13th Beam Telescopes and Test Beams Workshop

Results of test-beam characterization of babyMOSS for the ALICE ITS3 upgrade

Caterina Pantouvakis[a,b]

on behalf of the ALICE Collaboration

[a] Università degli Studi di Padova, [b] INFN Sezione di Padova

Outline

1. Introduction: the ALICE ITS3 upgrade and the first stitched prototypes

2. Test beam overview: experimental setup, DUTs and measurements

3. Test beam data analysis

    1. Threshold scan and fake hit rate scan measurements
    2. Corryvreckan analysis workflow:
        - Initial steps: geometry definition, ROI, noisy pixel masking
        - Tracking and alignment
        - DUT results: efficiency and spatial resolution

4. Discussion of results

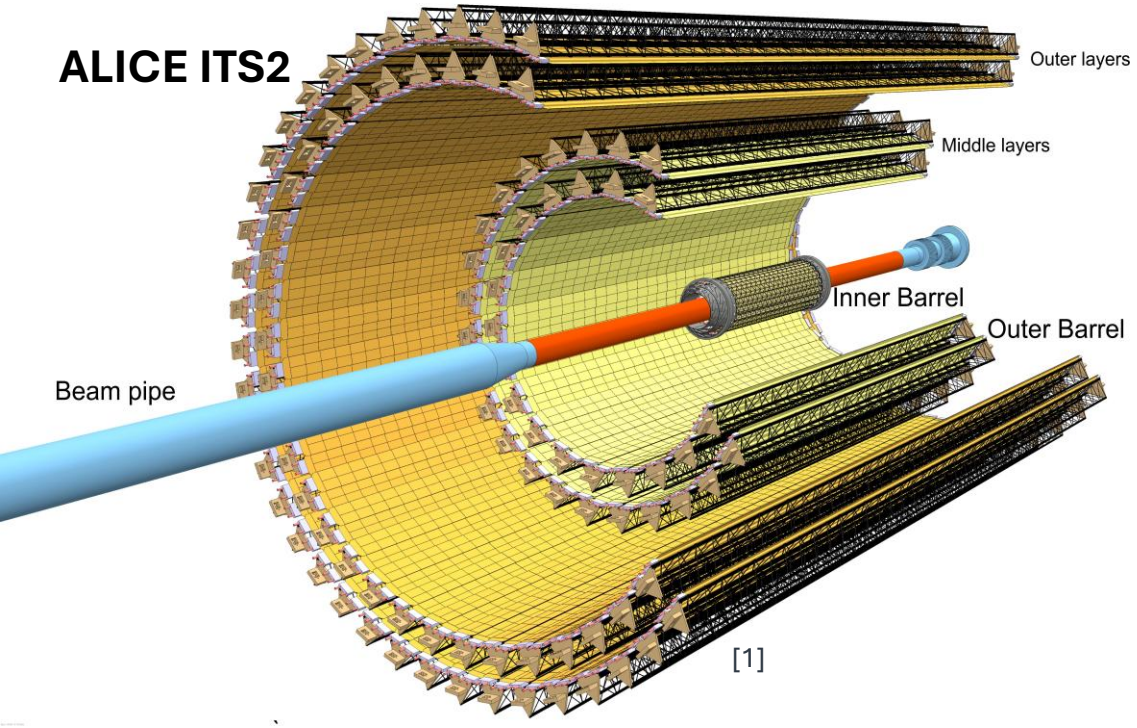
5. Summary

ALICE ITS2

The current tracking system of the ALICE experiment for charge particle tracking and vertex reconstruction is the Inner Tracking System (**ITS2**), installed during the LHC Long Shutdown 2.

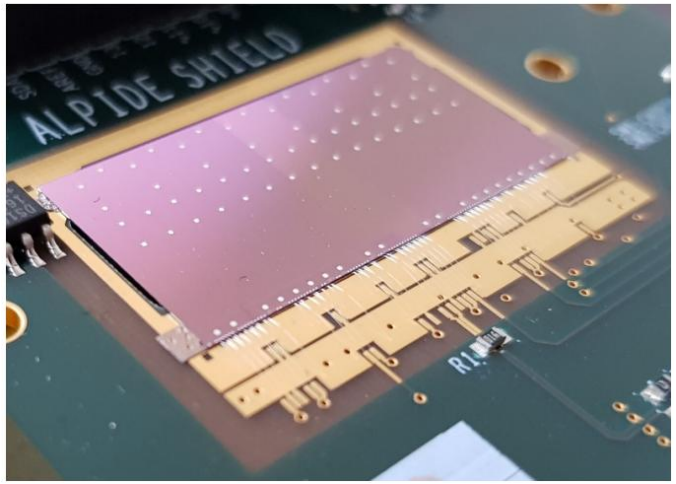
With a covered area of 10 m^2 and 12.5 Gpixels, **ITS2** is the **largest scale implementation of Monolithic Active Pixels Sensors (MAPS)** in HEP experiments.
All layers are equipped with the **ALPIDE** chip, based on 180 nm CMOS technology, with a size of 15 × 30 mm^2 and a pixel size of 29.24 × 26.88 μm^2.

ALICE ITS2



[1]

ALPIDE



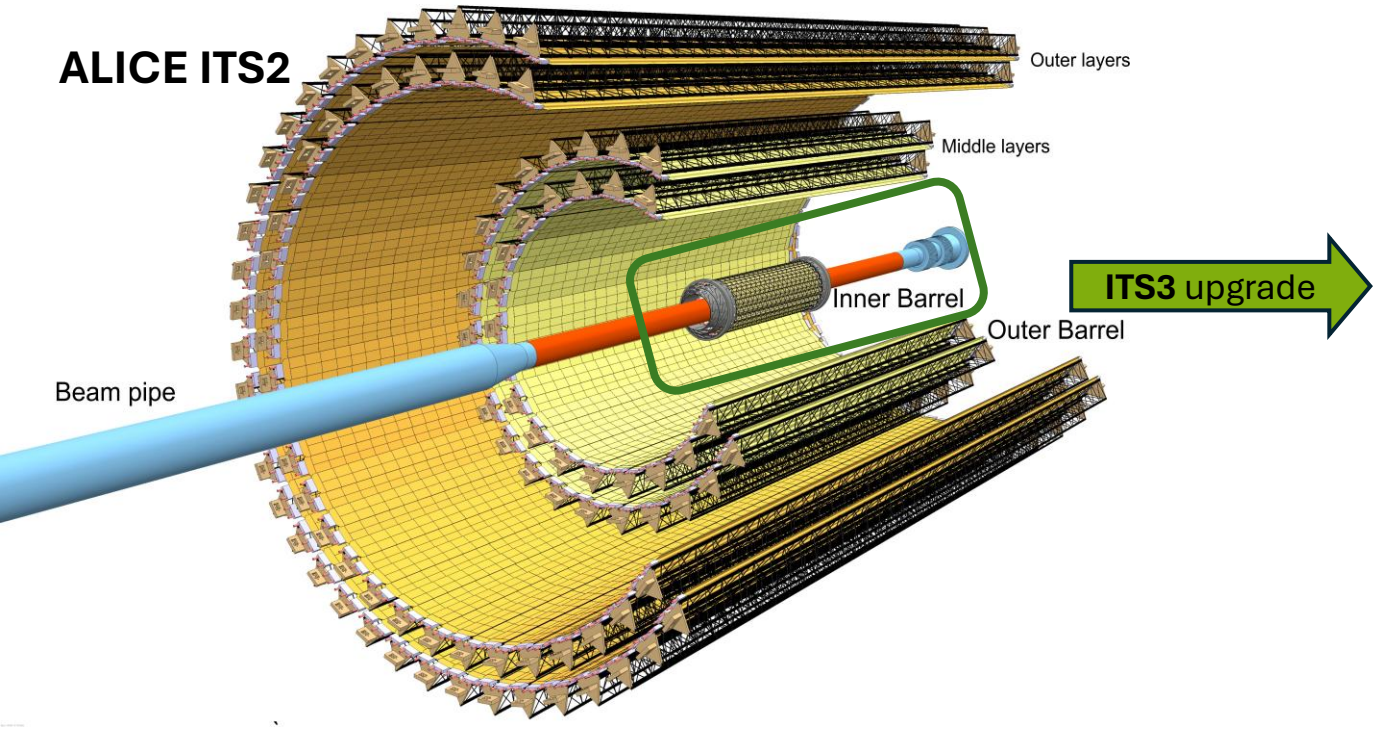
[2]

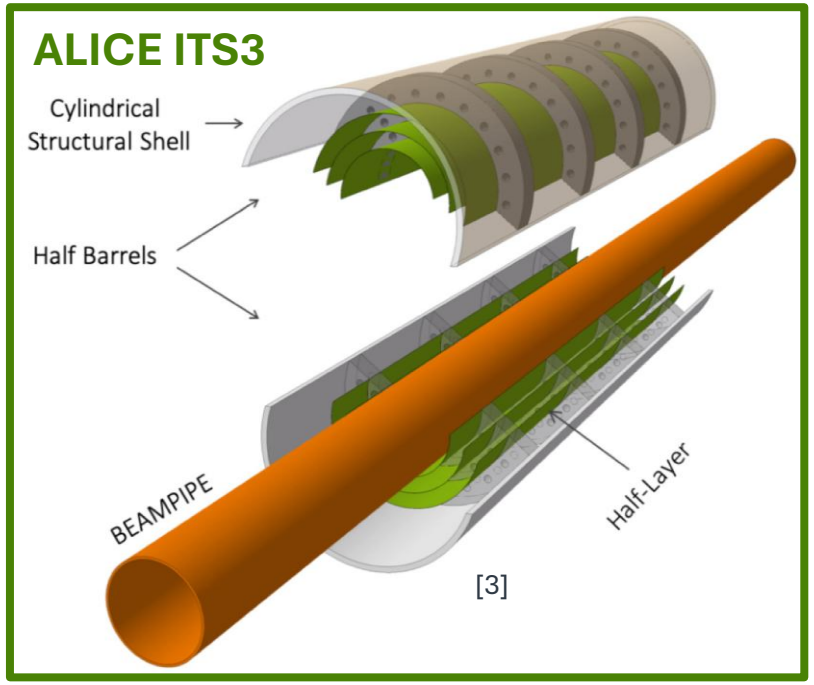
ALICE ITS3 upgrade

In the next LHC Long Shutdown 3, the three innermost layers of the ITS2 will be replaced by the ITS3 to further improve the impact parameter resolution especially at low p_T.
ITS3 will be made of **ultra-light wafer-scale stitched MAPS bent to cylindrical shape.**

Sensor R&D:

- Pixel design and process optimization in 65 nm CMOS technology
- Stitching to get wafer-scale sensors → one half layer will consist of one single MAPS sensor
- Bending → material budget/layer: 0.09% X_0

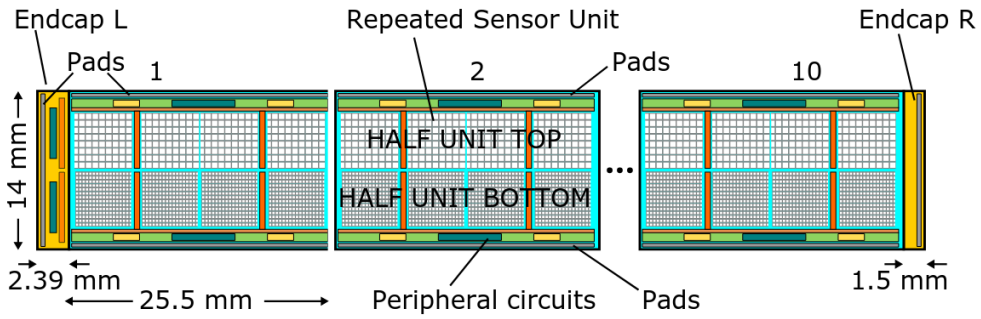


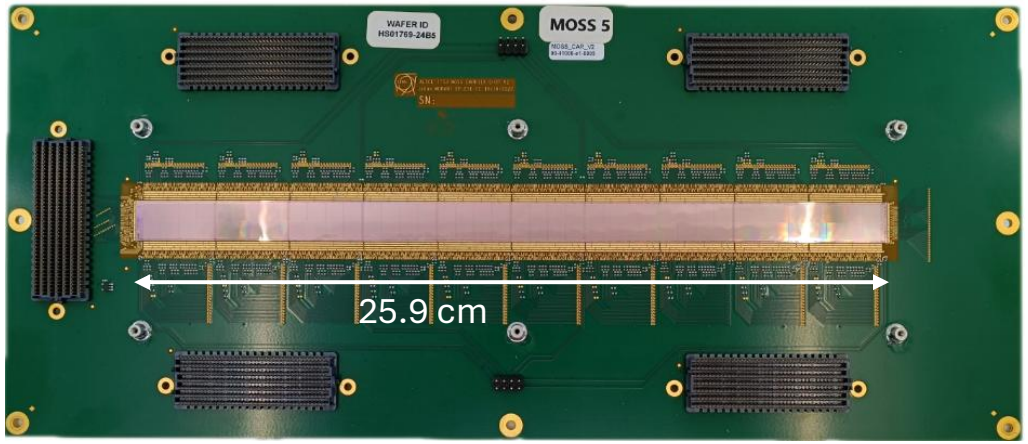


Stitched prototypes for the ITS3

MOSS

One of the two **large stitched sensor ASICs**, designed and manufactured in the first Engineering Run (ER1), is the MOnolithic Stitched Sensor (MOSS).
It is made of 10 Repeated Sensor Units (RSUs) and two end-cap regions.





babyMOSS

Smaller chips, with only one RSU pixel array, were included in the wafer map for characterization and irradiation studies.

The **RSU** is divided in **2 Half-Units (HUs)** with 4 regions each.

