Beam test of a 180 nm CMOS Pixel Sensor for the CEPC vertex detector

Shuqi Li

Institute of High Energy Physics, Chinese Academy of Sciences

On behalf of CEPC vertex detector group

18.04.2023

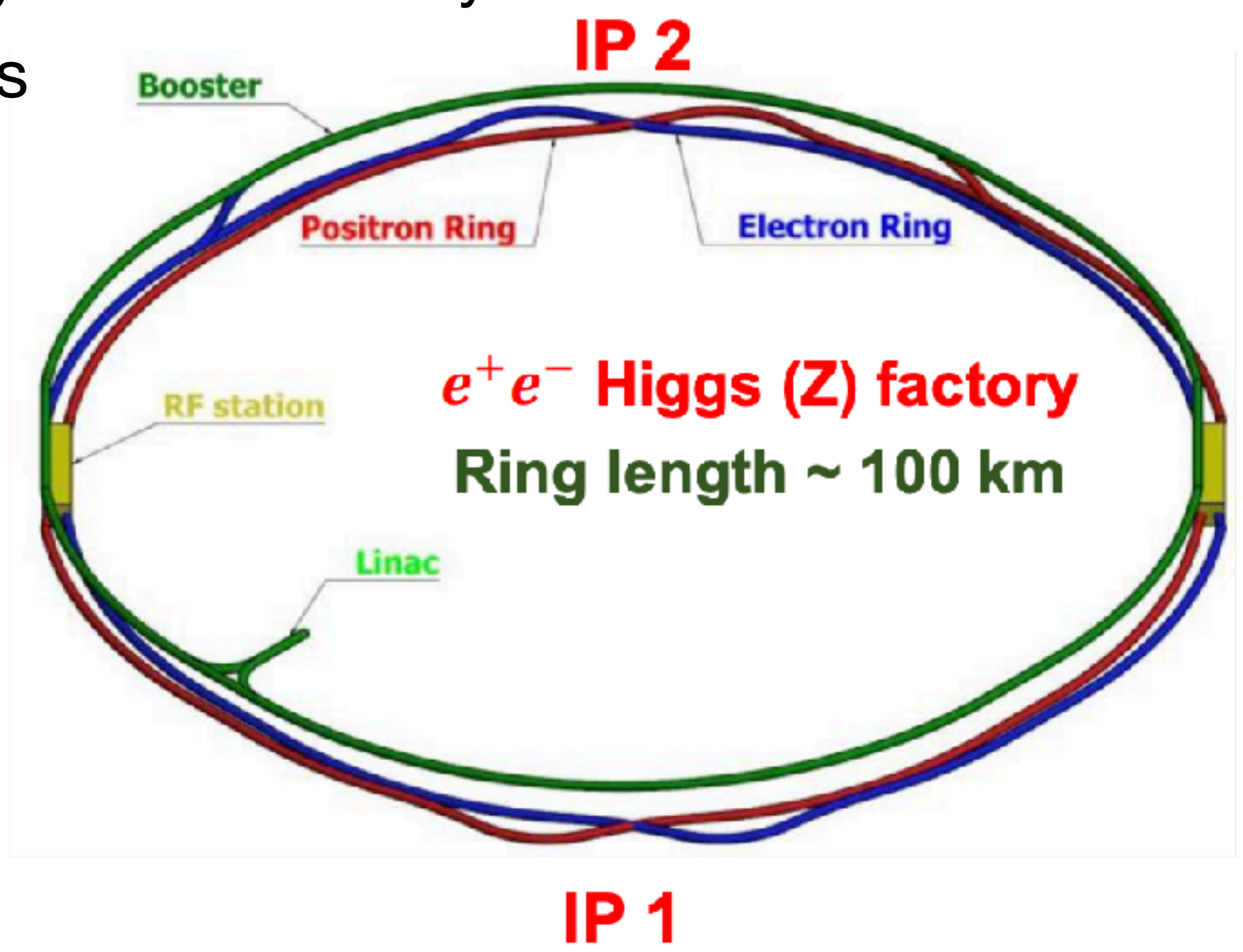
11th BTTB

Outline

- Vertex detector for CEPC
- TaiChu pixel sensor
- Test Beam @ DESY II
- Beam data analysis and results
- Summary and outlook

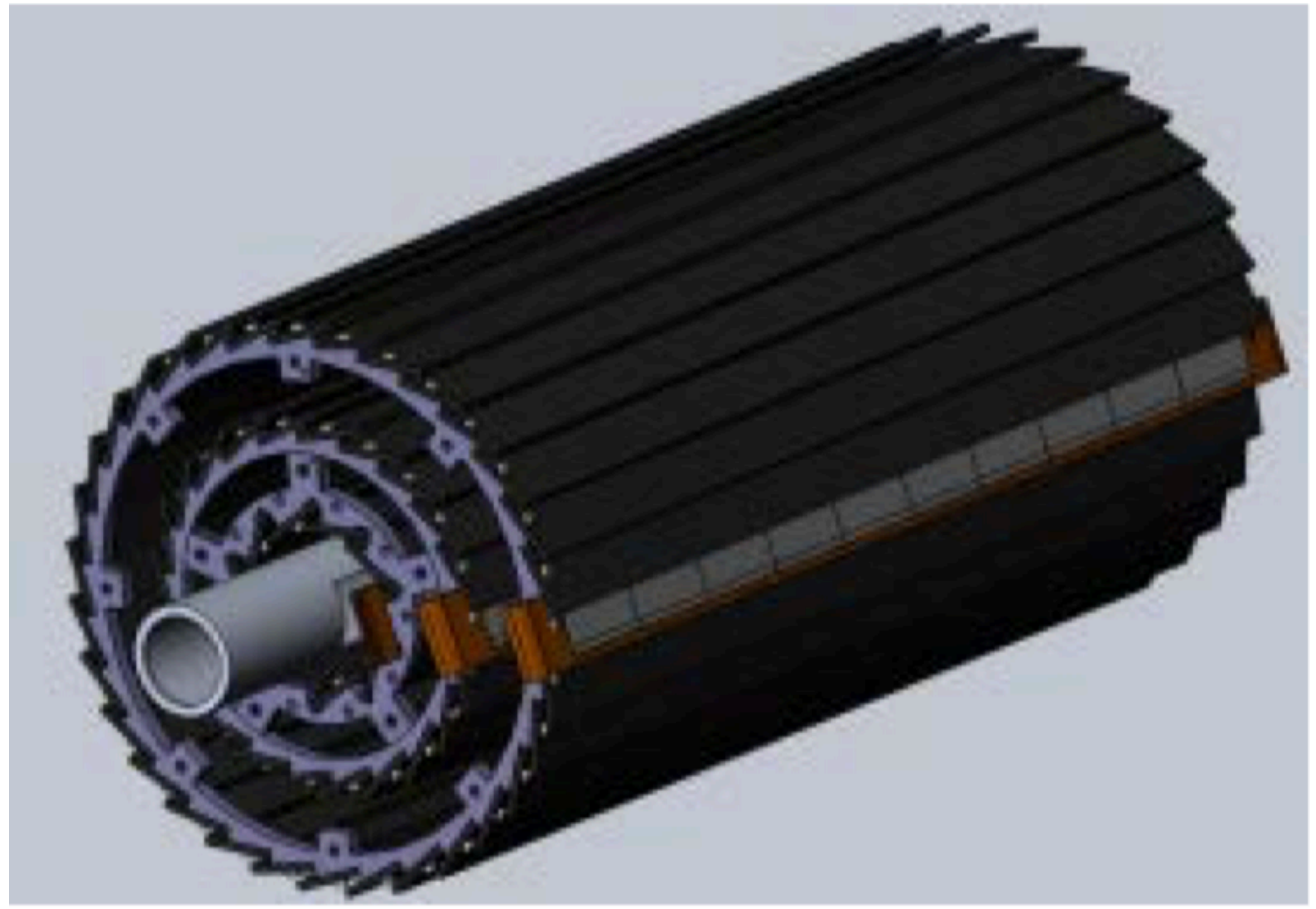
Vertex detector for CEPC

- **Circular Electron Positron Collider (CEPC)**
  - frontier high-energy research facility proposed by Chinese particle physics community
  - precise measurement of physical properties of Higgs, W and Z bosons
  - search for new physics beyond standard model



- **Vertex detector**
  - high spatial resolution (3 - 5um)
  - high speed readout (dead time < 500 ns @ 40 MHZ at Z pole)
  - radiation tolerance (per year): 1 MRad TID
  - low material budget

Full size vertex detector prototype



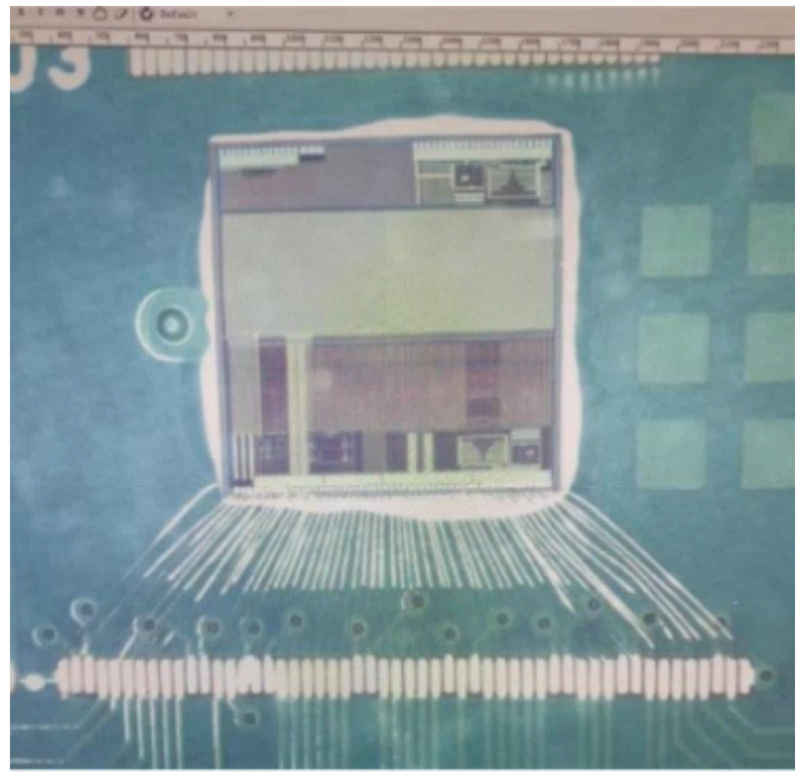
TaiChuPix sensor

- **A Monolithic Active Pixel Sensor (MAPS) prototype**
  - designed for the CEPC baseline vertex detector
  - based on a 180 nm TowerJazz CMOS Imaging Sensor (CIS) technology

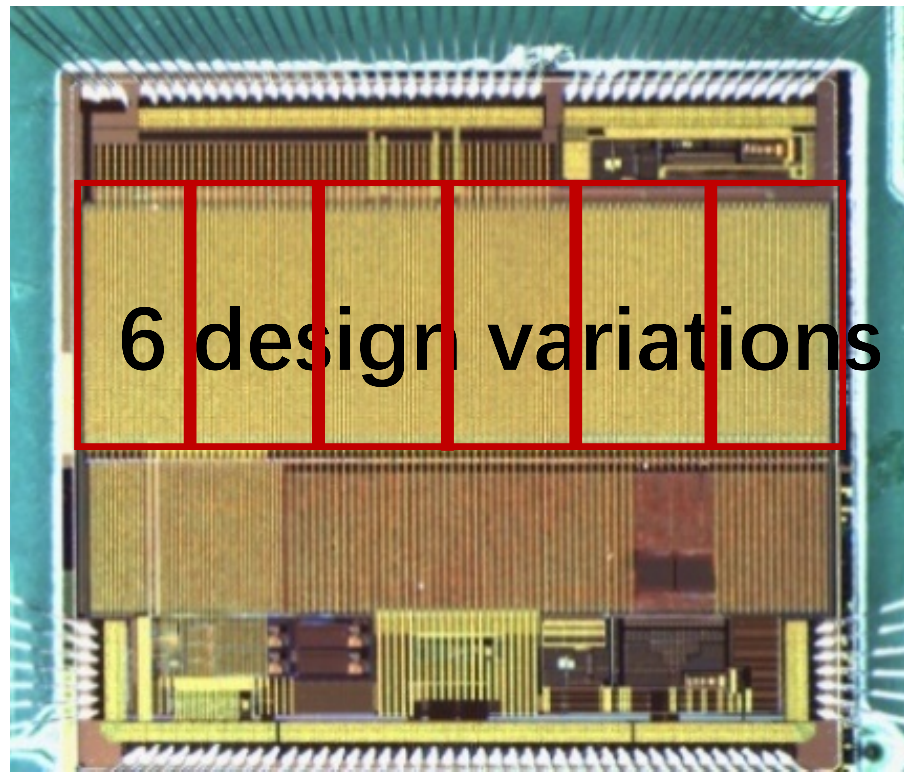
    25 um high-resistive epitaxial layer

    pixel pitch 25 um

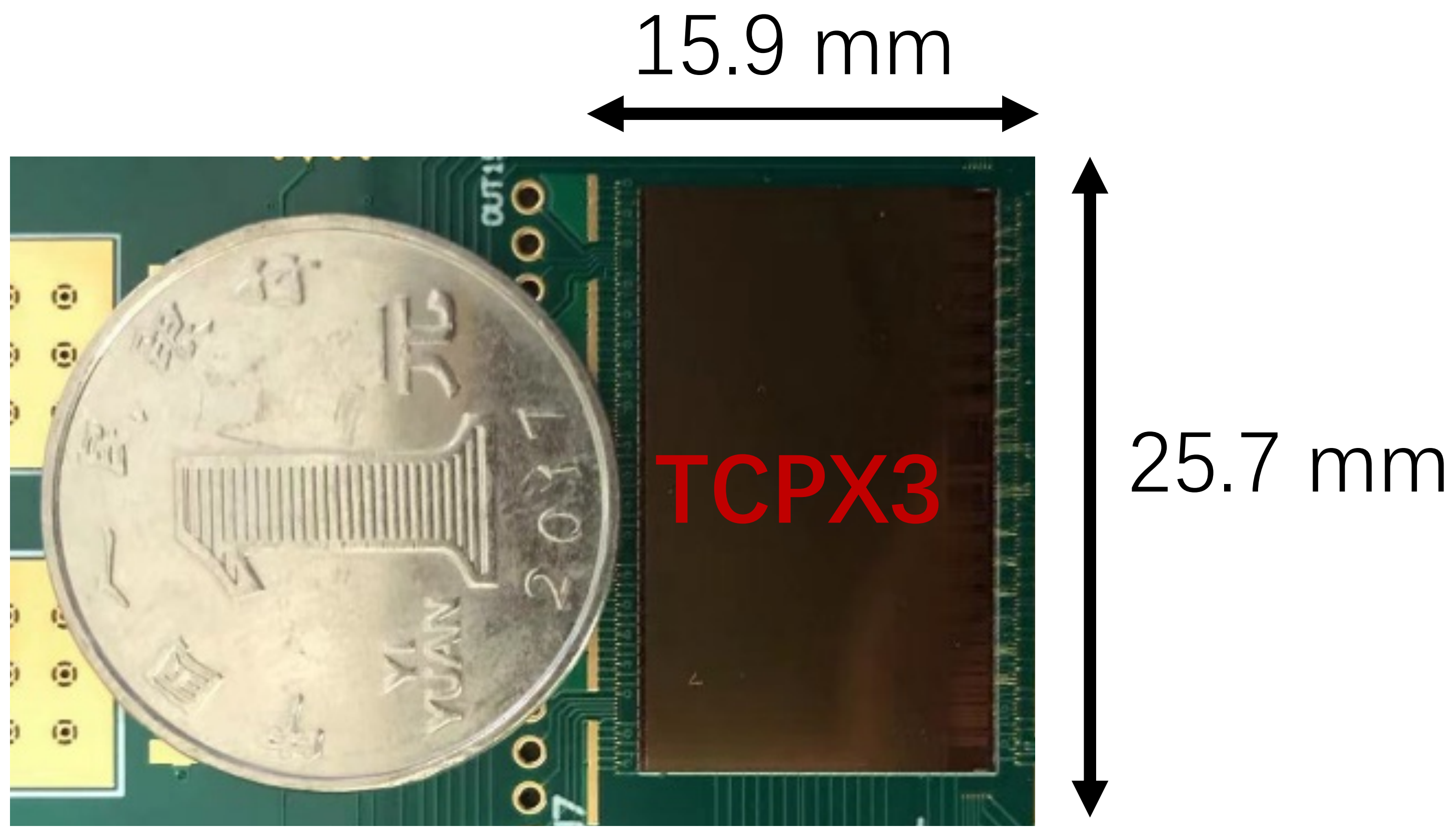
- **The evolution of the TaiChuPix sensor**
  - 2 Multi-Project Wafers TaiChuPix-1 and TaiChuPix-2 designed and tested during 2019 and 2020
  - a full-scale prototype TaiChuPix-3 with engineering run received and tested during 2022-2023



TaiChuPix-1



TaiChuPix-2



TaiChuPix-3

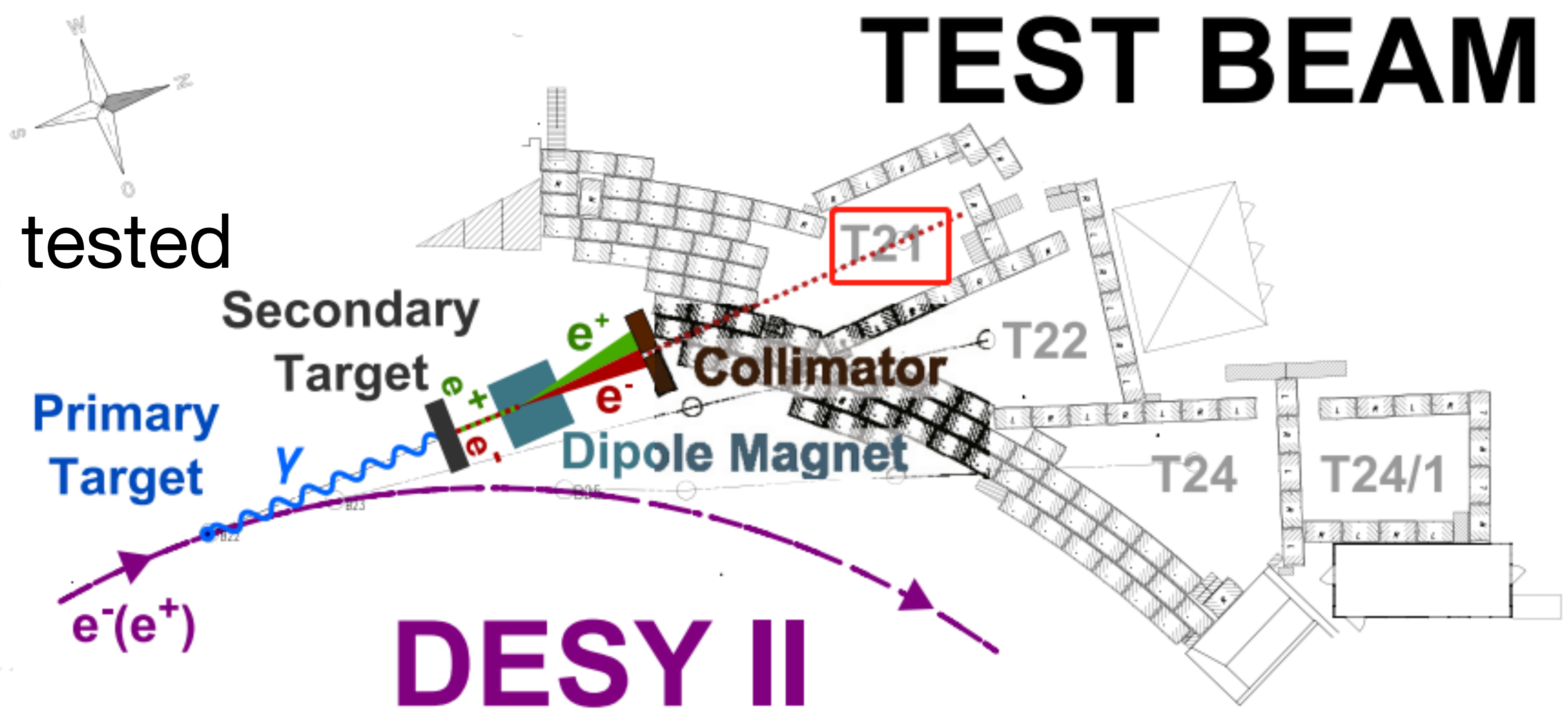
Test Beam @ DESY II

- **The beam test was performed in December 2022 at TB21**
- **Beam test setup**
  - 2 detector under test (DUT) TaiChupix3 with <u>different processes</u> tested

