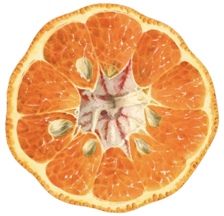
Monte Carlo simulations of a beam telescope setup based on a 65 nm CMOS Imaging Technology

Sara Ruiz Daza
On behalf of the Tangerine Collaboration



4th Allpix Squared User Workshop
23 May 2023, DESY (Hamburg)

HELMHOLTZ

UNIVERSITÄT BONN

DESY.

The Tangerine Project

Towards Next Generation Silicon Detectors

- Research and development of **new silicon sensors** for future lepton and electron-ion colliders, and test beam telescopes.

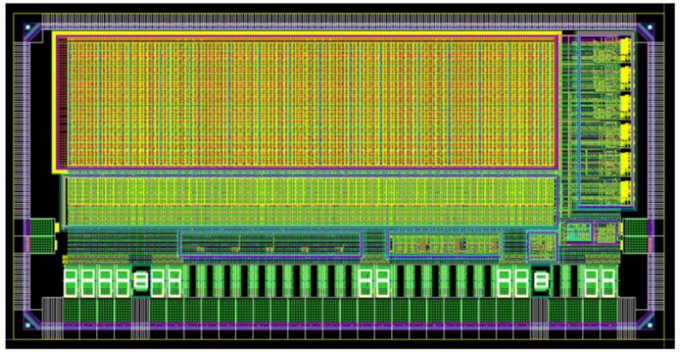
- Project goal: development of a sensor with **high spatial** (~ 3 µm) **and time resolution** (1-10 ns), and a **low material budget** (~ 50 µm Si).

- Comprising **all the steps of sensor R&D**: electronics design, sensor design based on simulations, prototype testing.

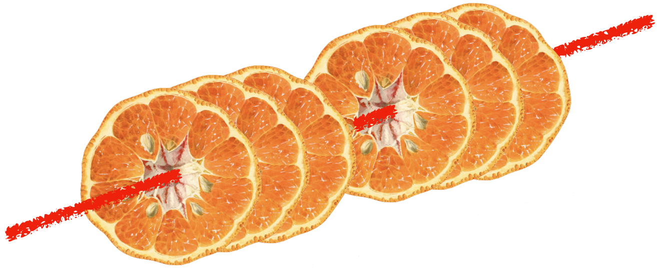
- Exploiting **monolithic sensors** based on a novel **65 nm CMOS imaging technology** with a **small collection electrode**.

- Primary initial goal: development of a **beam telescope** as integration step.

↪ *This talk presents the first simulations.*

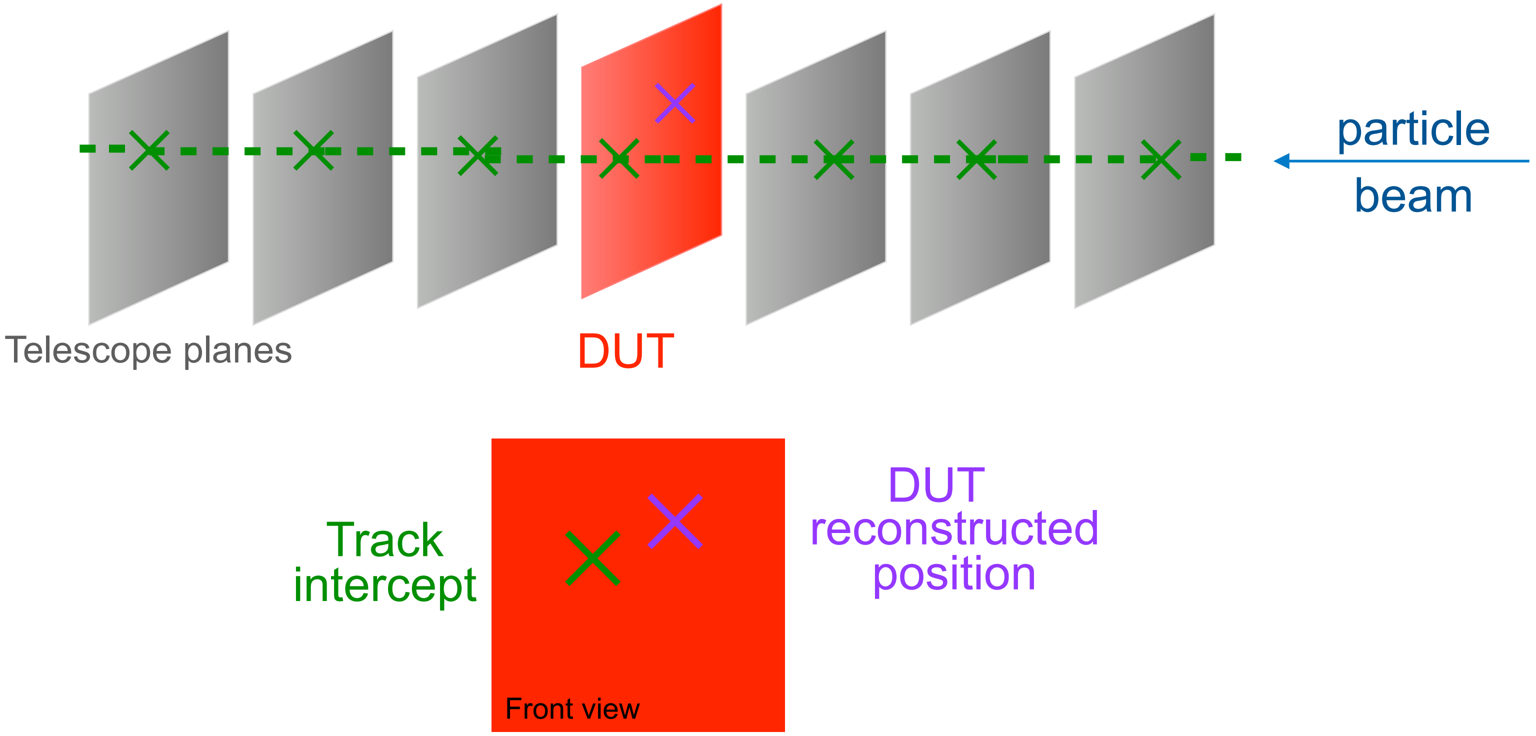


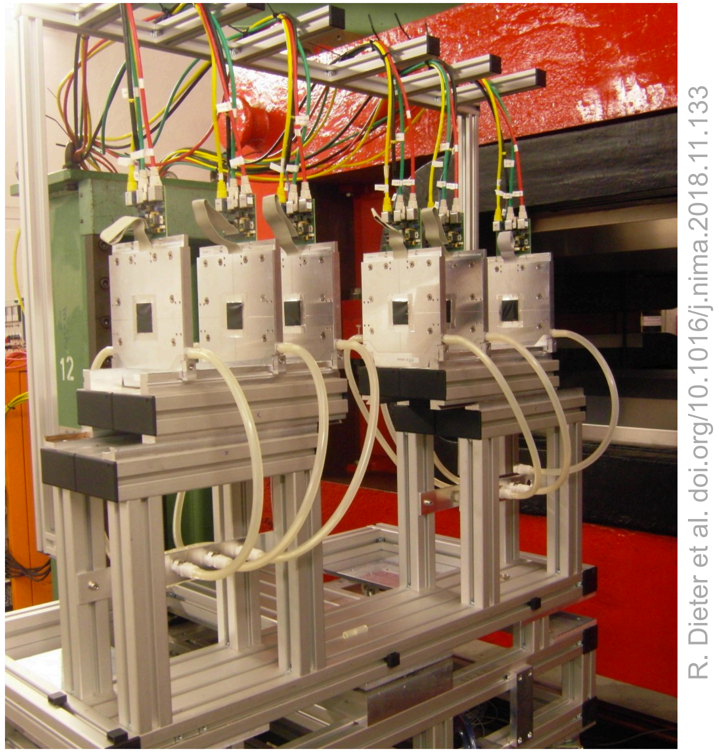
H2M Test Chip



Test beam telescope

- Used for **testing and characterisation of new devices**.





DESY beam telescope

- **Some studies:**
  - <u>Resolution</u>: Correlate the sensor response to the hit position.
  - <u>Efficiency</u>: the DUT should have registered a hit; dit it or did it not?

The telescope planes should reach a **high** (and known) **tracking resolution at the position of the DUT** (Device under Test).

Monte Carlo simulations and data analysis workflow

TCAD, Allpix², Corryvreckan

- Generic **doping concentrations** and precise **electric fields** are simulated using technology computer-aided design (**TCAD**).

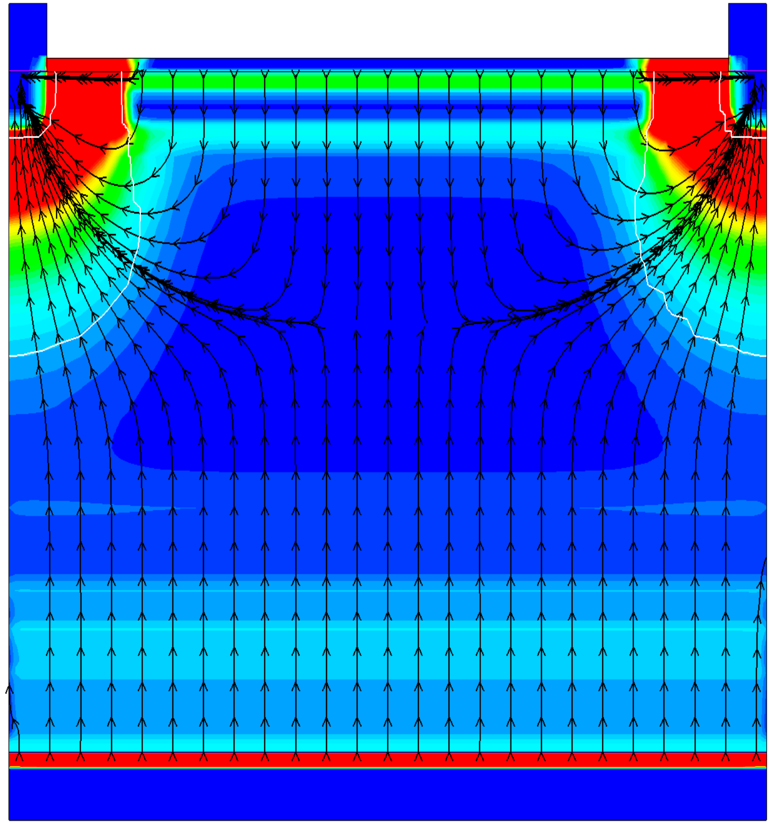
  Challenge: high computational cost and time-consuming simulations.

  ↪ See talk of M. A. Del Rio Viera

- **Full response of the sensor and the test beam telescope** with high statistics is simulated with **Allpix²**.

- **Data analysis of the test beam telescope** is performed using **Corryvreckan.**

Sentaurus TCAD SYNOPSYS® Silicon to Software™ → ap² allpix squared →

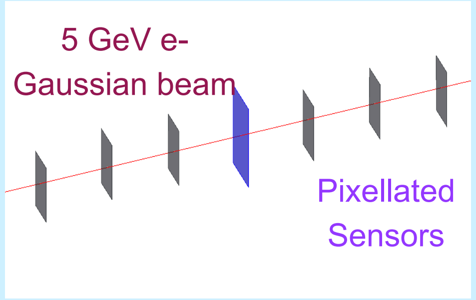


A. Simancas

Monte Carlo simulations and data analysis workflow

Build Geometry

[GeometryBuilderGeant4]



Electric Field and Doping Profiles Initialization

[ElectricFieldReader]
[DopingProfileReader]

Energy Deposition and Charge Carrier Creation

[DepositionGeant4]

Charge Propagation

[GenericPropagation]

Charge Transfer

[SimpleTransfer]

Digitization

[DefaultDigitizer]

Write Data To File

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[CorryvreckanWriter]

Analysis

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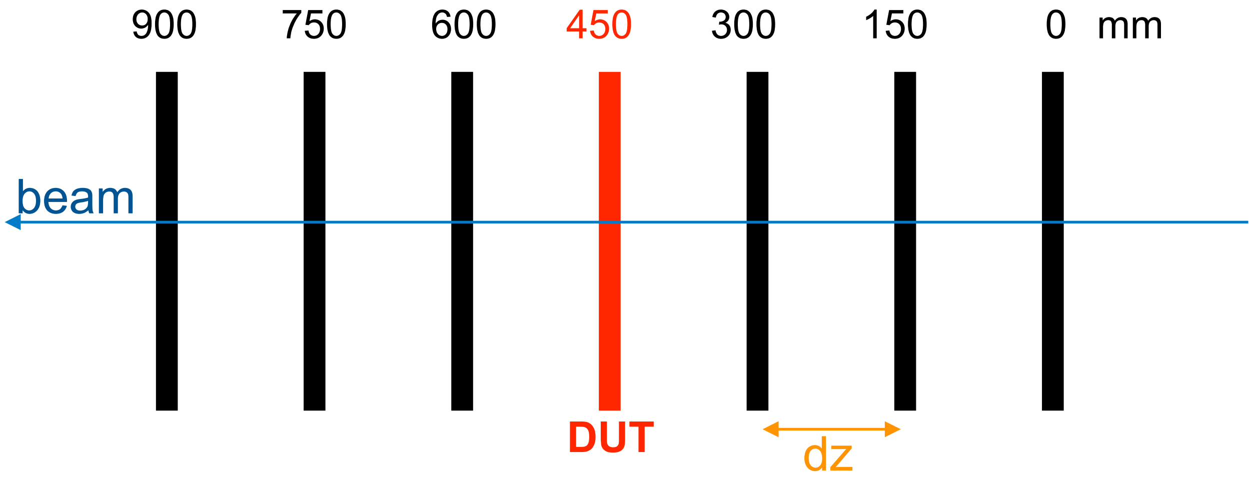
- …

Beam telescope setup for the first simulations



- **6 parallel planes**, perpendicular to a 5 GeV e^- Gaussian spread beam.
- Each telescope plane consist of **1024x1024 pixels, pixel pitch 20 µm**.
- **DUT** is simulated as a 'silicon box': 50 µm thick (0.05% X/X_0).
- **Random misalignment and alignment correction** for position and orientation is included.

```
[telescope0]
type = "detector_model"
position = 0um 0um 0mm
orientation_mode = "xyz"
orientation = 0deg 0deg 180deg
alignment_precision_position = 1mm 1mm 100um
alignment_precision_orientation = 0.2deg 0.2deg 0.2deg

[telescope1]
…
[telescope2]
…
[box1]
…
[telescope3]
…
[telescope4]
…

[telescope5]
type = "detector_model"
position = 0um 0um 900mm
orientation_mode = "xyz"
orientation = 0deg 0deg 180deg
alignment_precision_position = 1mm 1mm 100um
alignment_precision_orientation = 0.2deg 0.2deg 0.2deg
```

```
type = "monolithic"
number_of_pixels = 1024 1024
pixel_size = 20um 20um
sensor_thickness = 50um
implant_size= 2.2um 2.2um
sensor_excess = 200um
```

```
[box1]
type = "box"
position = 0um 0um 450mm
orientation_mode = "xyz"
orientation = 0deg 0deg 180deg
size = 30mm 30mm 50um
material = "silicon"
role = "passive"
```

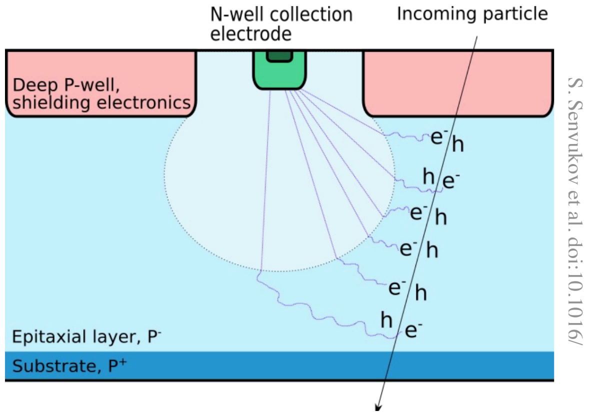
Investigated sensor layouts

Lateral view of the pixel cell

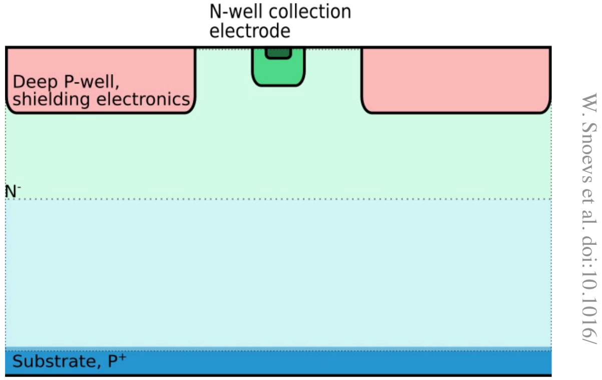
Top view of the pixel cell

In-pixel efficiency and cluster size

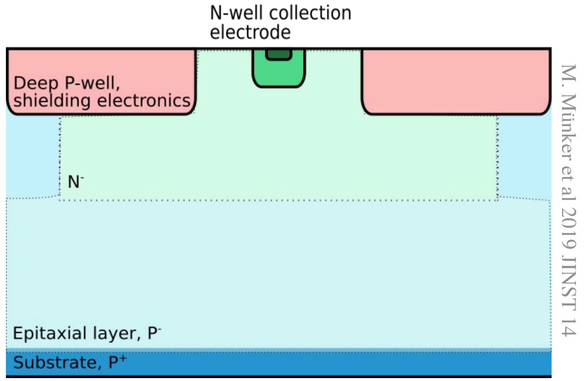
Standard Layout

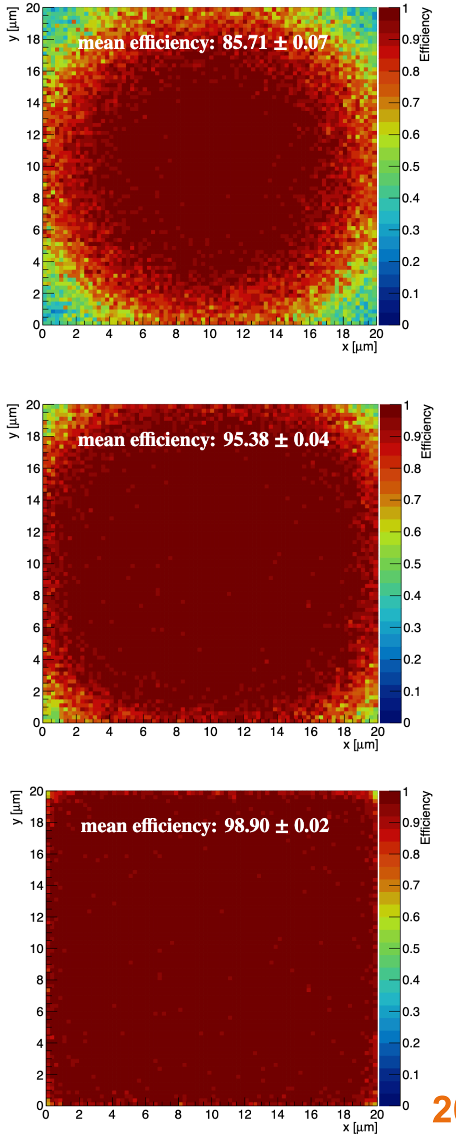


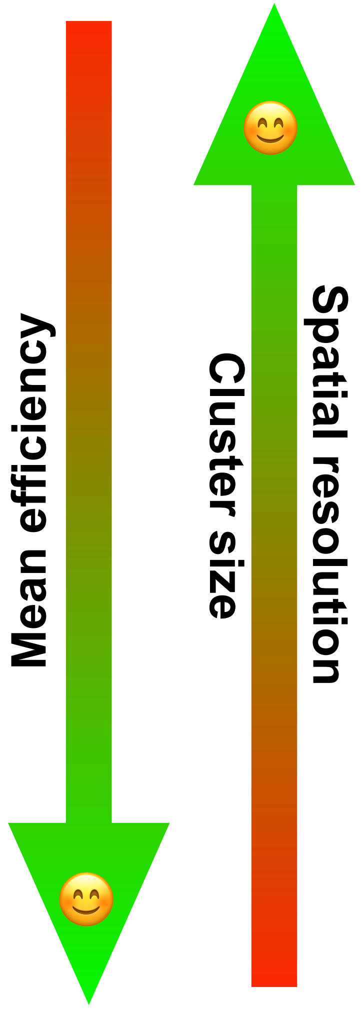
N-blanket Layout

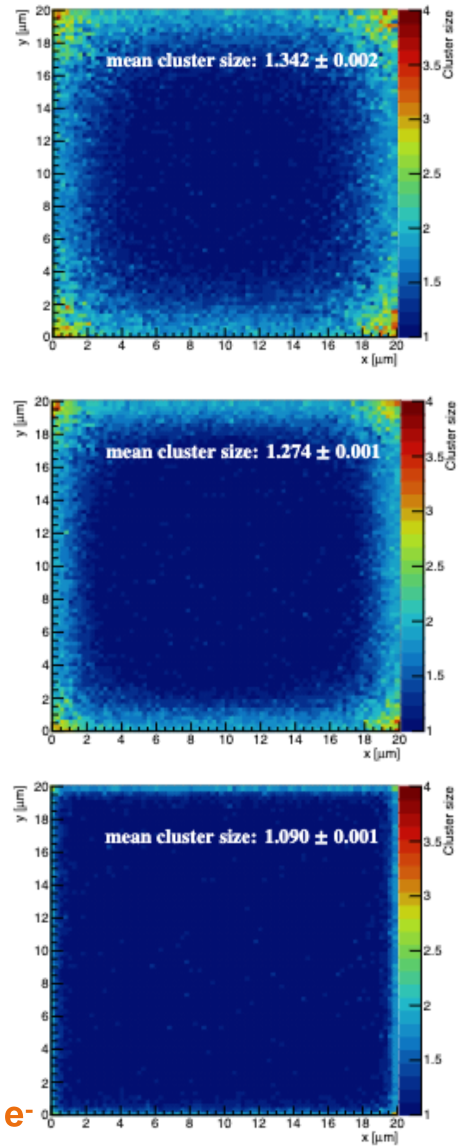


N-gap Layout









Simulations

20x20 µm², THL = 200 e-

Monte Carlo simulations and data analysis workflow

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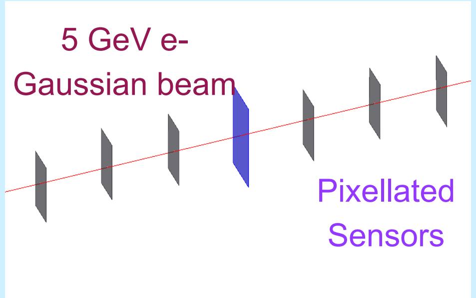

