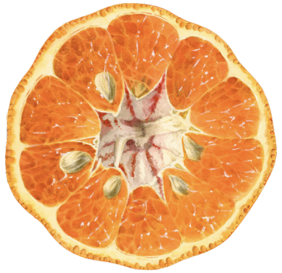
# Beam telescope simulations in Allpix Squared

The Tangerine Project



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3rd Allpix Squared User Workshop
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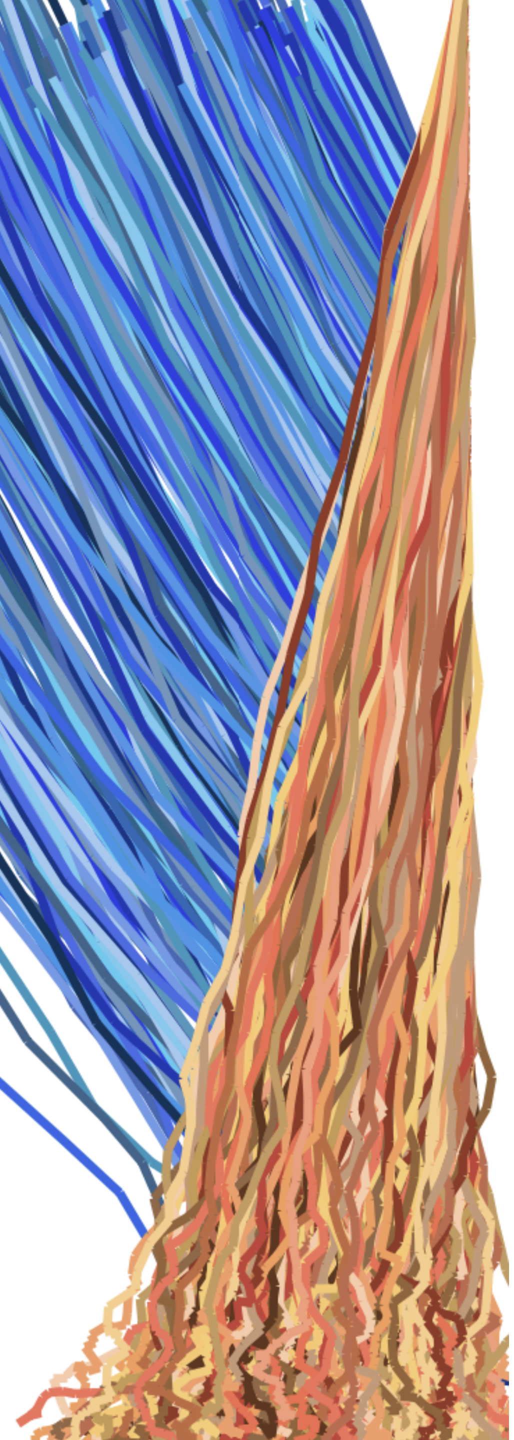
HELMHOLTZ UNIVERSITÄT BONN DESY.



# Overview

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

# Introduction

## The Tangerine project (Towards Next Generation Silicon Detectors)

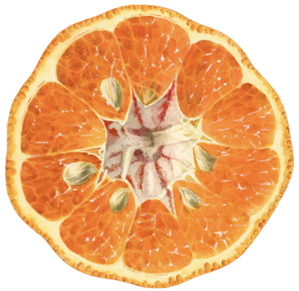
- Research and development of **new silicon sensors** for future lepton colliders and test beam telescopes.

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

  ✔ Small sensor capacitance

  ✔ Low analogue power consumption

  ✔ Large signal-to-noise ratio



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

- Primary initial goal: development of a **test beam telescope**.

  → **Simulations have already started!**

# Monte Carlo simulations and data analysis workflow

## TCAD, Allpix$^2$, Corryvreckan

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

- **Full response of the sensor and the test beam telescope** with high statistics is simulated with **Allpix$^2$**.