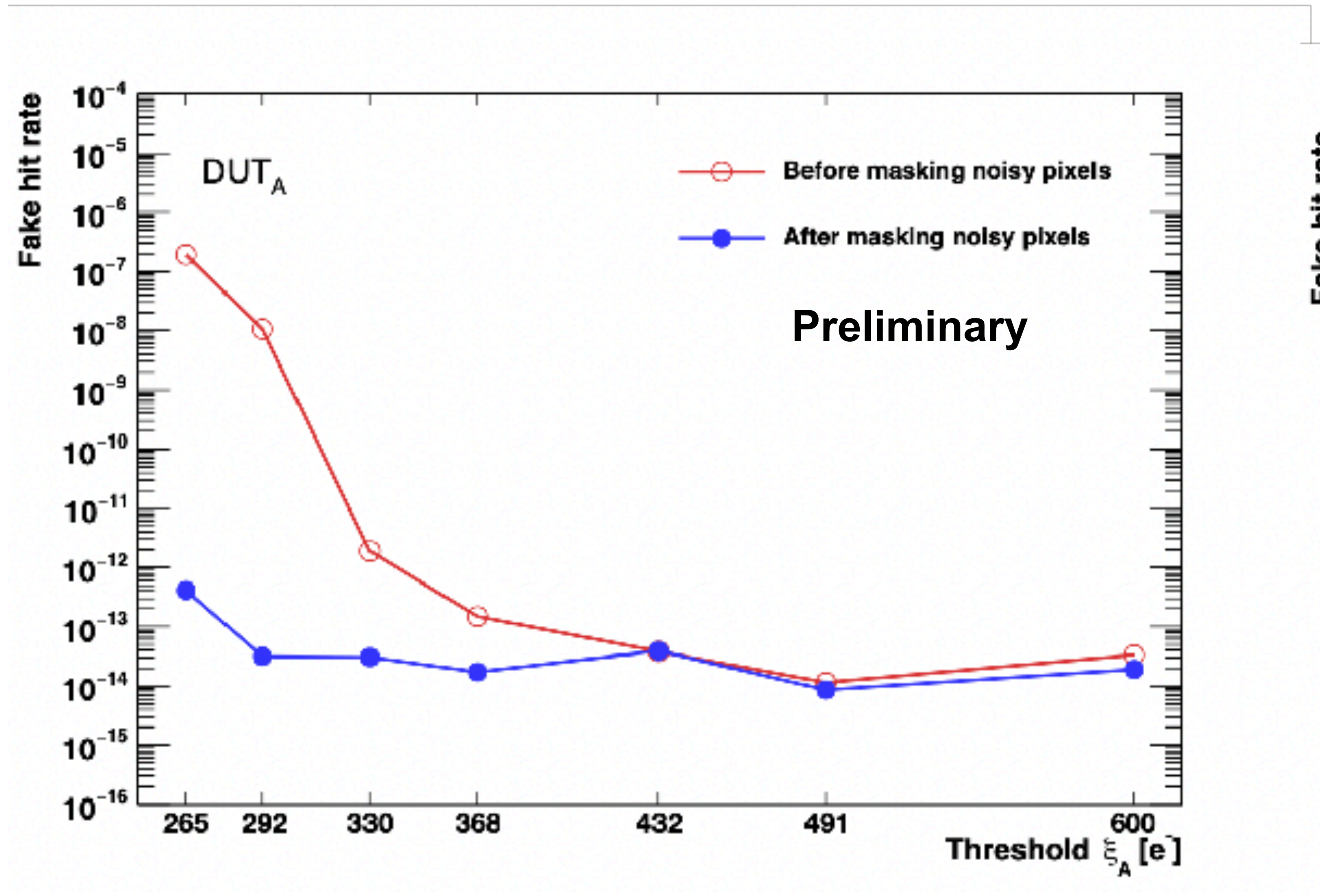
    DUT_A with the standard back-bias diode process together with an extra deep N-layer mask (full depletion)

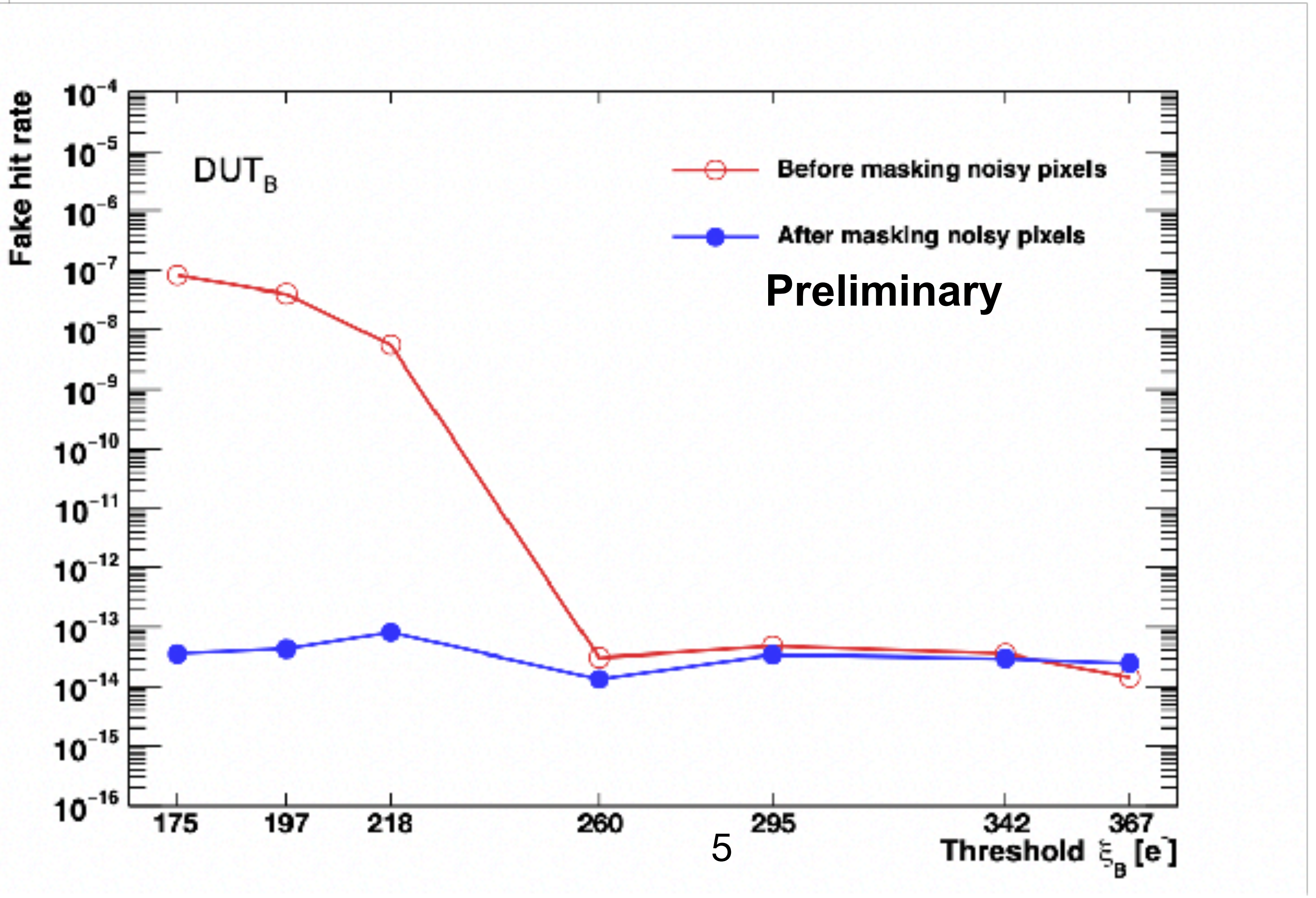
    DUT_B without the extra deep N-layer (non full depletion)

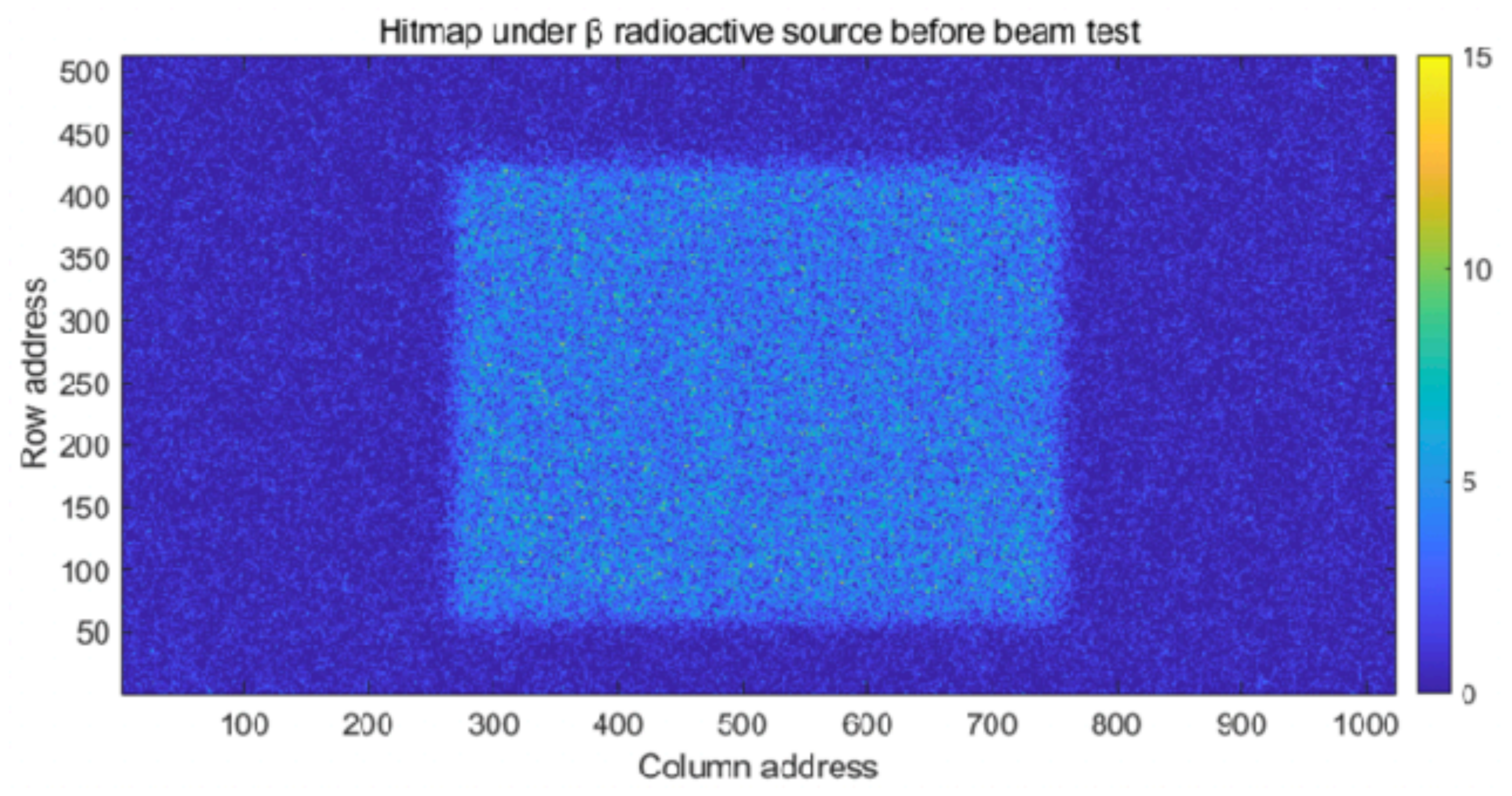
  - radioactive source ^{90}Sr test on TaiChuPix-3 before beam test
  - fake hit rate with threshold scan



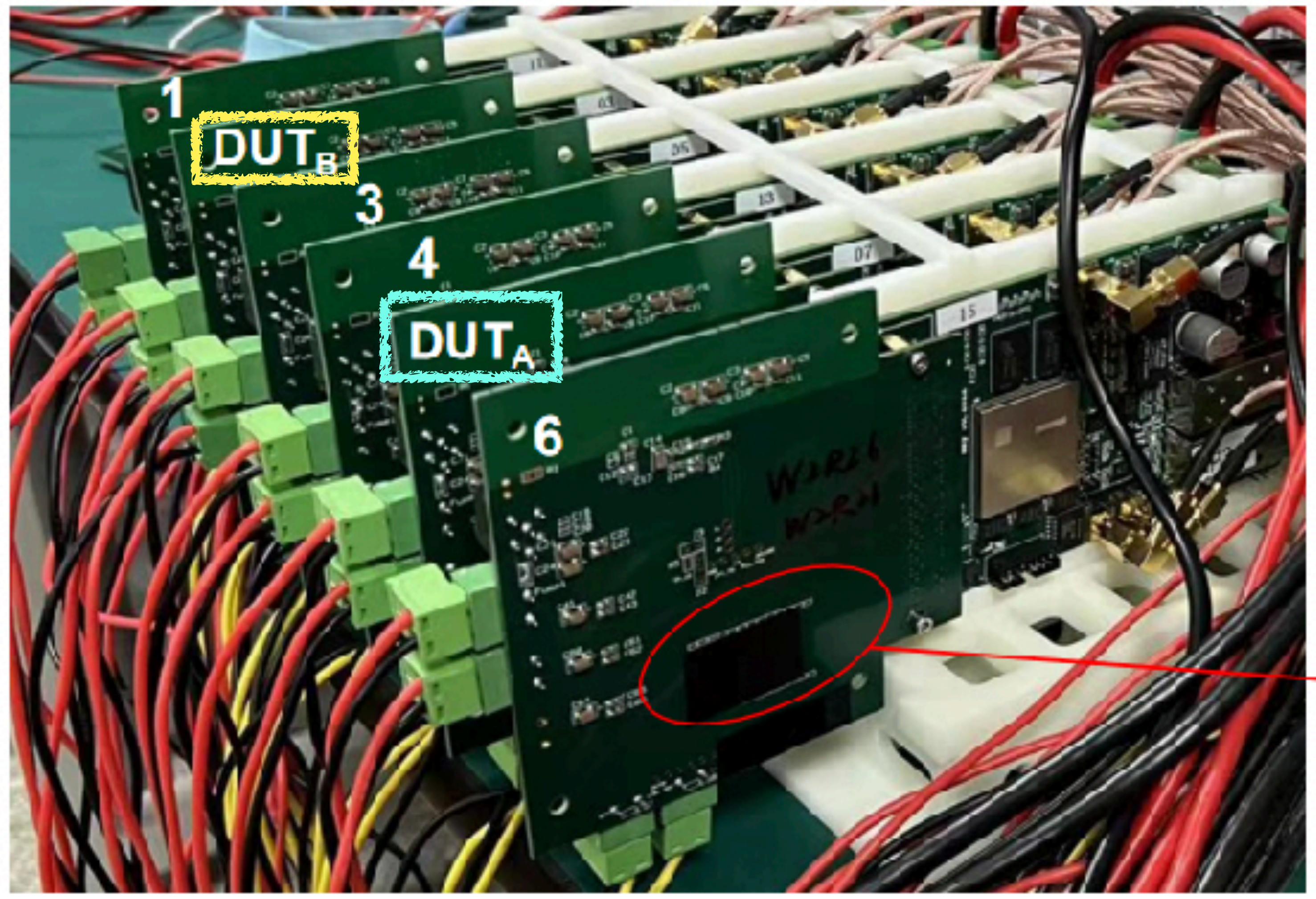
noisy pixels masked due to only one common on-chip DAC

