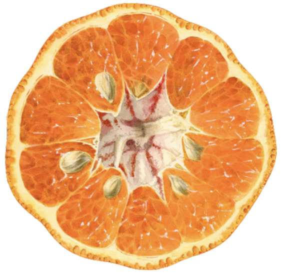
Monte Carlo simulations of a beam telescope setup based on a 65 nm CMOS Imaging Technology



The Tangerine Project

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On behalf of the Tangerine Collaboration

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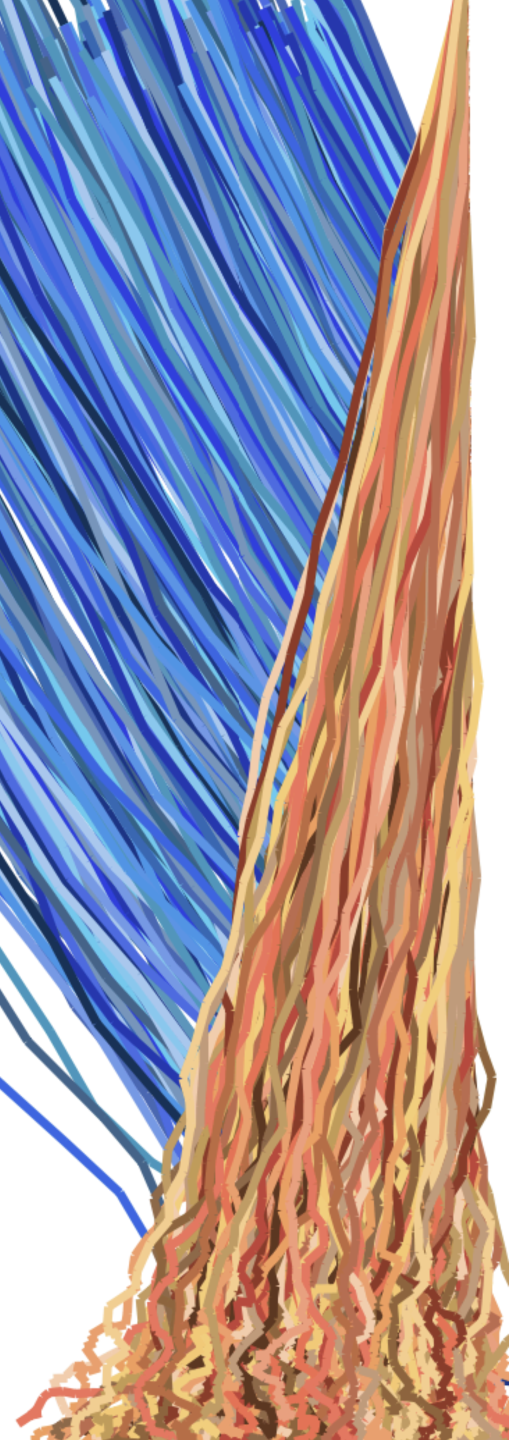
DESY.



Overview

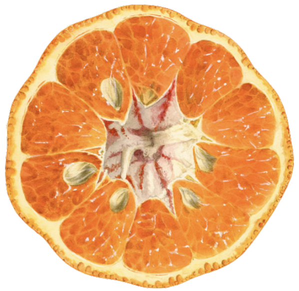
- ➤ Introduction
- ➤ Monte Carlo simulations and data analysis workflow
- ➤ Preliminary studies
- ➤ First results of the test beam telescope simulations
- ➤ Summary & Outlook

Introduction

The Tangerine project (Towards Next Generation Silicon Detectors)

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

- Exploiting **monolithic sensors** based on a novel **65 nm CMOS imaging technology** with a **small collection electrode**:
  - ✔ Small sensor capacitance
  - ✔ Low analogue power consumption
  - ✔ Large signal-to-noise ratio



- <u>Project goal:</u> development of a sensor with **high spatial and time resolution**, and a **low material budget**.

- <u>Primary initial goal:</u> development of a **test beam telescope**.

  → **Simulations have already started!**

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**).

  ↪ See talk of A. Simancas

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

  ↪ See talk of M. A. Del Rio Viera

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

Test beam telescope simulations in Allpix²

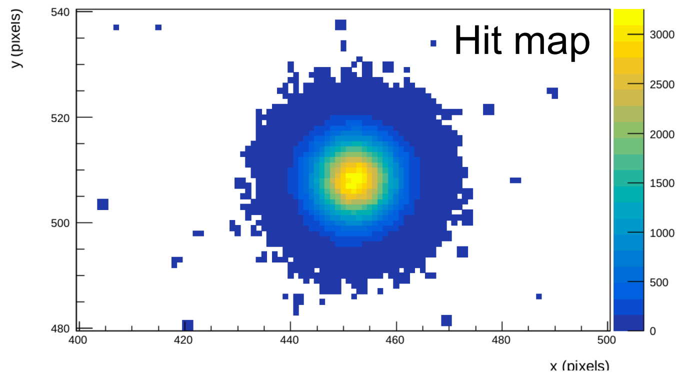
Integration with Corryvreckan

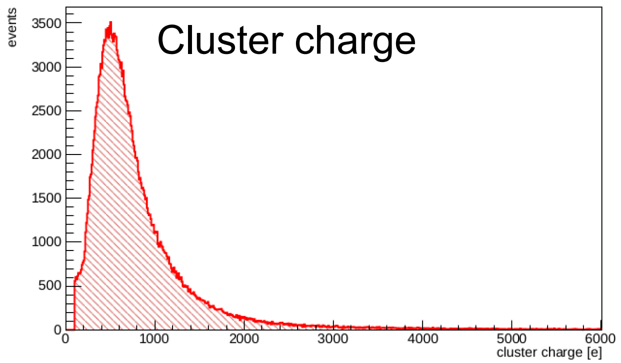
↪ See talk of S. Spannagel

Hands-on tutorials on Allpix² & Corryvreckan: today and on Thursday.

- Framework dedicated to reconstructing and analyzing test beam data.
- Based on a modular concept like Allpix².
- Easily integrated with Allpix².

[CorryvreckanWriter] → Allpix² → data.root, geometry.conf → [FileReader] → Corryvreckan





Preliminary studies with Allpix²

From the initial energy deposition until the digitisation stage

- Different studies have been carried out in the different stages of the simulations.

