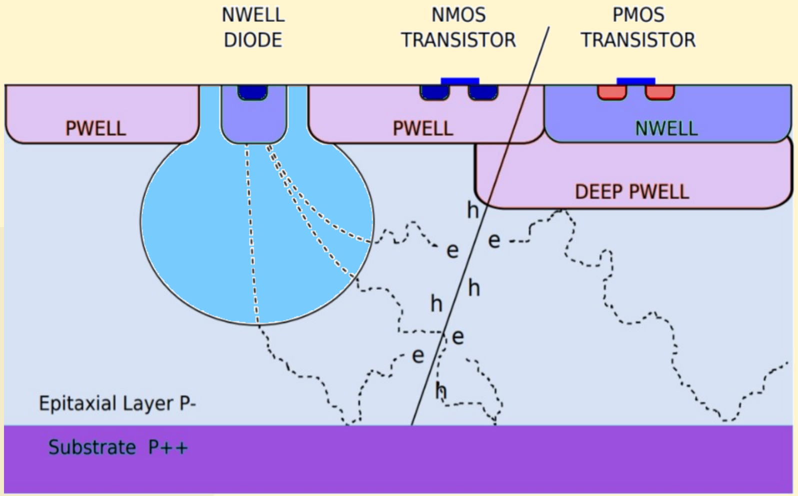
Simulation of MAPS for the Octopus Project

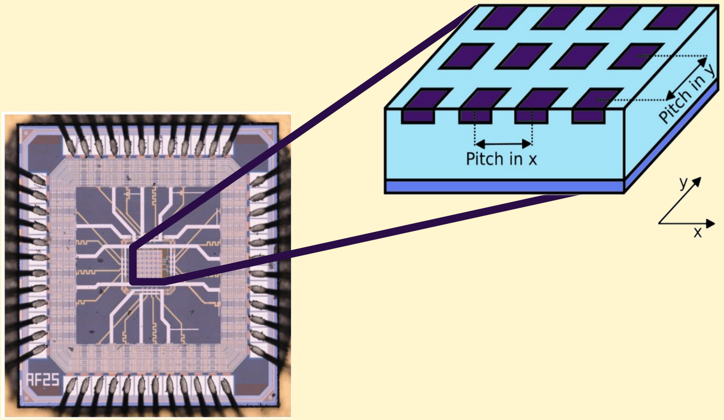
Fabrizio Santin, Università di Napoli “Federico II” – Naples, Italy
Supervisors: Anastasiia Velyka, Gianpiero Vignola

29/08/25

Monolithic Active Pixel Sensors (MAPS)

- CMOS active-pixel sensor optimized for detection of the ionizing radiation.
- Both the sensor and the readout electronics are integrated onto the same silicon substrate (monolithic).
- Excellent spatial resolution at low noise, power consumption, material budget, and cost.





Currently, MAPS have only been used in the context of HEP by STAR HFT (RHIC, USA) and ALICE (LHC).

The OCTOPUS Project

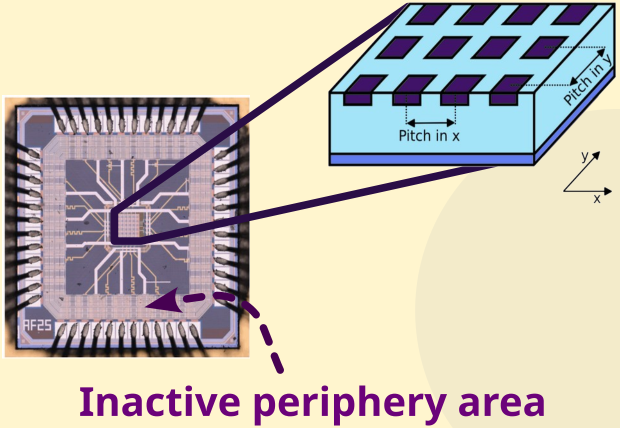
The European Committee for Future Colliders (ECFC) states:

«all-silicon trackers are required for future hadron colliders such as FCC-hh and are one of the most competitive option also for e^+e^- Higgs factories. […] CMOS MAPS are planned for other experiments such as CBM, the LHCb tracker, and Mu3e. MAPS technologies are especially suited for applications requiring low-mass and excellent position resolution called for at electron machines.»

(Source: The 2021 ECFA detector research and development roadmap – CERN,2020)

The OCTOPUS Project concerns the simulation, development and evaluation of monolithic fine-pitch pixel sensors, targeting the vertex-detector requirements of future Lepton Colliders:

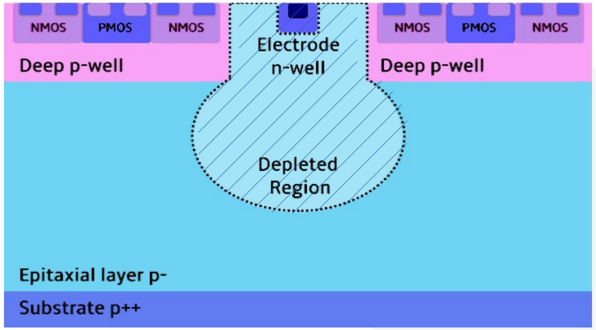
- 3 µm single-point resolution;
- 5 ns time resolution;
- thinning to 50 µm;
- average power consumption below 50 mW/cm2;
- minimal inactive periphery area;
- sensor architecture scalable to a large-area detector system.



MAPS Layouts

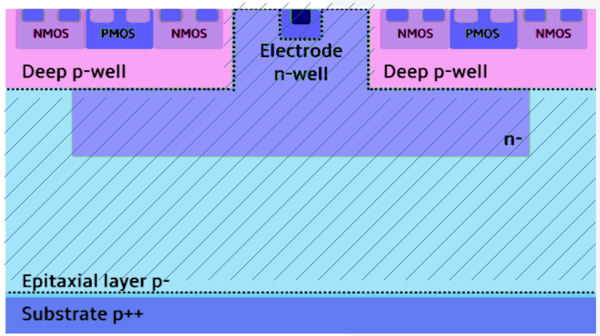
Standard

- Good spatial resolution (charge sharing)
- More space for electronics (larger pitch)
- Slow charge collection (diffusion)
- Low efficacy at high thresholds



N-Gap

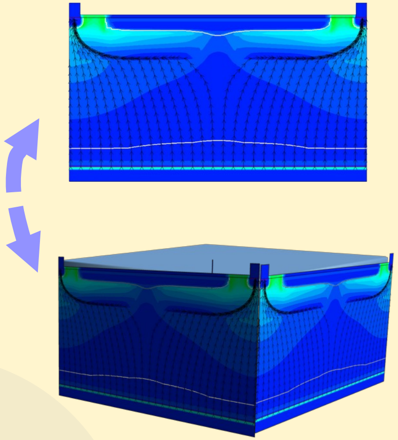
- Fast charge collection (drift)
- High efficacy at high thresholds
- Limited spatial resolution (binary)
- Less space for electronics (smaller pitch)

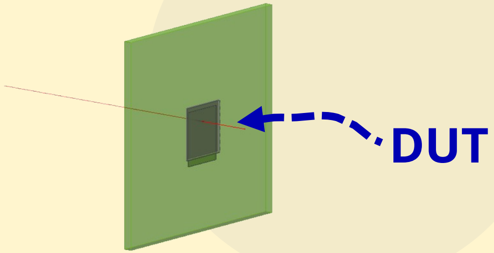


= Depleted Region

Project Overview

Sentaurus TCAD
SYNOPSYS®
Silicon to Software™



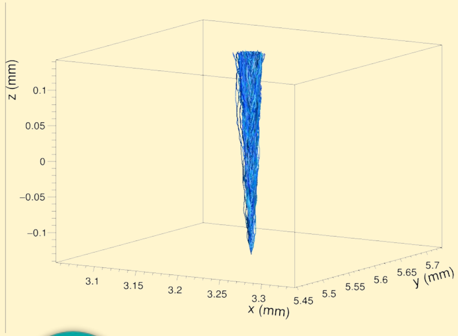


Single pixel simulation

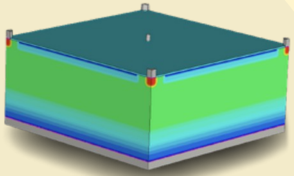
Composite detector simulation

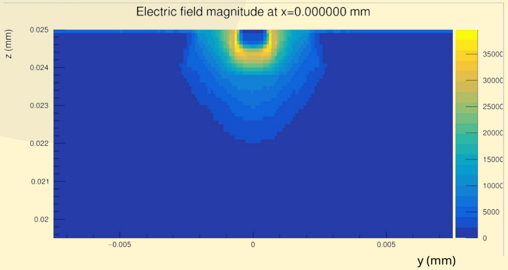
Threshold scan of detector performance

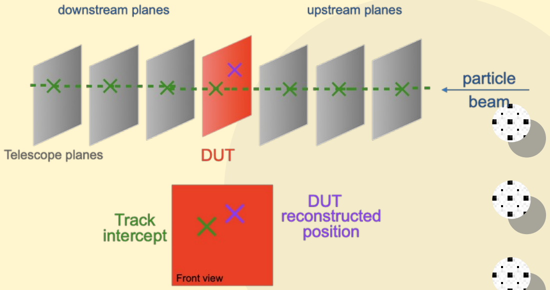
Data analysis and comparison with test beam data



ap²
allpix squared







Chain of Simulation

TCAD

- Simulation of in-pixel electric field and doping concentration
- Outputs in non-homogeneous grids (meshes)
- In each grid vertex, the Poisson equation is evaluated

