The Measurement of Position Resolution of RD53A Pixel Modules

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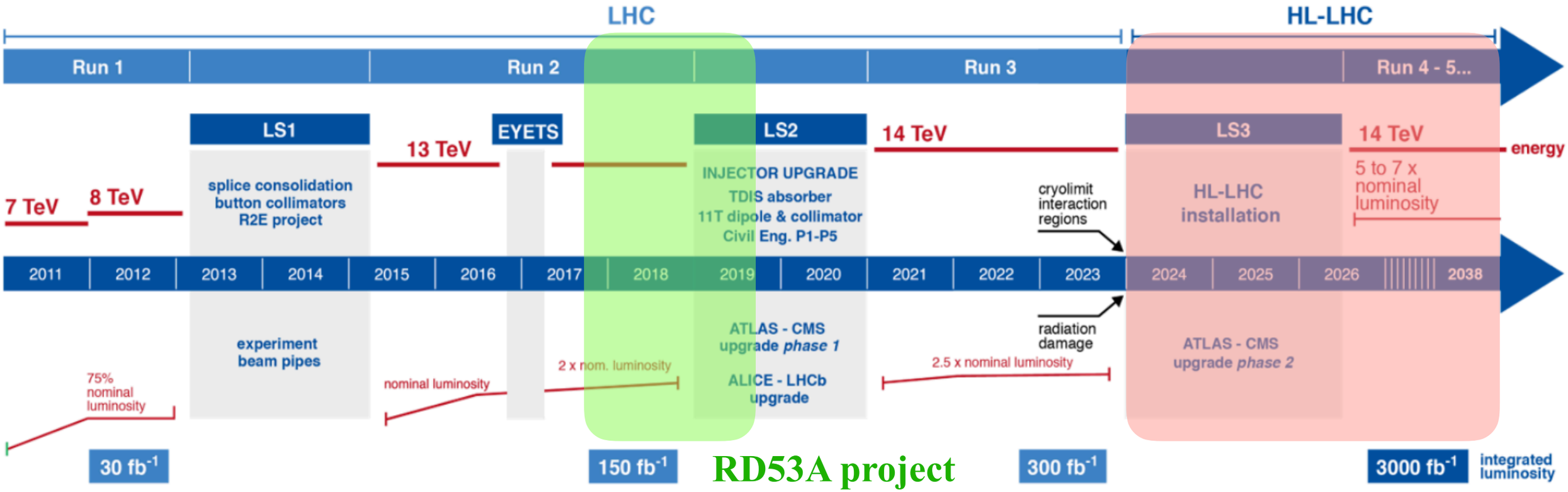
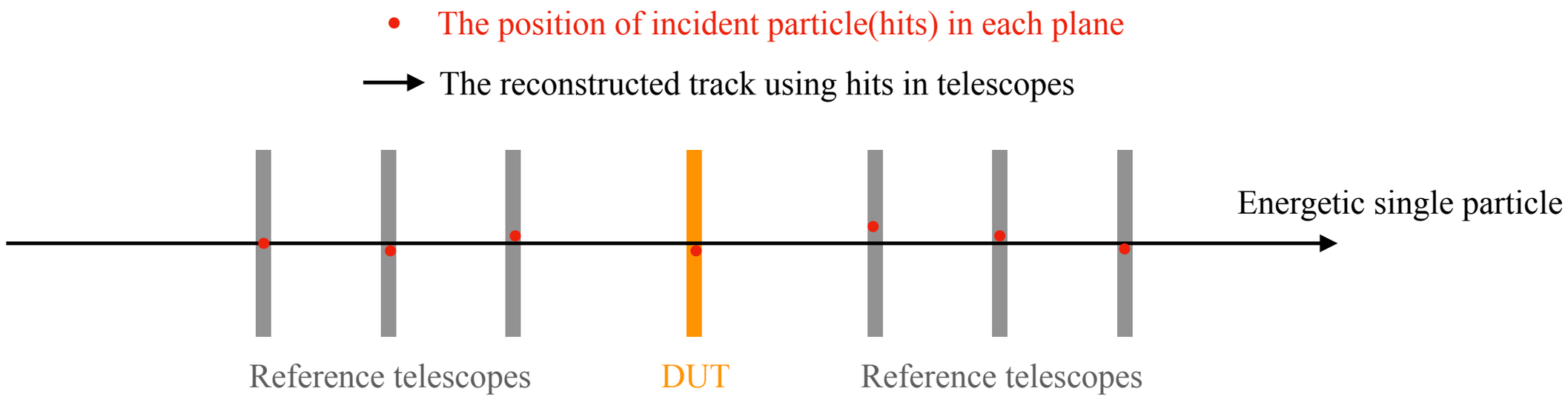
RD53A pixel modules



RD53A project

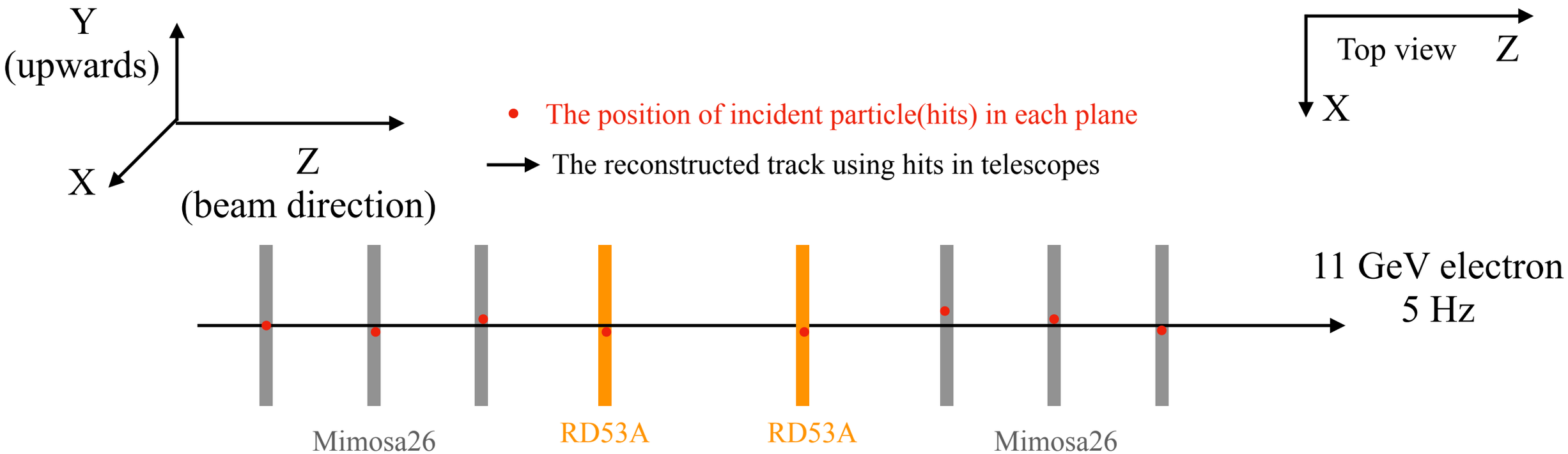
- Pixel detector upgraded for HL-LHC upgrades of ATLAS and CMS
- Demonstrate the suitability of the chosen 65nm CMOS technology
- Only for testing, forms the basis for the production designs

Testbeam setup



- The testbeam determines how devices under test (DUT) respond to a single particle passing through the active area
- Sensors in reference telescopes have better position resolution than DUTs
- Use hits in telescopes to reconstruct the track, and extract position resolution of DUT from the difference between track position and hit position on DUT

Testbeam at SLAC

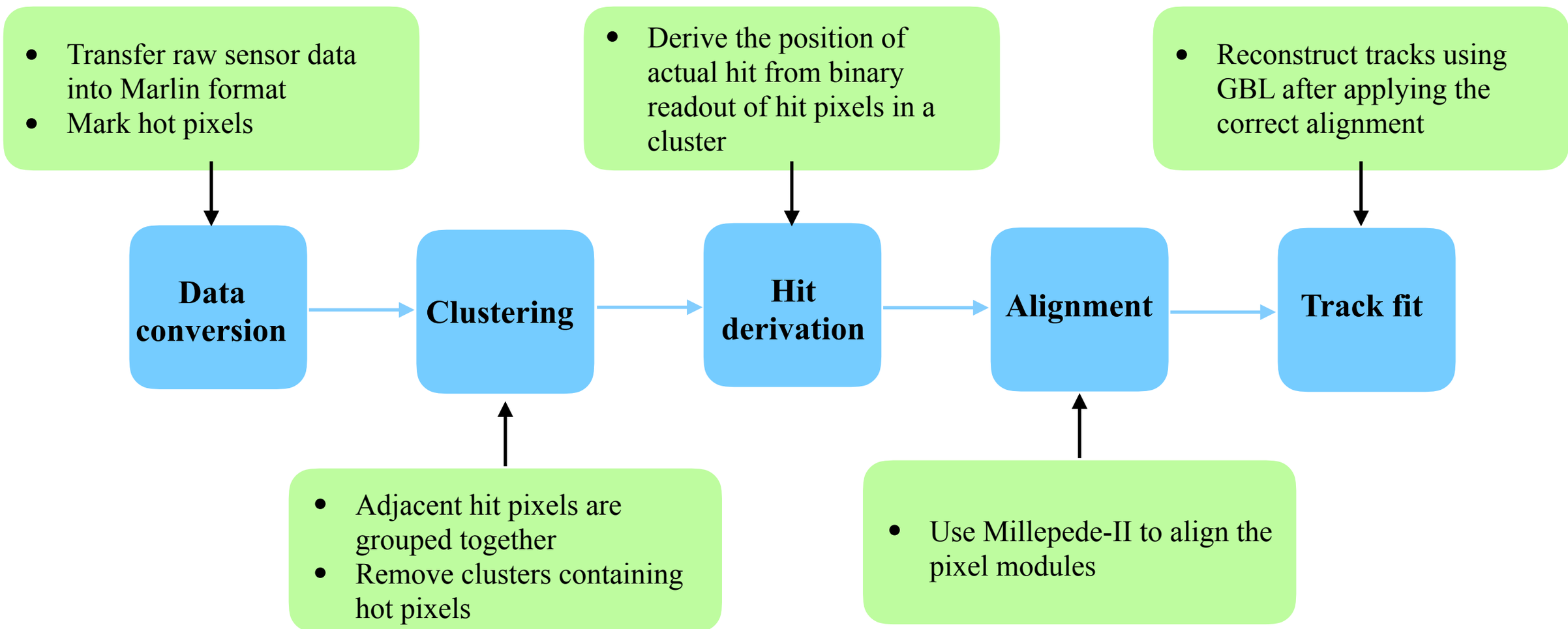


- Testbeam data is collected in November 2018 at SLAC
- Reference telescopes: Mimosa26 with 18.4μm×18.4μm pixel
- Two different device under test (DUTs): RD53A modules
  - ★ 50μm×50μm pixel
  - ★ 100μm×25μm pixel
- Data is collected by YARR (https://github.com/Yarr/Yarr)

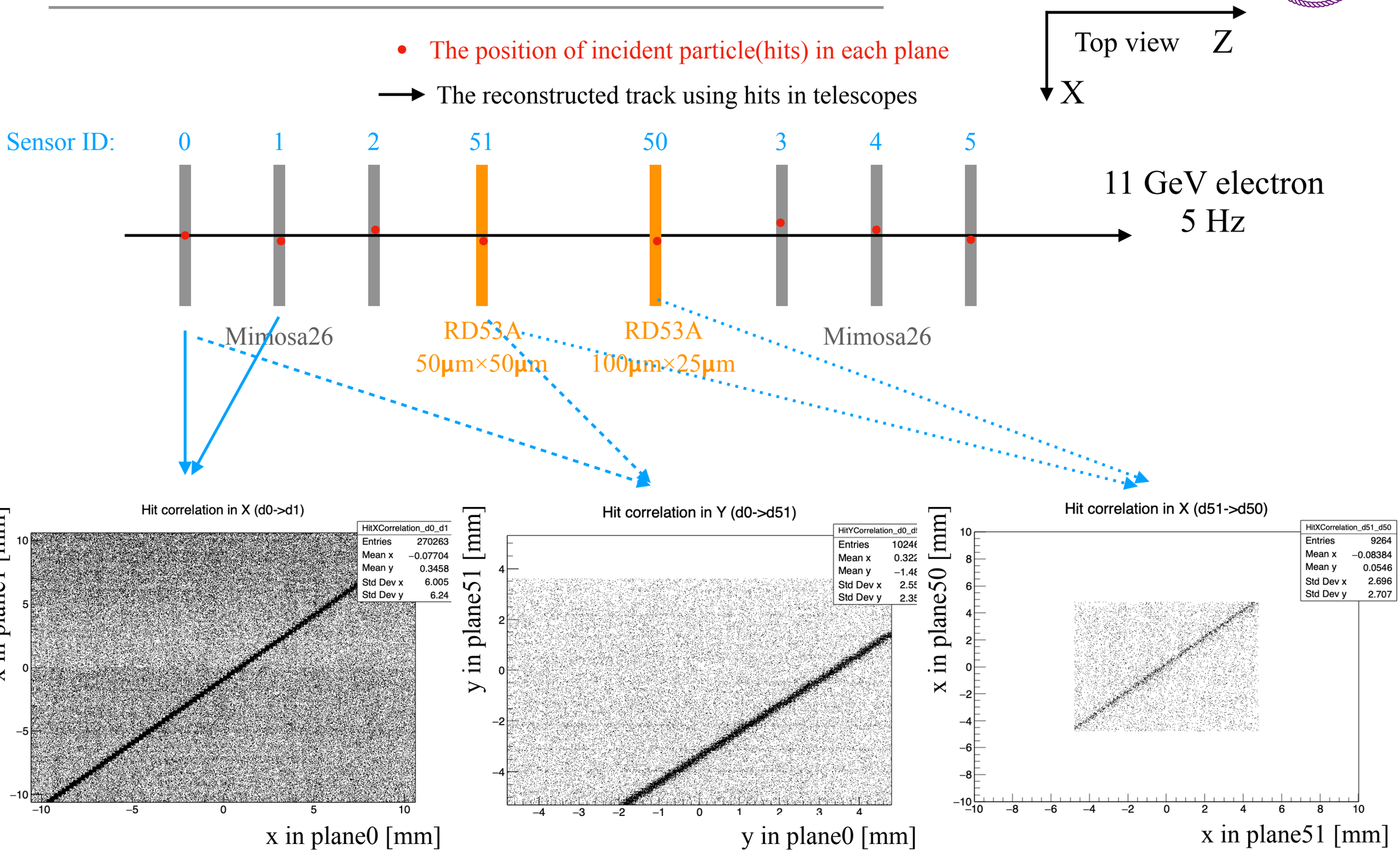
The Offline testbeam analysis

- **EUTelescope v2.0.0** is a very generic and versatile collection of **Marlin(Modular Analysis & Reconstruction for the Linear Collider)** processors, dedicated to processing of testbeam data

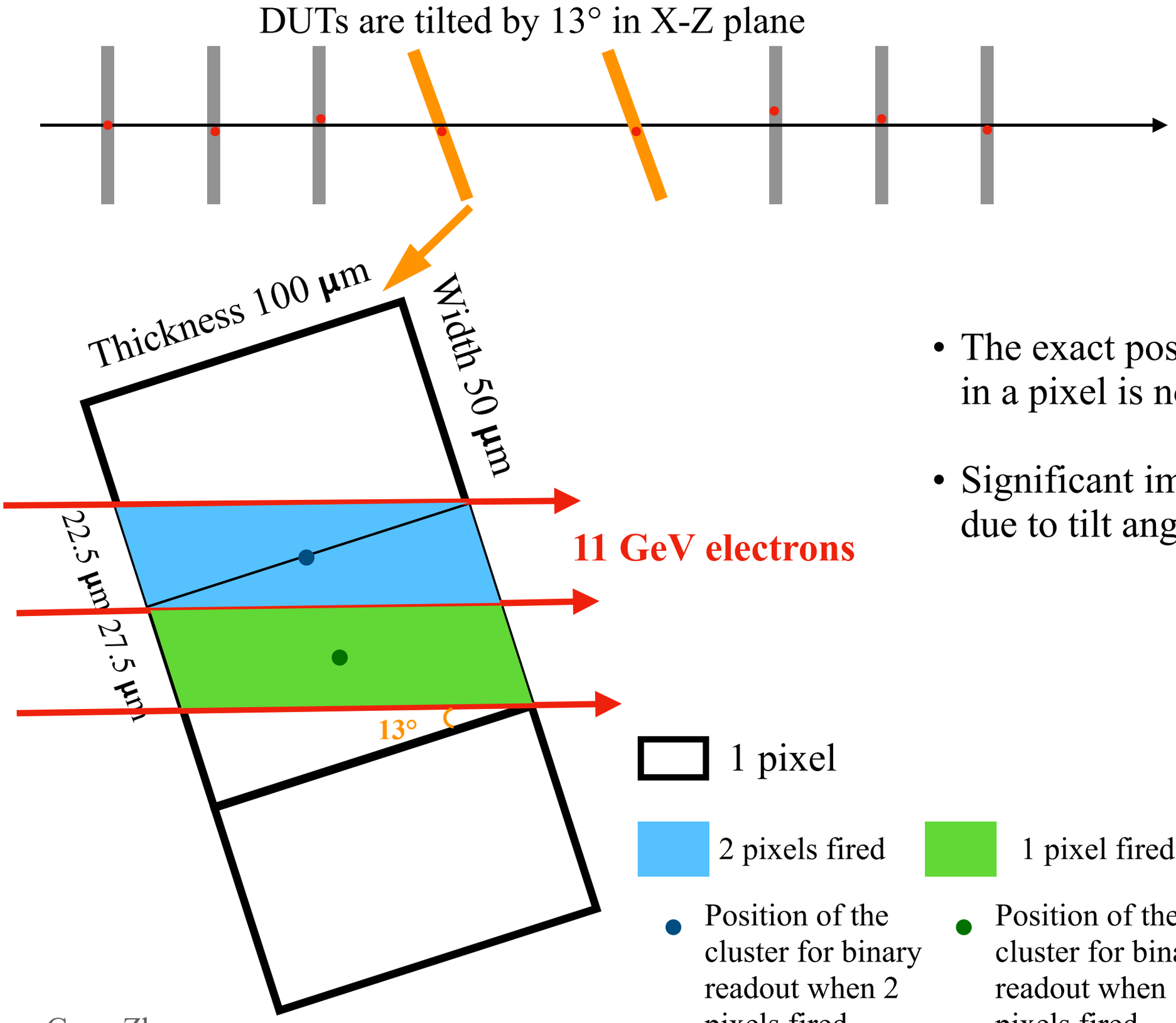
- Track reconstruction algorithm: General Broken Lines(GBL) fitter (https://www.terascale.de/wiki/generalbrokenlines/)



