Penetrating Particle Analyser (PAN*). Silicon tracker development. Beamtest results

Daniil SUKHONOS

On behalf of the PAN collaboration

*Penetrating Particle ANalyzer (PAN) X.Wu et al., Adv. Space Res. 63, 8, 2672-2682 (2019) https://doi.org/10.1016/j.asr.2019.01.012

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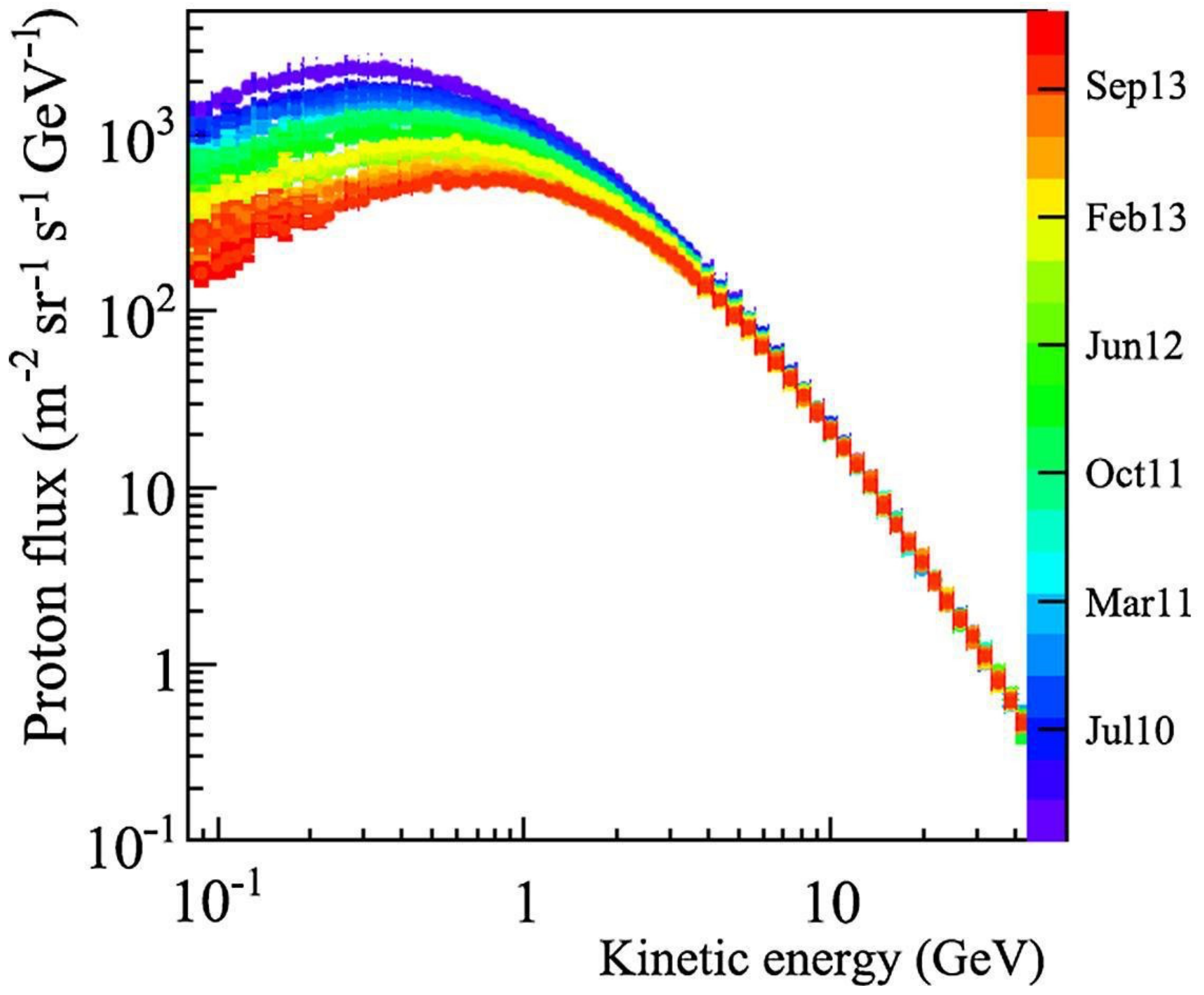
PAN: enables precise penetrating particle detection in deep space!

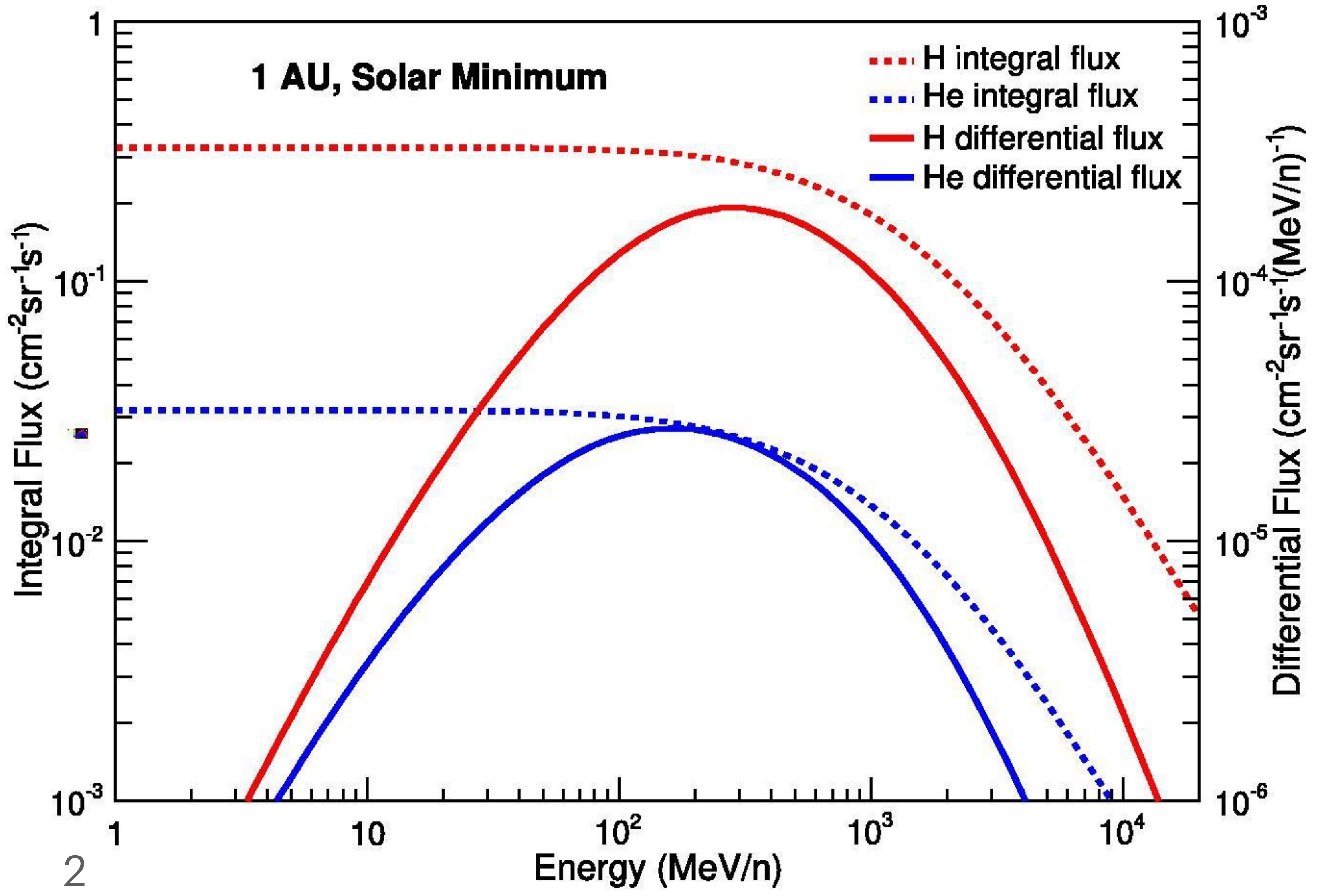
Penetrating Particle Analyzer

PAN is a **generic instrument technology** for deep space and interplanetary missions

- Capable of precise measurement and monitoring in **real time** the flux, composition, direction of penetrating particles (> ~100 MeV/nucleon) in **deep space, around moons, planets, …**
- ~20% energy resolution for proton at 1 GeV, "unprecedented" in deep space
- PAN fills a gap in observation and technology: ground-breaking!

Evolution of proton spectra from the solar cycle 24 measured near Earth by PMAELA





Proton and Helium fluxes at 1 AU outside Earth's Magnetosphere. Calculation by SPENVIS toolkit

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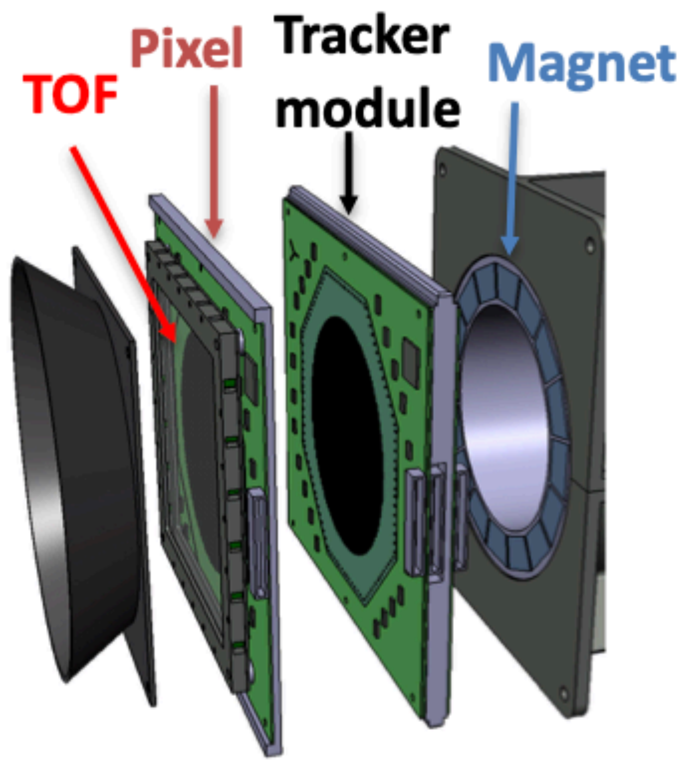
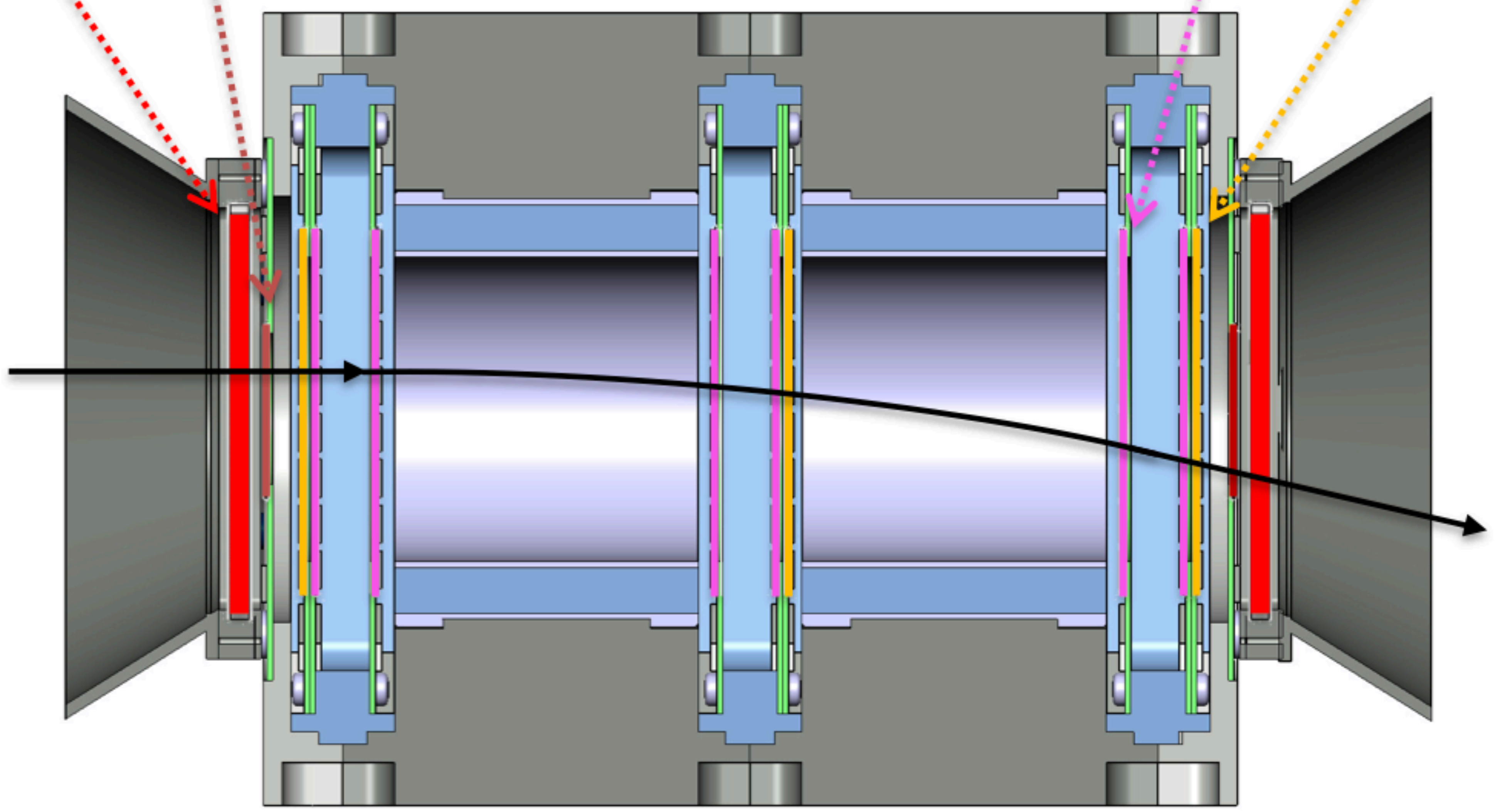
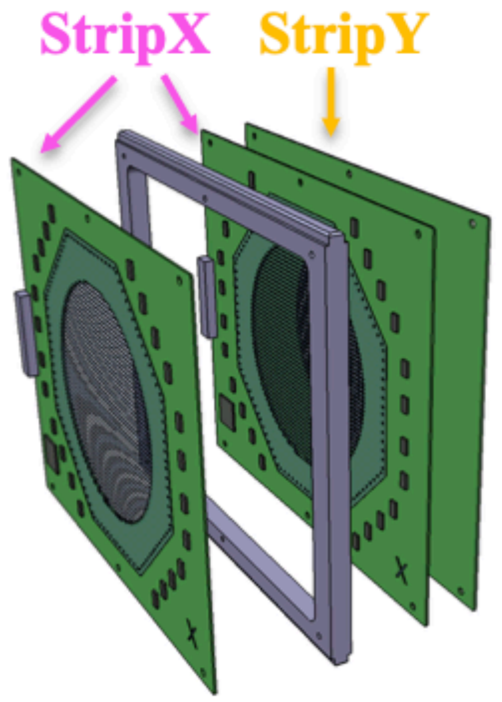
Penetrating Particle Analyzer

