Tangerine: Monte Carlo simulations of MAPS in a 65 nm imaging process

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10th Beam Telescopes and Test Beams Workshop

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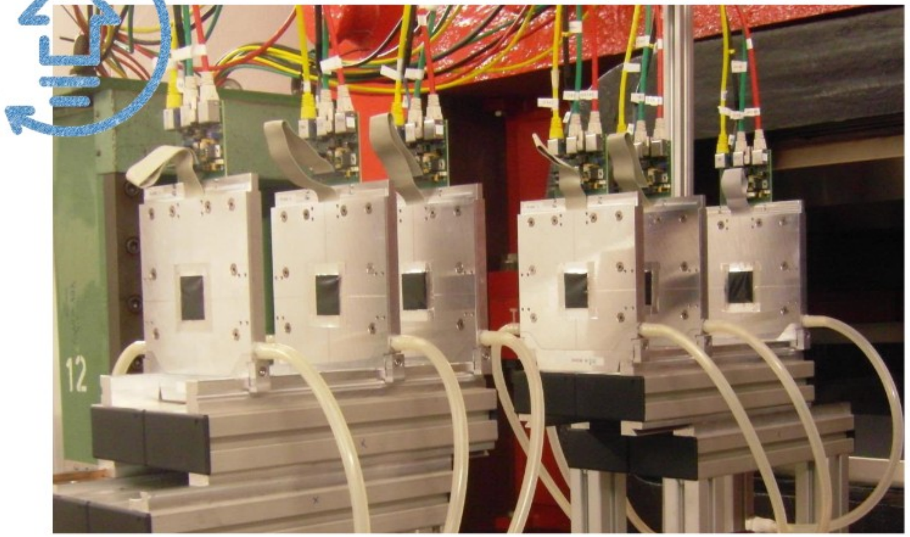
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

UNIVERSITÄT BONN

The Tangerine Project - Towards Next Generation Silicon Detectors

Goal: Design a monolithic pixel detector in 65nm CMOS imaging technology

- **Main application**: beam telescope
- **Potential applications**: linear collider experiments, etc.



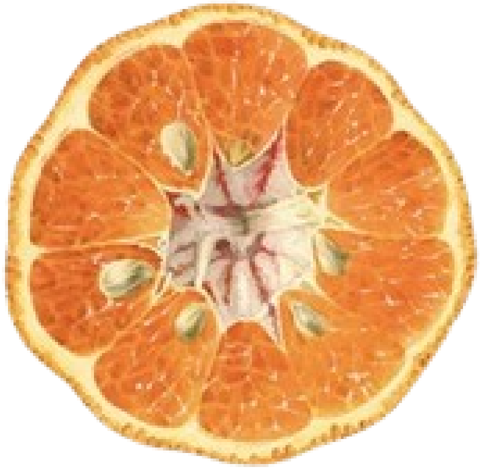
MIMOSA Beam Telescope, DESY II Test Beam Facility

Performance targets:

- Position resolution ≤ 3 µm
- Time resolution ~ 1 – 10 ns
- Material budget ~ 50 µm Si

The Tangerine Project - Towards Next Generation Silicon Detectors

- **The Tangerine project's goal** is to develop the next generation of small collection electrode **monolithic silicon pixel detectors** using the **65 nm CMOS** imaging process.



Monolithic Silicon Pixel Detector using 65 nm CMOS imaging process:

- **Higher logic density**
- **Lower power consumption** (compared to previously used processes).

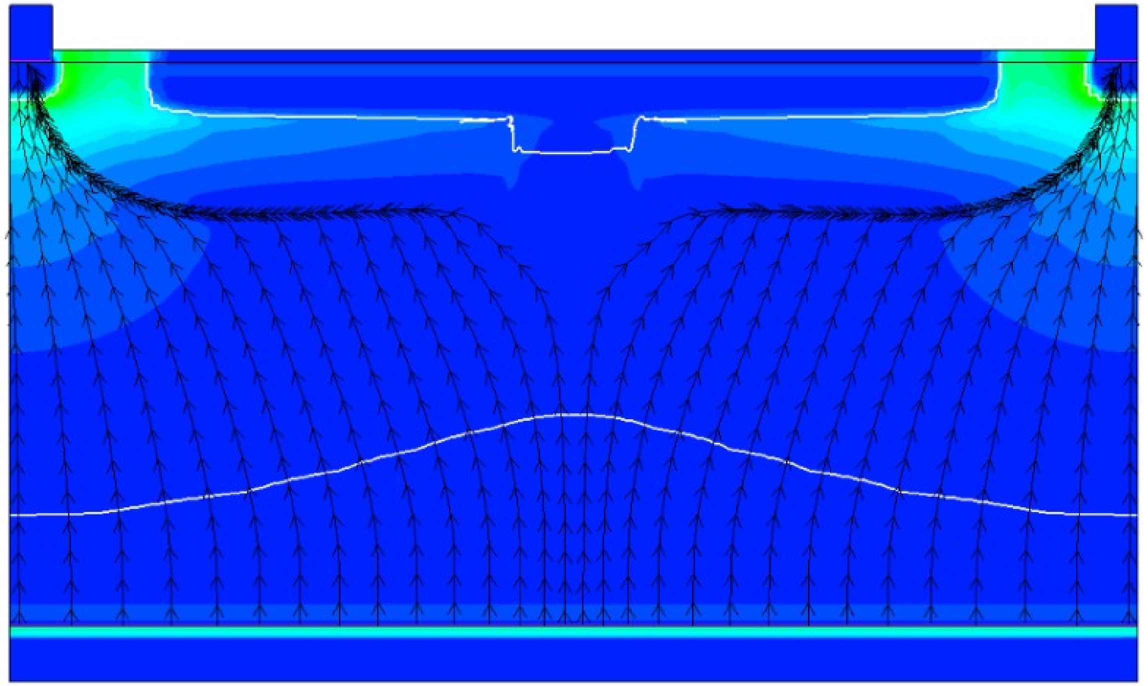
In monolithic sensors:

- The **sensitive volume and readout are in a single chip**
- **Lower material budget**, and **reduced cost** and **production effort** (compared to hybrid sensors).

Technology computer-aided design (TCAD)

The **electric field** and the **doping concentration** in silicon detectors are certainly **complicated**.

TCAD is utilized in order to obtain this important profiles that characterize the detector layout.



https://doi.org/10.48550/arXiv.2206.05474

Shoutout to **Anastasiia Velyka, Adriana Simancas, Larissa Mendes**

Allpix Squared (Allpix^2)

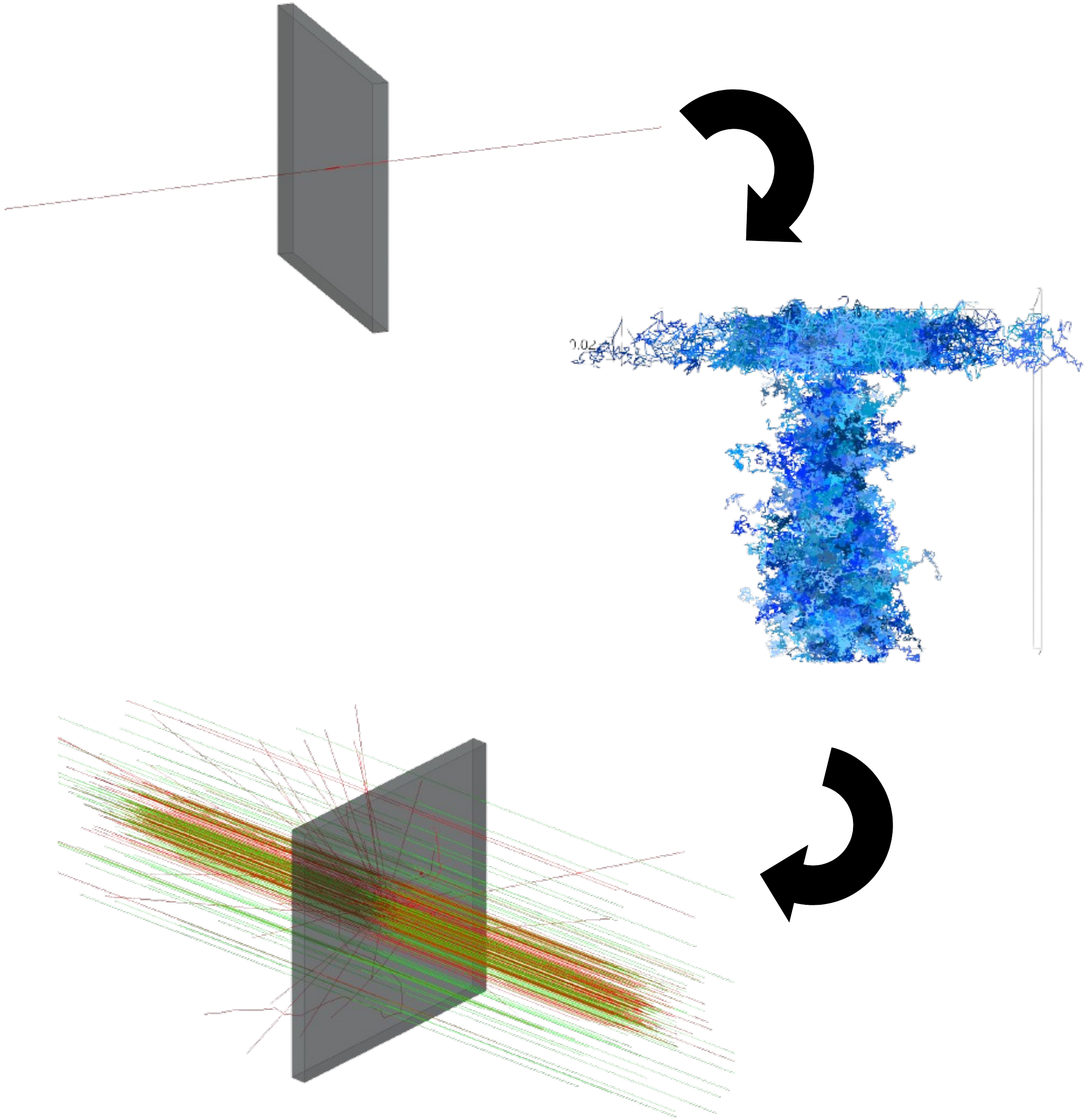
A combination of **TCAD** and **Monte Carlo (MC)** simulations are used.

Allpix^2 is a generic **simulation framework for silicon detectors**, written in modern C++.

Motivation:

- Reduced simulation **time** and **simplicity** compared to the **TCAD** only approach
- **Value** of the simulation results
- Reduced **cost**
- **Reproducibility** of performance

Monte Carlo Setup



1) A particle is **randomly*** shoot through the sensor.

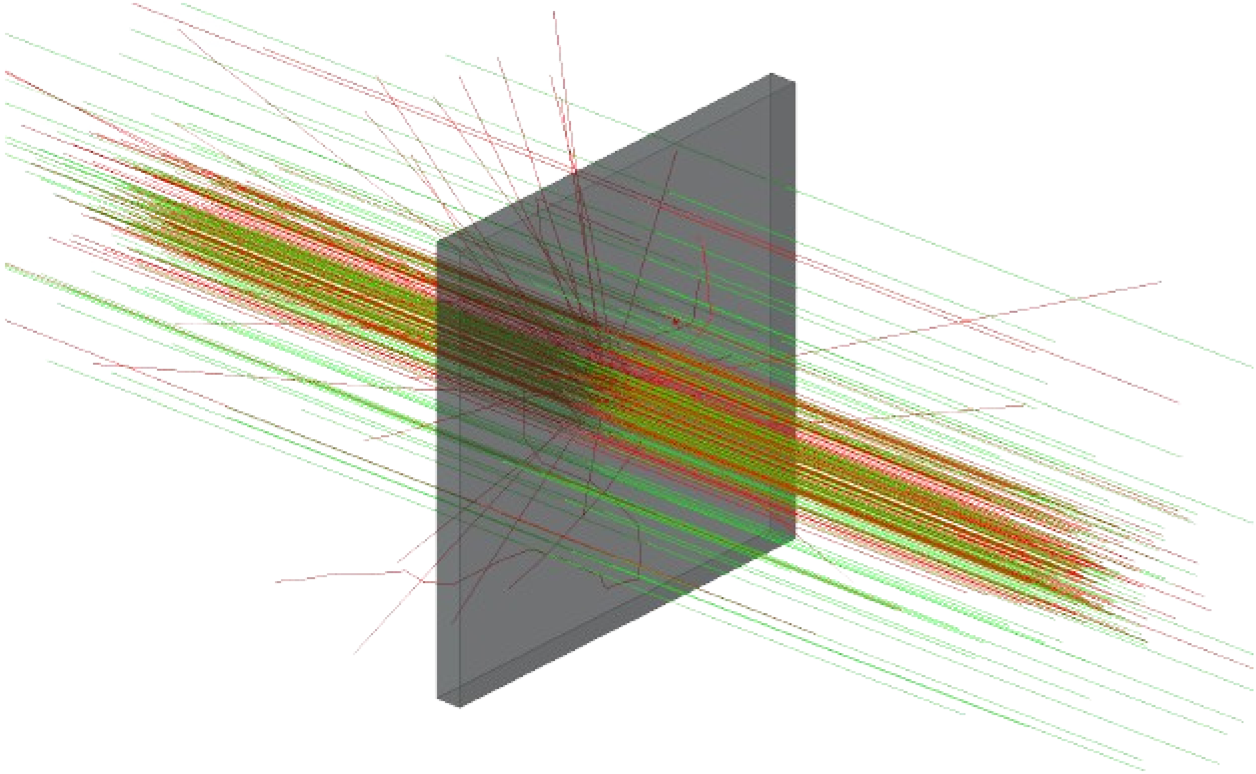
2) **Ionization** (And other Physics processes: Diffusion, Drift, Recombination...).