Correlation of hits between 2 planes

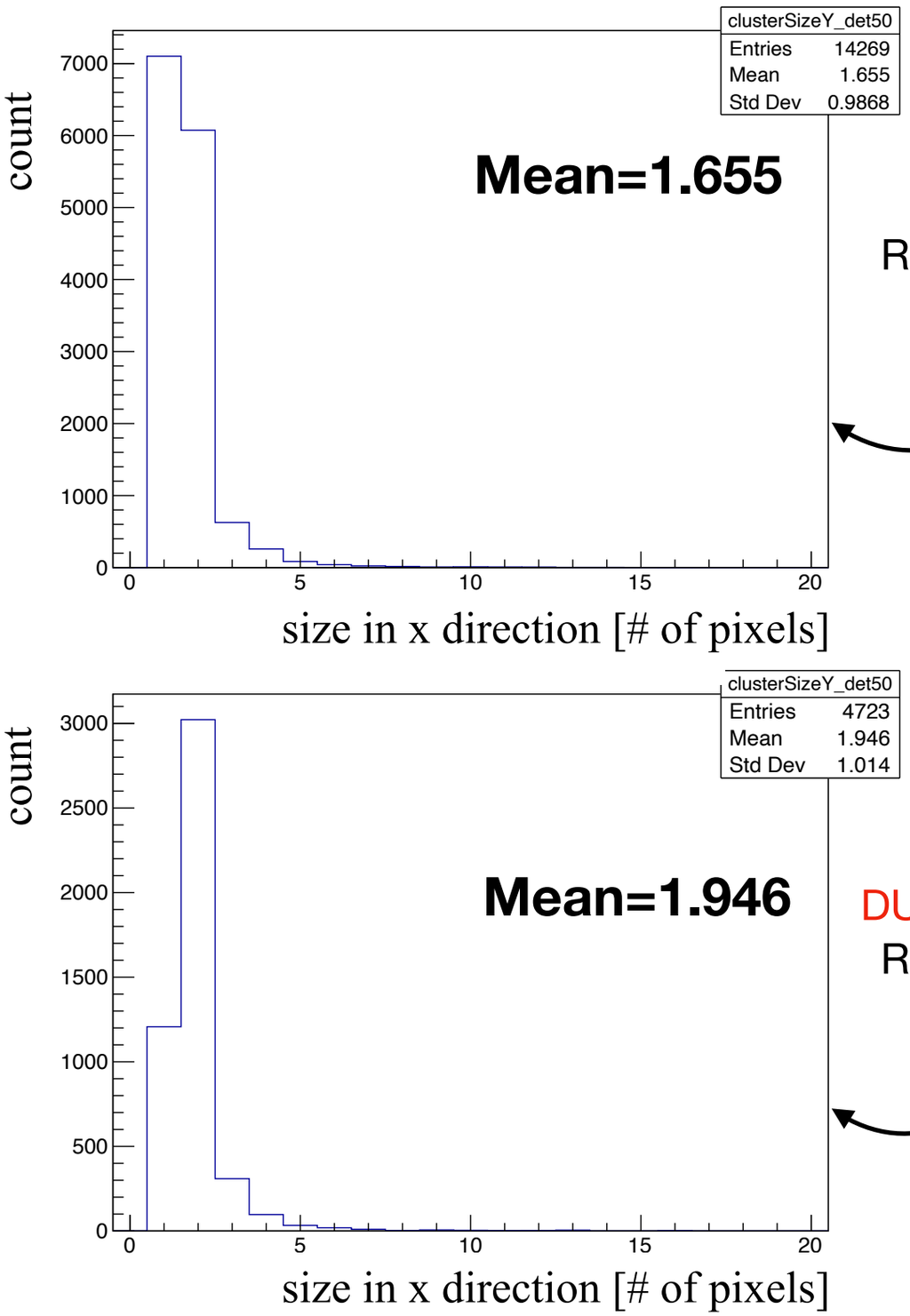


Effect from tilt angle



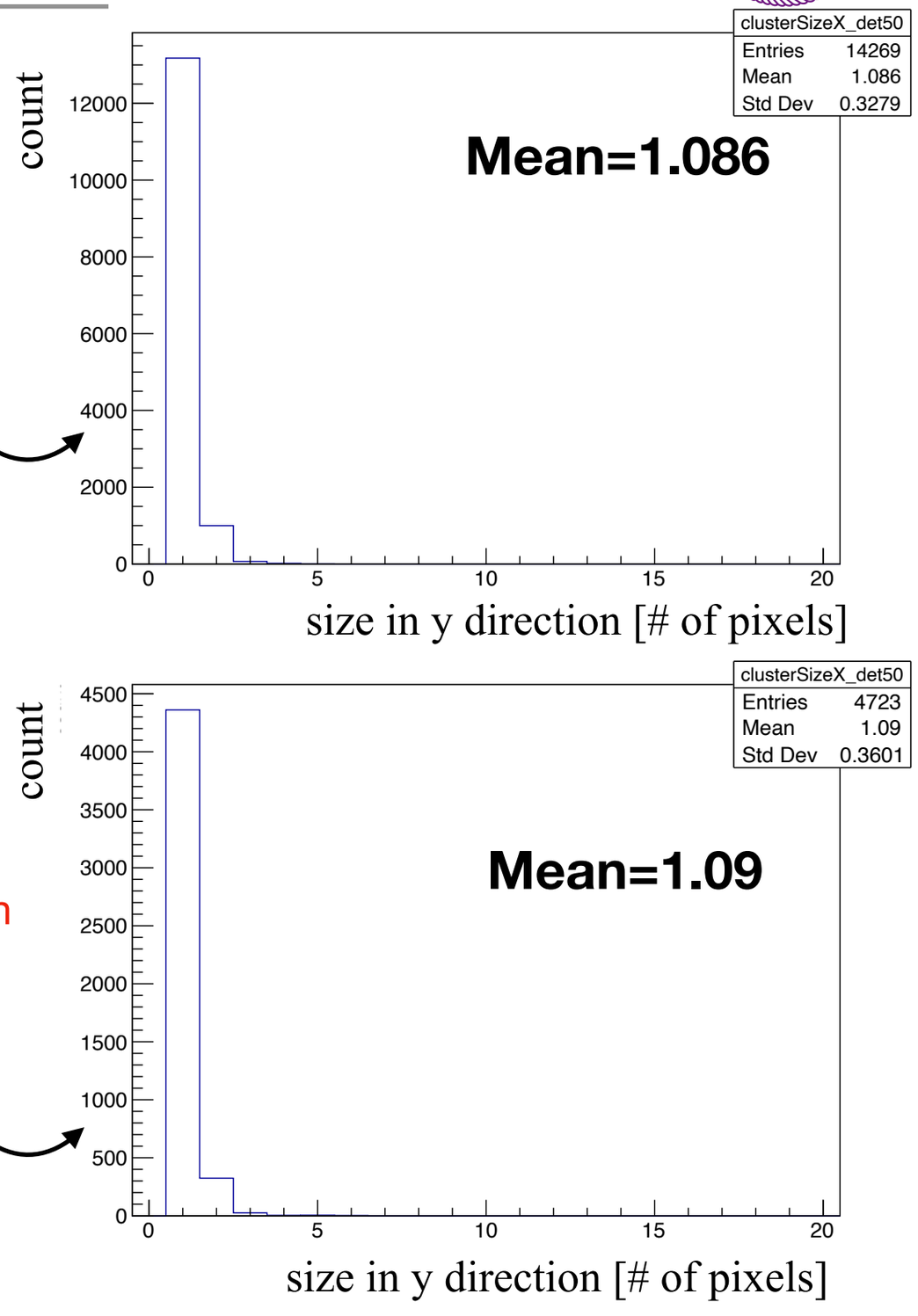
- The exact position of incident particle in a pixel is not resolvable
- Significant improvement in resolution due to tilt angle

Cluster size



Non-tilted DUT

RD53A 25μm×100μm



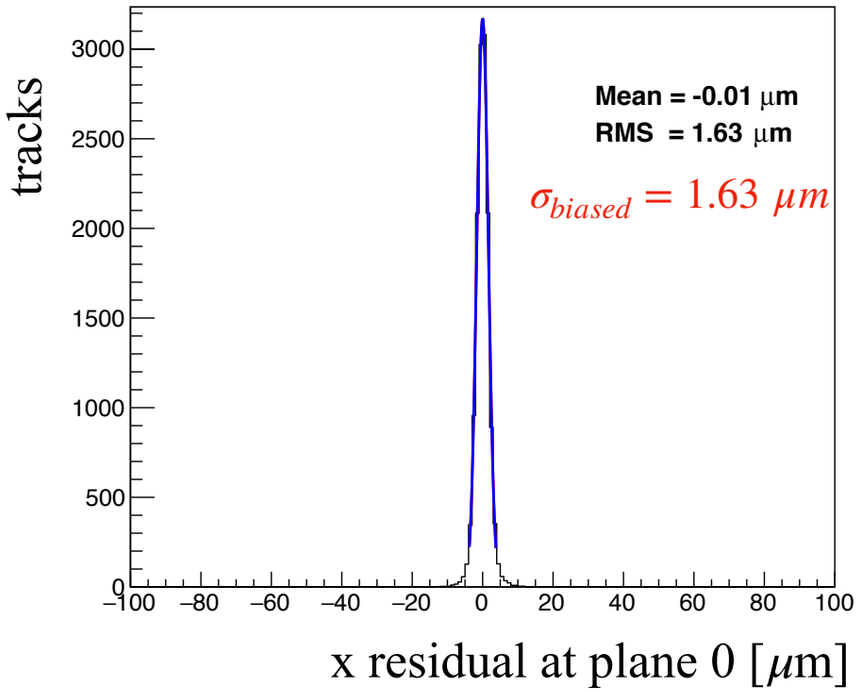
DUT tilted in x direction

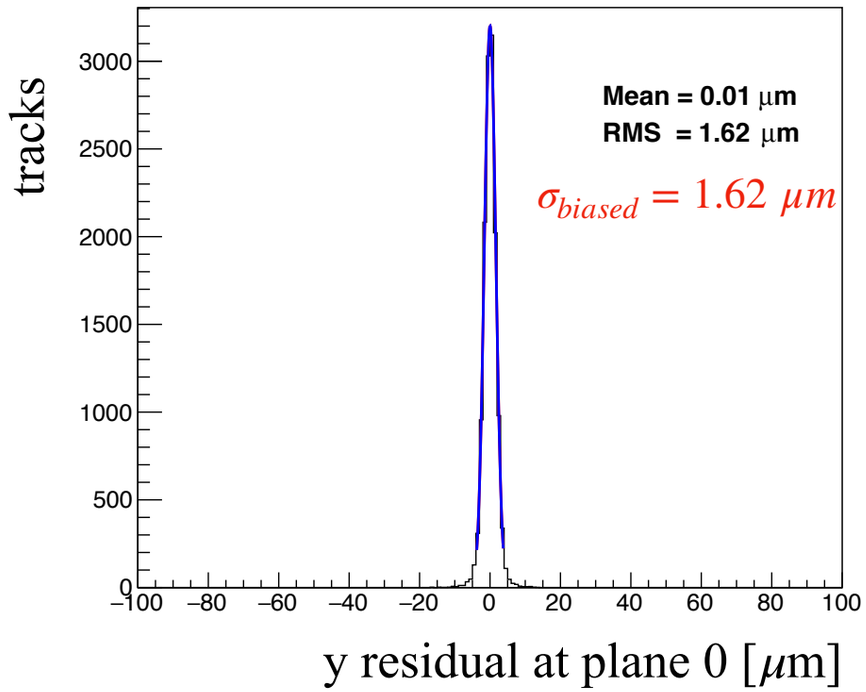
RD53A 25μm×100μm

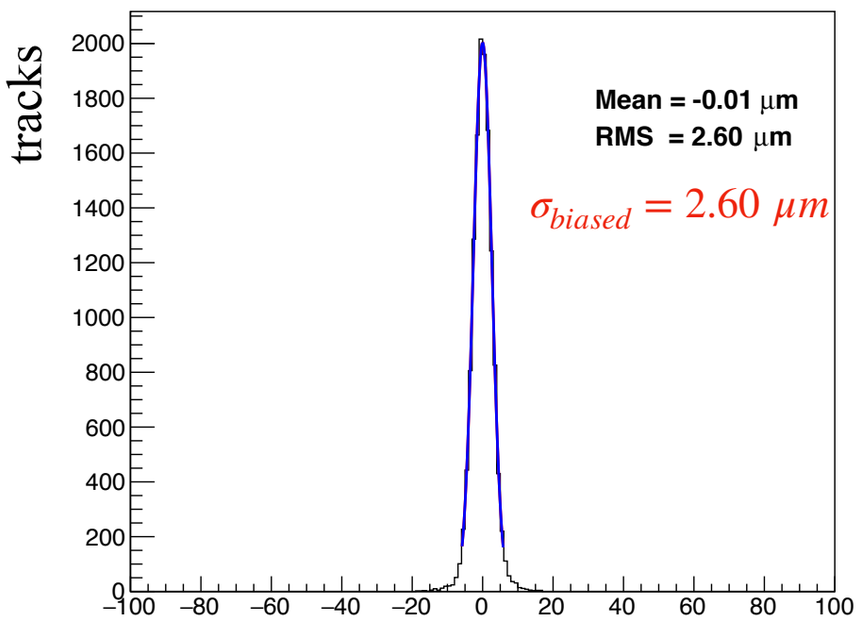
- The larger cluster size in tilted direction demonstrates the smaller equivalent pixel width

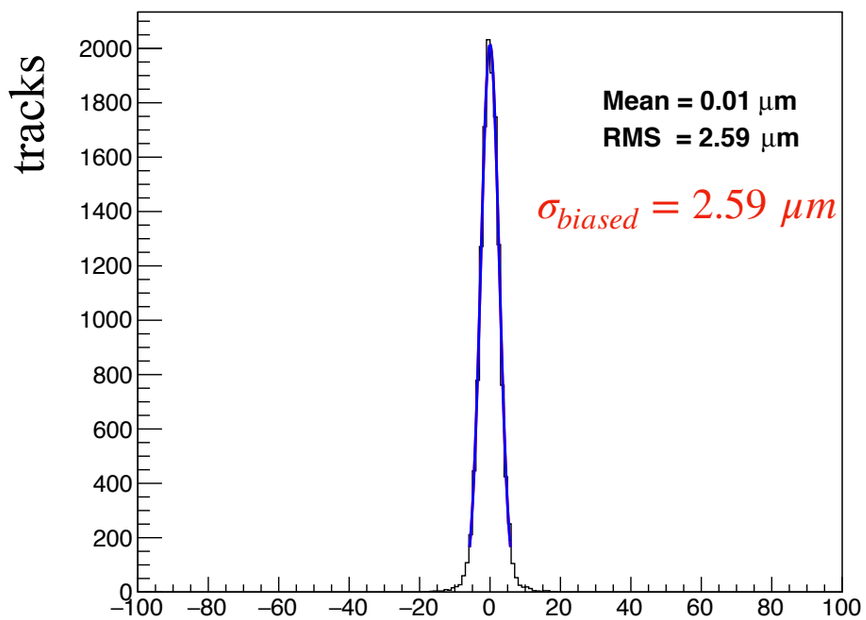
Position resolution (Mimosa26)

- residual = hit position - track position
- Biased residuals as hits on Mimosa26 are used in track fitting
- $\sigma^2_{biased} = \sigma^2_{intrinsic} - \sigma^2_{tracking}$



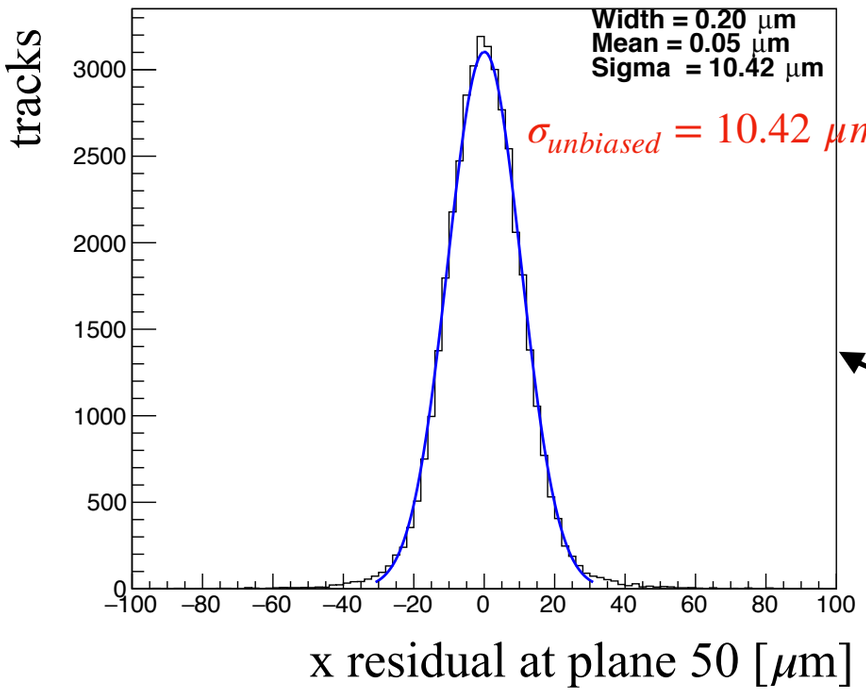




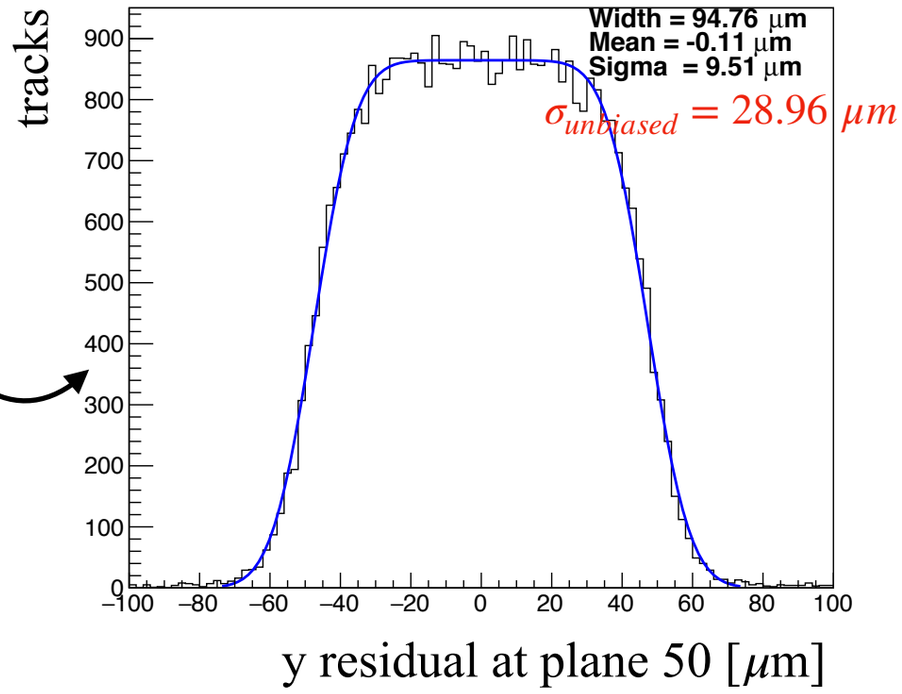


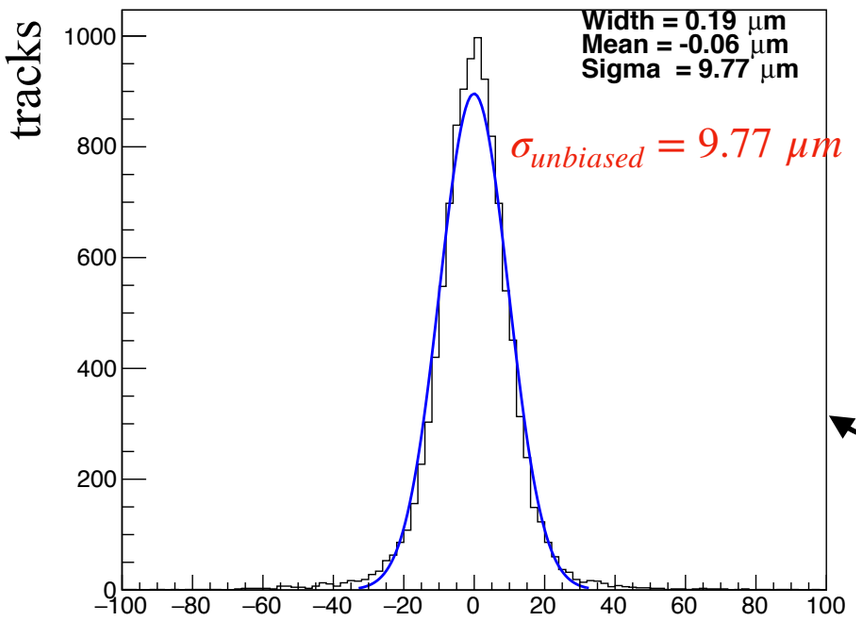
Position resolution (RD53A)

- Unbiased residuals as hits on DUTs are excluded in track fitting $\sigma^2_{unbiased} = \sigma^2_{intrinsic} + \sigma^2_{tracking}$
- Fit function = Box(width) convolved with Gaussian (Mean,Sigma)
- $\sigma^2_{unbiased}(DUTs) = width^2/12 + sigma^2$

