This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654168

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

Testbeam Studies of ATLAS ITk Strip modules at DESY-II

Emma Buchanan
On behalf of the ITK Strip Testbeam Group

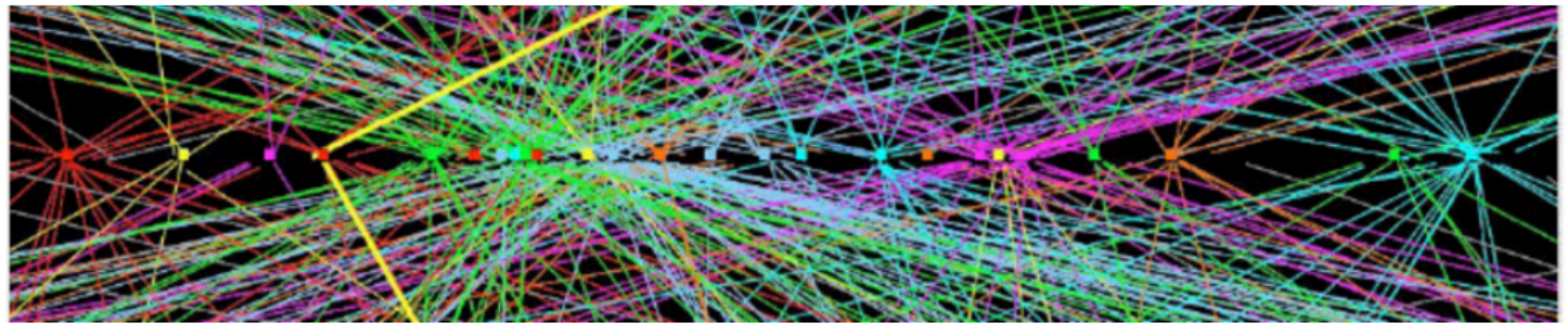
BTTB 2021

Institute of High Energy Physics
Chinese Academy of Sciences

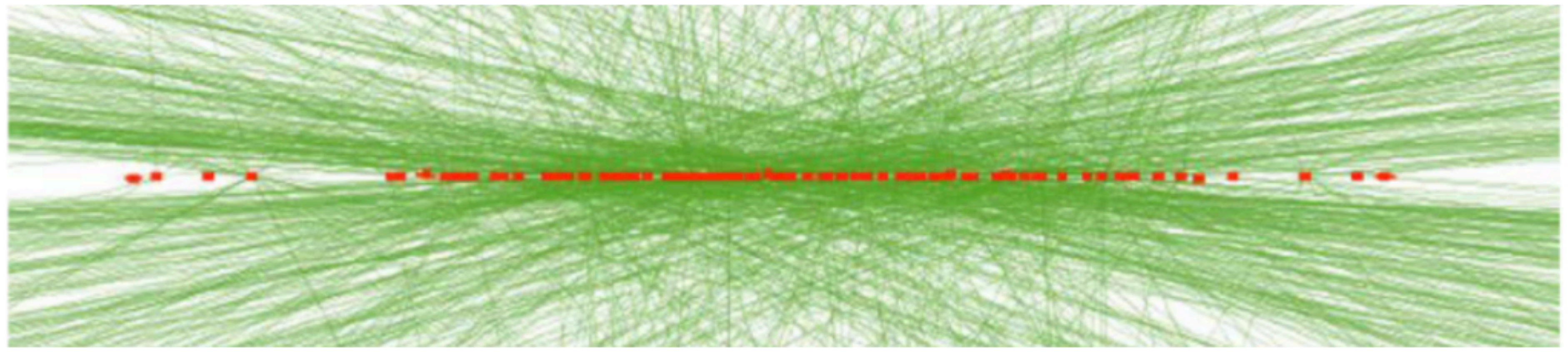
HL-LHC

- The High-Luminosity upgrade of the LHC is scheduled to begin colliding protons in 2026
- The peak instantaneous luminosity will be up to **7.5×10^{34} cm^{-2}s^{-1}**
- The mean number of interactions per bunch crossing **μ=200** (currently μ=50)
- Expected total integrated luminosity of **4000 fb^{-1}**
- The current Inner Detector in the ATLAS experiment does not meet the requirements of the High-Luminosity LHC upgrade
- Current tracking system will need to be upgraded to cope with the increased occupancies and radiation damage

LHC (25 vertices)



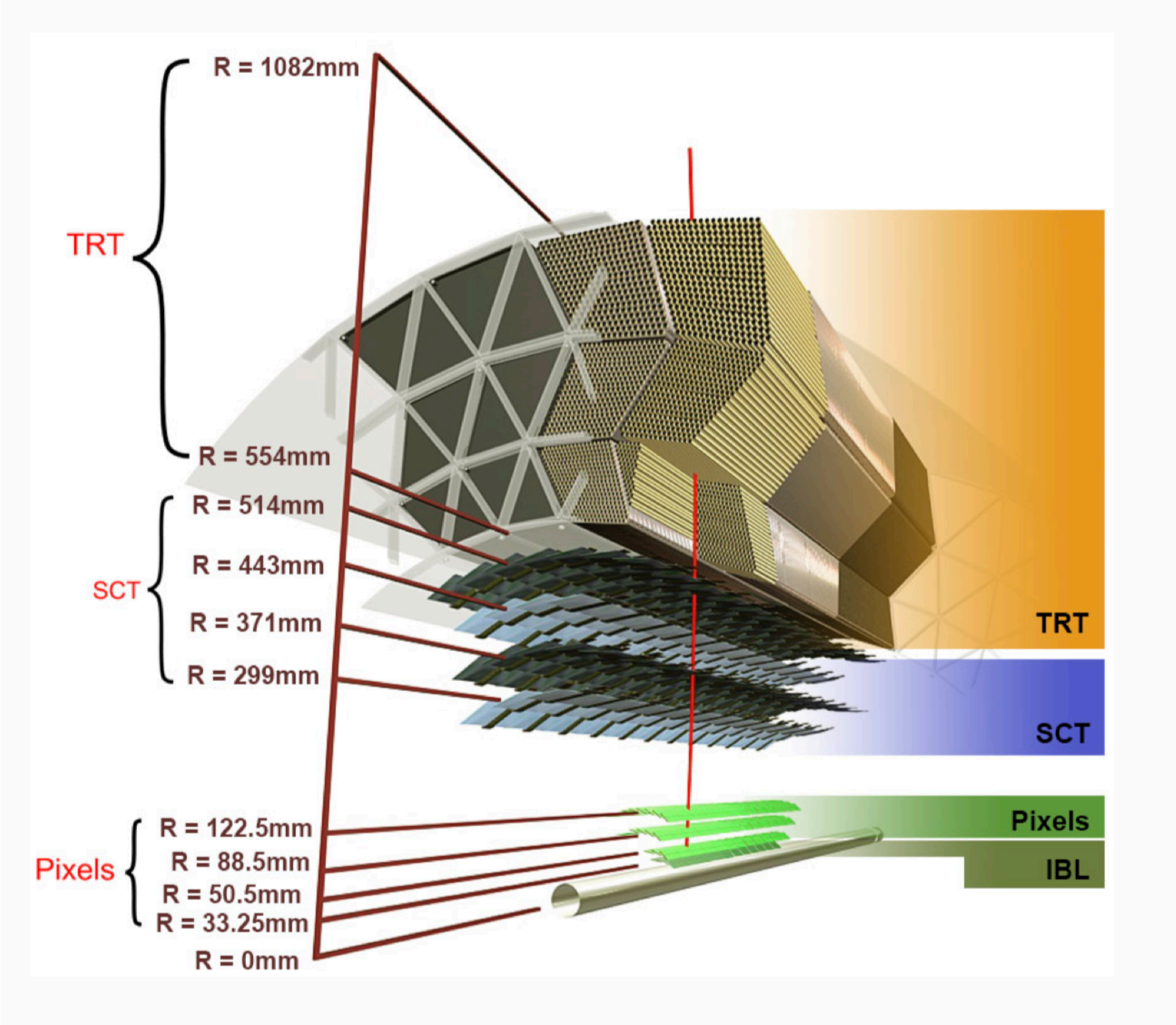
HL-LHC (200 vertices)



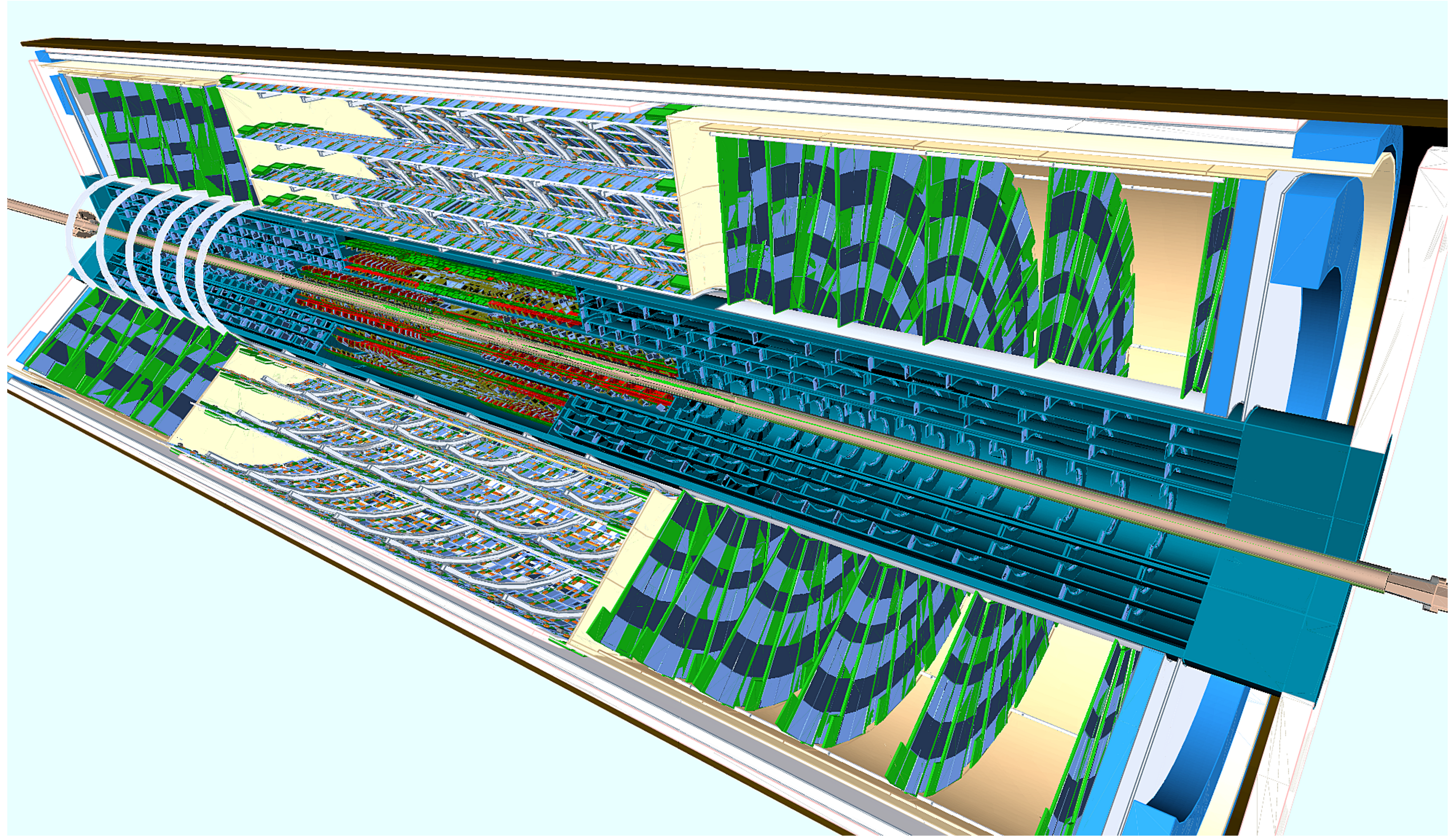
HL-LHC: High Luminosity LHC
LS: Long Shutdown
TeV: Tera electron Volt

ATLAS Tracking Detector Upgrade

Current Inner Detector (ID)

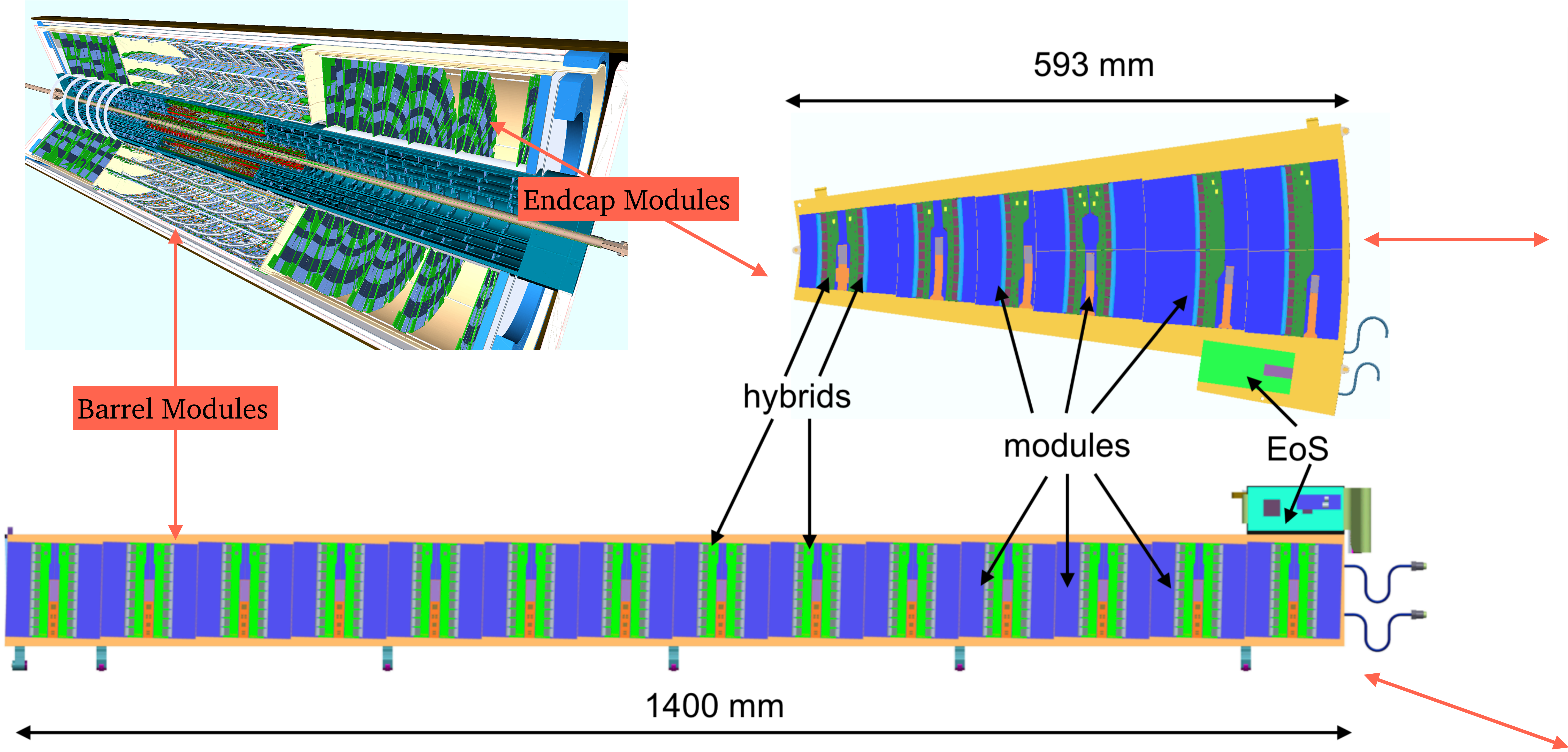


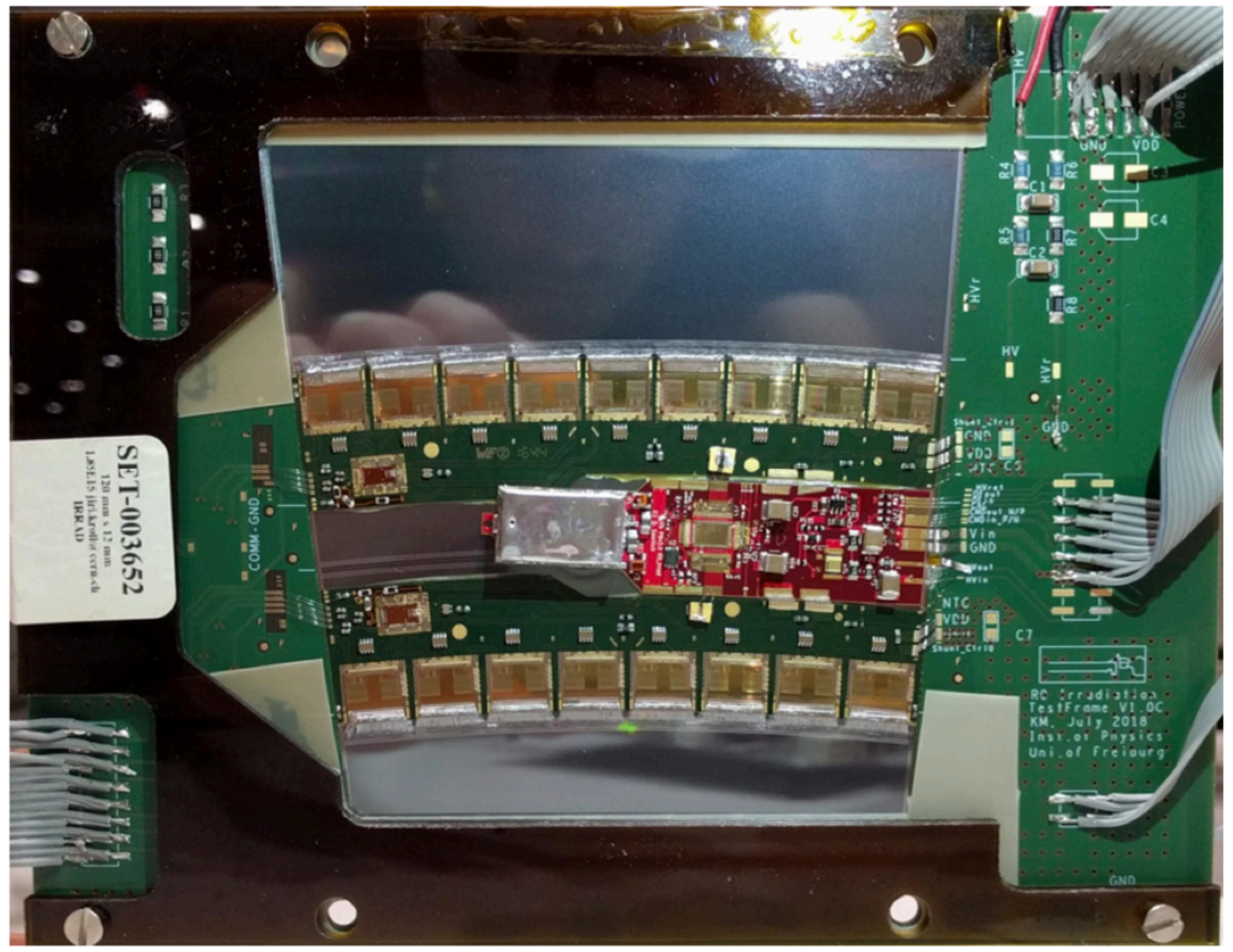
New Inner Tracker (ITk)

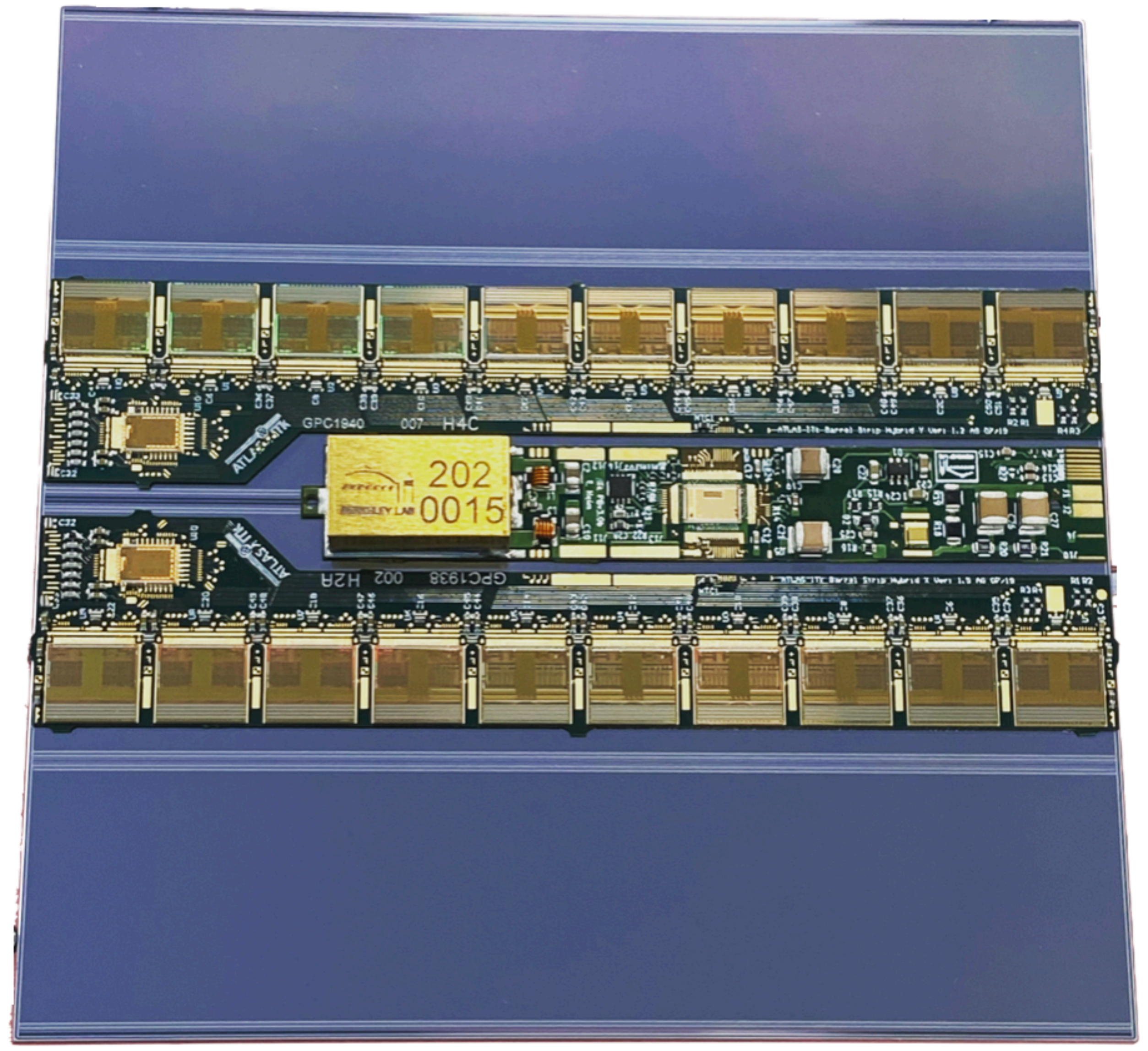


- Currently the Inner Detector uses both silicon layers and a Transition Radiation Tracker
- The new Inner Tracker will be an all-silicon tracker
  - Pixels nearest the interaction region and strips in the outer regions