ALLPIX^2

- **GEANT4** based simulator of particle interactions with detectors
- Simulates the response of the sensor in terms of collected charge
- Provides the mesh_converter, to make the TCAD output meshes homogeneous

Frontend

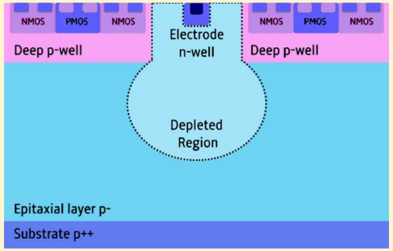
- For a simple analysis, ALLPIX^2 can be used as a frontend, which can be set up with different levels of threshold
- A threshold scan is done to evaluate efficiency and spatial resolution
- For further studies, more complex softwares can be used (LTSpice)

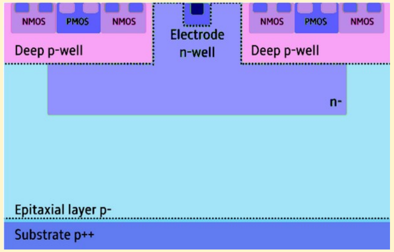
Monte Carlo Simulations

For establishing a working chain of analysis: test on known Standard and N-Gap configurations.

Final Objective: detector performance for different Standard Layout configurations of doping concentrations and geometries.

DUT = 20x20 pixels



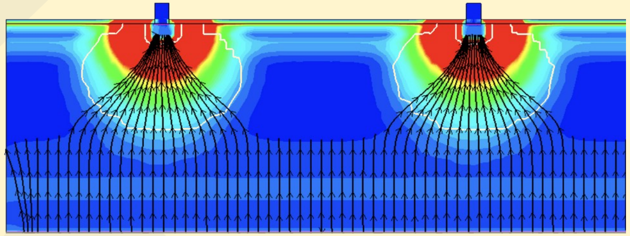


Detector Performance:

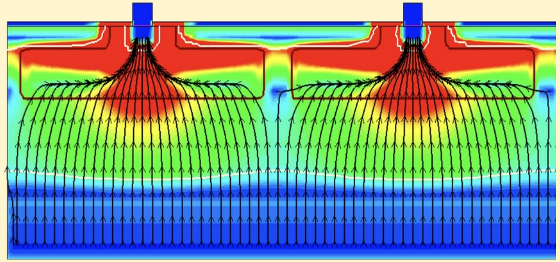
Cluster Size = Number of pixels activated by MIP;

Residuals = Reconstructed particle position - Monte Carlo “truth value”;

Efficiency = Percentage of detected particles passing through the device.

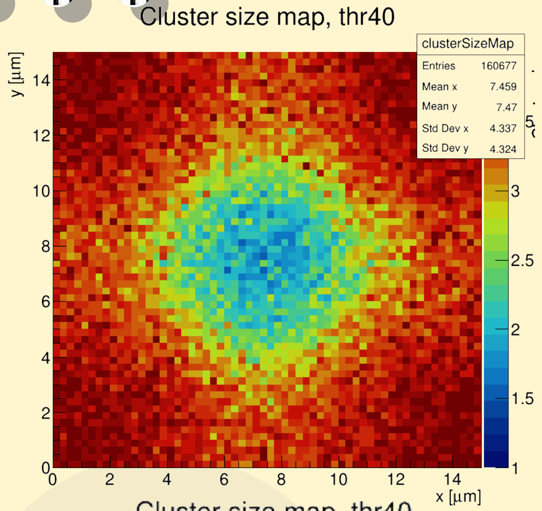


Standard Layout
Electric Field (2 pixels)

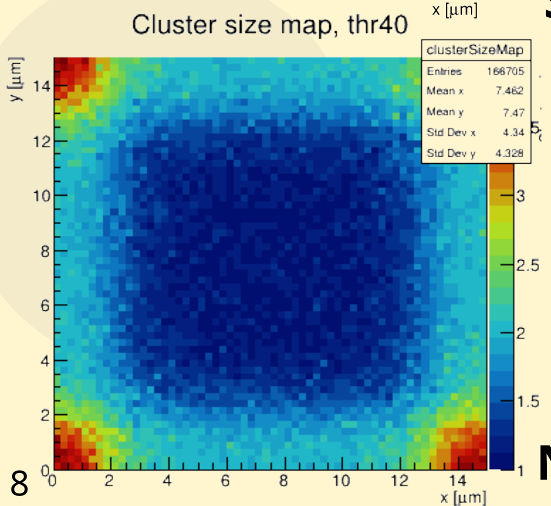


N-Gap Layout
Electric Field (2 pixels)