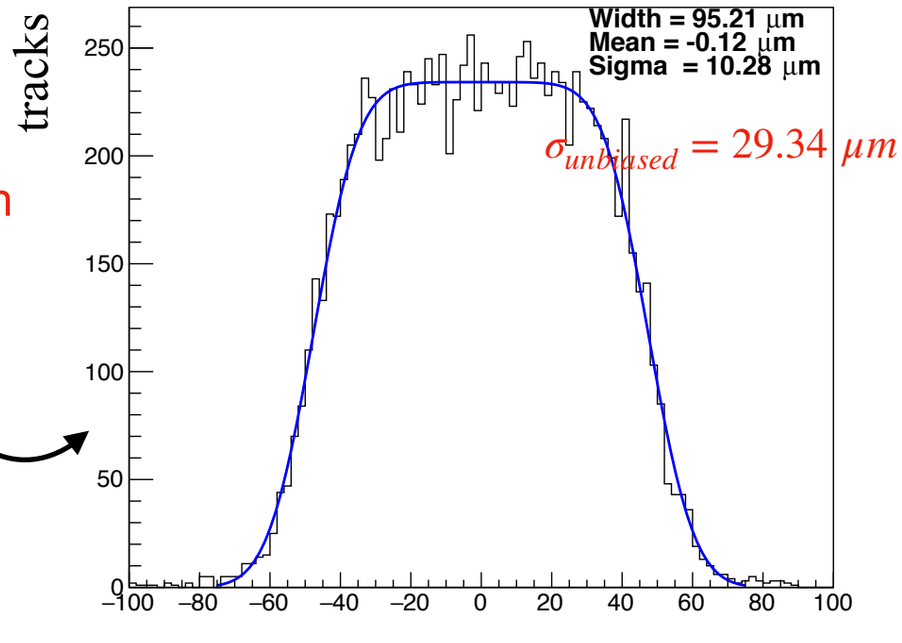


Non-tilted DUT
RD53A 25μm×100μm



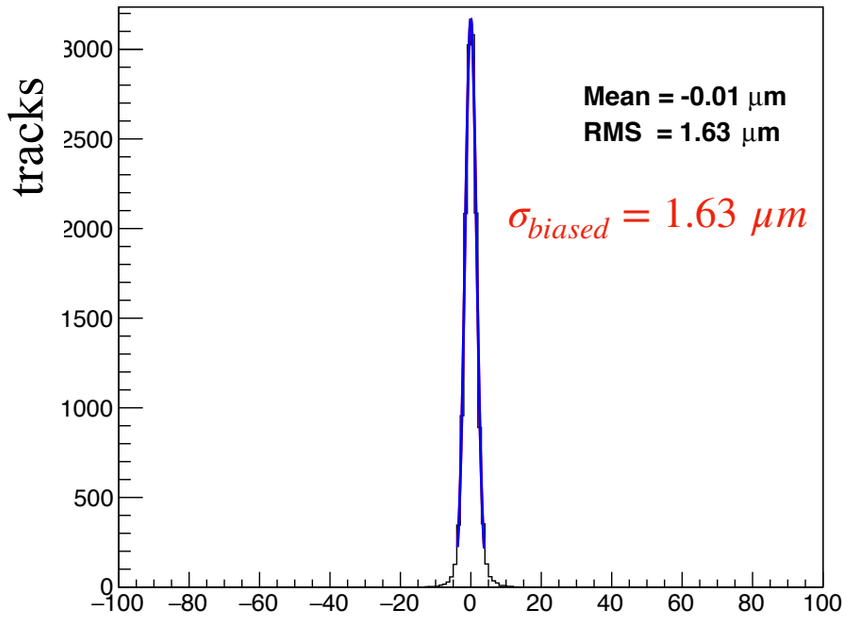


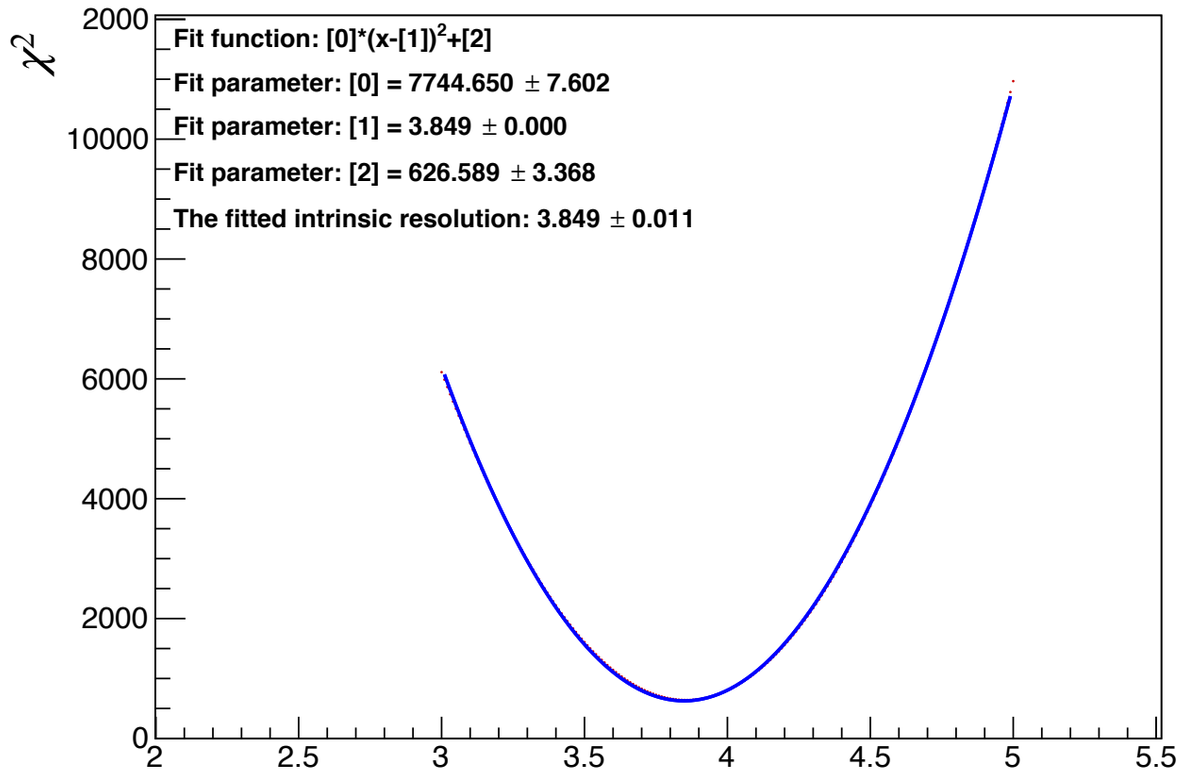
DUT tilted in x direction
RD53A 25μm×100μm



Tracking resolution on DUTs

- Track-resolution-simulator: https://github.com/simonspa/resolution-simulator/tree/master
- The same geometry of SLAC testbeam setup
- Need intrinsic resolution of Mimosa26 as input





Measured

Measured

Scanned

Simulated

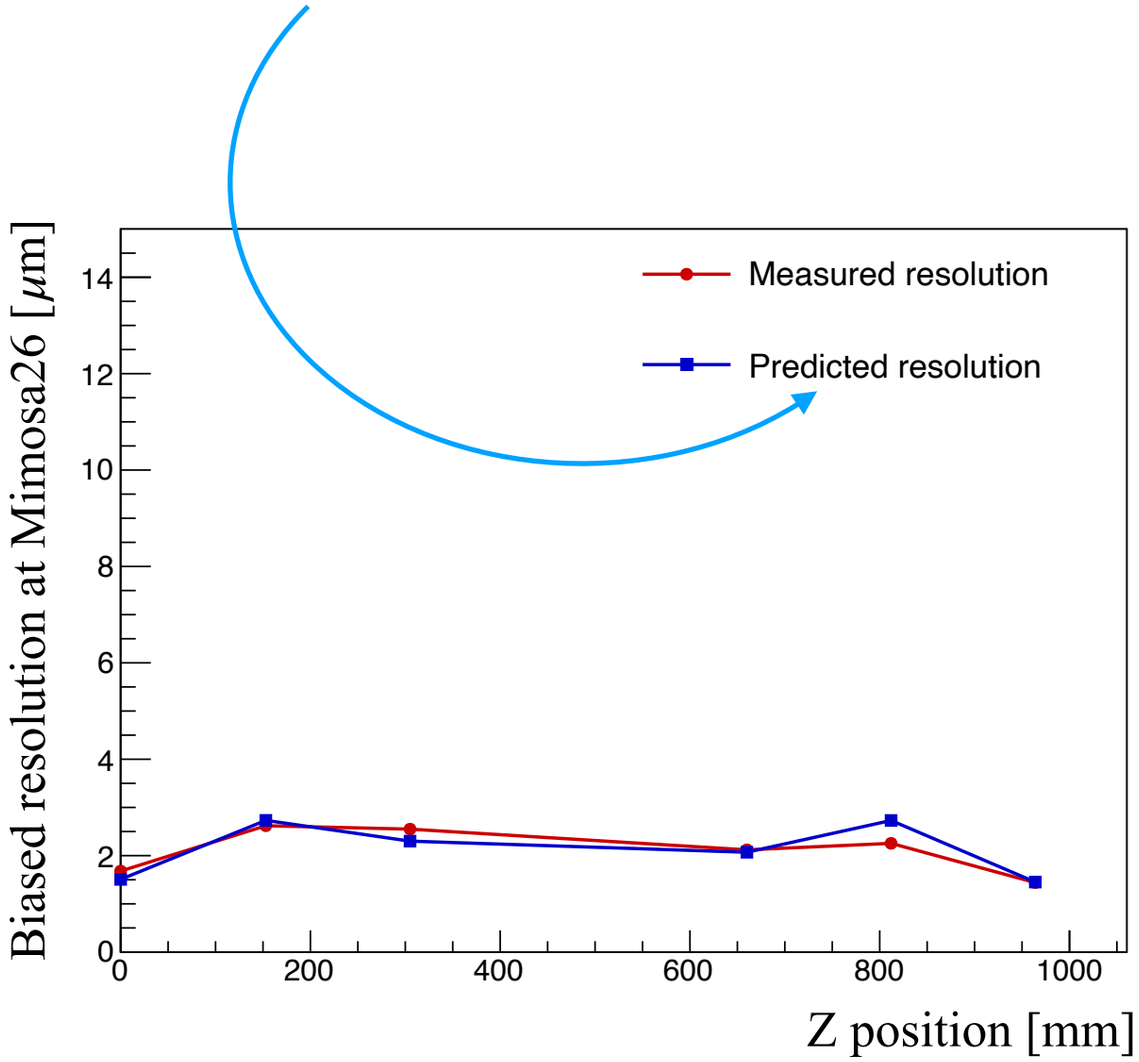
$$\chi^2 = \sum_i \frac{(\sigma_{biased,i} - \sqrt{\sigma^2_{intrinsic} - \sigma^2_{track,i}})^2}{V[\sigma_{biased,i}]}$$

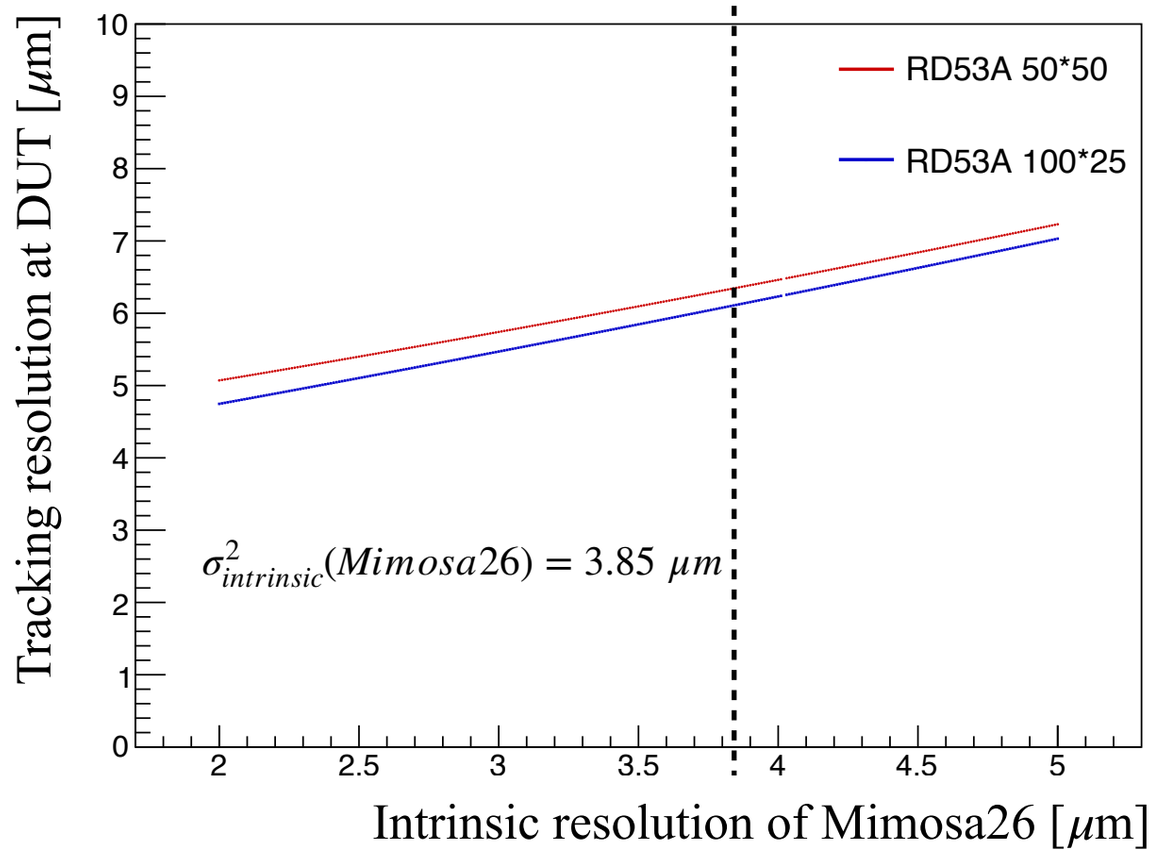
i are the six mimosa26

Tracking resolution on DUTs

- The intrinsic resolution of Mimosa26 is measured as 3.85 μm

$$\sigma^2_{biased}(Mimosa26) = \sigma^2_{intrinsic}(Mimosa26) - \sigma^2_{tracking}(Mimosa26) = 3.85^2 - \sigma^2_{tracking}(Mimosa26)$$





Results

- The position resolutions of non-tilted RD53A modules are both comparable with $pitch/\sqrt{12}$

pitch: the length or width of a pixel

- RD53A modules with 50×50 μm^2 benefit more from 13° tilt angle

- Systematics include uncertainty of material estimation, beam energy, tracking resolution and Z position of DUTs

	RD53A 50μm×50μm non-tilted side(50μm)	RD53A 50μm×50μm tilted side(50μm)	RD53A 100μm×25μm non-tilted side(100μm)	RD53A 100μm×25μm tilted side(25μm)
$pitch/\sqrt{12}$	14.4	14.4	28.8	7.2
Non-tilted	14.51 ± 1.05	14.58 ± 1.04	28.16 ± 0.67	7.92 ± 1.73
13° tilted	14.04 ± 1.07	10.86 ± 1.09	28.54 ± 0.75	6.81 ± 1.82
$\frac{13^\circ\ tilted}{Non-tilted}$	0.97 ± 0.10	0.74 ± 0.09	1.01 ± 0.04	0.86 ± 0.30

Conclusions

- The intrinsic position resolution of non-tilted and tilted RD53A modules with 50×50 μm^2 and 100×25 μm^2 pitch are measured using 11 GeV electron beam at SLAC
- The position resolution of 50×50 μm^2 RD53A reduces by 26% when tilted by 13°, and 14% for 100×25 μm^2 RD53A
- This information is useful for deciding on the design and geometry of the pixel layers in phase 2 upgrade

Thank you!

Backup

Challenges for pixel at HL-LHC

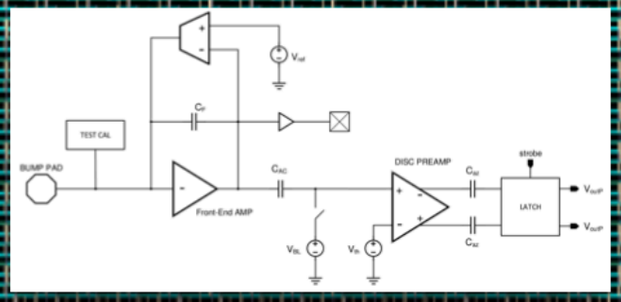
Generation	Run 1 (FEI3, PSI46)	Runs 2+3 (FEI4, PSI46DIG)	Runs 4+5
Chip Size	7.5 x 10.5 mm^2 8 x 10 mm^2	20 x 20 mm^2 8 x 10 mm^2	> 20 x 20 mm^2
Transistors	3.5 M 1.3 M	87 M	~1 G
Hit Rate	100 MHz/cm^2	400 MHz/cm^2	~2 GHz/cm^2
Hit Memory / Chip	0.1 Mb	1 Mb	~16 Mb
Trigger Rate	100 kHz	100 kHz	200 kHz - 1MHz
Trigger Latency	2.5 µs 3.2 µs	2.5 µs 3.2 µs	6 - 20 µs
Readout rate	40 Mb/s	320 Mb/s	1-4 Gb/s
Radiation	100 Mrad	200 Mrad	1 Grad
Technology	250 nm	130 nm 250 nm	65 nm
Power	~1/4 W/cm^2	~1/4 W/cm^2	1/2 - 1 W/cm^2

Three front-ends on RD53A

RD53A is a chip-of-chips with 3 analog front-ends
(output of the cores is the same for each)

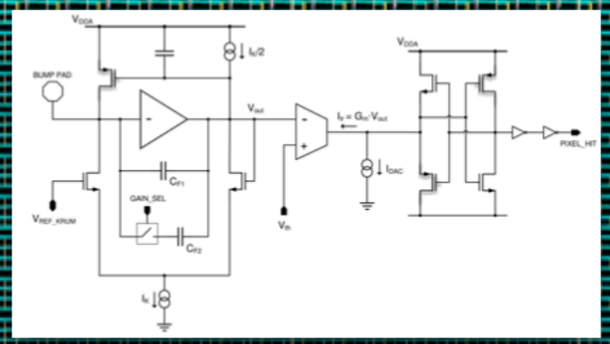
11.8 mm ; 192 pixels

Synchronous



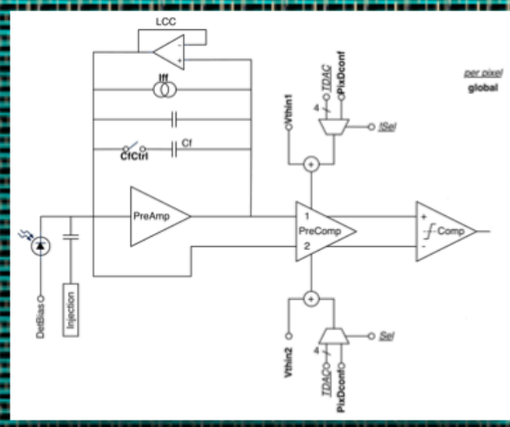
synchronous discriminator can be used for a fast ToT counter

Linear



single amplification stage for minimal power consumption

Differential

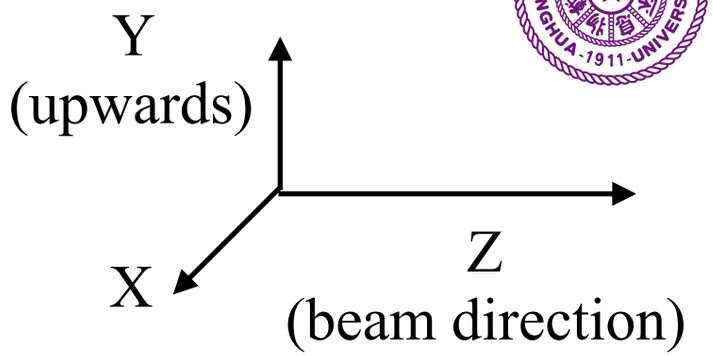


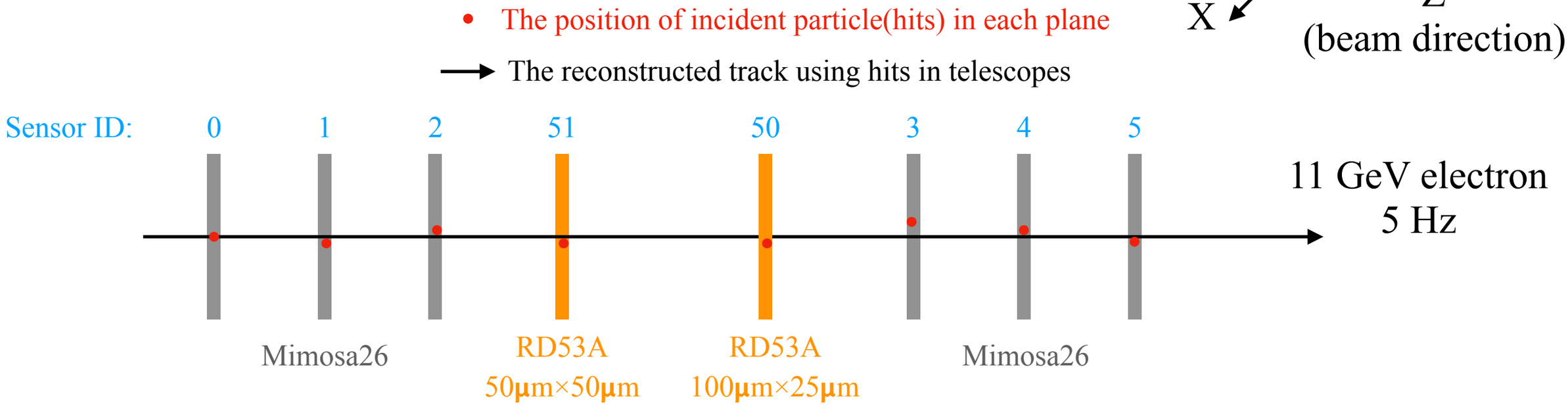
differential threshold reduces coherent noise

