Offline analysis for CEPC vertex detector test beam at DESY

Shuqi Li[1], Yiming Hu[2], Xinhui Huang[1], Wei Wang[1], Gang Li[1], Linghui Wu[1], Zhijun Liang[1], Xuewei Jia[1], Hao Zeng[1], Joao Guimaraes de Costa[1]

1 IHEP
2 NJU
8/06/2023

Introduction

- Motivation
  - Building a standalone offline analysis framework for CEPC vertex detector TaiChu pixel chip test beam
  - Track reconstruction

    no magnetic

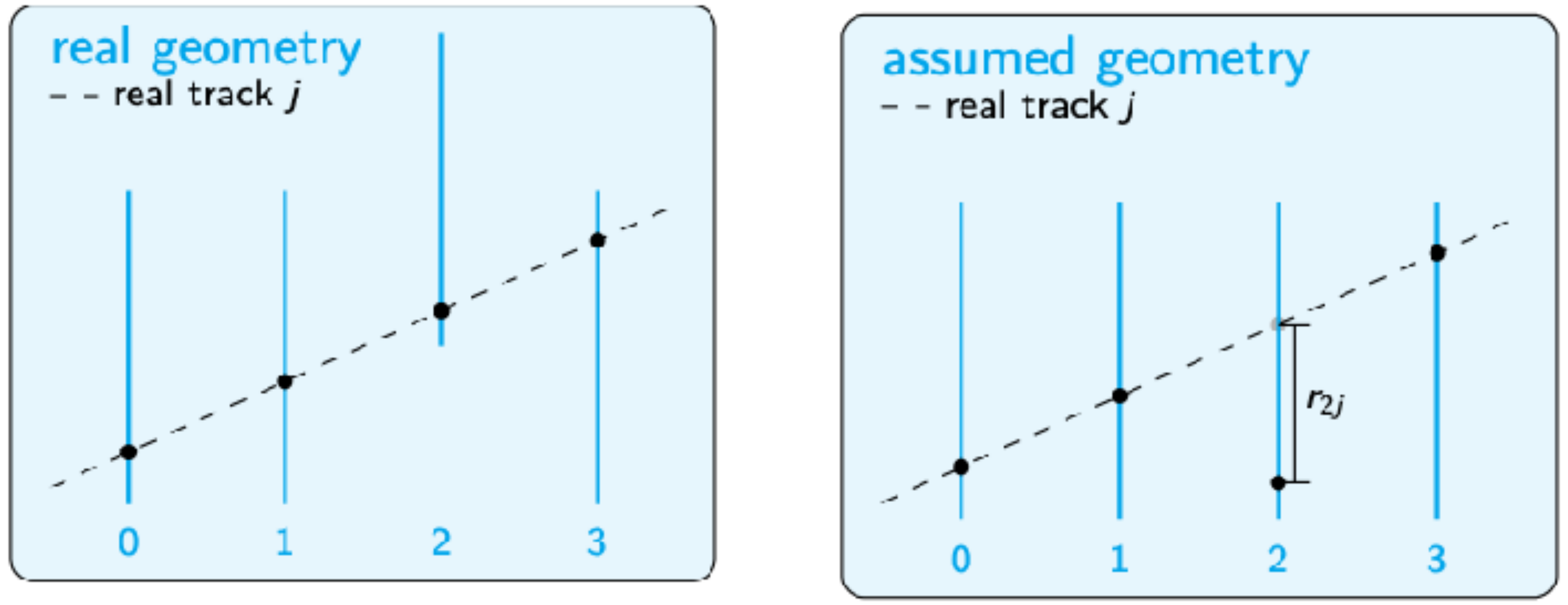
    straight line fit

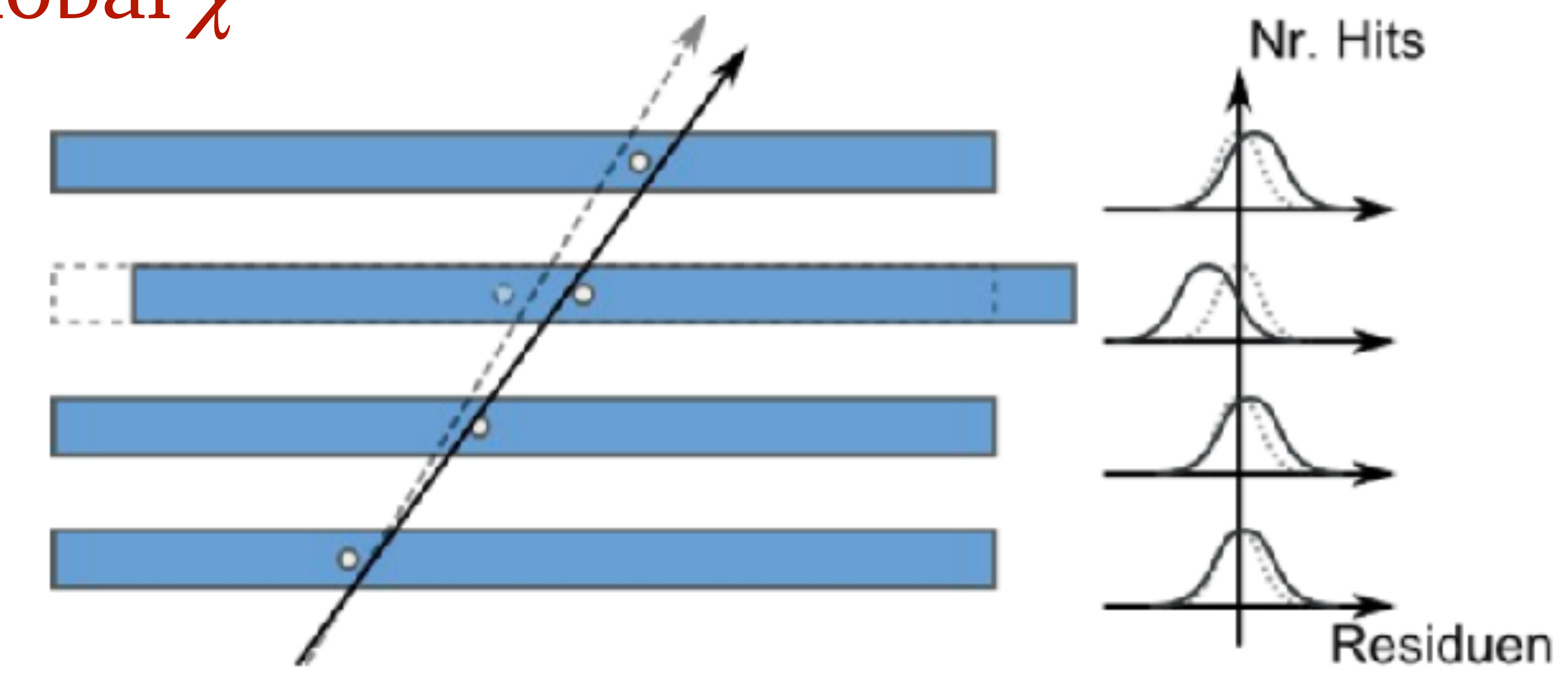
  - alignment

    correction for the misalign chip position

    misalignment effects the resolution of detector

    find the solution of real geometry for global tracks based on global χ^2



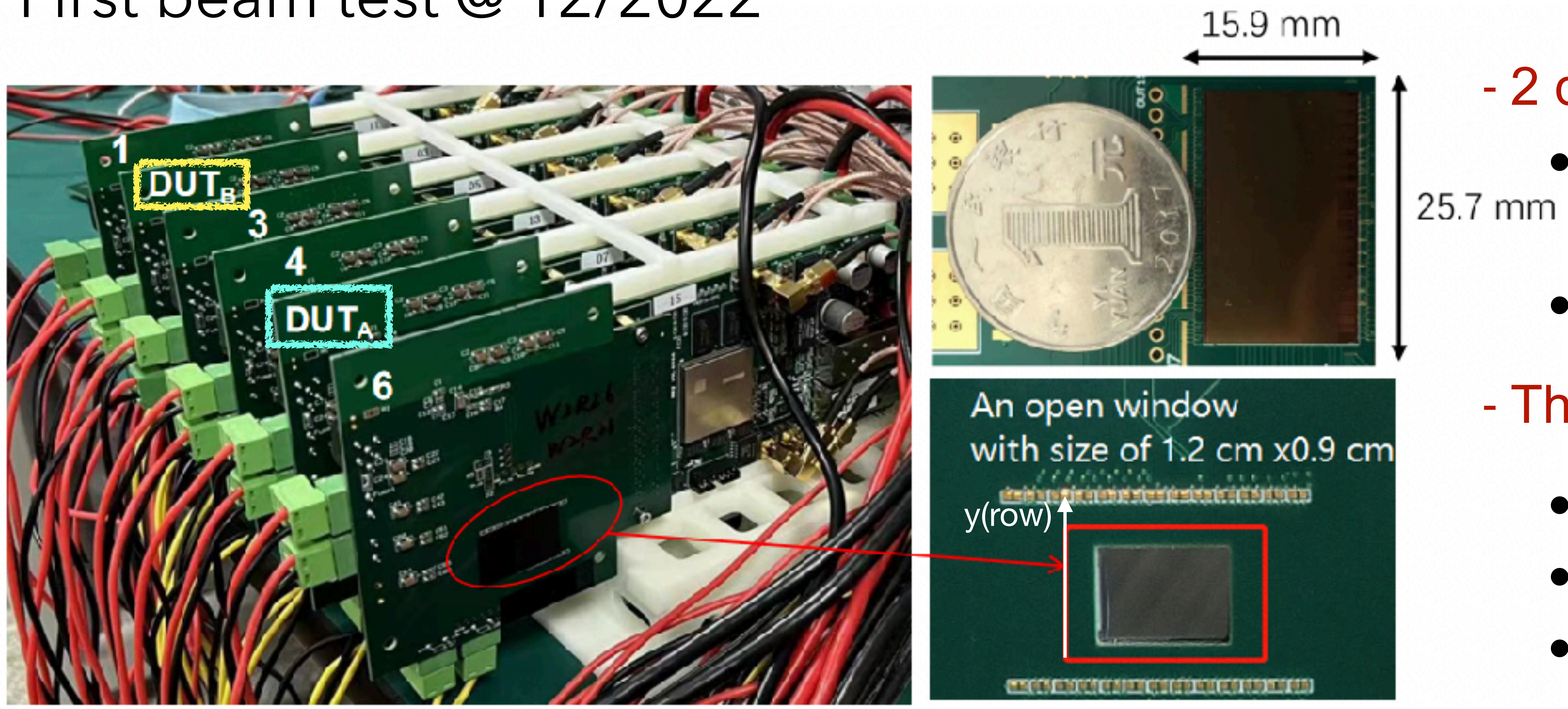


Residual: distance of measured hit with the intersection point of track in the measured chip

- TaiChu silicon pixel detector
  - Pixel size: 25 um, 1024 columns x 512 rows
  - Theoretical resolution: 25um/sqrt(12) ~ 7.22 um
  - The experimental resolution should be better than theoretical resolution due to charge sharing

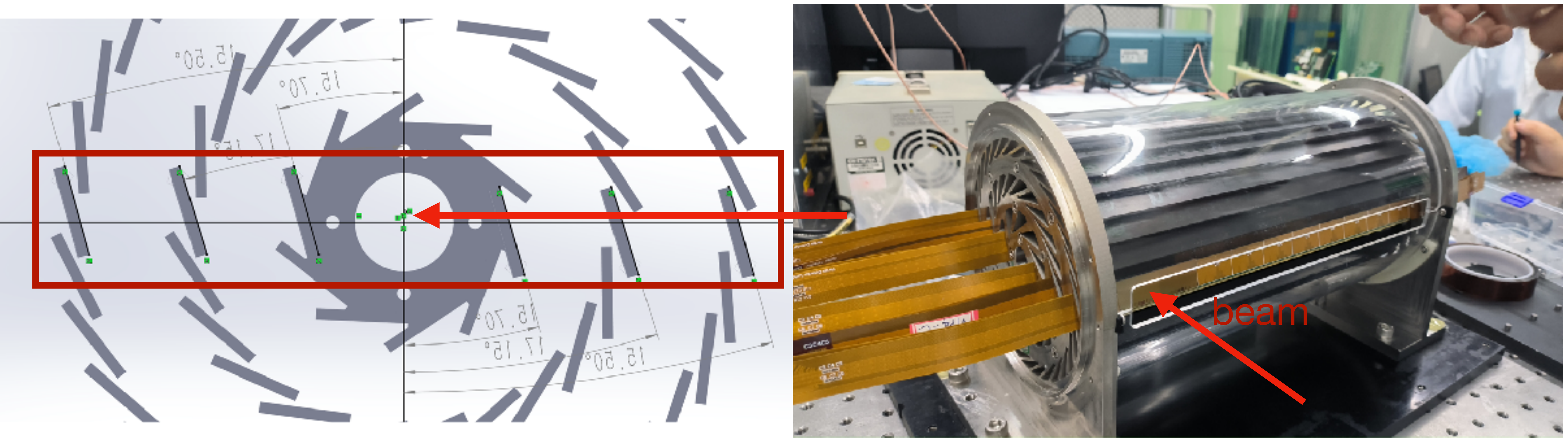
Beam test @ DESY

- First beam test @ 12/2022



- 2 detector under test (DUT) with different processes 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)
- The offline analysis results of first beam test mainly include:
  - Threshold scan on cluster size, spatial resolution, efficiency
  - Comparing the results from 2 DUTs
  - mainly used 4 GeV electron beam