  ➤ Better understanding of the sensor
  ➤ More control of the simulations
  ➤ **Verification of the simulations**

- Some examples:

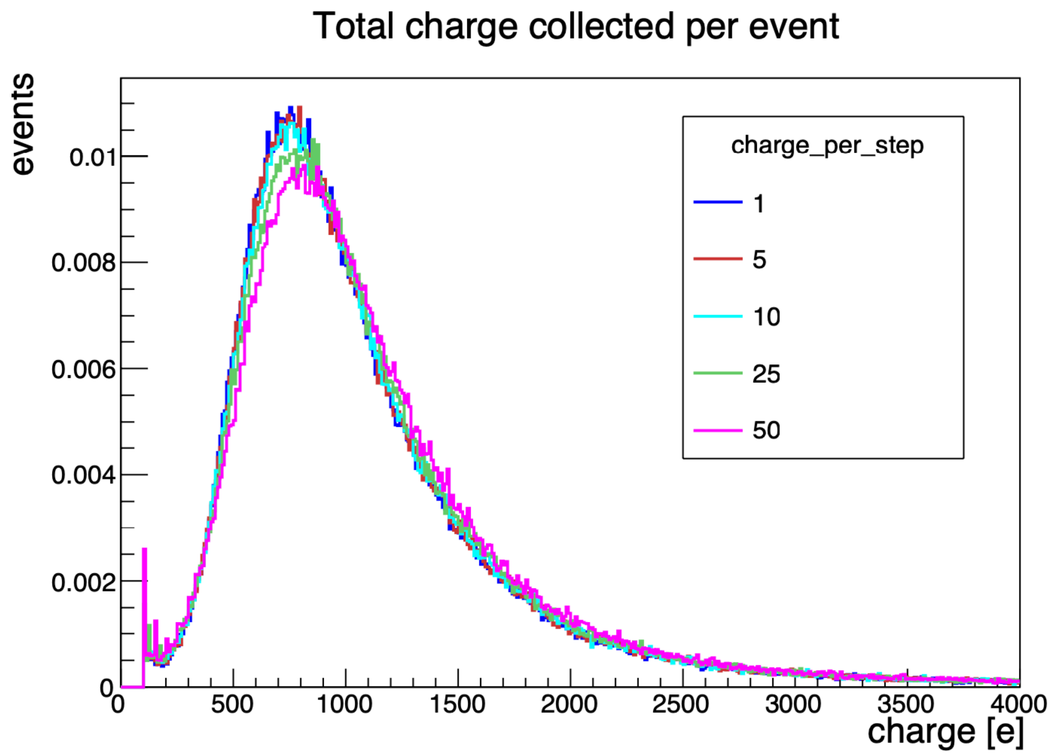
  - Adapting the TCAD mesh into Allpix²
  - Study of the maximum step length of the energy deposition
  - Study of the maximum number of charge carriers propagated per step
  - …

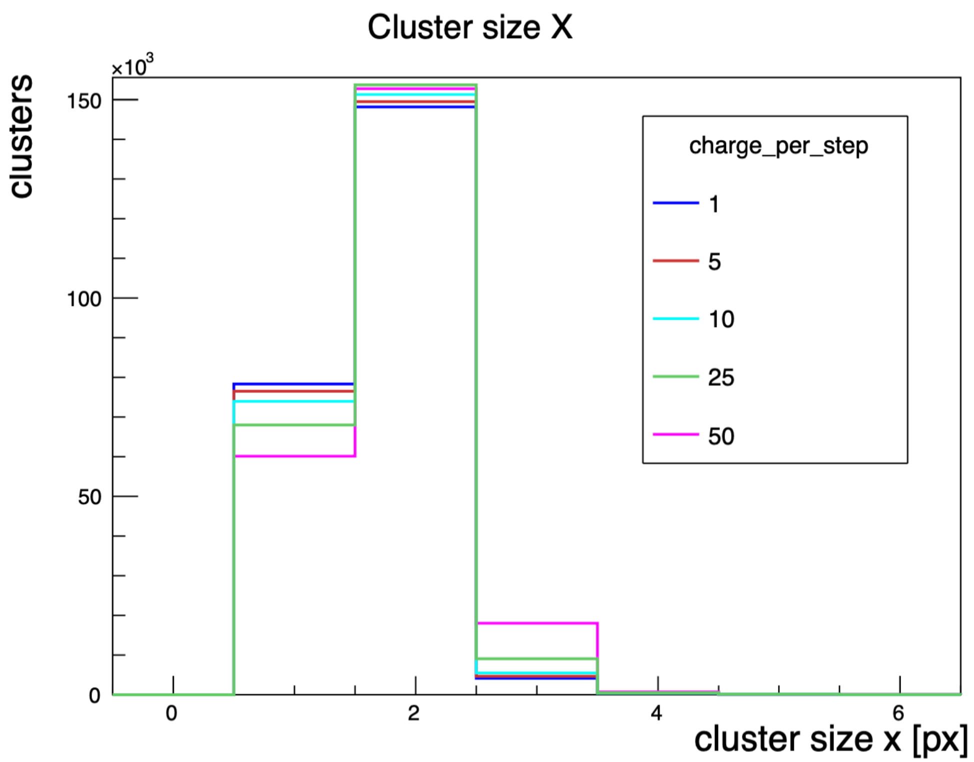
Sensor-dependent studies!

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 time of the simulations shows a roughly linear dependance on the number of charge carriers propagated together.





- 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 per step	Efficiency [%]	Resolution in x [µm]
1	99.990 ± 0.002	2.29 ± 0.01
5	99.988 ± 0.002	2.35 ± 0.01
10	99.988 ± 0.002	2.44 ± 0.01
25	99.982 ± 0.002	2.70 ± 0.01
50	99.975 ± 0.002	3.09 ± 0.01

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

Sensor-dependent studies!

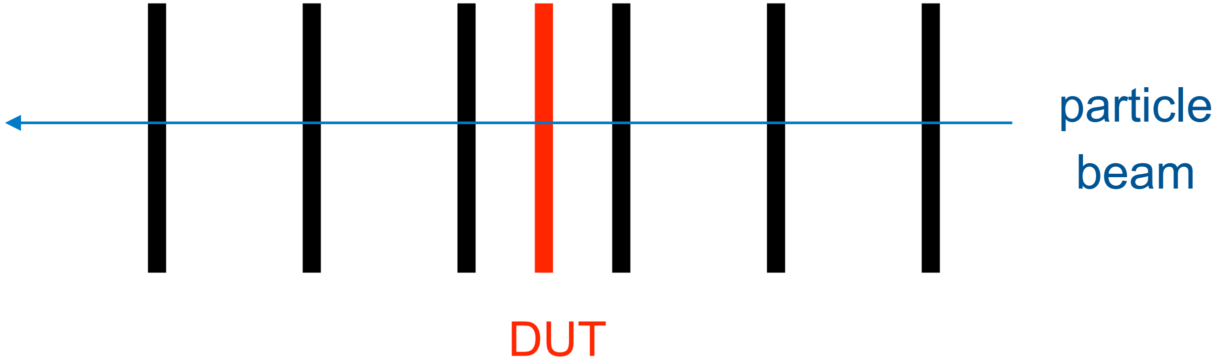
Sensor simulations are understood and verified…
… We can start simulating the test beam telescope!

