Offline analysis for CEPC vertex detector test beam at DESY

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11/01/2023

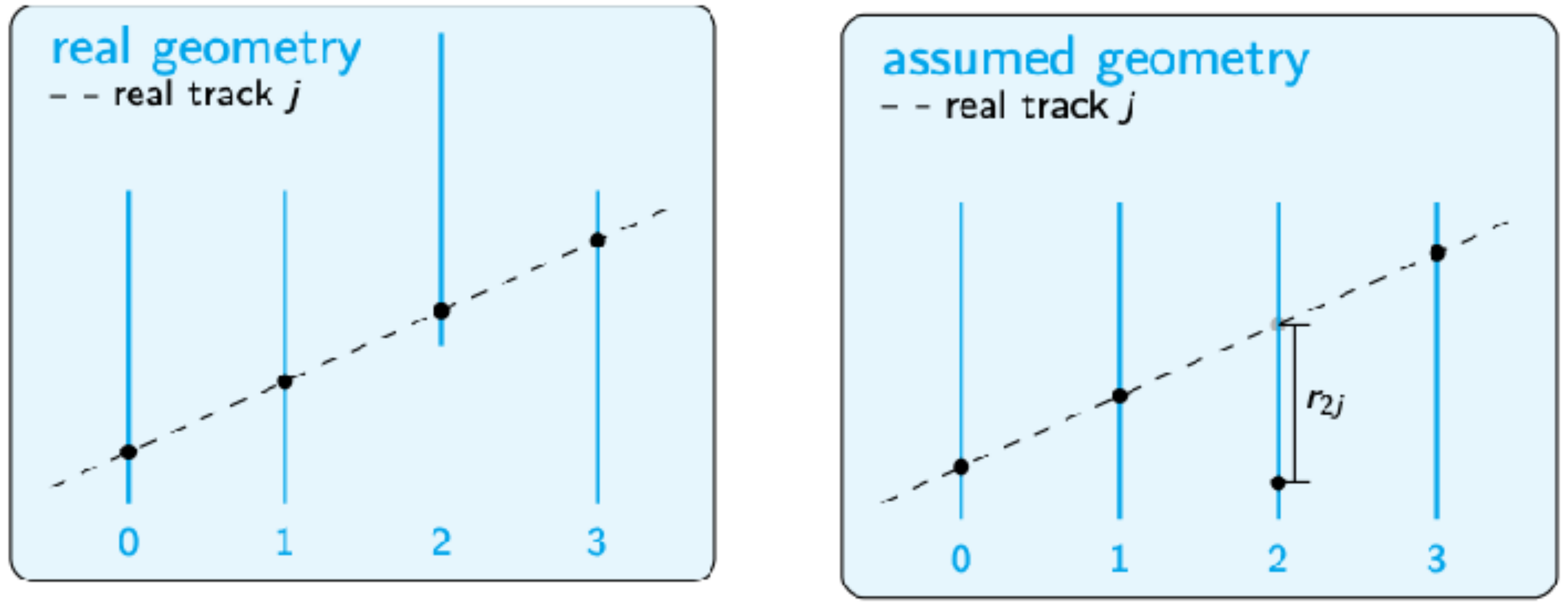
Introduction

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

    no magnetic

    straight line fit

    no considering multi-scattering currently

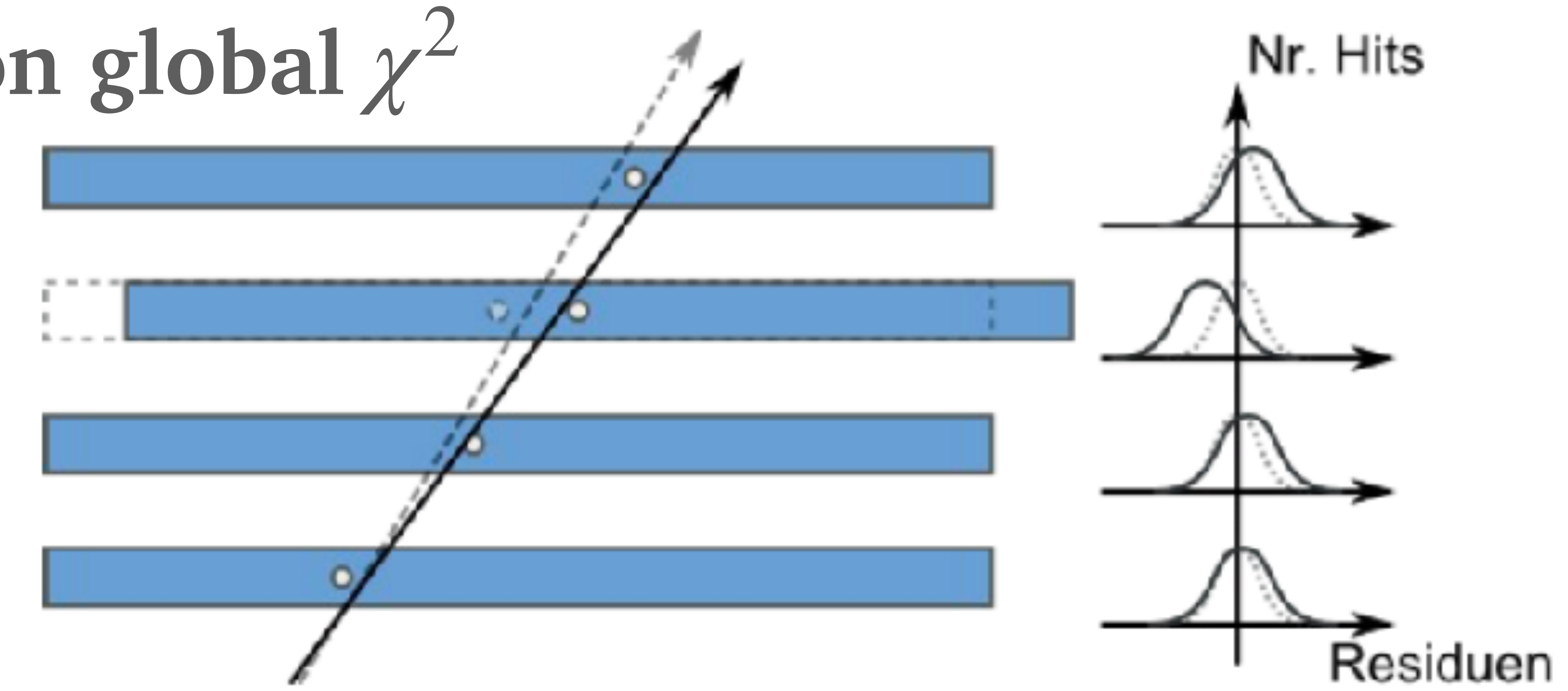


  - Track alignment

    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

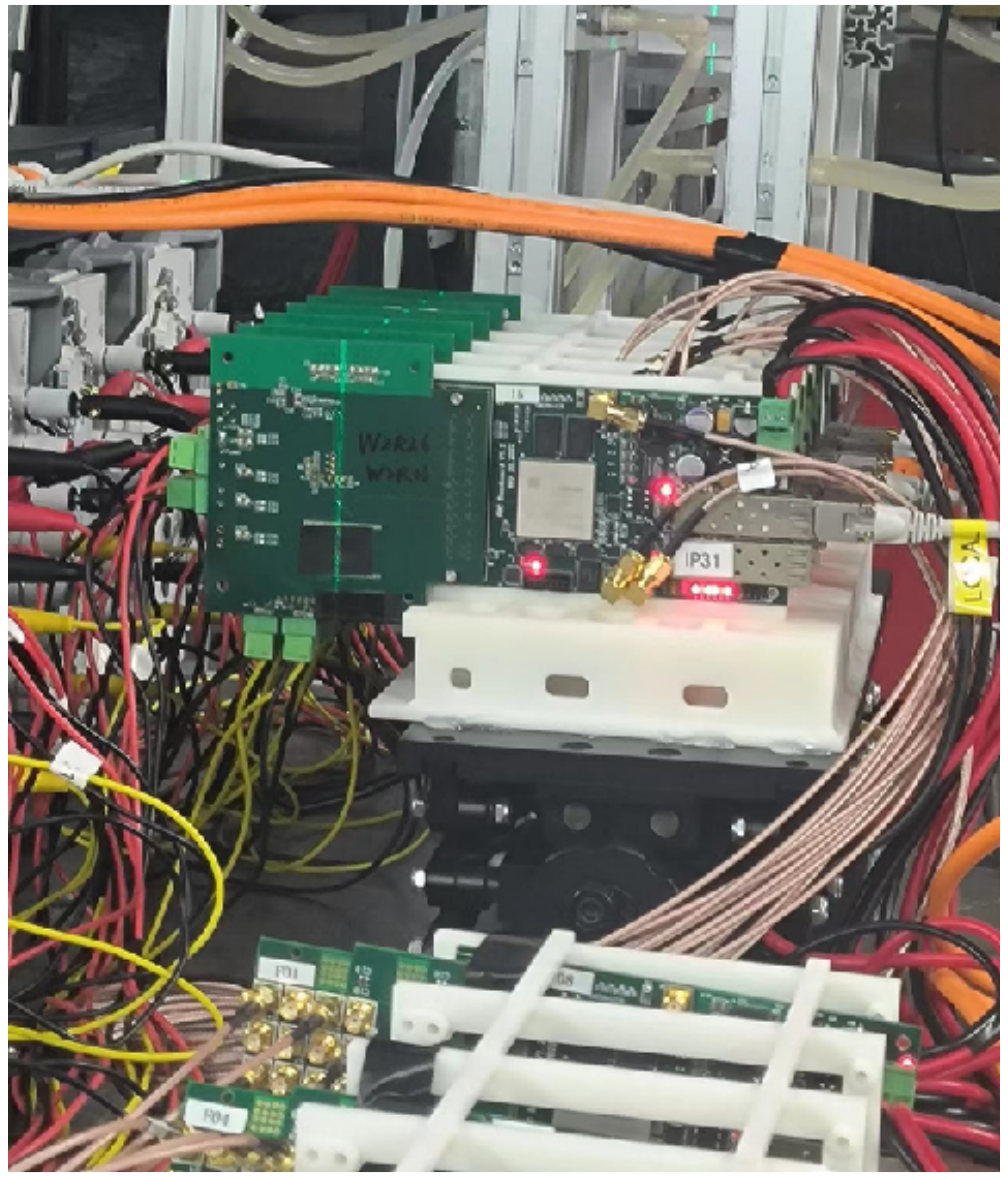


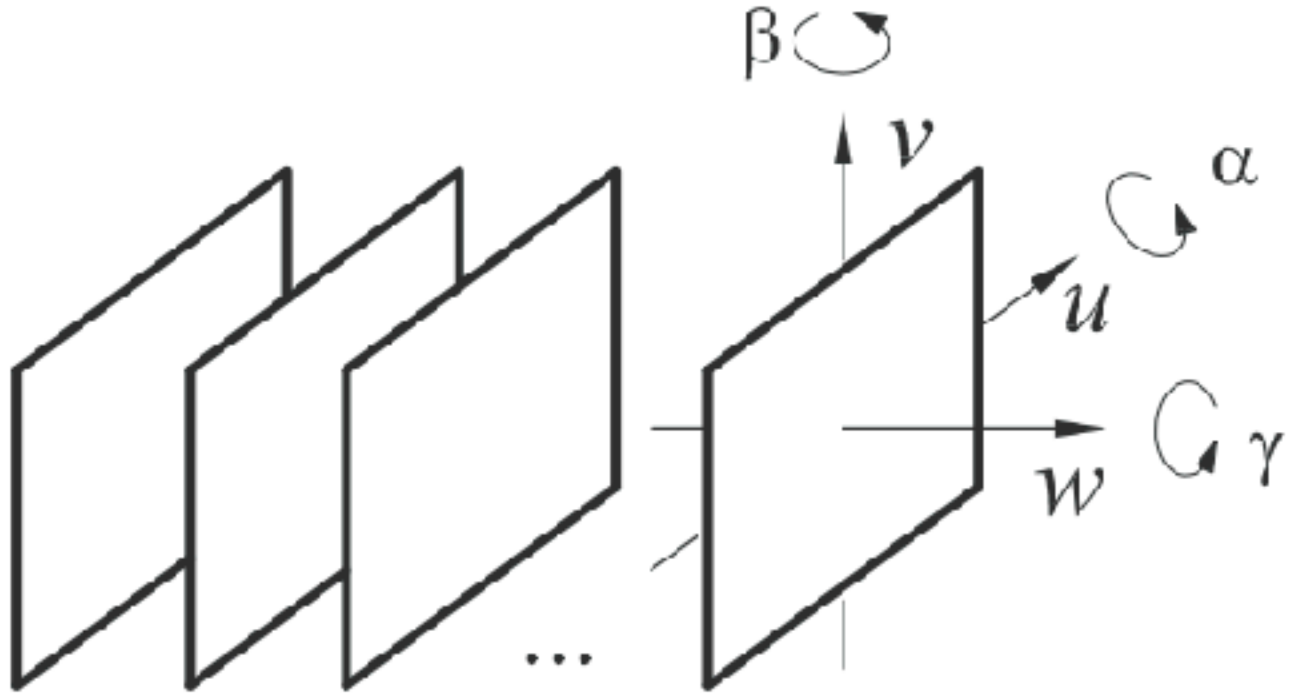
Residual: distance of measured hit with the intersection point of track in the measured chip

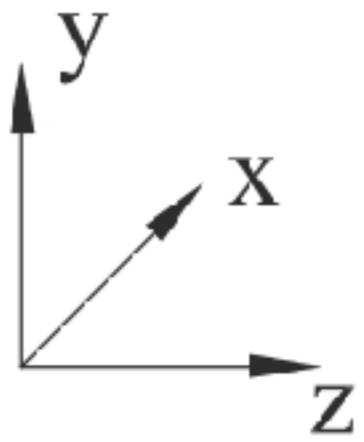
- TaiChu silicon pixel detector
  - Pixel size: 25 um
  - Theoretical resolution: 25um/sqrt(12) ~ 7.22 um
  - The experimental resolution should be better than theoretical resolution due to charge sharing

Track reconstruction

- Setup
  - 6 layer chips
  - 4cm between each other
  - electron beam energy 3-6 GeV
  - One of the chips is the detector under test (dut), the others are the telescope
- Steps for track finding and reconstruction
  - Finding hits in every chip with same time stamp of FPGA (+/- 1)
  - Forming adjacent hits into a cluster
  - No considering multiple clusters on one chip for one track currently
- 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)**