PAN: versatile integrated instrument concept

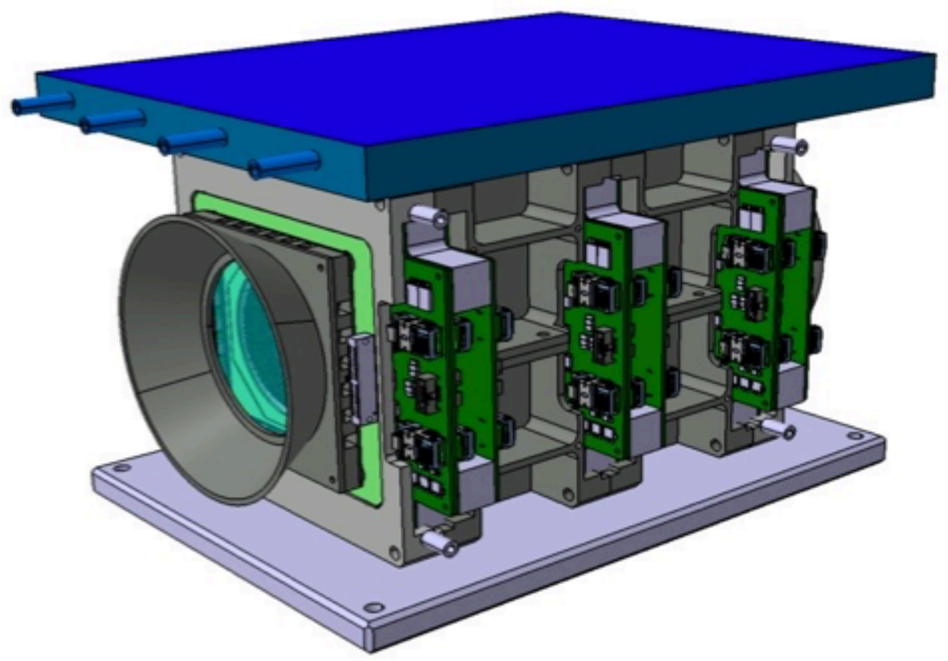
- Excellent rigidity resolution thanks to fine pitch thin (StripX, StripY) silicon detectors
- In addition: TOF, PIXEL







- TOF: Plastic scintillator with SiPM readout
  - Provide a trigger
  - Measure Z
  - Measure Time of Flight
  - Provide a low energy particle counter



StripY: measure the particle direction in Y with an angular resolution ~0.2°

- Also provide trigger
- Measure Z (both Strip-X and Strip-Y)

- PIXEL: 3-d points with 55 μm Si pixels
  - **No measurement degradation even during the most intense solar storms**
  - **Provide a high rate particle counter**
  - Improve tracking (a fraction of events)
  - Measure Z (a fraction of events)
  - Only partial coverage for power saving

All the goodies for just <10 kg, < 30 W, 30 × 20 × 20 cm³ !!!

PAN Microstrip Silicon Sensors

1. Silicon Wafer **common** properties for both types of silicon strip detectors.

Device type	Single side AC-readout /double metal
Silicon Type	N-type, Phosphorus doped
Crystal orientation	<100>
Chip thickness	**150±15 µm**
Front and back side metal	AL
Full depletion voltage	Max. 50 V
Breakdown voltage	Min. 100 V
Tot. leakage current (at 1.5·V_depl)	max. 3 µA

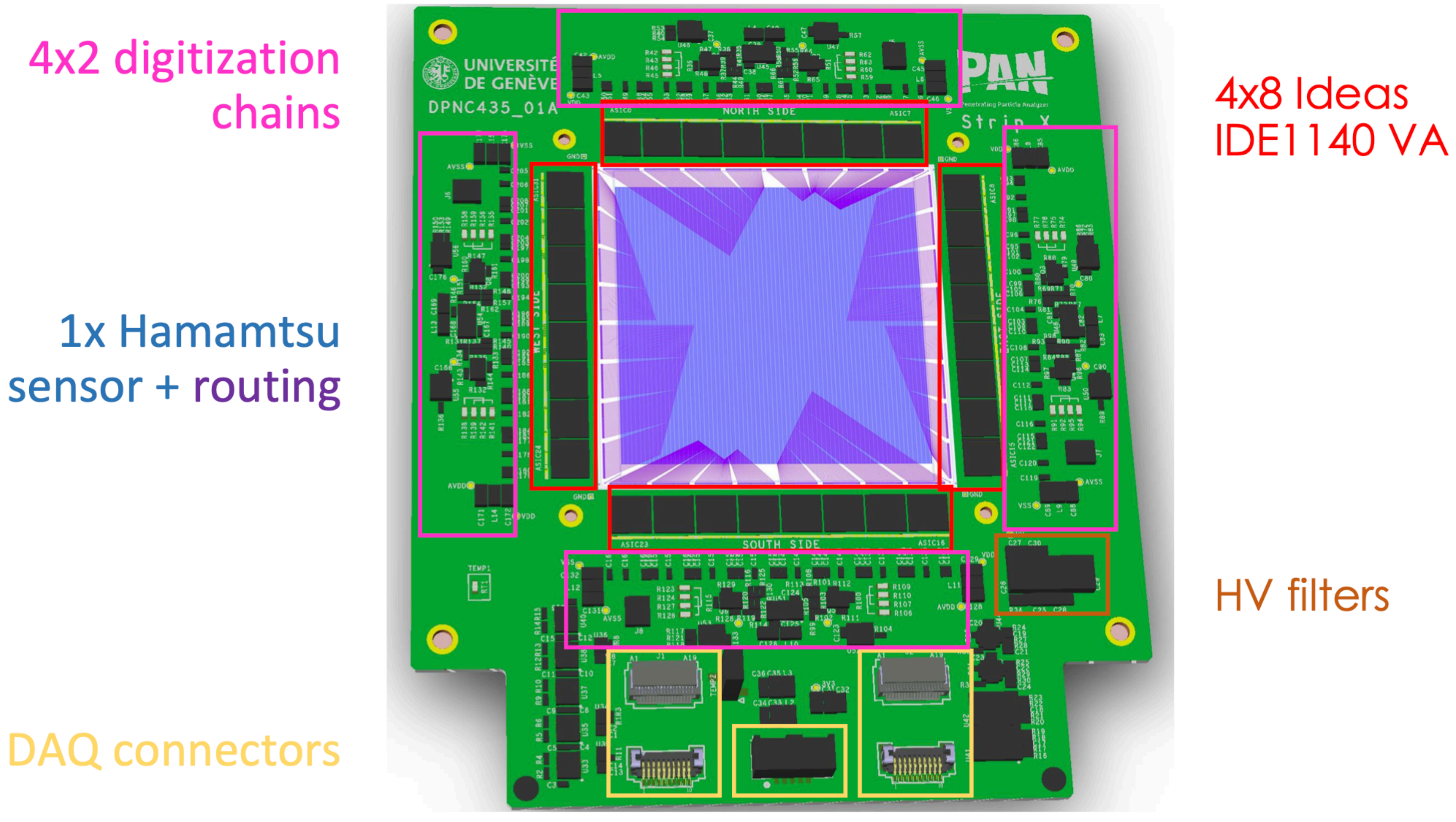
2. Strip **X sensor** properties.

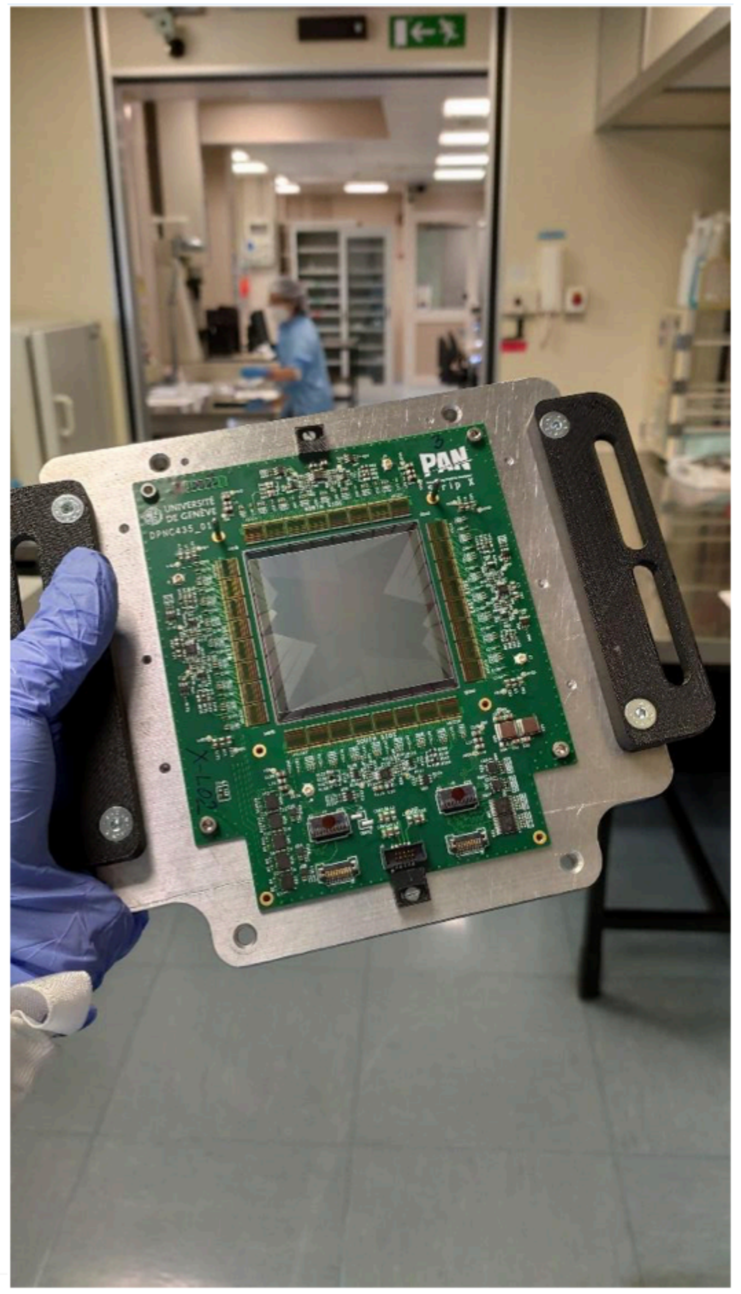
X sensor overall size	59000±20 x 59000±20 µm
Active area	51200 x 51200 µm
Number of Strips	**2048 ch**
Strip pitch	25 µm
Strip width	13 µm
Readout AL width	10 µm
Readout PAD pitch	96 µm

3. Strip **Y sensor** properties.

Y sensor overall size	59000±20 x 59000±20 µm
Active area	Circular with D=51200 µm
Number of Strips	**128 ch**
Strip pitch	400 µm
Strip width	380 µm
Readout AL width	10 µm
Readout PAD pitch	91.2(2lines) µm