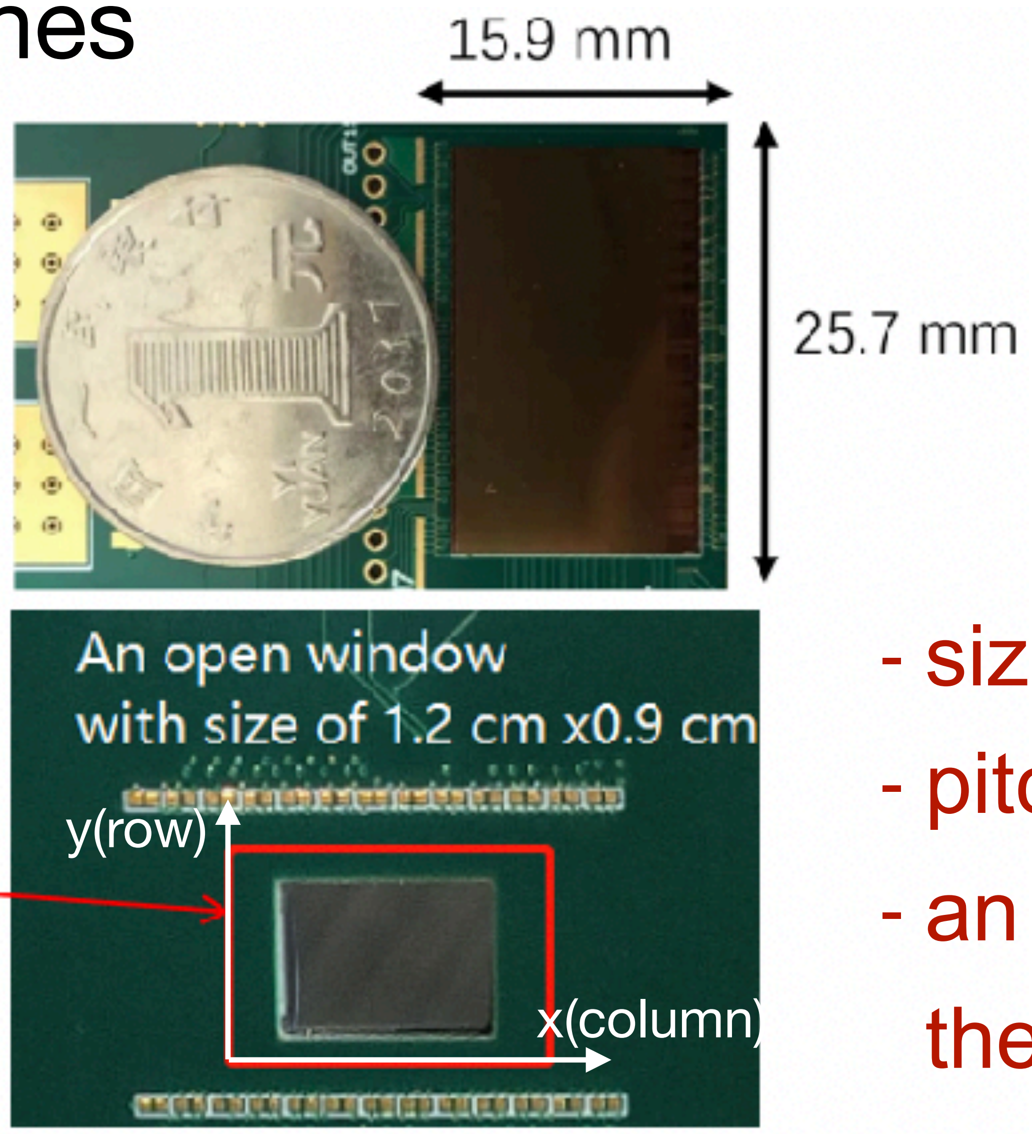


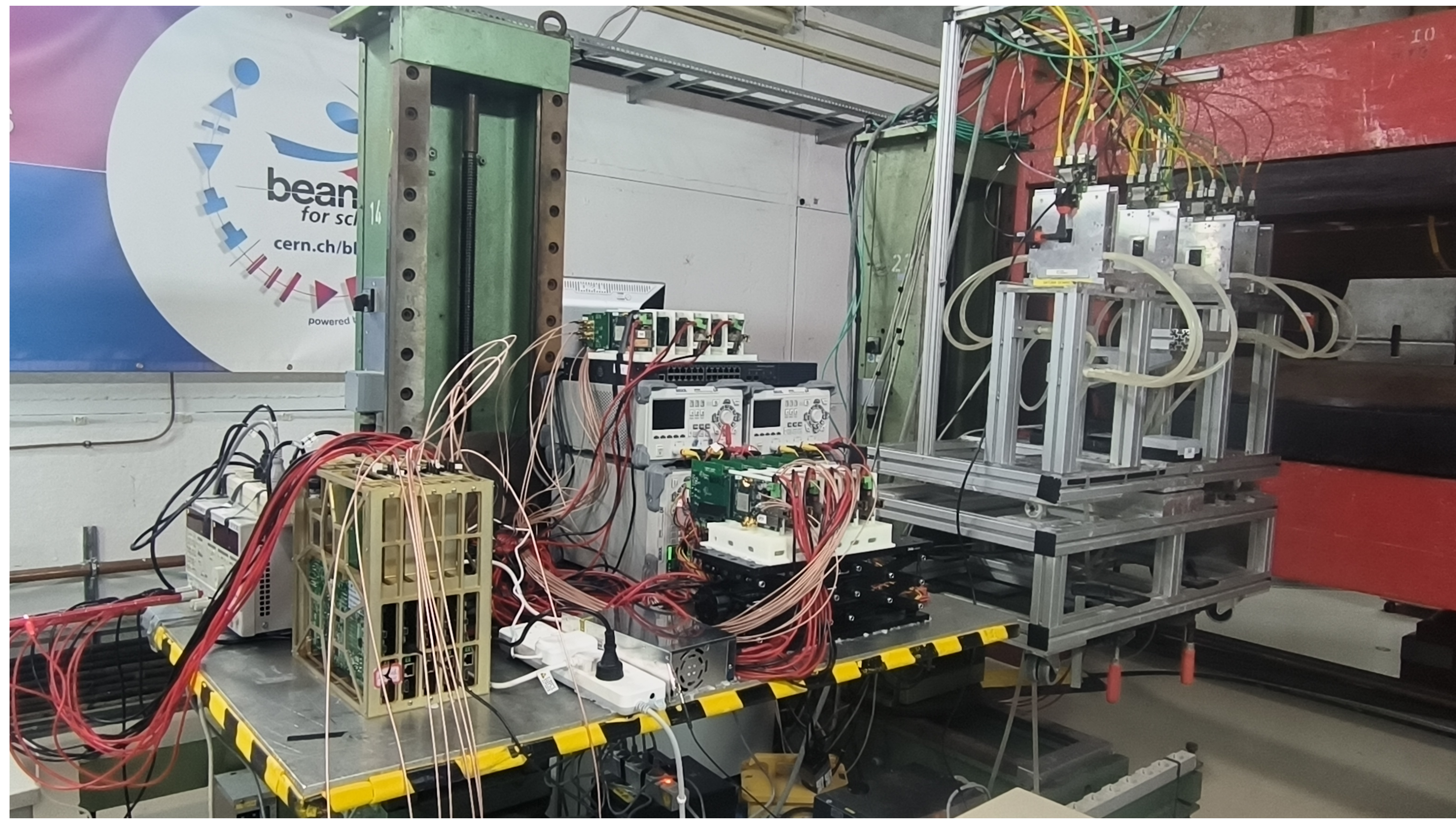




- The detector system includes 6 test modules based on the TaiChuPix-3 chips
- When one chip taken as DUT, another 5 planes composed of the telescope
- 4 cm between neighbouring planes

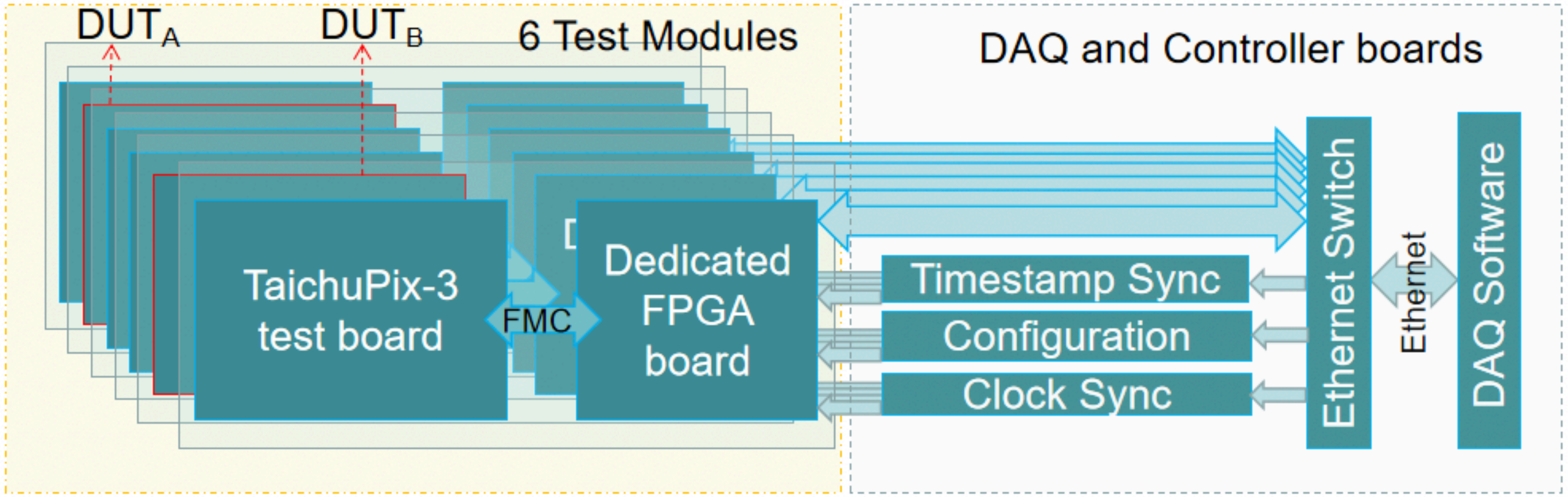






- size: 1024 columns x 512 rows
- pitch: 25 um
- an open window used to decrease the multi-scattering from the PCB board

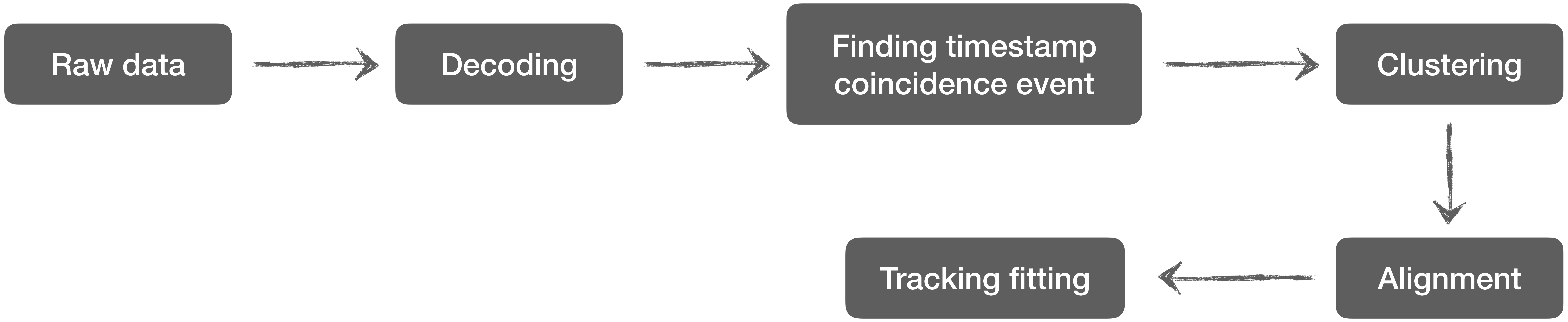
The work flow of the test system



- The data of 6 channels read out by a specialised DAQ software shan
- A 20 MHZ clock (Clock Sync) used to synchronize the data of 6 channels
- A timestamp synchronization board used to calibrate the time delay from each channel

Beam data analysis and results

- **The flow chart of offline analysis**

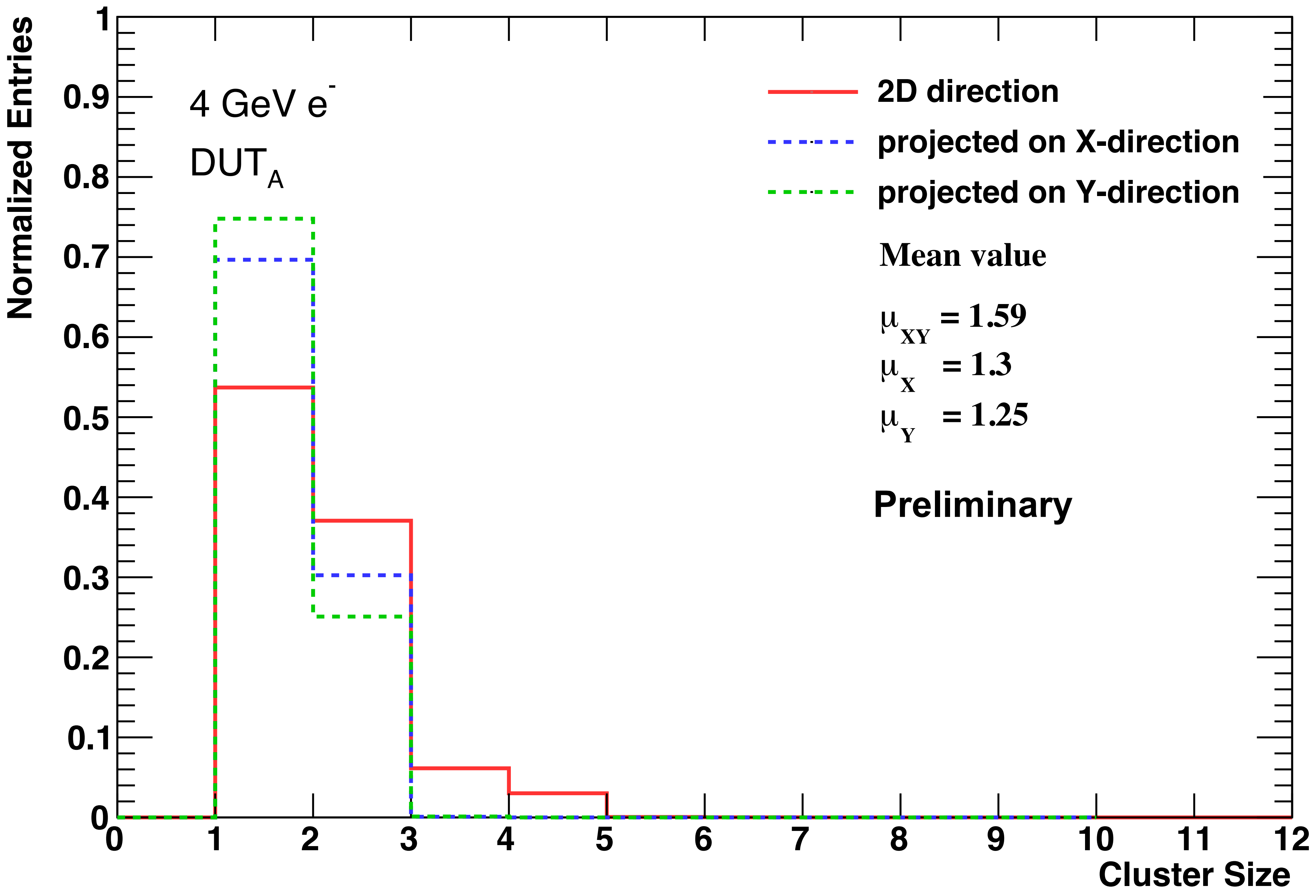


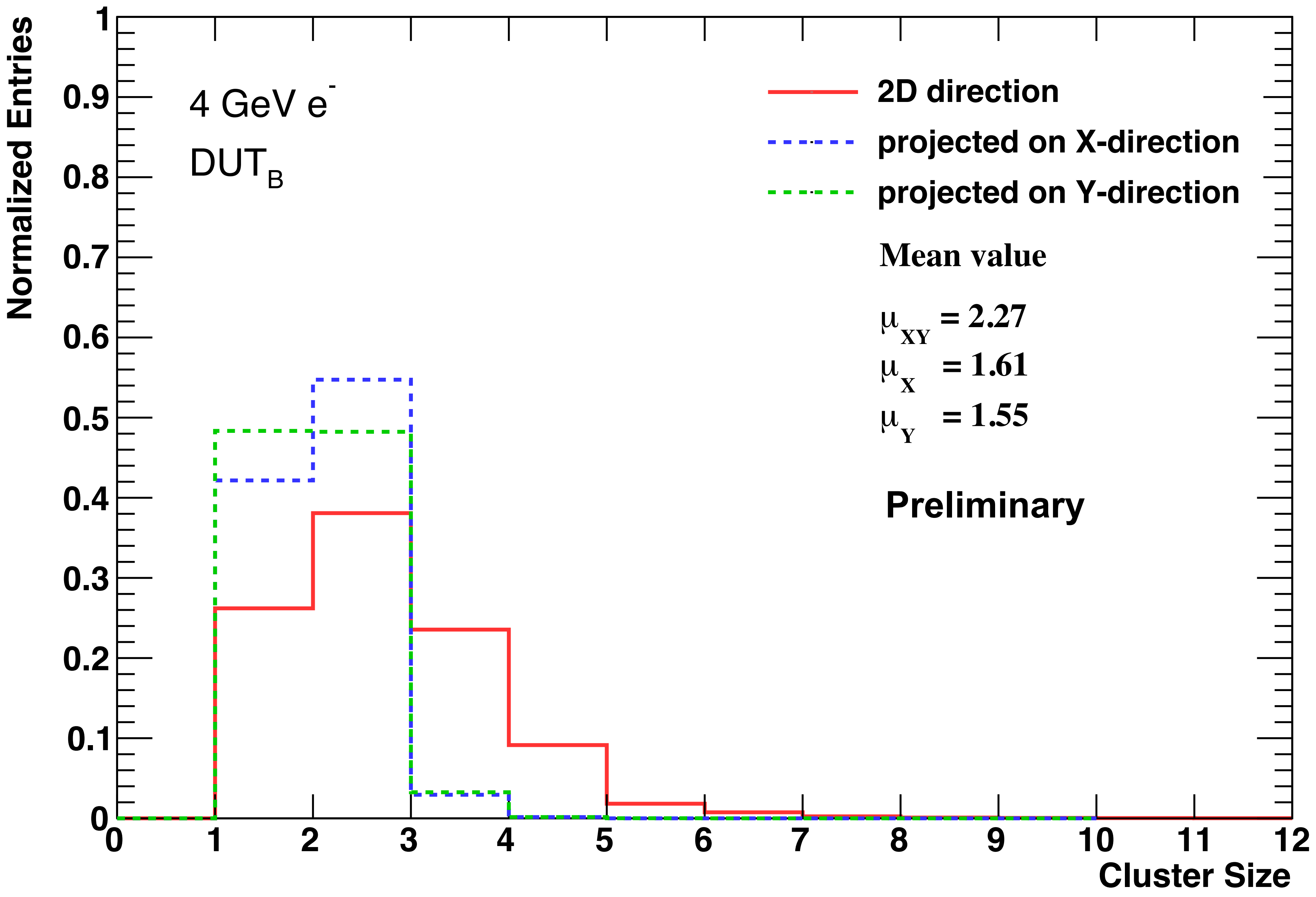
- The hit information encoded with a **32-bit format**
- The centre of the cluster is the **geometric centre of the gravity of the neighbouring fired pixels**
- The alignment procedure using the Millepede program
- **Least squares straight line fit**
- no correction for multiple scattering in this result

➡ Cluster size

‣ Cluster size distribution

- The peak value for DUT_A is 1 pixel, around 2 pixels for DUT_B
- Less charge sharing effects in DUT_A with full depletion