Track 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

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

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

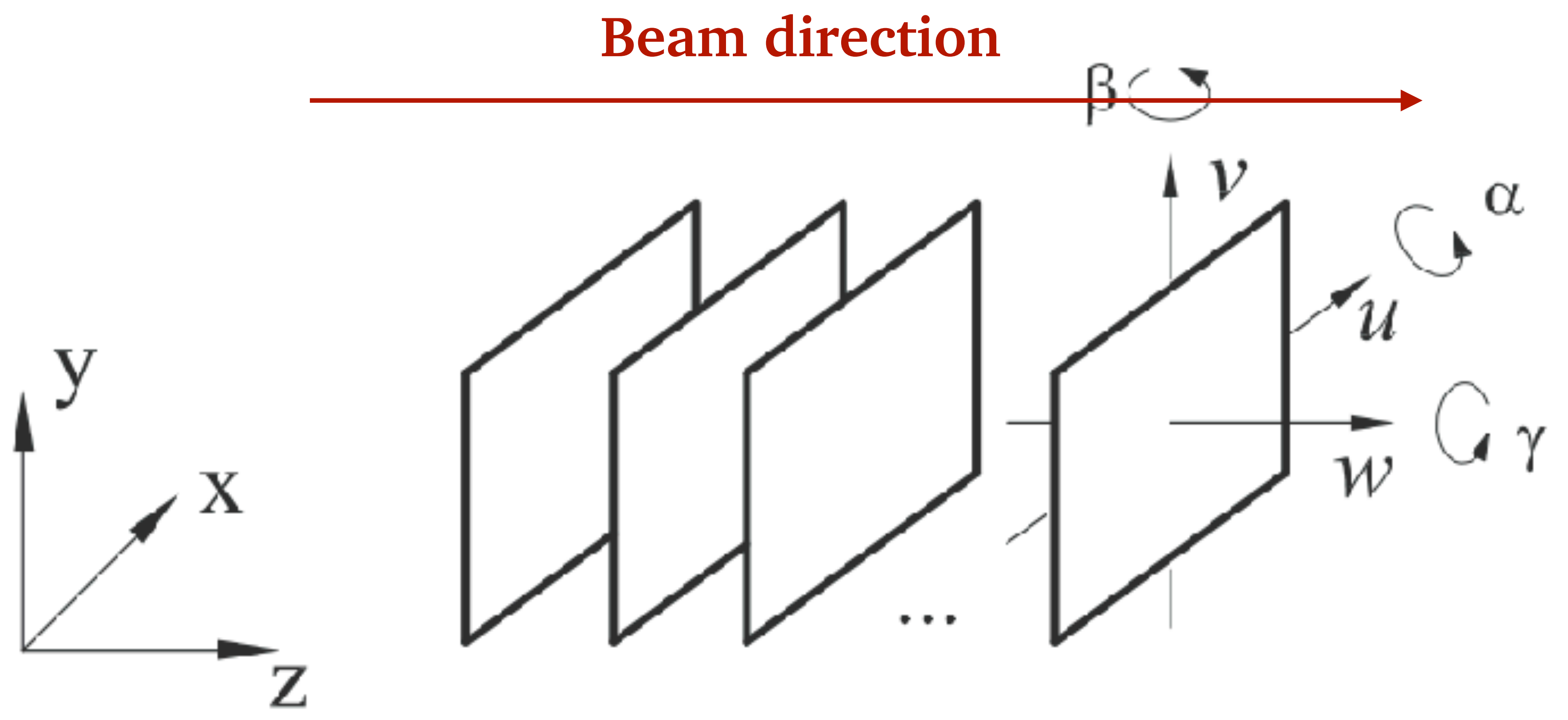
  - invert the Matrix C to find alignment correction Δp
  - reduce matrix C for alignment only

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

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

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

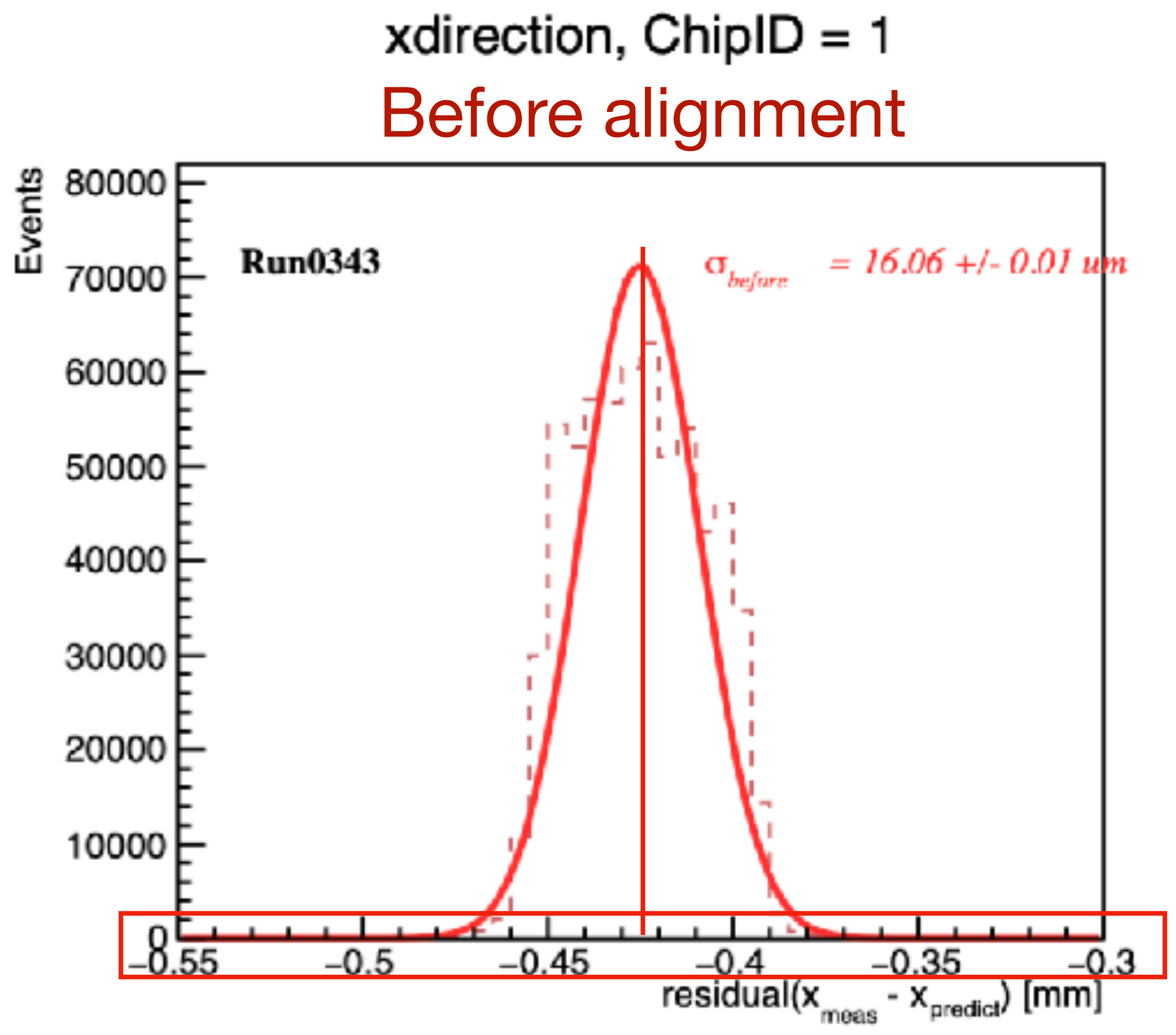
- Six alignment parameters considered
  - Translation along X, Y, Z direction
  - Rotation around X, Y, Z axis

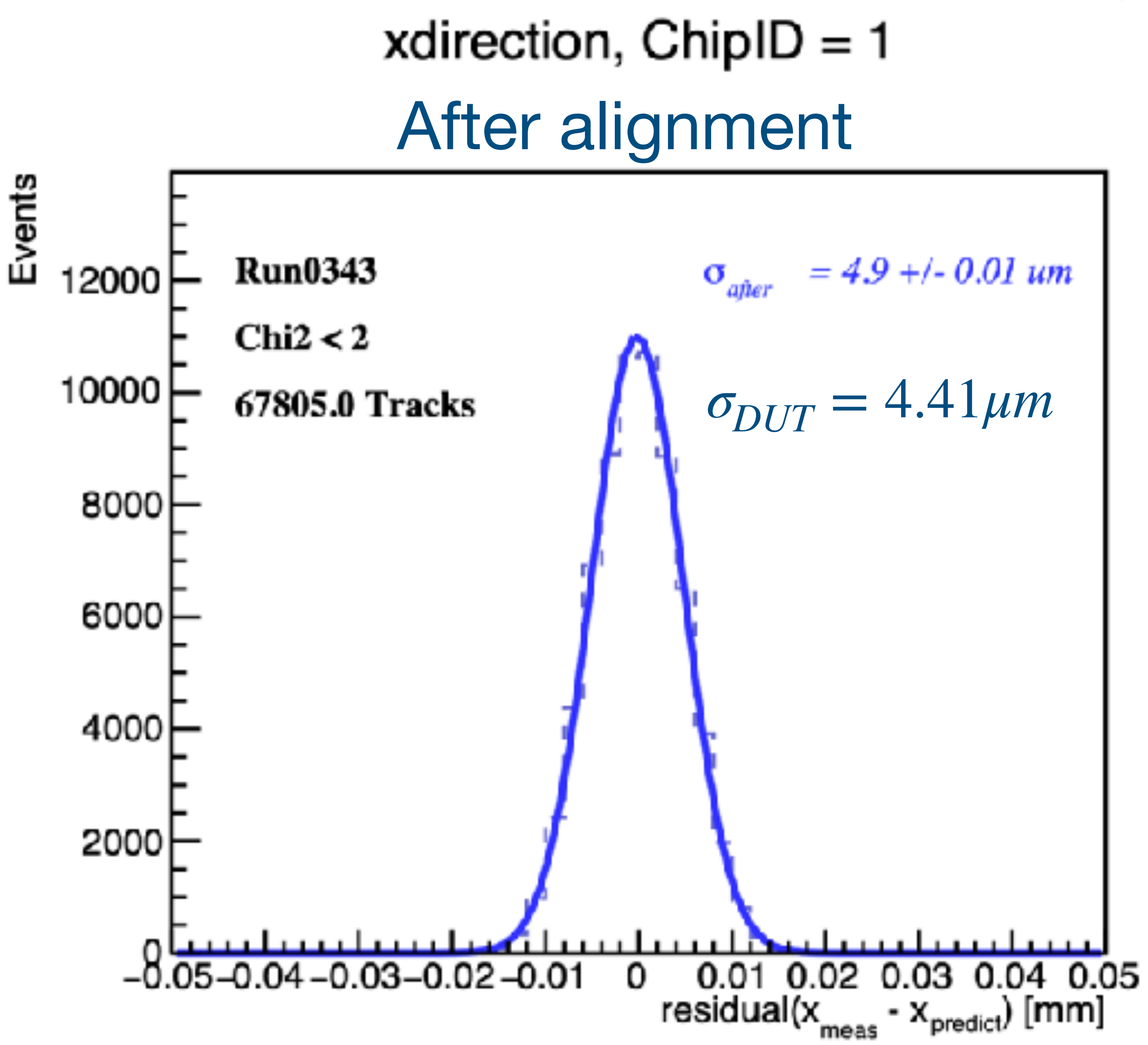


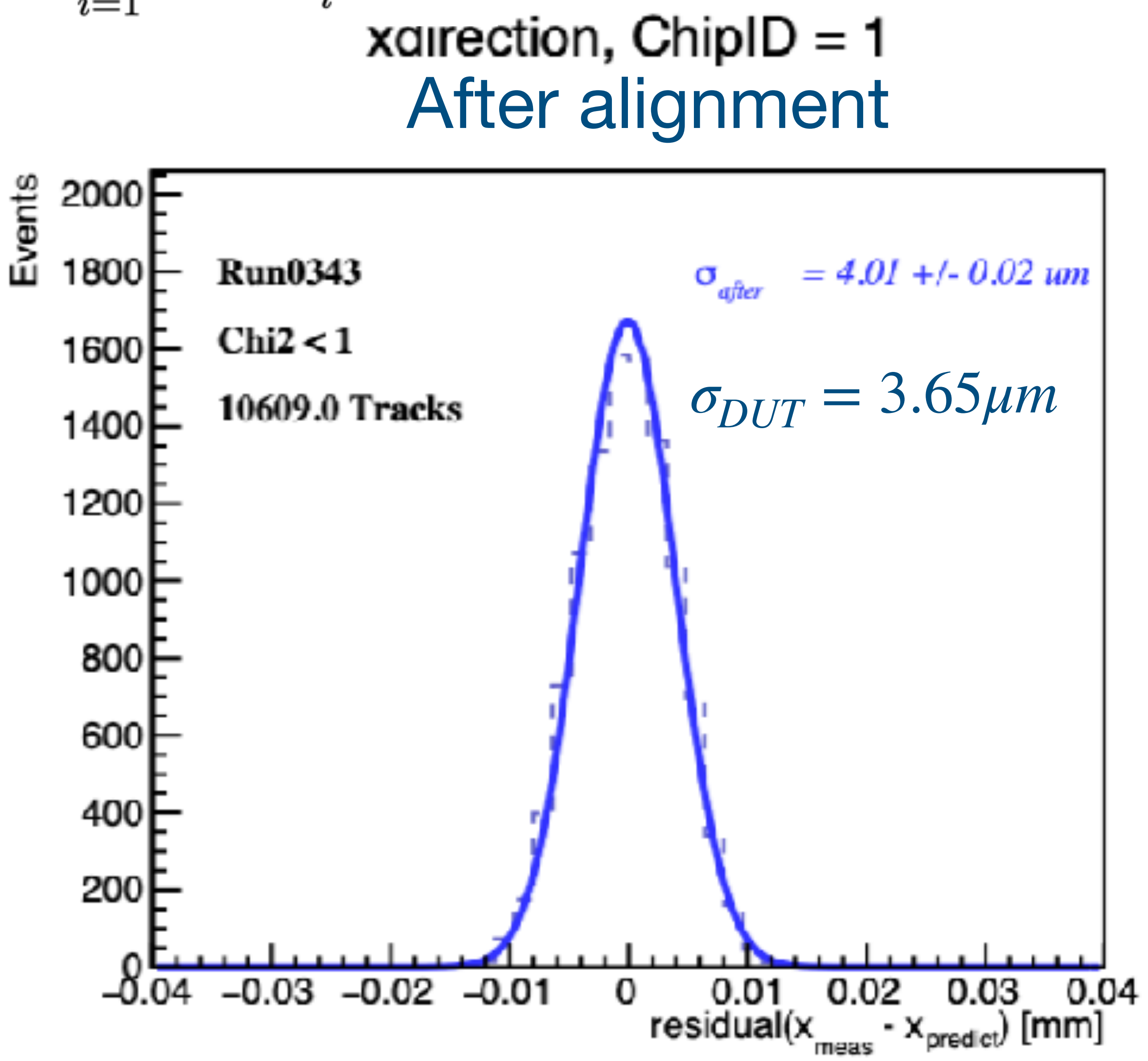
Residual plots before and after alignment (4GeV)

