Simulations of 65 nm silicon sensors using Allpix Squared

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3rd Allpix Squared User Workshop

Hamburg, May 10th 2022

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

UNIVERSITÄT BONN

The Tangerine Project - Towards Next Generation Silicon Detectors

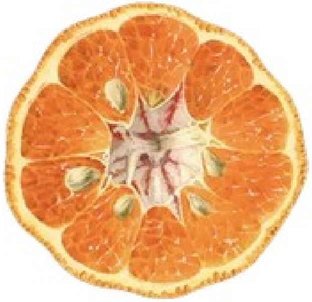
Goal: Design a monolithic pixel detector in 65nm CMOS imaging technology

- **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).

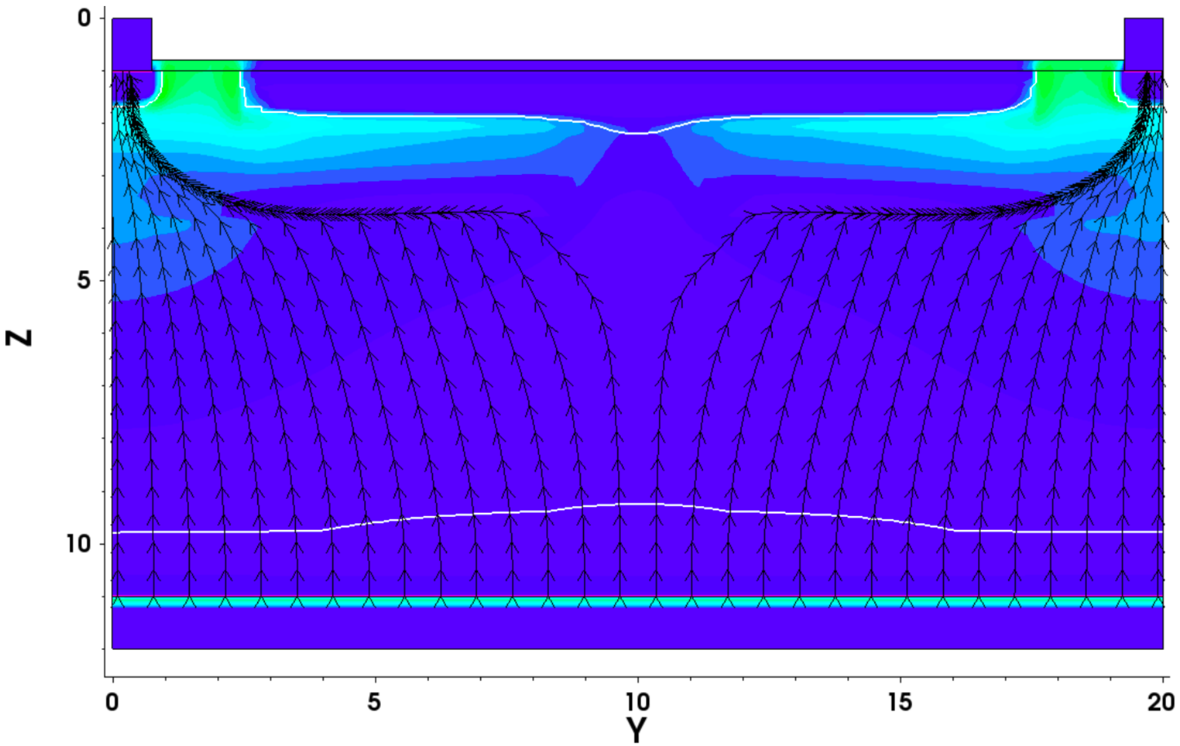
In monolithic sensors:

- 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**.



SYNOPSYS®

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

Allpix Squared (Allpix^2)

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

```
[ElectricFieldReader]
model = "mesh"
file_name = "ElectricField.apf"
field_offset=0.5,0.5
depletion_depth= 40um
log_level="debug"

[DopingProfileReader]
model = "mesh"
file_name = "DopingConcentration.apf"
field_offset=0.5,0.5
doping_depth= 40um
log_level="debug"
```

Motivation:

- **Value** of the simulation results
- Reduced **cost**
- **Reproducibility** of performance

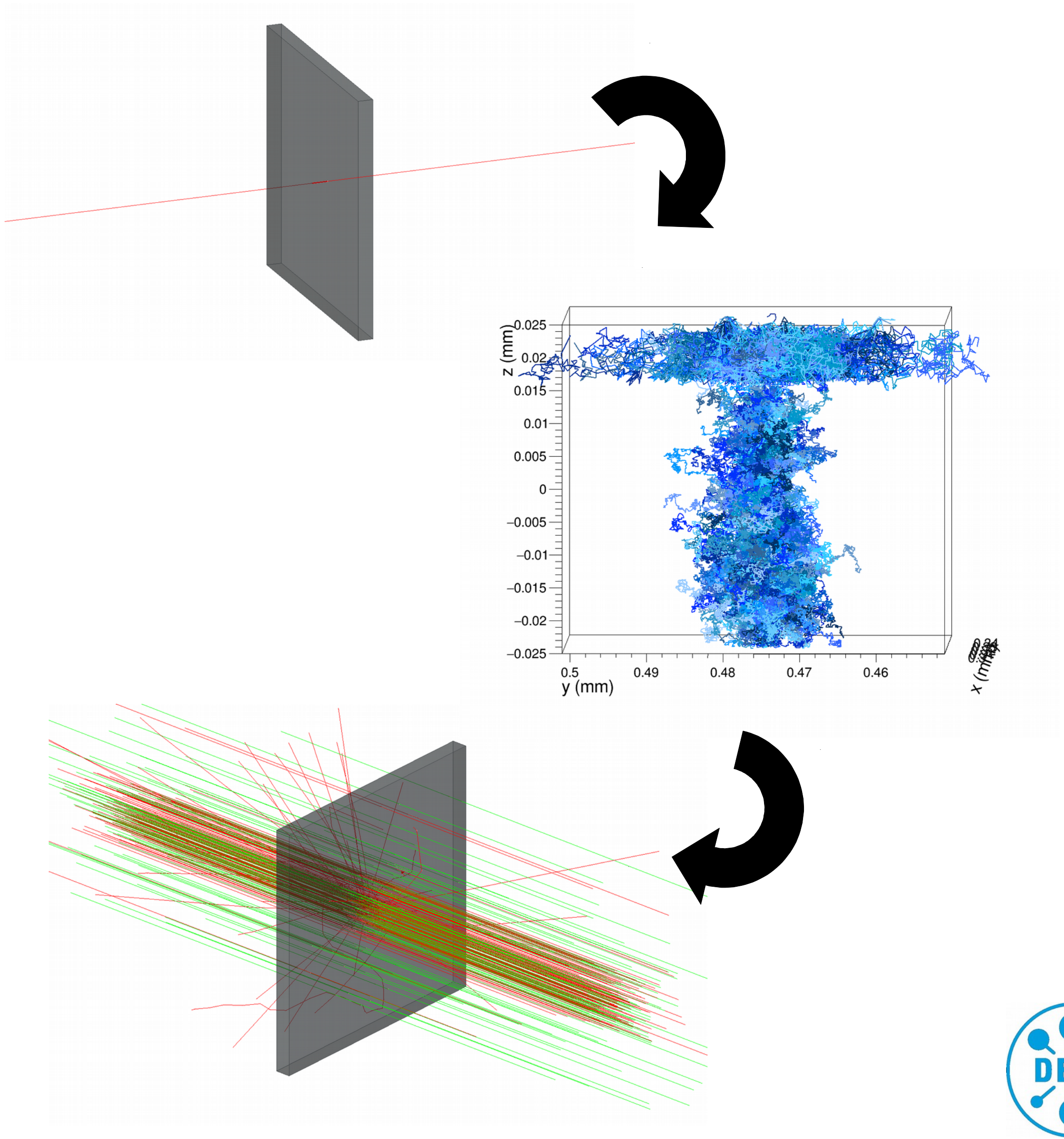
Monte Carlo Setup

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

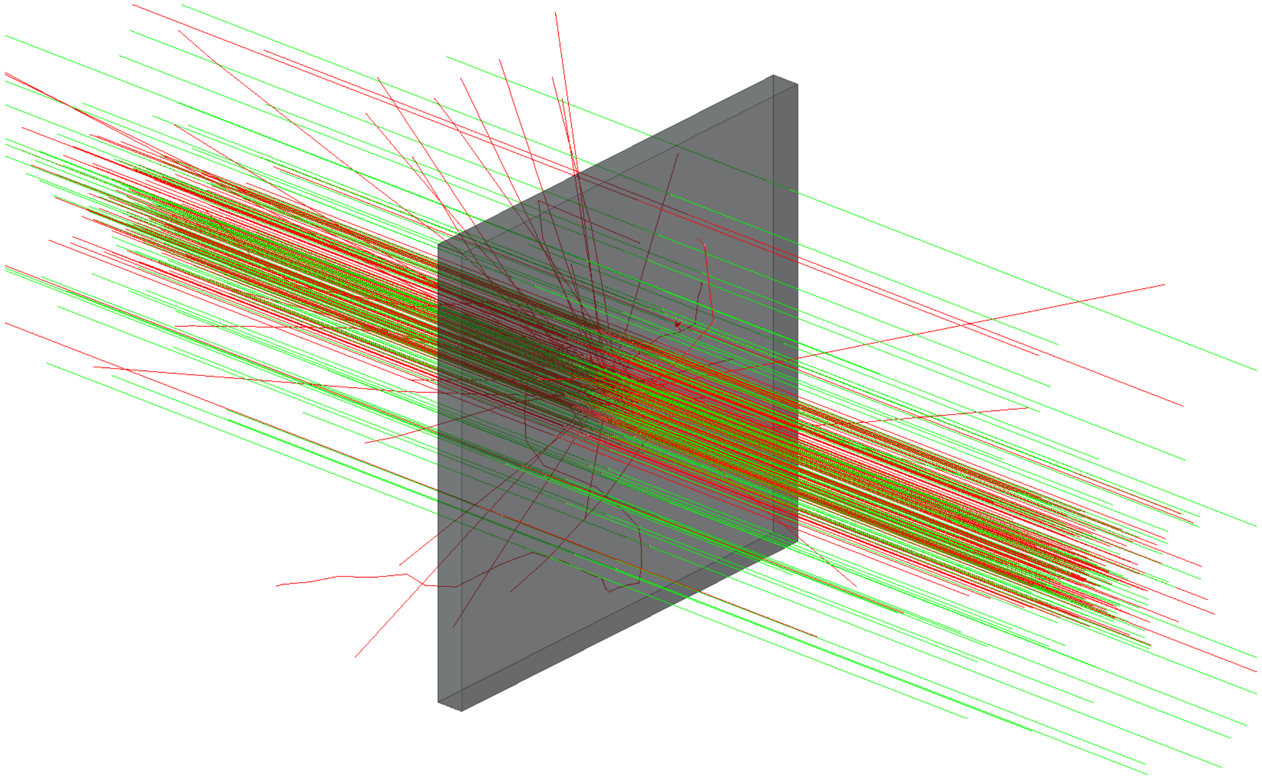
2) **Ionization** (And other Physics processes: Diffusion, Drift, Recombination...).