↪ See talk of M. A del Rio Viera

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

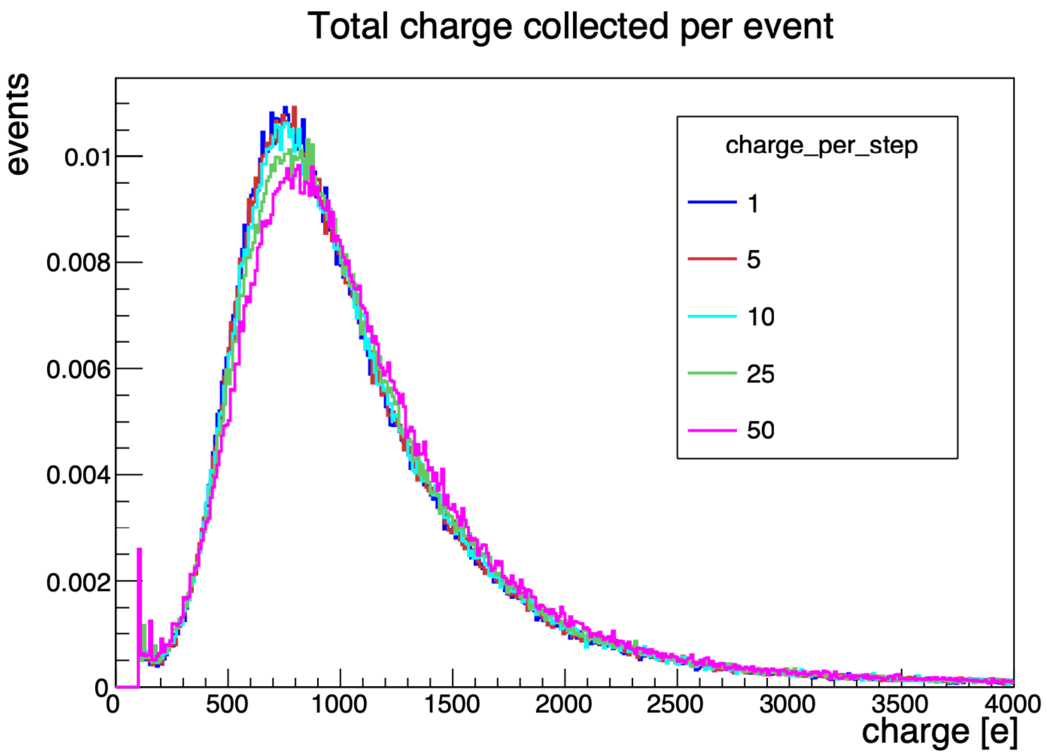
- <u>Some examples:</u>

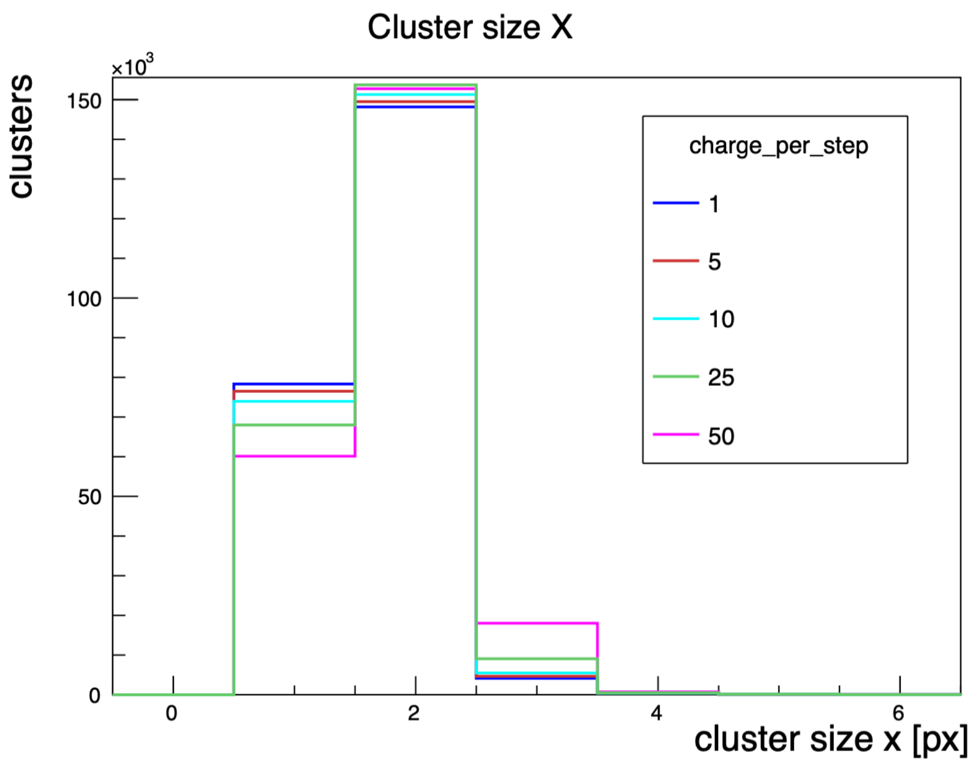
  - Adapting the TCAD mesh into Allpix²
  - Study of the maximum step length of the energy deposition
  - Study of the maximum number of charge carriers propagated per step
  - …

# 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**.**

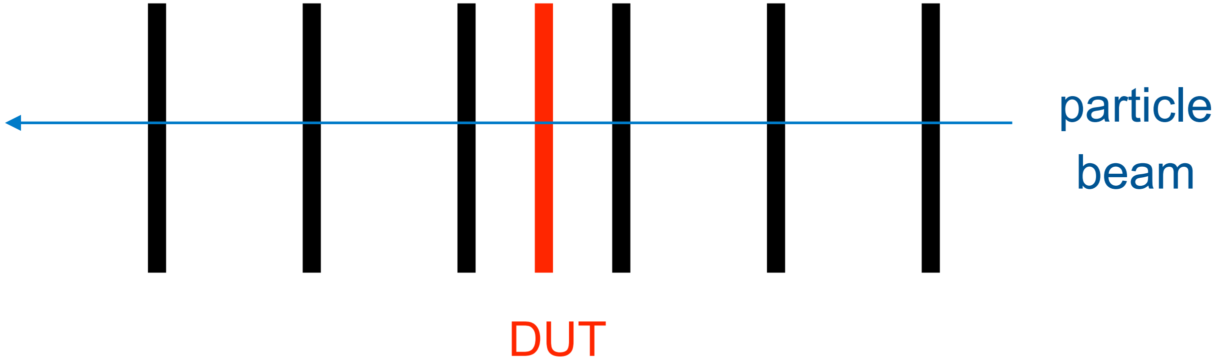
**Sensor simulations are understood and verified…**
**… We can start simulating the test beam telescope!**