Test beam telescope

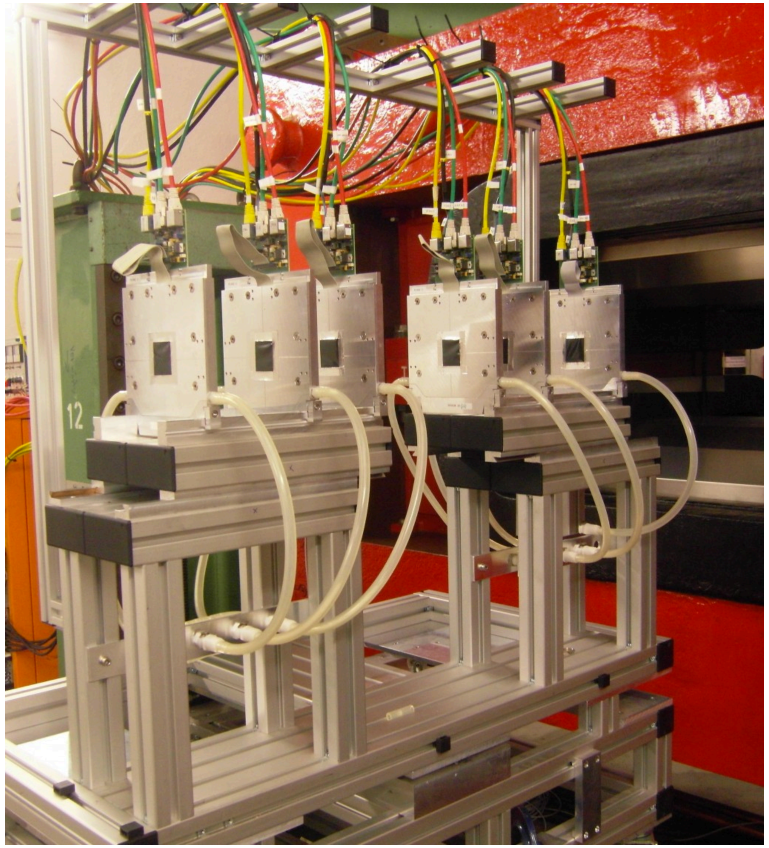
Sensor simulations are understood and verified…
… We can start simulating the test beam telescope!

What is a test beam telescope?

- Used for testing and characterisation of new devices.



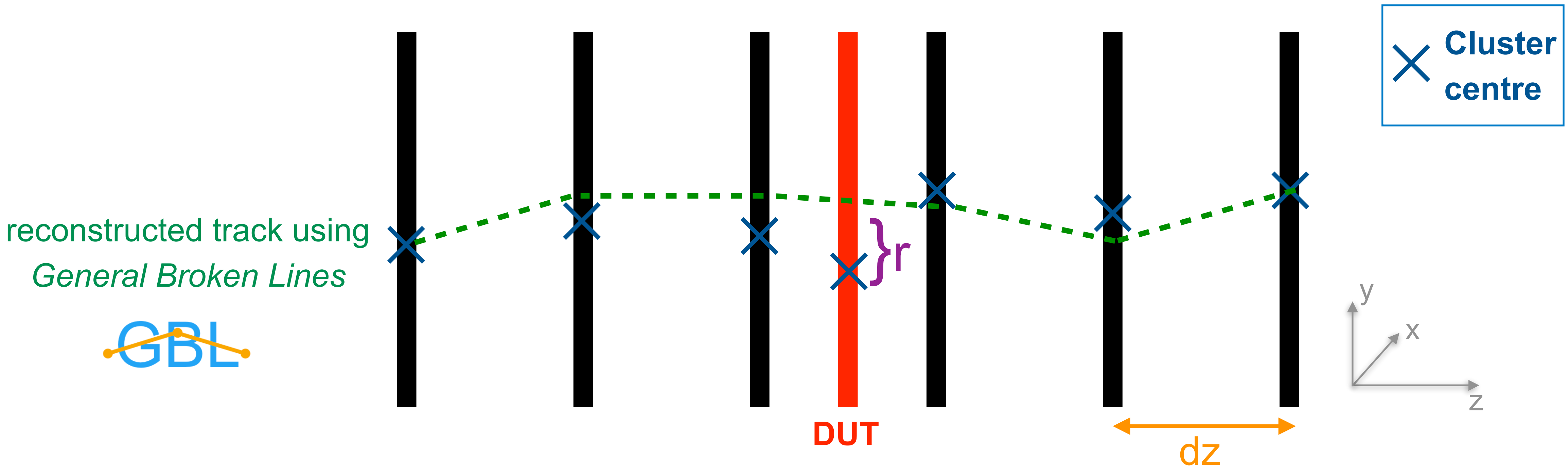
- The telescope planes should reach a high (and known) tracking resolution at the position of the DUT (Device under Test).



