

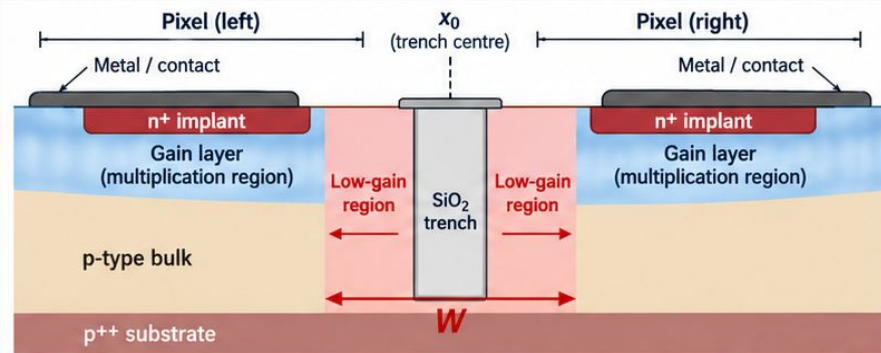
TI-LGAD Testbeam analysis update on wafer 11, 5 and 2

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02/10/26

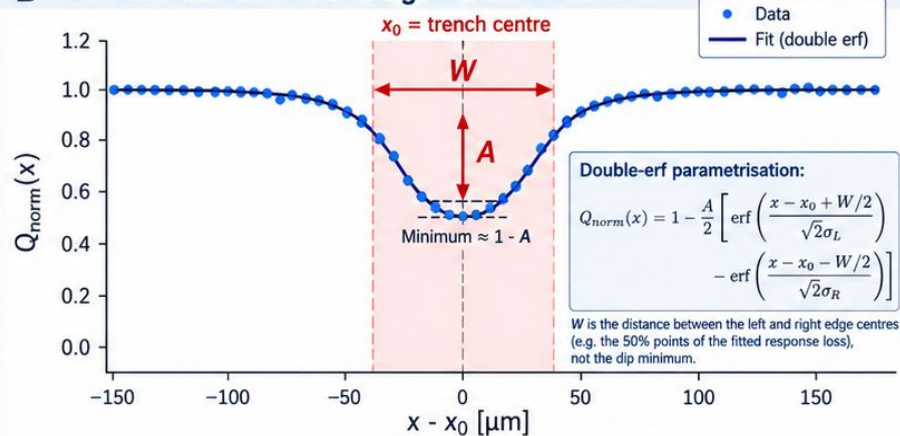
Conceptual parametrisation of TI-LGAD trench response

A TI-LGAD cross-section (two neighbouring pixels)

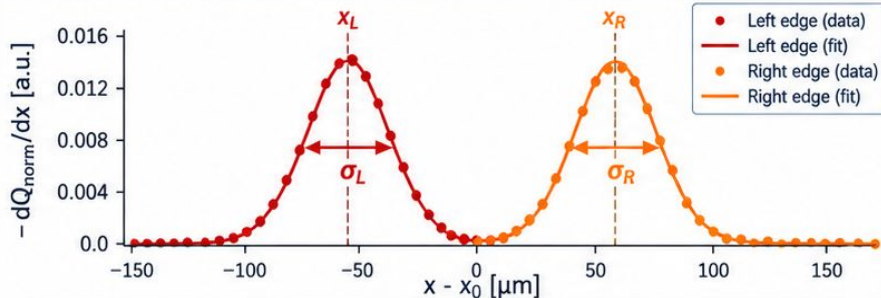


W is not the physical etched trench width only,
but the effective response-loss width extracted from the signal profile.

B Normalised collected charge across the trench

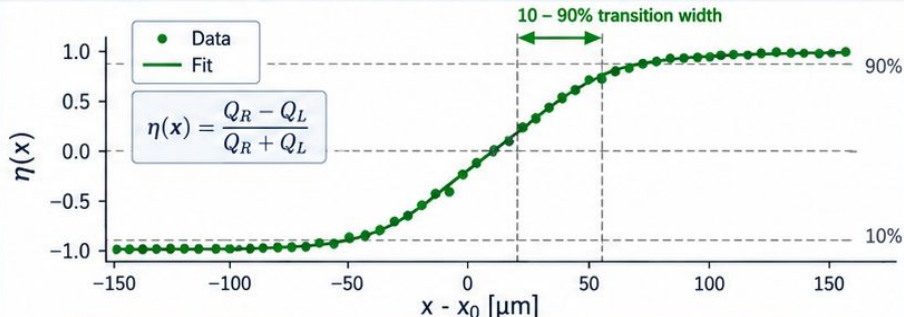


C Edge response and extraction of σ



σ_L and σ_R quantify edge broadening / transition sharpness;
they are extracted from the fitted left and right edges, even when the central response shows a dip.

D Charge-sharing across the trench



η provides an independent charge-sharing observable complementary to $Q_{\text{norm}}(x)$.

Parameter summary

x_0 : trench centre from the fit / symmetry point

W : effective trench-affected width

A : relative charge-loss amplitude

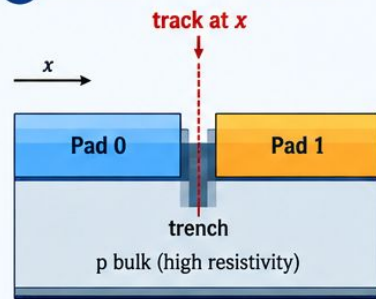
σ_L, σ_R : edge-transition widths

$\eta(x)$: charge-sharing observable

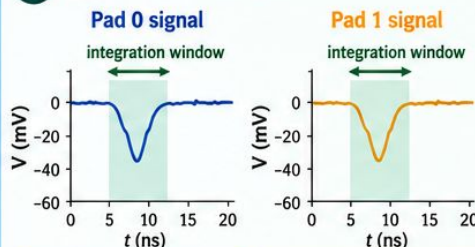
Applicable to both test beam and TCT scans

A From detector signals to normalised total response

1 Geometry and track position



2 Signals from both pads



$$Q_L(x) = \int_{t_1}^{t_2} V_L(t) dt$$

$$Q_R(x) = \int_{t_1}^{t_2} V_R(t) dt$$

3 Normalisation and total response

Each pad is normalised to its own bulk response (far from the trench):