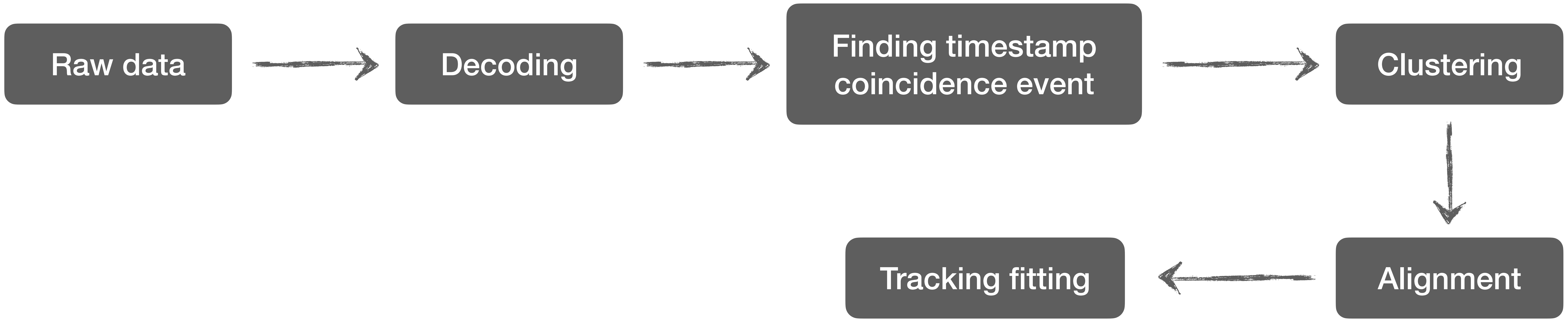
- Second beam test @ 4/2023



- The offline analysis results of second beam test mainly include:
  - Threshold scan on cluster size, spatial resolution, efficiency of chip with modified process
  - preliminary study on impact parameters
  - mainly used 6 GeV electron beam

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**

Track reconstruction

- Steps for track finding and reconstruction
  - Finding hits in every chip with time coincidence
  - Clustering: geometric centre of gravity of fired neighbouring pixels

- Track fitting
  - least squares line fitting

    x = a1z + b1;

    y = a2z + b2;

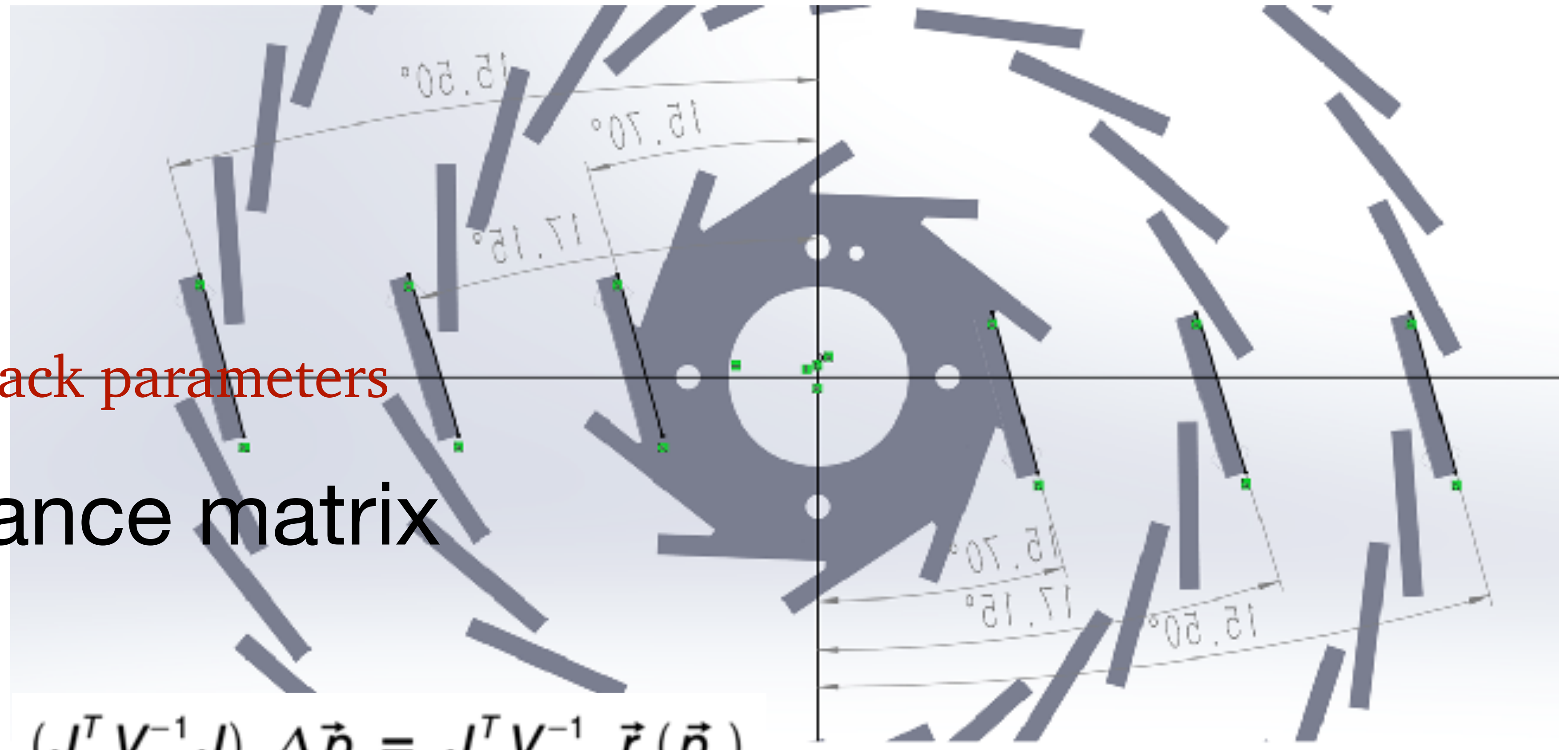
    Chi2 definition: $\chi^2(\alpha) = \sum_{i=1}^{n} \frac{f(x_i, \alpha) - e_i)^2}{\sigma_i^2}$, sigmax = sigmay = 25um/sqrt(12)
  - General broken lines method (correction for multiple scattering)

    has been applied on the data from first test beam results, silicon chip and air are the scatter

    still being developing for second test beam results

Alignment

- Method - millepede matrix method



p: alignment parameters, q: track parameters

  - minimize: $\chi^2 = \sum_{i \in tracks} \vec{r}_i^{\,T} V_i^{-1} \vec{r}_i$ · is residual $\vec{r}_i(\vec{p}, \vec{q}_i)$, V is the covariance matrix

$$\frac{d\chi^2(\vec{p})}{d\vec{p}} = 0 \longrightarrow \chi^2(\vec{p}) = \chi^2(\vec{p}_0) + \left.\frac{d\chi^2(\vec{p})}{d\vec{p}}\right|_{\vec{p}=\vec{p}_0} (\vec{p} - \vec{p}_0) \longrightarrow \underbrace{(J^T V_i^{-1} J)}_{C} \Delta\vec{p} = \underbrace{J^T V_i^{-1} \vec{r}_i(\vec{p}_0)}_{b}$$

$$C \; \Delta\vec{p} = \vec{b}$$

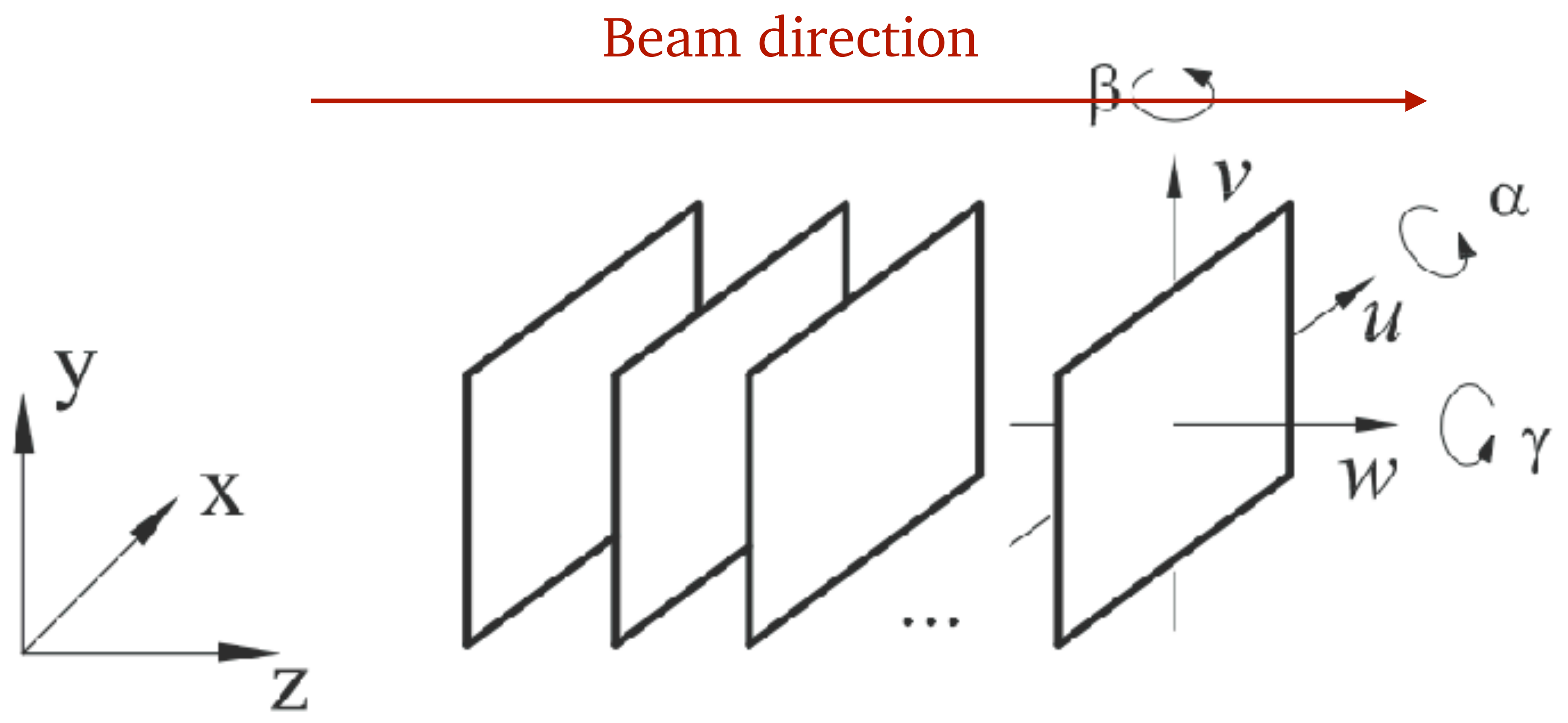
  - invert the Matrix C to find alignment correction Δp
  - reduce matrix C for alignment only

$$S = C_{11} - C_{12} C_{22}^{-1} C_{21}$$

$$\begin{pmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{pmatrix} \begin{pmatrix} \Delta\vec{p}_1 \\ \Delta\vec{p}_2 \end{pmatrix} = \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \end{pmatrix} \longrightarrow \begin{pmatrix} \Delta\vec{p}_1 \\ \Delta\vec{p}_2 \end{pmatrix} = \begin{pmatrix} S^{-1} & -S^{-1} C_{21}^T C_{22}^{-1} \\ -C_{22}^{-1} C_{21} S^{-1} & C_{22}^{-1} - C_{22}^{-1} C_{21} S^{-1} C_{21}^T C_{22}^{-1} \end{pmatrix} \begin{pmatrix} \vec{b}_1 \\ \vec{b}_2 \end{pmatrix} \longrightarrow \Delta\vec{p}_1 = S^{-1} \left(\vec{b}_1 - C_{21}^T C_{22}^{-1} \vec{b}_2 \right)$$

  - Matrix S with smaller size than C, and C_{22} is easy to invert

- Six alignment parameters considered
  - Translation along X, Y, Z direction
  - Rotation around X, Y, Z axis



Spatial resolution studies

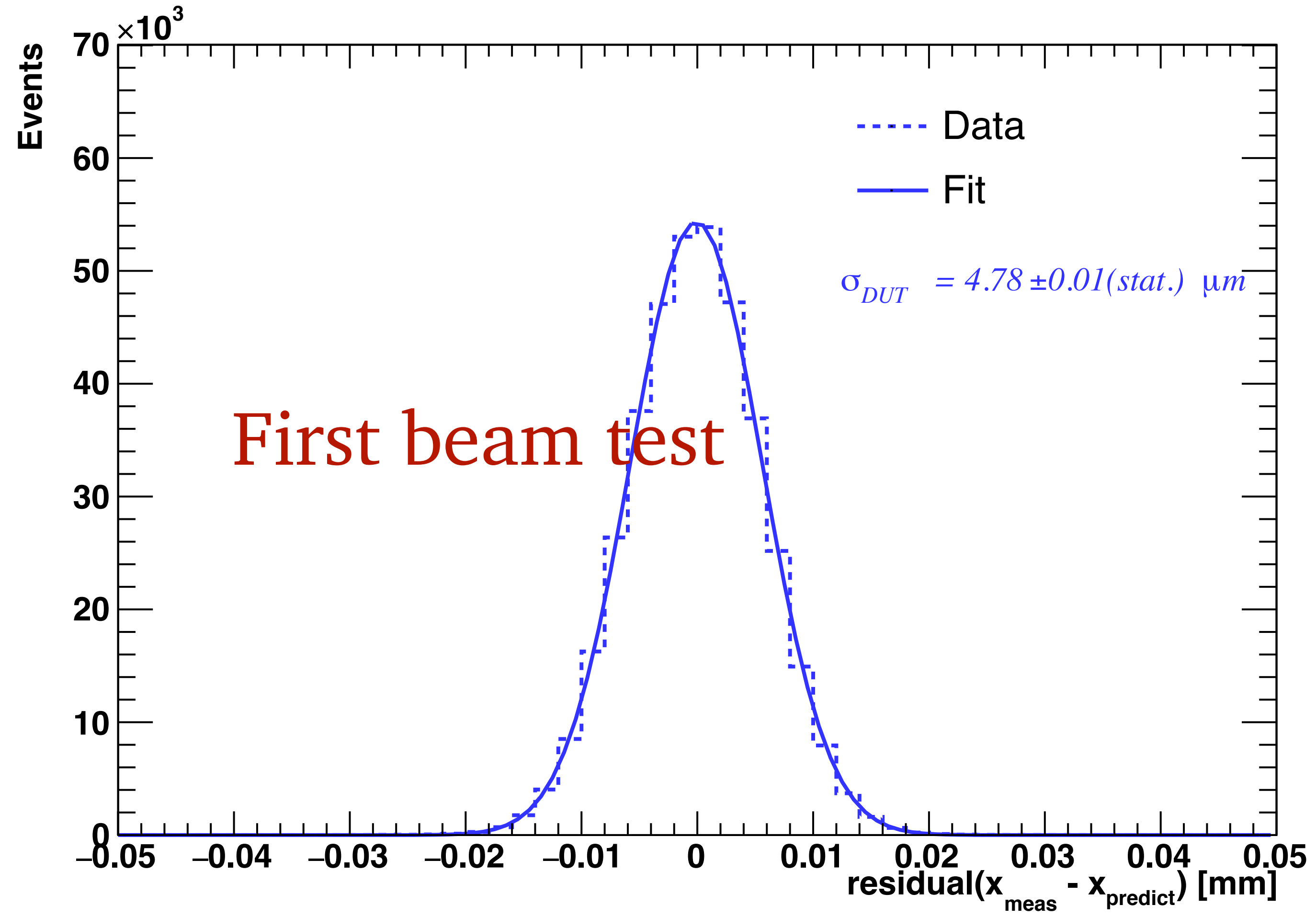
- The spatial resolution of DUT
  - applying the alignment parameters to the measured hit position
  - the spatial resolution of DUT evaluated from the unbiased residual distribution