ATLAS ITK Strip Detector



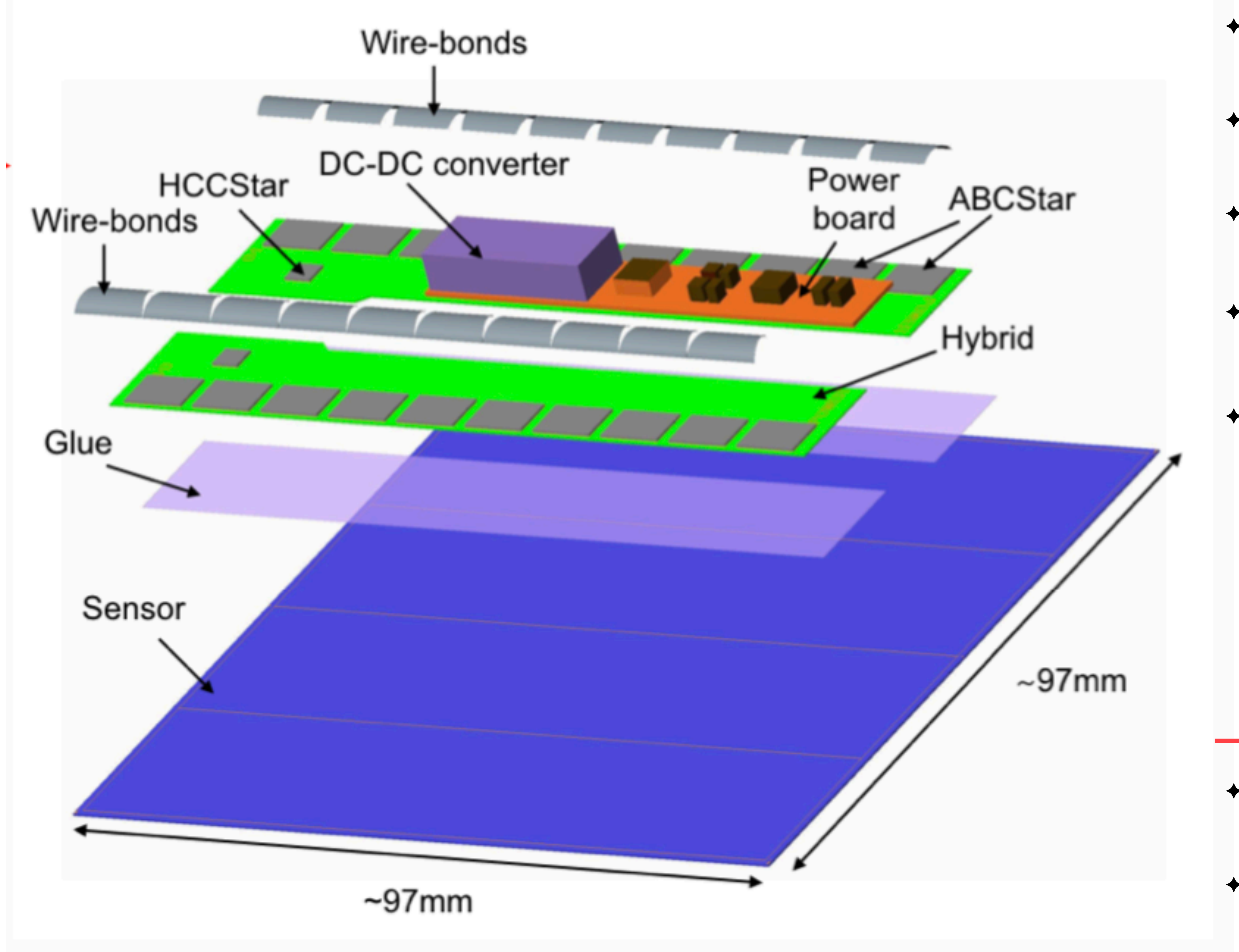




- The strip detector has both barrel and endcap modules
- 2 different designs for the barrel and 6 different designs for the endcap

Module Design

Short Strip (SS) Module



Sensor

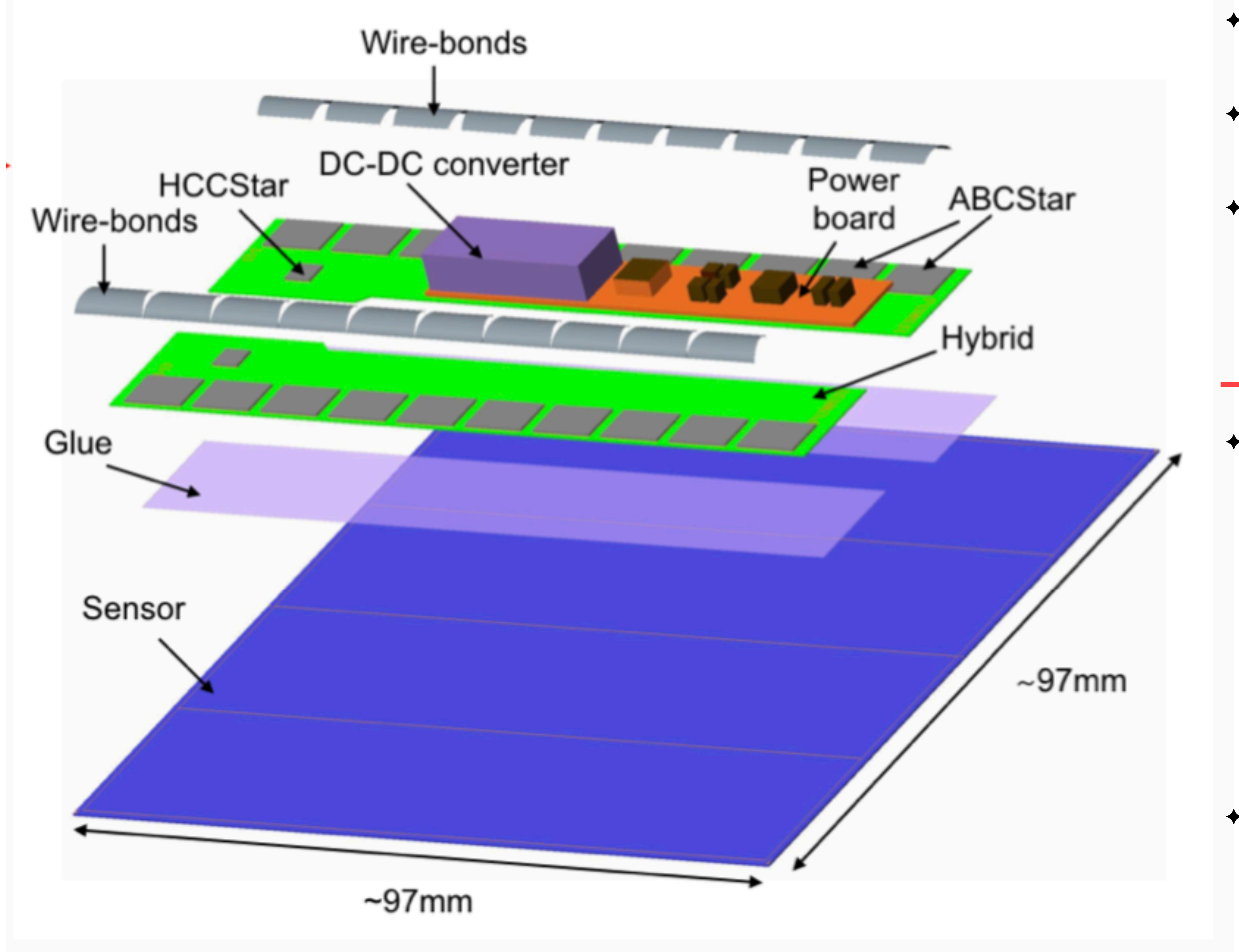
- n$^+$-on-p strip sensor
- 320 µm thick
- Strip pitch 75.5 µm
- 9.7 x 9.7 cm^2
- Short Strip (**SS**) and Long Strip (**LS**) layouts
  - **SS** - 24.1 mm long strips in four segments
  - **LS** - 48.2 mm long strips in two segments

Hybrid

- **One** hybrid for a **LS** module and **two** for a **SS** module
- 10 ABCStars (ATLAS Binary Chips) per hybrid
  - Converts incoming charge signal into hit information
  - Final chipset design - ready for production
- 1 HCCStar (Hybrid Controller Chip) per hybrid
  - Interface between ABCStar and End-of-Substructure card

Module Design

Short Strip (SS) Module

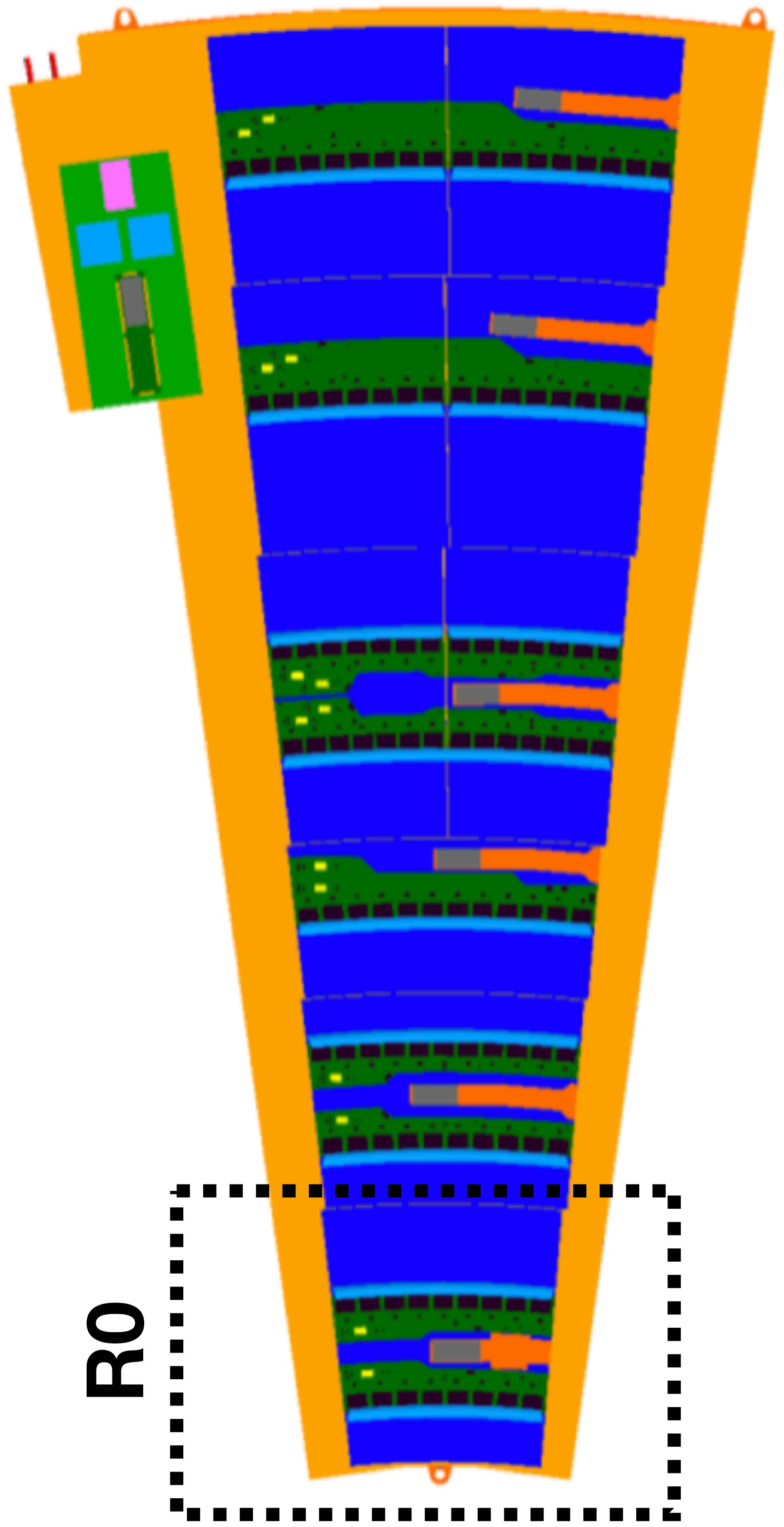


Powerboard

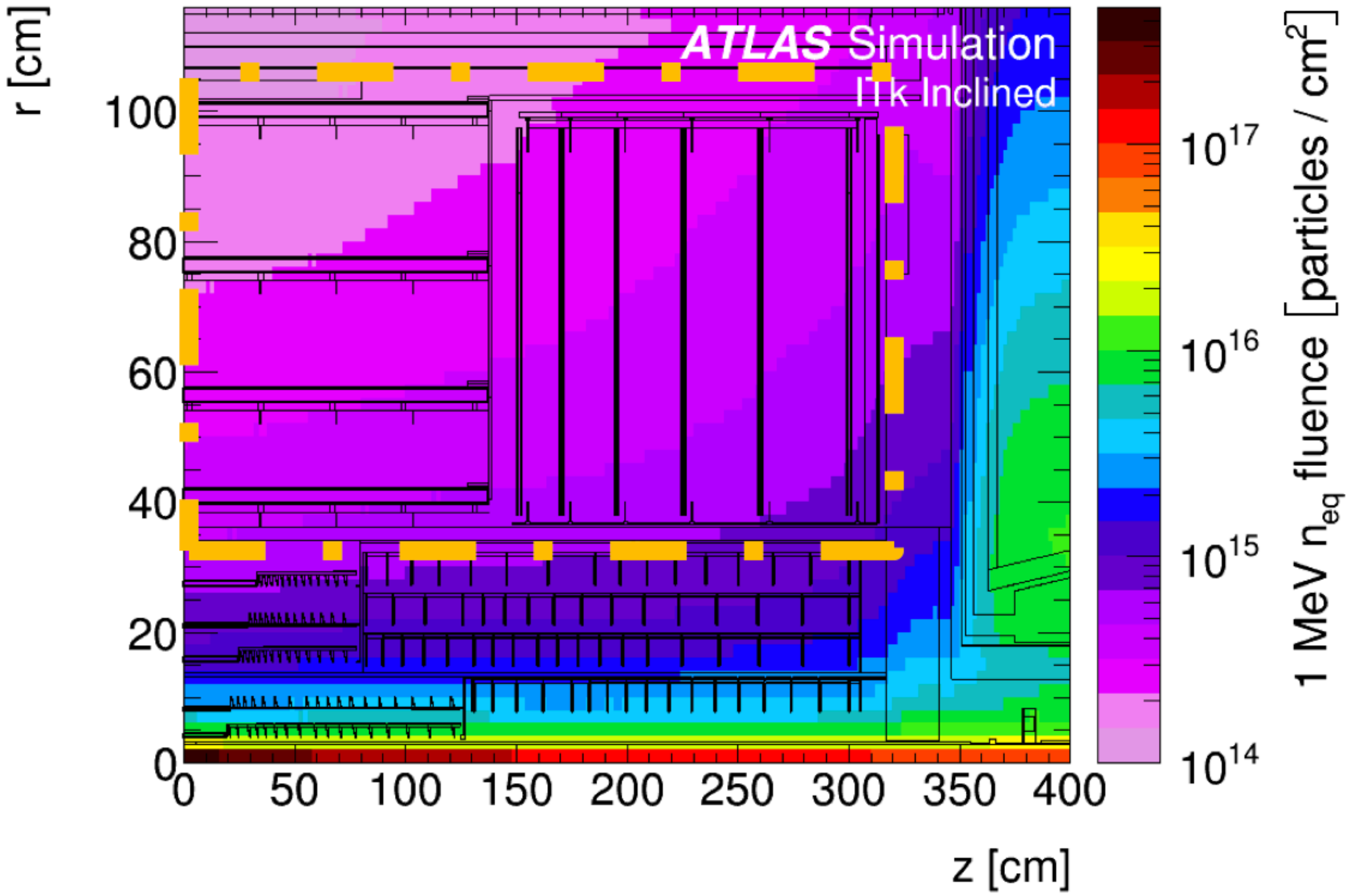
- One per module
- Provides low voltage for the ASICs
- Switchable sensor HV bias

Endcap Modules

- Key difference is the sensor design
  - Radial Strips
  - Strip Pitch: 69 µm to 85 µm
  - Small stereo angle rotation of 20 mrad
- Hybrids with various number of ASICs and 1 or 2 HCCs

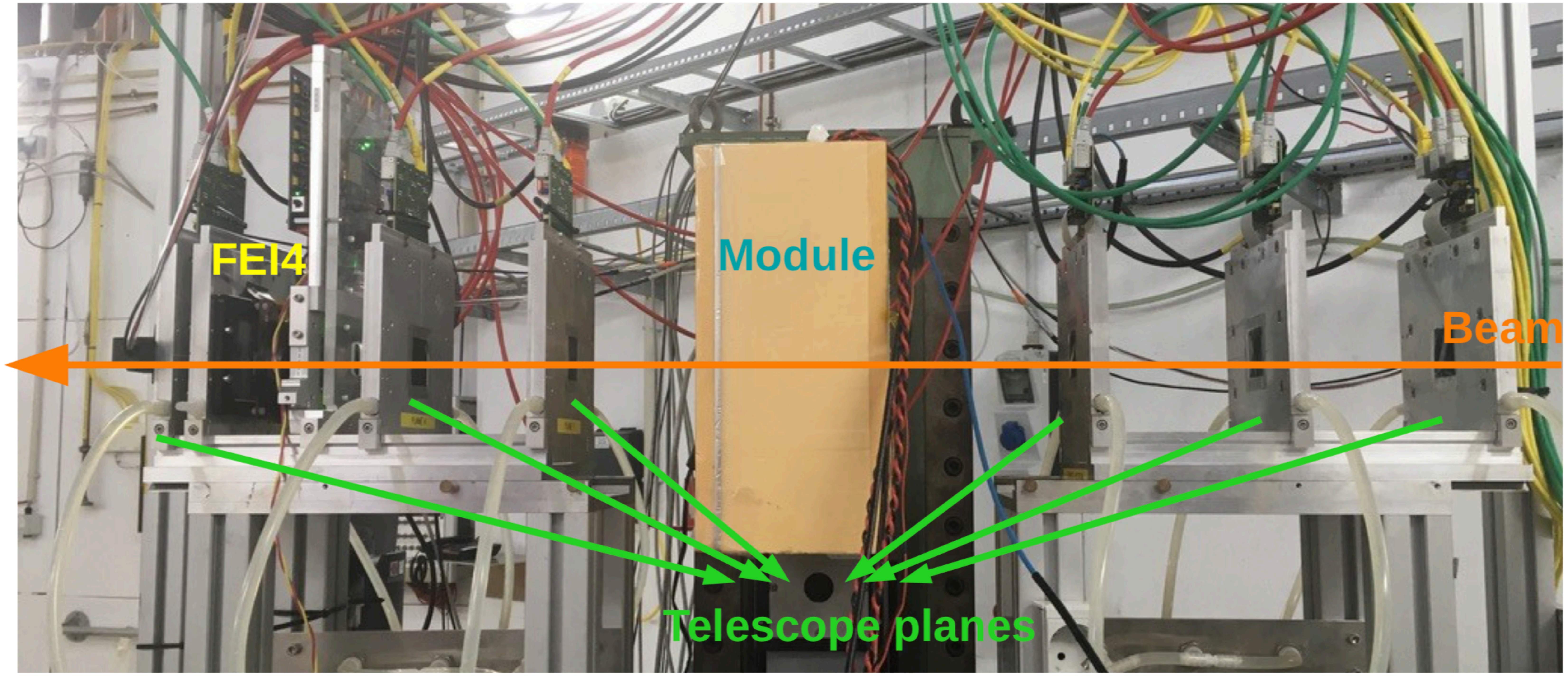


Upgrade Performance Requirements



- The maximum non-ionizing dose of about 1.1 x 10^{15} n_{eq}/cm^2 is expected in the forward innermost region of the strip detector
- This expected dose includes a safety factor of 1.5
- Performance requirements at the end-of-lifetime:
  - **Efficiency > 99%**
  - **Noise-occupancy < 10^{-3}**
  - **Signal-to-noise ratio >10**
- To test that the modules fulfil the requirements we test them at DESY testbeams both before and after irradiation

DESY Testbeam and the EUTDET Telescope




LS Module installed as DUT

- DESY provides an electron beam with energy up to 6 GeV
- Telescope has **six mimosa planes** and **one FEI4 timing plane** which is needed for time tagging the telescope tracks
- The DUTs are installed in the centre
- Telescope has a pointing resolution ~5-10 µm
- Track reconstruction is done using the EUTelescope framework (transition to Corryvreckan will be discussed later)

2019 & 2020 Testbeams

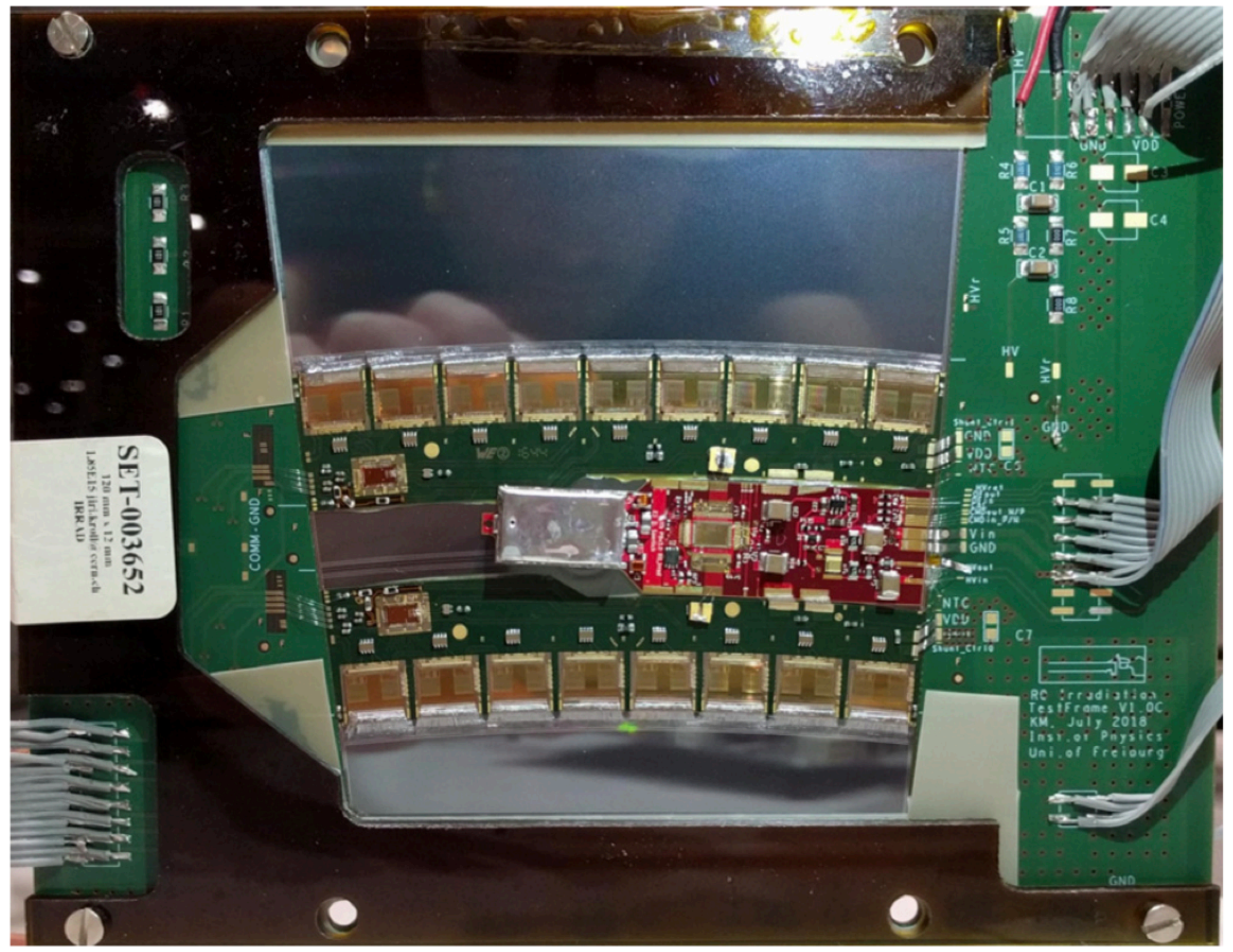
Testing ABCStar Modules for the first time at testbeams

- April 2019
  - **Non-irradiated LS** and **R0** modules mounted back to back
- June 2019
  - **Irradiated R0** module
- September 2019
  - **Non-irradiated SS** module and an **irradiated LS** module installed separately
- November 2020
  - Investigation of a new timing plane made of ITk Strip Detector Module parts