3) **Repetition (**Same energy and direction**).**

4) **Analysis**

* Gaussian Beam like

Monte Carlo Setup



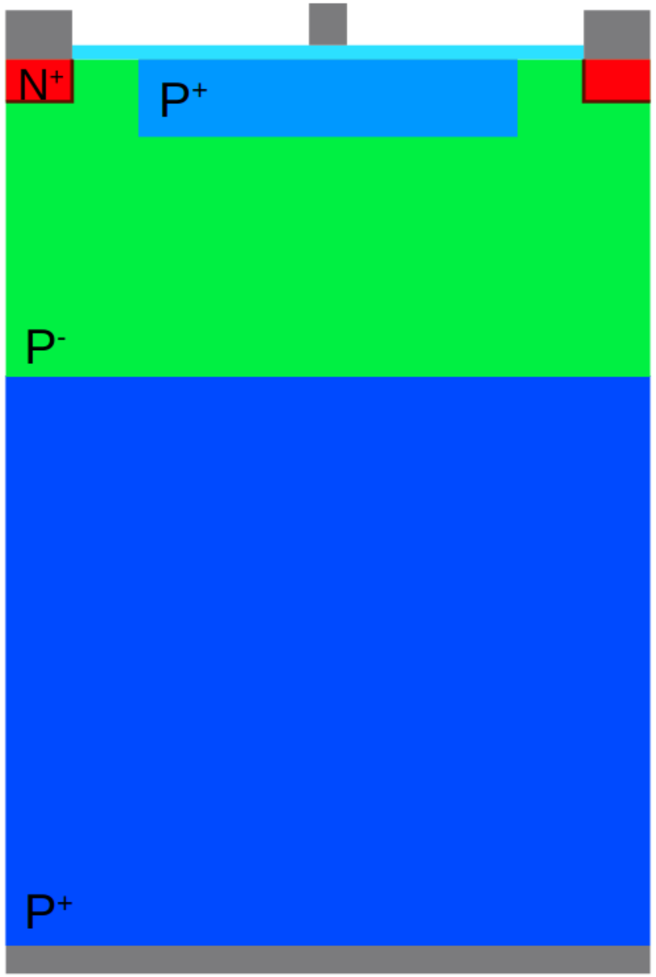
In our case, the beam is a Gaussian electron beam with a **5 GeV** energy (a **DESY** like type of beam).

The number and size of the pixels in the sensor can be adjusted depending in our needs, a typical size being **20x20 μm²**.

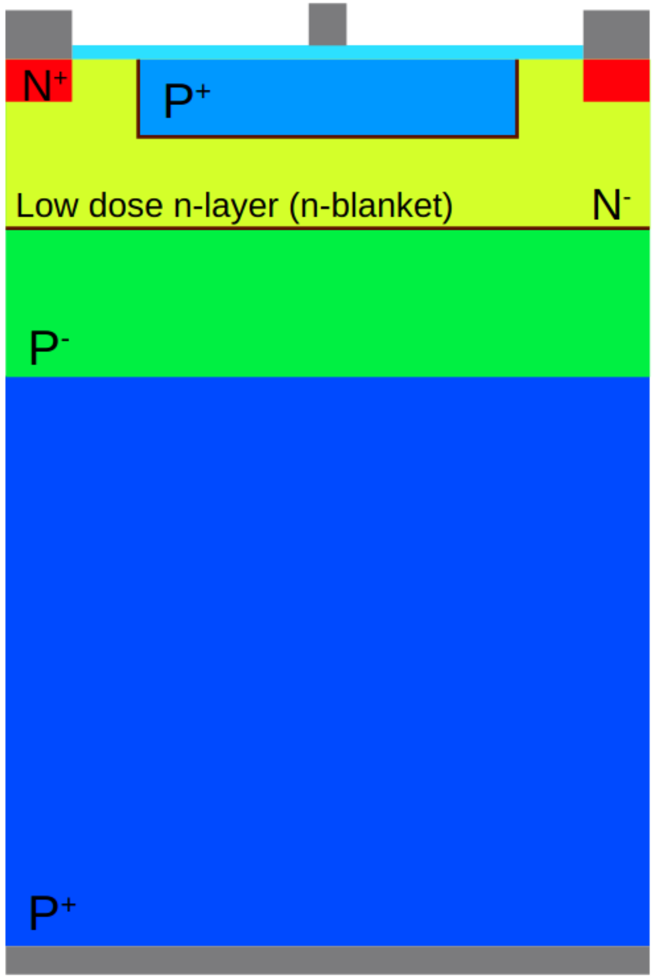
Important quantities for us to obtain are:

- **Efficiency**
- **Hit Map**
- **Cluster Size and Cluster Charge**
- **Spatial Resolution**
- **...**