50 x 50 µm² pixels

20 mm ; 400 pixels

Testbeam at SLAC

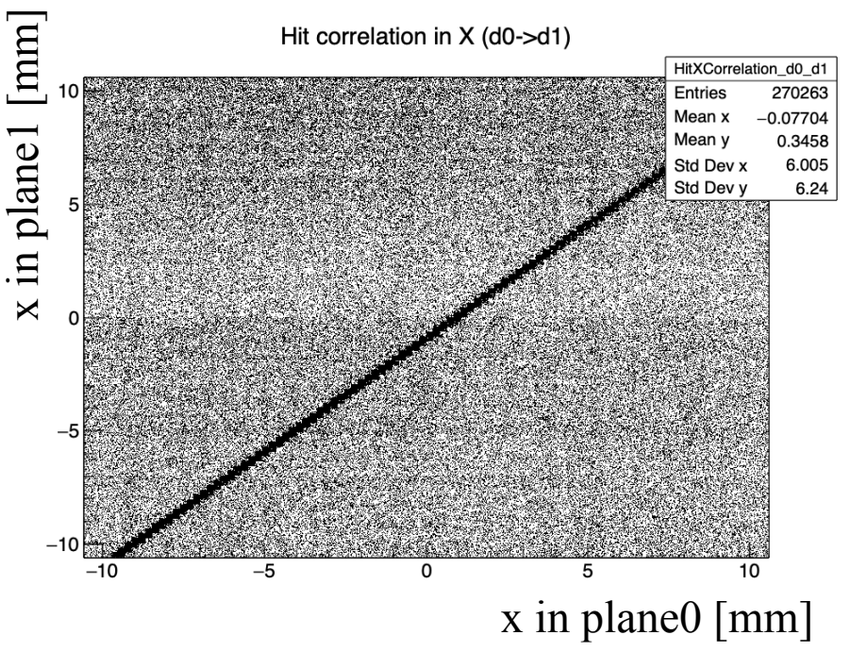


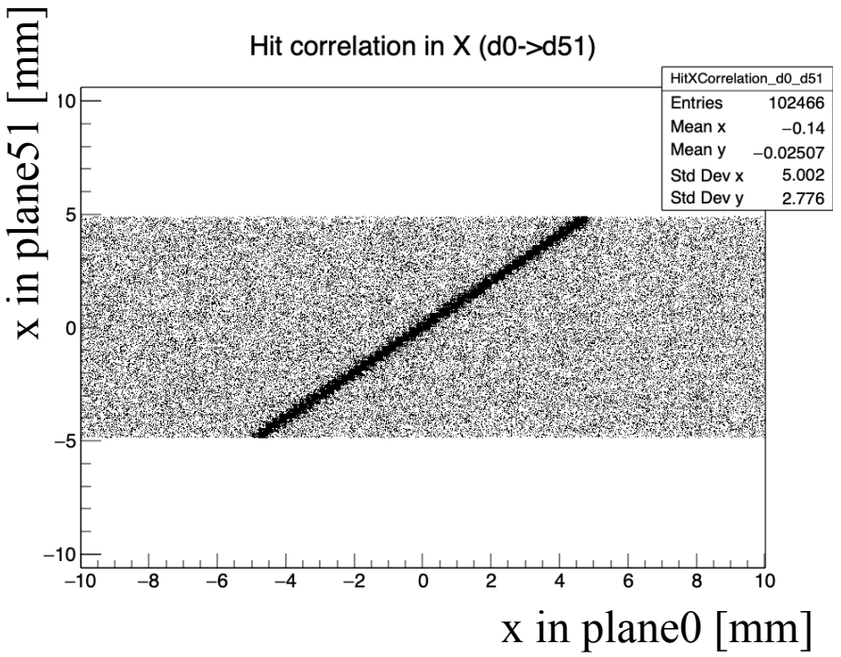


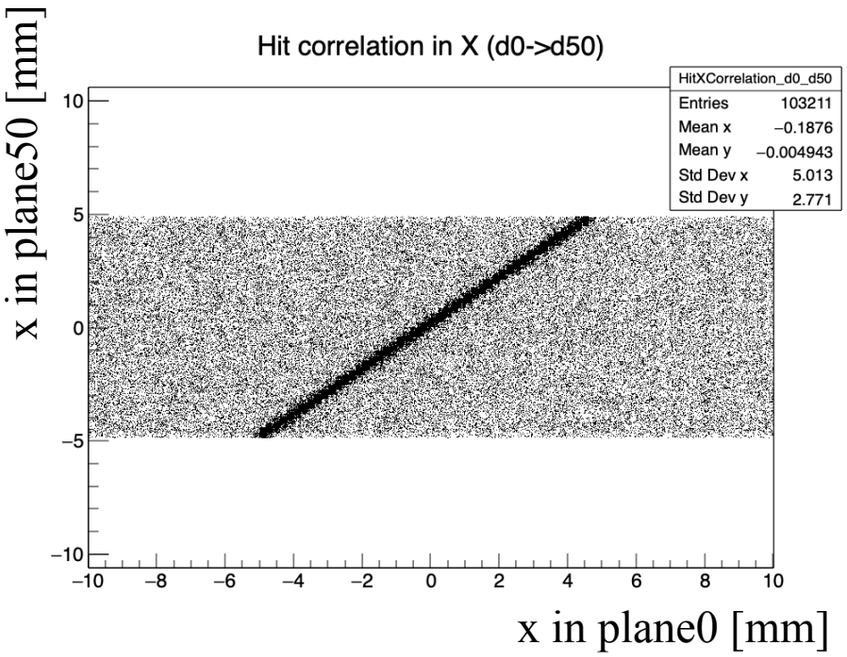
- Reference telescopes: Mimosa26 with 18.4**μ**m×18.4**μ**m pixels, 1152 pixels in x direction, 576 pixels in y direction, 21.2mm×10.6mm

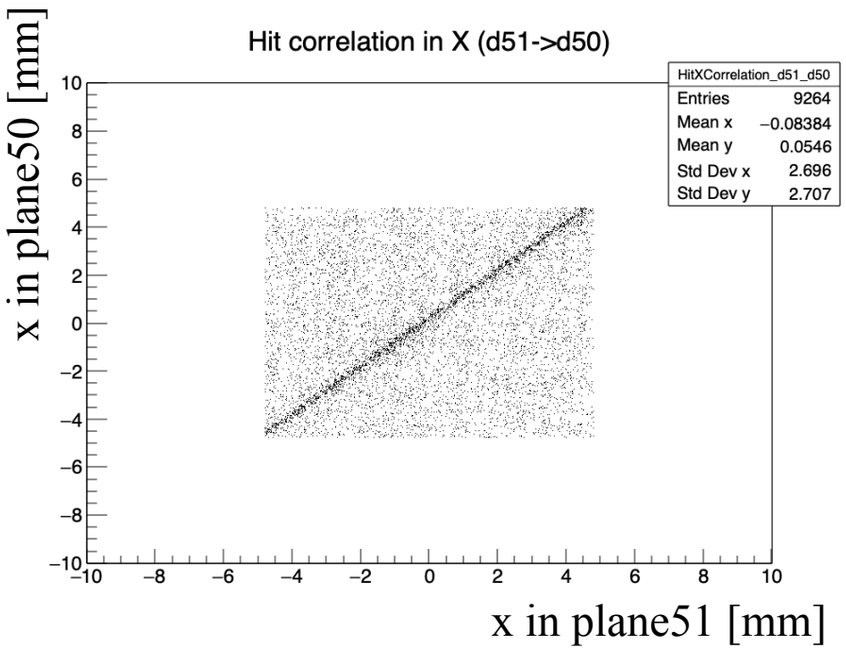
- Two different device under test (DUTs) rotated by 90° in X-Y plane: RD53A modules, 20.0mm×9.6mm
  - ★ 50**μ**m×50**μ**m sensor: 400 pixels in x direction, 192 pixels in y direction
  - ★ 100**μ**m×25**μ**m sensor: 200 pixels in x direction, 384 pixels in y direction

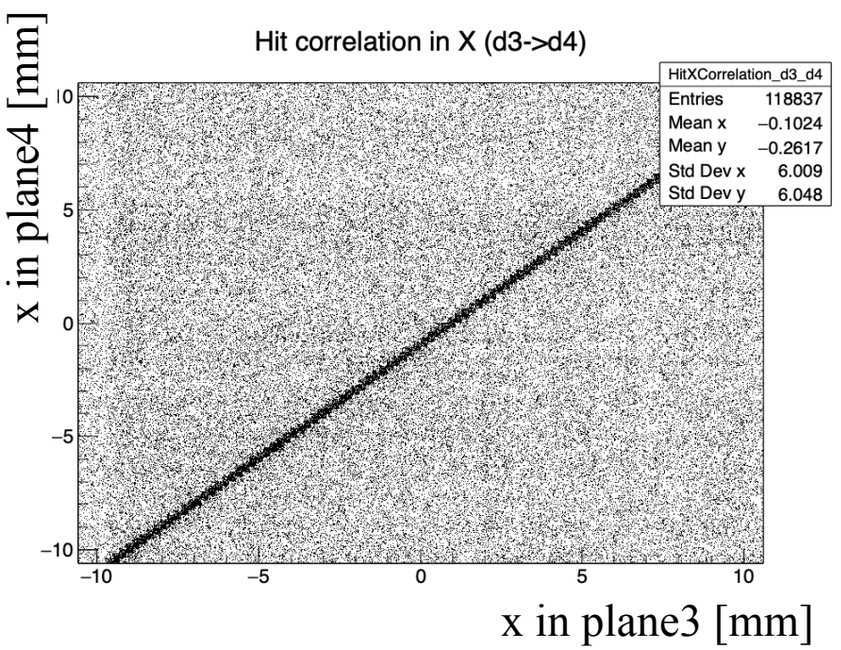
Correlation in x direction

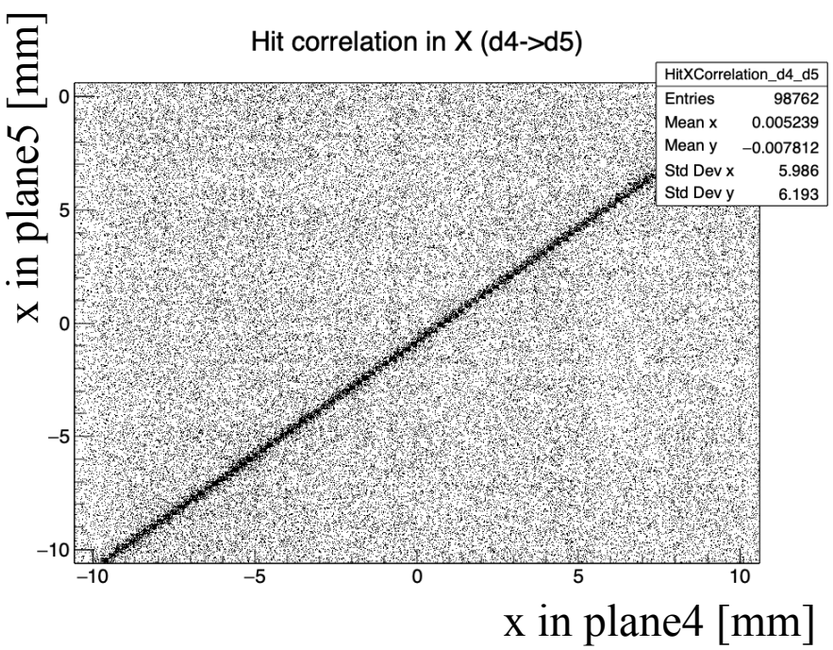






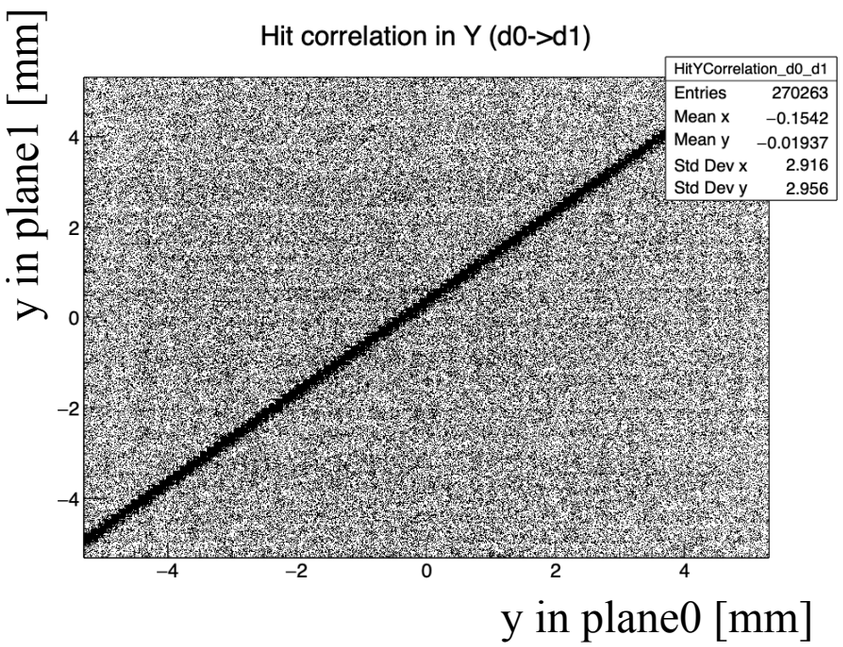


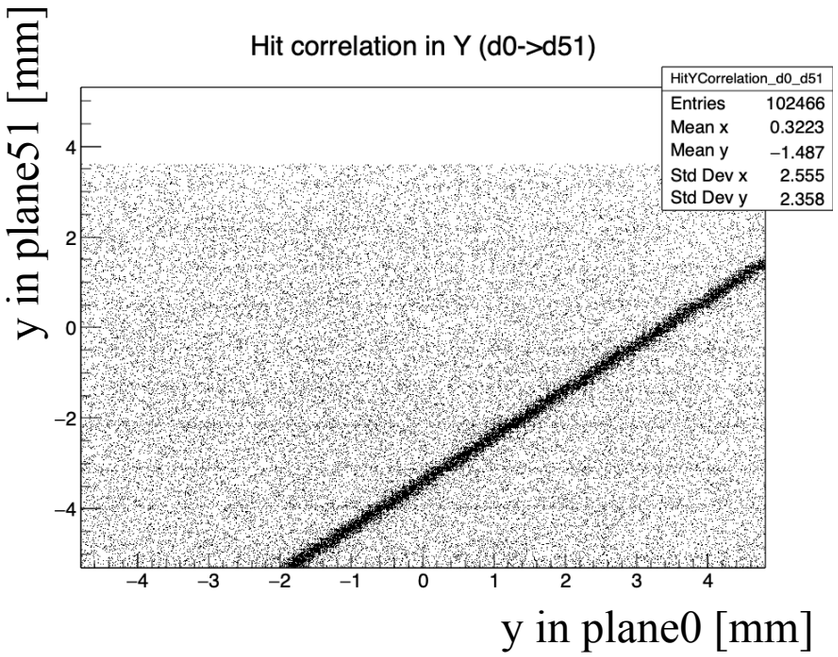


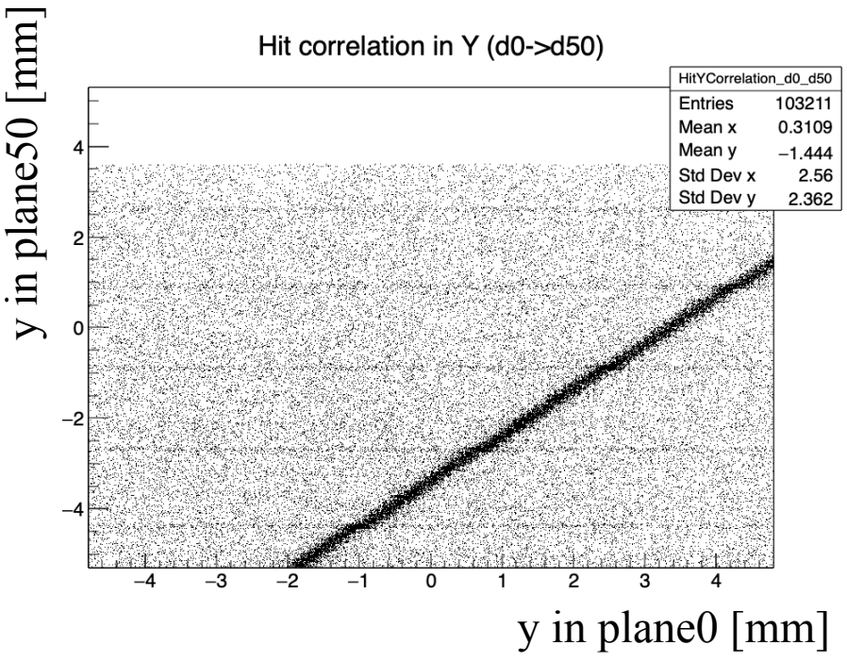


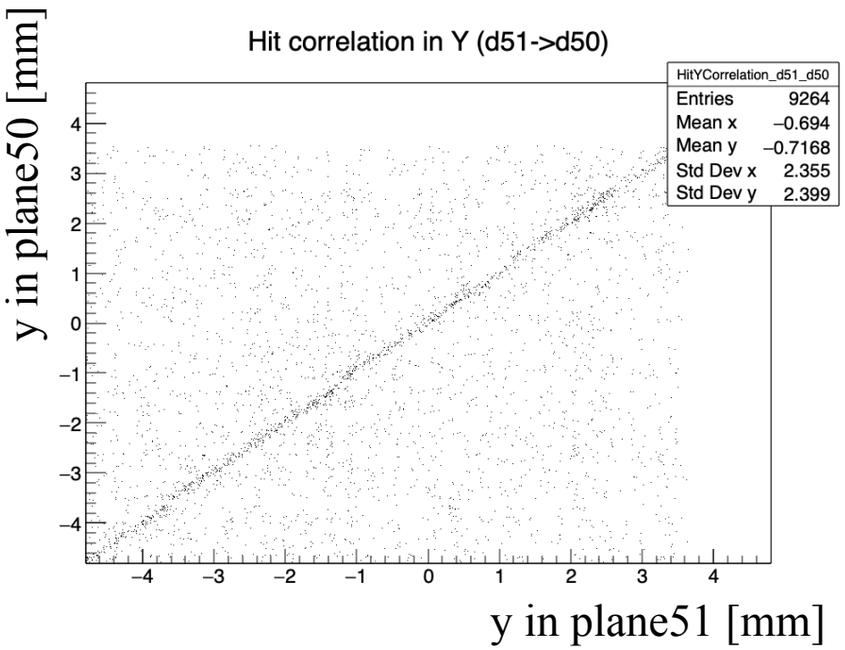
Telescopes: plane0~5, RD53A 50μm×50μm: plane51, RD53A 100μm×25μm: plane50