# Test beam telescope

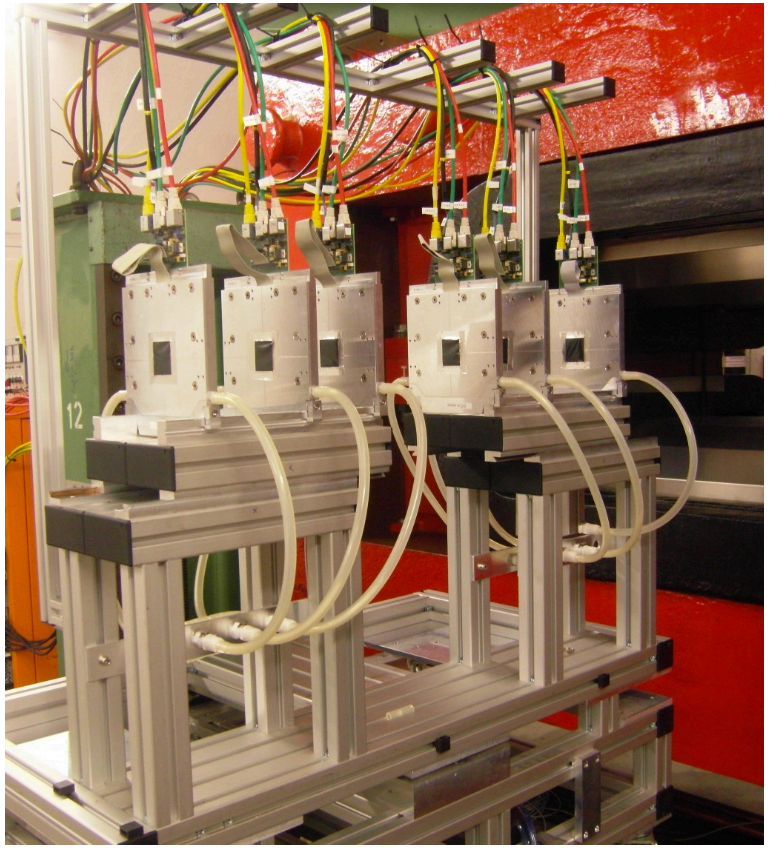
**Sensor simulations are understood and verified…**
**… We can start simulating the test beam telescope!**

## What is a test beam telescope?

- Used for testing and characterisation of new devices.



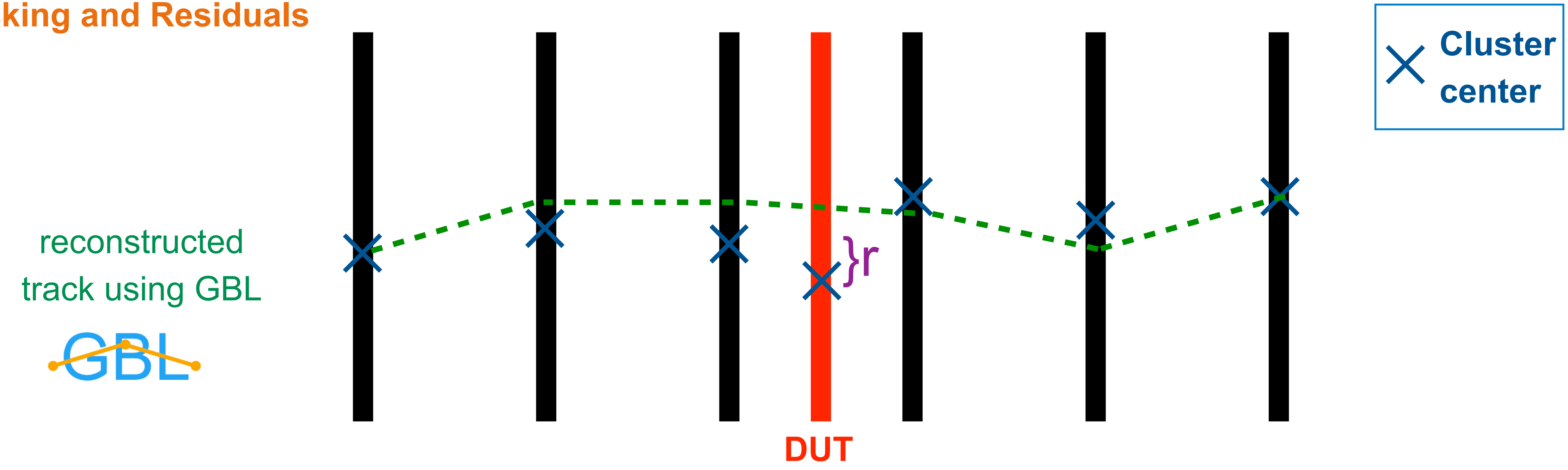

- The telescope planes should reach a high (and known) tracking resolution at the position of the DUT (Device under Test).