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

  - assuming same intrinsic resolution for all chips

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

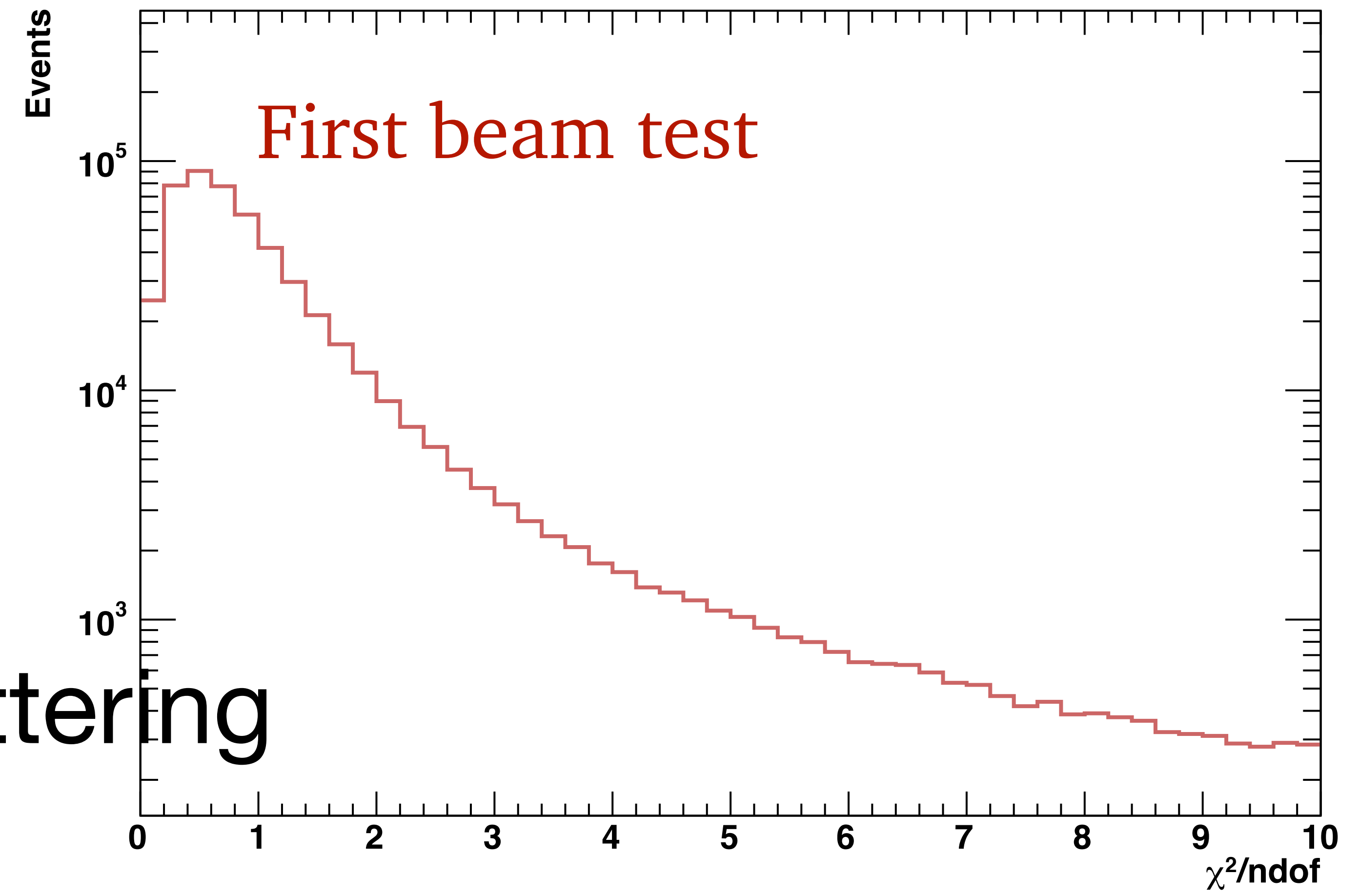
    - z_i is the z position of plane in global coordinate
    - unbiased residual $\sigma_{res,unbiased}$: the difference between measured hit position on DUT and the predicted one extrapolated from the track of telescope



  - least squares straight line fit

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

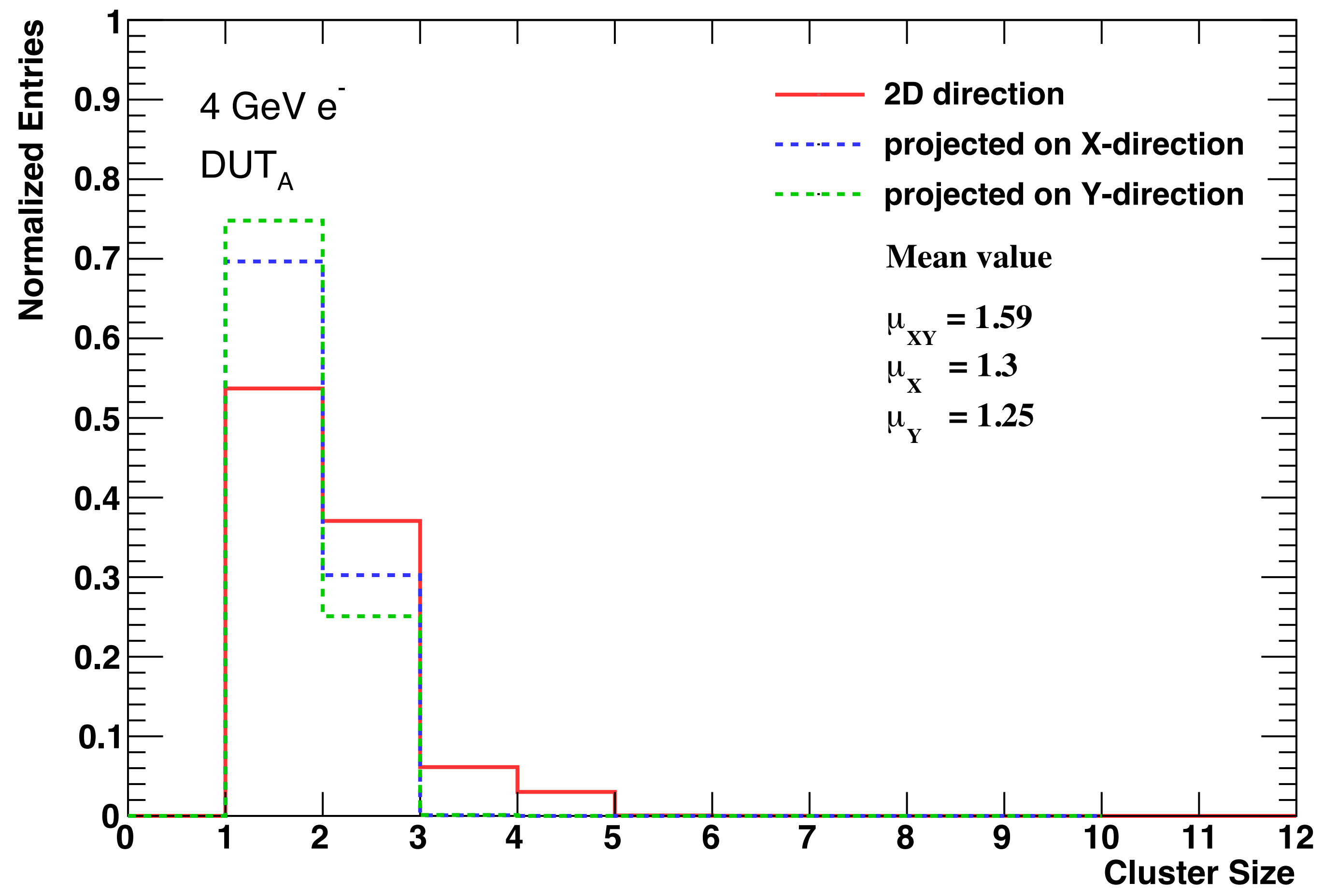
$$\sigma_{x,y} = \frac{25\mu m}{\sqrt{12}}$$, 25 um is the pixel pitch