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

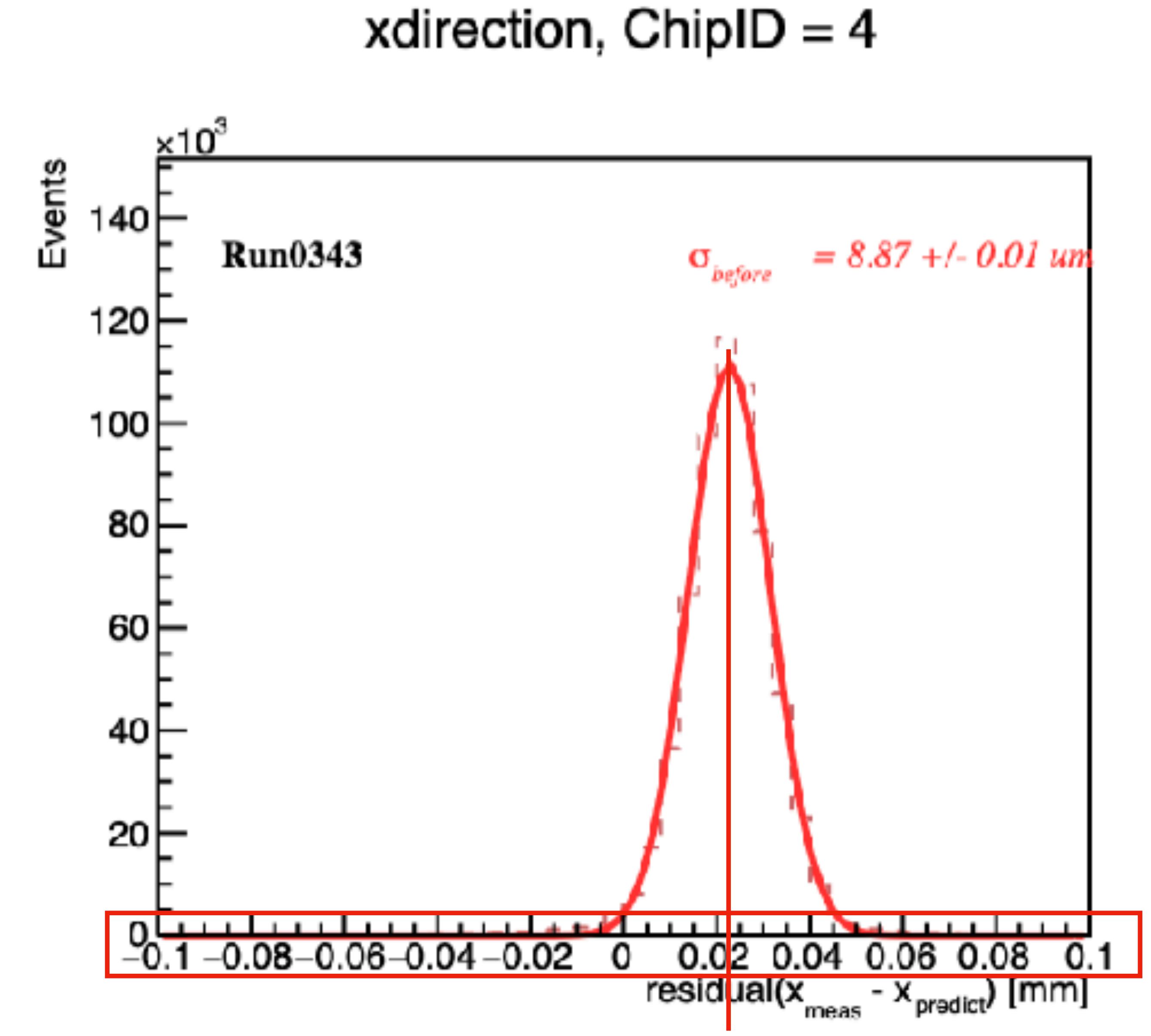
χ^2definition: $\chi^2(\alpha) = \sum_{i=1}^{n} \frac{f(x_i,\alpha) - e_i)^2}{\sigma_i^2}$ **, n = 5, sigmax = sigmay = 25um/sqrt(12)**

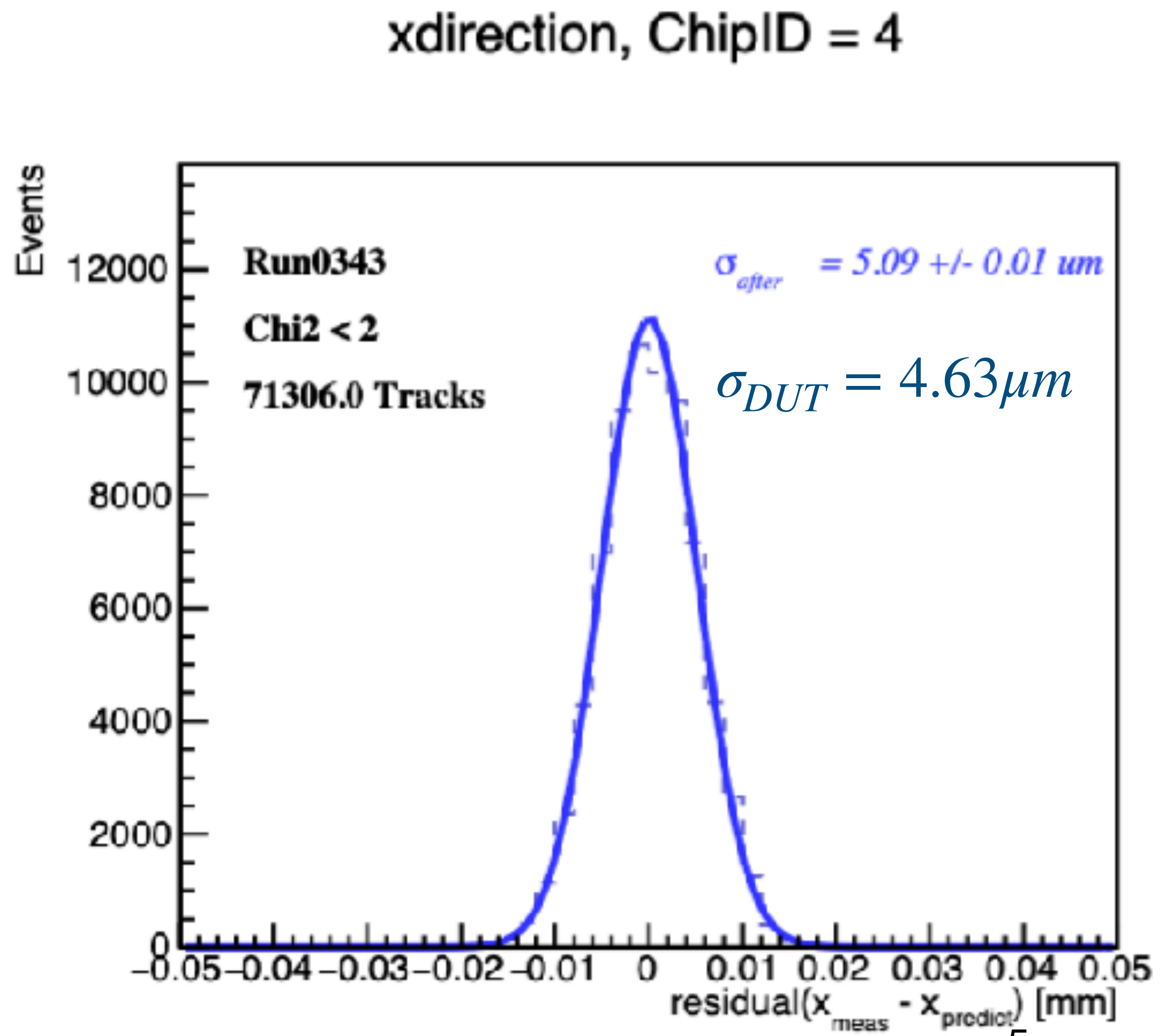


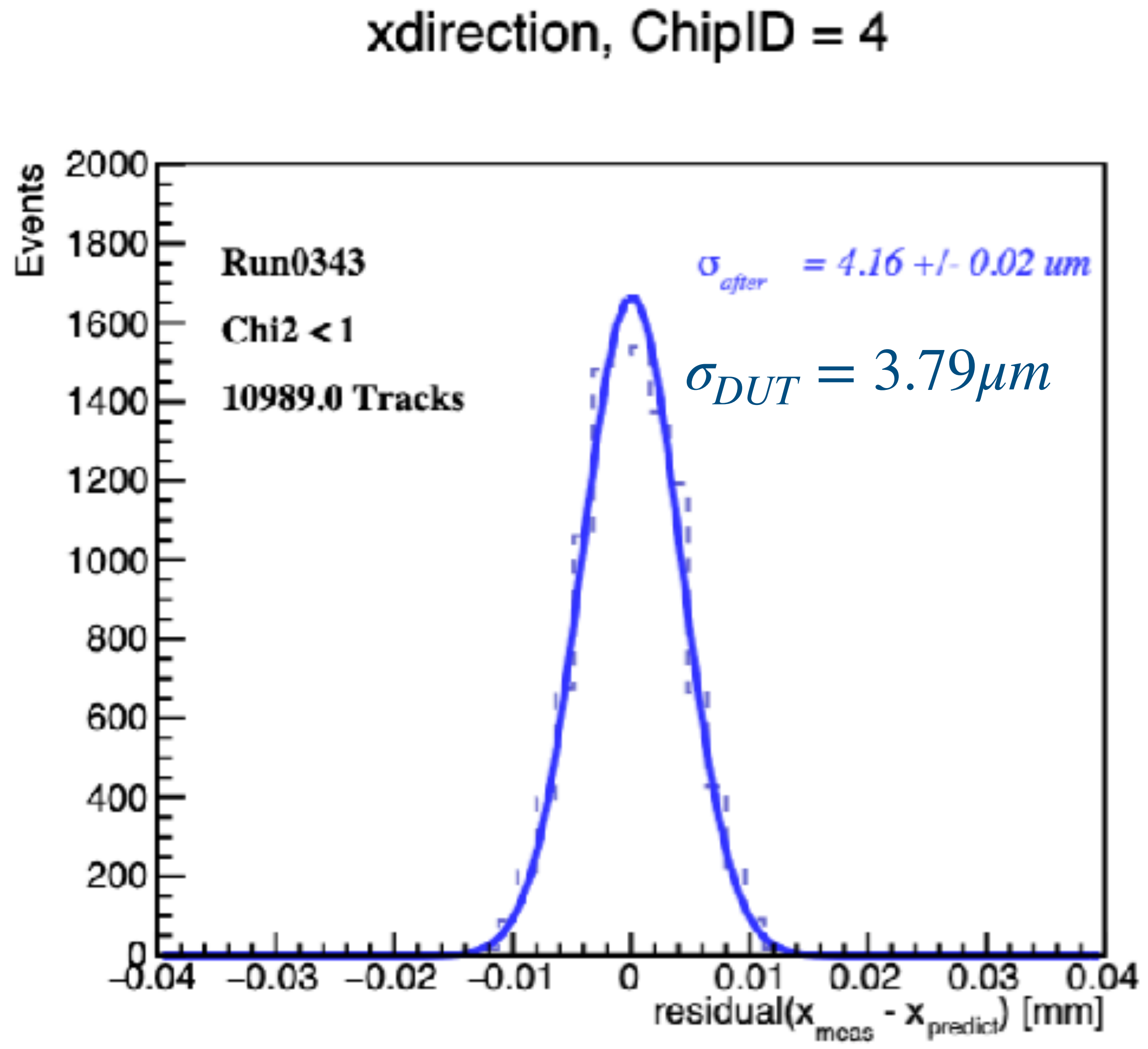




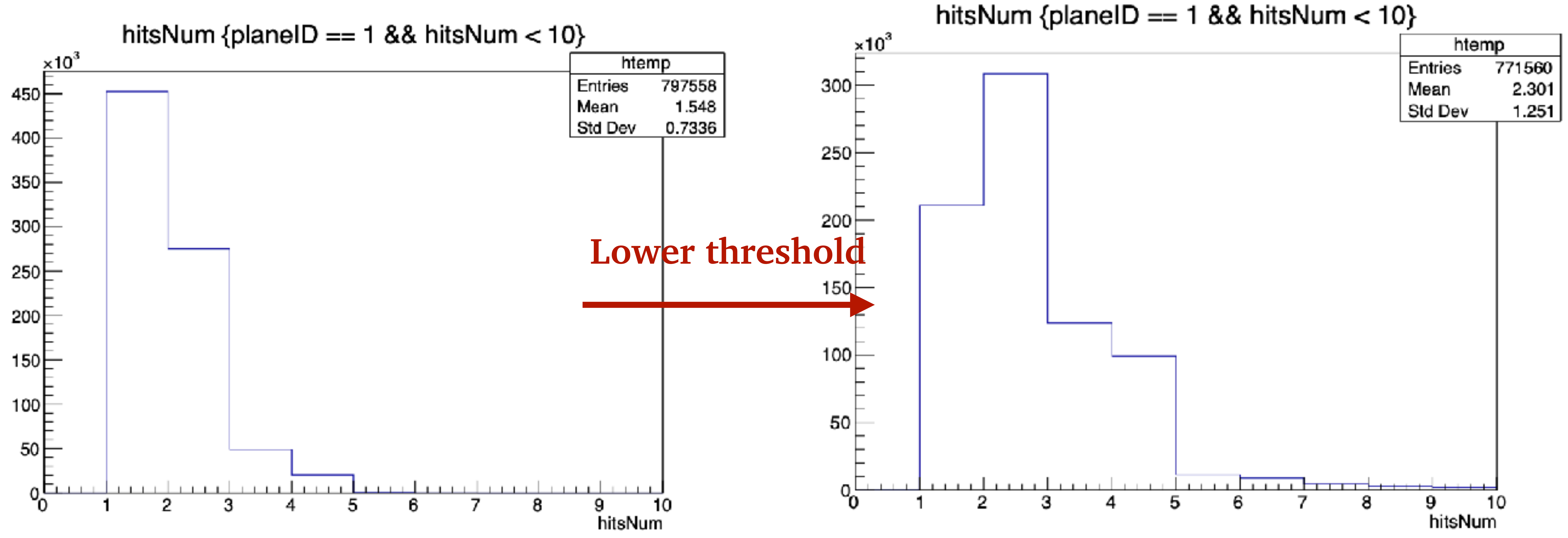
- The misalignment can be well corrected.
- The spatial resolution can reach < $5\mu m$
- $\sigma_{meas}^2 = \sigma_{DUT}^2 + \sigma_{tel}^2$
- $\sigma_{DUT} \approx 0.91\sigma_{meas}$