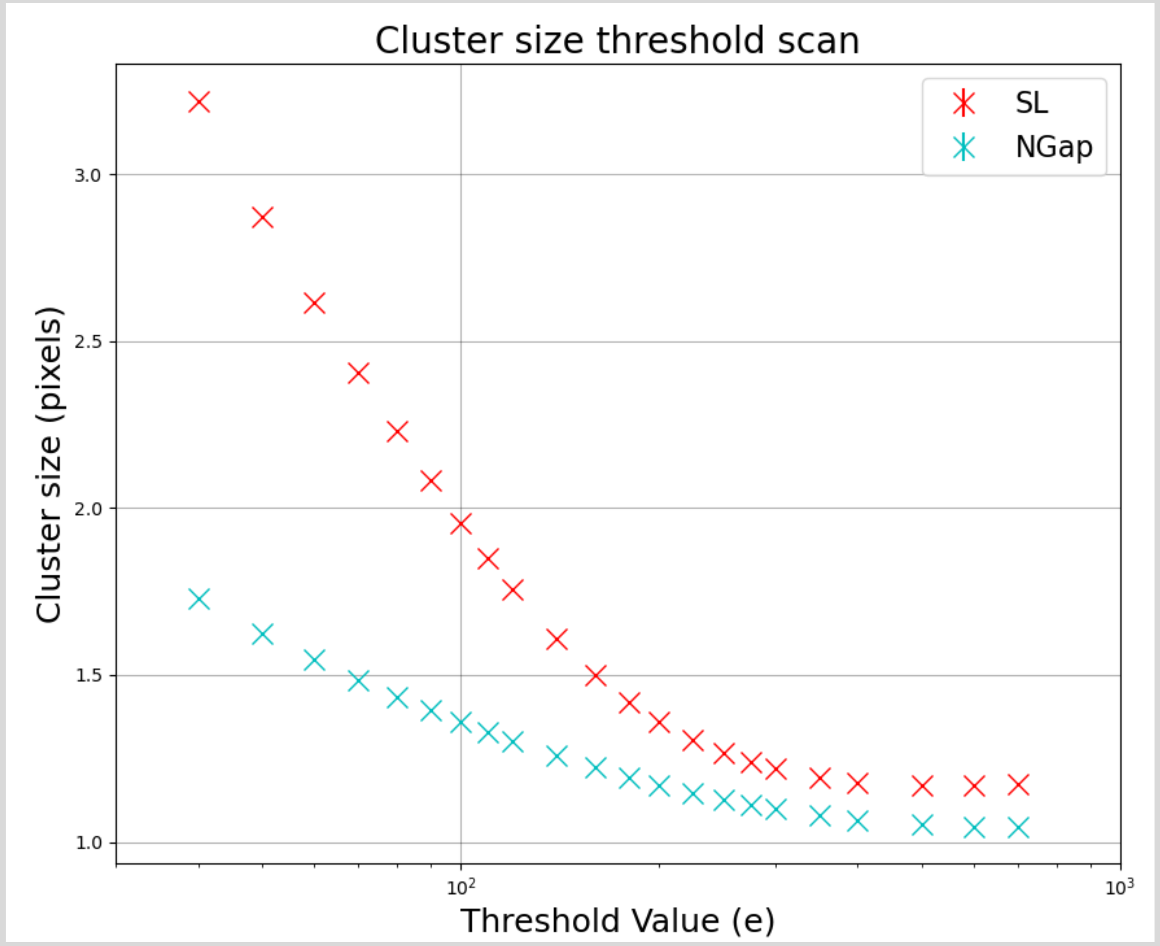
Test: Cluster Size



SL

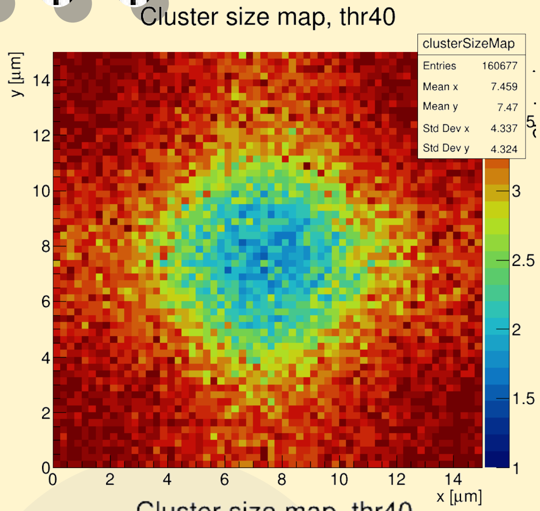


NGap

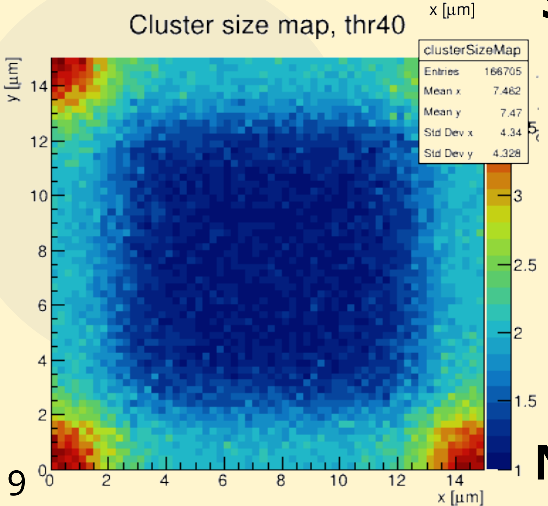


Higher cluster size for Standard Layout: **charge sharing**

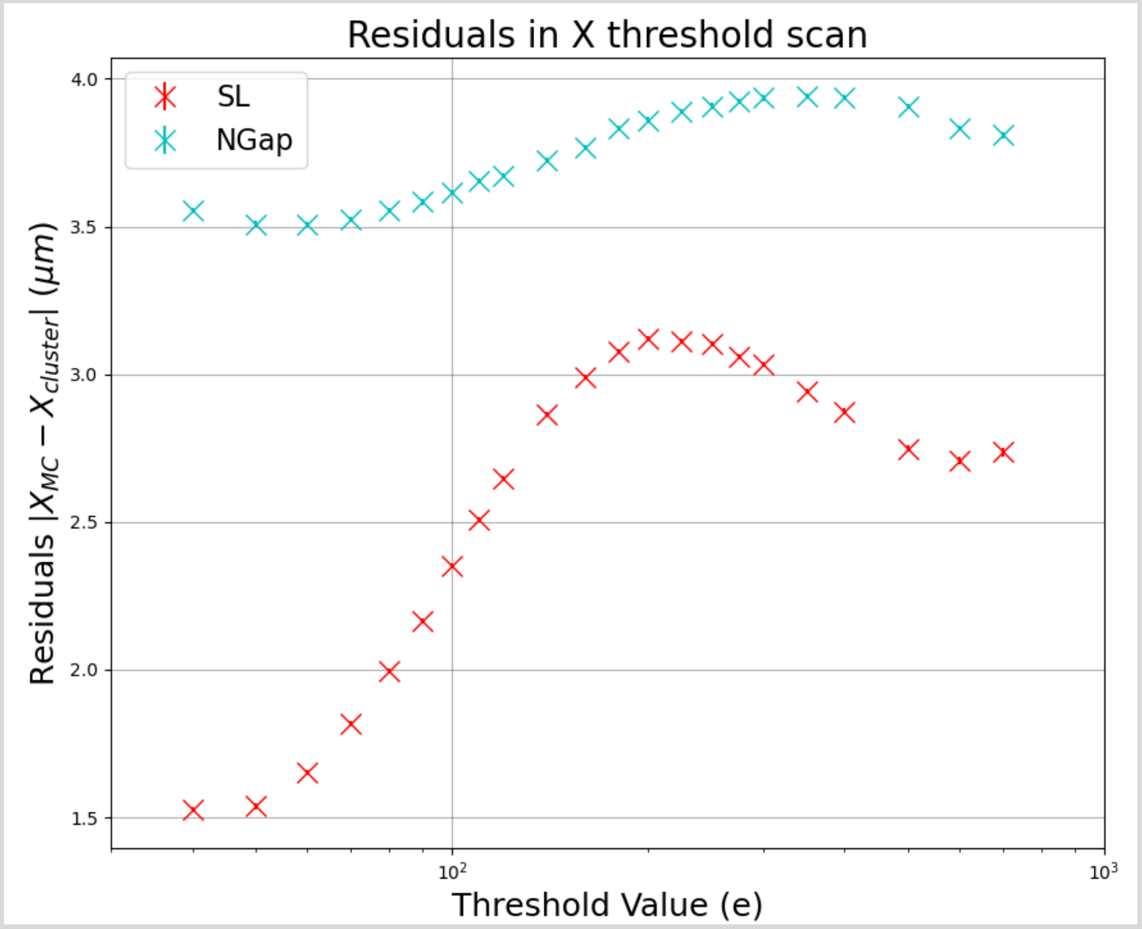
Test: Spatial Resolution



SL

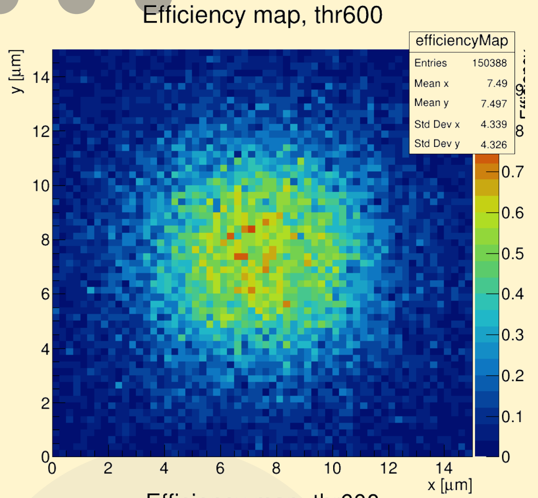


NGap

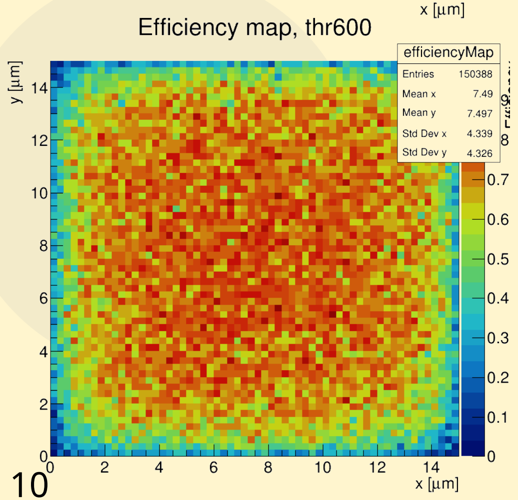


Higher residuals for N-Gap Layout: **binary resolution**

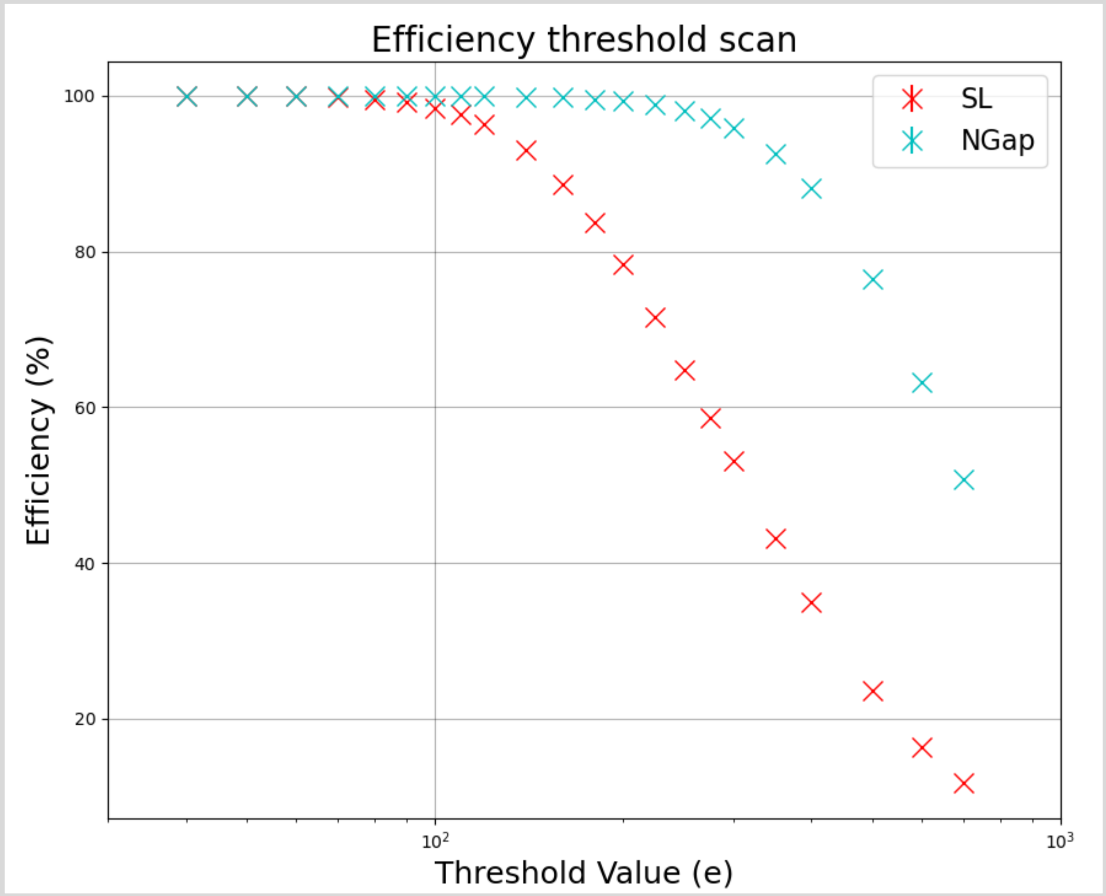
Test: Efficiency



SL



NGap



Higher efficiency for N-Gap Layout: **fast charge collection**

Simulation of New Configurations

DUT = 20x20 pixels

Standard Layout with varying values of doping profile concentration, wells properties and bias voltage.