Top HU: **22.5 μm** pitch

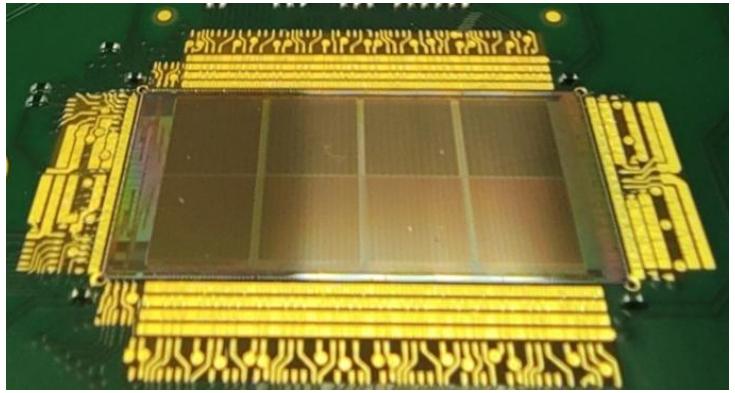
Bottom HU: **18 μm** pitch

Front end electronics flavours

	Standard	Larger input transistor	Larger discriminator input transistor	Larger common-source transistor
	Standard	Standard	Standard	Slightly different layout

14 mm

30 mm



[4]

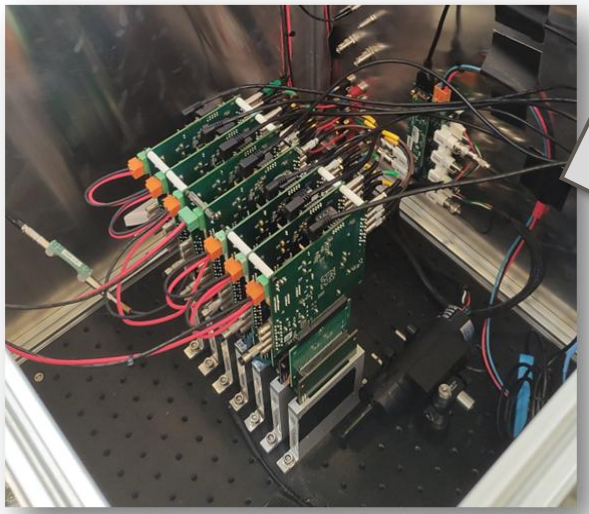
Test beam overview

First ER1 prototypes became available in Summer 2023. Since then, a long and extensive testing campaign on ER1 prototypes is going on, both with laboratory and test beam measurements.

Goal: Evaluation of the sensor performance, before and after irradiation, with respect to the ITS3 requirements.

CERN @ PS T10 (September 2024) Test Beam

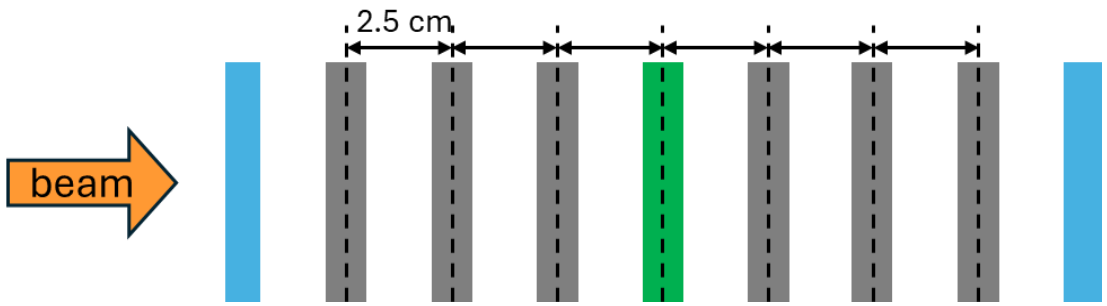
- 10 GeV π^- beam
- EUDAQ2-based acquisition system [5]
- babyMOSS telescope
- 3 babyMOSS tested as Device Under Test (DUT)



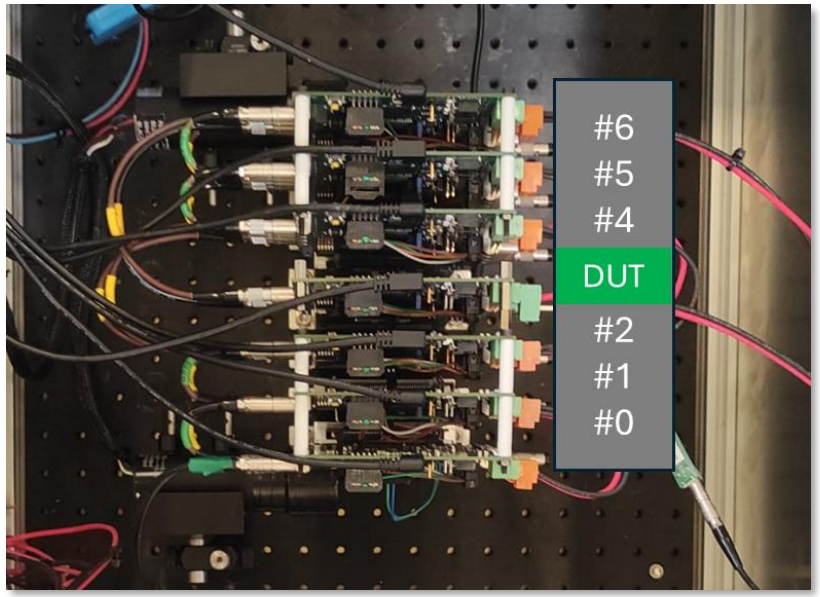
Test beam: telescope and DUTs

The telescope is fully constituted of babyMOSS chips, readout with the MOSS-RAISER DAQ system.

- 6 **babyMOSS tracking planes**
- 2 **scintillators** coupled to PMTs to generate trigger signal
- Trigger logic based on TRG/BSY chain
- No control on temperature during data acquisition



Details on babyMOSS telescope in [I. Panasenko's talk]



DUT 1: babyMOSS-2_1_W22C7
Non irradiated

- Threshold scan (region by region)
  - Common threshold scan

DUT 2: babyMOSS-2_2_W02F4
10^{13} 1 MeV n_{eq}/cm^2

- Threshold scan (region by region)

DUT 3: babyMOSS-3_3_W02F4
10^{13} 1 MeV n_{eq}/cm^2

- Threshold scan in parallel (region 0+2 and 1+3)

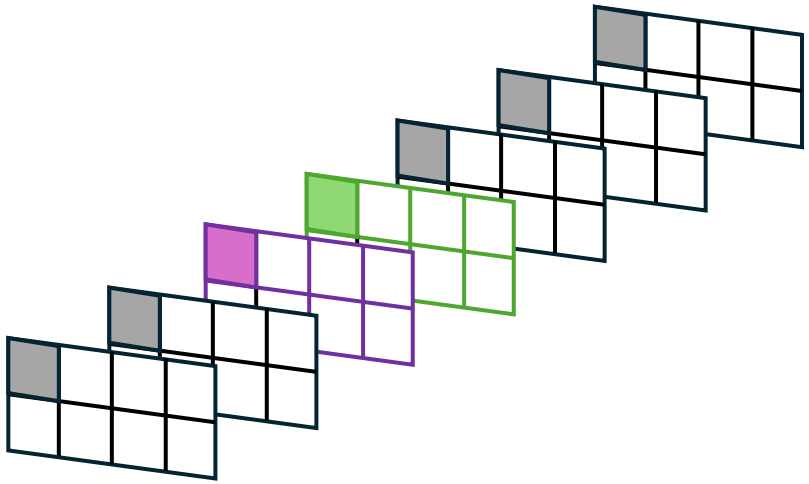
10^{13} 1 MeV n_{eq}/cm^2 is the expected ITS3 radiation level (NIEL)

Test beam analysis flow with Corryvreckan

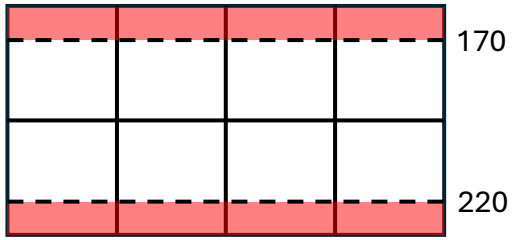
Data analysis is carried out using the **Corryvreckan** [6] software for test beam data analysis

1 Geometry definition

- Geometry definition of both tracking planes and DUT: analysis is done **region-by-region** and plane 2 is the **reference plane**
- Definition of **ROI** for track reconstruction to exclude regions covered by PCB



ROI definition:
for top HU row < 170
for bottom HU row < 220



2 Noisy pixel identification

- Corryvreckan module `MaskCreator` is used for all tracking planes
- Pixels to be masked for the DUT are obtained from fake hit rate (FHR) measurement analysis

Overall: **# masked pixels/region ≤ 6**

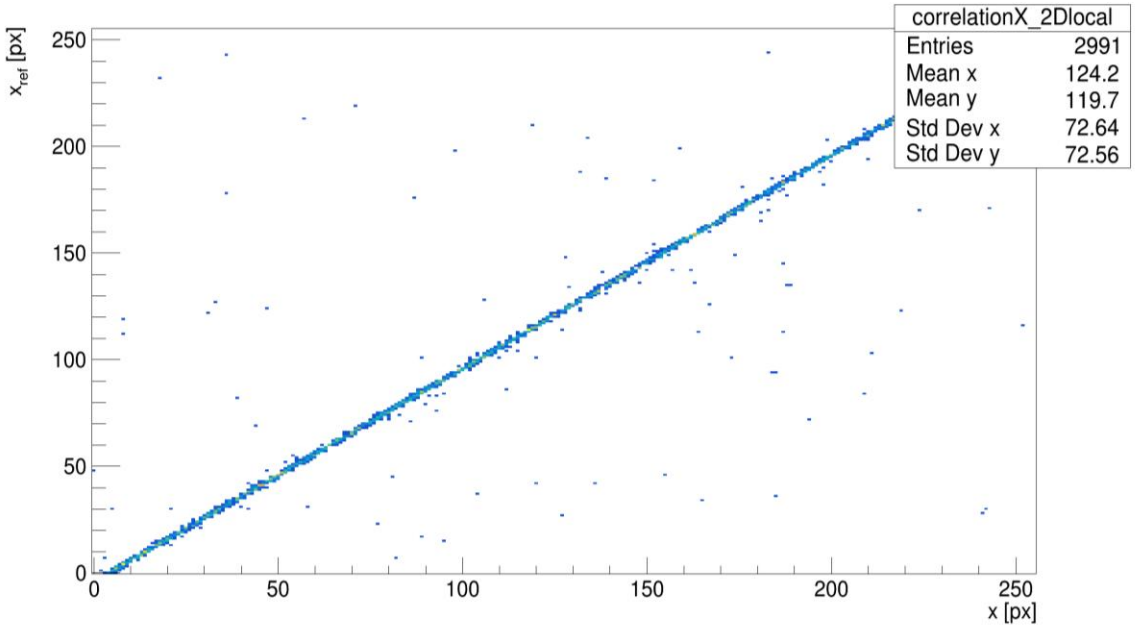
Test beam analysis flow with Corryvreckan

Data analysis is carried out using the **Corryvreckan** [6] software for test beam data analysis

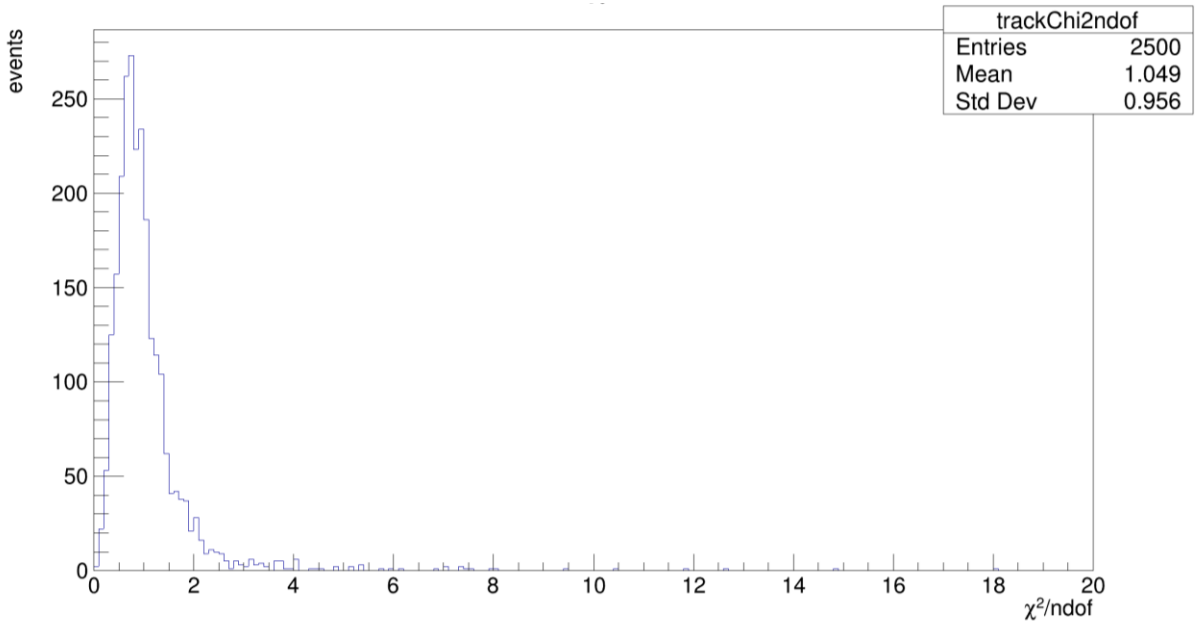
3 Alignment

- Prealignment (**`Prealignment`**)
- Only telescope: track reconstruction (**`Tracking4D`**) and alignment of tracking planes (**`AlignmentMillepede`**)
- Telescope + DUT: track reconstruction (**`Tracking4D`** with DUT included) and alignment of all planes (**`AlignmentMillepede, AlignmentDUTResidual`**)