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

4) **Analysis**



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**
- **...**

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

Simulation Results (Comparison between Mobility Models)

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Jacoboni-Canali

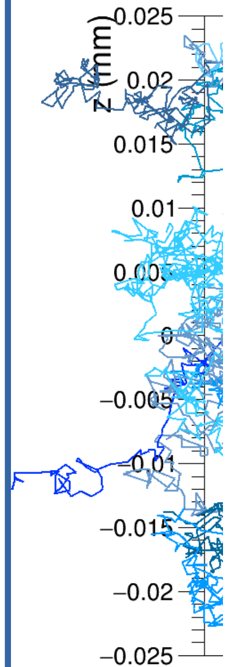
$$\mu(E) = \frac{v_m}{E_c} \frac{1}{(1 + (E/E_c)^{\beta})^{1/\beta}}$$

```
[GenericPropagation]
temperature = 293K
mobility_model="jacoboni"
recombination_model = "srh_auger"
charge_per_step = 5
timestep_min = 0.5ps
timestep_max = 0.05ns
integration_time = 25ns
propagate_electrons = true
```

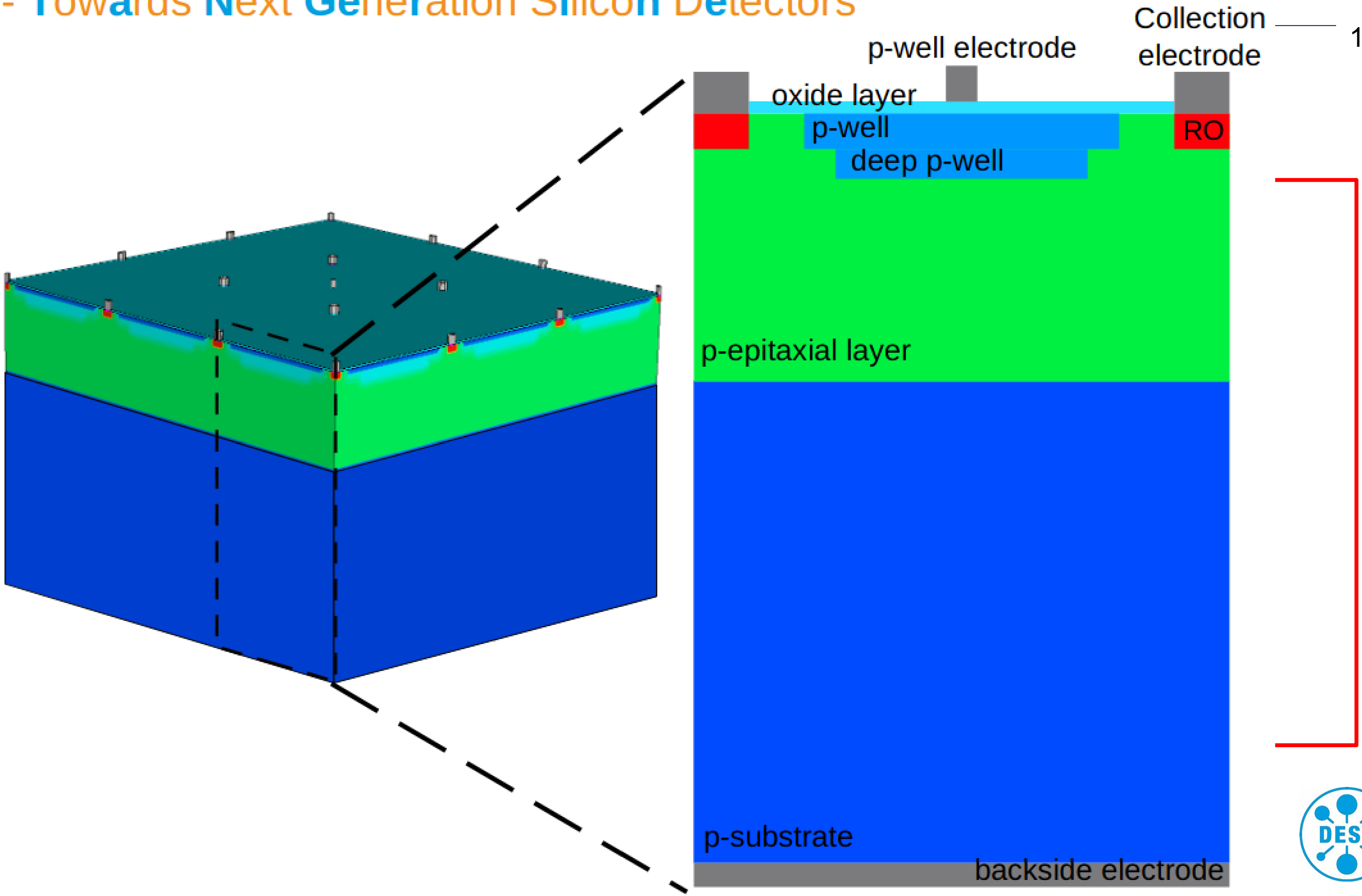
Masetti-Canali

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

Linegra

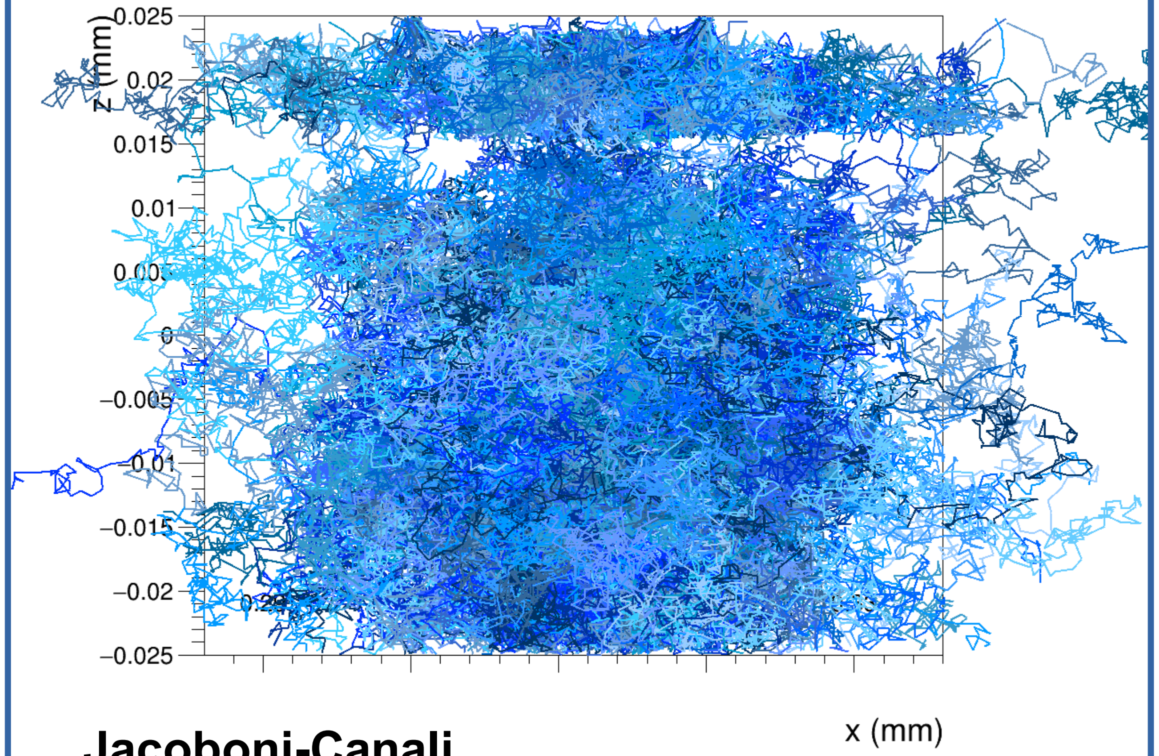


Jacob

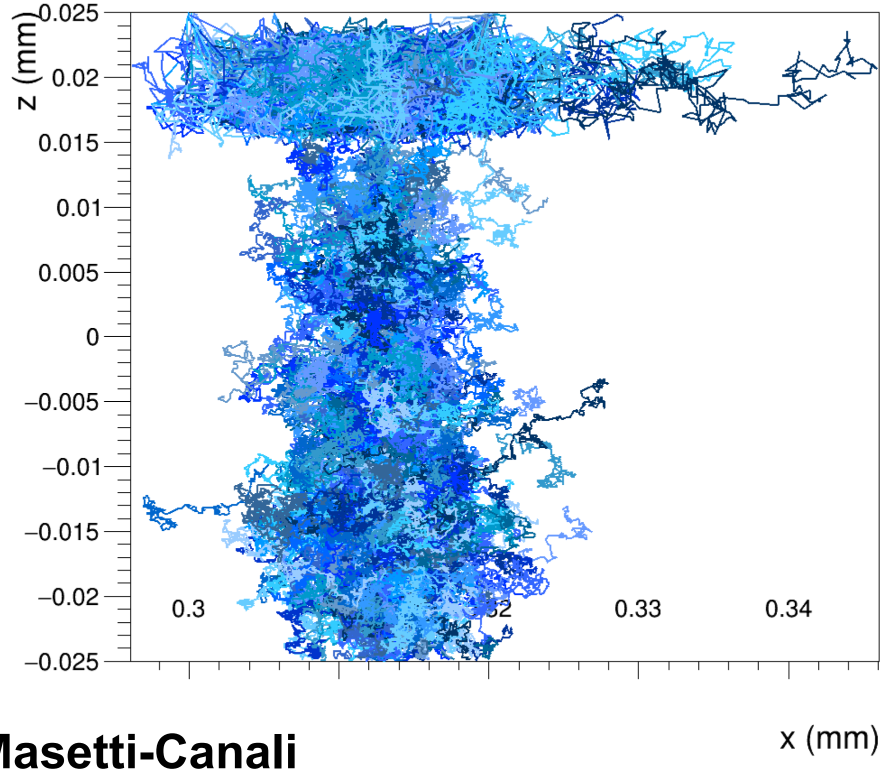


Linegraphs

```
output_linegraphs = true
```

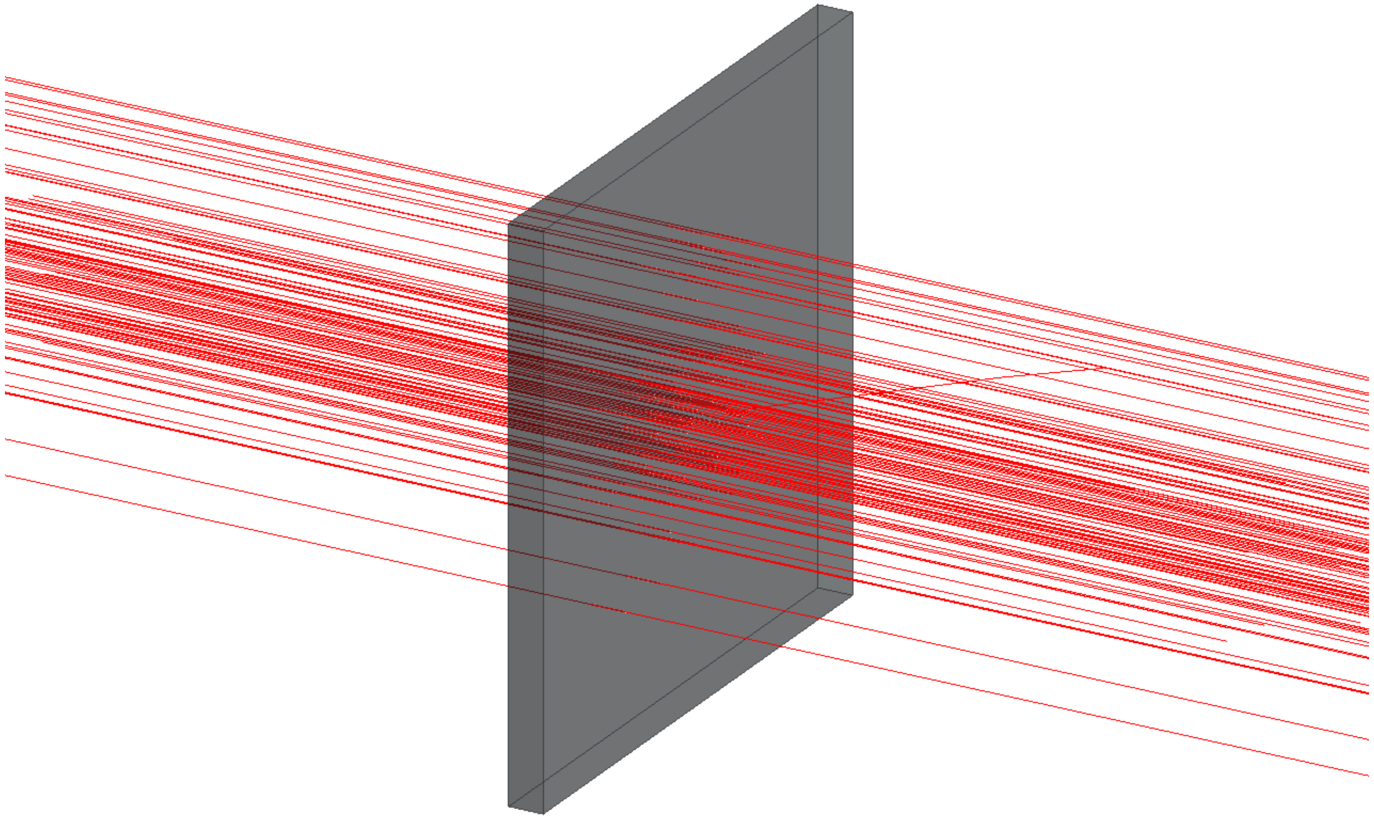


Jacoboni-Canali



Masetti-Canali

Efficiency



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

Fired = Number of Events that fired a pixel

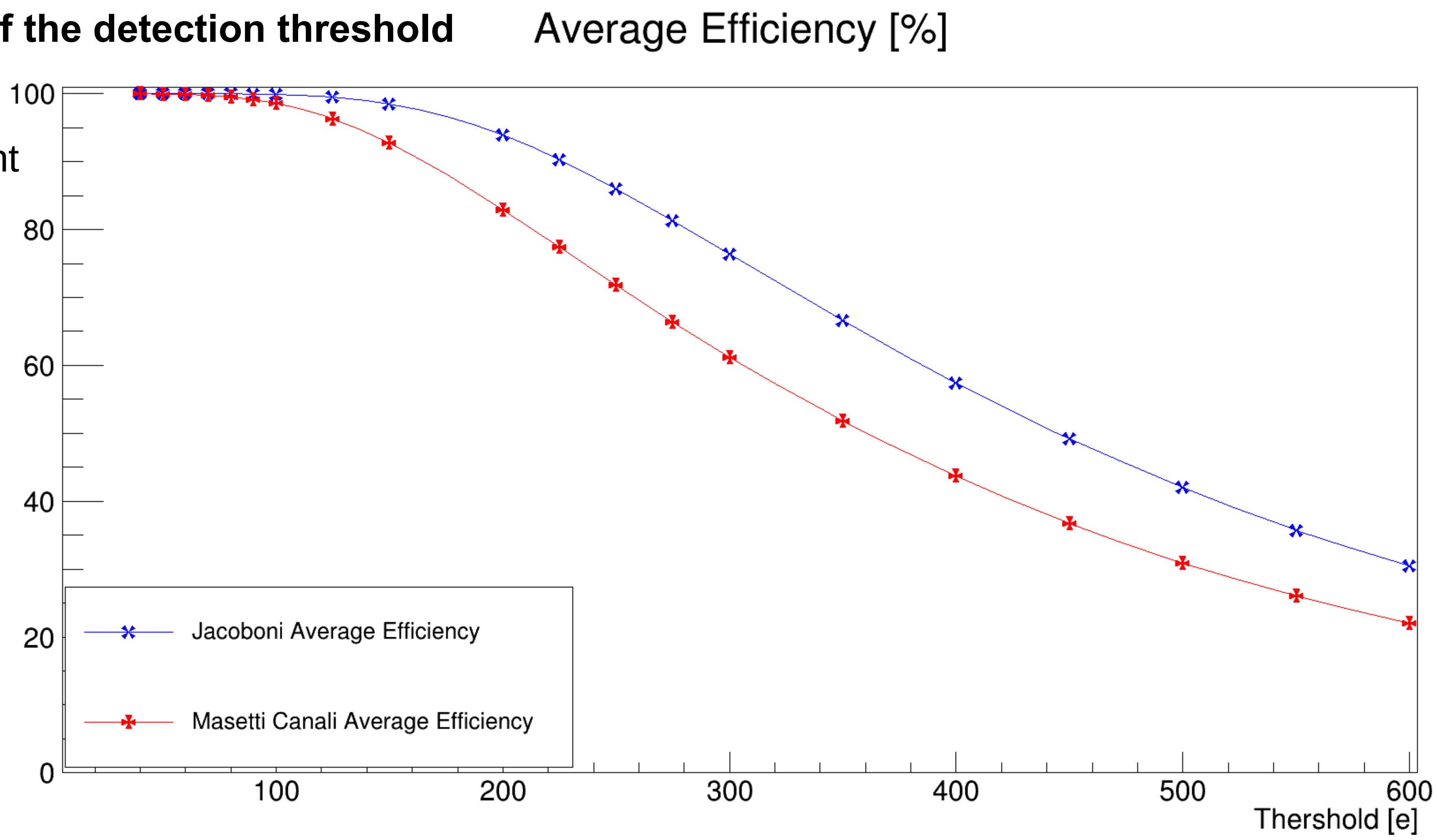
Events = Number of particles shot

Number of events ~ 500000

Efficiency as a function of the detection threshold