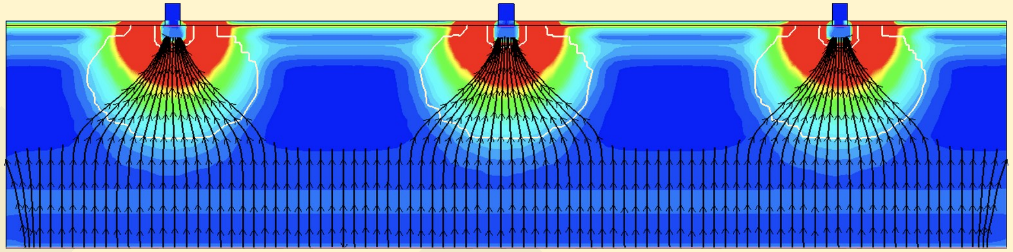
The varying parameters are:

P - Phosphorus concentration of the read-out implant from low (1) to high (4);

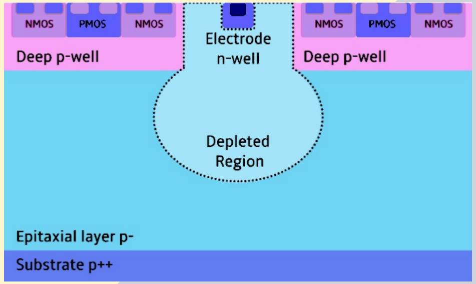
B - Boron concentration of the p-wells from low (1) to high (3)

By changing P and B, the electric field generated in the pixel changes, as does the detector performance.

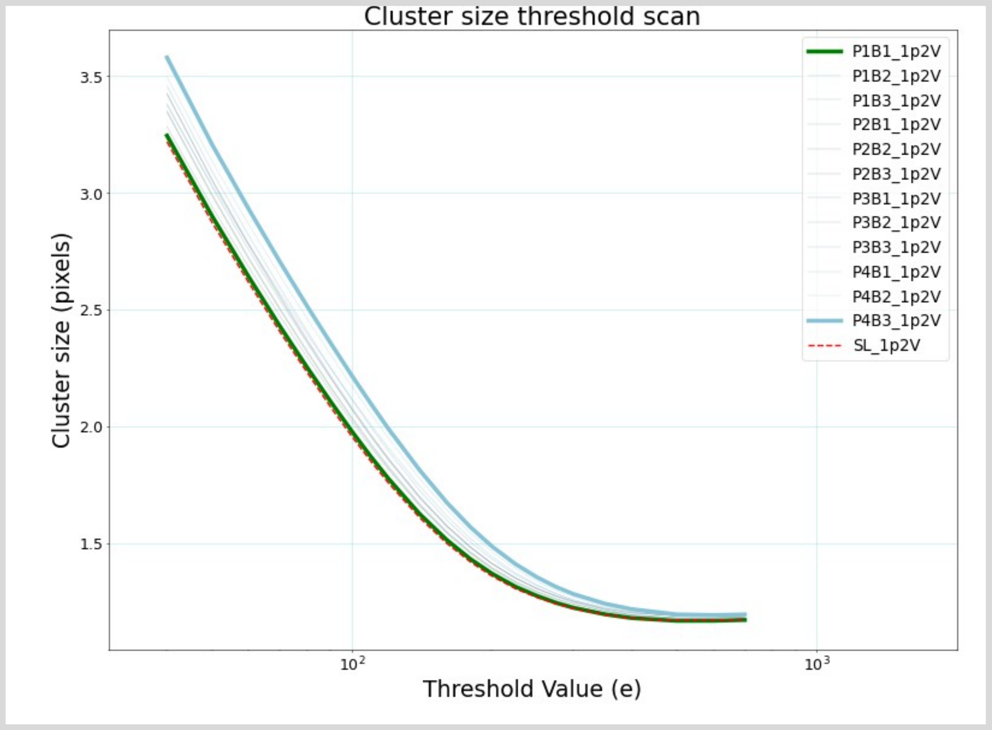
For comparison, the default flat doping profile (SL_1p2V) will also be shown.



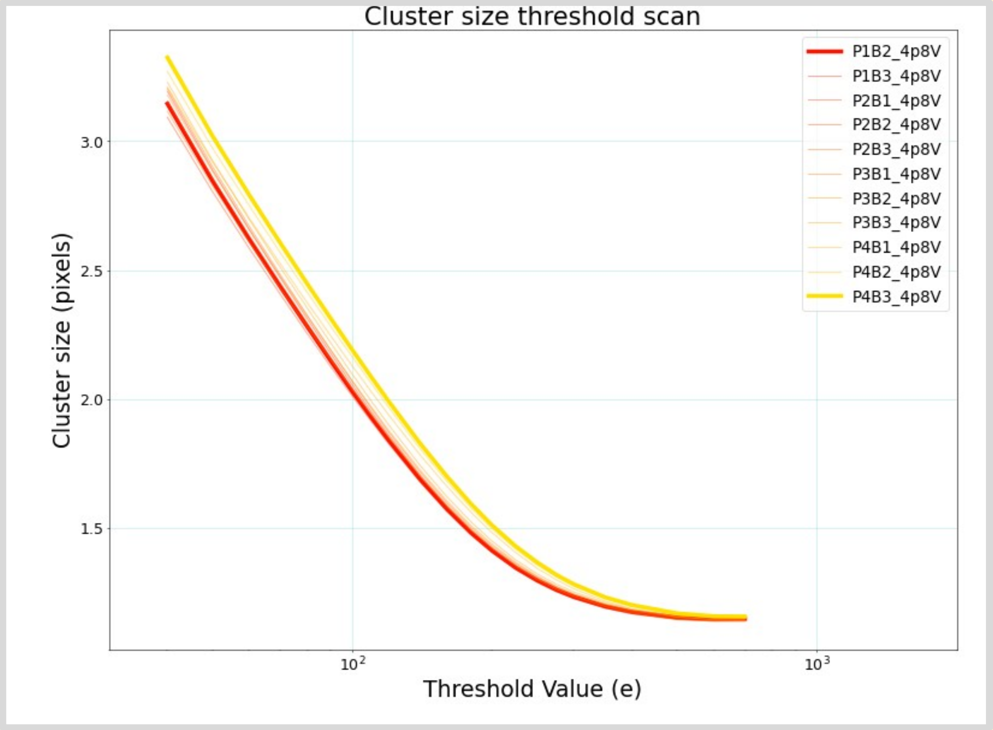
Standard Layout
Electric Field (3 pixels)