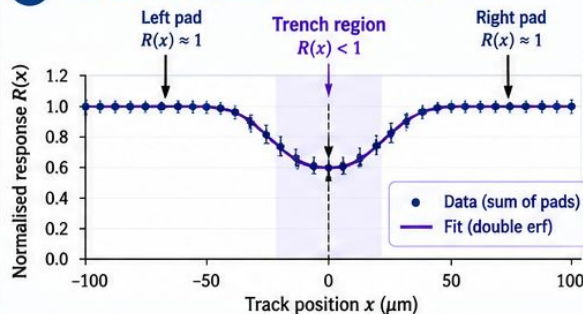
$$q_L(x) = \frac{Q_L(x)}{Q_{L,bulk}}$$

$$q_R(x) = \frac{Q_R(x)}{Q_{R,bulk}}$$

Total (charge-sharing independent) normalised response:

$$R(x) = q_L(x) + q_R(x)$$

4 Measured behaviour (typical example)



Response deficit:

$$D(x) = 1 - R(x)$$

- $R(x) \approx 1$ away from trench (full response)
- Dip at trench due to incomplete charge collection
- Charge sharing alone would give $R(x) \approx 1$ (no dip)

B Parametrisation with a double error function

1 Fitting function

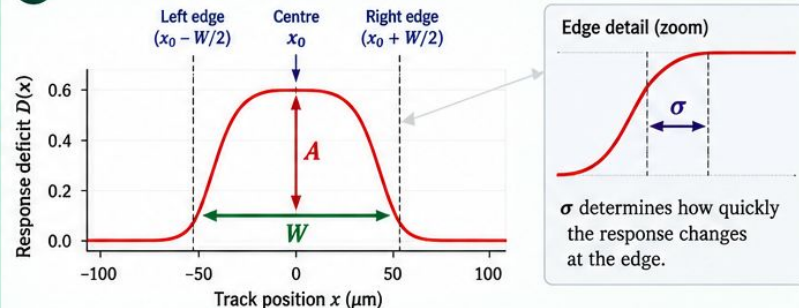
The response deficit $D(x)$ is described by a double error function:

$$D(x) = 1 - R(x) = \frac{A}{2} \left[\text{erf} \left(\frac{x - (x_0 - W/2)}{\sqrt{2}\sigma} \right) - \text{erf} \left(\frac{x - (x_0 + W/2)}{\sqrt{2}\sigma} \right) \right]$$

2 Meaning of the parameters

- x_0 – centre of the response deficit (trench position)
- A – depth of the response deficit (maximum loss, $0 \leq A \leq 1$)
- W – effective width of the affected region (distance between midpoints)
- σ – transition sharpness (controls the edge slope)

3 Visual meaning of W and σ



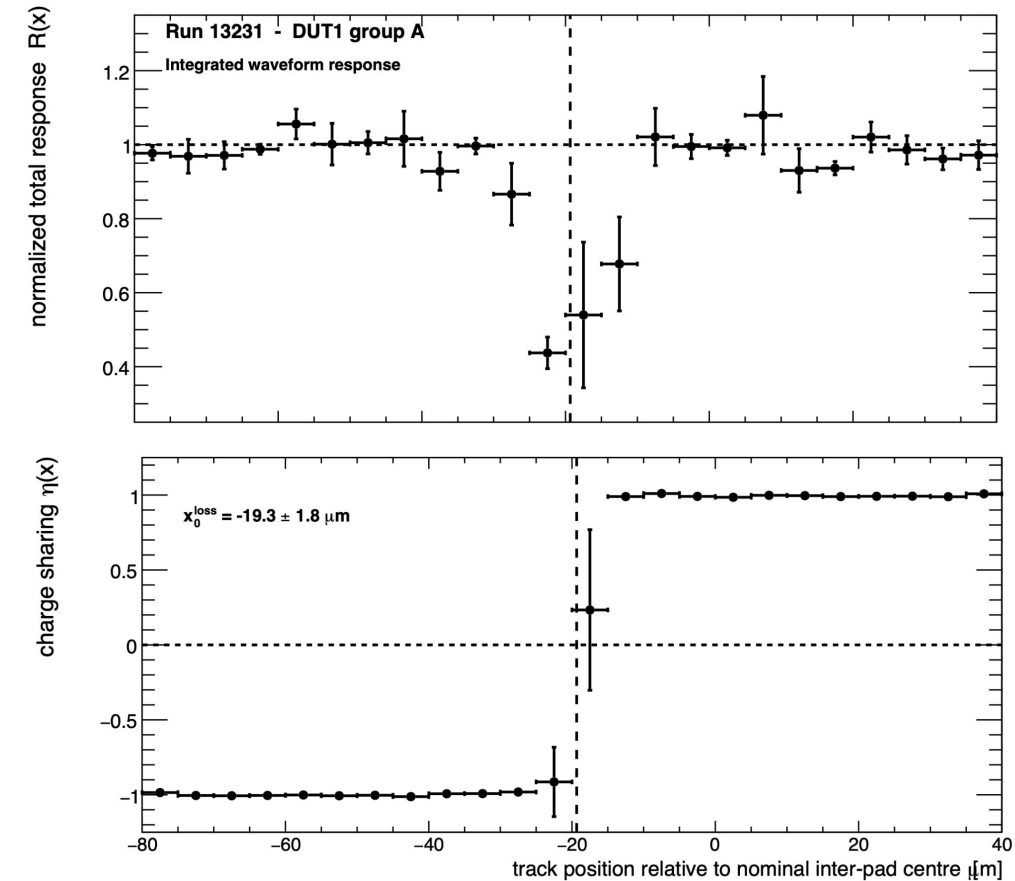
4 Figure of merit

Integrated response loss (area of the deficit):

$$F = A \cdot W$$

- Single, design-independent number
- Quantifies the overall impact of the trench
- Can be compared across different TI-LGAD designs