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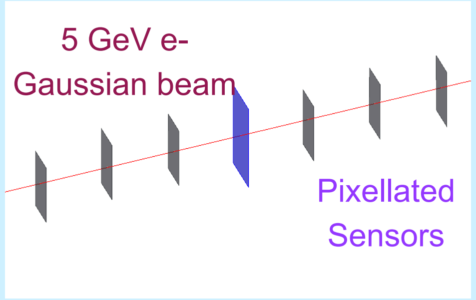

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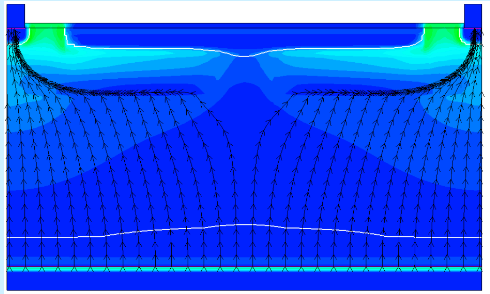

↪ See talk of A. Simancas

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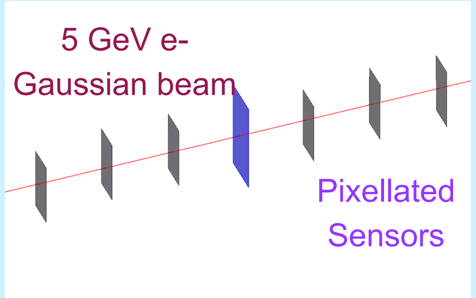

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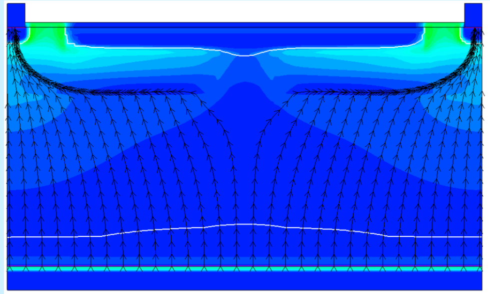

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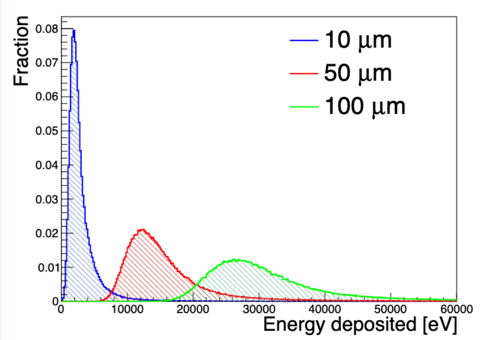

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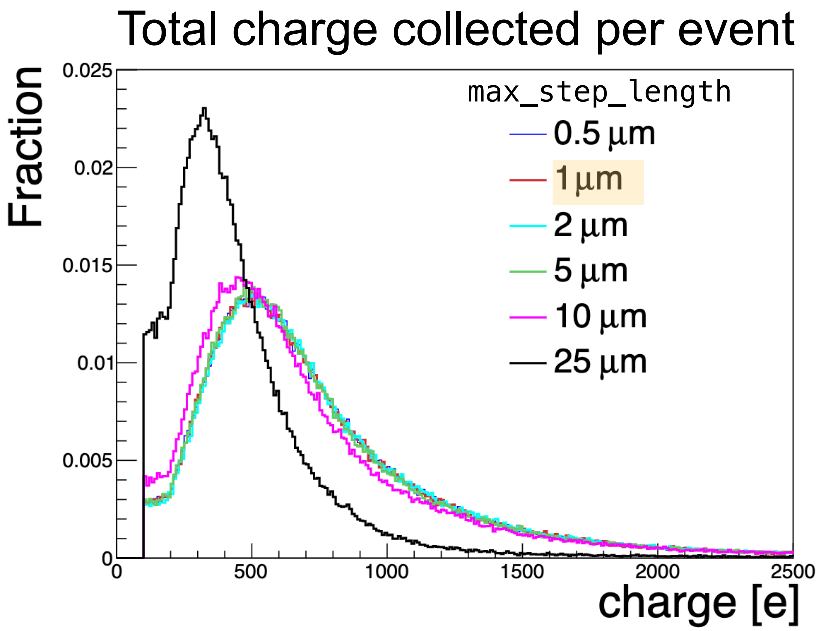
Energy deposition and charge carrier creation

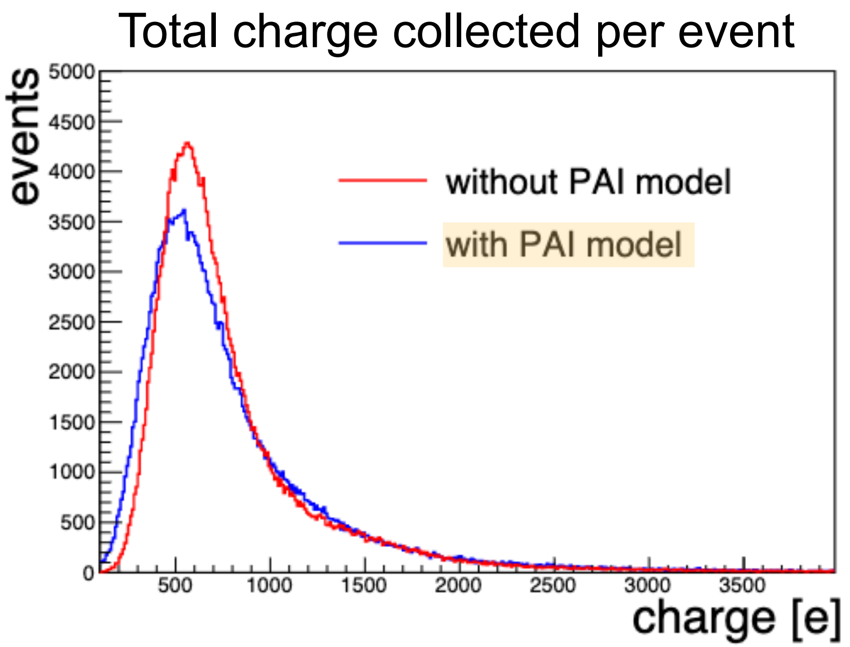
Example of configuration

```
[DepositionGeant4]

physics_list = FTFP_BERT_LIV

number_of_particles = 1
particle_type = "e-"
source_energy = 5GeV
source_type = "beam"
source_position = 0um 0um -20mm
beam_size = 100um
beam_direction = 0 0 1

max_step_length = 1um

enable_pai = true
```

Found problems with other Geant4 physics list (negative local time and long negative step lengths).

5 GeV e^- Gaussian spread beam.





All the parameters have been verified.

Sensor-dependent studies!

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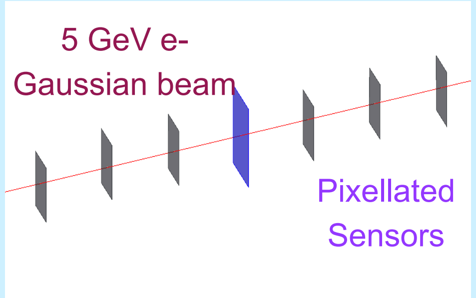

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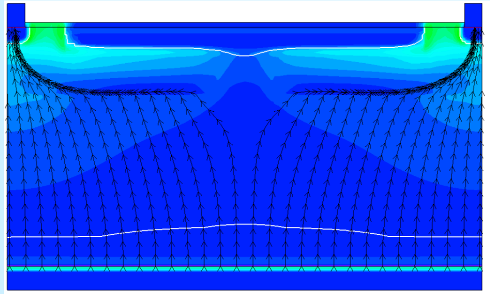

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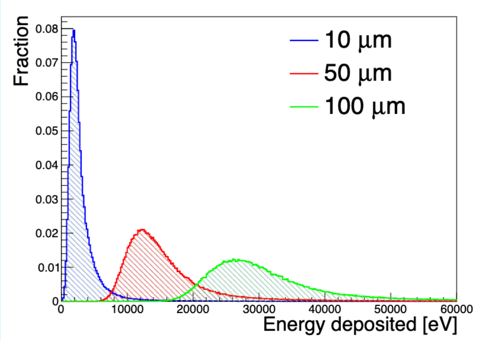

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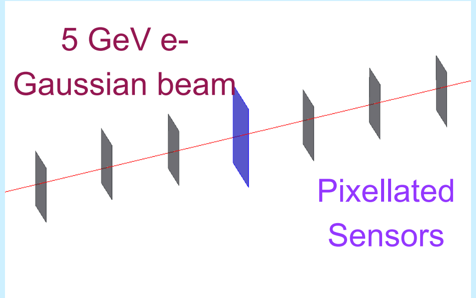

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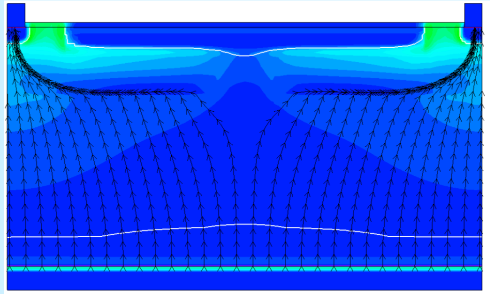

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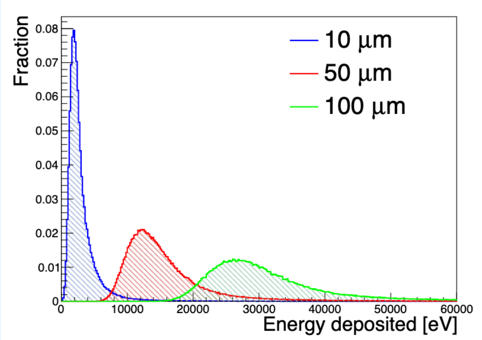

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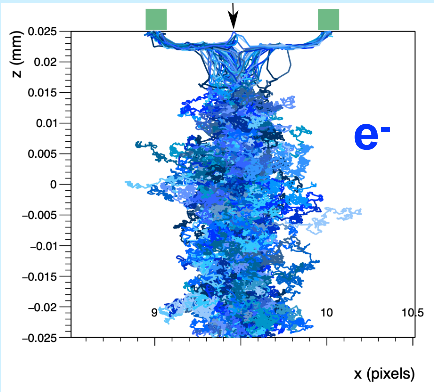

↪ See talks from last year of: M.A. Del Rio Viera & S. Ruiz Daza

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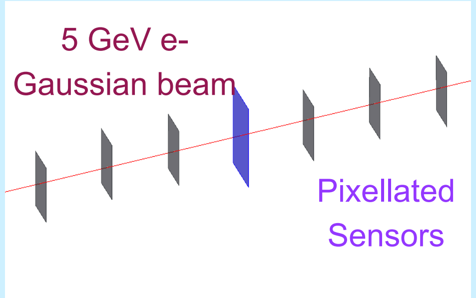

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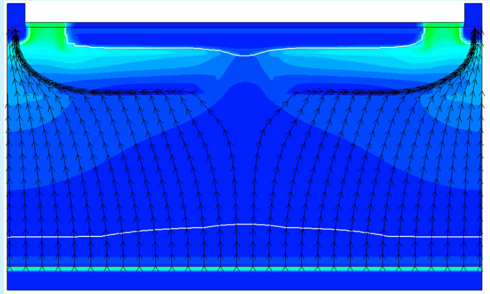

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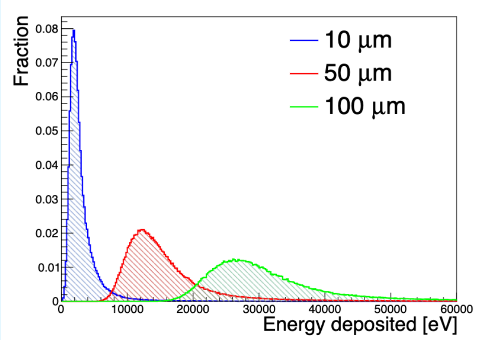

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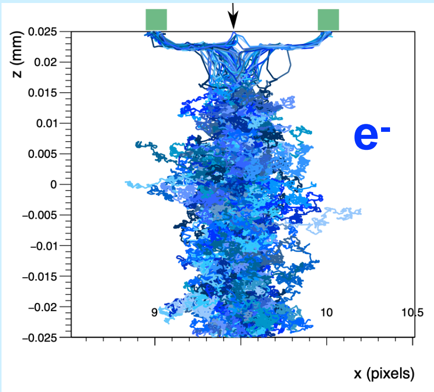

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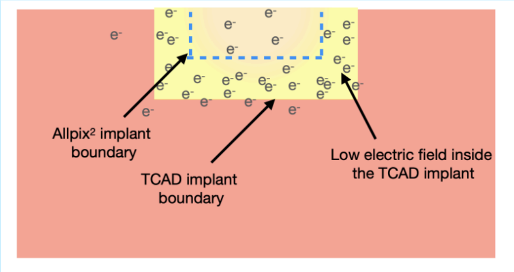

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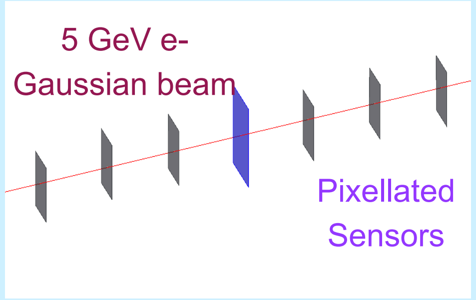

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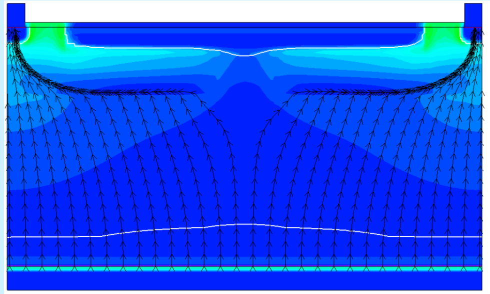

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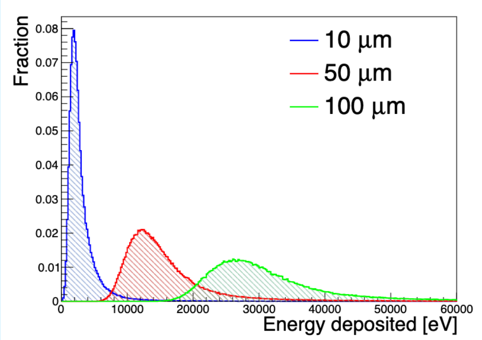

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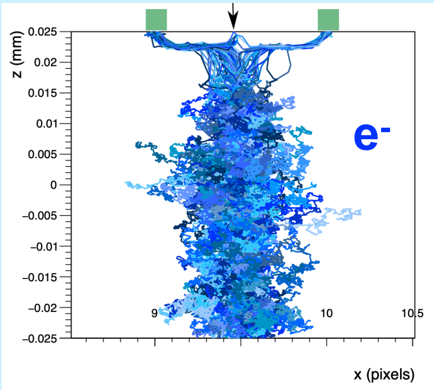

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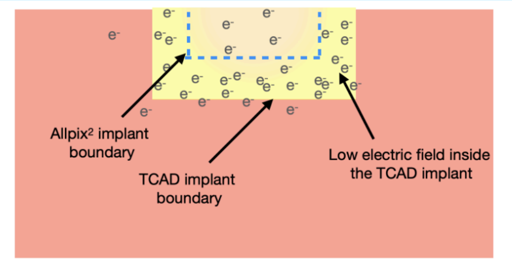

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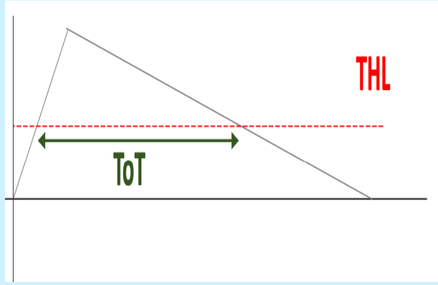

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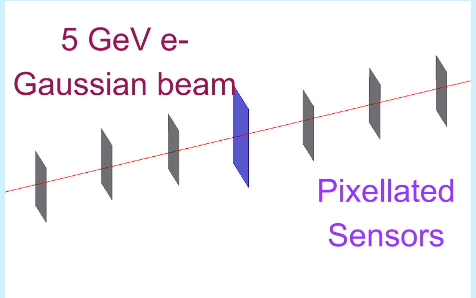

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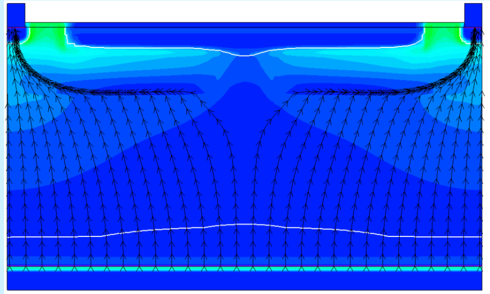

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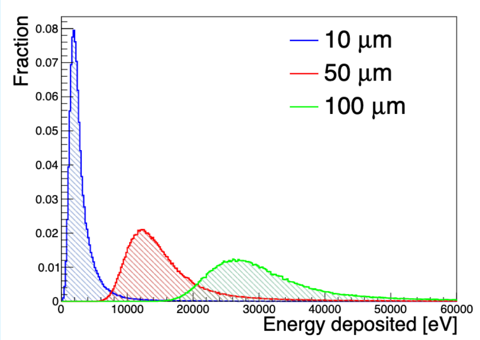