Cluster Size



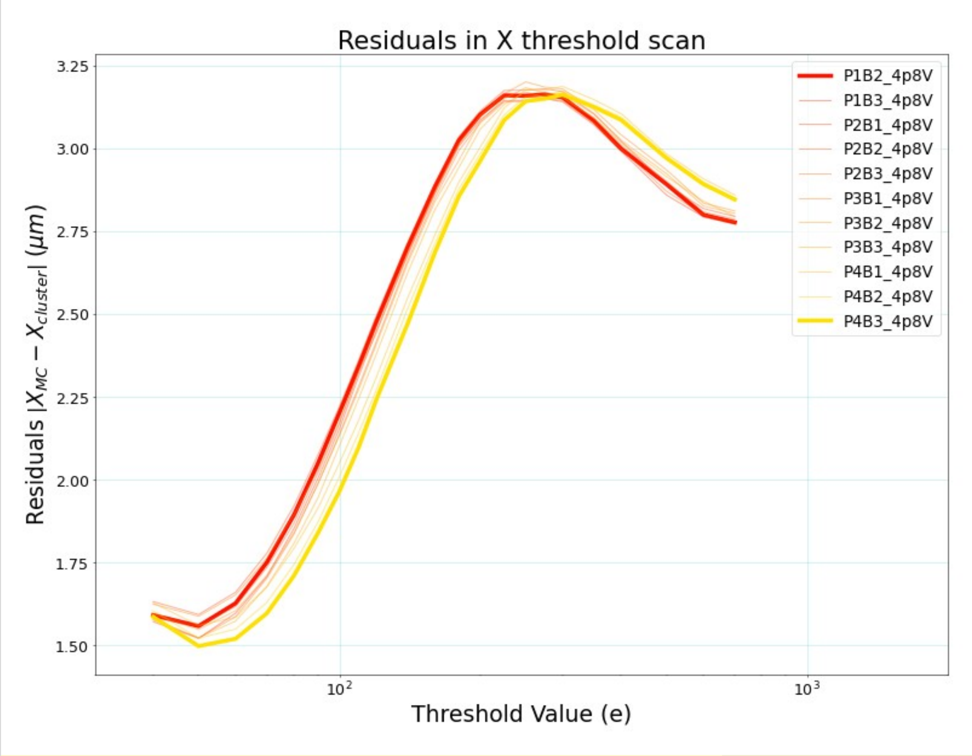
1.2 V



4.8 V

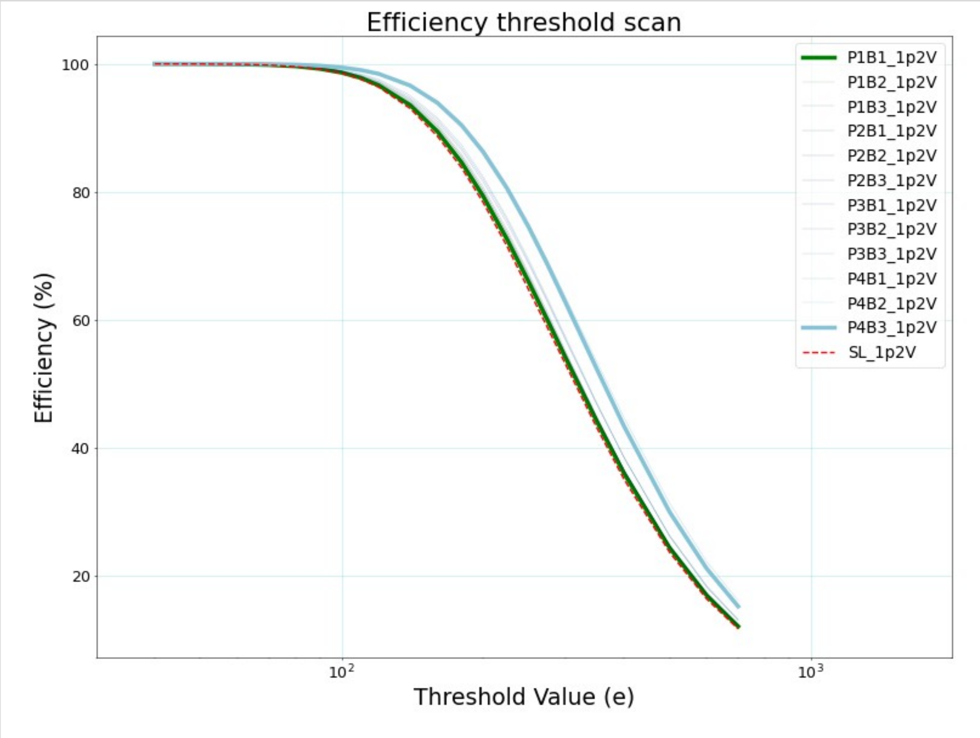
Residuals

1.2 V

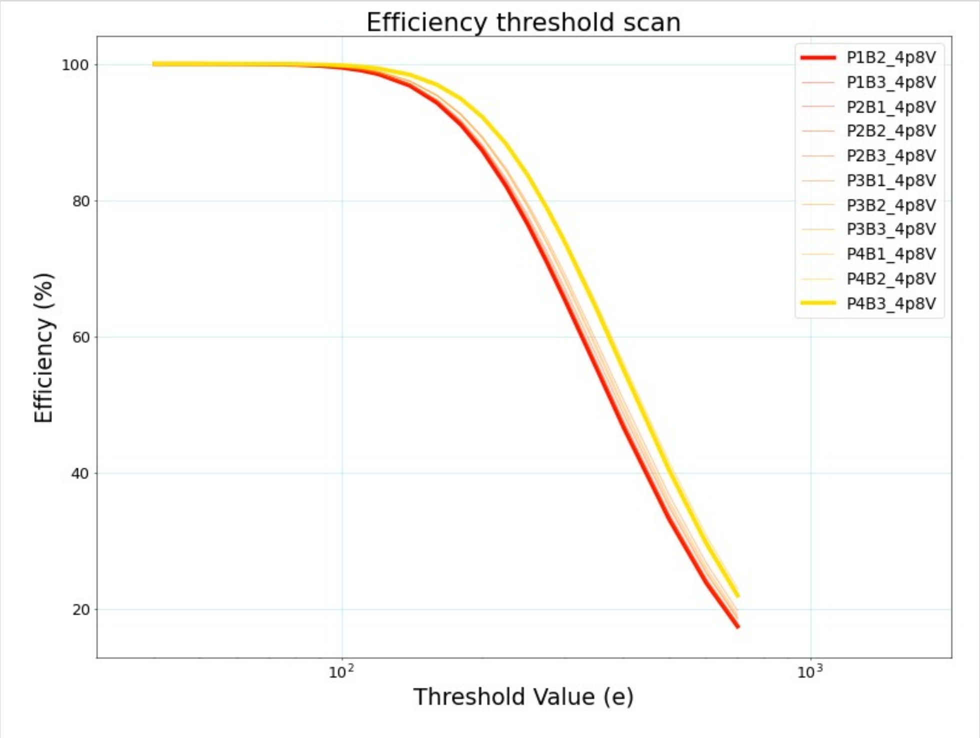


4.8 V

Efficiency



1.2 V



4.8 V

Comparison with beam test data

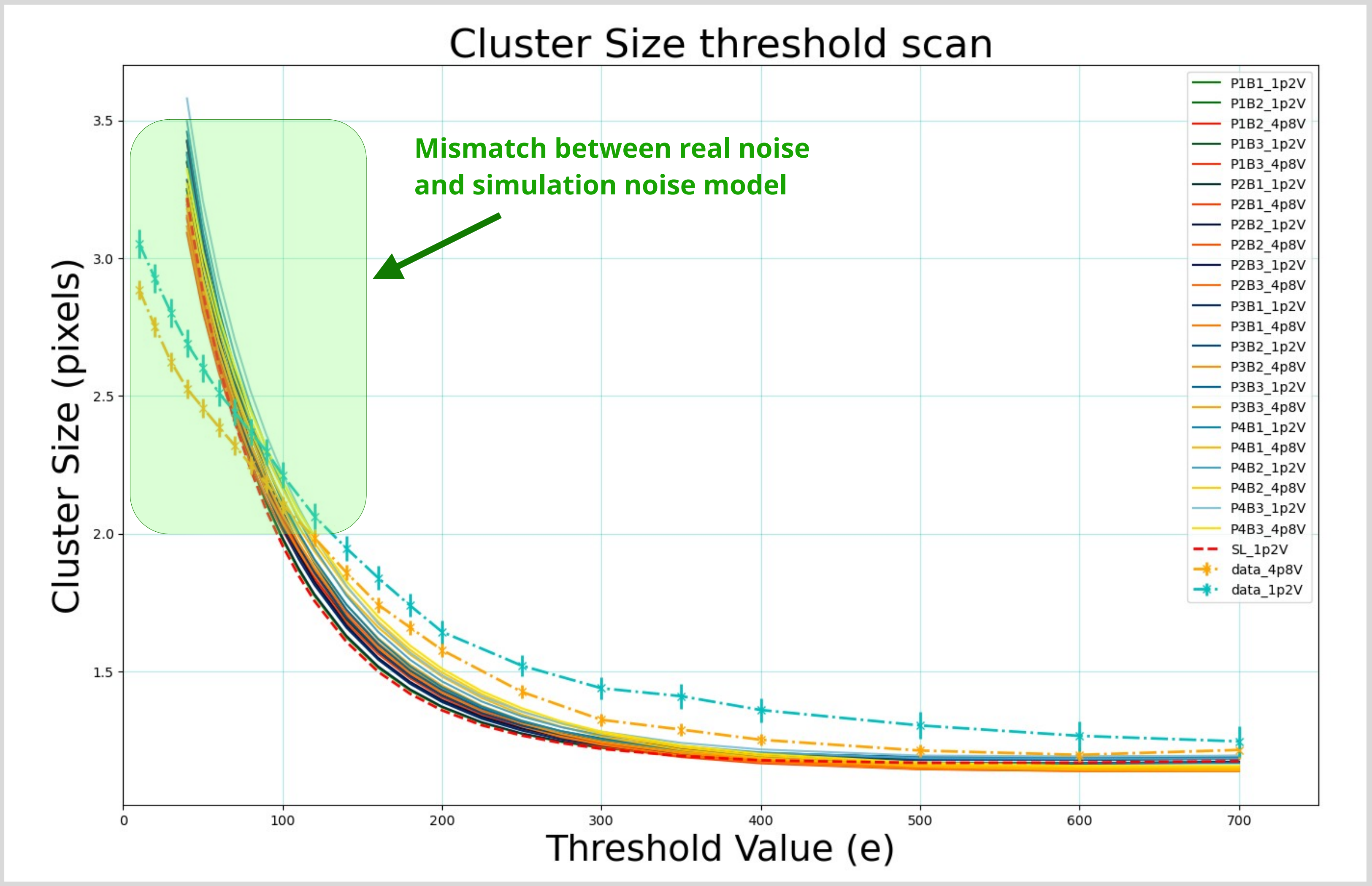
At this level of simulations, the comparison with experimental data can be easily made for cluster size and efficiency, while the experimental spatial resolution is inferred by a more complex analysis than the one simulated here.

