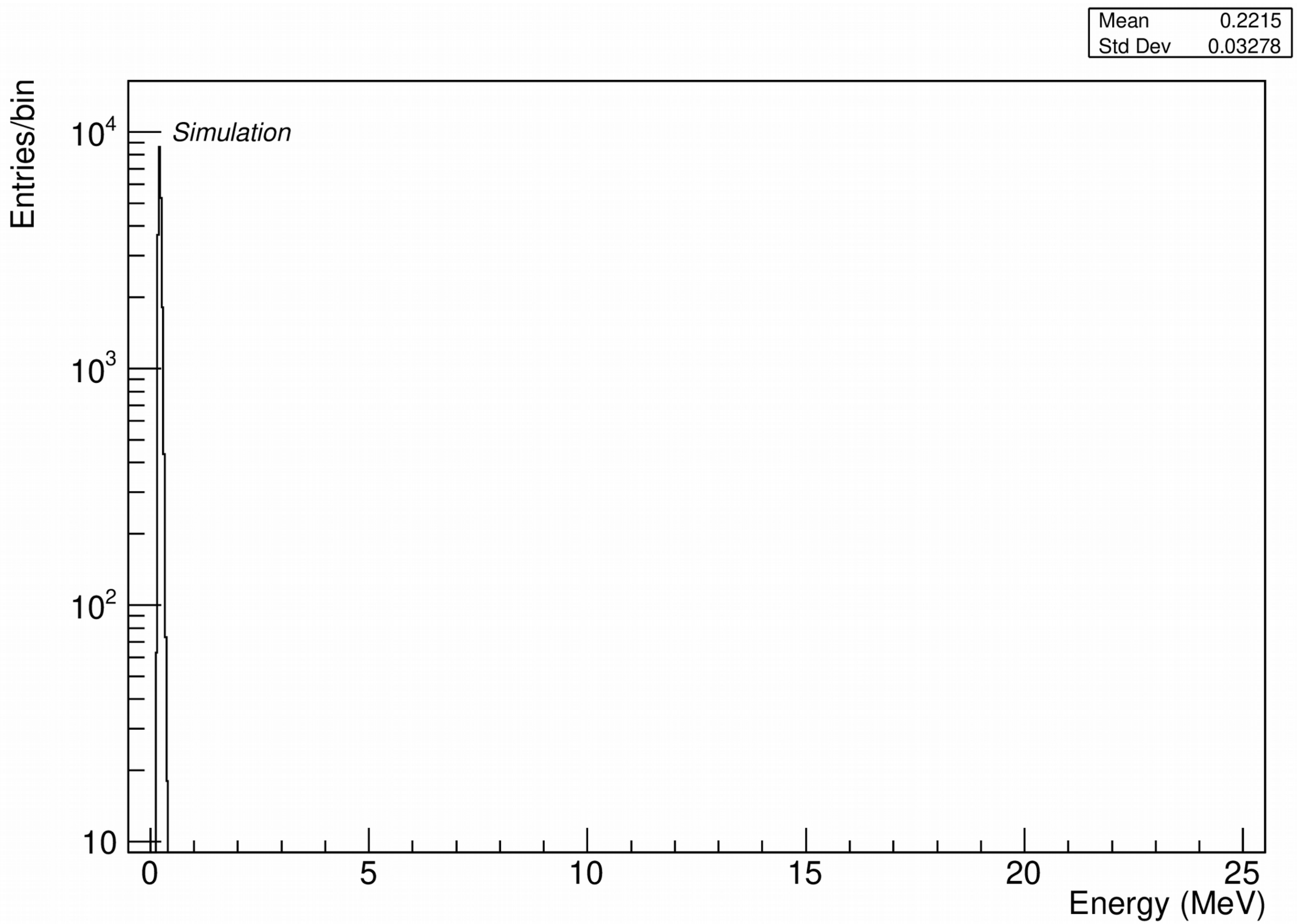
- For each event our program calculates the stored energy in each strip/pixel, respectively, and when dividing this energy by the energy required for a single electron-hole production in silicon (= 3.67 eV) one can get the charge collected in each pixel/strip in electrons. If this charge exceeds the threshold of 10000/1700 electrons, respectively, we consider that we have got a hit in the examined strip/pixel in the current event.