DESY beam telescope

Test beam telescope

Track reconstruction & Residuals



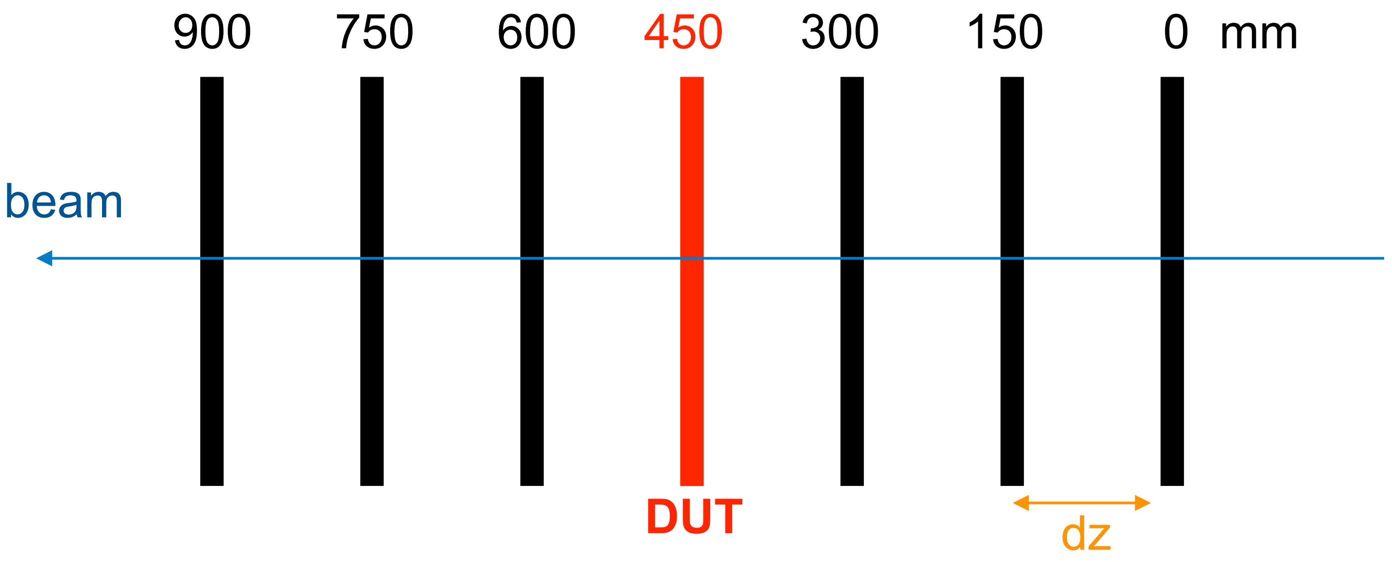
Unbiased residual (r_u^2) : x/y track intercept on this plane - x/y associated cluster on this plane

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

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

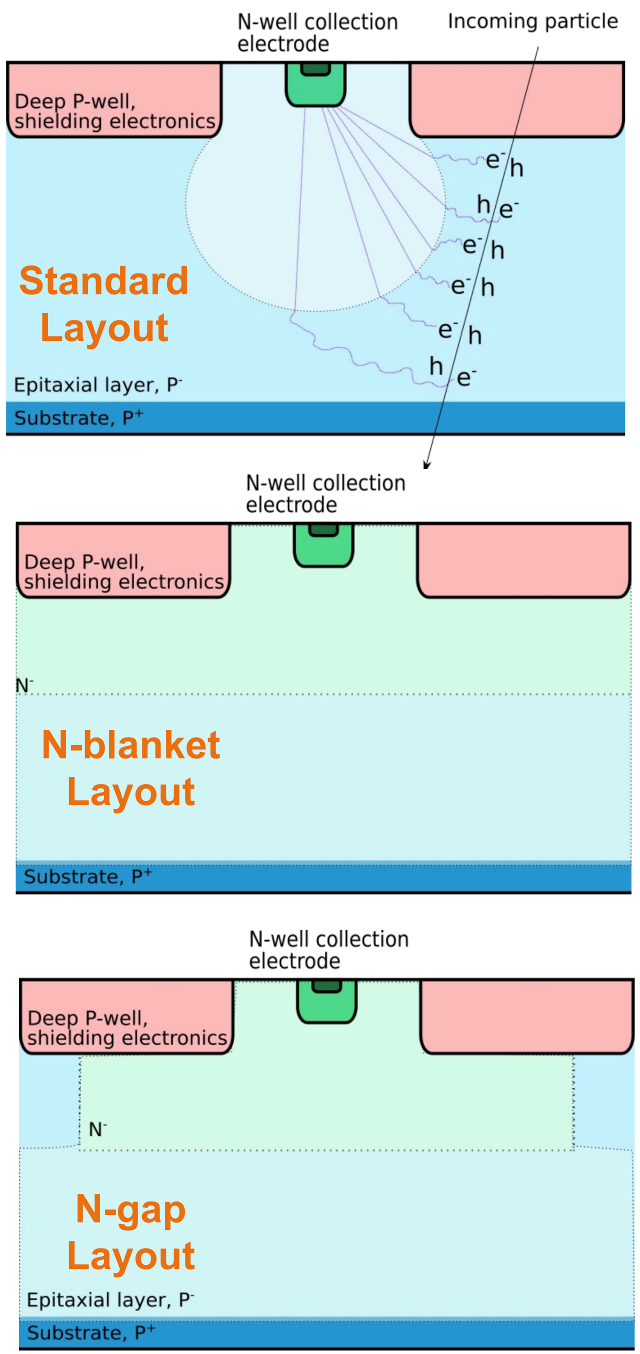
$$r_b^2(z) = \sigma_{int}^2 - \sigma_{t,b}^2(z)$$

Beam telescope setup for the first simulations



- 6 parallel planes, perpendicular to a 5 GeV e^- beam.
- Each telescope plane consist of 1024x1024 pixels.
- 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.

- Digitisation is still not fully simulated, only the threshold for a hit to be detected is applied.



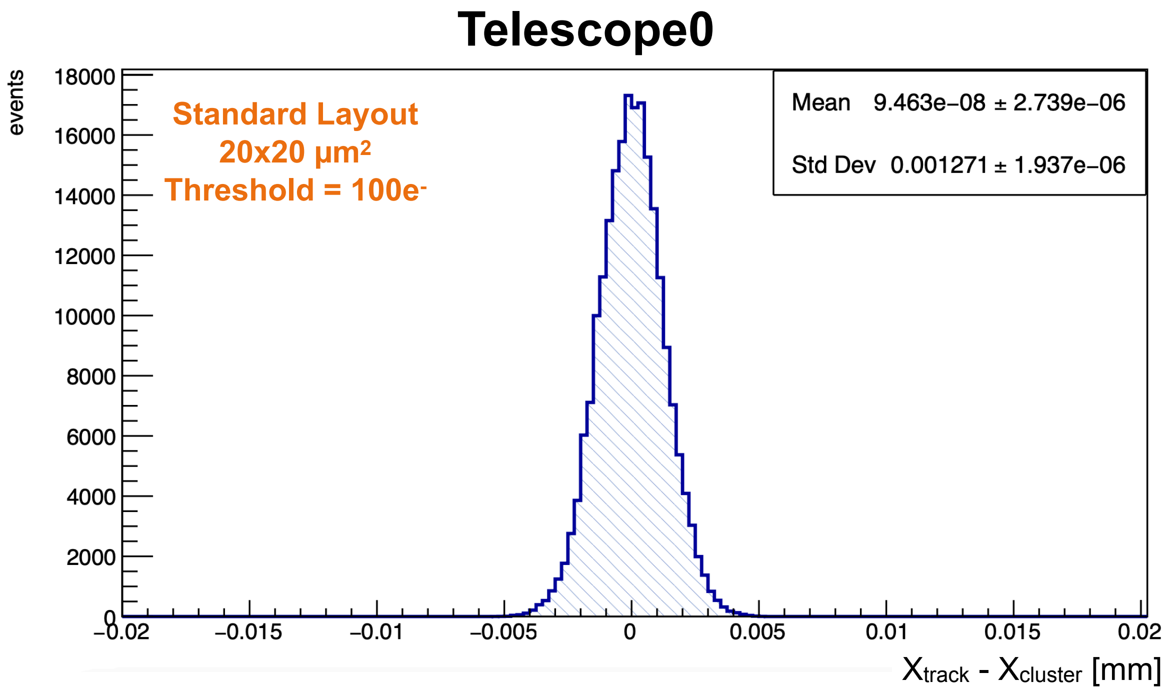
S. Senyukov et al. doi:10.1016/j.nima.2013.03.017

