JadePix-3 Beam Telescope

The Developments and Recent Measurements

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HKUST JOCKEY CLUB INSTITUTE FOR ADVANCED STUDY

Outline

- Introduce the sensor briefly
- Telescope Activities
- Preliminary Result on DESY Test Beam

Overview of the JadePix-3 design

"Status report on MAPS in China", 2021 CEPC workshop, Yunpeng Lu

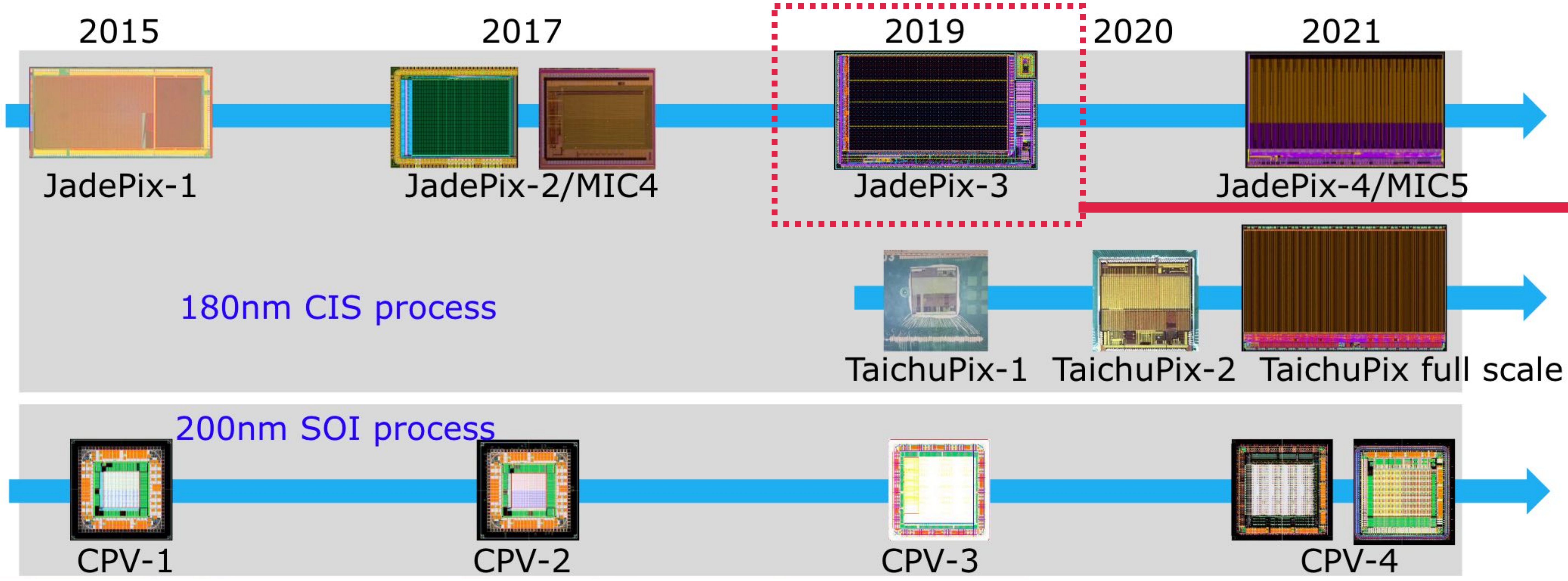


Fig.1 Roadmap of silicon pixel sensor for vertex detector in China.

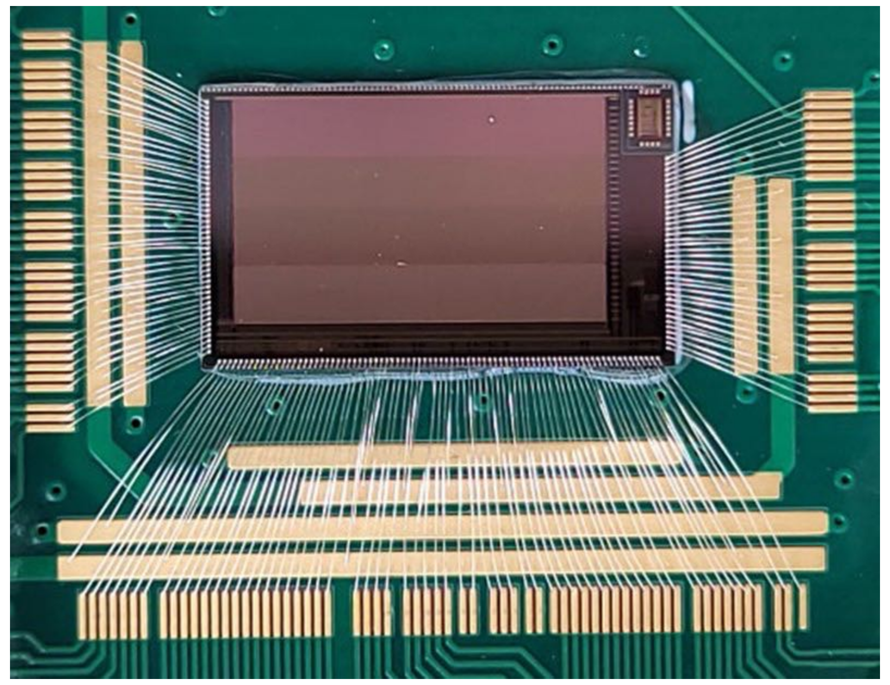


Fig.2 How the sensor wired bonded to a custom Printed Circuit Board (PCB).

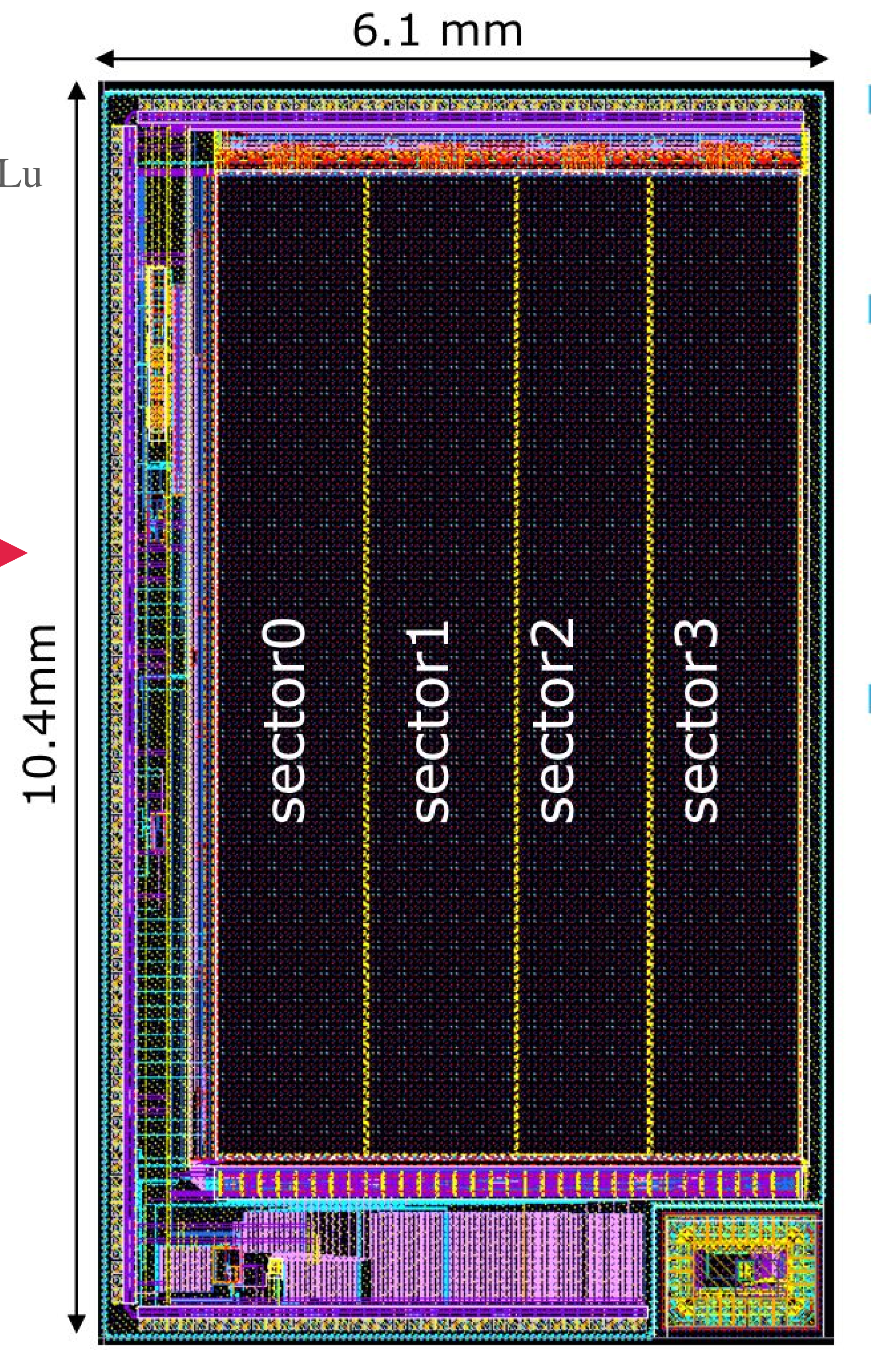


Fig.3 JadePix–3 layout, 4 parallel sectors, scalable in the column direction

JadePix–3 is designed targeted on **high resolution, low power consumption** and **fast readout.**

Produced using TowerJazz 180nm CMOS Technology.

4 sectors are designed to study different analog front–end and digital circuit. (See Table.1)

Sensor Size: $10.4mm(row) \times 6.1mm(col)$

Minimal Pixel Size: $16um \times 23.11um$

Pixel array: $512(row) \times 192(col)$

Tabel. 1 The matrix design of JadePix–3

Sector	Diode	Analog	Digital	Pixel Size
0	2+2 um	FE_V0	DGT_V0	16 x 26 um^2
1	2+2 um	FE_V0	DGT_V1	16 x 26 um^2
2	2+2 um	FE_V0	DGT_V2	16 x 23.11 um^2
3	2+2 um	FE_V1	DGT_V0	16 x 26 um^2

Single Sensor Test

- The IPbus-based DAQ system was developed for a full test of the sensor.
- Test methods: electrical pulse test, infra-red laser beam test, radioactive source (^{90}Sr) test.
- Test results in summary:
  - Threshold: 90 e^- to 140 e^-
  - Noise hit rate: below an upper limit of 1×10^{-10}/frame/pixel
  - Power consumption: 127 mW
  - Spatial resolution: below $3um$ (infra-red laser beam test)
- Publication: Design and Characterization of the JadePix-3 CMOS pixel sensor

  https://doi.org/10.1016/j.nima.2022.167967

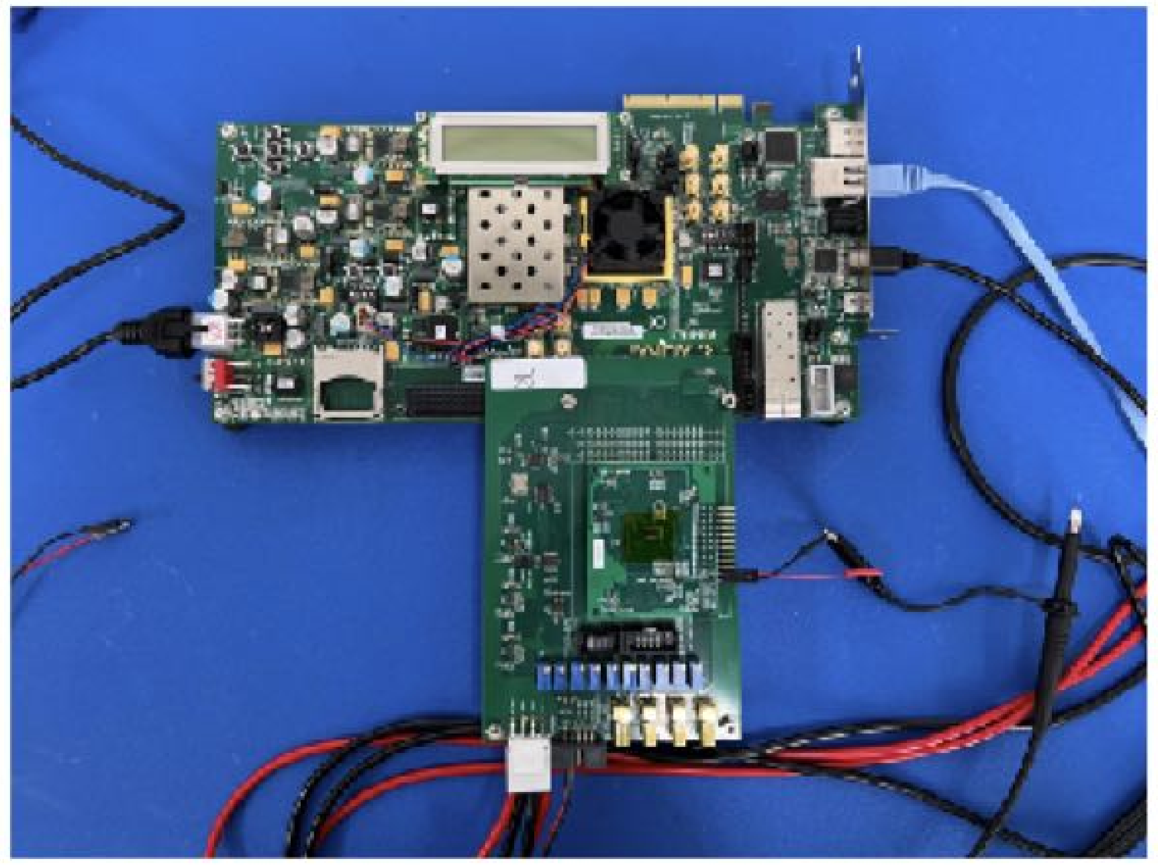


Fig.1 The electronics of single-chip test system

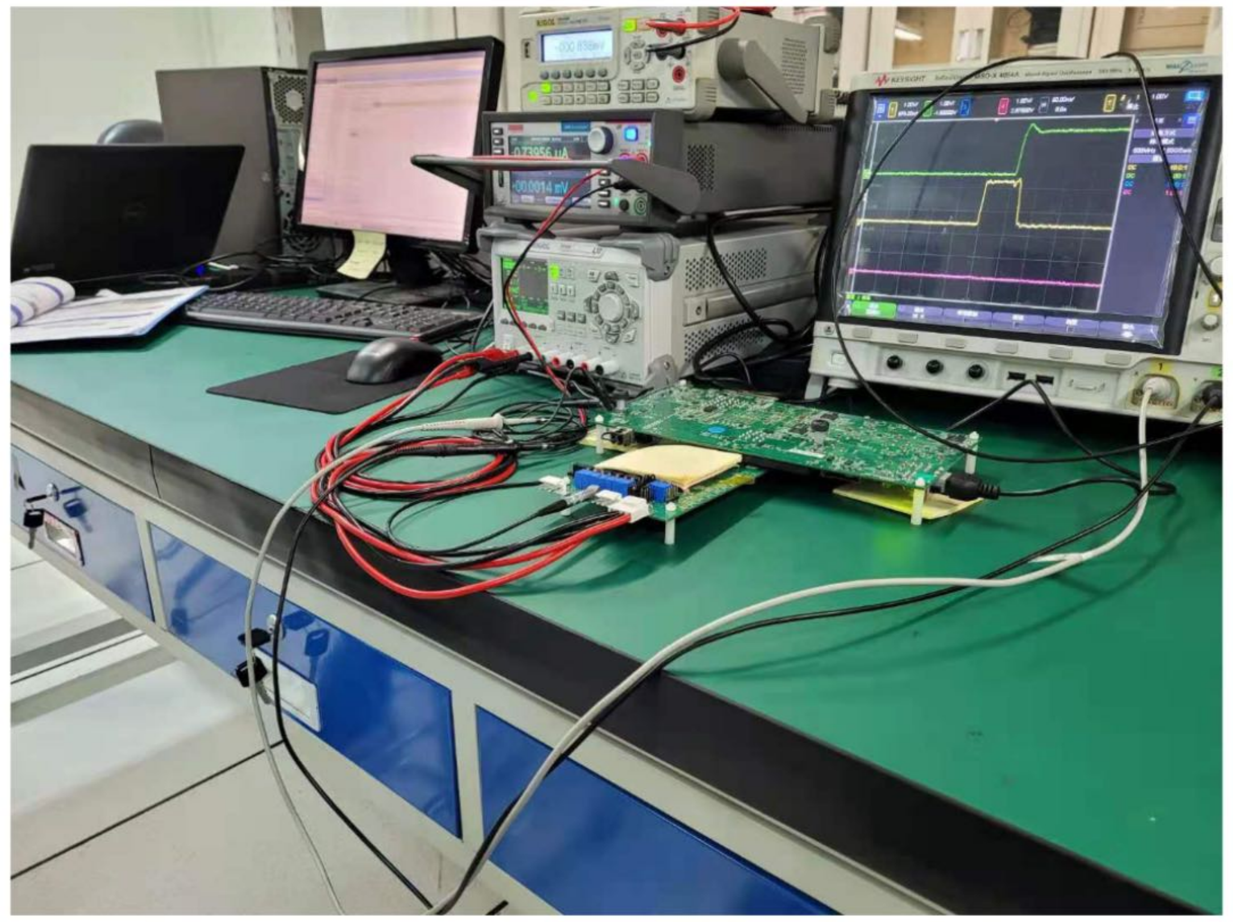


Fig.2 The test setup at CCNU

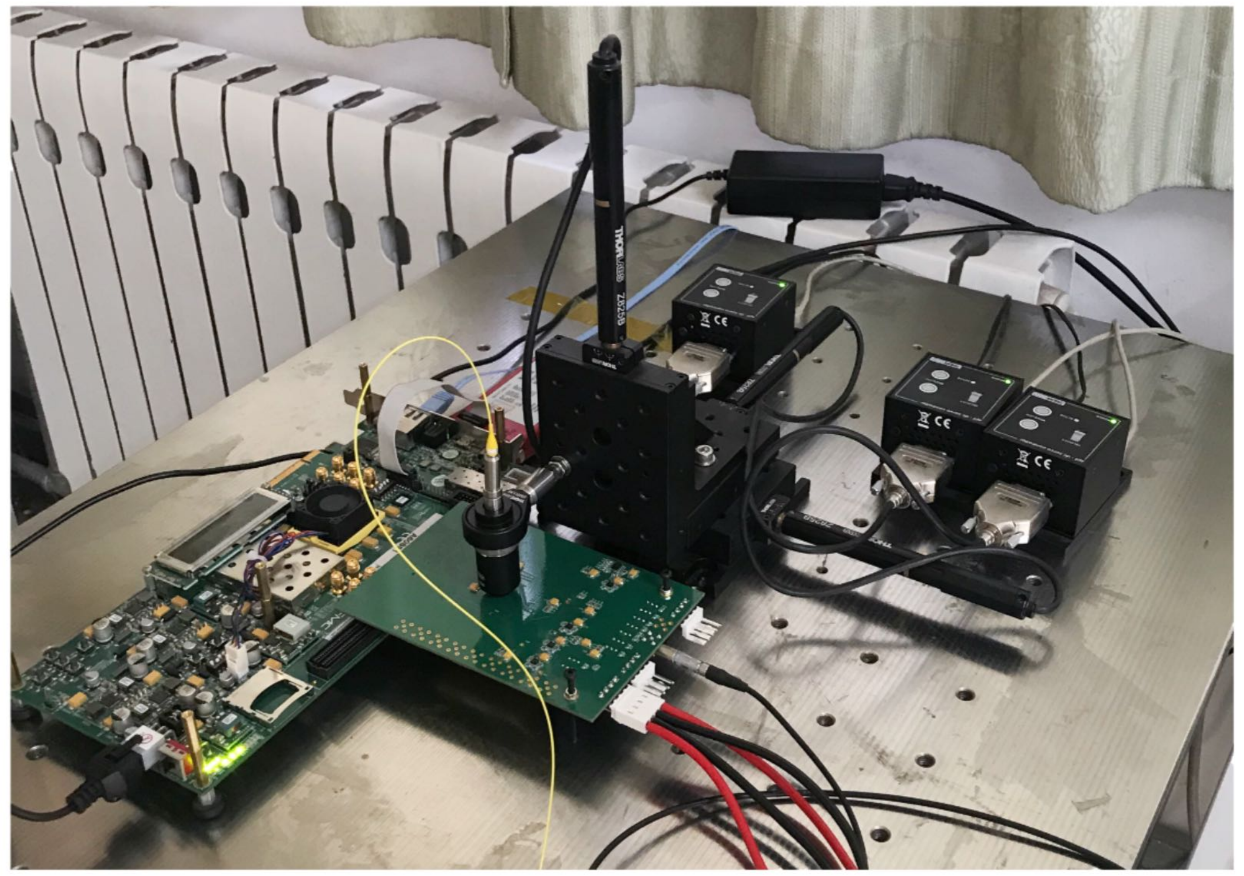


Fig.3 The laser test setup at IHEP

Motivations and Activities

- Develop a readout system for multi-layer chips, which is applicable to various chips under research, such as JadePix-4 and CPV-4.
- Master the data analysis of multi-sensors and the measurement method of spatial resolution.

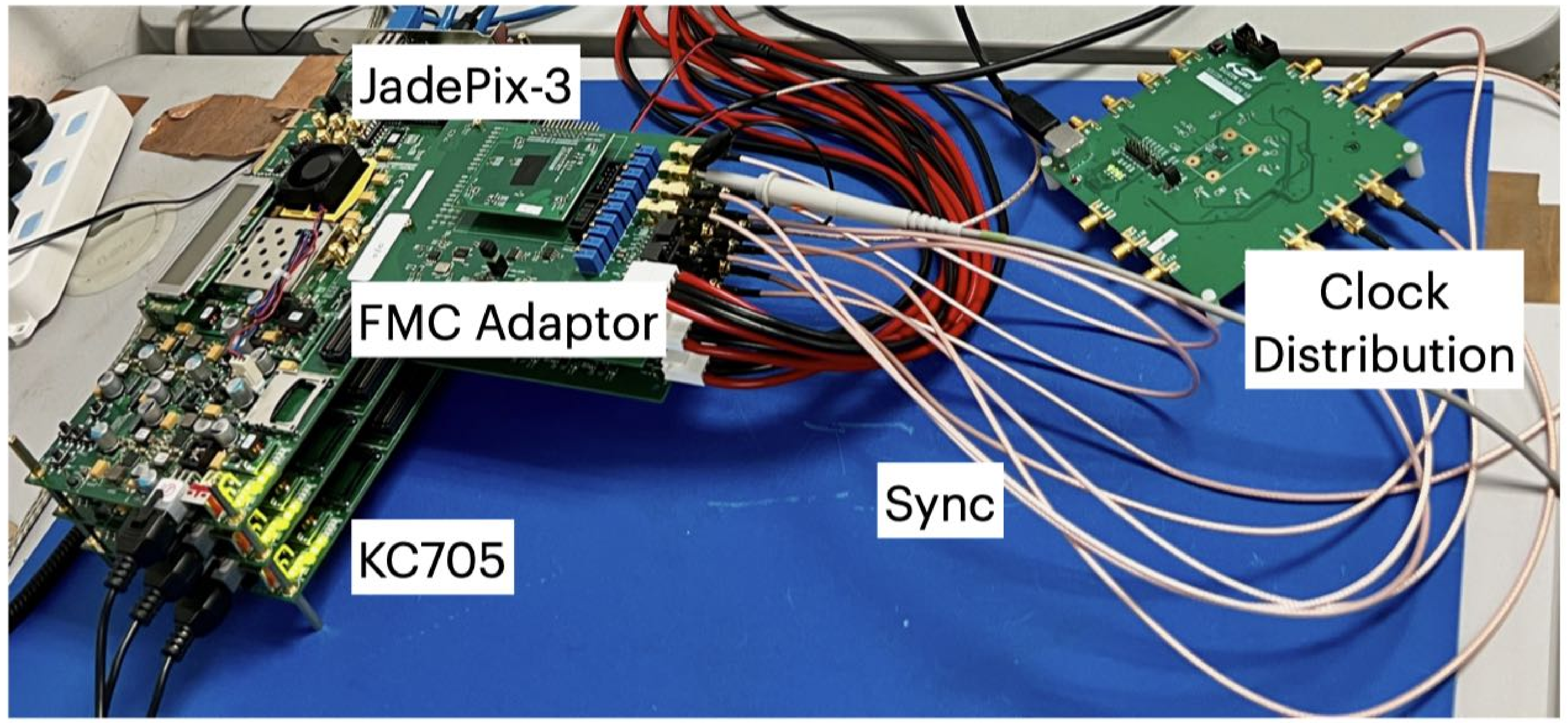


Fig.1 The prototype of the telescope with 3 planes.