Kinetic energy of beam protons along the z-direction (multiple events)

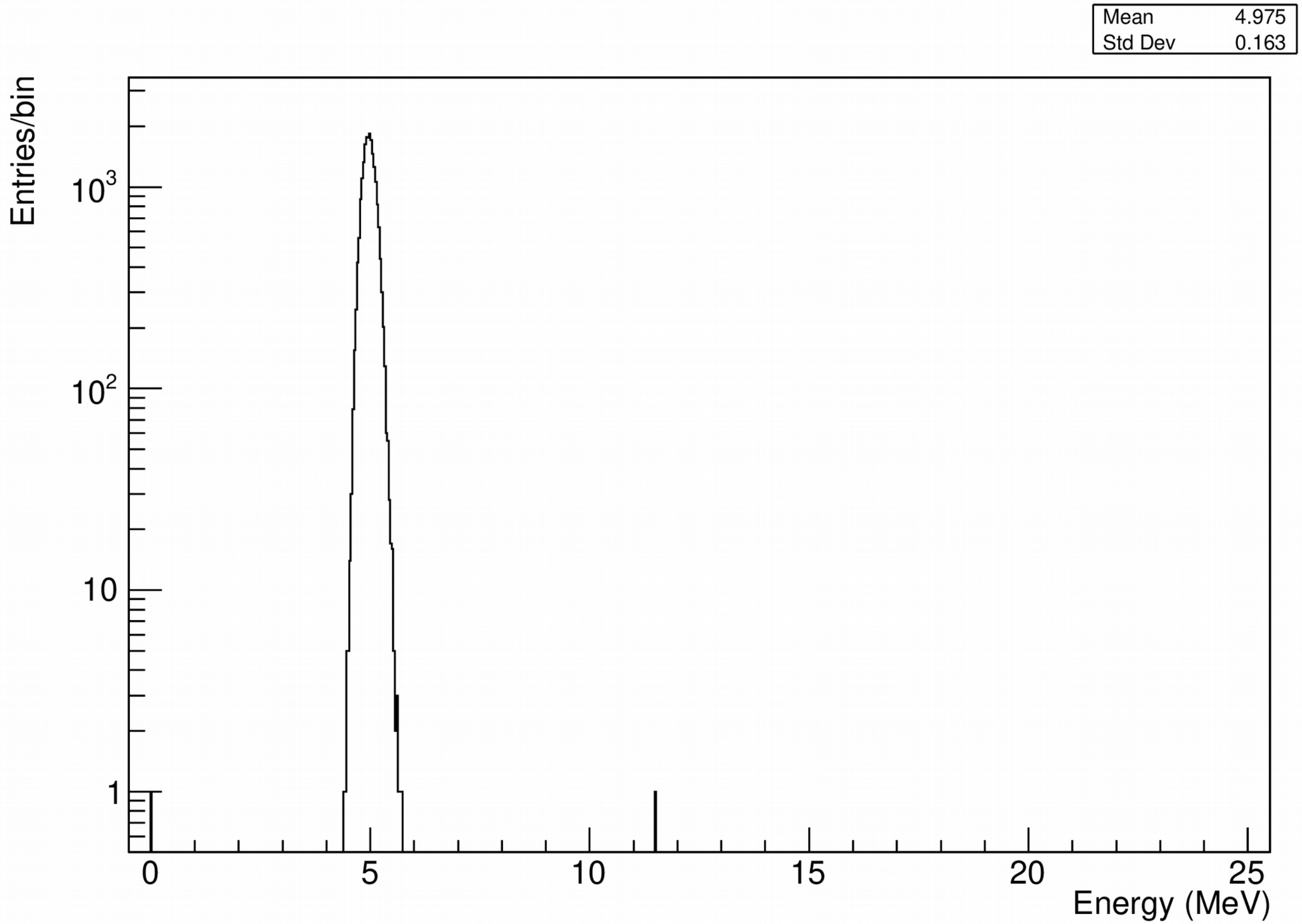


Kinetic energy of beam particles (25 MeV protons) along z-direction (simulation).