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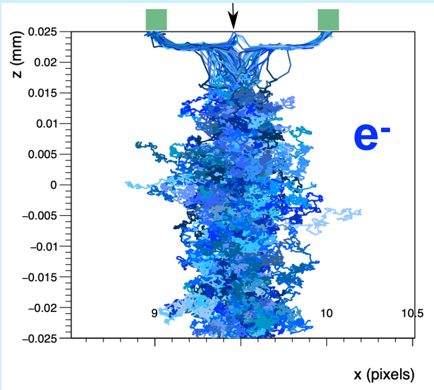

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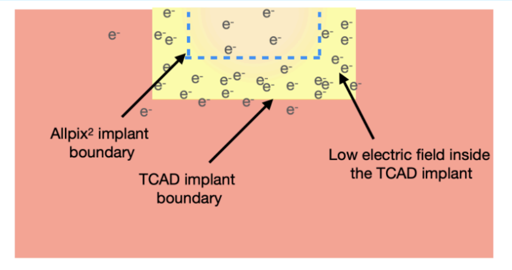

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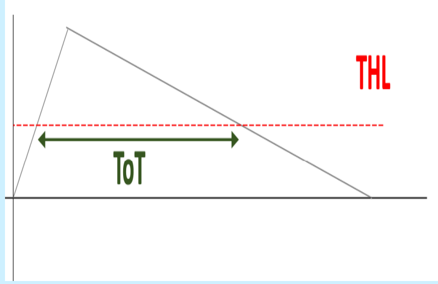

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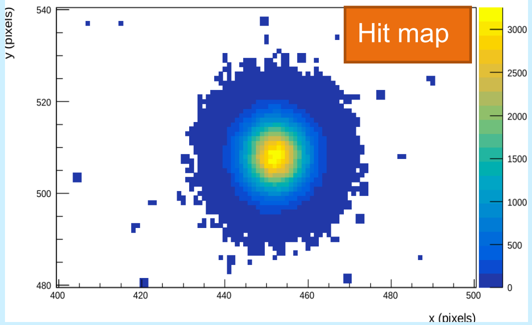

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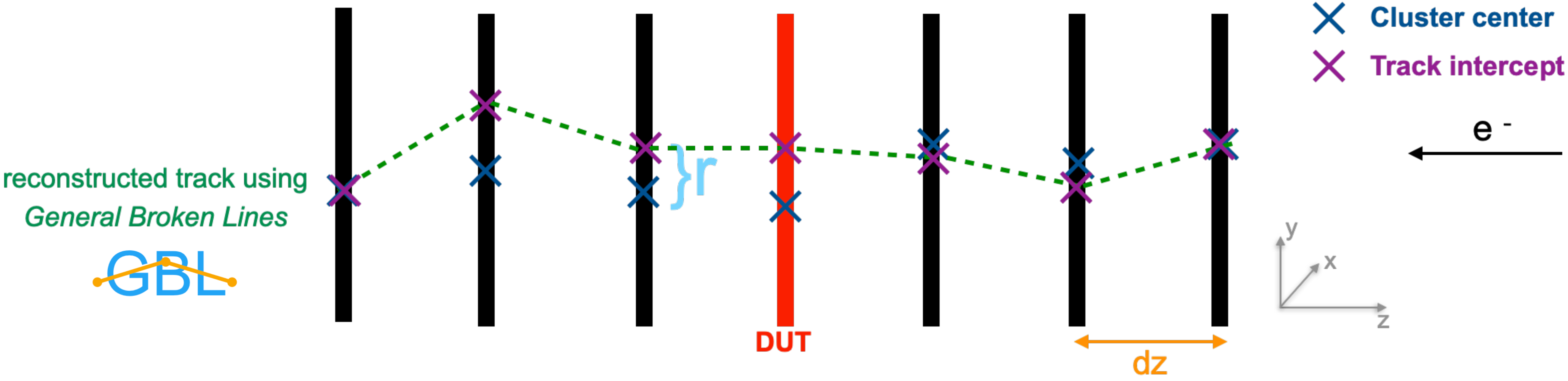
Test beam telescope

Track reconstruction & Residuals



Unbiased residual (r_u^2) : x/y track intercept on this plane - x/y associated cluster on this plane

Biased residual (r_b^2) : x/y track intercept on this plane - x/y track cluster on this plane

$$r_u^2(z) = \sigma_{int}^2 + \sigma_{t,u}^2(z)$$

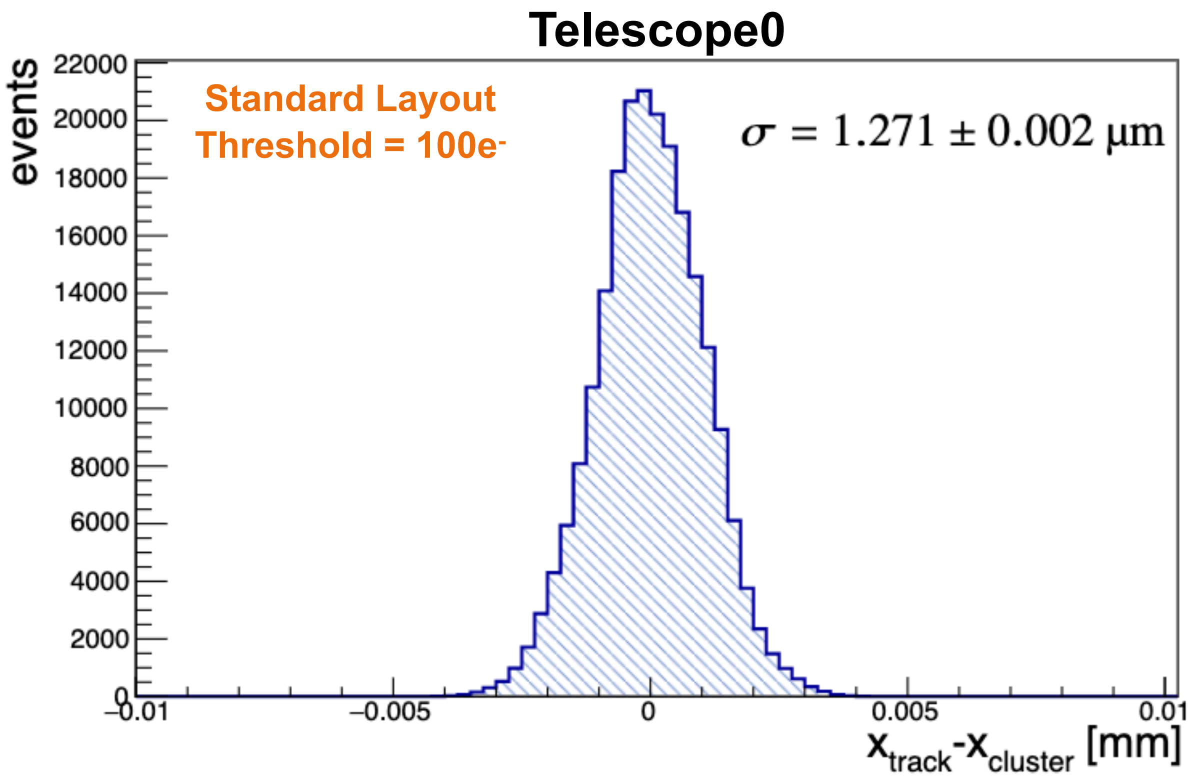
$$r_b^2(z) = \sigma_{int}^2 - \sigma_{t,b}^2(z)$$

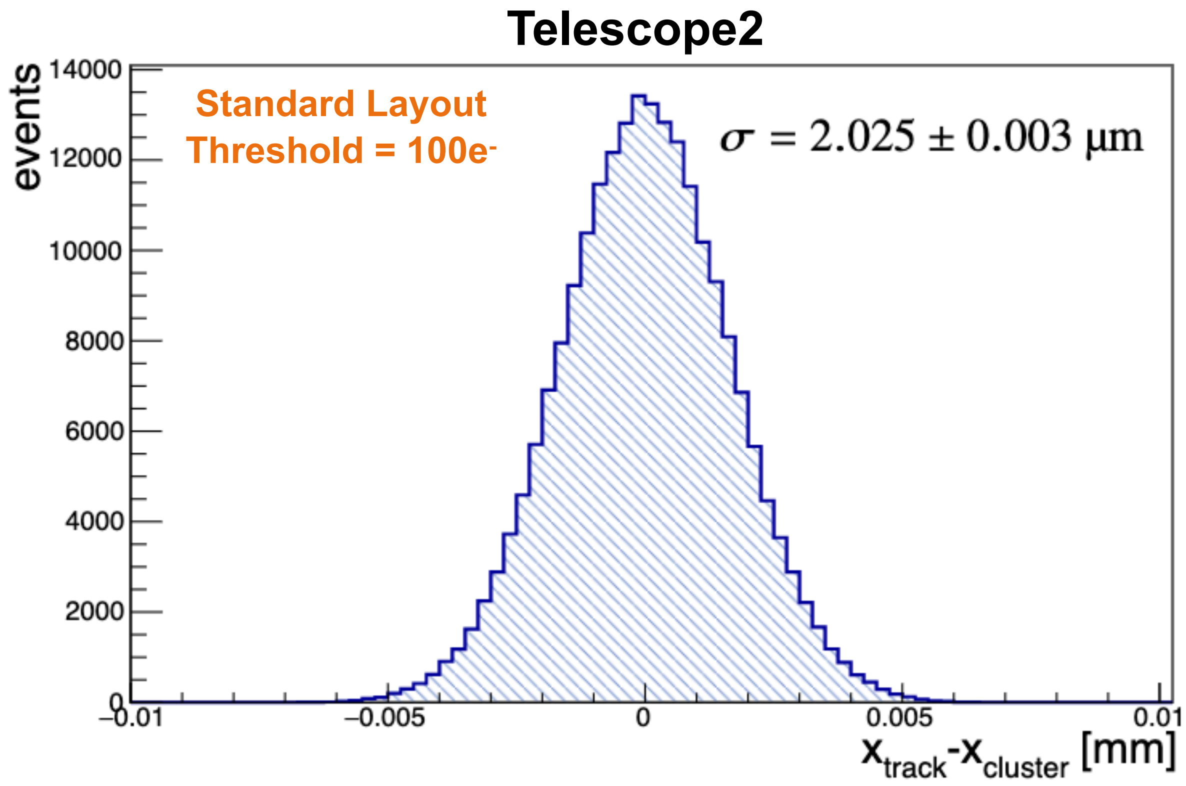
Intrinsic resolution (σ_{int}^2)

Tracking resolution ($\sigma_{t,b}^2(z)$)

Resolution at the different telescope planes

Biased residual distributions in X, dz = 150 mm



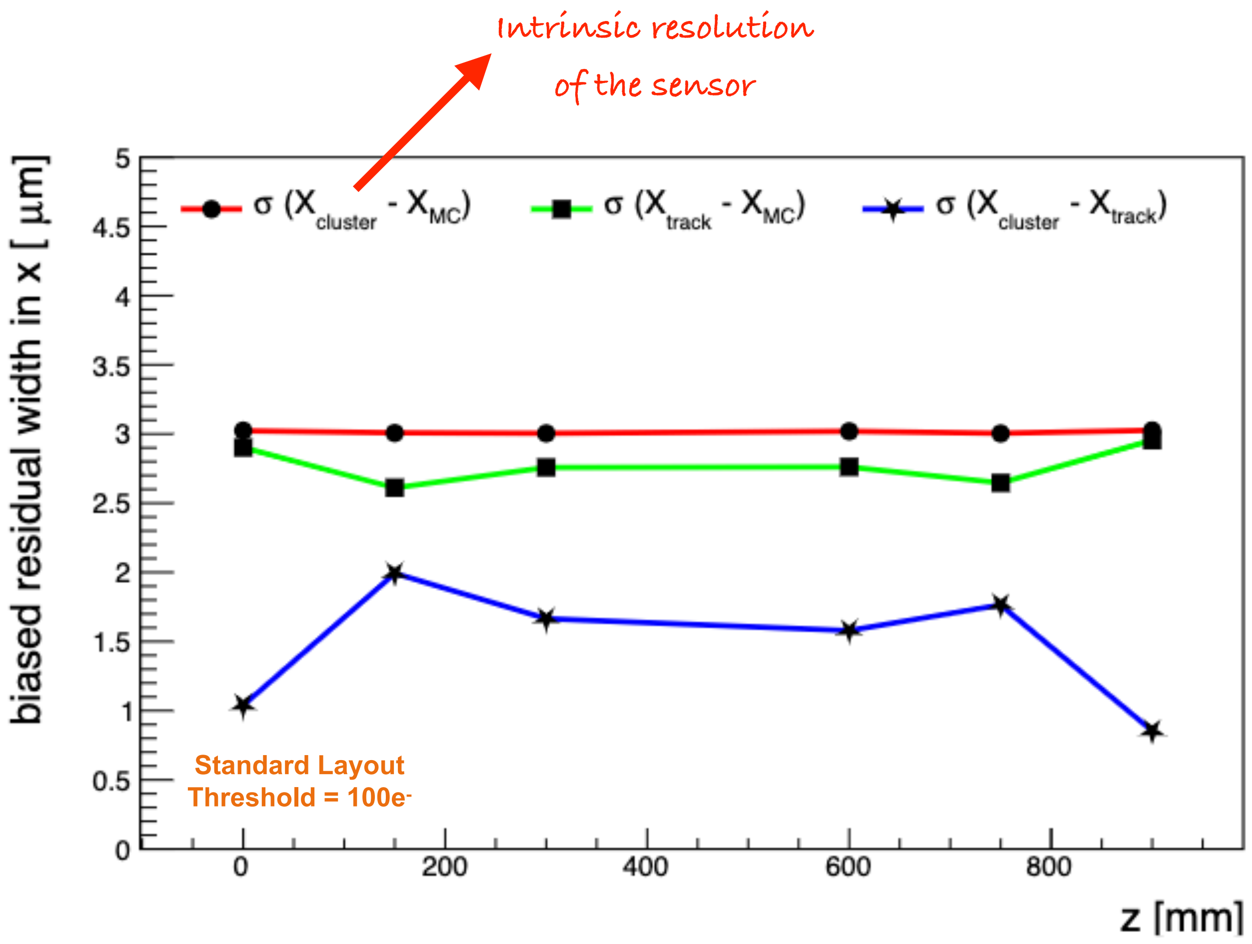


- Residual width obtained from the standard deviation of the distributions.
- Different biased residual widths for the different planes.

$$r_b^2(z) = \sigma_{int}^2 - \sigma_{t,b}^2(z)$$

Resolution at the different telescope planes

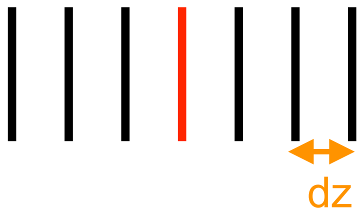
Biased residual distributions in X, dz = 150 mm

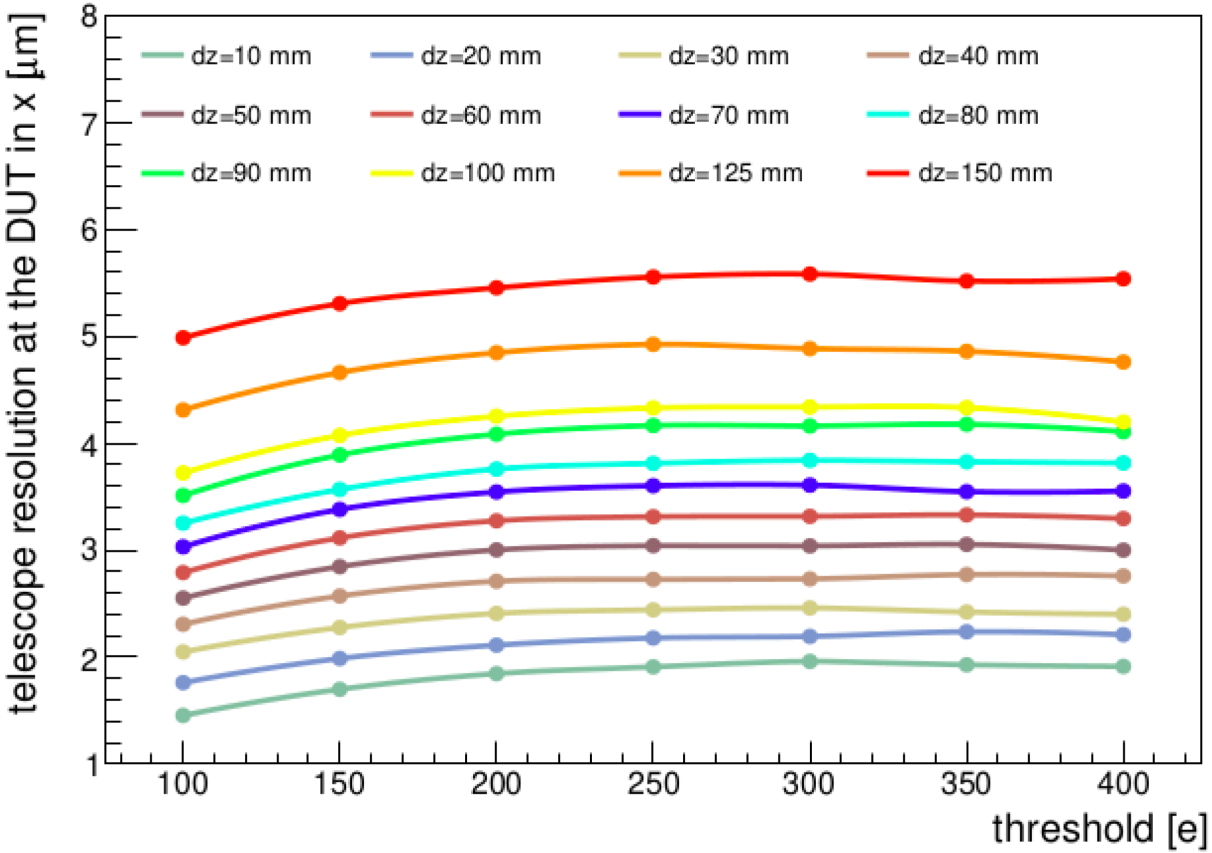


- Error bars are smaller than the dot size: 250 000 events per data point.
- The tracking resolution deteriorates towards the outer planes.
- Biased residual width for the outermost plates are smaller than the ones for the inner planes, as expected for track model.