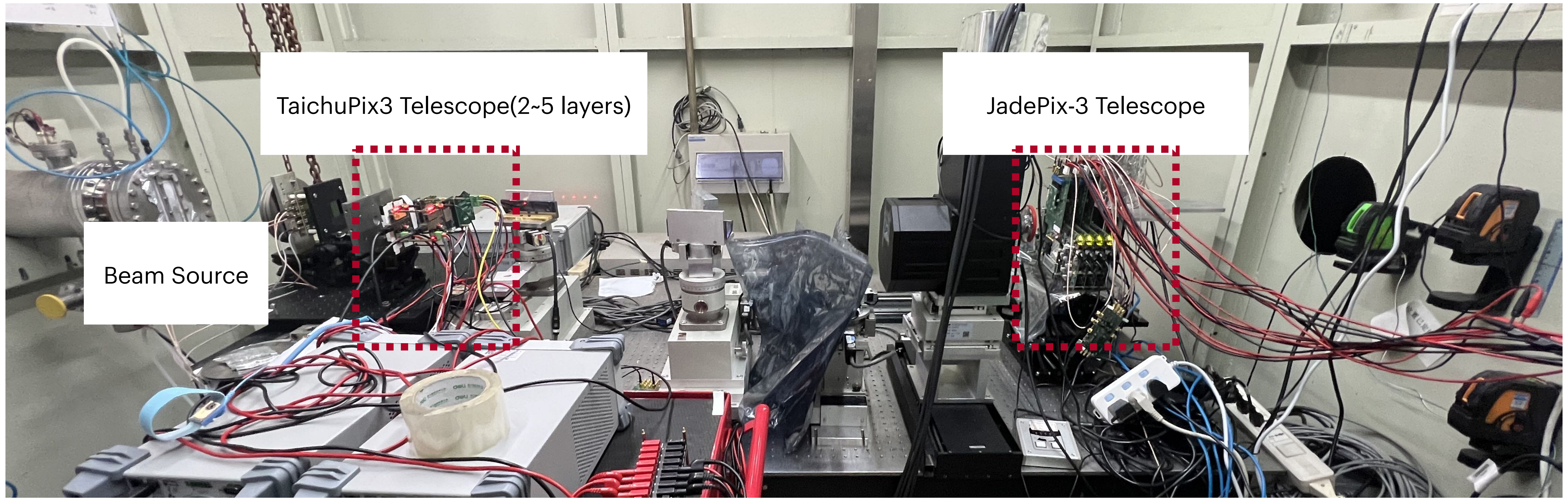
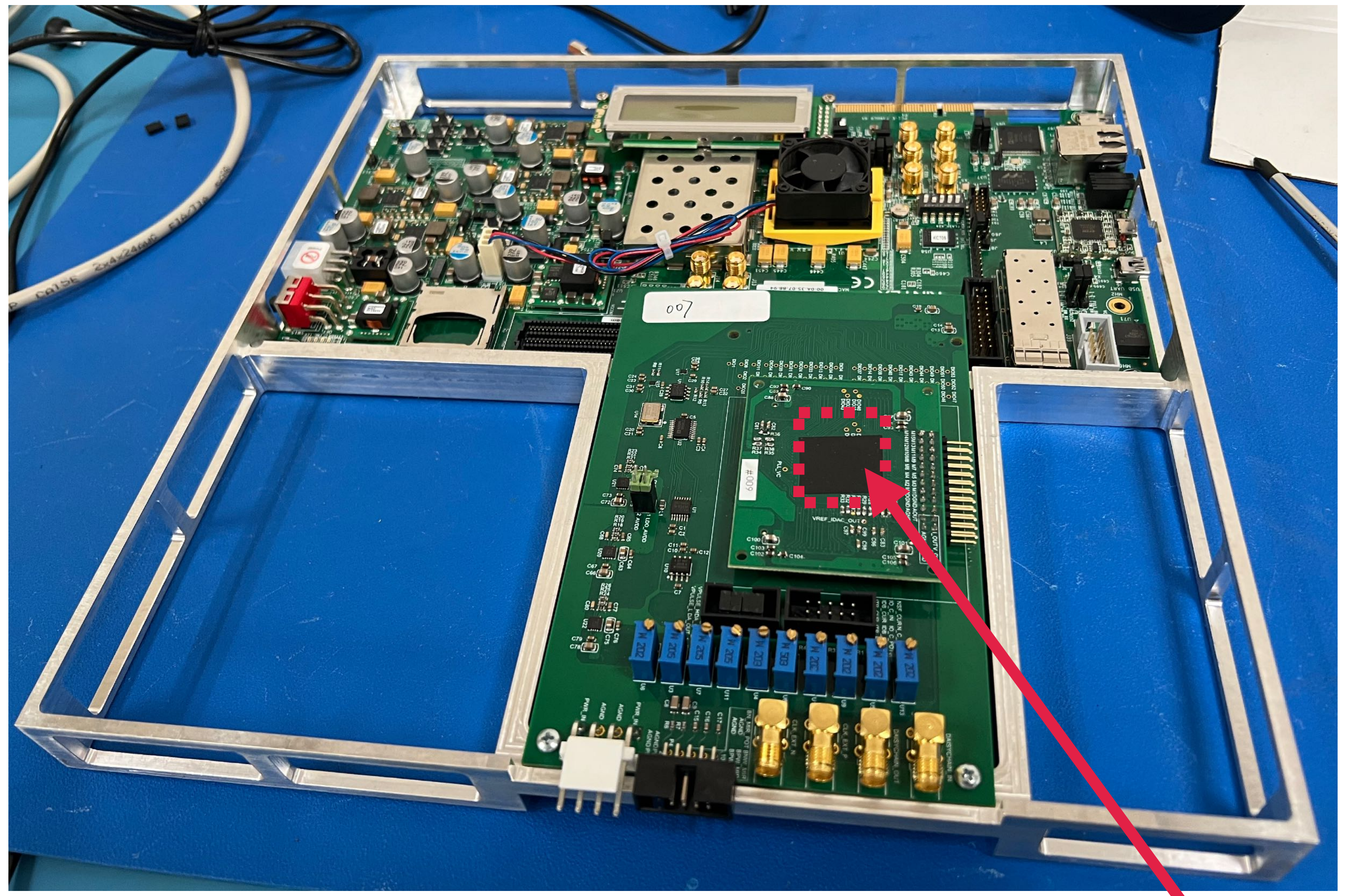


Fig2. Beam test setup at BSRF, 4 planes was equipped.

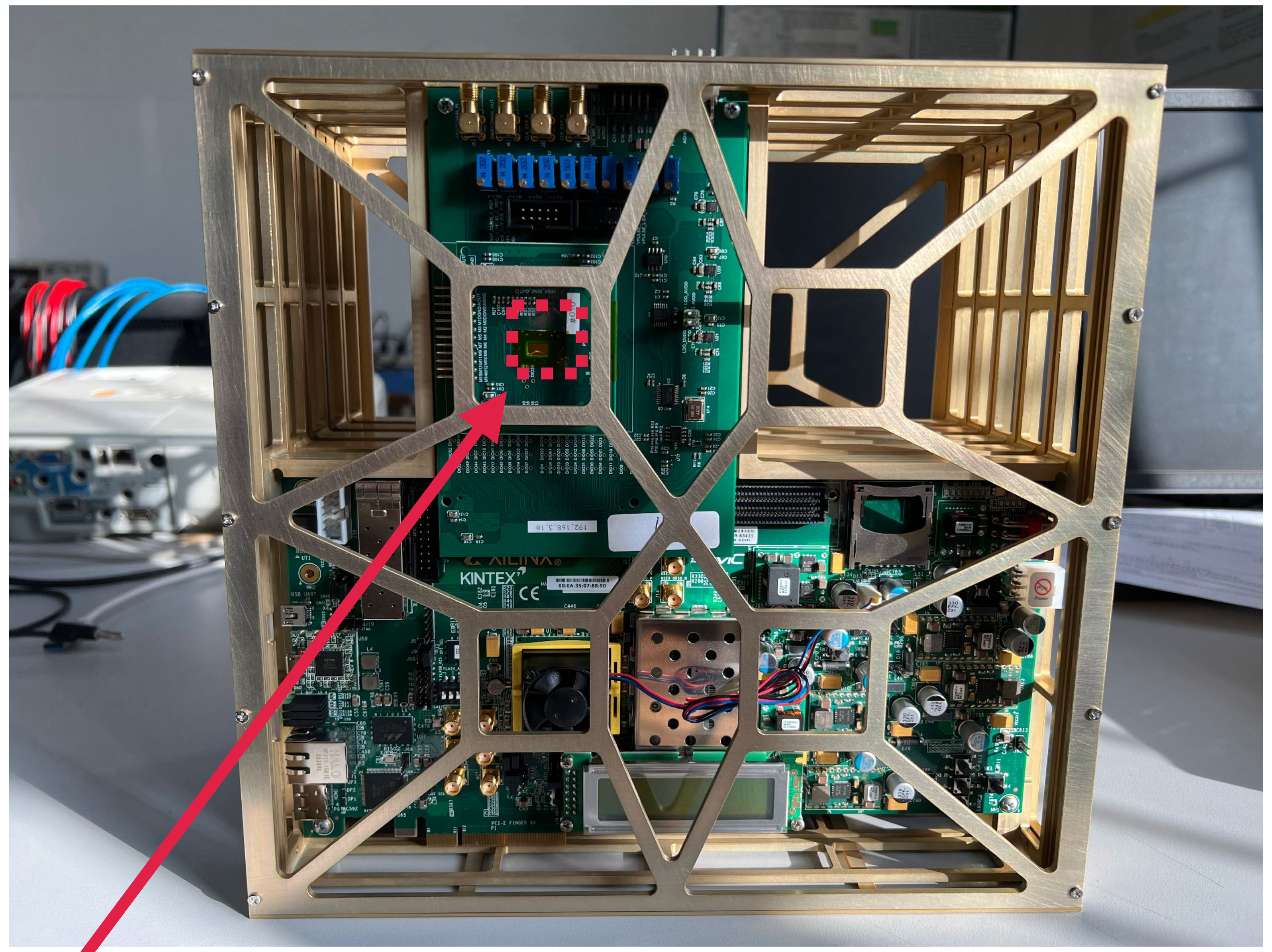
1. Cosmic-ray test use this prototype. Several tracks were found.
2. The clock and synchronization design is developed.
3. IPbus-based DAQ system with multiple clients was developed.

1. Test by an electron beam for the first time at the Beijing Synchrotron Radiation Facility(BSRF).
2. We got 15 thousand trajectories in total (0.1 Hz/cm^2).
3. Corryvreckan was used in offline data analysis for the first time.

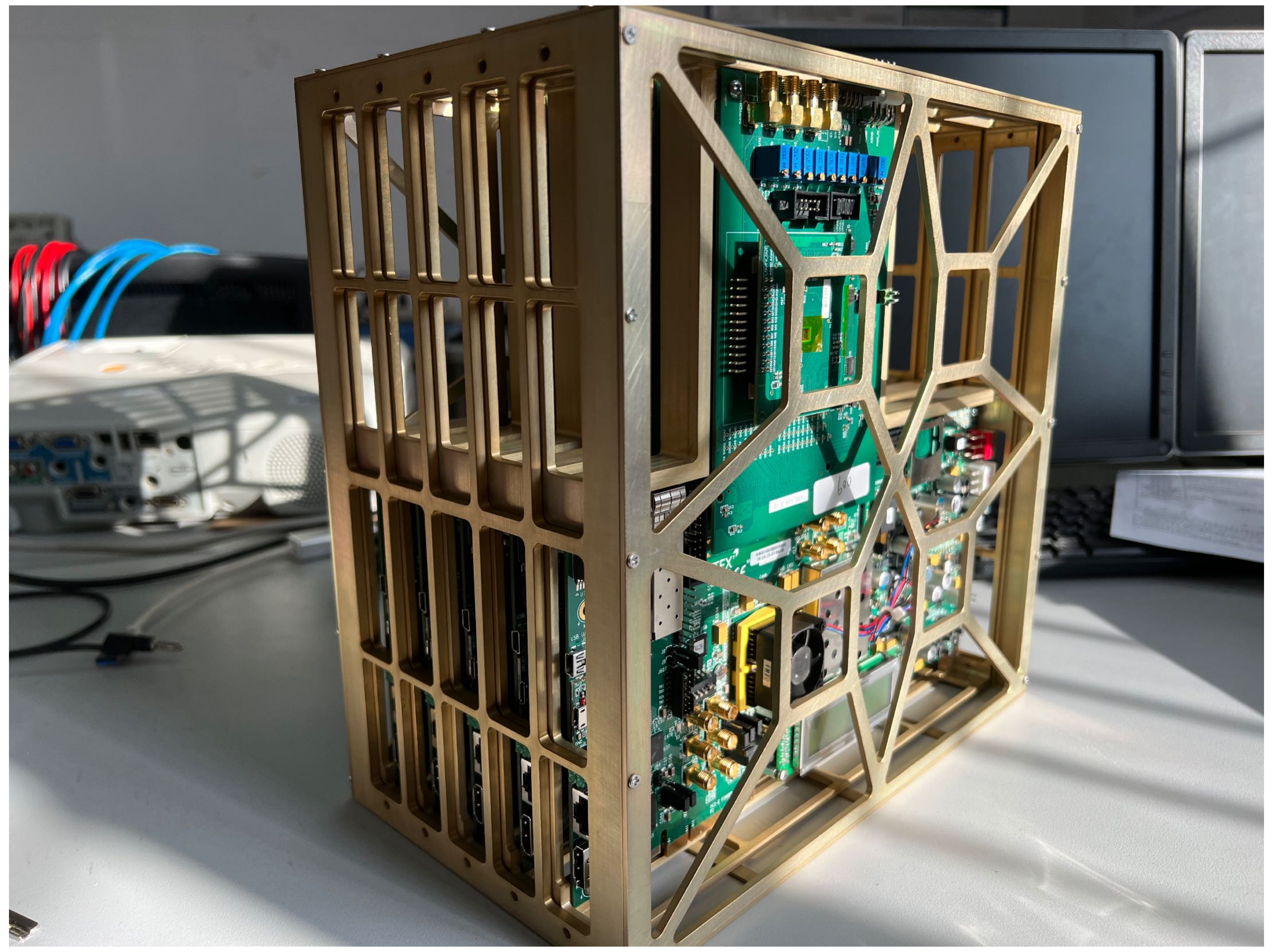
Metal Frame



Signal plane structure



Front view



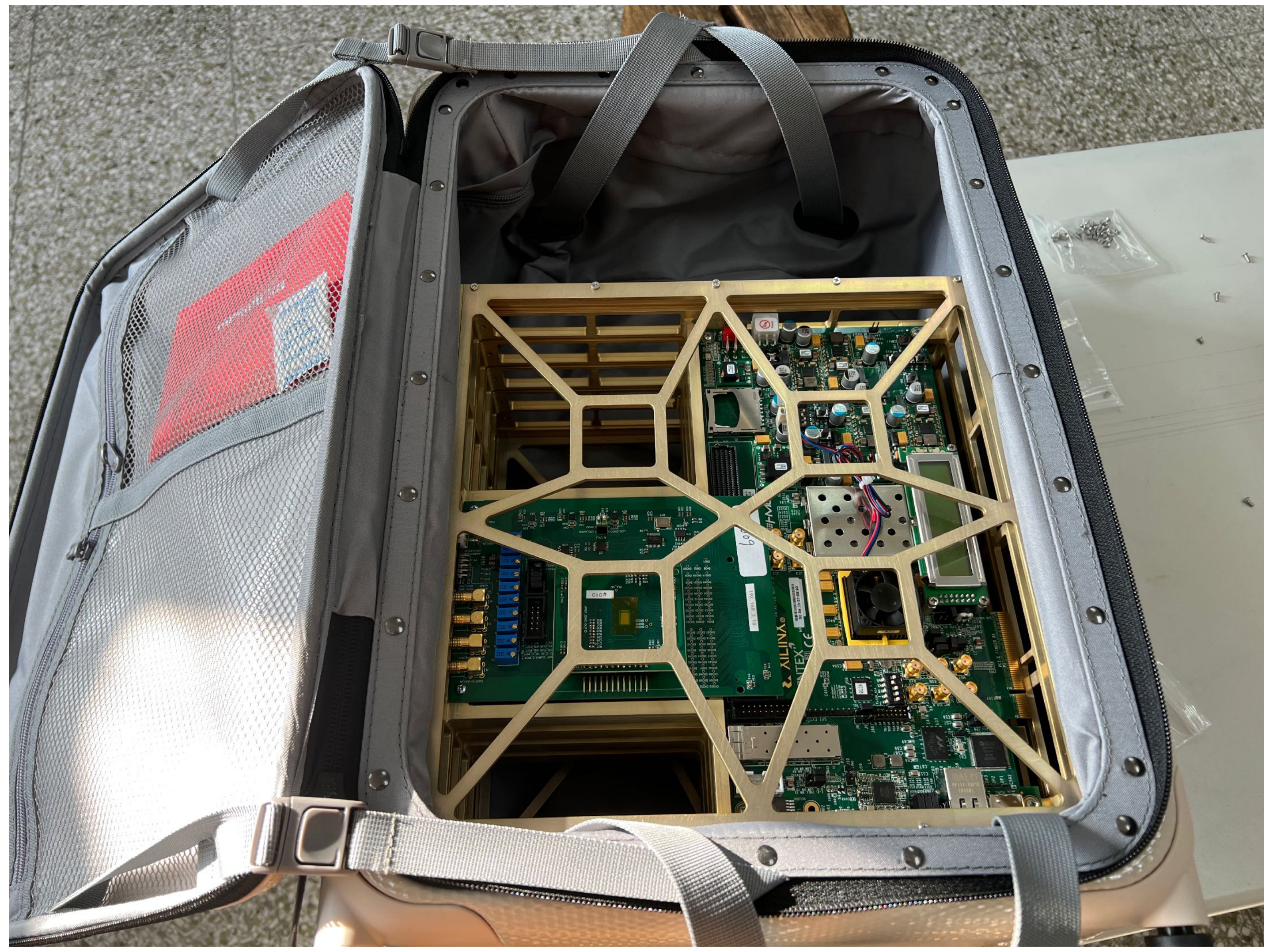
Side view

Sensor

For protection and transportation:

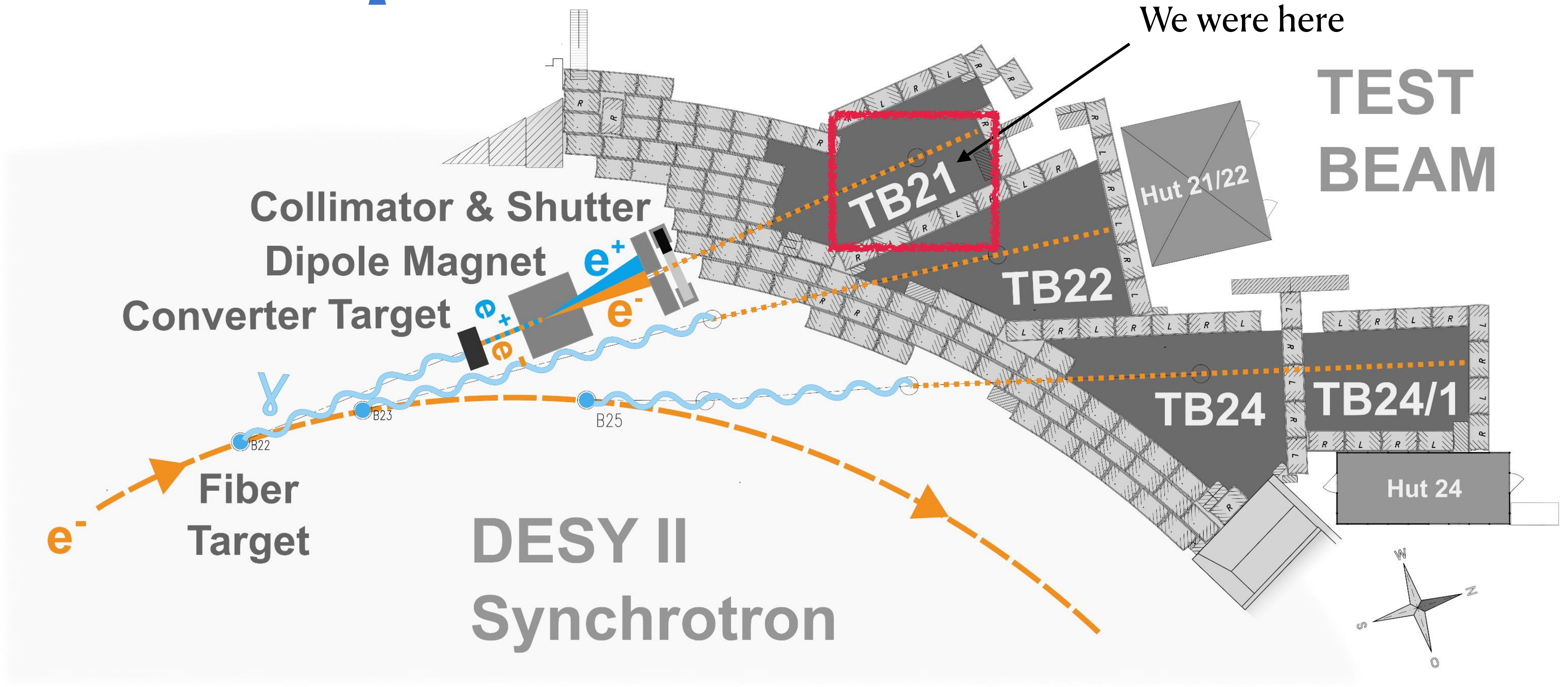
We designed and produced a metal frame (magnesium–aluminum alloy).

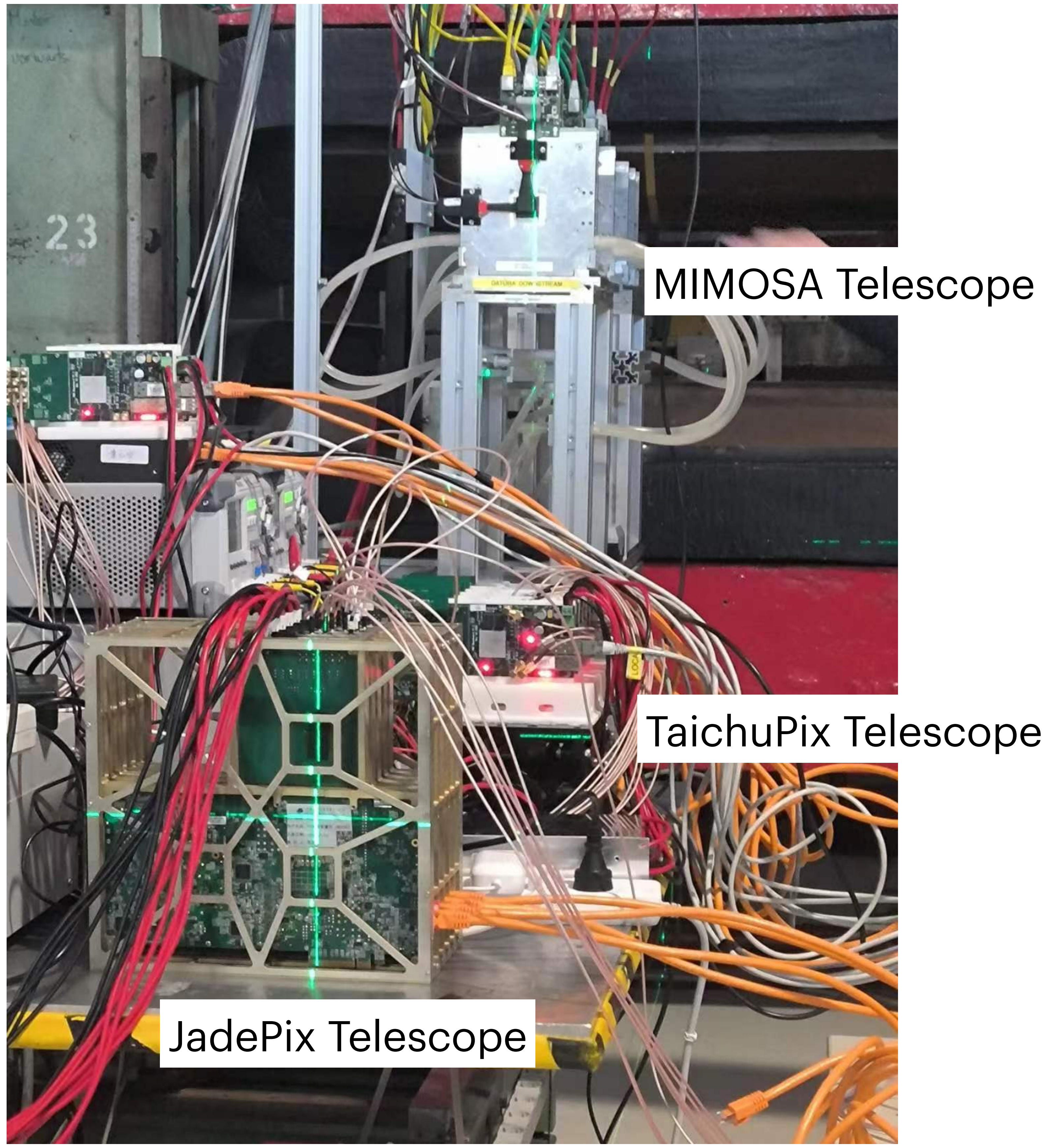
Maximum of 5 planes can be equipped.