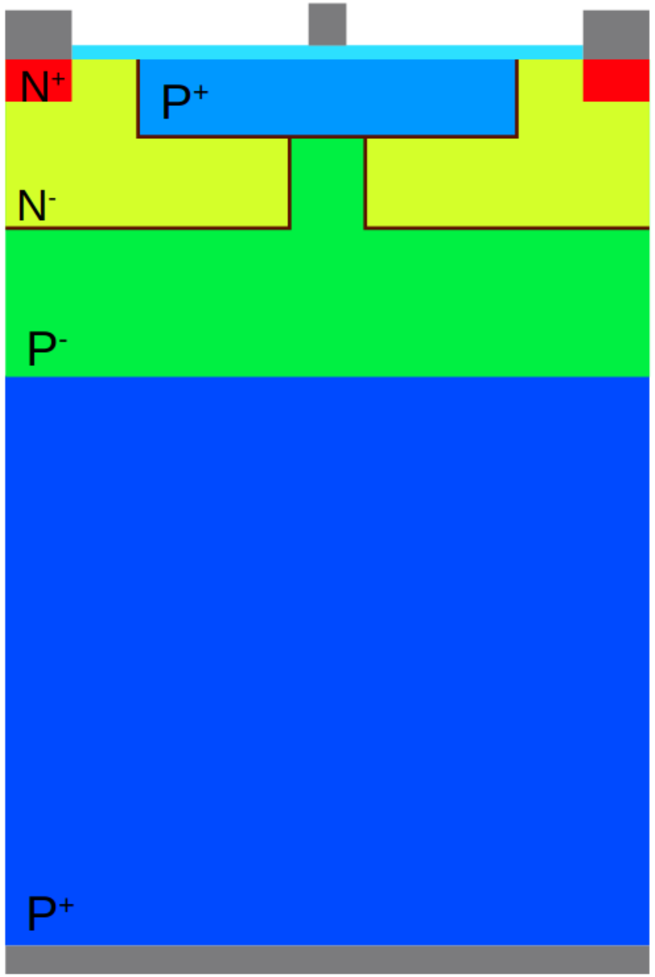
Standard Layout



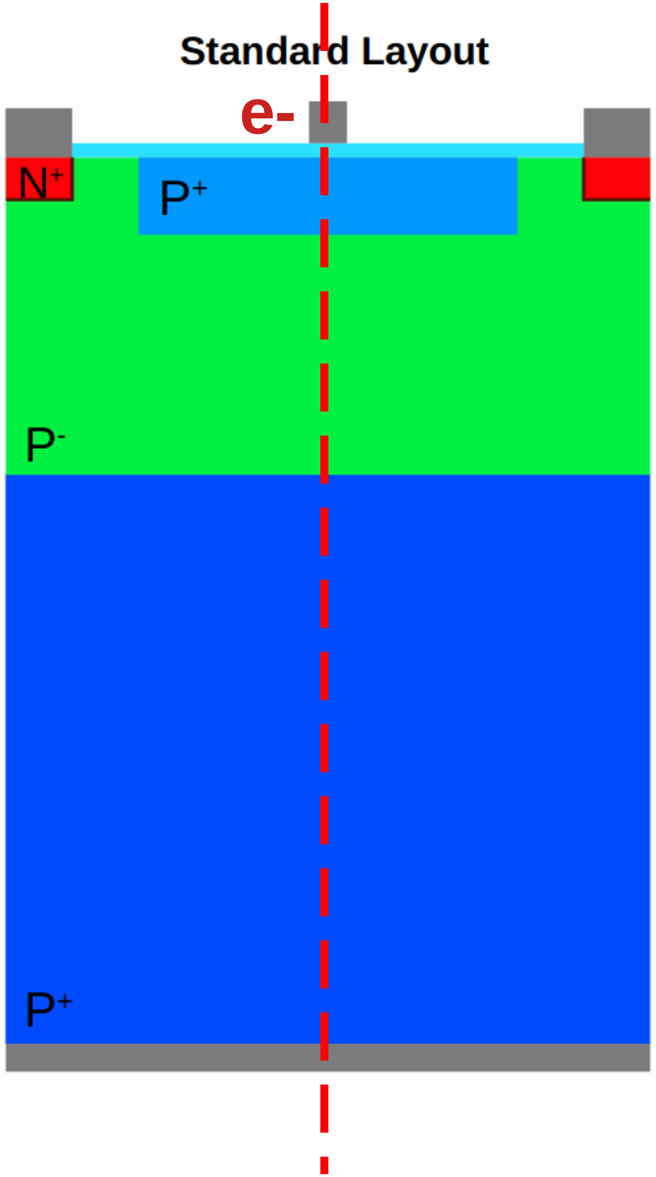
N-blanket Layout



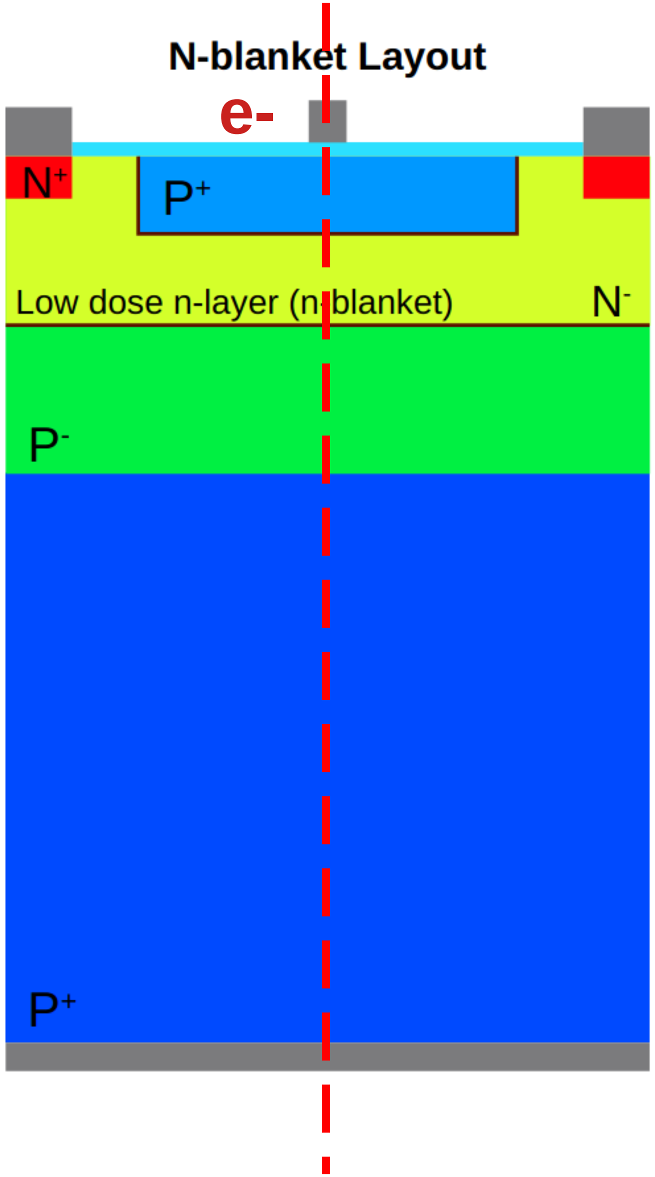
N-gap Layout



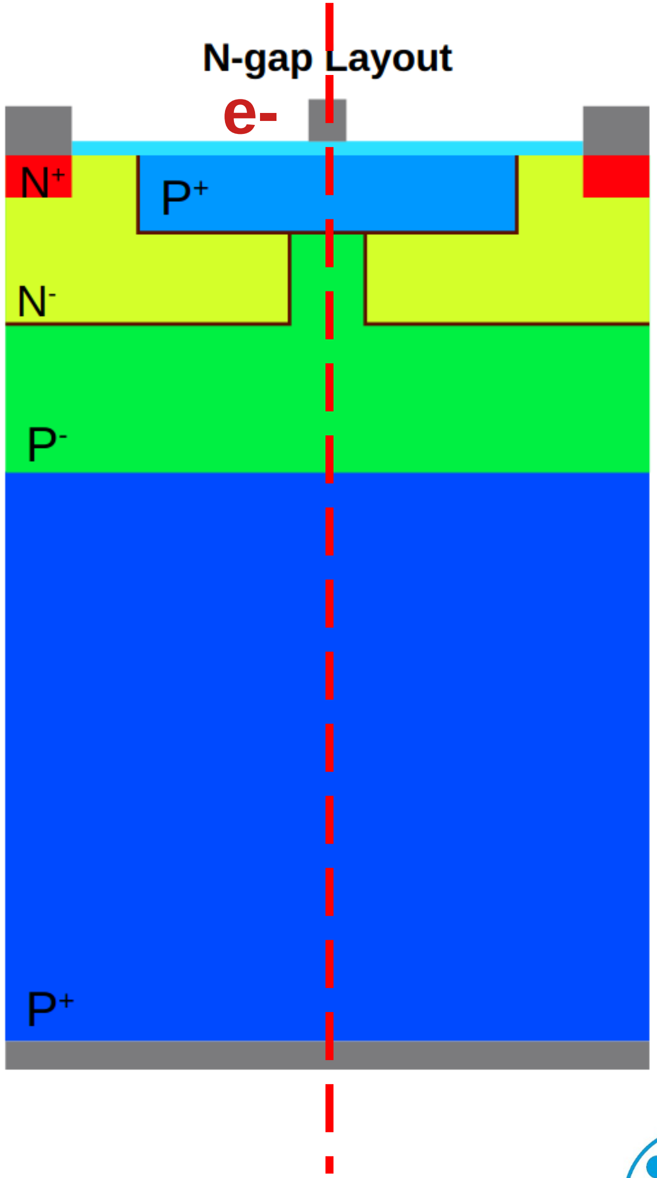
Standard Layout



N-blanket Layout



N-gap Layout

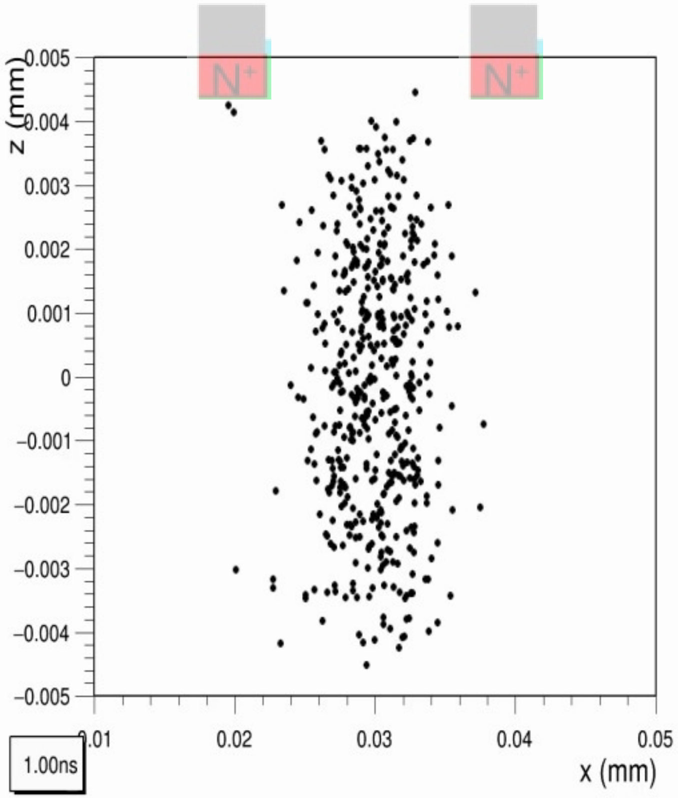


Standard layout

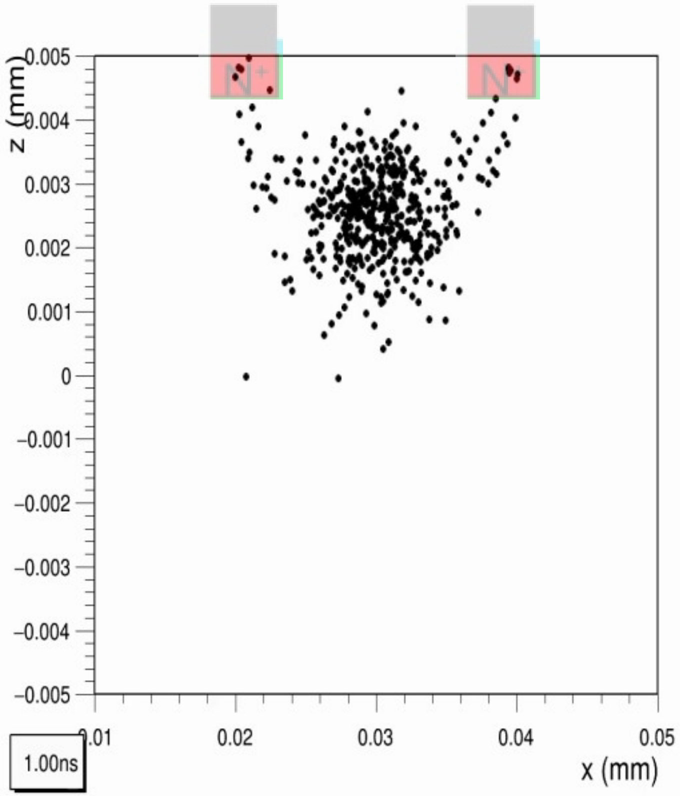
N-blanket layout

N-gap layout

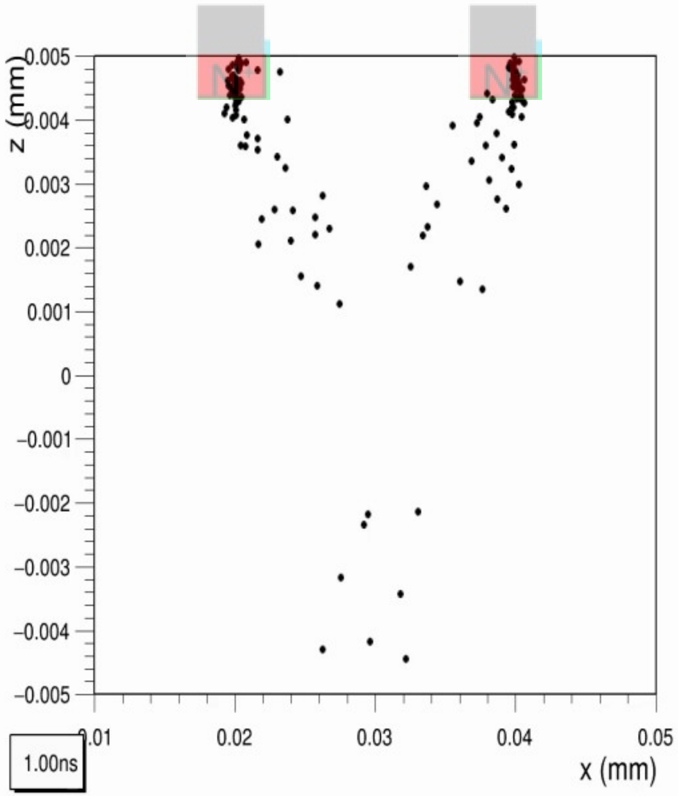
Standard layout