X – Detector Architecture

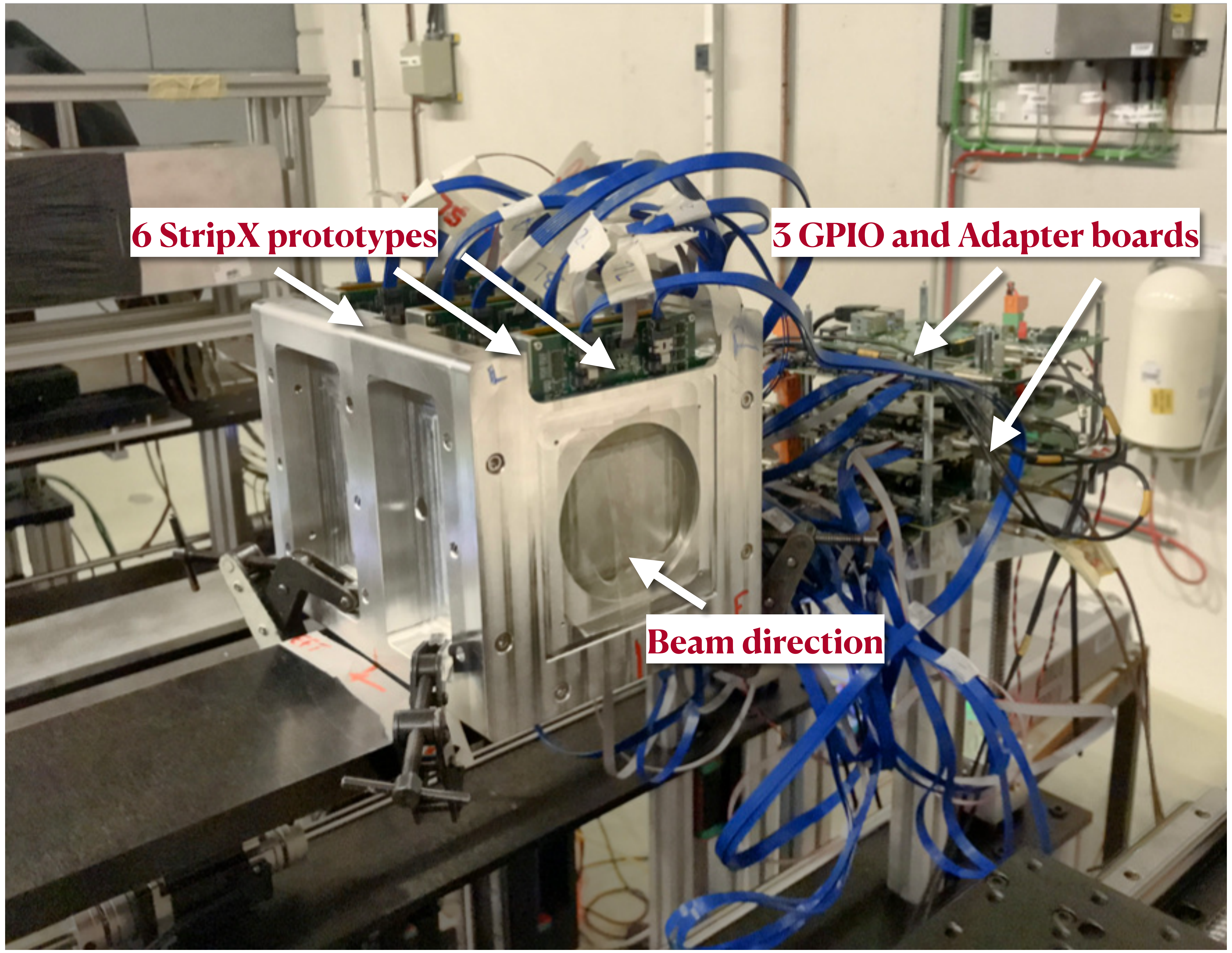




Strip X Beam Test in November 2021

T9 beam line (CERN, East Area)

- **Objectives**:
  - Test the performance of **6 StripX** prototypes
  - Test the DAQ capability to readout **6 StripX** boards
  - Perform runs with/without magnets installed.



StripX detectors inside the experimental area of T9 beam line.

Penetrating Particle Analyzer

Beam and DAQ Parameters

- Beam parameters:
  - Particles: π^-.
  - Momentum: **10 GeV/c.**
  - H/V dimensions: **~1.0 cm** FWHM.
  - Beam trigger in coinc. with **2 Cherenkov detectors** for better energy resolution

Beam axis

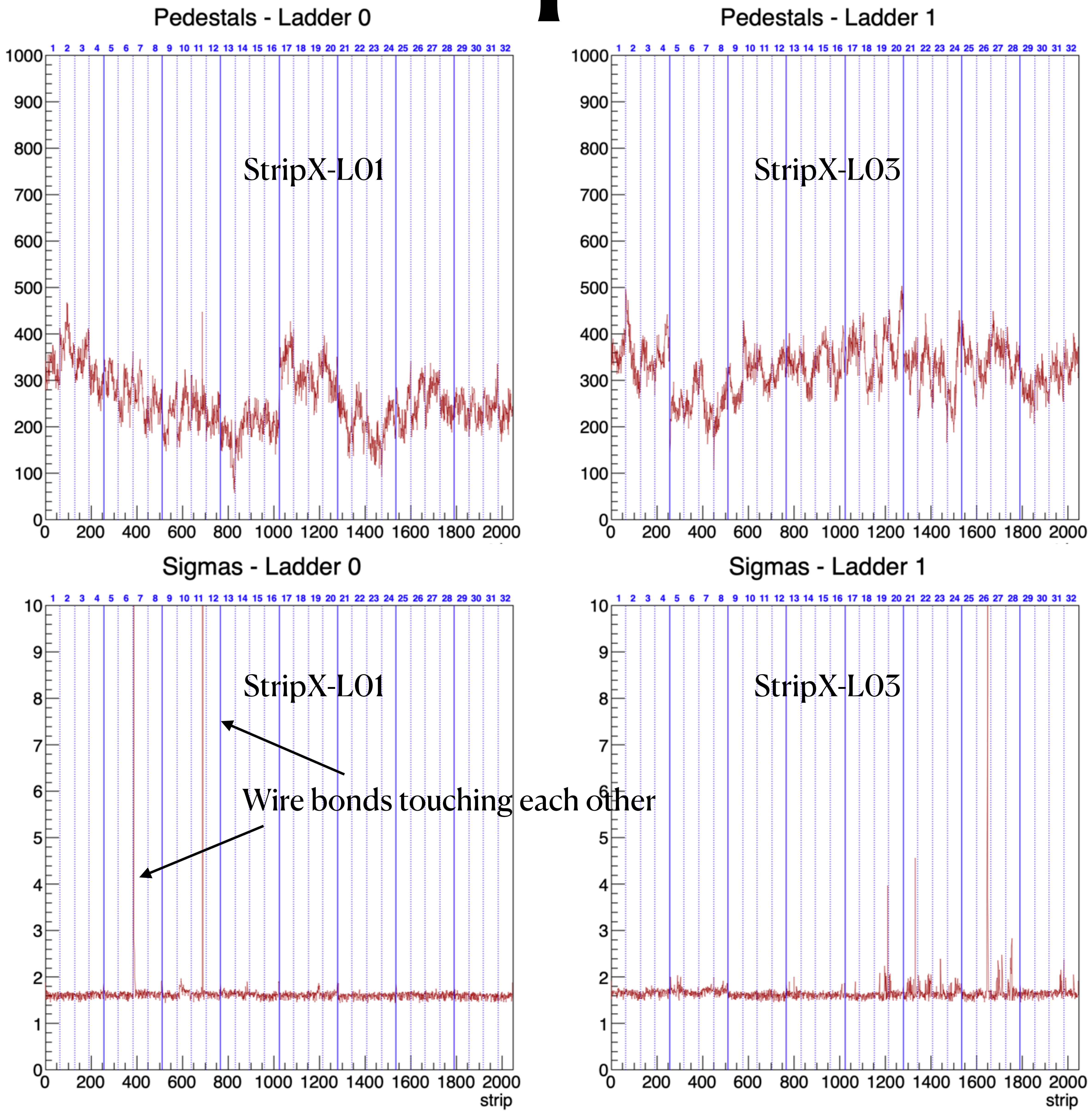
Boards: **0, 3, 5**

- DAQ configuration:
  - StripX boards bias voltage: **40 V**.
  - **6 StripX** boards read by **3 GPIO** boards and 3 Adapter boards connected to a PC through USB.
  - **GPIO software**: “socket” mode, controlled via a TCP connection.
  - **Visualisation** software: based on **ROOT**, controlling the GPIO software.
  - **Visualisation** software: starts a calibration, a normal DAQ, an offline analysis.

Penetrating Particle Analyzer

Board 0: StripX-L01 + StripX-L03

- Pedestals from a calibration run.
- Standard deviation of ADC values per channel from a calibration run (CN subtracted): **~1.5-2.5 ADC units**.

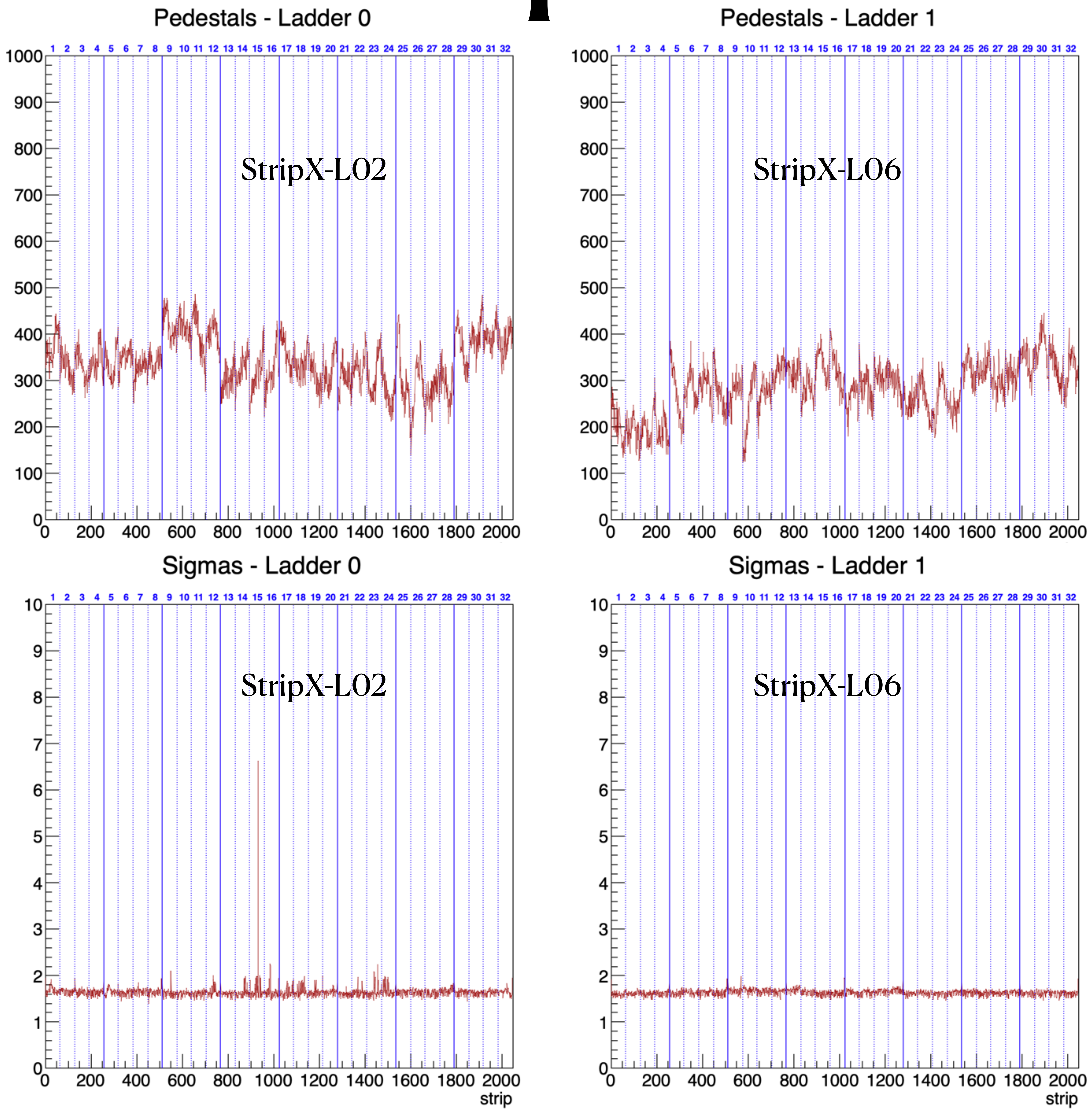


Penetrating Particle Analyzer

Board 3: StripX-L02+ StripX-L06

- Pedestals from a calibration run.

- Standard deviation of ADC values per channel from a calibration run (CN subtracted): **~1.5-2.5 ADC units**.