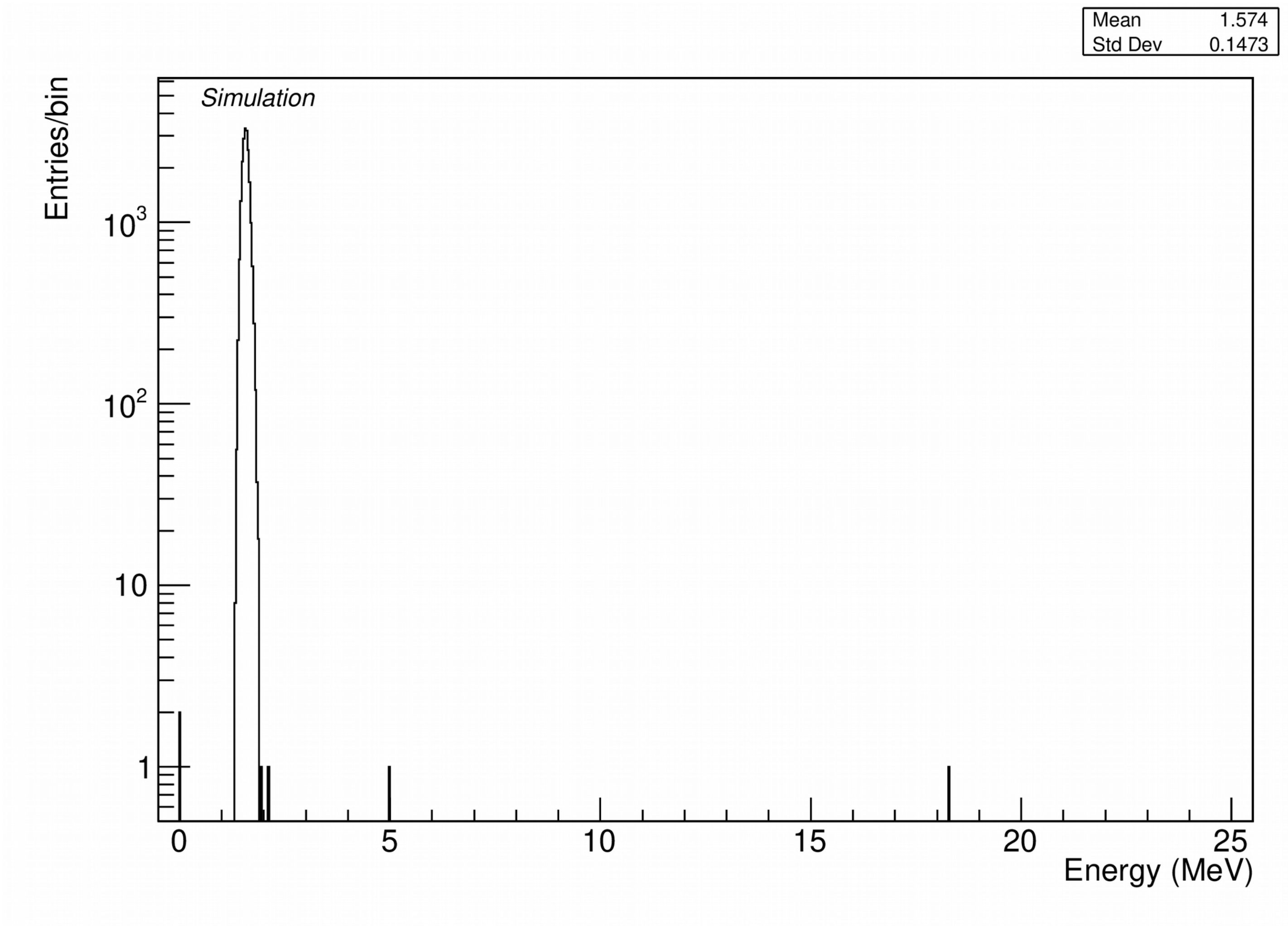
Energy deposition in Al foil



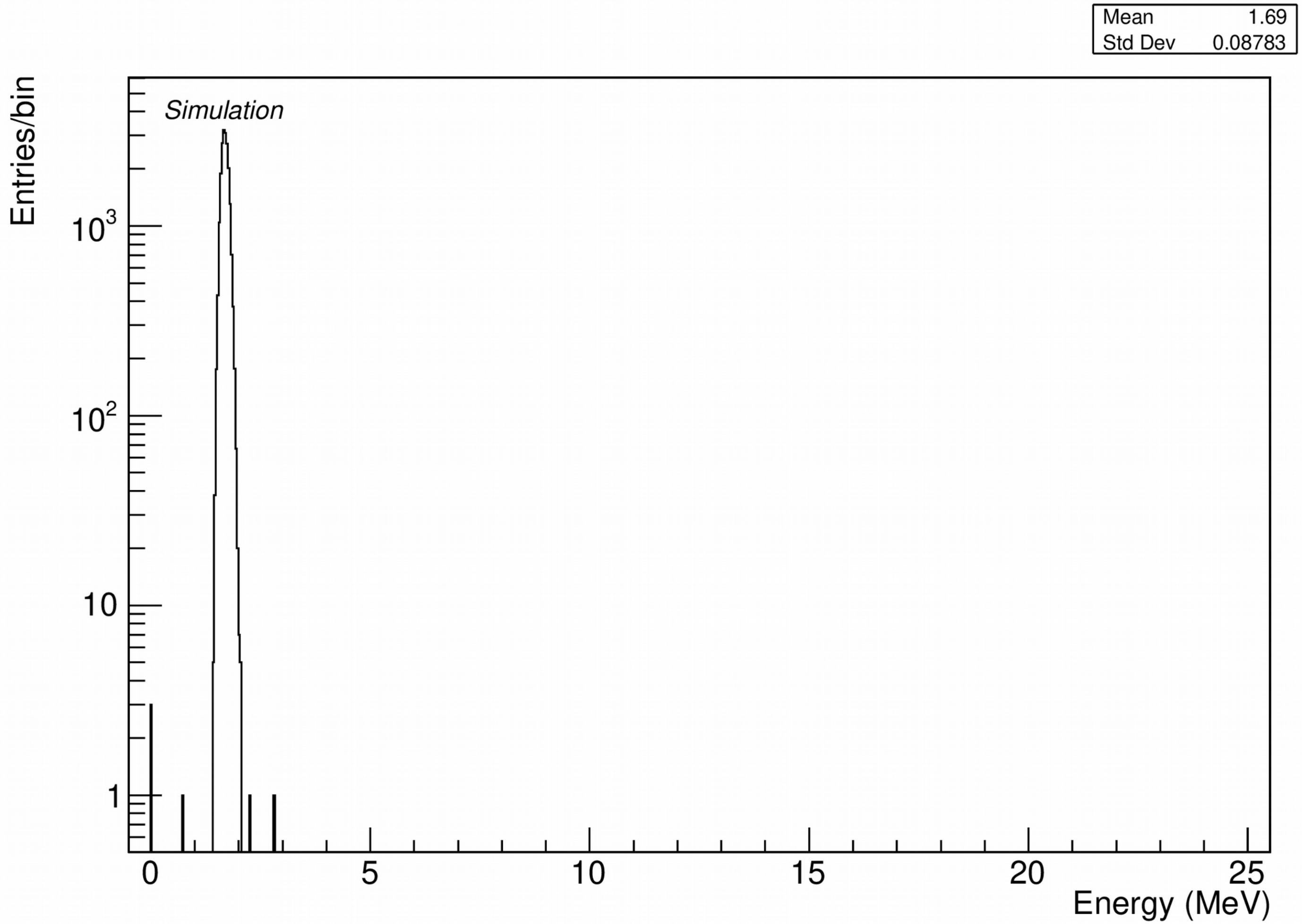