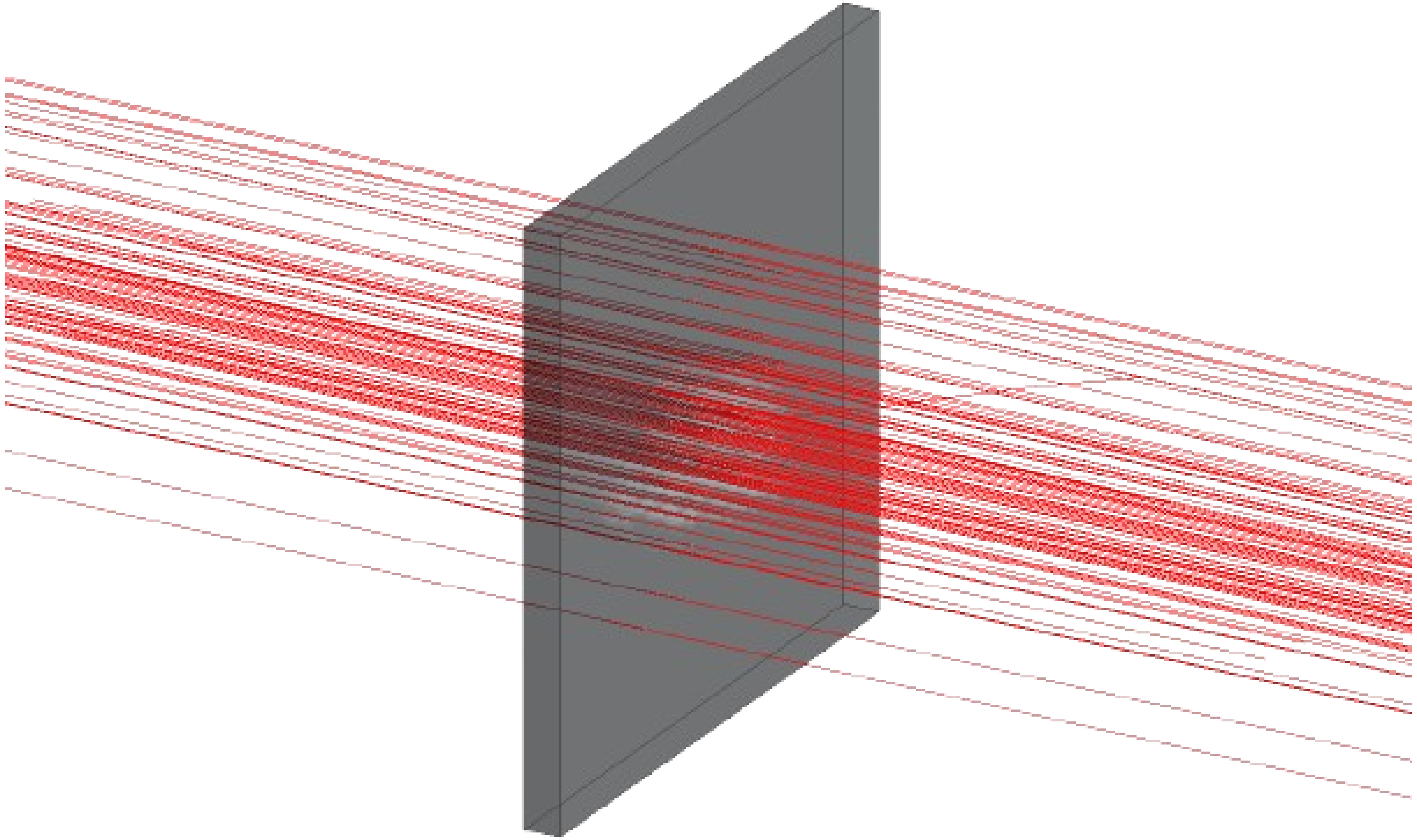
N-blanket layout



N-gap layout



Efficiency



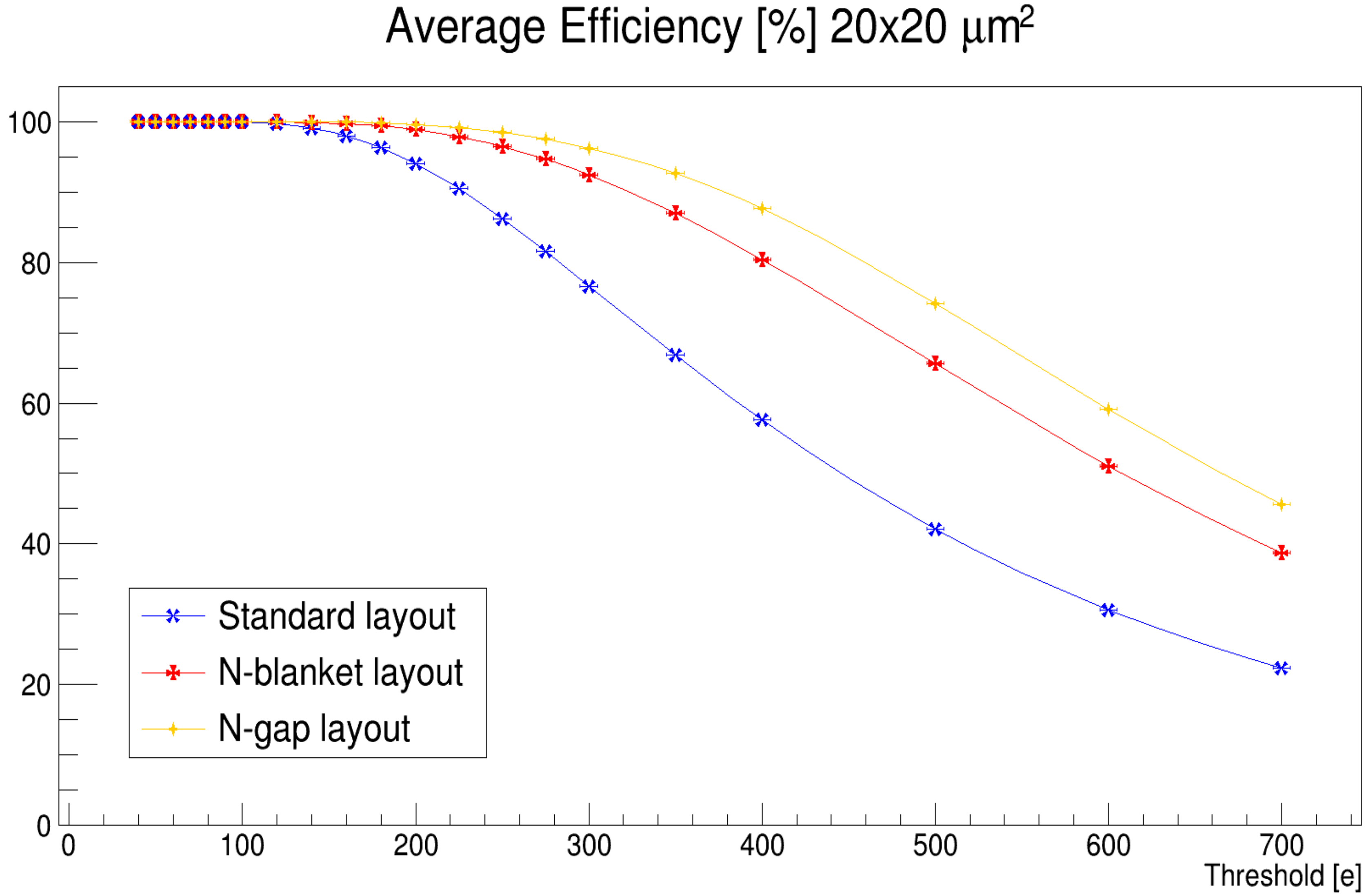
$$Efficiency = \frac{Fired}{Events}$$

Fired = Number of Events that fired a pixel

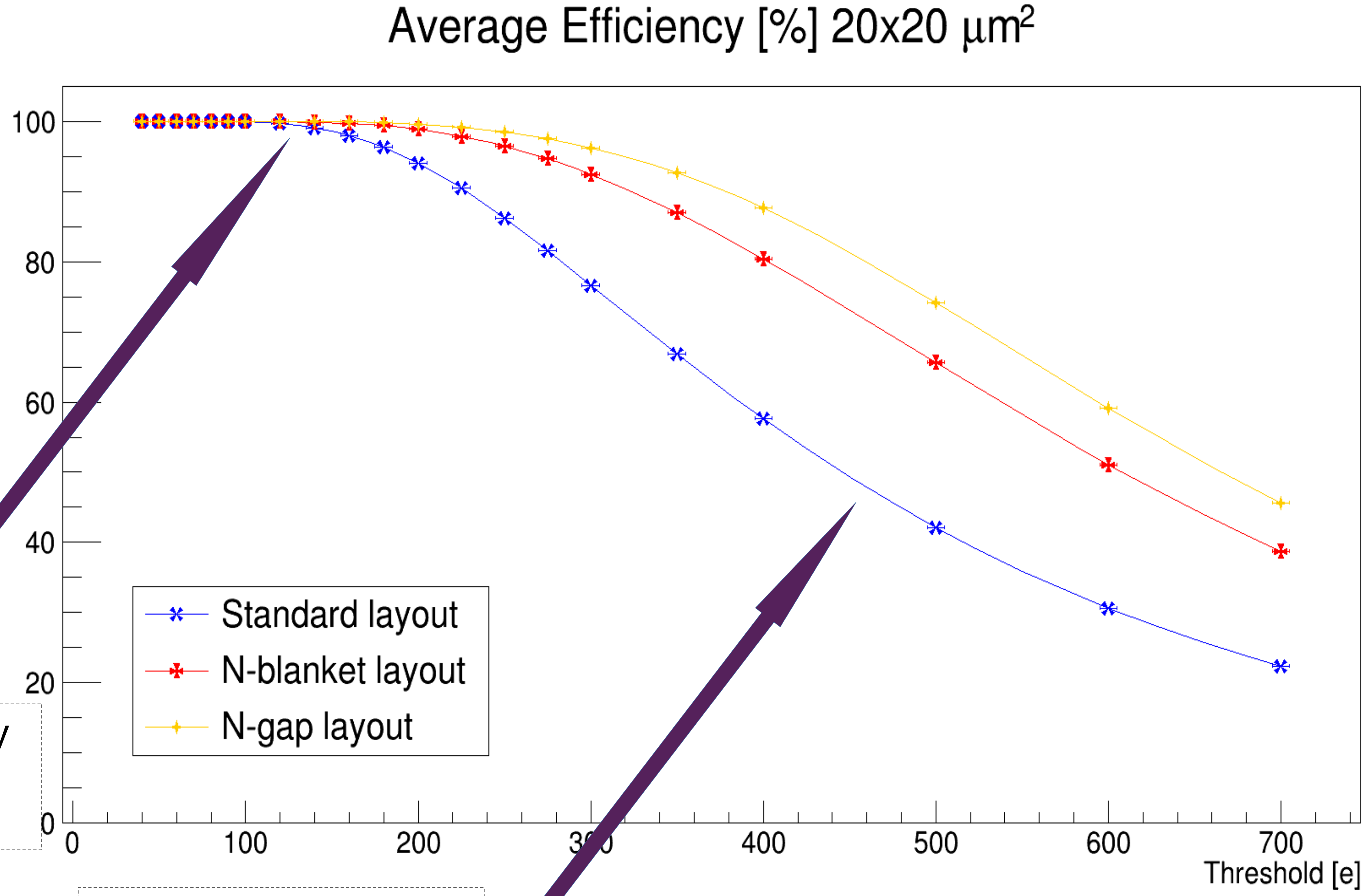
Events = Number of particles shot

Number of events ~ 500000

Layouts Comparison



Layouts Comparison



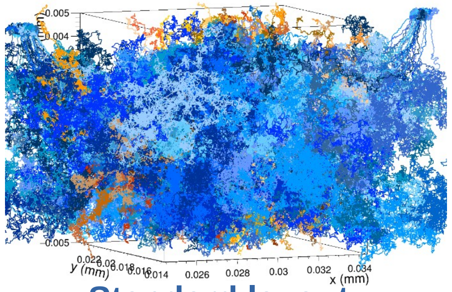
Maximum efficiency at low detection thresholds