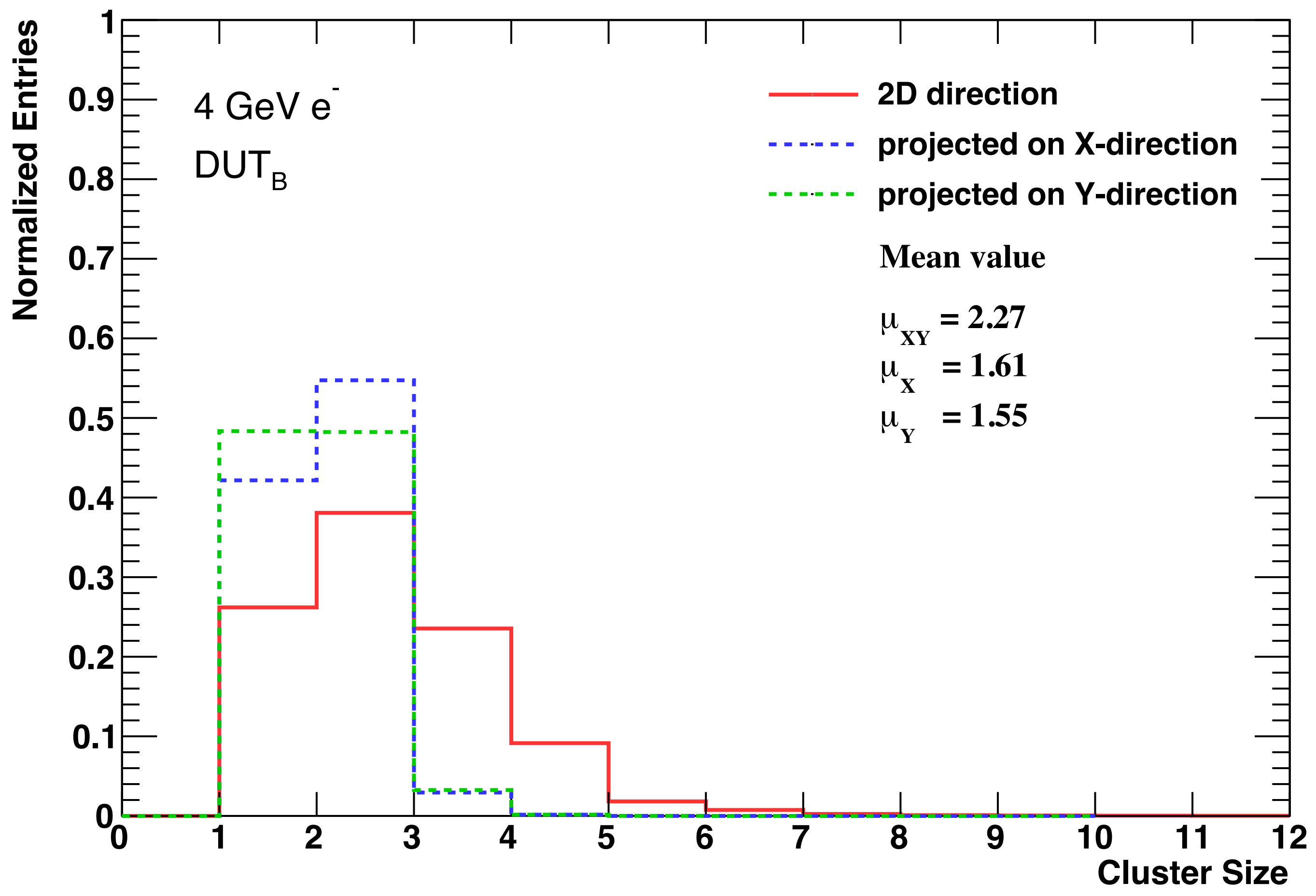


  - a track quality χ^2 cut added to decrease the effects from multi scattering

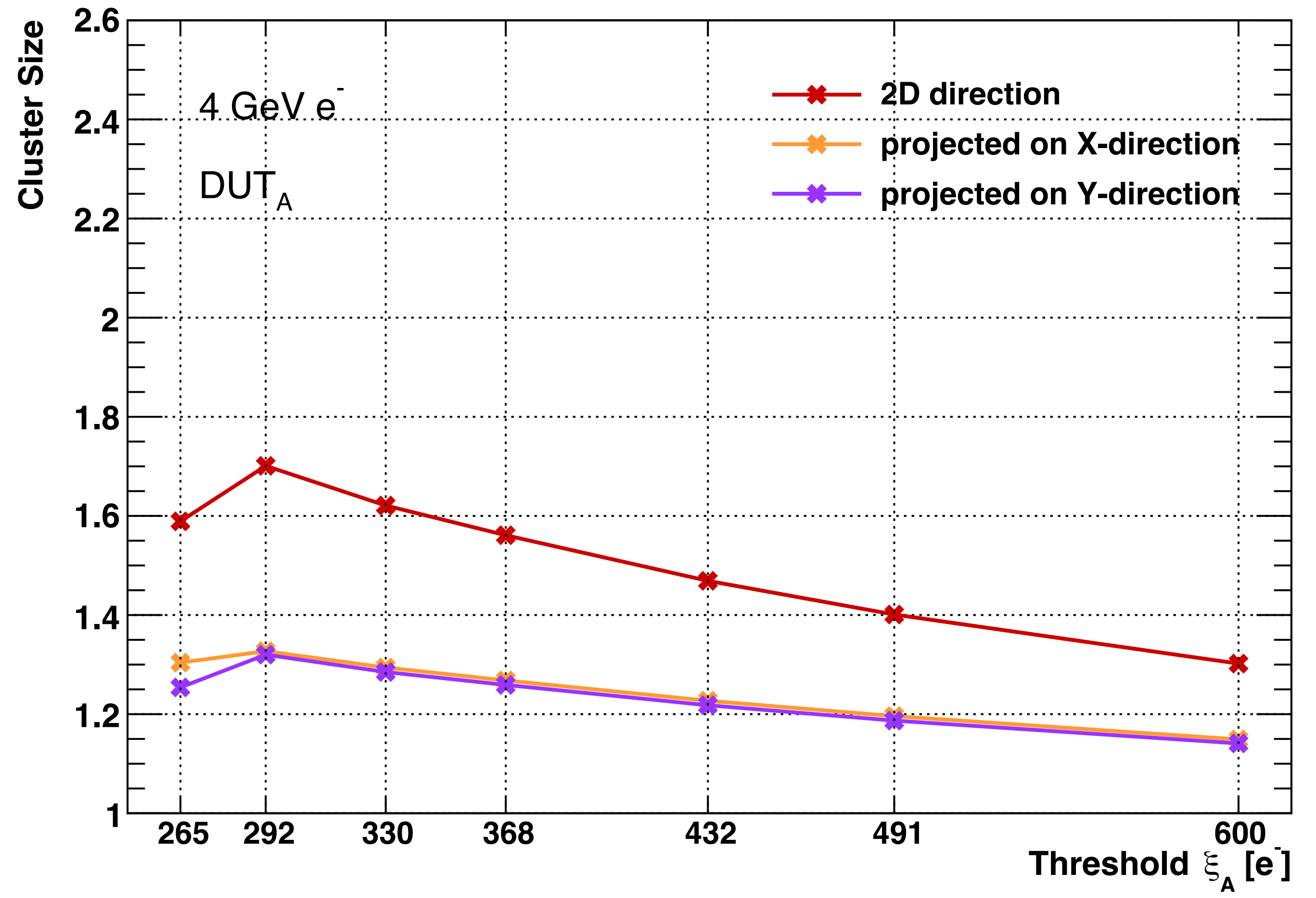
Offline analysis results on first test beam

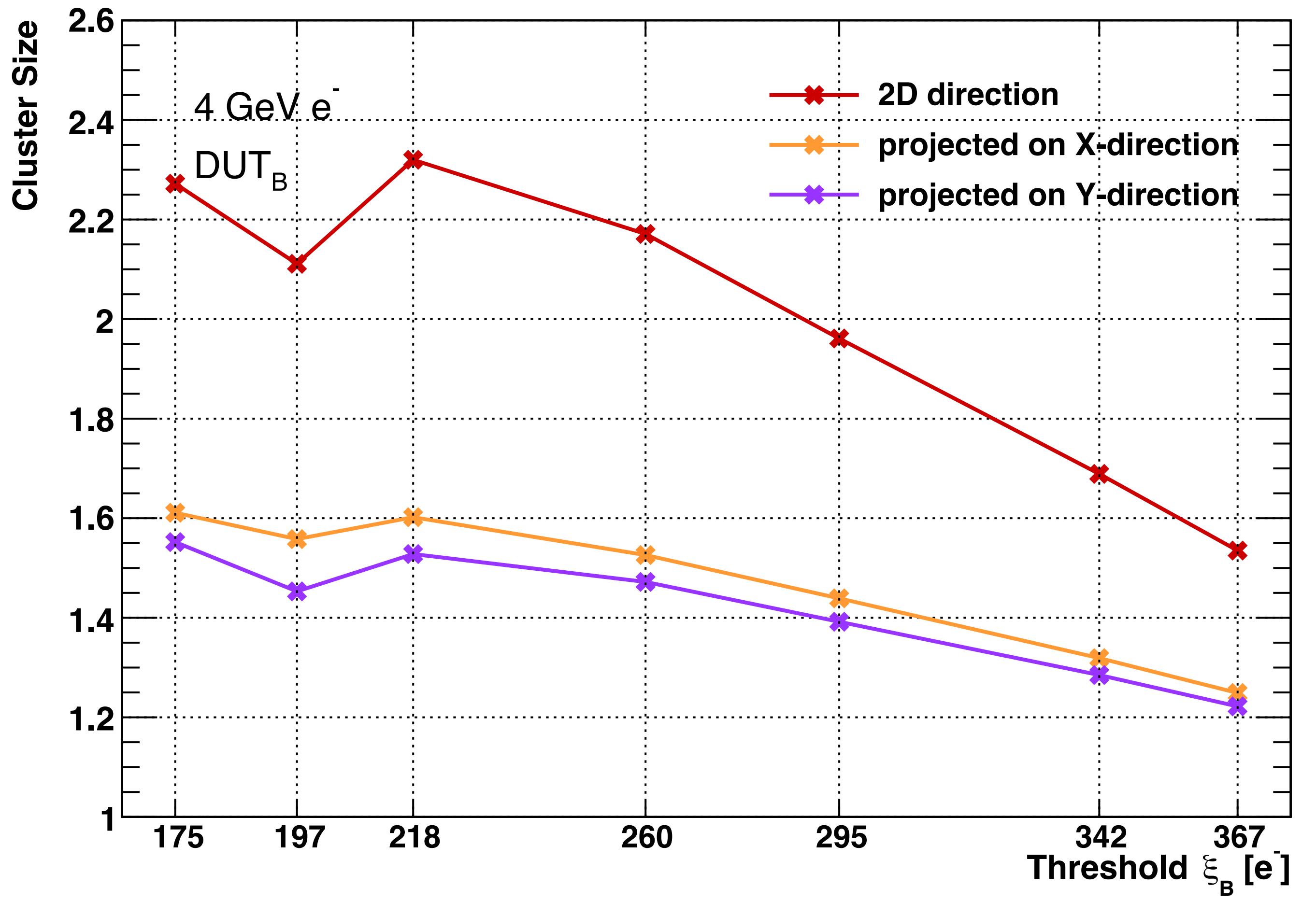
- Cluster size



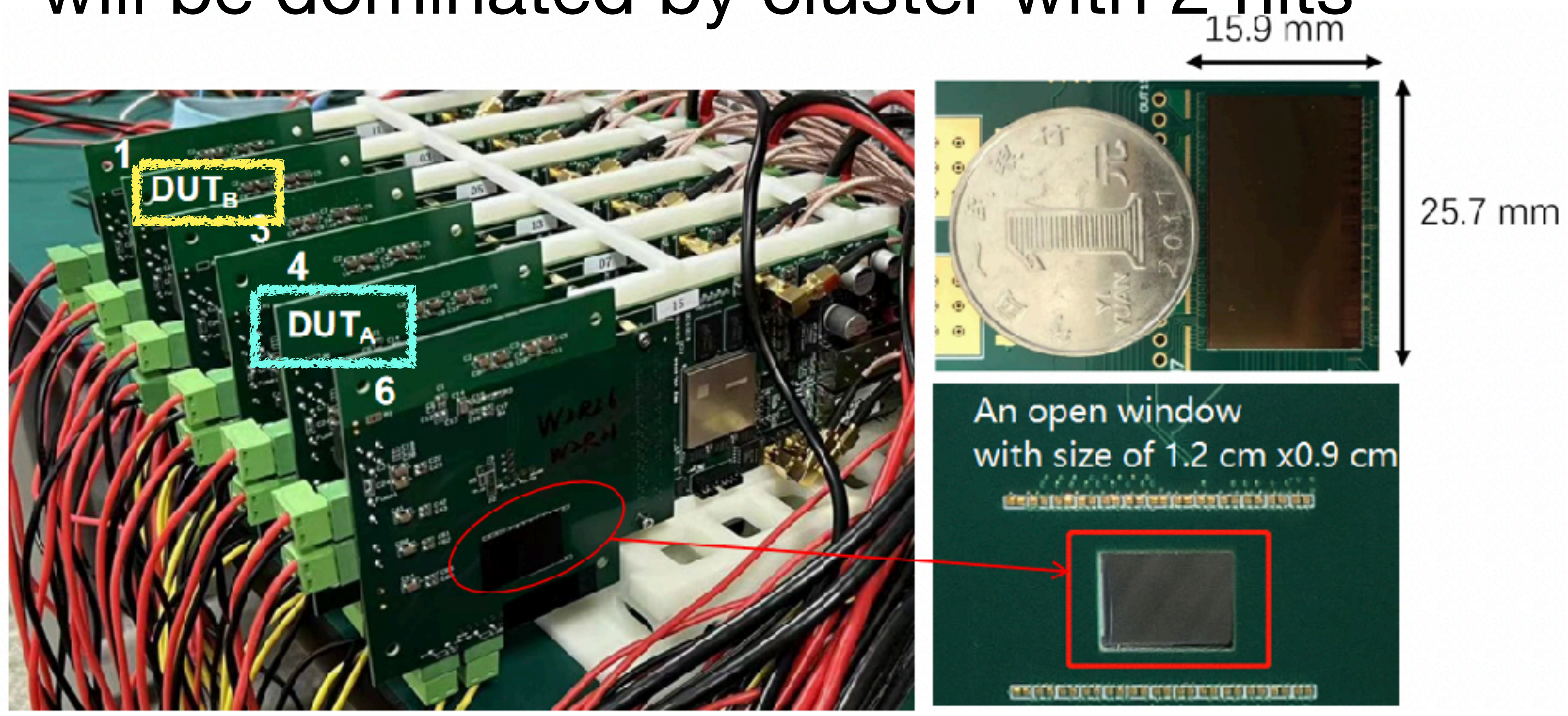


- The peak value for DUT_A is 1 pixel, around 2 pixels for DUT_B
- Less charge sharing effects in DUT_A with full depletion