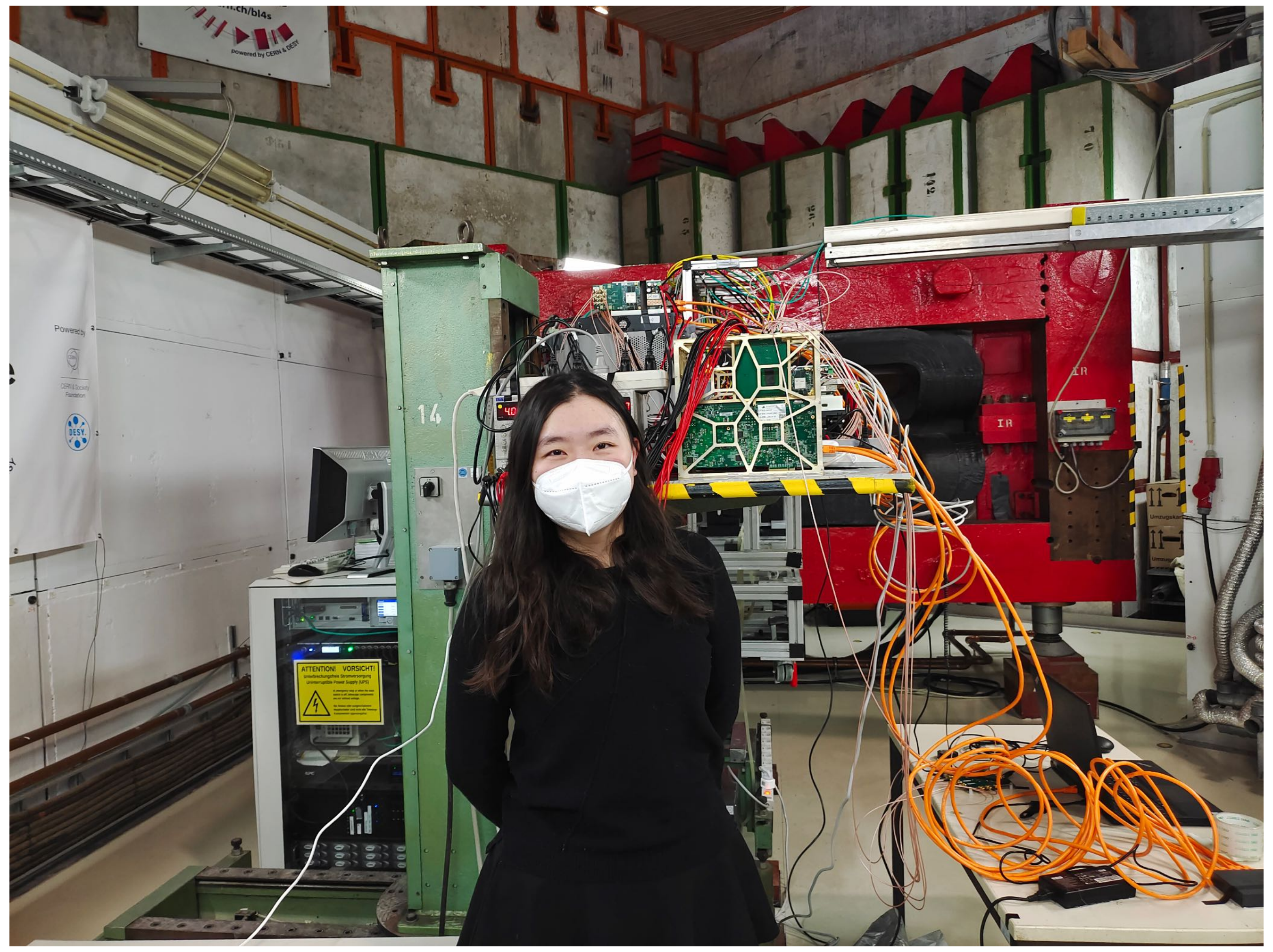
Good for transportation

Test Setup at DESY TB21



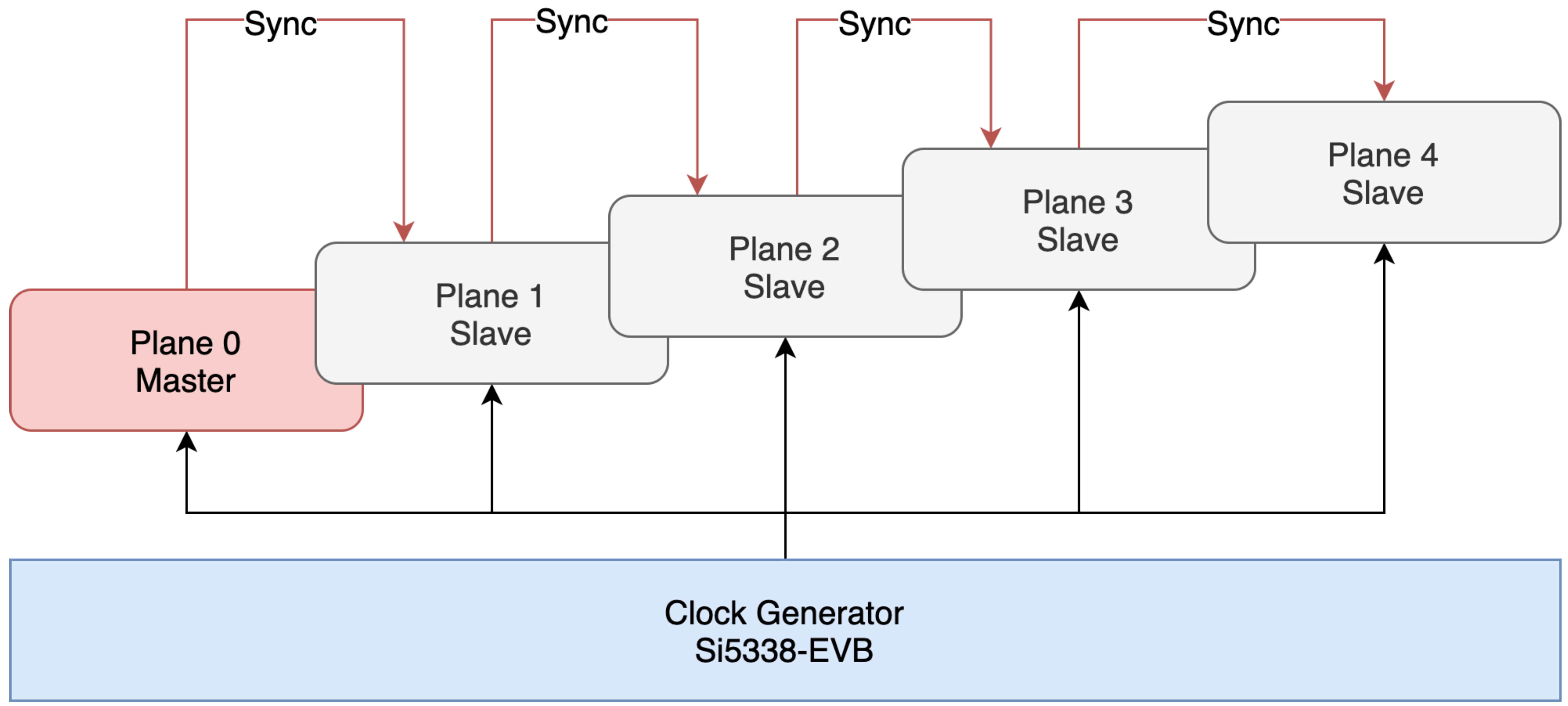


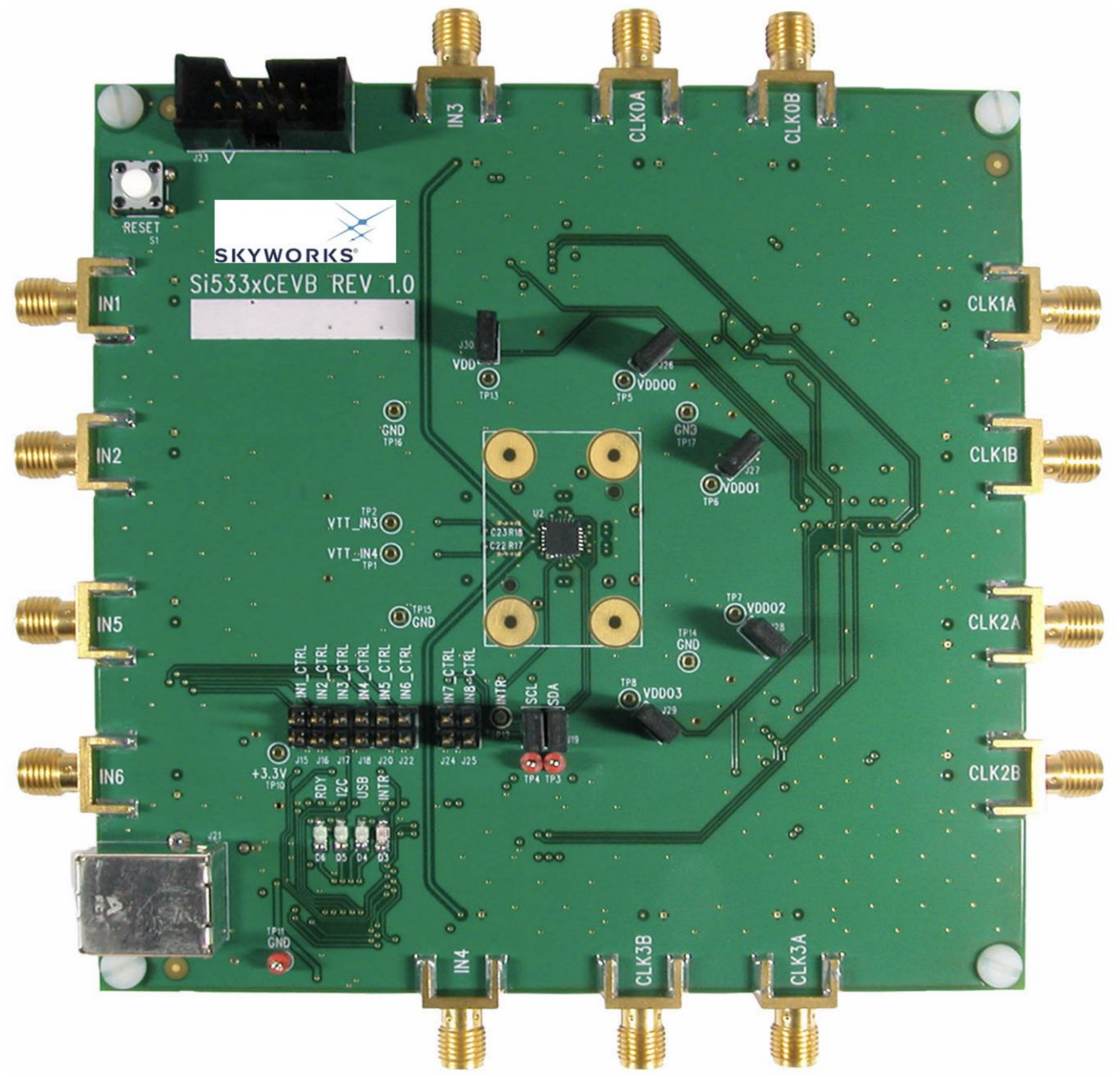
Test Setup @DESY Dec.2022



- The electron or positron beams are converted bremsstrahlung beams from carbon fibre targets in the electron–positron synchrotron DESY II.
- up to 1000 particles per cm^2 and energies from 1 to 6 GeV, an energy spread of ~5% and a divergence of ~1 mrad.
- 5 layers of MIMOSA
- 6 layers of TaichuPix–3
- 4 layers of JadePix–3
- Due to various reasons, our DAQ system was operated remotely in China.

The Clock and Synchronization design





The commercial clock generator (SI5338x–EVB)

Clock: A commercial clock generator is adopted to distribute the synchronization clocks for telescope planes.

- However, the clock generator was broken during the beam test, and independent clock sources on FPGA boards were used, which made offline data analysis more complicated.

Synchronization signal:

- At first, a plane is configured as master, the master receive a software sync signal and convert it to a hardwired signal.
- The hardwired synchronization signal is transferred from the master plane to the last plane via a daisy–chain structure.

Si5338–EVB

Clock Issue

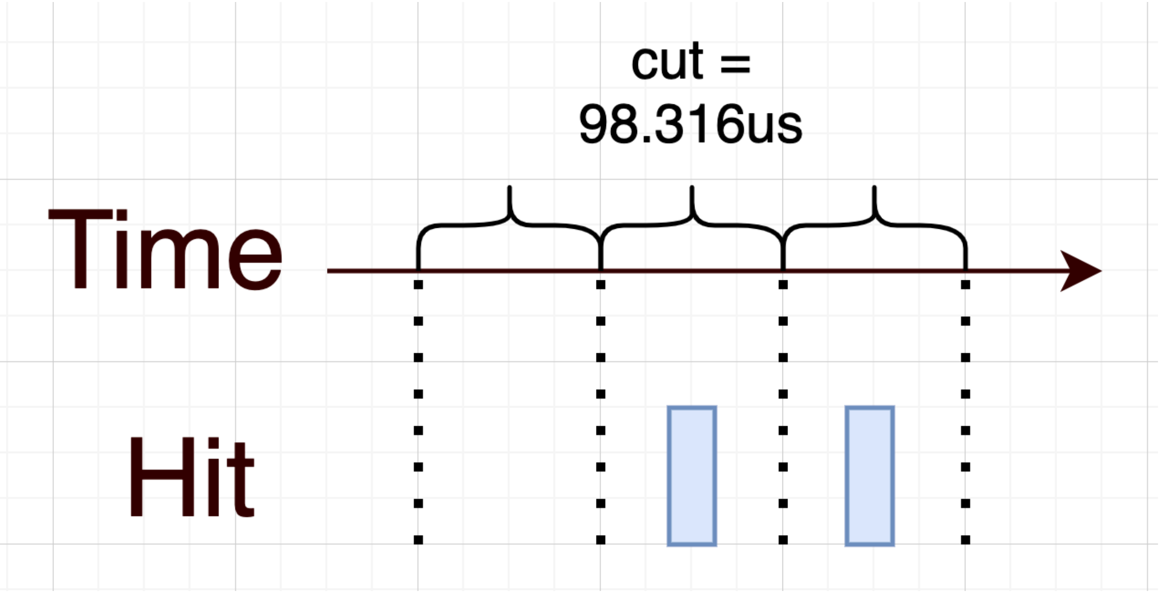


Fig.1 Normal time cut.

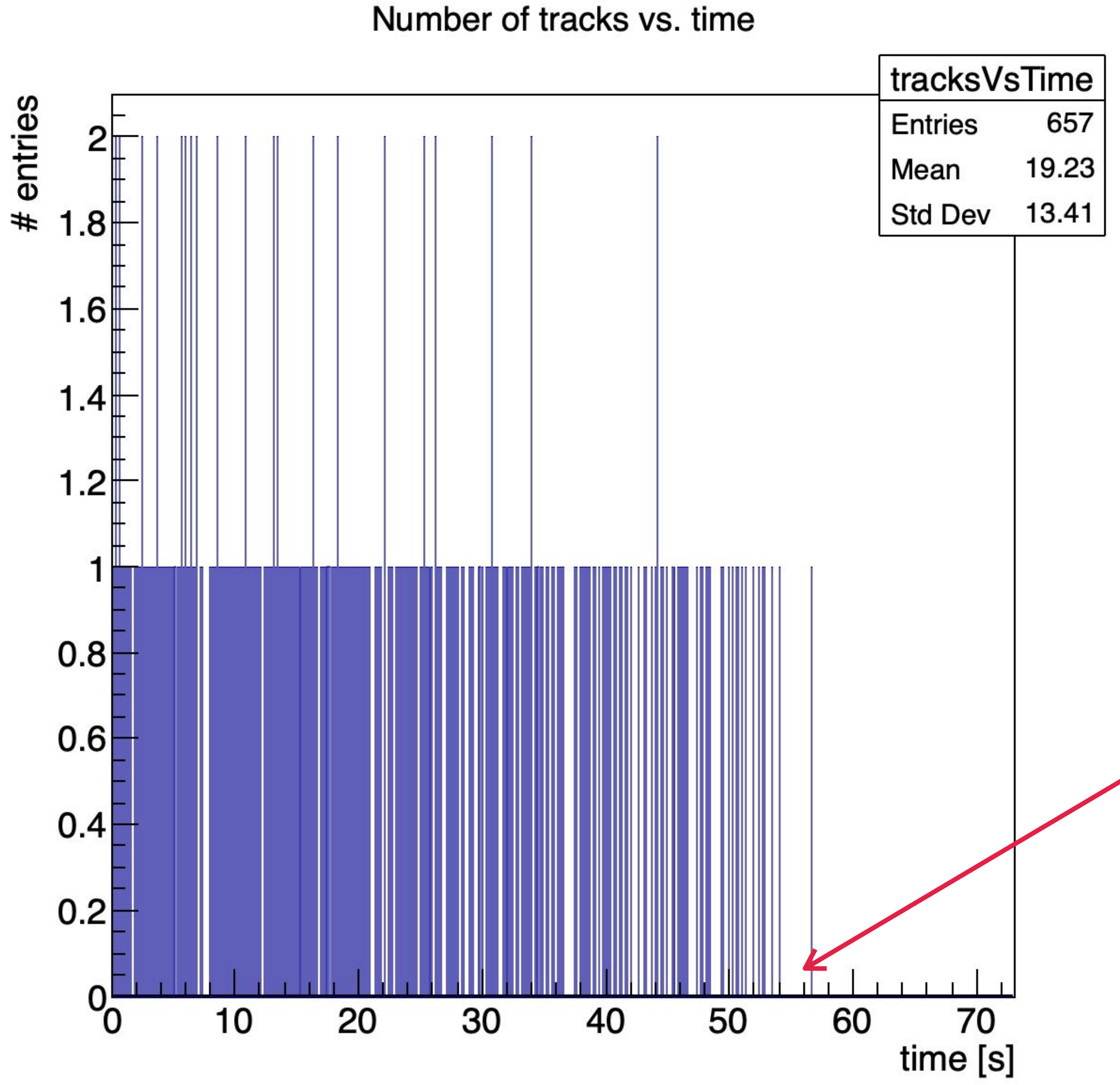
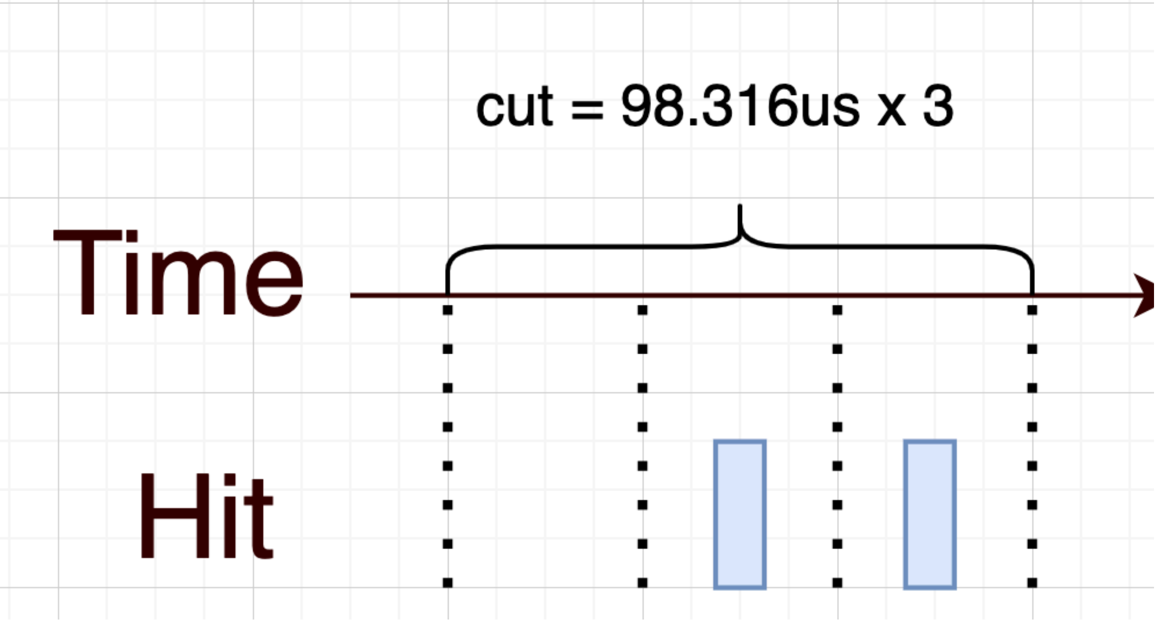


Fig.2 The number of tracks vs time.

- Loss track soon after 50 seconds.

- For frame-based DAQ system, the time cut of tracking should be the frame period.
- But with this time cut, we will loss track soon because of the time offset will accumulated and be lager than the time cut soon.

- It's hard to **fix time offset,** but expanding the time cut length can <u>**reduce**</u> the impact, by this, we can recover some tracks.
- Figure 3 shows the tracks between 50s and 120s are recovered.
- We can not recover all the tracks, nevertheless, the amount of data required for most analytical tasks is sufficient.



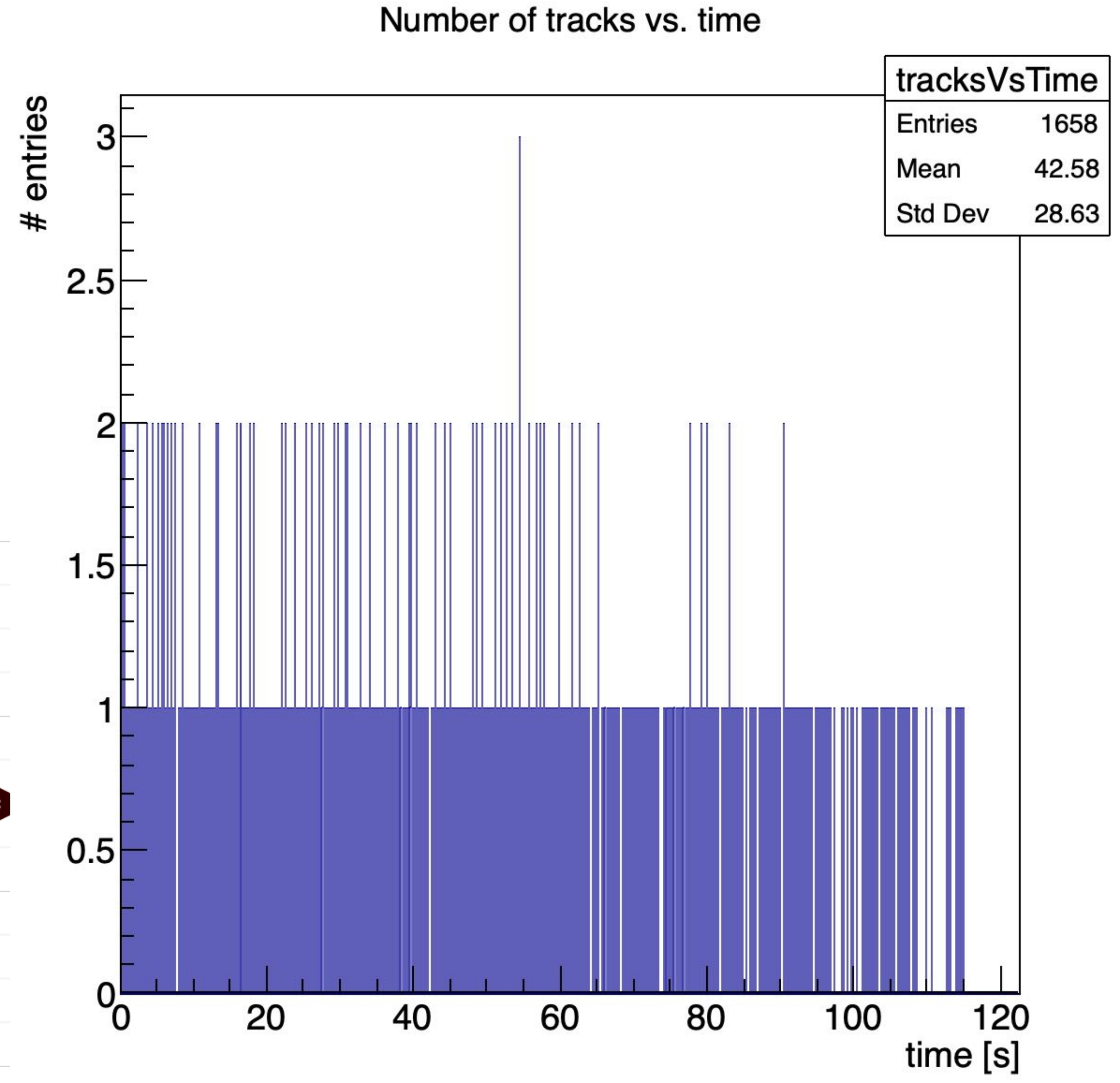


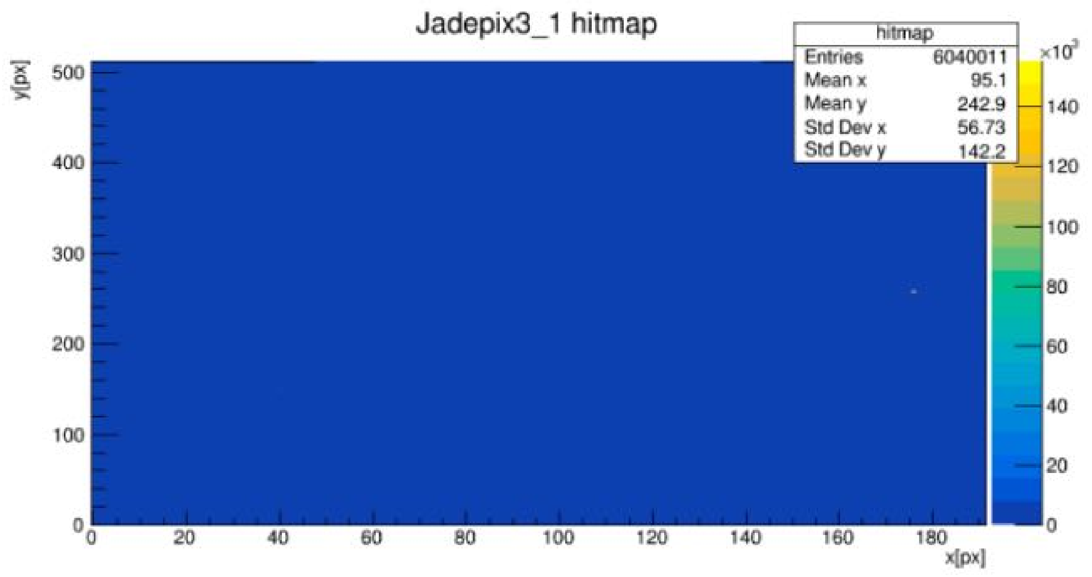
Fig.3 Tracks between 50s and 120s are recovered.