Tracking resolution and efficiency

Standard layout

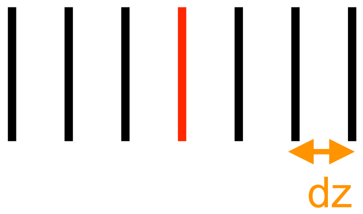




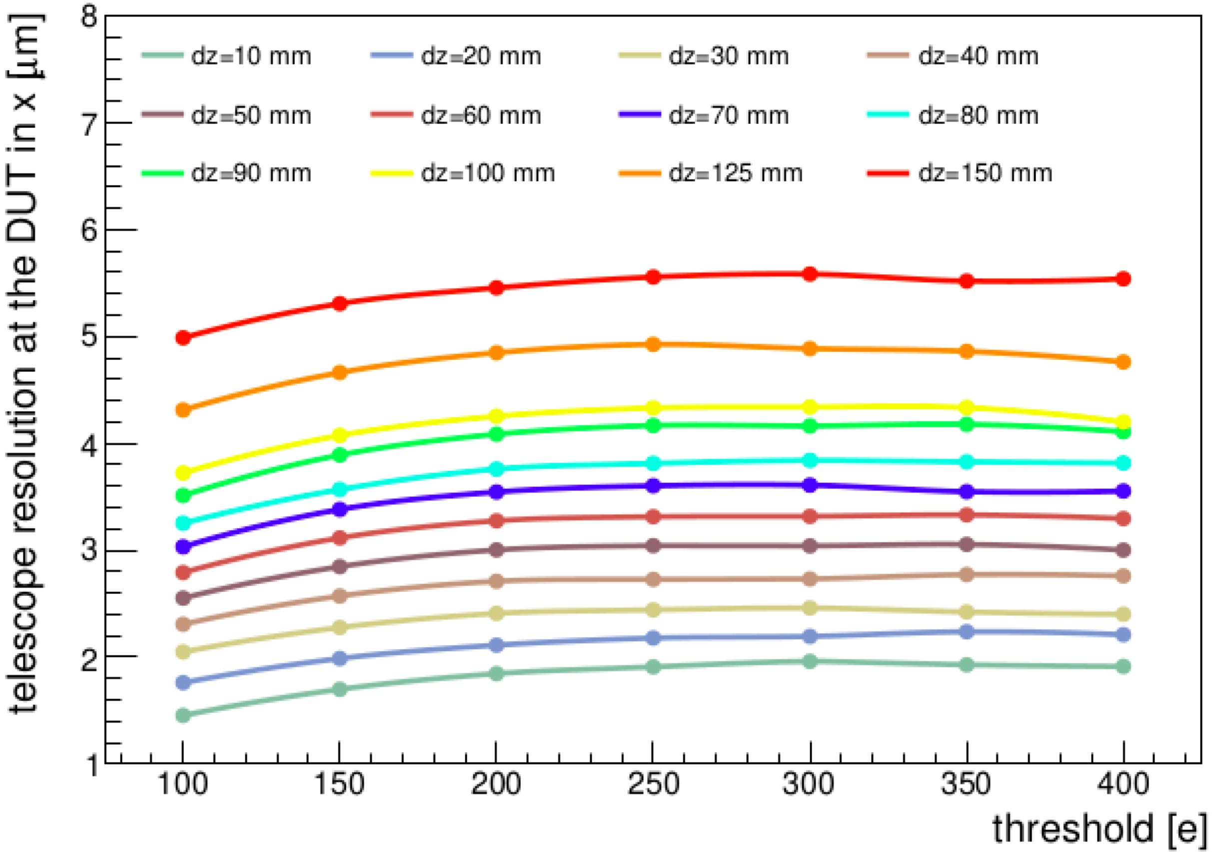
- A **smaller dz** improves the tracking resolution for the detection thresholds.
- An **increase in the detection threshold** does not result in a large deterioration of the tracking resolution, as is the case of the intrinsic resolution of a sensor. **Tracking efficiency** is highly deteriorated.

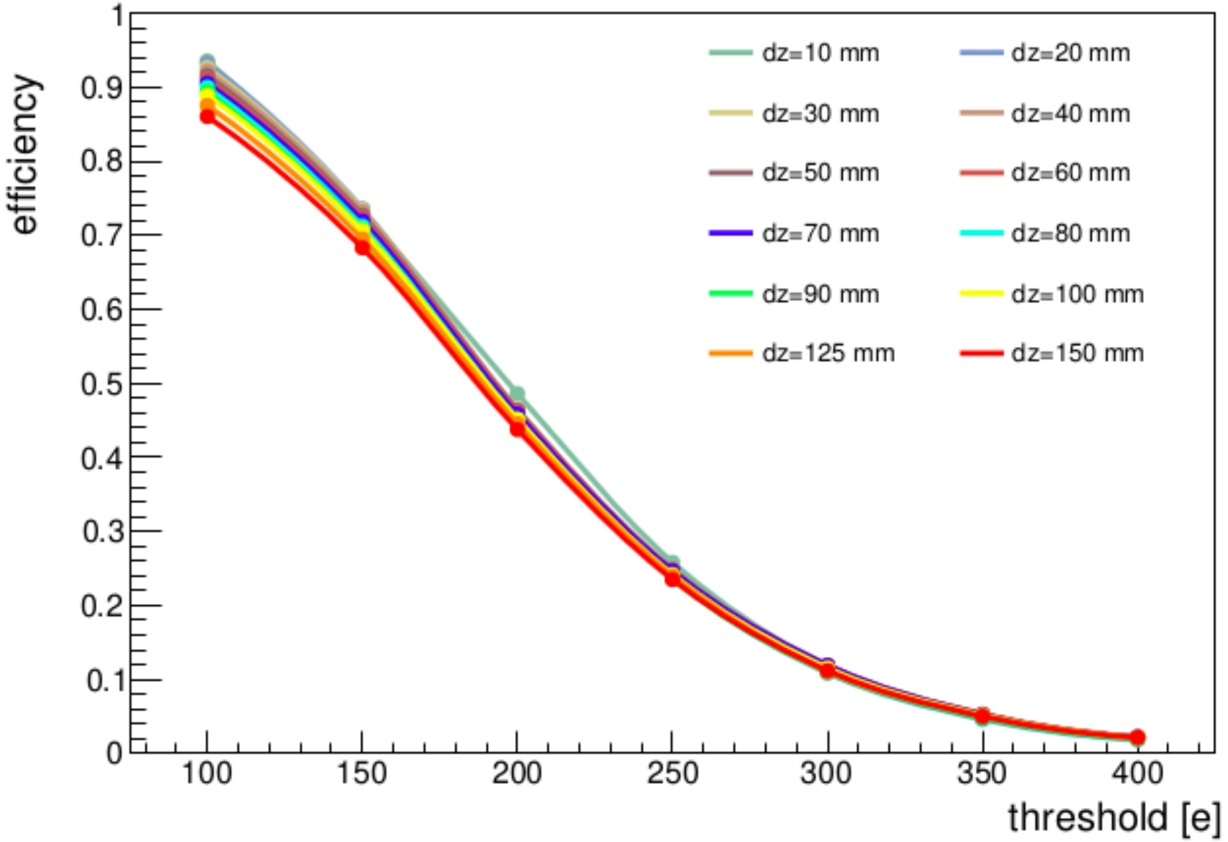
Tracking resolution and efficiency

Standard layout



$$\text{Efficiency} = \frac{\text{number of reconstructed tracks}}{\text{number of simulated events}}$$





- A **smaller dz** improves the tracking resolution for the detection thresholds.
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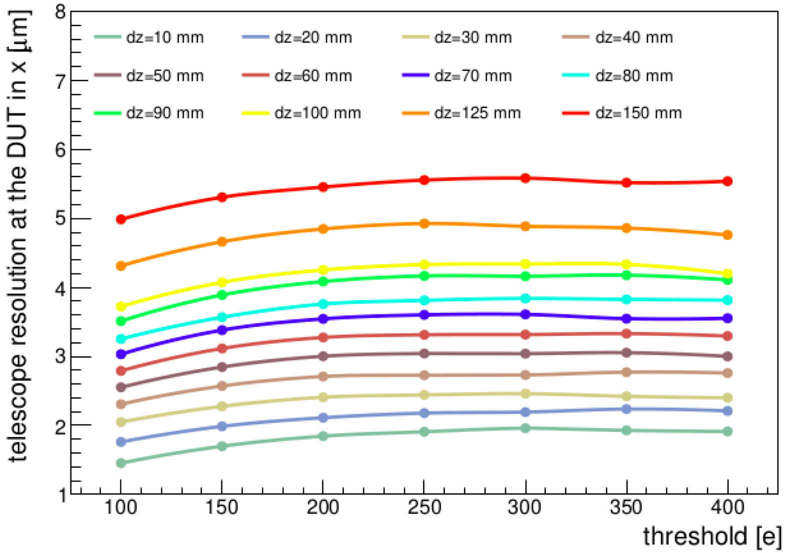
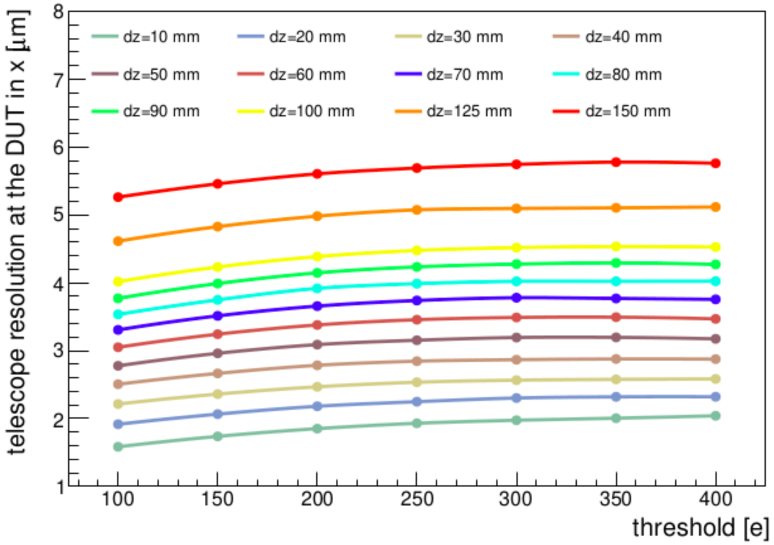
Tracking resolution and efficiency