X-correlation plot of DUT vs reference plane for DUT1 top region 2



Track χ^2/ndof distribution



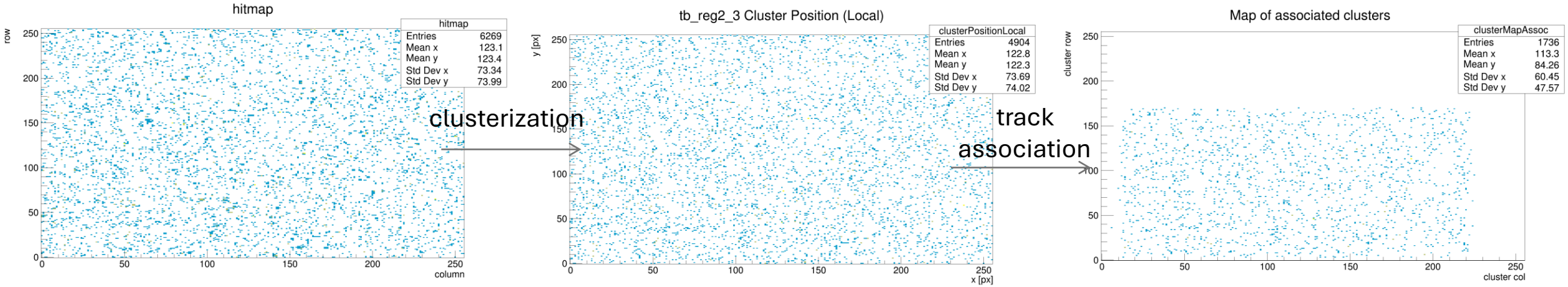
Test beam analysis flow with Corryvreckan

Data analysis is carried out using the **Corryvreckan** [6] software for test beam data analysis

4 DUT analysis for efficiency and final residuals

- **`DUTAssociation`** module with χ^2/ndof cut = 3 and spatial cut = 100 μm
- **`AnalysisDUT`** and **`AnalysisEfficiency`** with χ^2/ndof cut = 3 and spatial cut sensor edge = 3 pixel

DUT final analysis for DUT 1 top region 2



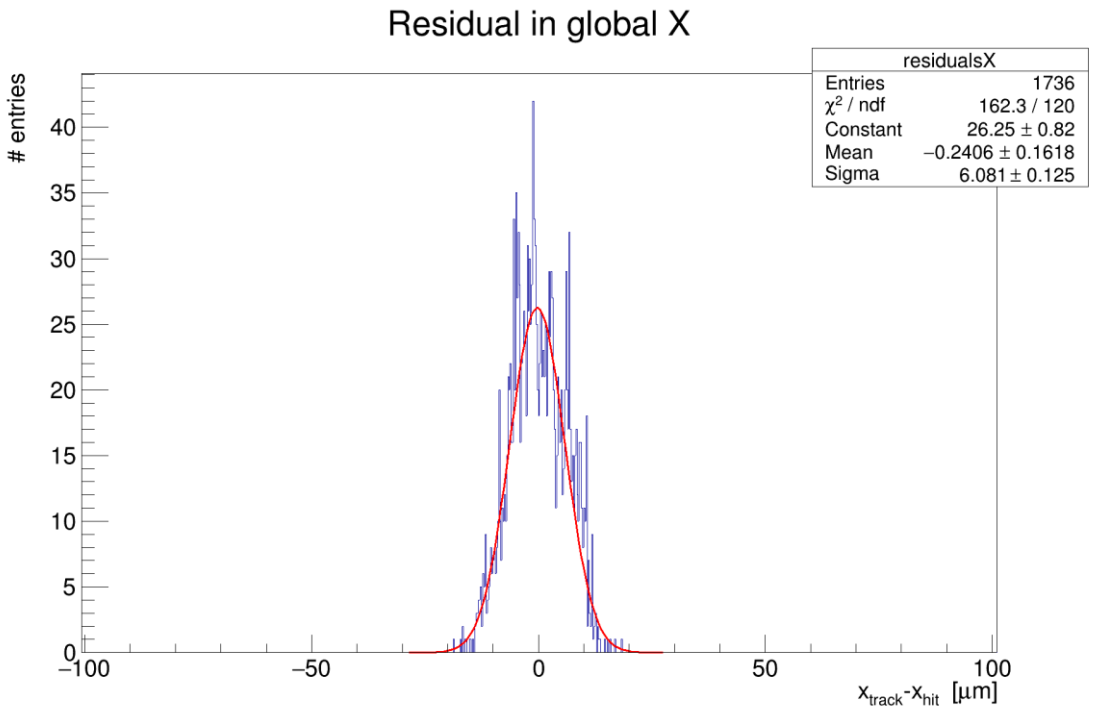
Test beam analysis flow with Corryvreckan

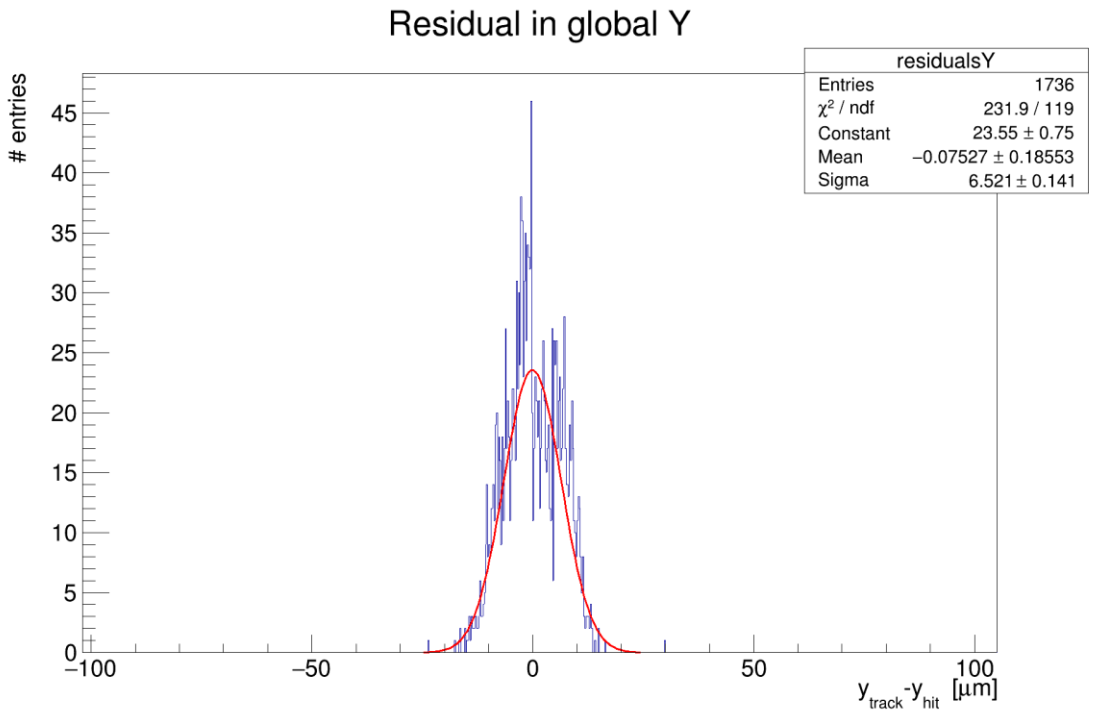
Data analysis is carried out using the **Corryvreckan** [6] software for test beam data analysis

4 DUT analysis for efficiency and final residuals

- **`DUTAssociation`** module with χ^2/ndof cut = 3 and spatial cut = 100 μm
- **`AnalysisDUT`** and **`AnalysisEfficiency`** with χ^2/ndof cut = 3 and spatial cut sensor edge = 3 pixel

DUT final analysis for DUT 1 top region 2



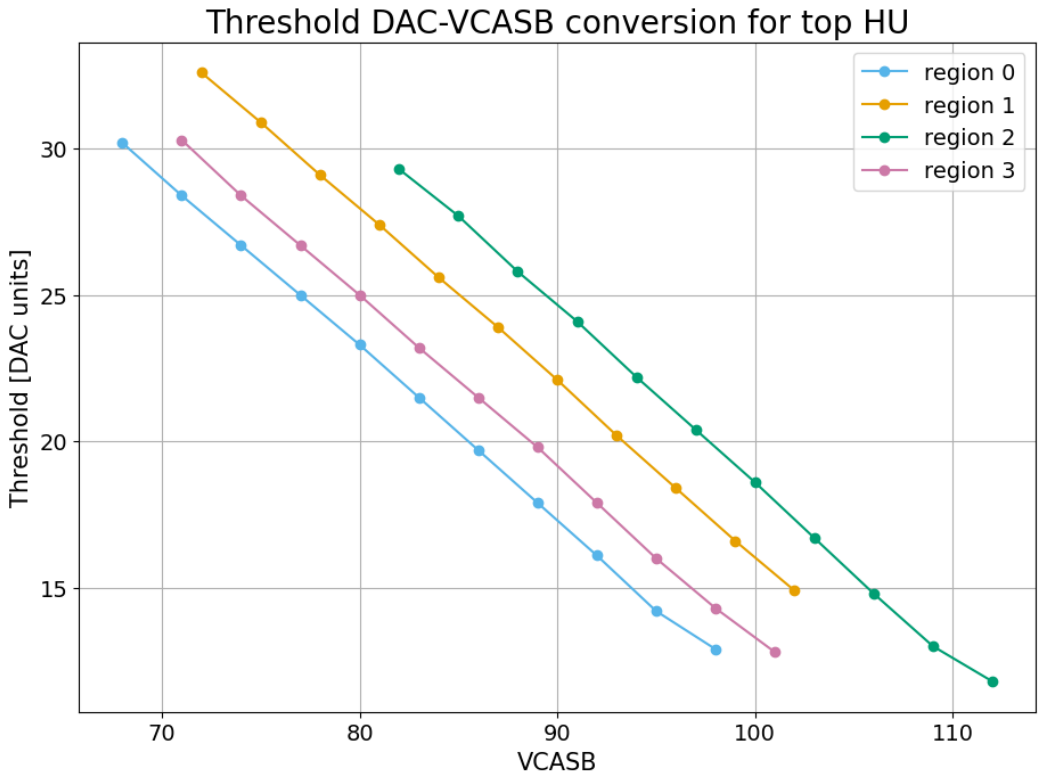


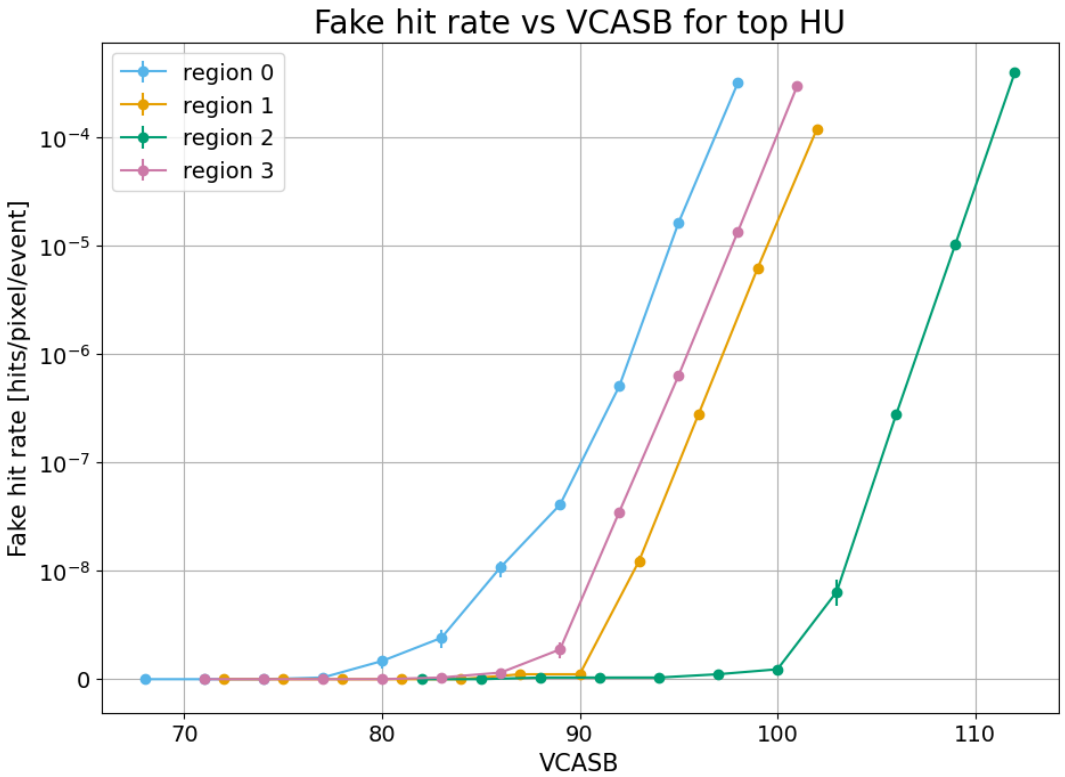
Threshold and fake hit rate scan studies

With no beam, threshold and fake hit rate scans were performed for all DUTs.

Threshold scan
VCASB is the digital parameter that controls pixels threshold, and it is inversely proportional to it.
This scan gives a conversion from VCASB to threshold in DAC units.

Fake hit rate scan
For a certain VCASB value and given a set number of triggers, the number of hits is measured to estimate the fake hit rate (FHR).