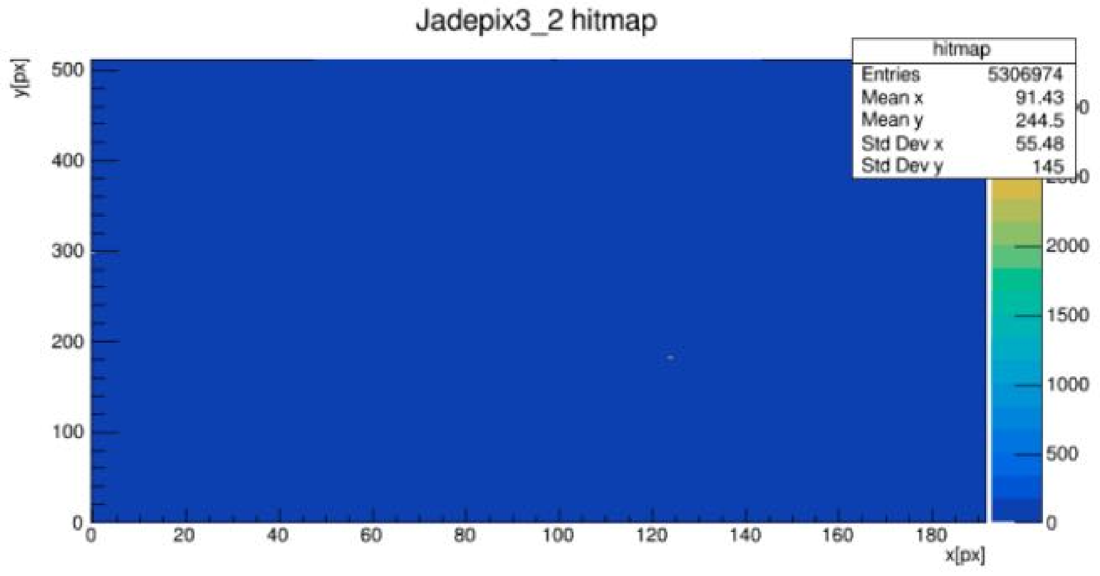
Mask Noise Pixel (First data processing)

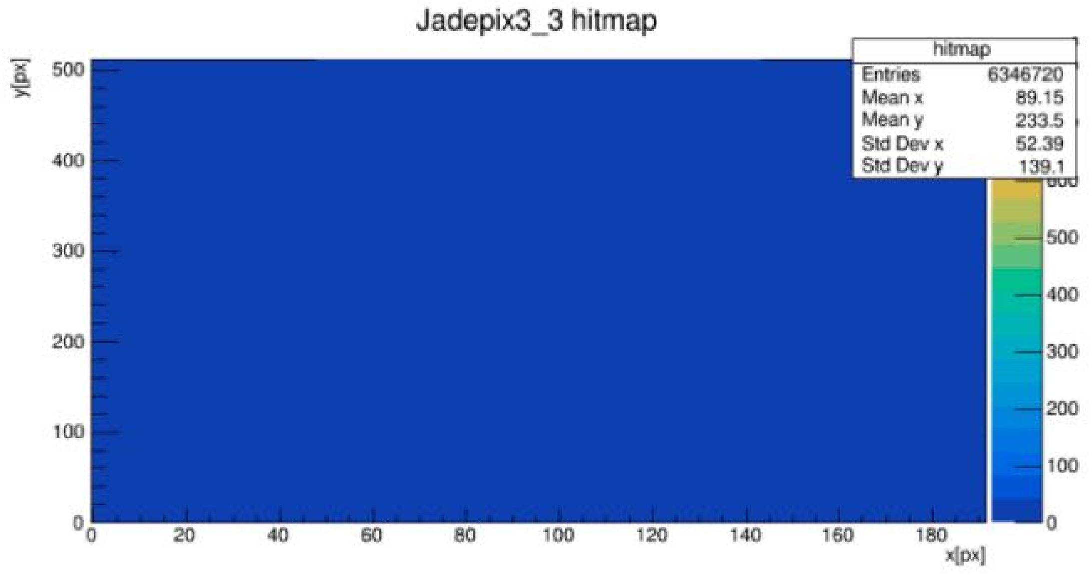
- Method: define a cut on a global pixel firing frequency. We mask pixels with a hit rate larger than $frequency\_cut \times mean\ global\ hit\ rate$
- By this method 6 pixels are selected as noise pixel, with $frequency\_cut = 50$

```
plane1 [41, 150] 1.0
plane1 [177, 259] 1.0
plane2 [38, 4] 1.0
plane2 [125, 183] 1.0
plane3 [70, 145] 1.0
plane3 [87, 343] 1.0
plane3 [100, 404] 1.0
```

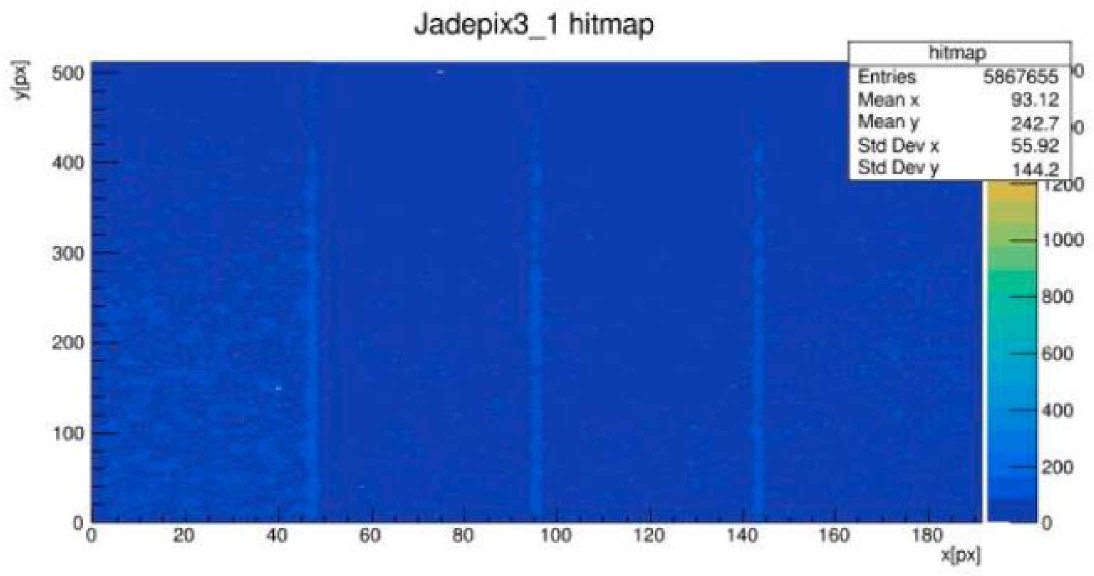
Hitmap of raw data.

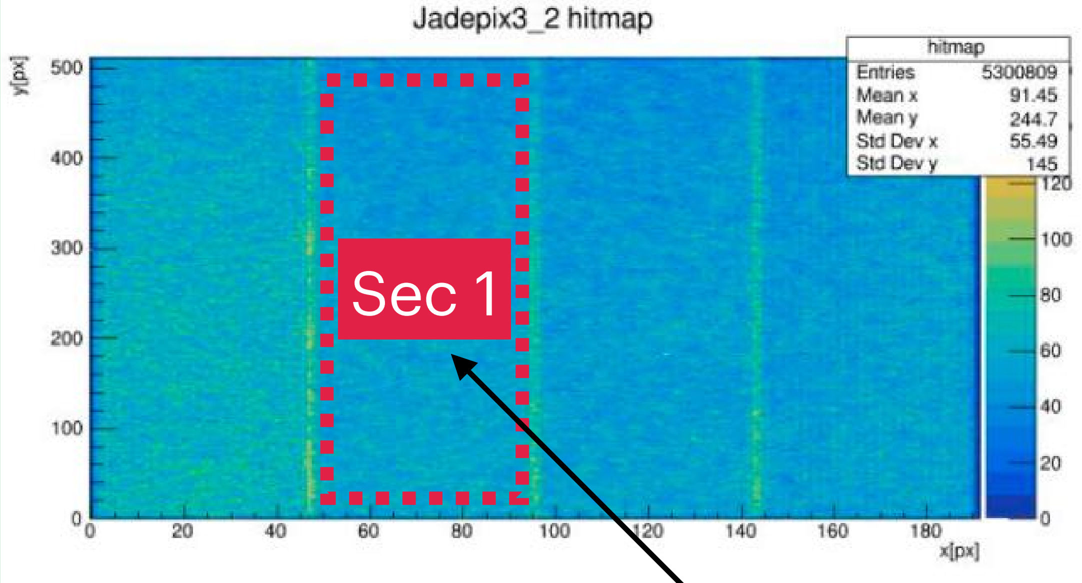


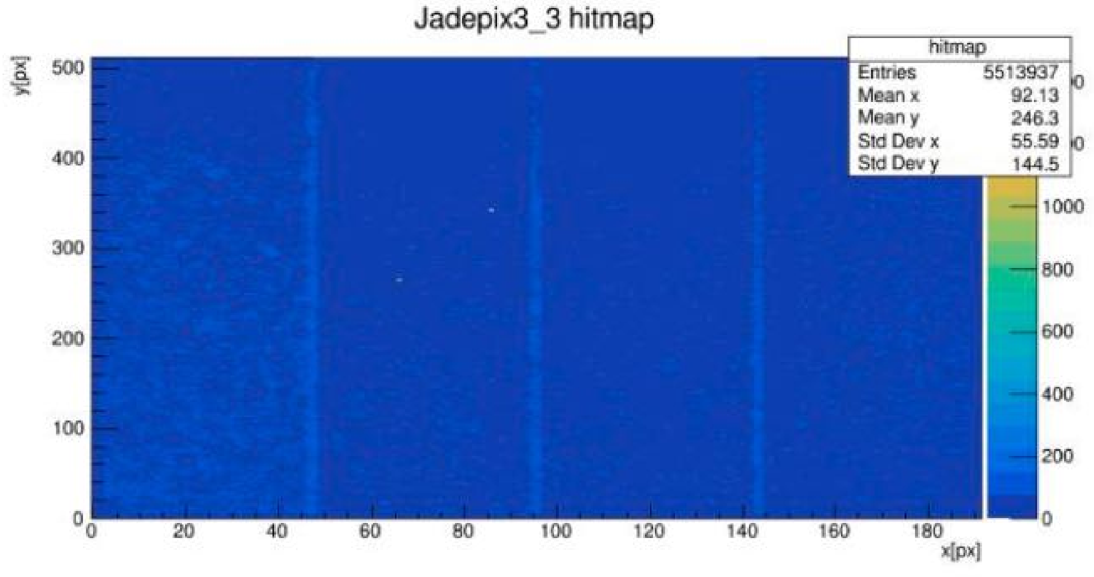




Hitmap after masking 6 noise pixels, the boundaries of 4 sectors are revealed. (Prove the sensor noise is quite low.)







The region of interest (**ROI**)

- To reduce the complexity of the data analysis, sector 1 is chosen as the region of interest, so the influence of sector boundaries and the different pixel sizes of sector 2 can be masked.

Cluster Size Results

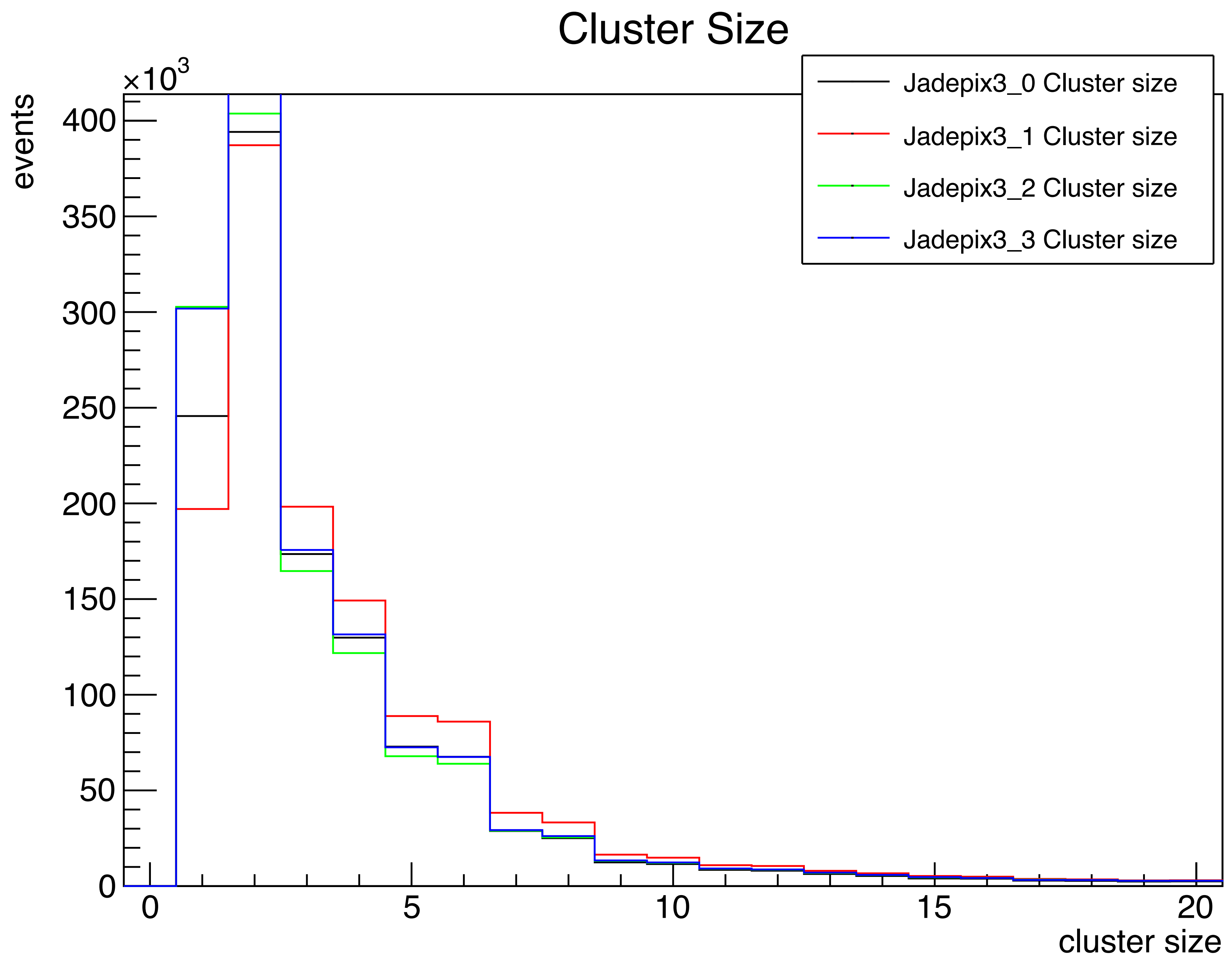


Fig.1 The cluster size distribution of 4 planes.

The mean cluster size of each plane:

3.4, 3.8, 3.4, 3.4

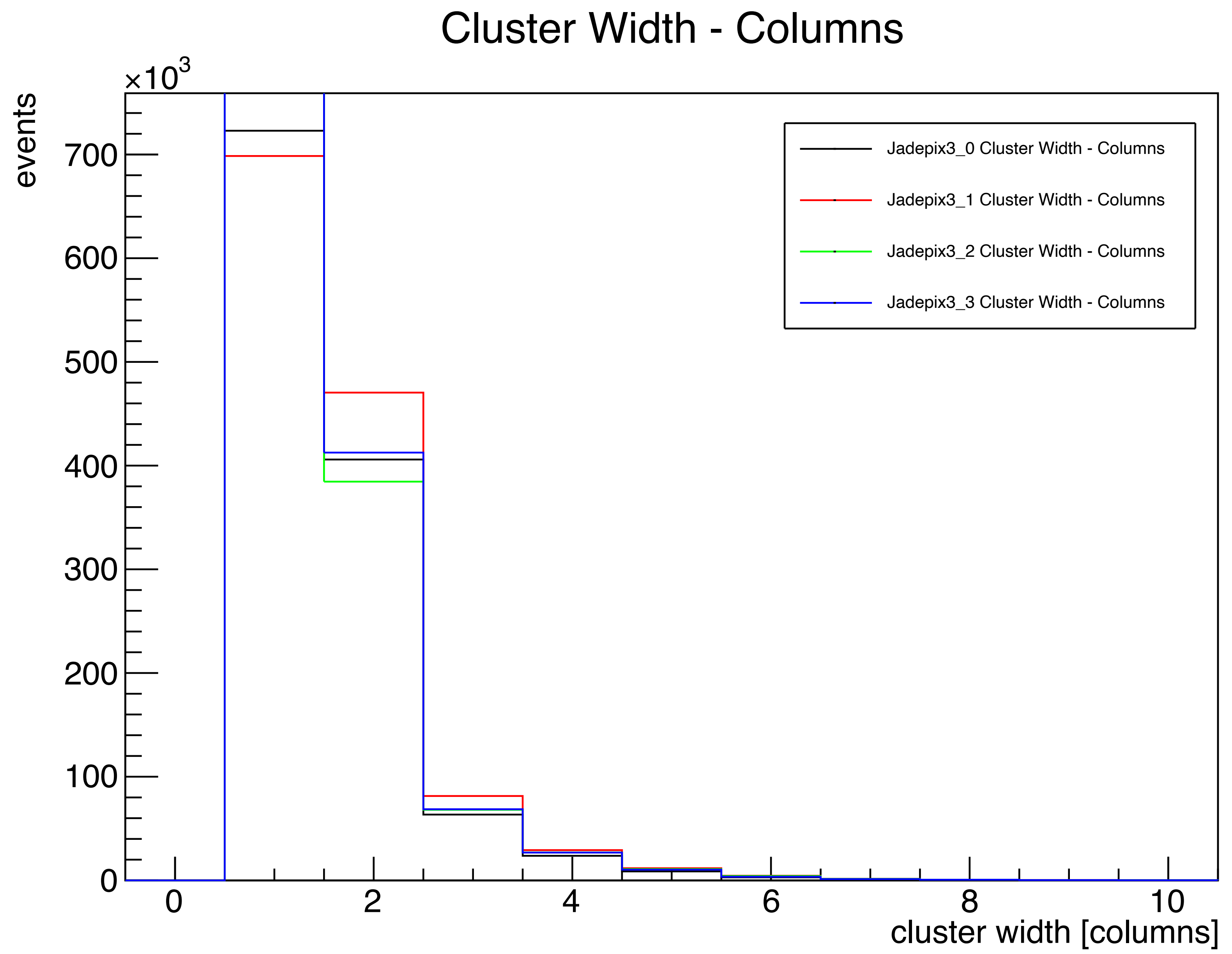


Fig.2 The cluster width distribution by **row** direction (16um).

The mean width of each plane:

1.5, 1.6, 1.5, 1.5

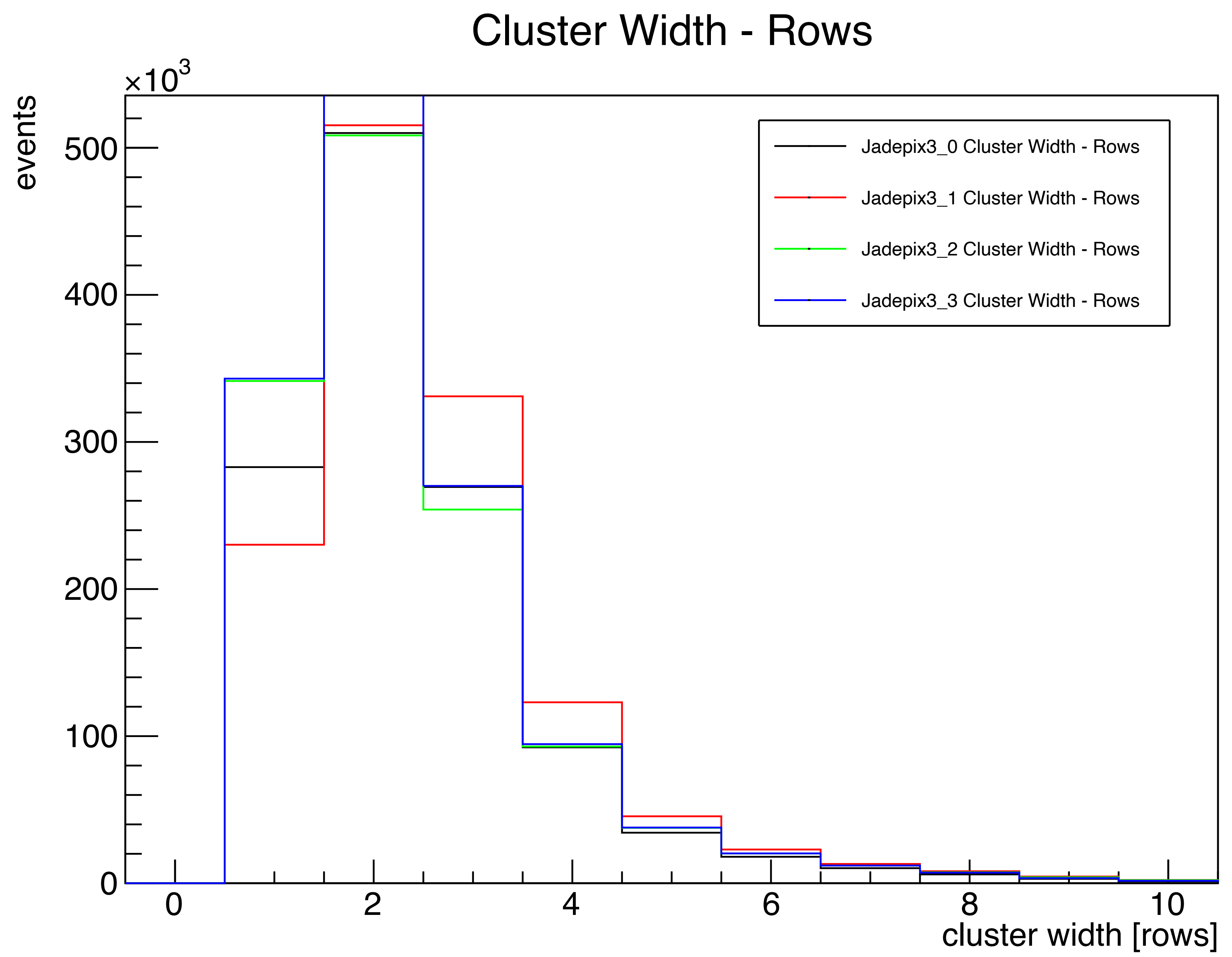


Fig.3 The cluster width distribution by **column** direction (26um).

The mean width of each plane:

2.4, 2.6, 2.3, 2.3

Alignment

The alignment procedure includes 2 steps:

1. Align the telescope plane, and ignore the DUT

- Pre–alignment (x, y geometry)
- Fine alignment (x, y geometry and x, y, z orientation)

2. Align the DUT, and freeze telescope geometry

- Pre–alignment (x, y geometry)
- Fine alignment (x, y geometry and x, y, z orientation)

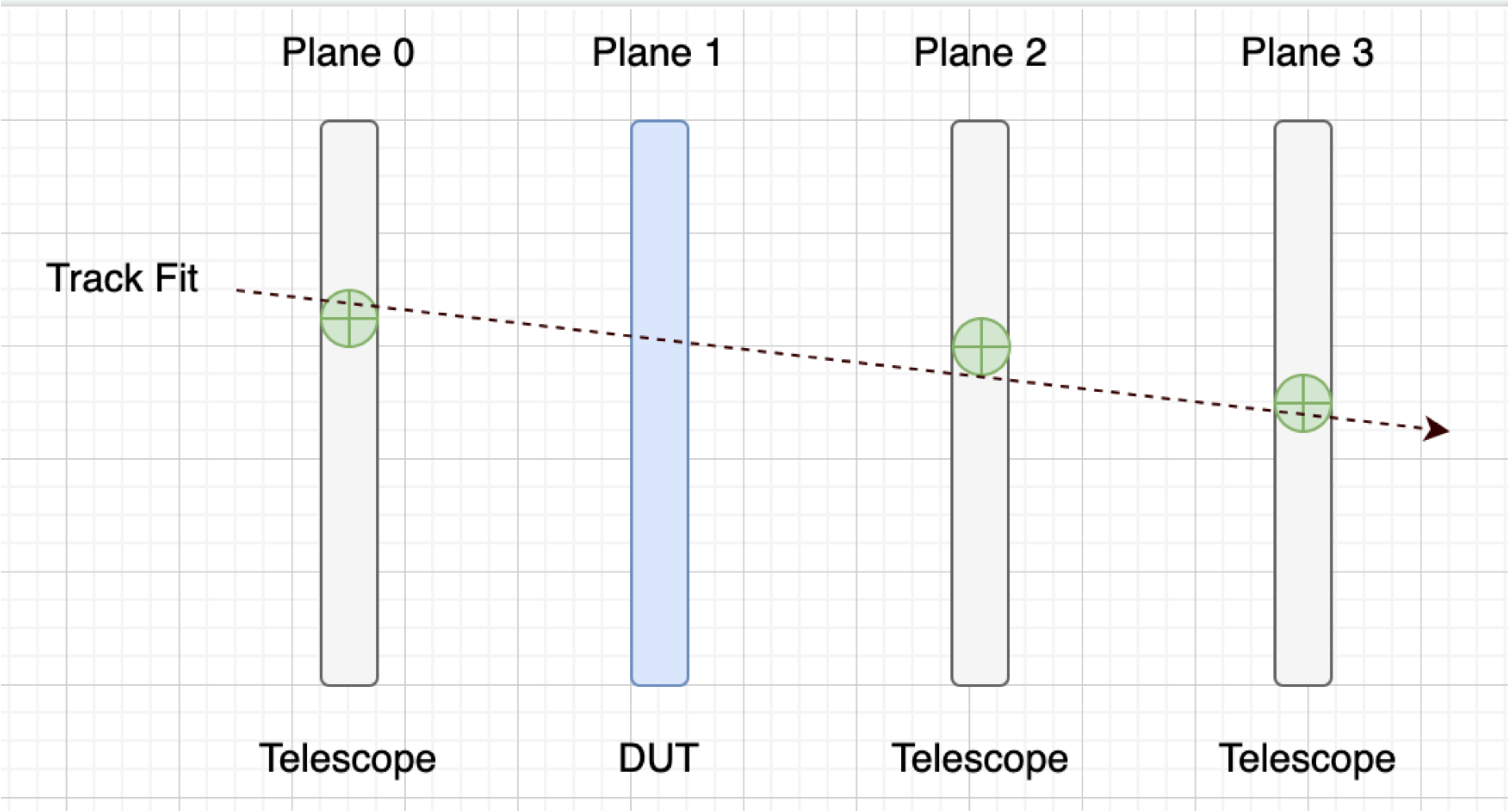


Fig.1 Tracking Fitting

- While tracking, the path of the particle is described as a straight line, **ignoring the effect of multiple scattering**.
- Hit uncertainties are taken into account.
- The χ^2 is defined by the resolution weighted sum of residuals r_p in global coordinates:

$$\chi^2 = \sum_{p=0}^{N} \frac{{r_{p_x}}^2}{\sigma_{p_x}} + \frac{{r_{p_y}}^2}{\sigma_{p_y}}$$