Efficiency decreases as we increase the detection threshold

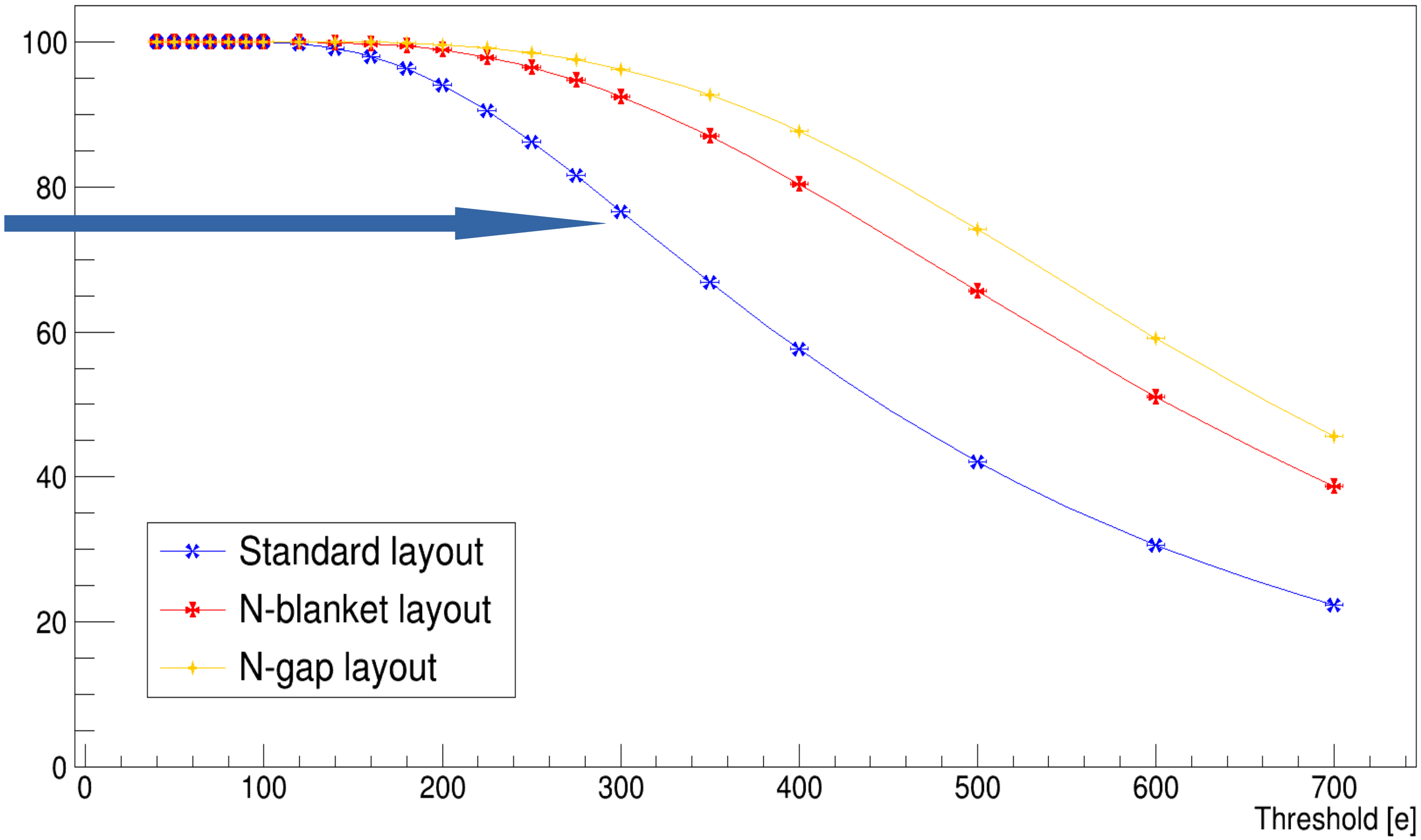
Layouts Comparison

Efficiency decreases drastically for **Standard layout**

Diffusion

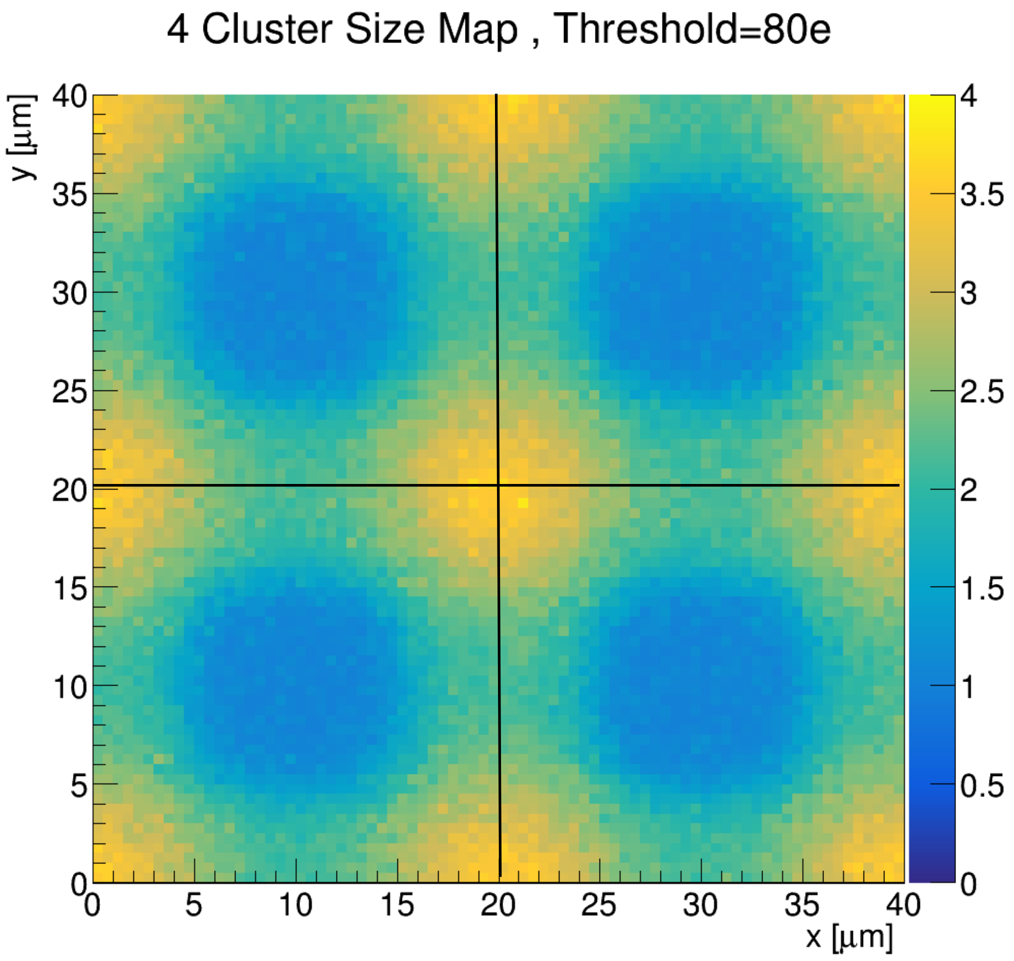


Standard layout linegraph



Average Efficiency [%] 20x20 µm²

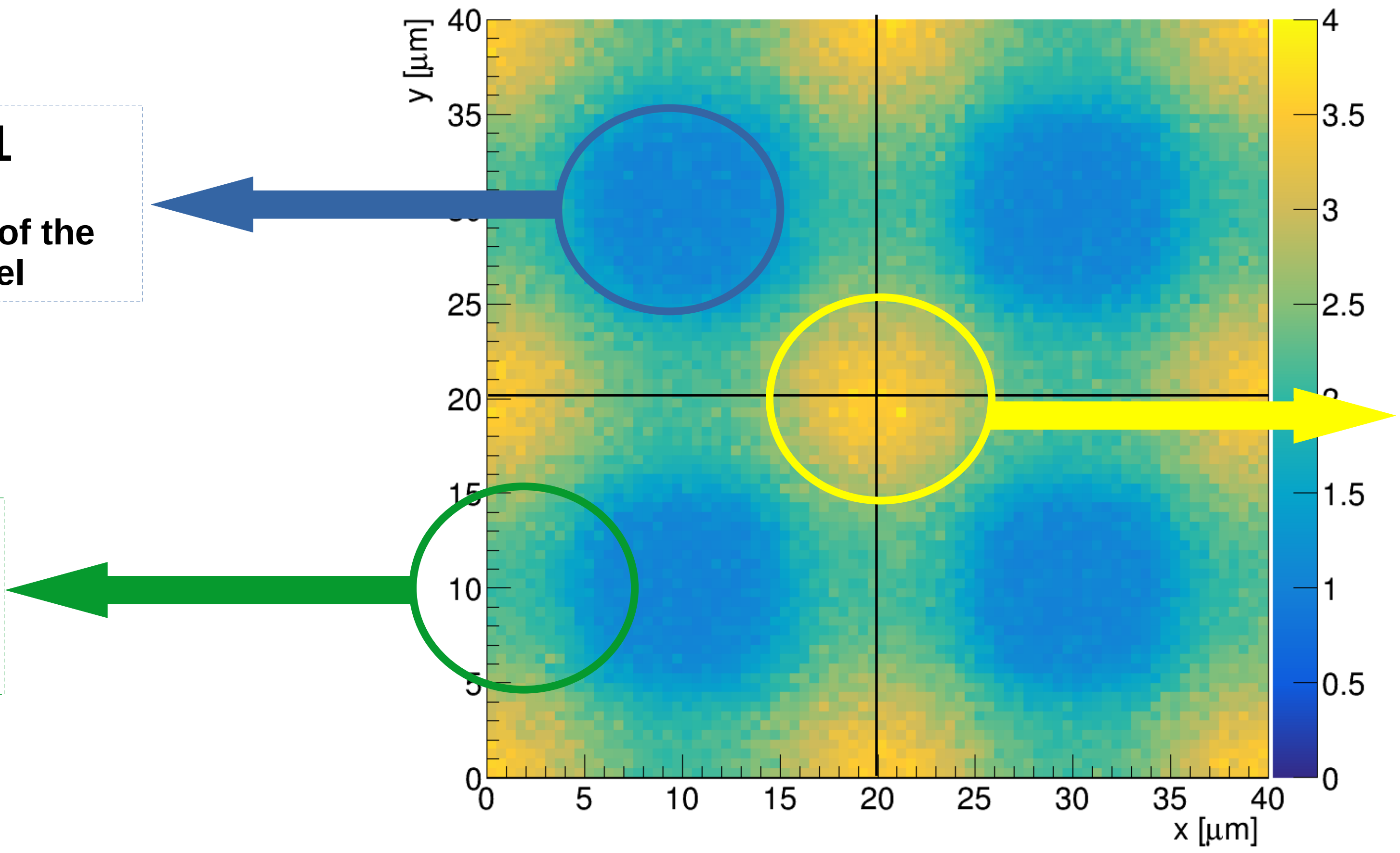
Cluster Size



Number of Pixels fired per event.

A **high** average **cluster size** (around 2) translates roughly to a **better** (smaller) **spatial resolution**.

Cluster Size (Map of 4 adjacent pixels)