Non-doping dependent Mobility Model

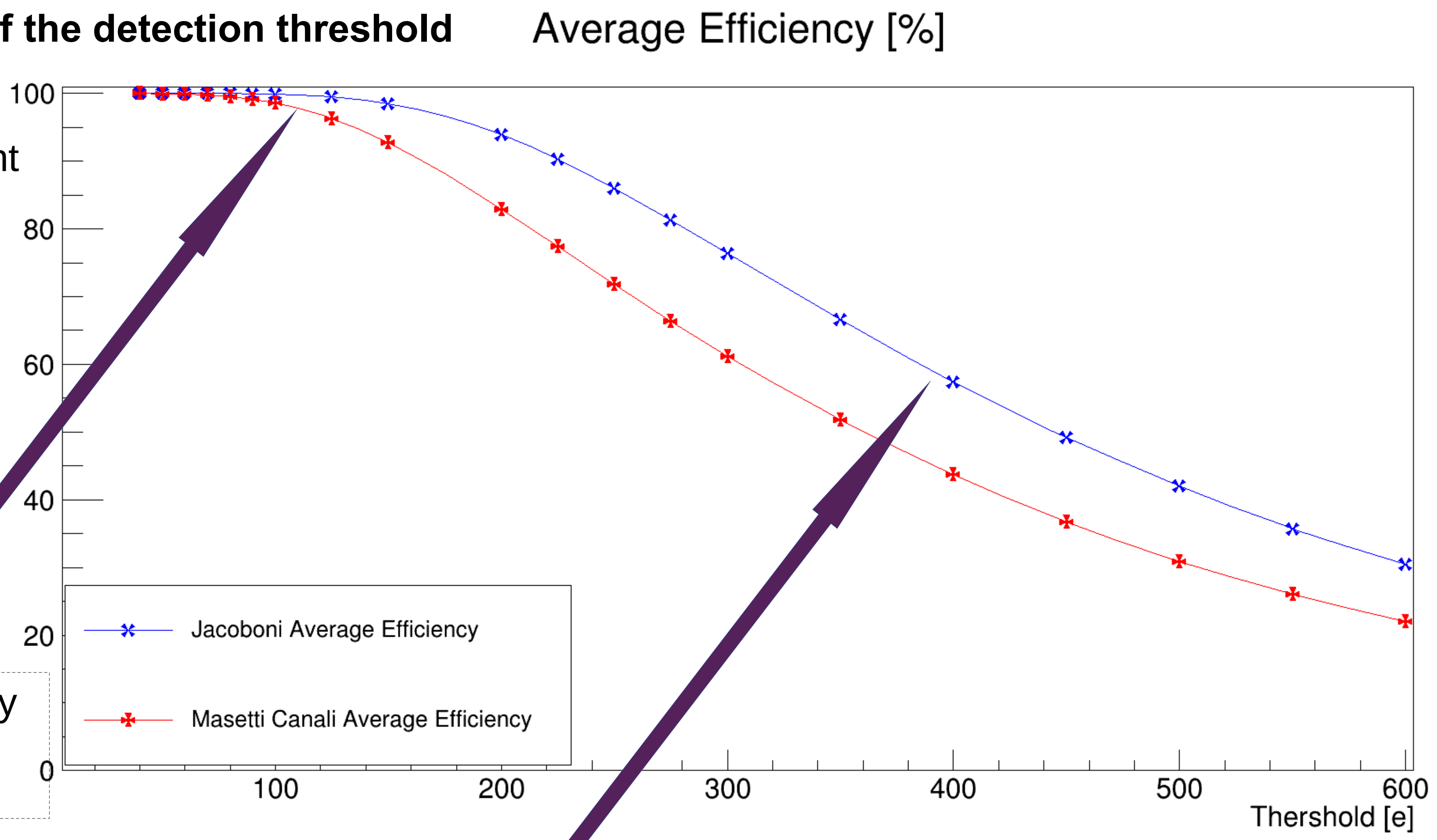
Doping dependent Mobility Model



Efficiency as a function of the detection threshold

Non-doping dependent Mobility Model

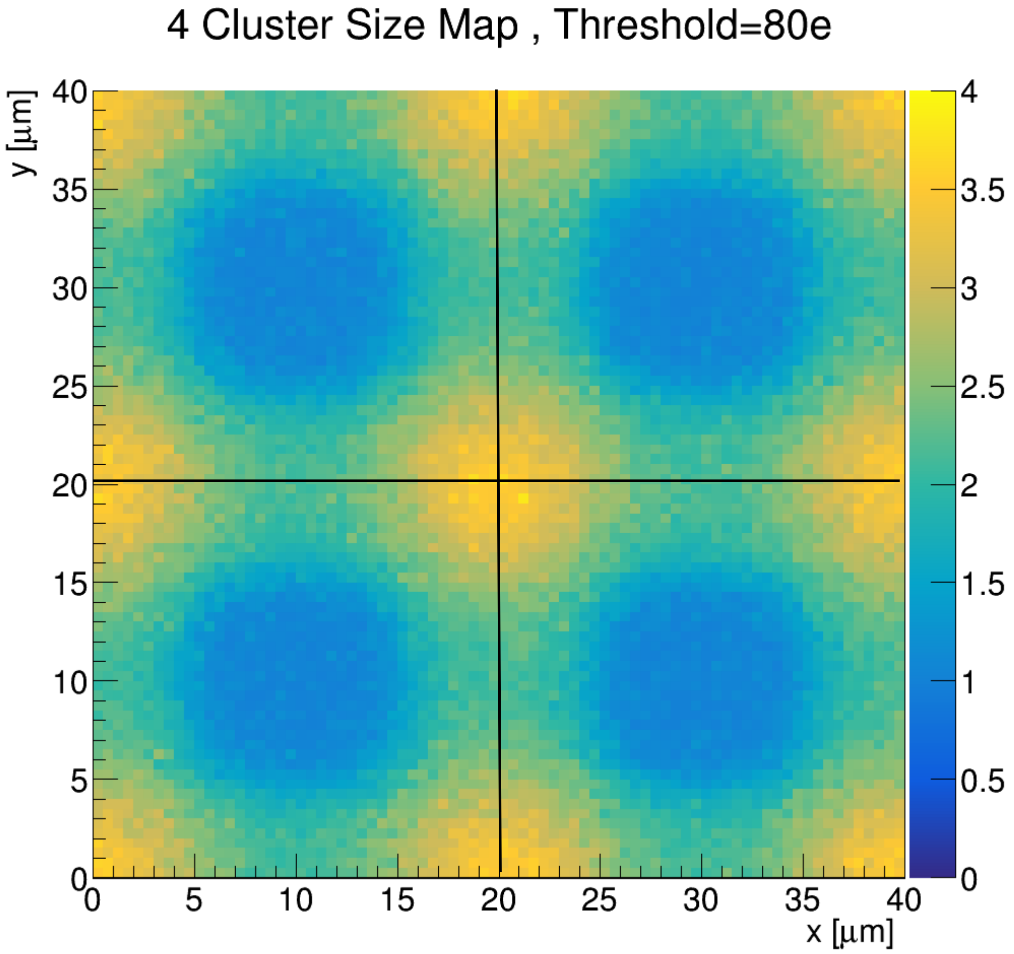
Doping dependent Mobility Model



Maximum efficiency at low detection thresholds

Efficiency decreases as we increase the detection threshold

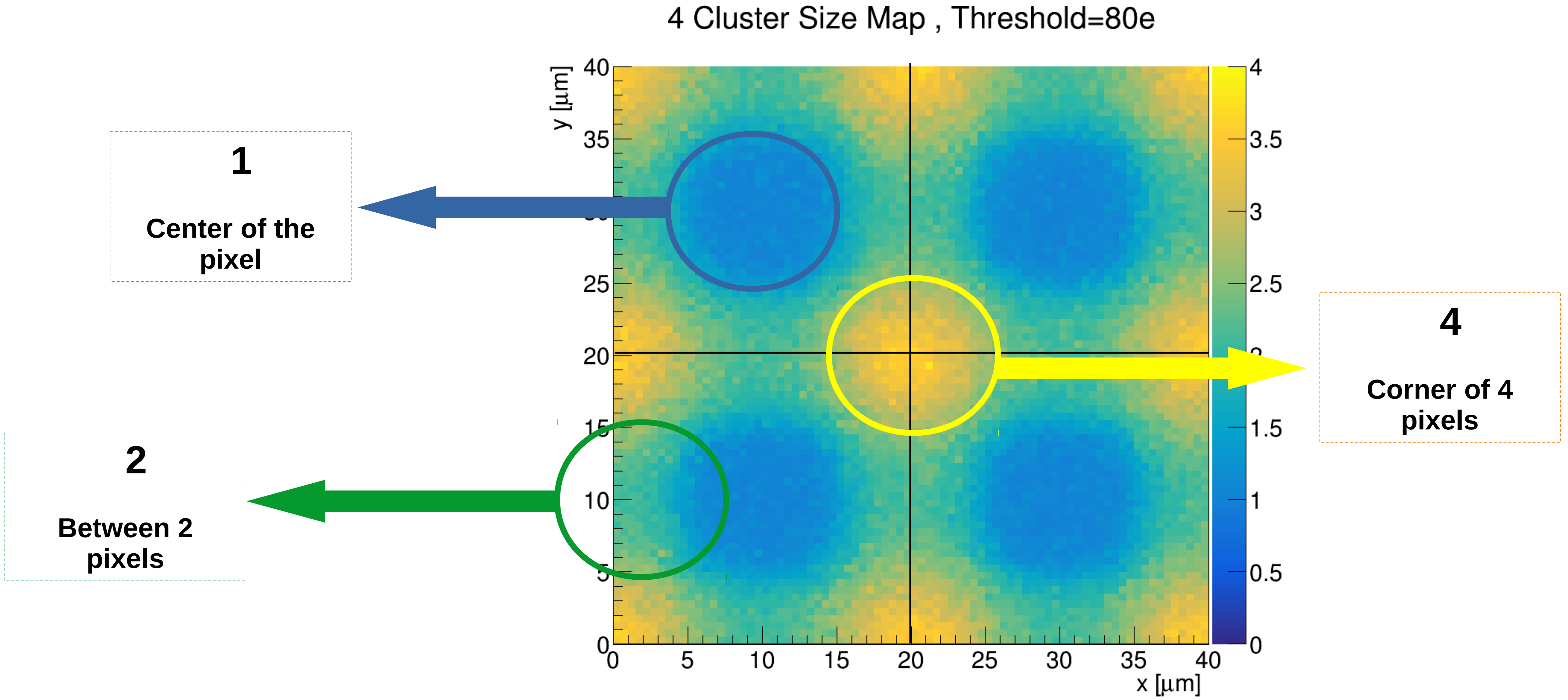
Cluster Size



Number of Pixels fired per event.

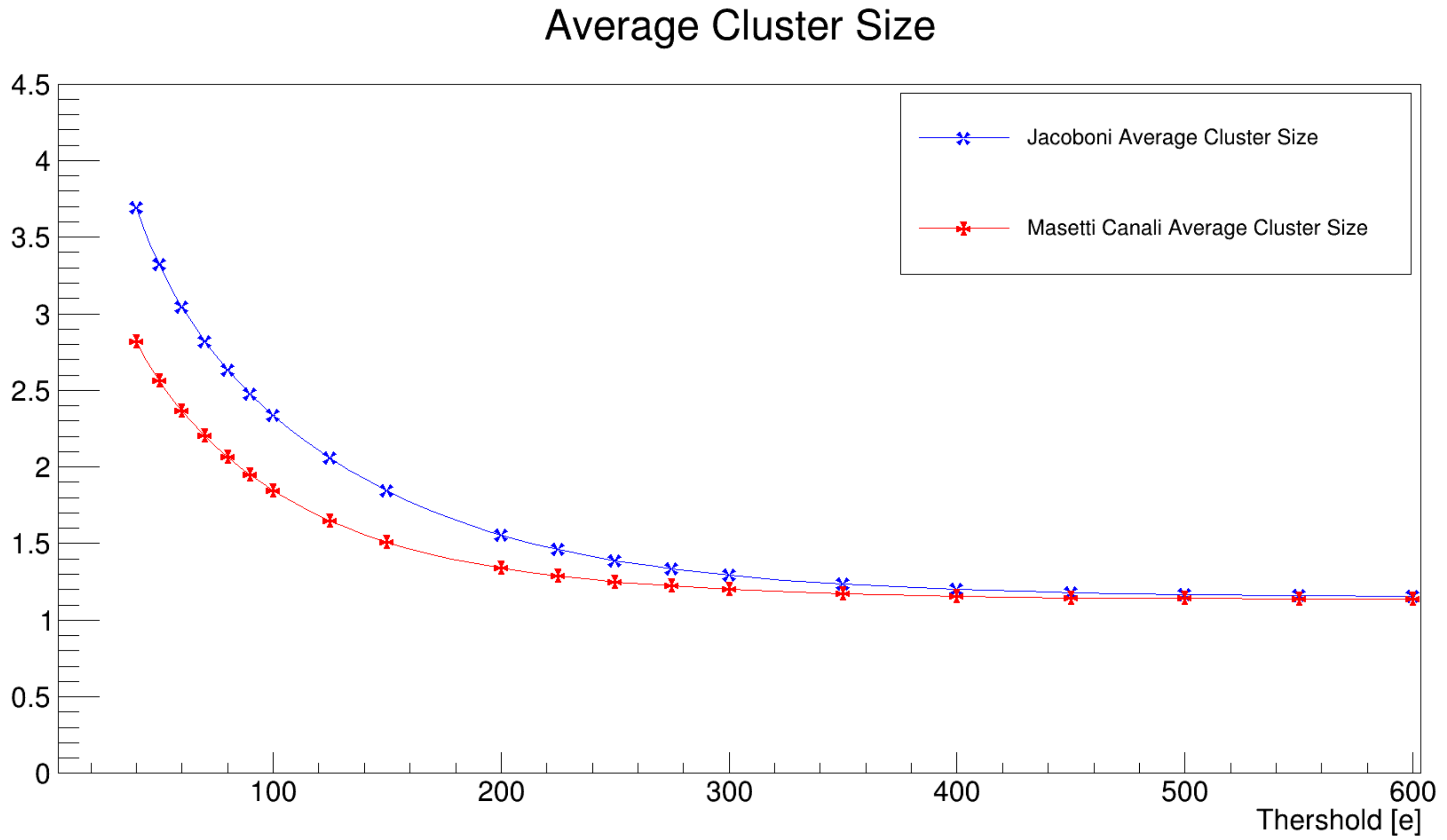
A high average cluster size translates roughly to a better (smaller) spatial resolution.