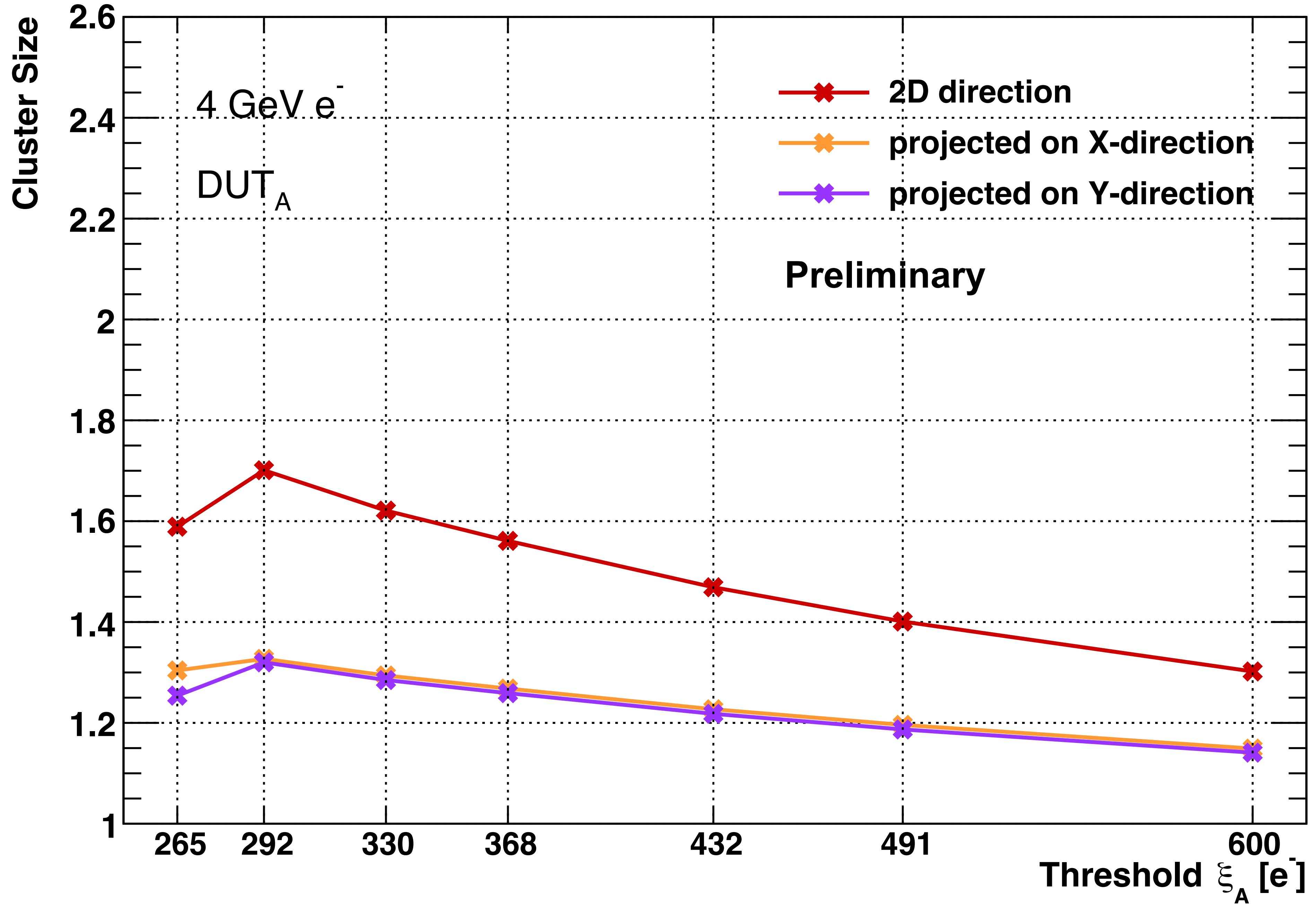


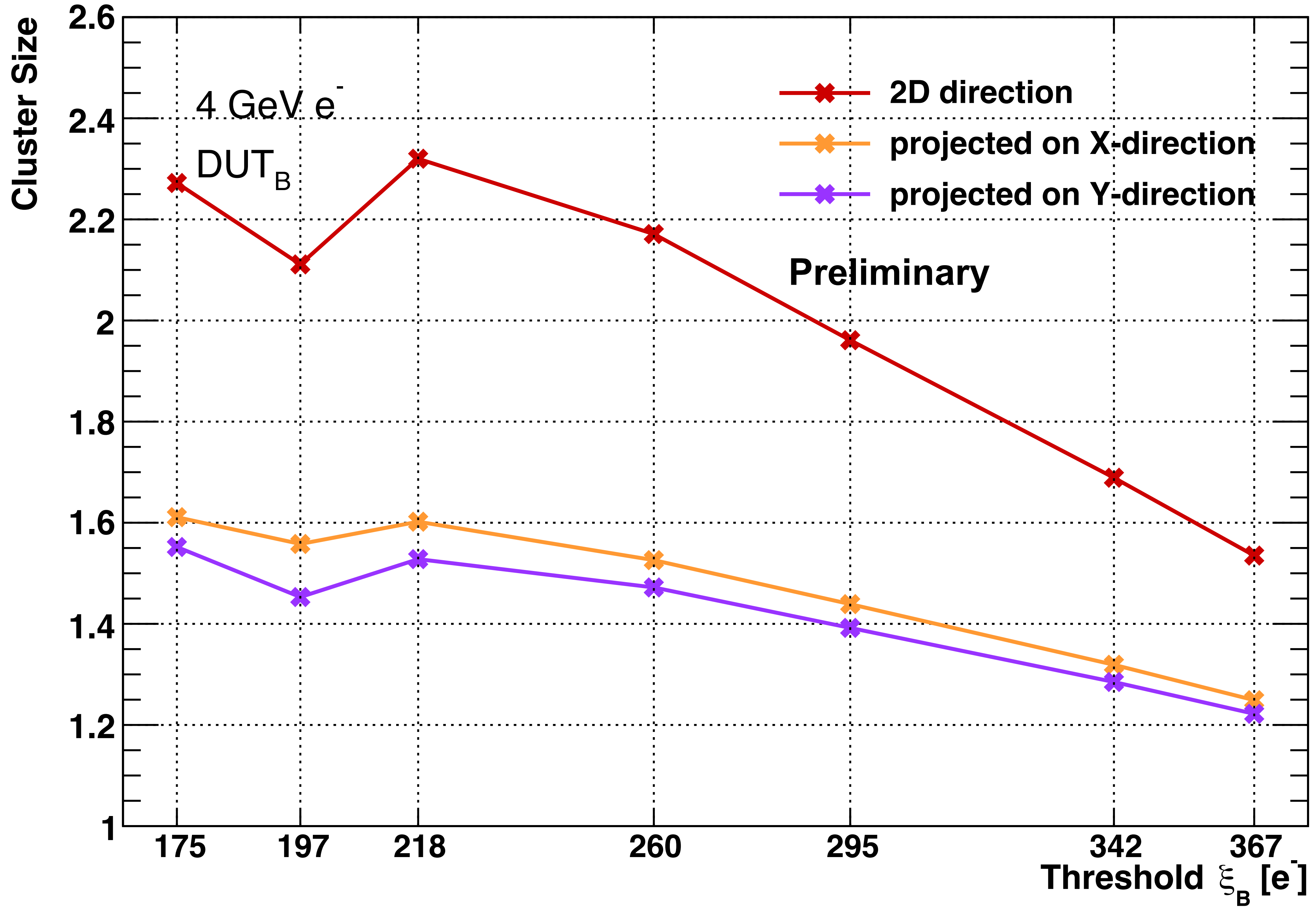
- X direction: column direction of the sensor
- Y direction: row direction of the sensor
- DUT_A: full depletion
- DUT_B: non full depletion

➡ Cluster size

Averaged cluster size as a function of the threshold

- In general, the higher the threshold, the smaller the cluster size
- If lowering the threshold, cluster size will be dominated by cluster with 2 hits



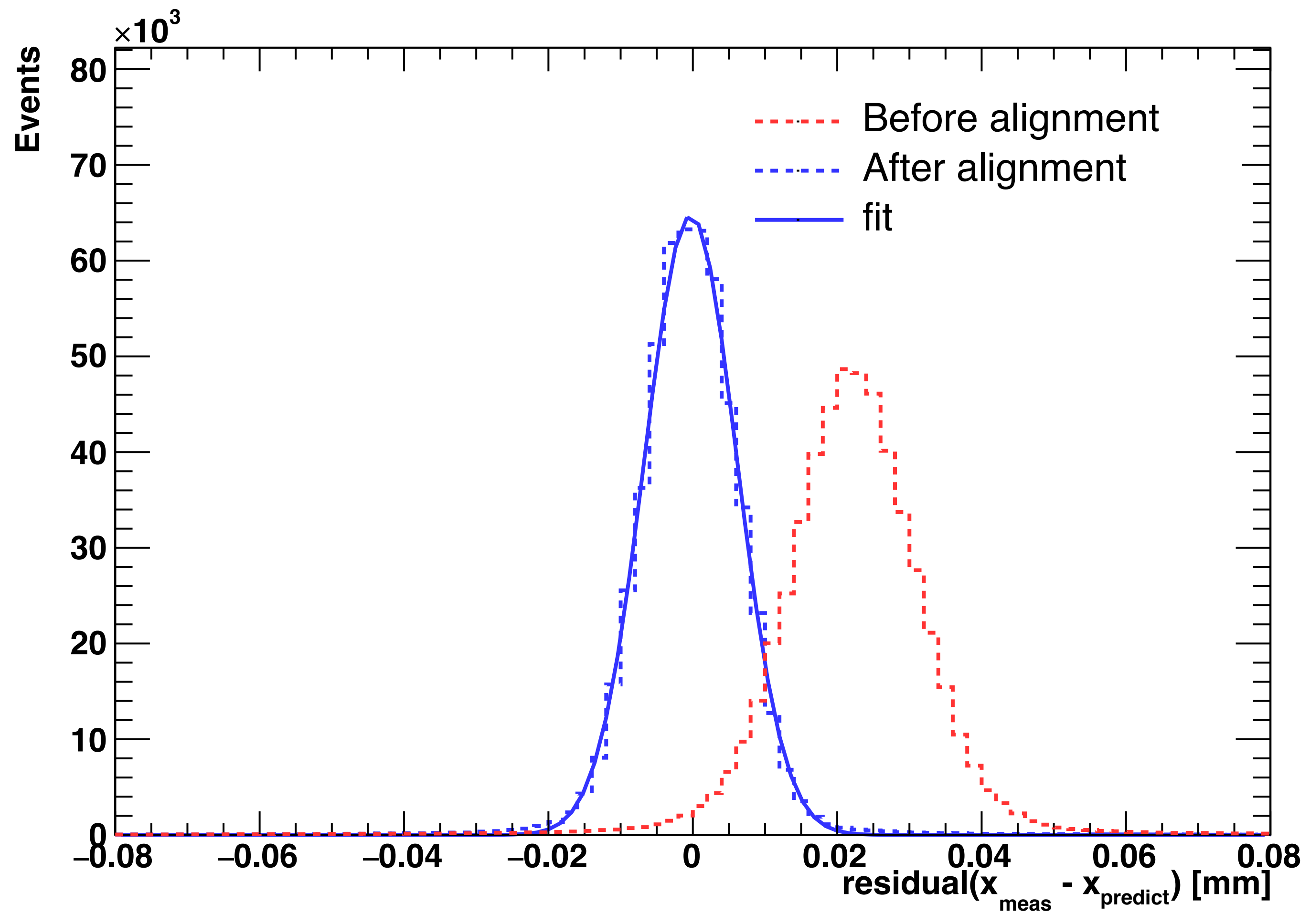


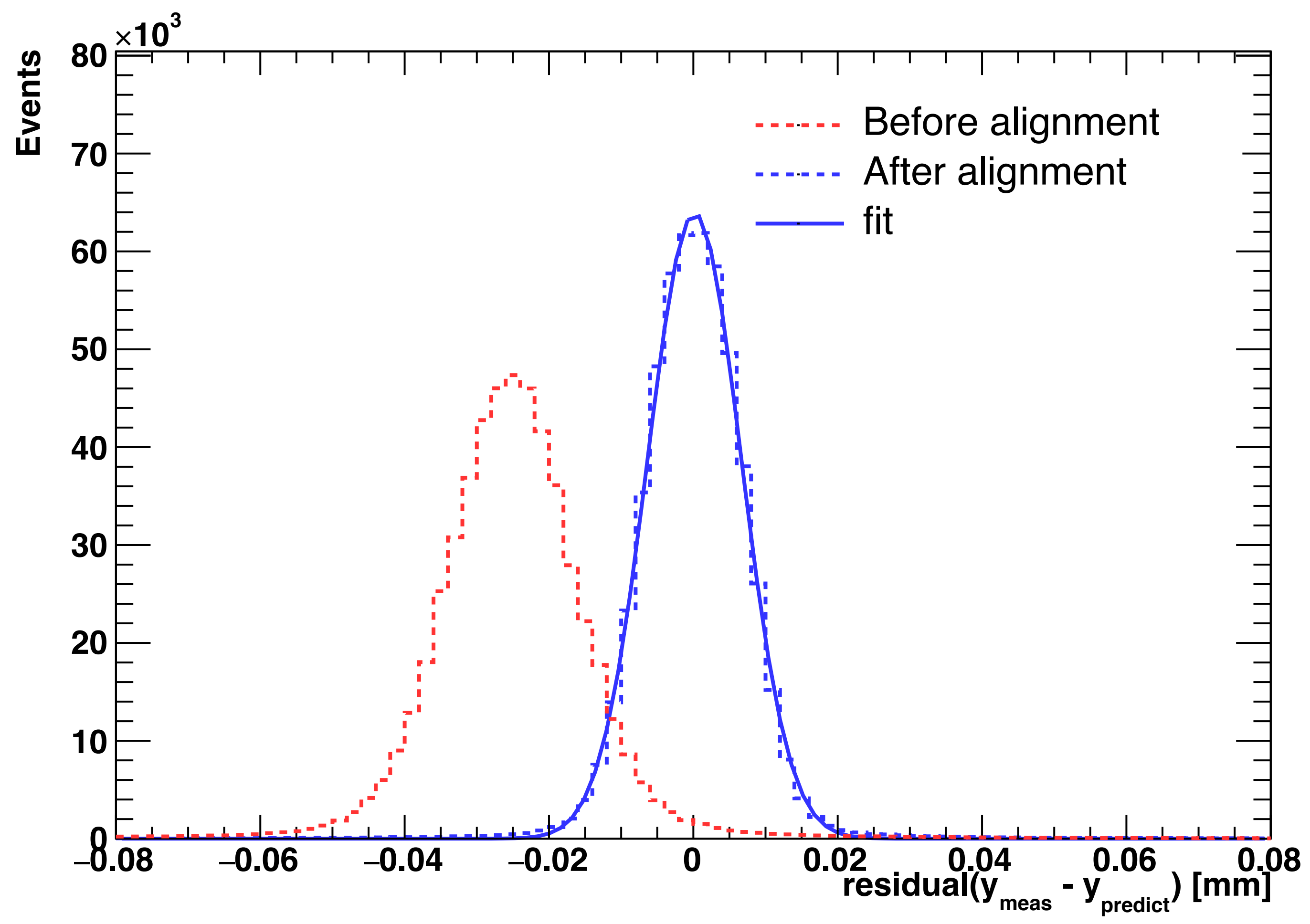
➡ Alignment

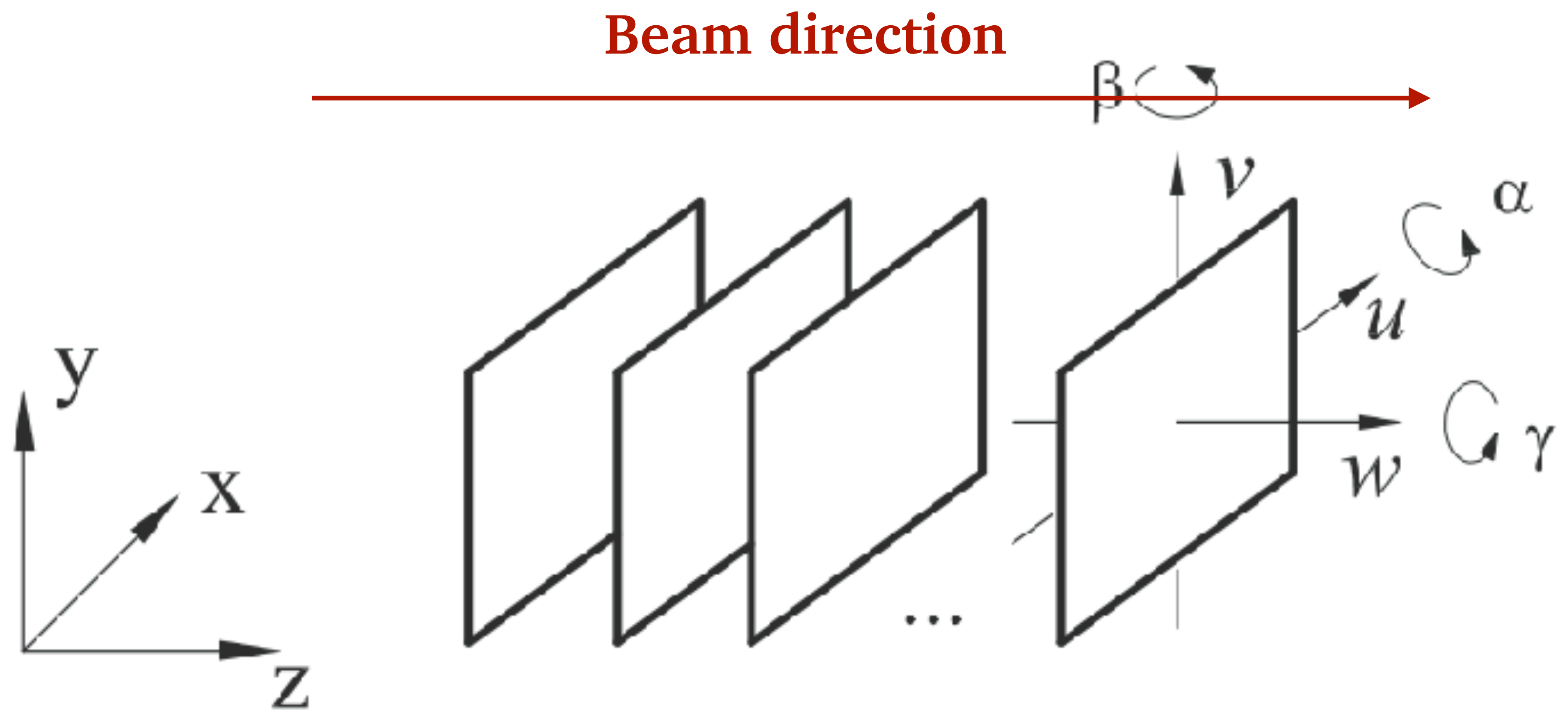
- The alignment parameters are determined iteratively by a general χ^2 minimization procedure

$$\chi^2 = \sum_{j \in tracks} \sum_{i \in hits} \vec{r}_{ij}^{\,T}(g, l_j) V_{ij}^{-1} \vec{r}_{ij}(g, l_j)$$

- The solution of above equation is calculated by the Millepede program
- Six alignment parameters considered
  - Translation along X, Y, Z direction
  - Rotation around X, Y, Z axis







➡ Spatial resolution studies

‣ The spatial resolution of DUT

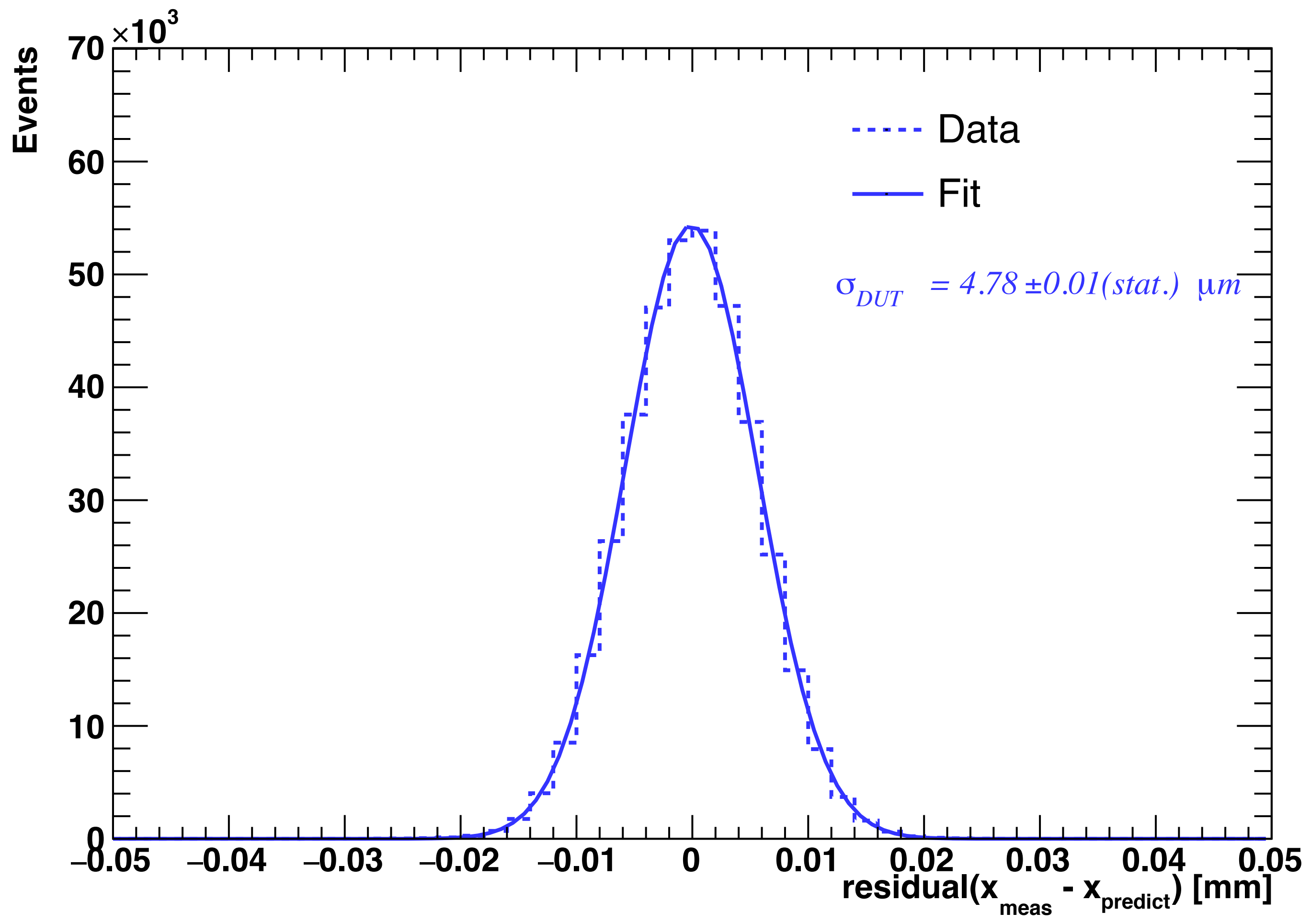
- applying the alignment parameters to the measured hit position
- the spatial resolution of DUT evaluated from the unbiased residual distribution

$$\sigma_{DUT} = \sqrt{\sigma^2_{res,unbiased} - k\sigma^2_{tel}}$$

- assuming same intrinsic resolution for the 6 planes

$$\sigma^2_{DUT} = \frac{\sigma^2_{res,unbiased}}{1+k}, k = \frac{\sum_i^N z_i^2}{N\sum_i^N z_i^2 - (\sum_i^N z_i)^2}$$