Alignment

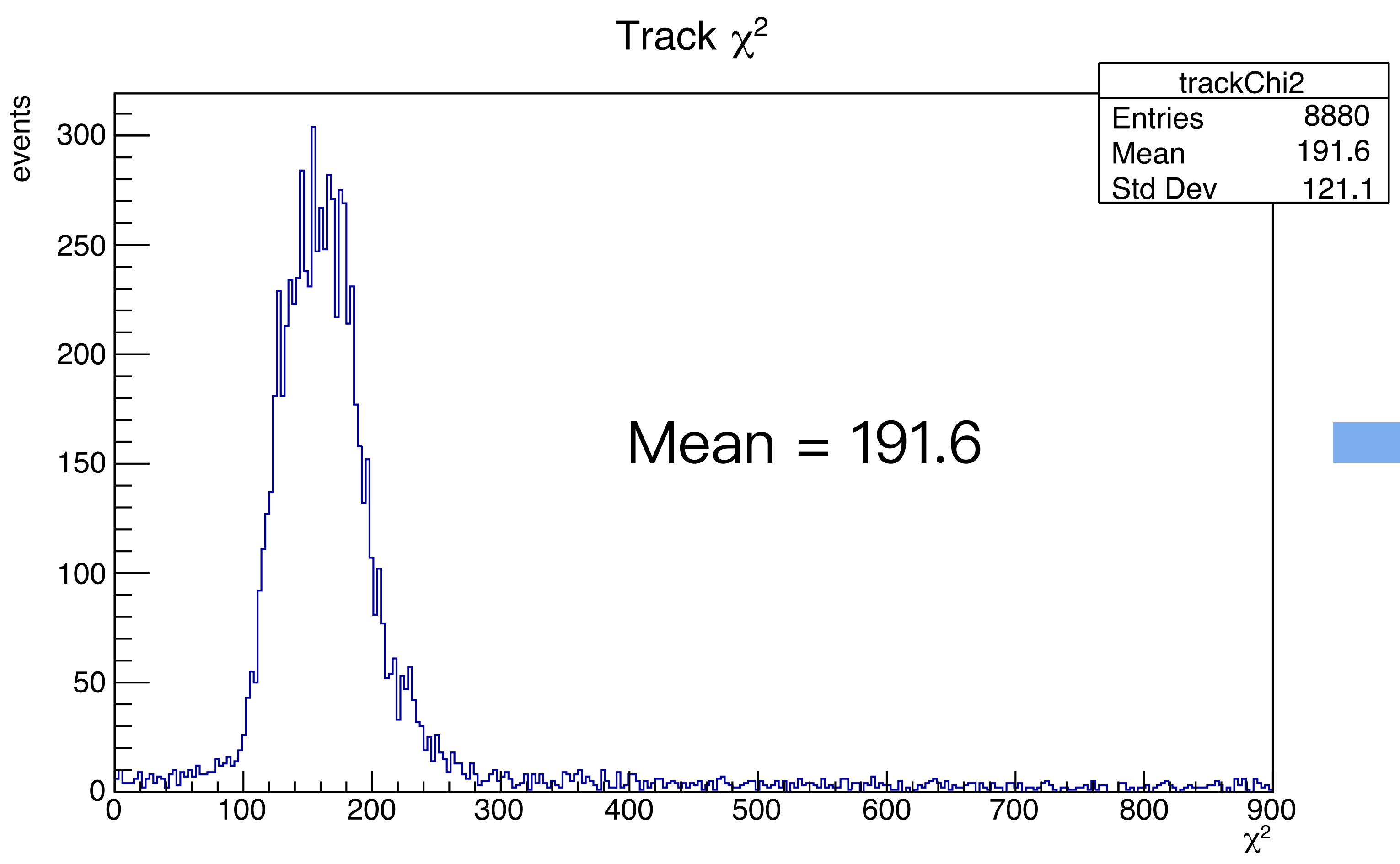
Pre–alignment method:

- Using the mean offset values in X and Y as the required translational shift to update the geometry.

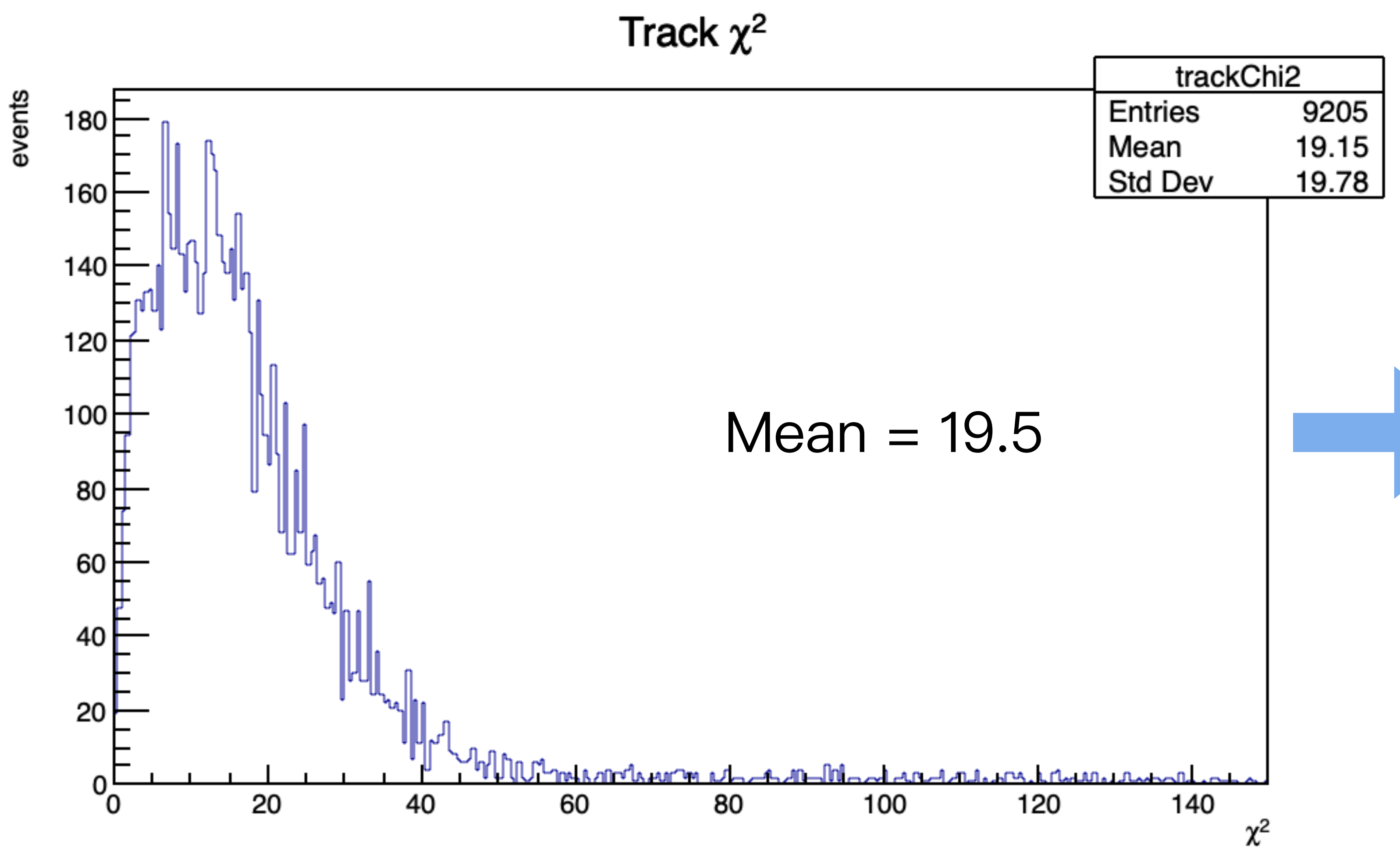
Alignment method:

- Perform translational alignment and rotational alignment using tracks
- Refit all of the tracks and the minimize the χ^2 of tracks

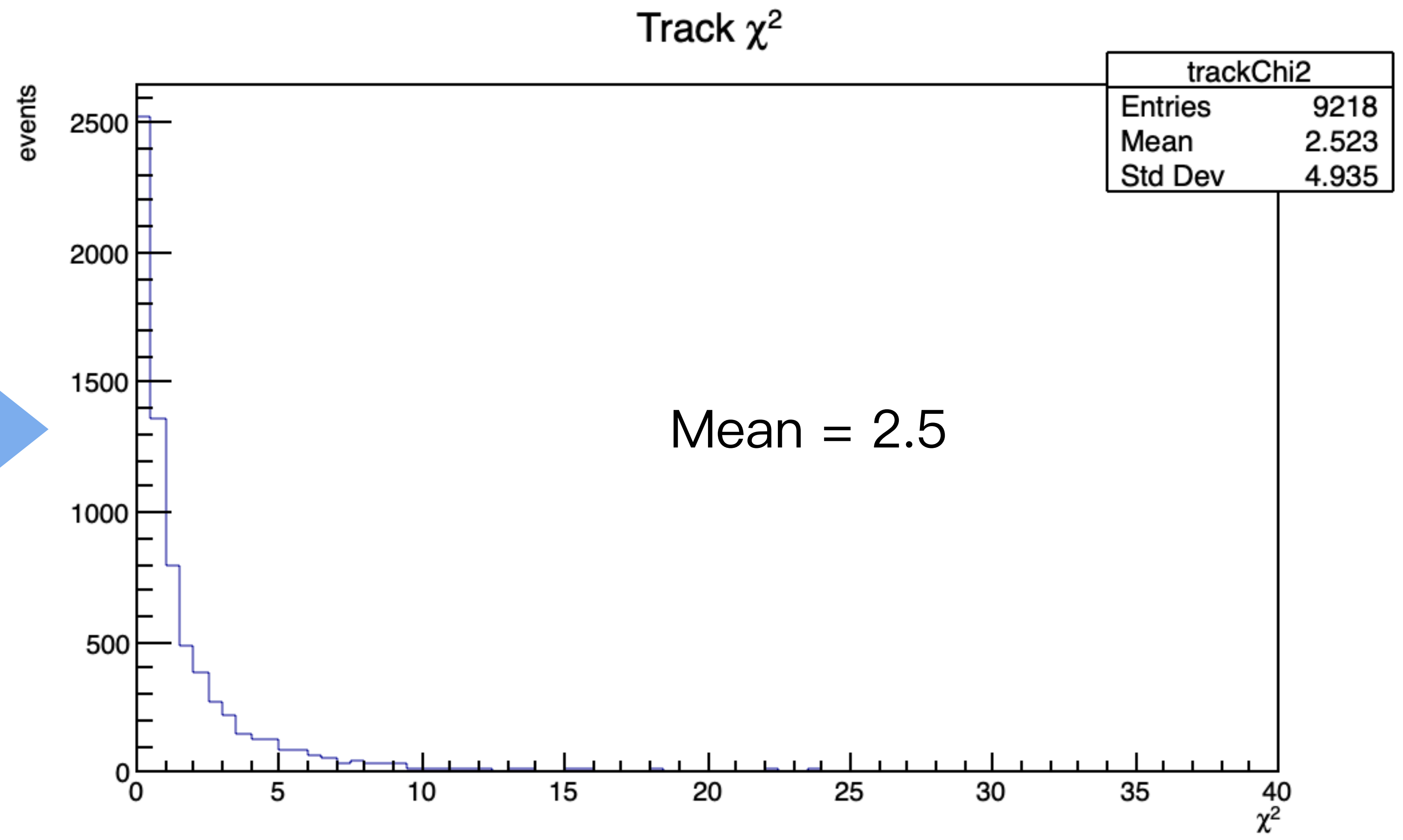
The mean value of χ^2 distribution will drop very significantly after alignment. (191.5 –> 19.5 –> 2.5)



χ^2 distribution before pre–alignment

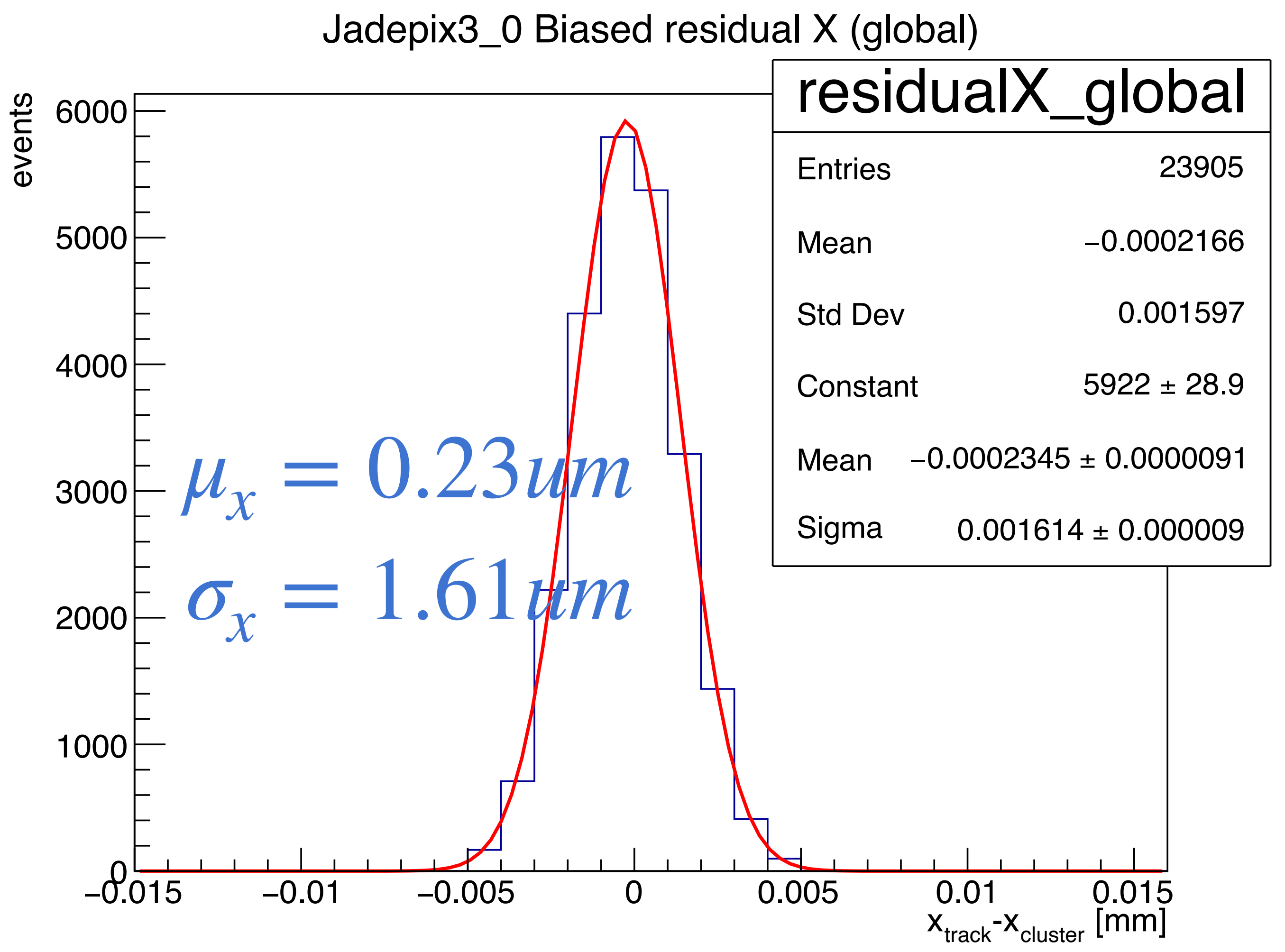


χ^2 distribution after pre–alignment

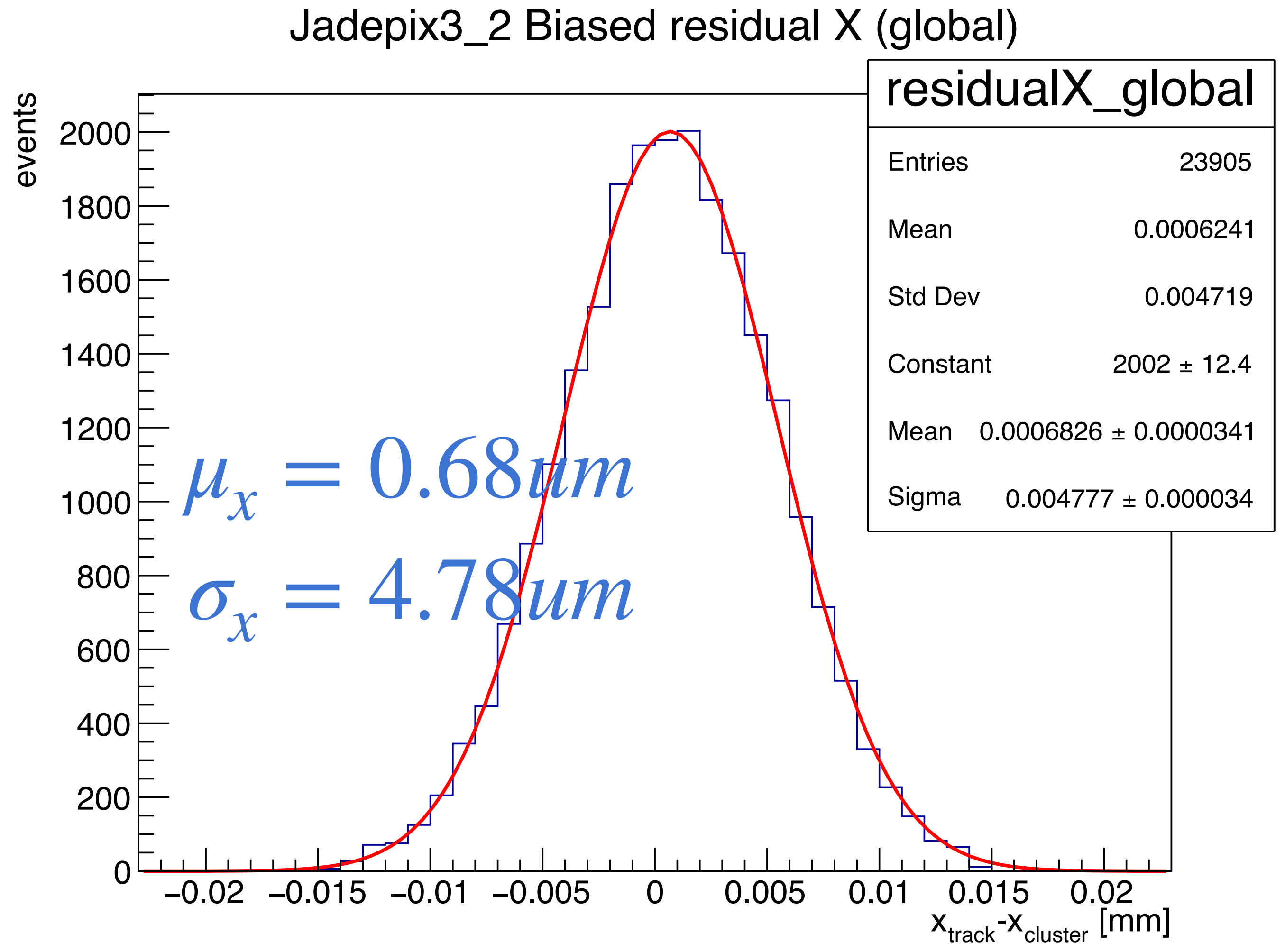


χ^2 distribution after fine–alignment

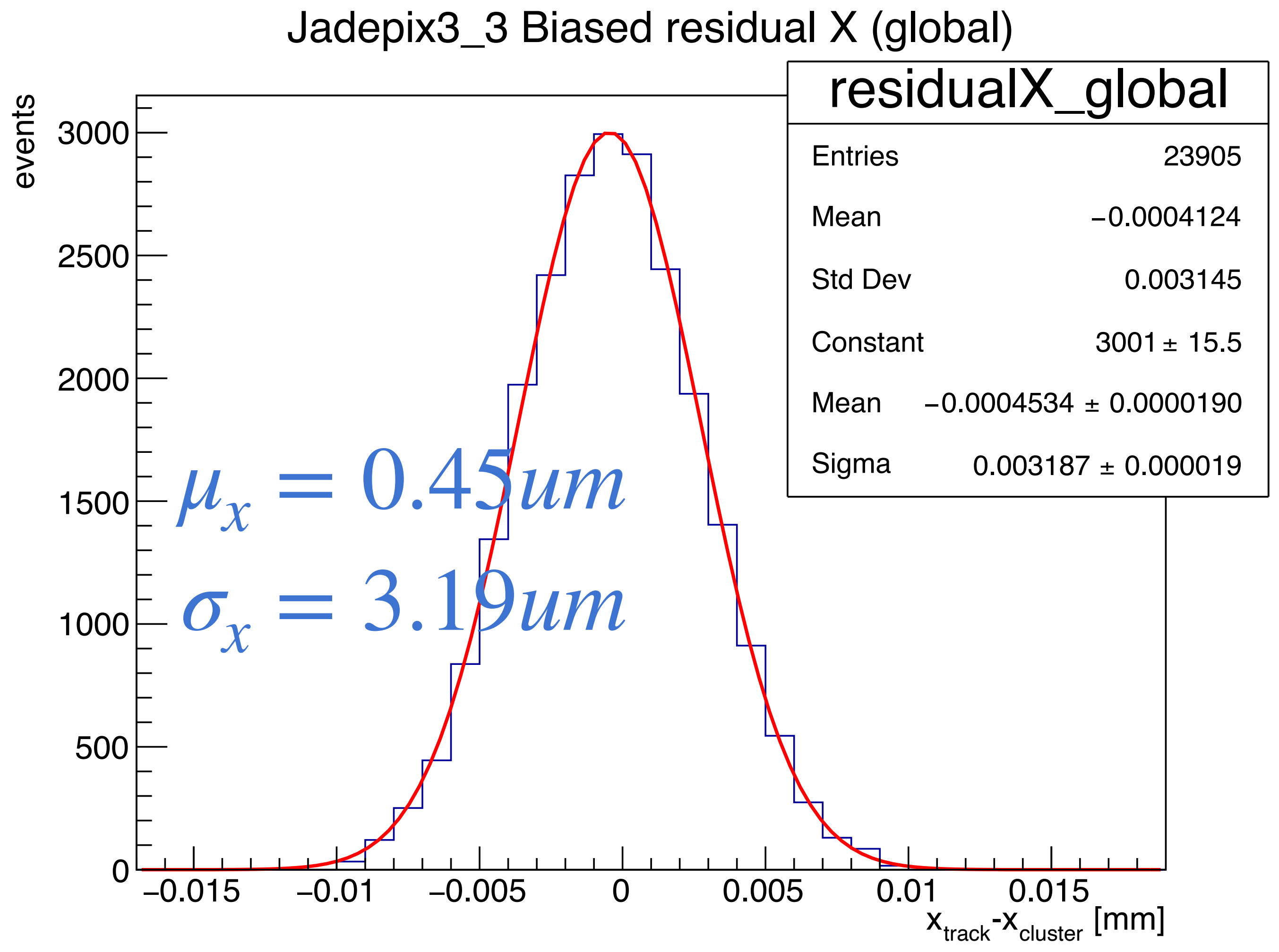
Biased Residual Distribution of Telescope Planes