4 Cluster Size Map , Threshold=80e

1

Center of the pixel

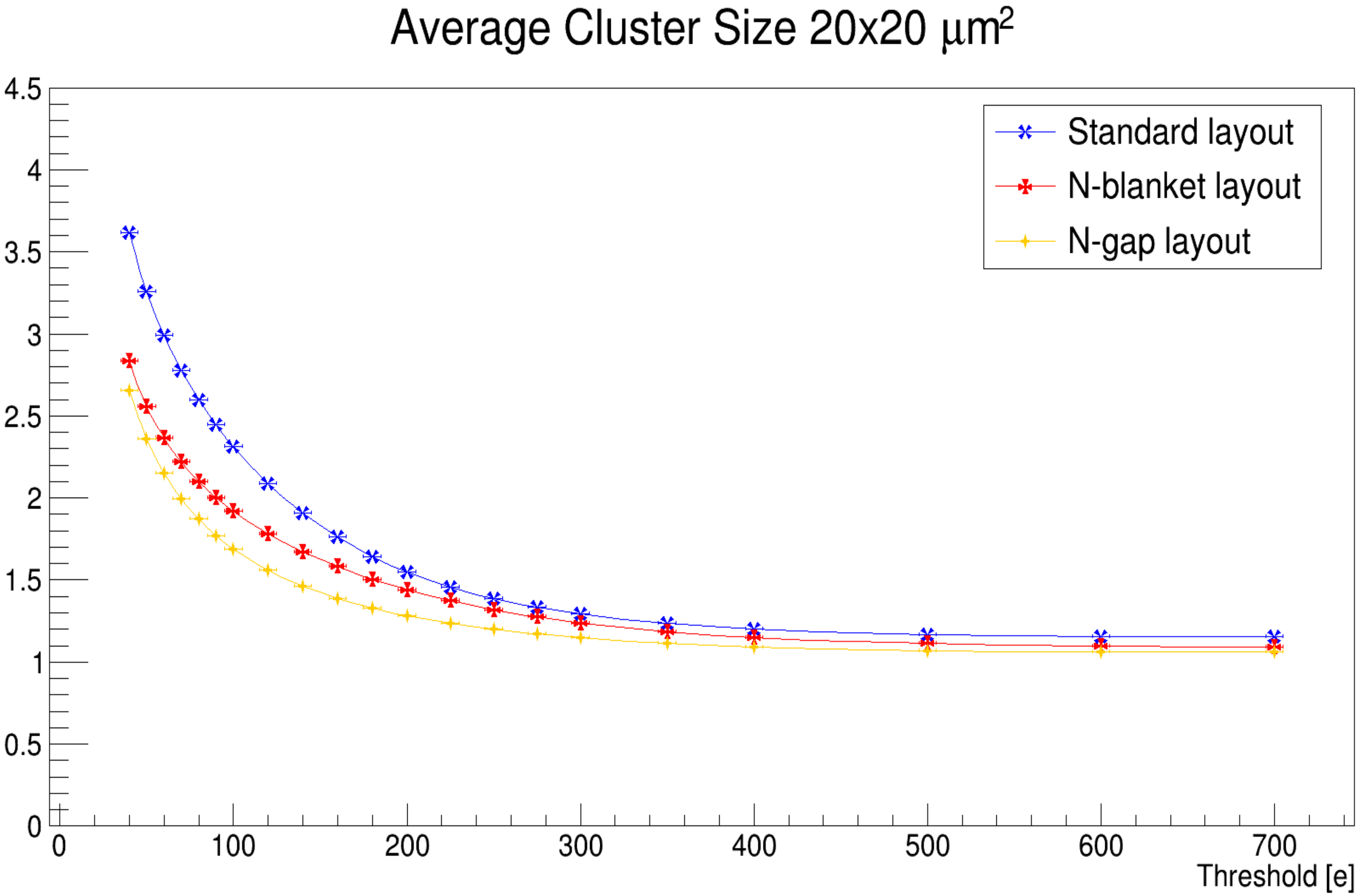
2

Between 2 pixels

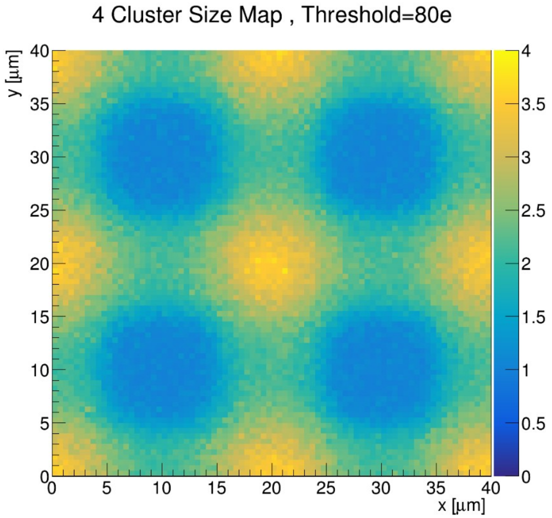
4

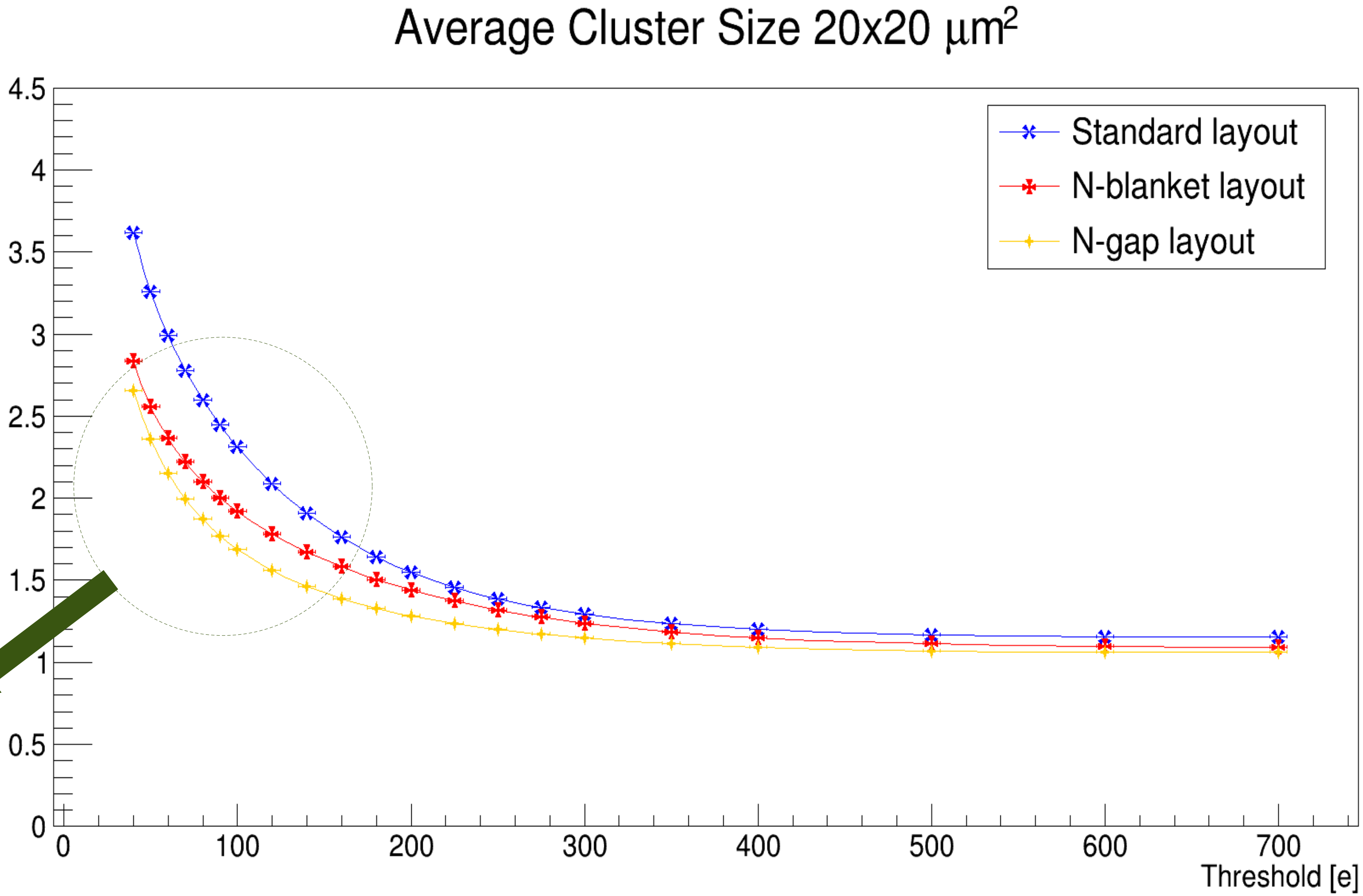
Corner of 4 pixels

Layouts Comparison

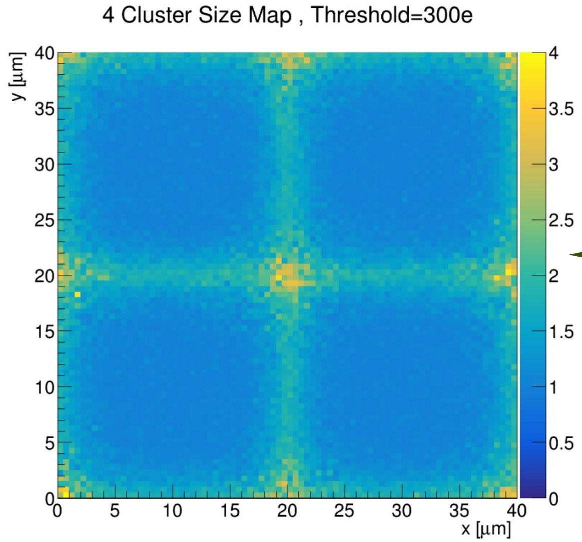


Layouts Comparison

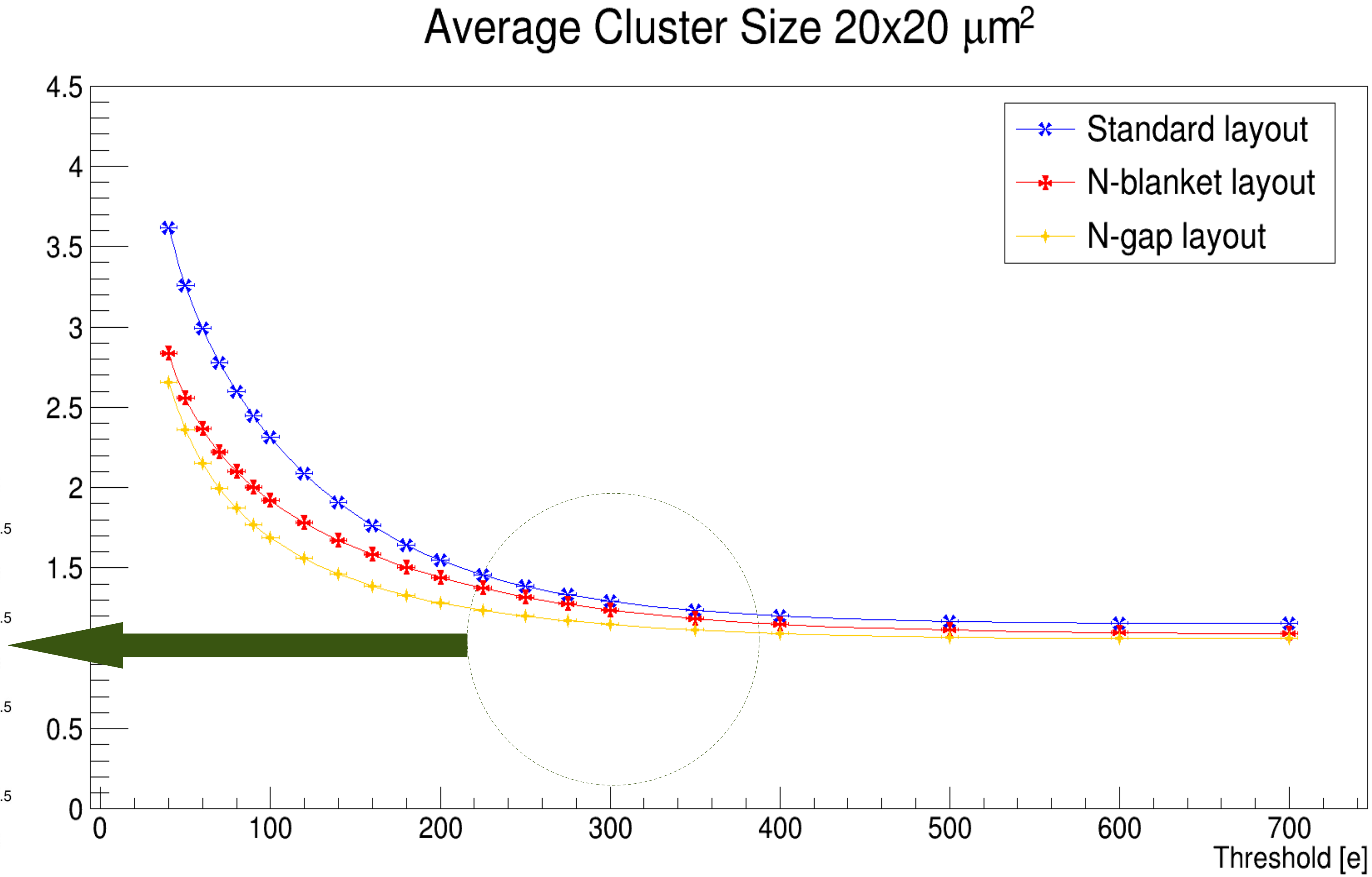




Layouts Comparison



4 Cluster Size Map , Threshold=300e

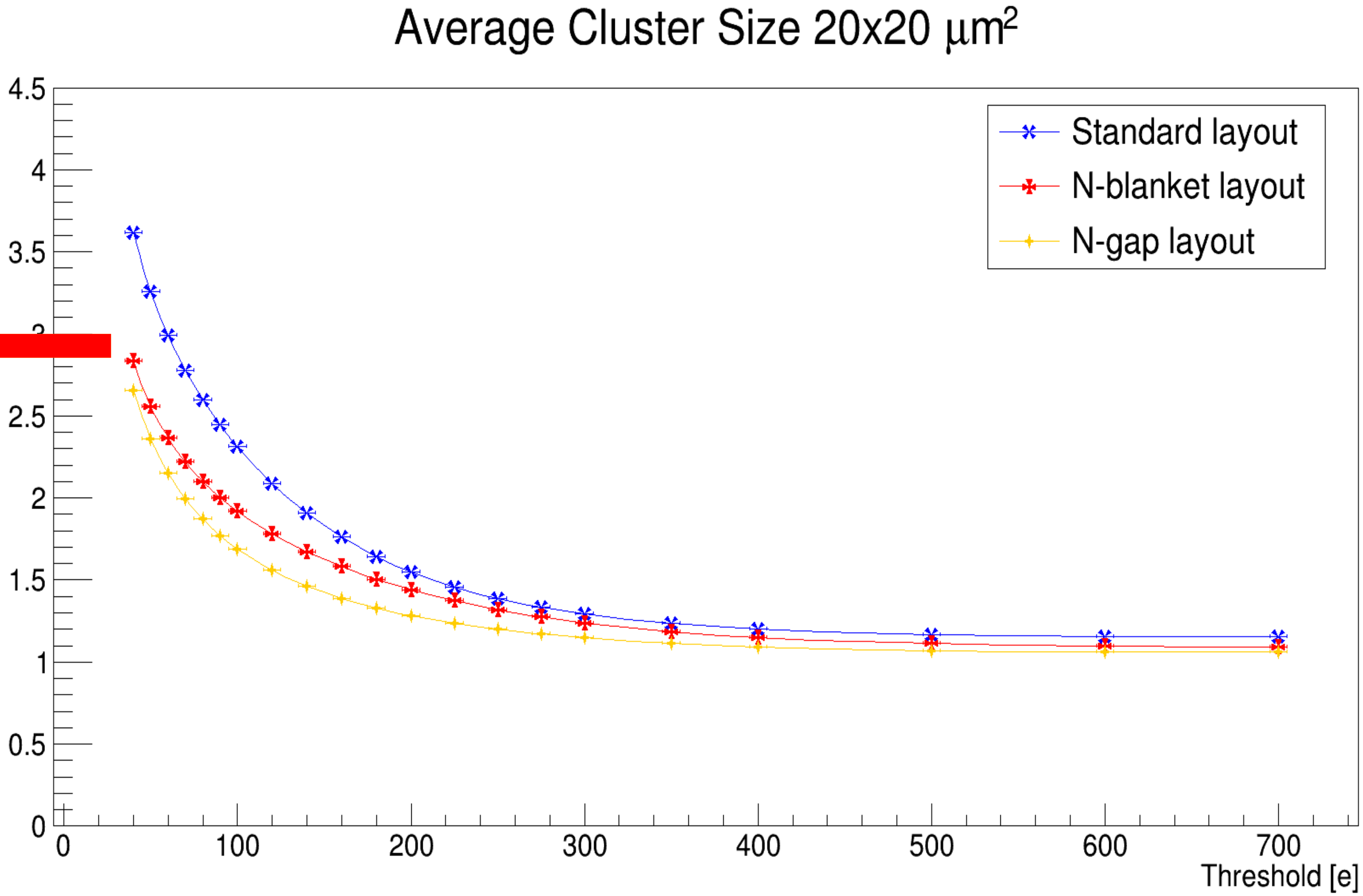


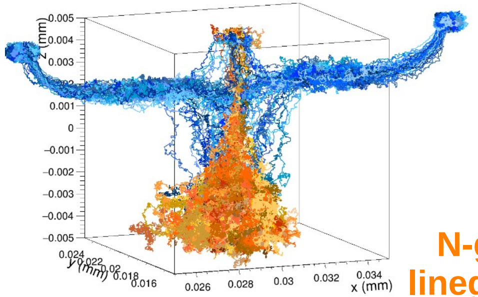
Average Cluster Size 20x20 µm²

Layouts Comparison

Smaller cluster size
N-blanket
&
N-gap

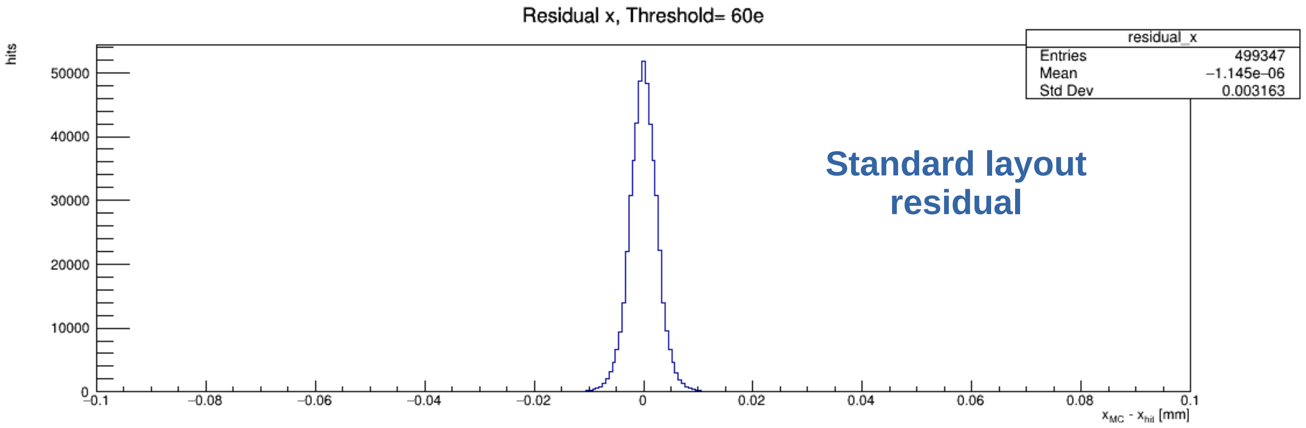
Drift



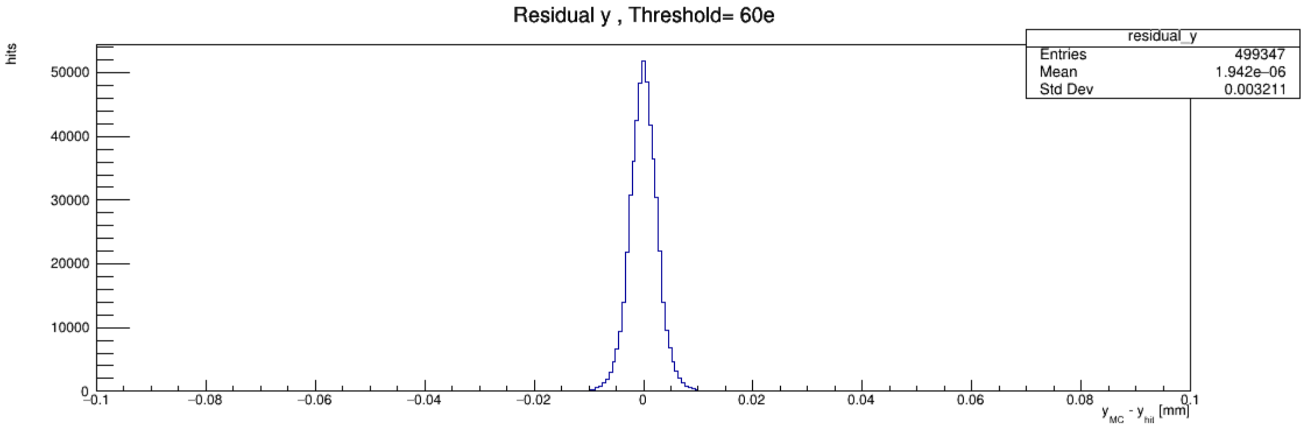


N-gap linegraph

Residuals ----> (Spatial Resolution)