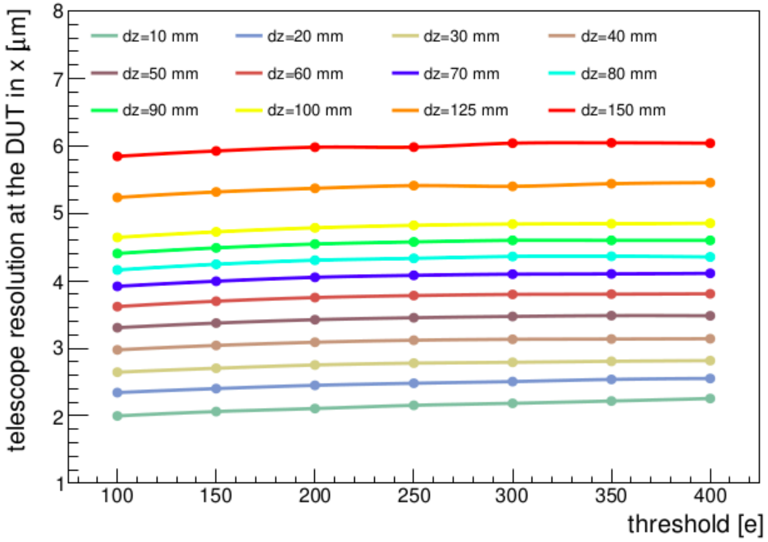
Standard layout



N-blanket layout

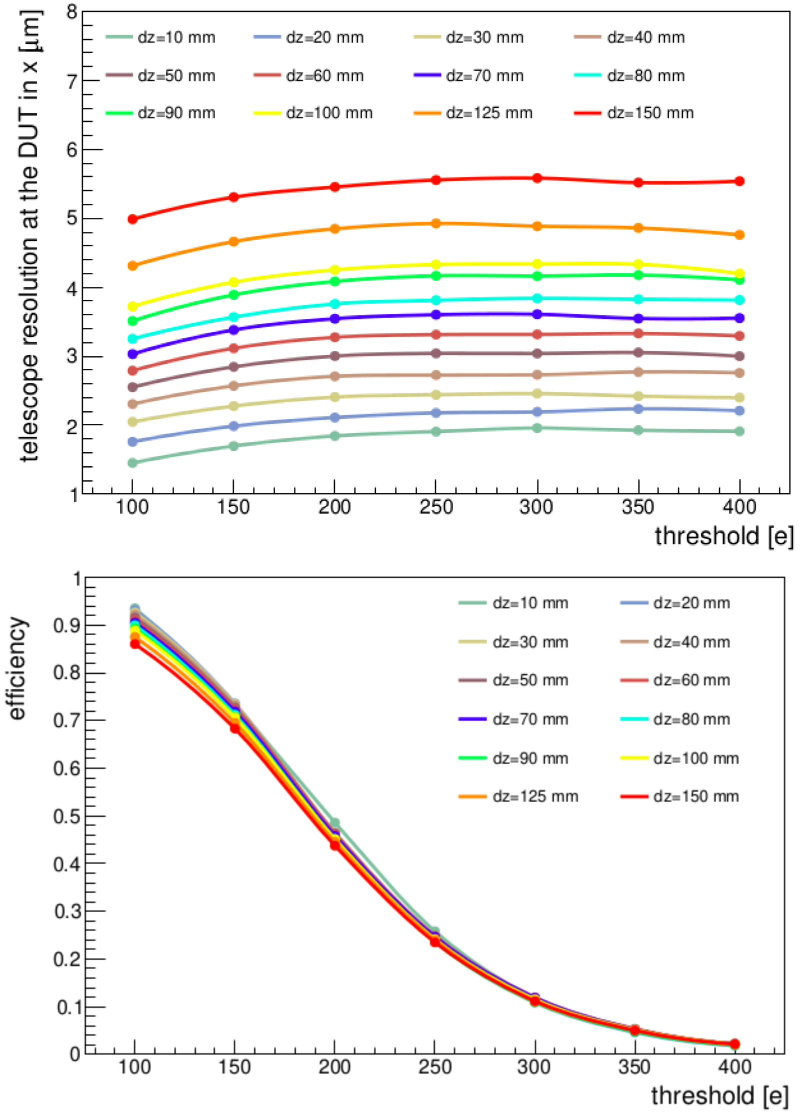


N-gap layout

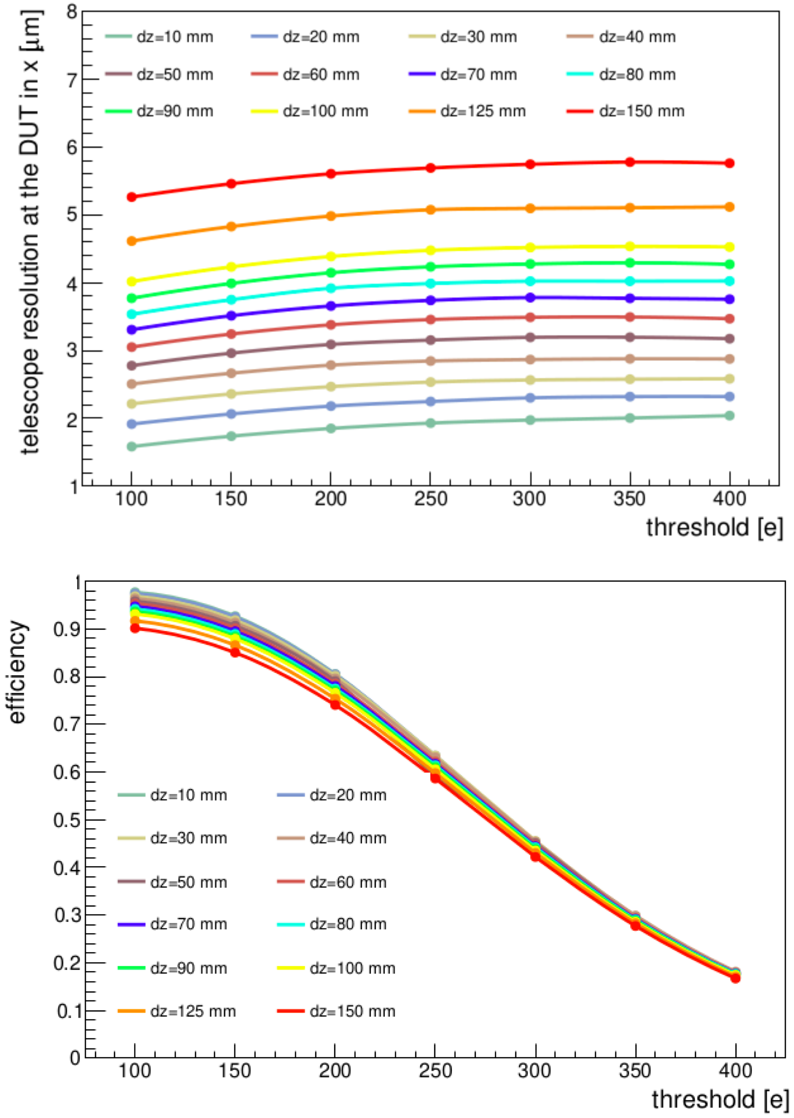


Tracking resolution and efficiency

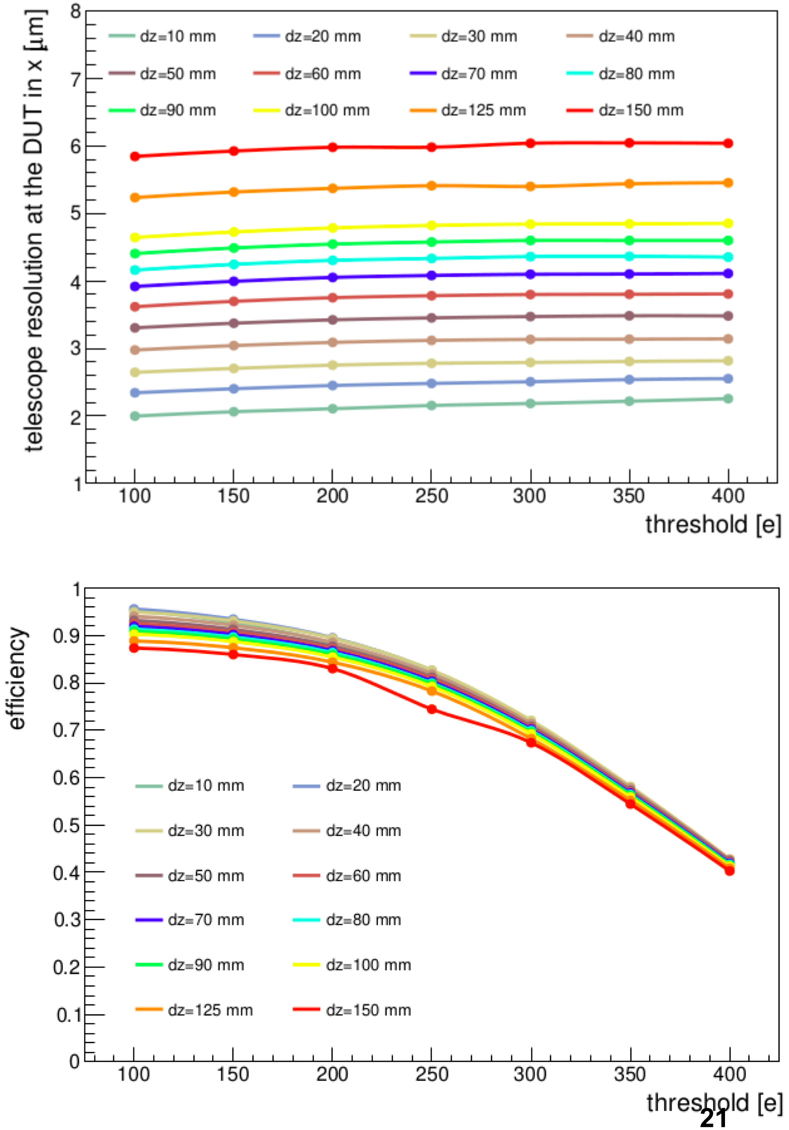
Standard layout



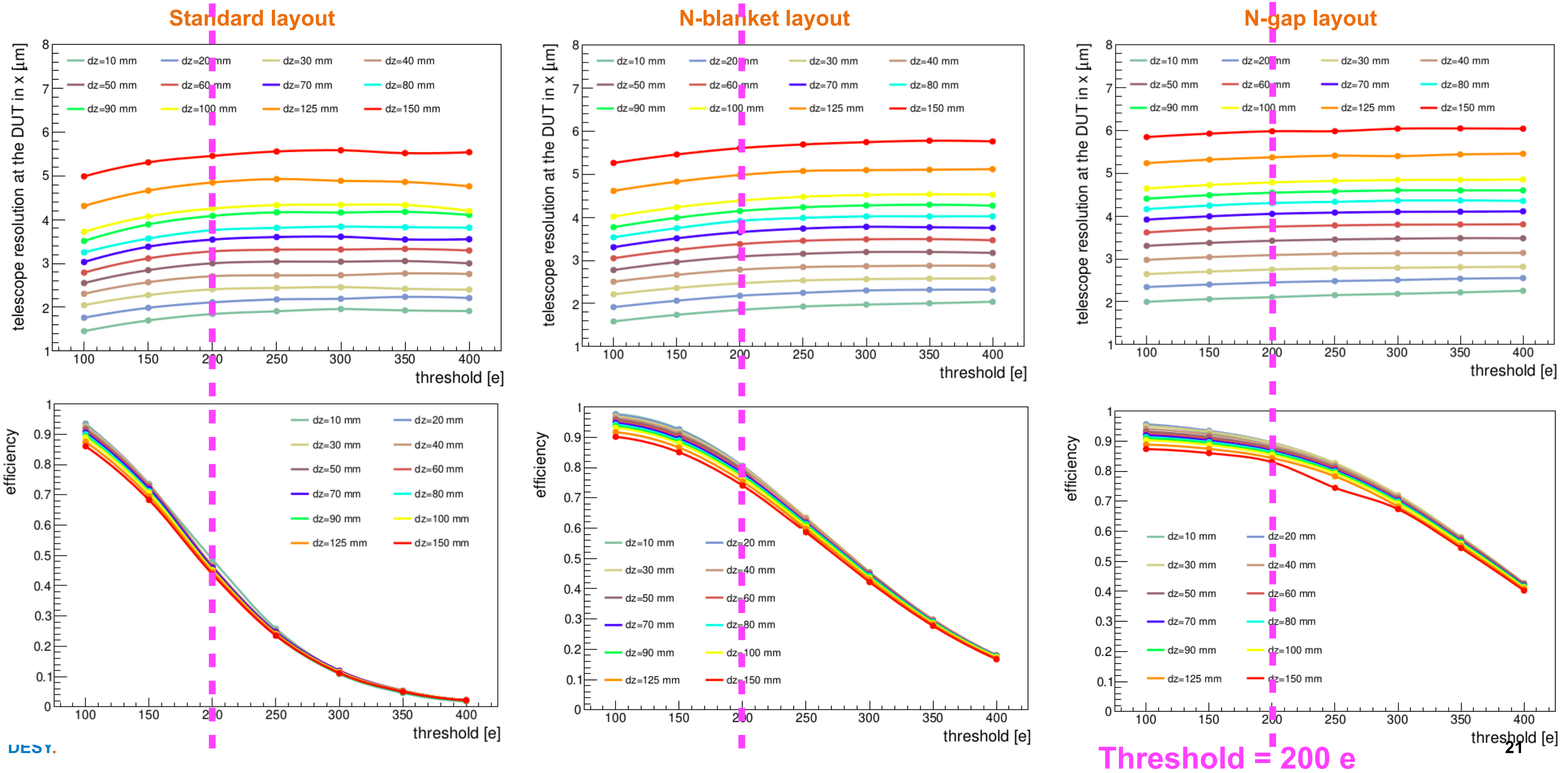
N-blanket layout



N-gap layout

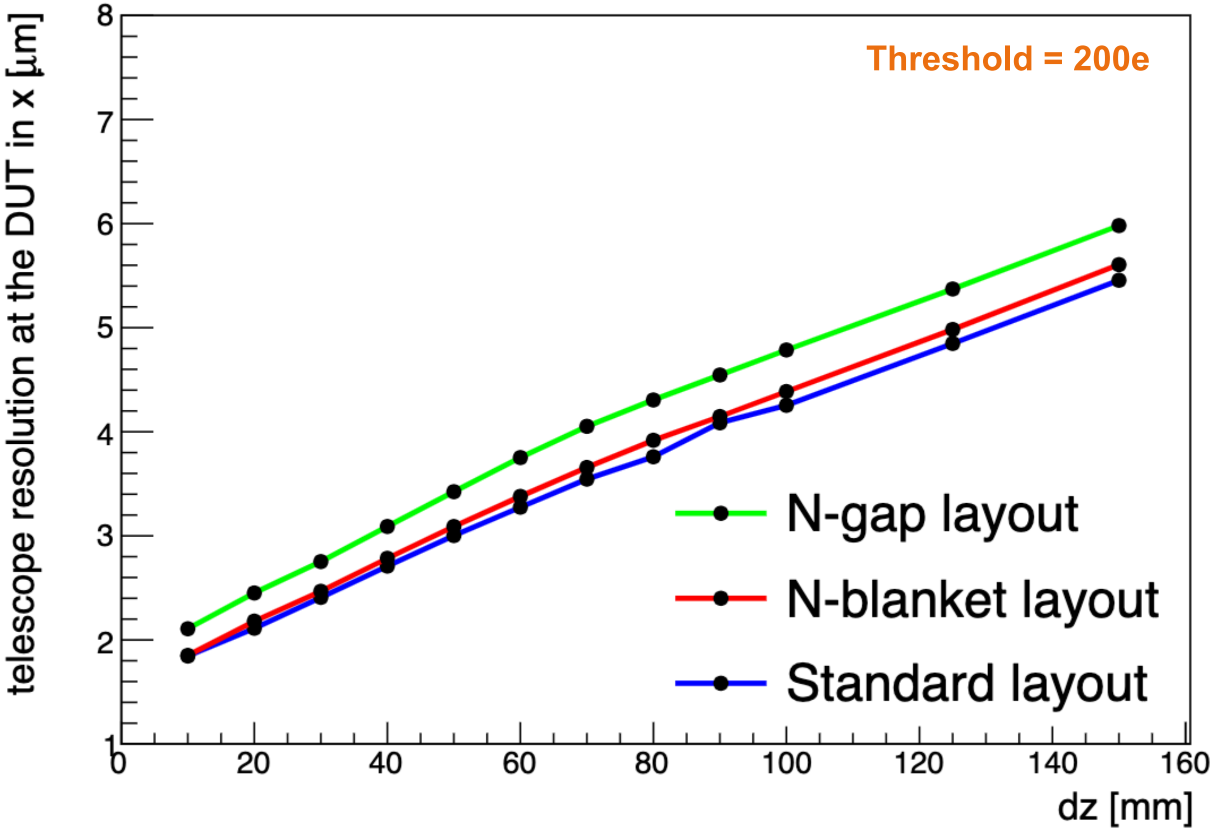


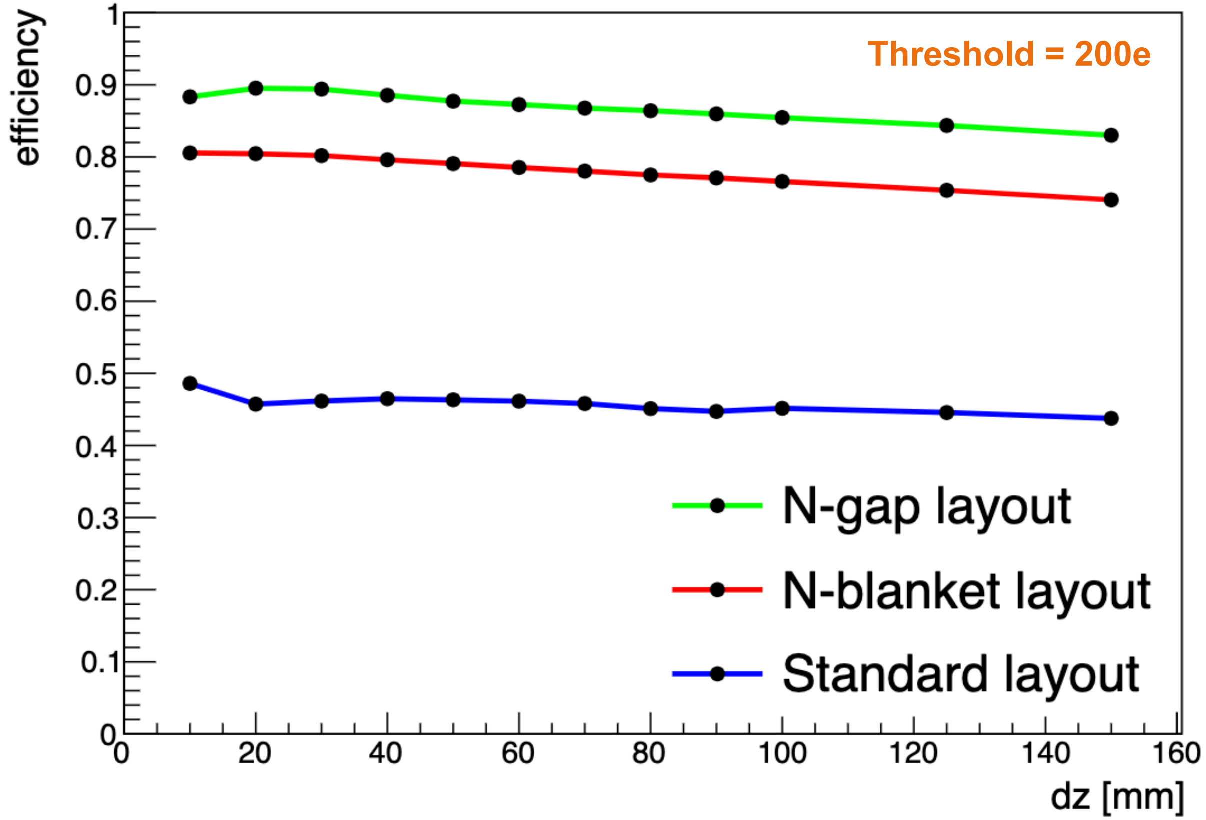
Tracking resolution and efficiency



Tracking resolution and efficiency

Layouts comparison





- Standard layout shows the best tracking resolution, but its tracking efficiency is deteriorated.
- Resolution slightly deteriorated for the n-gap layout, and high efficiency.

Summary & Outlook

Summary

- **TCAD + Allpix²** + **Corryvreckan** = fast, flexible, precise and complete studies.
- Test **beam telescope** has been simulated with different geometries.

  → **N-gap layout** showed a good spatial resolution and best efficiency compared with the other layouts.

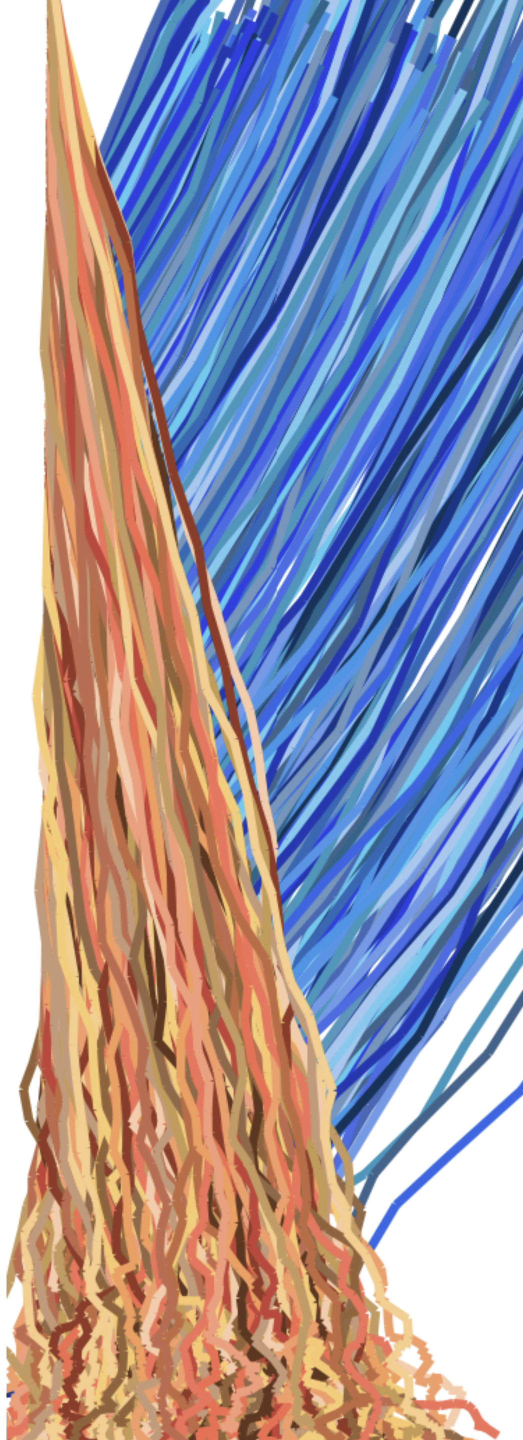
Outlook

- Improving sensor simulations.

  → Based on **our next test-chip prototypes**.

  → Including a more **complex digitisation stage**.

- Easily **extend the beam telescope studies**: vary the material budget of the DUT, distance DUT-innermost plane, sensor designs…



Thank you!

Contact

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Sara Ruiz Daza

sara.ruiz.daza@desy.de

Back up

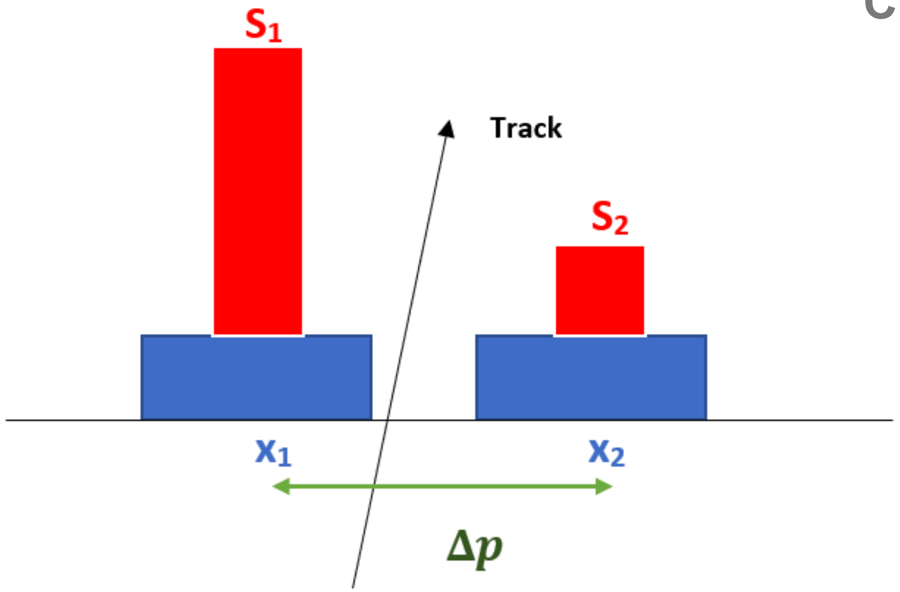
Reconstructed cluster centre

Cluster size 1

Reconstructed position: x_1

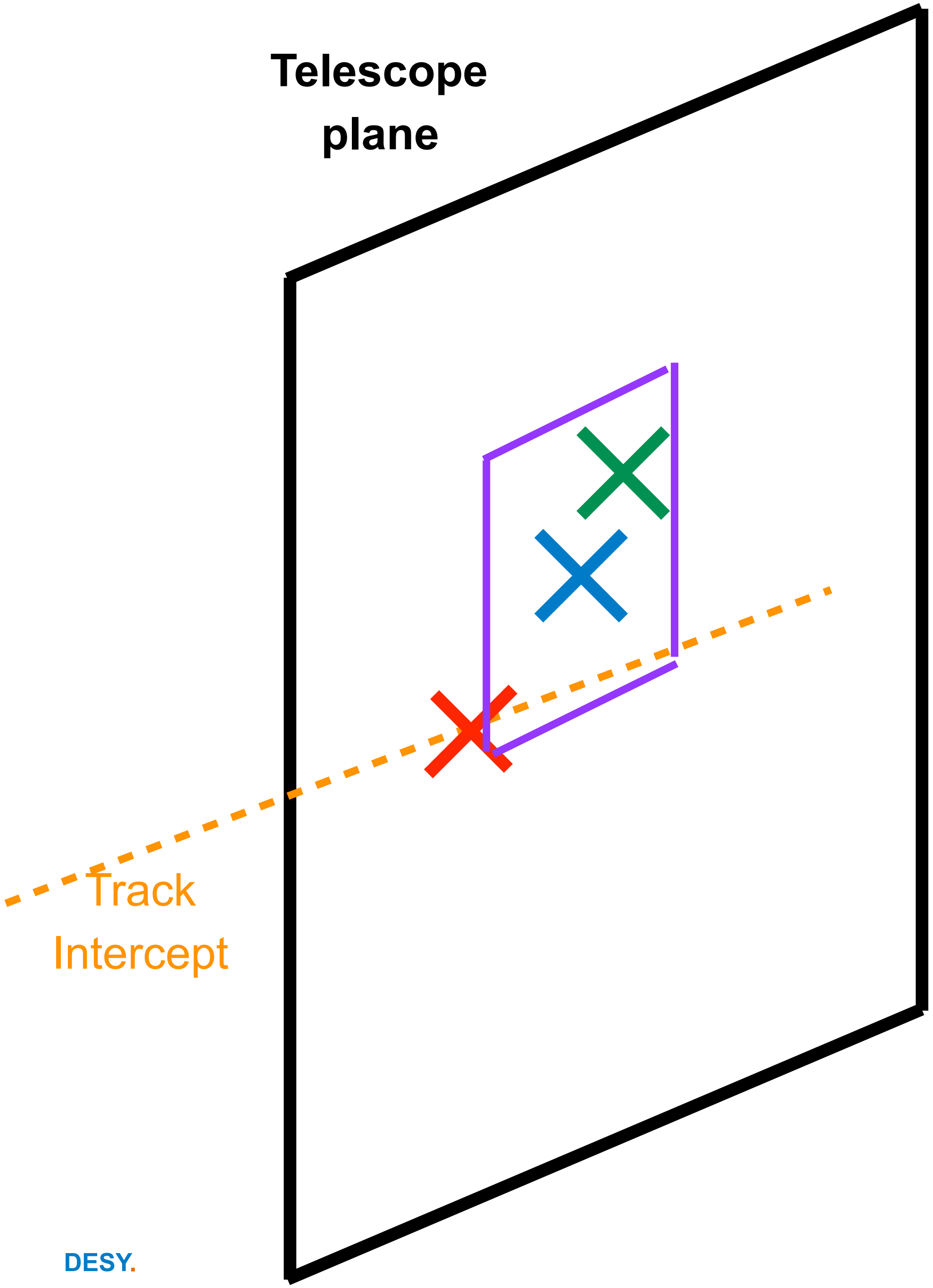
Resolution: $\sigma = \frac{\Delta p}{\sqrt{12}}$

Cluster size 2



Reconstructed position: $x = \frac{s_1 x_1 + s_2 x_2}{s_1 + s_2}$ charge-weighted cluster center reconstruction

Resolution: $\sigma = \sqrt{\left(\frac{\delta x}{\delta x_1}\right)^2 + \left(\frac{\delta x}{\delta x_1}\right)^2}$ **Better resolution**



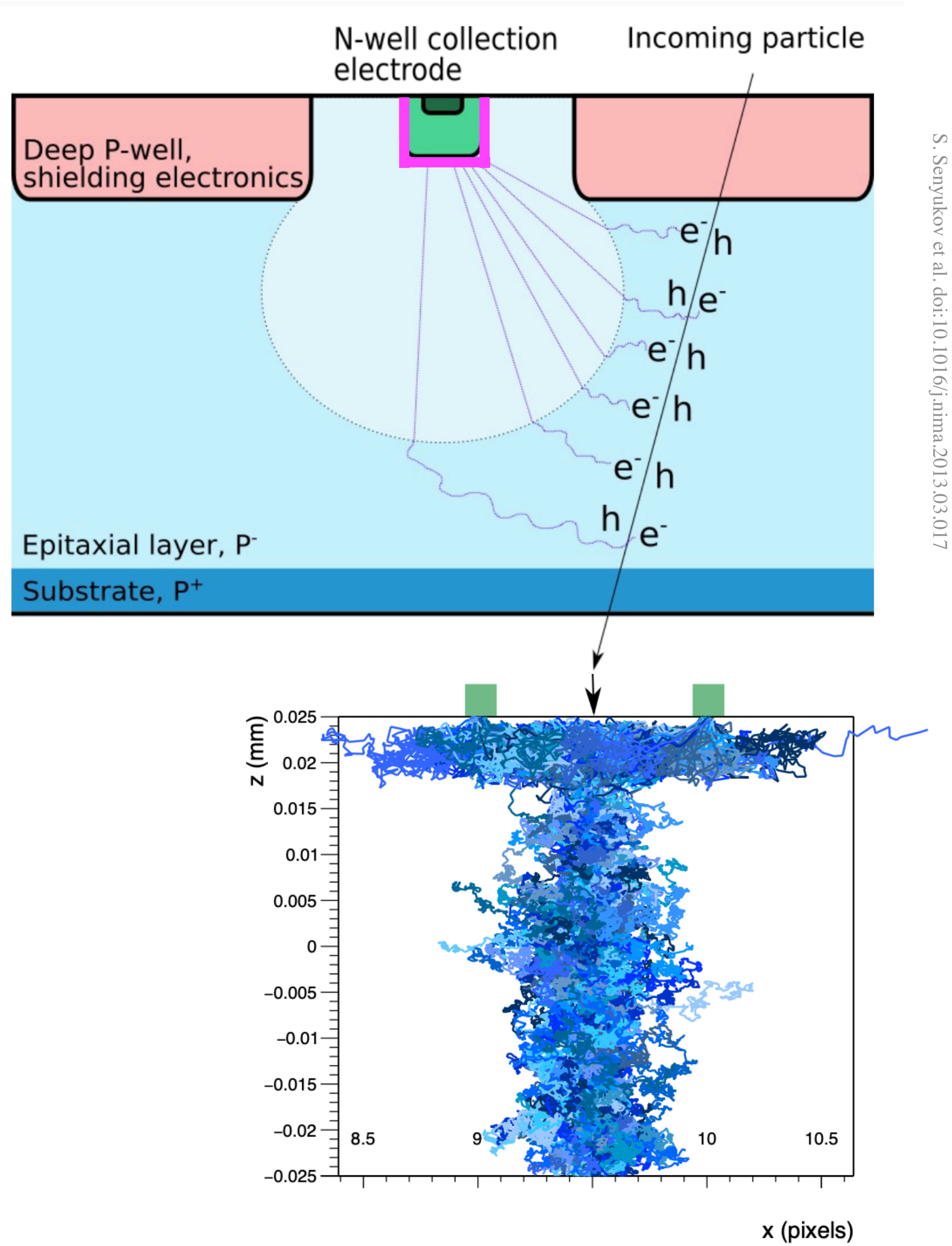
- Cluster centre position is used for tracking
  —> cluster centre is closer to the track intersection than MC
  $\sigma(X_{track} - X_{MC}) > \sigma(X_{cluster} - X_{track})$

- At the outermost planes, $\sigma(X_{cluster} - X_{track})$ becomes even smaller because GBL does not have scatters information, so only local residuals are available.