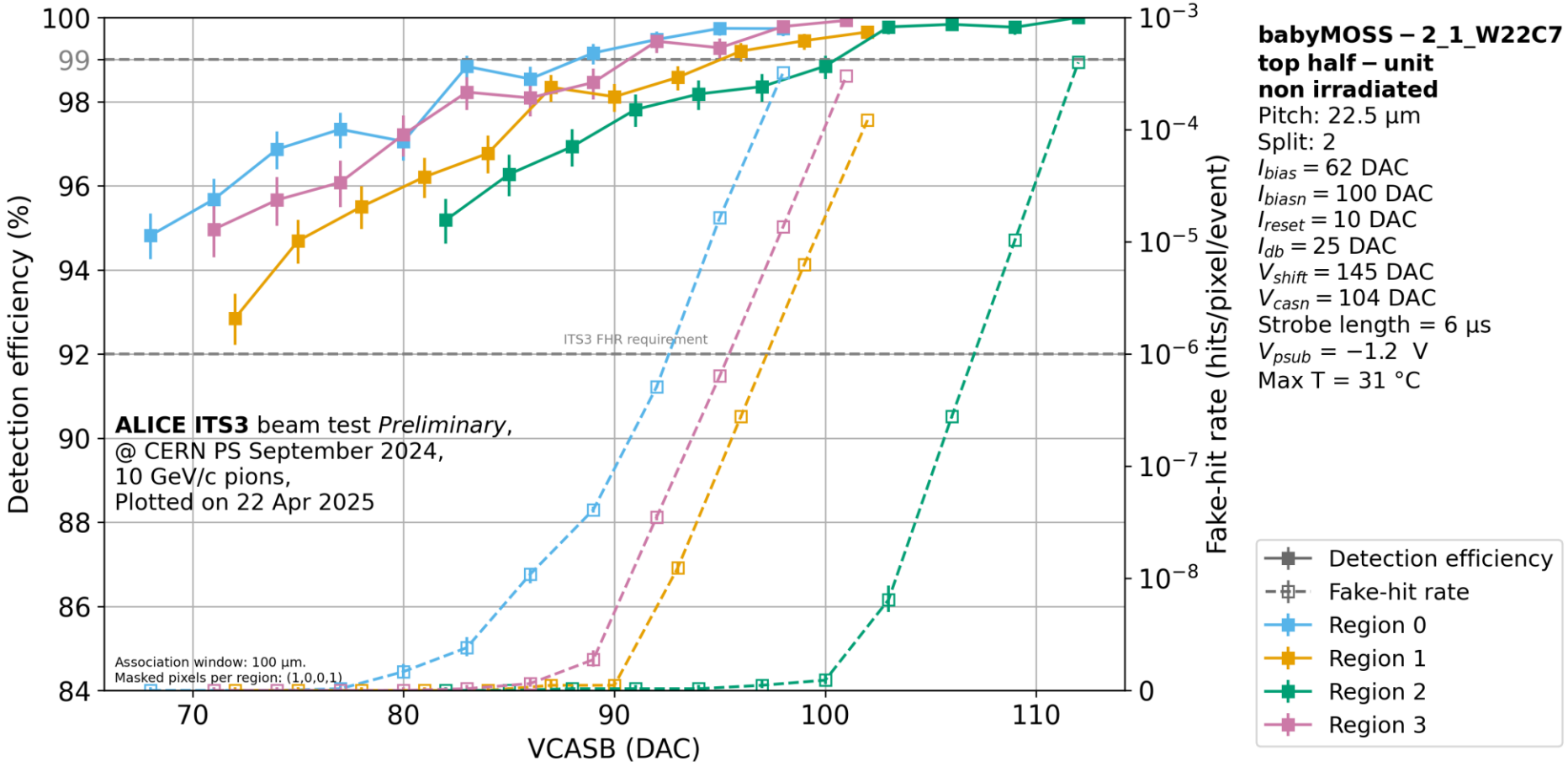




Threshold scan measurements at test beam

Using threshold scan results, it is possible to plot the results of efficiency and spatial resolution as a function of threshold in DAC units leading to much more uniform behaviour when comparing the different regions.

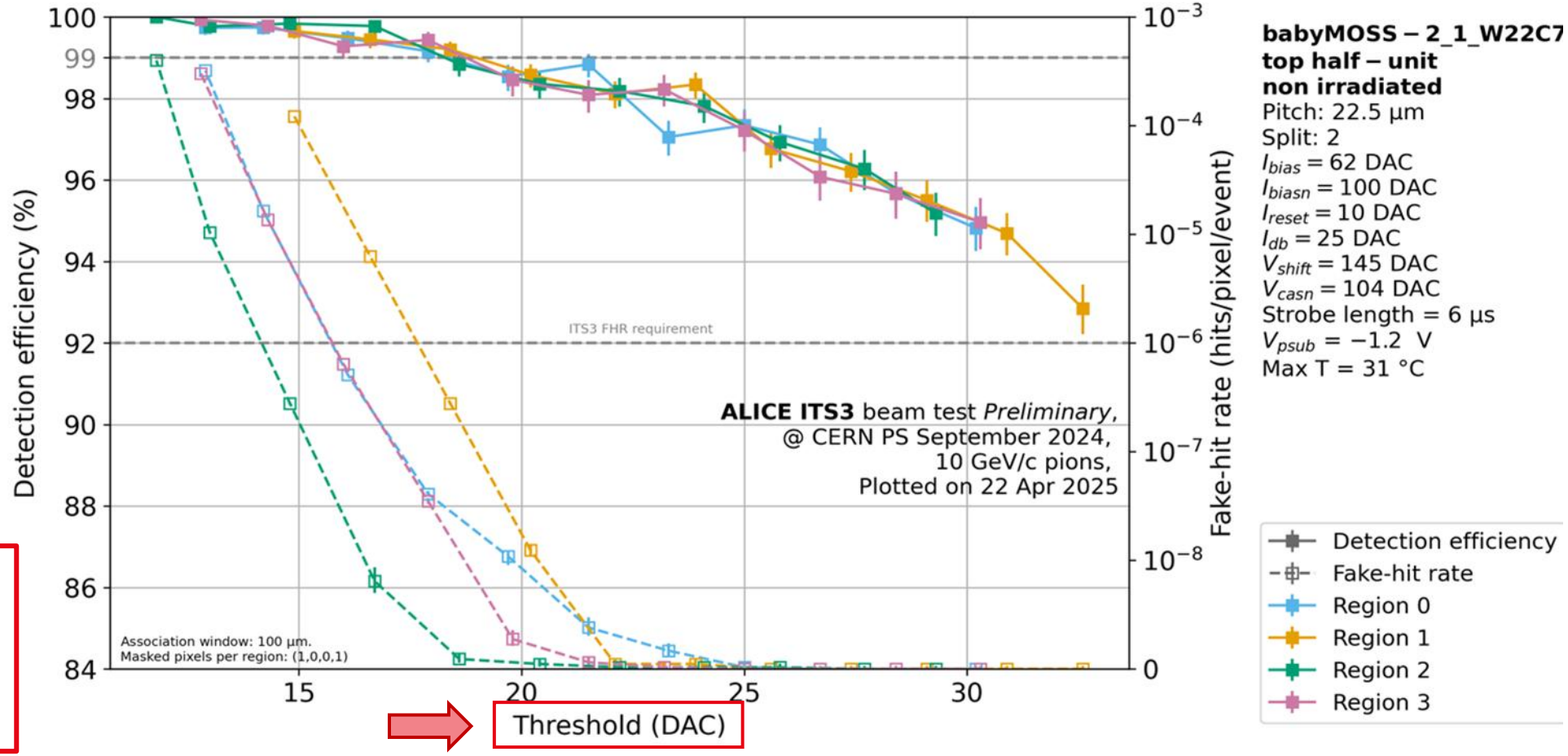
Example for top HU of DUT 1:



Threshold scan measurements at test beam

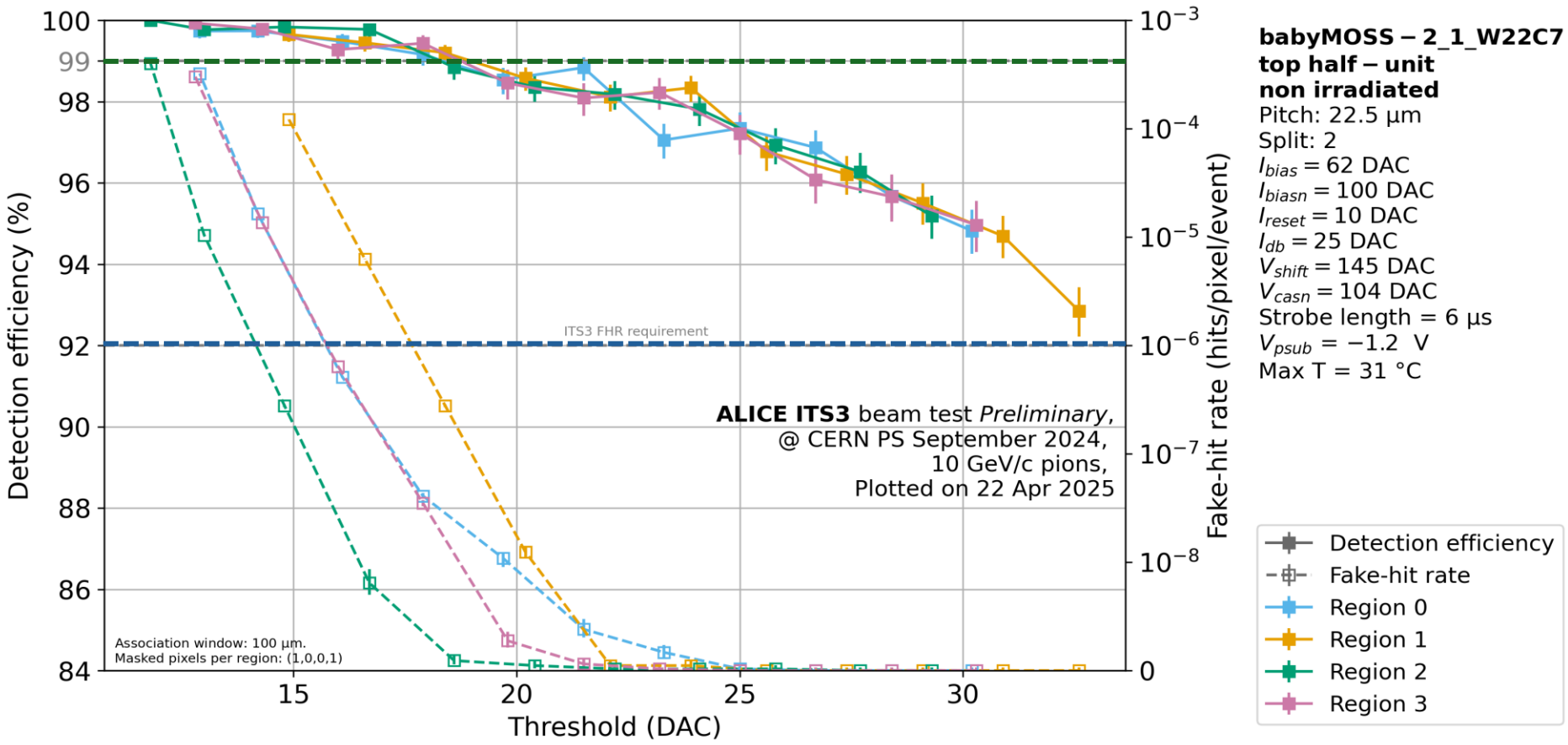
Using threshold scan results, it is possible to plot the results of efficiency and spatial resolution as a function of threshold in DAC units leading to much more uniform behaviour when comparing the different regions.

Example for top HU of DUT 1:



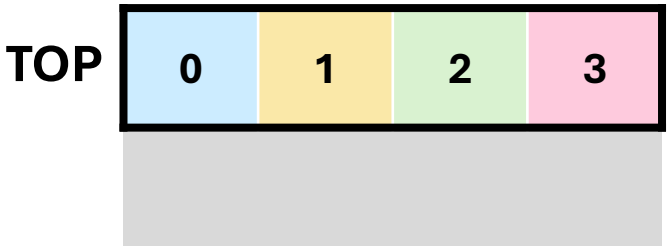
From now on, results with only threshold in DAC units will be shown