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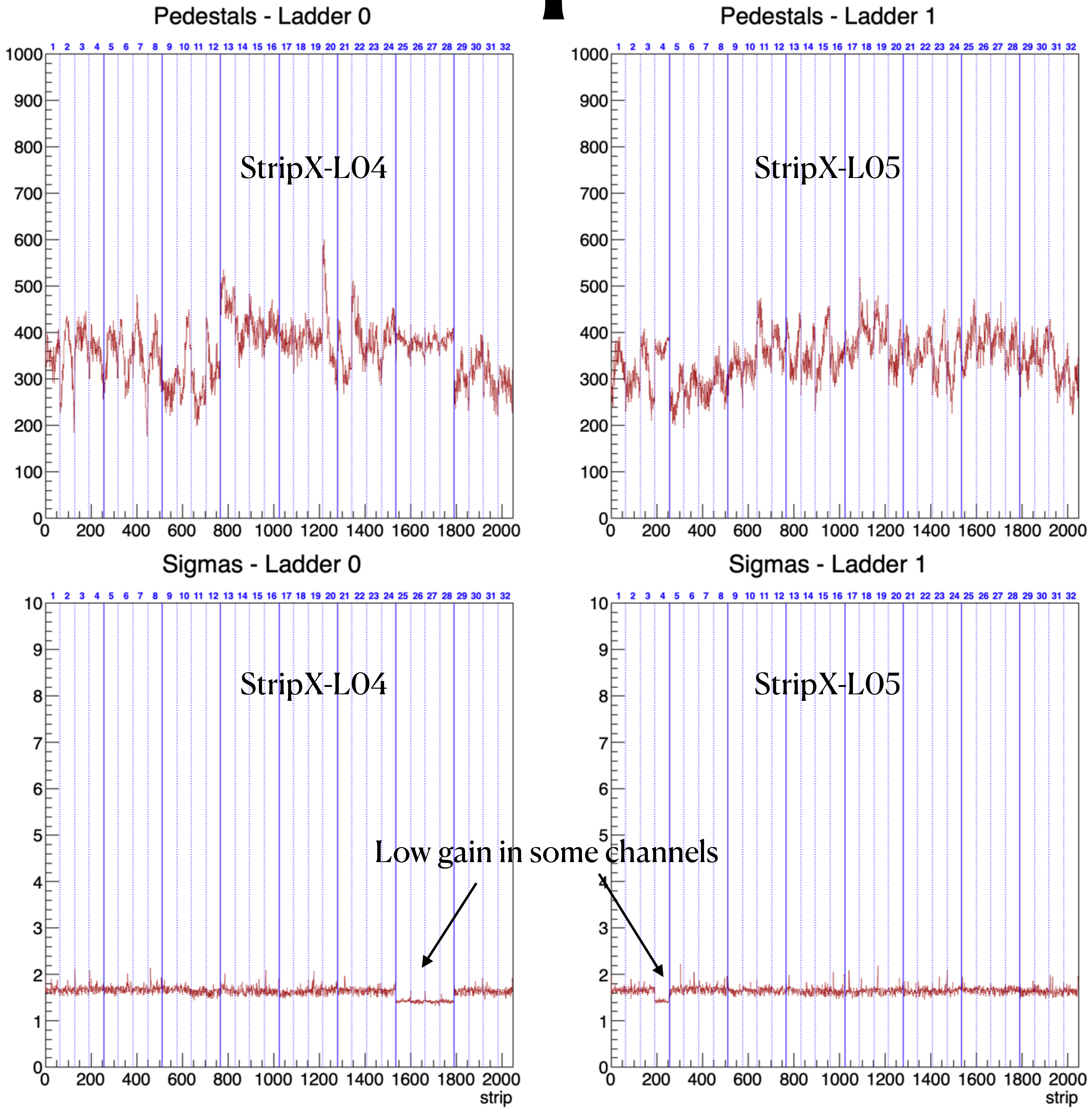
Board 5: StripX-L04 + StripX-L05

- Pedestals from a calibration run.
- Standard deviation of ADC values per channel from a calibration run (CN subtracted): **~1.5-2.5 ADC units**.



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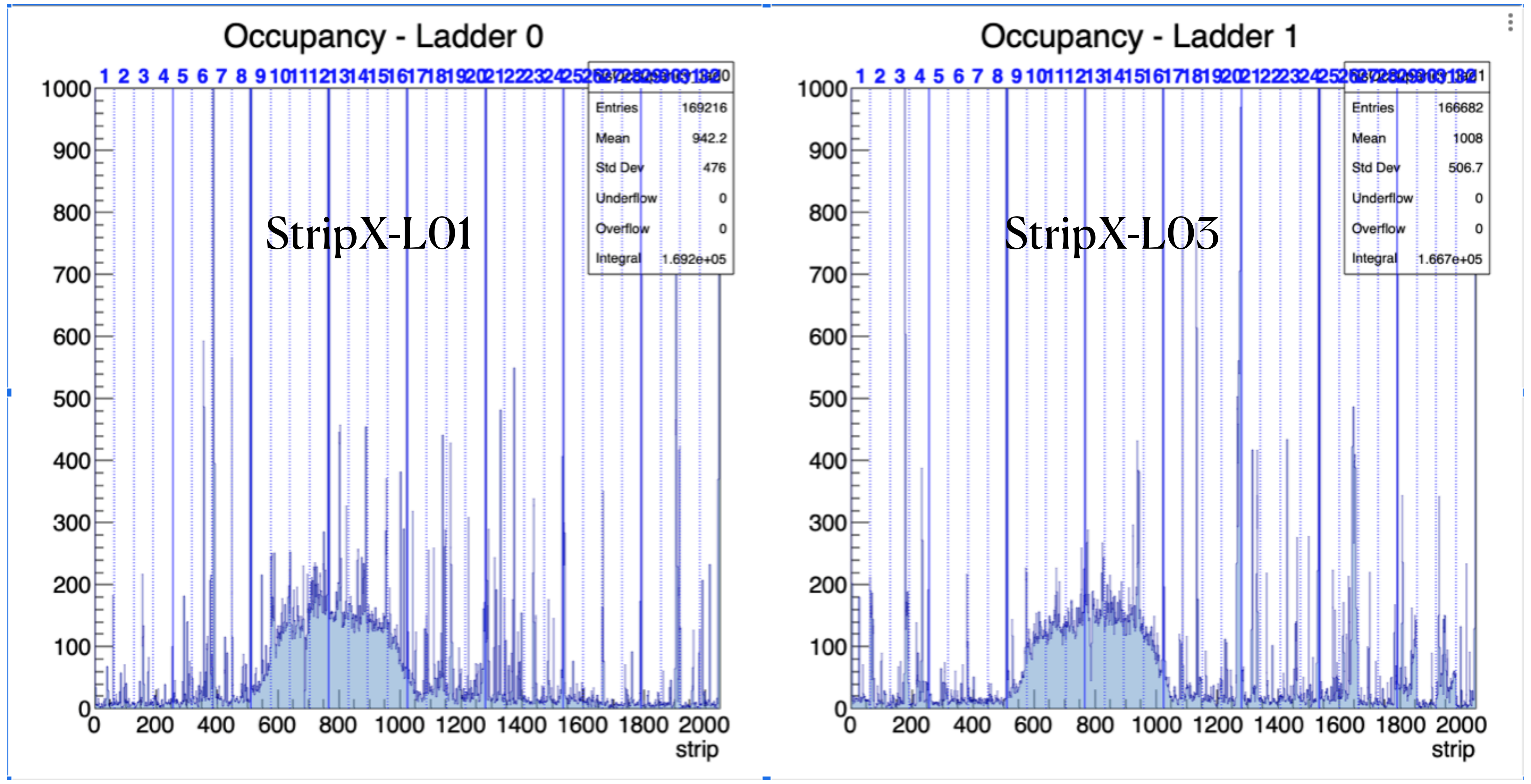
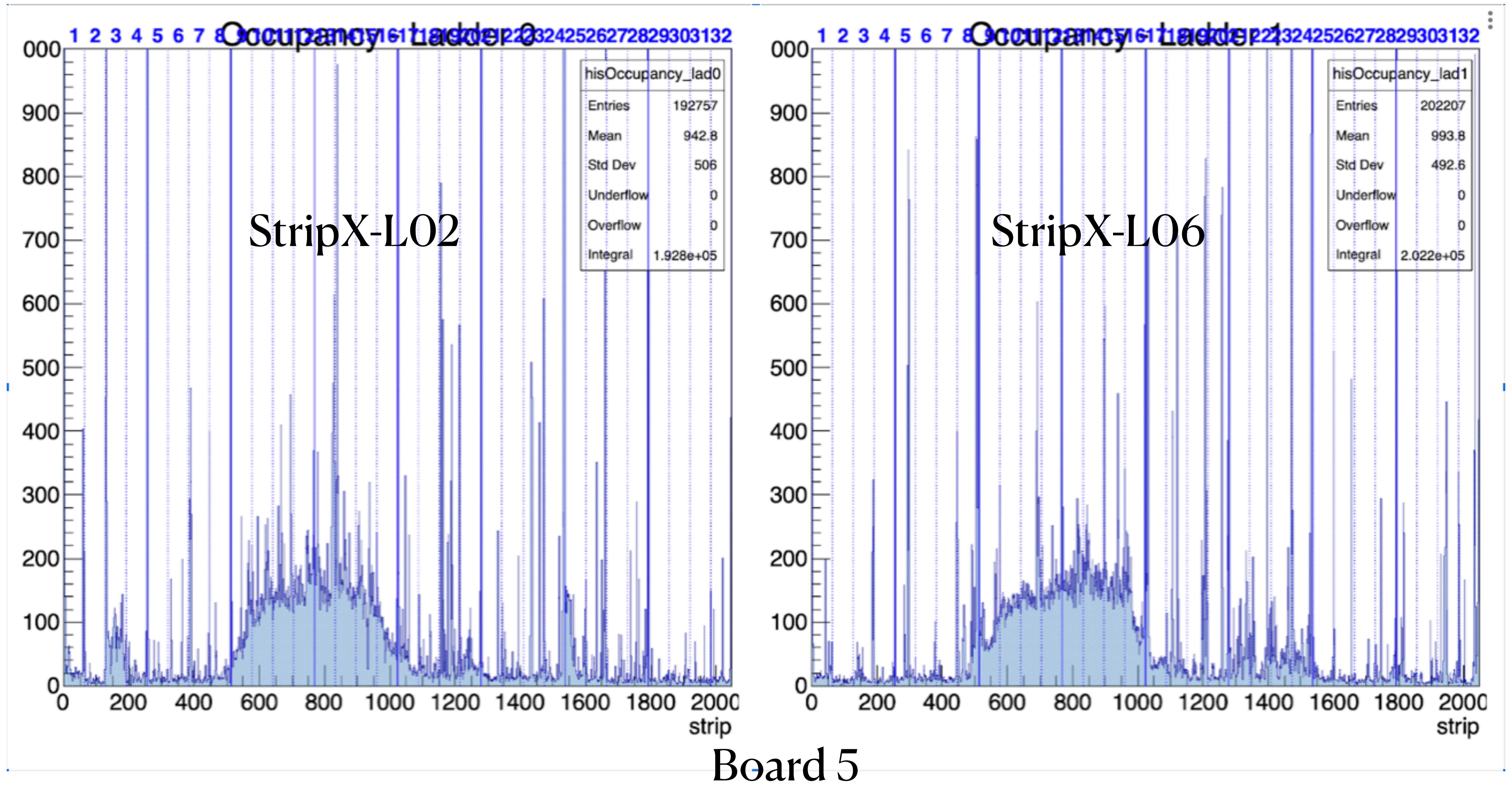
Channel Occupancies with Clusters

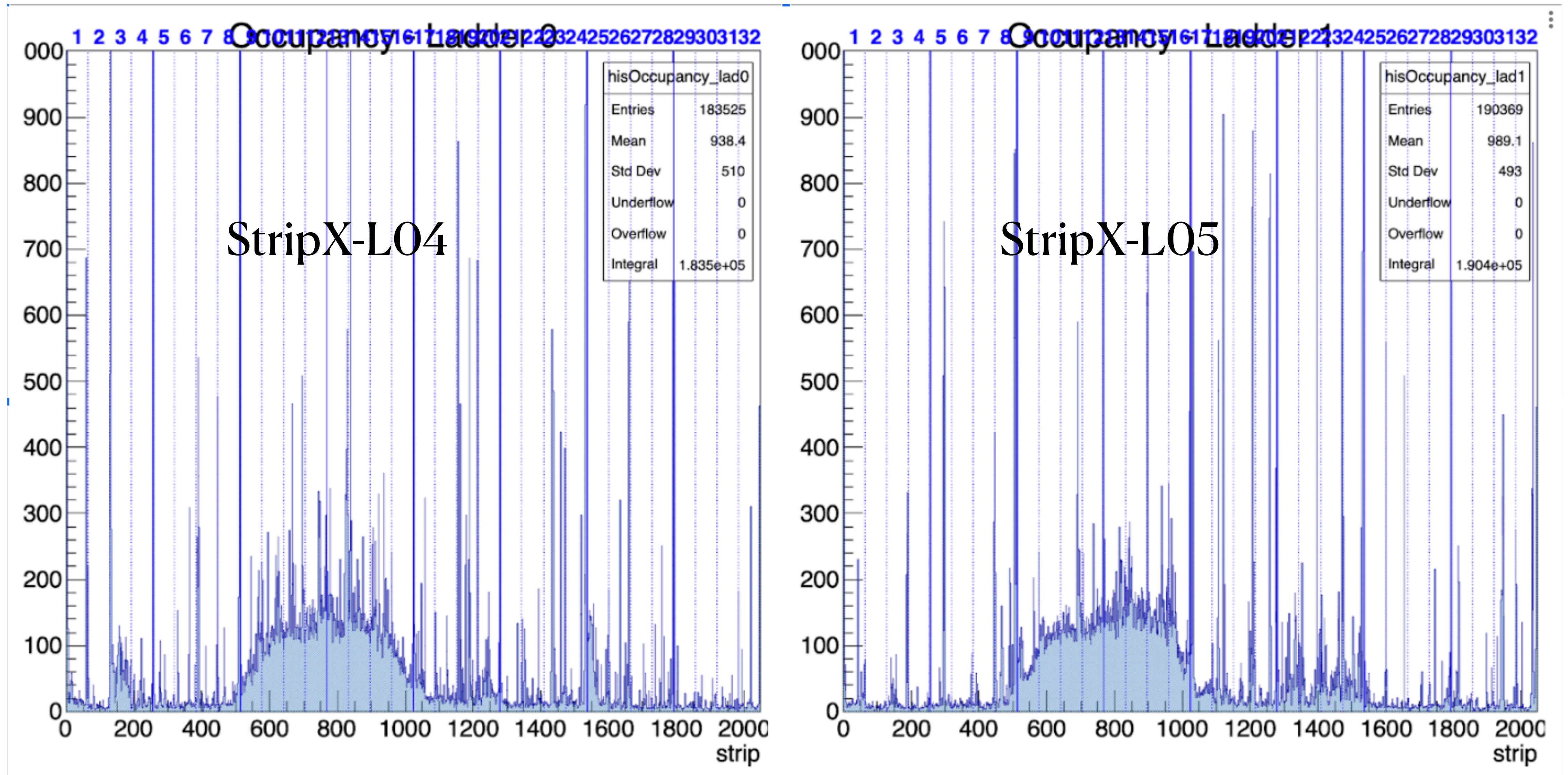
Board 0



Board 3



Board 5



- Clustering algorithm performed with settings:
  - High threshold: **4 SNR** (signal/noise ratio)
  - Low threshold: **1.5 SNR**

Tracks Fitting. Magnets NOT Installed

- Input: a synchronised ROOT file with clusters per event (CoGs, sizes, integrals, SNR distributions)

- Processing:

  - Linear χ^2 fit $Y_{fit} = Slp \cdot Z_{det} + Int_{z=0}$, where Slp - a track slope, $Int_{z=0}$ - an intercept of the track at the layer 0.