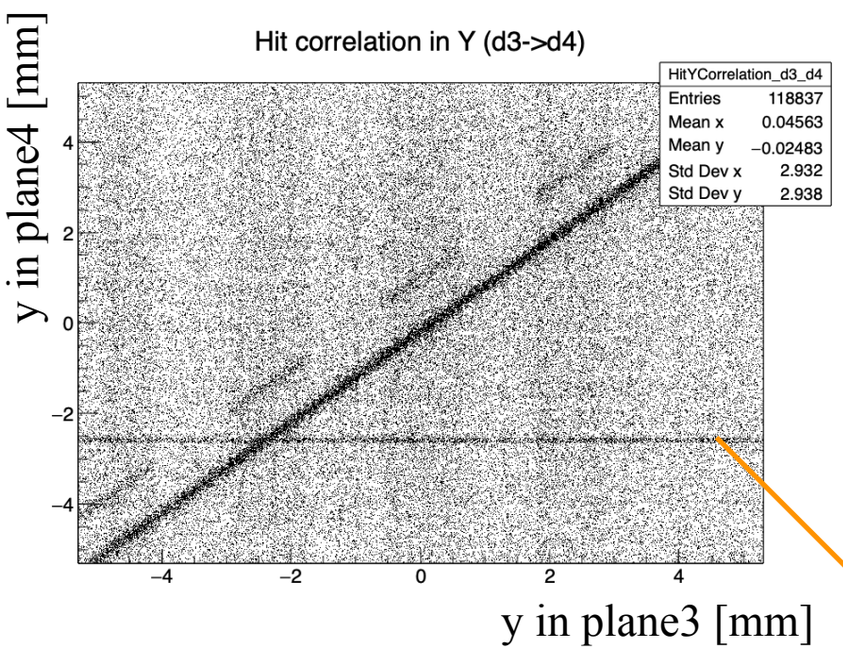
Correlation in y direction

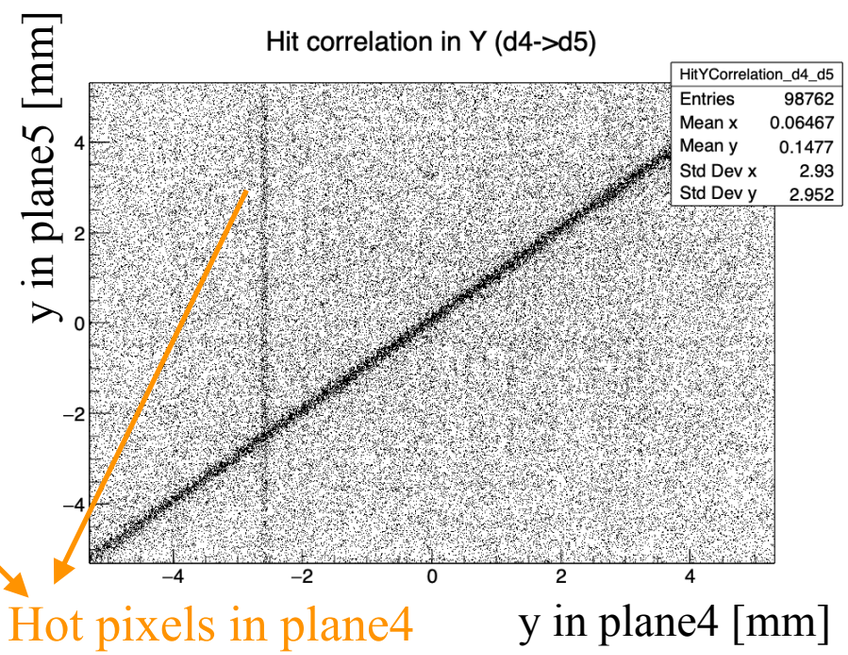






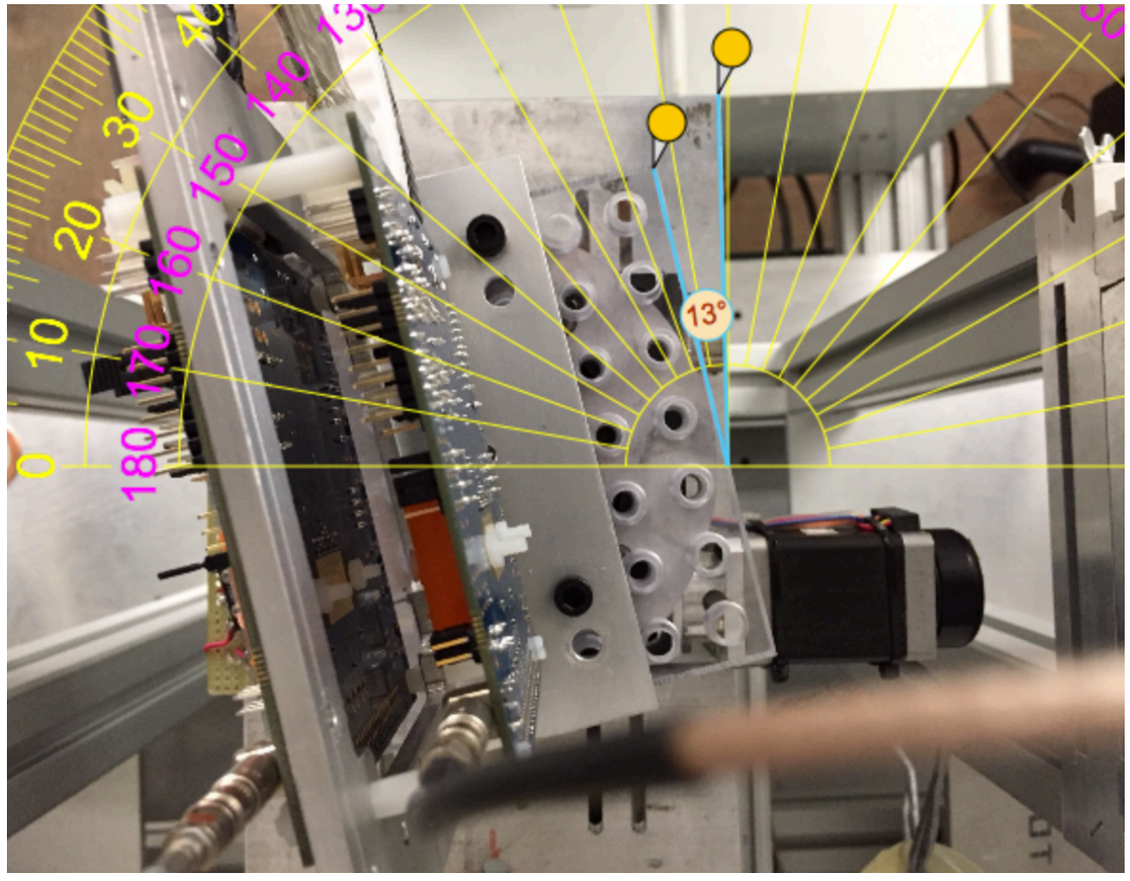






Telescopes: plane0~5, RD53A 50μm×50μm: plane51, RD53A 100μm×25μm: plane50

Tilted DUTs



Tilt angle: 13° in XZ plane

After 3 iterations of GBL alignment

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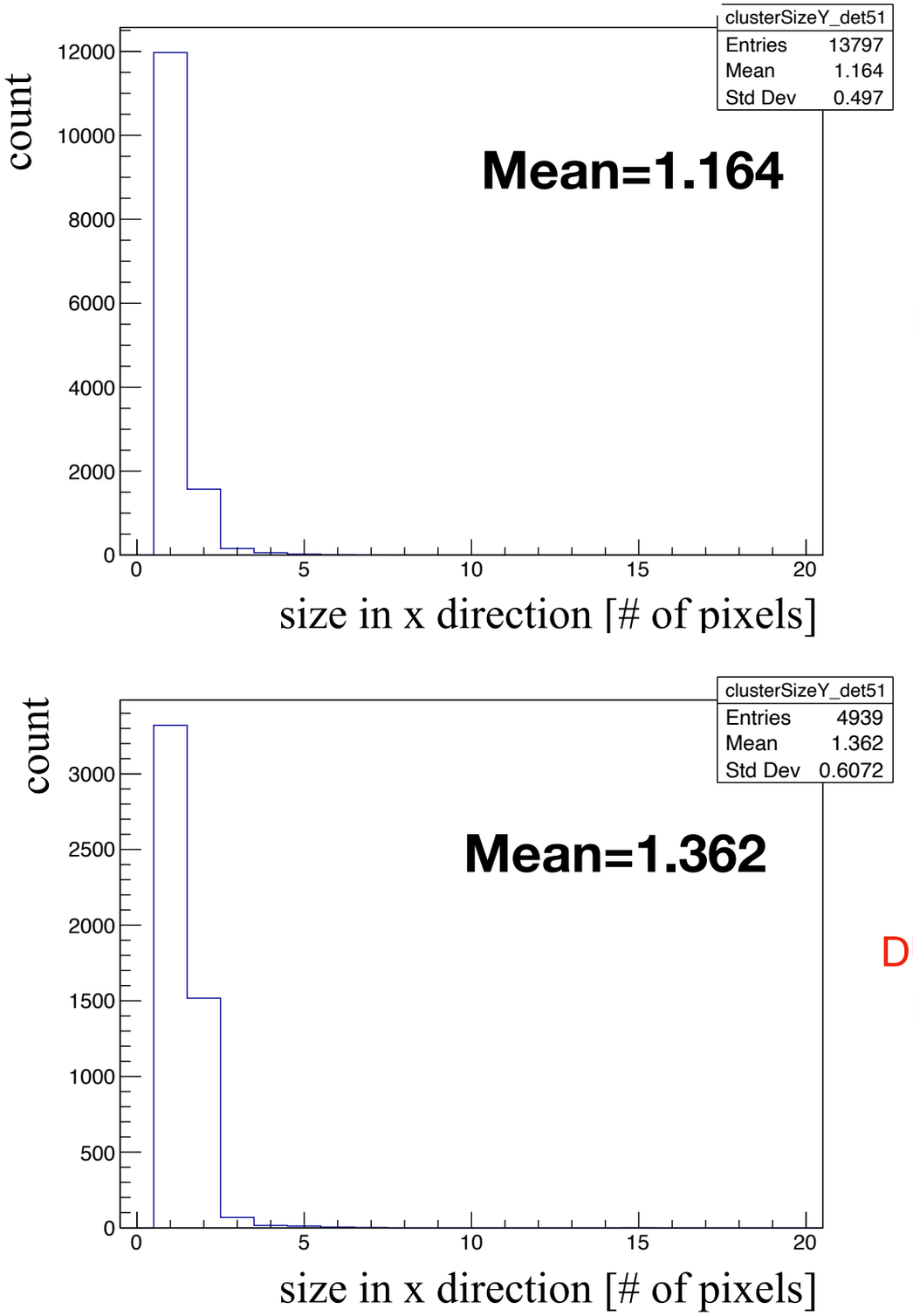
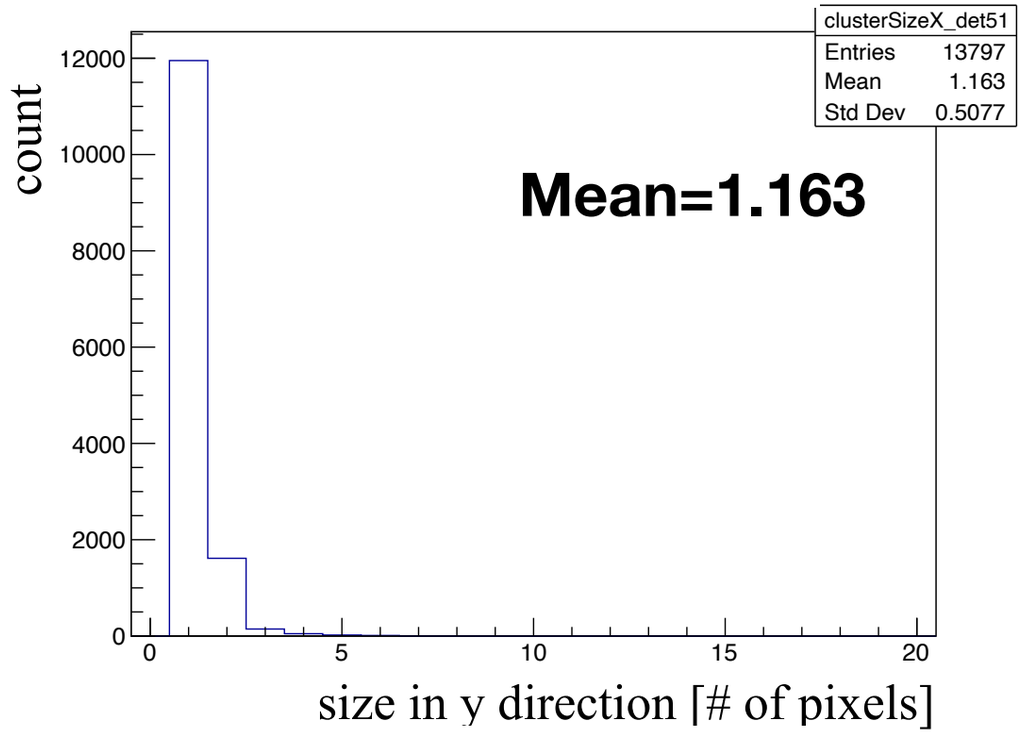
Cluster size



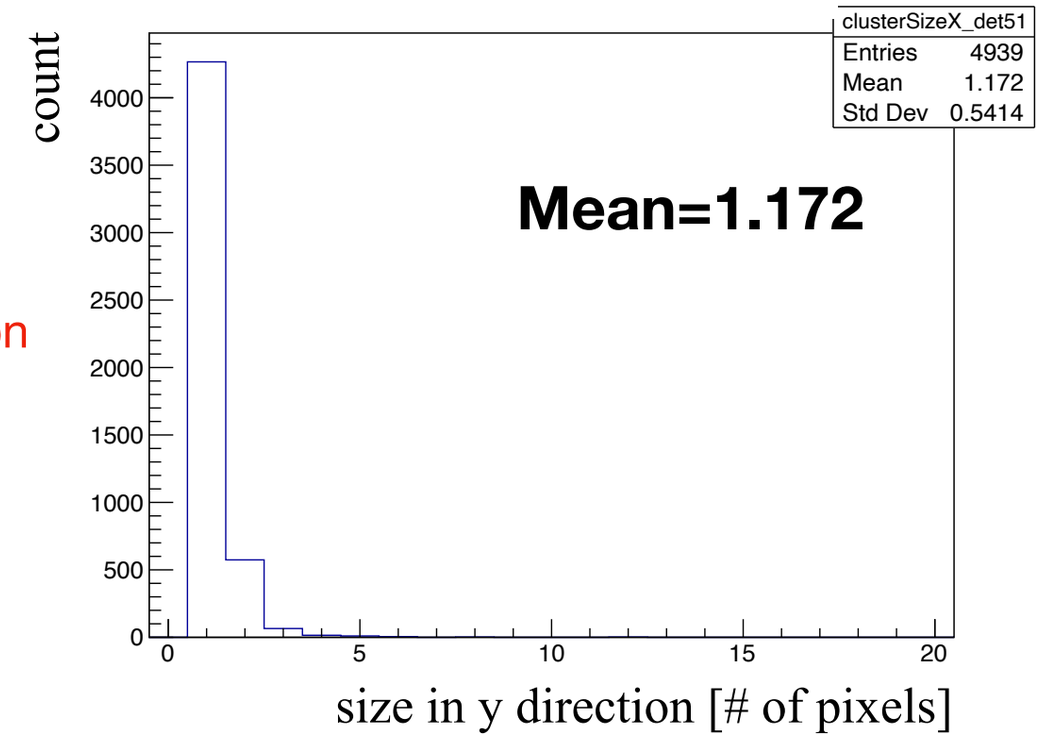
Non-tilted DUT

RD53A 50μm×50μm



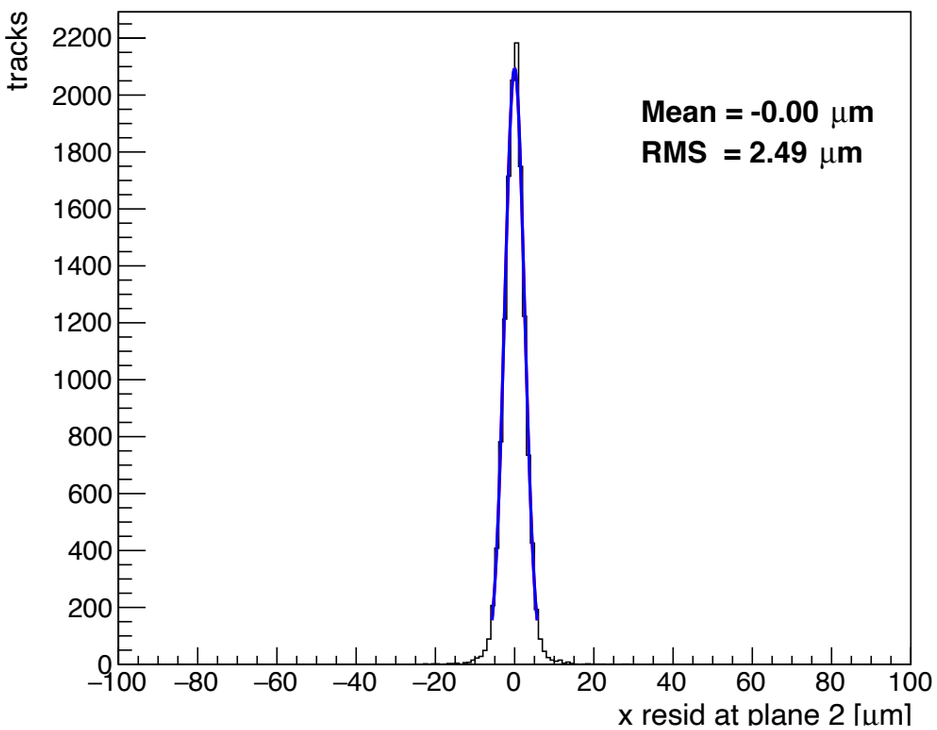
DUT tilted in x direction

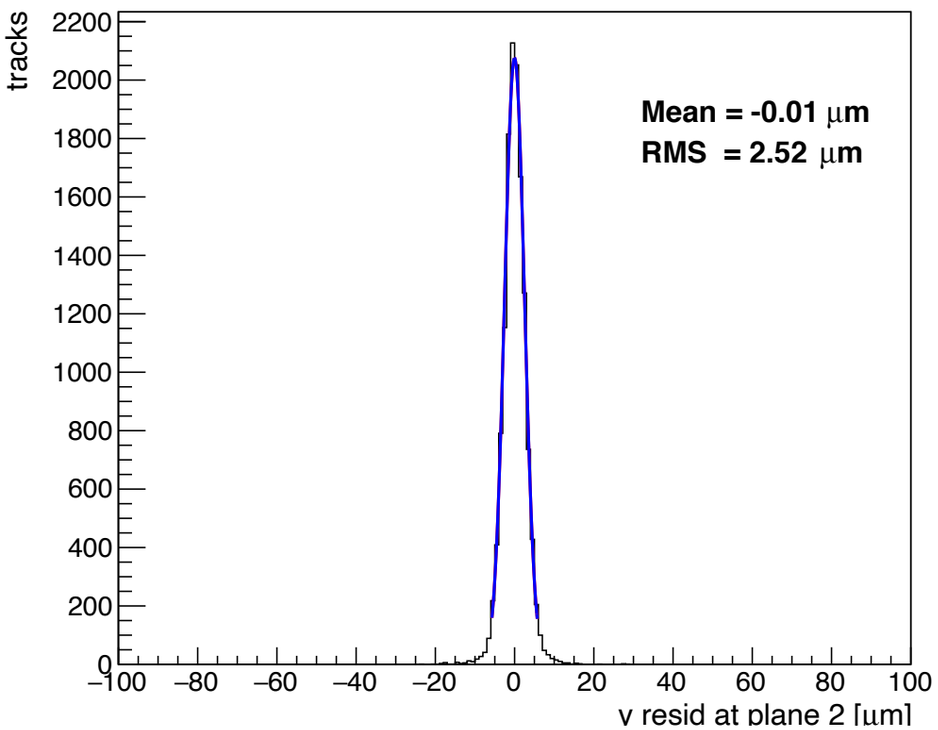
RD53A 50μm×50μm

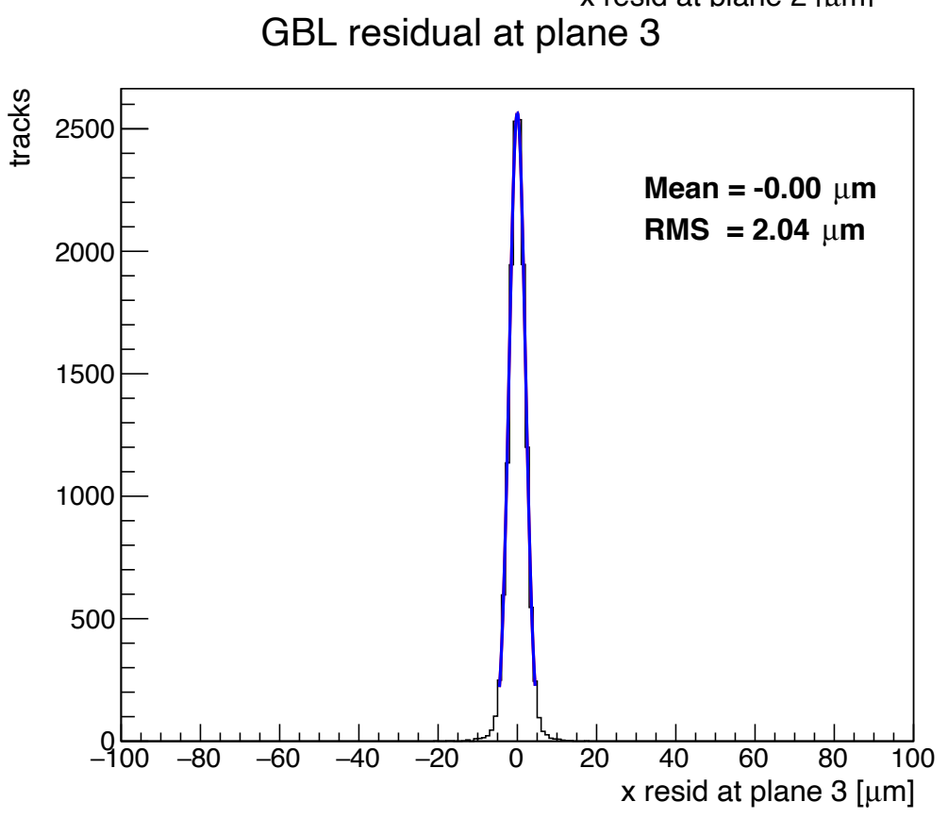


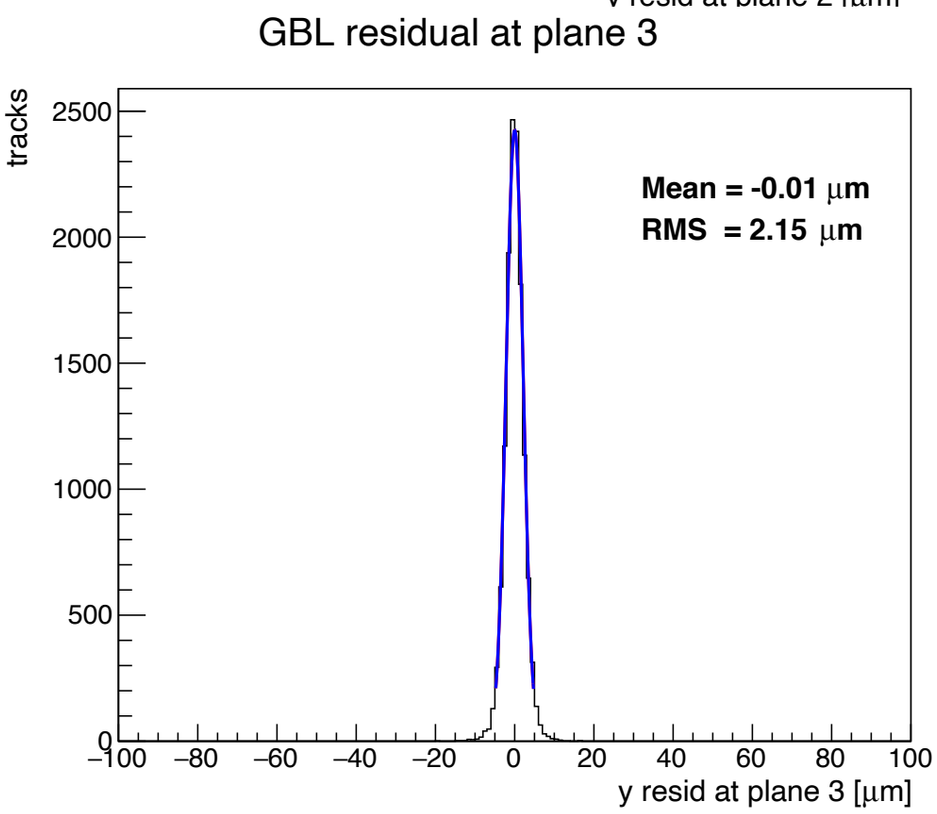
- Cluster size in tilted direction increase