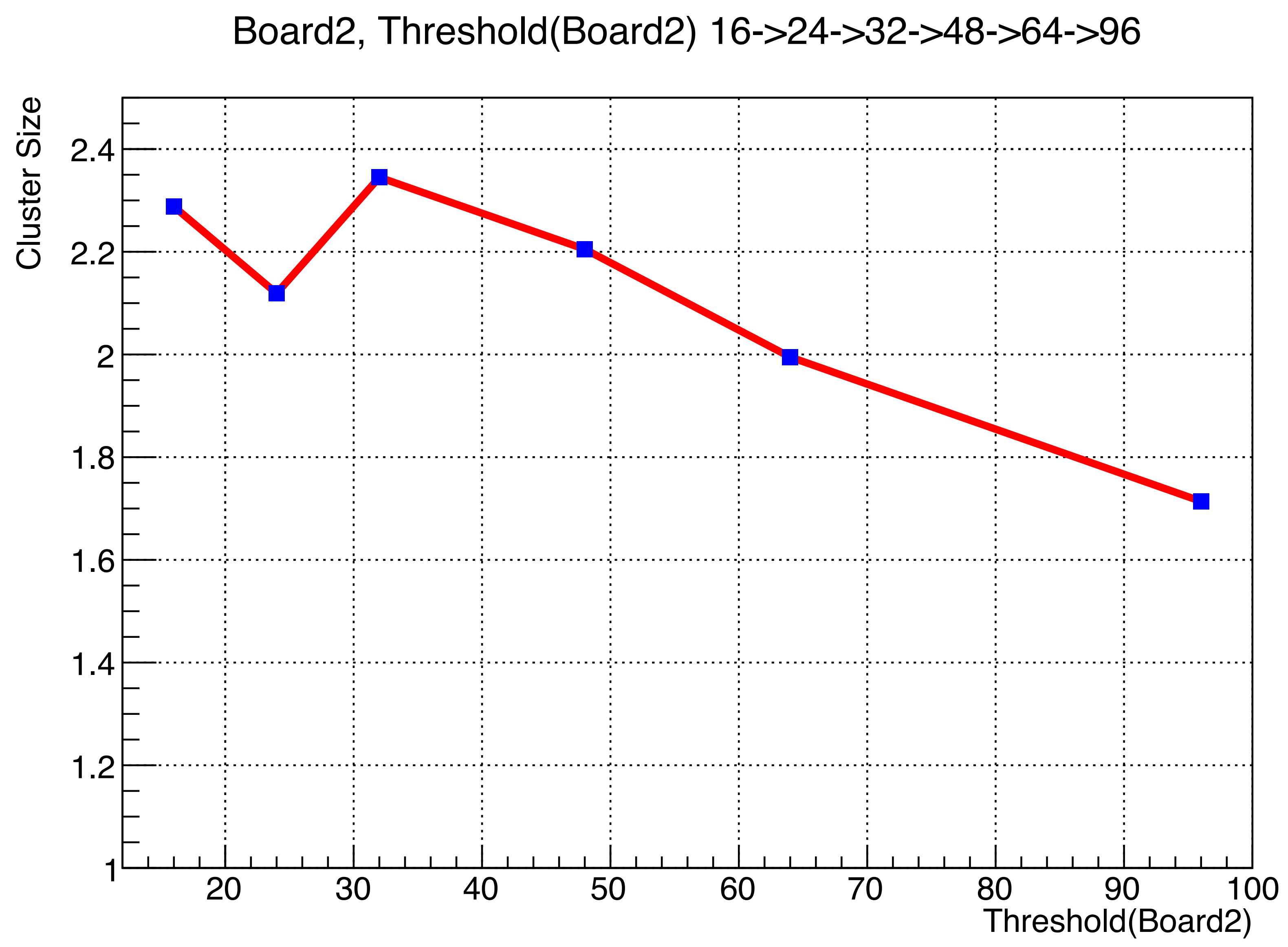


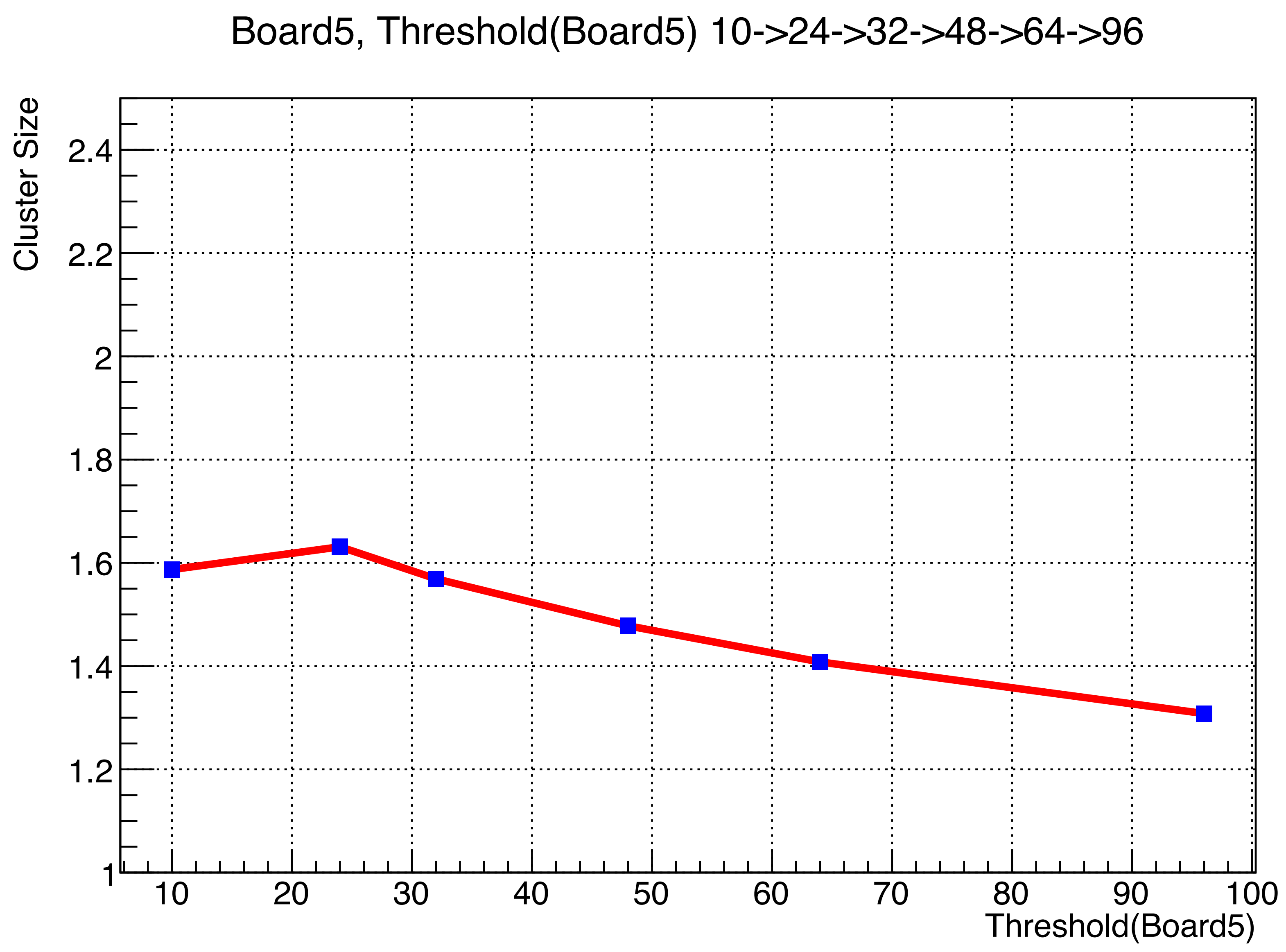


Cluster size vs. chip threshold (4GeV)



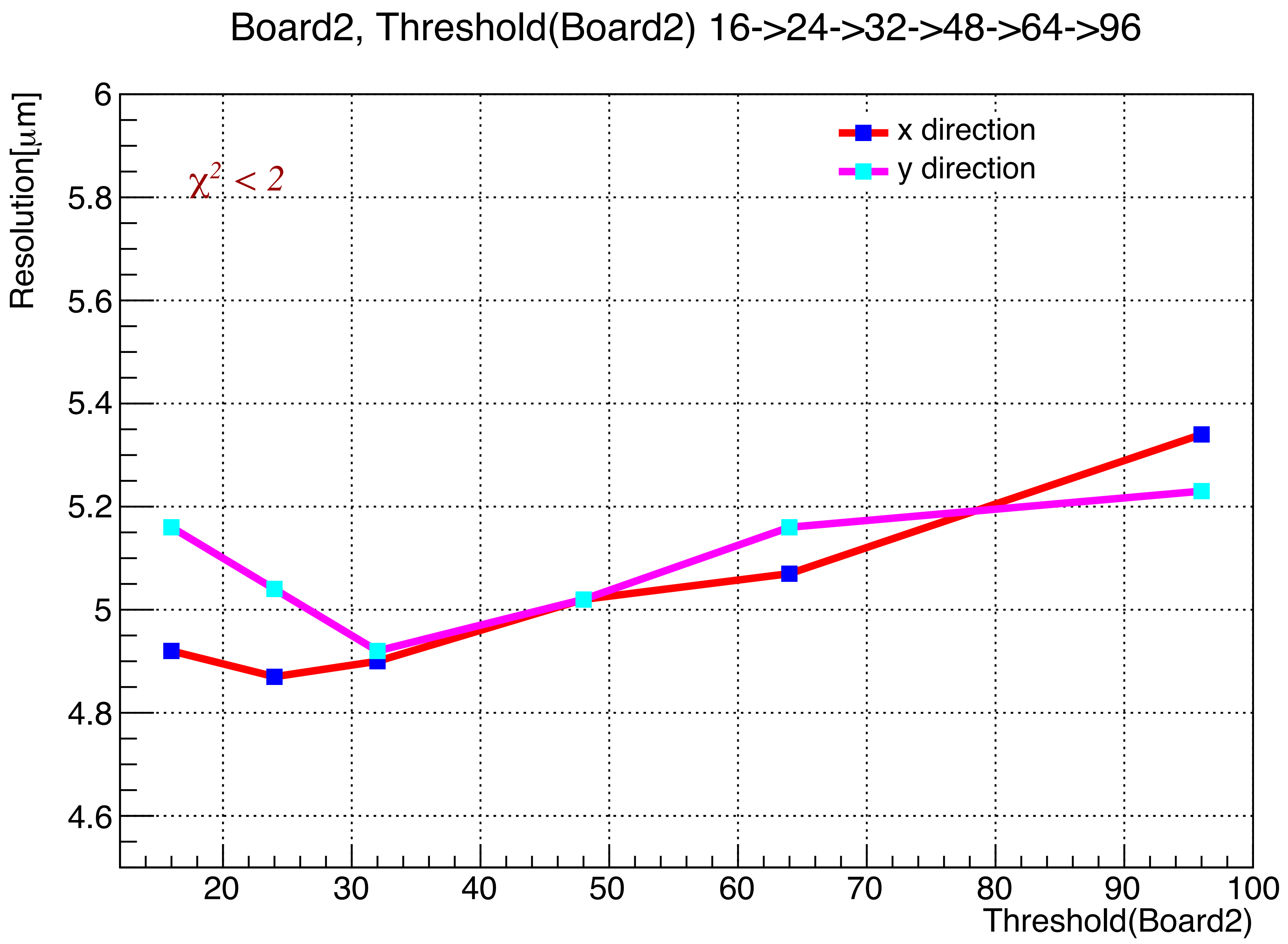
- If lowering the threshold, cluster size will be dominated by cluster with 2 hit

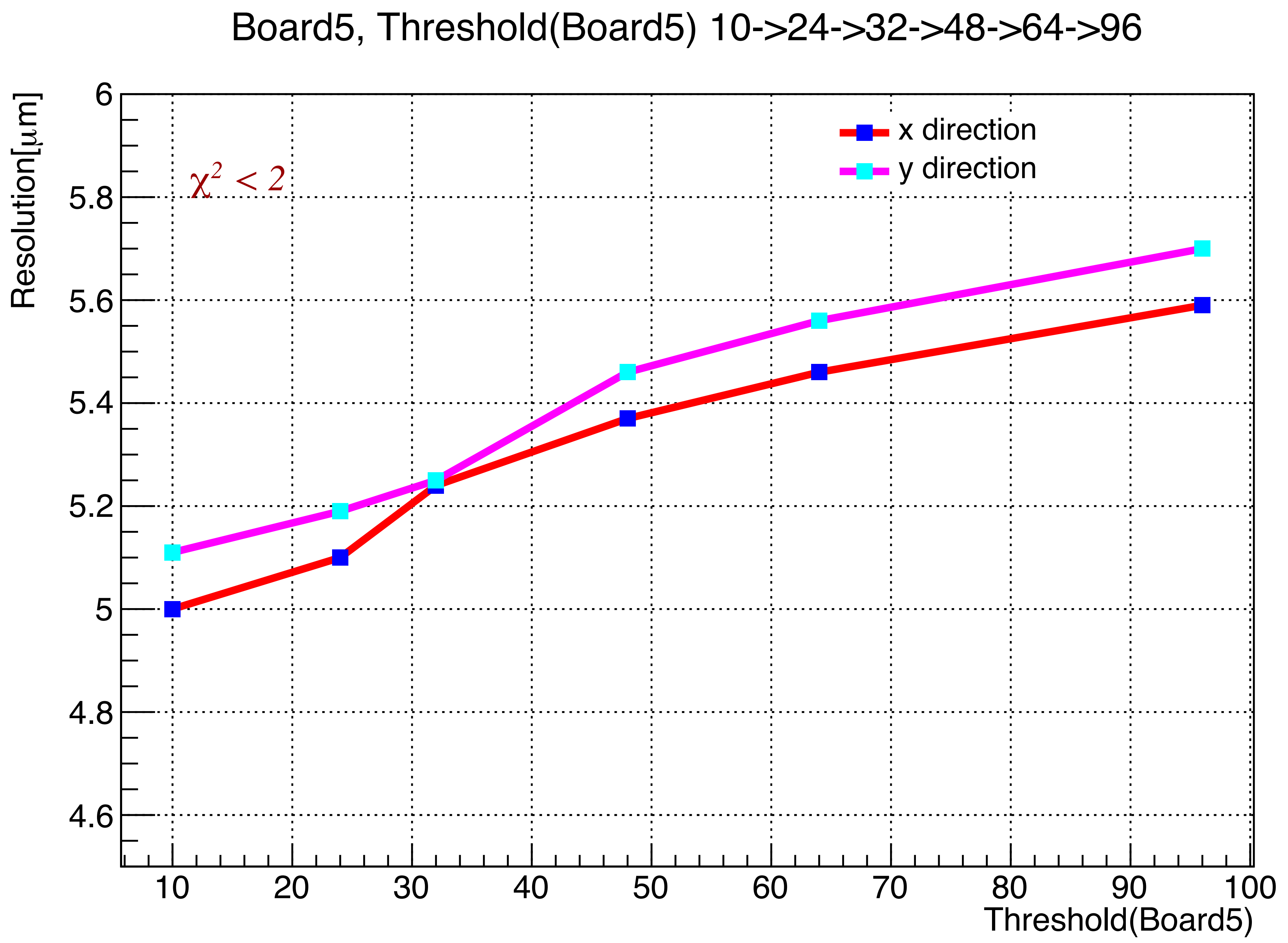




- Board2 with modified technology has a larger depletion layer than Board5 with standard technology
- In general, the higher the threshold, the smaller the cluster size

- Spatial resolution vs. chip threshold (4GeV)