  - Only events with **1 cluster** in every layer are fitted.

- Performance metrics: χ^2/NDF, p-value, unbiased residuals per layer, RMS of unbiased residuals per track

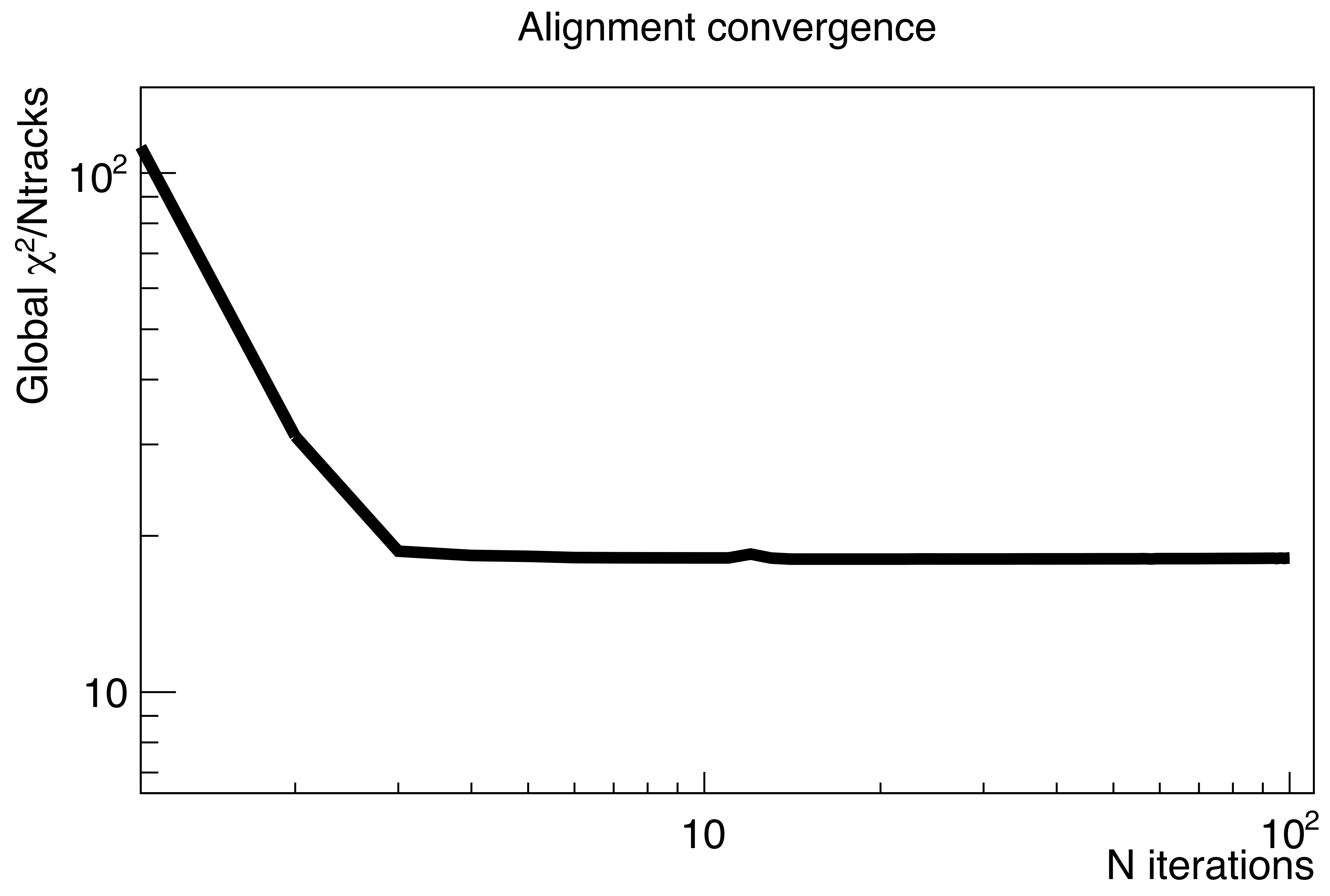
Gradient Descent Alignment

- Based on minimisation of a global
  $$\chi^2 = \sum_t \sum_p (Y_t^{fit} - Y_{t,p}^{hit})^2/\text{Ntracks}$$

- 18 parameters to vary:
  $$Y'_{CoG} = Y_{CoG} + \Delta_{Y,i} - Z_{det} \cdot \theta_{X,i},$$
  $$Z'_{det} = Z_{det} + \Delta_{Z,i} + Y_{CoG} \cdot \theta_{X,i}$$

- $\Delta_{Y,i}, \Delta_{Z,i}, \theta_{X,i}$ - shifts and a tilt around X of the i-th layer

- Perform gradient descent for N iterations:
  $\overrightarrow{x_N} = \overrightarrow{x_{N-1}} - \gamma_{N-1} \nabla \chi^2(\overrightarrow{x_{N-1}})$, $\overrightarrow{x_N}$ - vector of parameters, γ_{N-1} - step size

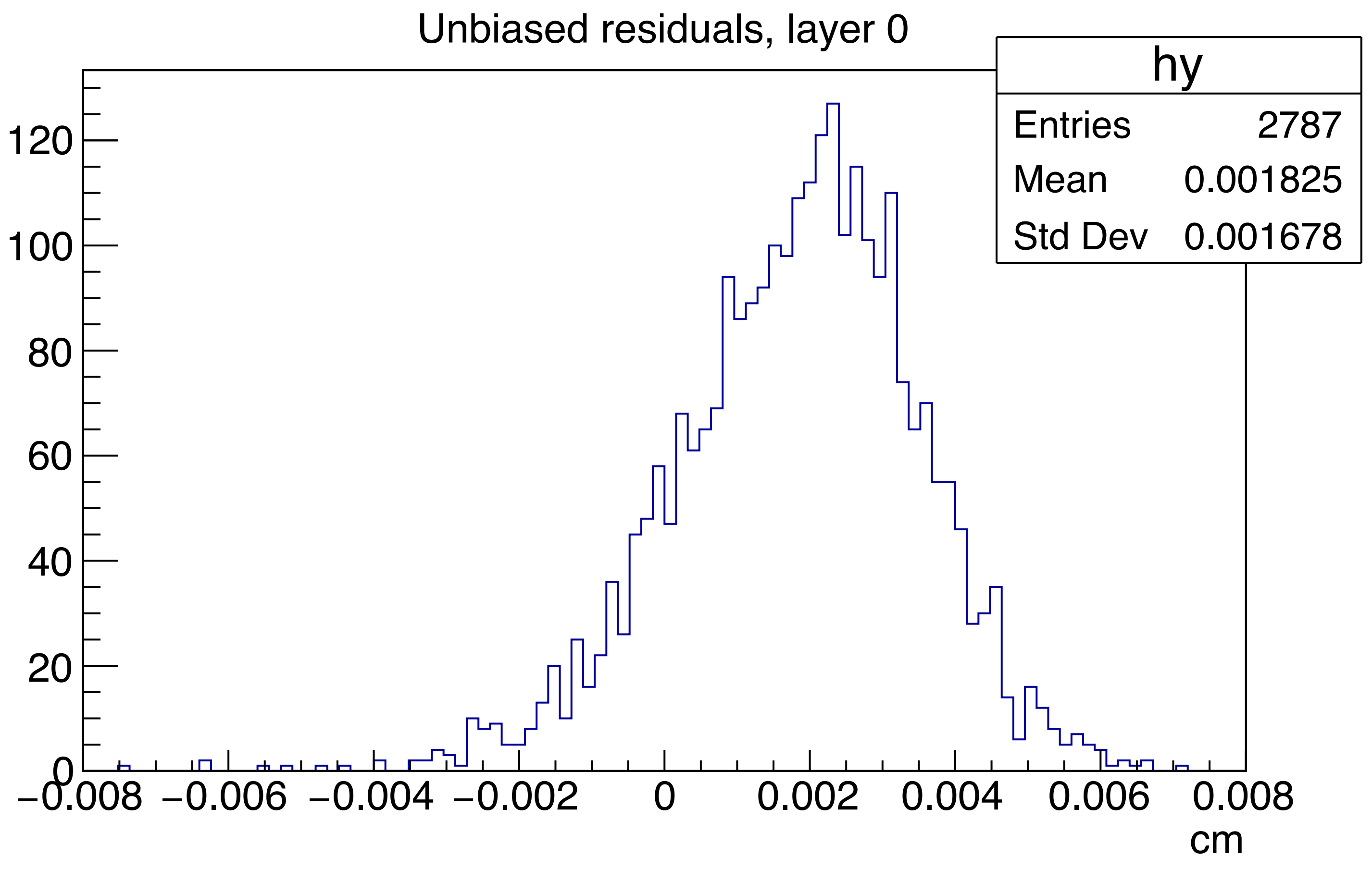


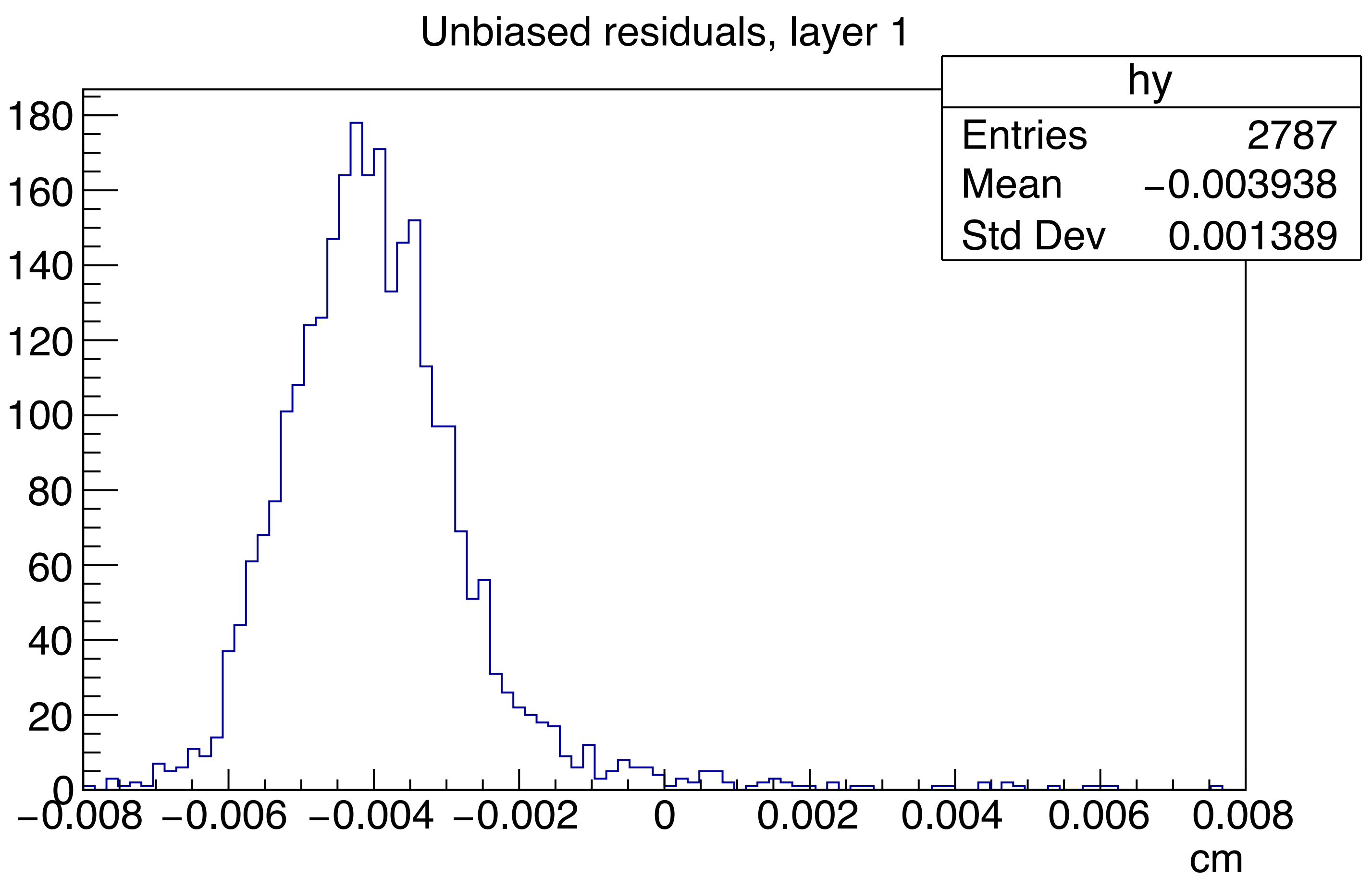
Converges after ~100 iterations!