Position resolution (Mimosa26)

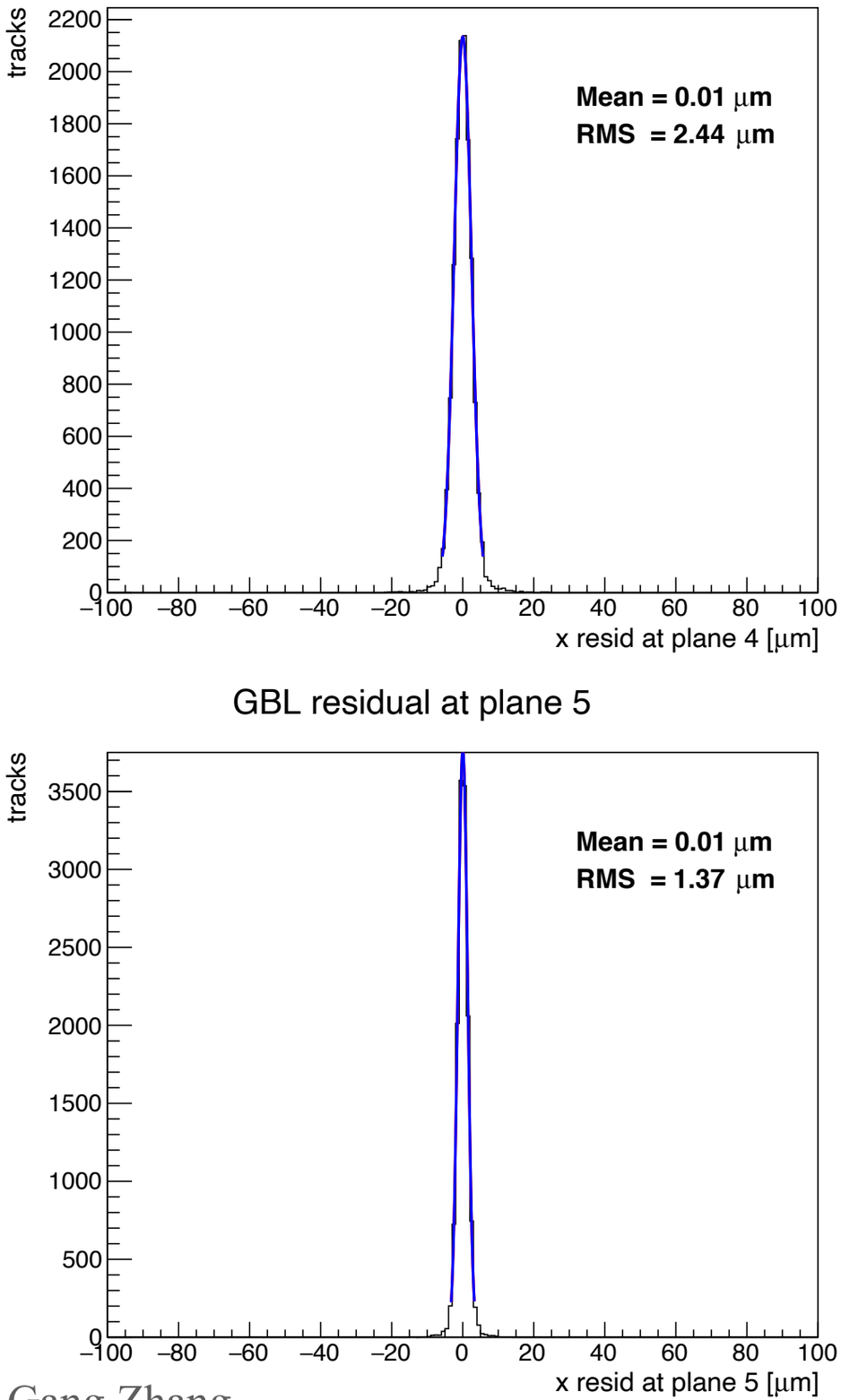


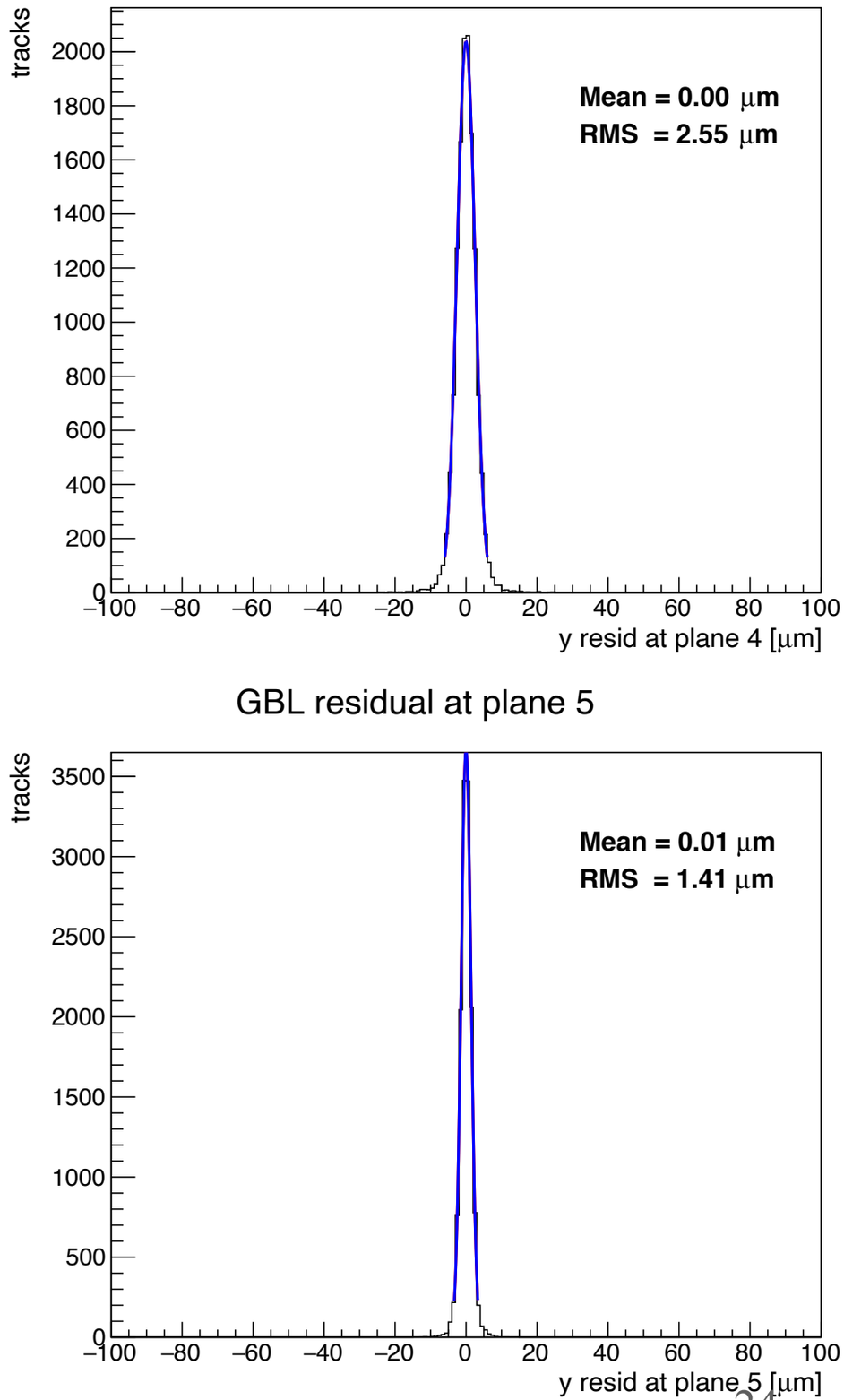






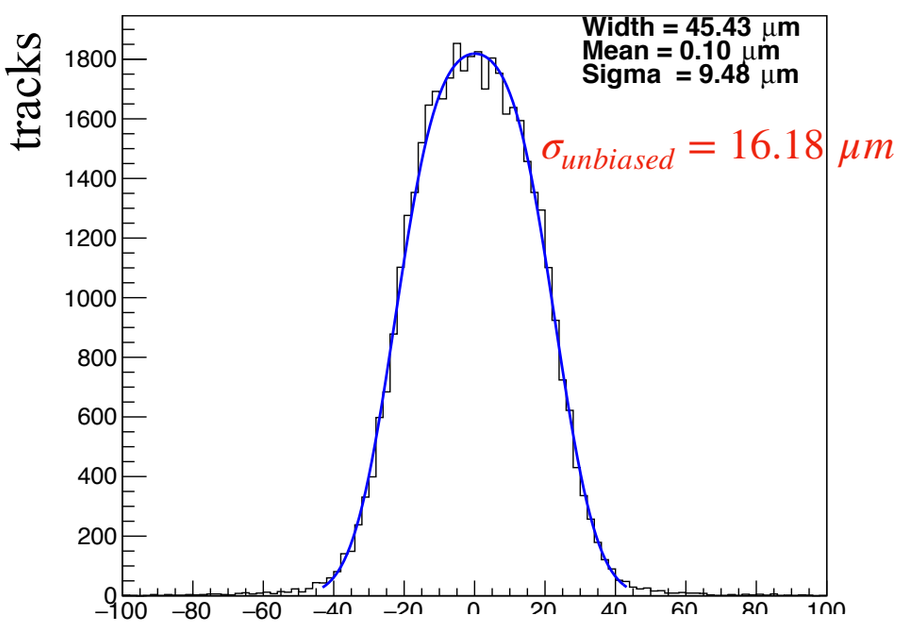
Position resolution (Mimosa26)





Position resolution (RD53A)

fit function = Box(width) convolved with Gaussian (Mean,Sigma)