Cluster Size (Map of 4 adjacent pixels)



Cluster Size as a function of the detection threshold

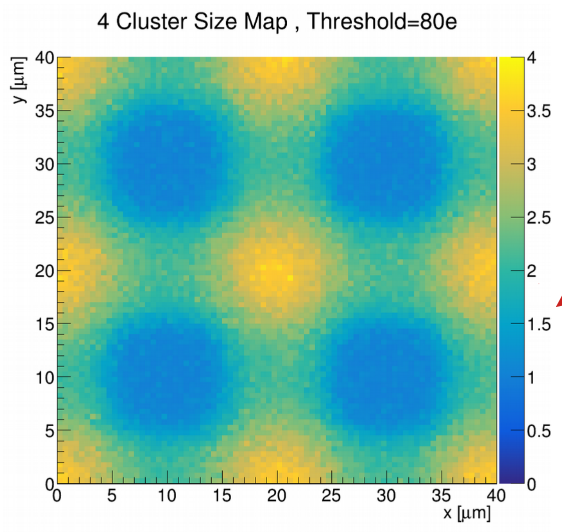
- Non-doping dependent Mobility Model (blue)
- Doping dependent Mobility Model (red)

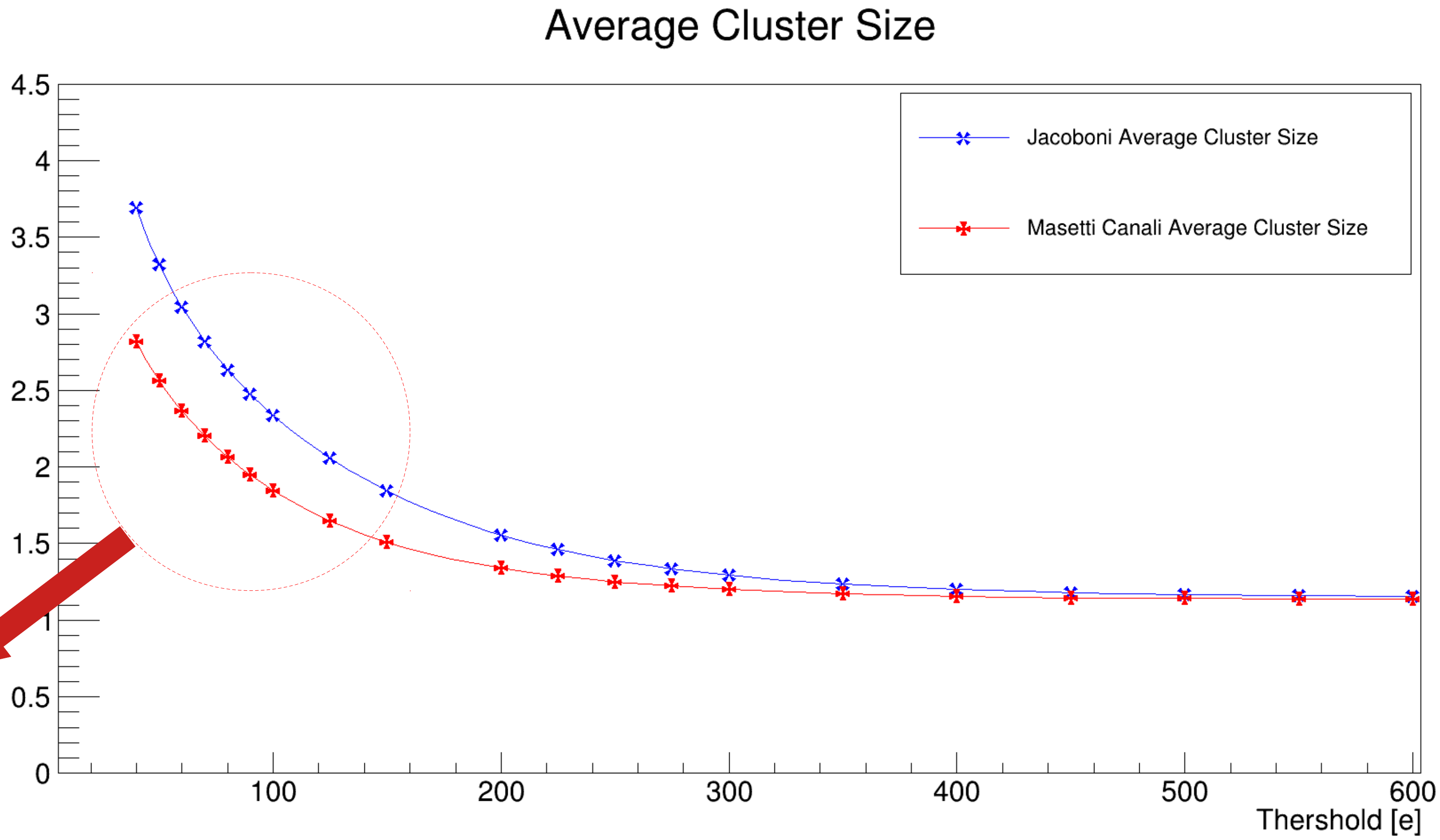


Cluster Size as a function of the detection threshold

Non-doping dependent Mobility Model

Doping dependent Mobility Model

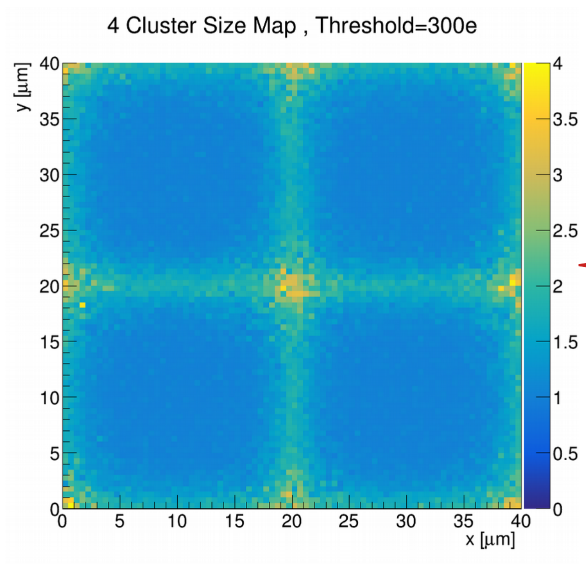