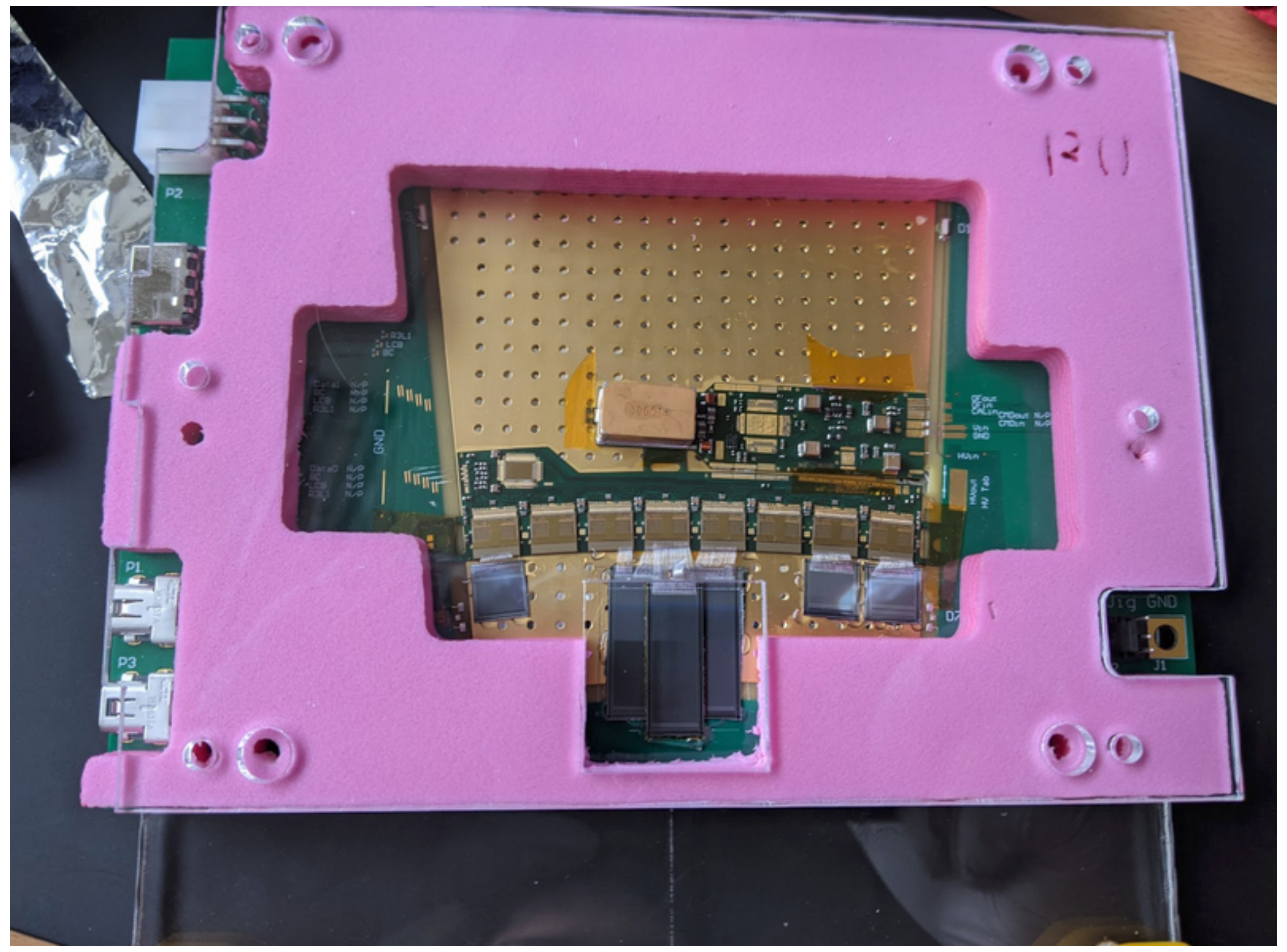
Sensor Irradiations

- **R0**: protons at CERN SPS to a NIEL fluence of $1.5\times10^{15}\ n_{eq}/cm^2$
- **LS**: neutrons at Ljubljana to a NIEL fluence of $5.1\times10^{14}\ n_{eq}/cm^2$

R0 Module

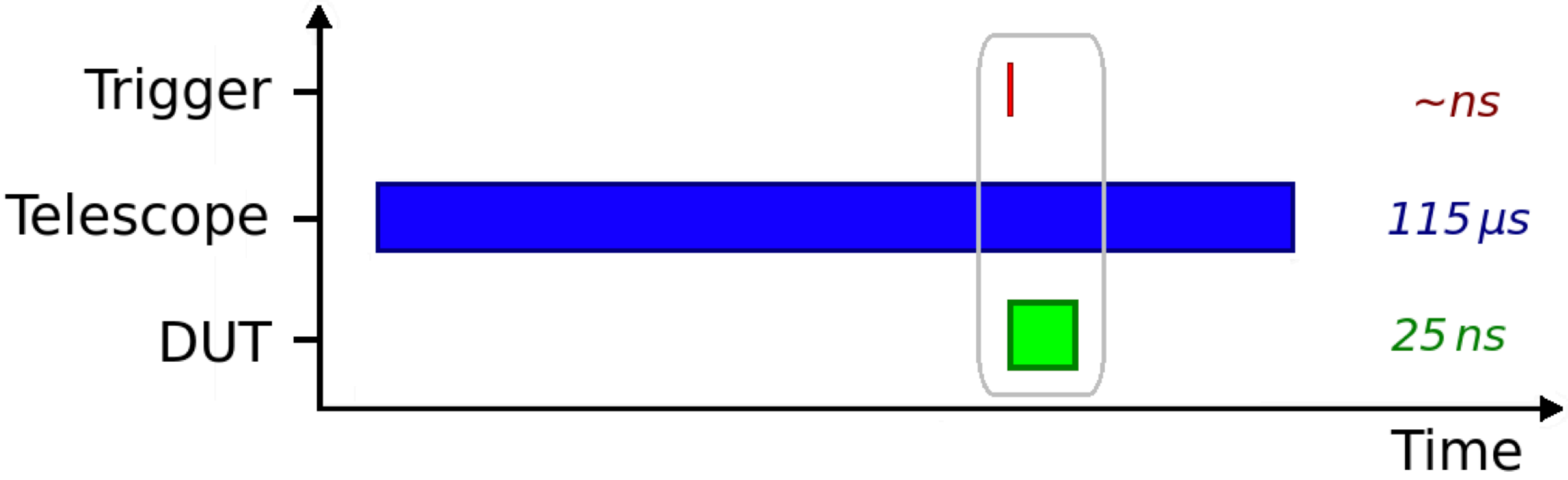


ITk Timing Plane



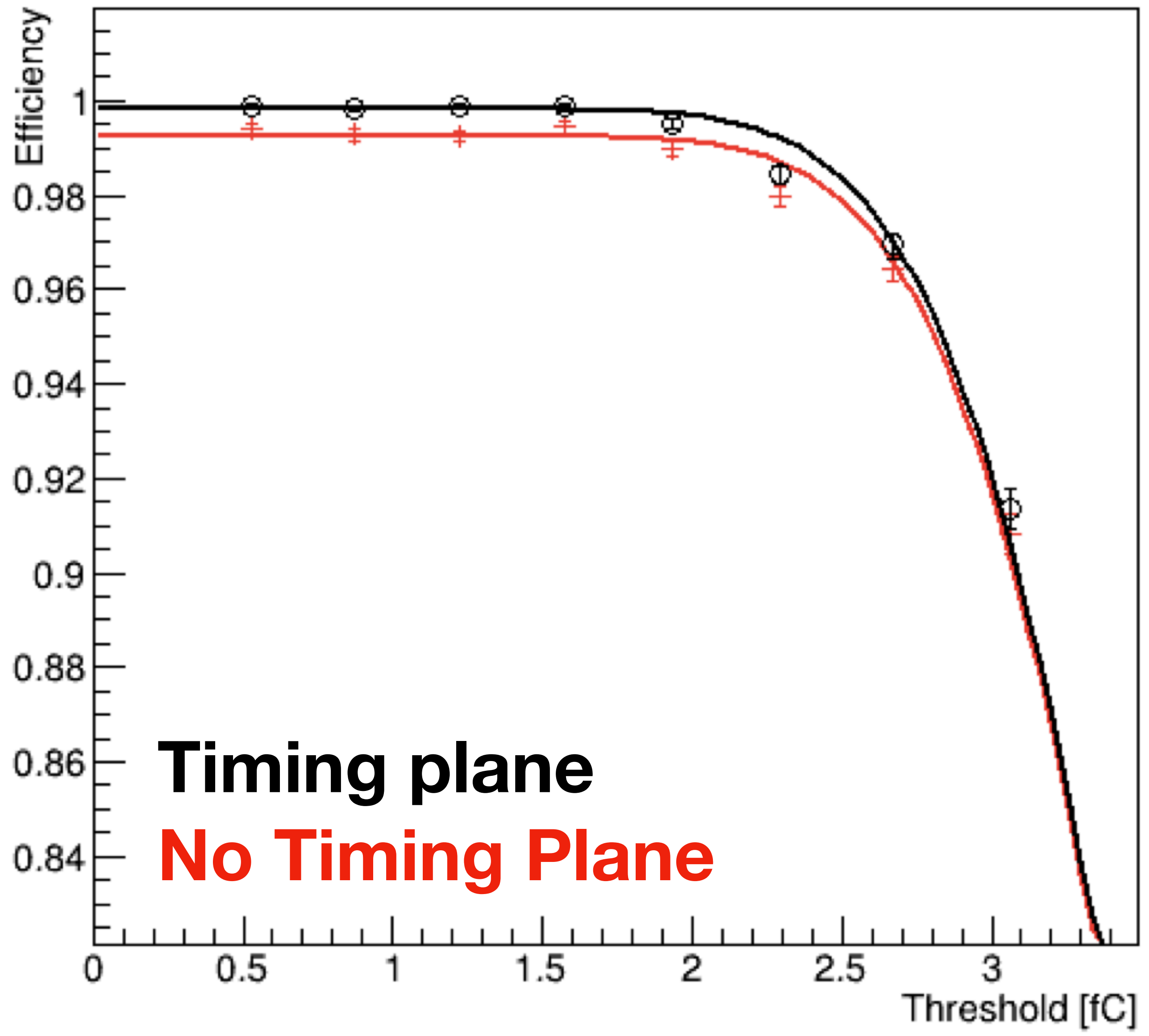
*The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)

Timing Plane - Why do we need one?



$$\epsilon = \frac{N_{tracks}^{DUT+FEI4}}{N_{tracks}^{FEI4}}$$

- Integration time of the Mimosa planes is ~115 µs
- Multiple triggers could arrive within this integration time, but only 1 hit is registered in the DUT
- Timing plane verifies that reconstructed track is relevant for an event that was read out by DUT
- Timing plane is crucial for efficiency measurements (due to >99% requirement!)



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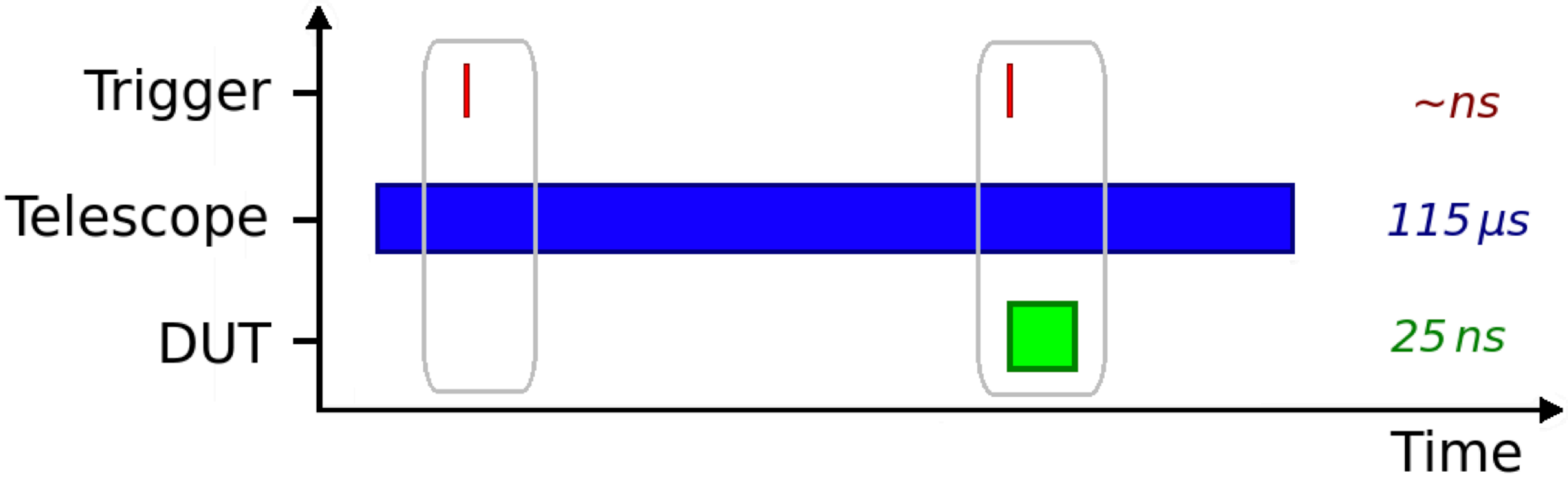

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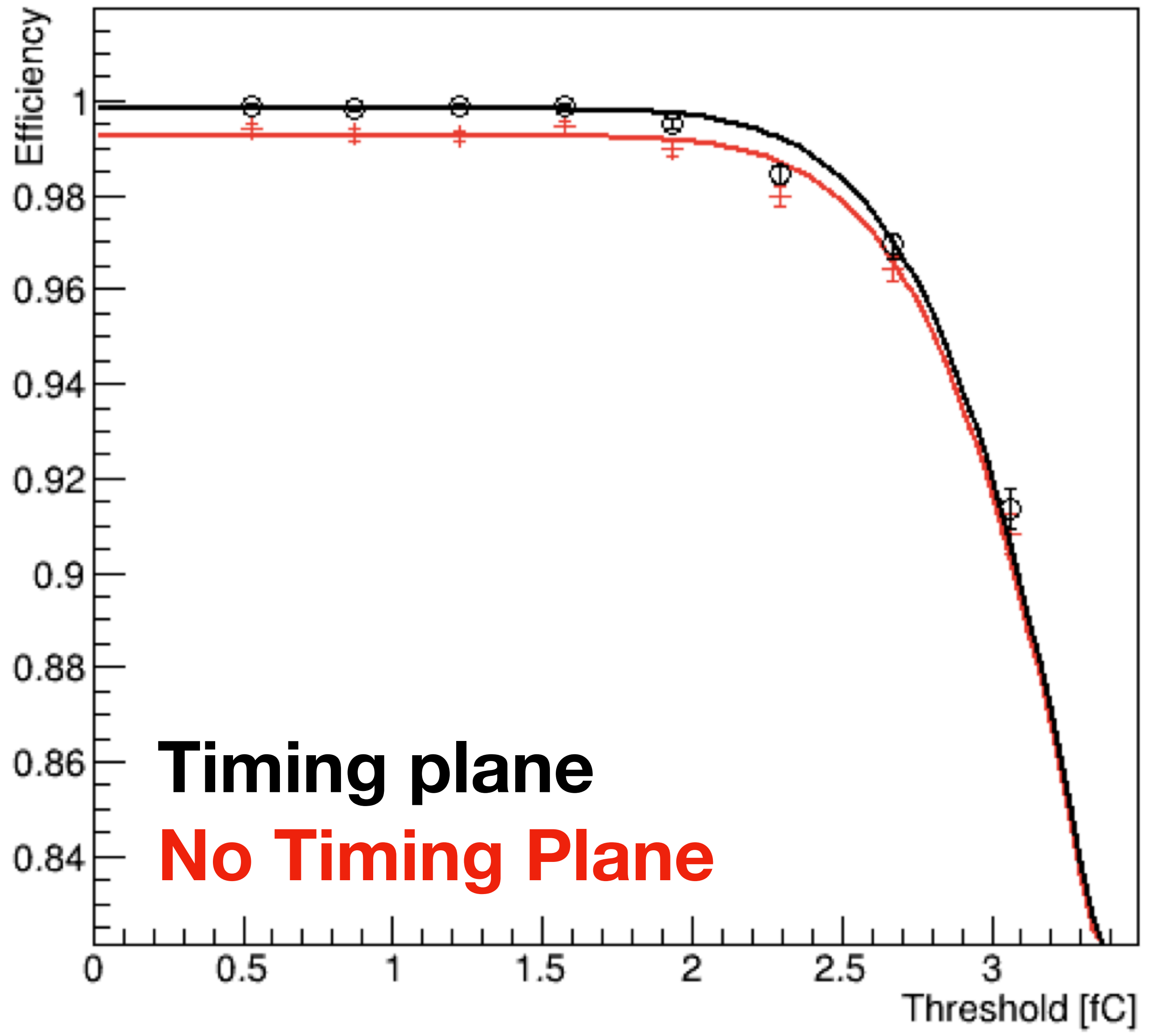

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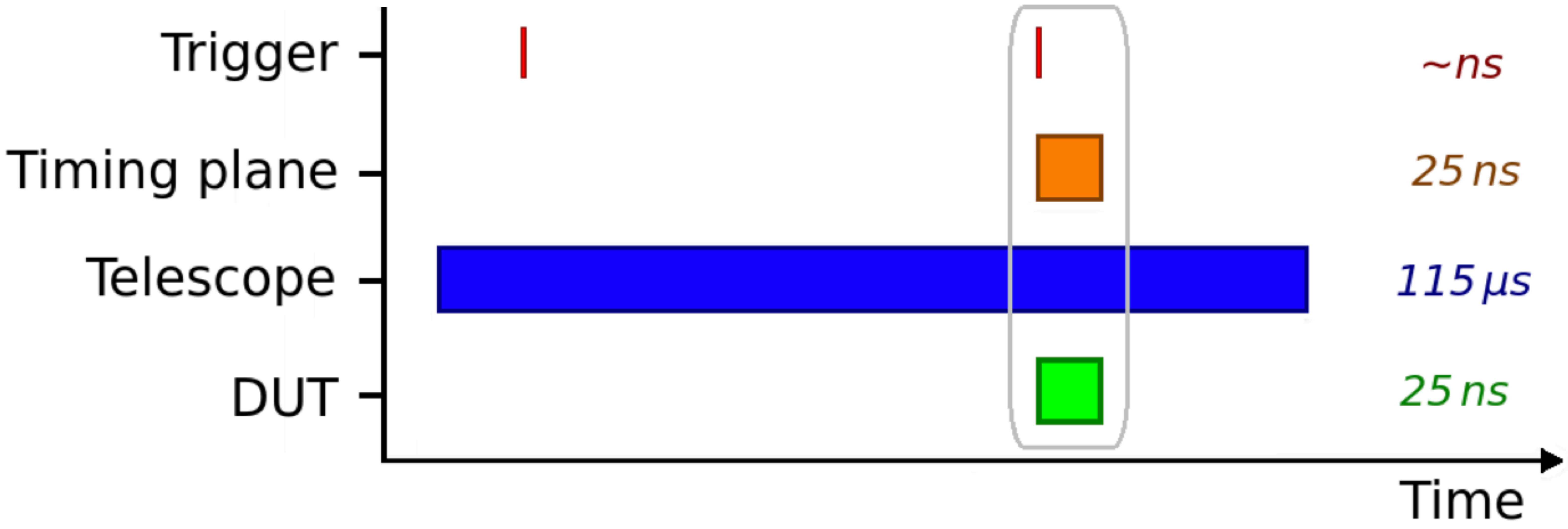