Non-irradiated DUT: efficiency for top HU

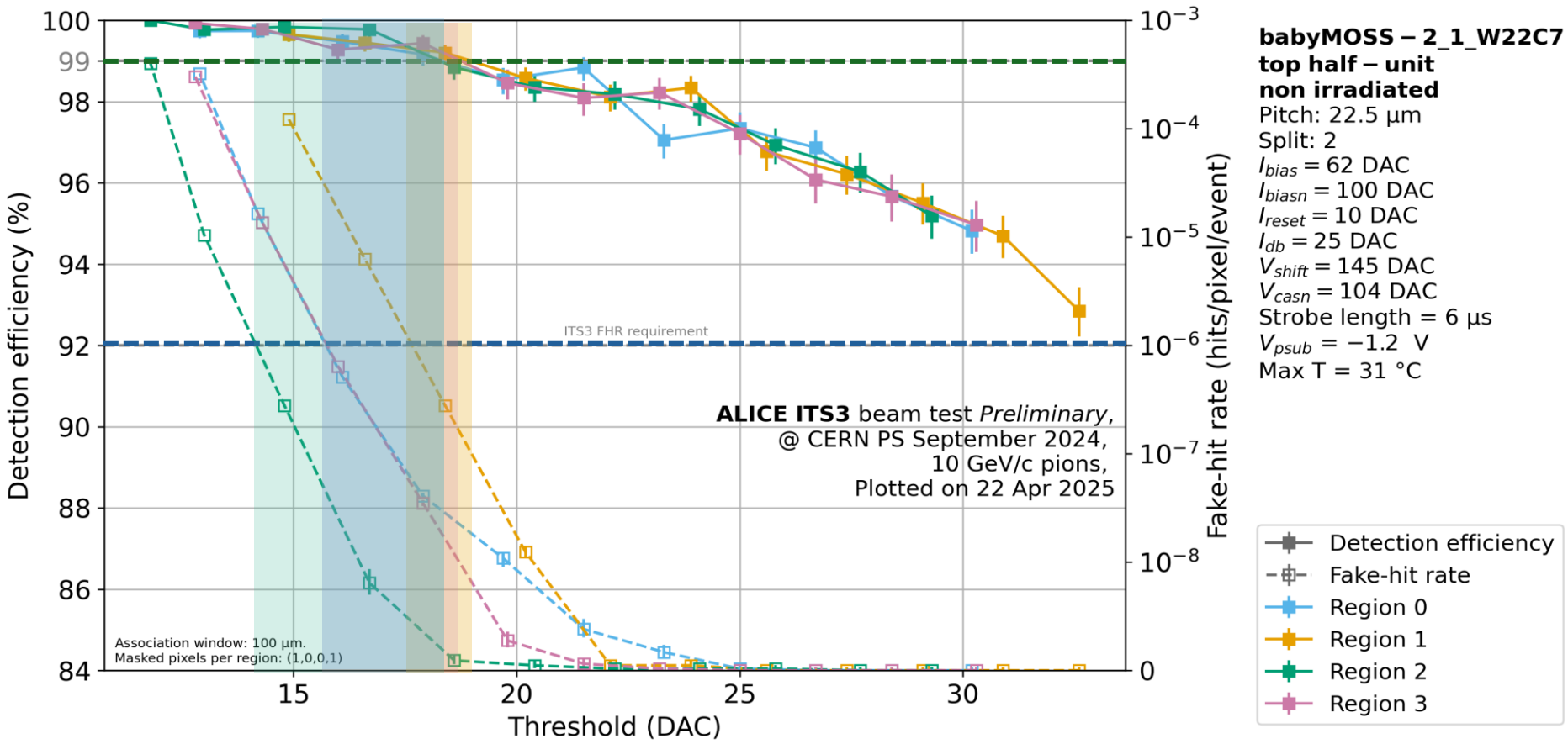


ITS3 requirements

Efficiency	**> 99 %**
FHR	**< 10^{-6}** hits/pixel/event

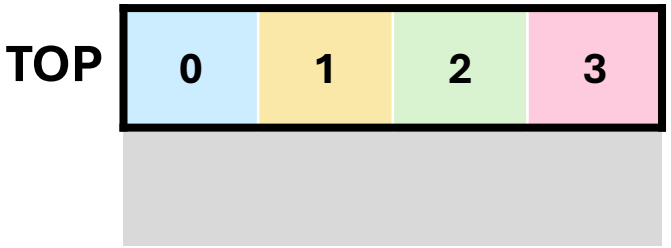


Non-irradiated DUT: efficiency for top HU

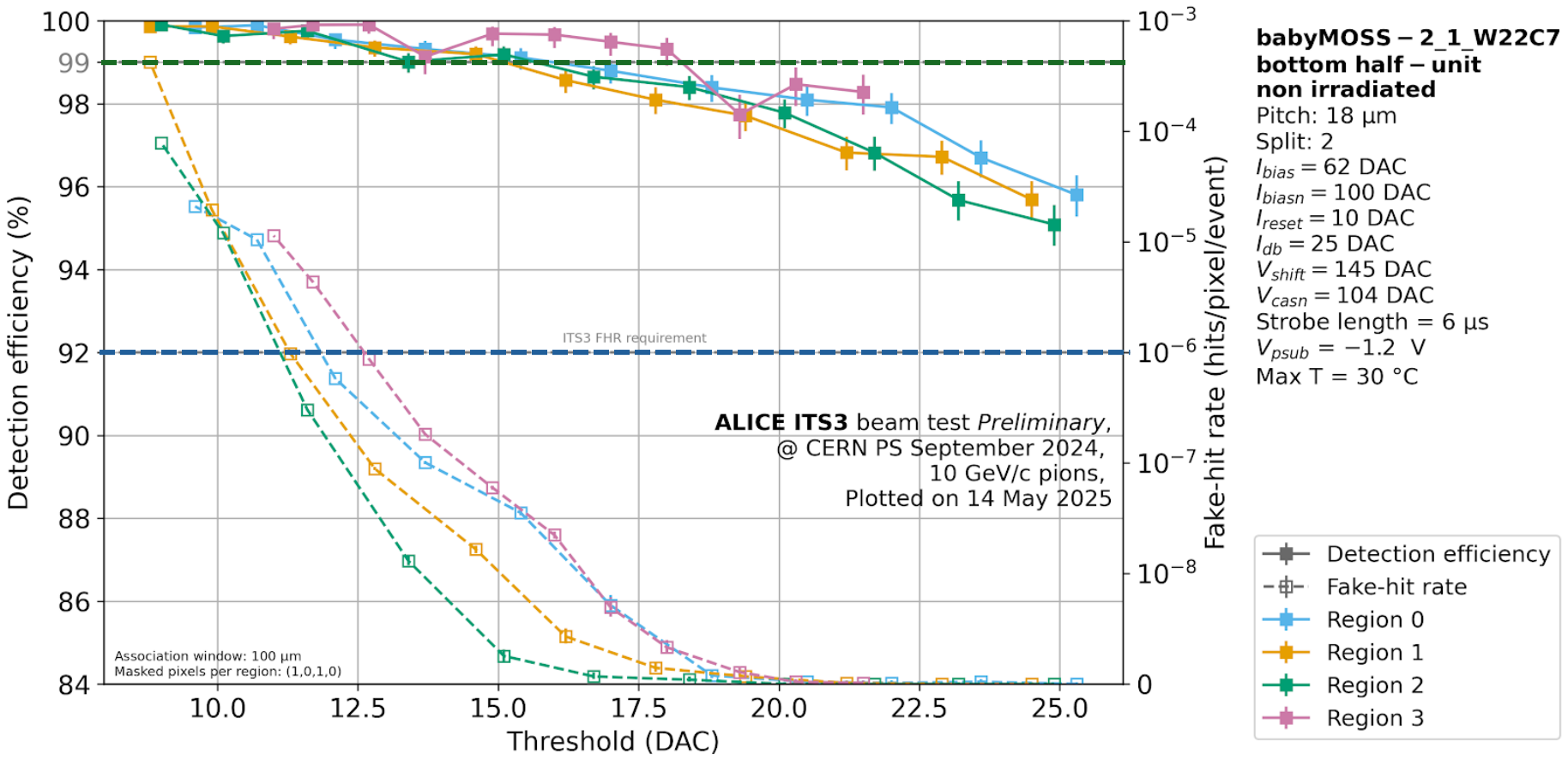


ITS3 requirements

Efficiency	**> 99 %**	✓
FHR	**< 10^{-6}** hits/pixel/event	✓

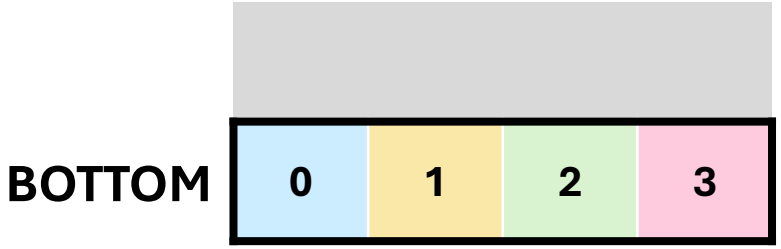


Non-irradiated DUT: efficiency for bottom HU

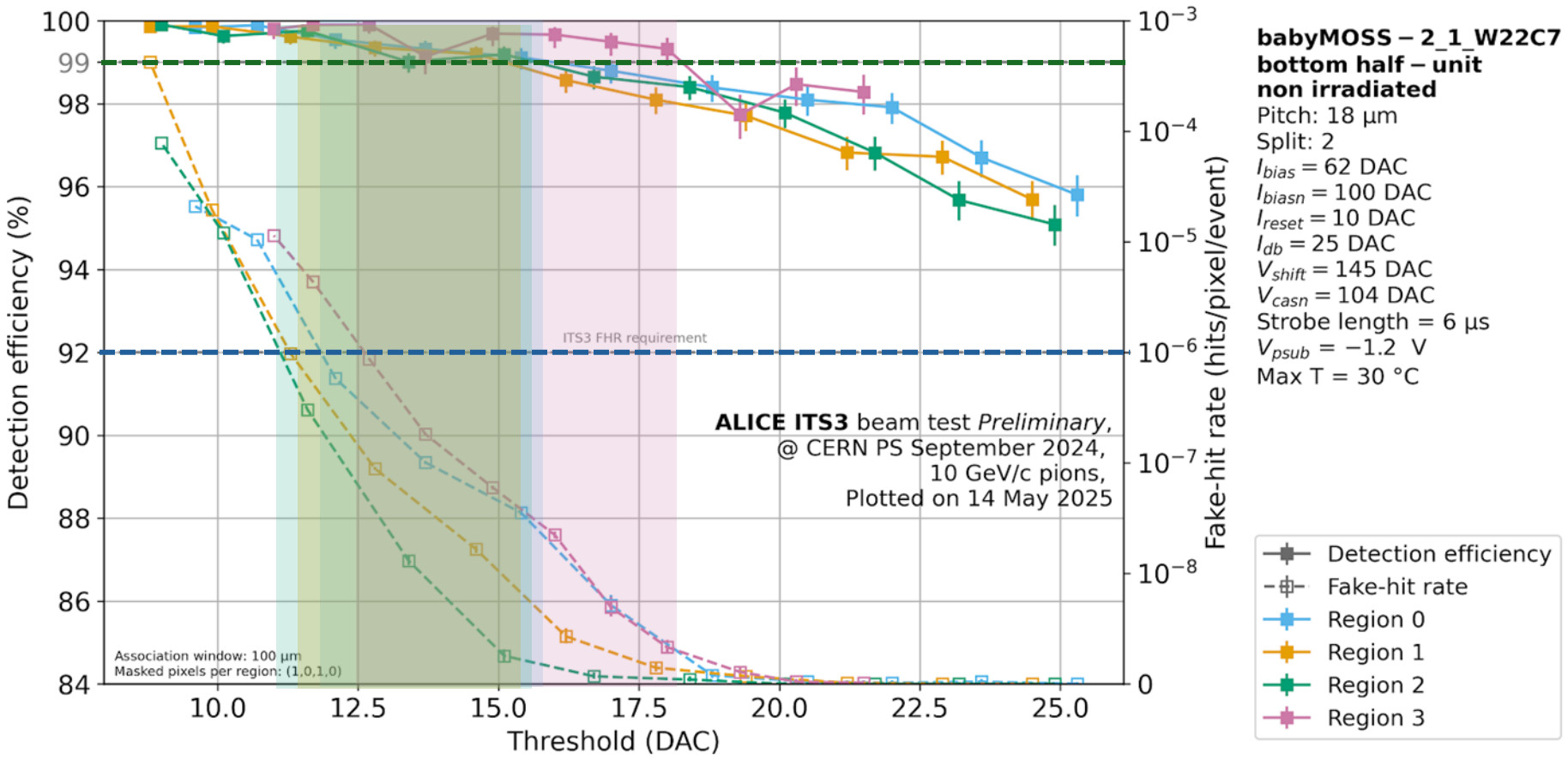


ITS3 requirements

Efficiency	**> 99 %**
FHR	**< 10^{-6}** hits/pixel/event

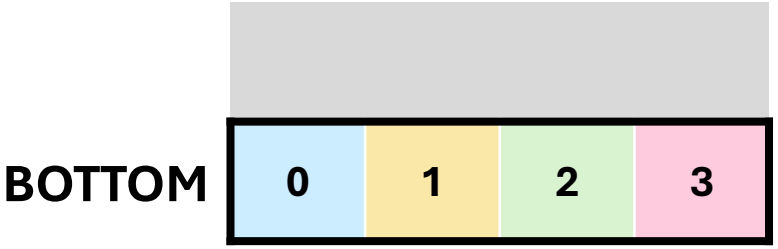


Non-irradiated DUT: efficiency for bottom HU



ITS3 requirements

Efficiency	**> 99 %**	✓
FHR	**< 10^{-6}** hits/pixel/event	✓



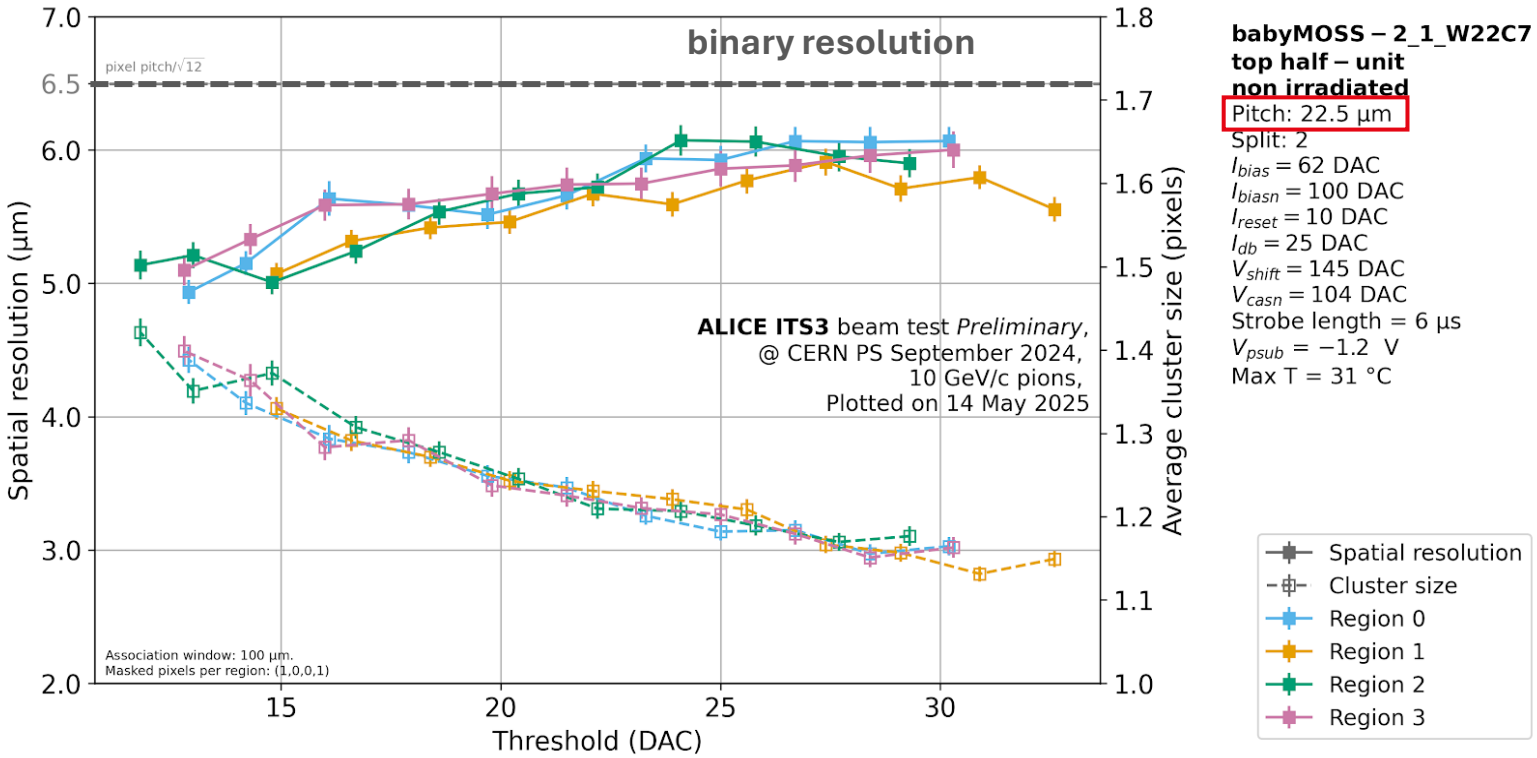
Non-irradiated DUT: spatial resolution

From the sigma of the gaussian fit of final residual distribution on the DUT, the spatial resolution is extracted as:

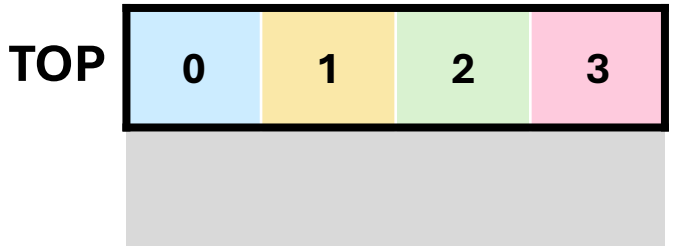
from TelescopeOptimizer tool [7]

$$\sigma_{i,DUT} = \sqrt{\sigma_{i,fit}^2 - \sigma_{telescope}^2} \quad i = x, y$$

$$\sigma_{DUT} = \frac{\sigma_{x,DUT} + \sigma_{y,DUT}}{2}$$



The resolution is below the **binary resolution** since the average cluster size is always > 1.