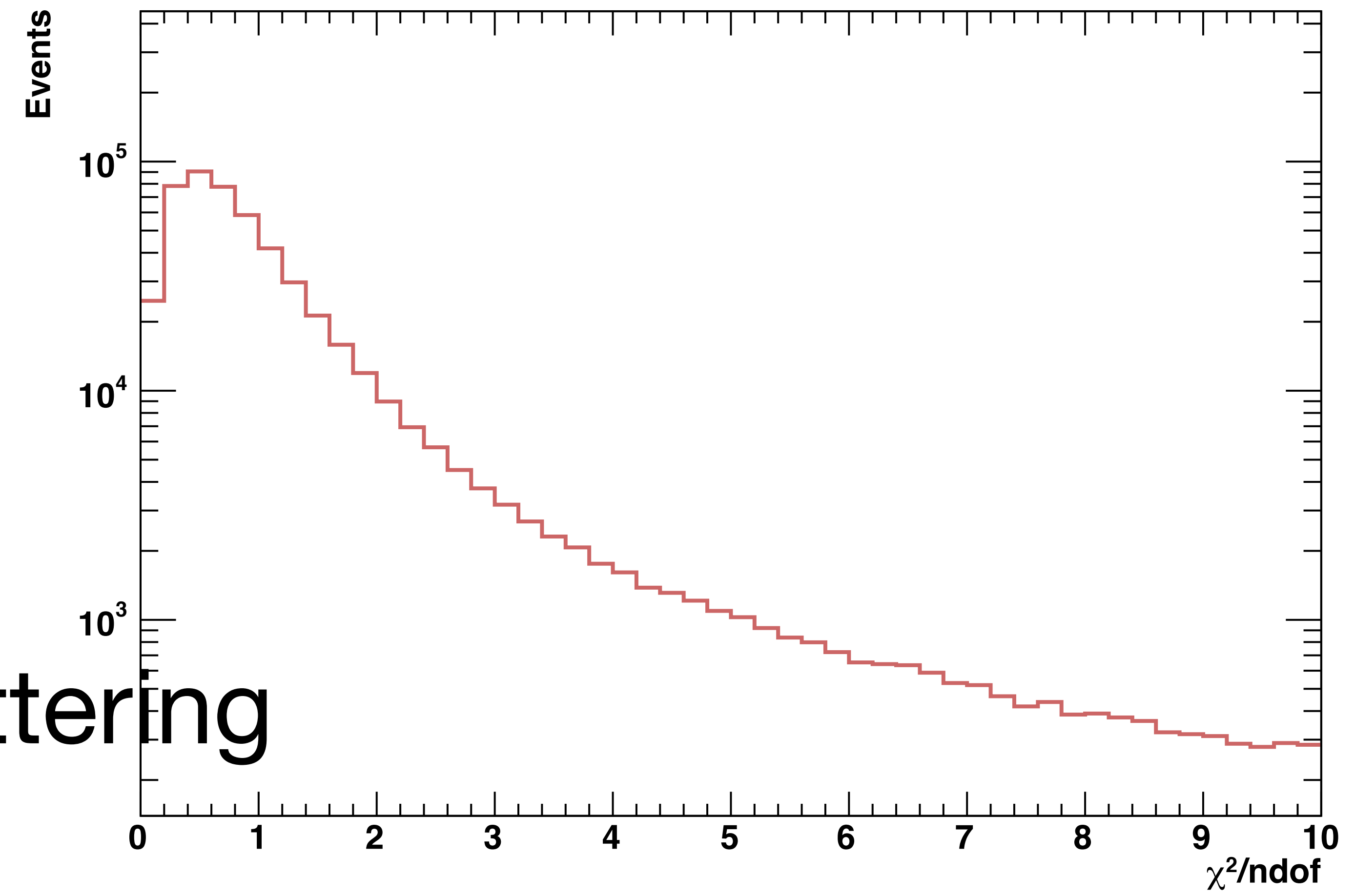
  - z_i is the z position of plane in global coordinate
  - unbiased residual $\sigma_{res,unbiased}$: the difference between measured hit position on DUT and the predicted one extrapolated from the track of telescope



- least squares straight line fit

$$\chi^2 = \sum_i^n \frac{(x_{pre}, y_{pre} - x_{mea}, y_{mea})^2}{\sigma_{x,y}}$$

$$\sigma_{x,y} = \frac{25\mu m}{\sqrt{12}}$$, 25 um is the pixel pitch

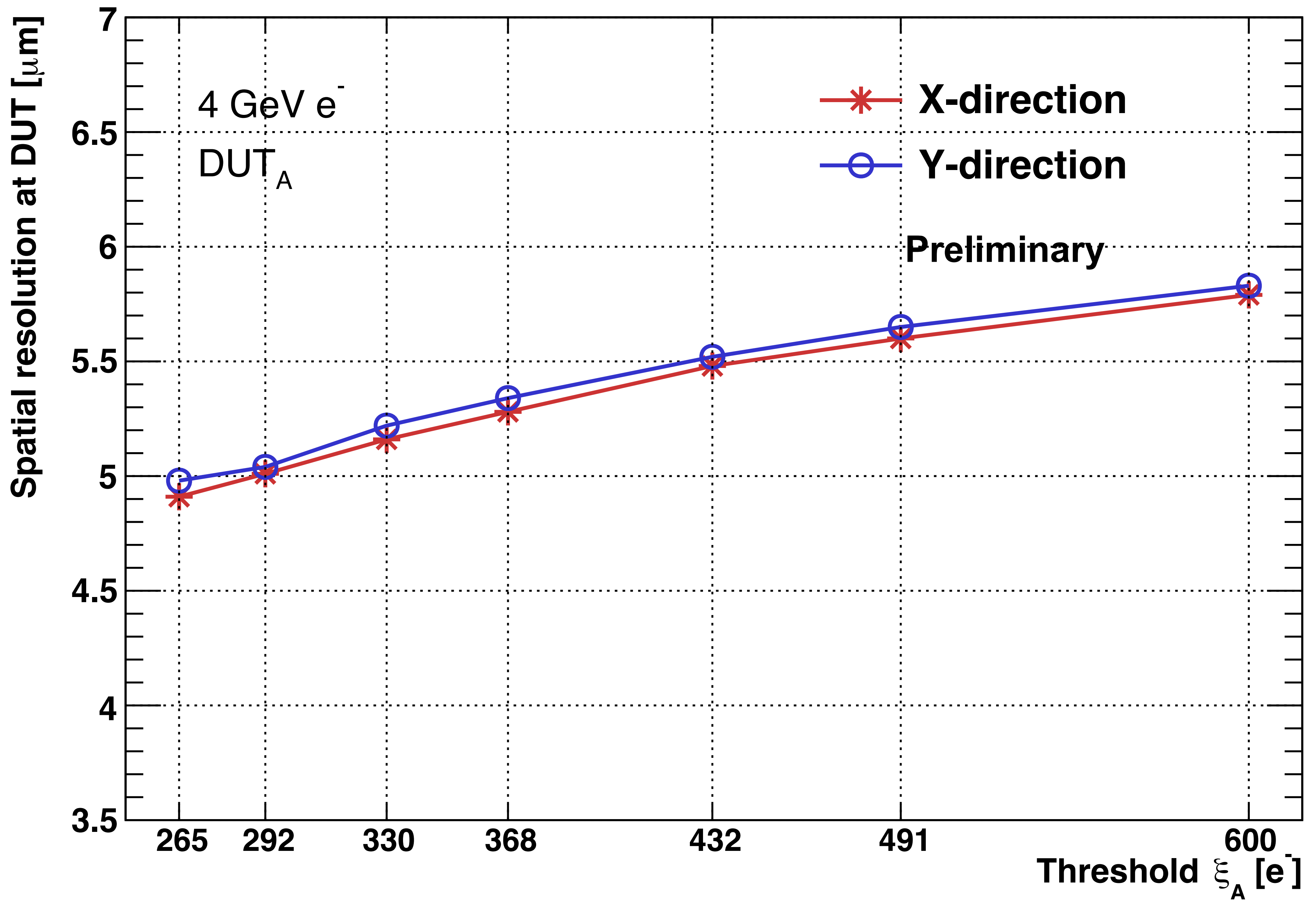


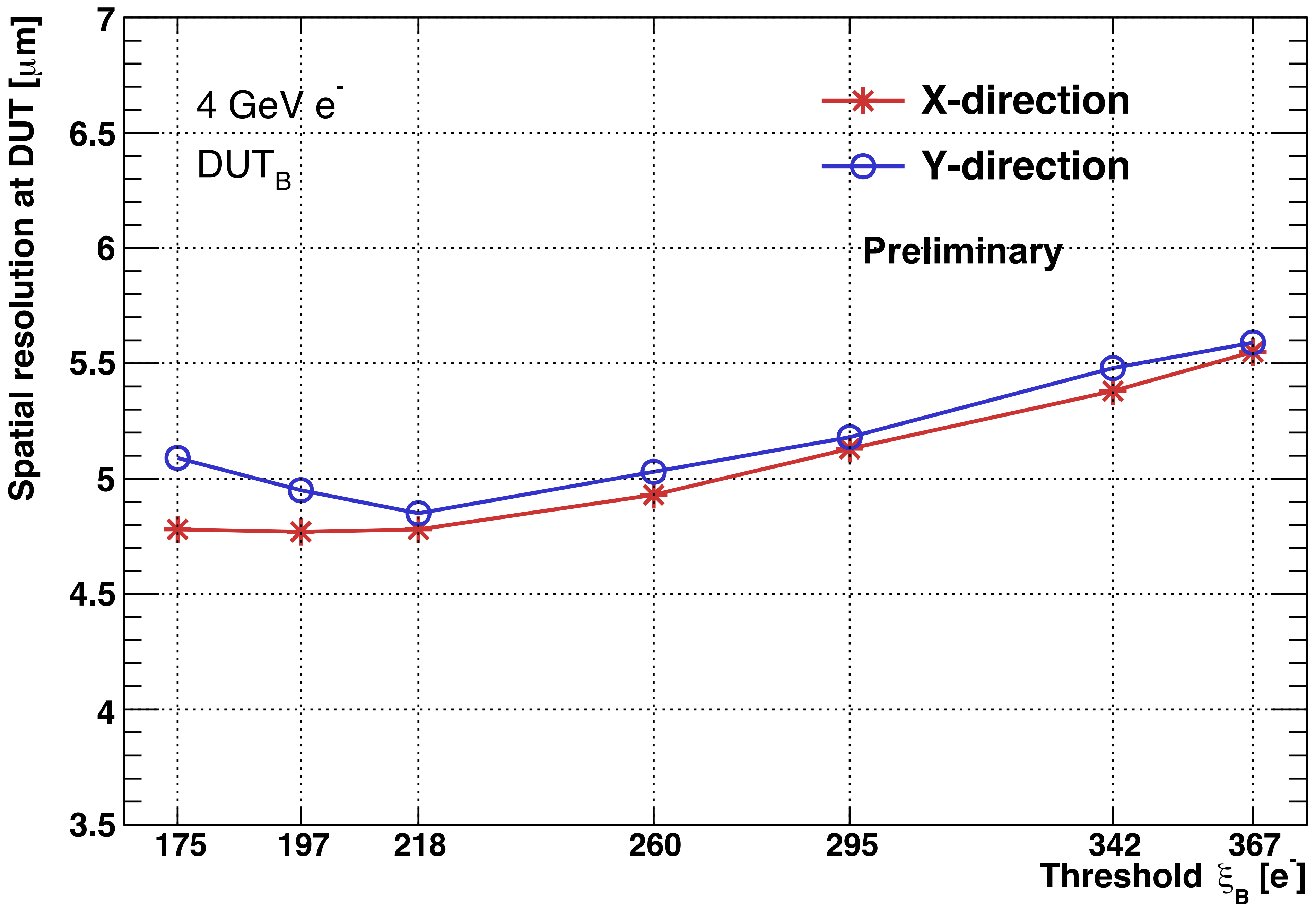
- a track quality χ^2 cut added to decrease the effects from multi scattering

➡ Spatial resolution studies

The spatial resolution as a function of threshold

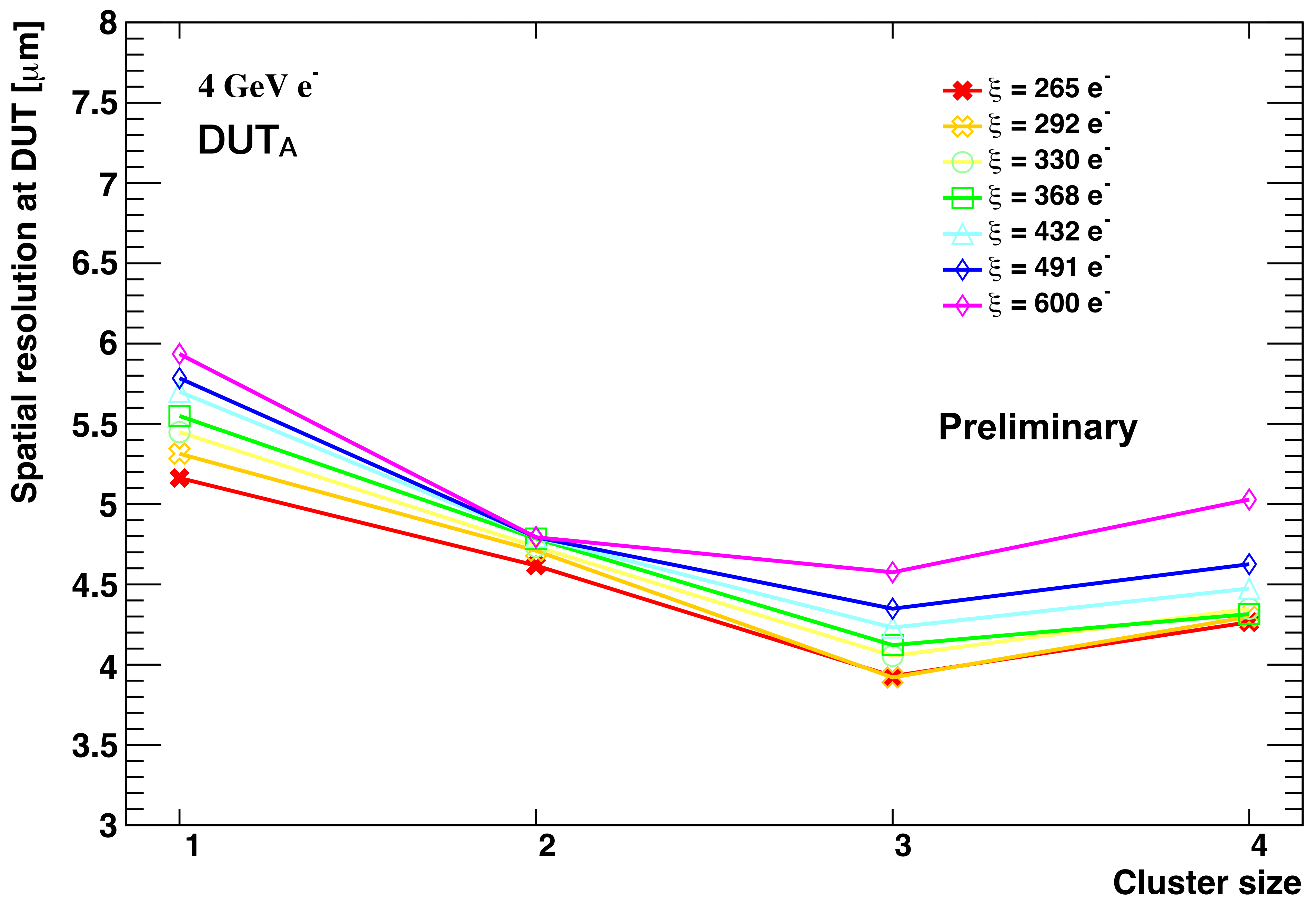
- The resolution gets worse due to the increased threshold
- for DUT_B, a worse resolution occurs when the threshold < 218 e^- since the larger noise at lower threshold