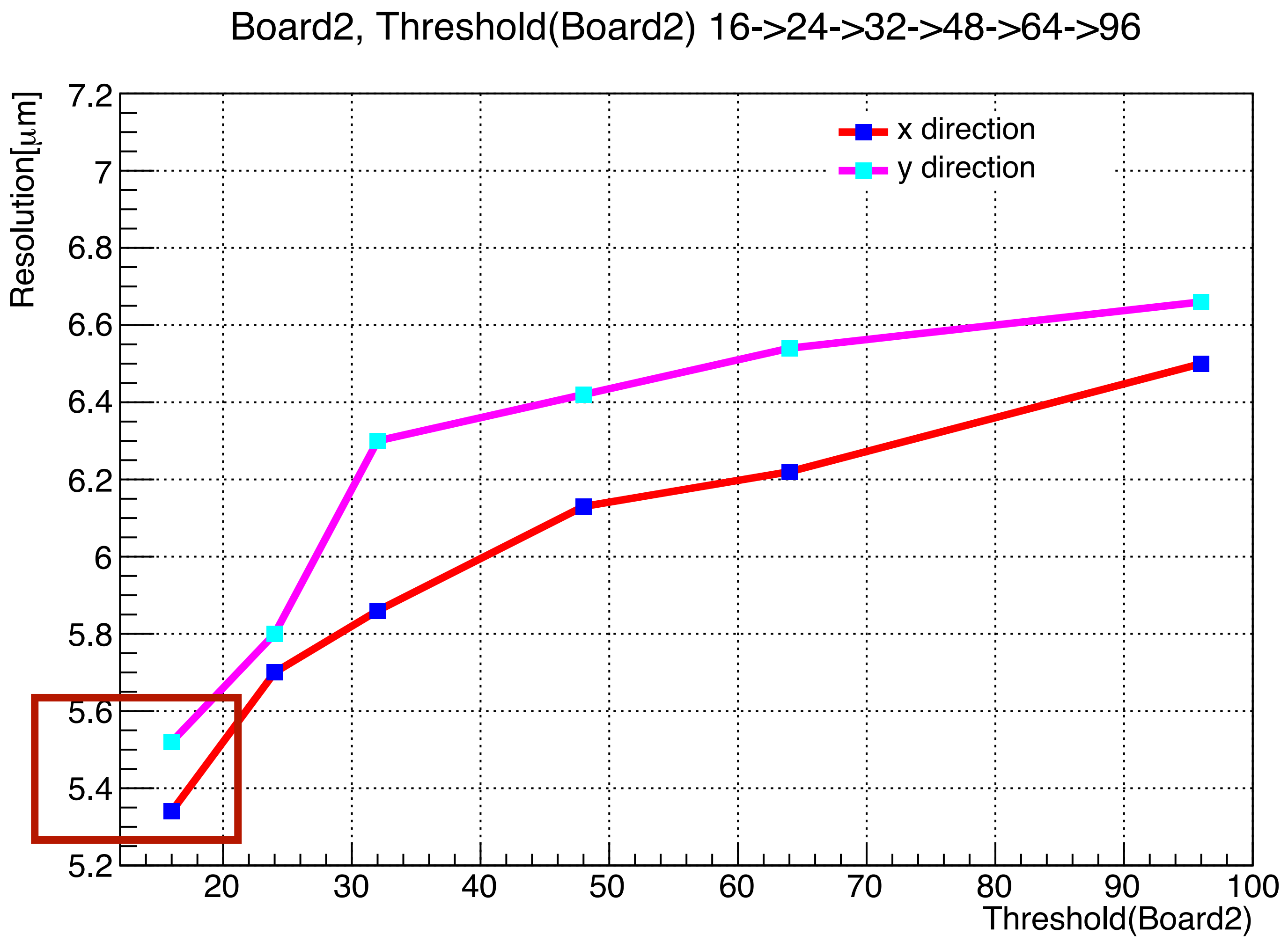


- Board2 with modified technology has a larger depletion layer than Board5 with standard technology
- In general, the higher the threshold, the worse the resolution

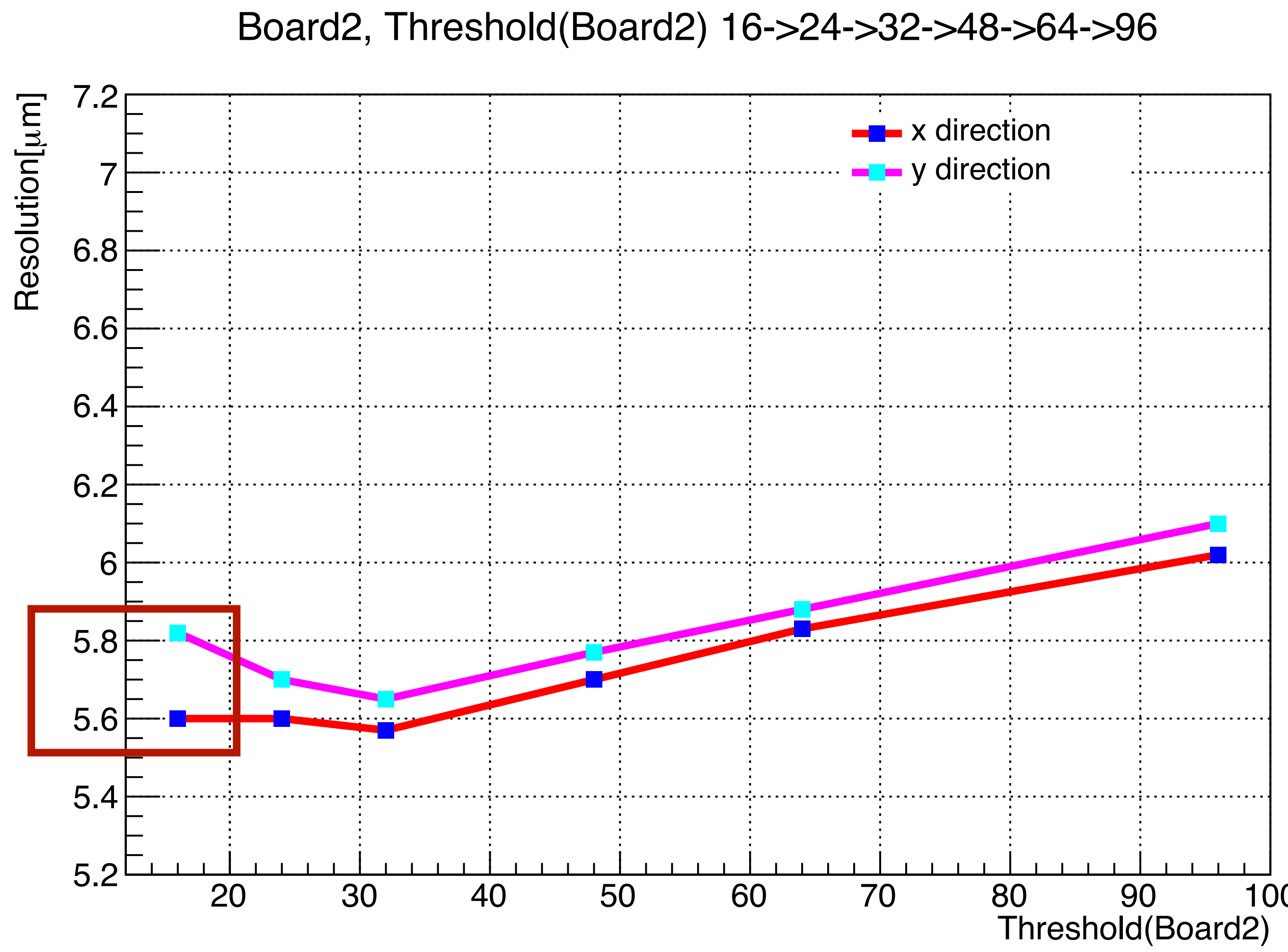
Spatial resolution vs. chip threshold (4GeV) [Comparison of Clustersize = 1 and Clustersize > = 1]

Board2(modified)

ClusterSize == 1

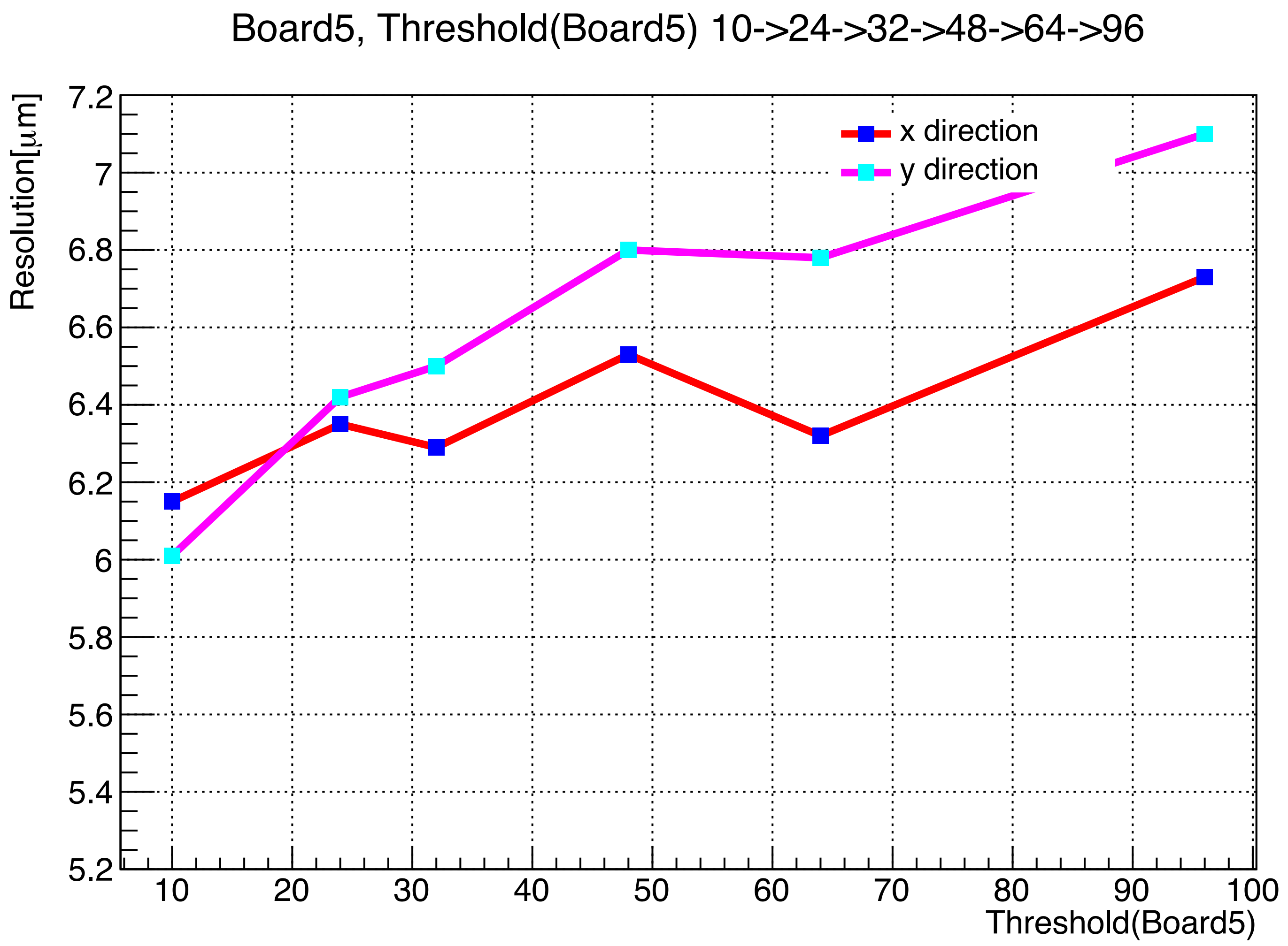


ClusterSize >= 1

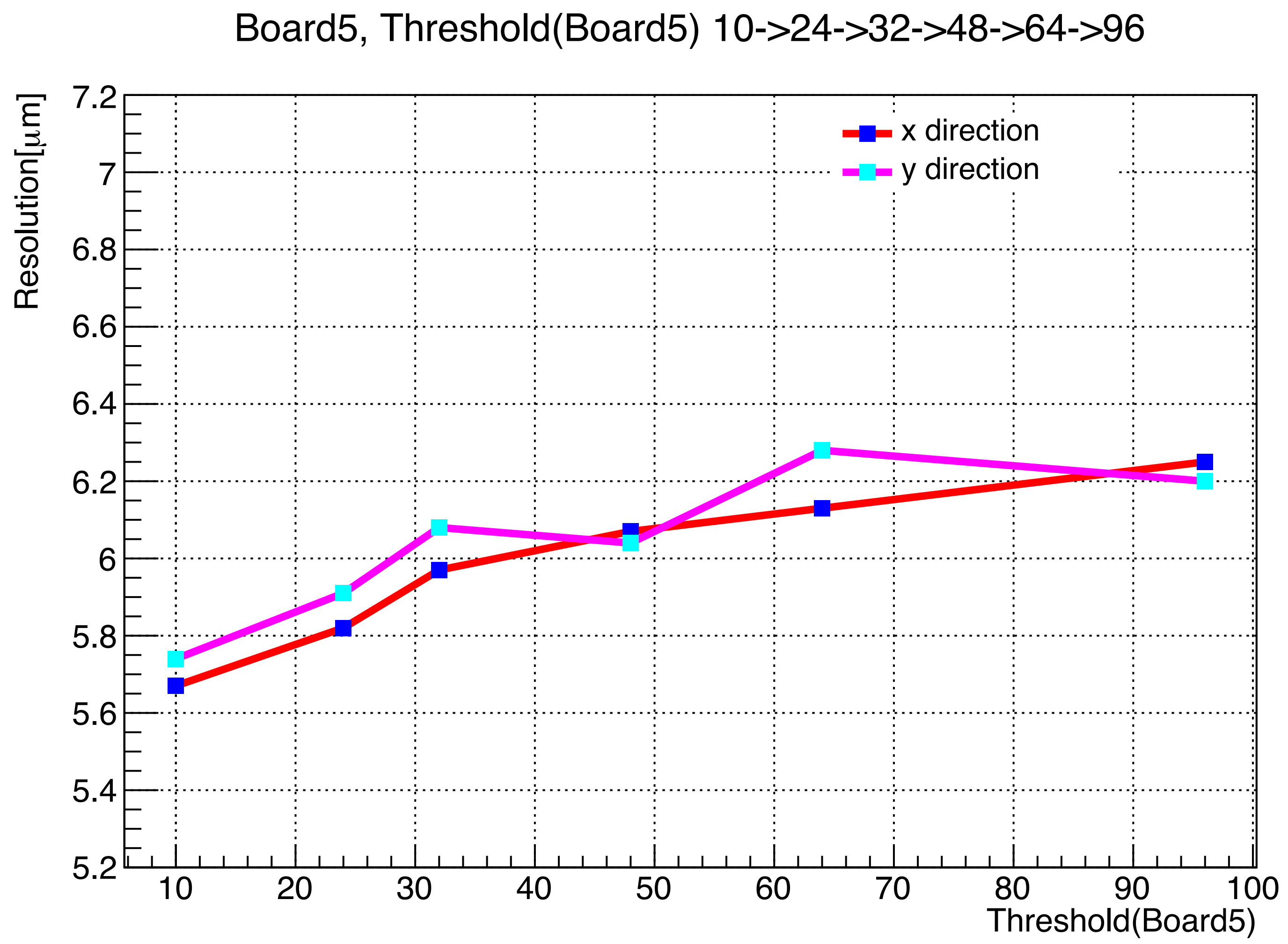


Board5(standard)