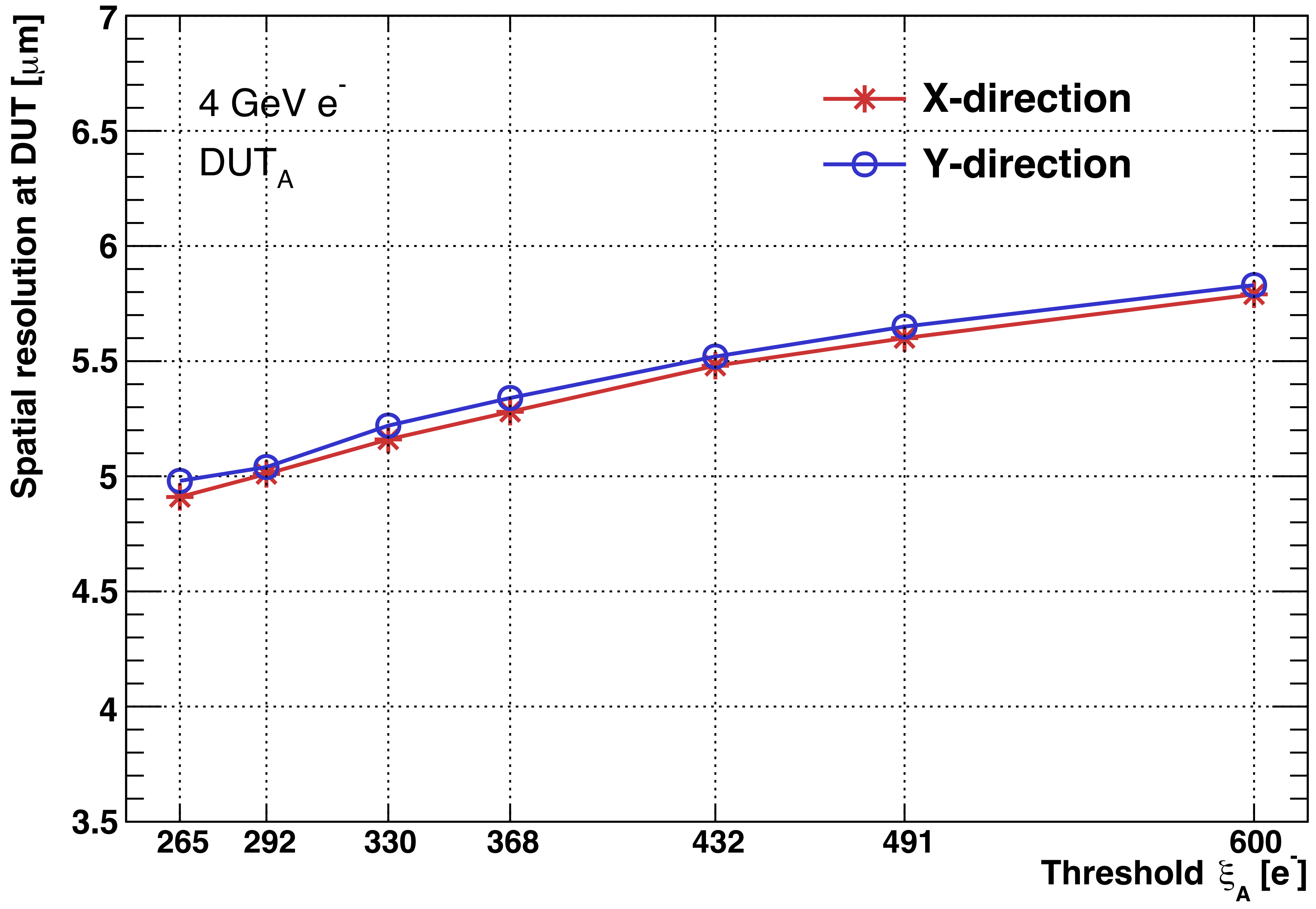


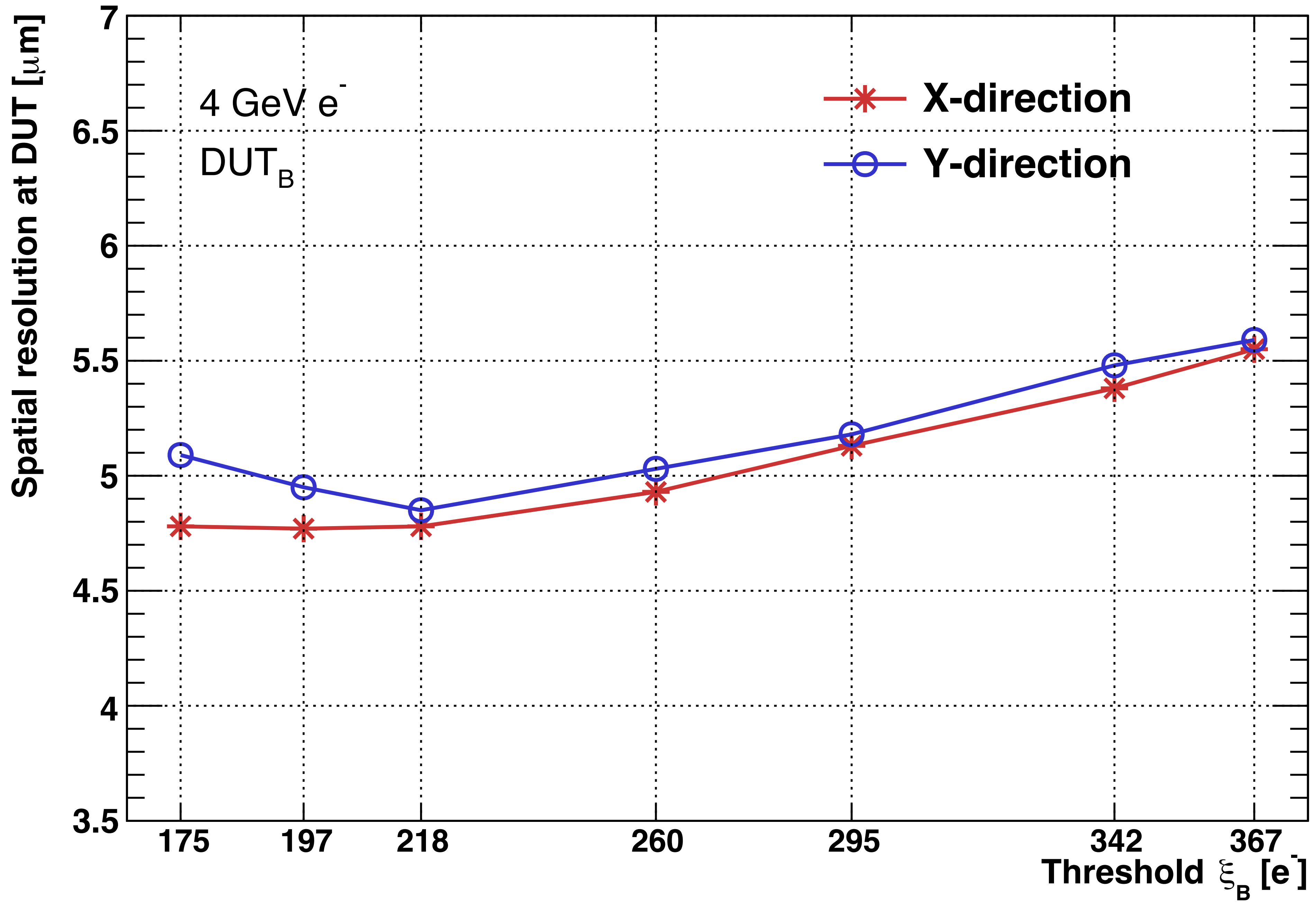


- In general, the higher the threshold, the smaller the cluster size
- If lowering the threshold, cluster size will be dominated by cluster with 2 hits



Spatial resolution vs. threshold (4GeV)



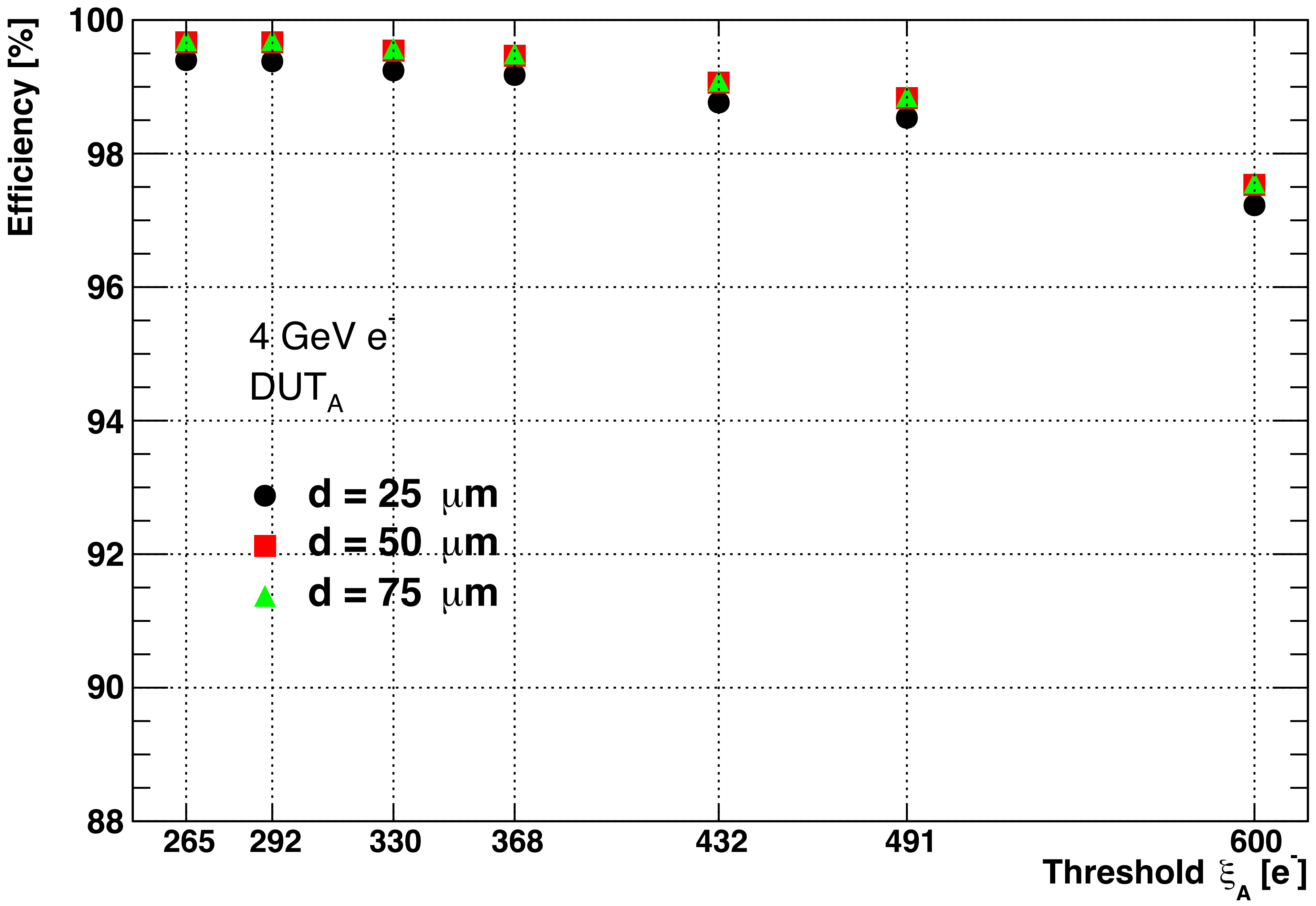


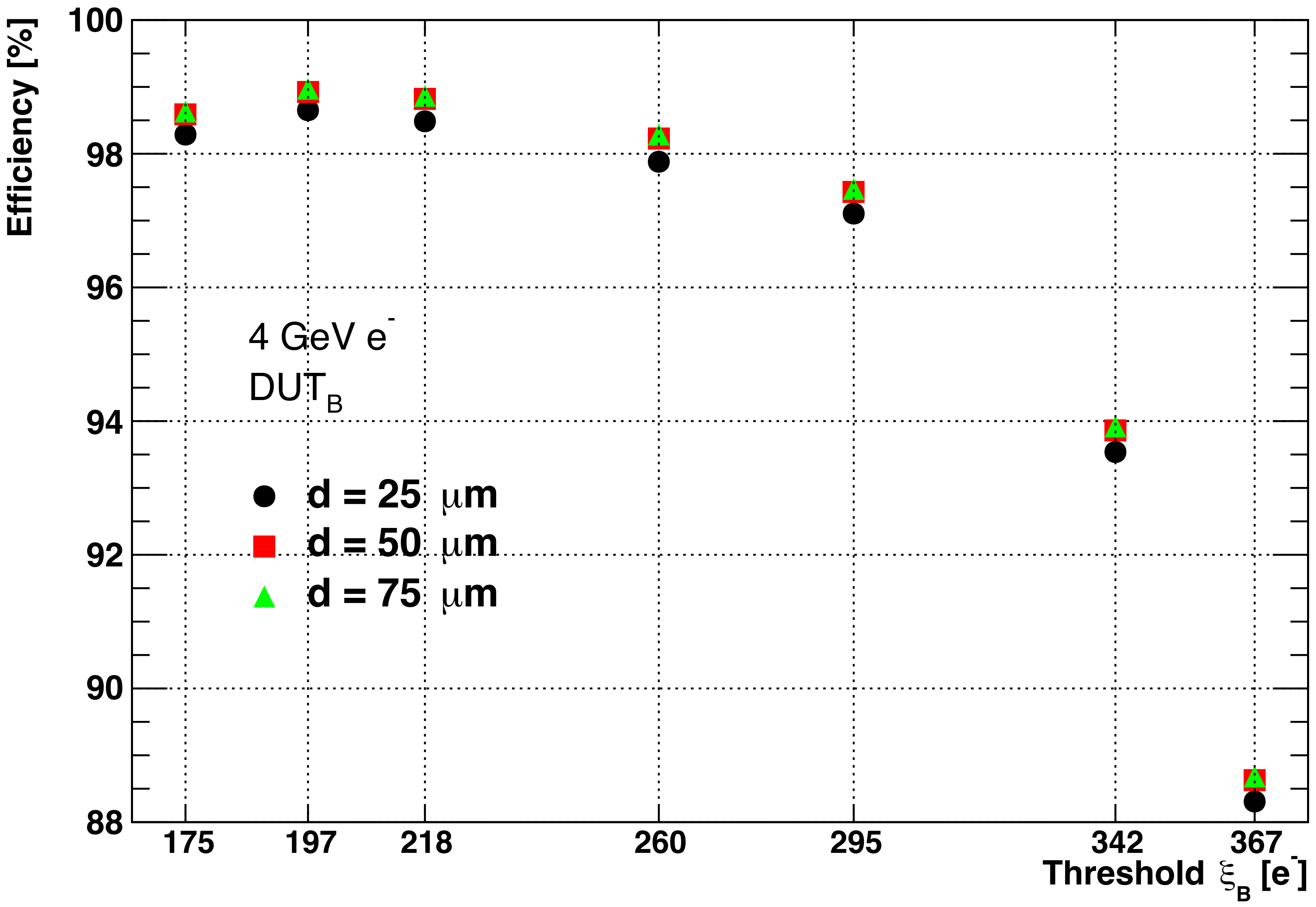
- The resolution gets worse due to the increased threshold
- for DUT_B, a worse resolution occurs when the threshold < 218 e^- since the larger noise at lower threshold

Efficiency vs. threshold (4GeV)

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

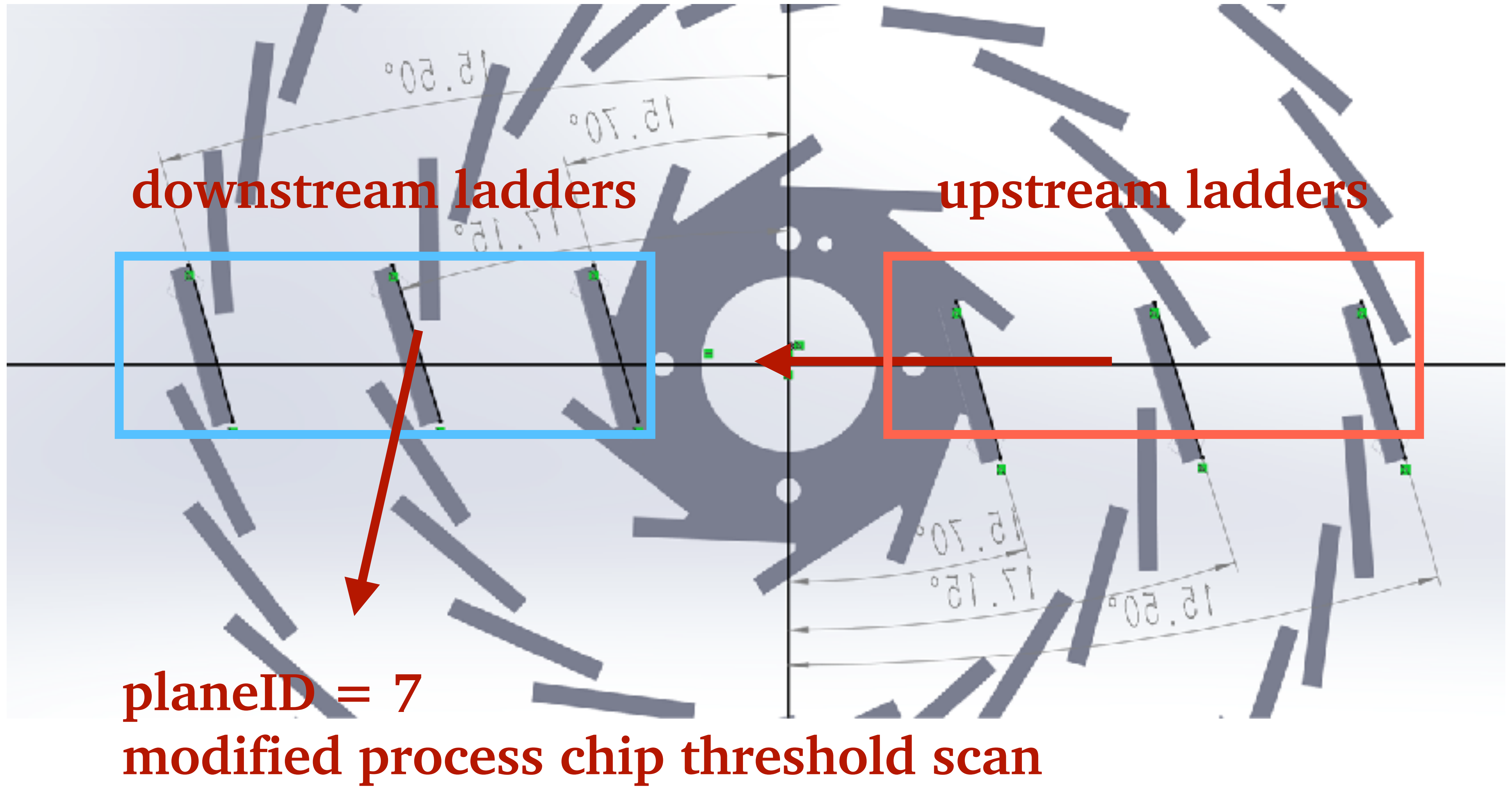
- Efficiency is the ratio of tracks that match the hit on the DUT within a distance d around the predicted hit from the telescope to all tracks of the telescope
- with increasing threshold, the efficiency decrease
- maximum eff. for DUT_A is 99%, maximum eff. for DUT_B is 98.5%