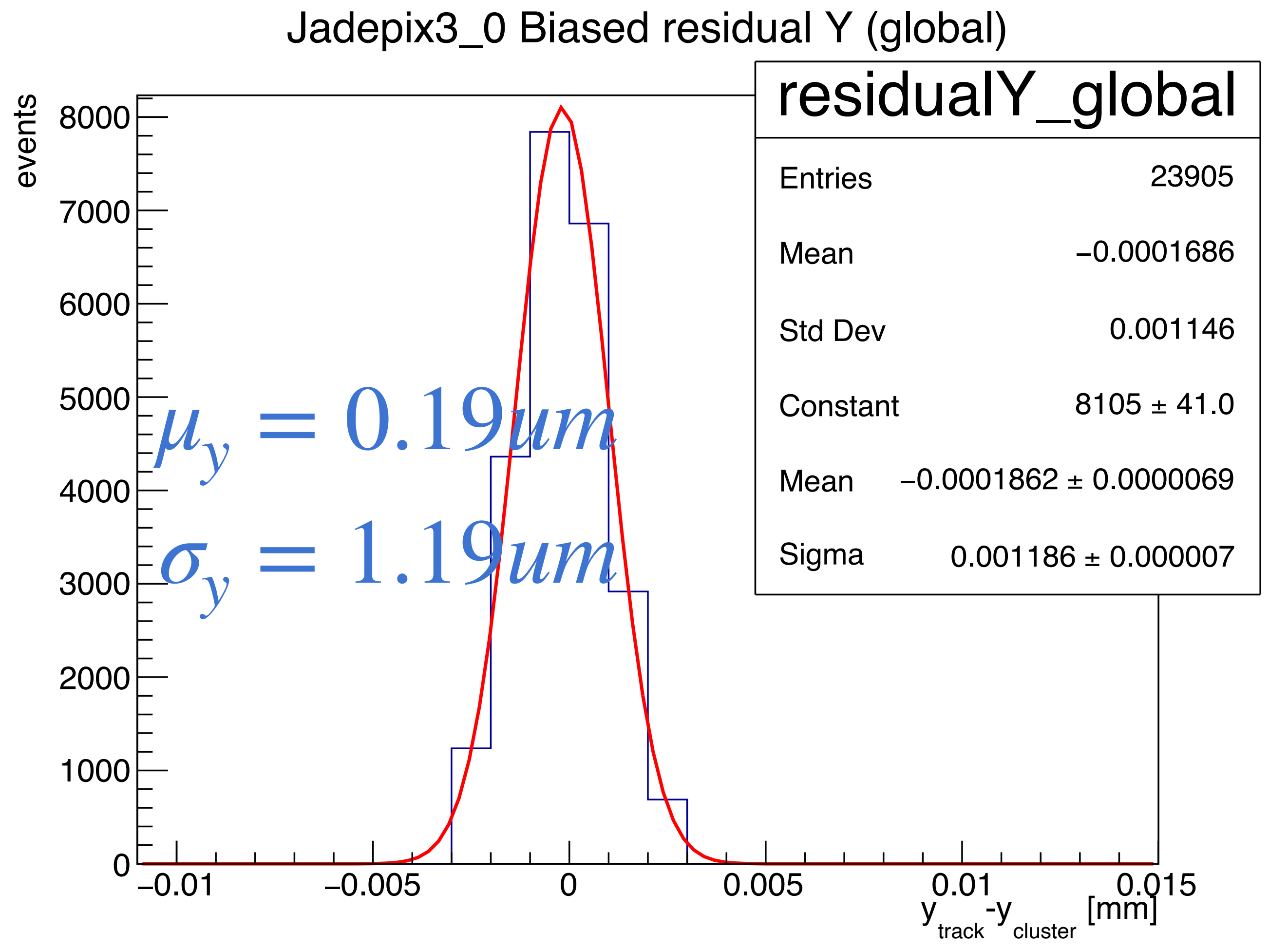
Residual Plane0 X



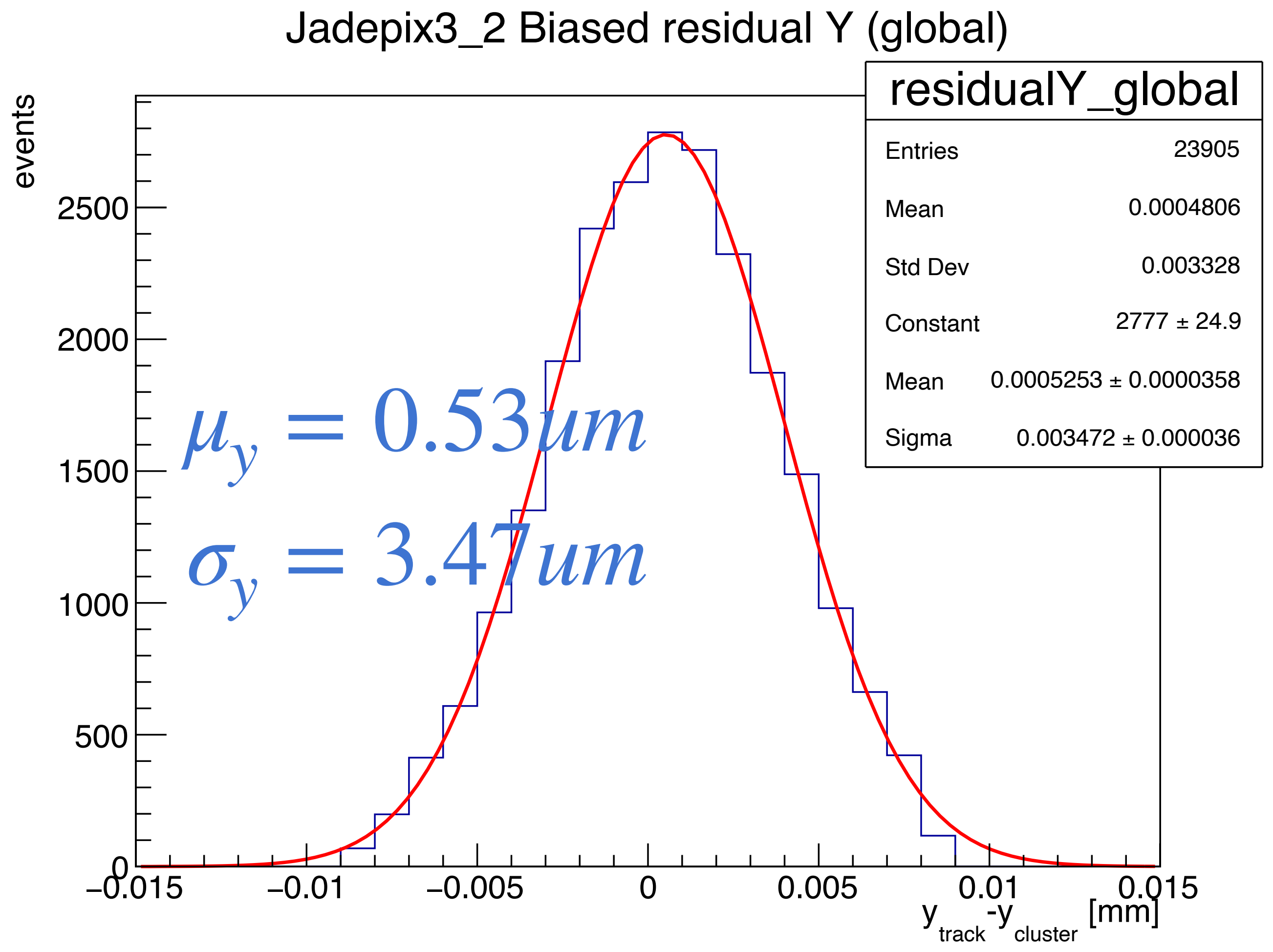
Residual Plane2 X



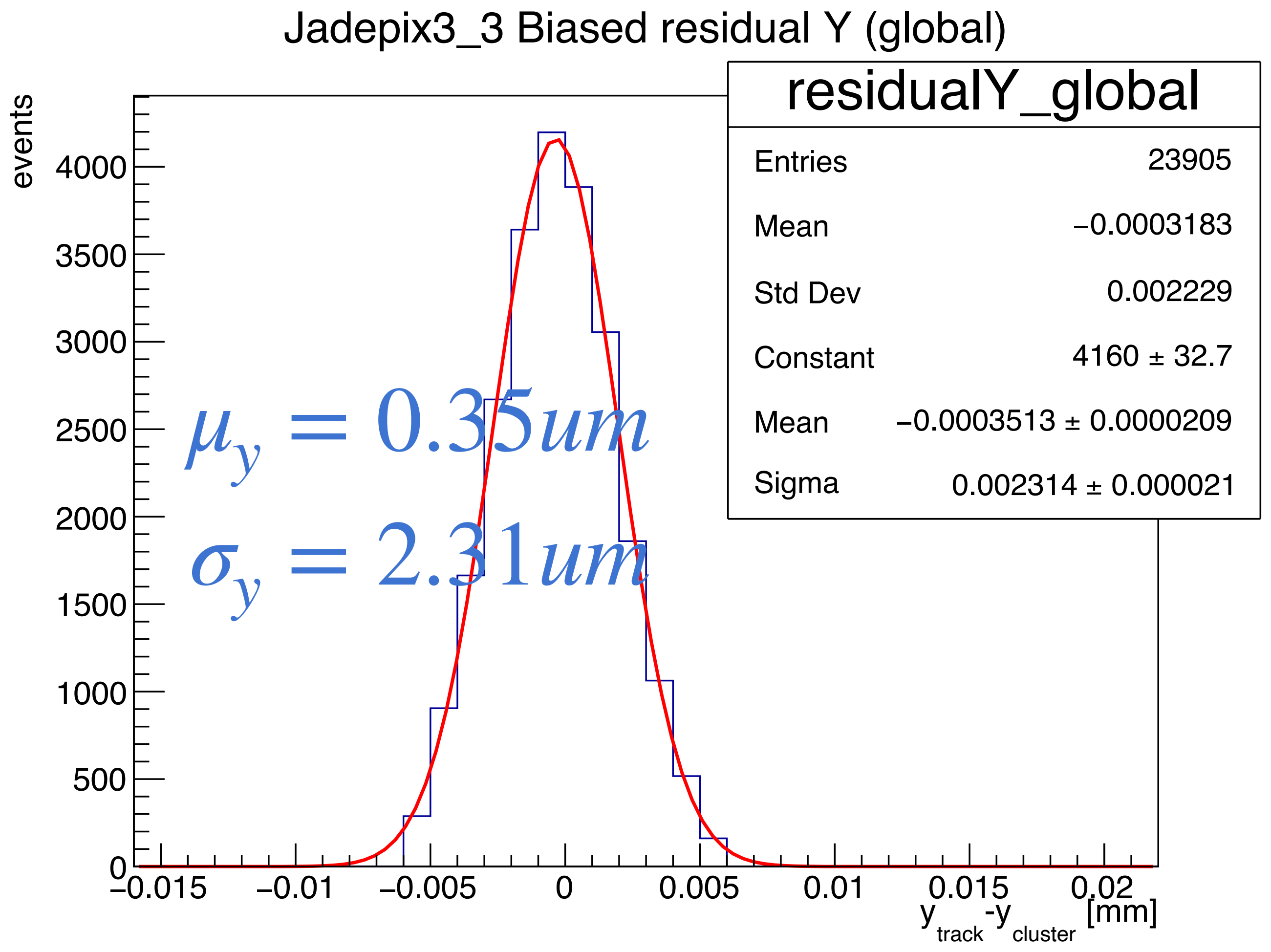
Residual Plane3 X



Residual Plane0 Y



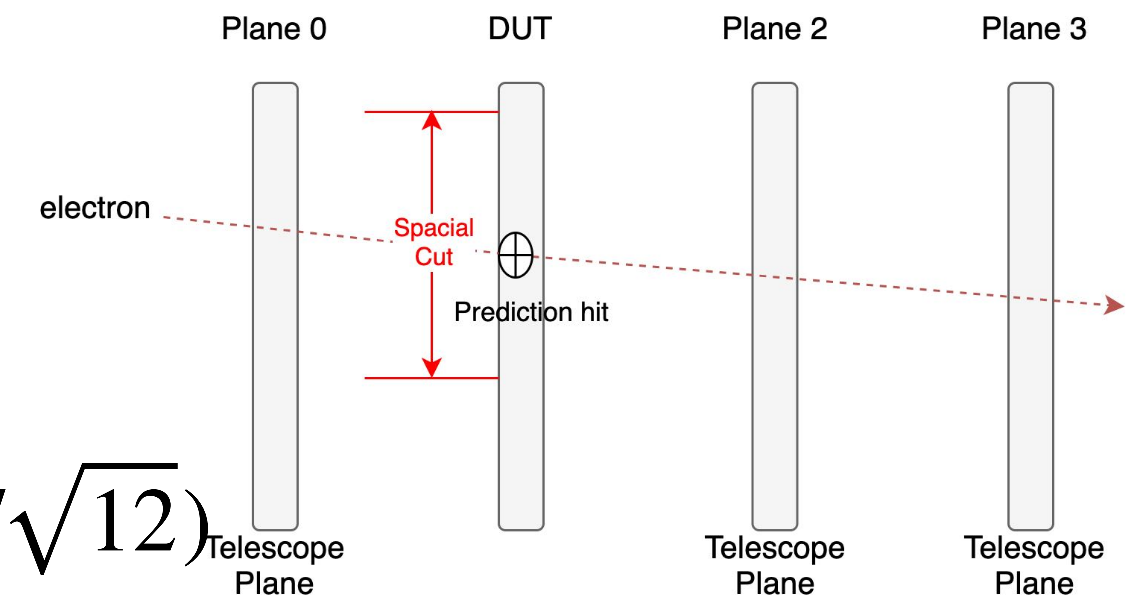
Residual Plane2 Y



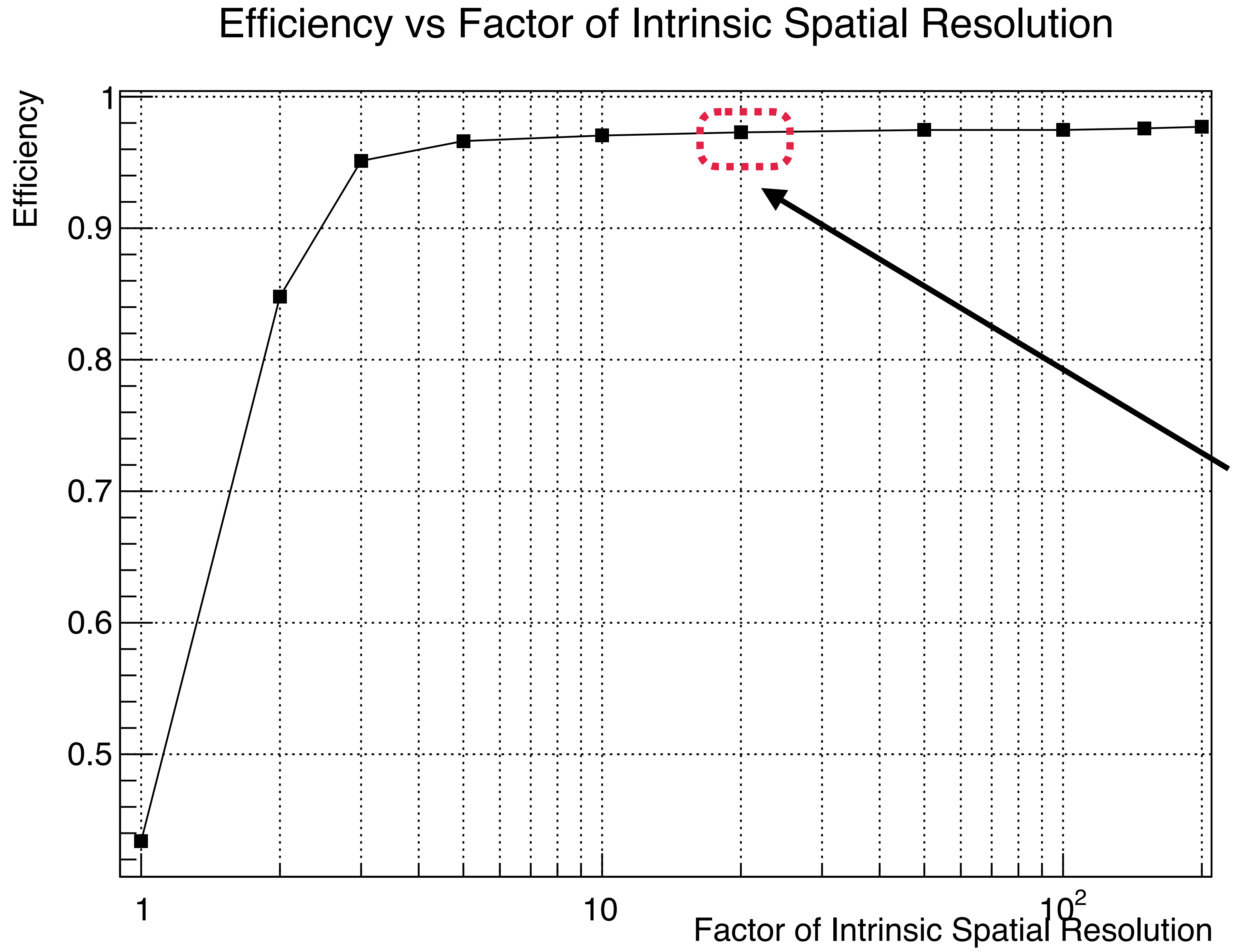
Residual Plane3 Y

The mean of the residual distribution(x, y) in the telescope plane is less than 1um , while the sigma is less than 5um, indicating that the telescope is well aligned.

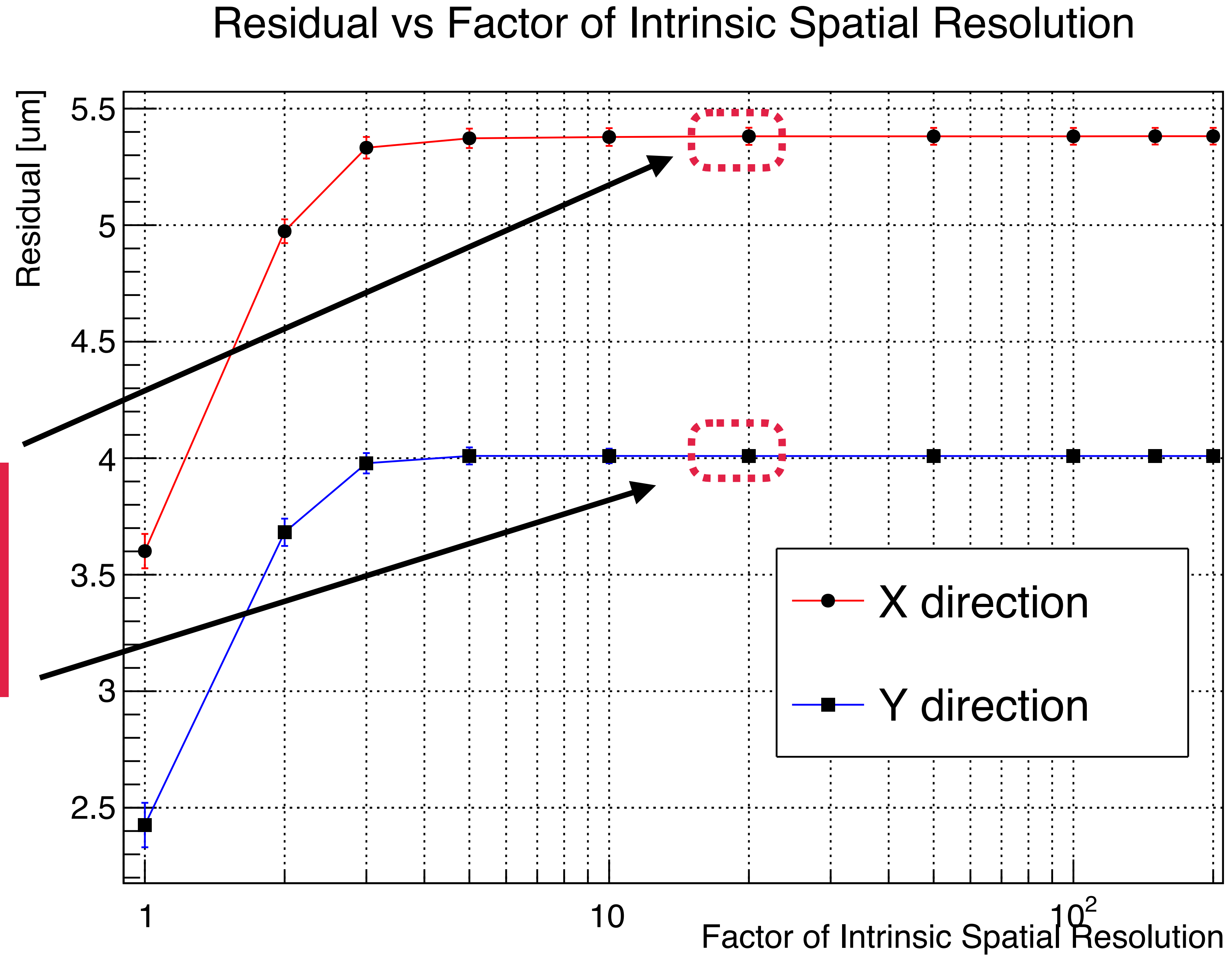
DUT Efficiency and Residual



- Establish an association between clusters on a DUT plane and a reference track.
- Define association for cuts in position: $FactorNumber \times IntrinsicSpatiaResolution(pitch/\sqrt{12})$

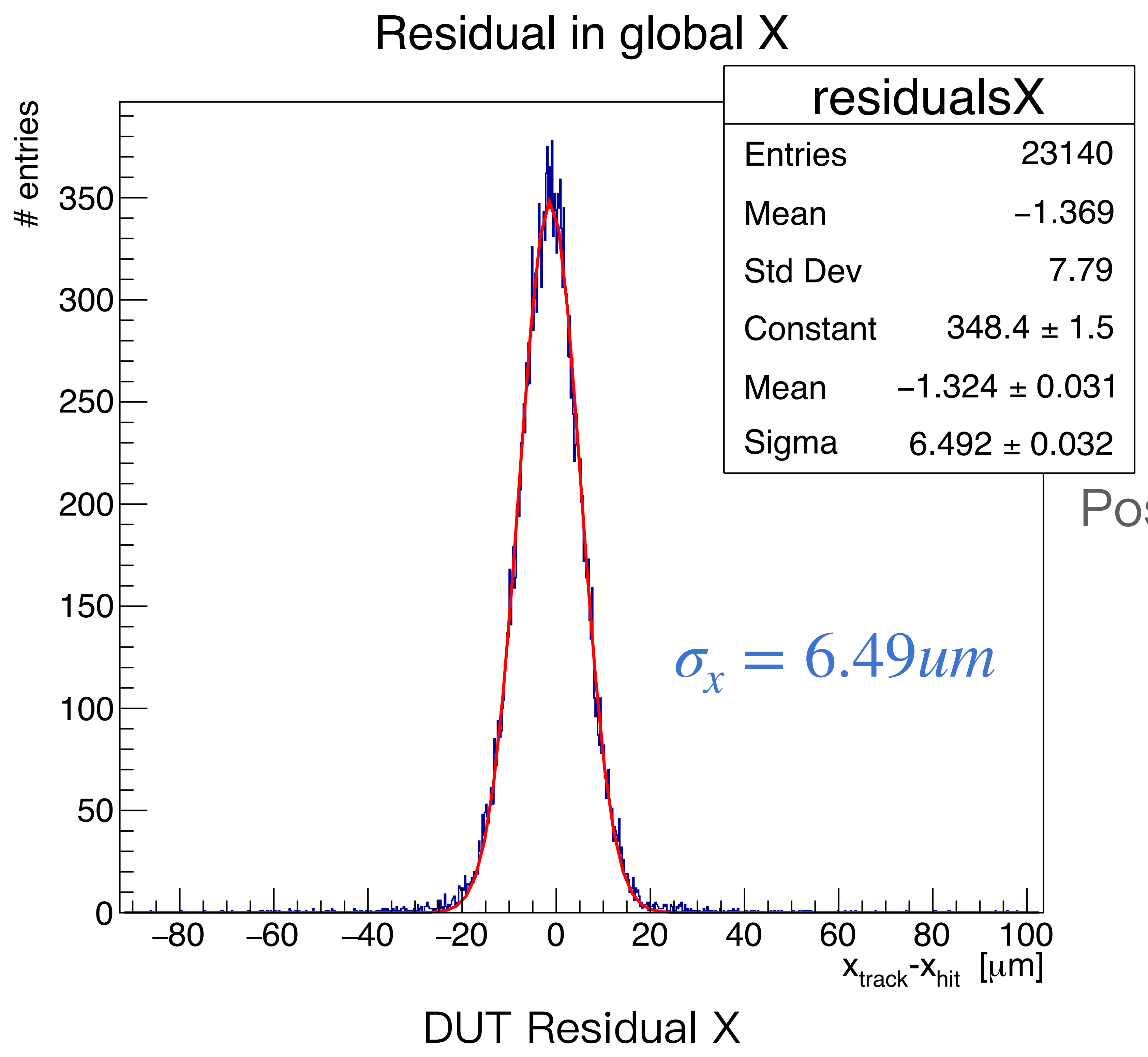


For the more analysis, factor number = 20 is set as a basic condition

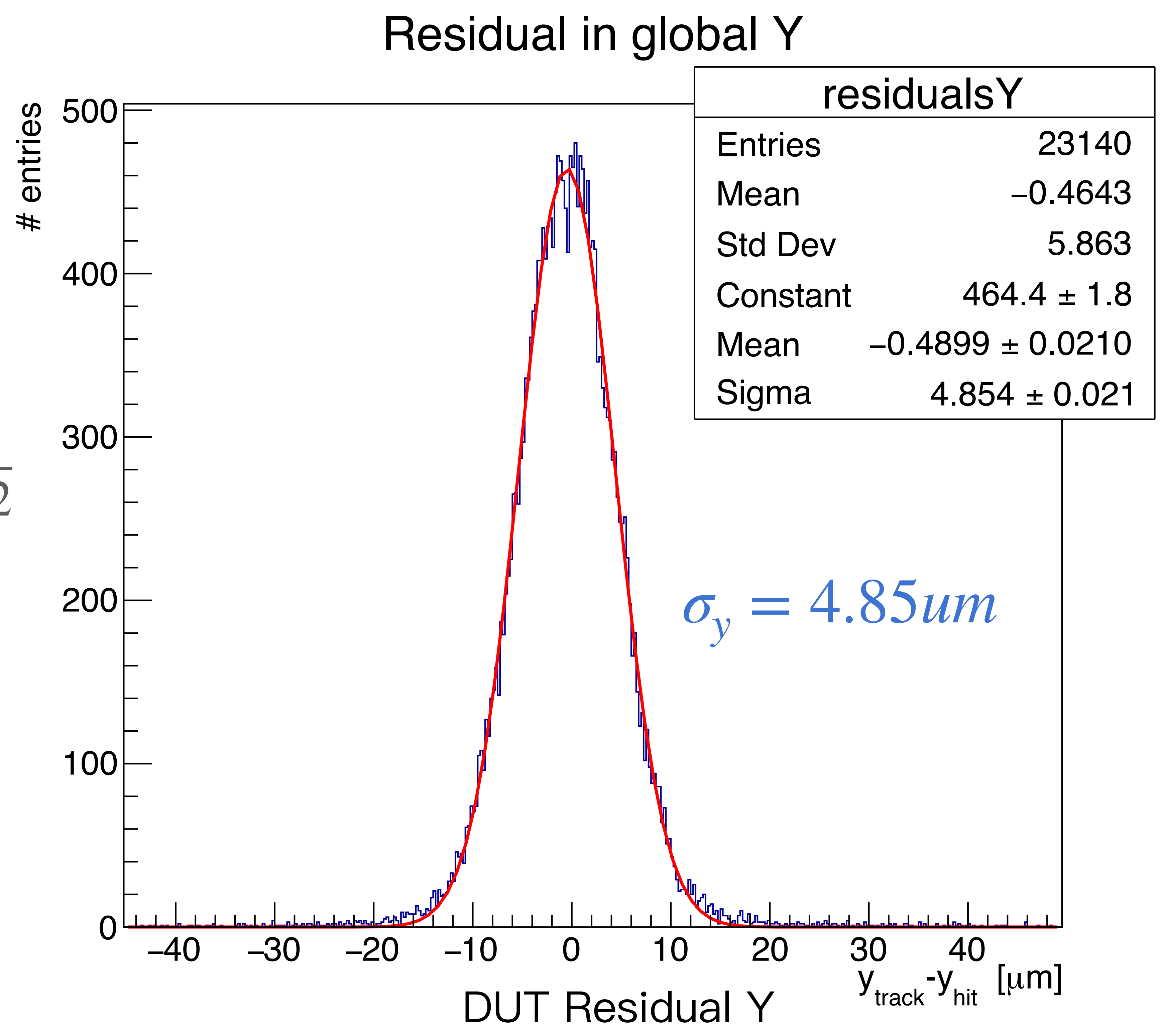


- From the figures we can see as the factor increases from 1 to 200:
  1. The detection efficiency increases sharply when it's less than 3, and then approaches the maximum value (~97%).
  2. The spatial resolution decreases when it is less than 3, and then approaches the maximum value (5.4 um in column direction, 4.0 um in row direction).