ClusterSize == 1



ClusterSize >= 1

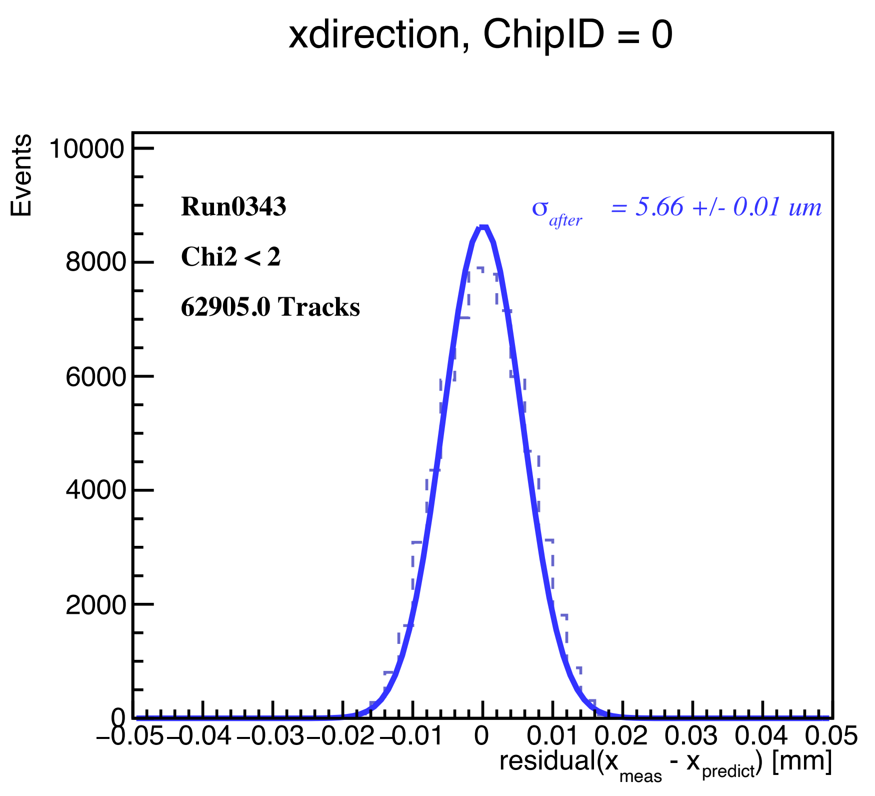


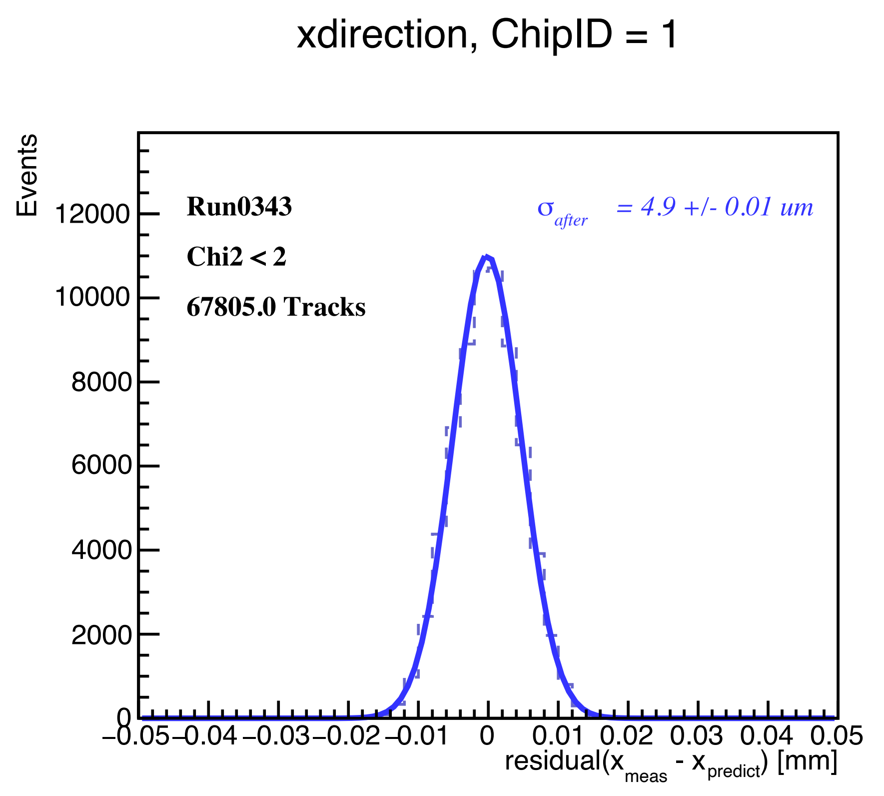
- Board2 with modified technology has a larger depletion layer than Board5 with standard technology
- ClusterSize = 1, only one hit in every cluster of every track (small statistics)
- ClusterSize >= 1, no cut on cluster size
- $\chi^2 < 8$
- Only when the modified chip2 threshold is equal to 16 (minimum threshold), the resolution of single hit is better than the resolution of multi-hit

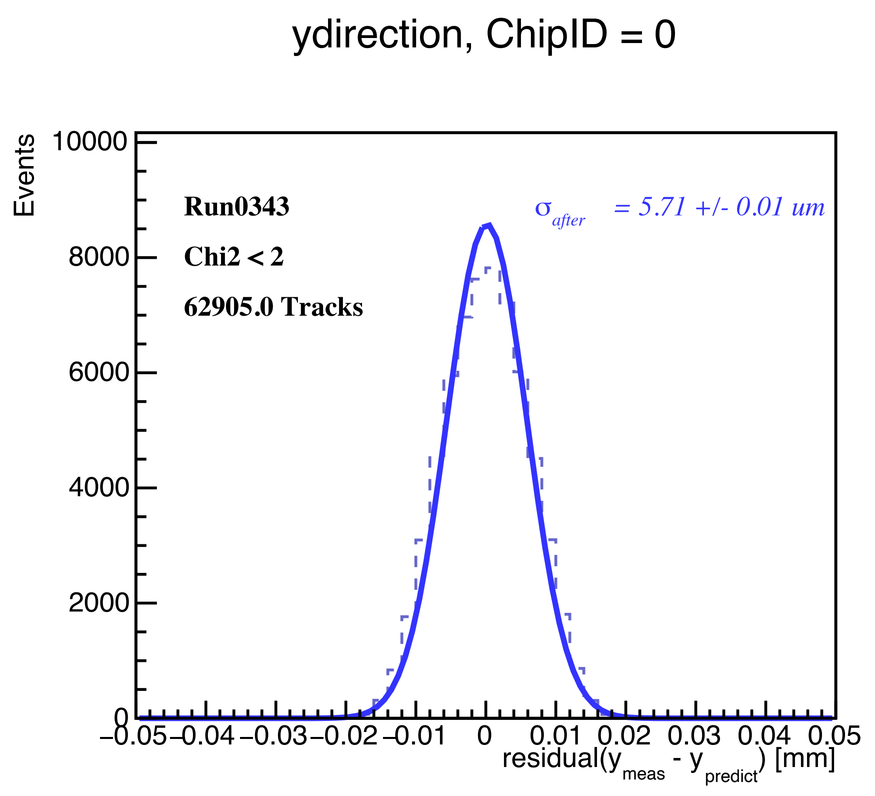
Summary

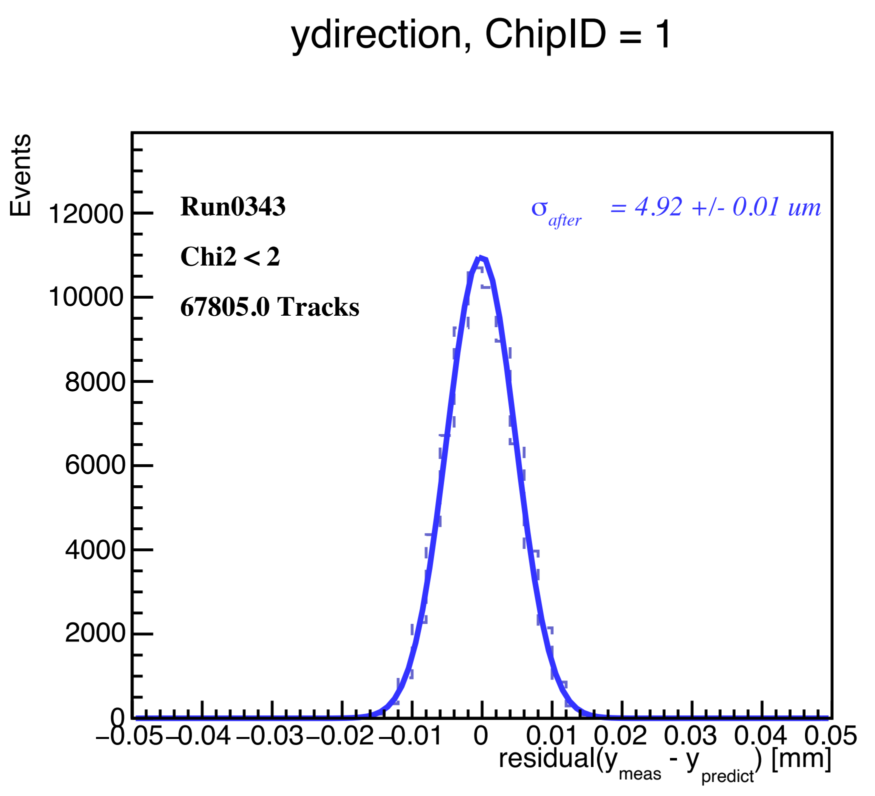
- The offline analysis framework can work well for CEPC vertex detector testbeam data
- The spatial resolution can < 5μm, satisfying MOST2 project index
- Next to do:
  - analyse more test beam data (different beam energy, the resolution of different region of chip...)
  - consider the multi-scattering effects using Kalman fitter

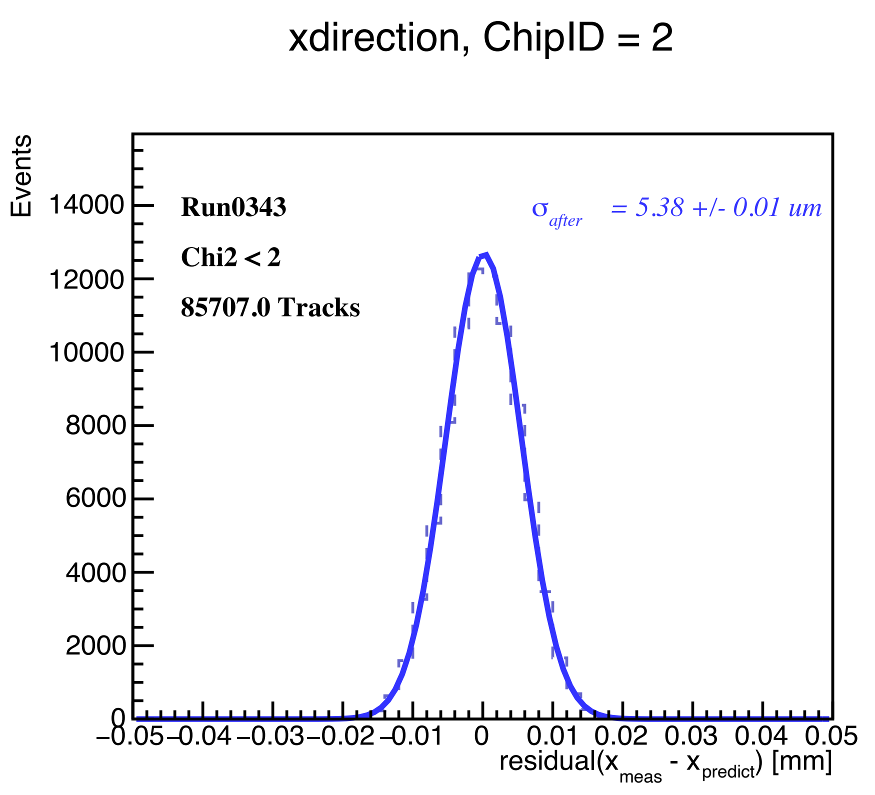
Backup

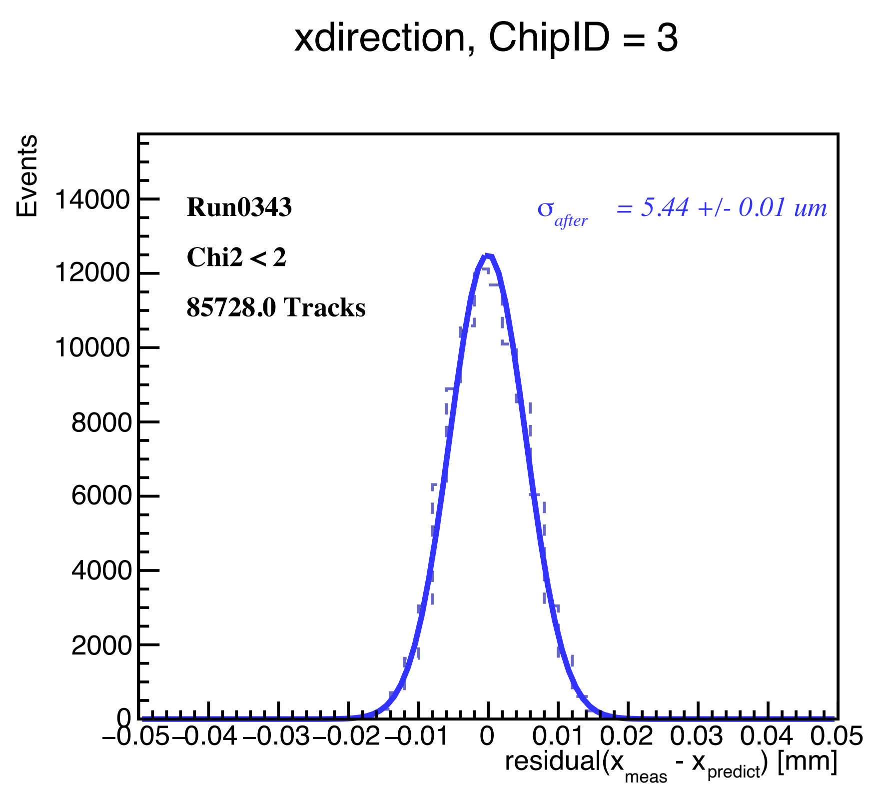

xdirection, ChipID = 0
Run0343
Chi2 < 2
62905.0 Tracks
σ_after = 5.66 +/- 0.01 um
Events
residual(x_meas - x_predict) [mm]

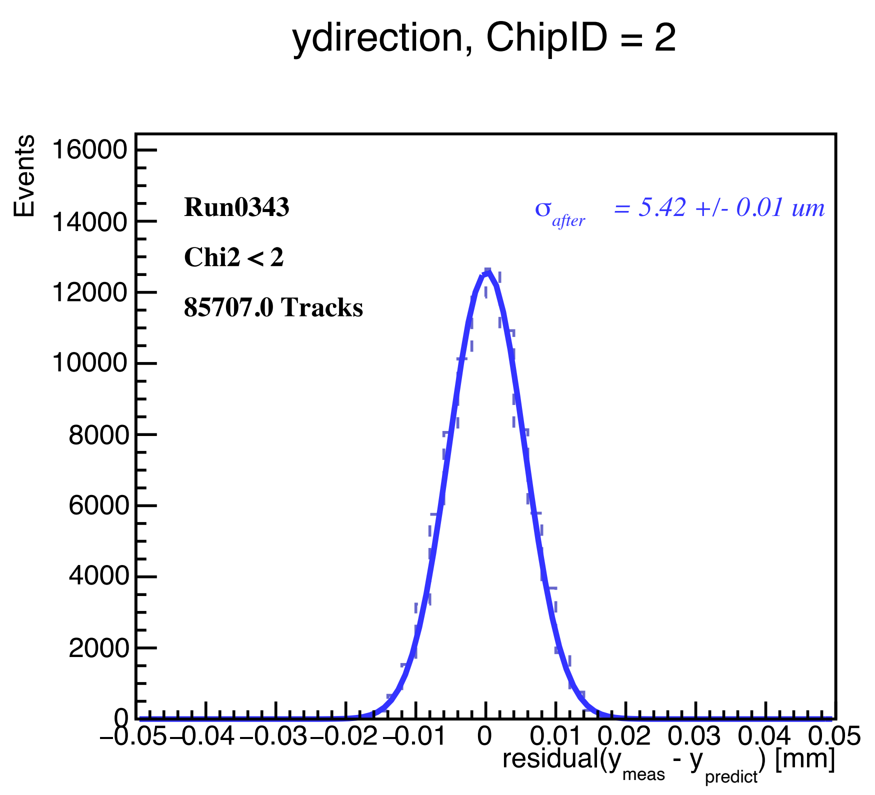

xdirection, ChipID = 1
Run0343
Chi2 < 2
67805.0 Tracks
σ_after = 4.9 +/- 0.01 um
Events
residual(x_meas - x_predict) [mm]