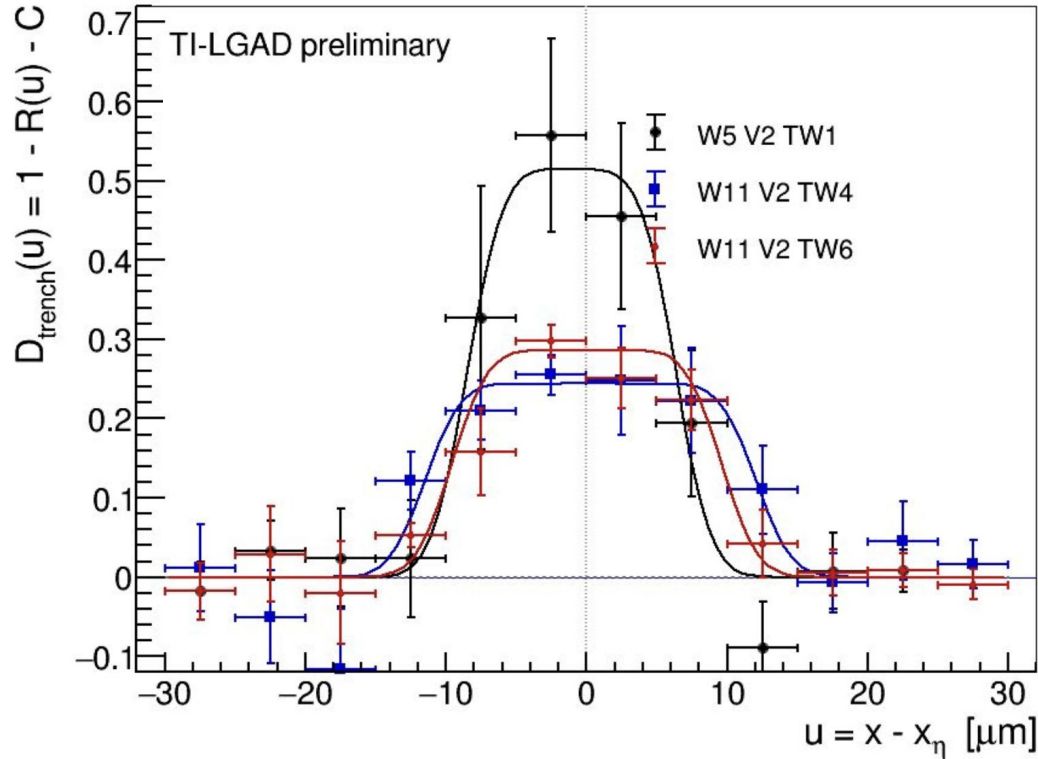
Testing the concept for wafer 5 (I)



$$r_L(x) = \frac{S_L(x)}{S_{L,\text{bulk}}}, \quad r_R(x) = \frac{S_R(x)}{S_{R,\text{bulk}}},$$
$$R(x) = r_L(x) + r_R(x)$$
$$\eta(x) = \frac{r_R(x) - r_L(x)}{r_R(x) + r_L(x)}$$

I normalize the integrated charge of each pad to its own bulk response. The sum $R(x)$ tells me whether charge is actually lost, while $\eta(x)$ tells me how the charge moves from one pad to the other.

Standardised TI-LGAD response-loss comparison



Common procedure

- Align each structure to the charge-sharing transition x_{η} :
 $\eta(x_{\eta})=0 \quad u=x-x_{\eta}$
- Same analysis for all structures: $5 \mu\text{m}$ bins, $|u| < 30 \mu\text{m}$ $\sigma=2 \mu\text{m}$
- The fitted response-loss centres are consistent with the charge-sharing centre:
 $u_0 \approx 0$

$$F = AW = \int D_{\text{trench}}(u) du$$

$$\begin{aligned} \text{W5 TW1} &: 7.66 \pm 1.92 \mu\text{m} \\ \text{W11 TW4} &: 5.85 \pm 1.13 \mu\text{m} \\ \text{W11 TW6} &: 5.42 \pm 0.66 \mu\text{m} \end{aligned}$$

The fitted $F=AW$ values are consistent with direct numerical integration, supporting F as a candidate common response-loss metric for TI-LGAD designs.

From measured inter-pixel efficiency to pitch impact

1 Measure $\epsilon(u)$

Use the two-pixel efficiency profile across the inter-pixel boundary. The local reference efficiency comes from nearby sidebands.

$$\epsilon(u) / \epsilon_{\text{local}}$$



2 Integrate deficit

Convert the efficiency dip into an equivalent fully inefficient width.

$$w_{\text{eff}}^{\epsilon} = \int [1 - \epsilon(u)/\epsilon_{\text{local}}] du$$



3 Scale to pitch

For one inter-pixel boundary per pitch, the equivalent 1D average loss is the effective width divided by the pitch.