Investigated sensor layouts (I)

Standard layout

- ALPIDE like sensor
- **Depletion**:
  - Evolves from small pn junction
  - Edges and corners not fully depleted
  - Size limited V_{bias}
- **Charge propagation:**
  - In depleted region: drift
  - In non-depleted region: diffusion
- **Spatial resolution:**
  - Charge sharing
  - Good spatial resolution
- **Efficiency**:
  - Deteriorated at higher thresholds

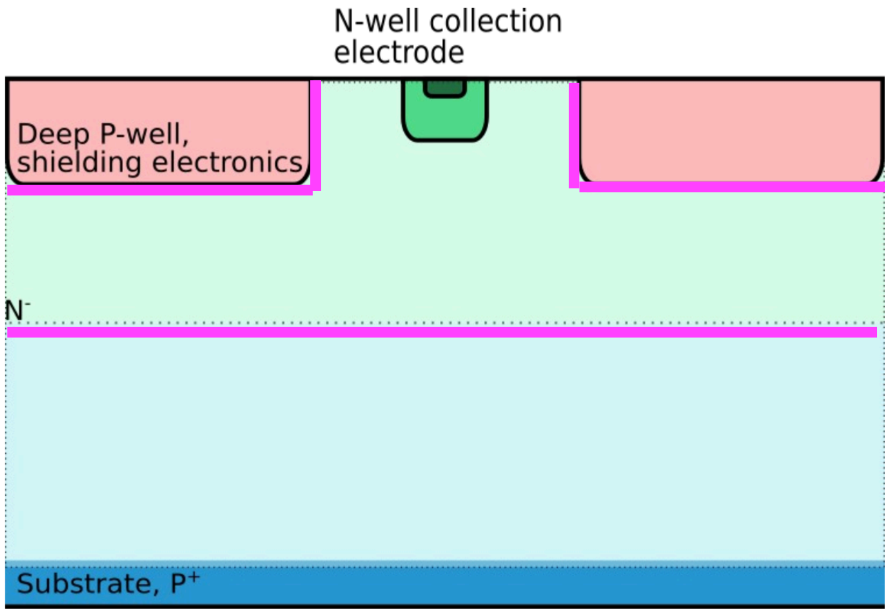


S. Senyukov et al. doi:10.1016/j.nima.2013.03.017

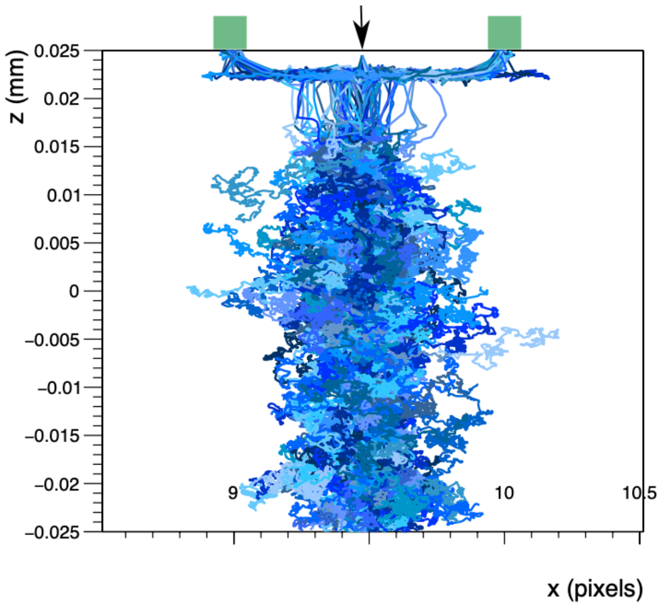
Investigated sensor layouts (II)

N-blanket layout

- **Depletion**:
    - Evolves from large pn junction
    - Full lateral depletion
- **Charge propagation:**
    - Dominated by drift
- **Spatial resolution:**
    - Charge sharing is reduced
    - Spatial resolution is deteriorated
- **Efficiency**:
    - Higher efficiency



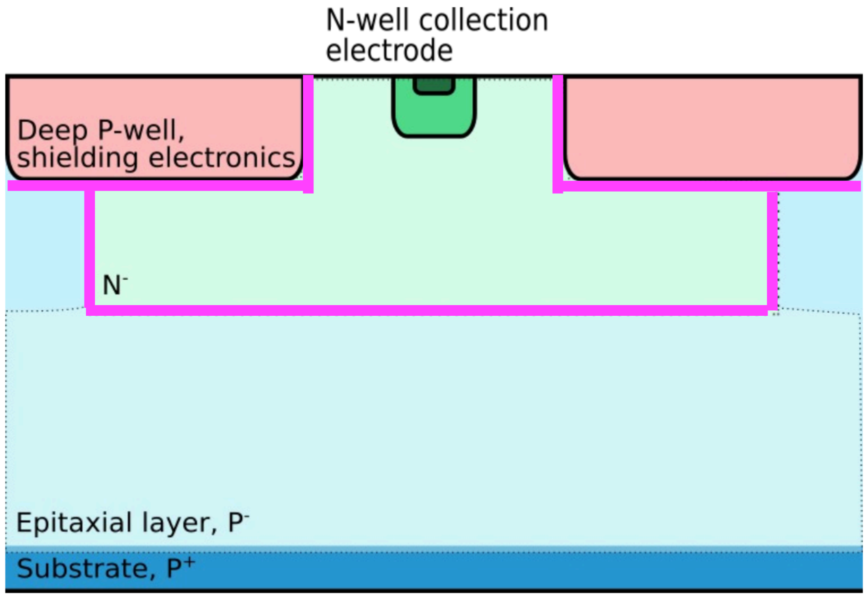
W. Snoeys et al. doi:10.1016/j.nima.2017.07.046



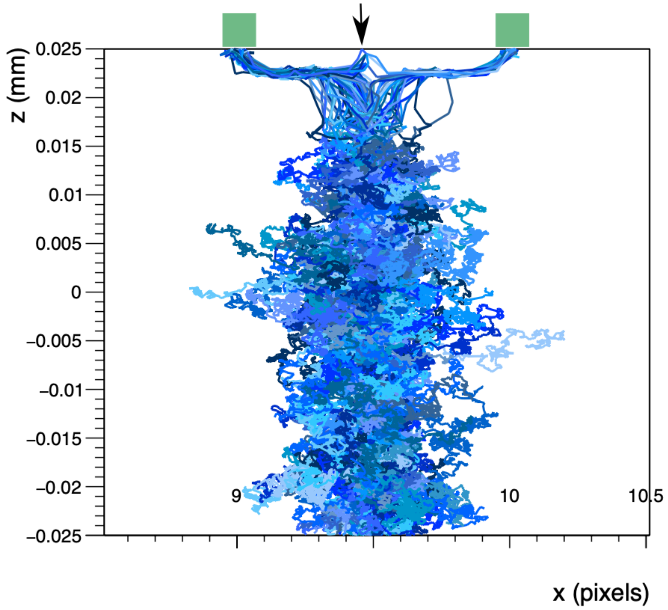
Investigated sensor layouts (III)

N-gap layout

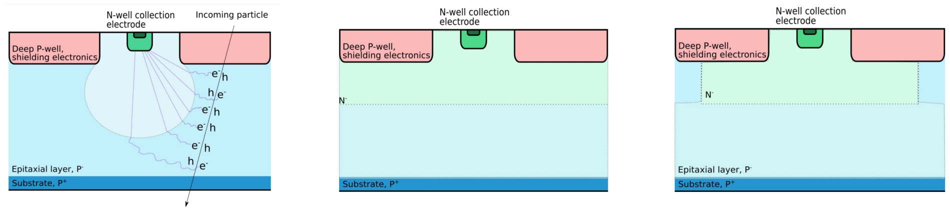
- **Depletion**:
  - Evolves from large pn junction
  - Full lateral depletion
- **Charge propagation:**
  - Vertical pn junction → increase lateral electric field
  - Dominated by drift and faster
- **Spatial resolution:**
  - Charge sharing is further reduced
  - Spatial resolution is further deteriorated
- **Efficiency**:
  - Higher efficiency