In the operating threshold range, **resolution is below 6 µm** for all top regions.

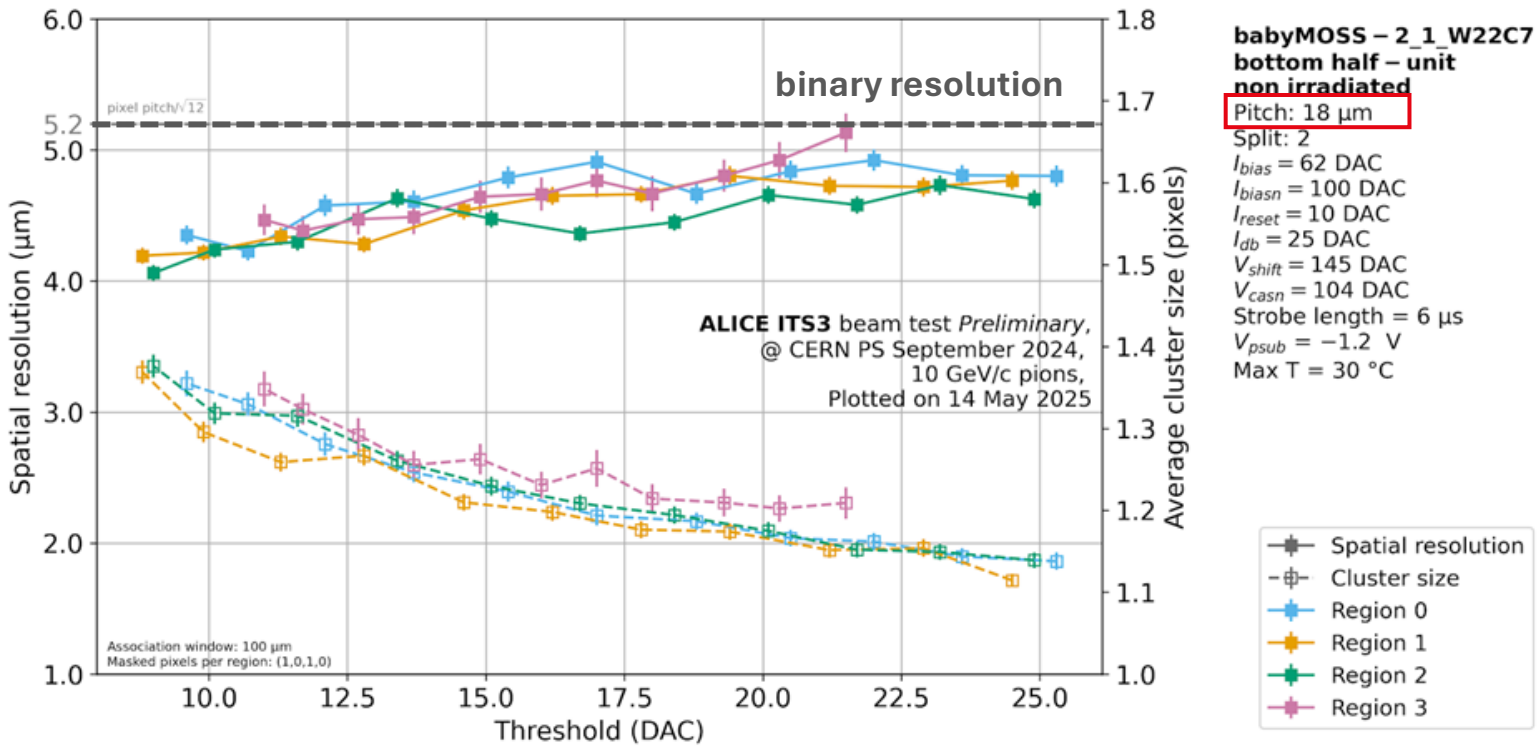
Non-irradiated DUT: spatial resolution

From the sigma of the gaussian fit of final residual distribution on the DUT, the spatial resolution is extracted as:

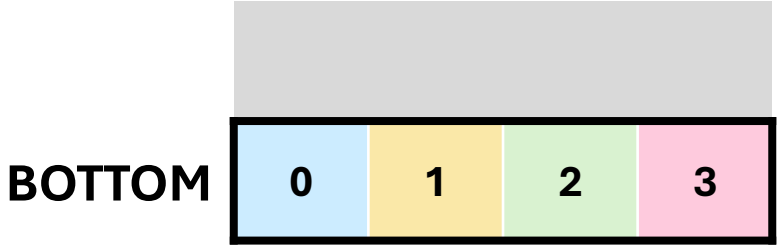
from TelescopeOptimizer tool [7]

$$\sigma_{i,DUT} = \sqrt{\sigma_{i,fit}^2 - \sigma_{telescope}^2} \quad i = x, y$$

$$\sigma_{DUT} = \frac{\sigma_{x,DUT} + \sigma_{y,DUT}}{2}$$



The resolution is below the **binary resolution** since the average cluster size is always > 1.



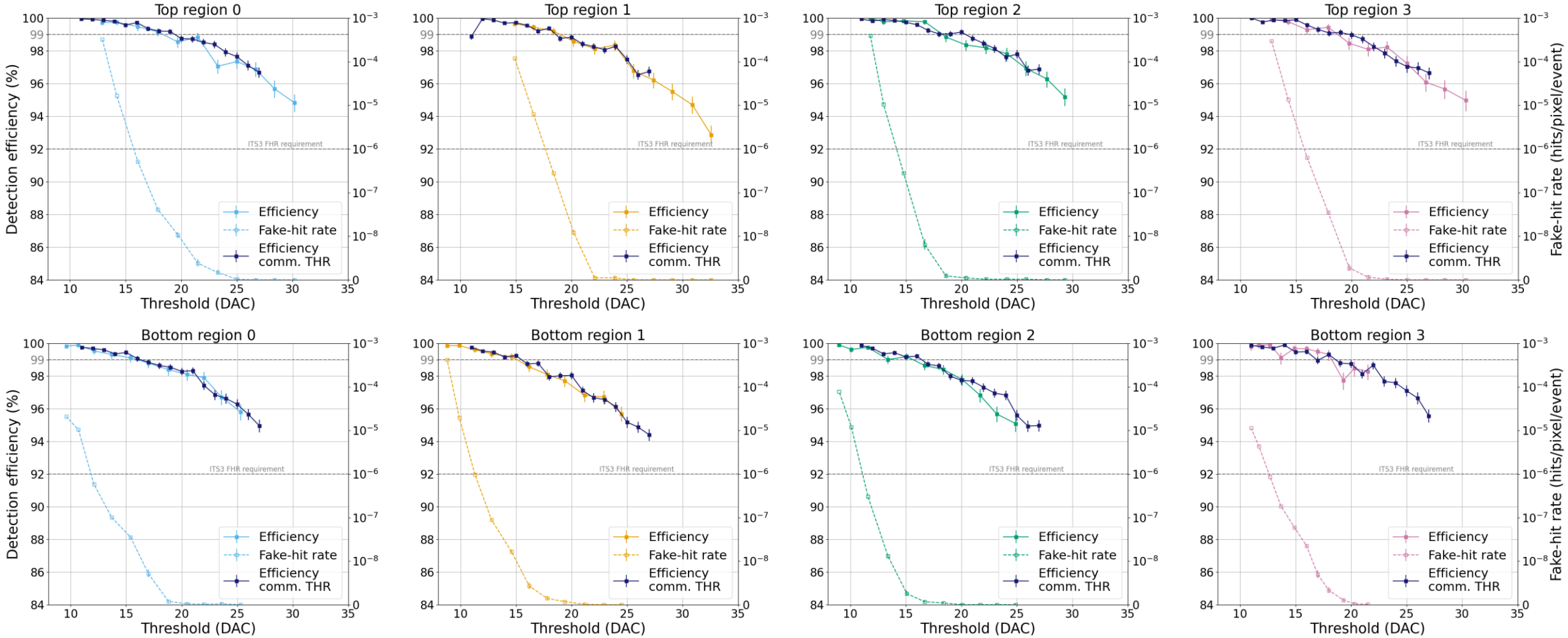
In the operating threshold range, **resolution is below 5 µm** for all bottom regions.

Results for non-irradiated DUT: common threshold scan

All regions were readout simultaneously setting the **same threshold for the entire chip**, choosing a proper VCASB range for each region.

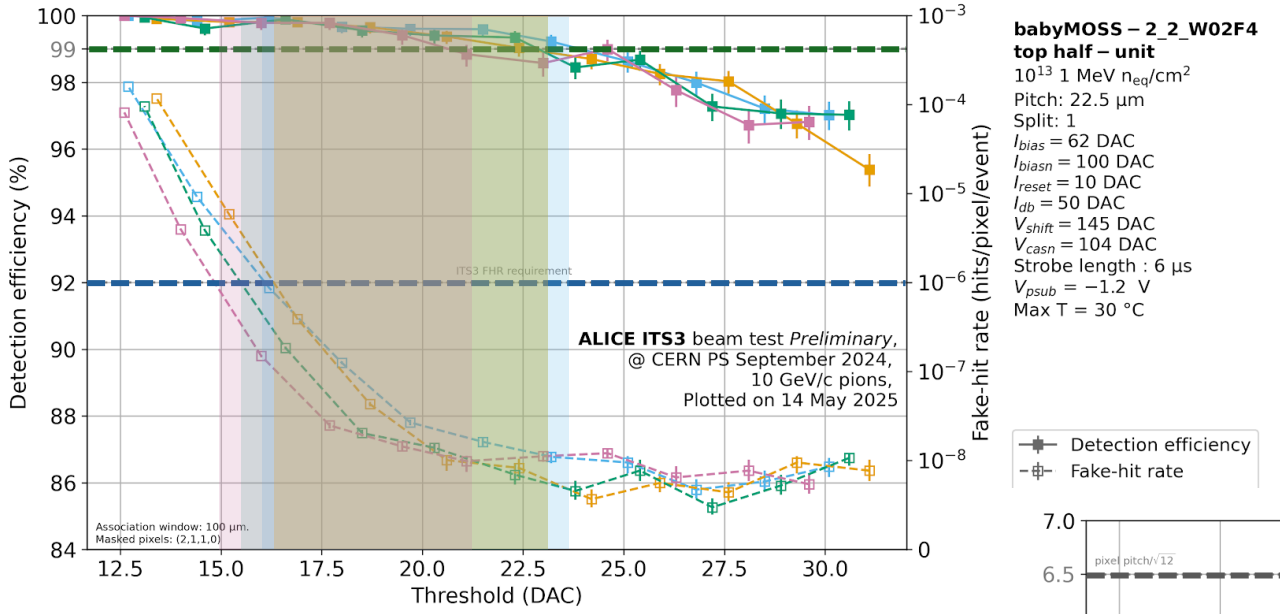
No impact on detection efficiency

Dark blue: common threshold scan
Light colors: single region scan



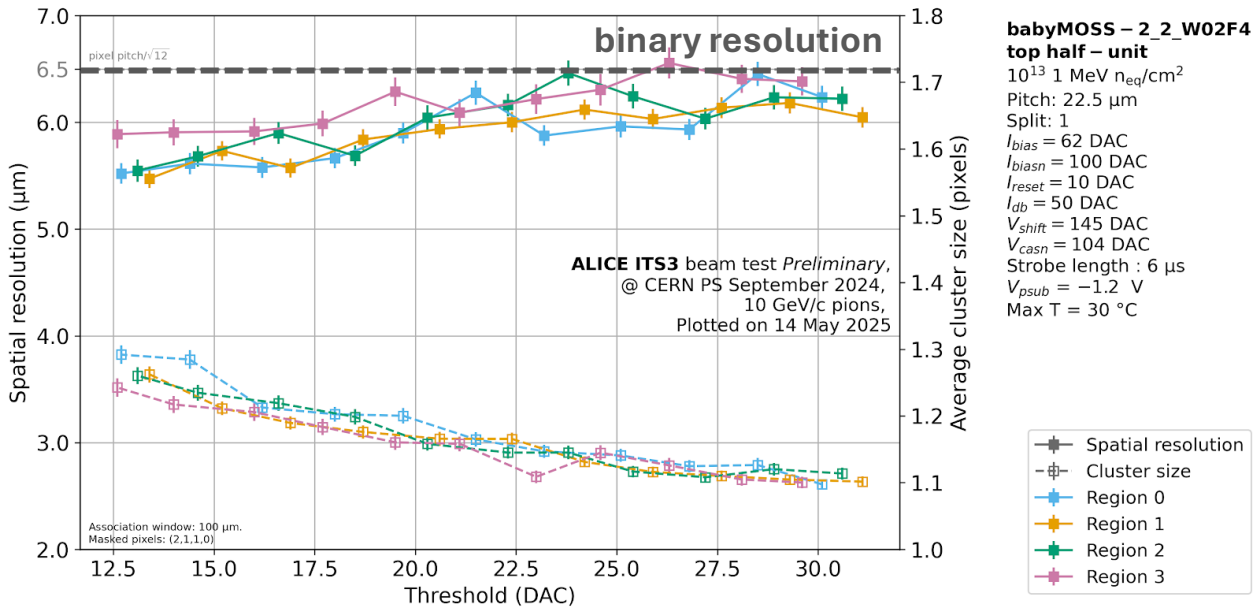
Irradiated DUT: top HU

Efficiency



Good operational margin for all regions.
No significant degradation of the sensor performance due to irradiation.