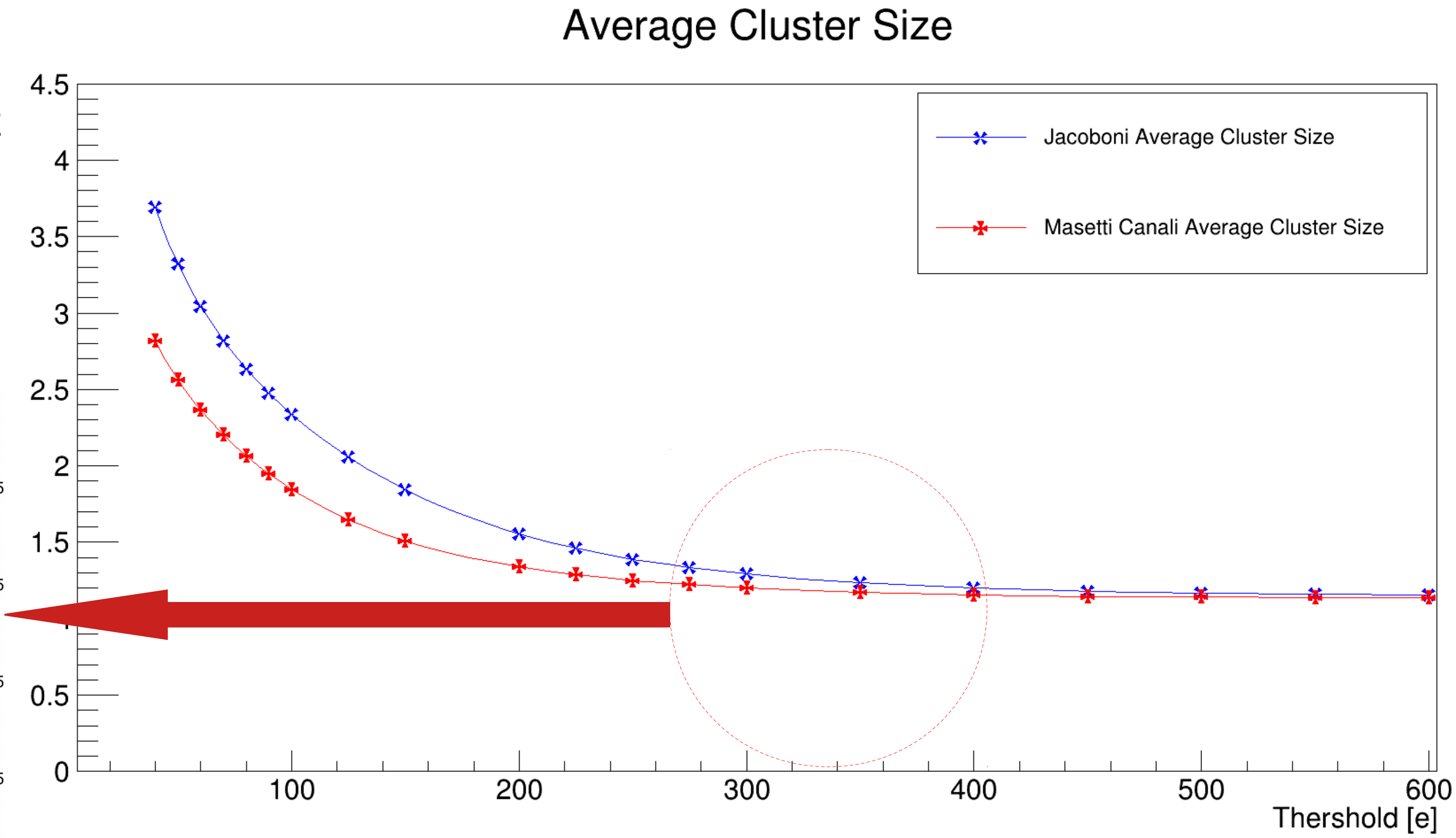


Cluster Size as a function of the detection threshold

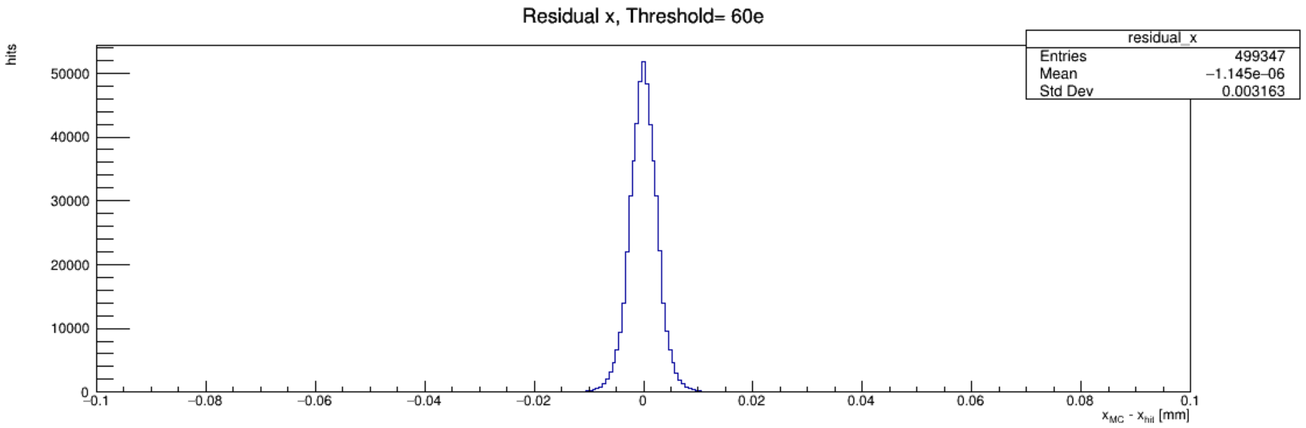
Non-doping dependent Mobility Model

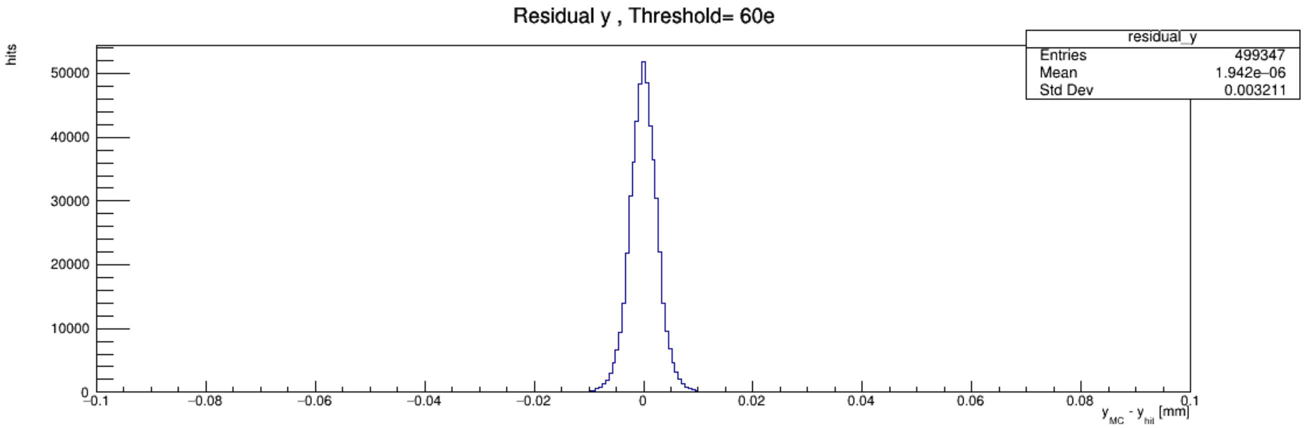
Doping dependent Mobility Model





Residuals ----> (Spatial Resolution)





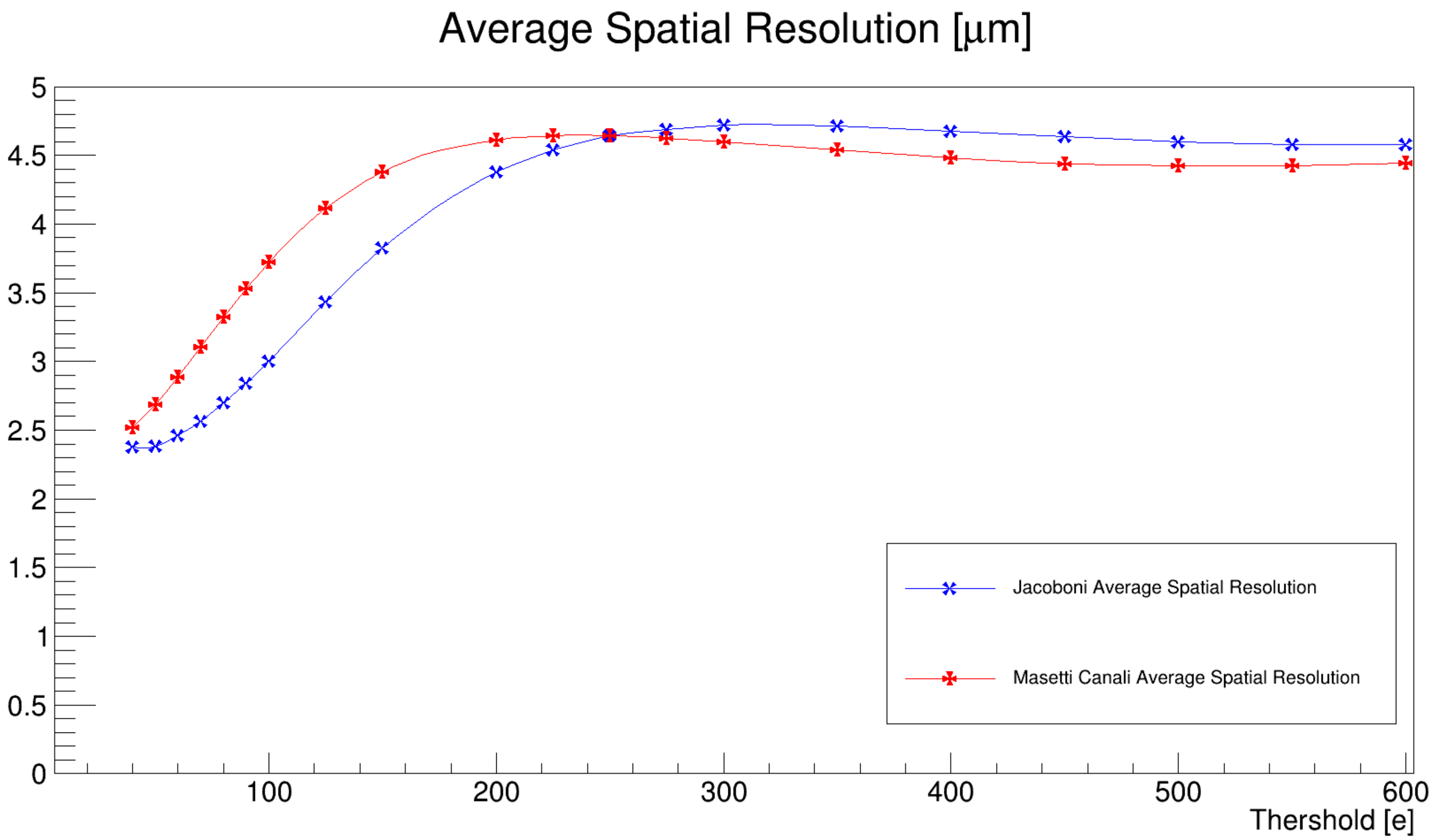
Residual: MC Particle incident position – Average cluster position