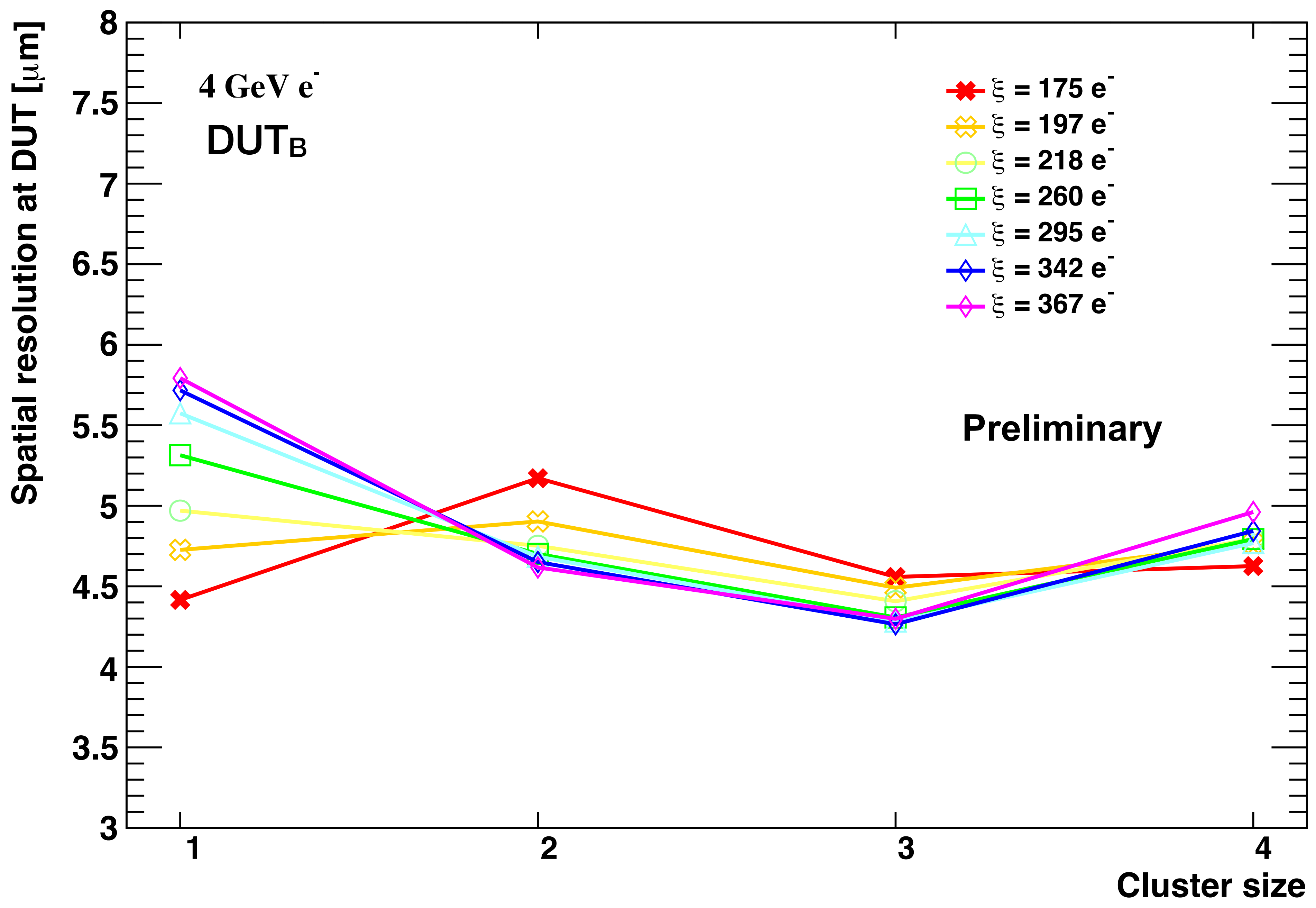




only statistical uncertainties included

The spatial resolution vs. different cluster size in different threshold





resolution only in x-direction

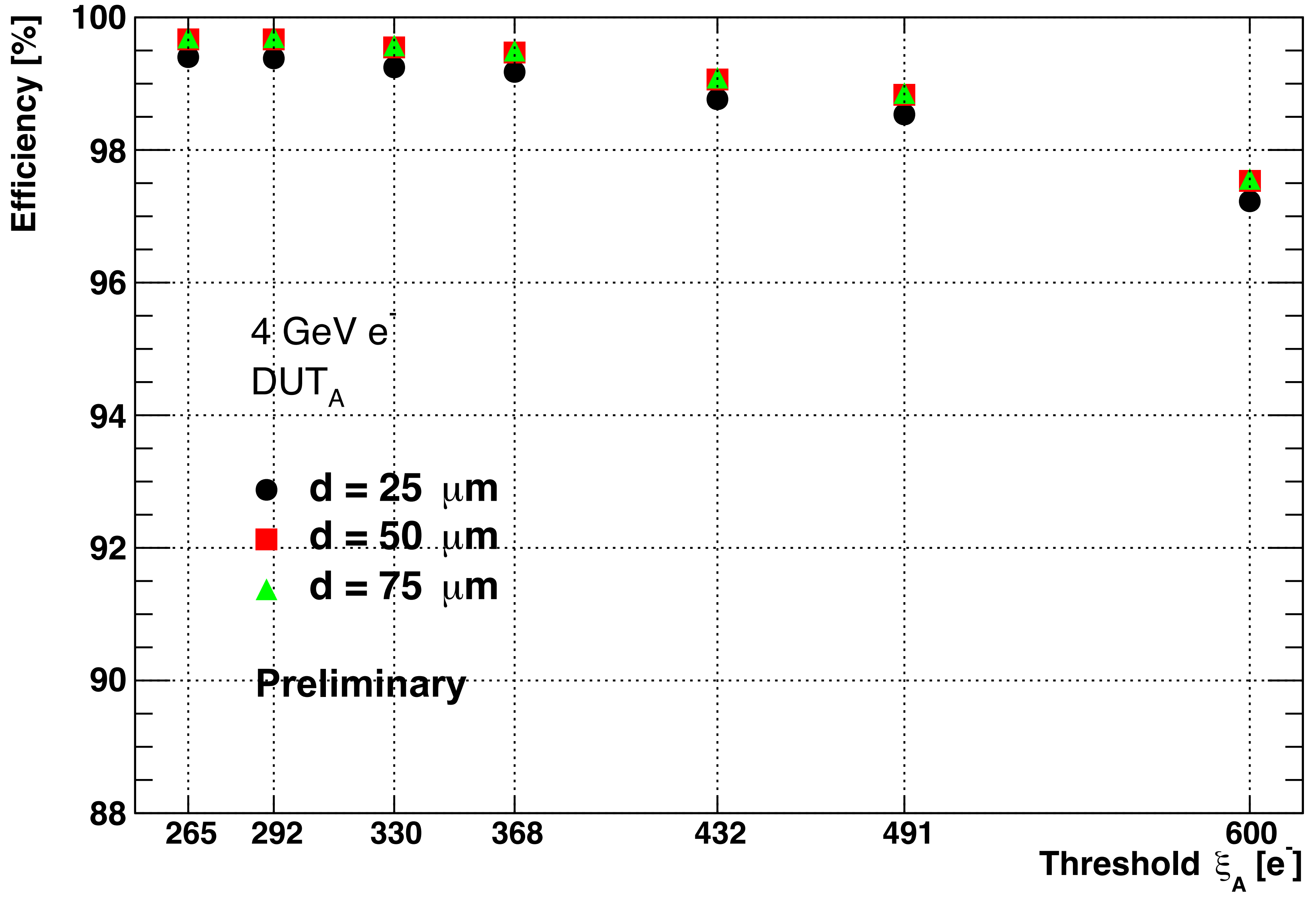
- For most case, the resolution is best when cluster size = 3
- for DUT_B with minimum setting threshold, the best resolution occurs when cluster size = 1, due to the increasing noise on minimum threshold.

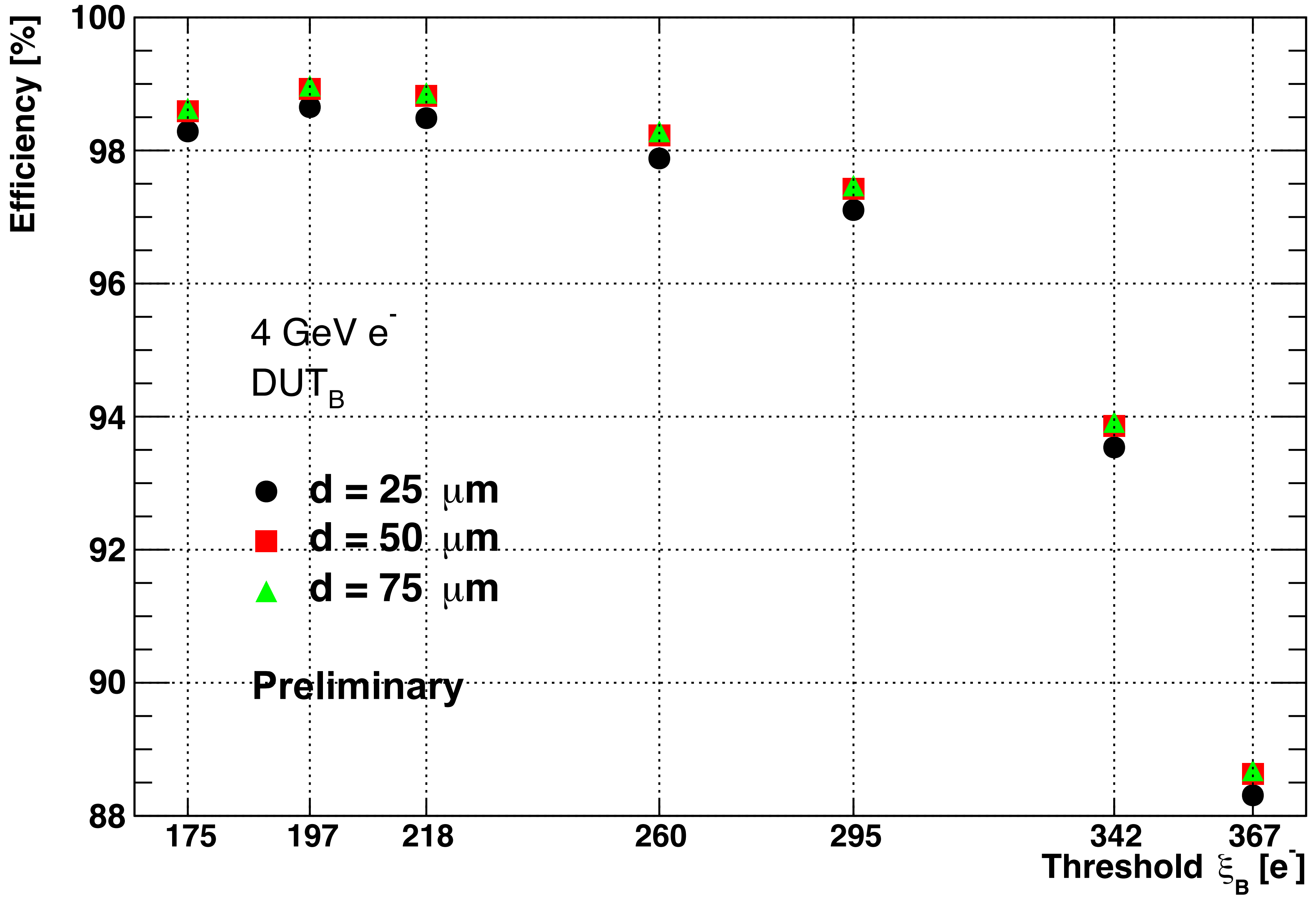
➡ Detection efficiency

- **Efficiency definition:**

$$\epsilon = \frac{N^{matched\ Tracks}_{|x_{meas},y_{meas}-x_{pre},y_{pre}|<d}}{N^{Tracks}_{tel}}$$

- with increasing threshold, the efficiency decrease
- maximum eff. for DUT_A is 99%, maximum eff. for DUT_B is 98.5%





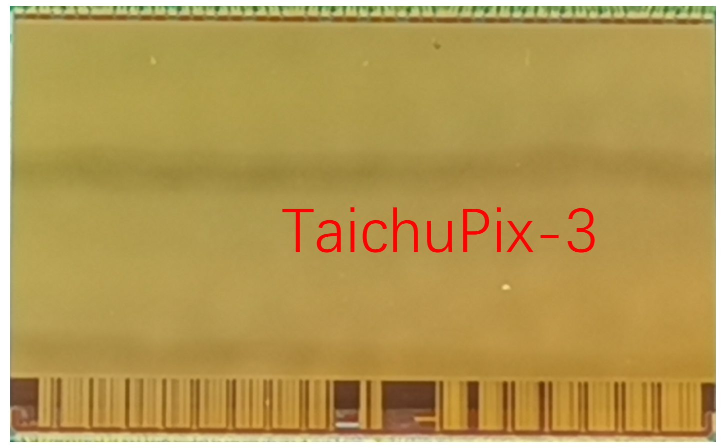
Summary and outlook

Beam test on a MAPS prototype TaichuPix-3.

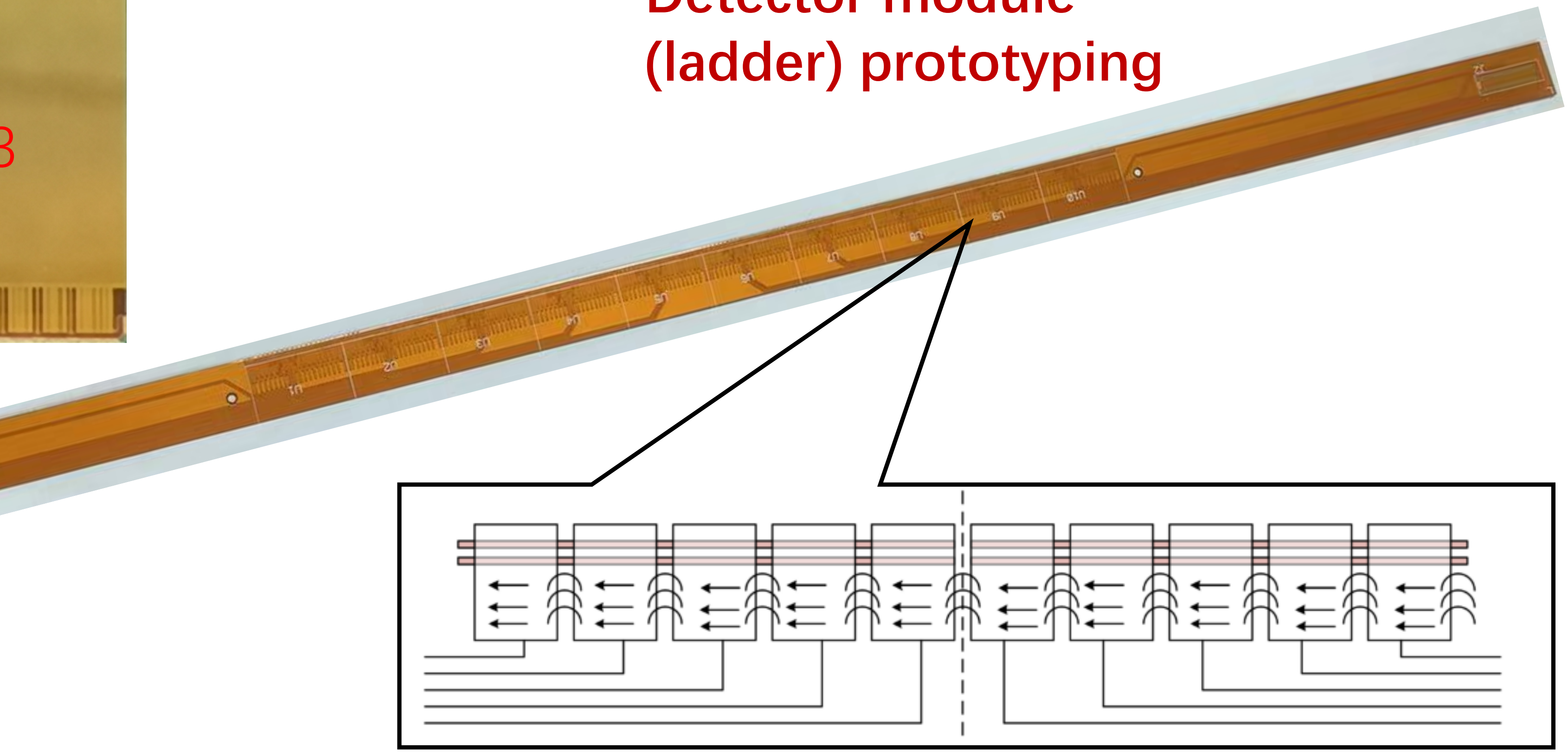
- 2 DUT with different processes verified using 4 GeV electron beam at DESY II TB21.
- The resolution can better than 5 um at setting minimum threshold
- The detection efficiency can > 98%