$$\epsilon = \frac{N_{tracks}^{DUT+FEI4}}{N_{tracks}^{FEI4}}$$

- Integration time of the Mimosa planes is ~115 µs
- Multiple triggers could arrive within this integration time, but only 1 hit is registered in the DUT
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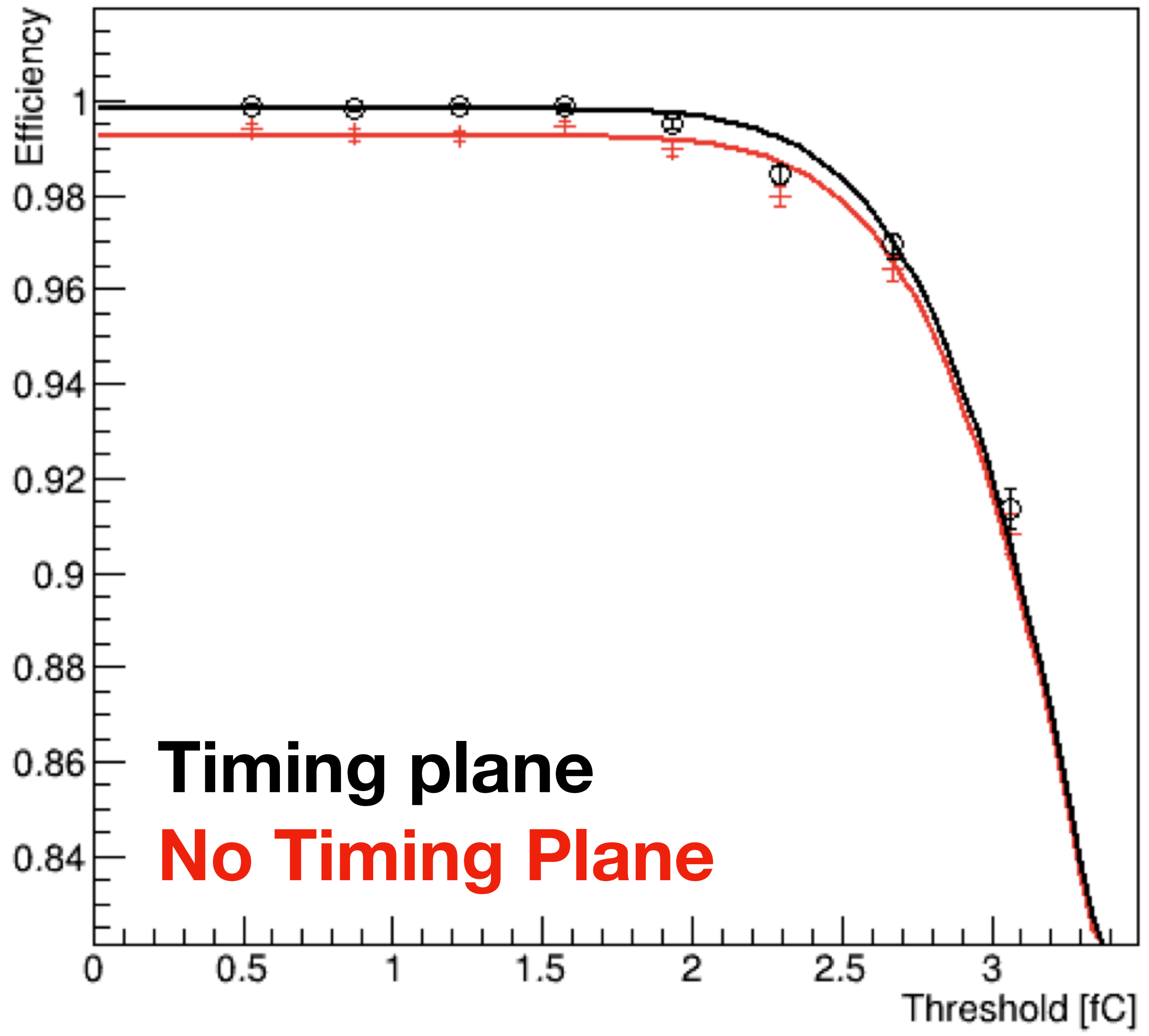
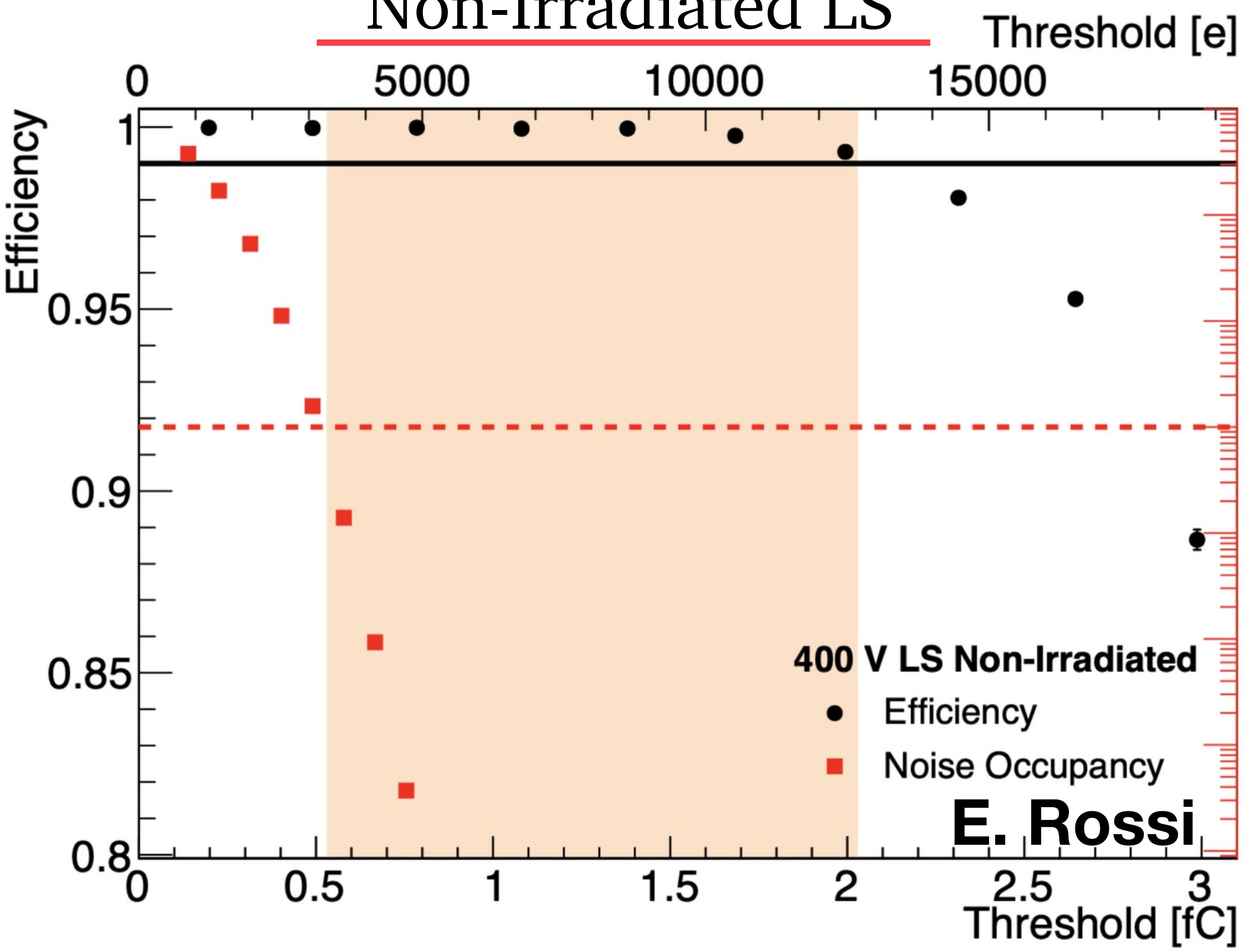
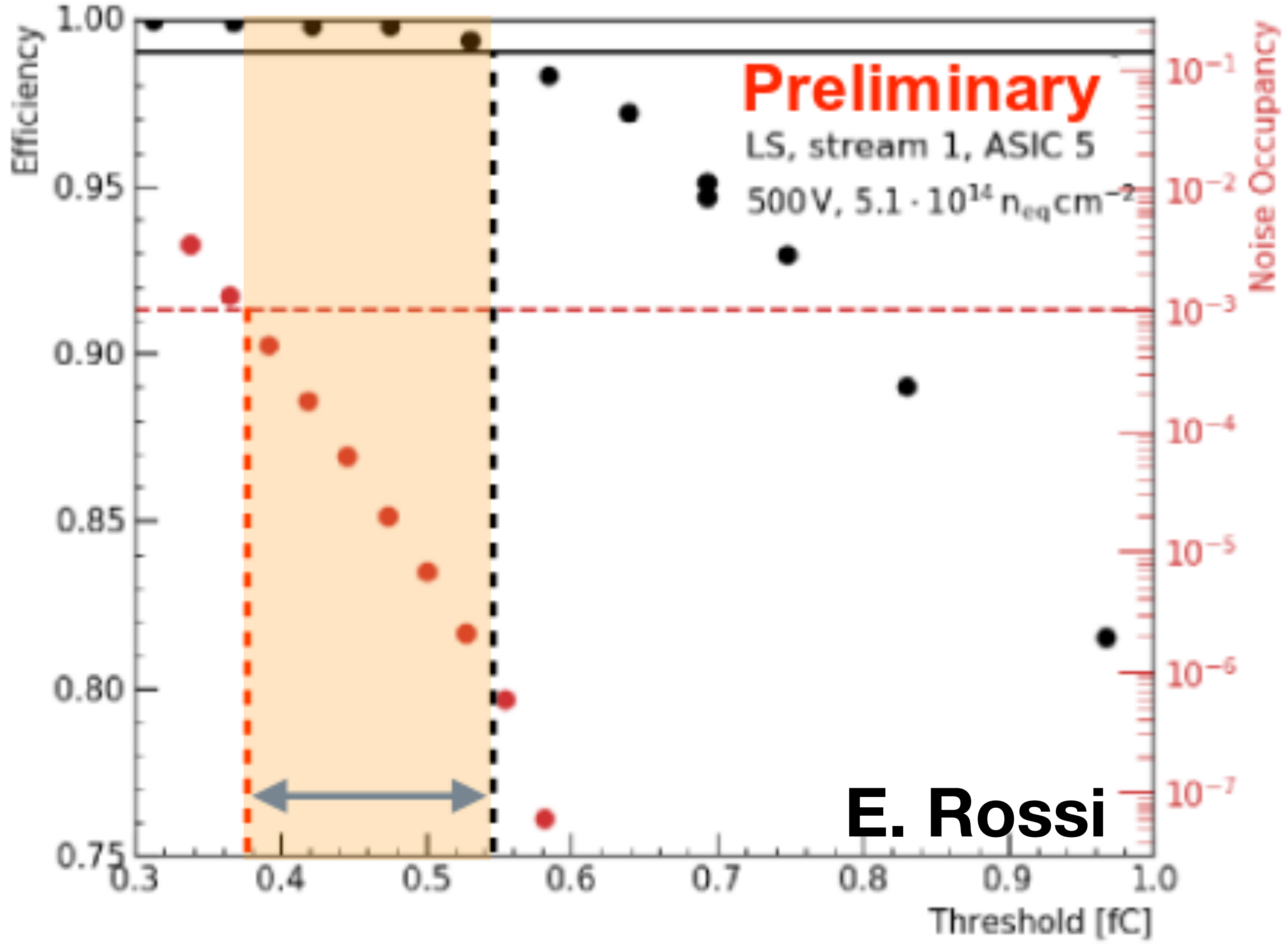


Noise Occupancy and Efficiency Comparisons

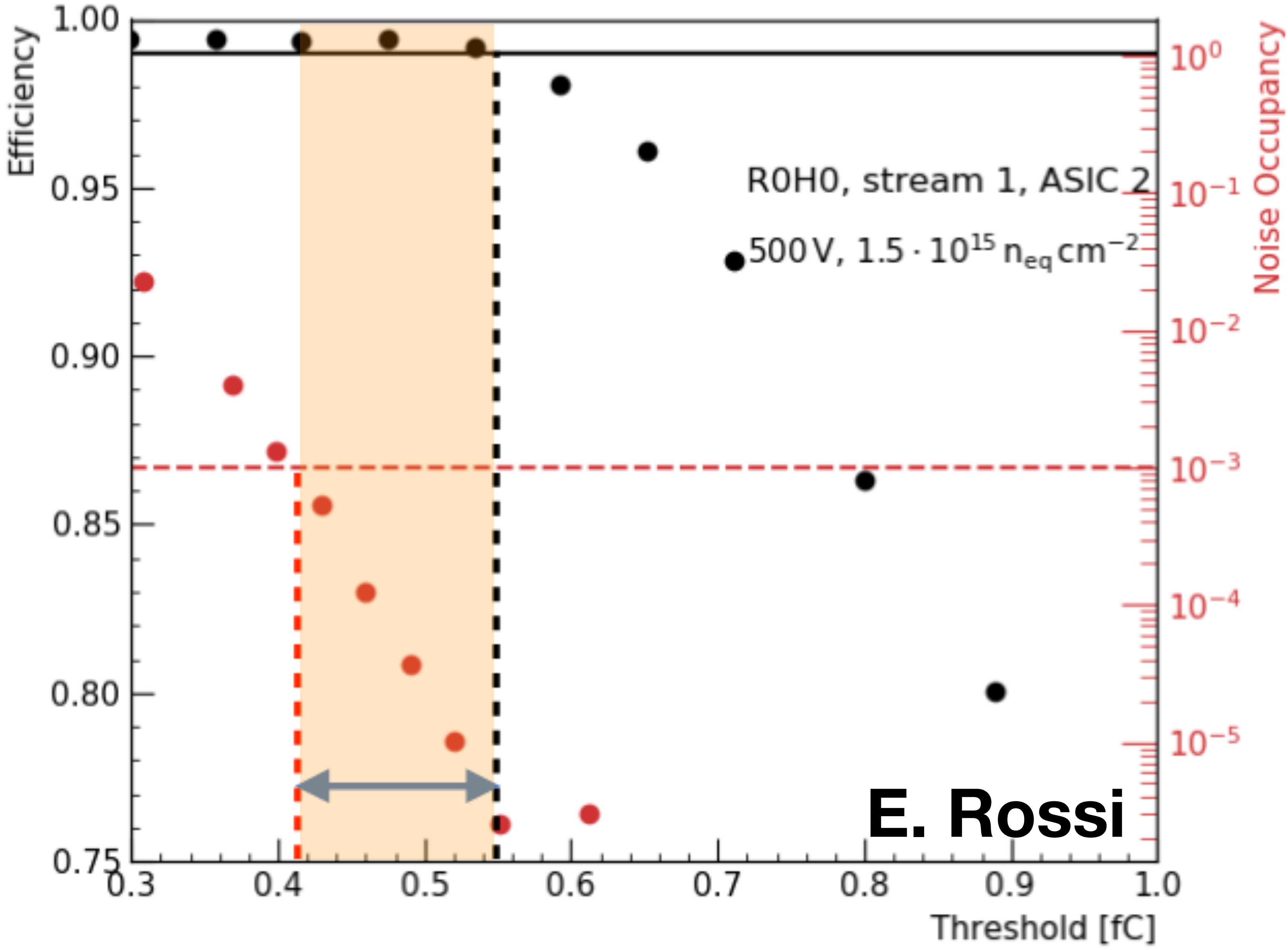
Non-Irradiated LS



Irradiated LS



Irradiated R0



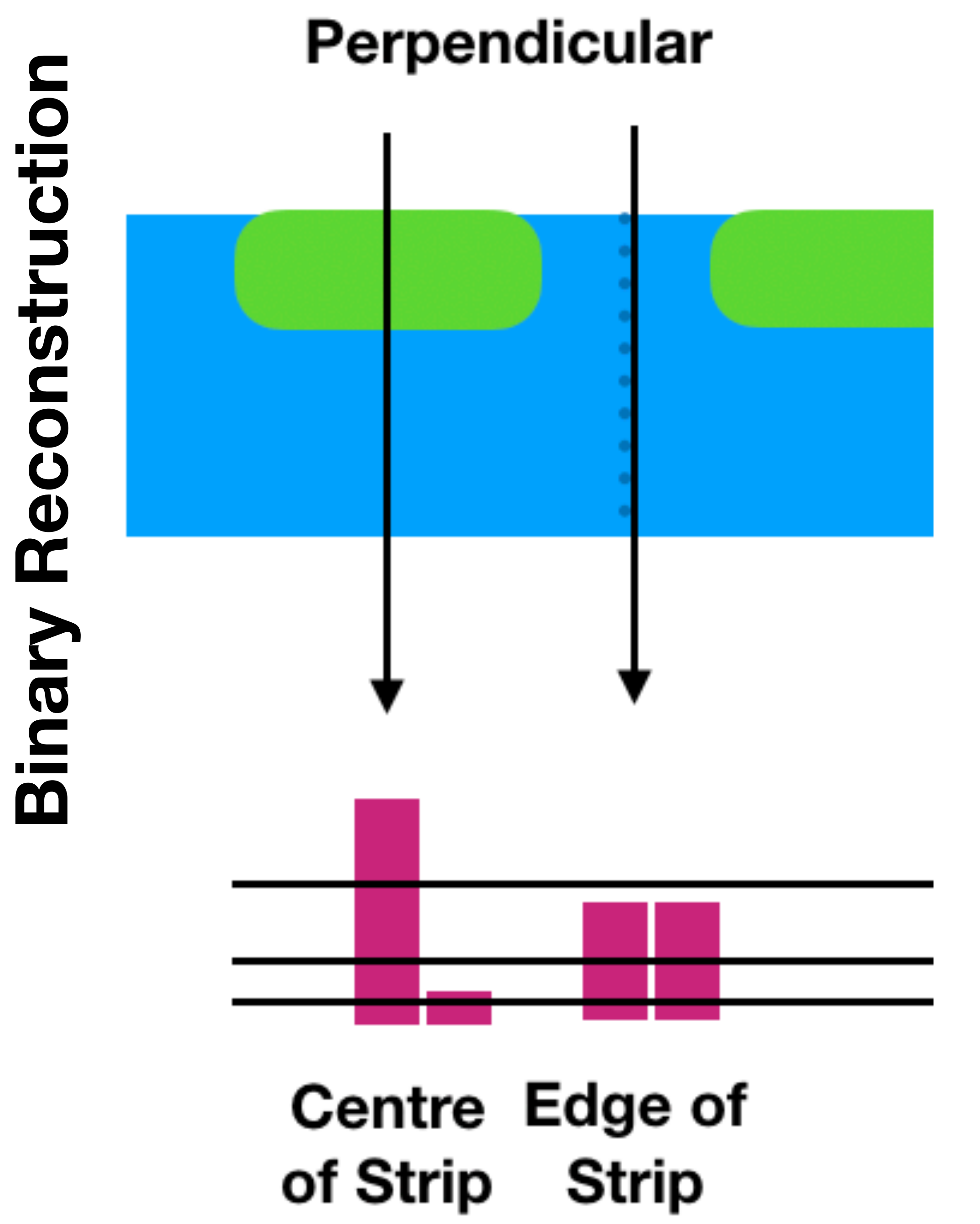
- ITk modules requirement: operating window where hit detection efficiency $> 99\%$ and Noise occupancy $< 0.1\%$
- These requirements are met, though operational window is smaller for irradiated modules
- All ABCStar modules have also satisfied the S/N requirement of > 10

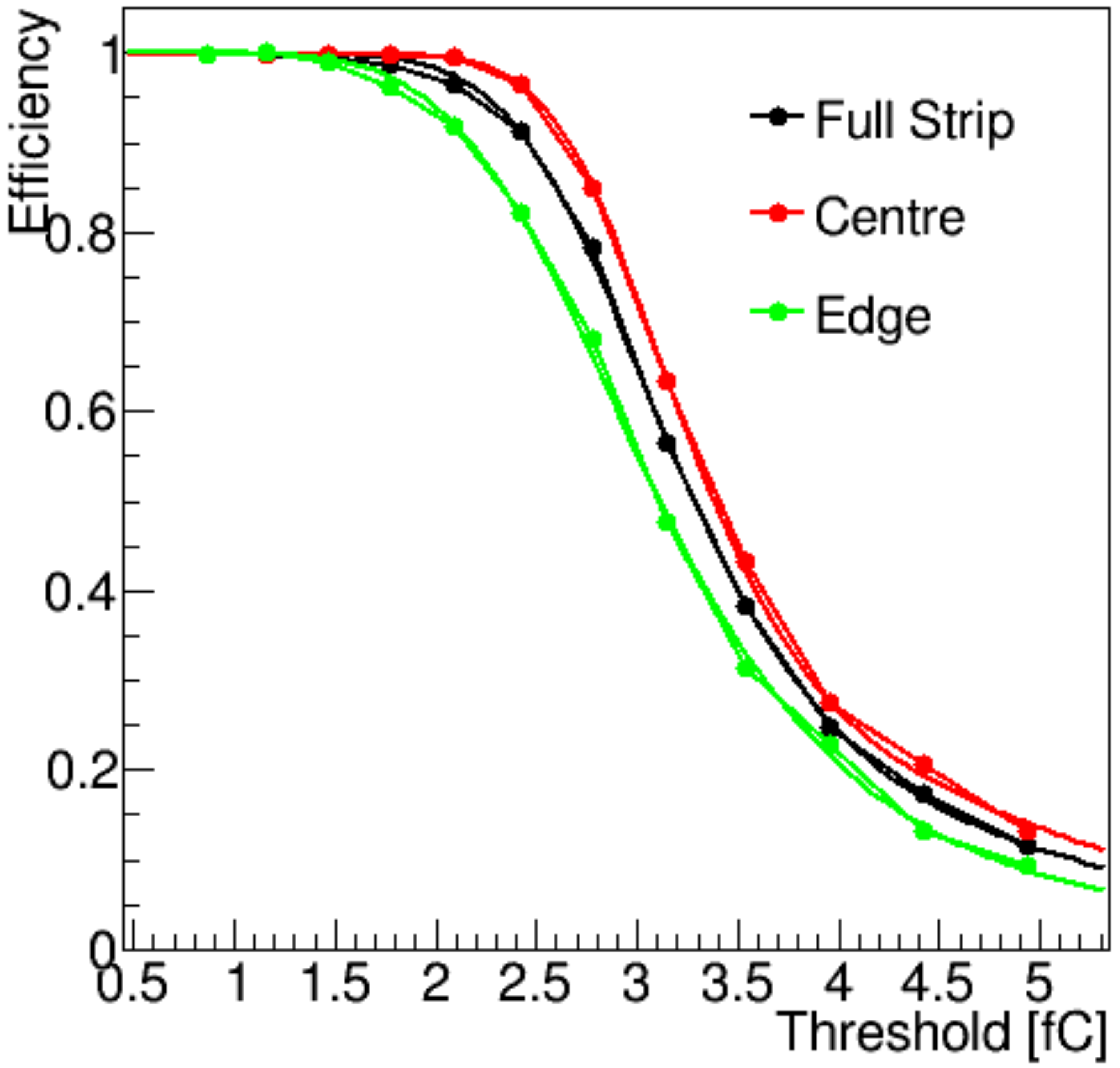
(E. Rossi) Module (ABCStar)	Signal [fC] (e.)	S/N
Unirrad. LS (400 V)	3.28 (20500)	23.8
Unirrad. R0S (400 V)	3.28 (20475)	29.3
Irrad. R0 innermost ring (500 V)	1.65 (9281)	14.8
Irrad. R0 second ring (500 V)	1.71 (9619)	13.2
Irrad. R0 third ring (500 V)	1.80 (10125)	11.9
Irrad. R0 outermost ring (500 V)	1.84 (10350)	11.6
Irrad. LS (500 V)	1.59 (9956)	15.9

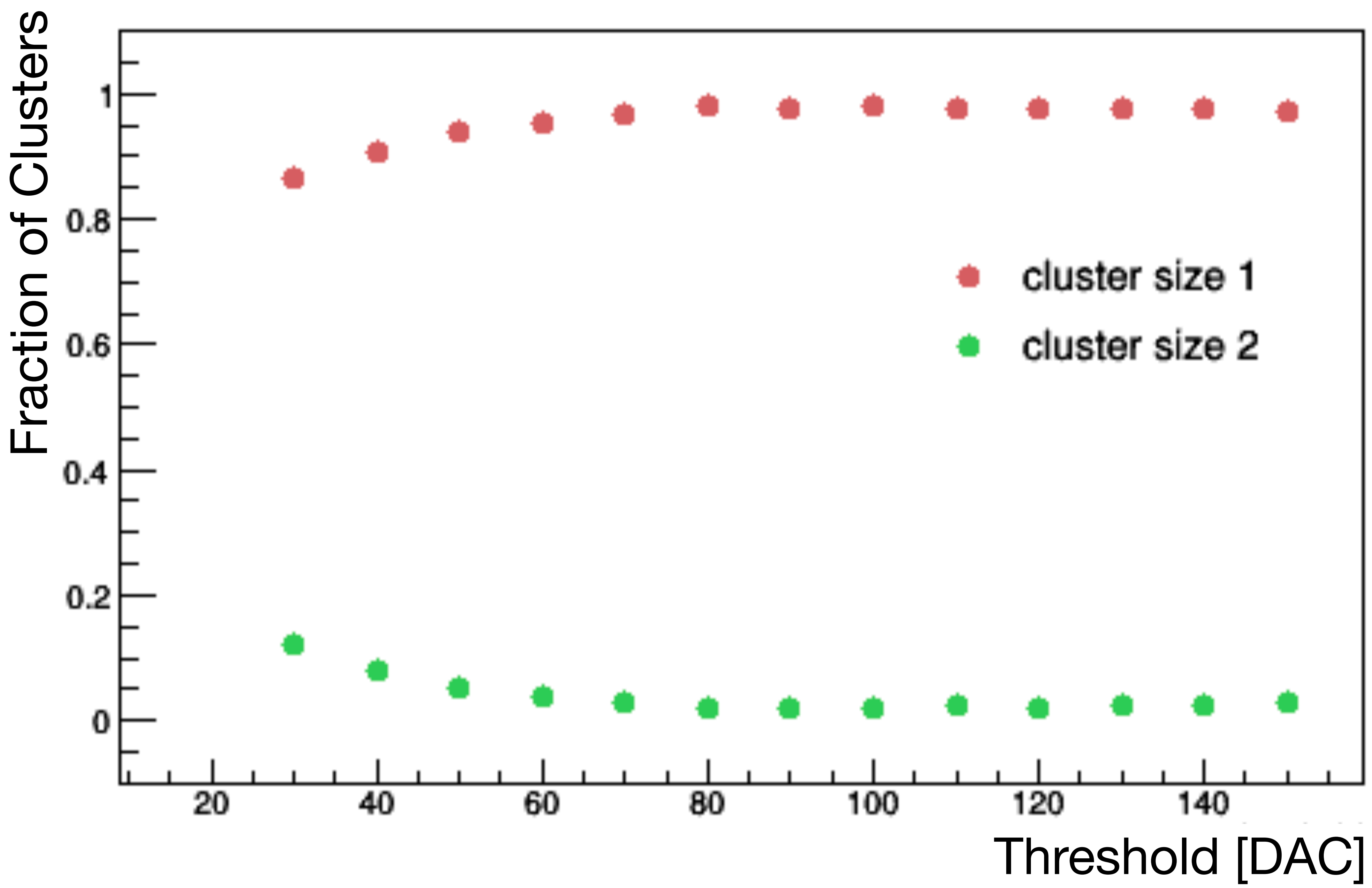
E. Rossi Thesis: http://cds.cern.ch/record/2743994/files/CERN-THESIS-2020-177.pdf

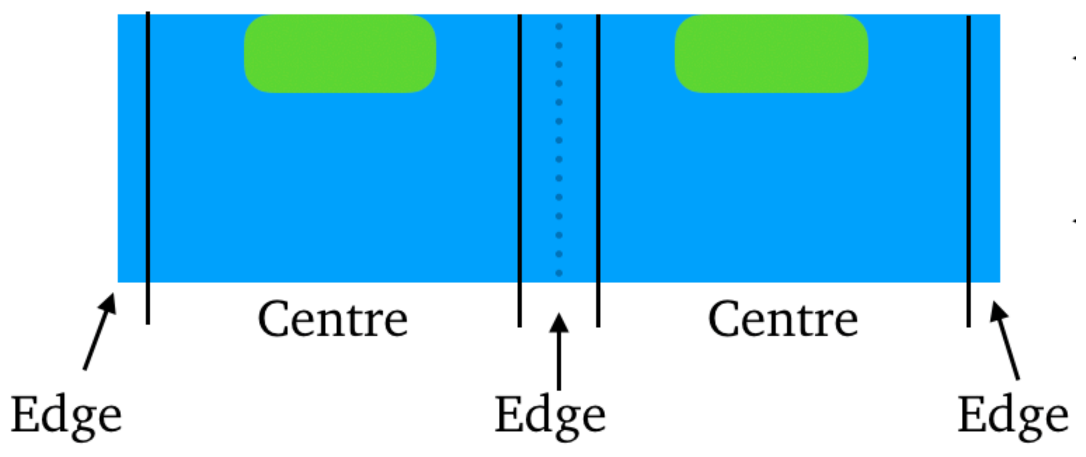
BTTB 2020 Talk: https://indico.cern.ch/event/813822/contributions/3648316/attachments/1979107/3295063/ATLAS_StripTB_ArturoRodriguez.pdf