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

Spatial Resolution as a function of the detection threshold

Non-doping dependent Mobility Model

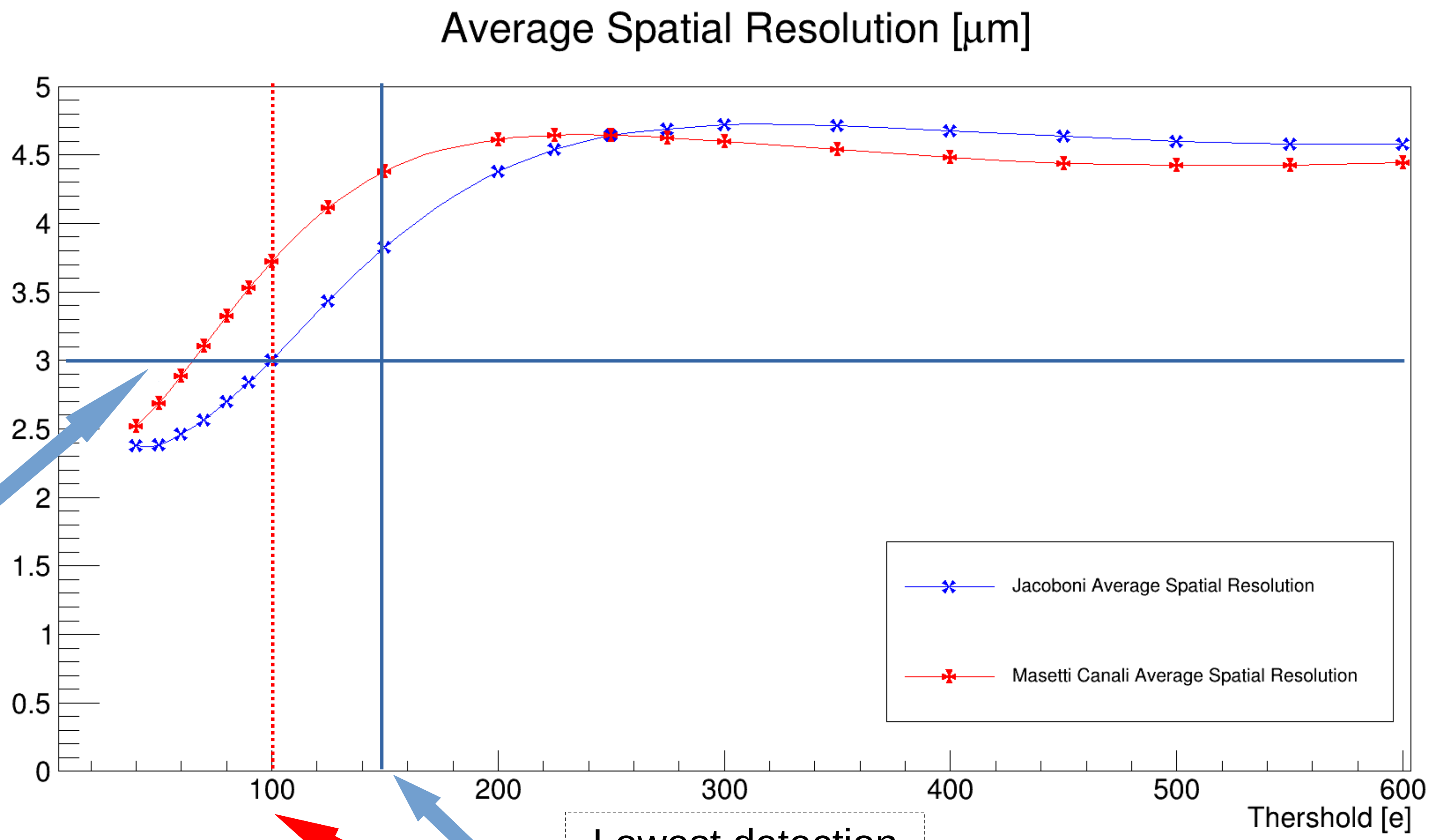
Doping dependent Mobility Model



Spatial Resolution as a function of the detection threshold

Non-doping dependent Mobility Model

Doping dependent Mobility Model



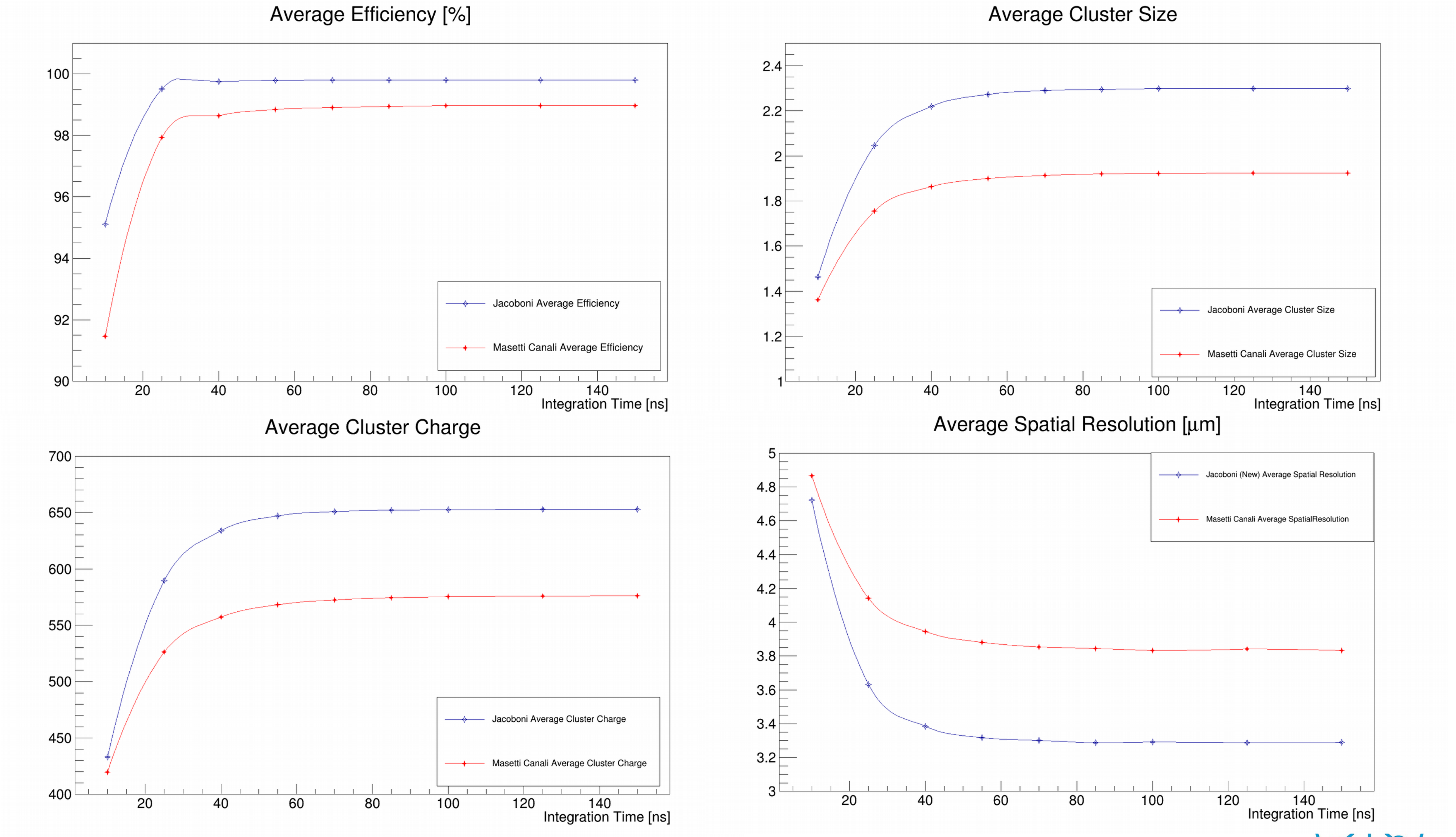
Desired resolution! What else can we change to achieve this?

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

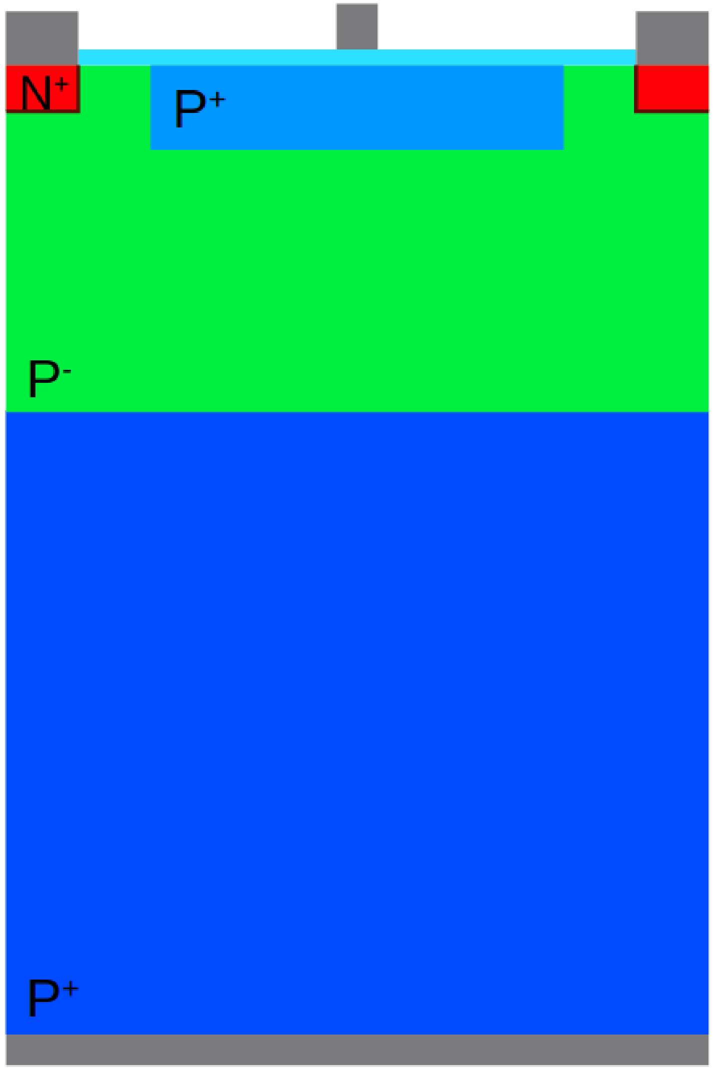
Integration time (Total Simulation time)