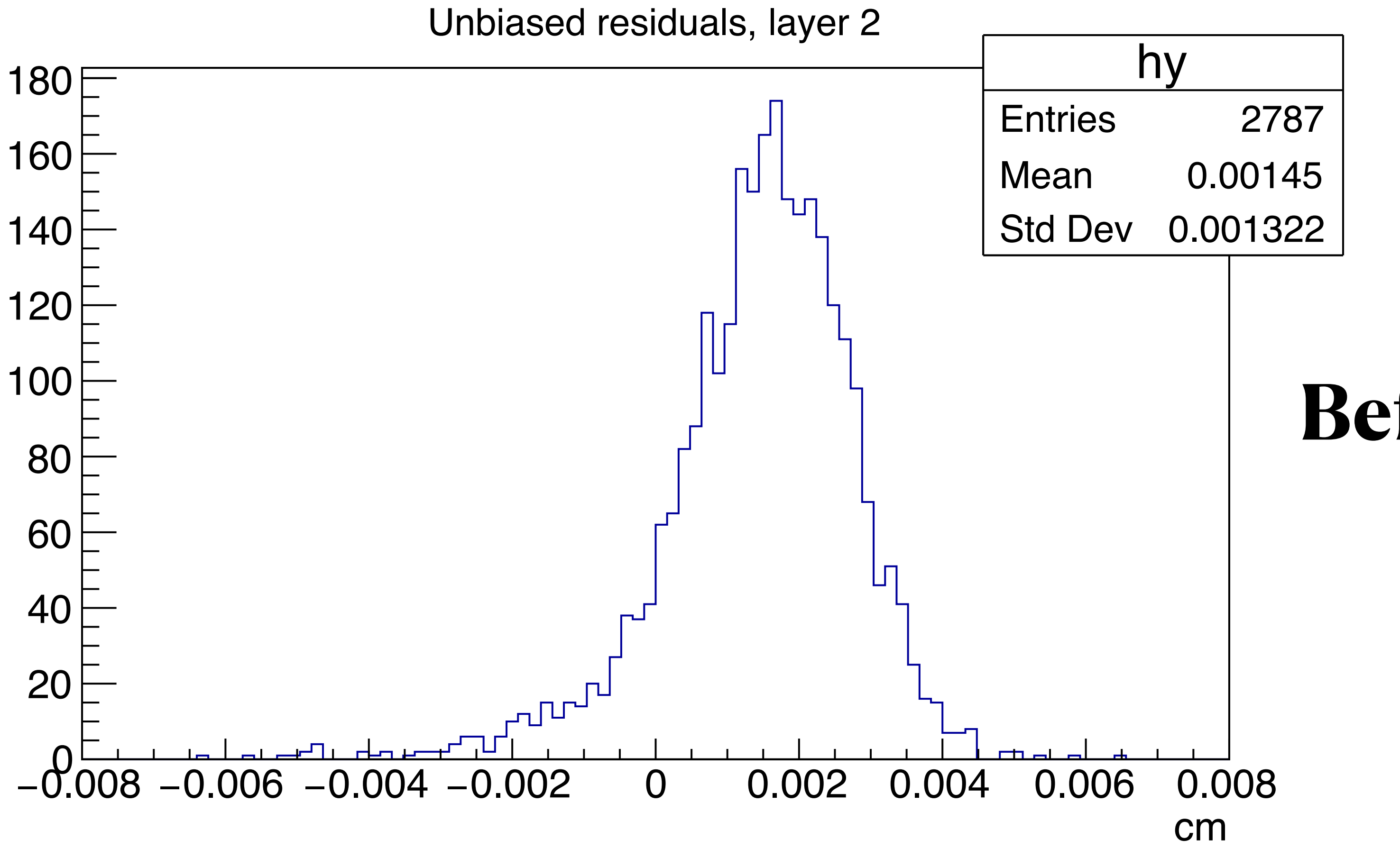
Unbiased residuals. Layers 0, 1, 2

$$\text{residual} = Y_{fit} - Y_{CoG}, \sigma_{12} = \sqrt{f \cdot \sigma_1^2 + (1-f) \cdot \sigma_2^2}$$