Preliminary Non-irradiated LS Module Results





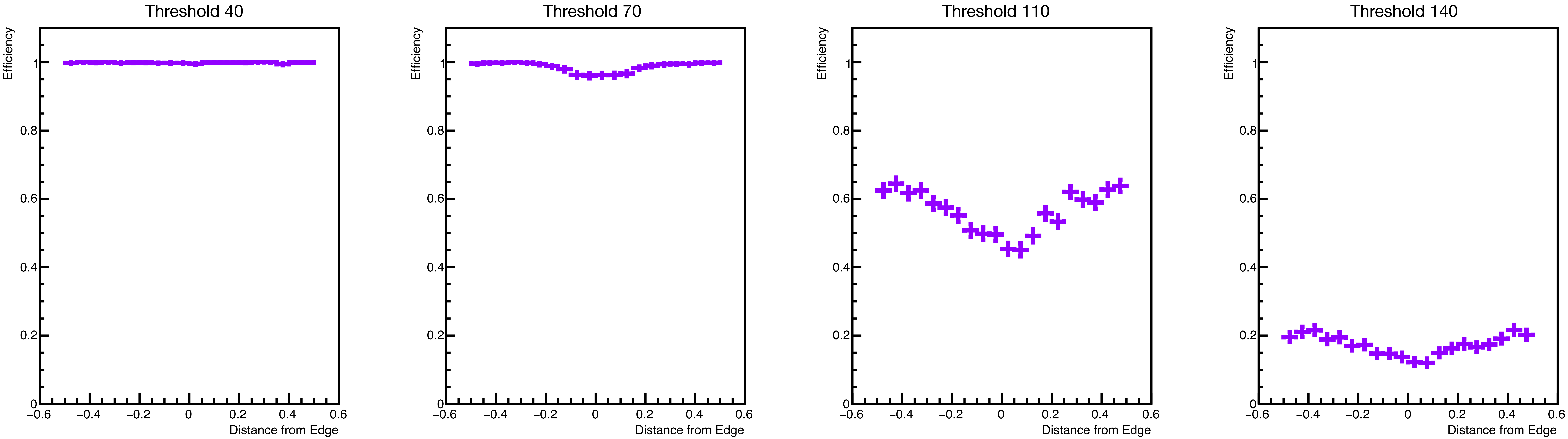




$$\epsilon = \frac{N^{DUT+FEI4}_{tracks}}{N^{FEI4}_{tracks}}$$

- Efficiency curves depending on incident track position for perpendicular tracks:
  - Highest efficiency is seen for tracks traversing centre of strip - charge collected by 1 strip
  - Lowest efficiency is seen for tracks traversing edge of the strip - charge is shared by 2 strips
- With increasing threshold, charge is “lost” and hence the fraction of size 1 clusters increases

Preliminary Non-irradiated LS Module Results

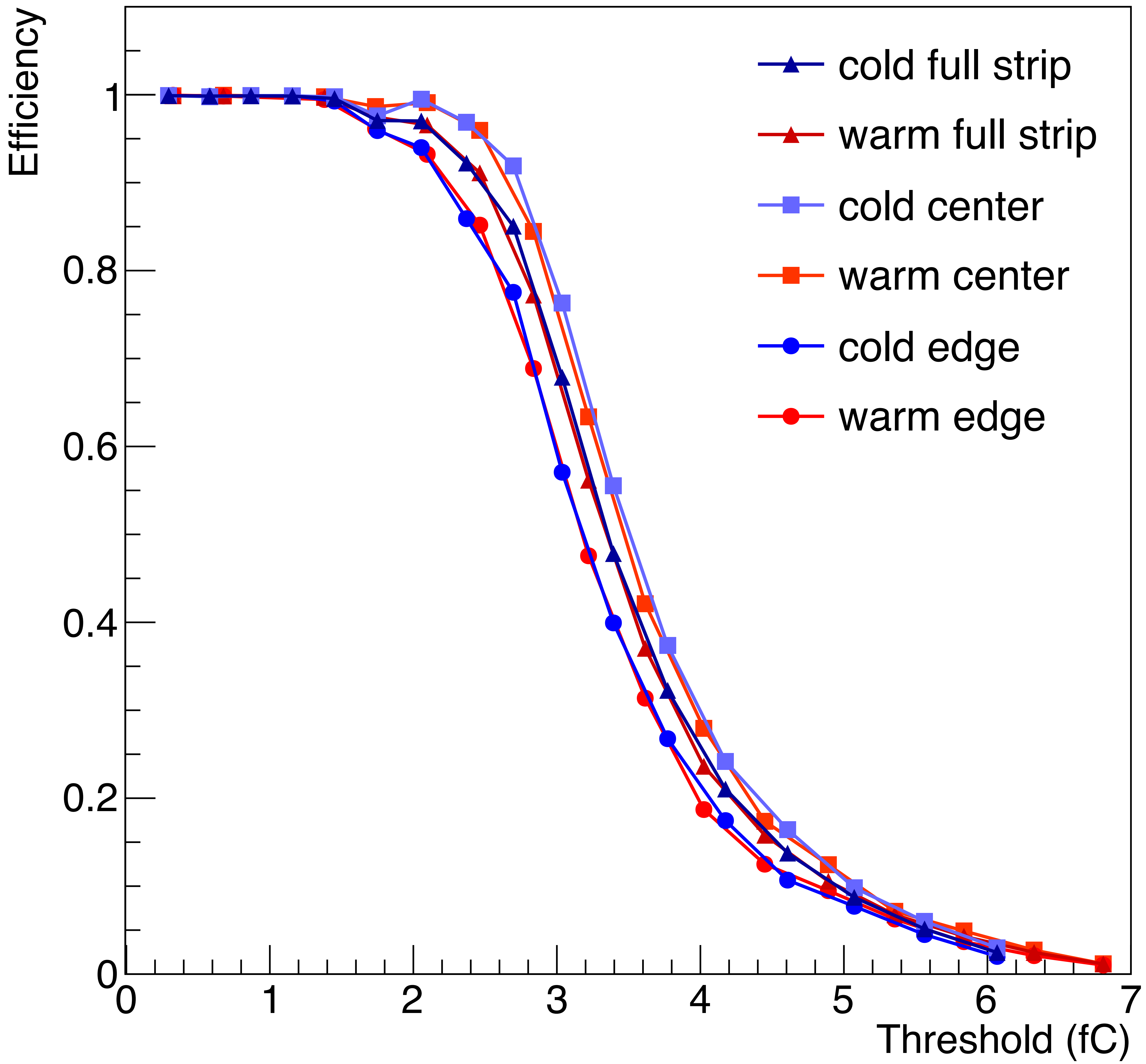


Intra-Strip Efficiency depending on the threshold

- At low threshold the full strip is >99% efficient
- As the thresholds start to increase, there is a clear dip in efficiency at the edge of the strip
- The overall efficiency over the strip decreases with increasing threshold as expected

Hot/Cold Comparisons of a non-irradiated SS Module

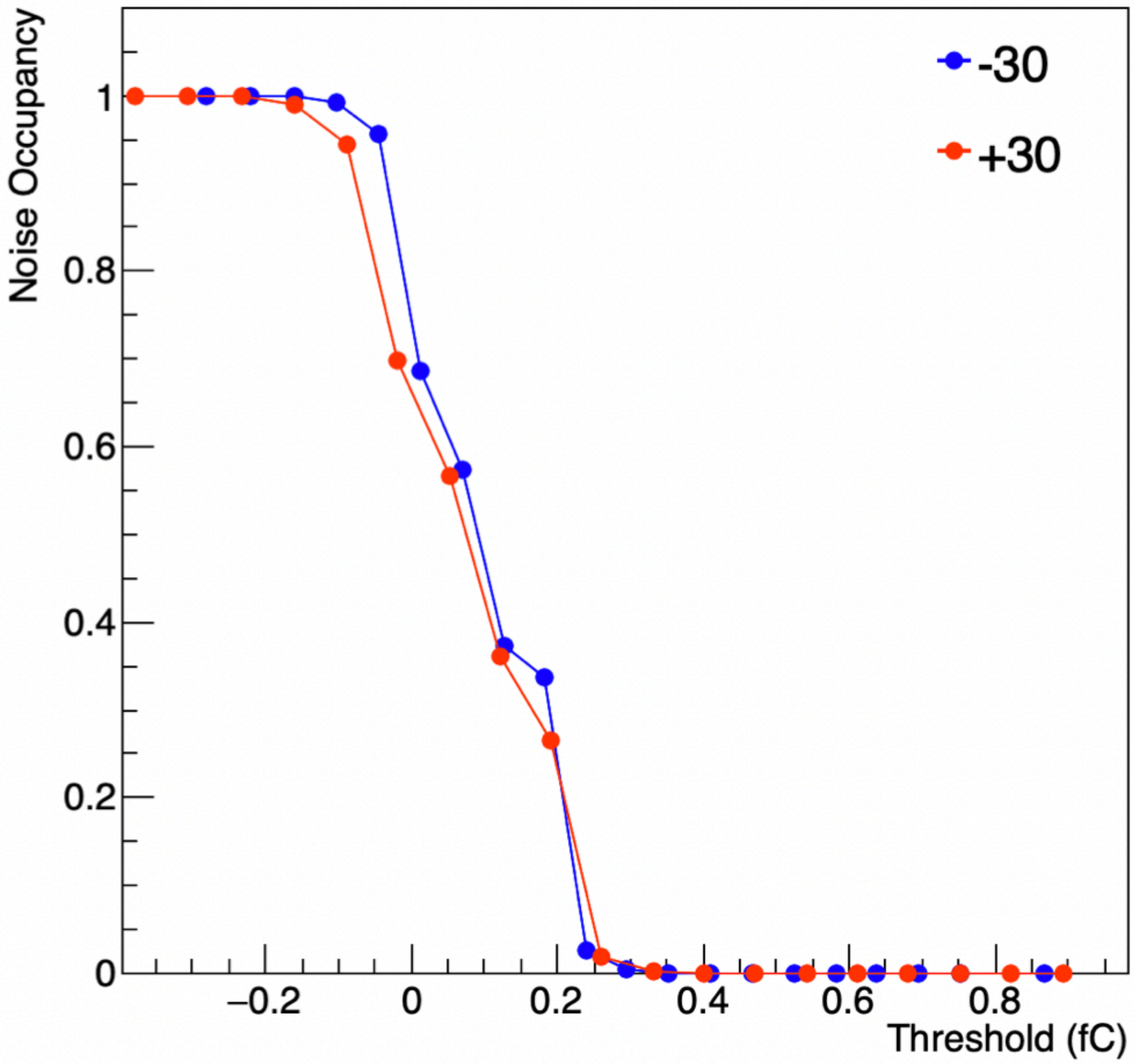
Comparison of Efficiency when the DUT is operated at different temperatures

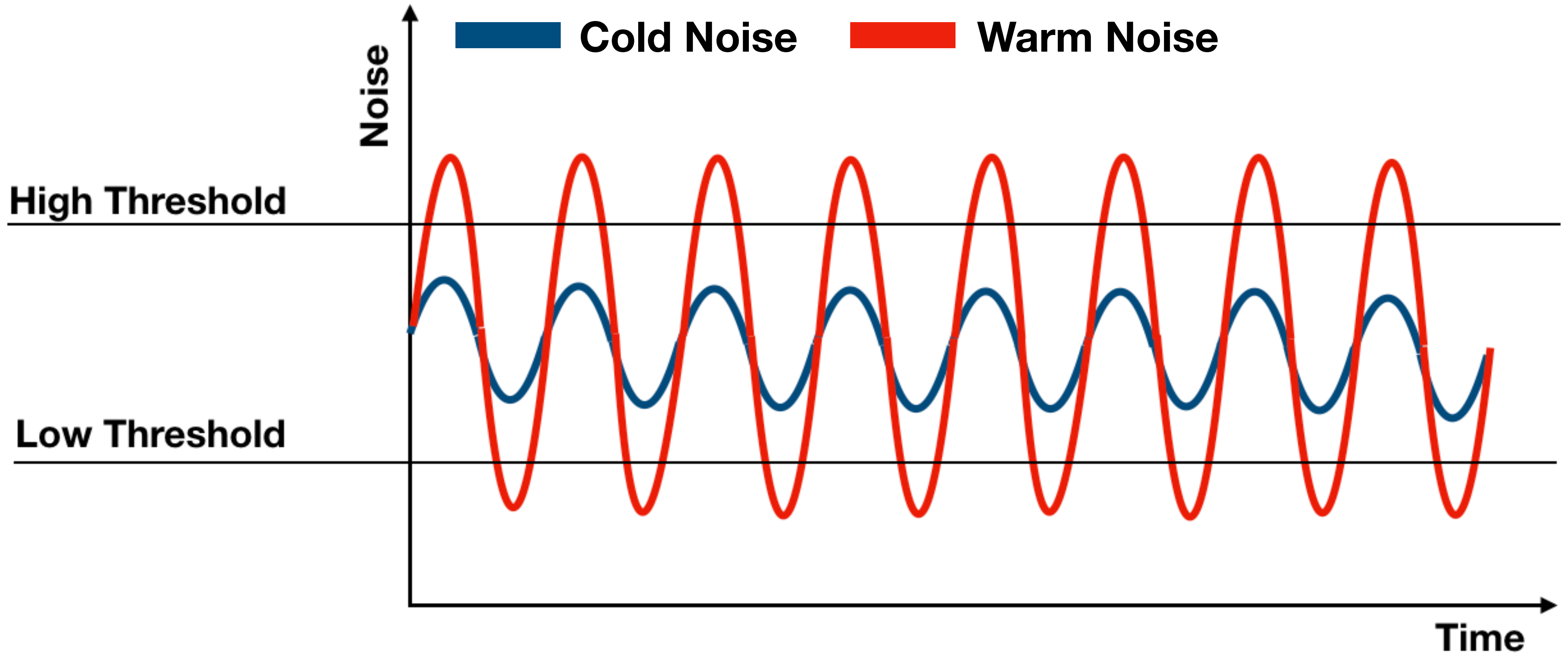


- Warm: 30 °C
- Cold: -30 °C
- There is no expected difference in efficiency when operating in warm and cold temperatures
- But there are expected differences in the noise

Hot/Cold Comparisons of a non-irradiated SS Module

Comparison of Noise Occupancy when the DUT is operated at different temperatures

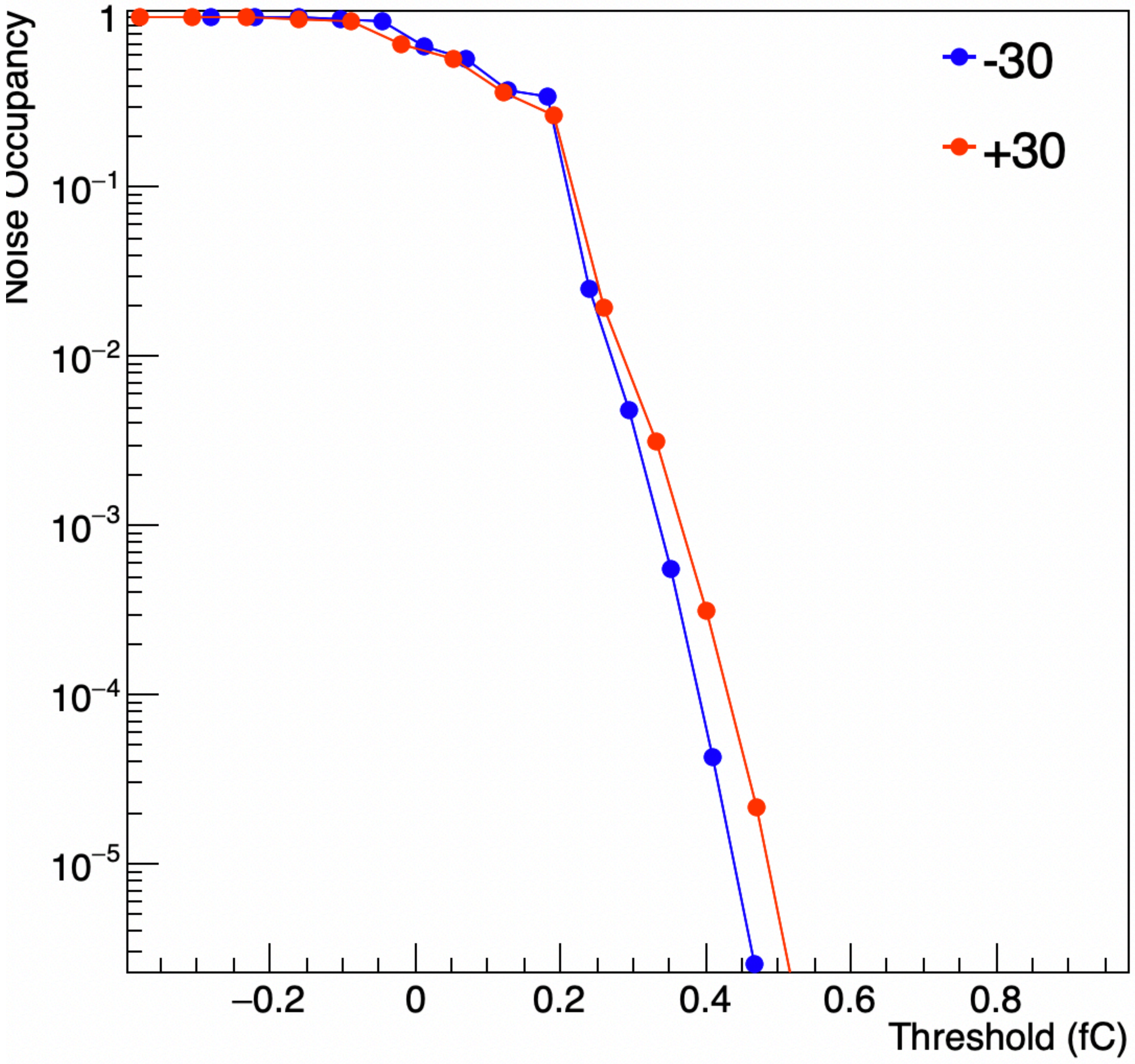


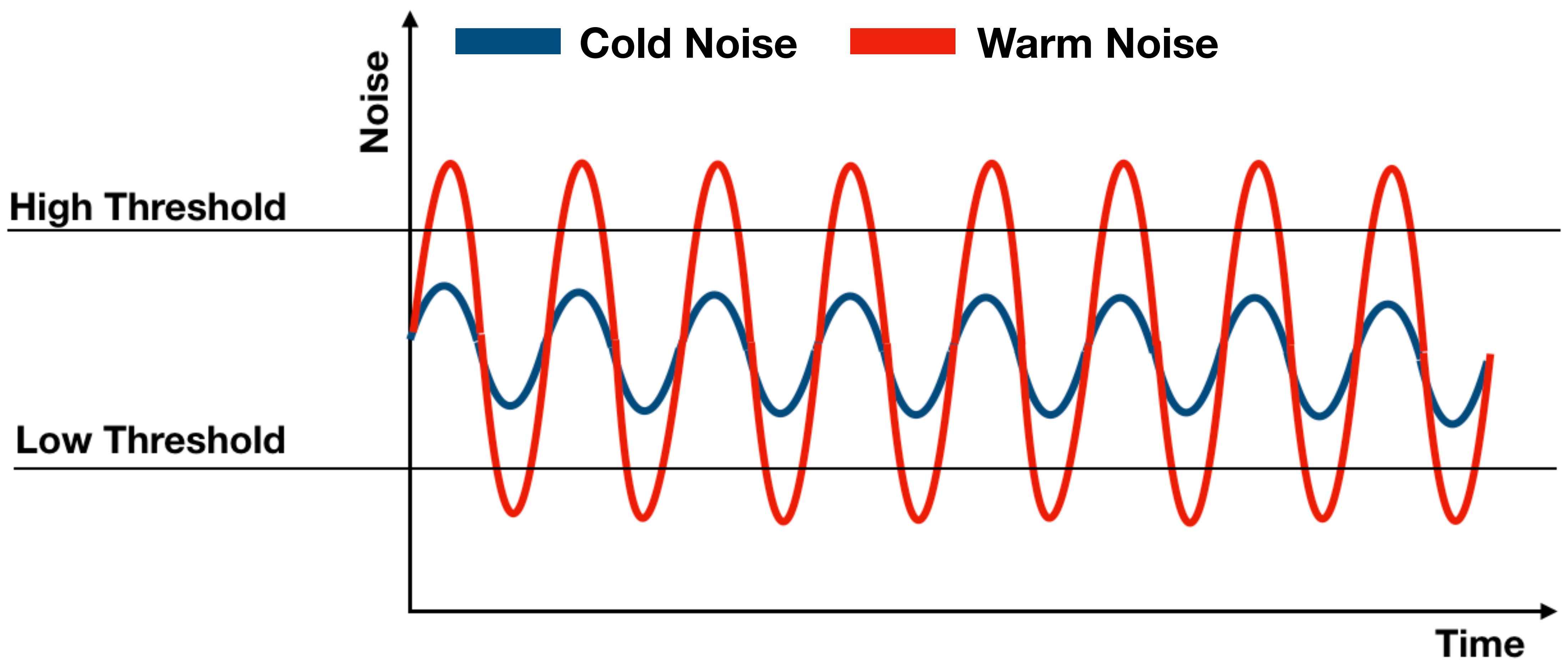


- At low threshold and warm temperatures, the noise is large and can fluctuate below threshold giving a lower noise occupancy
- At high threshold, the majority of noise when the module is operated cold is below threshold giving a lower noise occupancy than the module operated at a warmer temperature