Vertex detector prototype for CEPC

CMOS pixel sensor prototyping

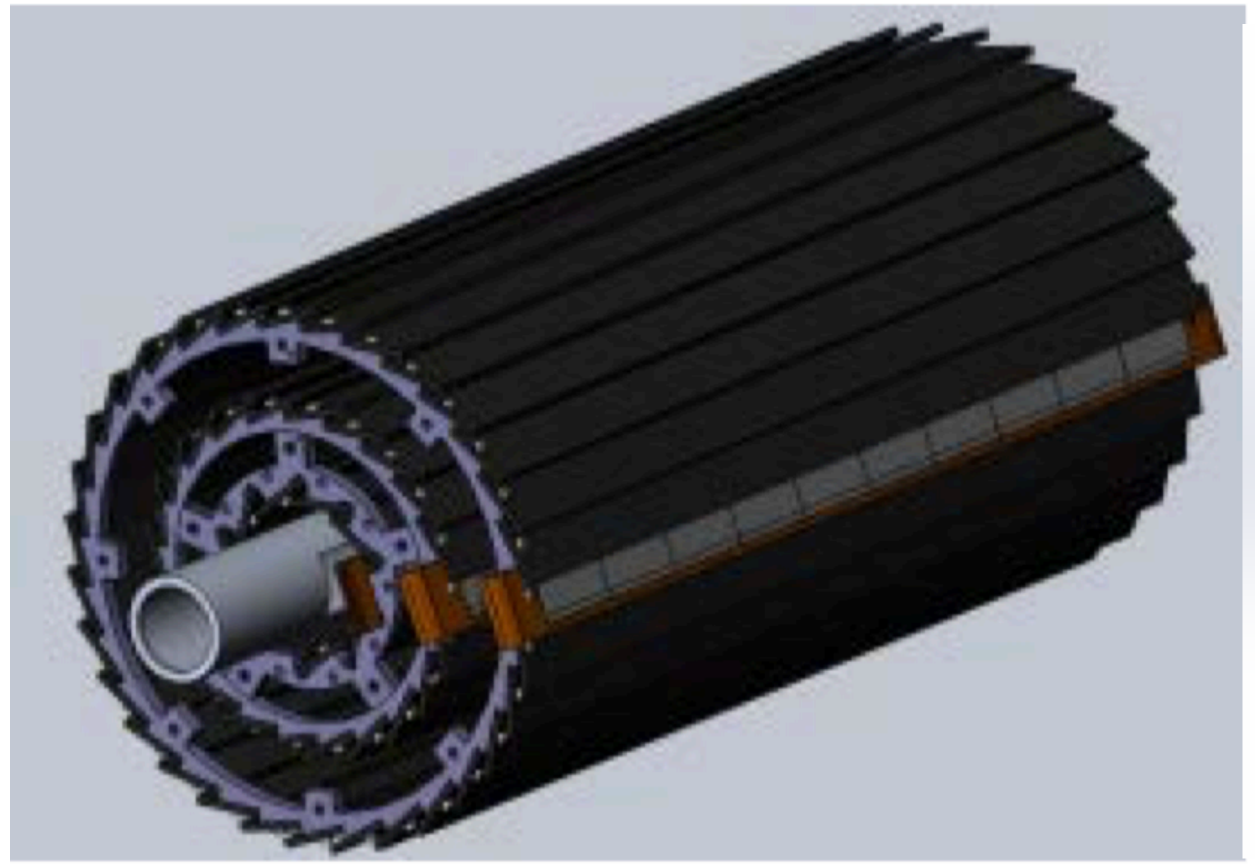


Detector module (ladder) prototyping

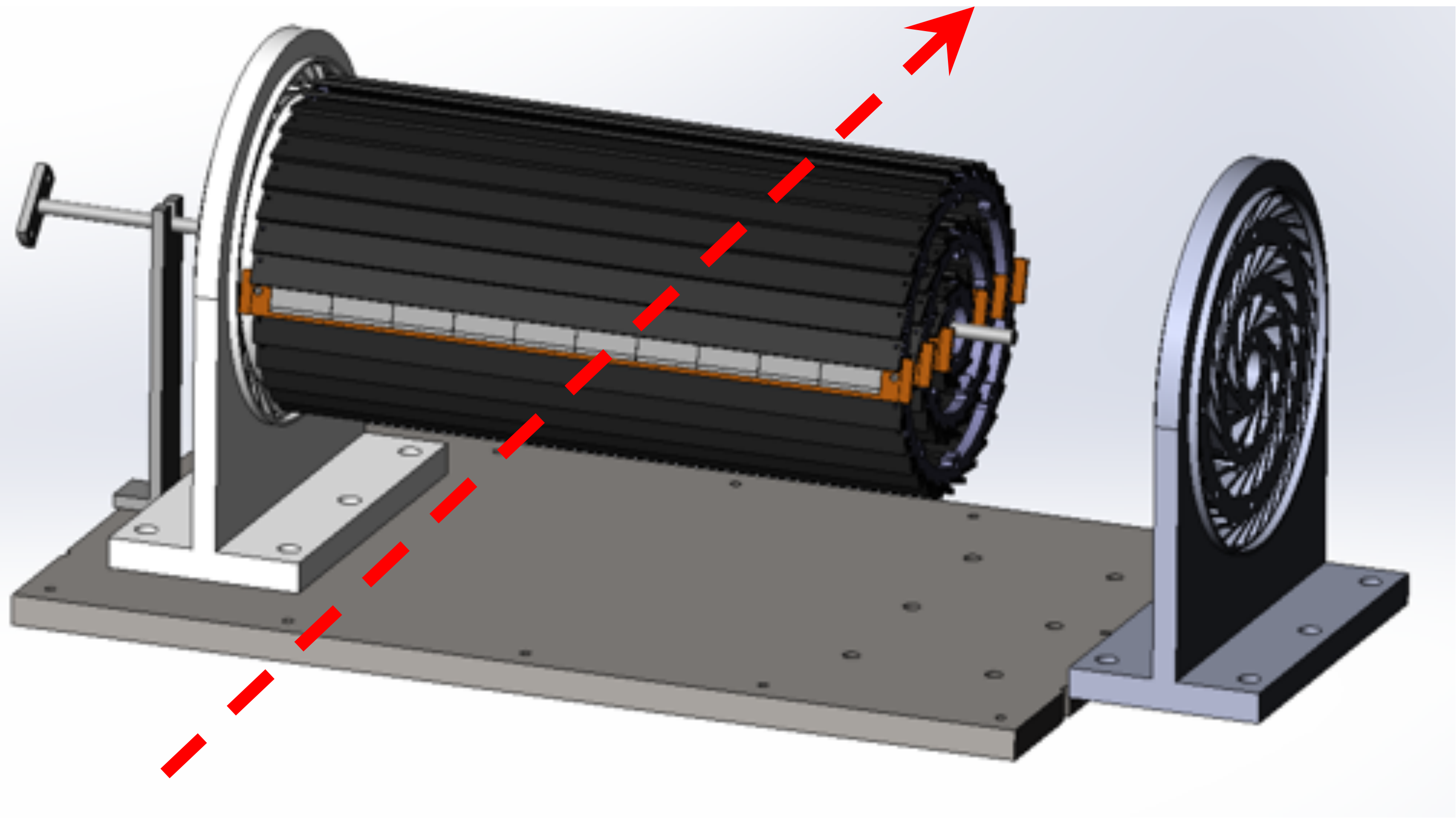


Double sided ladder
10 sensors/ladder side, read out from both ends

Full size vertex detector prototype

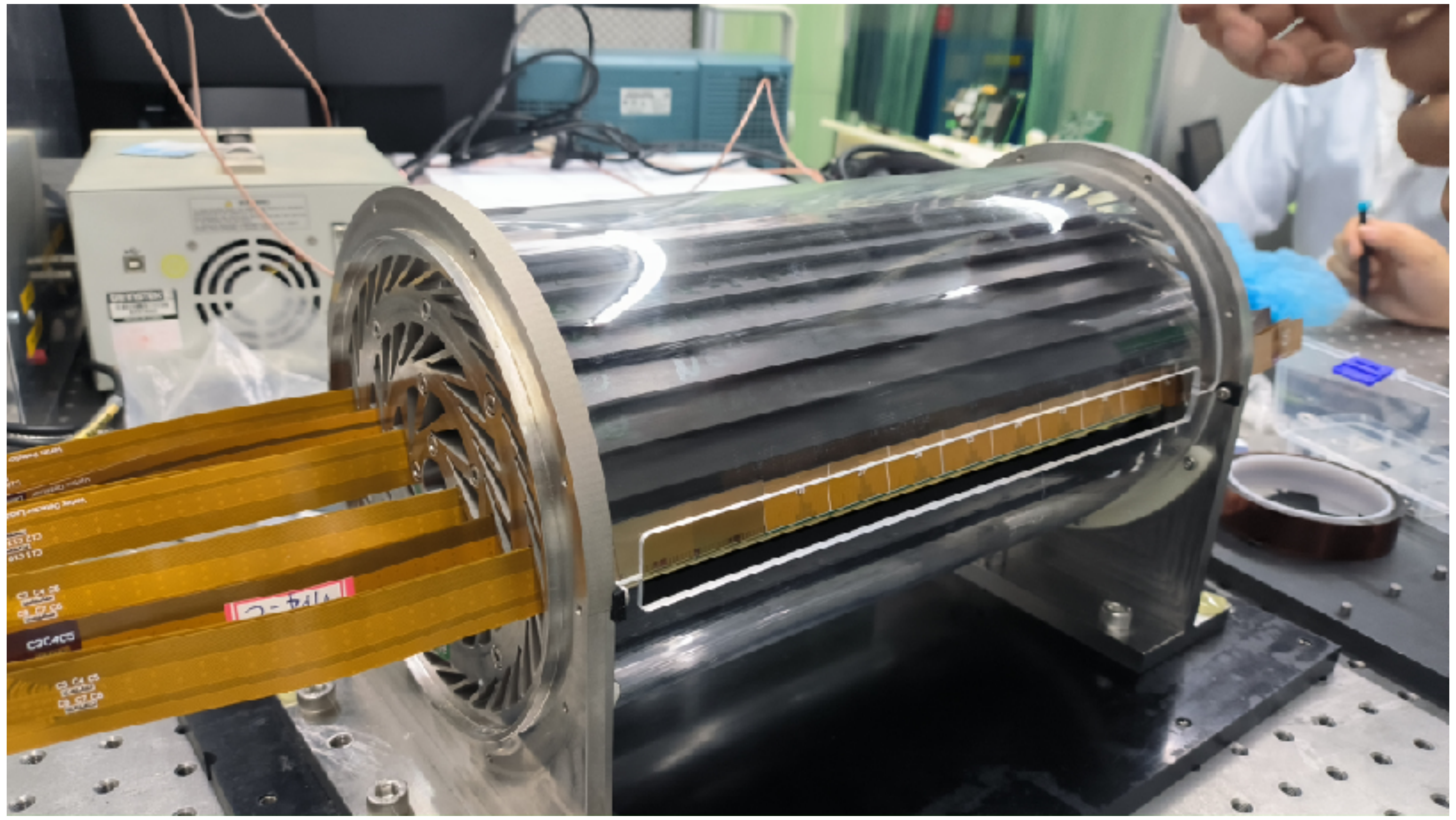


Beam test to verify its spatial resolution



Summary and outlook

- The characterisation of vertex detector prototype is testing @ DESY II TB21
- The data taking and analysis are working on progress
- Hoping that we can get excellent results!



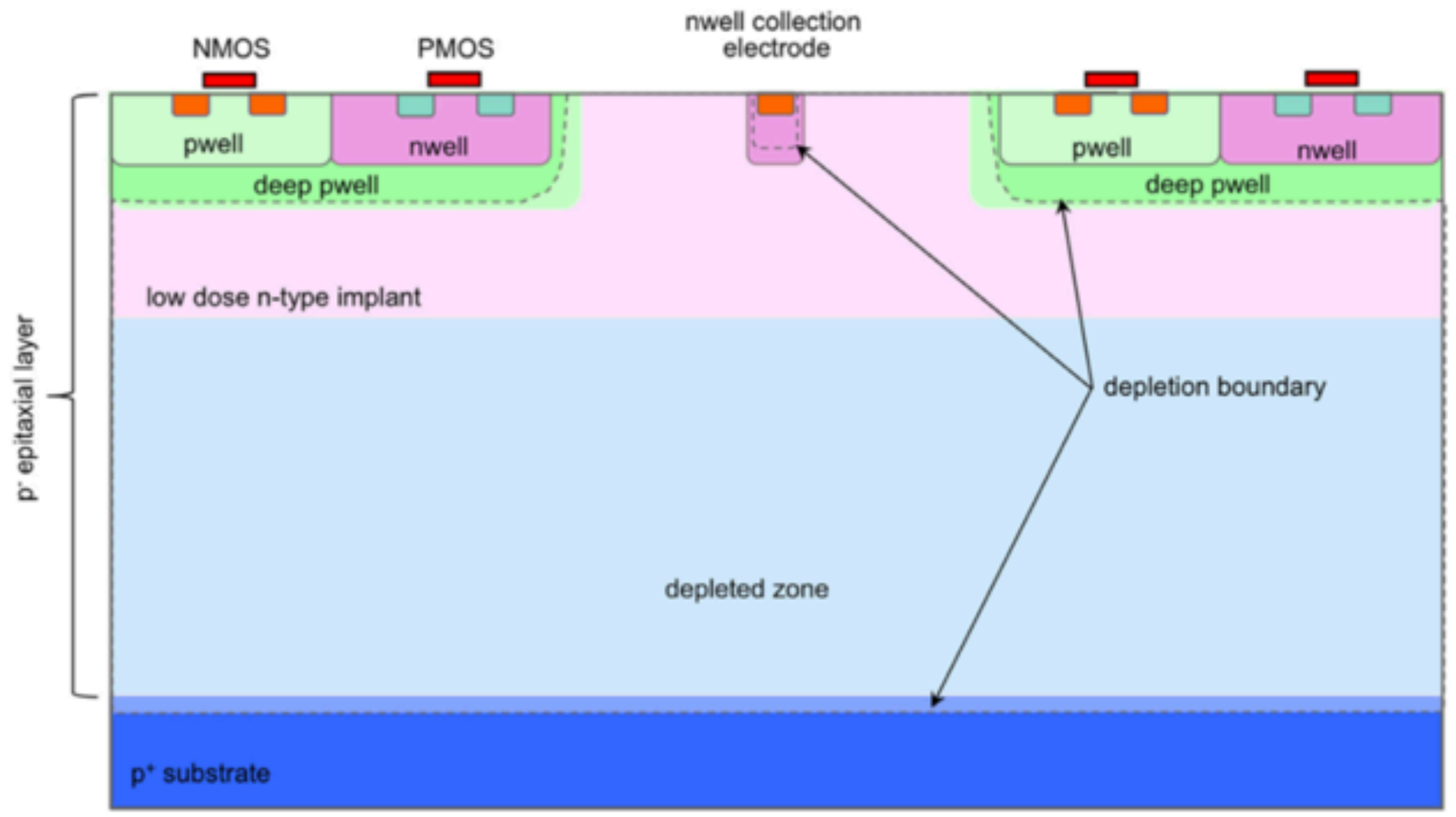
6 layers ladders with double sided TaichuPix3 chips

Thanks for DESY providing the beam!!!

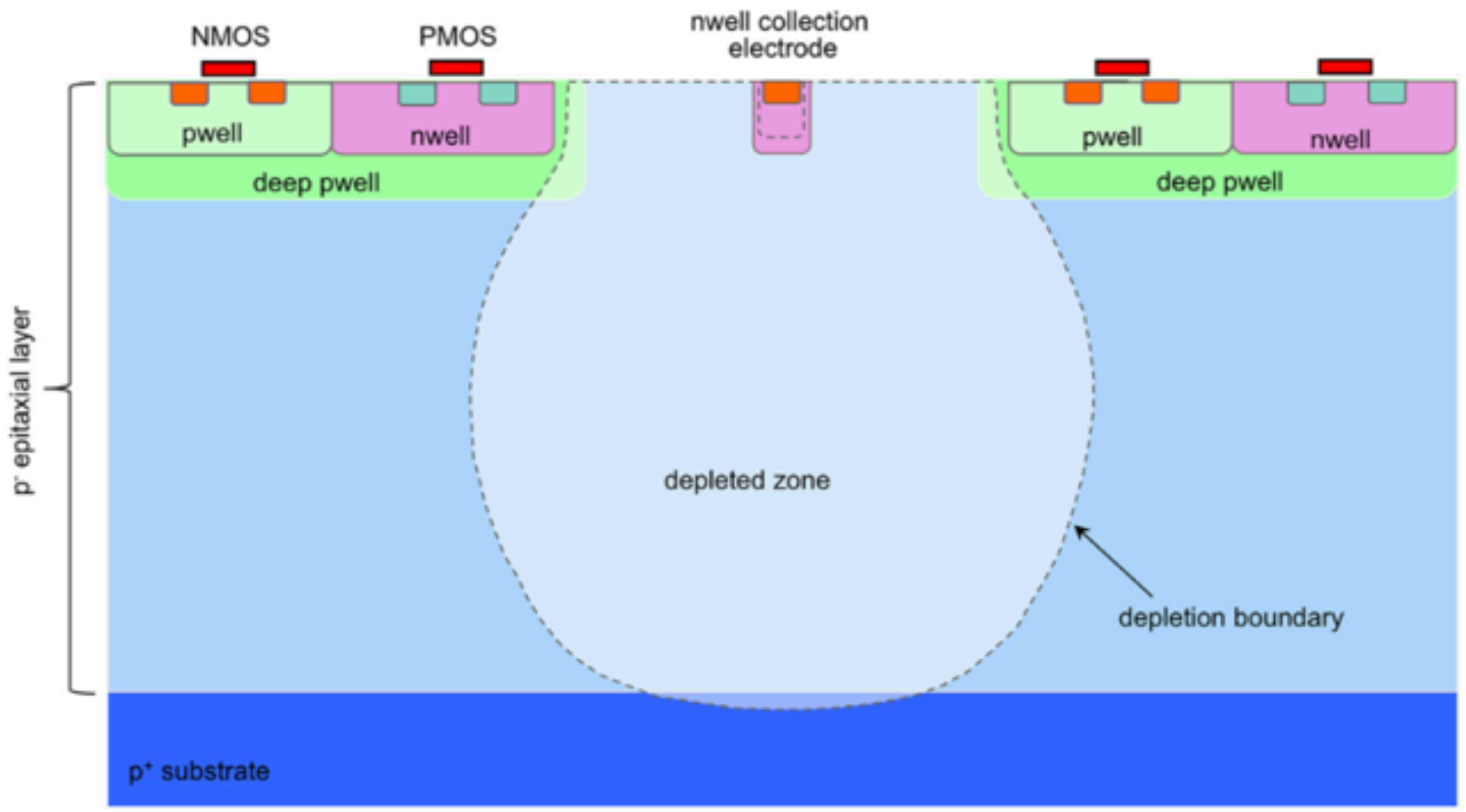
Backup

chip_id: 4bits
timestamp_chip: 8bits
timestamp_FPGA: 28bits
column: 9bits
row: 10bits
pattern: 4bits
valid: 1bit

- The data of 6 channels read out by a specialised DAQ software shan
- A 20 MHZ clock (Clock Sync) used to synchronize the data of 6 channels
- A timestamp synchronization board used to calibrate the time delay from each channel



modified DUTA
full depletion

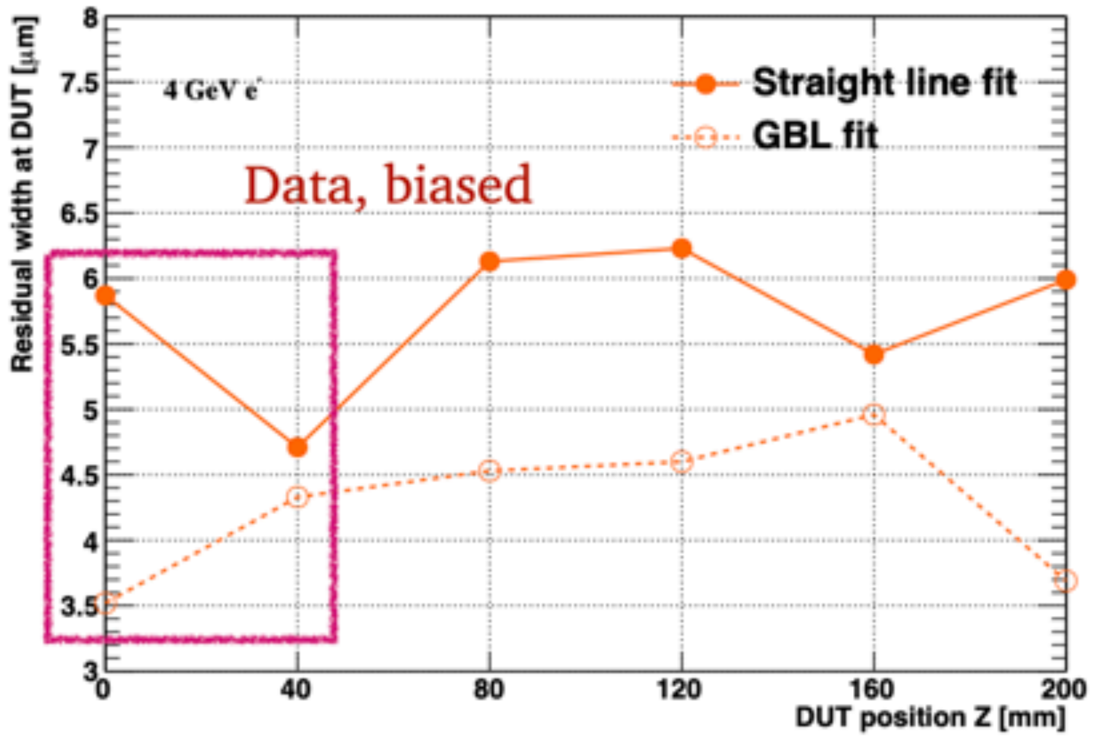


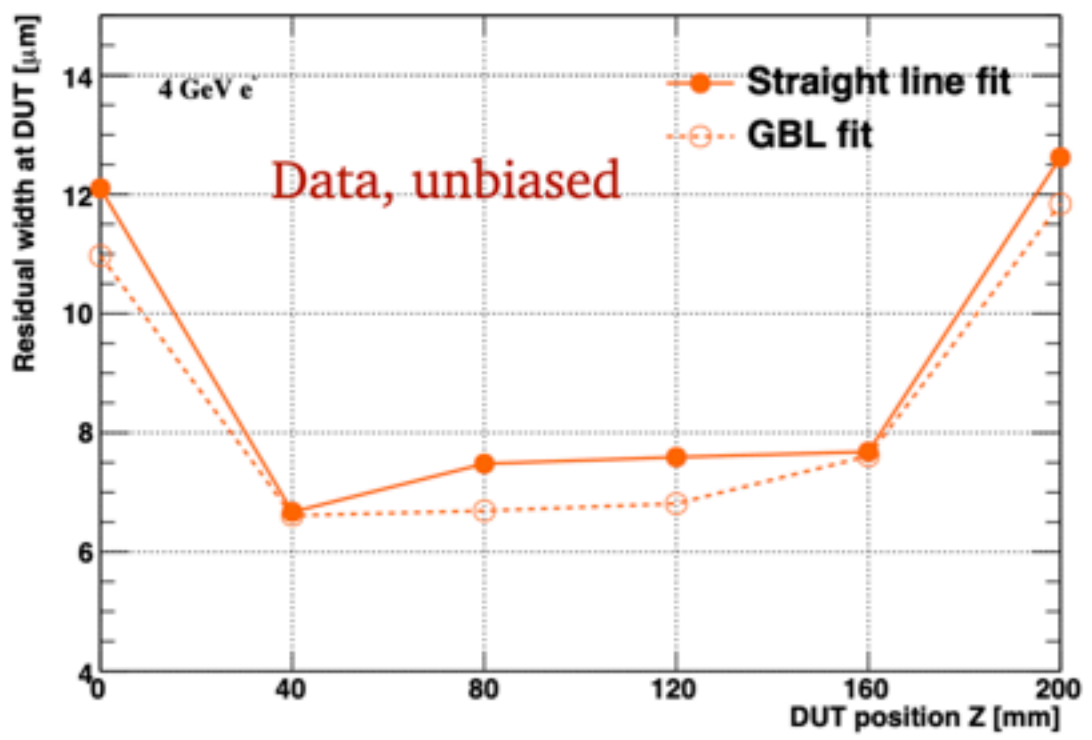
Standard DUTB
no full depletion

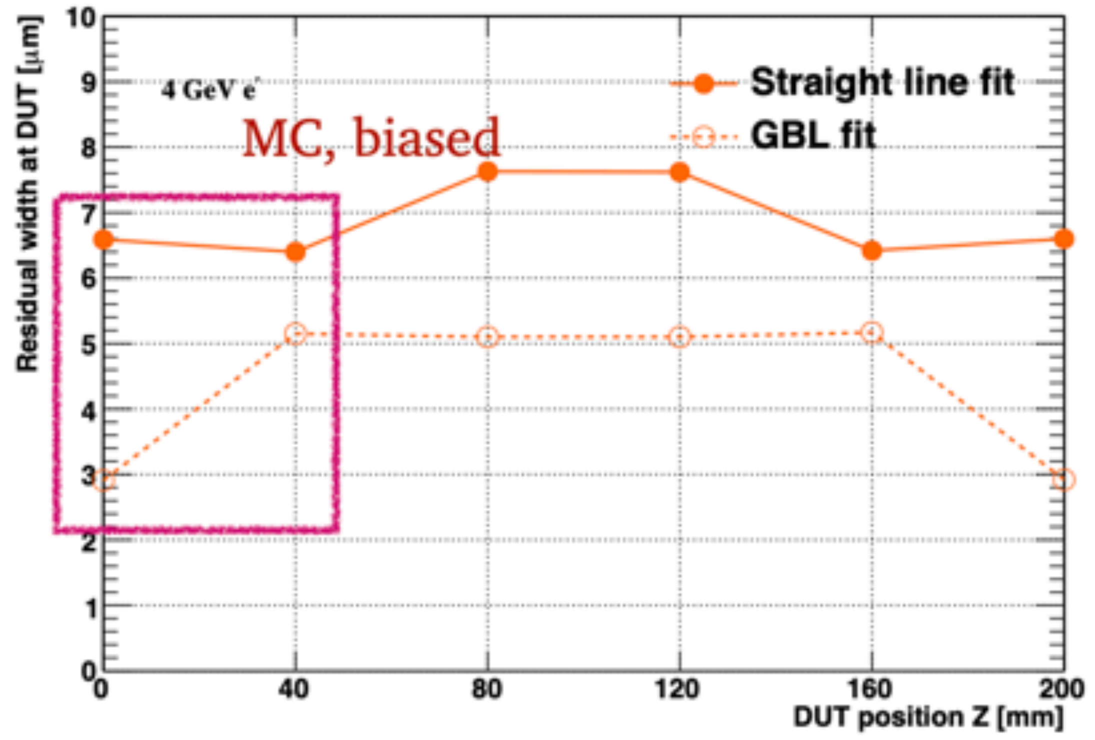
Biased residual width intric resolution(DUT) track resolution(telescope) unbiased residual width