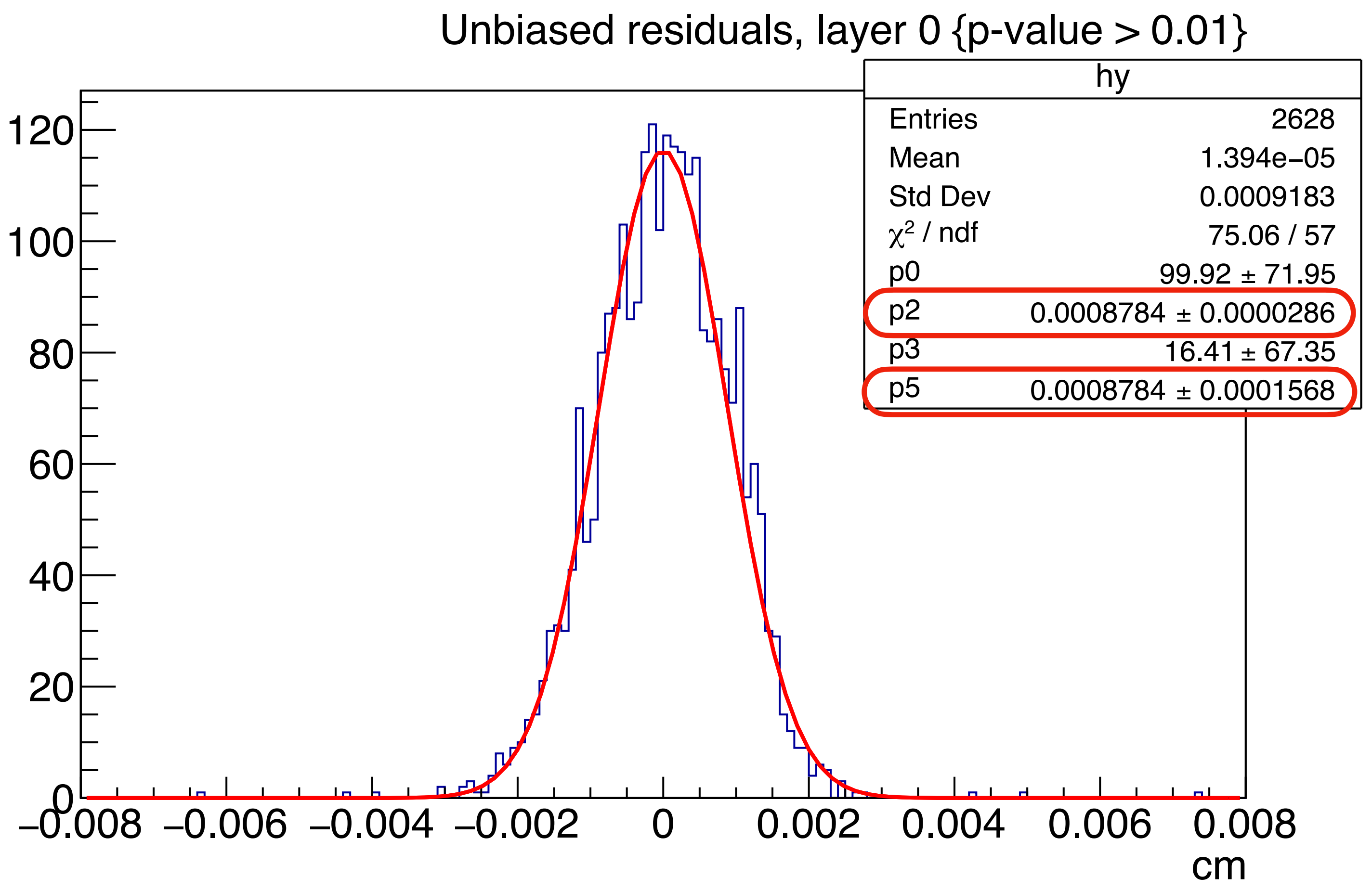
Before alignment

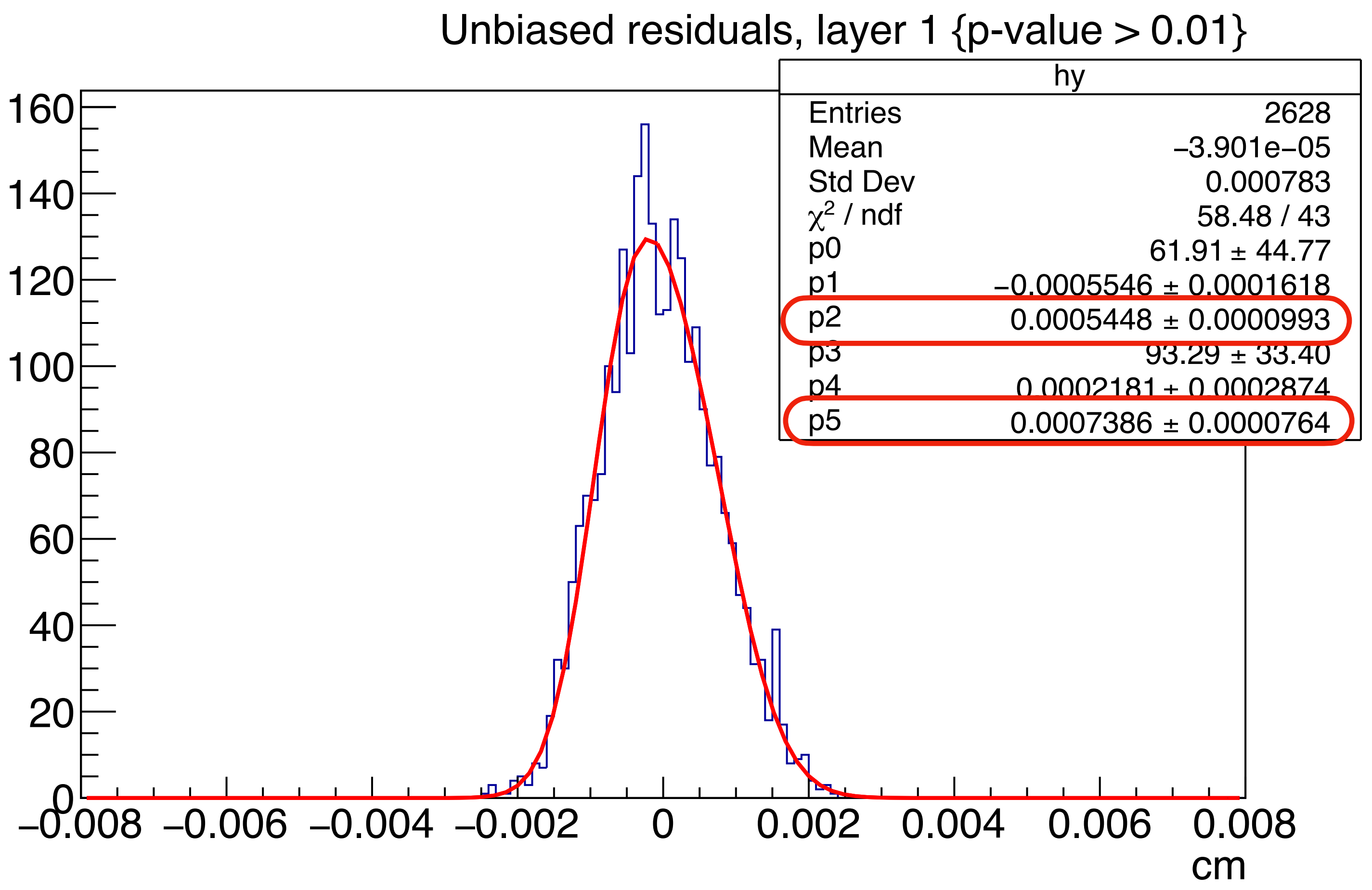


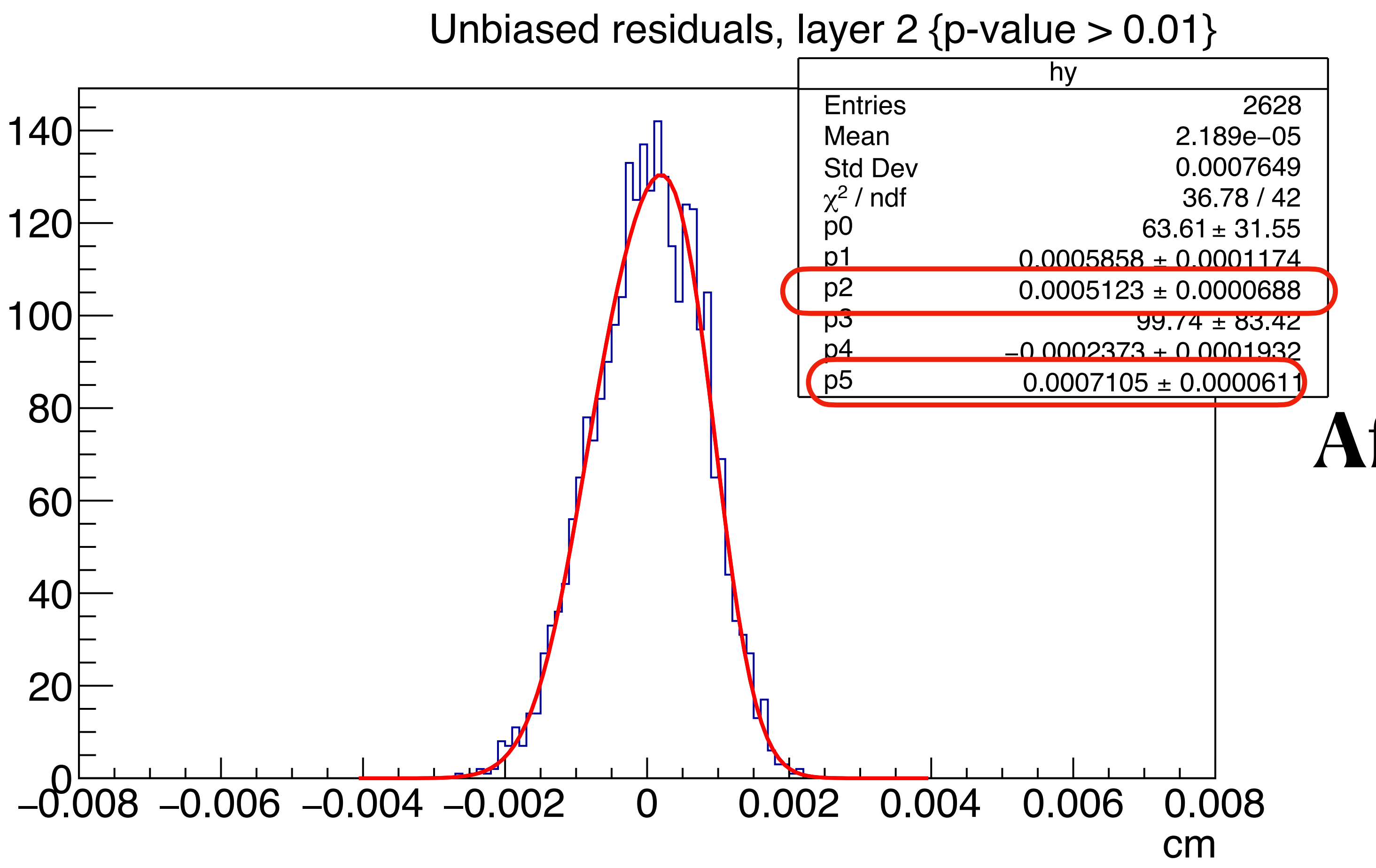




After alignment



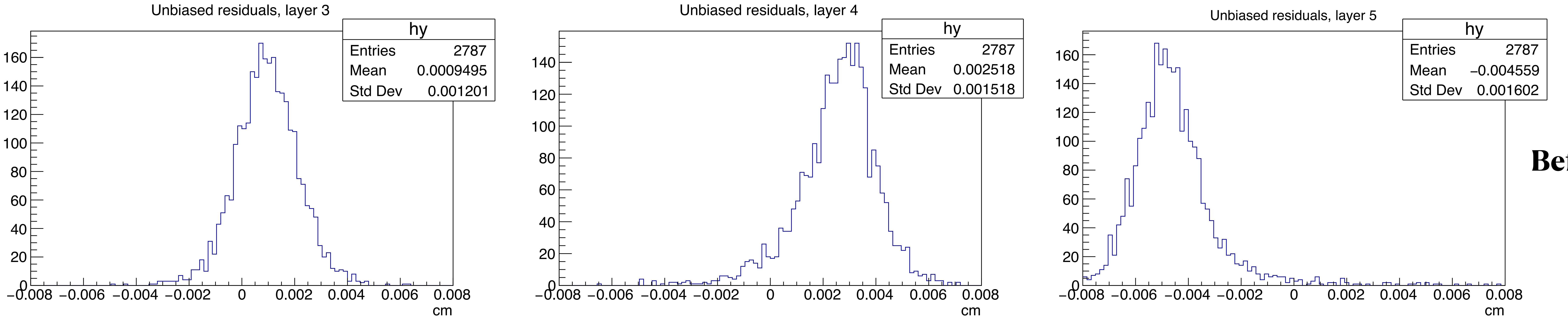




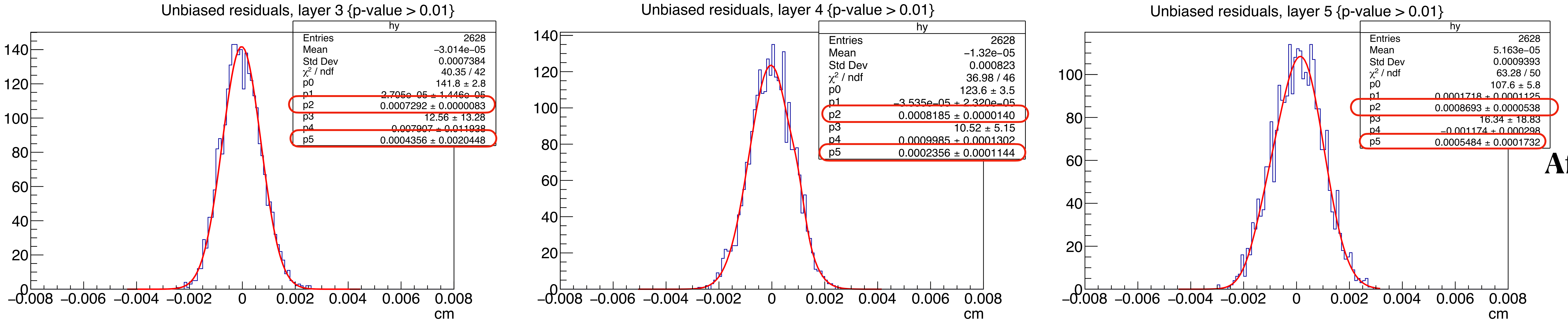
$\sigma_0 = 8.78 \pm 0.29\,\mu m$ $\sigma_1 = 6.68 \pm 0.86\,\mu m$ $\sigma_2 = 6.40 \pm 0.64\,\mu m$

Unbiased residuals. Layers 3, 4, 5

$$\text{residual} = Y_{fit} - Y_{CoG}, \sigma_{12} = \sqrt{f \cdot \sigma_1^2 + (1-f) \cdot \sigma_2^2}$$



Before alignment

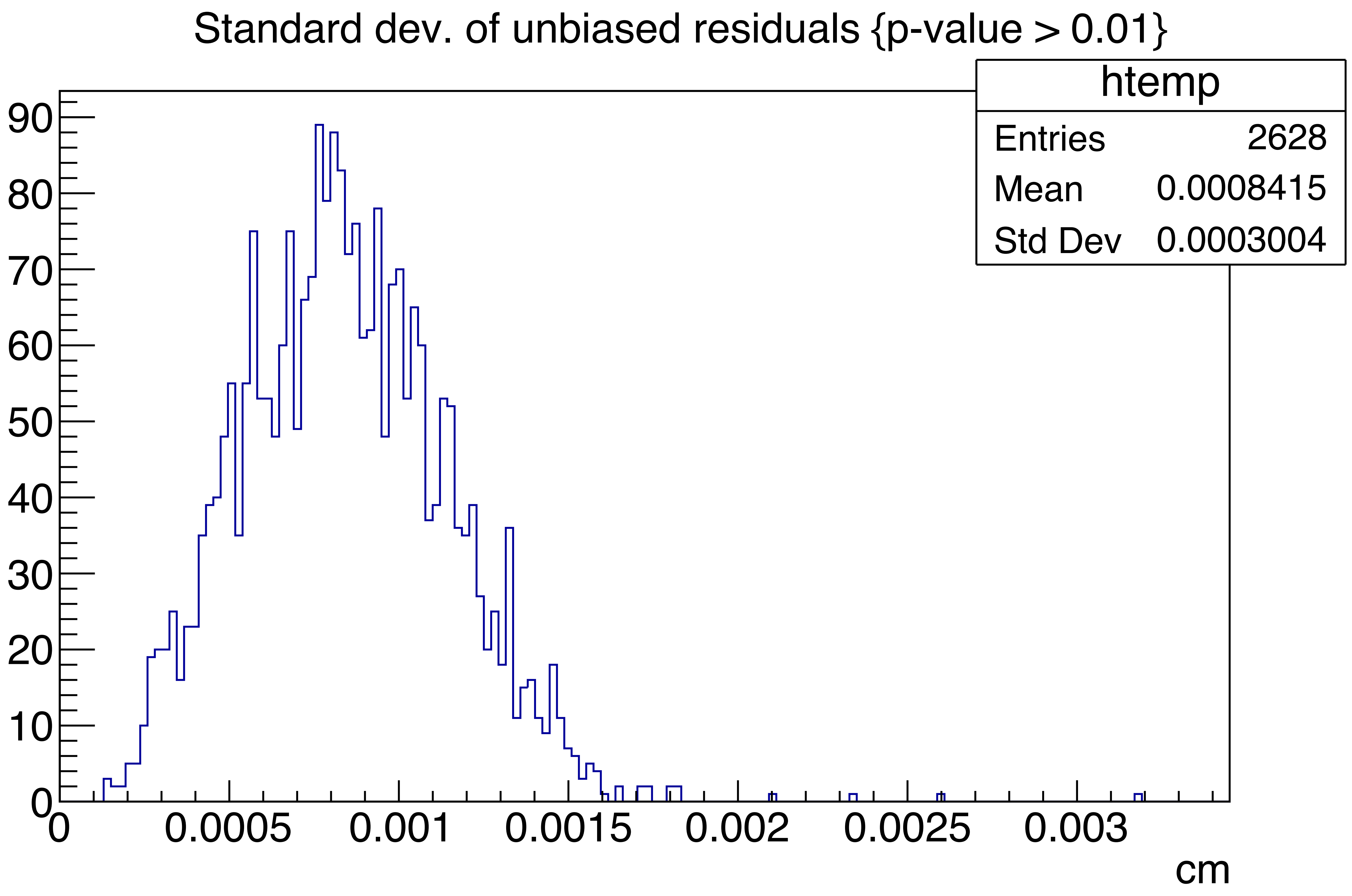


After alignment

$\sigma_3 = 6.86 \pm 0.63\,\mu m$ $\sigma_4 = 7.89 \pm 0.34\,\mu m$ $\sigma_5 = 8.34 \pm 0.81\,\mu m$