DUT Residual Distribution



Position cut: $20 \times pitch/\sqrt{12}$



1. The residuals of the DUT in the x and y directions are 6.5um and 4.9um, respectively.
2. The next step: To get the spatial resolution from the residual distribution

Spatial Resolution

Results from the EUDET telescope with high resolution planes, https://doi.org/10.1016/j.nima.2010.03.015

- The single plane resolution (σ_{DUT}) can be obtained from the measured residual width (σ_{meas}) and the telescope resolution width (σ_{tel}) using equation (1):

$$\sigma_{meas}^2 = \sigma_{DUT}^2 + \sigma_{tel}^2 \quad (1)$$

- The telescope resolution can be determined **assuming that the reference planes all have the same intrinsic resolution, using equations** (2) (3):

$$\sigma_{meas}^2 = k\sigma_{plane}^2 \ (2), \quad k = \frac{\sum_i^N z_i^2}{N\sum_i^N z_i^2 - (\sum_i^N z_i)^2} \ (3)$$

- **If the device under test is of the same type of the reference planes**, the intrinsic resolution of the single telescope plane and of the overall telescope can be derived directly from measured residual width:

$$\sigma_{plane}^2 = \frac{\sigma_{meas}^2}{1+k} \ (4) \quad \text{and} \quad \sigma_{tel}^2 = \frac{k}{1+k}\sigma_{meas}^2 \ (5)$$

For the setup shown in Fig.1 ($N = 3,\ k = \frac{3}{7}$)

- $\sigma_x(tel) = 3.5\ um, \sigma_y(tel) = 2.7\ um$
- $\sigma_x(DUT) = 5.4\ um, \sigma_y(DUT) = 4.1\ um$

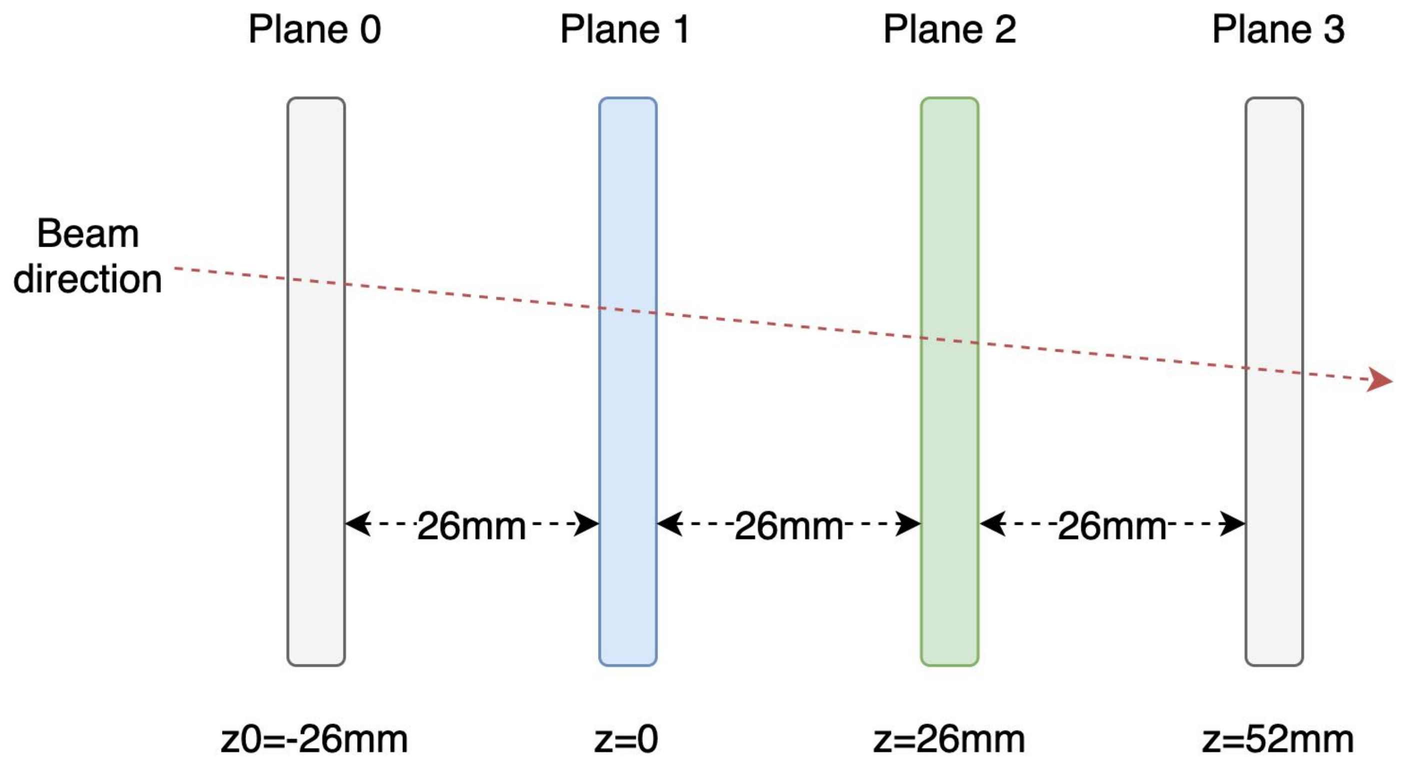
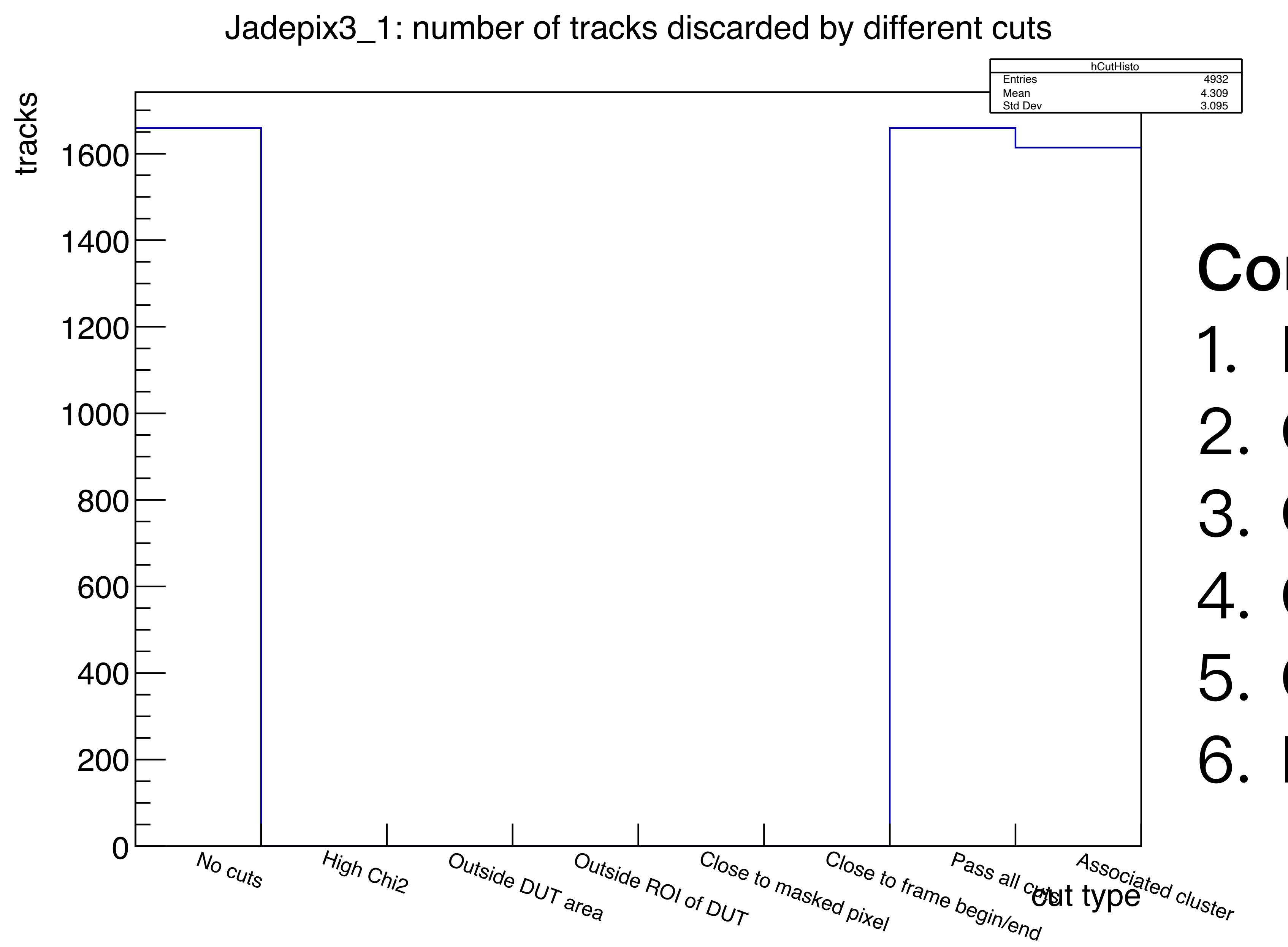


Fig.1 The structure setting for reconstruction

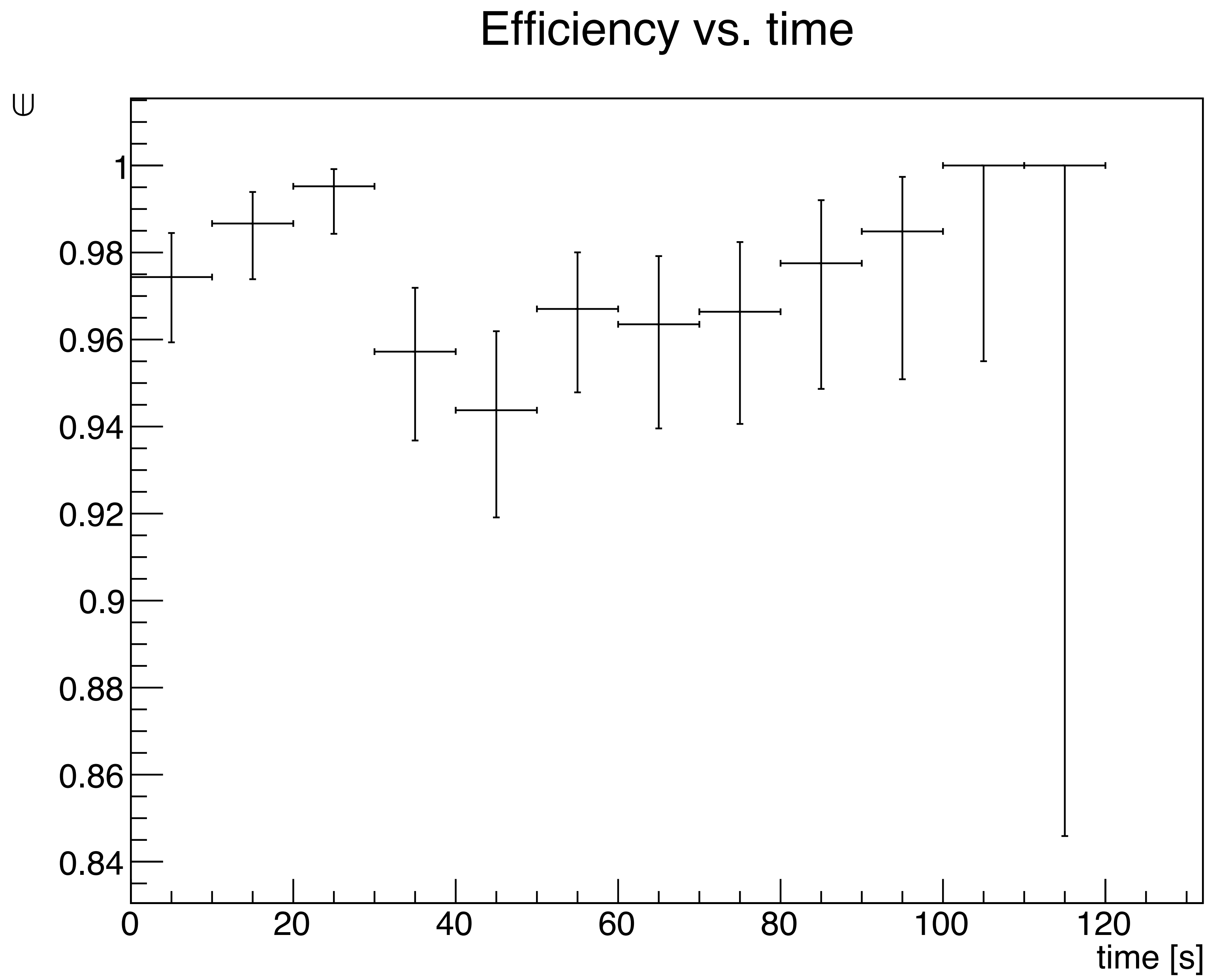
DUT Efficiency

$$\text{Total Efficiency} = \frac{\text{Number of Tracks which meet criteria}}{\text{Number of Total Tracks}}$$



Conditions for Track deselection:

1. High Chi2
2. Outside DUT area
3. Outside ROI of DUT
4. Close to masked pixel
5. Close to frame edge
6. DUT association cut



120 seconds valid run time:

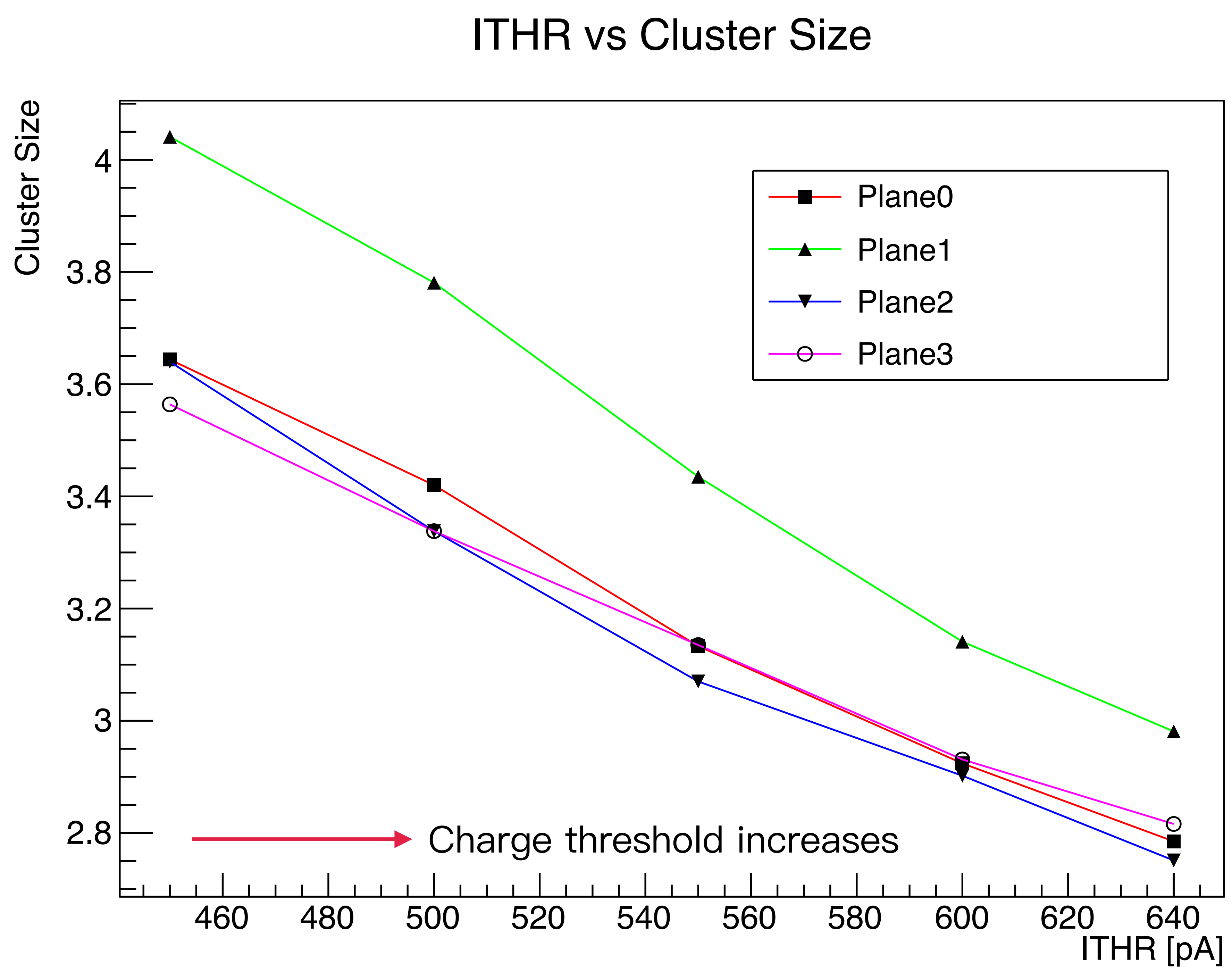
Total efficiency of DUT: **97.3%,** measured with 1614/1659 matched/total tracks

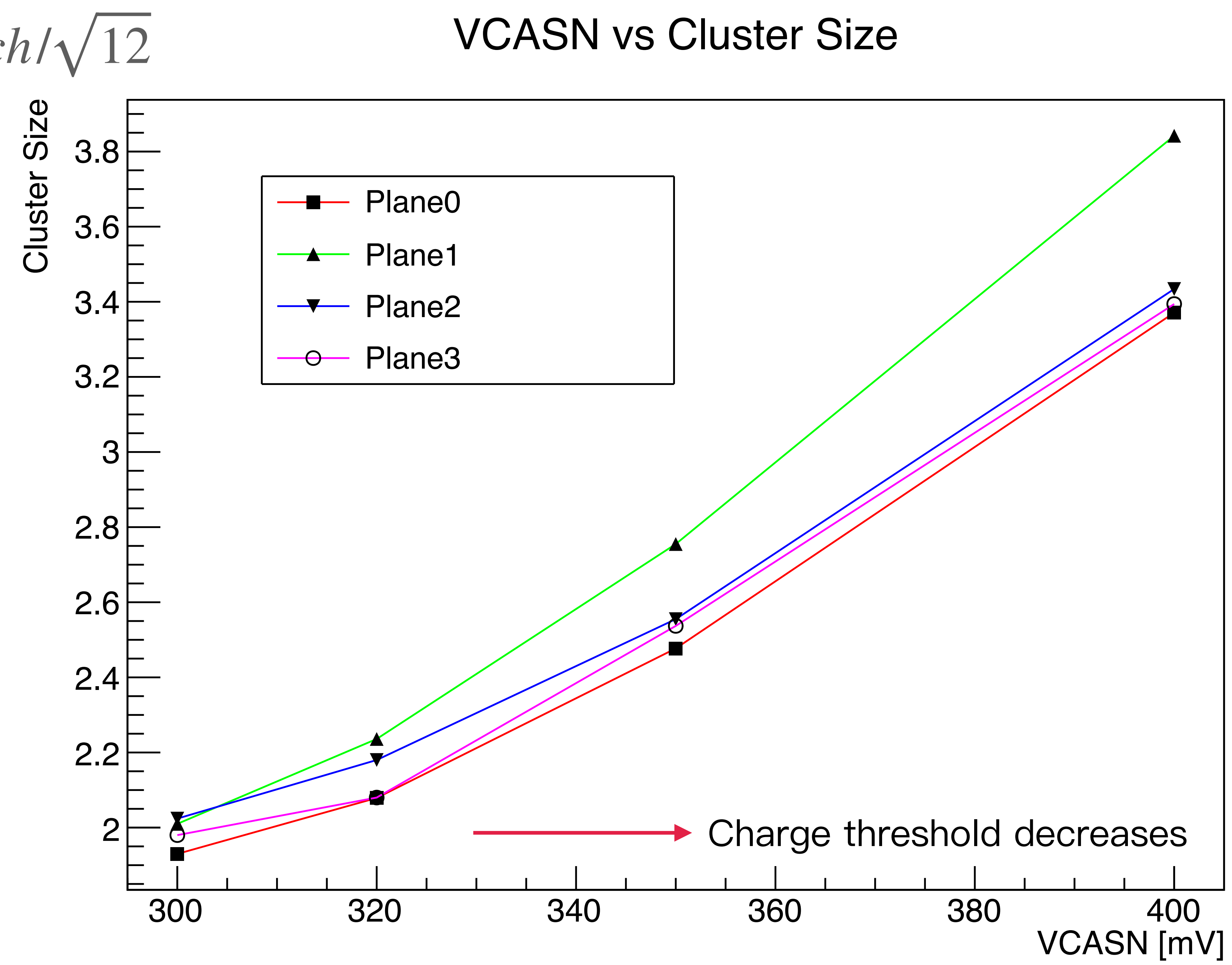
We have found that clocking issues have a significant impact on efficiency.

Cluster Size vs Threshold

There are several Digital to Analog Converters(DAC) which regulate voltages and currents in the front-end circuits of pixels.
The most relevant DACs which control the charge threshold are voltage threshold(VCASN) and current threshold(ITHR),

Position cut: $20 \times pitch/\sqrt{12}$

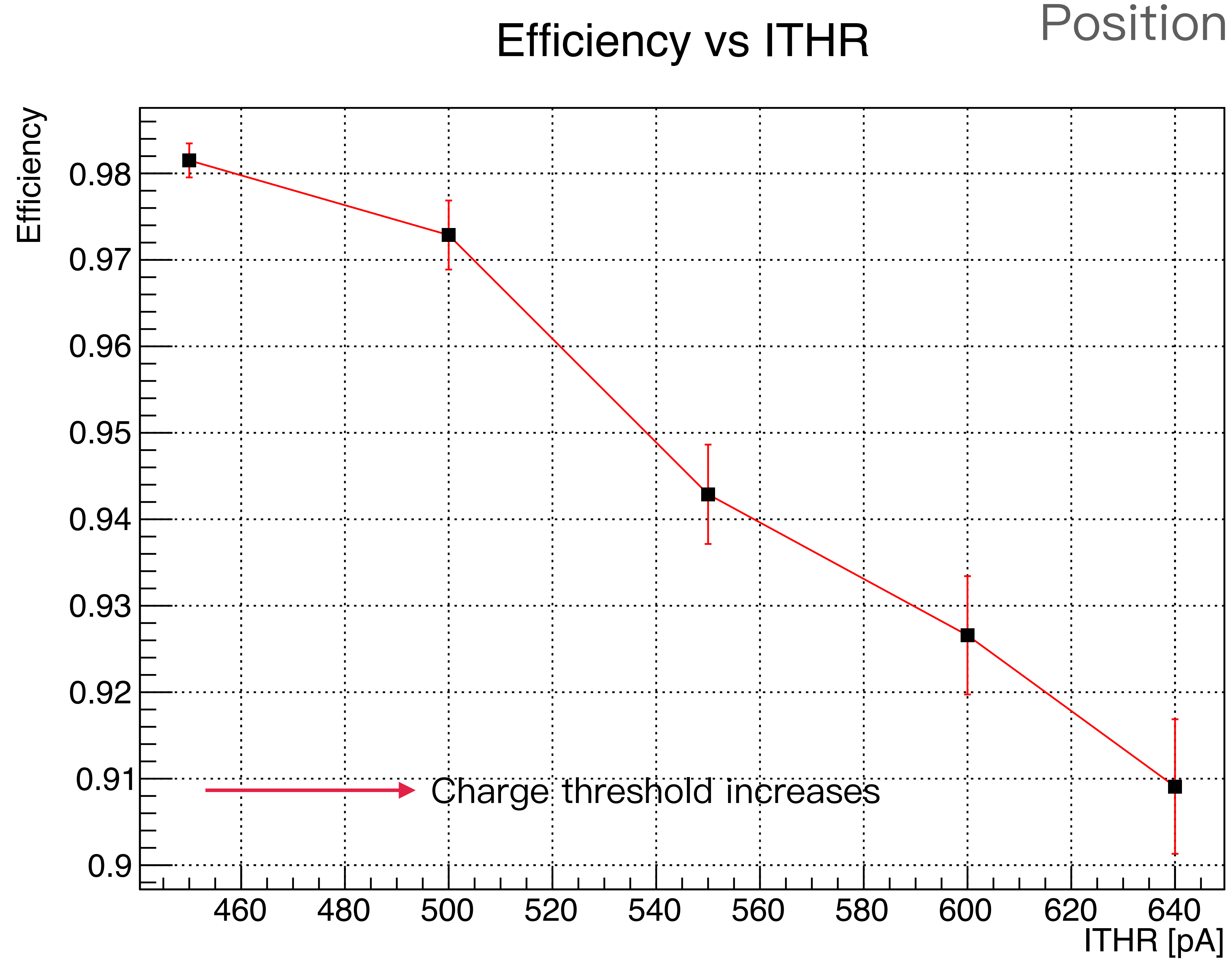


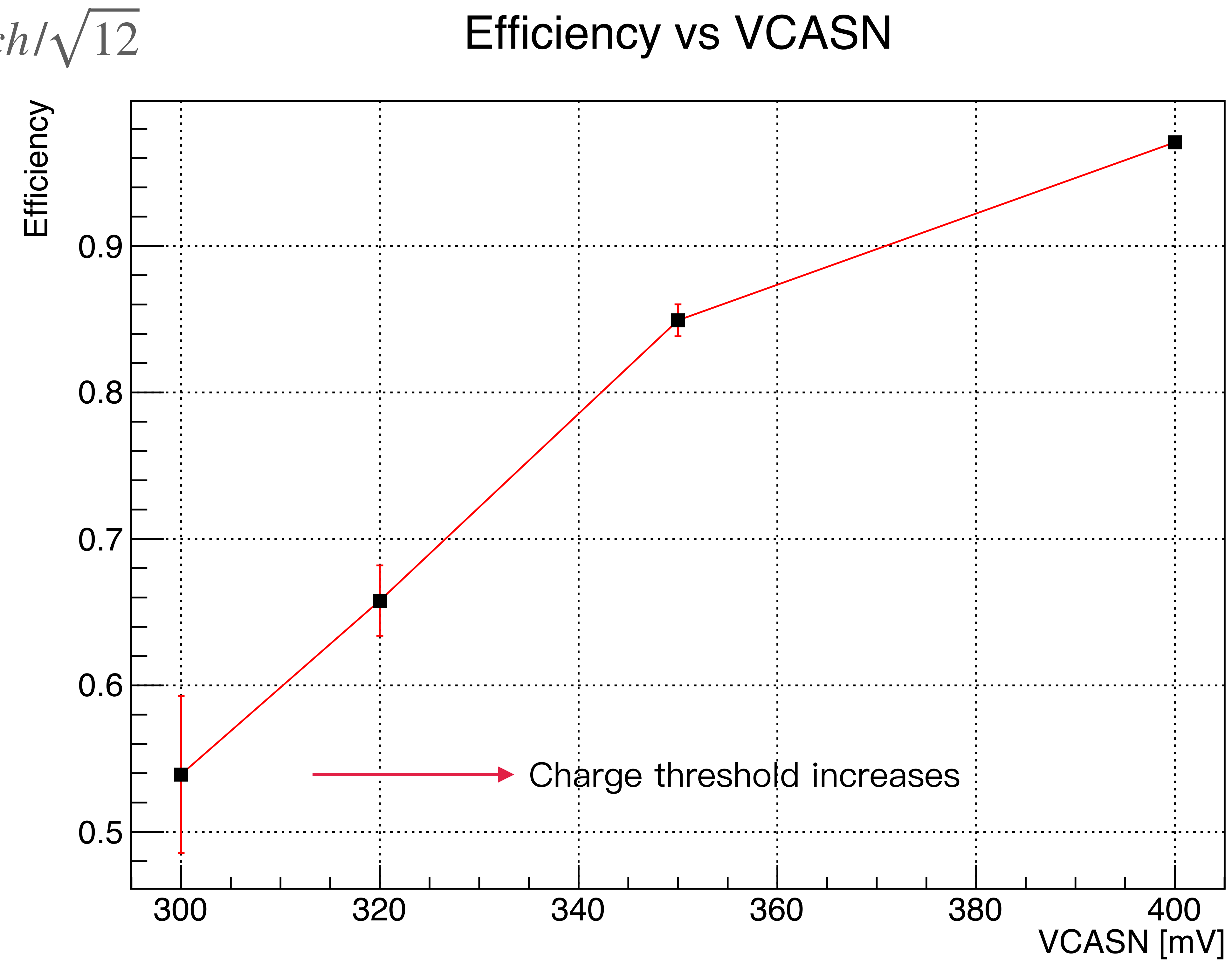


1. As ITHR increases (charge threshold increases), the cluster size decreases from 3.6 to 2.8 (plane0/2/3)
2. As VCASN increases (charge threshold decreases), the cluster size increases from 2.0 to 3.3 (plane0/2/3)
3. The trend in test results is in line with our expectations.