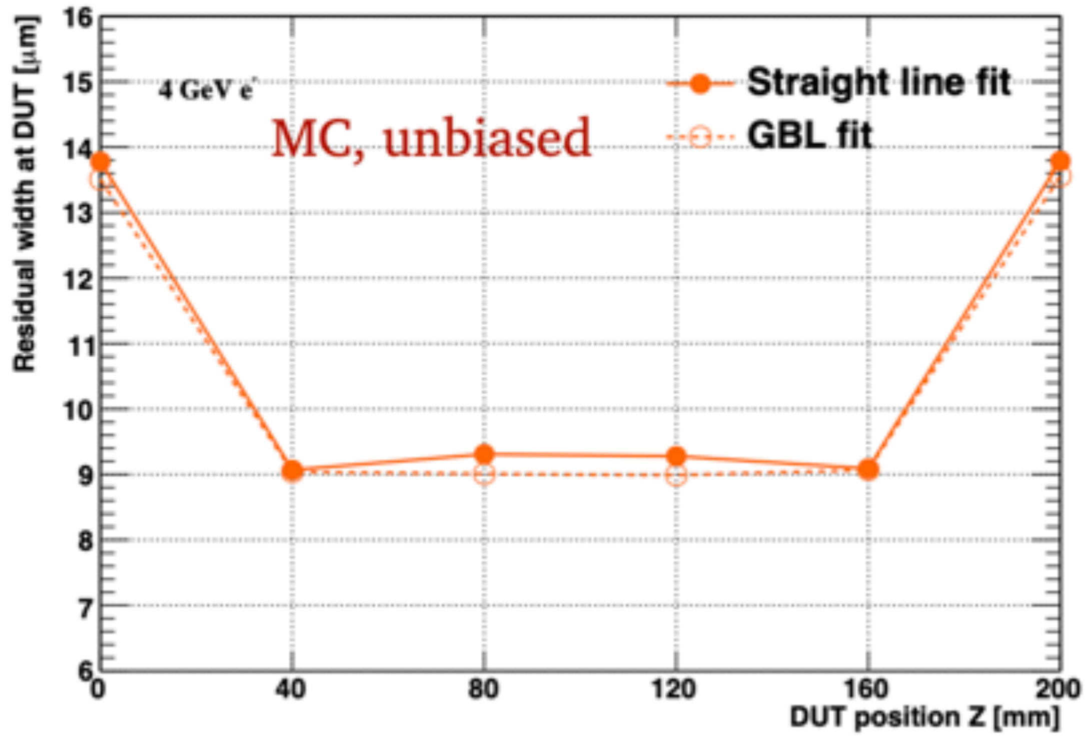
$$r_b^2(z) = \sigma_{int}^2(z) - \sigma_{t,b}^2(z).$$

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

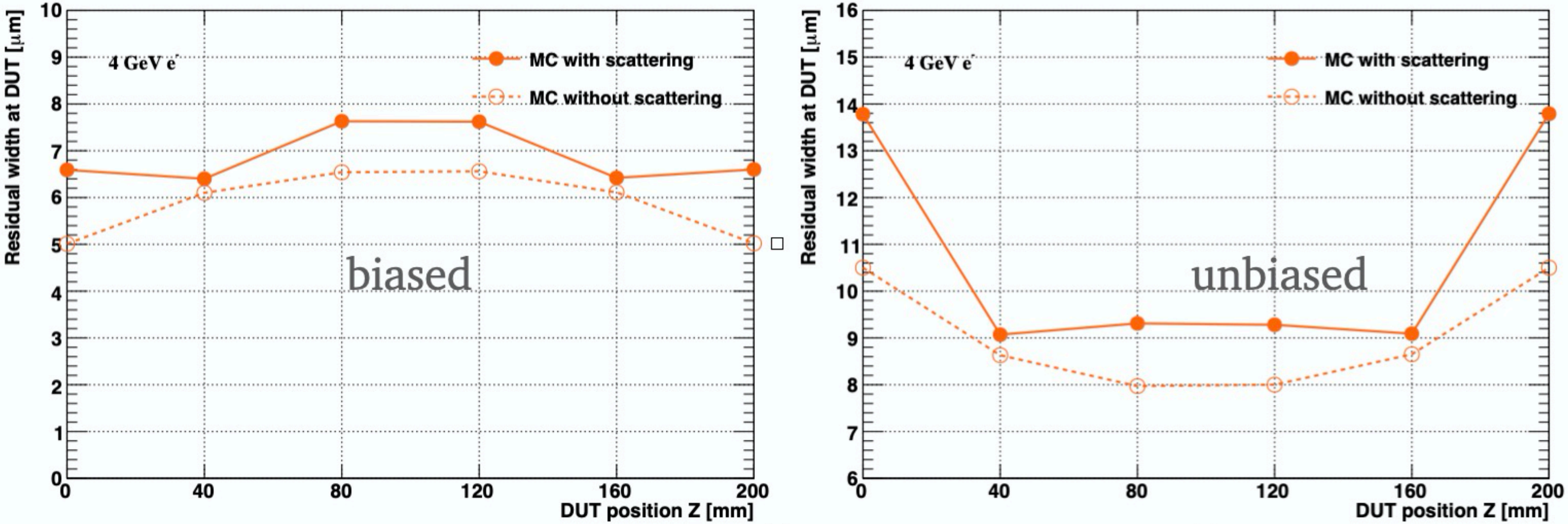




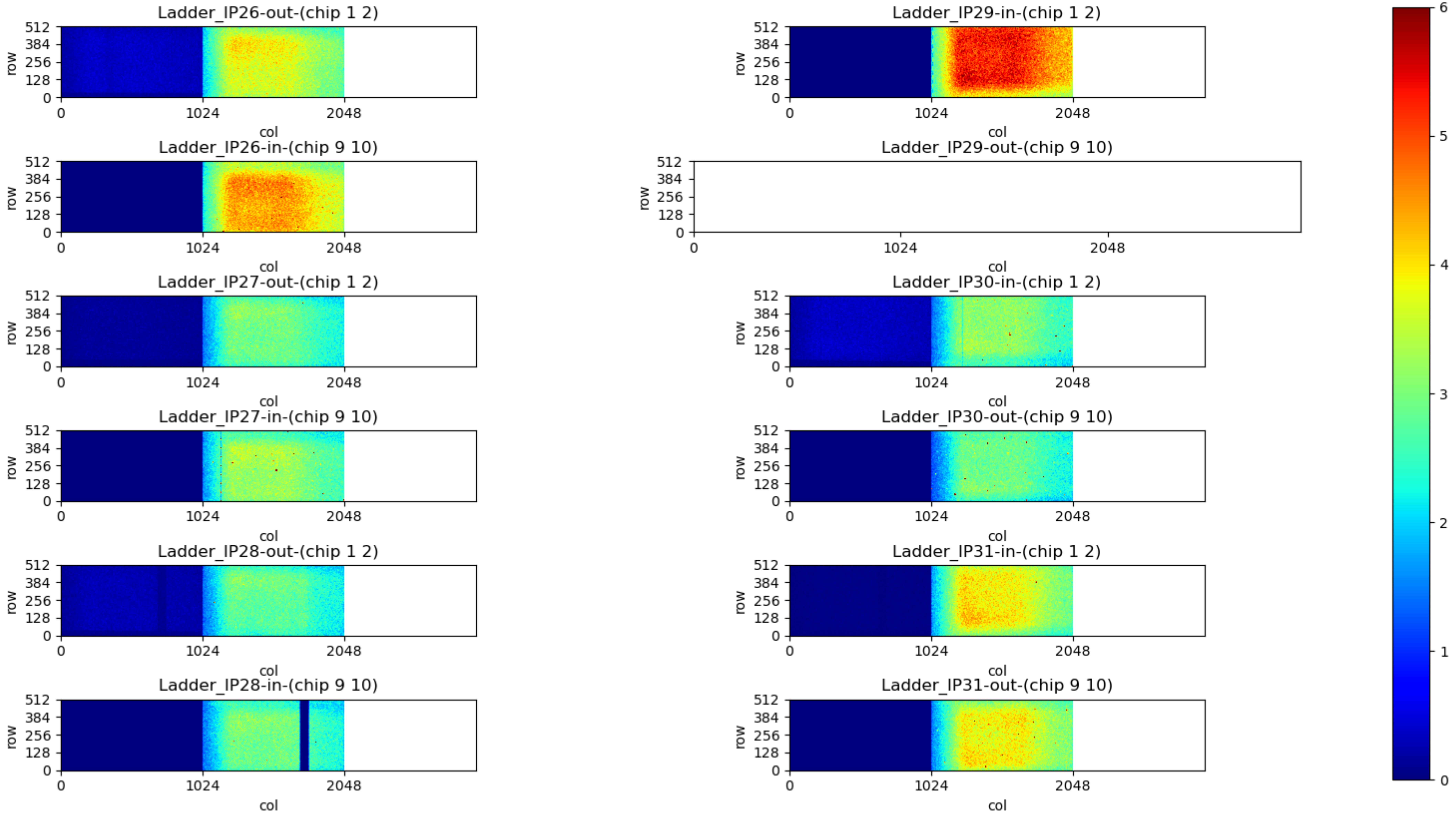




Adding detector smearing,
gRandom.Gauss(0,1)*sigma
sigma = 25um/sqrt(12) = 7.2um

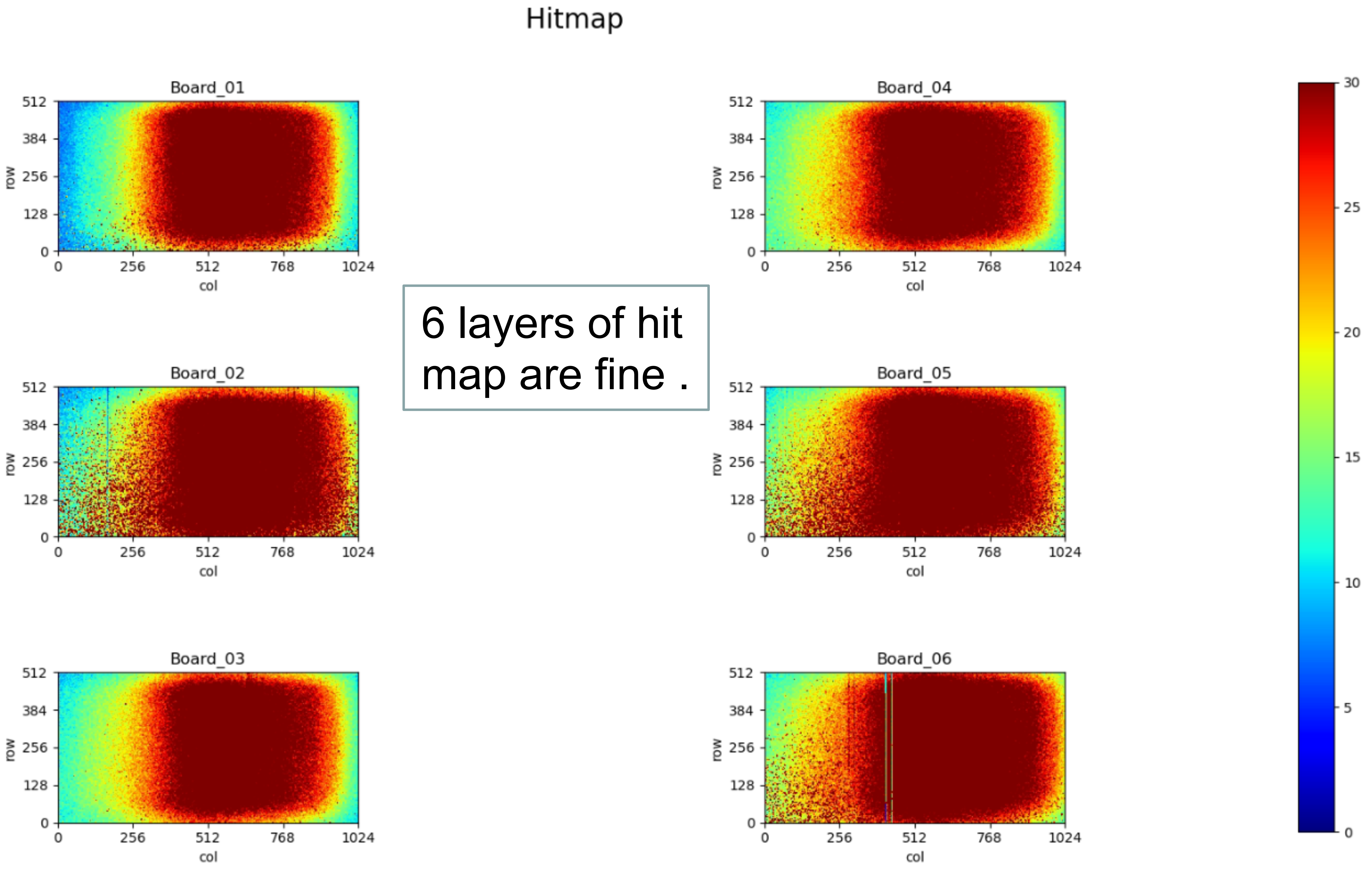

4 GeV e⁻
MC with scattering
MC without scattering
biased
Residual width at DUT [μm]
DUT position Z [mm]
4 GeV e⁻
MC with scattering
MC without scattering
unbiased
Residual width at DUT [μm]
DUT position Z [mm]

Hitmap



Ladder_IP26-out-(chip 1 2)
Ladder_IP26-in-(chip 9 10)
Ladder_IP27-out-(chip 1 2)
Ladder_IP27-in-(chip 9 10)
Ladder_IP28-out-(chip 1 2)
Ladder_IP28-in-(chip 9 10)
Ladder_IP29-in-(chip 1 2)
Ladder_IP29-out-(chip 9 10)
Ladder_IP30-in-(chip 1 2)
Ladder_IP30-out-(chip 9 10)
Ladder_IP31-in-(chip 1 2)
Ladder_IP31-out-(chip 9 10)
row
col
0
128
256
384
512
1024
2048
1
2
3
4
5
6

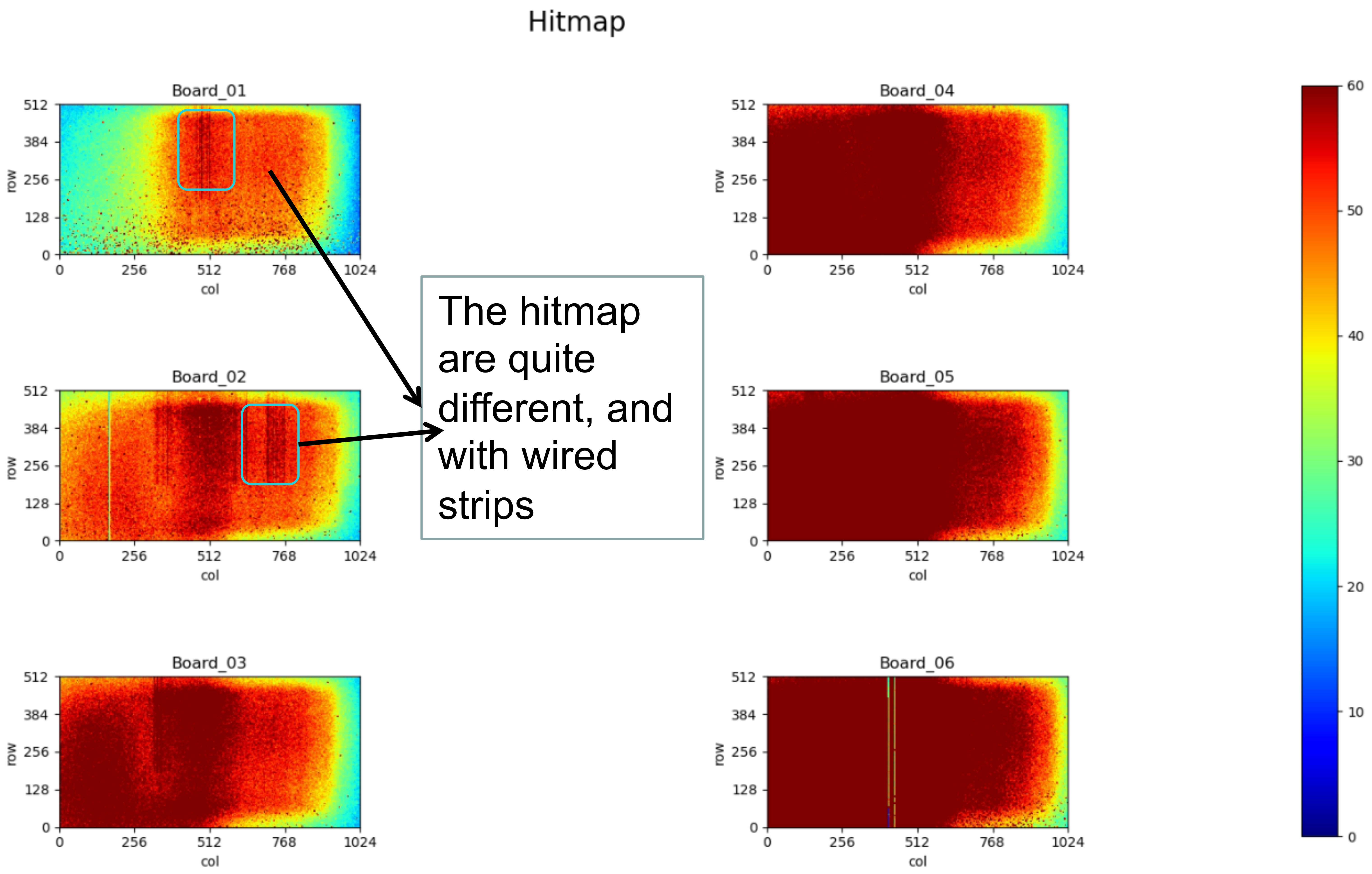
Hitmap of 4 GeV beam



6 layers of hit map are fine .

Jia Zhou
Tianya Wu
Hongyu Zhang

Hitmap of 5 GeV beam



Jia Zhou
Tianya Wu
Hongyu Zhang