RMS of Unbiased Residuals per Track

After alignment



$\text{Mean} = 8.42 \pm 0.06\,\mu m$

Alignment parameters

Layer: 0

$\Delta_{Y,0}$: 0.026 um

$\Delta_{Z,0}$: -0.014 um

$\theta_{X,0}$: 2.773e-05

Layer: 1

$\Delta_{Y,1}$: -0.433 um

$\Delta_{Z,1}$: 0.016 um

$\theta_{X,1}$: -3.944e-04

Layer: 2

$\Delta_{Y,2}$: 2.56902 um

$\Delta_{Z,2}$: 2.950e-04 um

$\theta_{X,2}$: 2.346e-04

Layer: 3

$\Delta_{Y,3}$: -1.4312 um

$\Delta_{Z,3}$: 3.301e-03 um

$\theta_{X,3}$: 1.313e-04

Layer: 4

$\Delta_{Y,4}$: 0.012 um

$\Delta_{Z,4}$: -0.008 um

$\theta_{X,4}$: -1.716e-05

Layer: 5

$\Delta_{Y,5}$: -0.394 um

$\Delta_{Z,5}$: 2.869e-03 um

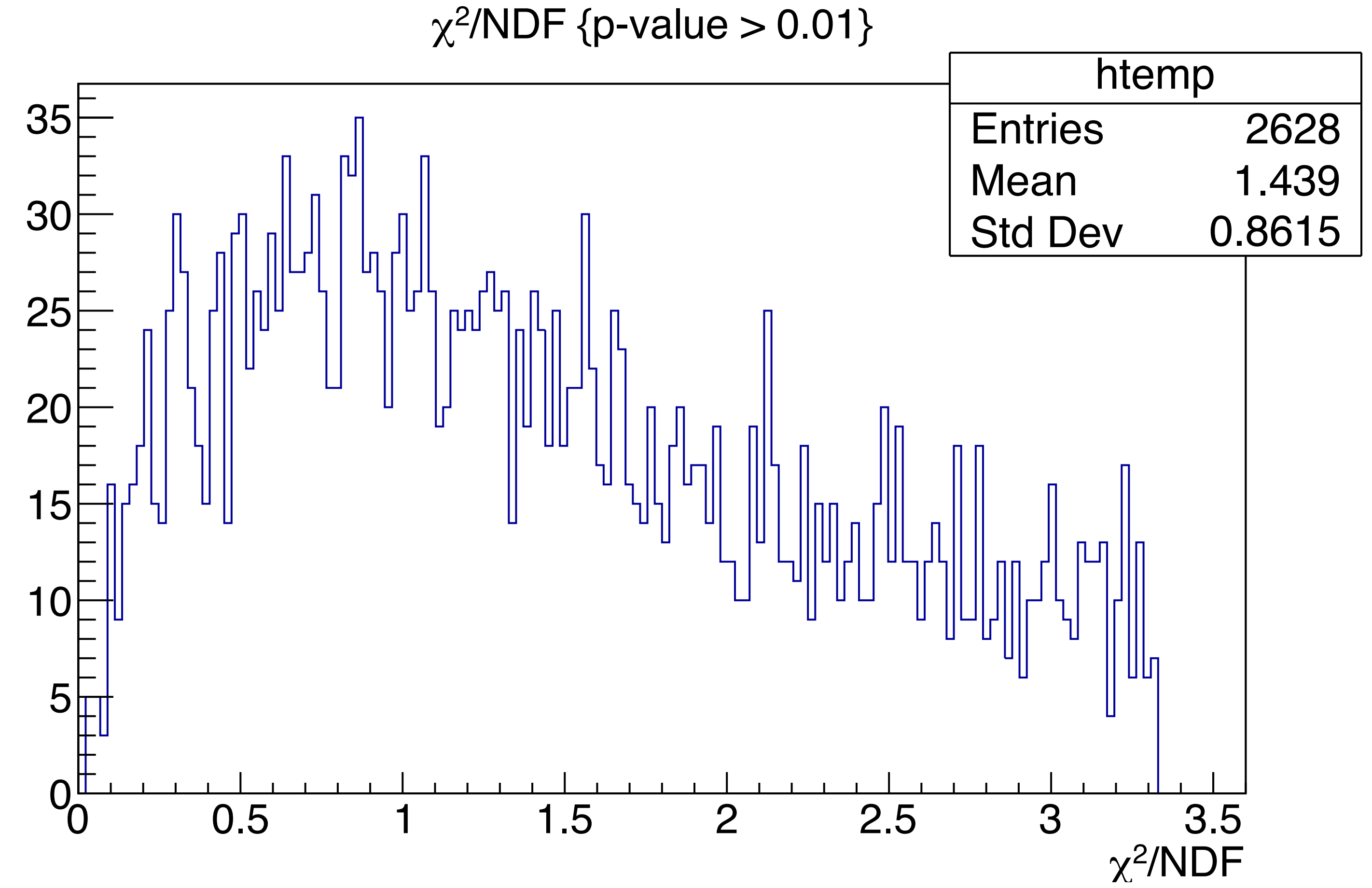
$\theta_{X,5}$: 4.306e-04

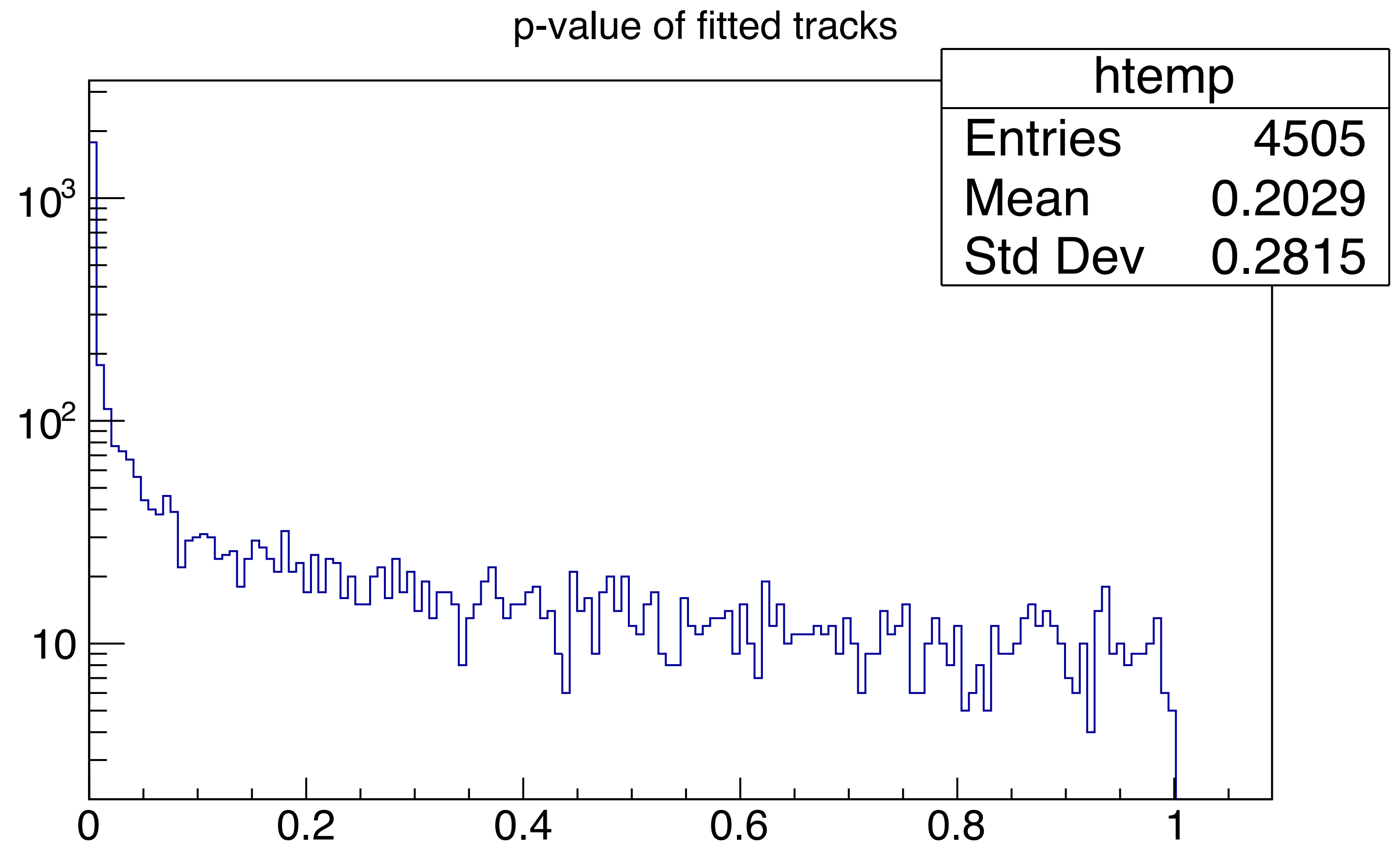
Layer: 0 - upstream **Layer: 5 - downstream**

Better Errors and MCS Contribution

- Corrected measurement errors:
  - If cluster size $== 1$: $\sigma_Y = p/\sqrt{12}$
  - Else: $\sigma_Y = \alpha \cdot p/\text{SNR}$
  - SNR - signal/noise averaged over the cluster
  - $\alpha \lessapprox \sqrt{1.5 + \text{clustSize}}^{1}$

After alignment





Scattering angle:

$$\theta_0 = \frac{13.6\text{MeV}}{p\beta c} z_c \sqrt{\frac{x_{det}}{X_{Si}}} \left[1 + 0.038 ln\left(\frac{x_{det}}{X_{Si}}\right)\right]$$

MCS contribution per layer for 10 GeV/c pions

	σ_{MCS}, μm
Layer 0:	0
Layer 1:	0.75
Layer 2:	5.30
Layer 3:	6.41
Layer 4:	12.30
Layer 5:	13.74

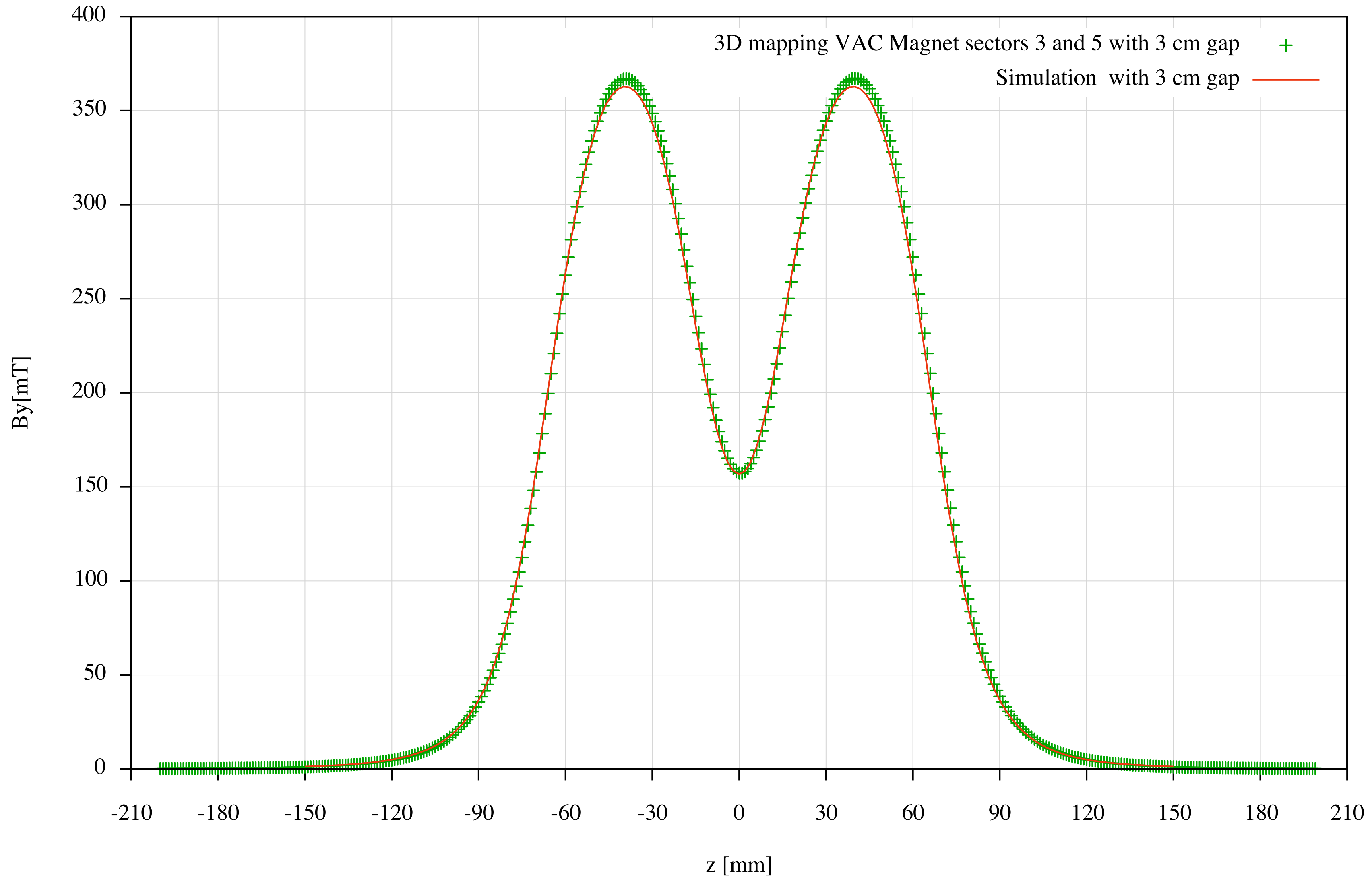
P-values are ≈flat.

$\chi^2/NDF \rightarrow 1$

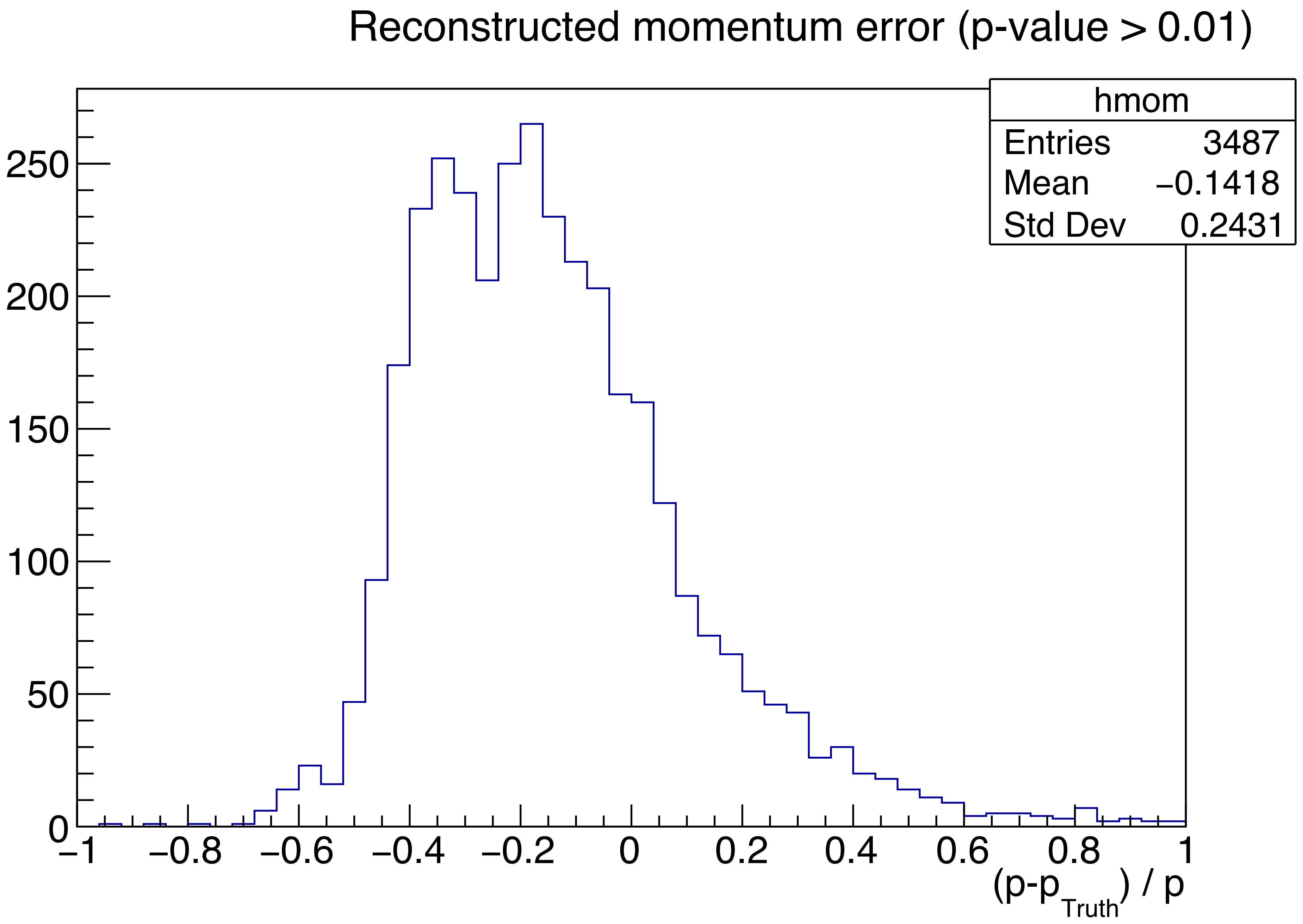
[1] : V. Radeka and R.A. Boie, Nucl. Instr. and Meth. 178 (1980) 543

Tracks Reconstruction Modifications

- Implementation of a **realistic** magnetic field map
- Adding **Kalman filter** based on GENFIT package for tracks fitting



Magnetic field map used for tracks reconstruction



Preliminary (!) results of the momentum resolution for 10 GeV/c π^-.
The tracks displacement due to bending is of the order of a few channels on the last station

Conclusion and Next steps

- **6 StripX layers** are working together producing meaningful data.
- Minimum sigma of the coordinate residuals: $6.40 \pm 0.64\ \mu$m for a middle layer
- Curved tracks reconstructed for beam test data. ~24 % momentum resolution achieved (preliminary!)

- Continue data taking using cosmic rays in our lab.
- Add StripY and ToF detectors to the current prototype.
- Prepare for the next beamtests in 2022.