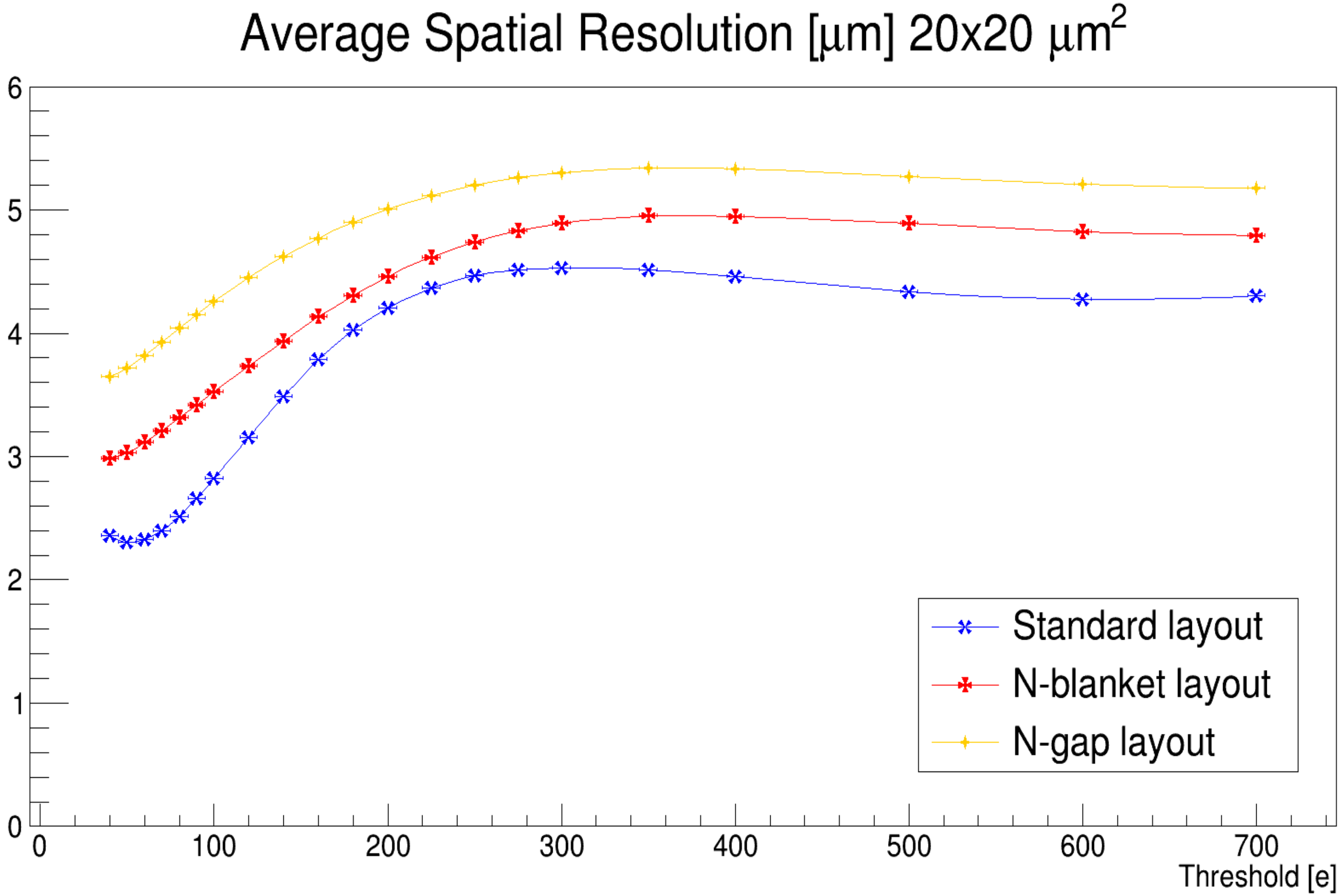
Standard layout residual



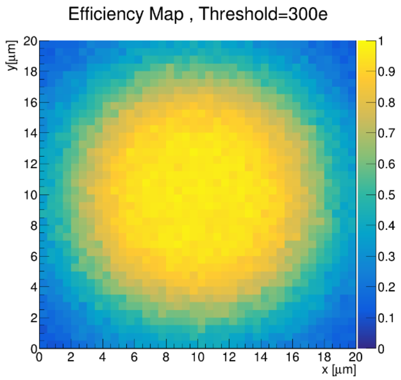
Residual: MC Particle incident position – Average cluster position

Spatial Resolution:
The RMS of the residual
(or in this case ~ Standard Deviation)

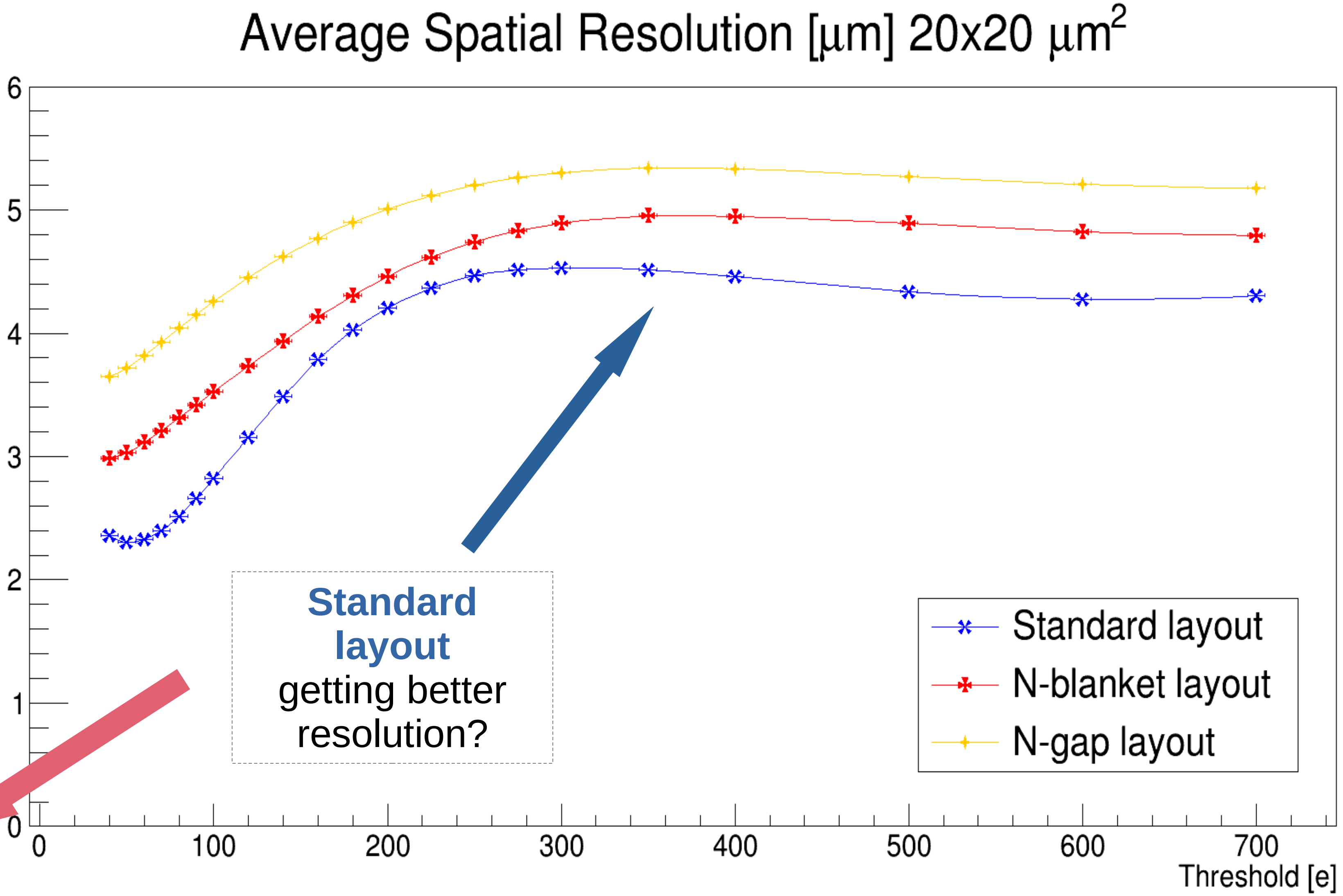
Layouts Comparison



Layouts Comparison

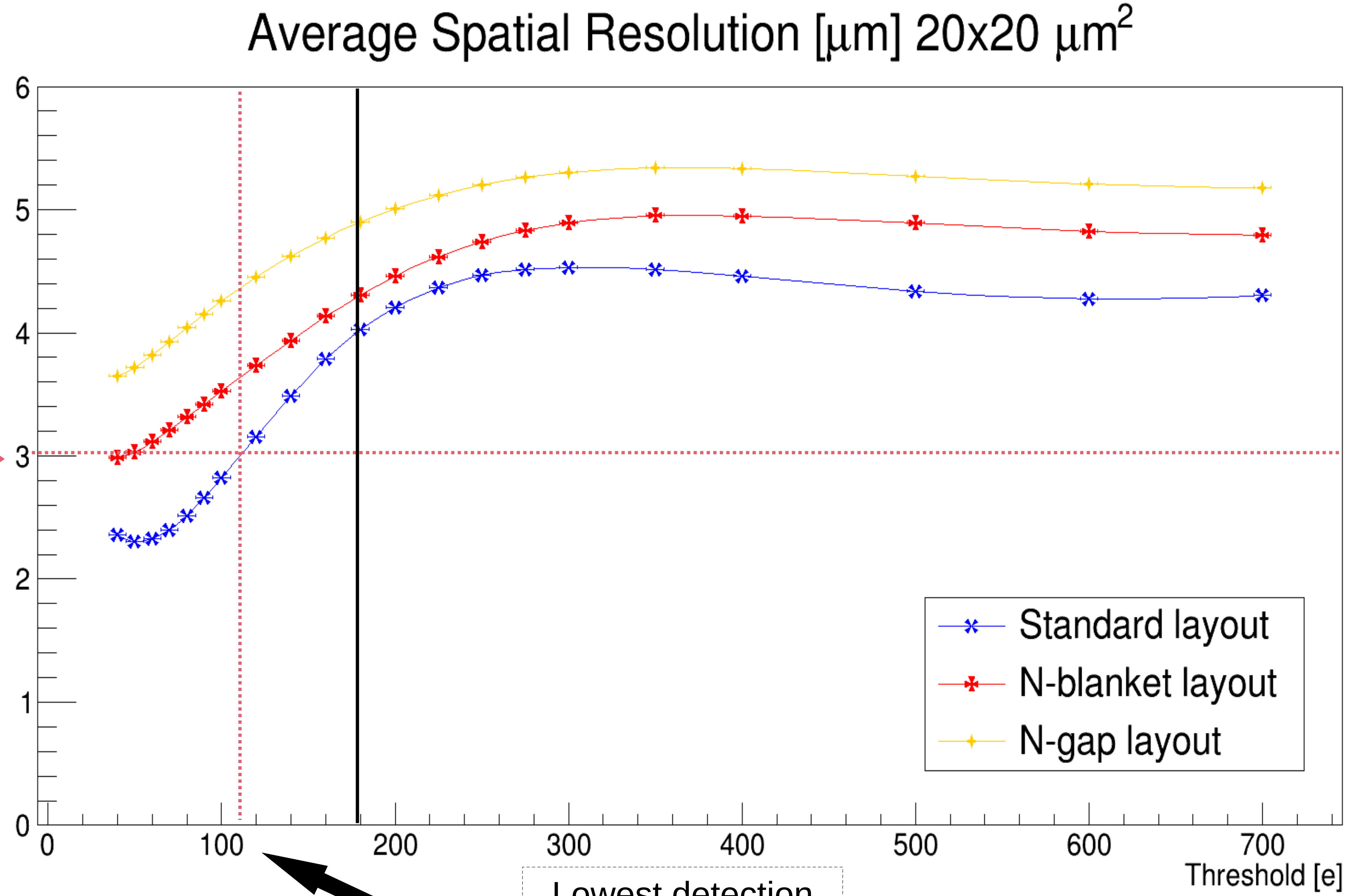


Low efficiency!



Standard layout getting better resolution?

Layouts Comparison



Desired resolution! What else can we change to achieve this?