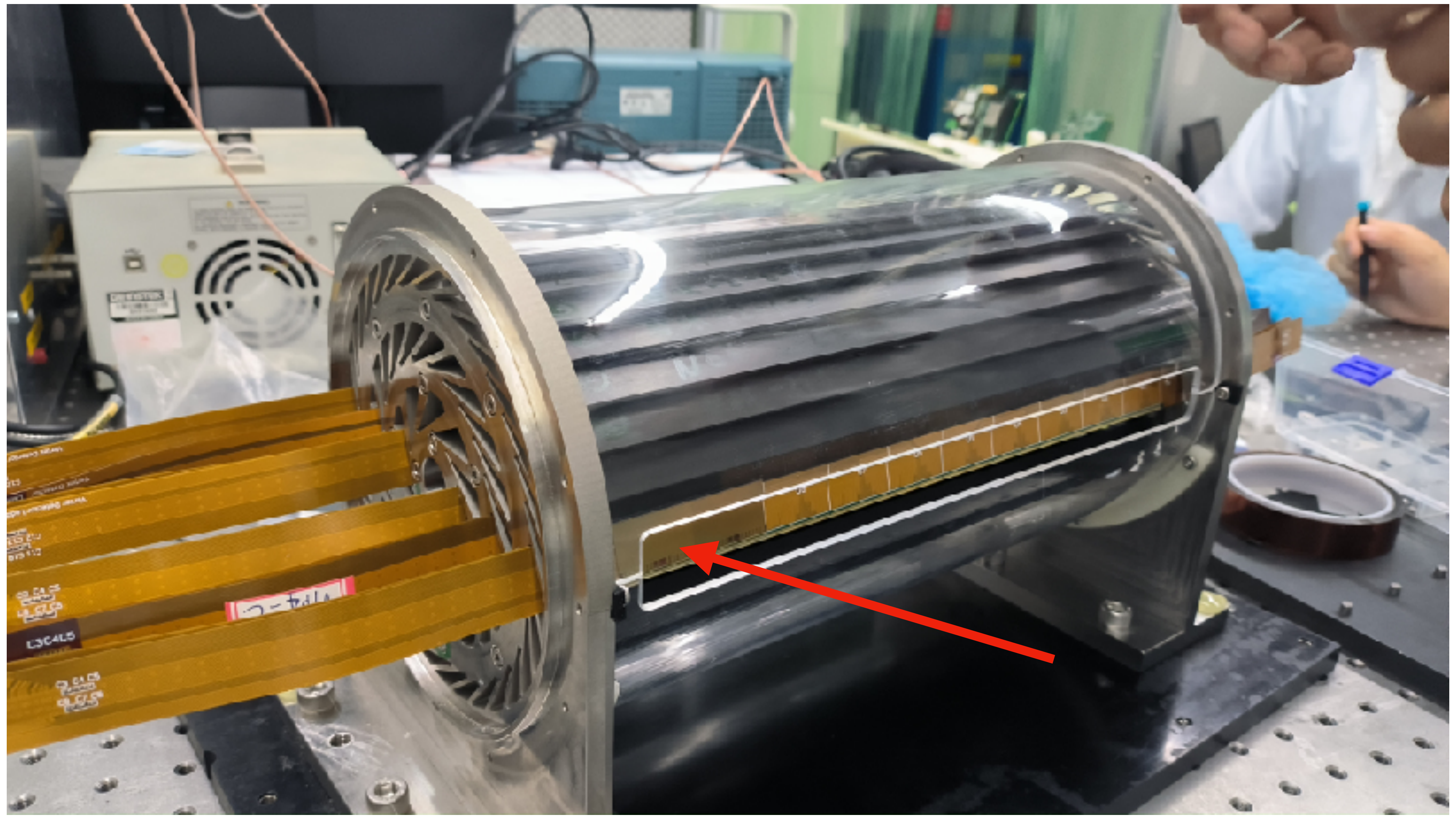




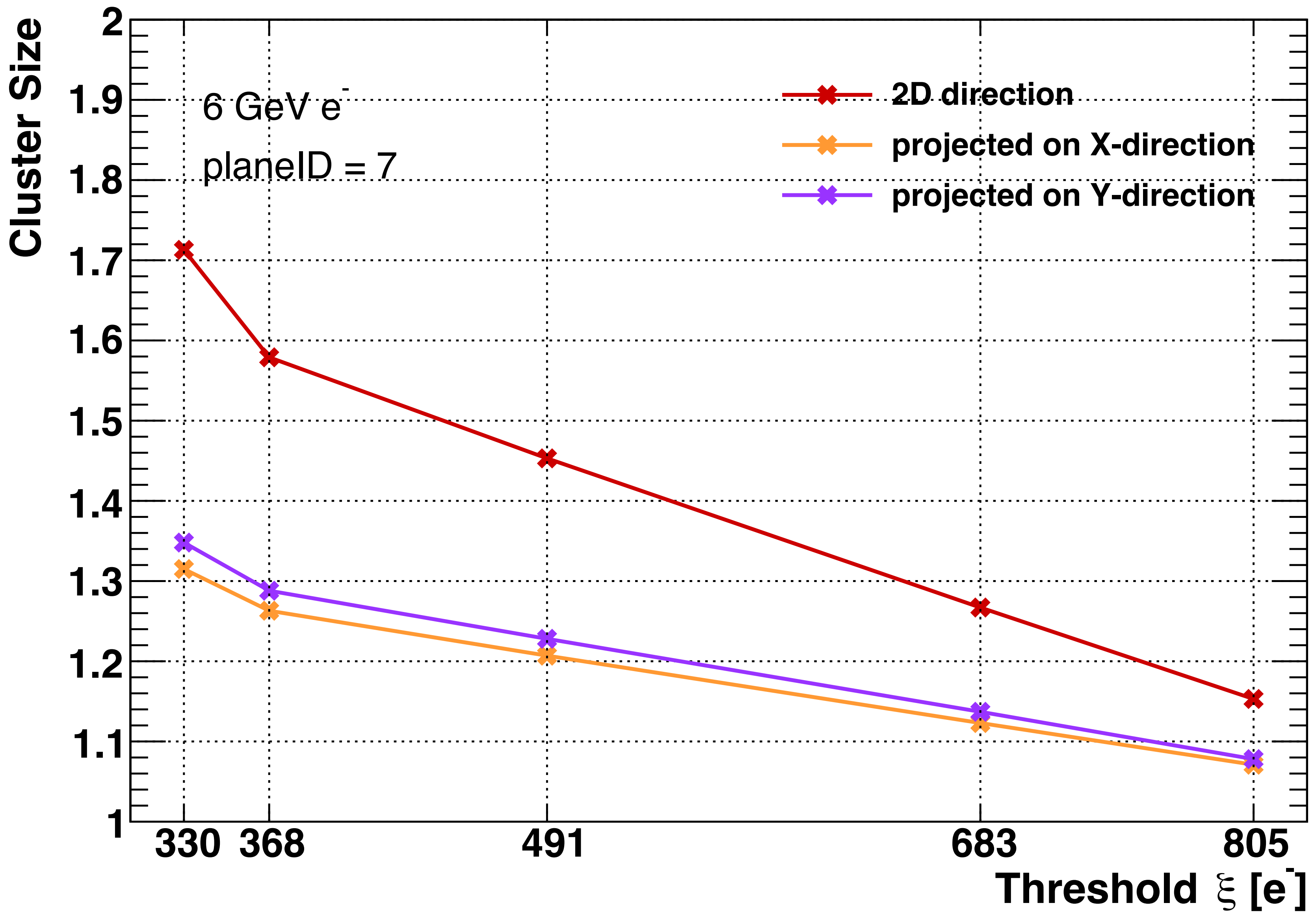
Offline analysis results on second test beam

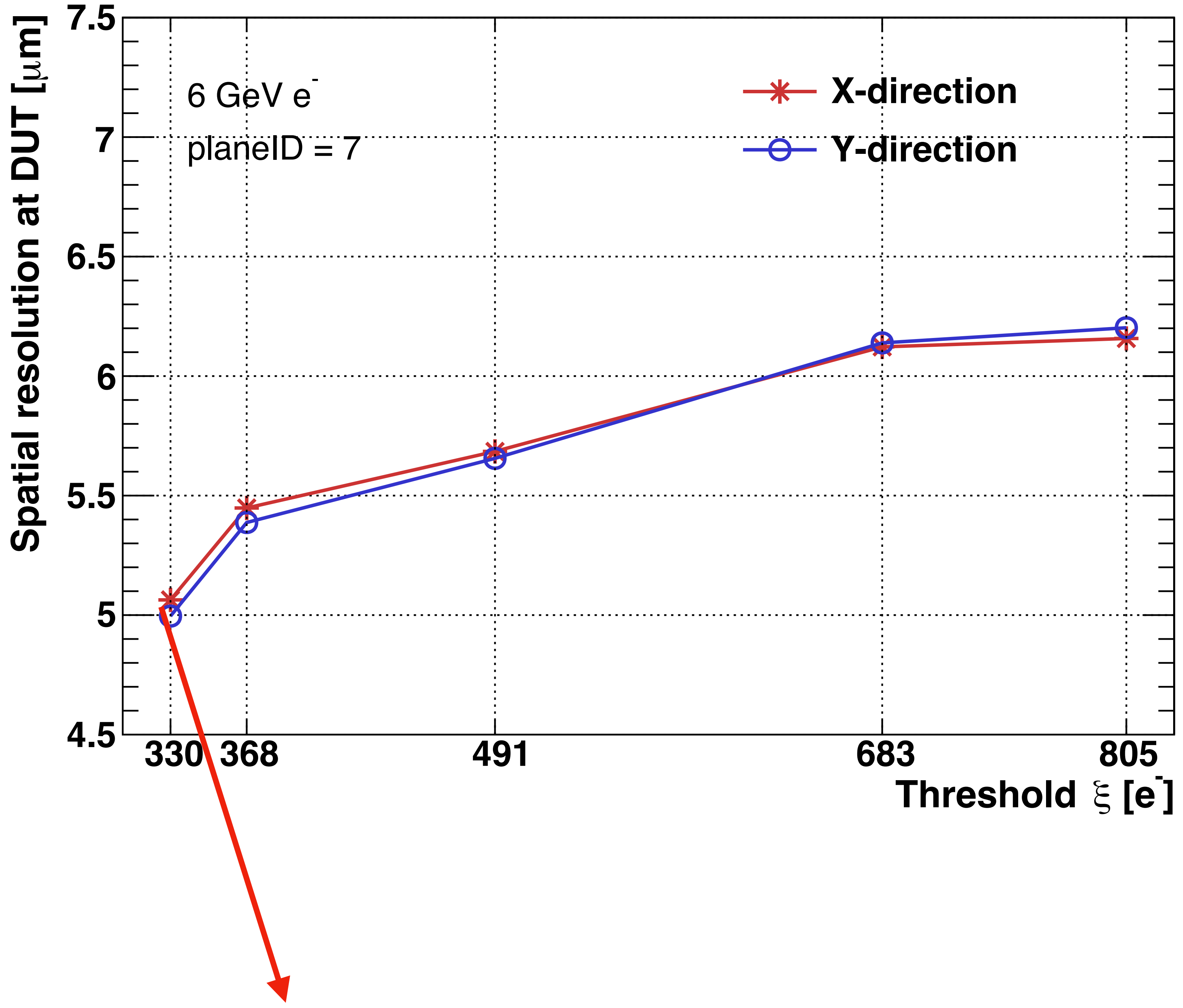
- Setup
  - Separate the full geometry into downstream and upstream ladders
  - Considering the real collision case and upstream with 5 measurement points, analysed the data from downstream ladders with 6 measurement points
  - planeID = 7 with modified process as the DUT