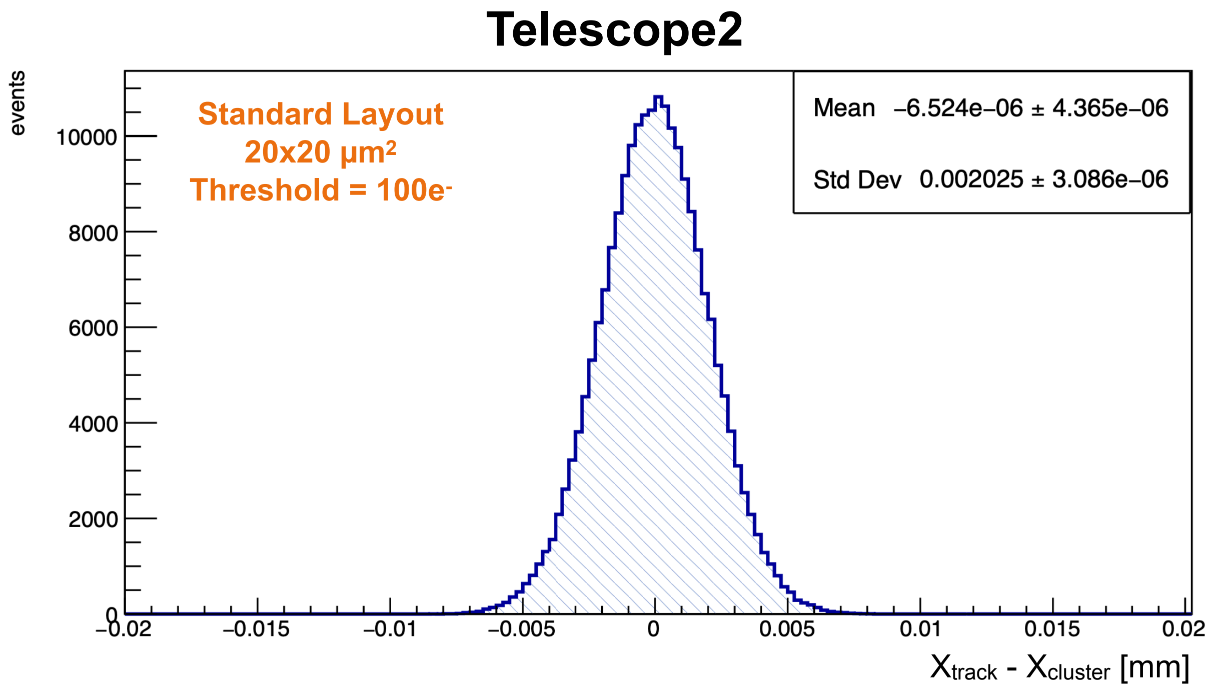
W. Snoeys et al. doi:10.1016/j.nima.2017.07.046

M. Münker et al 2019 JINST 14 C05013

Resolution at the different telescope planes, dz = 150 mm

Biased residual distributions in X



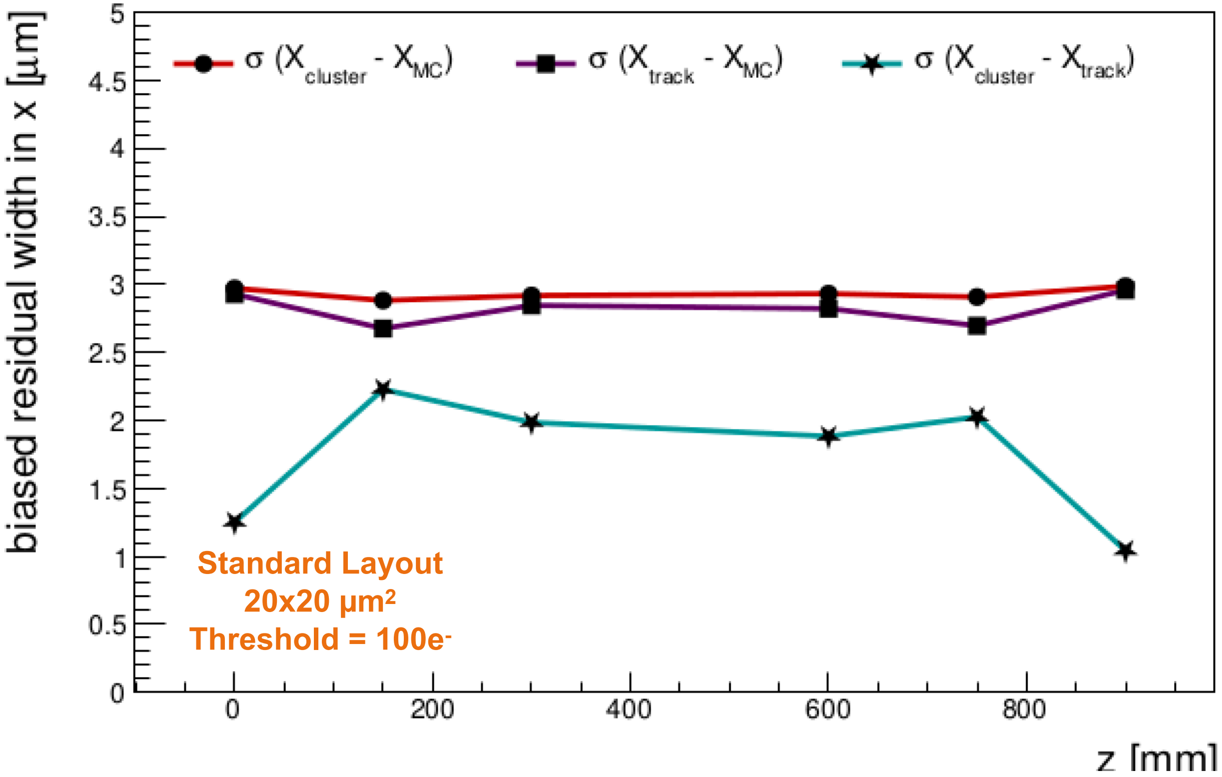


- Biased residual width obtained from the standard derivation of the distributions.
- Different biased residual widths for the different planes.