DUT Efficiency vs Threshold

Position cut: $20 \times pitch/\sqrt{12}$

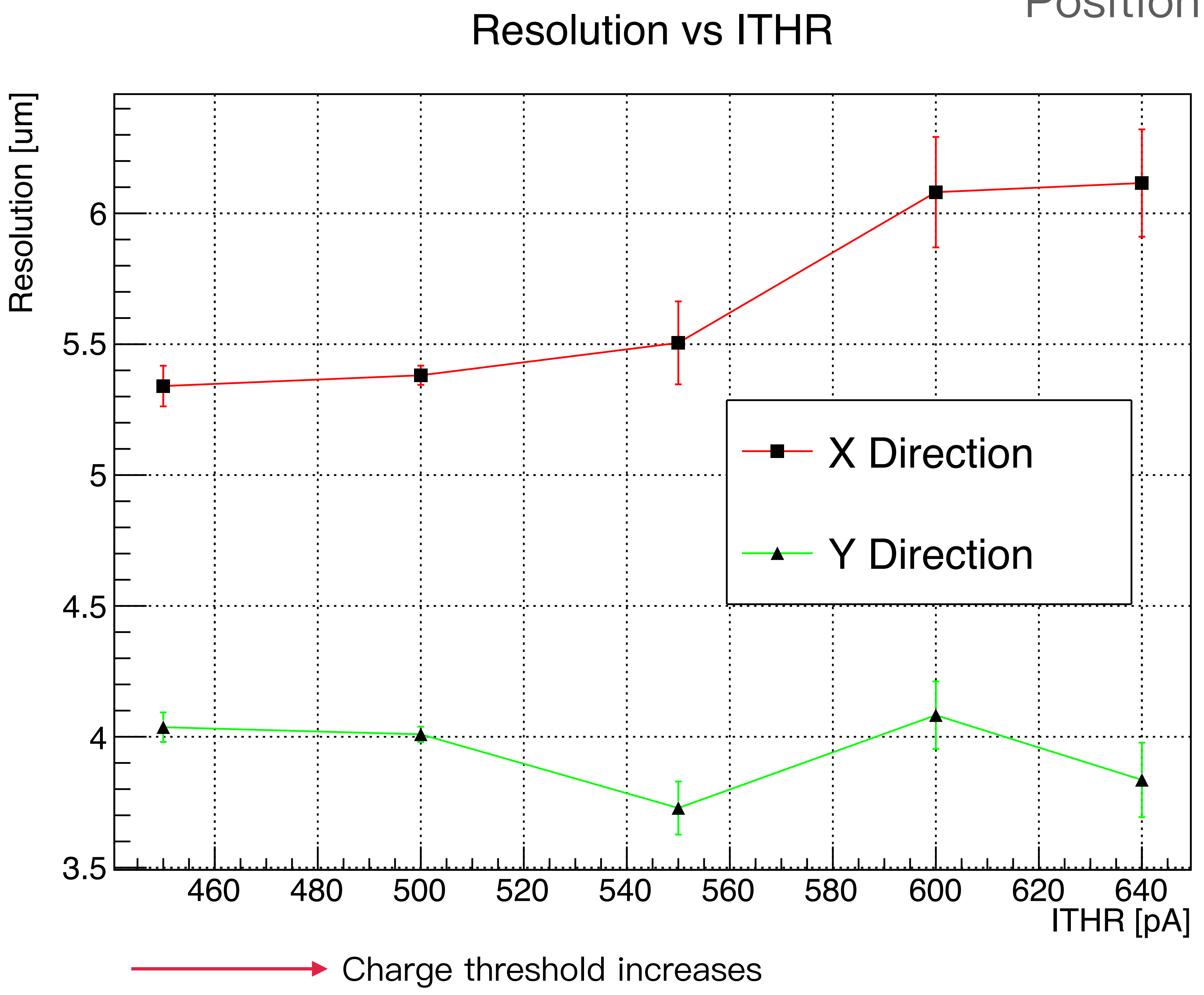


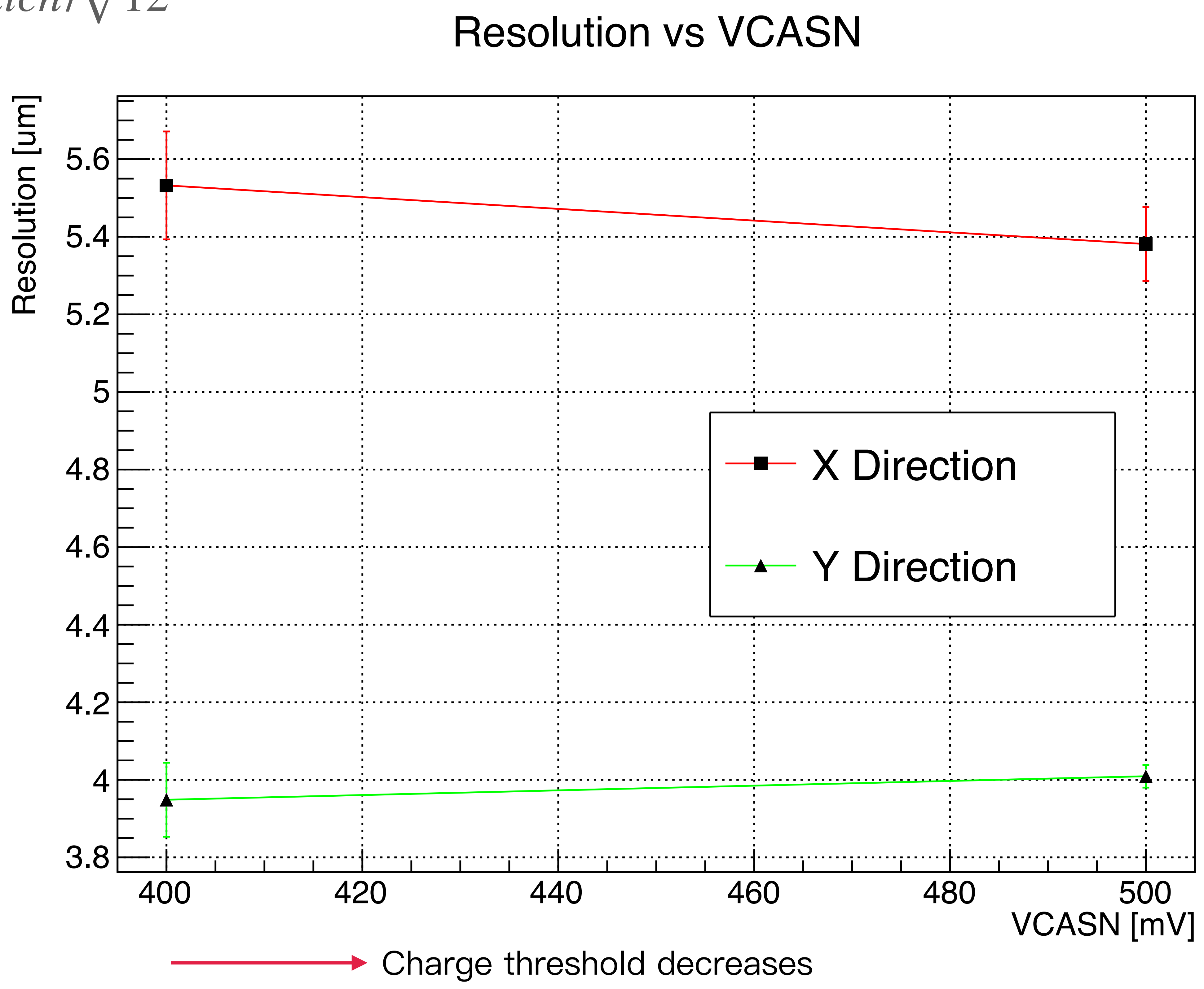


1. As ITHR increases (charge threshold increases), the detection efficiency reduces from 98% to 91%.
2. As VCASN increases (charge threshold decreases), the detection efficiency rises from 52% to 98%.
3. The trend in test results is in line with our expectations.

Spatial Resolution vs Threshold

Position cut: $20 \times pitch/\sqrt{12}$





With the change of the threshold charge, no significant change in the spatial resolution was found.

We don't have enough sampling points, there are only 5 threshold settings in total.

And because of the clock issue, we don't have enough data for this analysis.

Conclusion

1. The multi–chip readout system has been developed and verified in different experiments.
2. Offline data analysis based on corryvreckan has been mastered.
3. We got the preliminary results of the beam test:
    - The spatial resolution in the column and the row direction should be better than $5.4um$ and $4.1um$, respectively.
    - The total efficiency can reach ~97% while we have the clock issue.

Outlook

1. 5 planes will be integrated into the JadePix telescope after fixing the clock issue.
2. We are preparing for the next beam test.

Acknowledgments

- We are very grateful to the TaichuPix group for the opportunity of testing our system.
- We would like to thank the DESY and the BSRF for the support of our experiments.

Thanks for your attention.

Backup

Offline Data Analysis

- **Corryvreckan** (referred as to corry) is adopted for JadePix telescope offline data analysis.
- It's a powerful framework to analyze test beam data and align tracker modules.
- For JadePix-3, a new event loader module (EventLoaderJadepix3) has been developed and integrated to the corry framework.

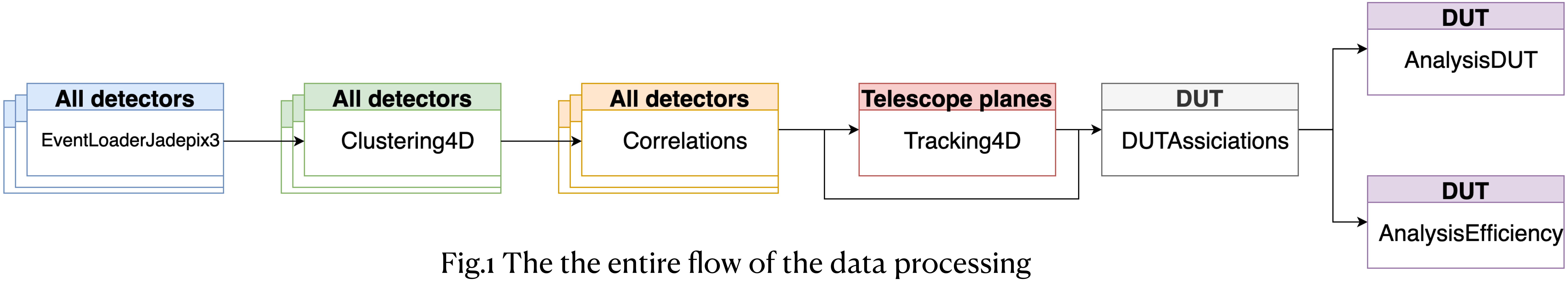


Fig.1 The the entire flow of the data processing

D. Dannheim et al., "Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data", J. Instr. 16 (2021) P03008, doi:10.1088/1748-0221/16/03/P03008, arXiv:2011.12730

Track Selection

In total, 1618 clusters are associated to 1614 tracks. (120s valid run time)

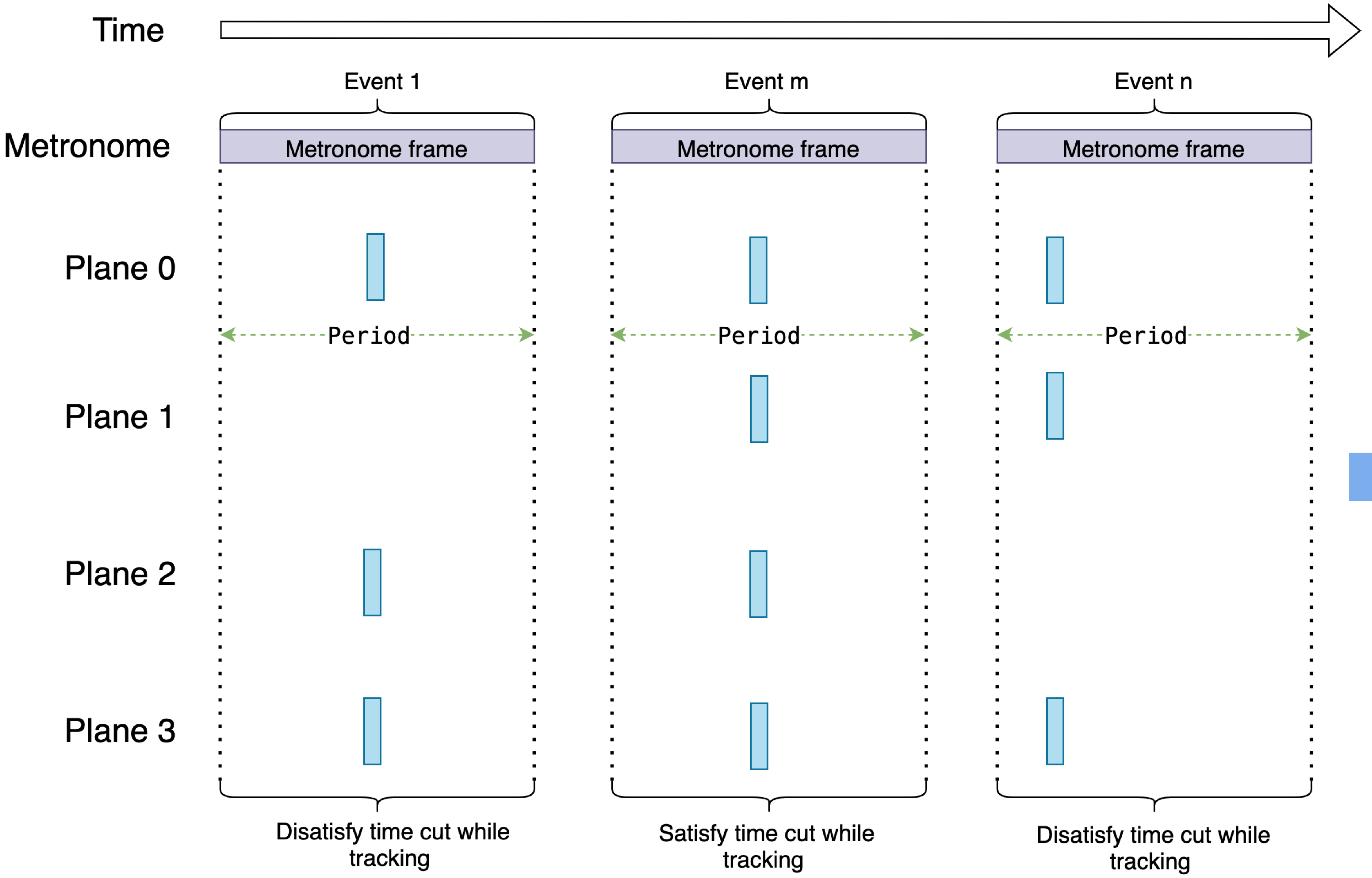
Track selection flow: 1659

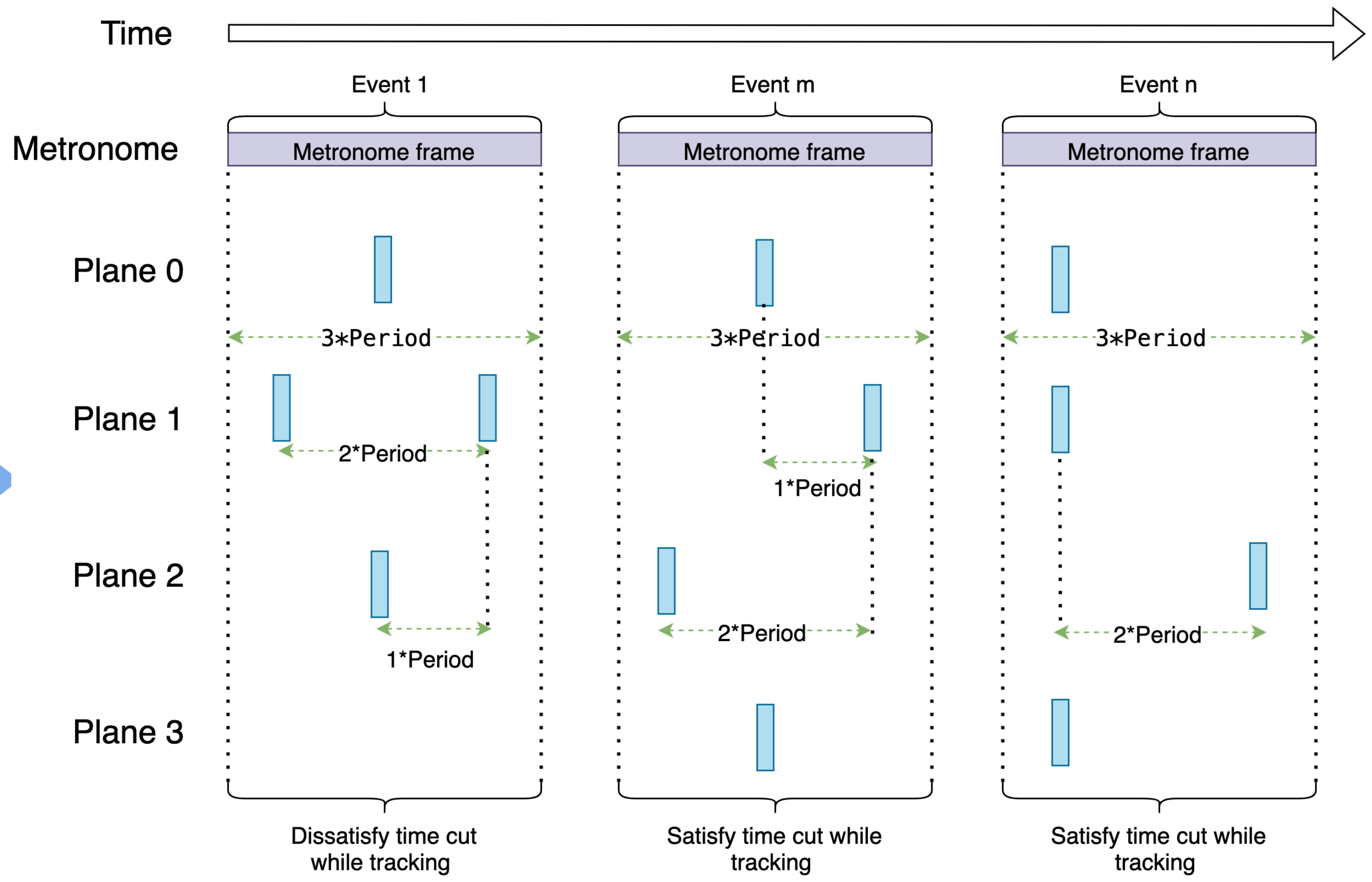
* rejected by chi2 –0
* track outside ROI –0
* track outside DUT –0
* track close to masked px –0
* track close to frame edge –0
* track without an associated cluster on required detector –0

Accepted tracks: 1659

JadePix-3 Event Loader

- Expand the metronome length and time cut length to reduce the impact of the non-homogeneous clock.





Period (rolling shutter readout): 98.316 us

Event length: 98.316 us

TimeCut(abs): 200 ns

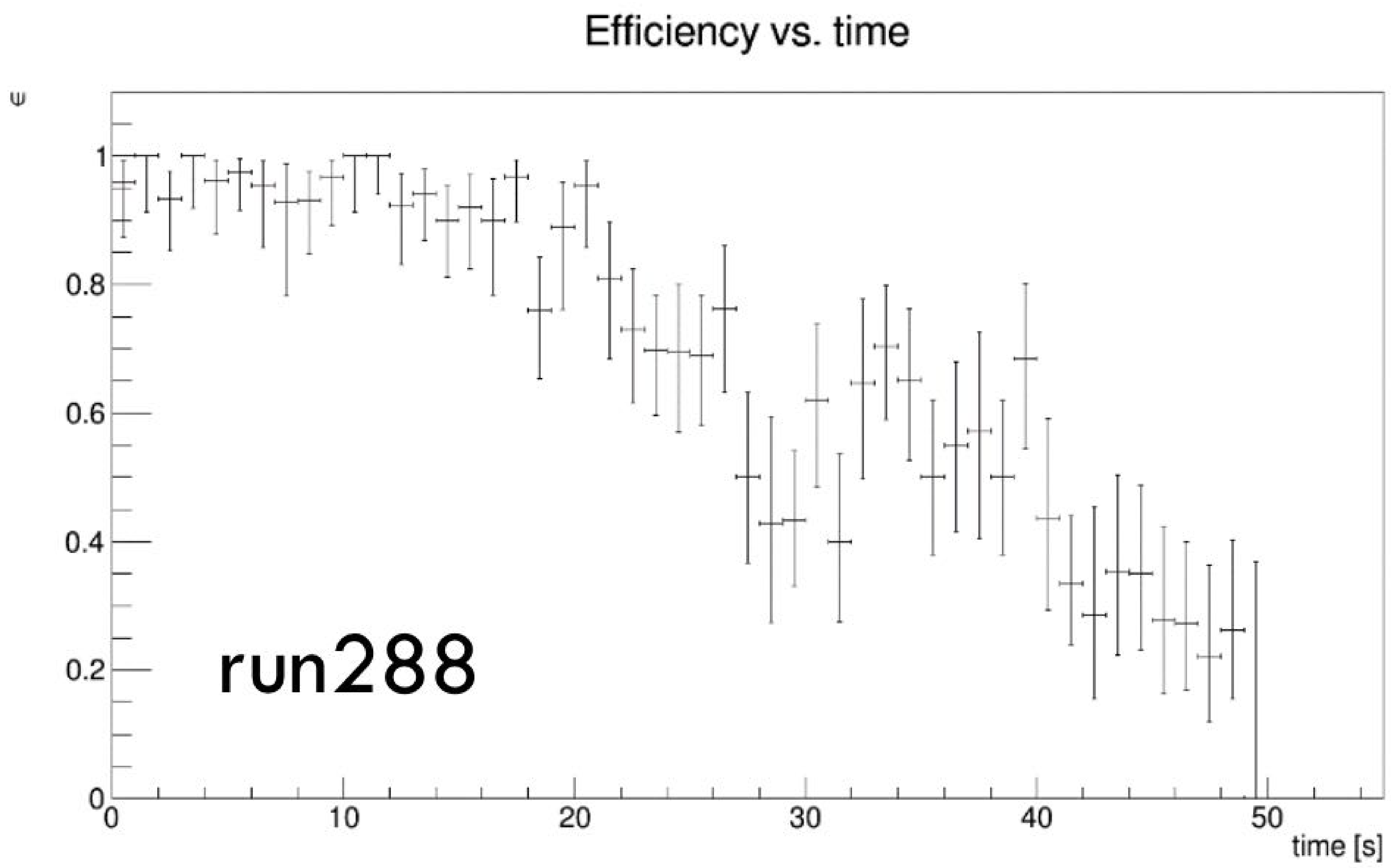
The timestamp of clusters must be the exactly same for a valid tracking.

New event length: 98.316 us $\times 3$

New TimeCut(abs): 98.317 us

For valid tracking, the maximum timestamp difference of clusters is 98.316 us $\times 2$.

Efficiency without expanding time cut



Sensor Threshold