$$L_{\epsilon}(p) = w_{\text{eff}}^{\epsilon} / p$$

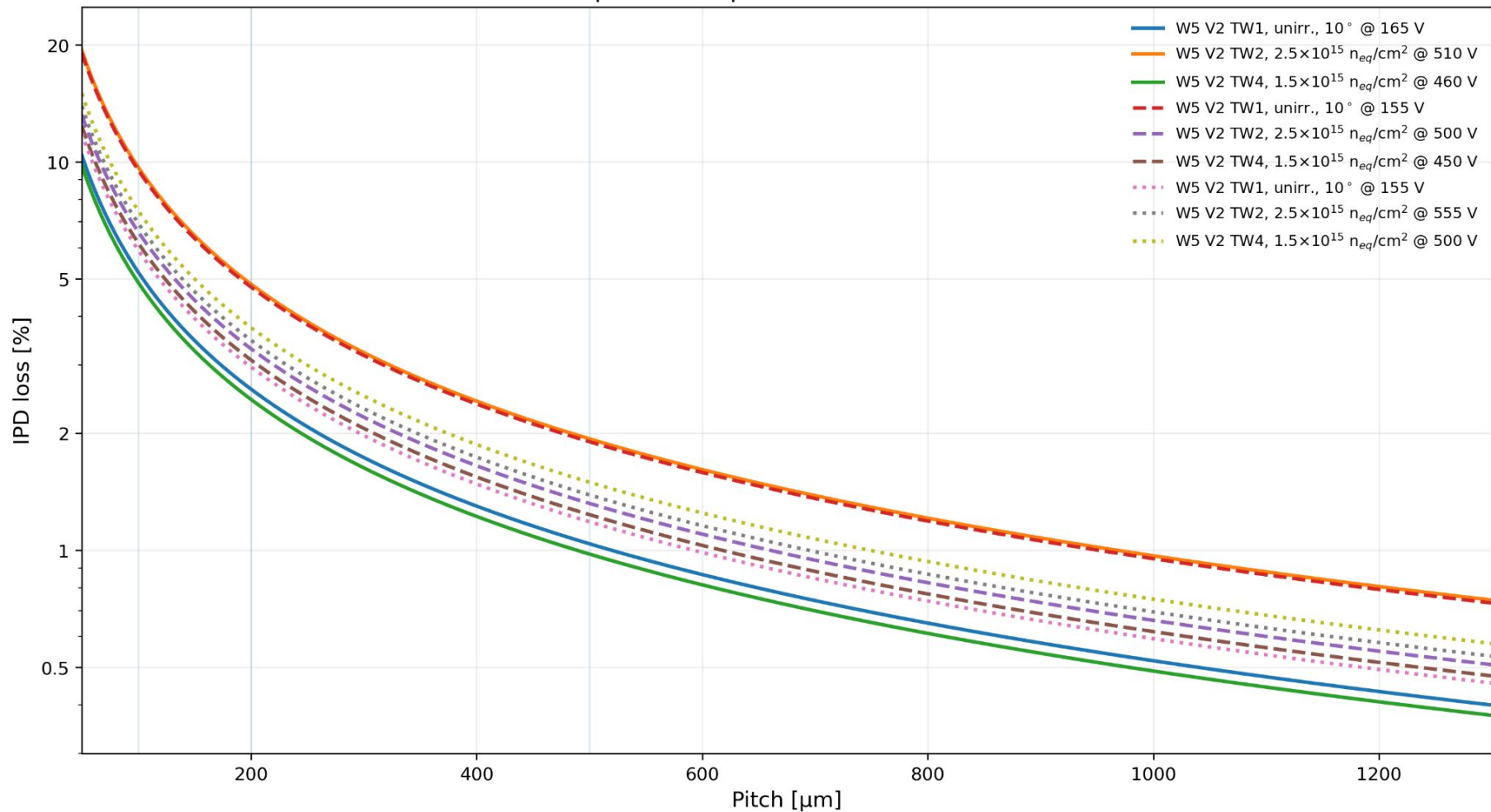
Interpretation

$w_{\text{eff}}^{\epsilon}$ is the width of an ideal zero-efficiency strip that would give the same integrated loss as the measured inter-pixel profile.

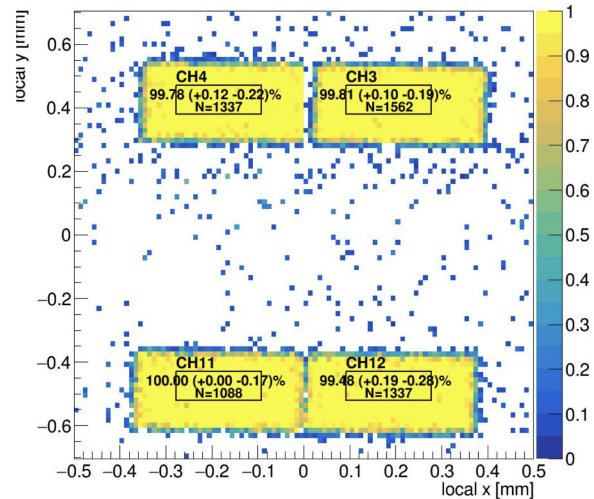
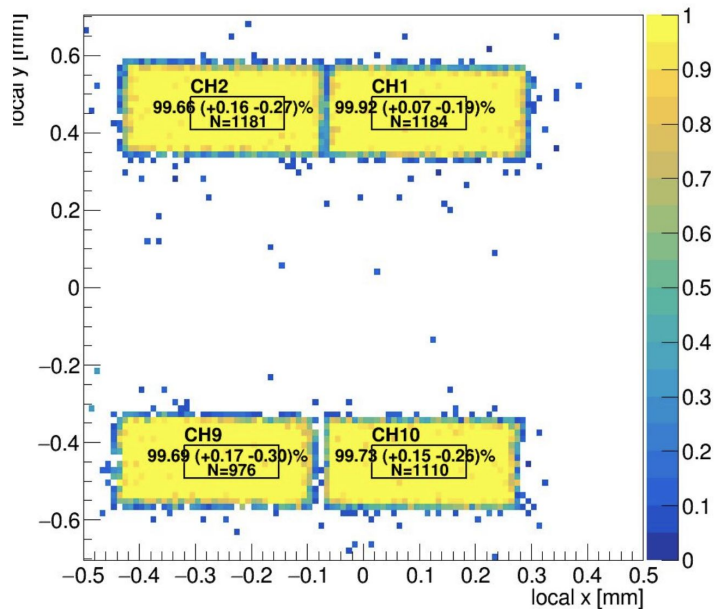
Quick numerical intuition

If $w_{\text{eff}}^{\epsilon} = 5 \mu\text{m}$: 5% at $p = 100 \mu\text{m}$ •
2.5% at $200 \mu\text{m}$ • 1% at $500 \mu\text{m}$

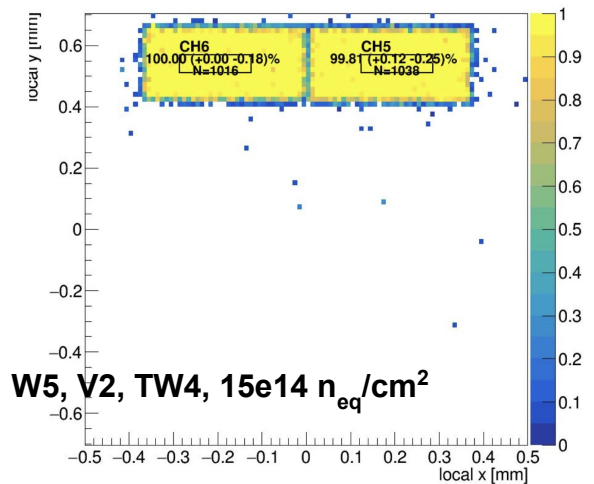
TI-LGAD pitch extrapolation — all validated runs