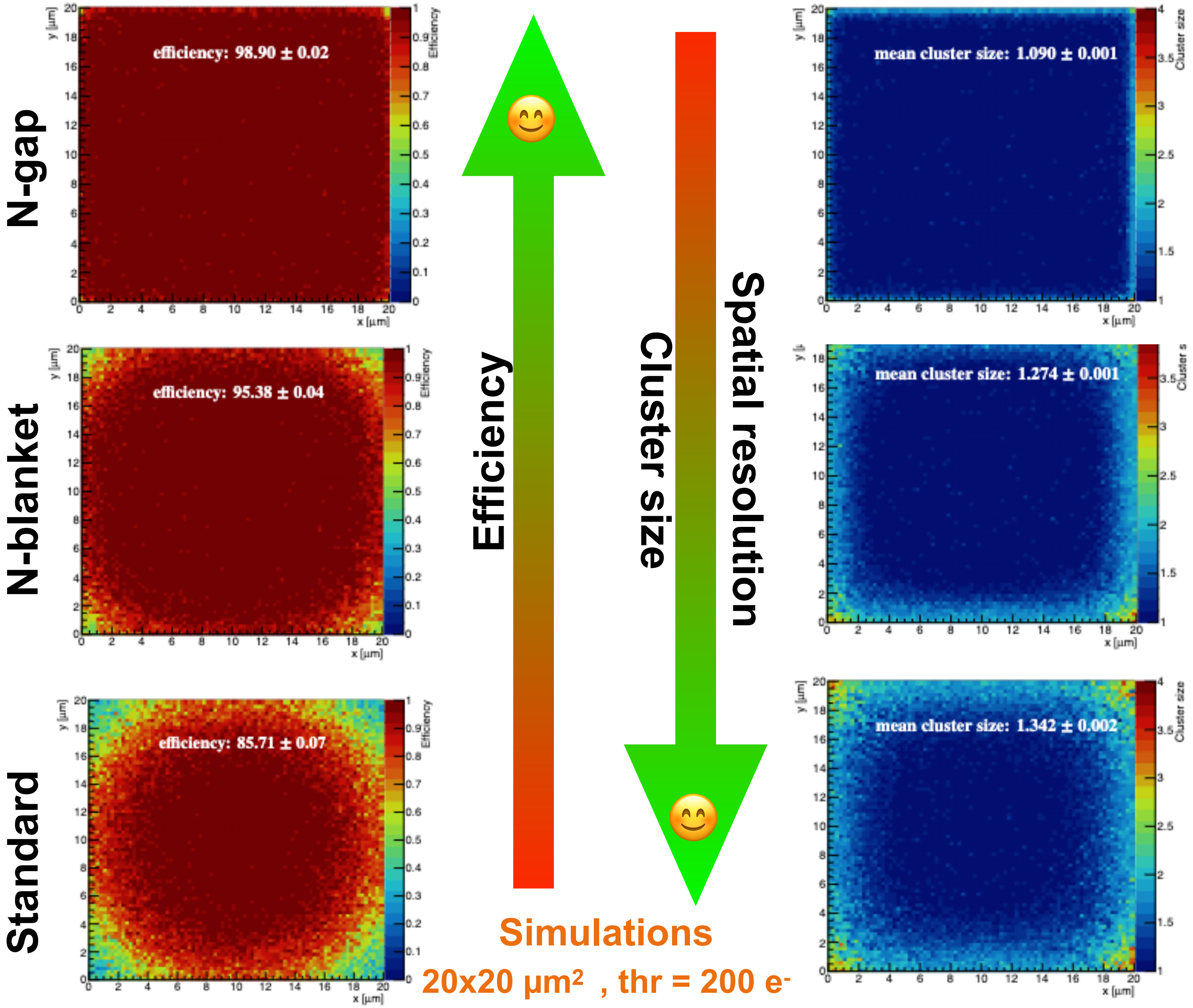
M. Münker et al 2019 JINST 14 C05013

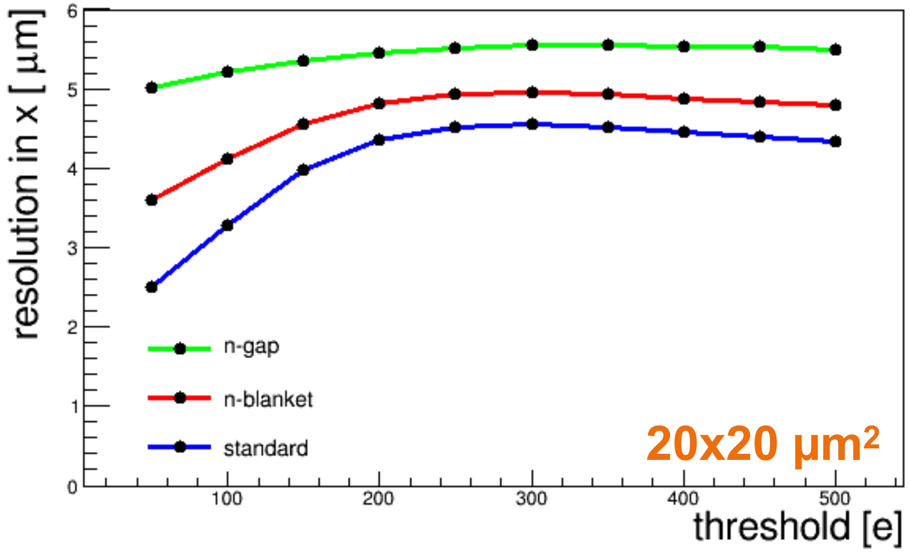


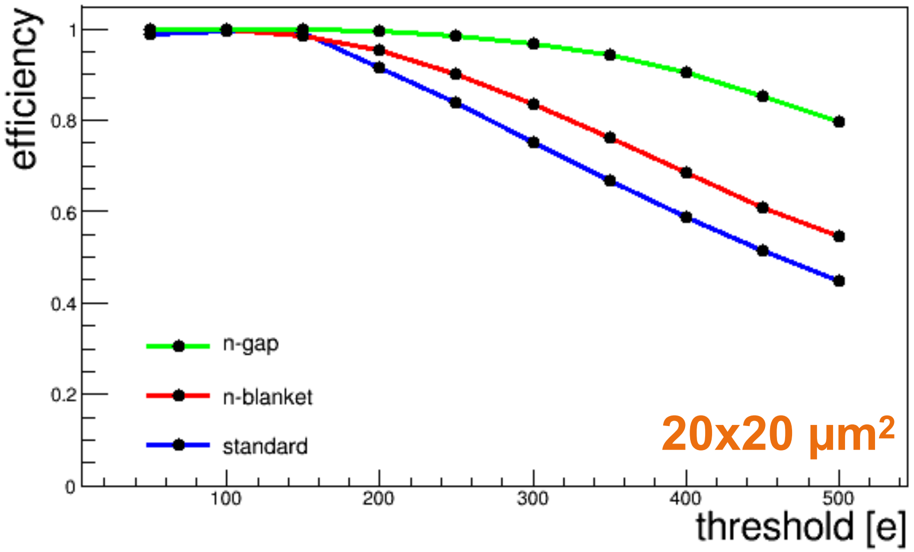
Investigated sensor layouts



In-pixel efficiency and cluster size



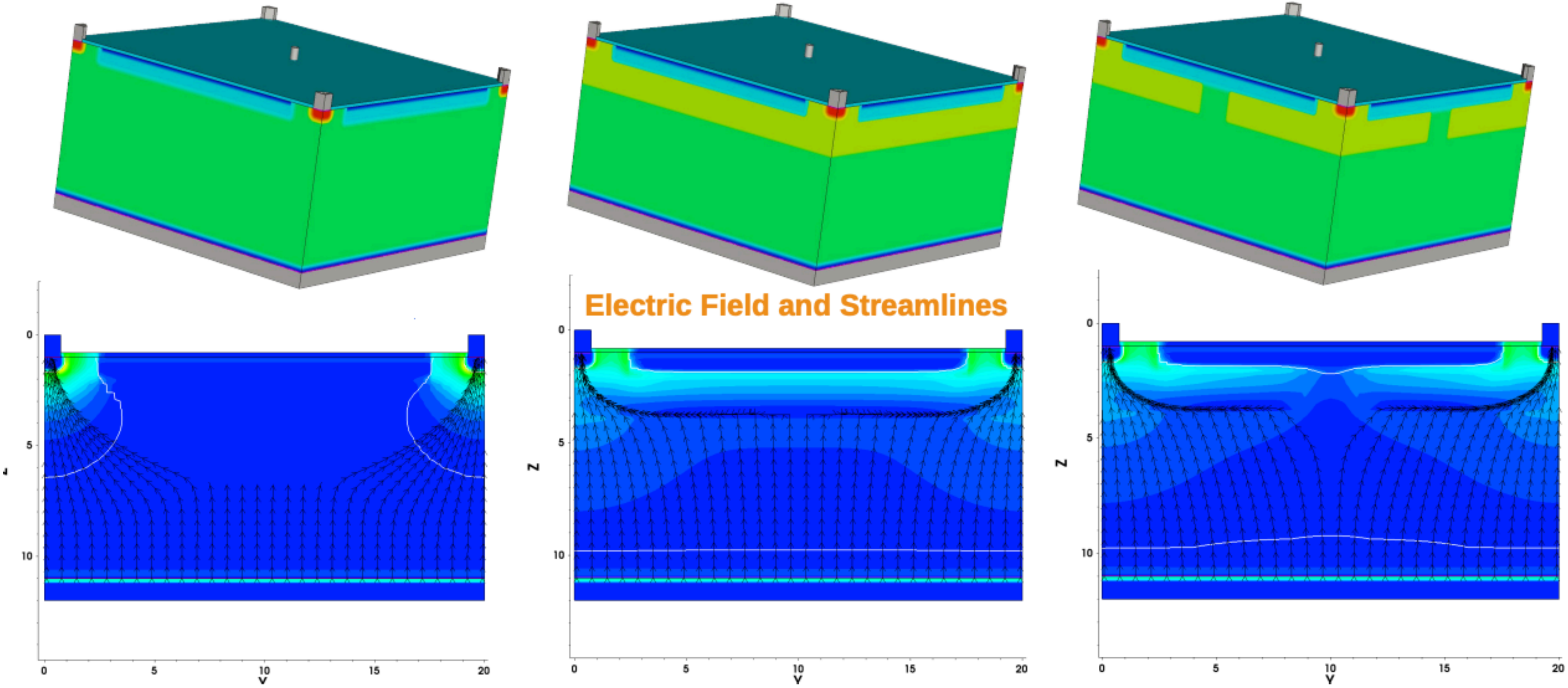




Standard Layout | N-blanket Layout | N-blanket with Gap Layout

Doping Concentration

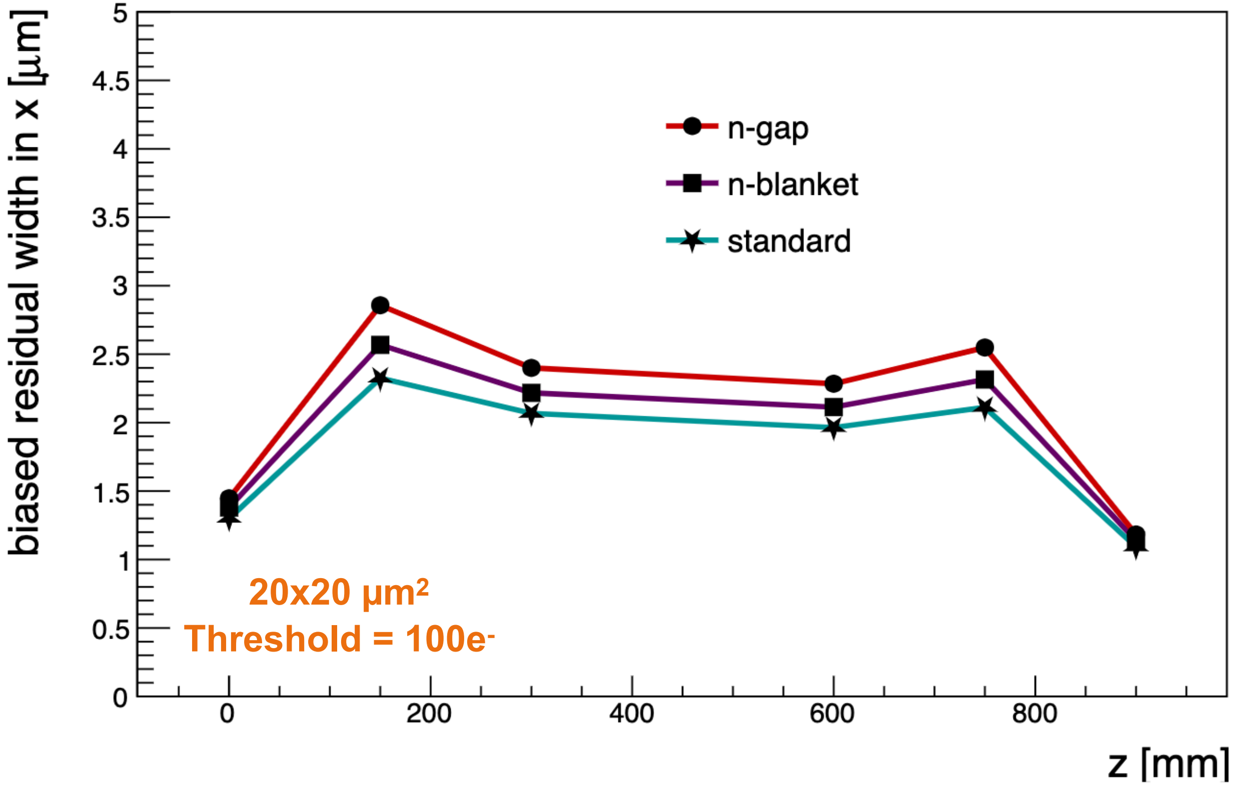
Electric Field and Streamlines

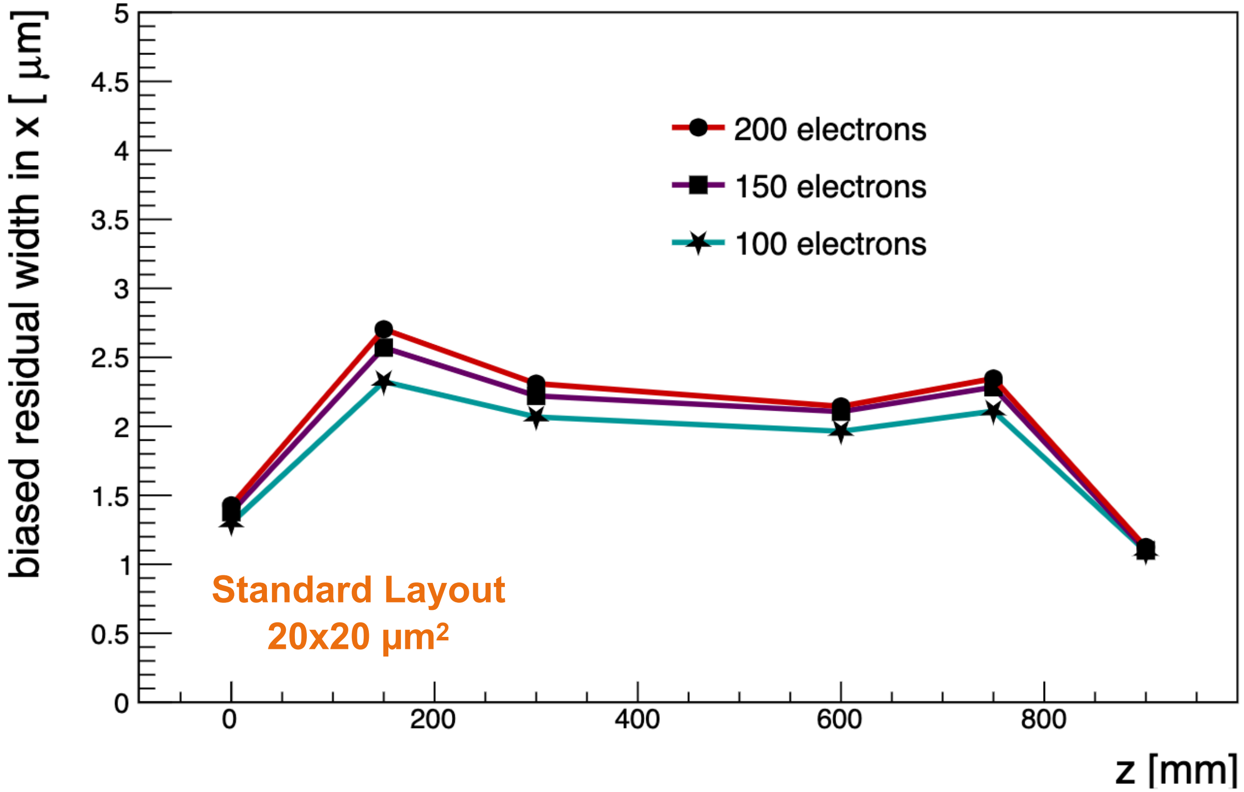


By A. Simancas

Telescope resolution at the different planes

Different layouts and threshold values comparison



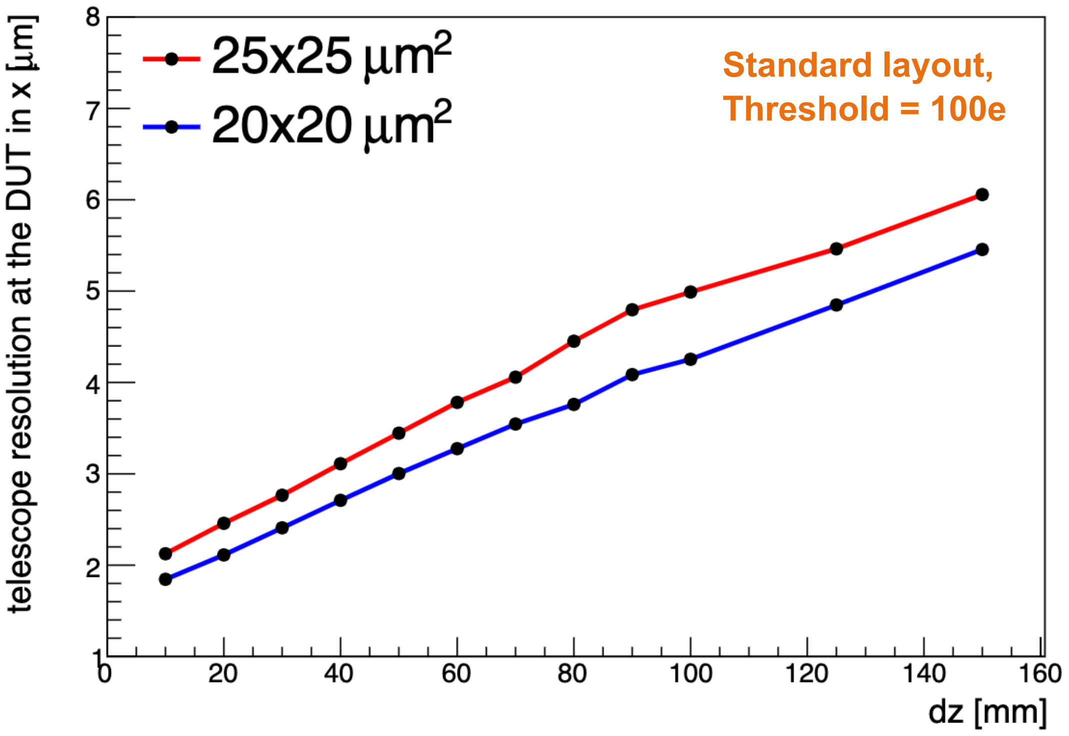


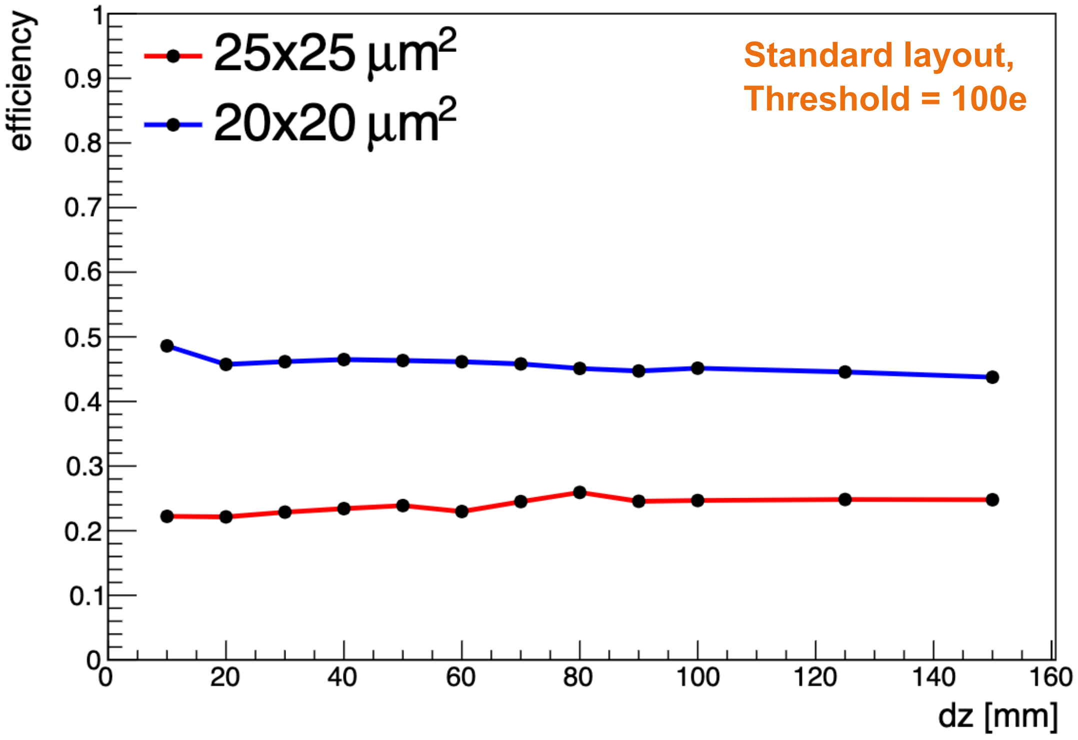
- The standard layout shows a better resolution (smaller biased residuals) at a threshold of 100 e^-. However, this layout is expected to have the lowest efficiency.

- At higher thresholds, charge sharing is reduced, and the resolution deteriorates.

Simulations with a larger sensor size

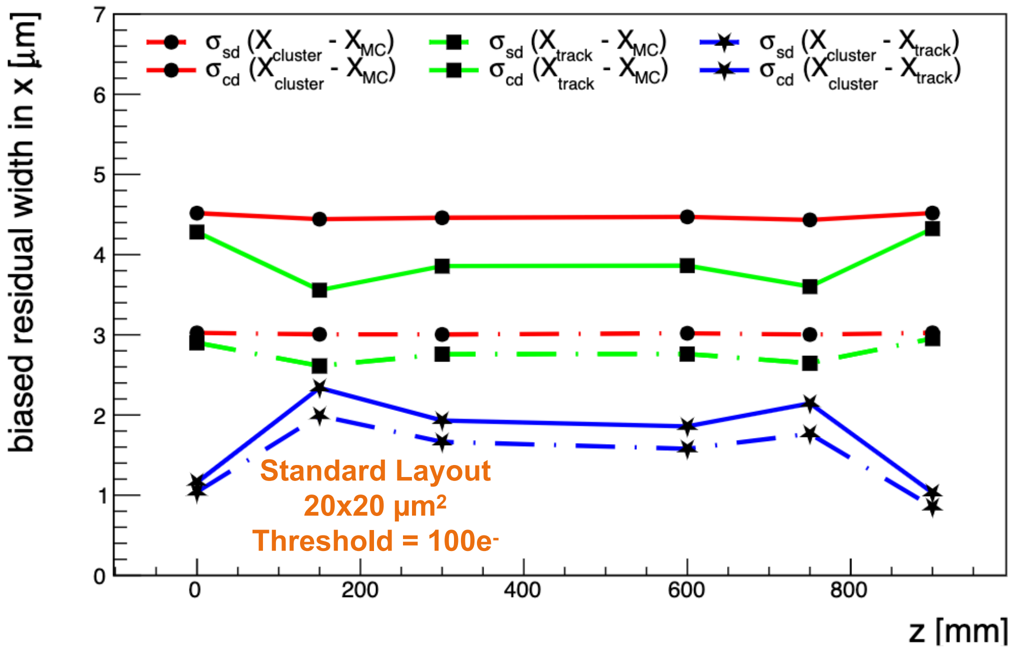
25x25 µm²

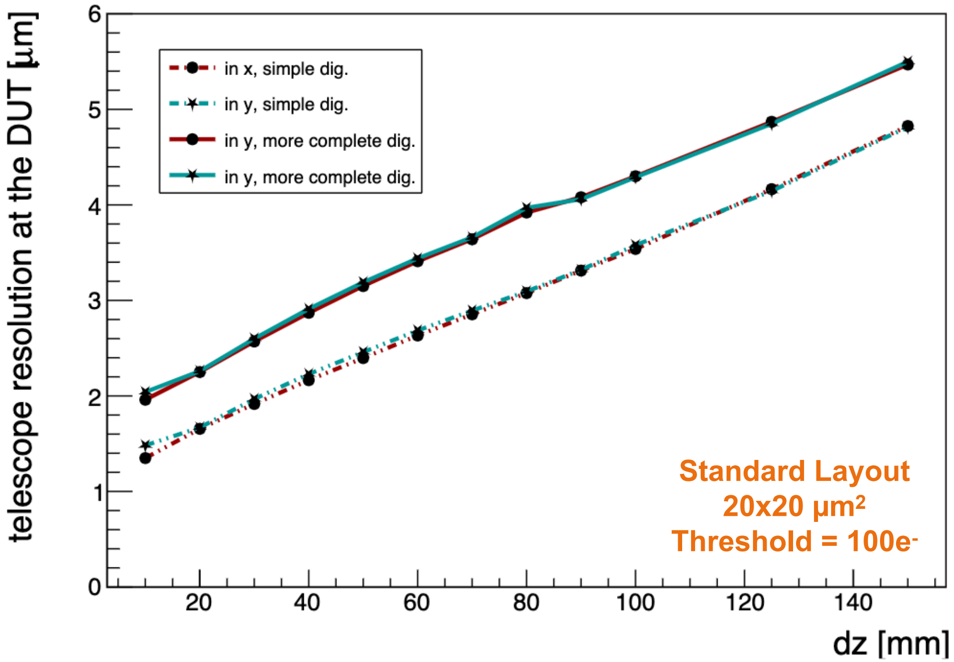




- For larger pixel sizes, the spatial resolution and efficiency is deteriorated.

A more complete digitization



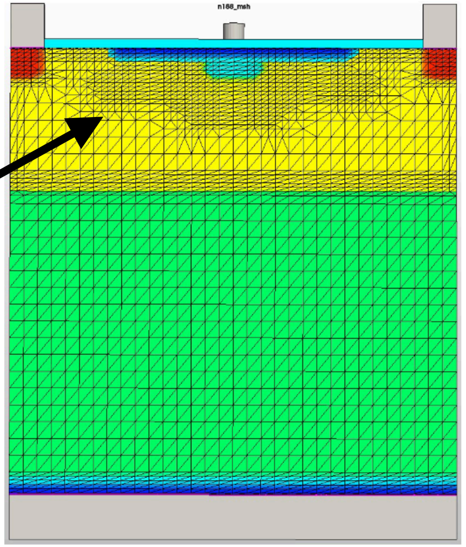



```
[DefaultDigitizer]
electronics_noise = 35e
threshold = 100e
threshold_smearing = 0e
qdc_resolution = 6
qdc_slope = 20e
qdc_offset = -100
```

- Tracking resolution deteriorated ~ 0.5 μm.