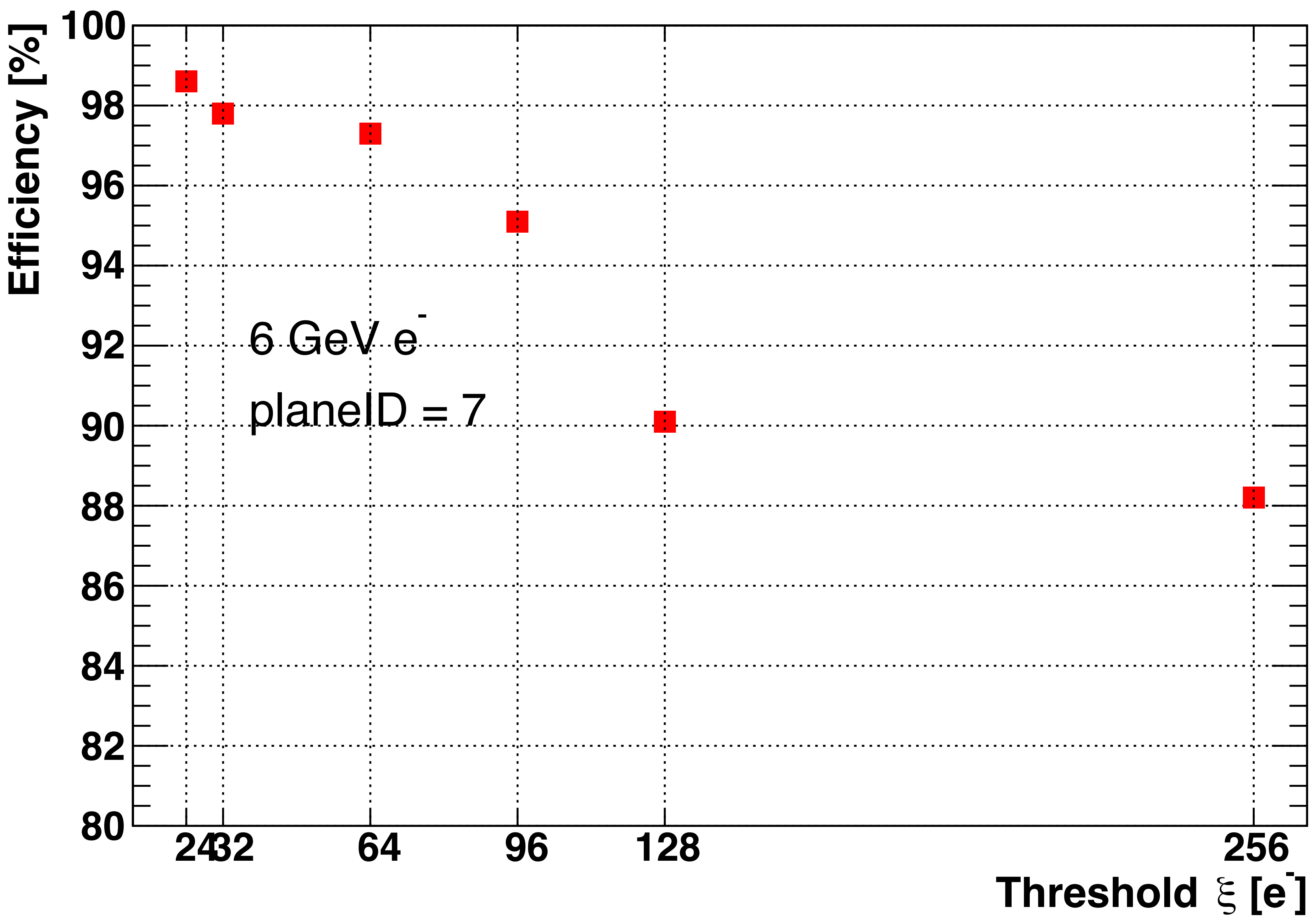




‣ cluster size, spatial resolution, efficiency vs. threshold

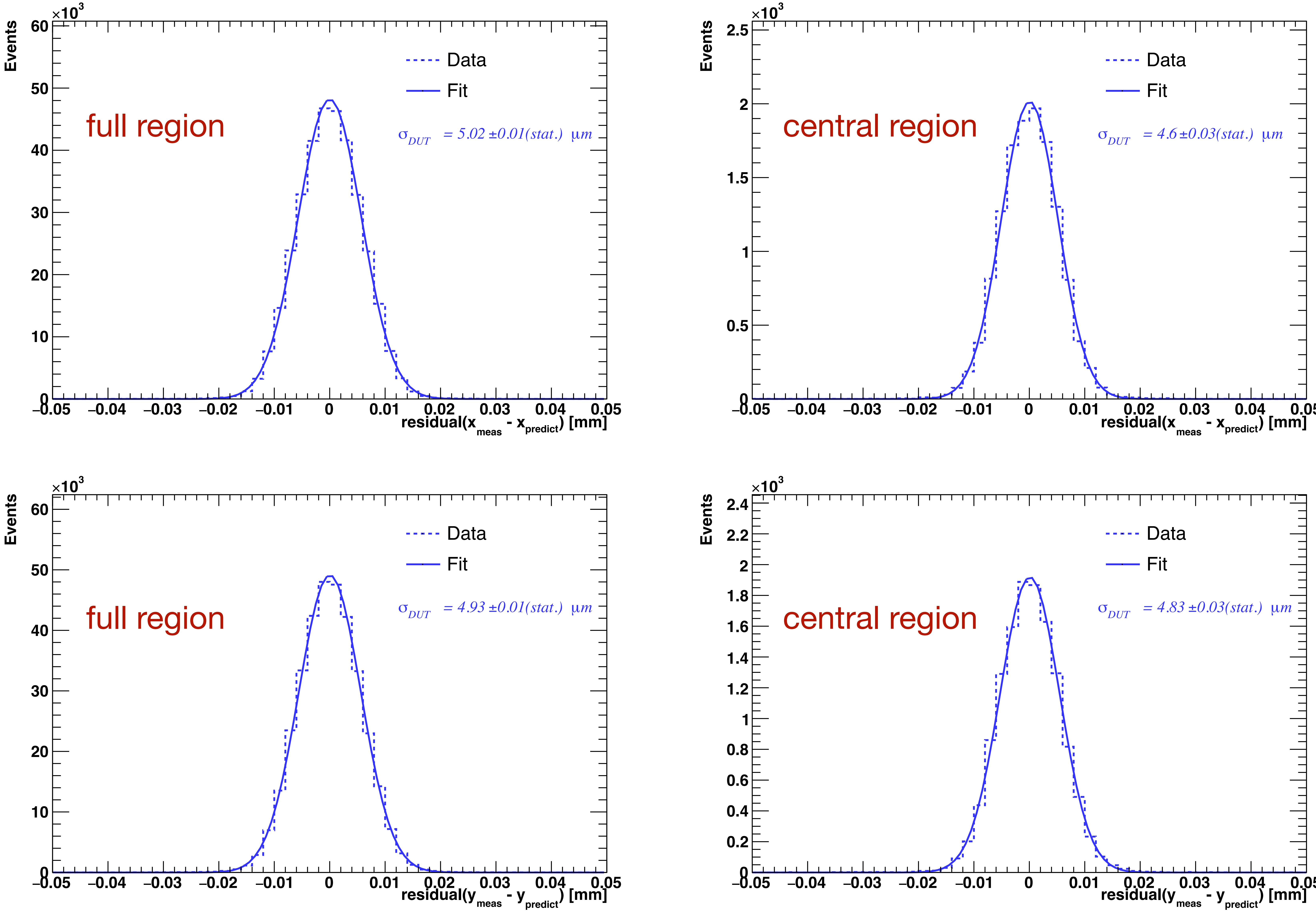






- Cross checked with another run with same threshold, shows same resolution
- The cluster size can match with first beam test results

Single point resolution

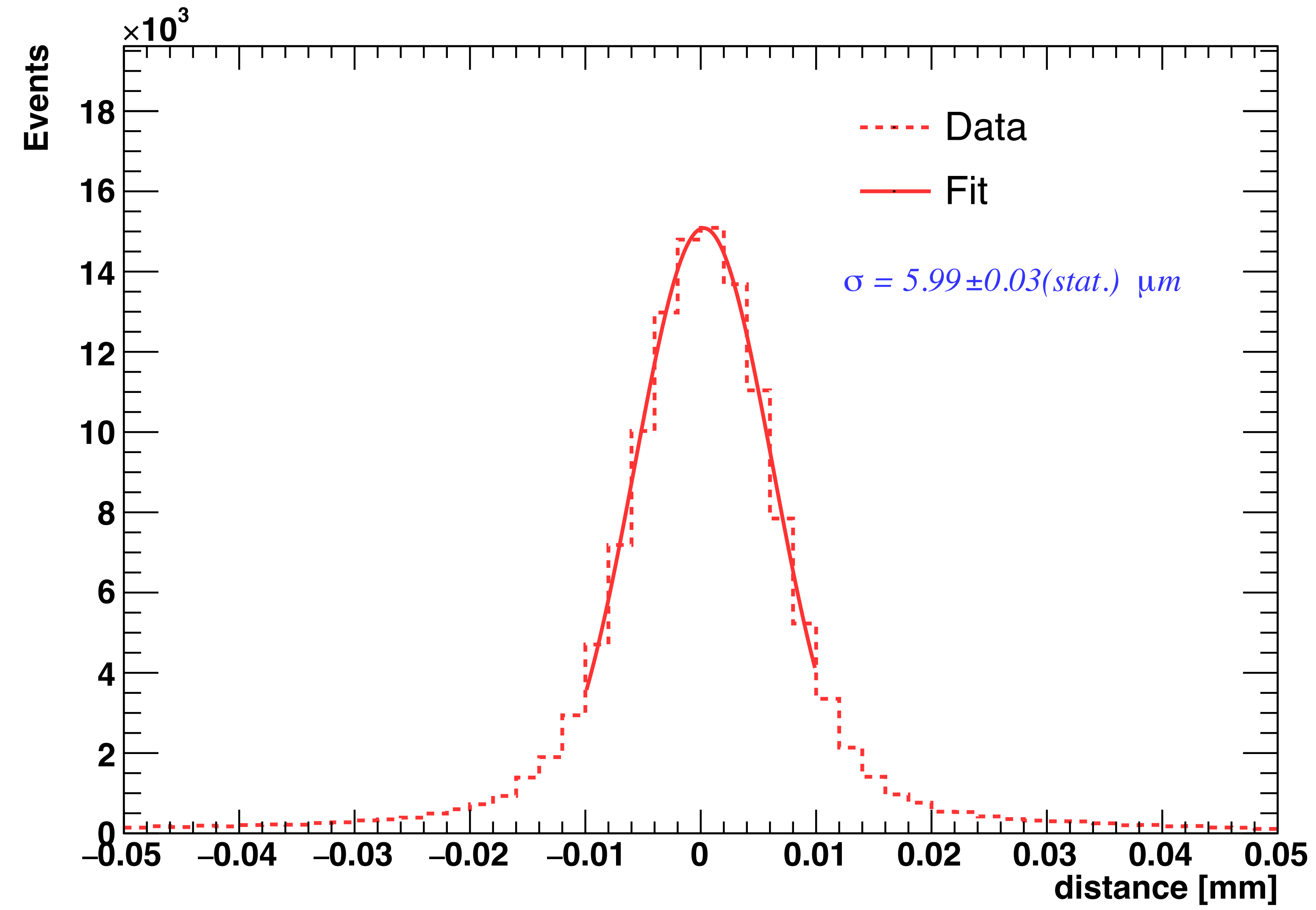


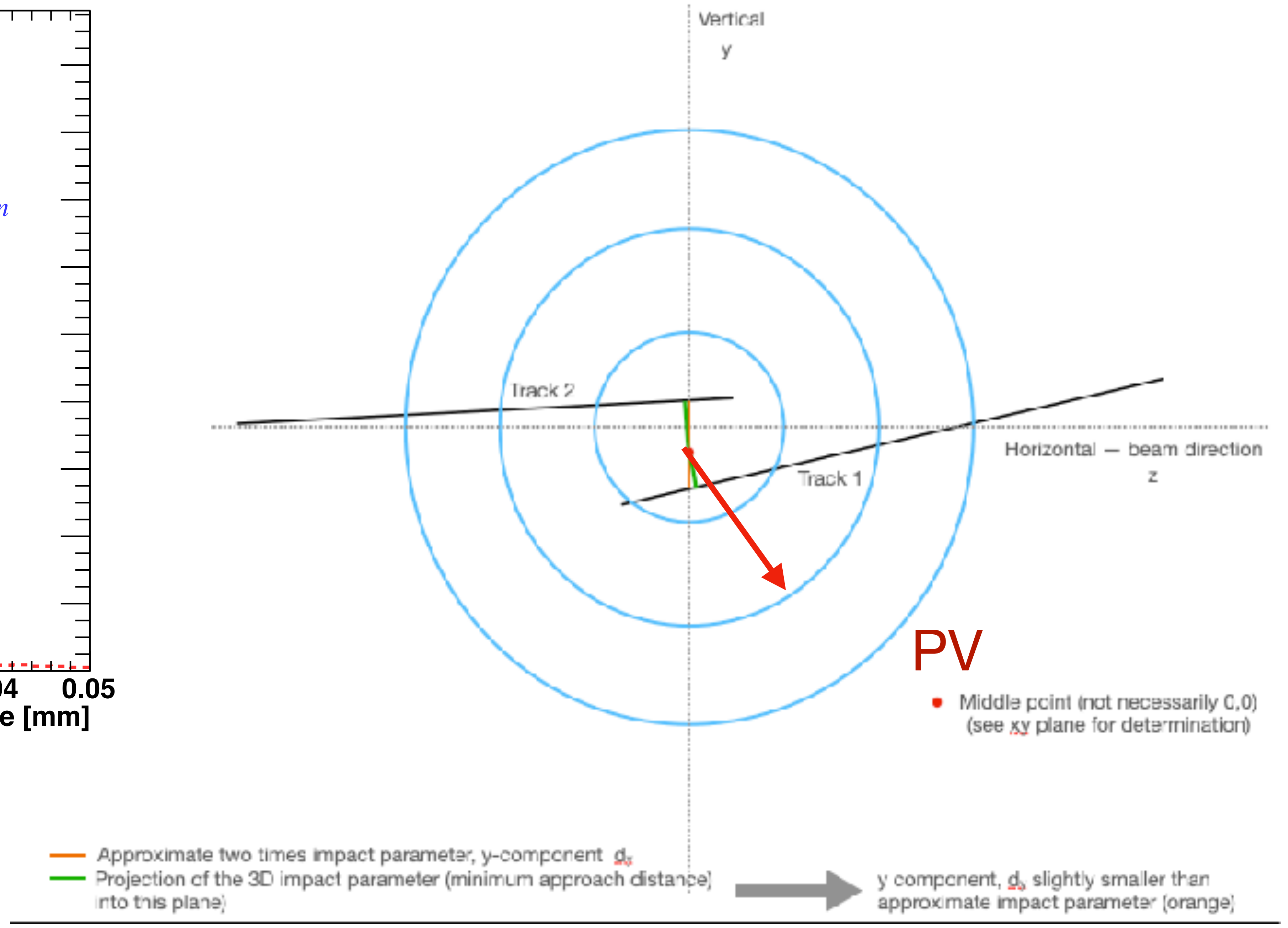
- lowest threshold
- 6 GeV electron beam
- if selected tracks through the central of chips, gives better spatial resolution