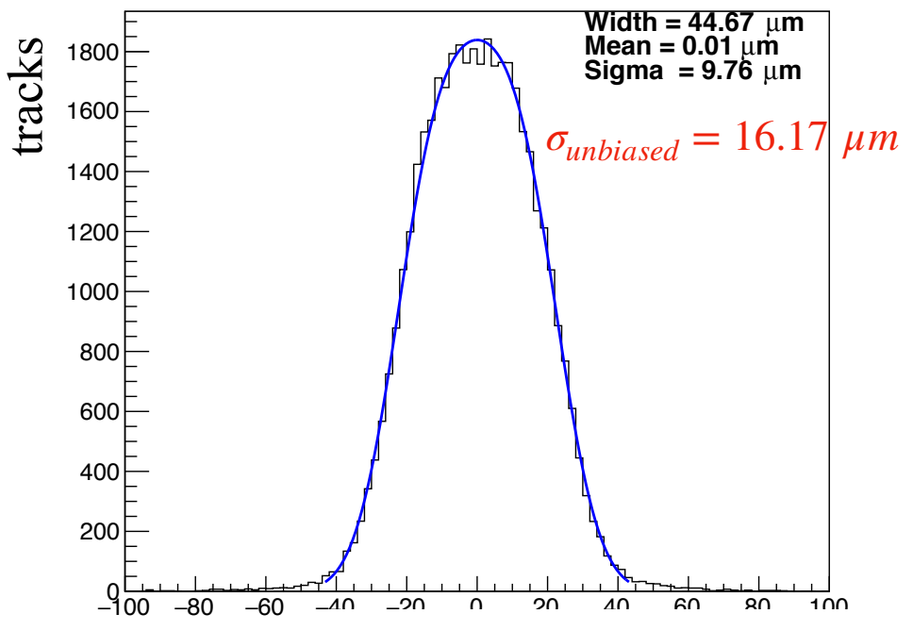


Non-tilted DUT

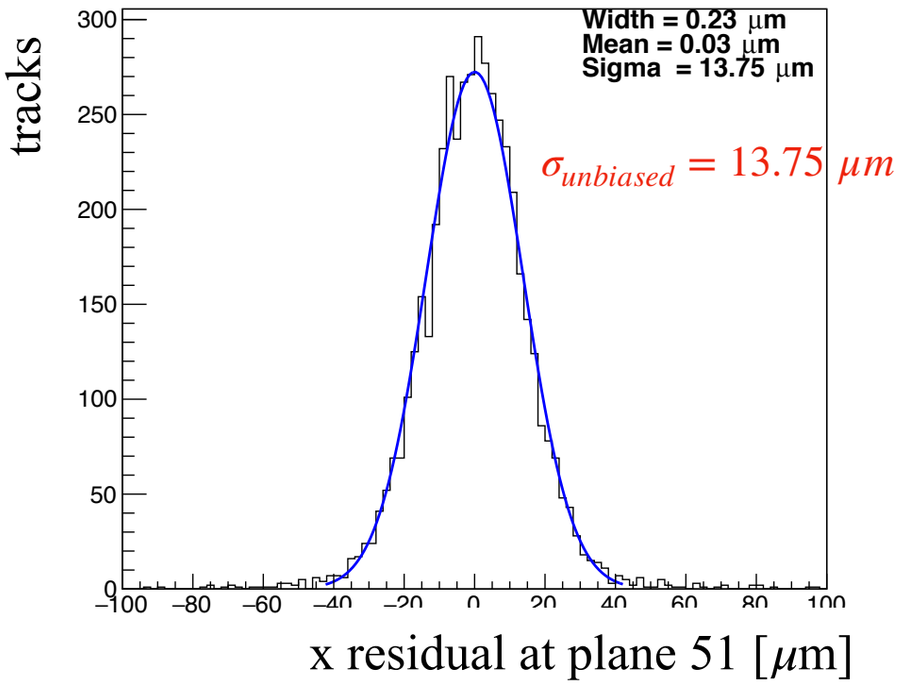
RD53A 50μm×50μm

$$\frac{pitch_x}{\sqrt{12}} = 14.4\ \mu m$$

$$\frac{pitch_y}{\sqrt{12}} = 14.4\ \mu m$$

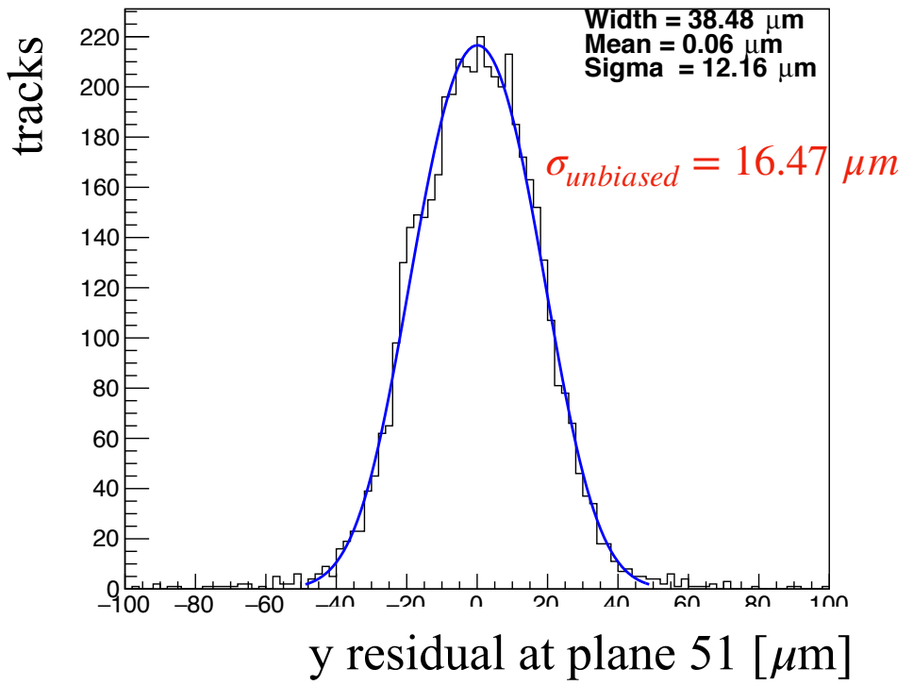


$$\sigma^2_{unbiased} = \sigma^2_{intrinsic} + \sigma^2_{tracking}$$

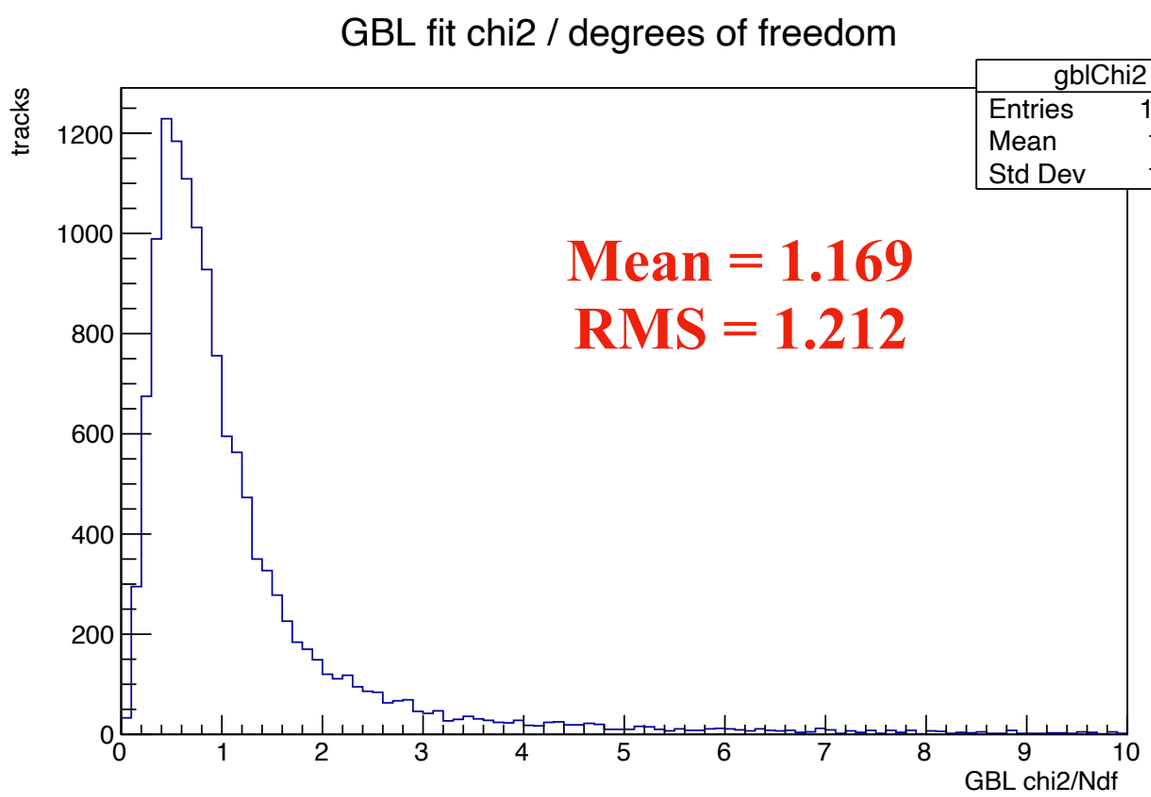


DUT tilted in x direction

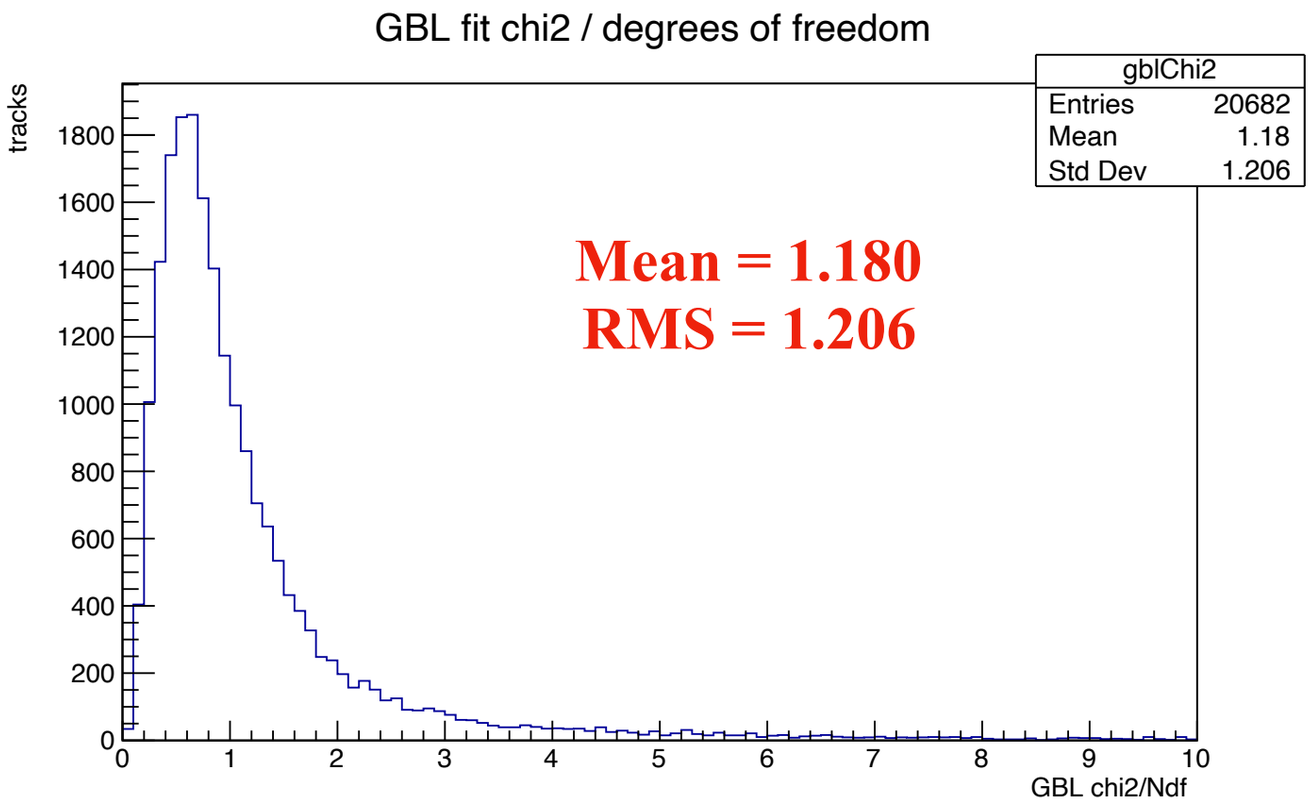
RD53A 50μm×50μm



Chi^2/d.o.f. comparison

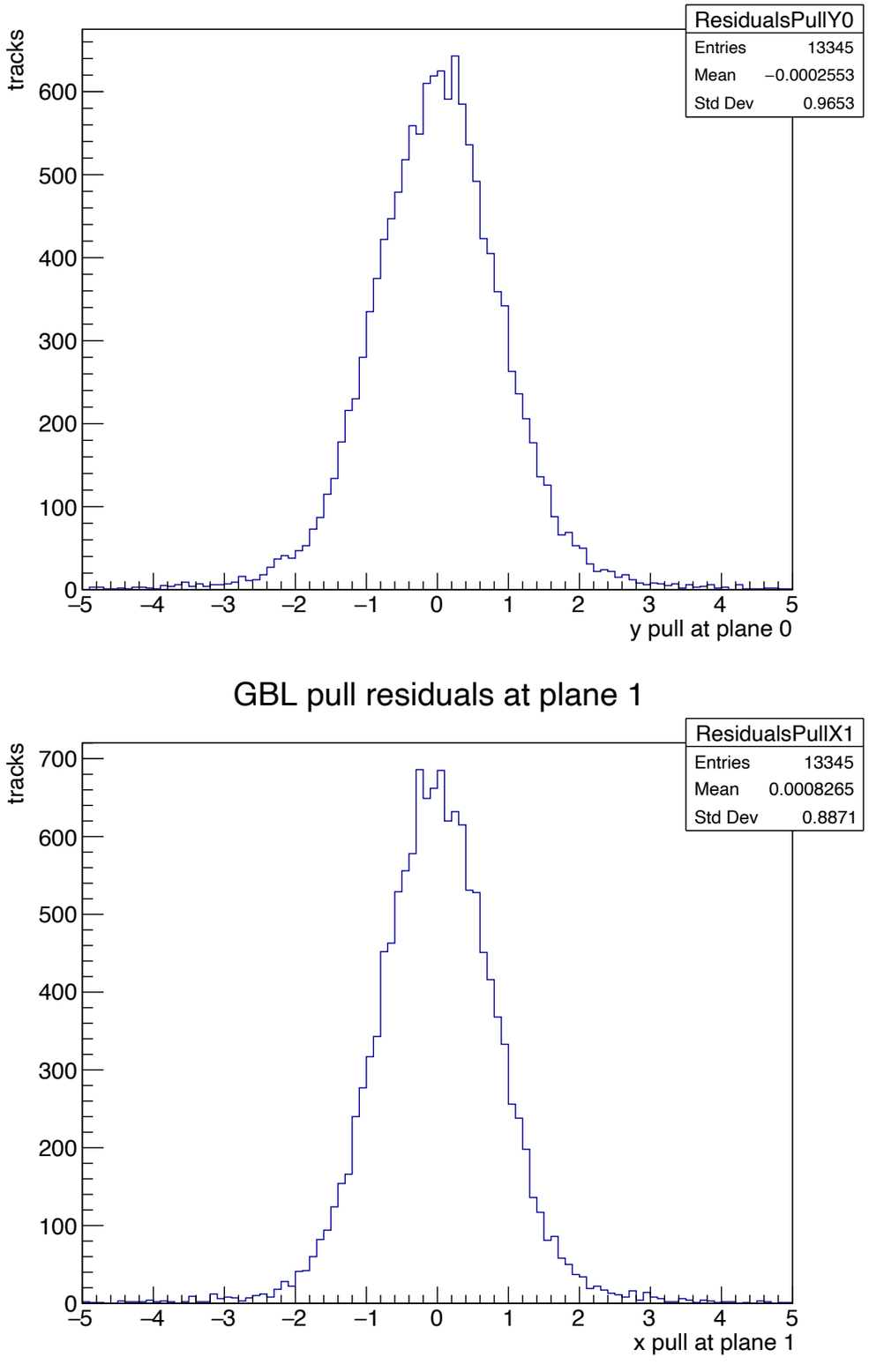


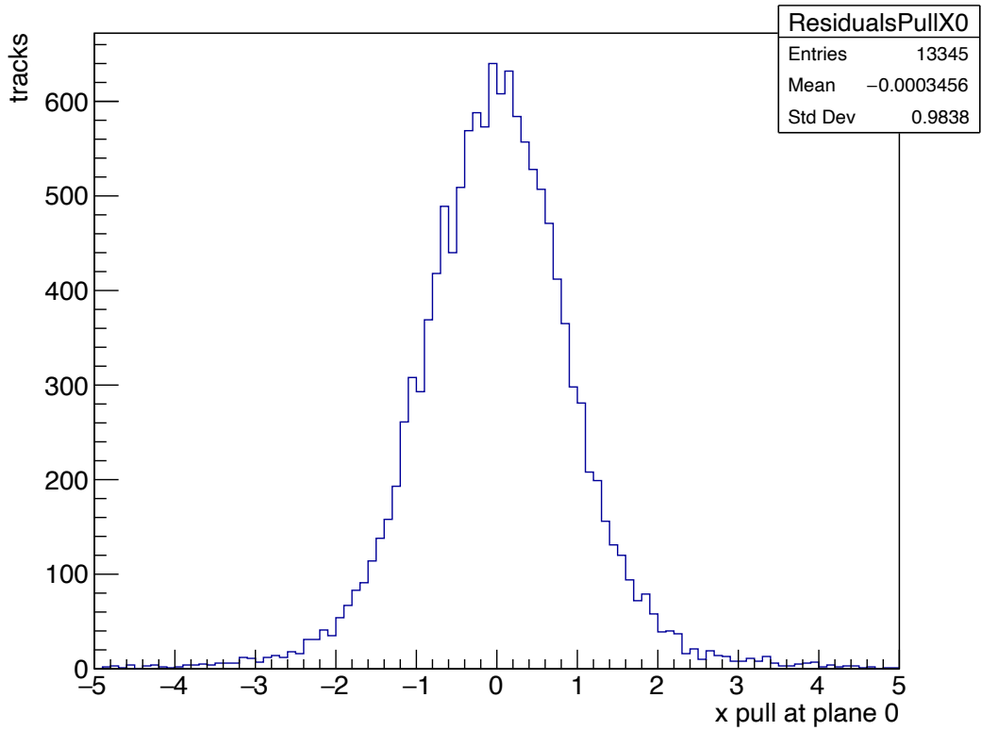
No tilt angle

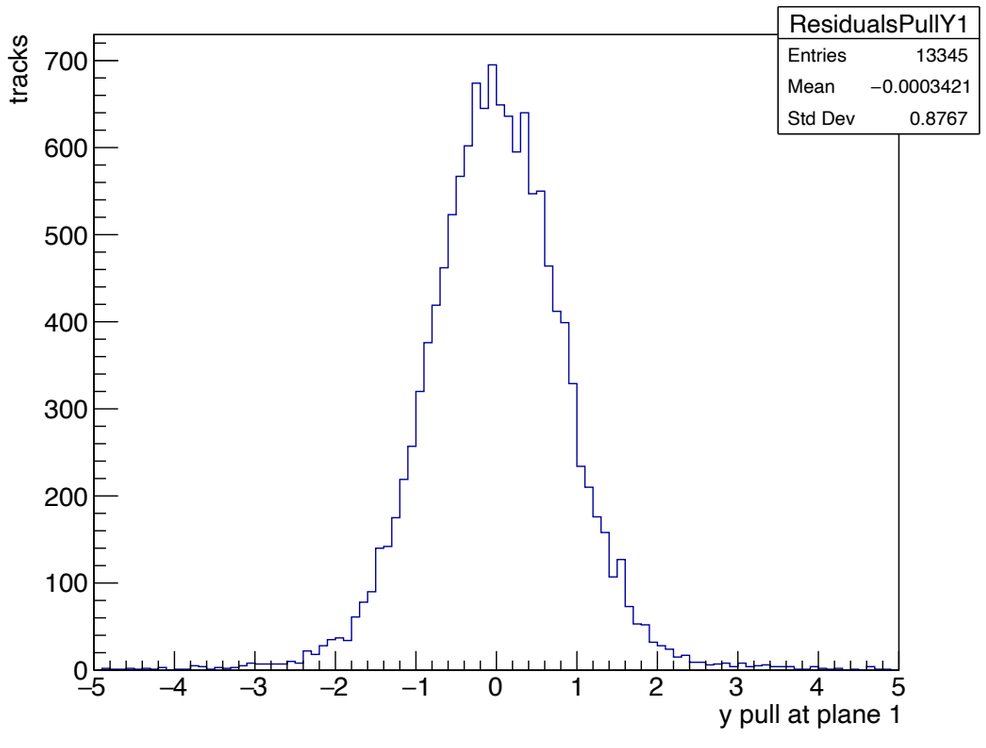


13° tilt angle

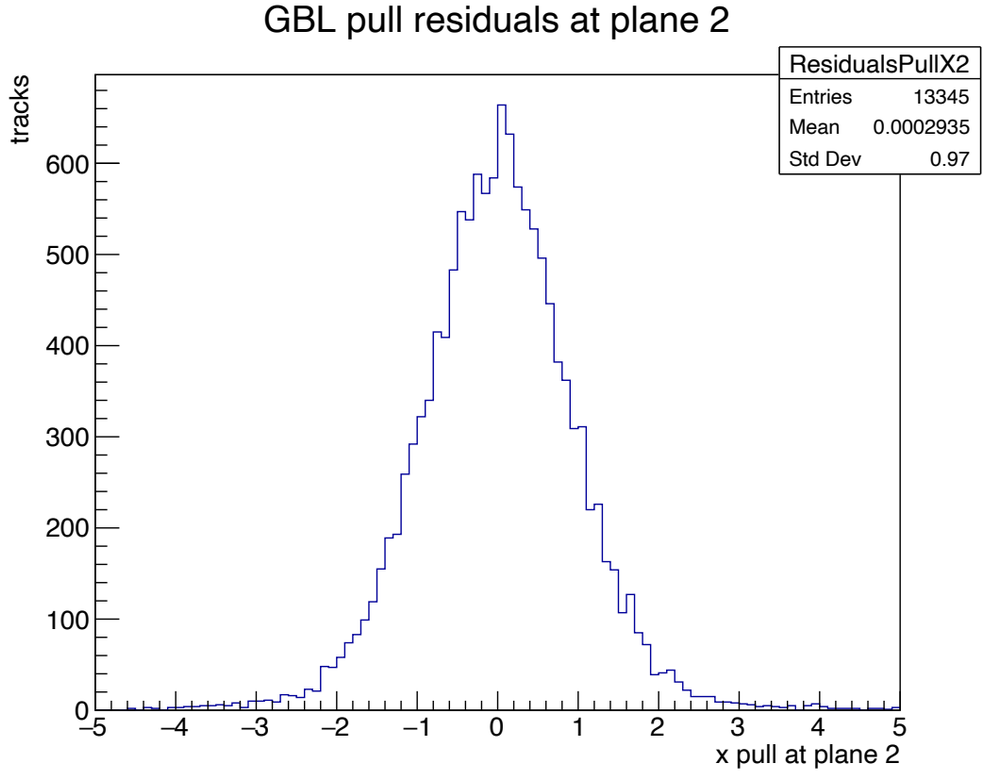
Pull distribution

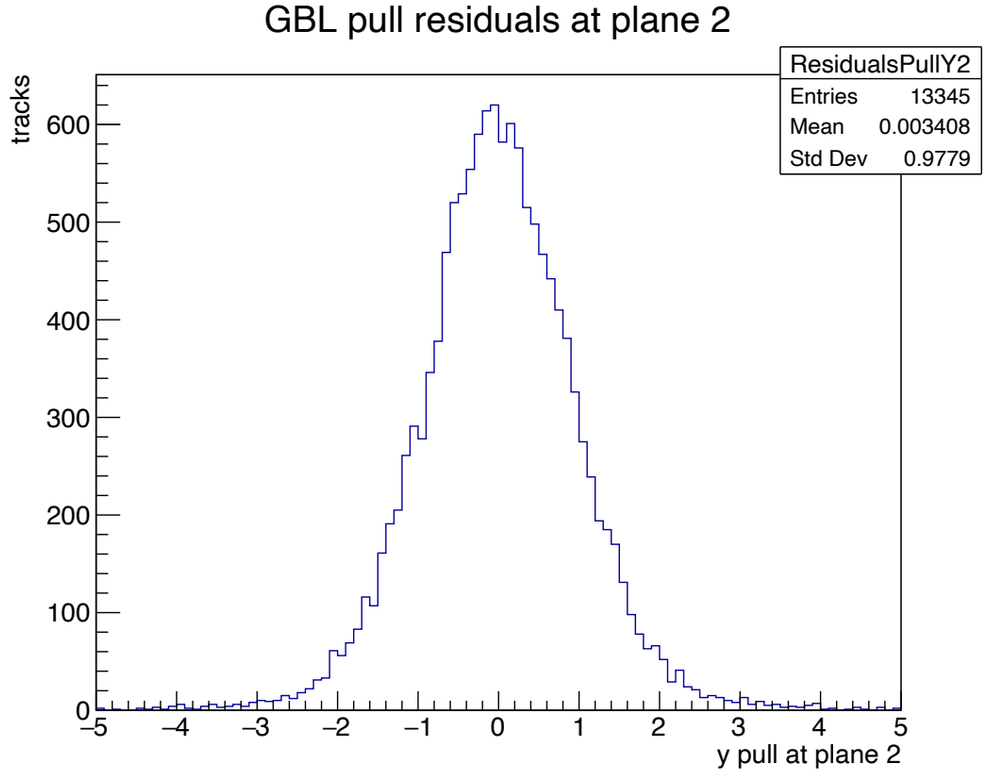


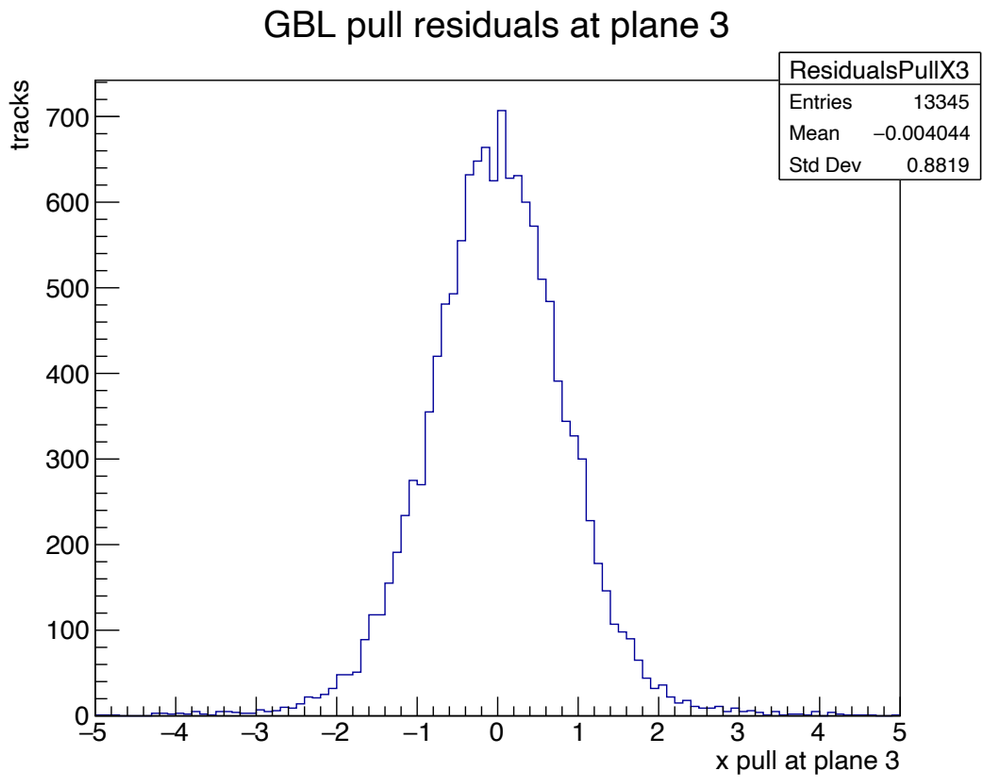


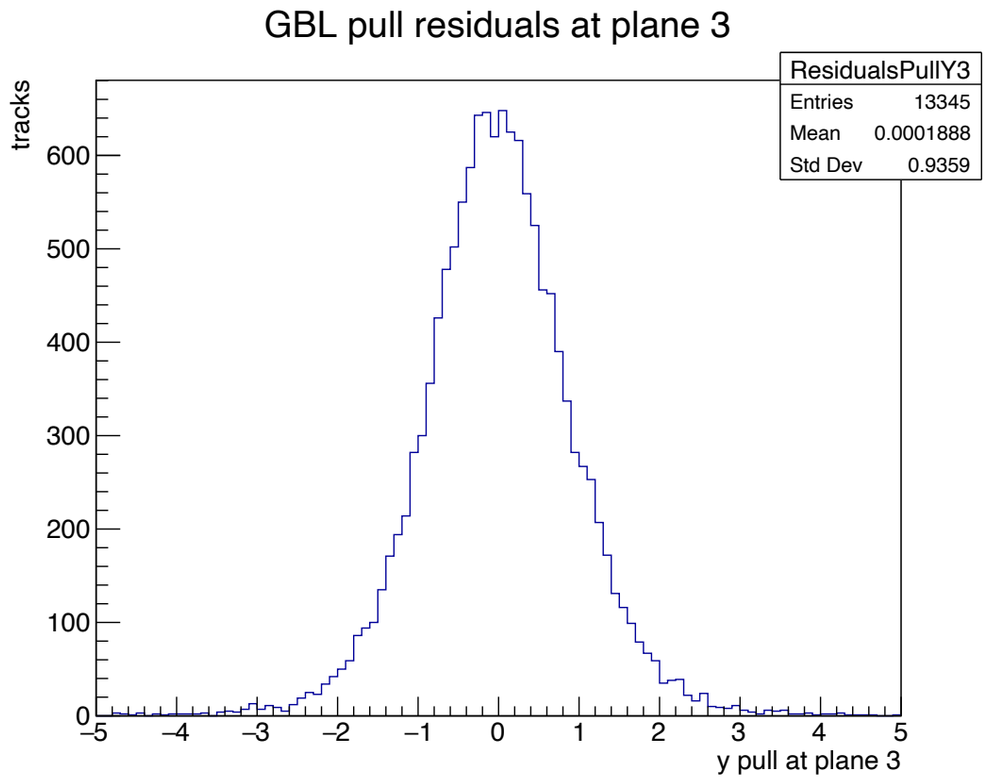


Pull distribution

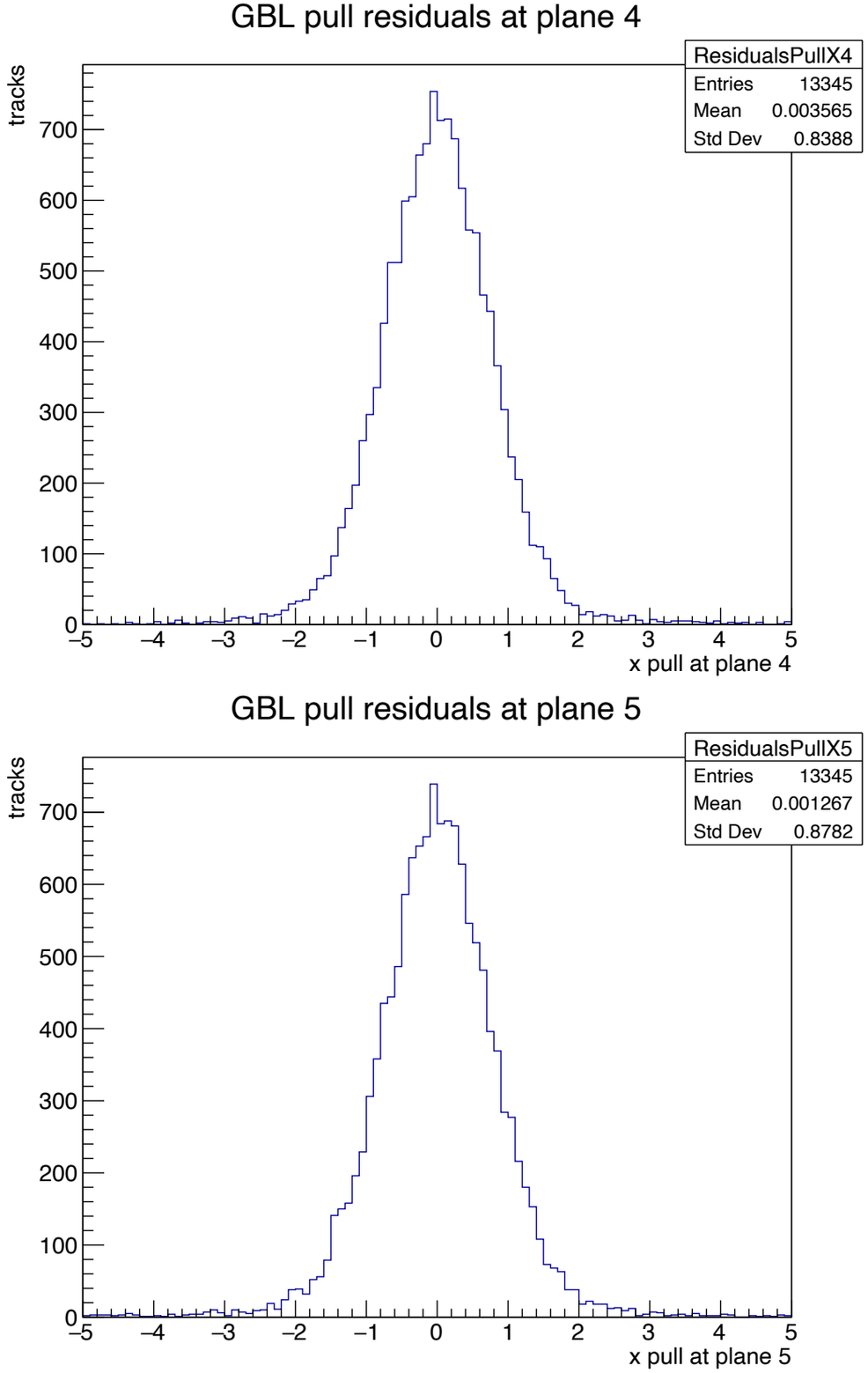


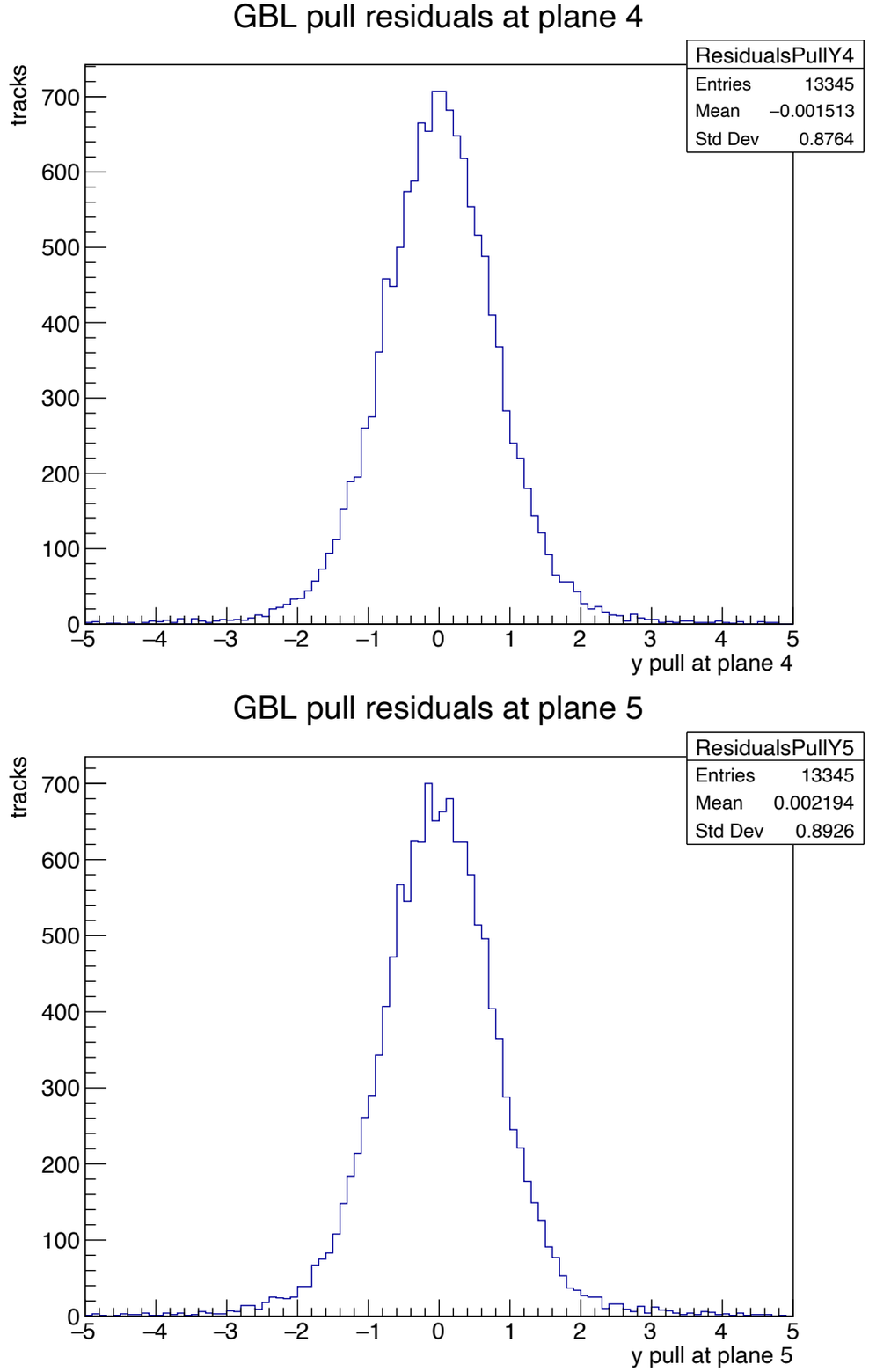






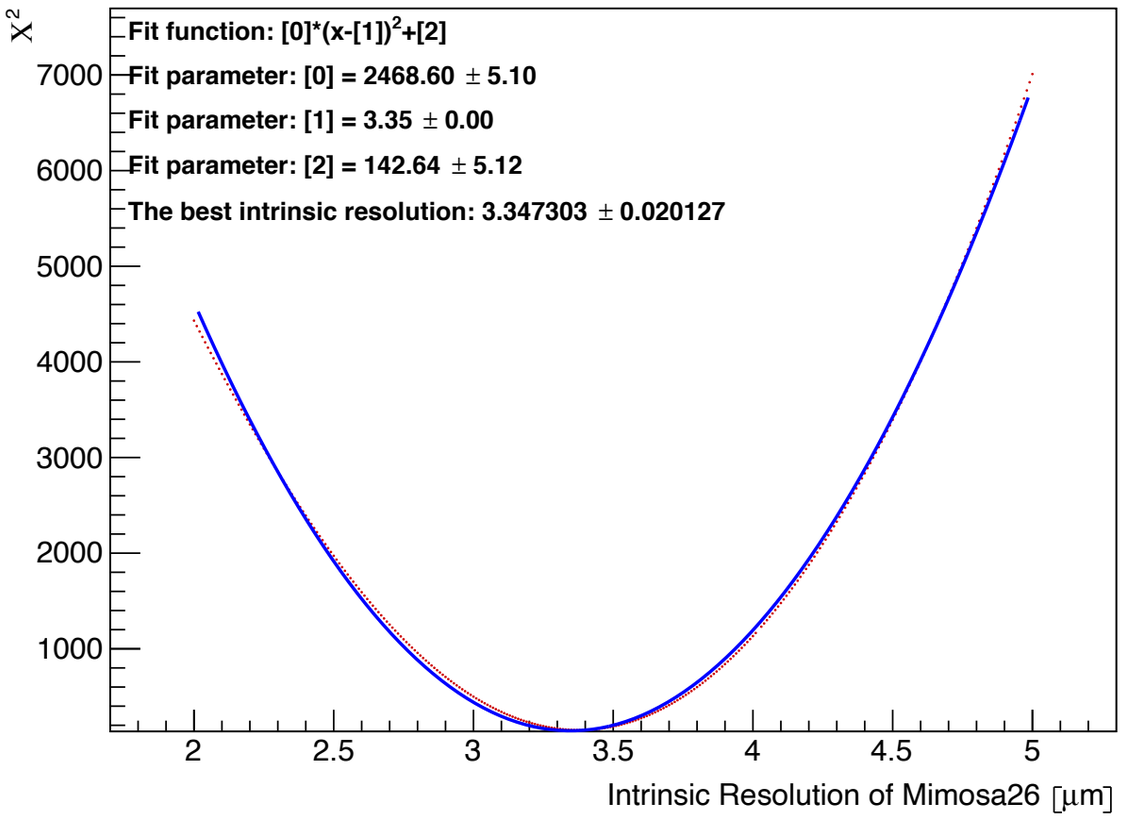
Pull distribution





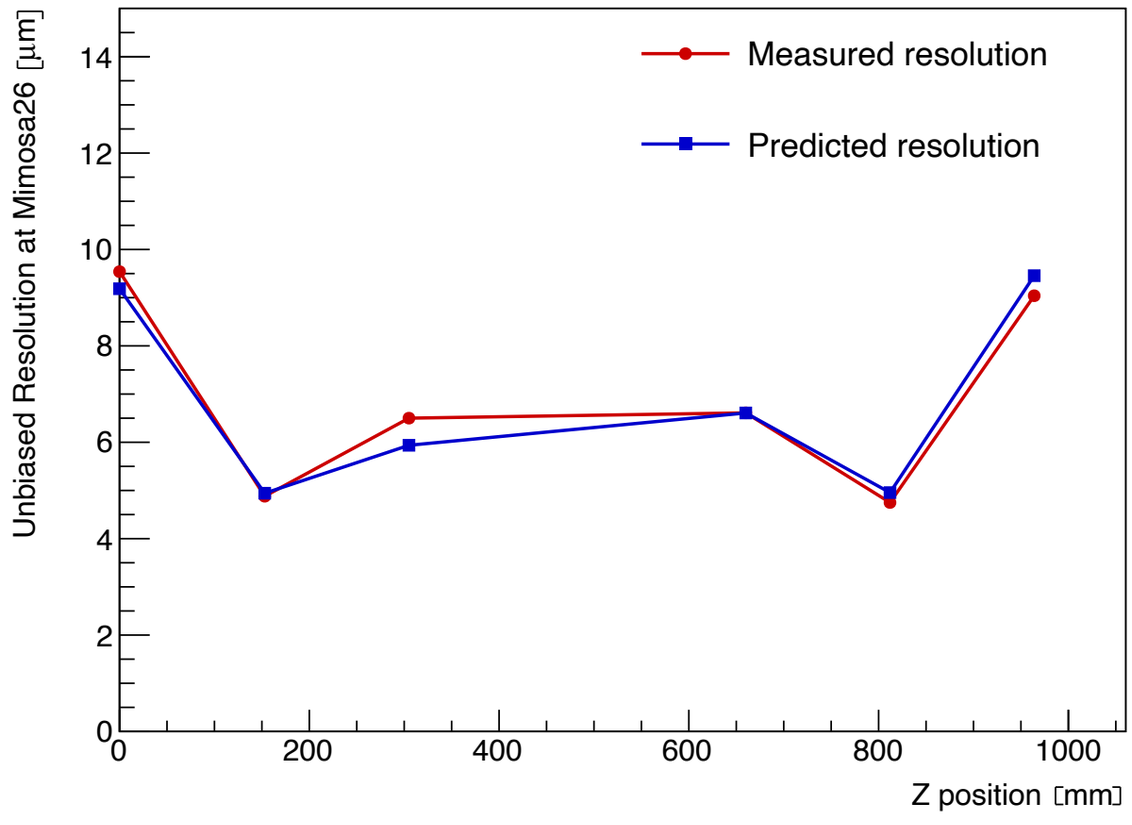
Tracking resolution based on simulator

- Scan intrinsic resolution of Mimosa26
- Simulate track resolution at each Mimosa26 plane