DESY beam telescope

# Test beam telescope

## Tracking and Residuals



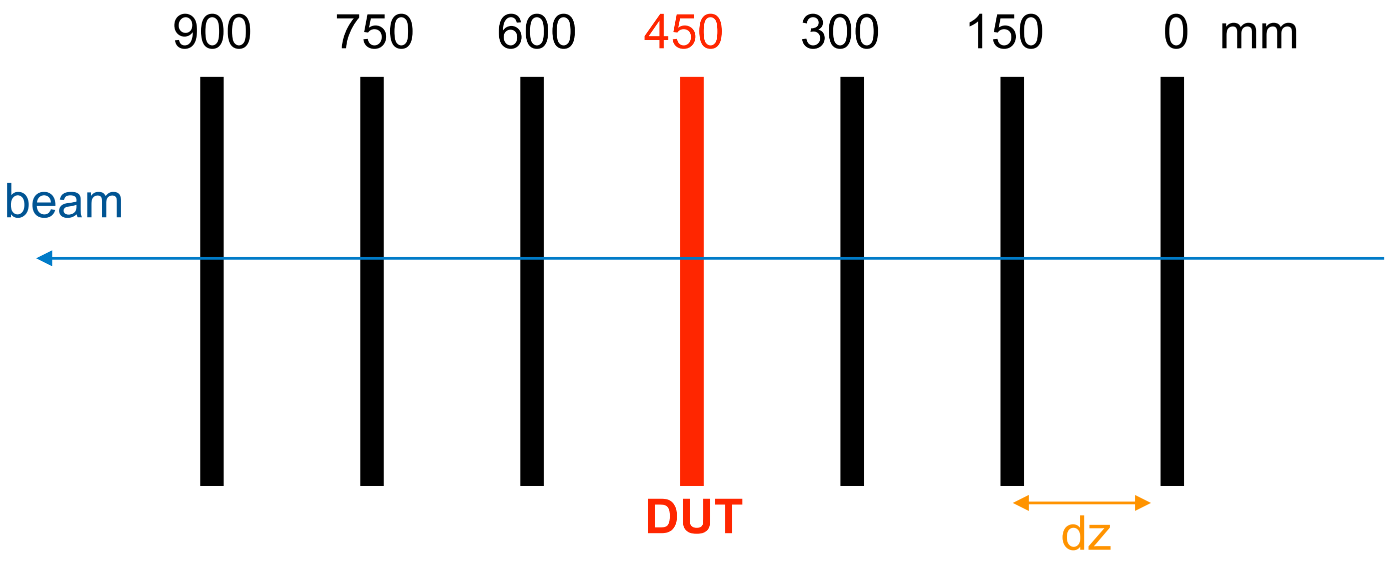

**Unbiased residual** $(r_u^2)$ : x/y track intercept on this plane - x/y associated cluster on this plane

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

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

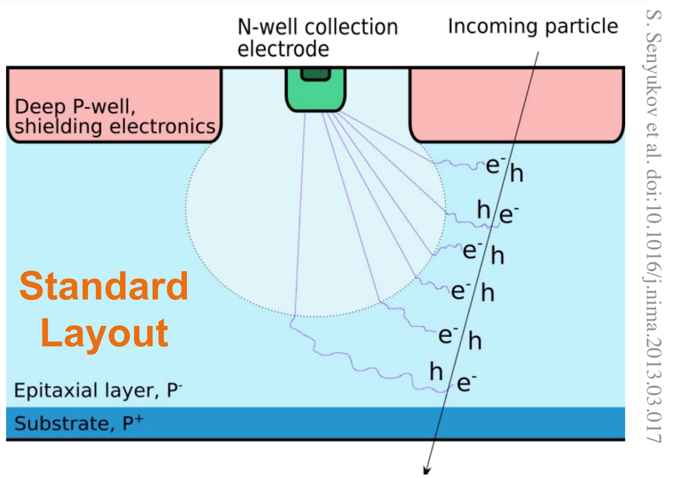
$$r_b^2 = \sigma_{int}^2 - \sigma_{t,b}^2$$

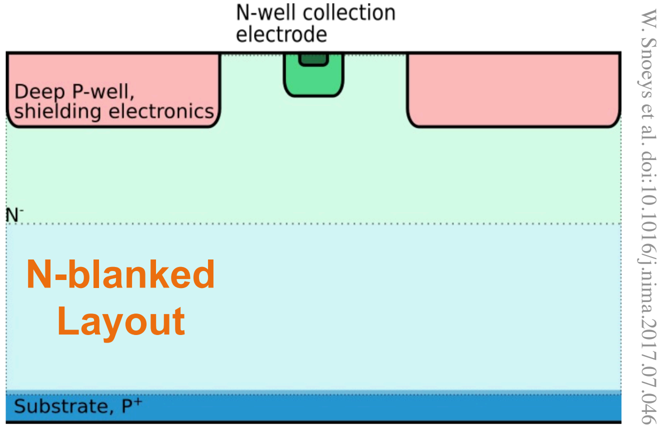
# Beam telescope setup for the first simulations

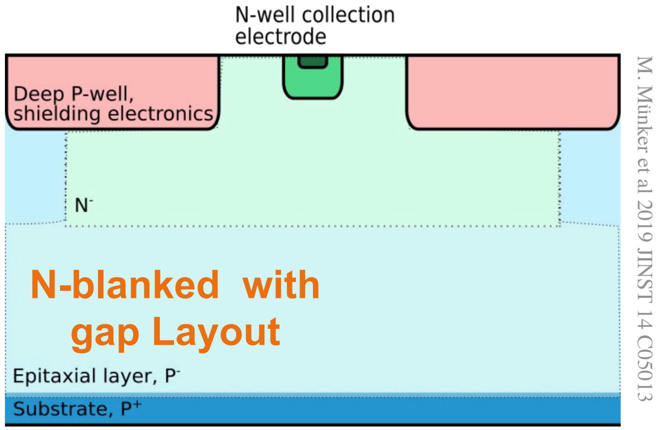



- 6 parallel planes, perpendicular to the 5 GeV $e^-$ beam.
- Each telescope plane consist of 1024x1024 pixels.
- DUT is simulated as a ‘silicon box’.
- Random misalignment and alignment correction for position and orientation is included.