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

Resolution at the different telescope planes, dz = 150 mm

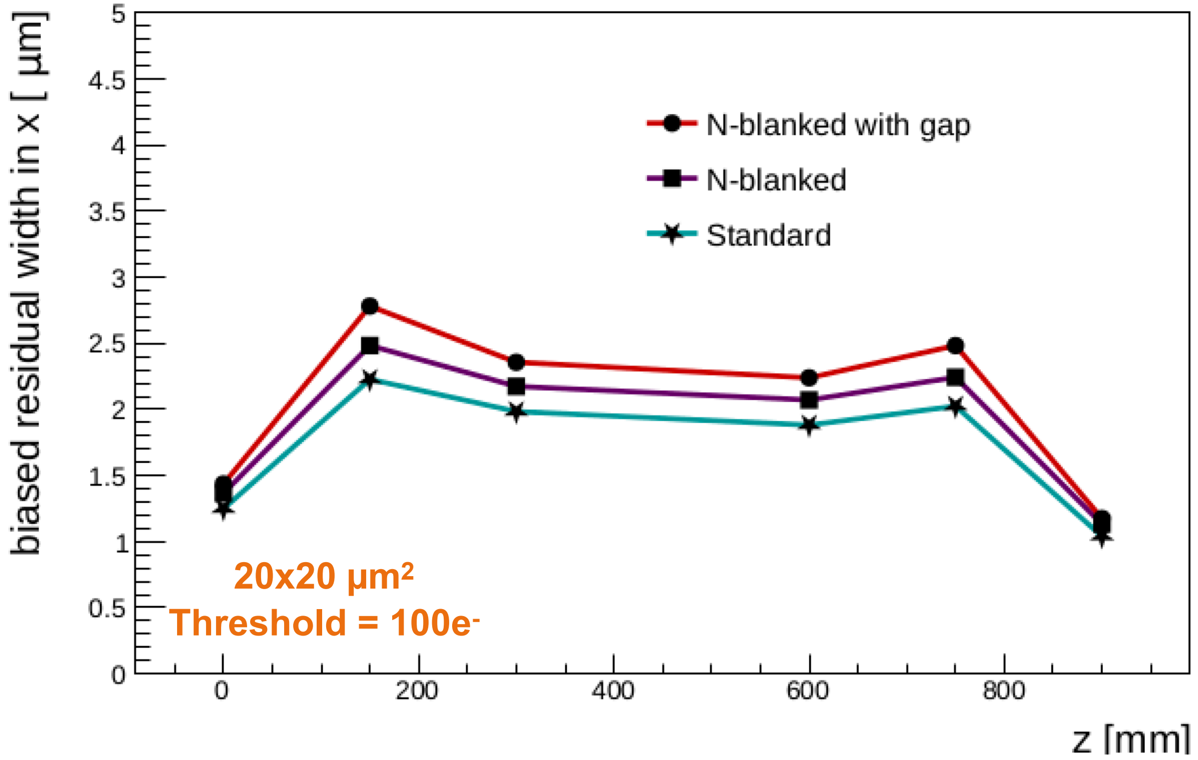
Biased residual distributions in X

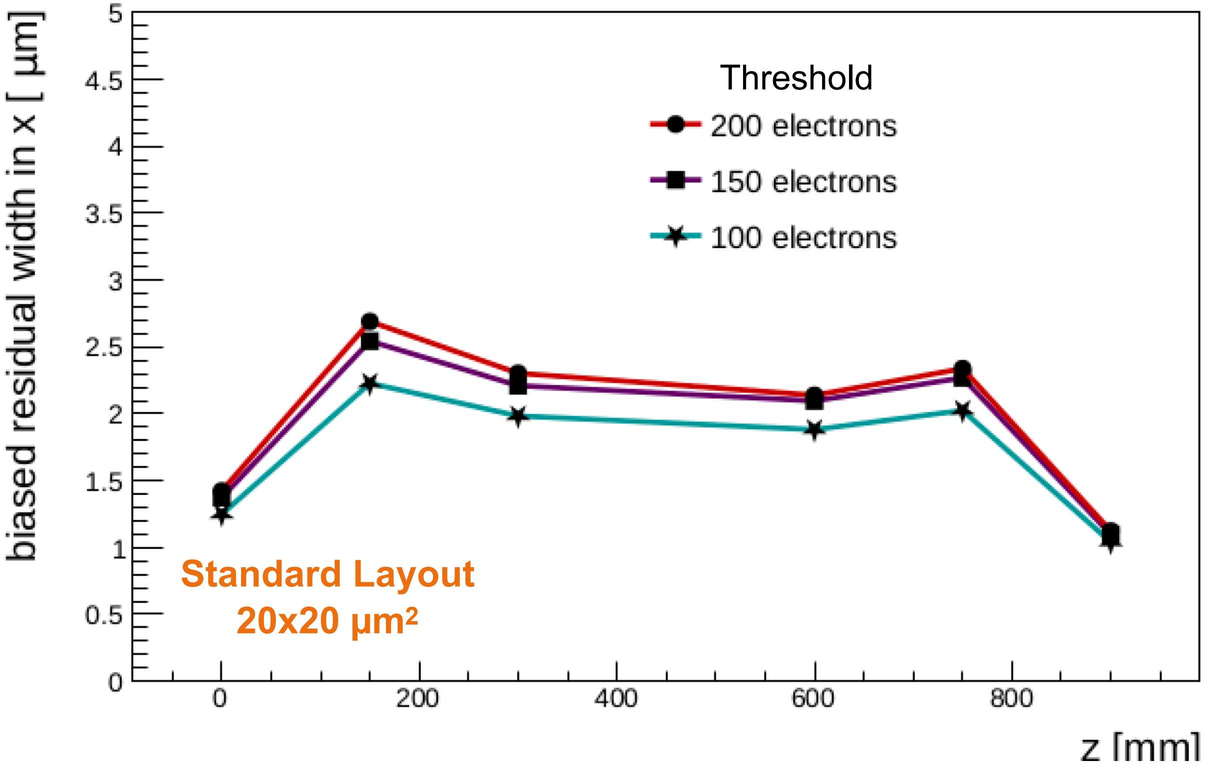


- Error bars are smaller than the dot size: 250 000 events per data point.
- The tracking resolution deteriorates towards the outer planes.
- Biased residual width for the outermost plates are smaller than the ones for the inner planes, as expected for track model.