Hot/Cold Comparisons of a non-irradiated SS Module

Comparison of Noise Occupancy when the DUT is operated at different temperatures

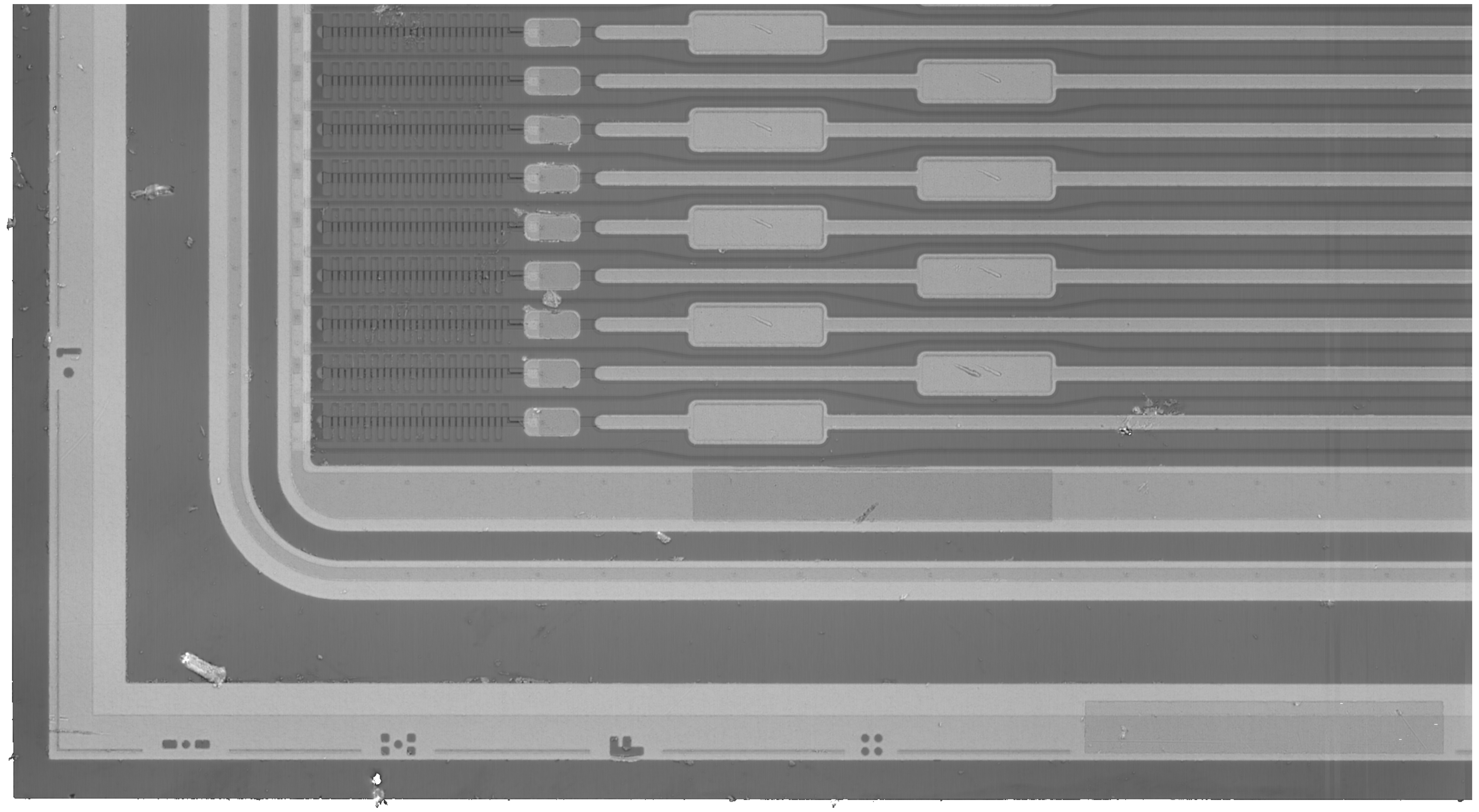




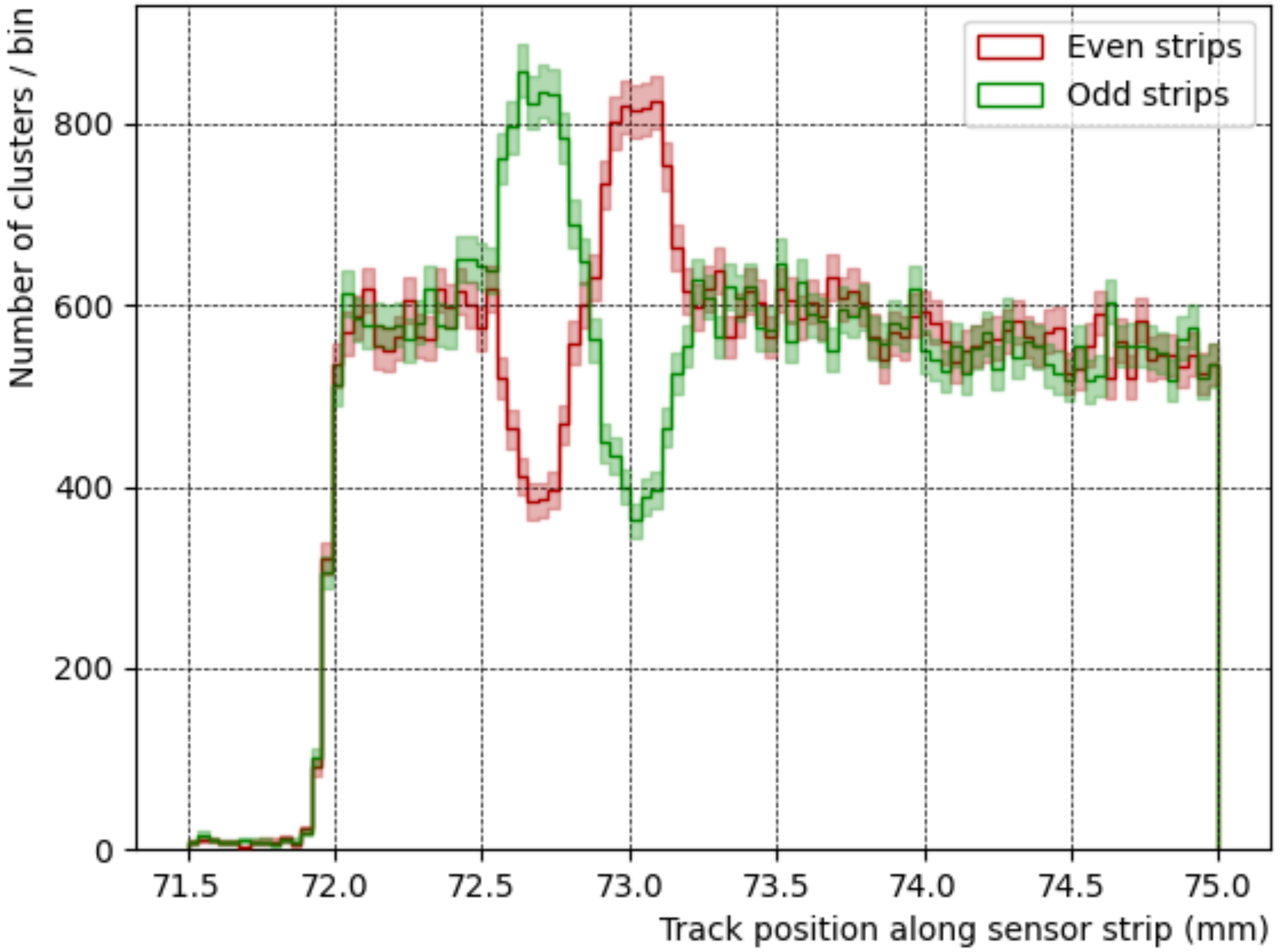
- At low threshold and warm temperatures, the noise is large and can fluctuate below threshold giving a lower noise occupancy
- At high threshold, the majority of noise when the module is operated cold is below threshold giving a lower noise occupancy than the module operated at a warmer temperature

Corner Studies - Non-Irradiated LS Module

- The beam was focused on the corner of the sensor
- We want to check the performance of the sensor in this region



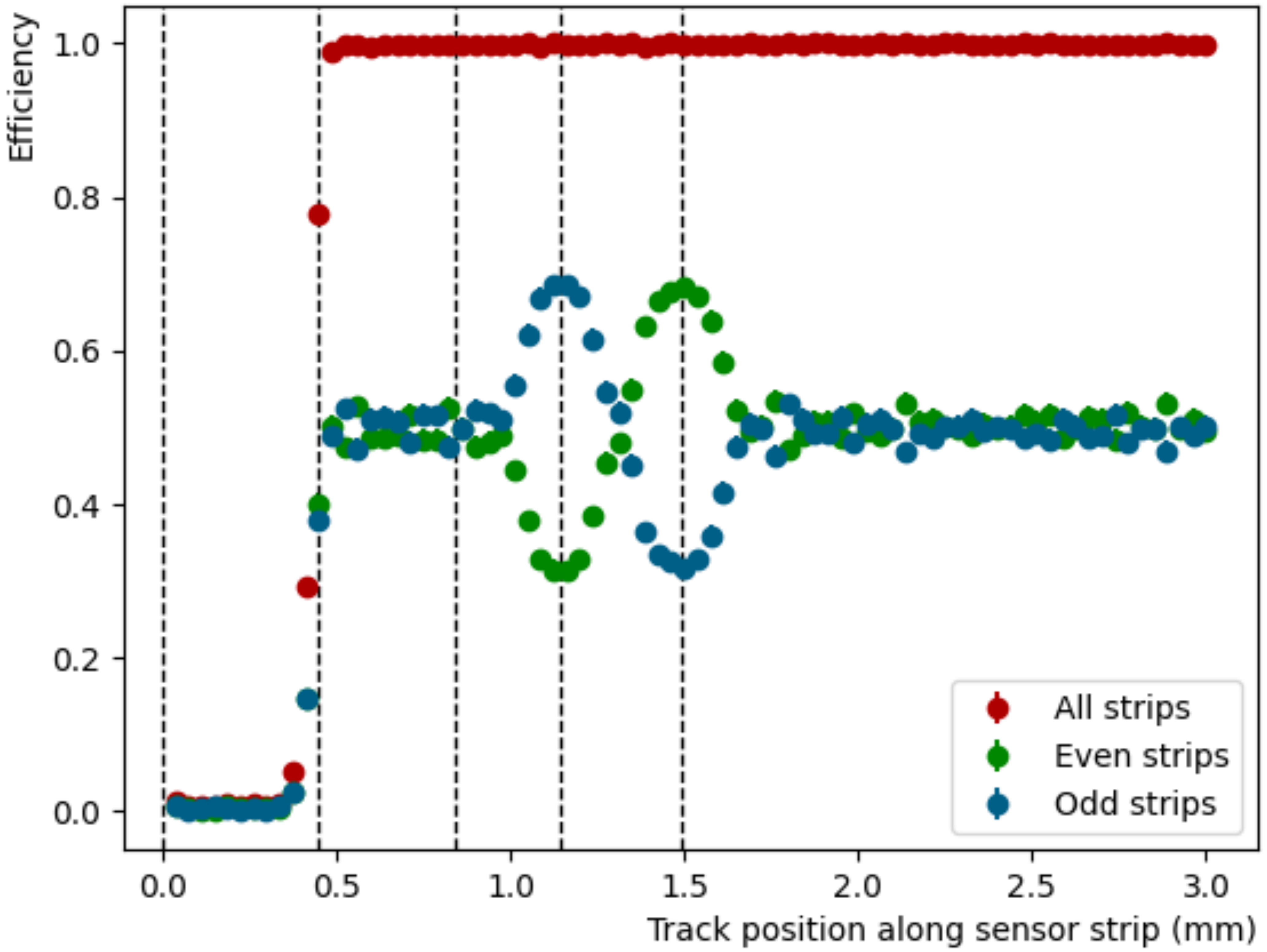
- Below bond pads, the width of the strip implant is increased to cover the full bond pad area
- P-stop implants are arranged around these bond pads, leading to uneven distances between p-stops and strip implants

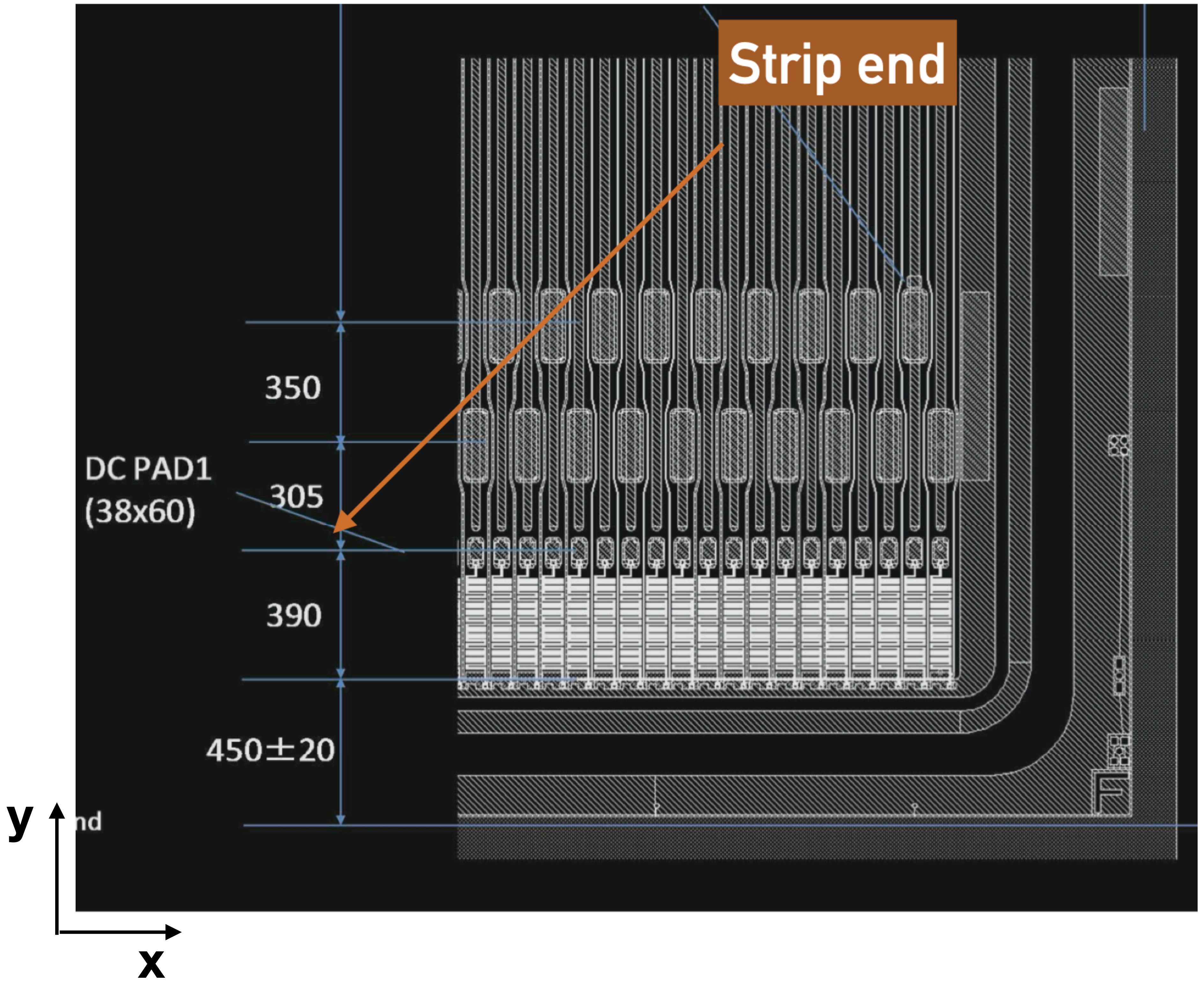


- When plotting the track position along the sensor for the even and odd strips the bond pad structure is visible

Corner Studies - non-irradiated LS Module

Efficiency along the y-direction





- Similar structure is seen when measuring the efficiency
- But when efficiency of all strips in this area is >99 %
- Slight decrease in efficiency for tracks very close to the edge of the active area of the sensor

EUTelescope and The Move to Corryvreckan

EUTelescope

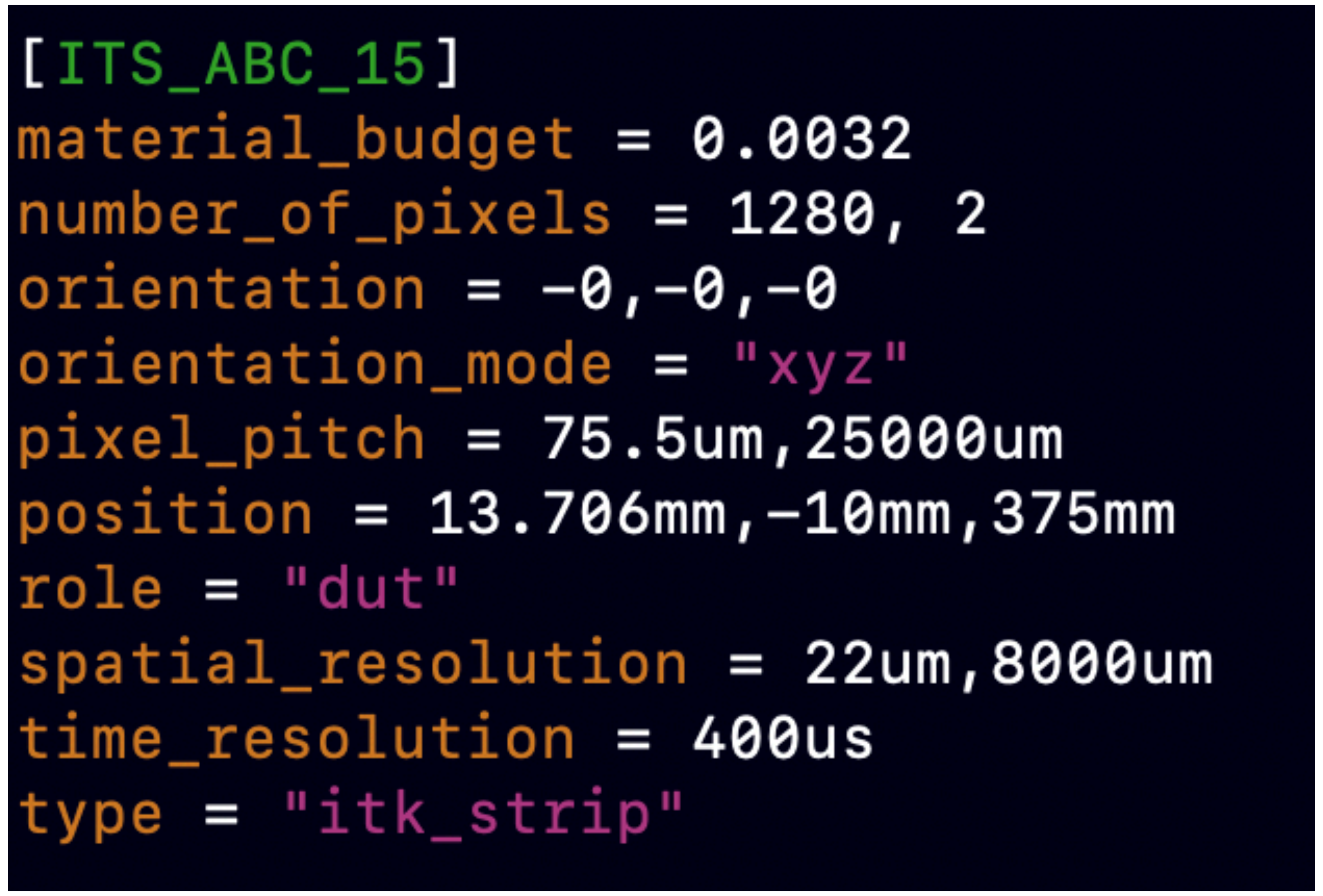
- EUTelescope was our standard reconstruction framework for the last decade
- So far we have been successful at reconstructing some of the ABCStar 2019 data
- However the reconstruction of endcap modules is complex due to the radial reconstruction
- Some of our recent students and postdocs that were experienced in EUTelescope have moved on to other projects and EUTelescope is not really a supported framework anymore
- Therefore we are now transitioning to the Corryvreckan reconstruction software

Corryvreckan

- Corryvreckan is widely tested in the pixel community but new to ITk Strip
- Should be straightforward to implement barrel modules (strips == long pixels)
- We first implemented the barrel module and compared results with EUTelescope
- Once we achieved this radial geometry will be implemented to allow for endcap analysis

Barrel Module Implementation in Corryvreckan

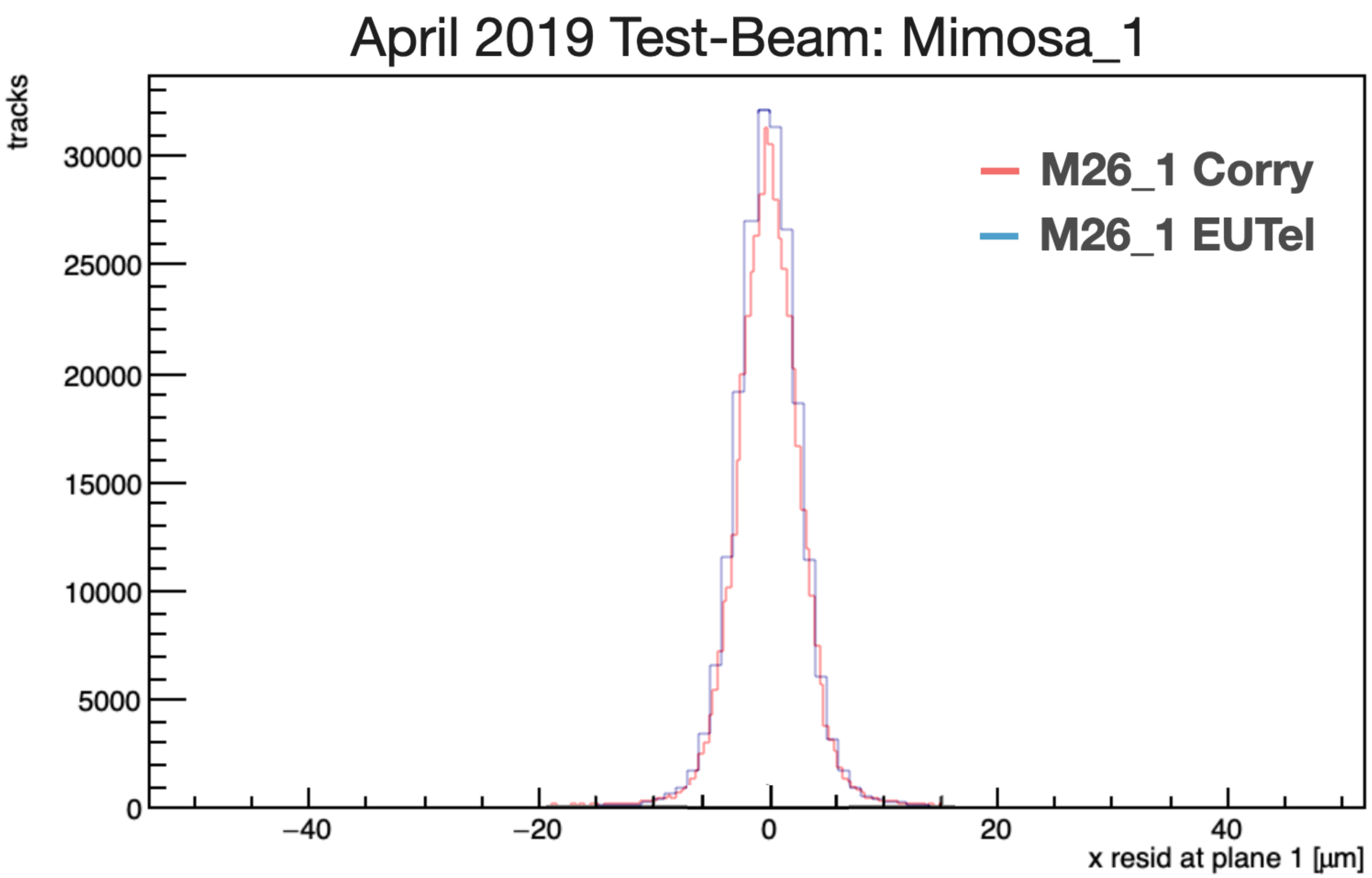
Example Geometry File for LS Module

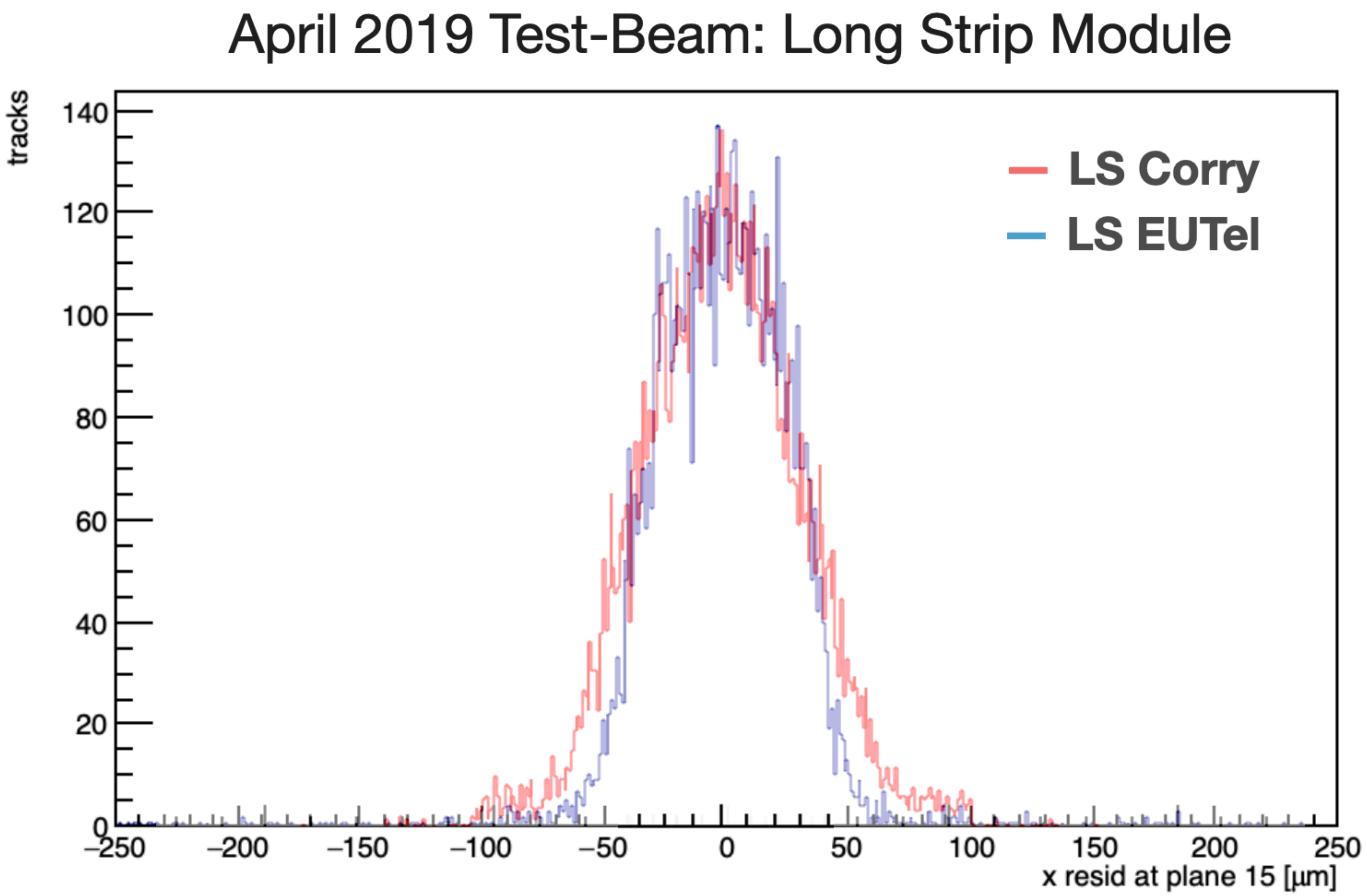


```
[ITS_ABC_15]
material_budget = 0.0032
number_of_pixels = 1280, 2
orientation = -0,-0,-0
orientation_mode = "xyz"
pixel_pitch = 75.5um,25000um
position = 13.706mm,-10mm,375mm
role = "dut"
spatial_resolution = 22um,8000um
time_resolution = 400us
type = "itk_strip"
```