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



# 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

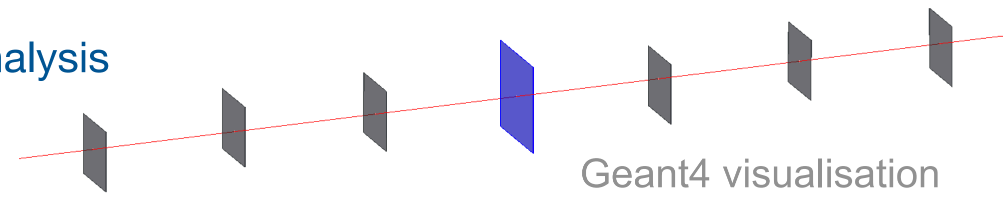
DUT is replaced by a silicon box

```
[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] | | |



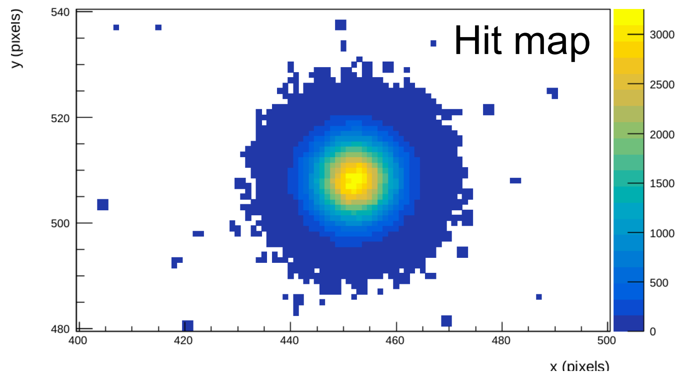
Geant4 visualisation

# Test beam telescope simulations in Allpix²

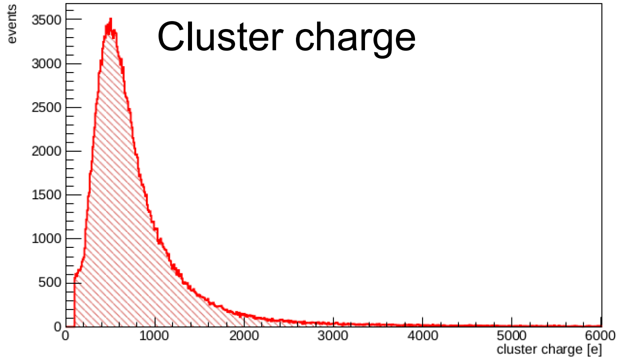
## Integration with Corryvreckan

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

ap² allpix squared → [CorryvreckanWriter] (Allpix²) → data.root / geometry.conf → [FileReader] (Corryvreckan) →

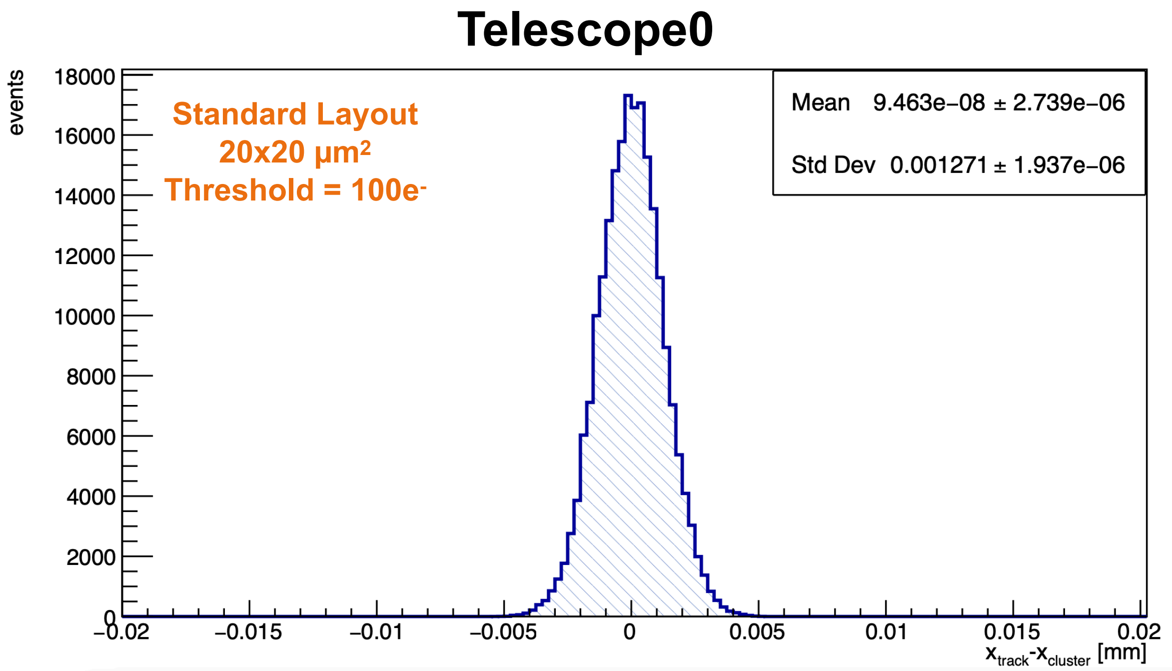


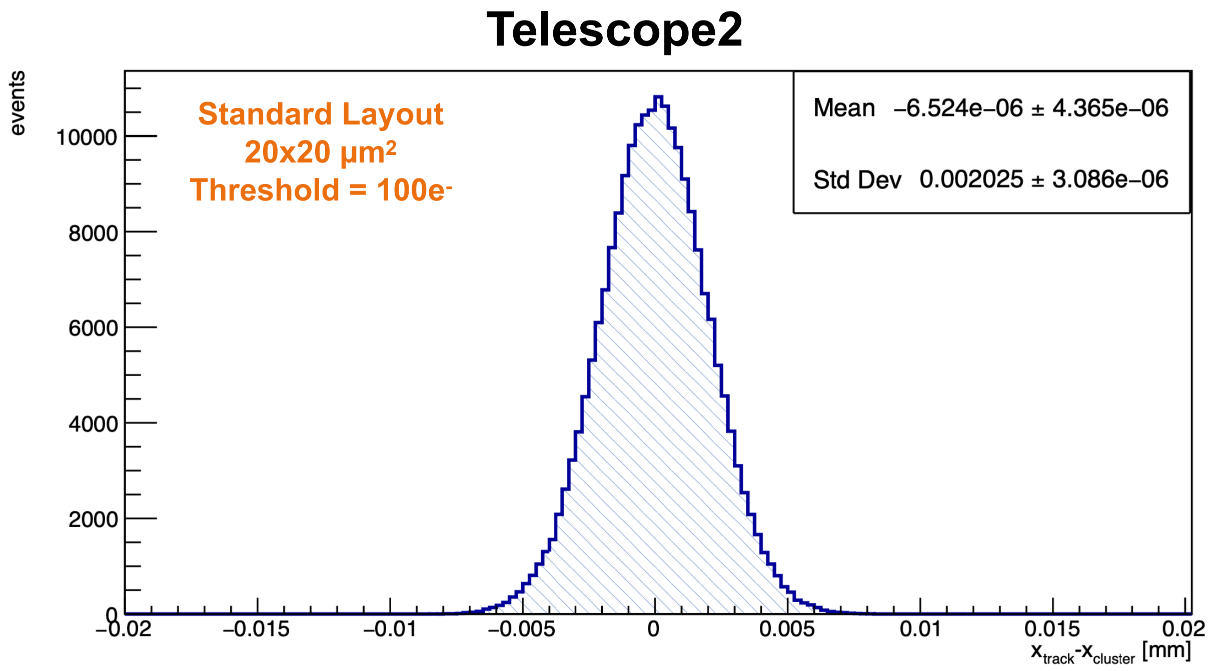