Energy deposition in first scintillator



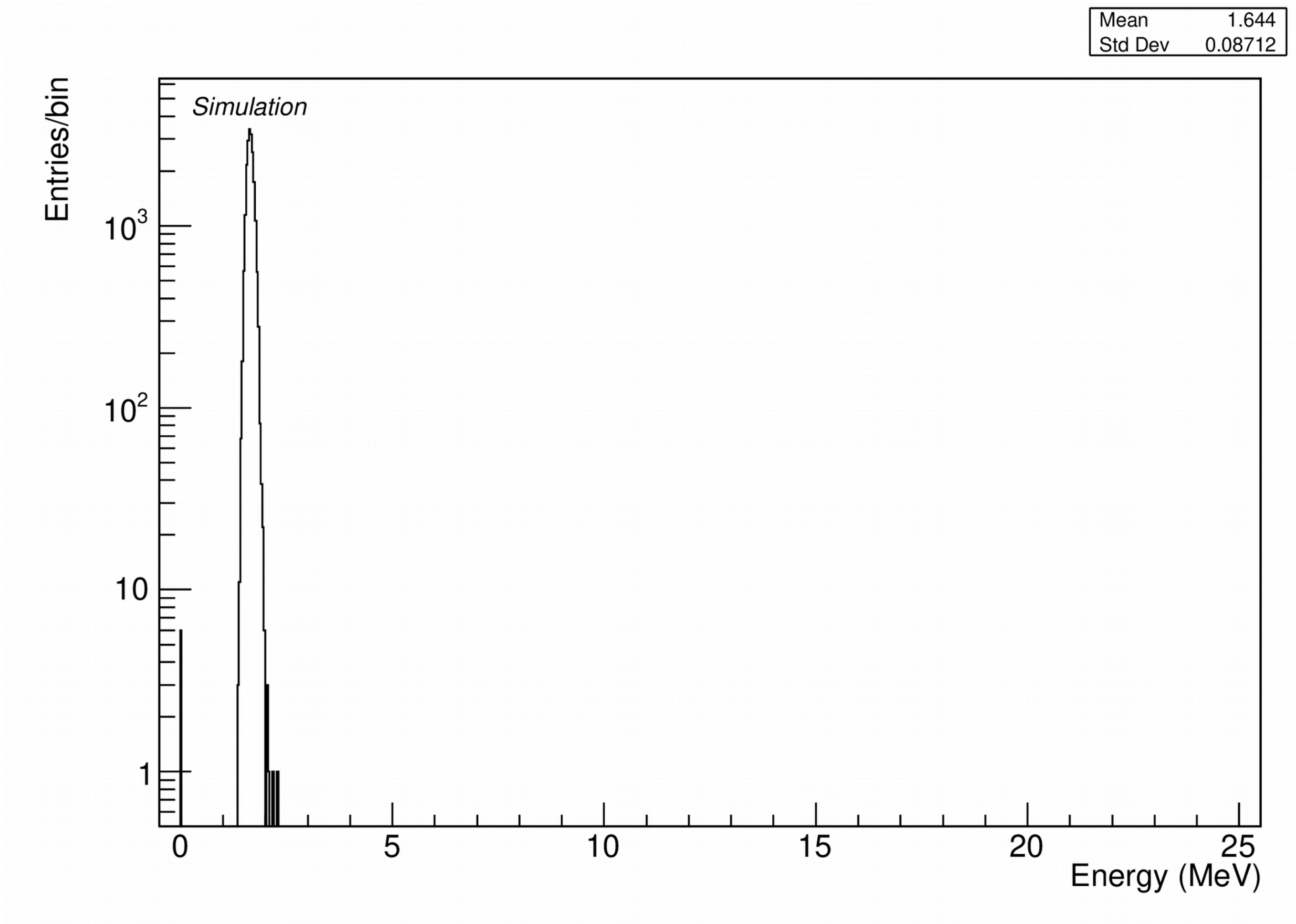
Energy deposition in first 2S sensor