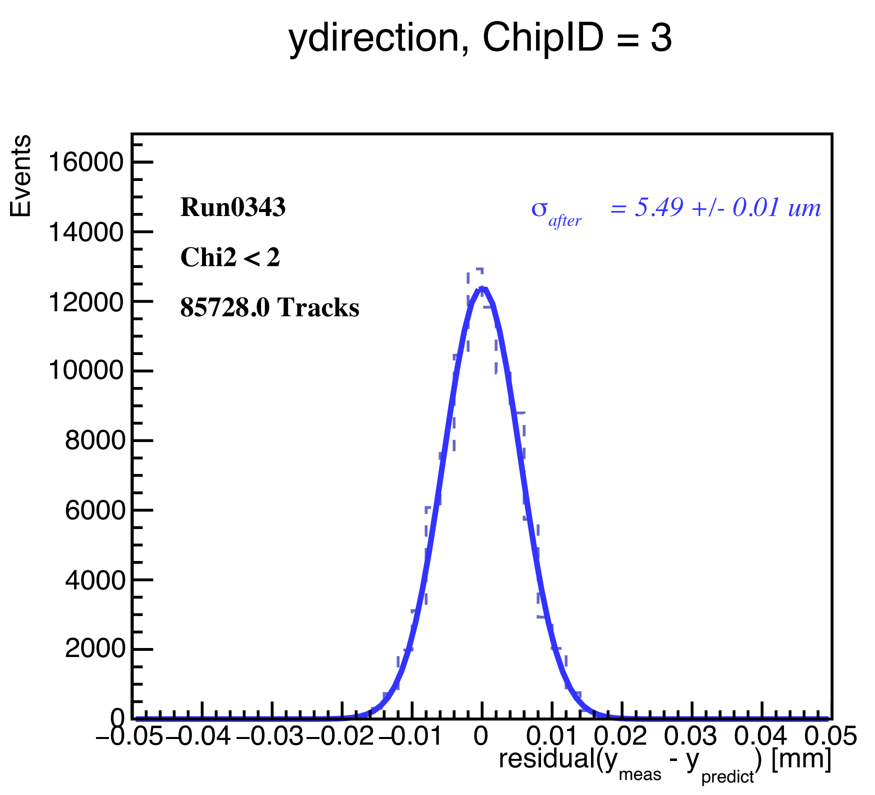

ydirection, ChipID = 0
Run0343
Chi2 < 2
62905.0 Tracks
σ_after = 5.71 +/- 0.01 um
Events
residual(y_meas - y_predict) [mm]

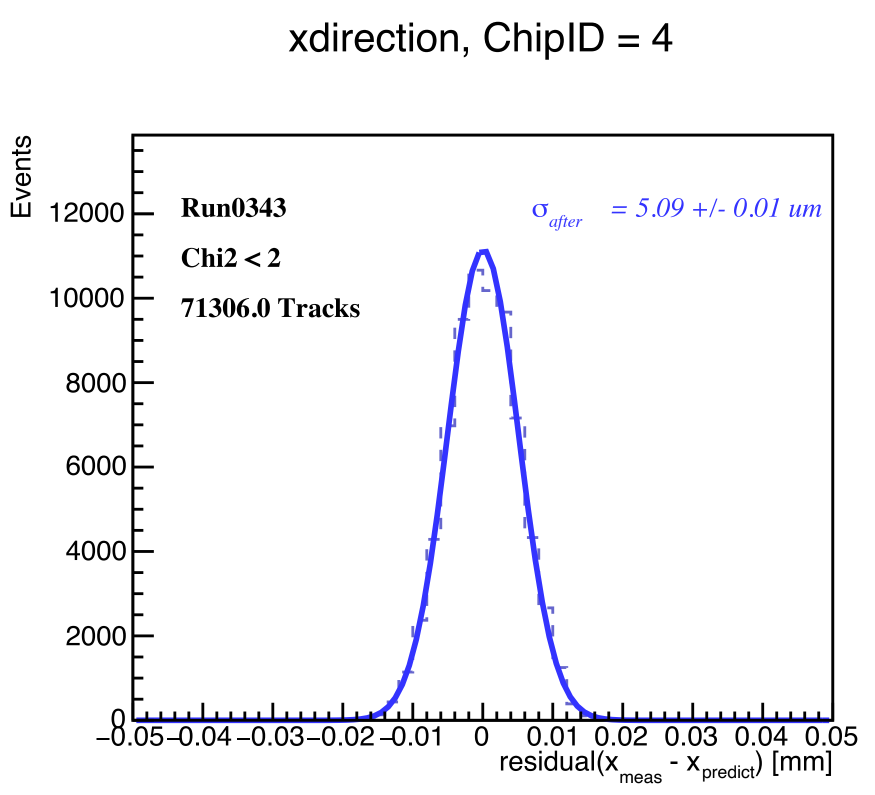

ydirection, ChipID = 1
Run0343
Chi2 < 2
67805.0 Tracks
σ_after = 4.92 +/- 0.01 um
Events
residual(y_meas - y_predict) [mm]

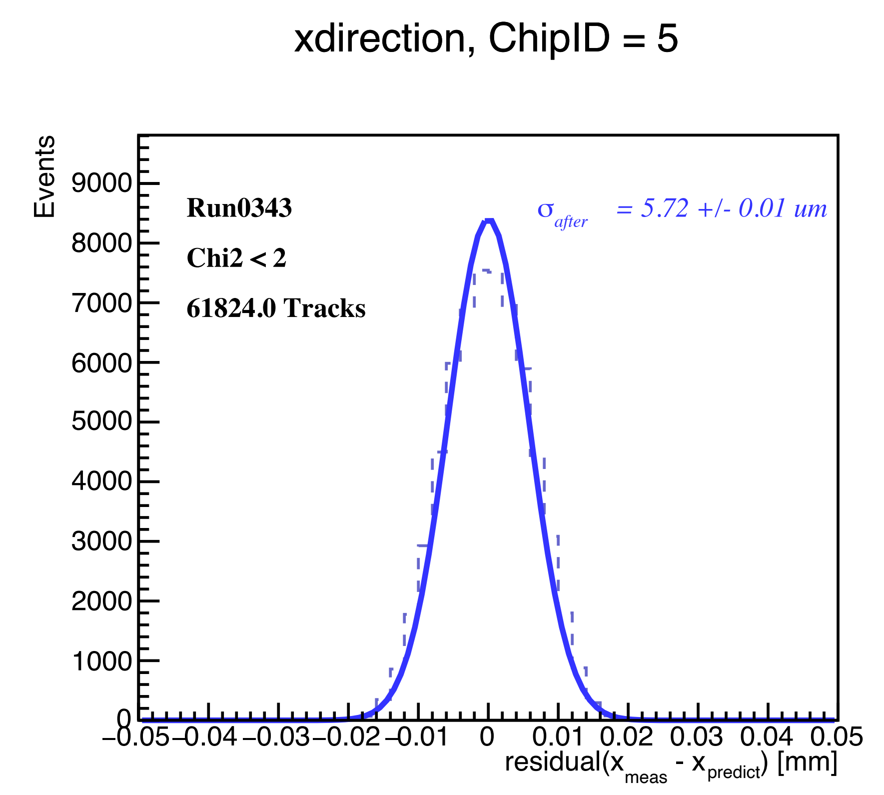

xdirection, ChipID = 2
Run0343
Chi2 < 2
85707.0 Tracks
σ_after = 5.38 +/- 0.01 um
Events
residual(x_meas - x_predict) [mm]

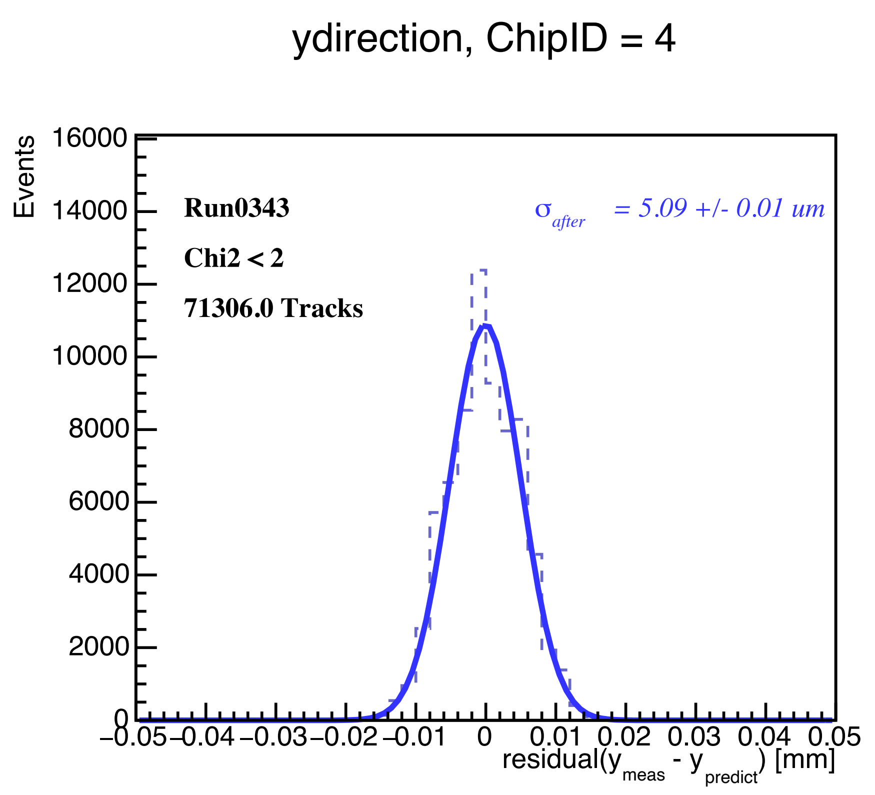

xdirection, ChipID = 3
Run0343
Chi2 < 2
85728.0 Tracks
σ_after = 5.44 +/- 0.01 um
Events
residual(x_meas - x_predict) [mm]

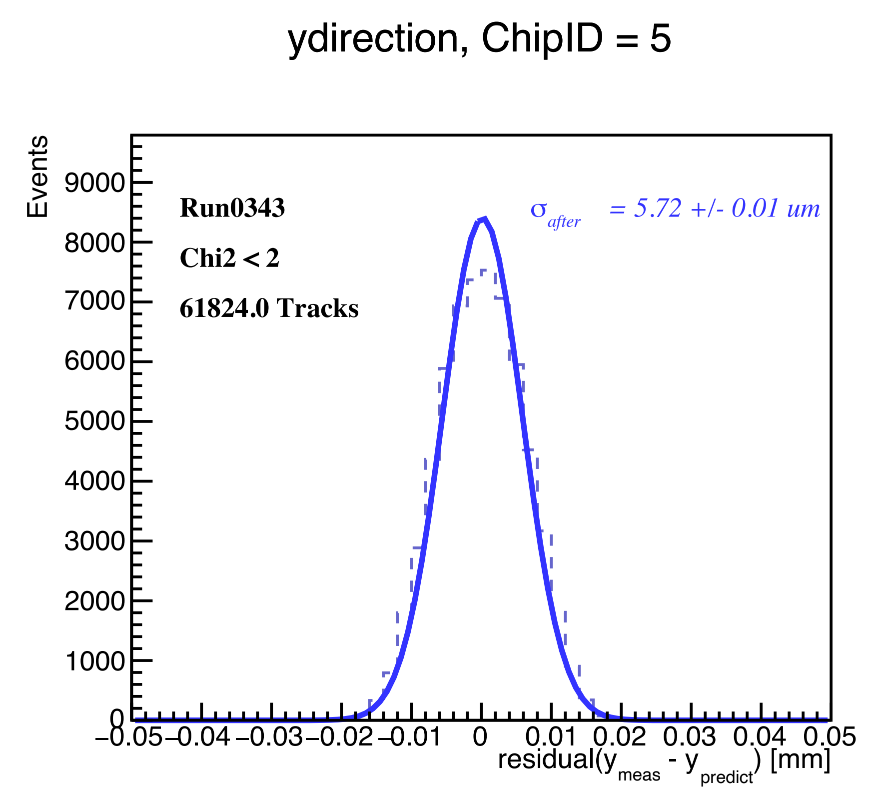

ydirection, ChipID = 2
Run0343
Chi2 < 2
85707.0 Tracks
σ_after = 5.42 +/- 0.01 um
Events
residual(y_meas - y_predict) [mm]

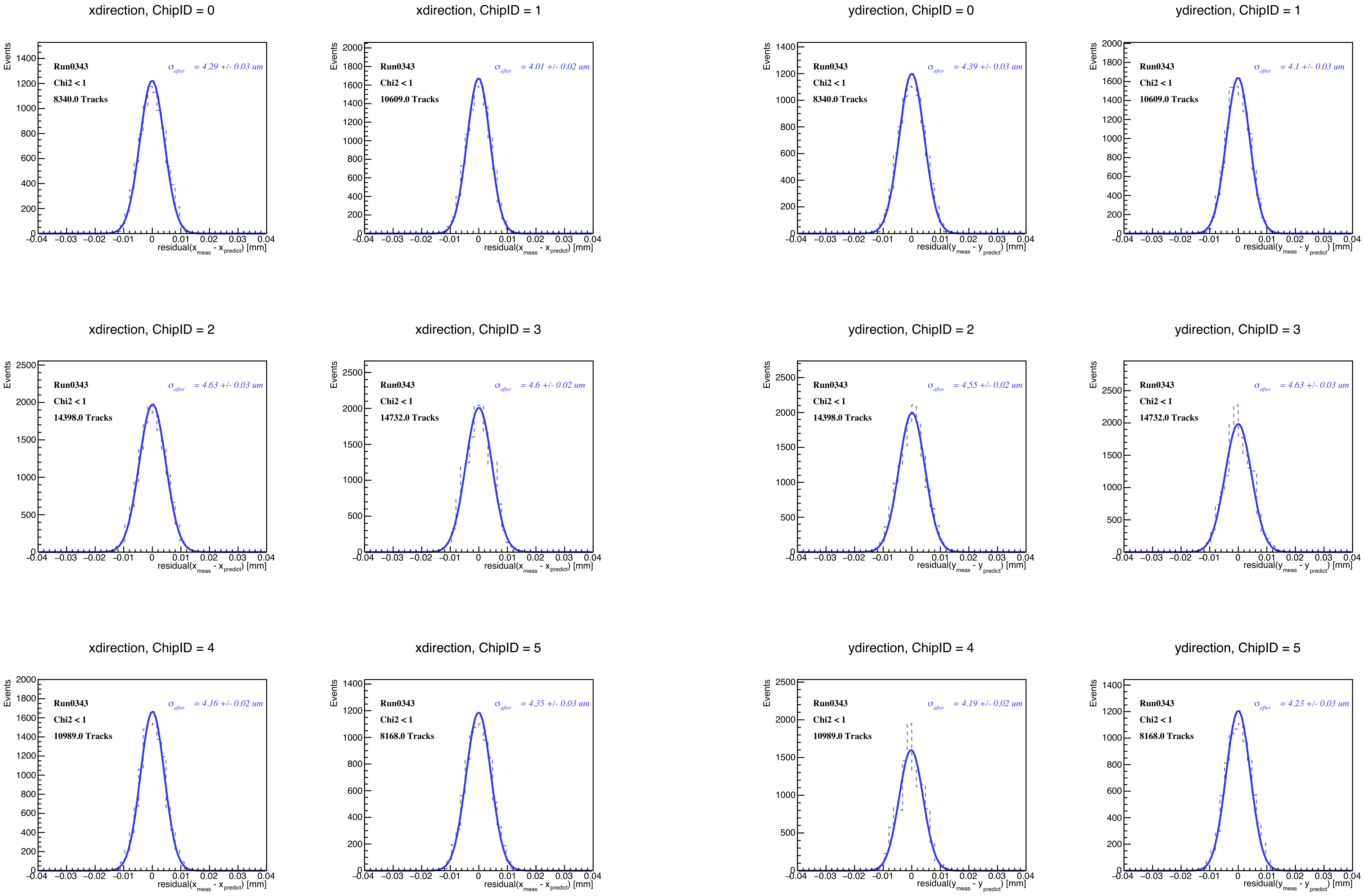

ydirection, ChipID = 3
Run0343
Chi2 < 2
85728.0 Tracks
σ_after = 5.49 +/- 0.01 um
Events
residual(y_meas - y_predict) [mm]


xdirection, ChipID = 4
Run0343
Chi2 < 2
71306.0 Tracks
σ_after = 5.09 +/- 0.01 um
Events
residual(x_meas - x_predict) [mm]