To determine which simulated curve is most compatible to the experimental one, the Root Sums Squared (RSS) have been evaluated:

$$RSS = \sqrt{\sum (y - y_0)^2}$$

Where y is simulated data, y_0 is experimental data

Comparison with beam test data



Comparison with beam test data: Cluster Size

1.2V

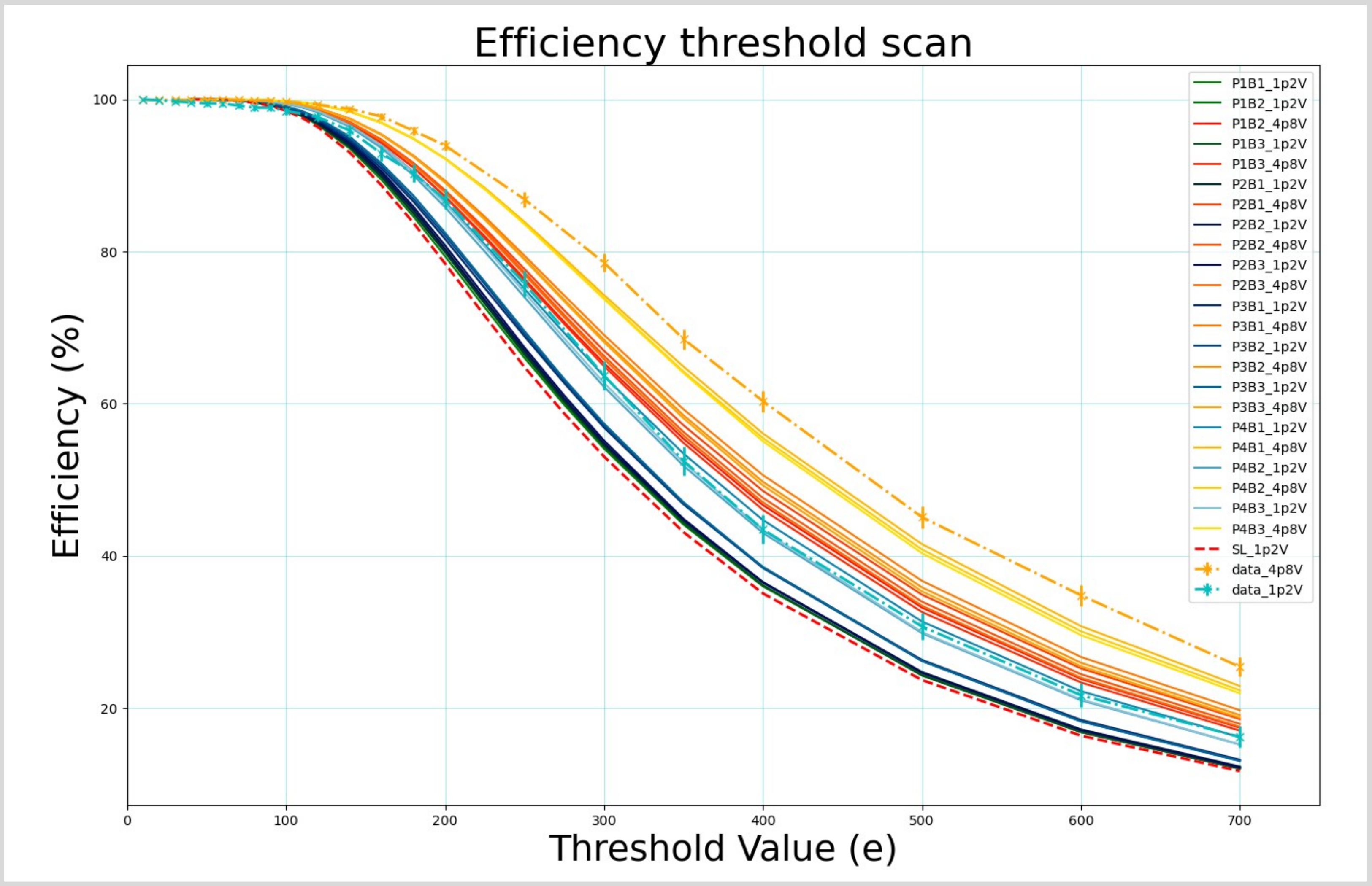
P	B	RSS (pixels)
1	1	**2.9**
\	2	3.1
\	3	3.3
2	1	**2.9**
\	2	3.1
\	3	3.4
3	1	**3.0**
\	2	3.2
\	3	3.4
4	1	**3.1**
\	2	3.5
\	3	3.8

4.8V

P	B	RSS (pixels)
-	-	-
1	2	2.7
\	3	2.8
2	1	**2.4**
\	2	2.7
\	3	2.8
3	1	**2.6**
\	2	2.7
\	3	2.9
4	1	**2.7**
\	2	2.9
\	3	3.1

Best match for low Boron concentartion (B1)

Comparison with beam test data



Comparison with beam test data: Efficiency

1.2V

P	B	RSS (%)
1	1	22.4
\	2	21.7
\	3	21.0
2	1	21.0
\	2	20.4
\	3	19.7
3	1	15.5
\	2	15.1
\	3	14.4
4	1	**3.1**
\	2	3.8
\	3	3.2

4.8V

P	B	RSS (%)
-	-	-
1	2	32.5
\	3	33.7
2	1	28.2
\	2	30.2
\	3	31.4
3	1	23.1
\	2	25.0
\	3	26.0
4	1	**9.9**
\	2	11.3
\	3	12.2

Best match for high phosphorus and low boron concentration (P4B1)

Summary

A working chain of simulation and analysis has been built and tested on known configurations of MAPS:

- As expected, the Standard Layout shows high capability of charge sharing between pixels, but low efficiency at high threshold, compared to the N-Gap Layout.

Once the validity of the analysis has been established, new configurations of Standard Layouts with varying concentrations of phosphorus in the read-out system and boron in the p-wells have been simulated and compared to real beam test data of a Standard Layout detector:

- Higher levels of phosphorus and boron concentration increase charge sharing and efficiency;
- Configurations with high phosphorus concentration and low boron show the most similar behaviour to the real detector, even though discrepancies still exist.

Noise-related parameters have been changed in the simulations to search for a better match, but no significant differences have been found.

Bibliography

- Ruiz Daza, S. (2022) *Monte Carlo Simulations of Detector Prototypes Designed in a 65 nm CMOS Imaging Process.* [Unpublished master's thesis] Rheinischen Friedrich-Wilhelms-Universität Bonn.
- Wennlöf, H., Dannheim, D., Del Rio Viera, M. et al. *Simulating monolithic active pixel sensors: A technology-independent approach using generic doping profiles*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 1073, 2025, 170227, ISSN 0168-9002.
- Vignola, Gianpiero: Studies of a Digital SiPM and MAPS Prototypes as Key Technologies for Future High-Energy Physics Experiments. - Bonn, 2025. - Dissertation, Rheinische Friedrich-Wilhelms-Universität Bonn.
- European Committee for Future Accelerators. Detector R&D Roadmap Process Group. (2021). *The 2021 ECFA detector research and development roadmap.*

“

THANK YOU

”

Backup

High Energy Physics (HEP)

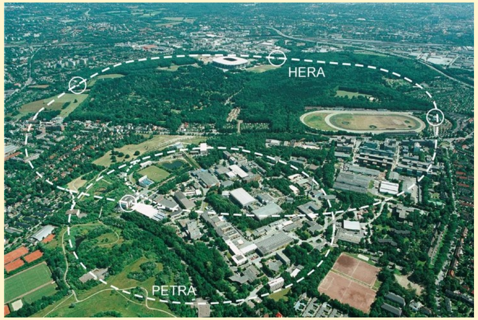
Study of the fundamental particles and forces that make up matter and radiation.

The sum total of the knowledge of all the forces and particles is known as **Standard Model**.

To test the predictions of the Standard Model, particle accelerators like LHC or HERA are necessary for high energy collisions, that replicate conditions similar to those just after the Big Bang.

The Large Hadron Collider is the world's largest and highest-energy particle accelerator.

- 27 km circumference, 175 m depth tunnel, near Geneva.
- The first collisions in 2010 at 3.5 TeV energy per beam, four times the previous world record.
- Higgs boson discovery at the LHC in 2012

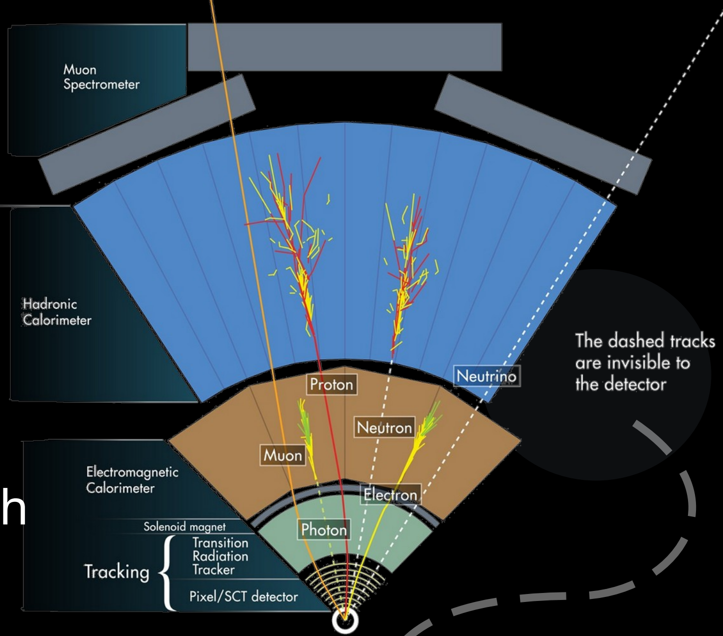


HERA is the only lepton–proton collider in the world to date.