# Resolution at the different telescope planes

## Biased residual distributions in X



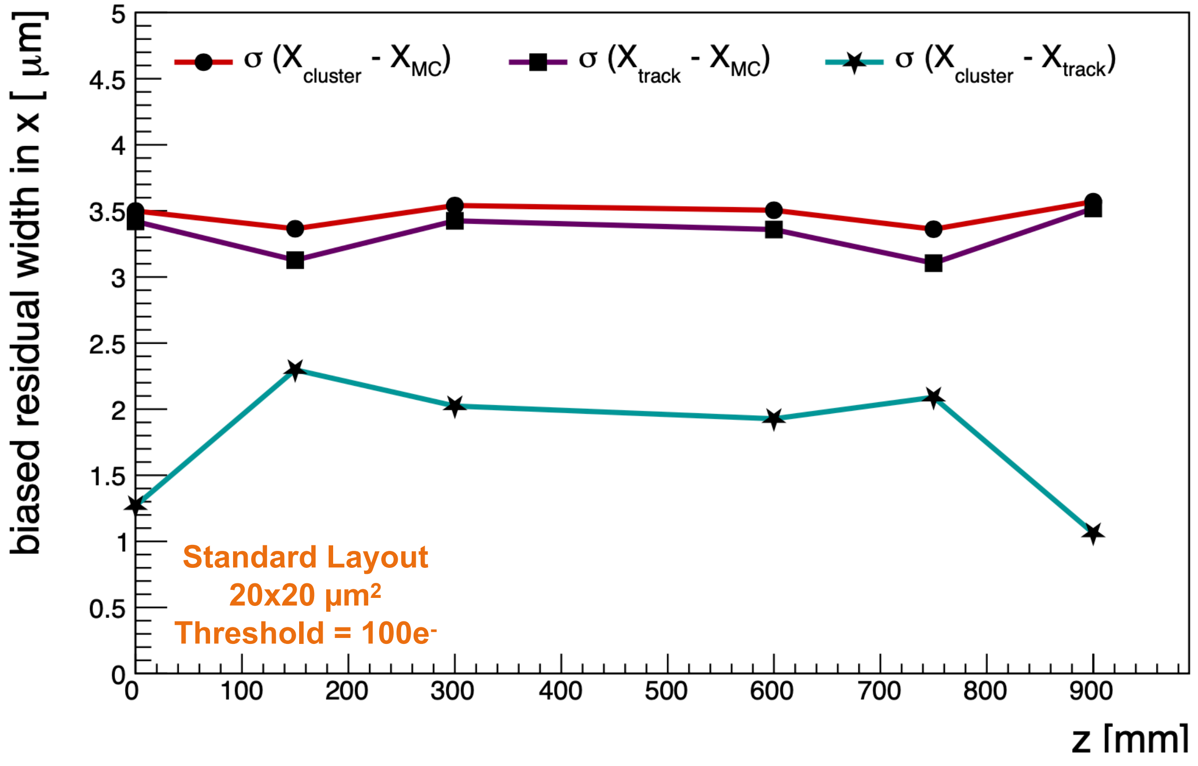




- Biased residual width obtained from the standard derivation of the distributions.
- Biased residual width for the outermost planes are smaller than the ones for the inner planes.

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

# Resolution at the different telescope planes

## 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.
- From the sensor simulations:

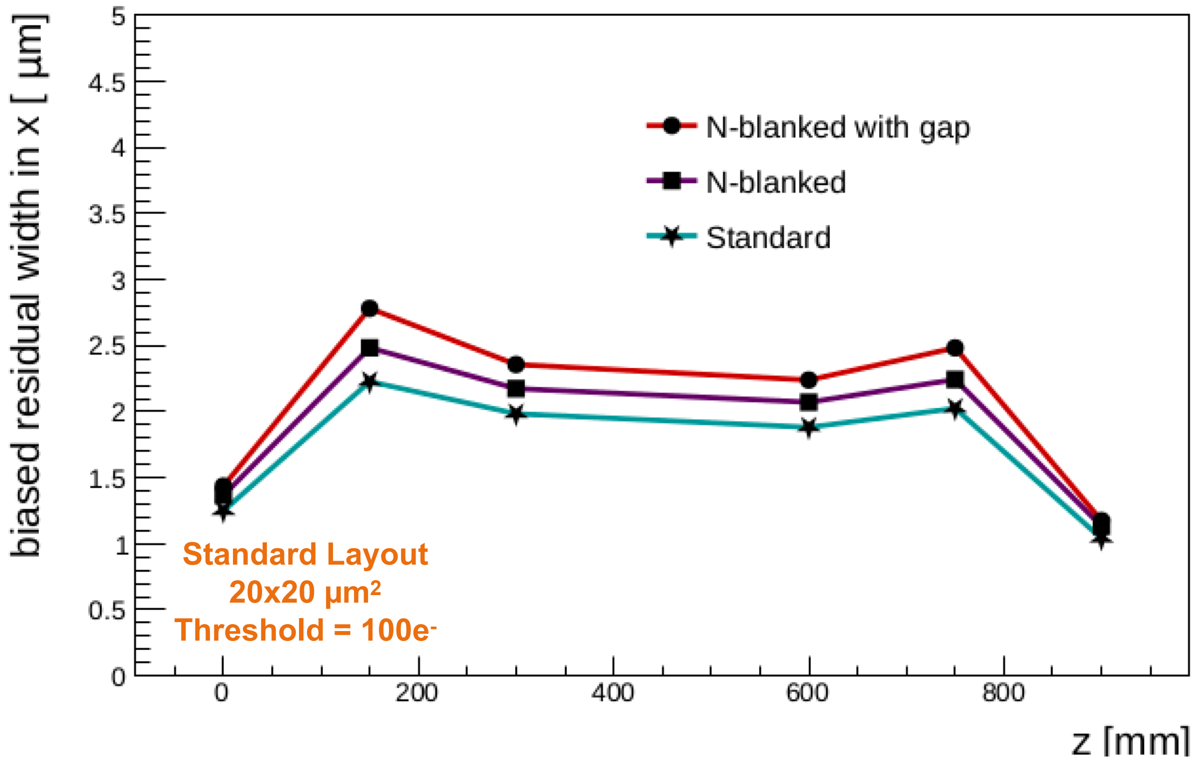
$$\sigma_{int} \sim 3.5\ \mu m$$

- Telescope resolution at the DUT position:

$$\sigma_{t,b} = \sqrt{\sigma_{int}^2 - r_b^2} = \sqrt{3.5^2 - 2^2} \sim 2.9\ \mu m$$