W5, V2, TW1-2, $0e14$ n_{eq}/cm^2 , angled at 10°

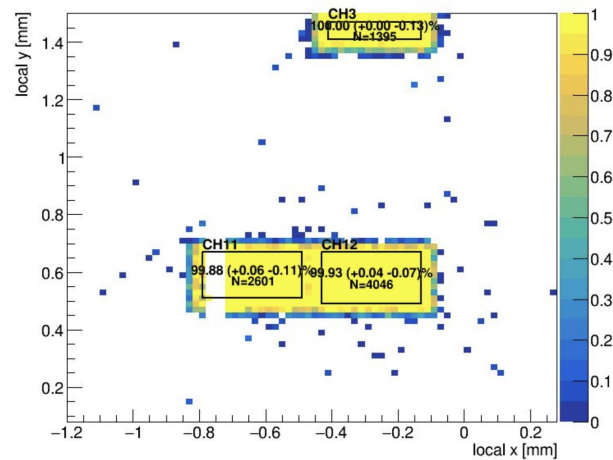
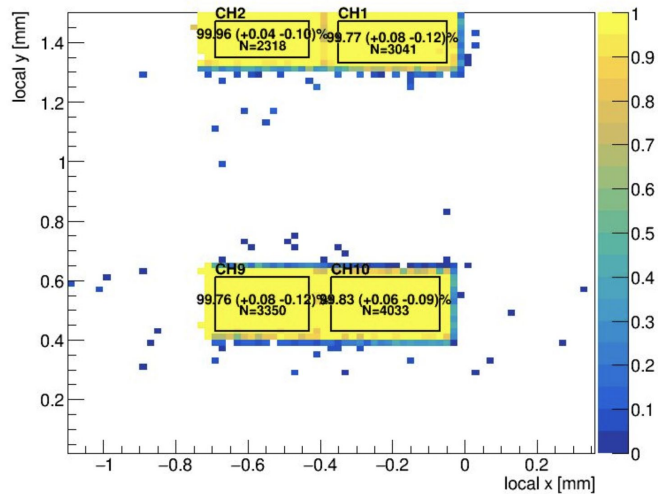


W5, V2, TW2-3, $25e14$ n_{eq}/cm^2

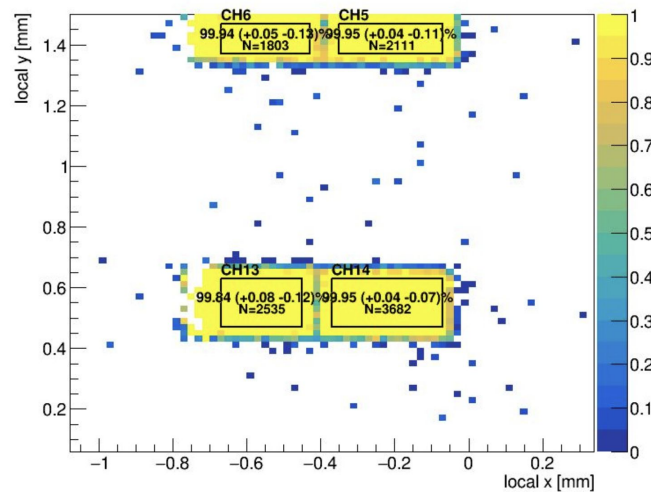


W5, V2, TW4, $15e14$ n_{eq}/cm^2

W11, V2, TW 4/6, $0e14 \text{ n}_{\text{eq}}/\text{cm}^2$

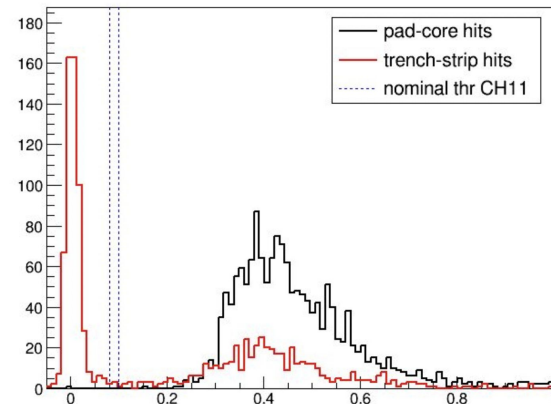
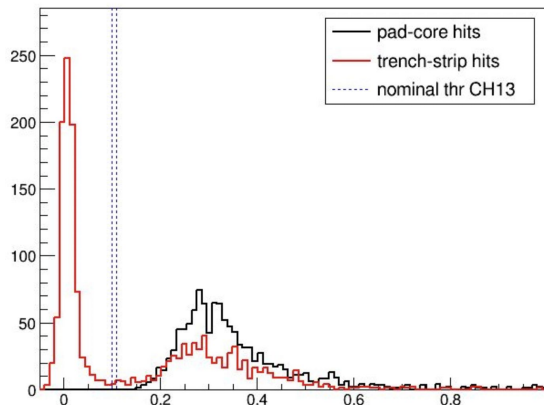
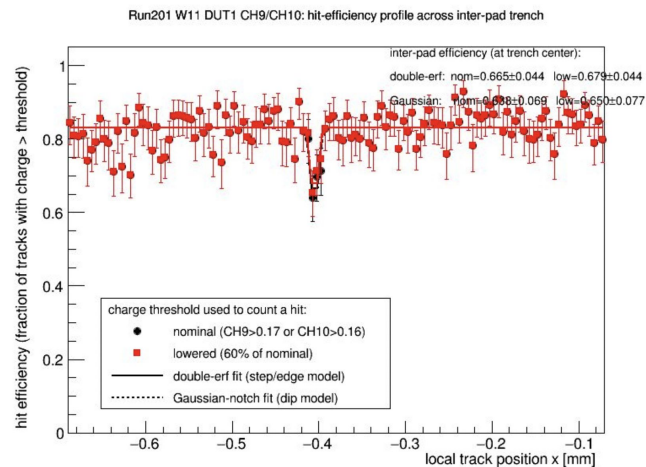