Lowest detection threshold is not always possible! (Noise, electronics)

Summary

	Efficiency	Cluster Size (and Spatial Resolution)	Collection Time (Simulation Time)	Conclusion
Standard	• Harsh drop on efficiency	• Largest of the three (thus smallest resolution)	• ~ 25 ns (Due difussion, longest simulation time)	• Best resolution but efficiency might be concerning
N-blanket	• Good efficiency	• Slightly larger than the N-gap (thus smaller than the N-gap)	• > 25 ns (Drift dominated but for a minimum region)	
N-gap	• Good efficiency	• Smallest of them all (thus largest resolution)	• > 25 ns (Drift dominated)	• Great efficiency, worth looking into it.

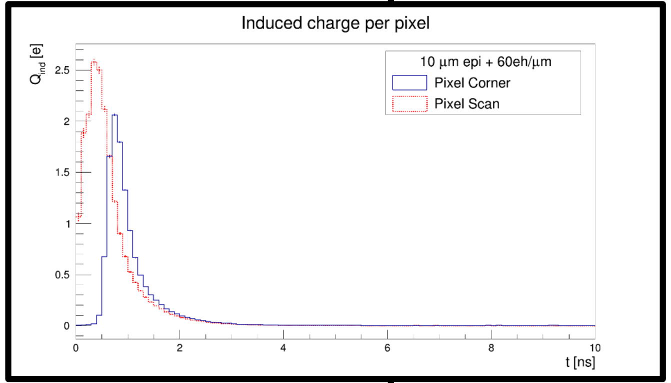
Conclusions and Next Steps!

Conclusions:

- Simulations provide many advantages and benefits.
- Improve from both parts on the simulation (both TCAD and MC).
- There still many parameters that can affect performance that could be worth looking into to achieve the desired capabilities.

Next Steps:

- Compare results with experimental data.
- Test the reproducibility, predictability and accuracy of the simulations.
- Fine tune and refine different parameters to achieve higher accuracy.
- Produce **Transient simulations** studies to understand the sensor response.



Thank you for your time!

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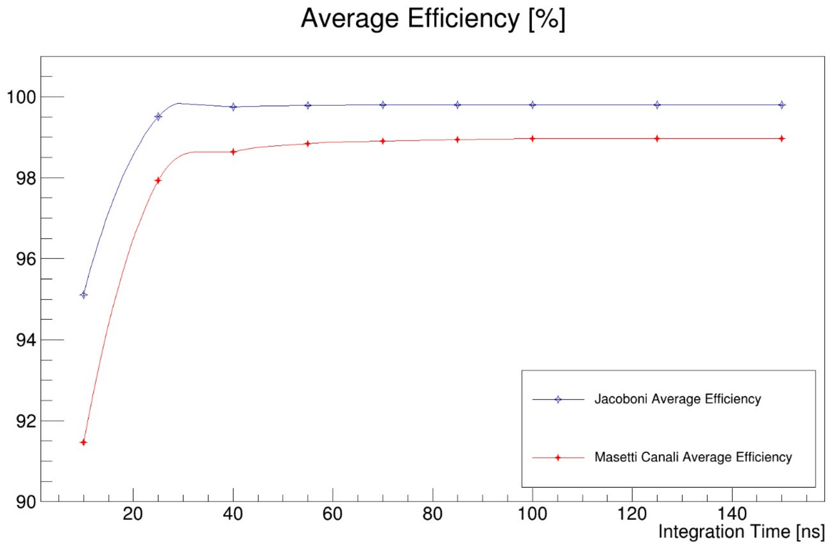
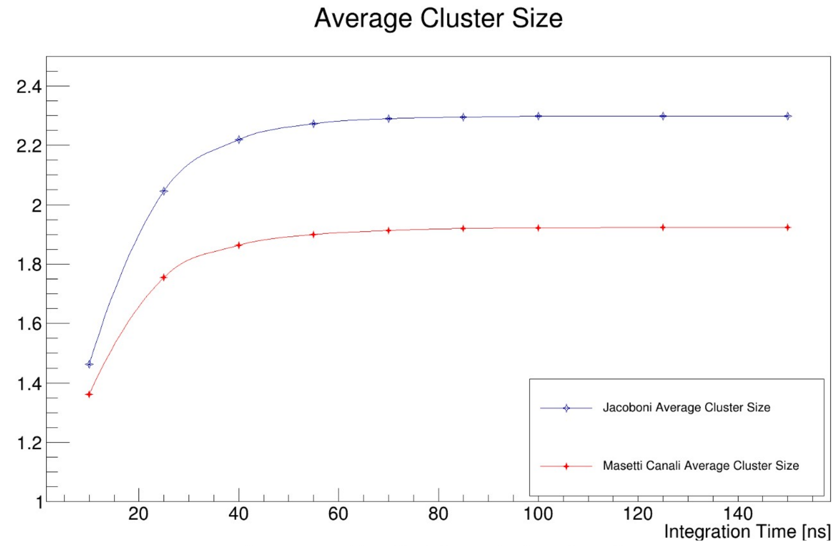
Backup

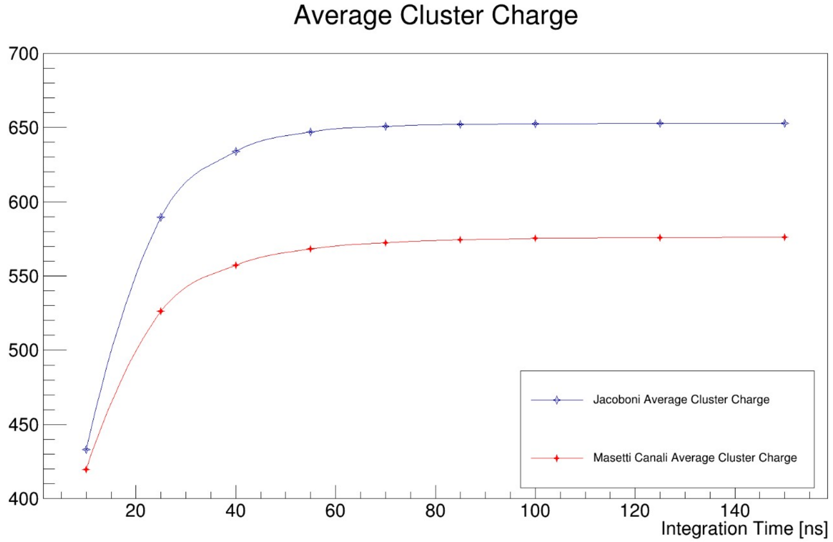
Integration time (Total Simulation time)

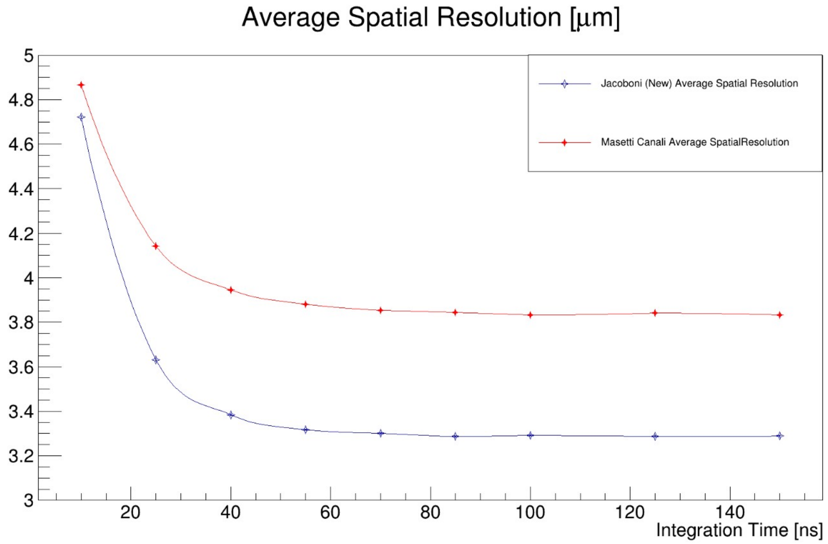
🟦 Non-doping dependent Mobility Model

🟥 Doping dependent Mobility Model









Simulation Results (Comparison between Mobility Models)

A **mobility model** refers to a model describing the electric field and doping concentration dependence of the charge carrier velocity.

We will compare the following two mobility models:

Jacoboni-Canali

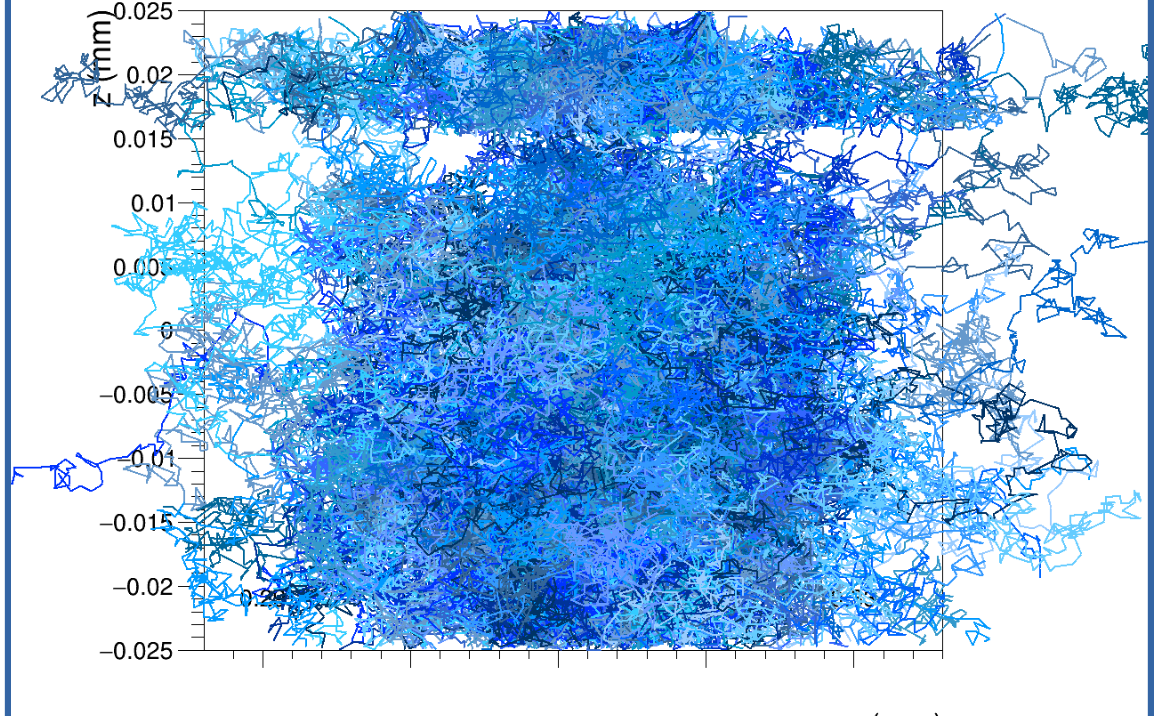
$$\mu(E) = \frac{v_m}{E_c} \frac{1}{\left(1 + (E/E_c)^{\beta}\right)^{1/\beta}},$$

Masetti-Canali

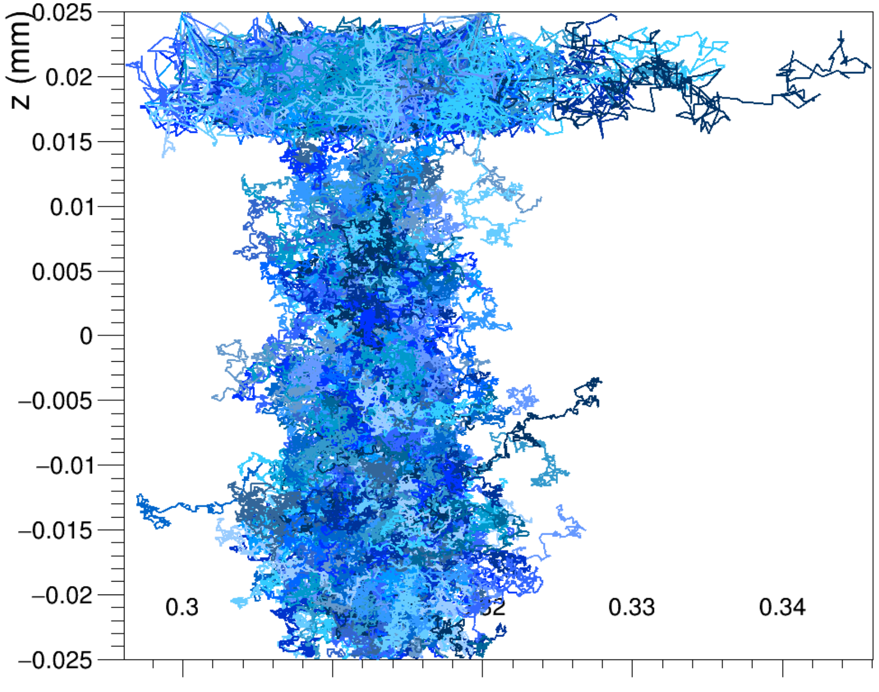
$$\mu(E,N) = \frac{\mu_m(N)}{\left(1 + (\mu_m(N) \cdot E/v_m)^{\beta}\right)^{1/\beta}}$$

Note that Jacoboni model does not depend on the **doping concentration** (explicitly) while Masetti does

Linegraphs



Jacoboni-Canali



Masetti-Canali