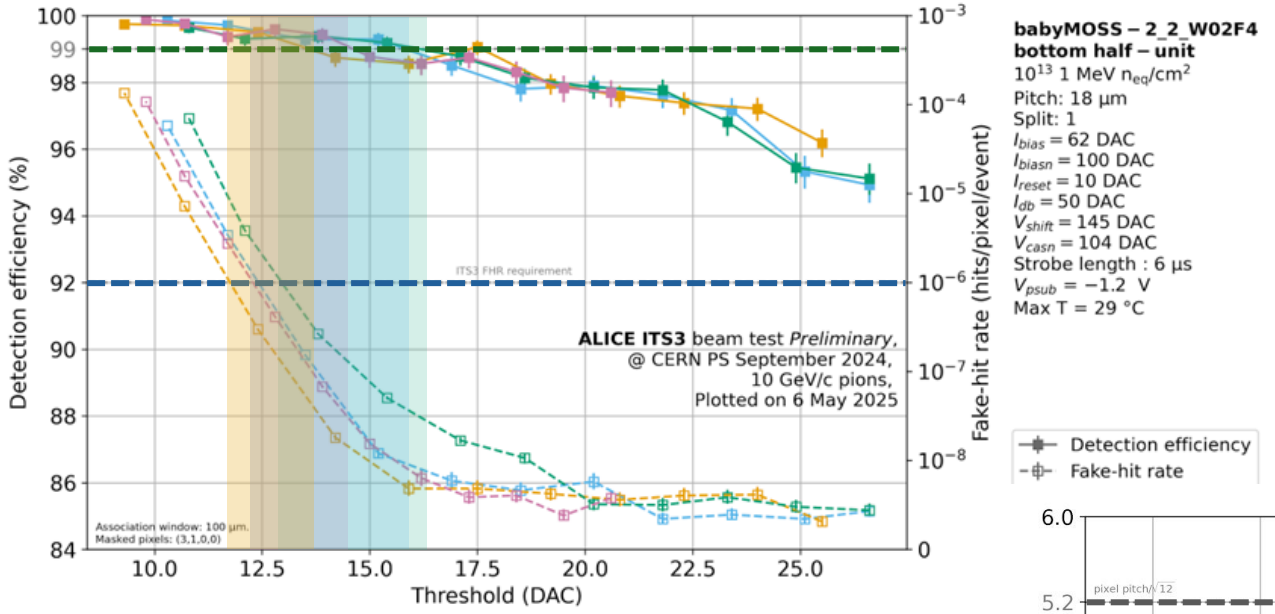
Spatial resolution



The second irradiated DUT, i.e. DUT3, shows similar performances (see backup)

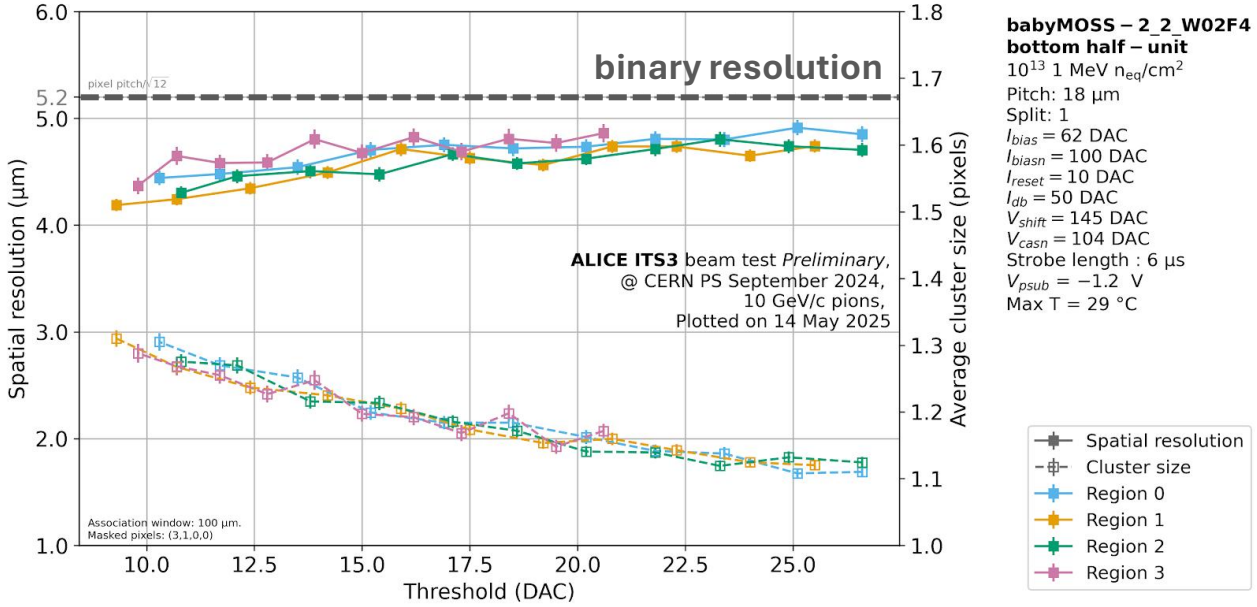
Irradiated DUT: bottom HU

Efficiency



Good operational margin for all regions.
No significant degradation of the sensor performance due to irradiation.

Spatial resolution



The second irradiated DUT, i.e. DUT3, shows similar performances (see backup)

Summary

- **Both non irradiated and irradiated DUTs** (at 10^{13} 1 MeV n_{eq}/cm^2) work well and have a **good operational range** in which they satisfy the ITS3 efficiency, FHR and spatial resolution requirements.
- Common threshold analysis for non irradiated DUT shows that detection efficiency is approximately the same as in the single region scan case, showing that there is no impact of cross-coupling between adjacent regions on detection efficiency.
- There is yet no clear evidence of a specific front-end electronics or pixel pitch variant that leads to an improvement of sensor perfomance.
- With this test beam measurements, the **babyMOSS telescope functioning** was **fully validated** for the first time.

Outlook

- Ongoing studies on **further sensor performance improvement** by tuning of chip parameters (e.g. strobe length).
- Current setup and analysis will be useful for **test beam characterization of next ITS3 ER2 prototype** (MOSAIX).

Thank you for the attention

Acknowledgment
The measurements leading to these results have been performed at PS T10 beamline at CERN.

References:

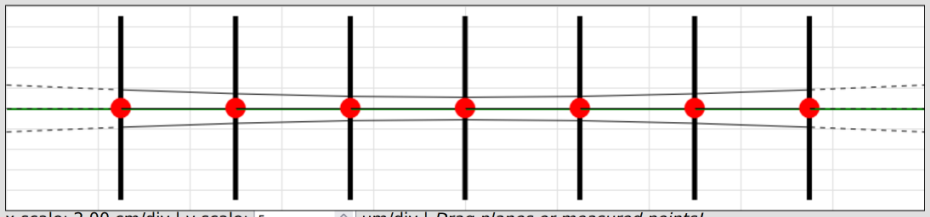
[1] https://alice-figure.web.cern.ch/node/30770
[2] https://ep-ese.web.cern.ch/project/alice-its
[3] M. Buckland, Development of the ITS3: A bent-silicon vertex detector for ALICE in the LHC Run 4, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1039, 2022,166875, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2022.166875
[4] ALICE collaboration, Technical Design report for the ALICE Inner Tracking System 3 - ITS3 A bent wafer-scale monolithic pixel detector, CERN-LHCC-2024-003, ALICE-TDR-021, Geneva, 2024, https://cds.cern.ch/record/2890181
[5] Liu, Y. et Al., EUDAQ2—A flexible data acquisition software framework for common test beams, Journal of Instrumentation, 14, 10, P10033, October 2019, 10.1088/1648-0221/14/10/P10033, https://dx.doi.org/10.1088/1648-0221/14/10/P10033
[6] D. Dannheim et al., “Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data”, J. Instr. 16 (2021) P03008, doi:10.1088/1648-0221/16/03/P03008, arXiv:2011.12730
[7] The Telescope Optimiser V1.0 | Copyright (C) 2016 Magnus Mager, CERN, https://mmager.web.cern.ch/telescope/tracking.html

Backup

Tracker telescope resolution

Using Telescope Optimiser [7] tool and binary resolution for bottom and top HU regions, tracker resolution is obtained.

HU = top



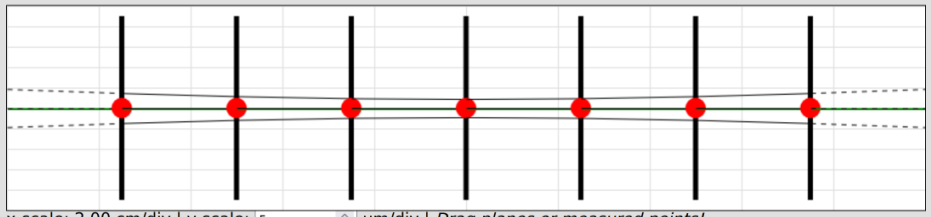
x-scale: 2.00 cm/div | y-scale: 5 µm/div | *Drag planes or measured points!*

Particle: n^+ / n^- (Pion) | Momentum: 10 GeV/c

Layout		Sensor			Tracking	MC track position		
Plane #	Position (cm)	Thickness (% X/X_0)	Resolution (µm)	Tracking used	Resolution (µm)	real (µm)	measured (µm)	reconstructed (µm)
	-2.5				5.74	0.0		0.0
1	0.0	0.05	6.5	☑	4.57	0.0	0.0	0.0
2	2.5	0.05	6.5	☑	3.62	0.0	0.0	0.0
3	5.0	0.05	6.5	☑	2.97	0.0	0.0	0.0
4	7.5	0.05	6.5	☐	2.74	0.0	0.0	0.0
5	10.0	0.05	6.5	☑	2.97	0.0	0.0	0.0
6	12.5	0.05	6.5	☑	3.62	0.0	0.0	0.0
7	15.0	0.05	6.5	☑	4.57	0.0	0.0	0.0
	17.5				5.74	0.0		0.0

equidistant | all as #1 | all as #1 | MC | measure | MC & measure

HU = bottom



x-scale: 2.00 cm/div | y-scale: 5 µm/div | *Drag planes or measured points!*

Particle: n^+ / n^- (Pion) | Momentum: 10 GeV/c

Layout		Sensor			Tracking	MC track position		
Plane #	Position (cm)	Thickness (% X/X_0)	Resolution (µm)	Tracking used	Resolution (µm)	real (µm)	measured (µm)	reconstructed (µm)
	-2.5				4.66	0.0		0.0
1	0.0	0.05	5.2	☑	3.67	0.0	0.0	0.0
2	2.5	0.05	5.2	☑	2.90	0.0	0.0	0.0
3	5.0	0.05	5.2	☑	2.40	0.0	0.0	0.0
4	7.5	0.05	5.2	☐	2.22	0.0	0.0	0.0
5	10.0	0.05	5.2	☑	2.40	0.0	0.0	0.0
6	12.5	0.05	5.2	☑	2.90	0.0	0.0	0.0
7	15.0	0.05	5.2	☑	3.67	0.0	0.0	0.0
	17.5				4.66	0.0		0.0

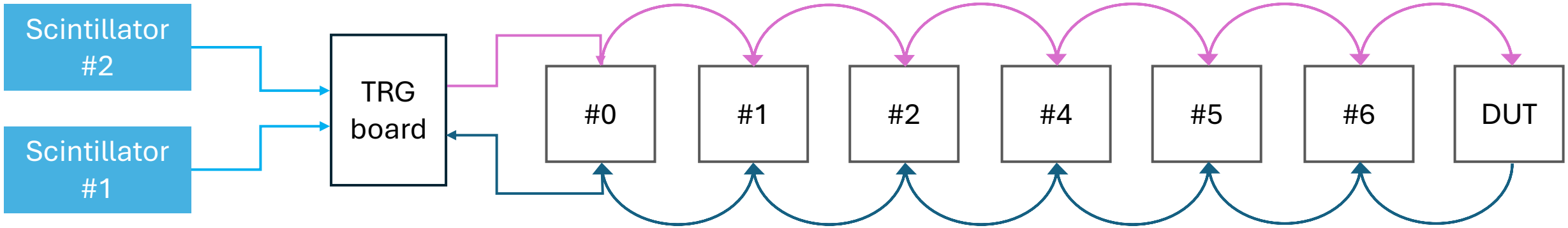
equidistant | all as #1 | all as #1 | MC | measure | MC & measure