- Minimize the different between measured and calculated unbiased resolution



$$\chi^2 = \Sigma_i \frac{(\sigma_{unbiased,i} - \sqrt{\sigma^2_{intrinsic} + \sigma^2_{track,i}})^2}{V[\sigma_{unbiased,i}]}$$

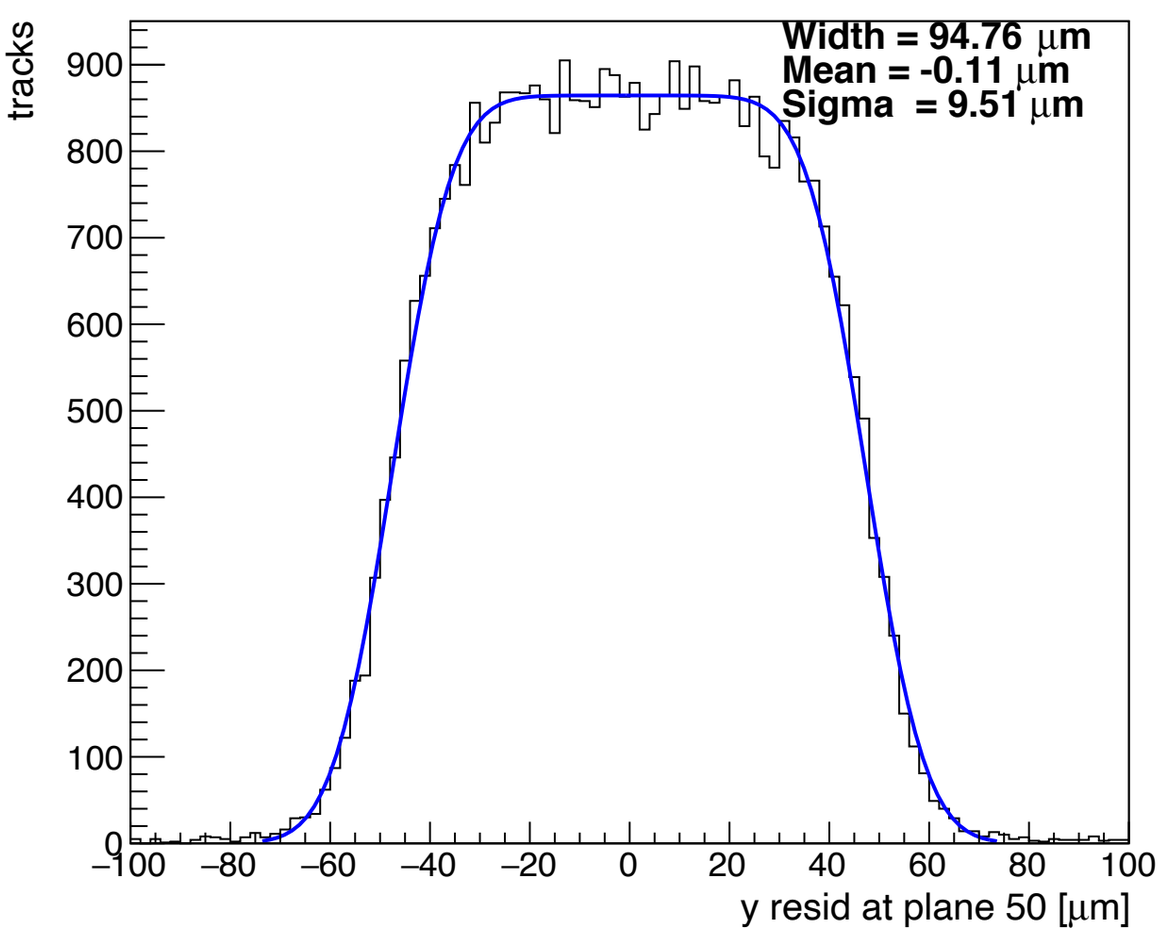
i are the six mimosa26



Use 3.35 micron as intrinsic resolution of Mimosa26 for predicted resolution

Intrinsic resolution

- With pitch of pixels increasing, the residuals should be fit by convolution of box and gaussian function



$$R_{unbiased} = R_{track} + R_{intrinsic}$$

$$\sigma^2(unbiased) = \sigma^2(track) + \sigma^2(intrinsic)$$

$$R_{unbiased} \approx Box(width) + Gauss(sigma)$$

$$\sigma^2(unbiased) = width^2/12 + sigma^2$$

$$\sigma^2(intrinsic) = width^2/12 + sigma^2 - \sigma^2(track)$$

Systematics

	RD53A 50μm×50μm non-tilted side(50μm)	RD53A 50μm×50μm tilted side(50μm)	RD53A 100μm×25μm non-tilted side(100μm)	RD53A 100μm×25μm tilted side(25μm)
10% variation of material on DUTs	0.13	0.12	0.03	0.07
track resolution	0.15	0.15	0.3	0.3
10% variation of beam energy	0.02	0.11	0.03	0.07
Z position+/-10 mm	1.03	1.02	0.6	1.7
total	1.05	1.04	0.67	1.73