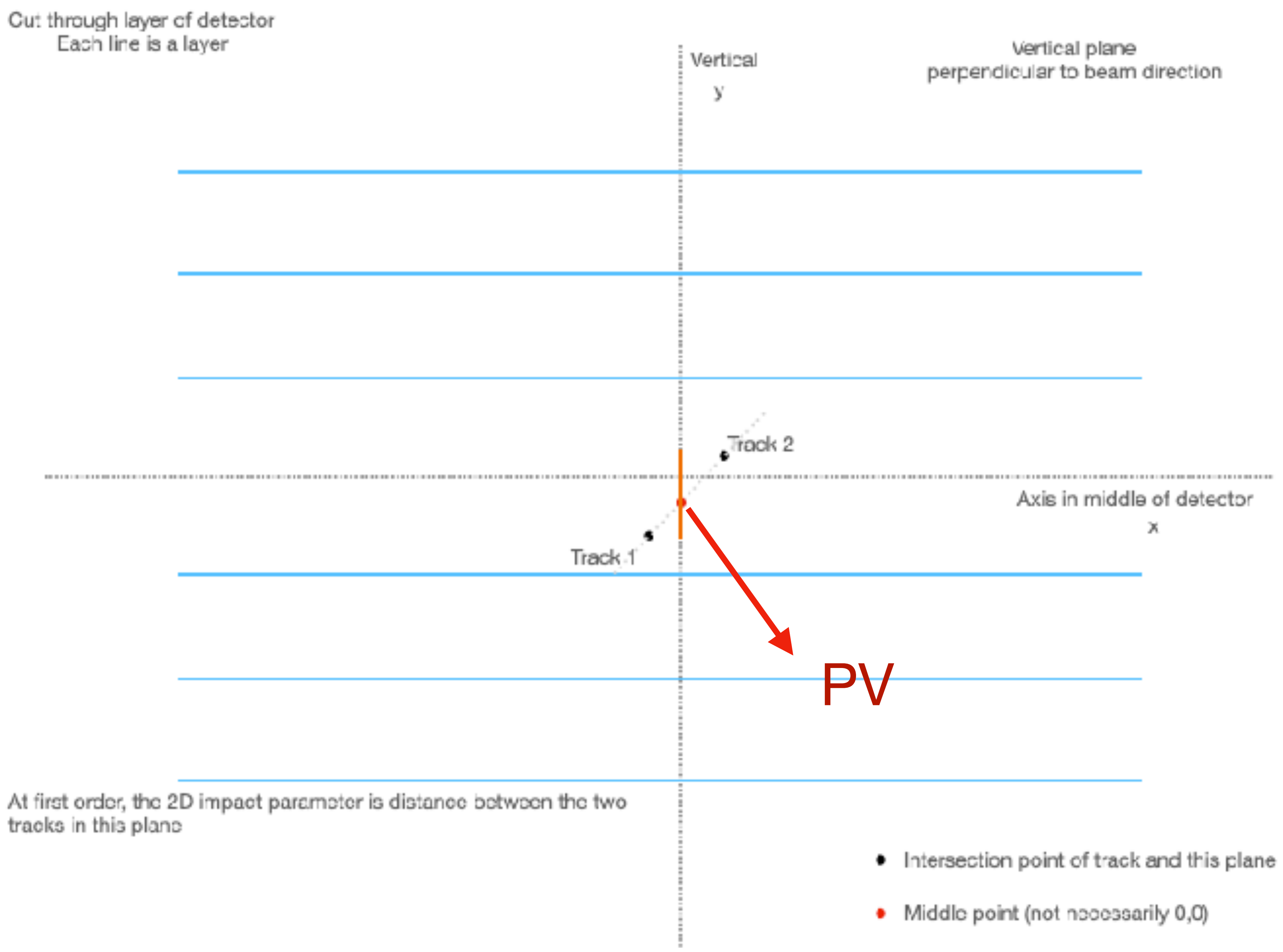
the chip is the rigid body, may not fully flat when install

worse multi-scatting on the edge area

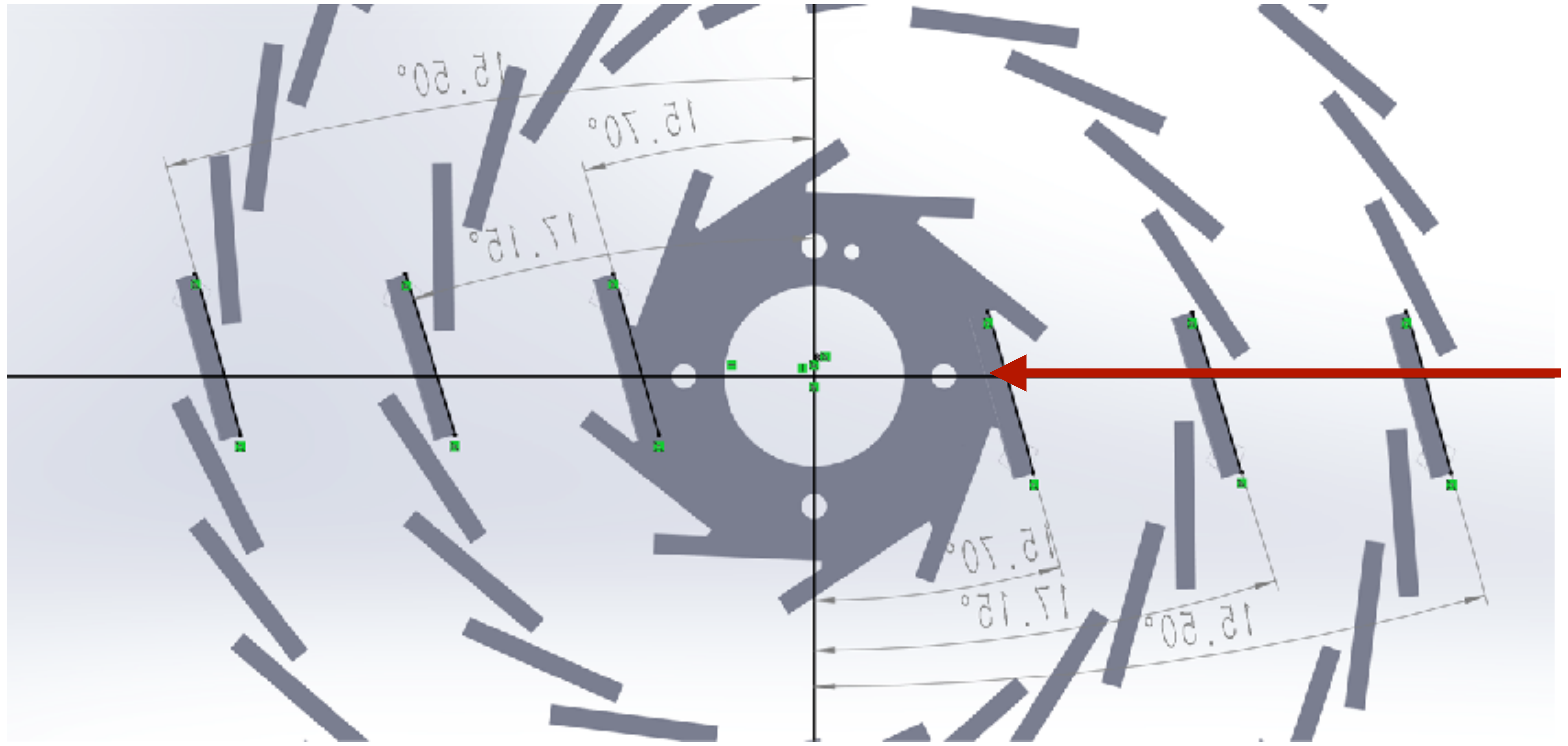
‣ impact parameter resolution







- determine the position of primary vertex
- calculate the distance between PV and tracks



Summary

- The offline analysis for CEPC vertex detector test beam data
- Next to do:
  - correct for multi-scattering
  - impact parameters study
  - When alignment, consider the bending of the chip

Backup

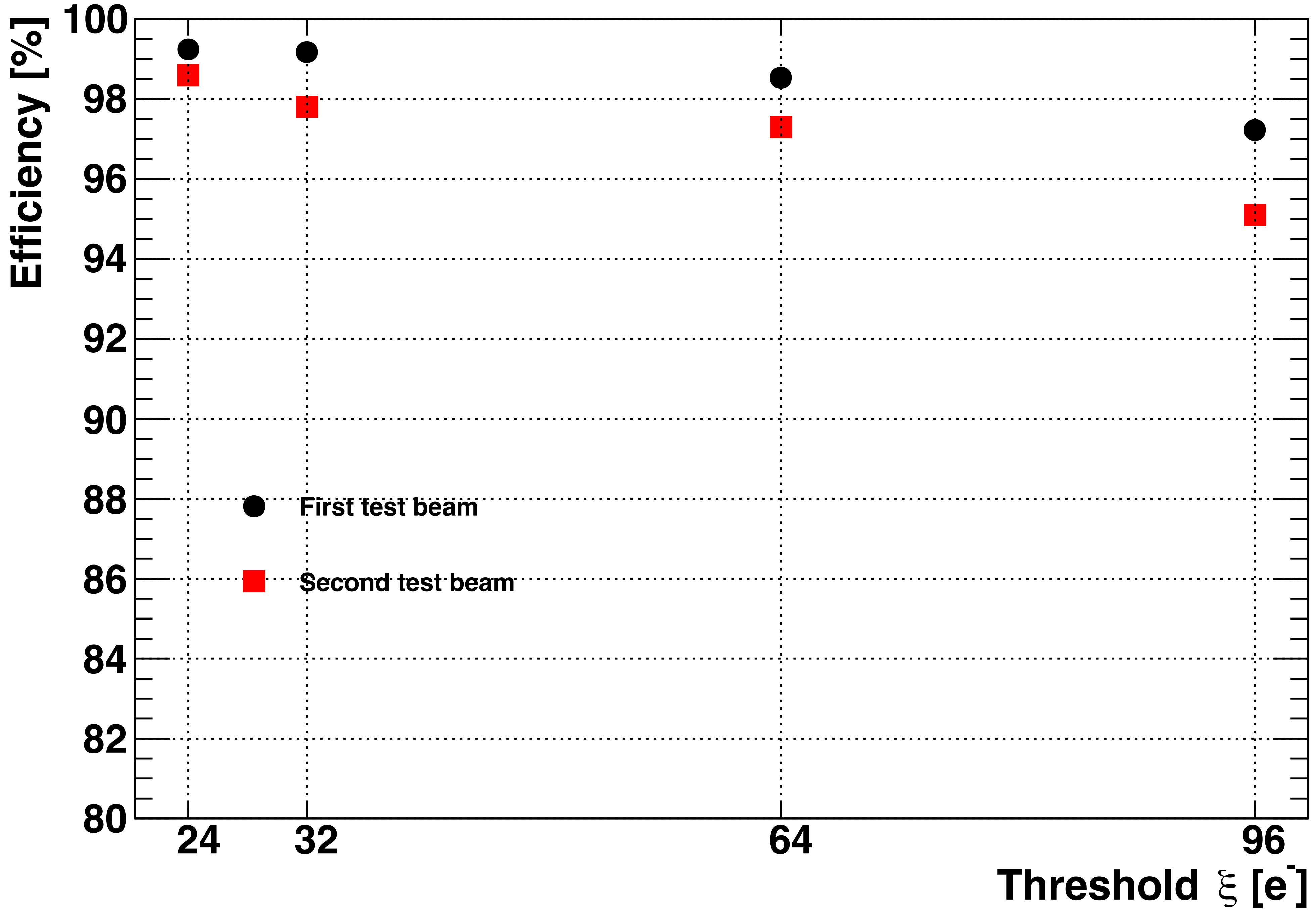
Preliminary results after correction for multi-scattering

- Using General broken lines package
  - refit correction for multi-scattering, equal to Kalman fitter in math
  - adding the silicon scatter (X/X0 = 150 um / 93.663 mm)
  - adding the possible scattering angle

$$\theta_0 = \frac{13.6MeV}{\beta cp} Z \sqrt{\frac{x}{X_0}}(1 + 0.038ln(\frac{x}{X_0}))$$

- std: standard process chip, mod: modified process
- SL: straight line fit, GBL: correction for multi-scattering
- No adding any cuts on tracks
- only list the residual width on x direction
- preliminary results, I still have several things need to be checked and understood ...

planeID	0 (std) thr = 16	1 (mod) thr = 64	2 (std) thr = 16	3 (mod) thr = 32	4 (std) thr = 96	5 (std) thr = 16
SL (biased)	5.87	4.71	6.13	6.23	5.42	5.99
GBL (biased)	3.52	4.33	4.53	4.6	4.96	3.69
SL (unbiased)	12.1	6.67	7.48	7.59	7.68	12.62
GBL (unbiased)	10.97	6.62	6.69	6.81	7.62	11.84



Efficiency [%]
100
98
96
94
92
90
88
86
84
82
80
24
32
64
96
Threshold ξ [e⁻]
First test beam
Second test beam