Telescope trigger logic

Trigger logic

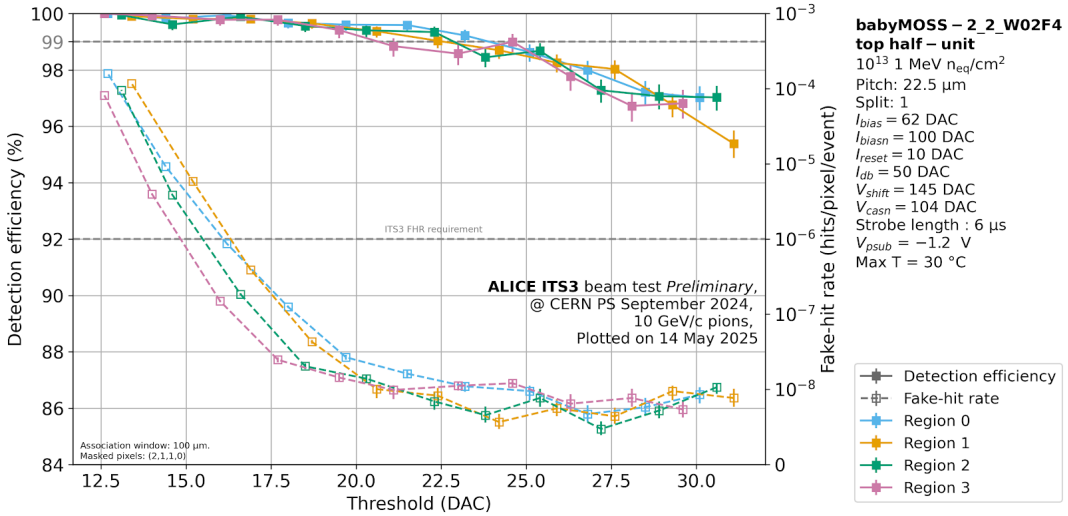
TRG/BSY chain

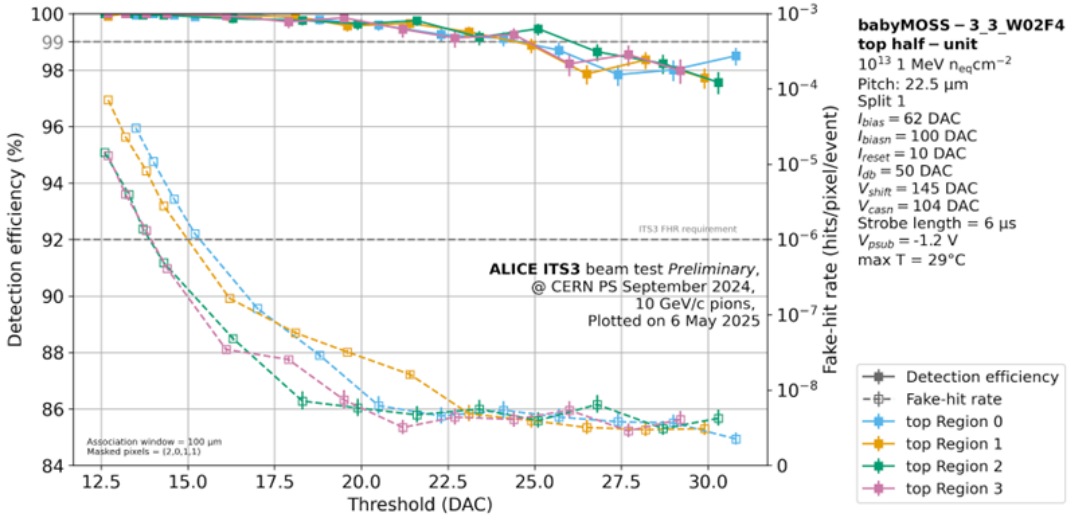
TRG board generates a signal that is propagated through all tracking planes and finally to DUT.
Then BUSY signal is sent back from DUT through all tracking planes.



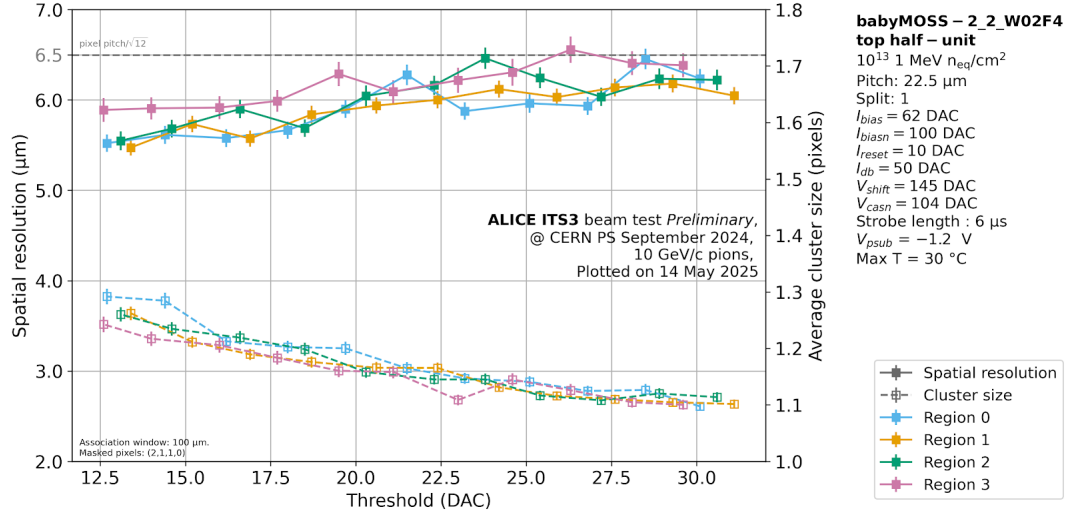
Comparison of irradiated DUTs: top HU

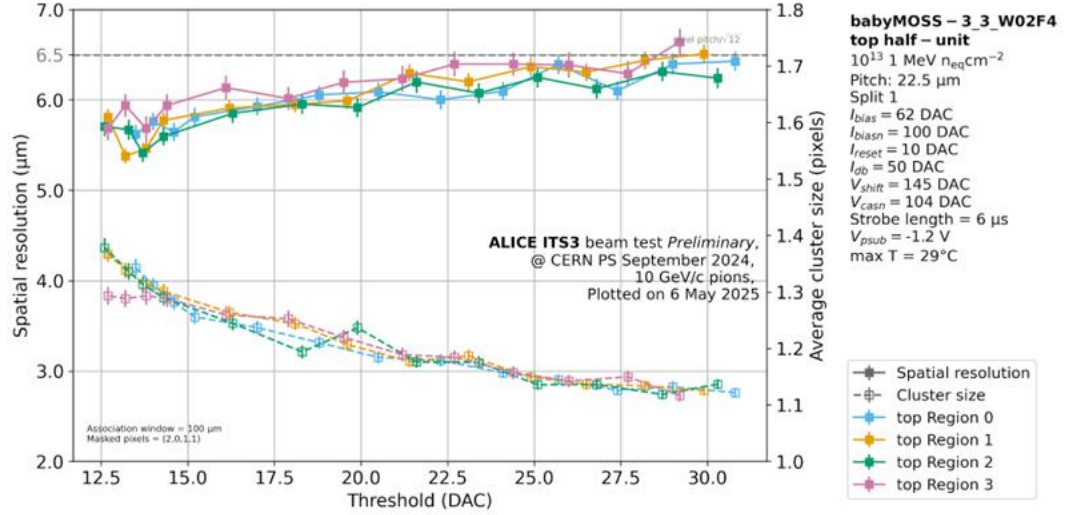
Efficiency: DUT2 – DUT3 comparison





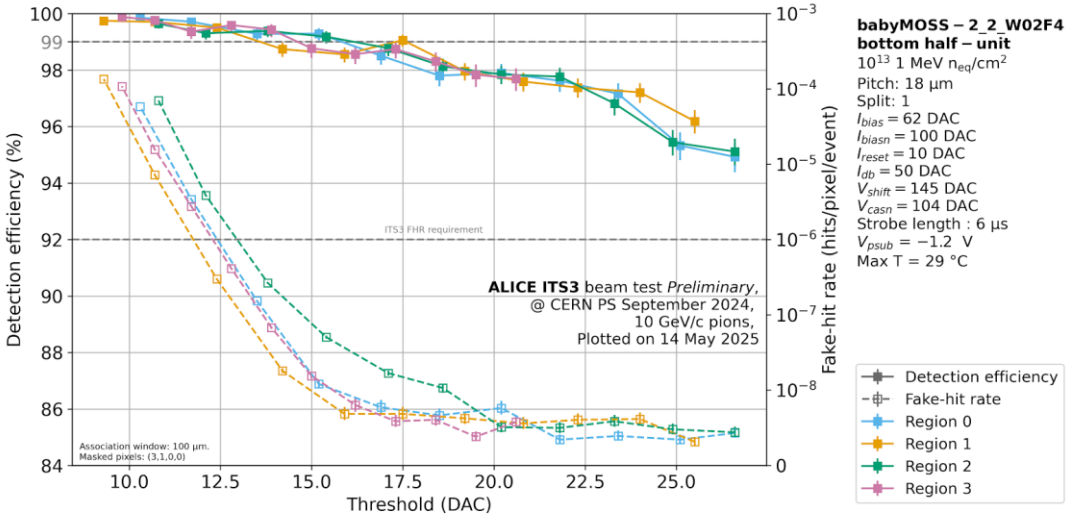
Spatial resolution: DUT2 – DUT3 comparison

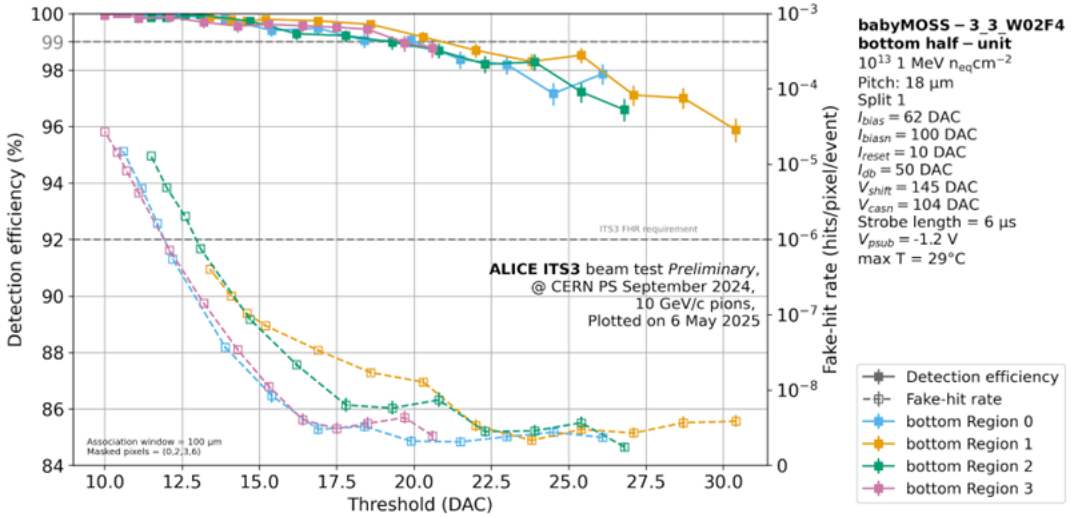
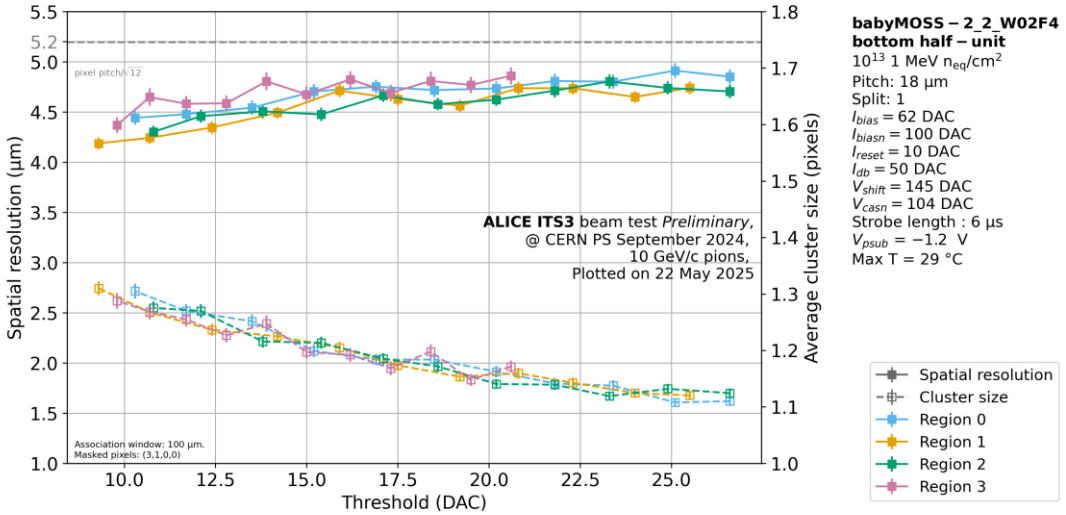
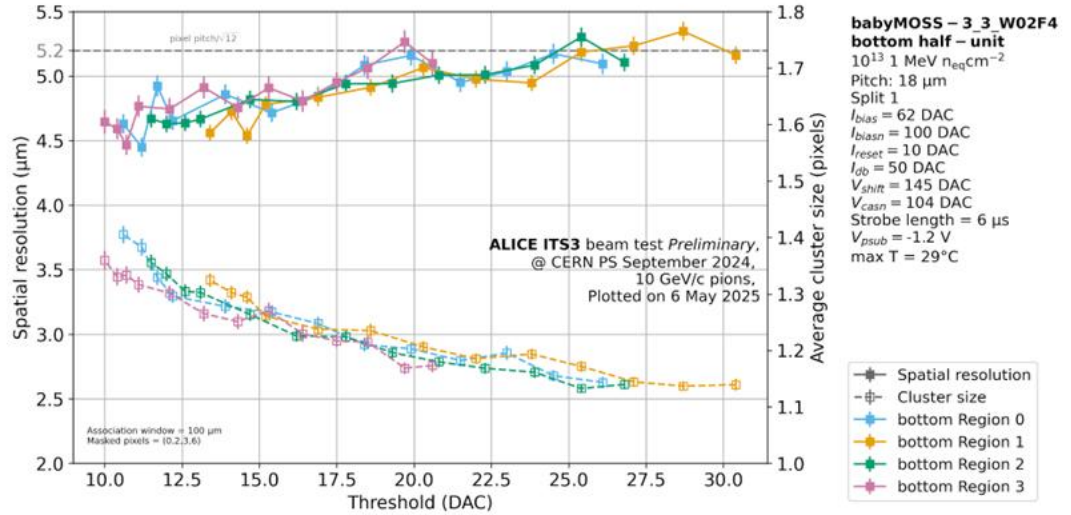




Comparison of irradiated DUTs: bottom HU

Efficiency: DUT2 – DUT3 comparison





Spatial resolution: DUT2 – DUT3 comparison