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.

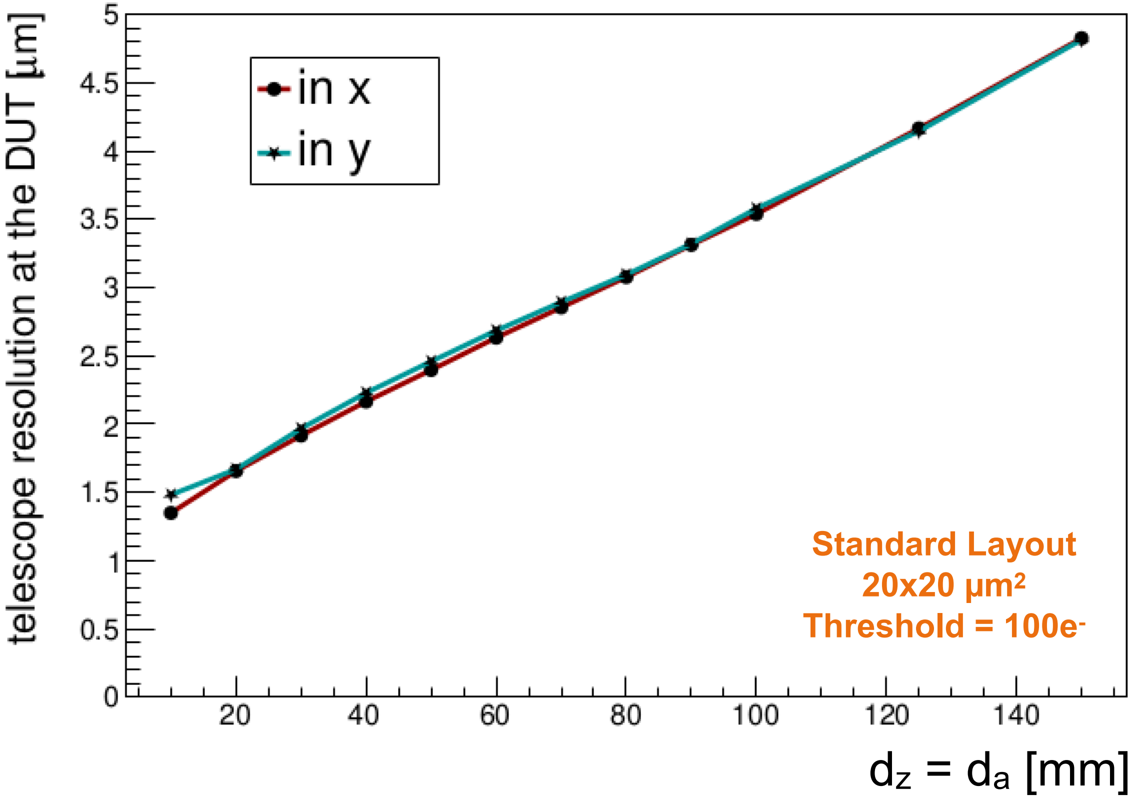
- At higher thresholds, charge sharing is reduced, and the resolution deteriorates.

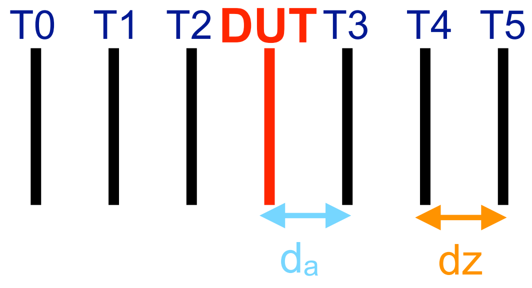
Telescope resolution at the DUT position

Different distance between planes

Telescope resolution at the DUT:

x/y track intercept on the DUT - x/y MC on the DUT





- $d_z = d_a$ varied simultaneously.
- Tracking resolution improves at smaller dz.
- Slightly different in x and y due to misalignment.

Summary & Outlook

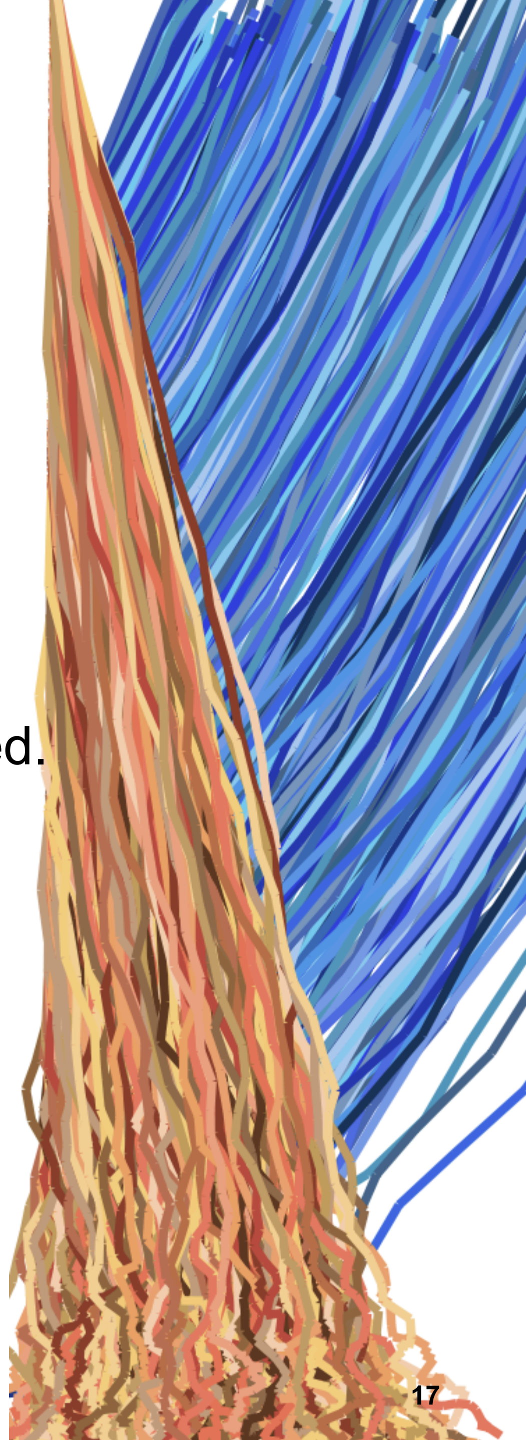
Summary

- Allpix^2 constitutes an excellent tool for the **simulation** of full devices and beam telescopes. Its easy integration with **Corryvreckan** allows for flexible, precise and complete studies.