# Telescope resolution at the different planes

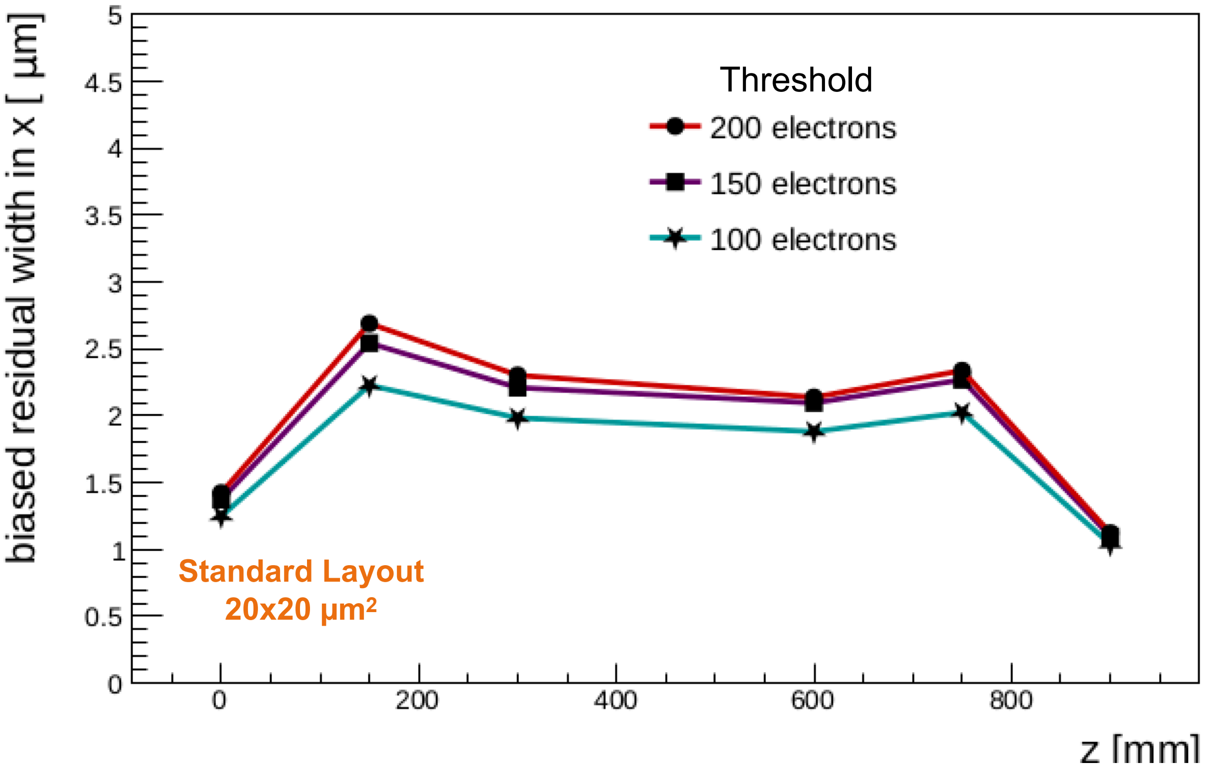
## Different layouts comparison




- The standard layout shows a better resolution (smaller biased residuals) at a threshold of 100 $e^-$.
- Compatible with our previous results of the intrinsic resolution of a sensor.

# Telescope resolution at the different planes

## Different threshold values




- At higher thresholds, charge sharing is reduced, and the resolution deteriorates.
- Compatible with our previous results of the intrinsic resolution of a sensor.
- Digitisation not fully simulated. Not applied: threshold smearing, noise from the digitisation, noise from the readout electronics…