W11, V2, TW 1/2, $0e14 \text{ n}_{\text{eq}}/\text{cm}^2$

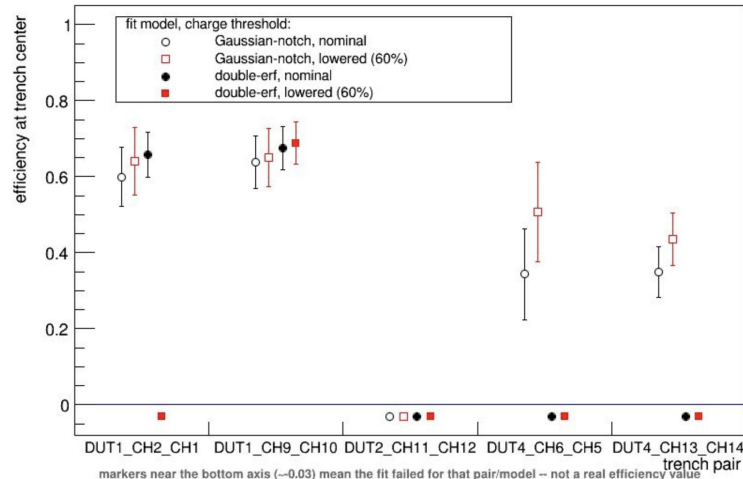
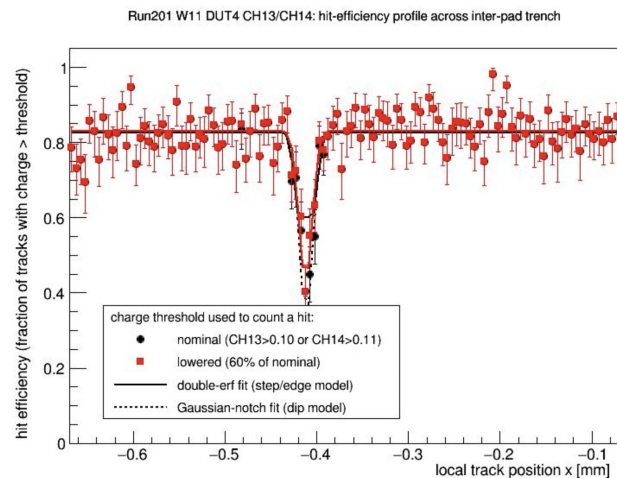