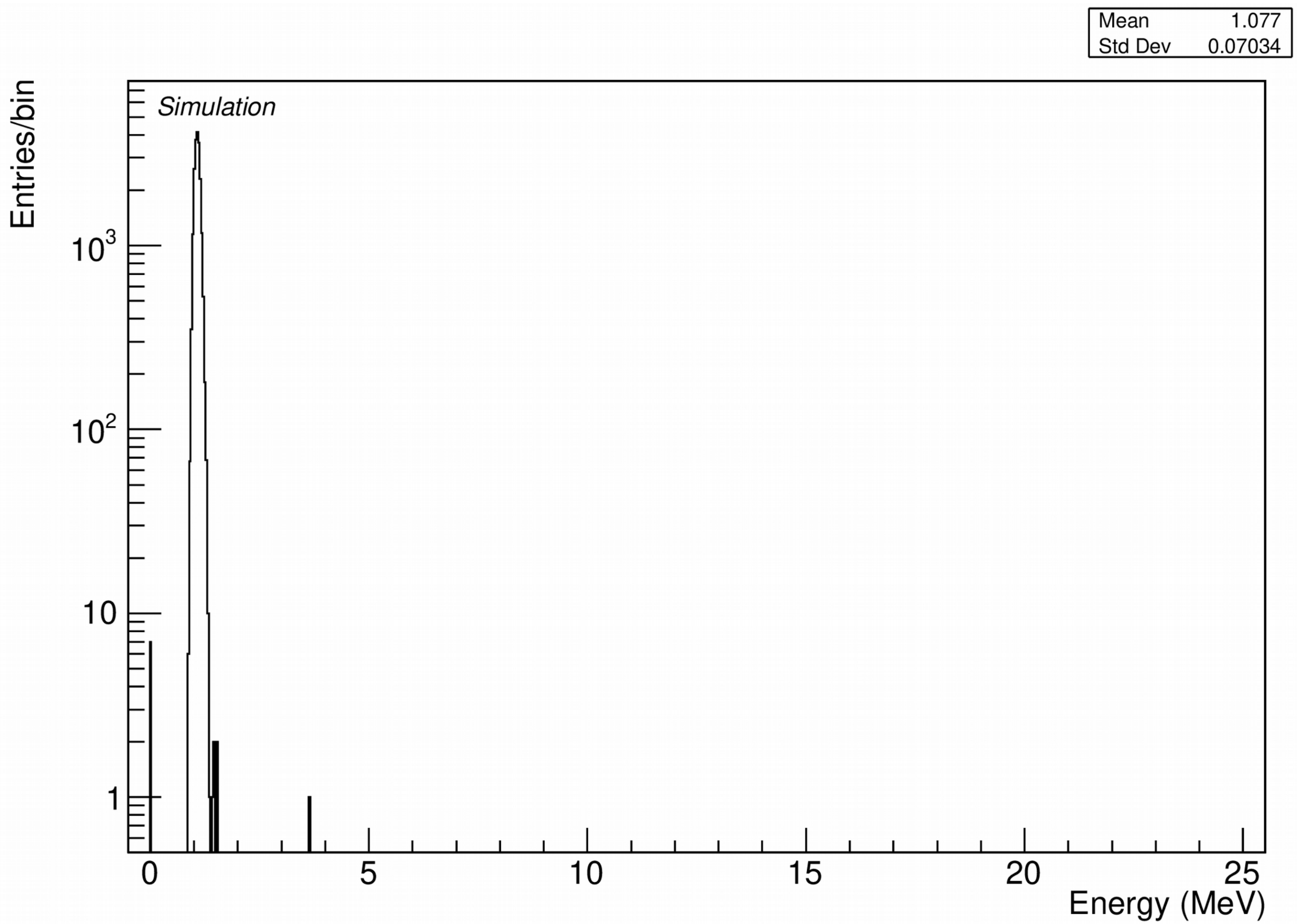
Energy deposition in second 2S sensor



Energy deposition in sensor of pixel module



Energy deposition in ROC of pixel module



Energy deposition in second scintillator