Non-doping dependent Mobility Model

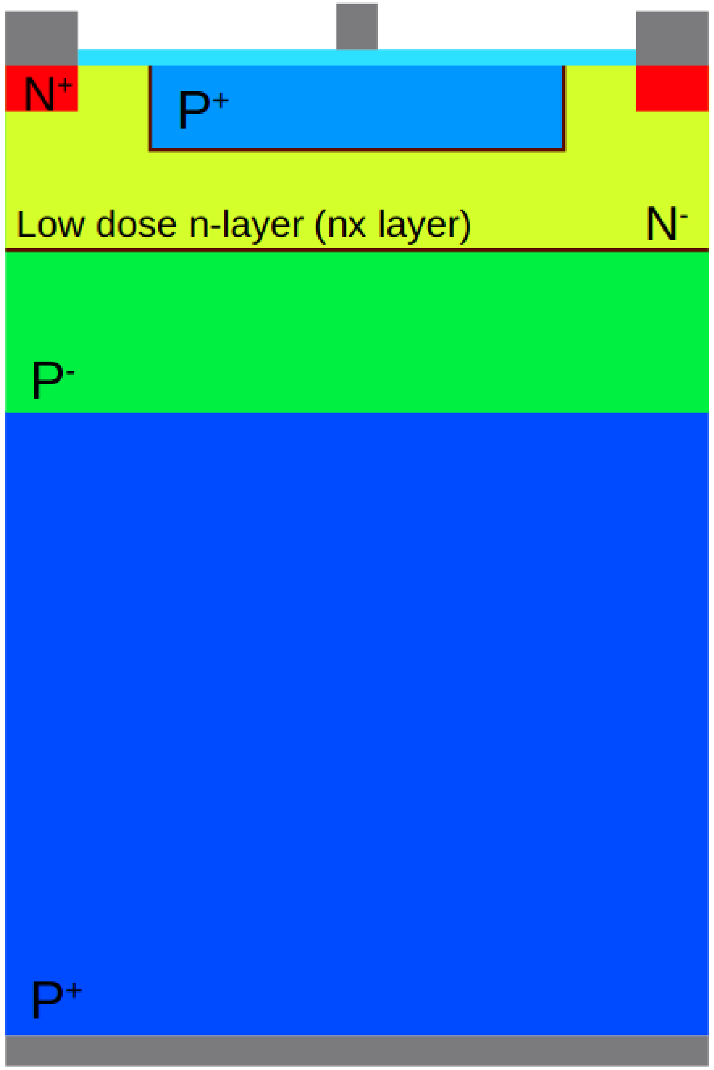
Doping dependent Mobility Model



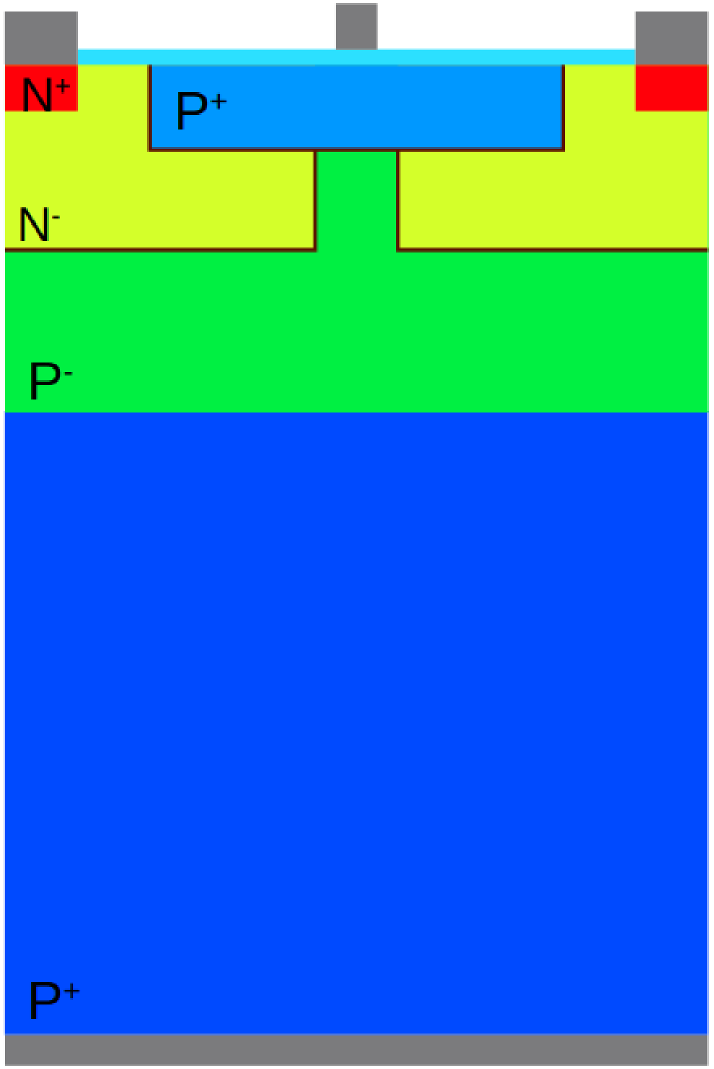
Standard Process



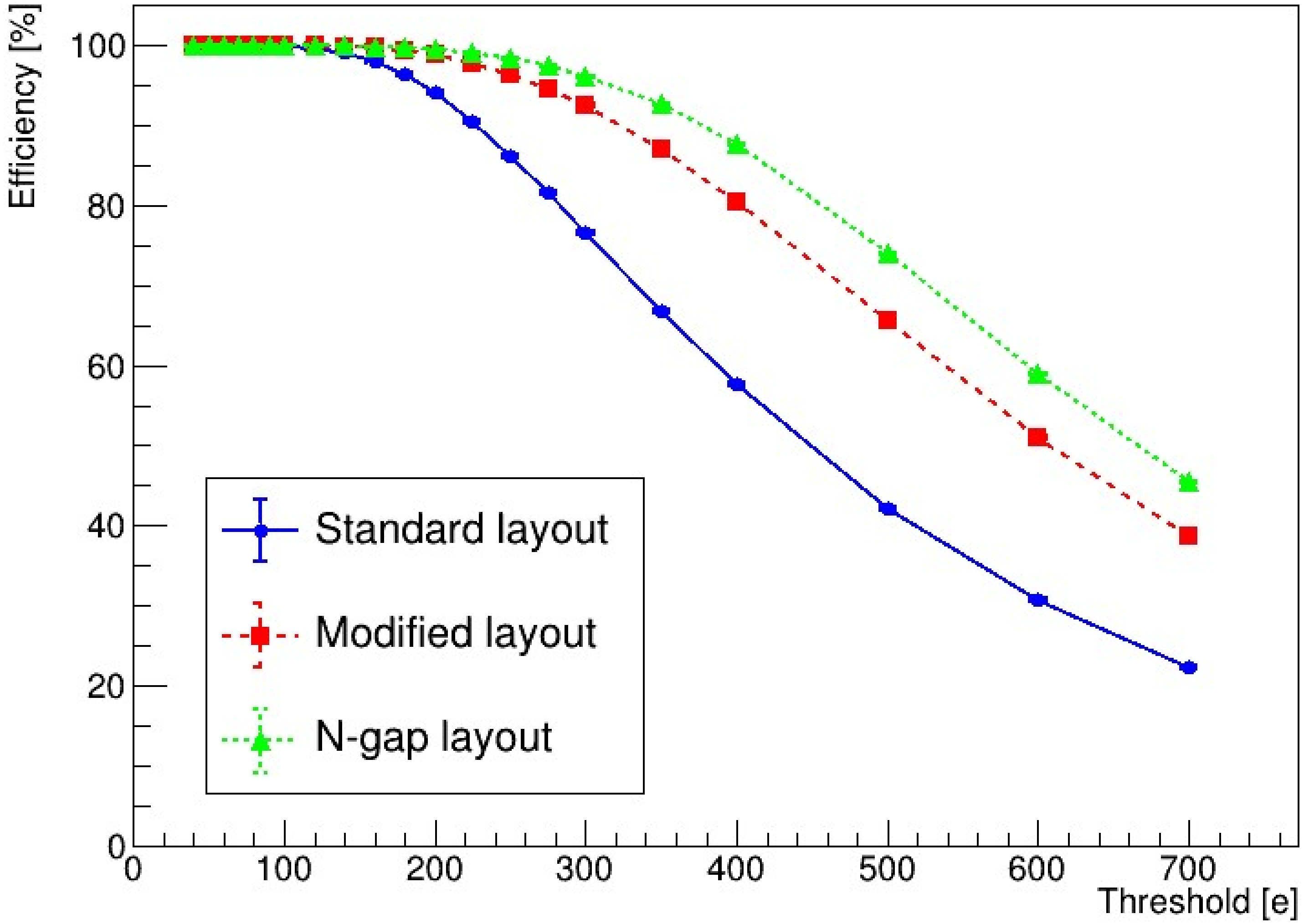
Modified Process



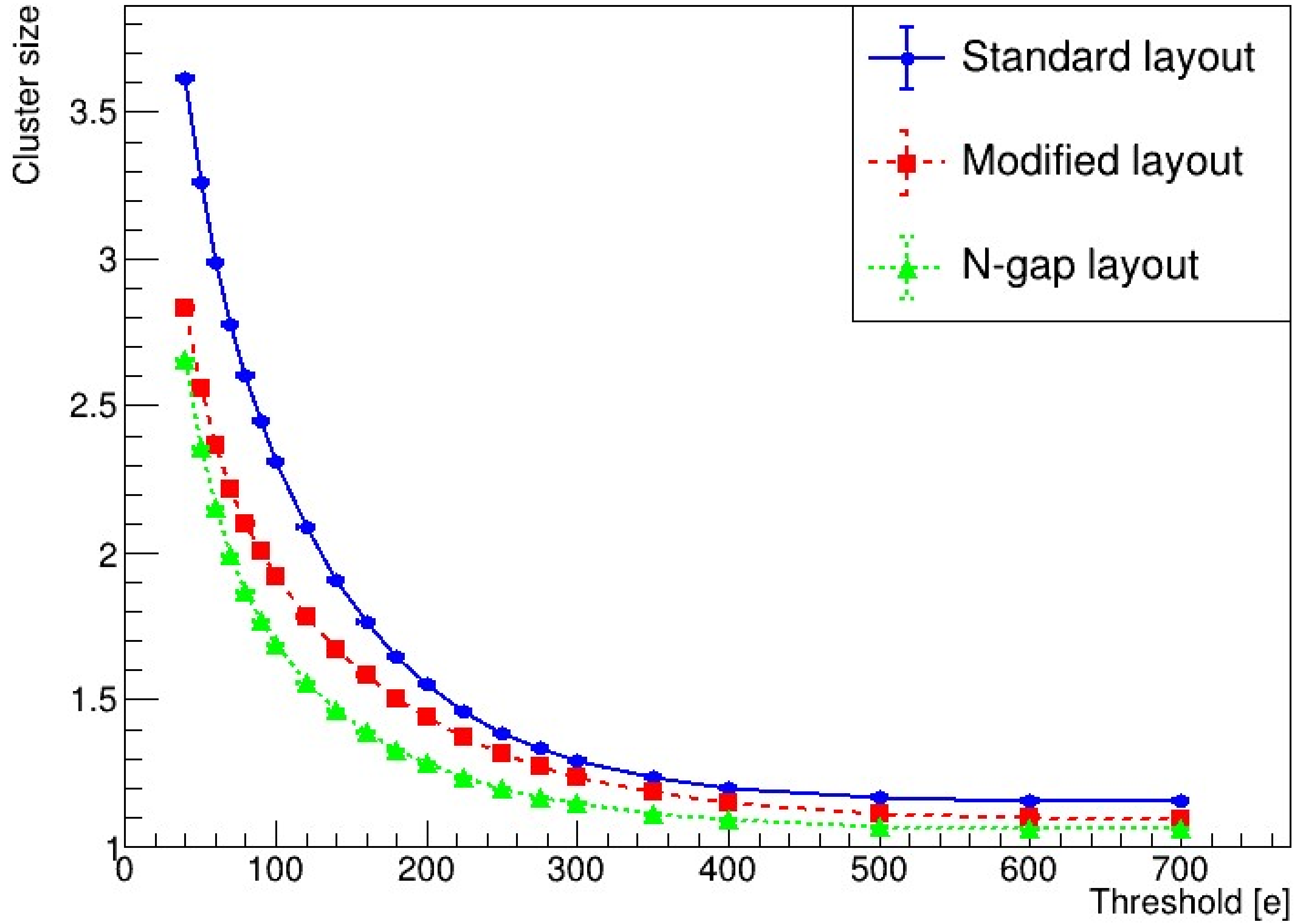
Modified Process with Gap



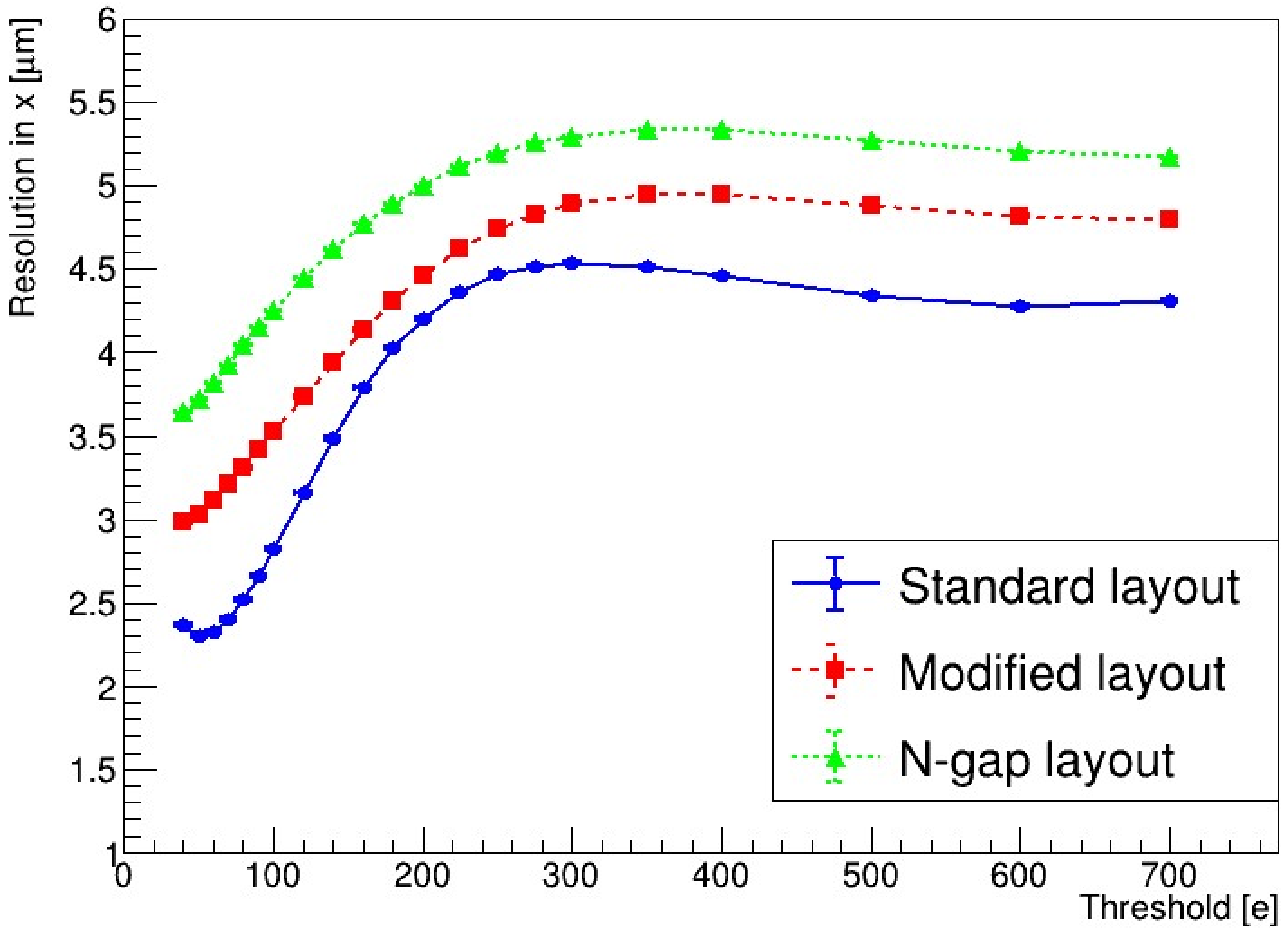
Layouts Comparison



Layouts Comparison



Layouts Comparison



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.

Thank you for your time!