W11, V3/4, TW5, $0e14 \text{ n}_{\text{eq}}/\text{cm}^2$

IPD results for wafer 11 V2 and V3/4

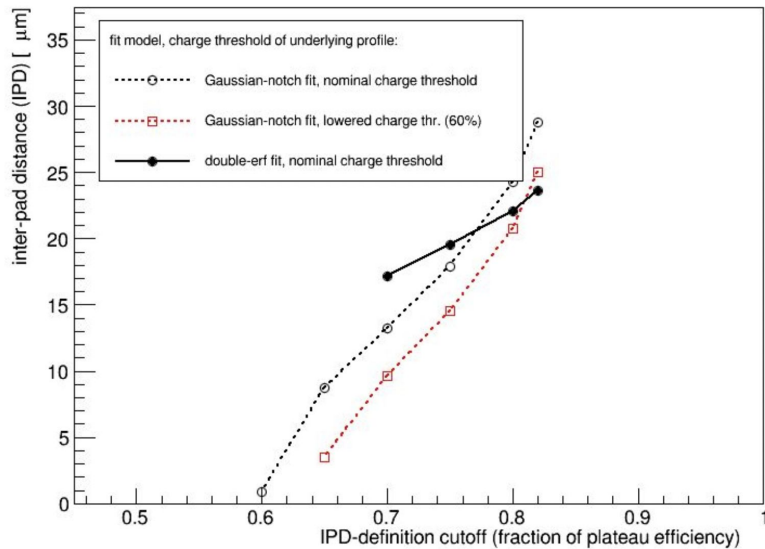


Run201 W11: inter-pad efficiency at trench center, all pairs

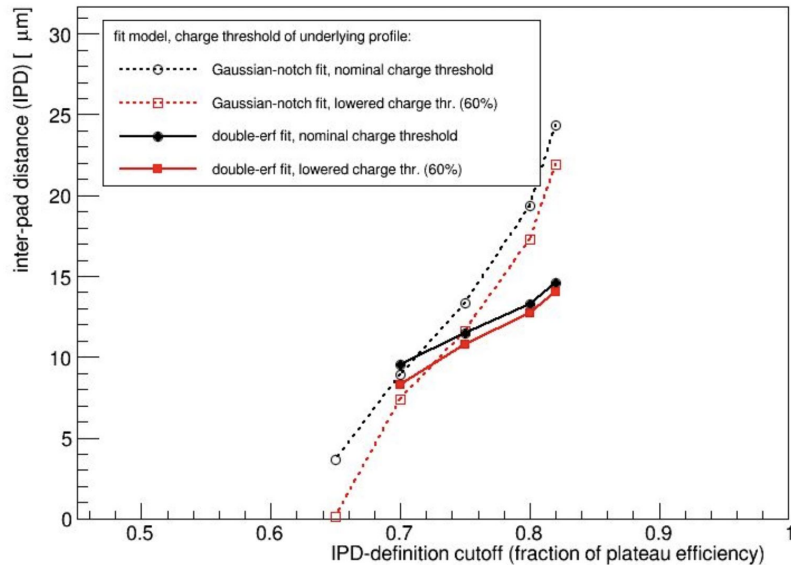


Wafer 11 V2 and V3/4

Run201 W11 DUT1 CH2/CH1: inter-pad distance vs IPD-definition cutoff

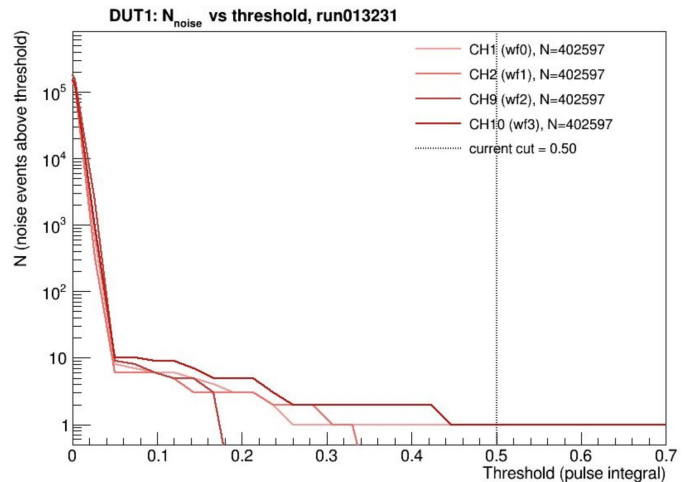


Run201 W11 DUT1 CH9/CH10: inter-pad distance vs IPD-definition cutoff

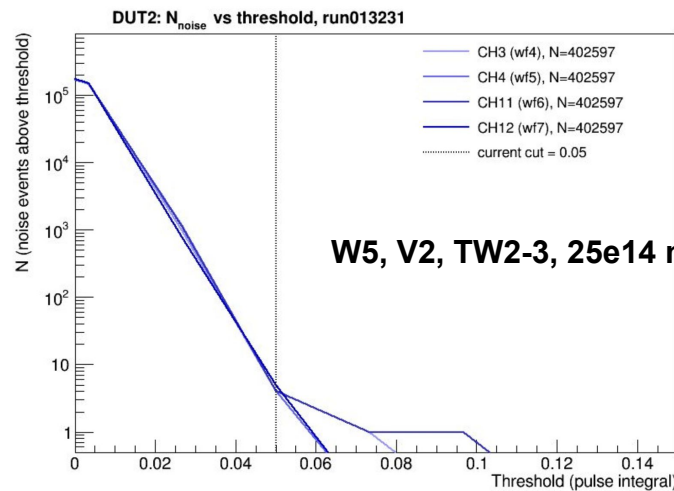


The lowered-threshold curve ($0.6 Q_{\text{thr}}$) is used to assess the sensitivity of the extracted IPD to the hit-threshold definition.