- Main changes needed to implement a strip detector in Corryvreckan
  - Geometry config
  - Spatial window when looking for DUT hits associated to a track
  - χ^2 calculation when running the alignment
- We also found we had to iterate the alignment more times to achieve a good alignment than is needed for the telescope

Comparison of EUTelescope and Corryvreckan for Barrel Module


April 2019 Test-Beam: Mimosa_1


April 2019 Test-Beam: Long Strip Module

- Mimosa_1 **EUTel** Std Dev: $\sigma = 3.39\ \mu\text{m}$
- Mimosa_1 **Corry** Std Dev: $\sigma = 3.08\ \mu\text{m}$

- LS **EUTel** Std Dev: $\sigma = 31.59\ \mu\text{m}$
- LS **Corry** Std Dev: $\sigma = 35.64\ \mu\text{m}$

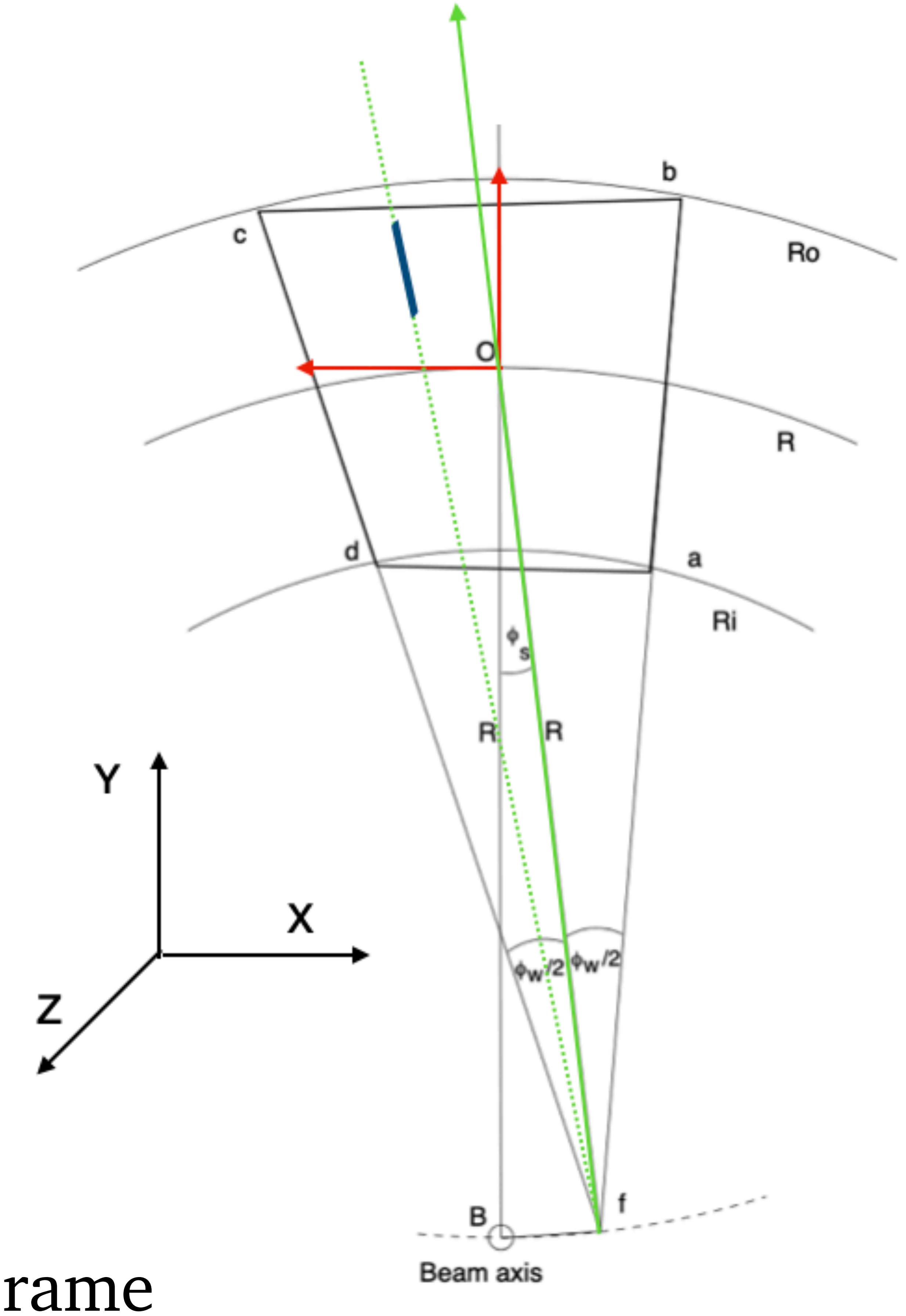
- These results are preliminary and further studies are ongoing for more detailed comparisons between the two frameworks

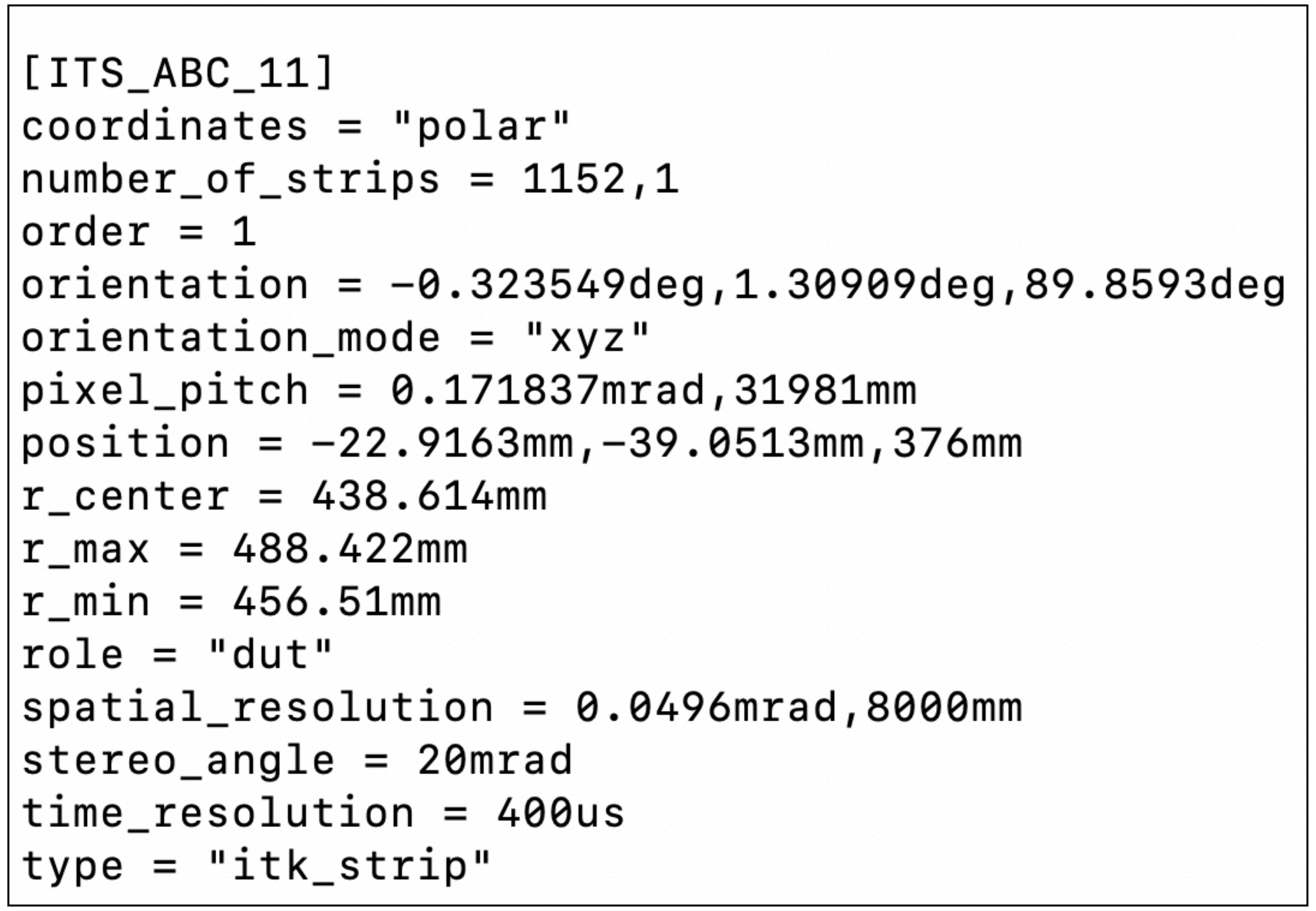
Corryvreckan Reconstruction of the R0 DUT

Specific R0 module geometry: A Built-in Stereo-angle Endcap strip sensor

- Strip pointed to focus point (f), which is defined by stereo-angle
- Implementation in corryvreckan
  - Describe endcap R0 module in a local polar coordinate system

Strip Frame: local Polar coordinate system focused at f
Sensor Frame : local Cartesian coordinate system on module center(O)
Global Frame : telescope global Cartesian coordinate system





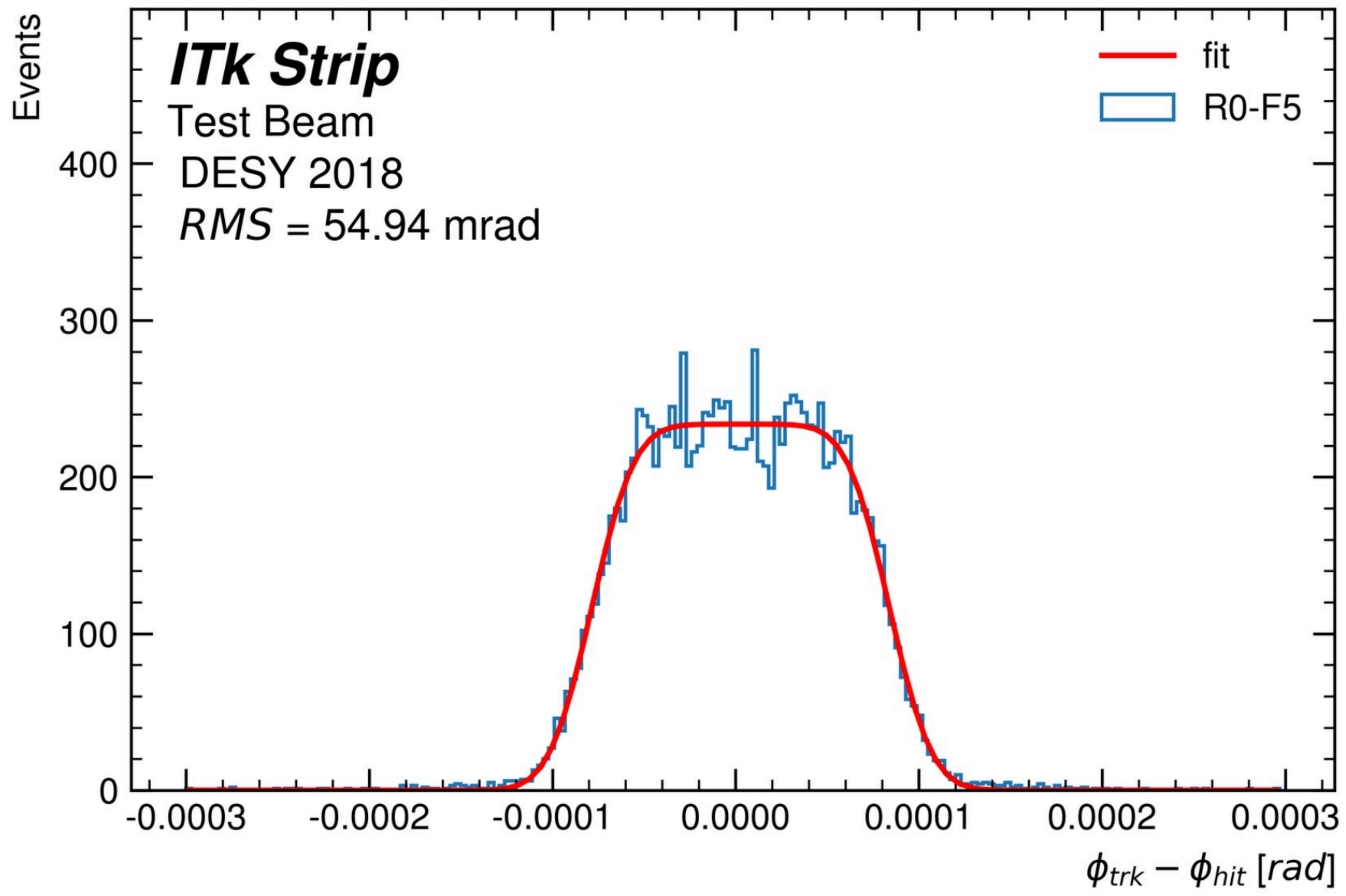
```
[ITS_ABC_11]
coordinates = "polar"
number_of_strips = 1152,1
order = 1
orientation = -0.323549deg,1.30909deg,89.8593deg
orientation_mode = "xyz"
pixel_pitch = 0.171837mrad,31981mm
position = -22.9163mm,-39.0513mm,376mm
r_center = 438.614mm
r_max = 488.422mm
r_min = 456.51mm
role = "dut"
spatial_resolution = 0.0496mrad,8000mm
stereo_angle = 20mrad
time_resolution = 400us
type = "itk_strip"
```

- Calculations are defined in Strip Frame
  - e.g., Clustering, Hit association, Residual calculation
- Global coordinate information retrieved from coordinate transform
  - local Polar coordinate <—> local Cartesian coordinate <—> global Cartesian coordinate

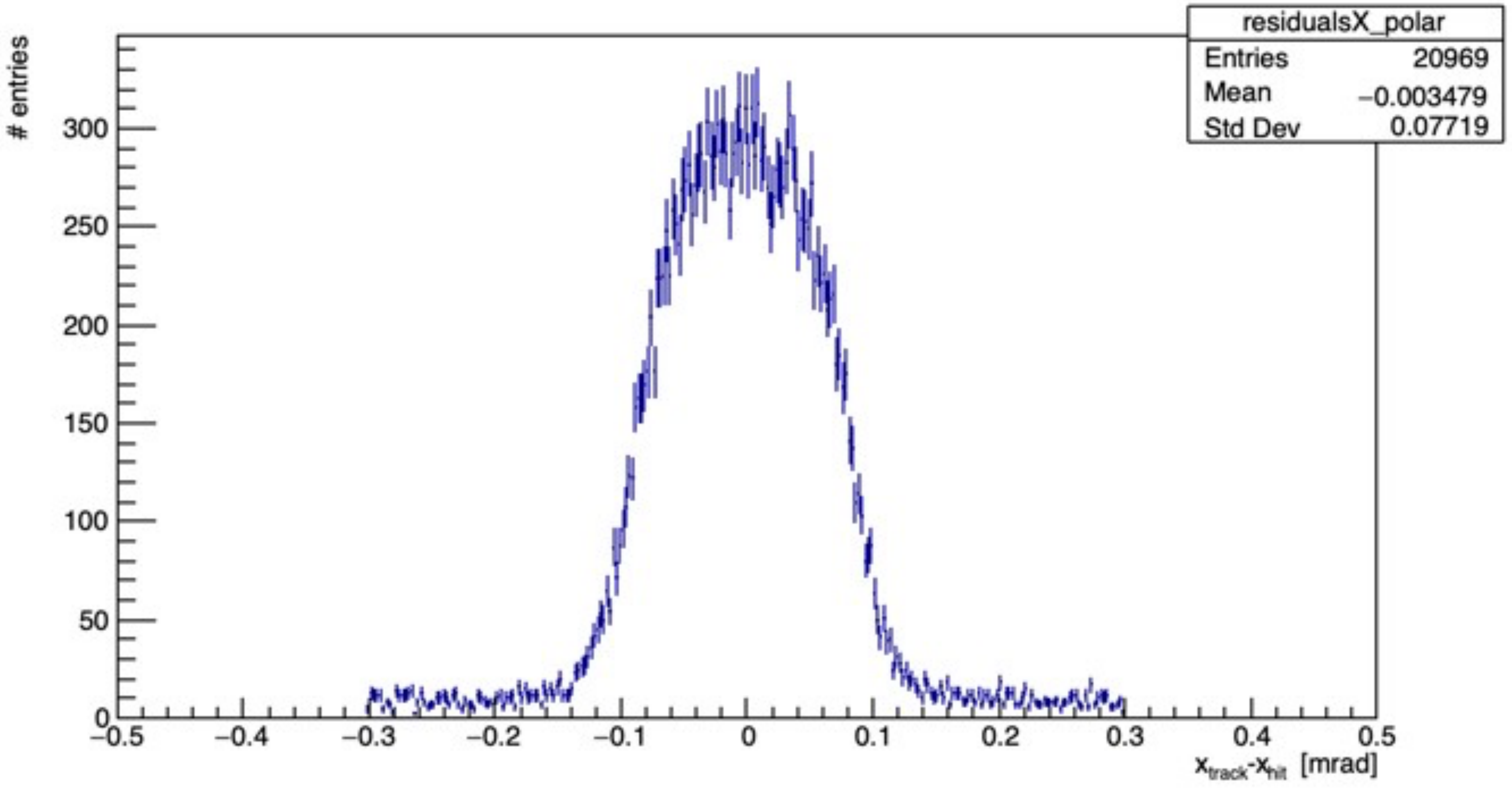
Jin Zhang

Comparison of EUTelescope and Corryvreckan for R0 Module

EUTelescope



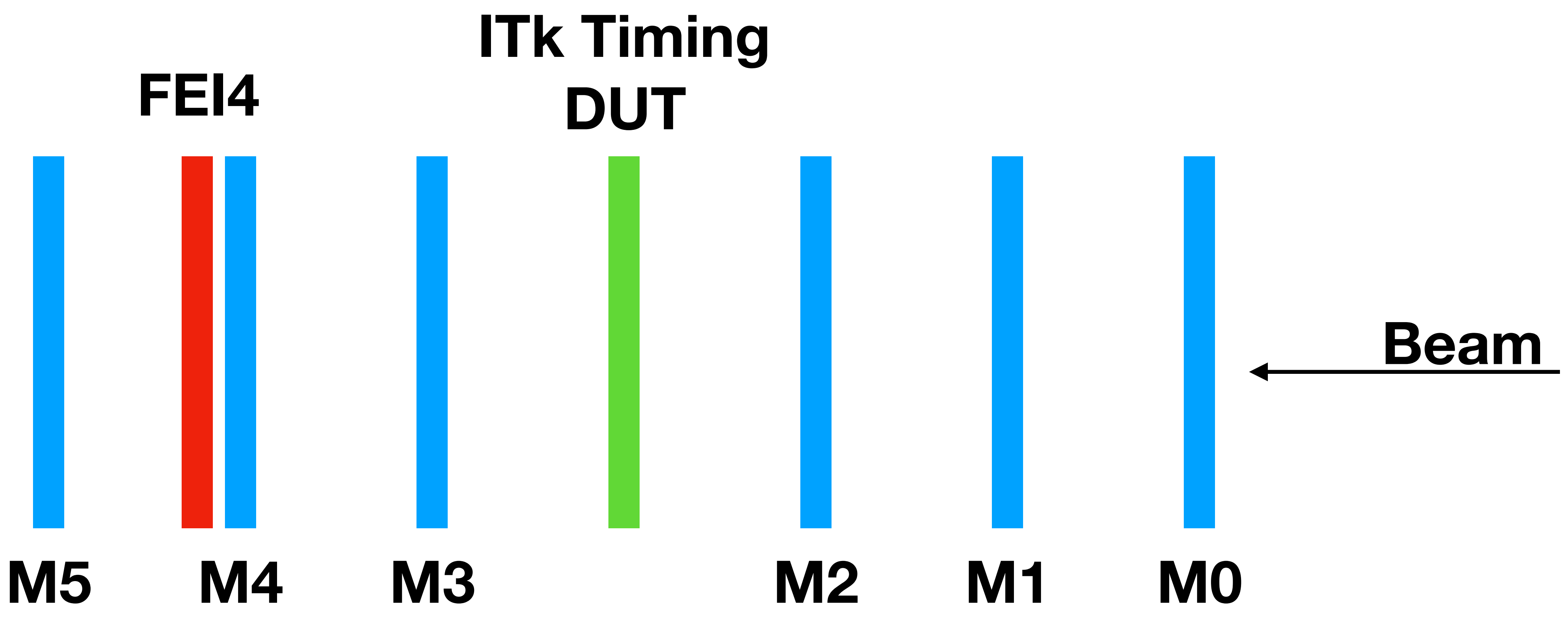
Corryvreckan



- **EUTel** Std Dev: $\sigma = 54.94$ mrad
- **Corry** Std Dev: $\sigma = 77.19$ mrad
- There are still improvements to be made to the alignment of the Corryvreckan reconstruction of the R0 but so far a good start!