# Summary & Outlook

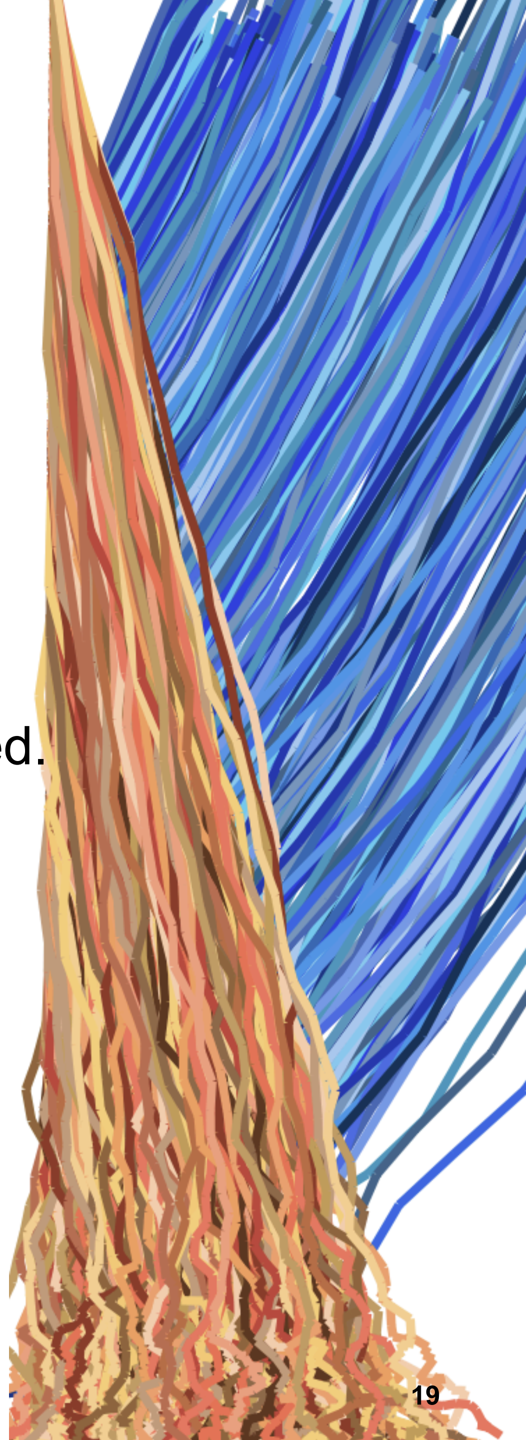
## Summary

- 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.
- Differences between **sensor layouts** and **threshold** values have been observed.

## Outlook

- **Efficiency** studies.
- Studying different **telescope setups**: different distance between planes, thresholds …
- Include the **digitisation stage** in the simulations: electronics noise, threshold smearing…



# Thank you

**Contact**

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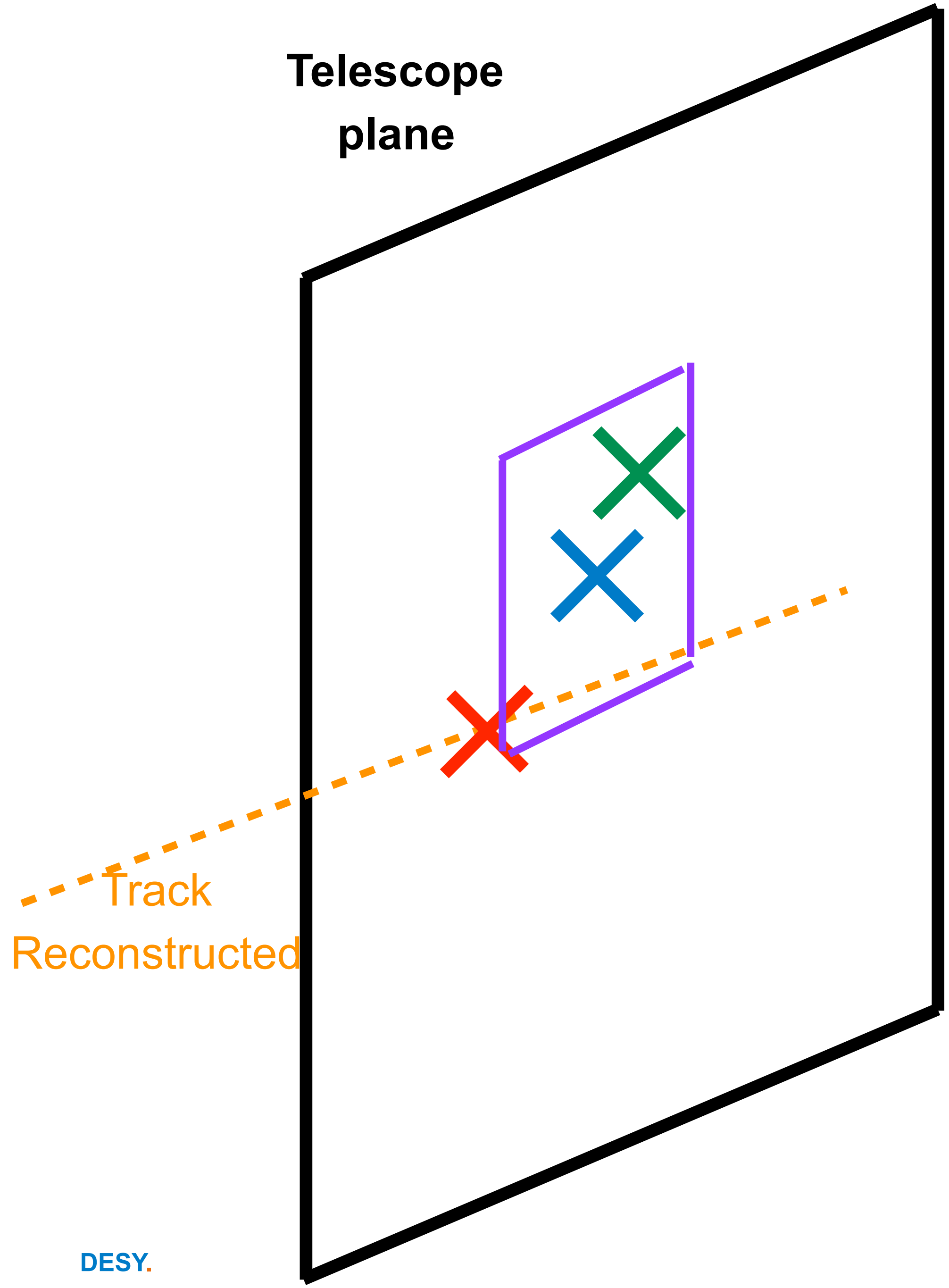
# Back up





- 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.