- Monte Carlo simulations at the **sensor level** have been carried out.
- Test **beam telescope** has started to be simulated with different geometries.
- Differences between **sensor layouts** and **threshold** values have been observed.

Outlook

- Include a more complete **digitisation stage** in the simulations: electronics noise, charge-to-digital converter…
- **Efficiency** studies.
- Studying different **telescope setups**: different distance between planes, threshold values, different layouts…



Thank you

Contact

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Back up

Test beam telescope simulations in Allpix²

Geometry configuration

```
[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
```

Specify the alignment precision along the three global axis

Specify the alignment precision along the three rotation angles

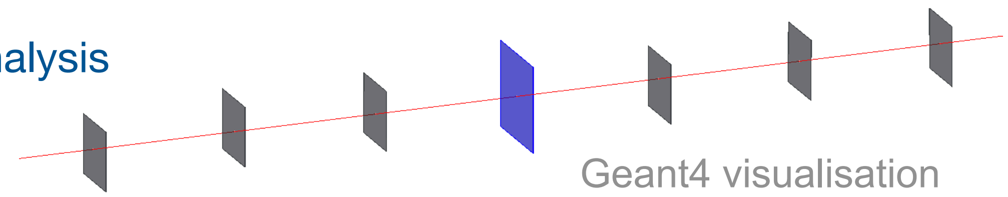
DUT is replaced by a silicon box

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

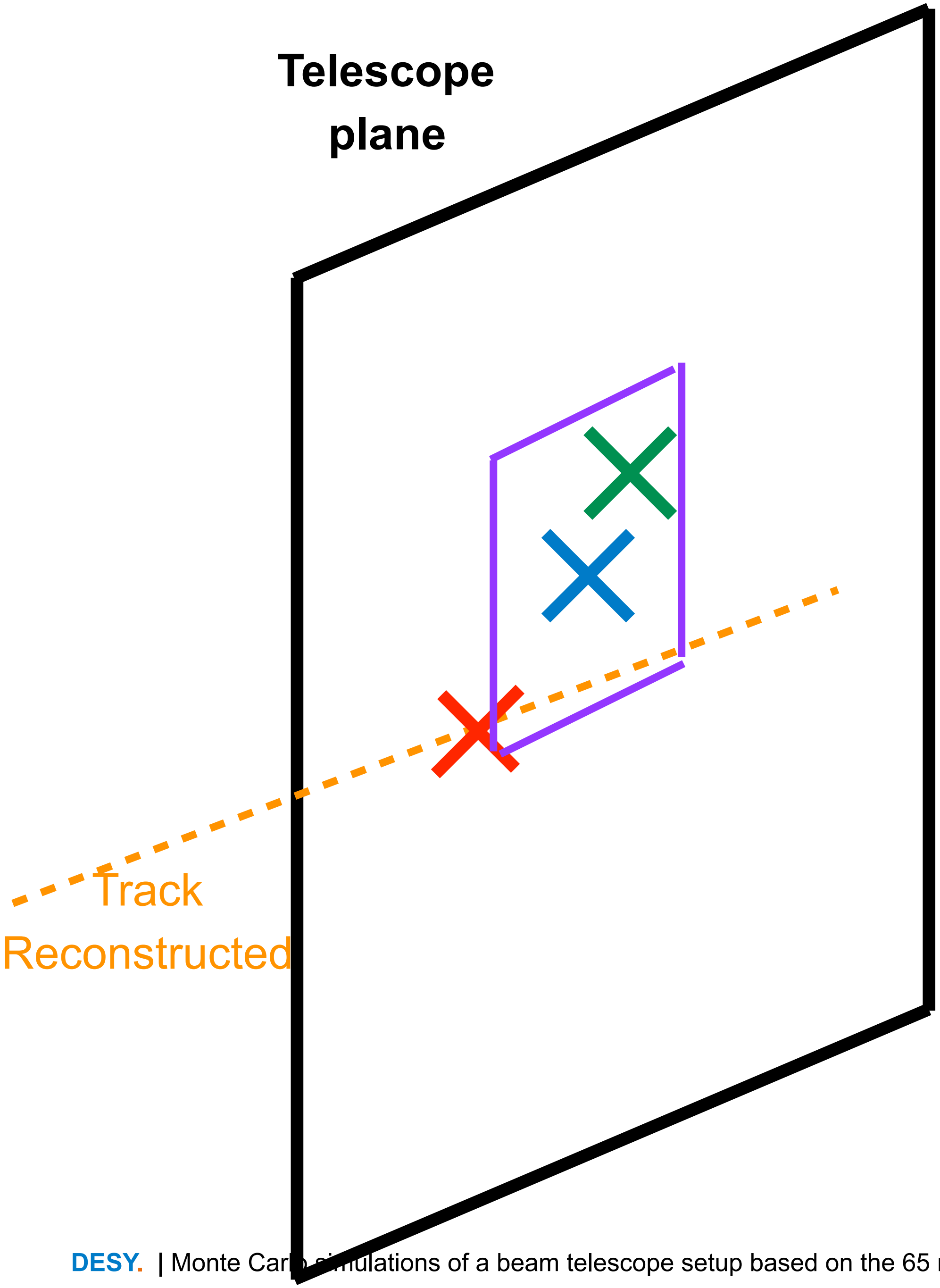
Test beam telescope simulations in Allpix²

Main configuration

[Allpix]		
[GeometryBuilderGeant4]	Constructs the Geant4 geometry	world_material = “air”
[DepositionGeant4]	Deposits charge carriers in the active volume of all detector	beam_direction source_position
[ElectricFieldReader]	Adds an electric field to the detector	model = “mesh”
[DopingProfileReader]	Adds a doping profile to the detector	model = “mesh”
[GenericPropagation]	Simulates the propagation of charge carriers in the sensor	mobility_model charge_per_step
[SimpleTransfer]	Transfers the charge from the implant side of the sensor to the ASIC	collect_from_implant
[DefaultDigitizer]	Describes the digitisation by the front-end electronics	threshold
[ROOTObjectWriter]	Saves the data into a ROOT file for further analysis	
[VisualizationGeant4]		
[CorryvreckanWriter]		



Geant4 visualisation



- 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.