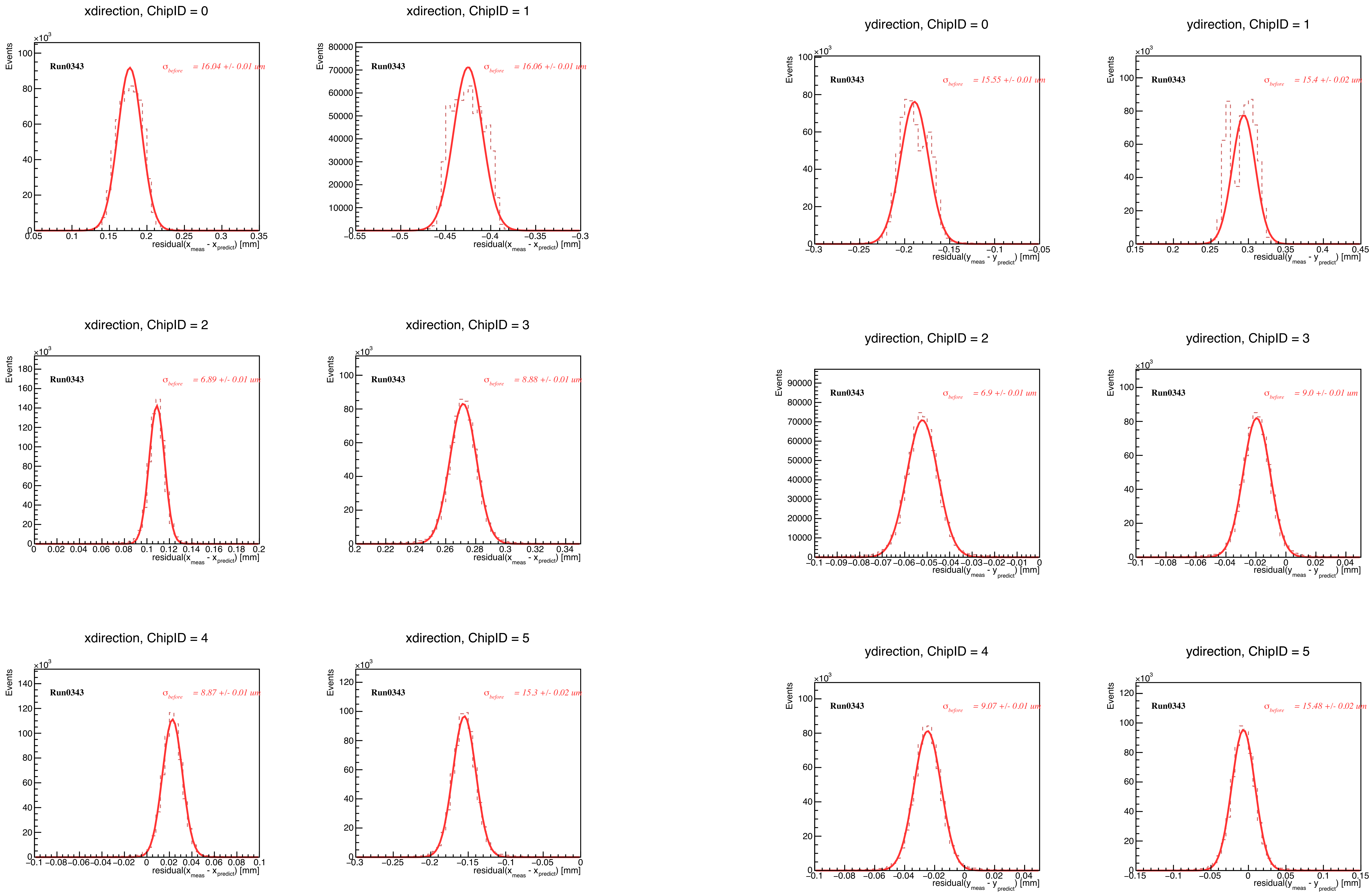

xdirection, ChipID = 5
Run0343
Chi2 < 2
61824.0 Tracks
σ_after = 5.72 +/- 0.01 um
Events
residual(x_meas - x_predict) [mm]


ydirection, ChipID = 4
Run0343
Chi2 < 2
71306.0 Tracks
σ_after = 5.09 +/- 0.01 um
Events
residual(y_meas - y_predict) [mm]


ydirection, ChipID = 5
Run0343
Chi2 < 2
61824.0 Tracks
σ_after = 5.72 +/- 0.01 um
Events
residual(y_meas - y_predict) [mm]



xdirection, ChipID = 0
Run0343
Chi2 < 1
8340.0 Tracks
σ_after = 4.29 +/- 0.03 um
xdirection, ChipID = 1
Run0343
Chi2 < 1
10609.0 Tracks
σ_after = 4.01 +/- 0.02 um
ydirection, ChipID = 0
Run0343
Chi2 < 1
8340.0 Tracks
σ_after = 4.39 +/- 0.03 um
ydirection, ChipID = 1
Run0343
Chi2 < 1
10609.0 Tracks
σ_after = 4.1 +/- 0.03 um
xdirection, ChipID = 2
Run0343
Chi2 < 1
14398.0 Tracks
σ_after = 4.63 +/- 0.03 um
xdirection, ChipID = 3
Run0343
Chi2 < 1
14732.0 Tracks
σ_after = 4.6 +/- 0.02 um
ydirection, ChipID = 2
Run0343
Chi2 < 1
14398.0 Tracks
σ_after = 4.55 +/- 0.02 um
ydirection, ChipID = 3
Run0343
Chi2 < 1
14732.0 Tracks
σ_after = 4.63 +/- 0.03 um
xdirection, ChipID = 4
Run0343
Chi2 < 1
10989.0 Tracks
σ_after = 4.16 +/- 0.02 um
xdirection, ChipID = 5
Run0343
Chi2 < 1
8168.0 Tracks
σ_after = 4.35 +/- 0.03 um
ydirection, ChipID = 4
Run0343
Chi2 < 1
10989.0 Tracks
σ_after = 4.19 +/- 0.02 um
ydirection, ChipID = 5
Run0343
Chi2 < 1
8168.0 Tracks
σ_after = 4.23 +/- 0.03 um
Events
residual(x_meas - x_predict) [mm]
residual(y_meas - y_predict) [mm]



xdirection, ChipID = 0
Run0343
σ_before = 16.04 +/- 0.01 um
xdirection, ChipID = 1
Run0343
σ_before = 16.06 +/- 0.01 um
ydirection, ChipID = 0
Run0343
σ_before = 15.55 +/- 0.01 um
ydirection, ChipID = 1
Run0343
σ_before = 15.4 +/- 0.02 um
xdirection, ChipID = 2
Run0343
σ_before = 6.89 +/- 0.01 um
xdirection, ChipID = 3
Run0343
σ_before = 8.88 +/- 0.01 um
ydirection, ChipID = 2
Run0343
σ_before = 6.9 +/- 0.01 um
ydirection, ChipID = 3
Run0343
σ_before = 9.0 +/- 0.01 um
xdirection, ChipID = 4
Run0343
σ_before = 8.87 +/- 0.01 um
xdirection, ChipID = 5
Run0343
σ_before = 15.3 +/- 0.02 um
ydirection, ChipID = 4
Run0343
σ_before = 9.07 +/- 0.01 um
ydirection, ChipID = 5
Run0343
σ_before = 15.48 +/- 0.02 um
Events
residual(x_meas - x_predict) [mm]
residual(y_meas - y_predict) [mm]

The first step in the characterization of the telescope as a tracking device was the measurement of the intrinsic resolution of the reference planes and the ultimate spatial resolution achievable combining all the hits into a track. The single plane resolution (σ_{DUT}) can be obtained from the measured residual width (σ_{meas}) and the telescope resolution (σ_{tel}) using Eq. (1)

$$\sigma^2_{\mathrm{meas}} = \sigma^2_{\mathrm{DUT}} + \sigma^2_{\mathrm{tel}} \tag{1}$$

The telescope resolution can be determined assuming that the reference planes all have the same intrinsic resolution using Eq. (2)

$$\sigma^2_{\mathrm{tel}} = k\sigma^2_{\mathrm{plane}} \tag{2a}$$

and

$$k = \frac{\sum_i^N z_i^2}{N\sum_i^N z_i^2 - (\sum_i^N z_i)^2} \tag{2b}$$

The formula for the geometrical scaling factor k defined in (2b) is based on the assumption that the DUT is positioned at $z=0$ and it reduces to $1/N$ if the reference planes are is symmetrically distributed around the DUT and the beam and telescope axes are parallel.

Efficiency

Run0323:

B2= W9R5 iTHR 64 ; B1 W2R3 ITHR 16 ; B3 W2R11 iTHR 16 ; B4 W9R6 ITHR32 ; B5 W2R29 ITHR10 ; B6 W2R12 ITHR16 ; Beam 4GeV

res k\Eff	1	2	3	4	5	6
1	0.98965	0.988425	0.986256	0.983358	0.990203	0.99068
2	0.996714	0.996881	0.997556	0.996325	0.997515	0.996402
3	0.997881	0.998177	0.998849	0.998072	0.998726	0.997648

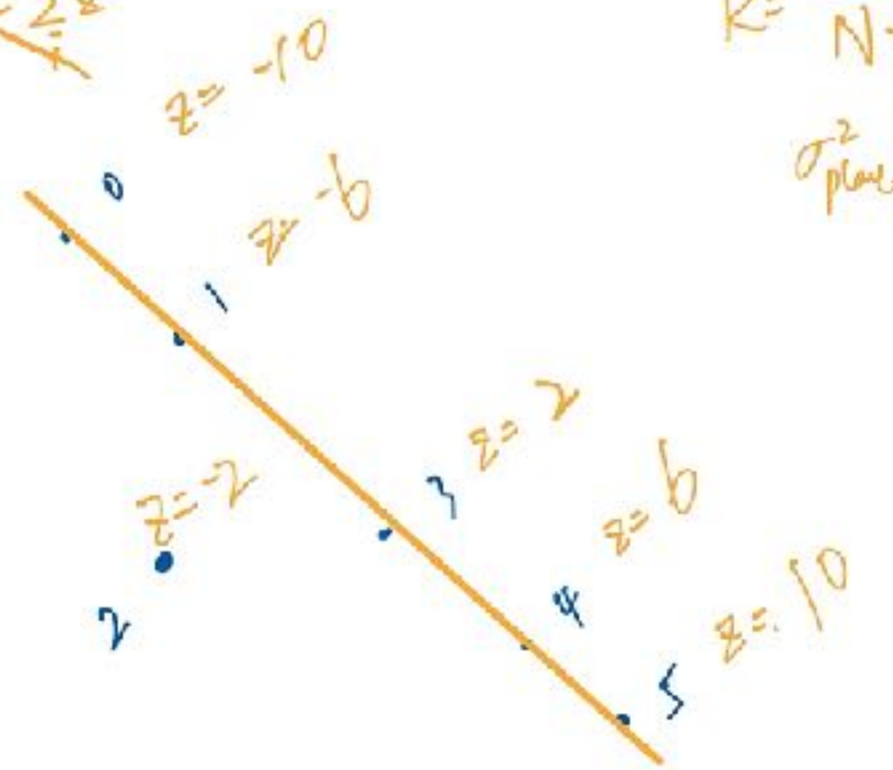
Run0324:

B2= W9R5 iTHR 64 ; B1 W2R3 ITHR 16 ; B3 W2R11 iTHR 16 ; B4 W9R6 ITHR32 ; B5 W2R29 ITHR24 ; B6 W2R12 ITHR16 ; Beam 4GeV

res k\Eff	1	2	3	4	5	6
1	0.989897	0.988696	0.986532	0.984041	0.989403	0.990067
2	0.996957	0.996826	0.997578	0.996378	0.997366	0.996201
3	0.998074	0.998126	0.998833	0.997983	0.998651	0.997496

$$k = \frac{1}{N - \frac{(\sum_i^N z_i)^2}{\sum_i^N z_i^2}} = \frac{1}{N}$$

~~$k = \frac{1}{N - \sum_i^N z}$~~



planeID=0. $\sum_i^N z_i^2 = 6^2+2^2+2^2+6^2+10^2 = 180$

$(\sum_i^N z_i)^2 = (-6-2+2+6+10)^2 = 100$

$$K = \frac{1}{N - \frac{100}{180}} = \frac{1}{5-0.55} = \frac{1}{4.44}$$

$$\sigma_{plane}^2 = \frac{1}{1+\frac{1}{4.44}}\sigma_{meas}^2 = \frac{4.44}{5.44}\sigma_{meas}^2$$

$$= 0.816\,\sigma_{meas}^2$$

$$\sigma = 0.903\,\sigma_{meas}$$

$k = \frac{1}{5}$ $\sigma_{tel}^2 = \frac{\frac{1}{5}}{1+\frac{1}{5}} = \frac{\frac{1}{5}}{\frac{6}{5}} = \frac{1}{5}\times\frac{5}{6} = \frac{1}{6}$ $\sigma_{tel}^2 = \frac{1}{6}\cdot\sigma_{meas}^2$ $\sigma_{tel} = \frac{1}{\sqrt{6}}\sigma_{meas}$

$= 0.408\,\sigma_{meas}$.

planeID=1 $\sum_i z_i^2 = 10^2+2^2+2^2+6^2+10^2 = 244$

$(\sum_i (z))^2 = (-10-2+2+6+10)^2 = 36$

$$k = \frac{1}{5 - \frac{36}{244}} = \frac{1}{5-0.147} = \frac{1}{4.853}$$

$$\frac{1}{1+\frac{1}{4.853}} = \frac{4.853}{5.853} = \sqrt{0.829} = 0.910$$

planeID=2 $\sum_i z_i^2 = 10^2+6^2+2^2+6^2+10^2 = 276$

$(\sum_i z)^2 = (-10-6+2+6+10)^2 = 4$

$$k = \frac{1}{5 - \frac{4}{276}} = \frac{1}{5-0.145} = \frac{1}{4.99}$$

$$\frac{1}{1+\frac{1}{4.99}} = \frac{4.99}{5.99} = \sqrt{0.833} = 0.912688$$