- Operated from 1992 to 30 June 2007 at DESY in Hamburg.
- Electrons and positrons collisions with proton center-of-mass energy of 320 GeV.
- Study of quarks, gluons and structure of protons, laying the foundation for the science done at LHC.

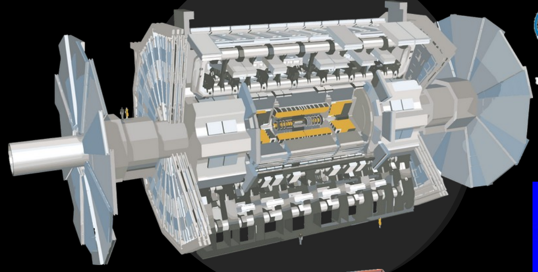
Particle Detectors

Particle and nuclear physics discoveries are driven by **detector innovation.**



Tracking: “correct” particle trajectory from signals in various layers
Calorimeters: measurement of particle energy through absorption of released energy

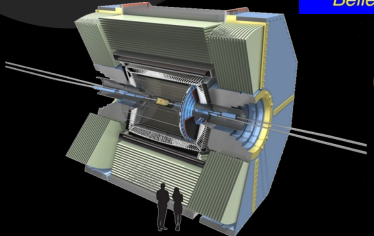
Demanding experiments, like the HEP collisions, favour detectors with
- high spatial resolution,
- high efficiency,
- good radiation resistance,
- small dimensions (low material budget).