ITk Strip Timing Plane

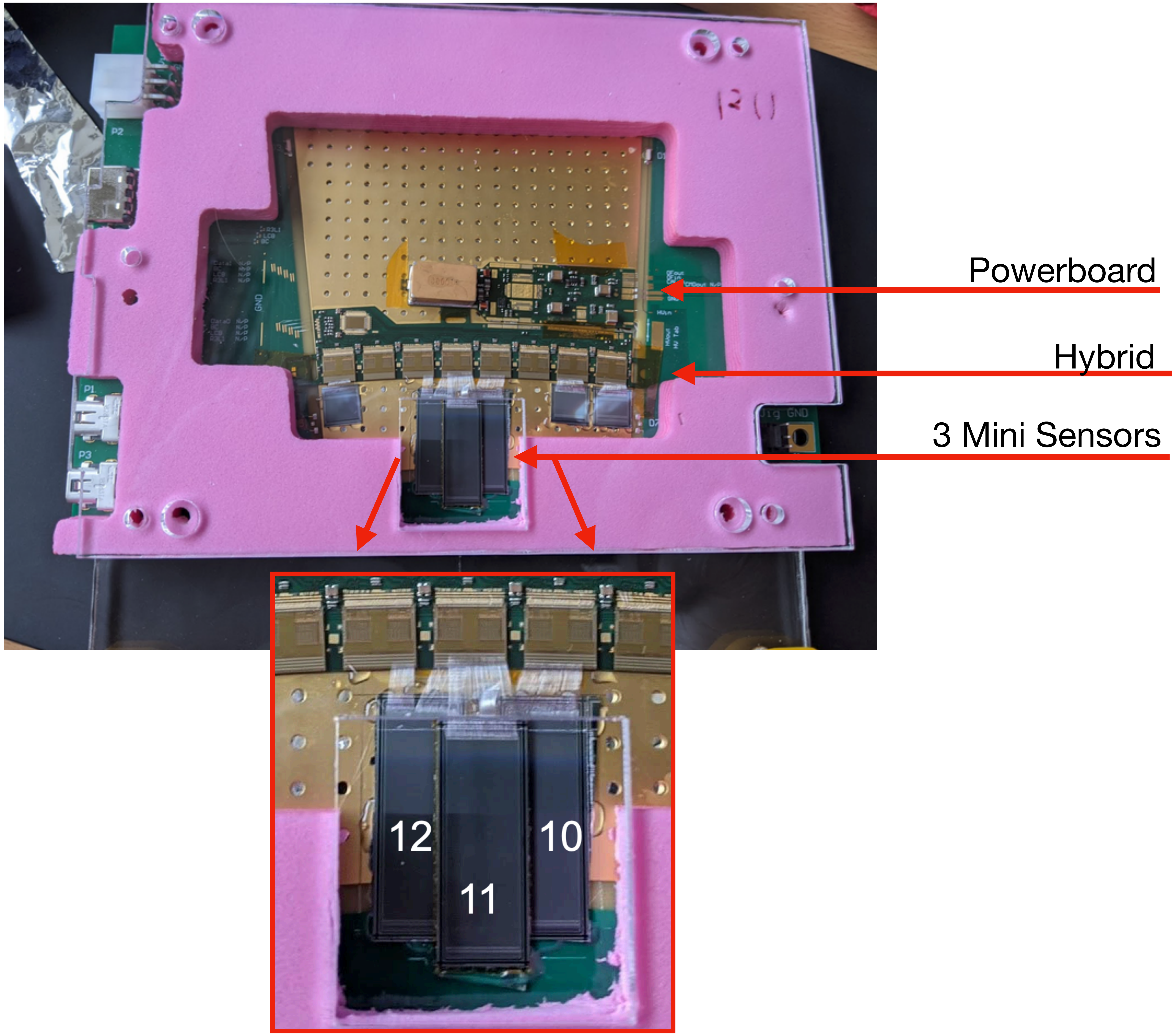
- Usually the FEI4 timing plane is used for ITk Strip Testbeams
- To reduce dependence on FEI4 availability we would like to have our own timing plane
- The ITk strip timing plane is made of 3 mini strip sensors with 105 channels each
- The timing plane was installed in the telescope as the DUT with the FEI4 used as the timing plane
- All analysis has been done using Corryvreckan!


FEI4

ITk Timing DUT

Beam

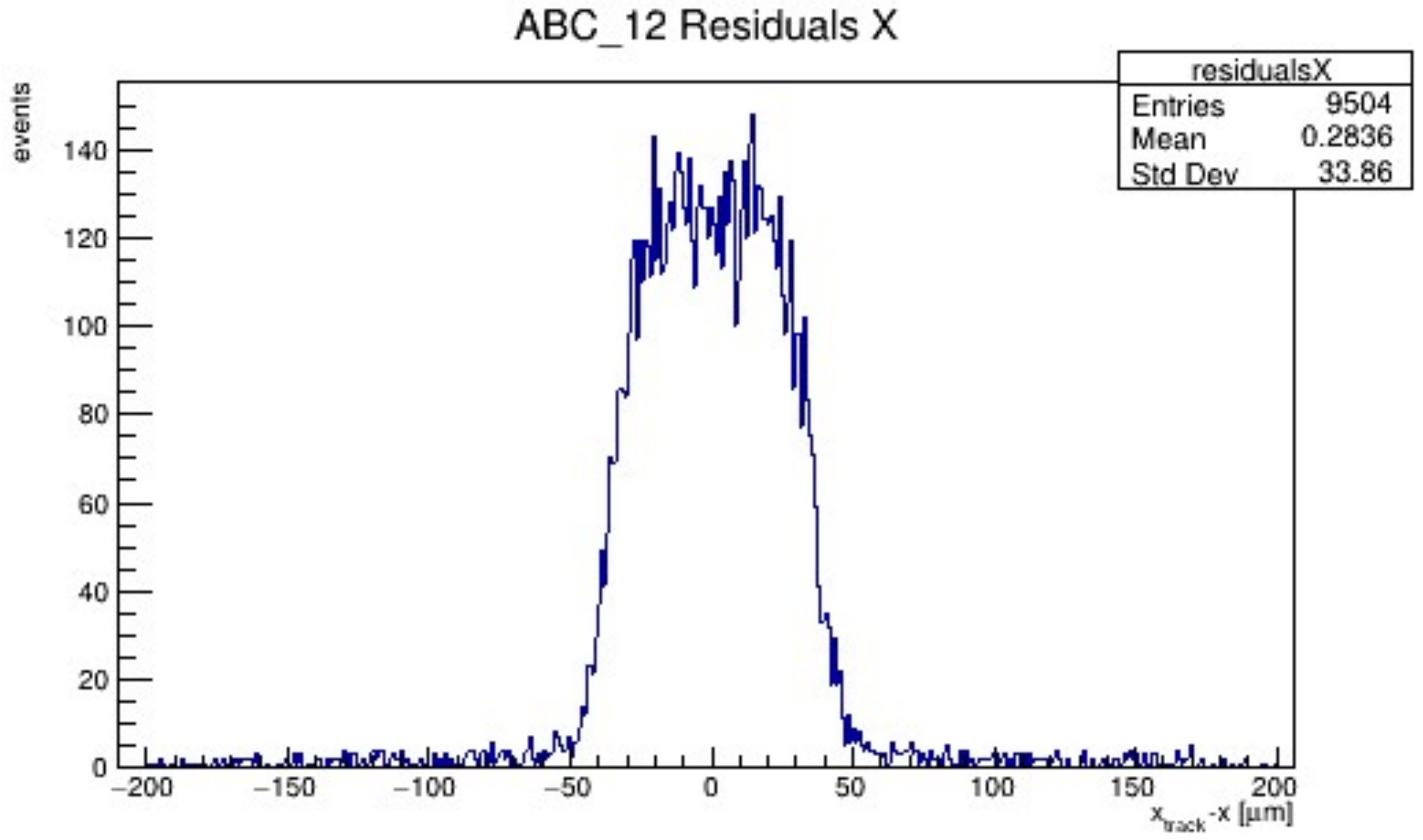
M5 **M4** **M3** **M2** **M1** **M0**

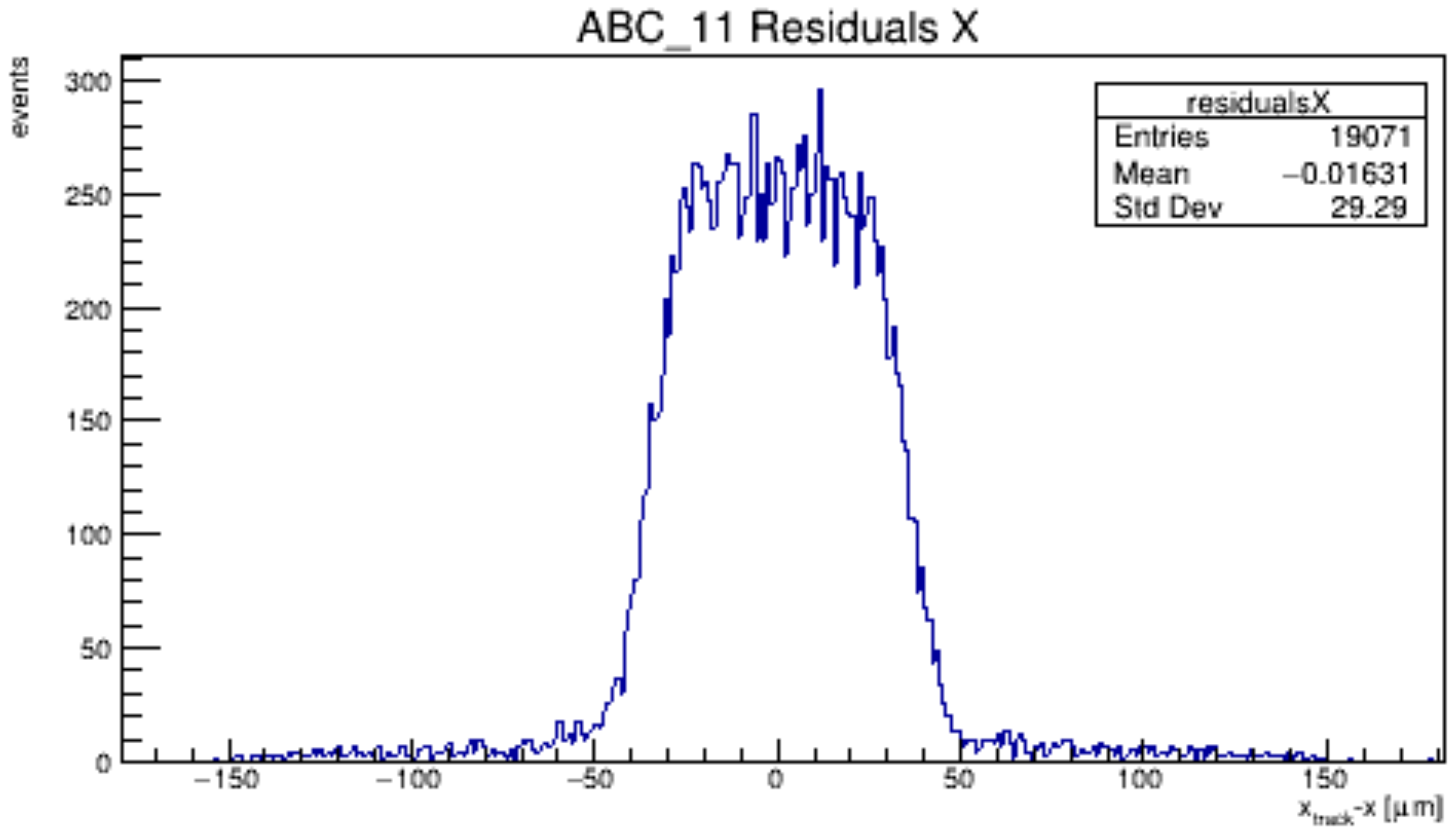

Powerboard

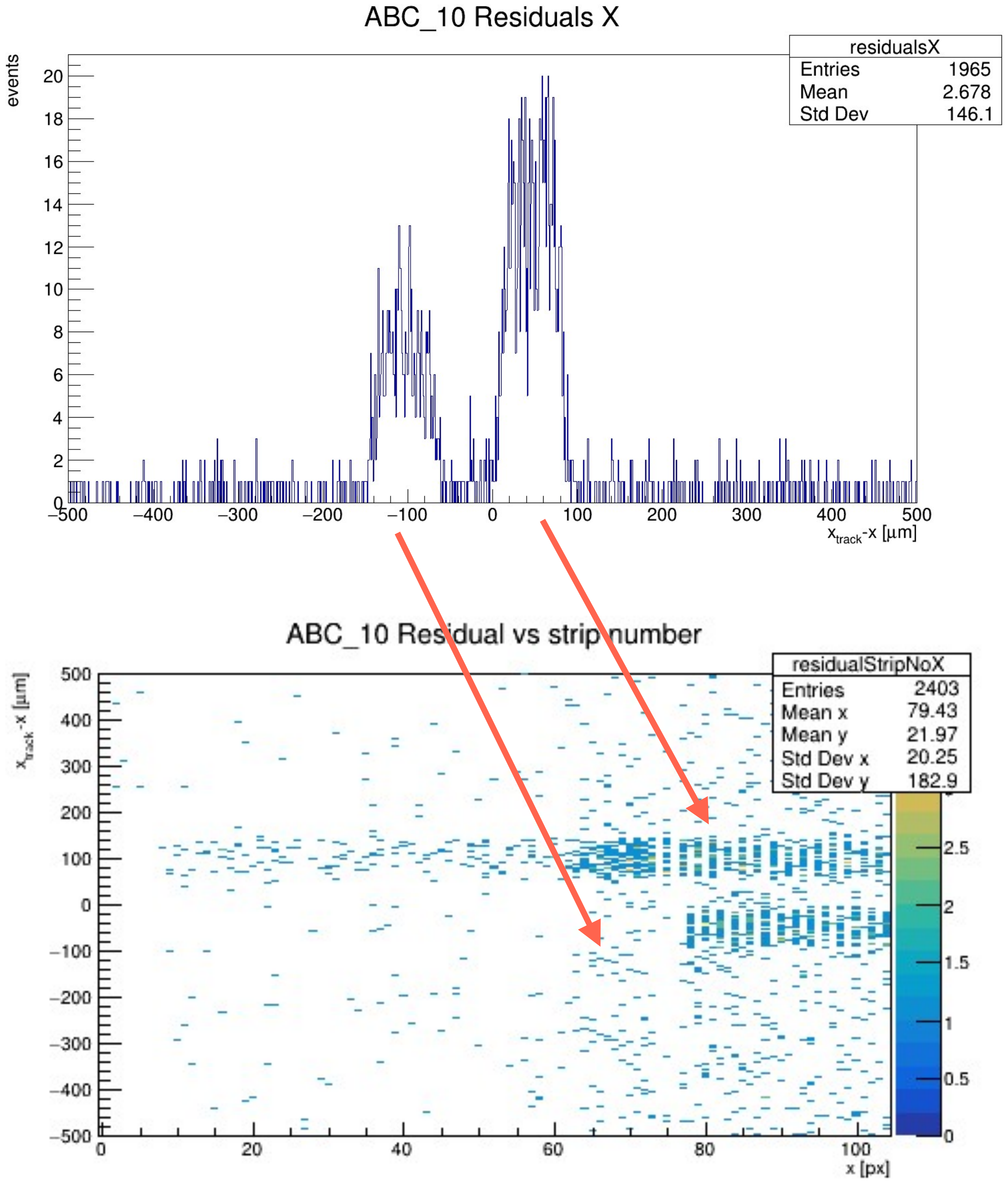
Hybrid

3 Mini Sensors

Reconstructing the ITk Strip Timing Plane with Corryvreckan





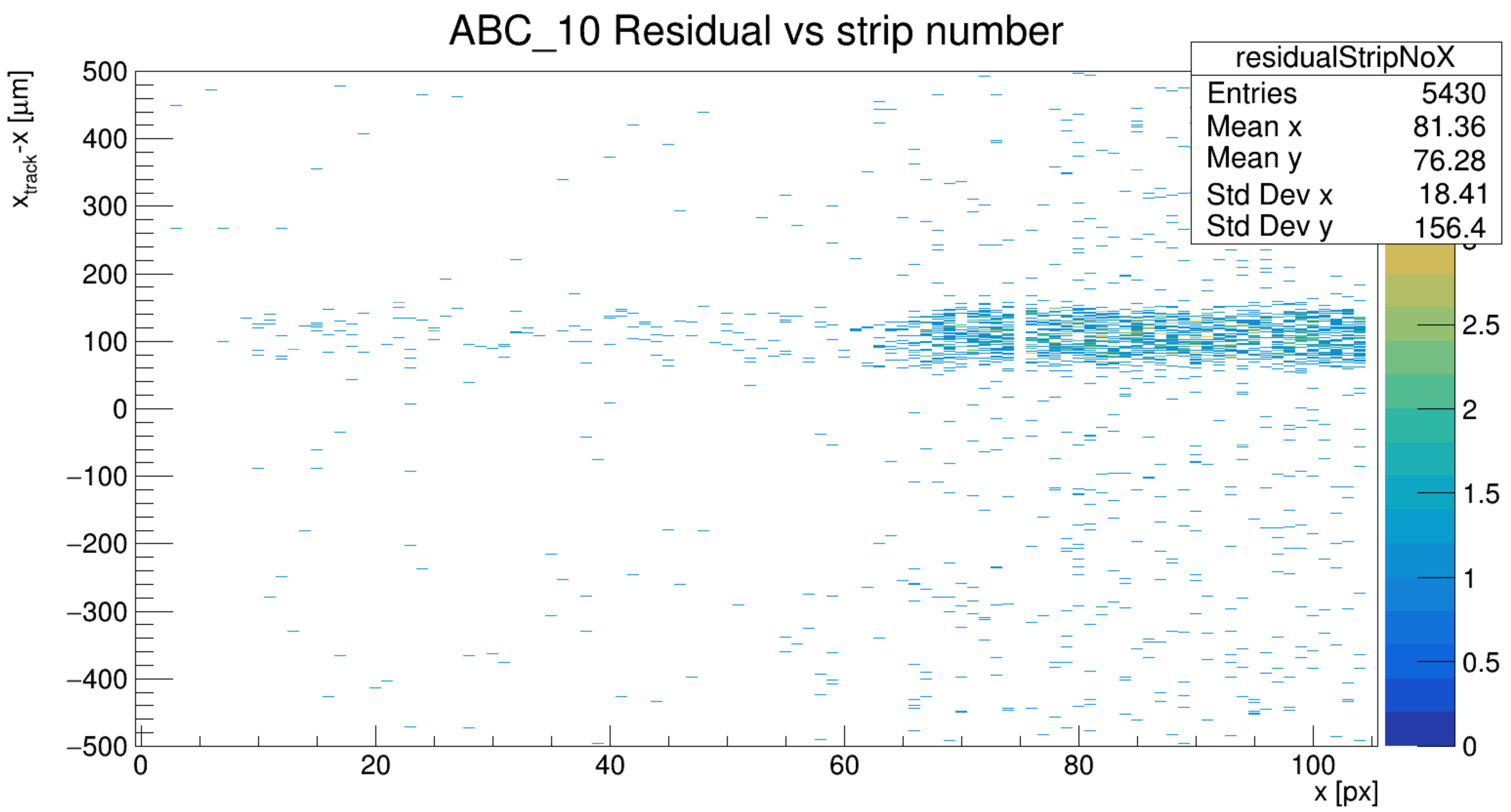


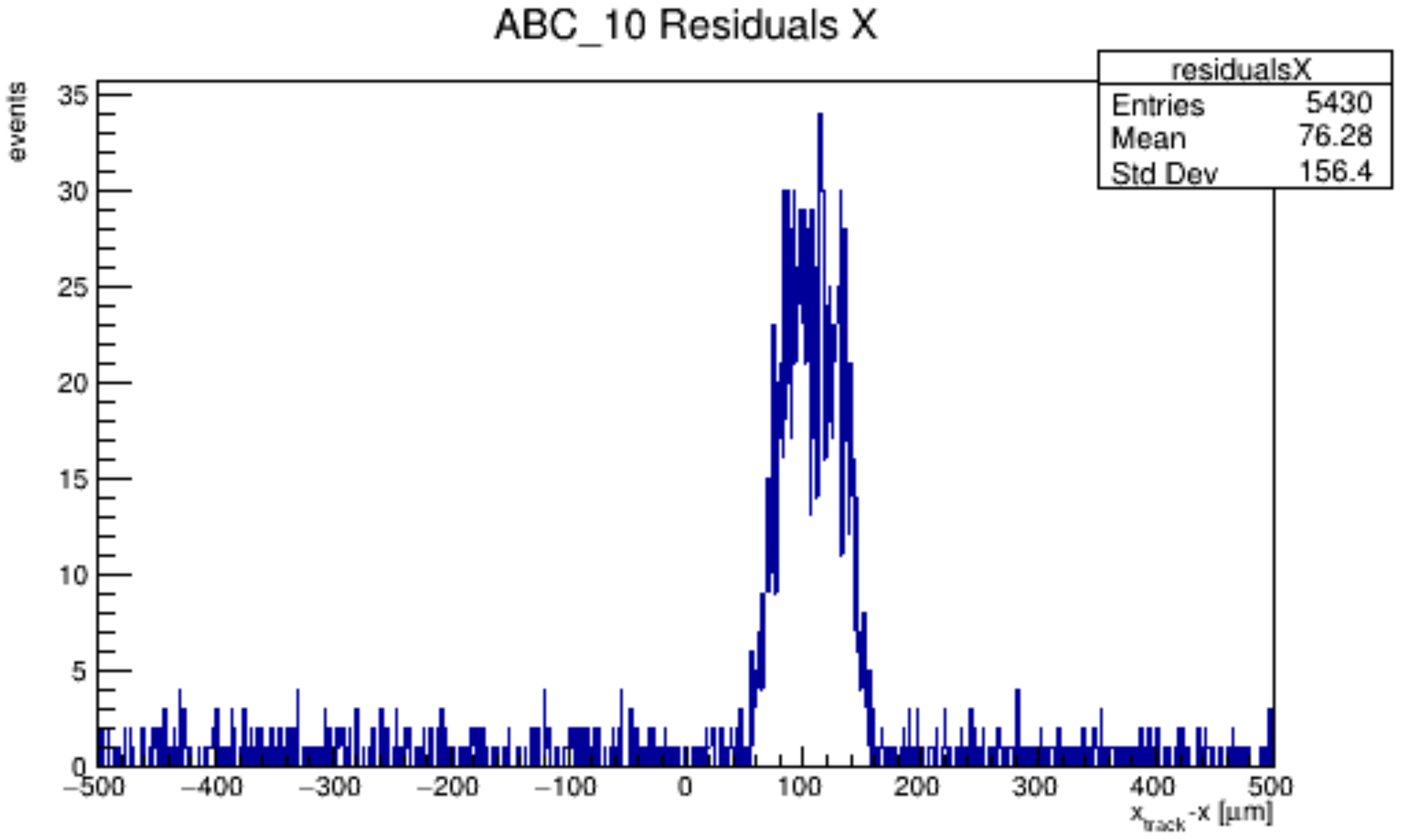
- Preliminary analysis has begun and the residuals have been measured for each of the mini sensors
- One of the residuals has a double peak feature
- From channel number 74, even strips are displaced by 2
- This then gives the wrong x position
- Leading to a double peaked residual

Reconstructing the ITk Strip Timing Plane with Corryvreckan

- On closer inspection of the module we found that the shift was due to wire bonding issues

Reconstructing the ITk Strip Timing Plane with Corryvreckan





- This can be corrected for in the conversion
- Once the alignment is rerun the residual no longer has a double peak feature
- Next steps are to check the efficiency performance to see if this would be a suitable timing plane for future testbeams

Conclusions

- ITk Strip prototype modules are tested at DESY to check performance
- Data has been collected for irradiated and non-irradiated barrel and endcap modules
- ABCstar modules have been shown to fulfil upgrade requirements for the efficiency, noise occupancy and the S/N
- Preliminary analysis of 2019 data has been performed using EUTelescope
- We are moving from the EUTelescope to the Corryvreckan framework
    - Both the barrel and endcap geometries have been implemented and we are currently comparing the Corryvreckan results with EUTelescope outputs
- In November 2020 we installed the new ITK Strip timing plane into the EUDET telescope to test its performance
    - Initial reconstruction has been done using Corryvreckan
    - Next steps are to check the efficiency of the R0 module, measured using FEI4 and the ITk Strip timing plane
    - We have data using Alpide as a timing plane but analysis is still to be performed