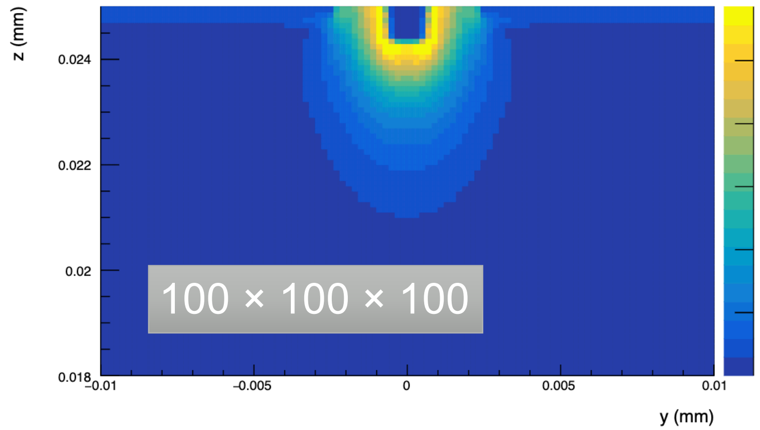
Number of divisions in TCAD-to-Allpix^2 conversion

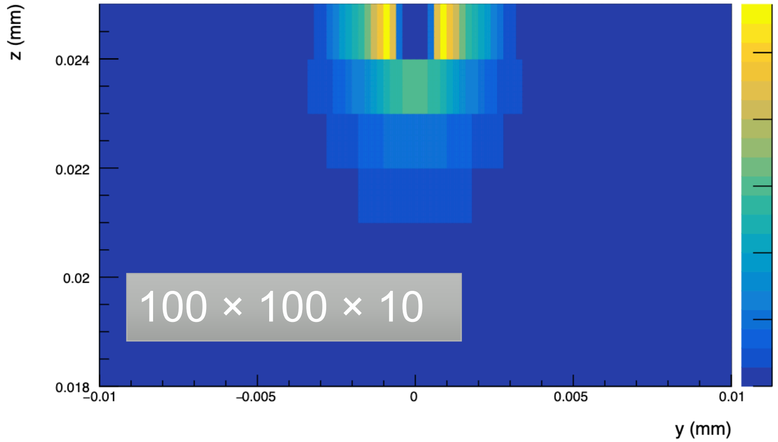
Mesh divisions	Cluster size in X	Resolution in X [μm]	Efficiency [%]
100×100×100	1.42 ± 0.01	3.29 ± 0.01	99.58 ± 0.02
100×100×50	1.43 ± 0.01	3.31 ± 0.01	99.72 ± 0.02
100×100×10	1.45 ± 0.01	3.33 ± 0.01	99.78 ± 0.02
300×300×100	1.43 ± 0.01	3.28 ± 0.01	99.58 ± 0.02
100×100× 100	1.43 ± 0.01	3.29 ± 0.01	99.58 ± 0.02
50×50×100	1.43 ± 0.01	3.29 ± 0.01	99.56 ± 0.02
20×20×100	1.43 ± 0.01	3.30 ± 0.01	99.58 ± 0.02
20×20×10	1.41 ± 0.01	3.41 ± 0.01	99.70 ± 0.02
500×500×300	1.42 ± 0.01	3.30 ± 0.01	99.60 ± 0.02



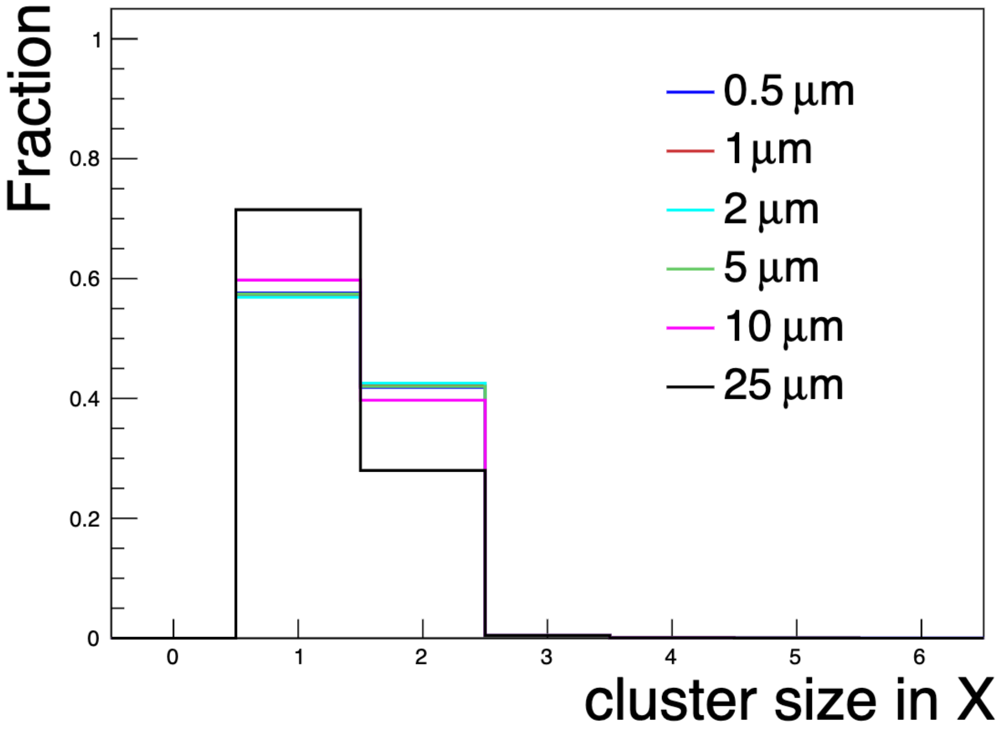
TCAD mesh granularity is adapted to the different region

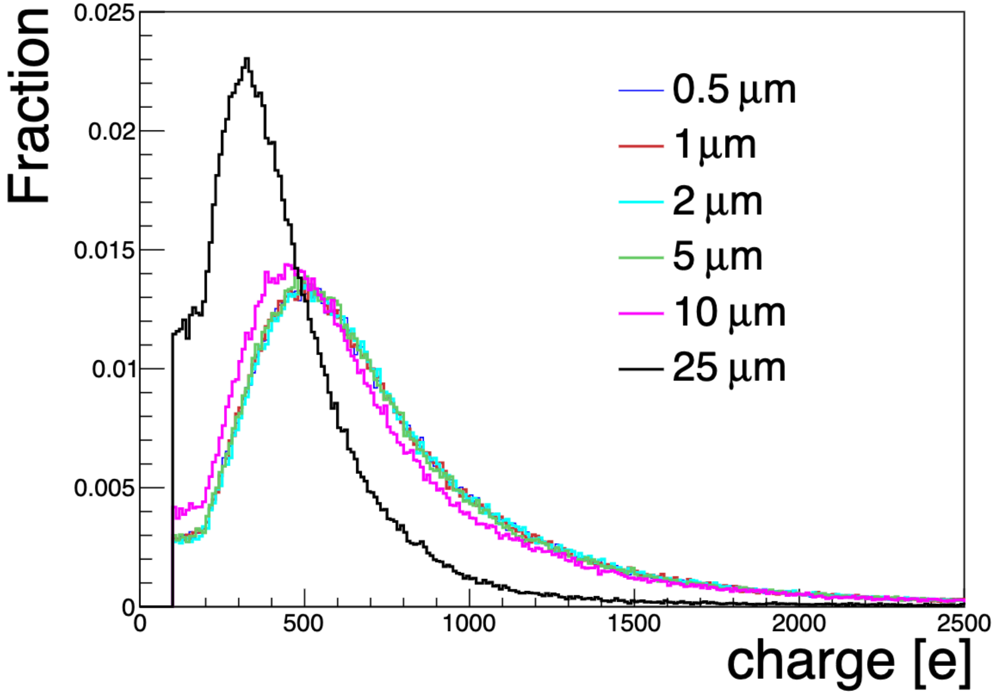
- Fields are adapted to a regularly spaced grid for faster field value lookup during simulation.
- Changes along the z-axis have a larger effect than changes in x and y (charge carriers collected via drift travel mainly vertically).





Maximum length of a simulation step

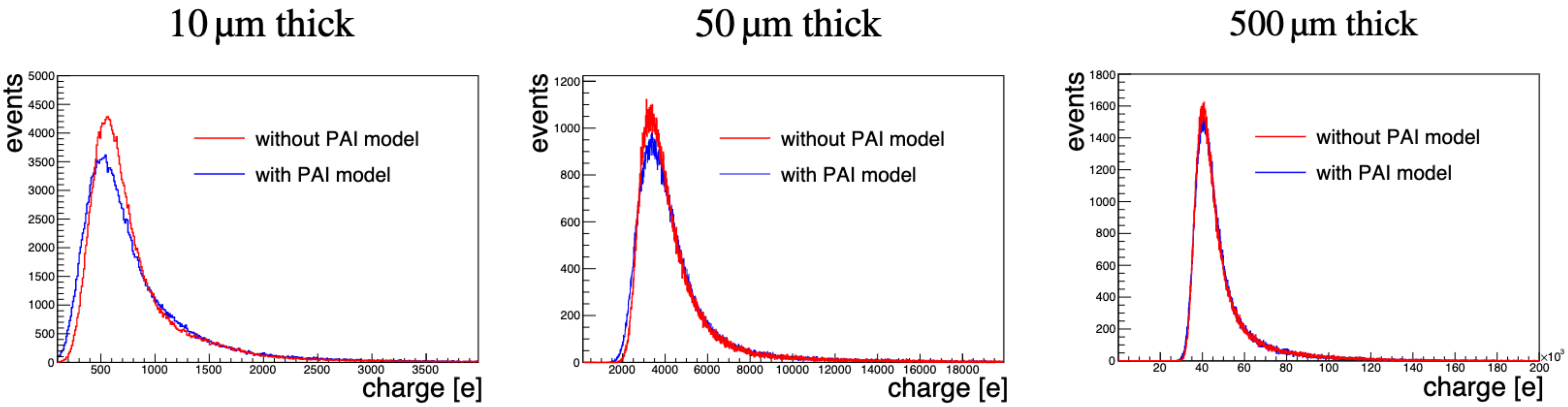




- The duration of the simulations is not affected by this parameter.

- Up to 5 µm maximum step length, there is no significant difference in these observables.
- Fo the 25 µm step length, charges are only deposited around two regions: close to the collection electrode (they drift) and in the substrate (they recombine) → cluster size 1 is dominant, and the less charges are collected.

Photoabsoption Ionization Model

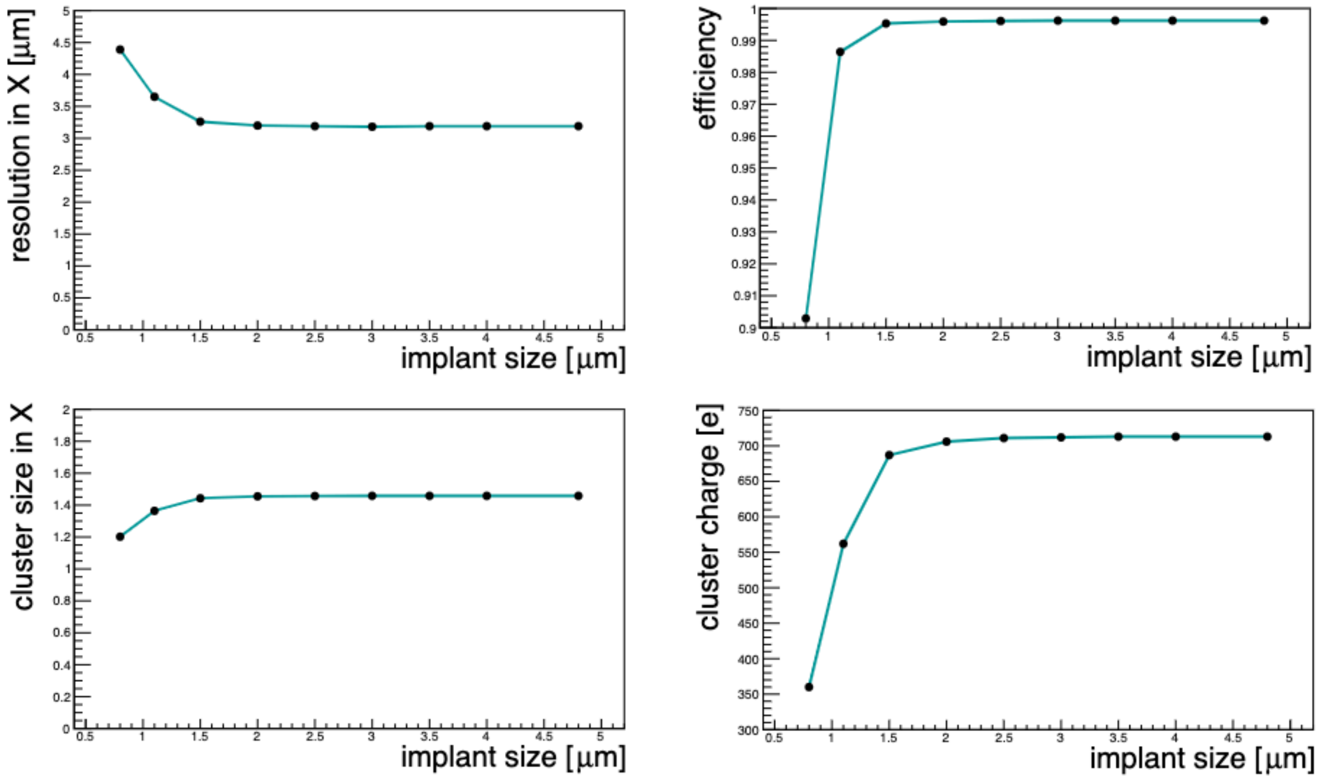


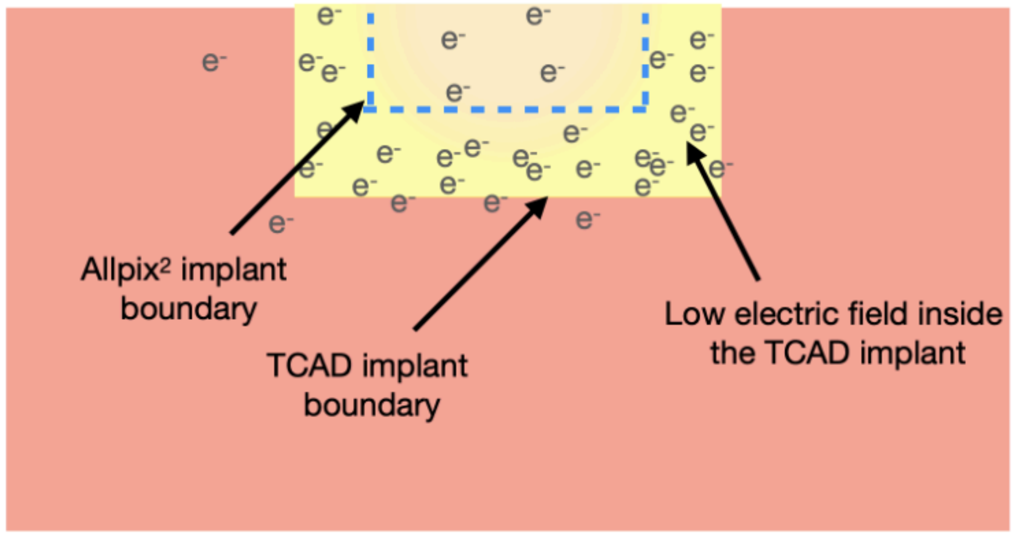
- In thin sensors, ionisation via photo absorption is significant → **PAI model has to be activated in our simulations.**
- For thick sensors, there is not significant difference.

Maximum number of charge carriers propagated per step

Maximum number of charge carriers propagated per step	Duration of the simulations	Resolution in X [μm]	Efficiency [%]
1	1 920 ms/event per worker	3.57 ± 0.01	98.91 ± 0.02
5	400 ms/event per worker	3.59 ± 0.01	98.91 ± 0.02
10	240 ms/event per worker	3.65 ± 0.01	98.89 ± 0.02
25	80 ms/event per worker	3.76 ± 0.01	98.90 ± 0.03
50	80 ms/event per worker	3.95 ± 0.01	98.80 ± 0.02

Collection implant size

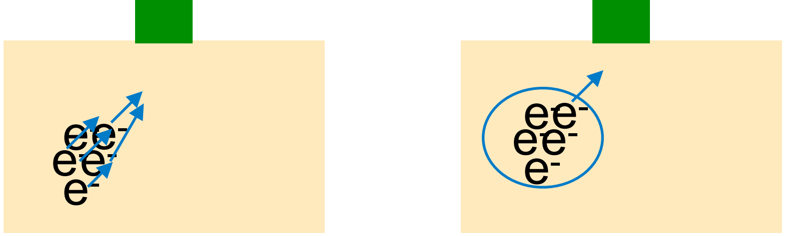




- Once the charge carriers arrive at the collection electrode defined by TCAD, they are mostly immobile and they have a small probability to reach the small implant defined in Allpix².
- A size at least as big as the TCAD implant size is needed.
- Size in Allpix²: 2.2 x 2.2 x 0.6 μm^3

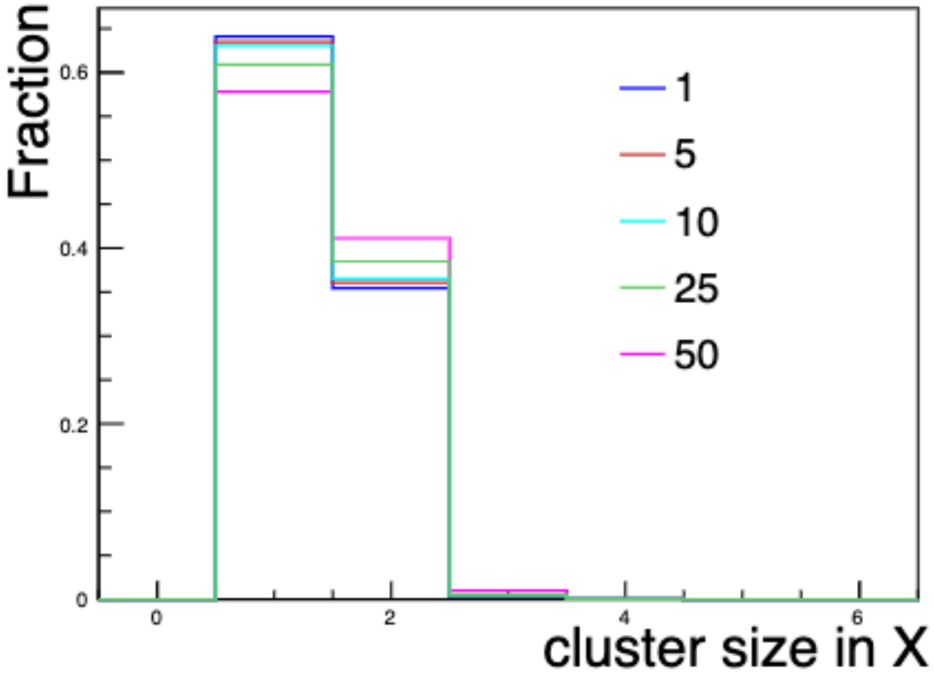
Example of a verification study

Maximum number of charge carriers propagated as a group

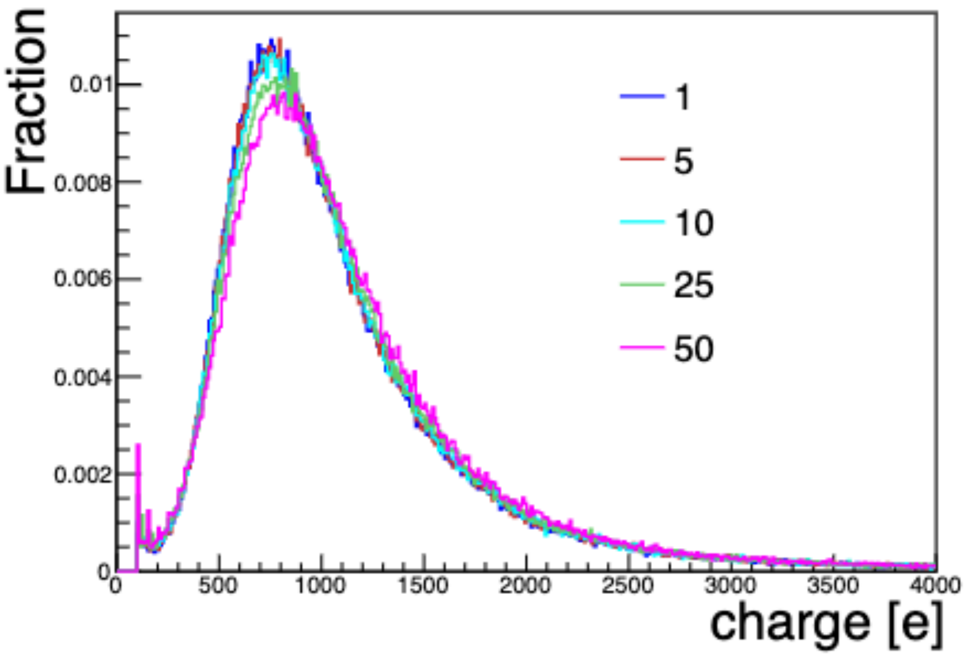


- A MIP transversing the sensor is expected to create ~800 e/h in the 10 μm thick epitaxial layer.
- The duration of the simulations shows a roughly linear dependance on the number of charge carriers propagated together.

Cluster size in X



Total charge collected per event



- No significant difference between groups of 1,5 or 10 charge carries propagated together.

Example of a verification study

Maximum number of charge carriers propagated as a group

Max. number of charge carries propagated as a group	Efficiency [%]	Resolution in x [µm]
1	98.91 ± 0.02	3.57 ± 0.01
5	98.91 ± 0.02	3.59 ± 0.01
10	98.89 ± 0.02	3.65 ± 0.01
25	98.90 ± 0.02	3.76 ± 0.01
50	98.80 ± 0.02	3.95 ± 0.01

- **Efficiency** does not change significantly → For efficiency simulations we can increase the maximum number of charges propagated as a group.
- **Resolution** is significantly affected → For resolution simulations, we should keep a small set of charge carriers propagated as a group**.**