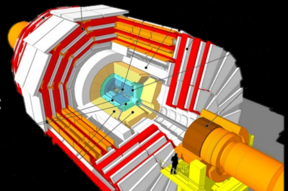


ATLAS EXPERIMENT

Belle II

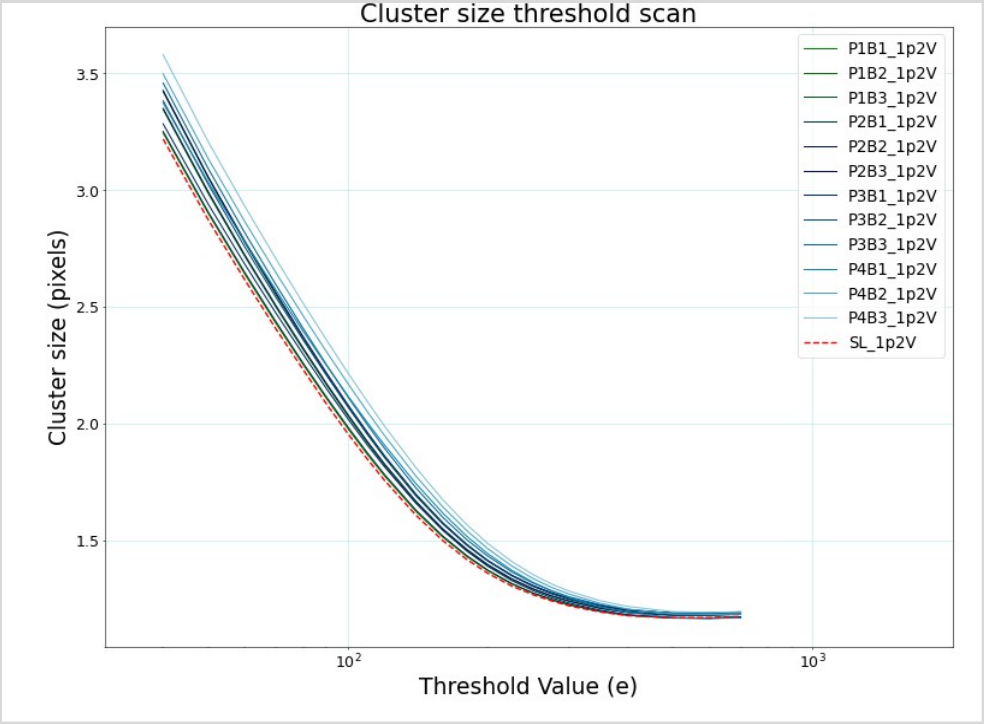
CMS



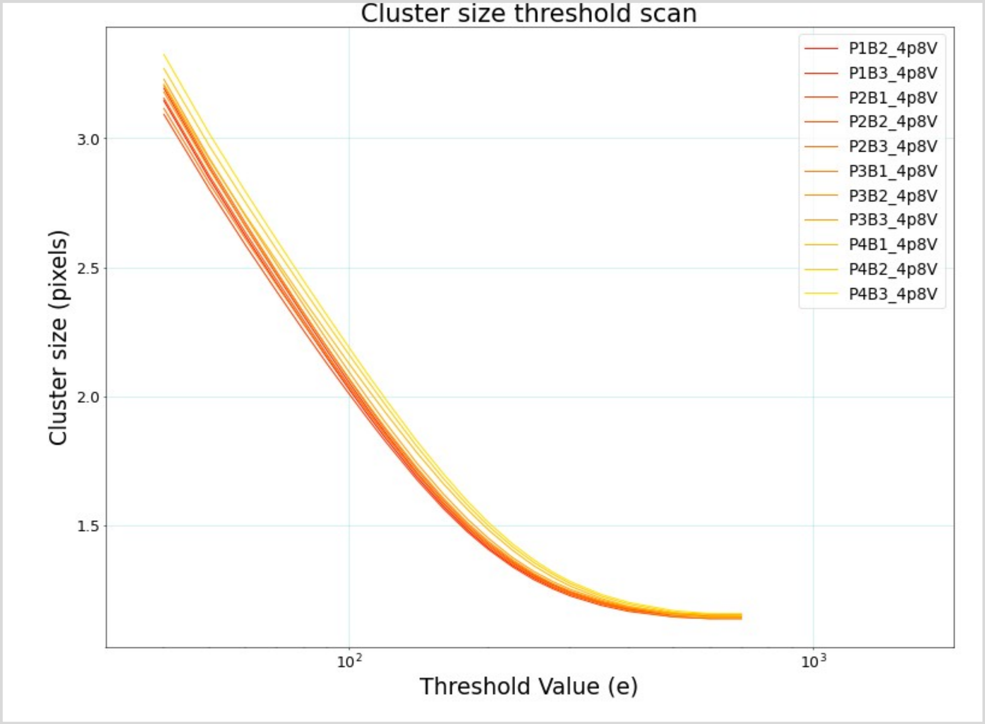


Monolithic Active Pixel Sensors

Cluster Size



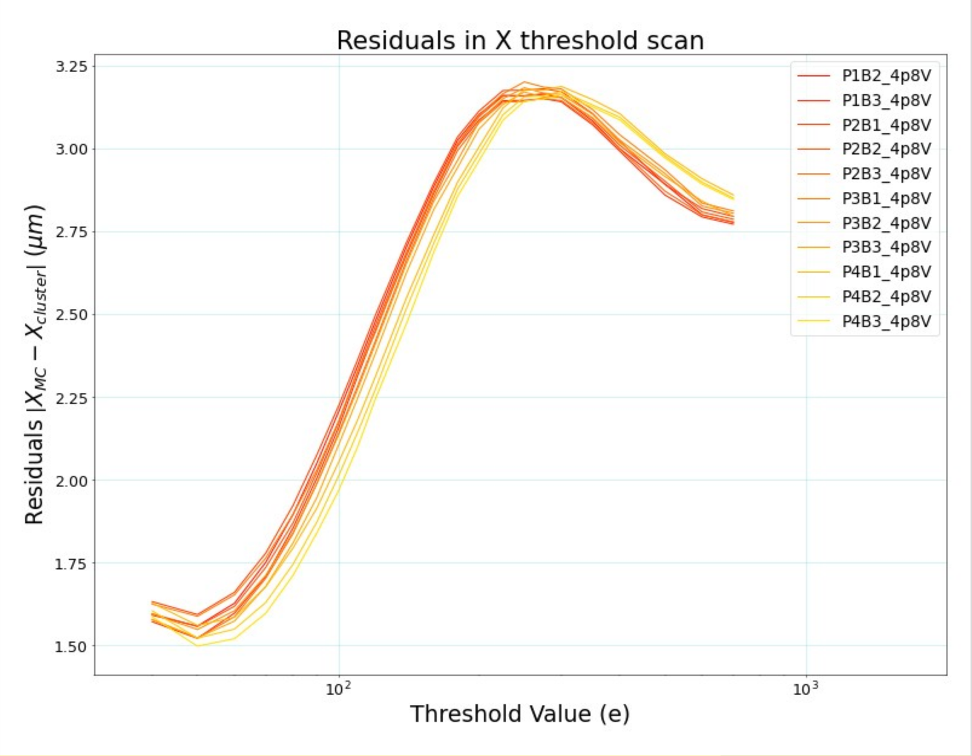
1.2 V



4.8 V

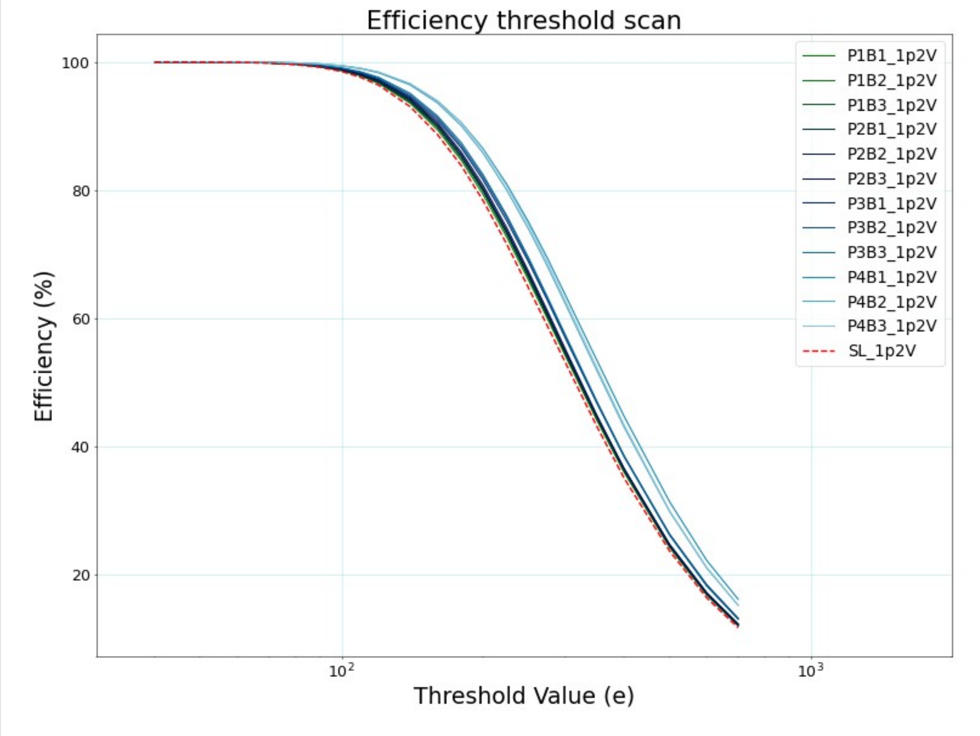
Residuals

1.2 V

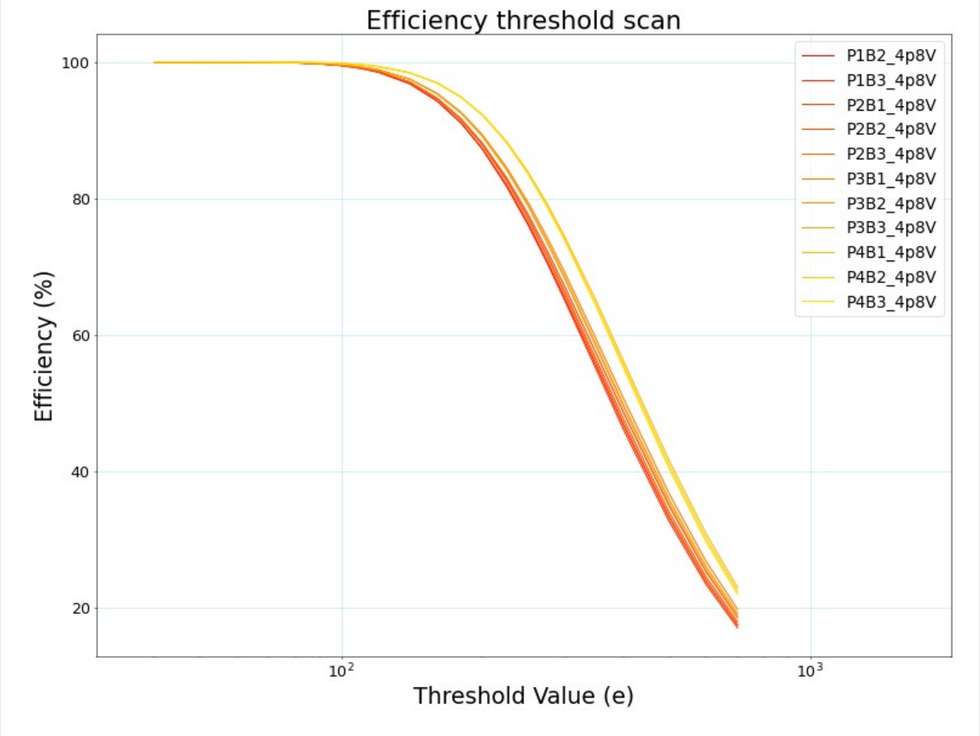


4.8 V

Efficiency

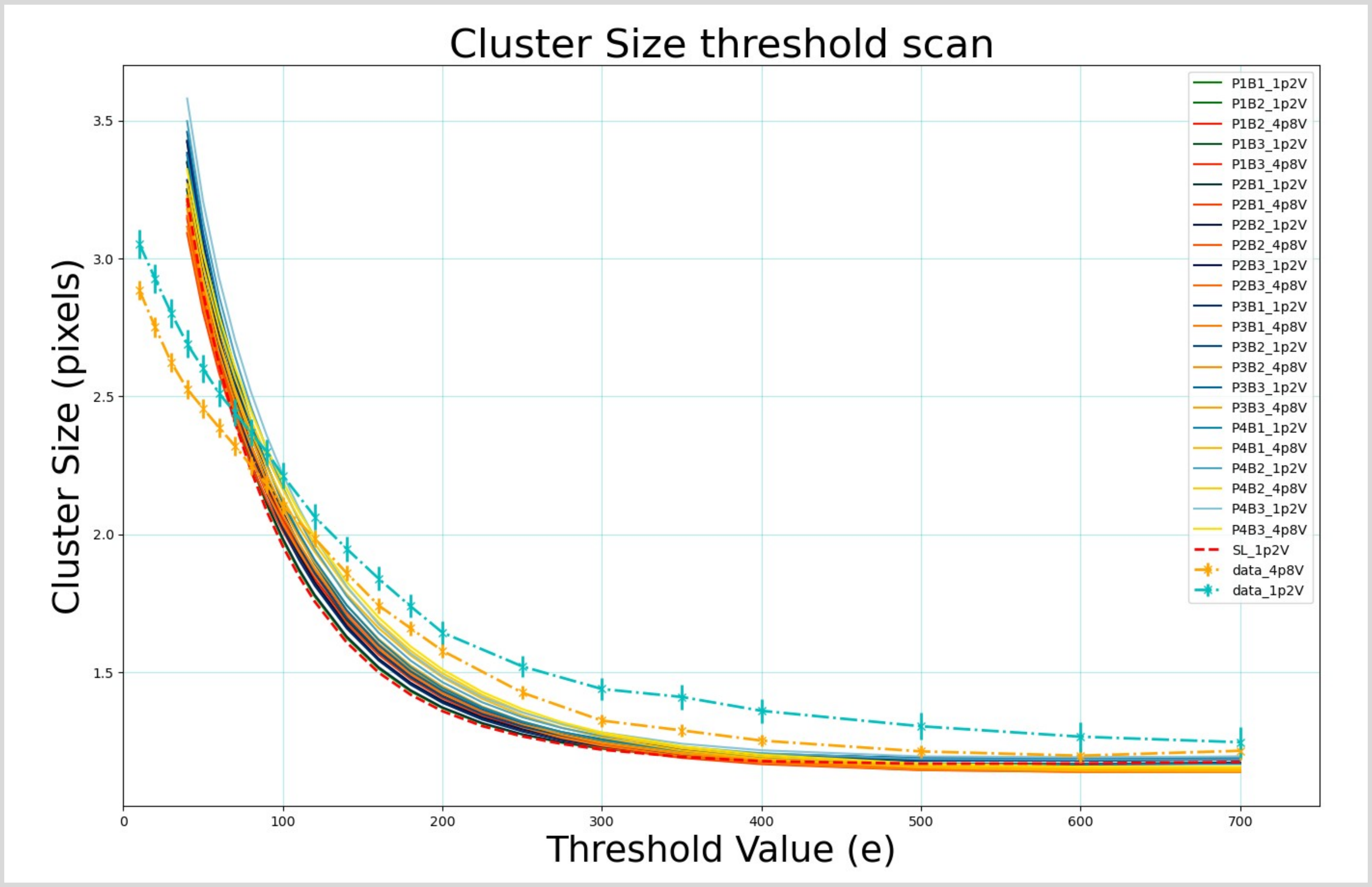


1.2 V



4.8 V

Comparison with beam test data



Comparison with beam test data