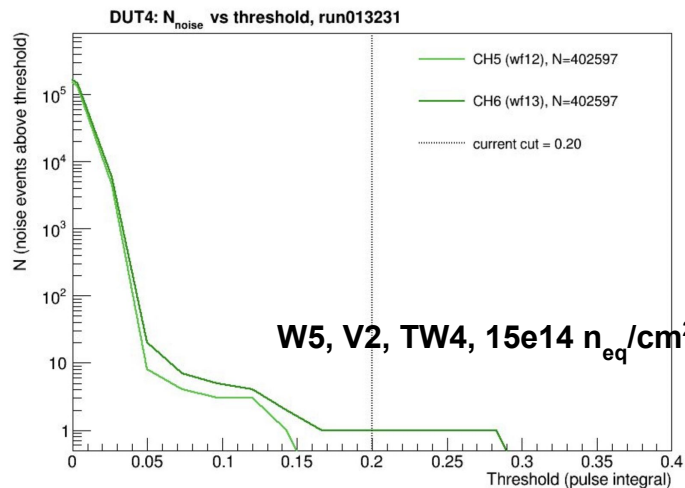
Wafer 5 analysis



W5, V2, TW1-2, $0e14 \text{ n}_{\text{eq}}/\text{cm}^2$, angled at 10°

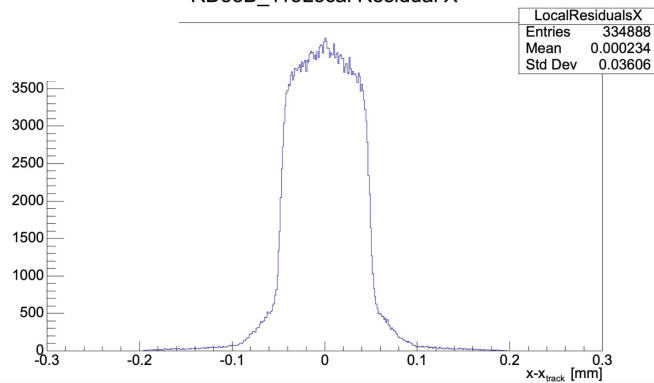


W5, V2, TW2-3, $25e14 \text{ n}_{\text{eq}}/\text{cm}^2$

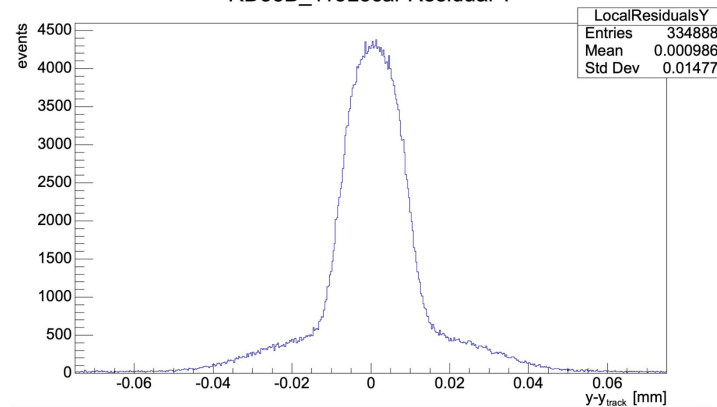


W5, V2, TW4, $15e14 \text{ n}_{\text{eq}}/\text{cm}^2$

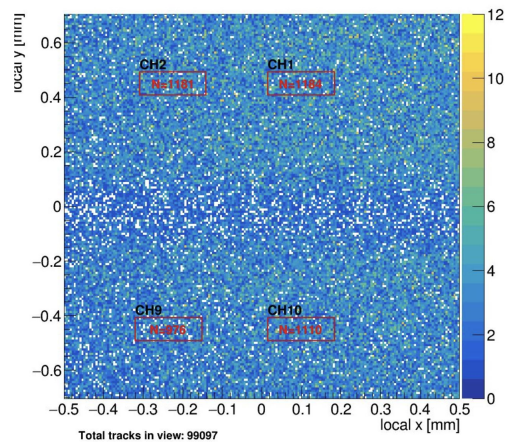
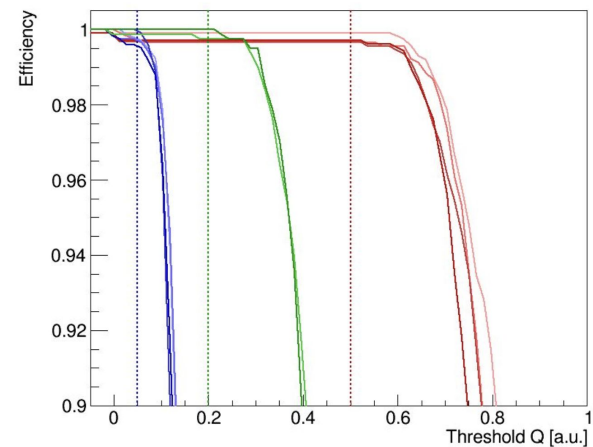
RD53B_115Local Residual X



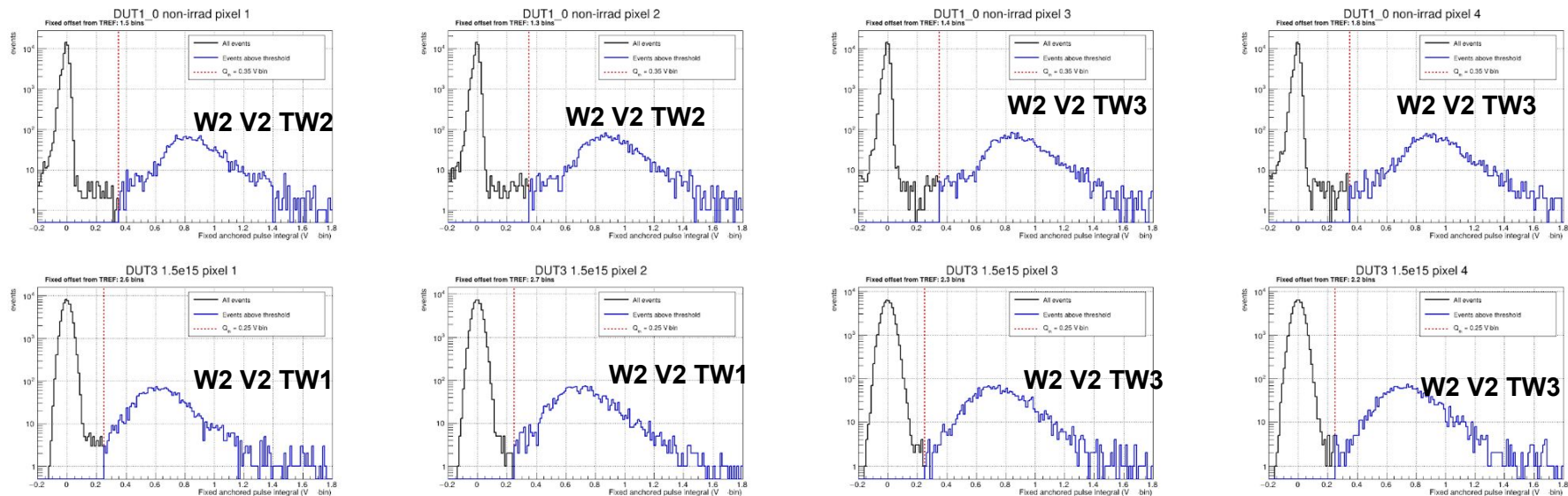
RD53B_115Local Residual Y



Tracks used - DUT1

DUT1: W5, V2, TW1-2, 0e14 n_{eq}/cm^2 , angled at 10° DUT2: W5, V2, TW2-3, 25e14 n_{eq}/cm^2 DUT4: W5, V2, TW4, 15e14 n_{eq}/cm^2 

Pulse-integral distributions for TI-LGAD pixels before and after irradiation



Top: non-irradiated DUT

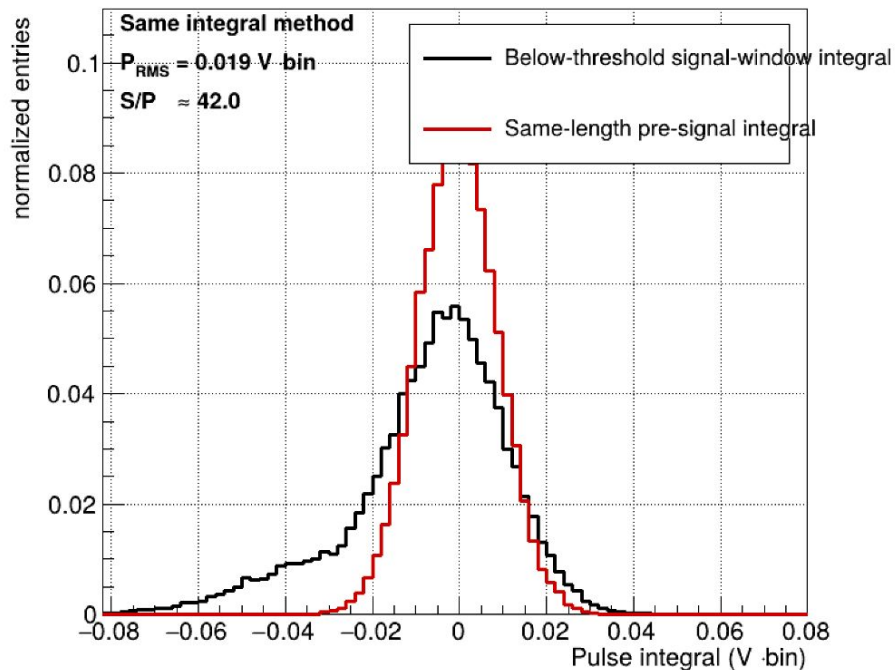
Bottom: DUT irradiated to $1.5 \times 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$

Black distributions contain all events, blue distributions show events passing the pulse-integral threshold

Pedestal Noise Comparison Before and After Irradiation

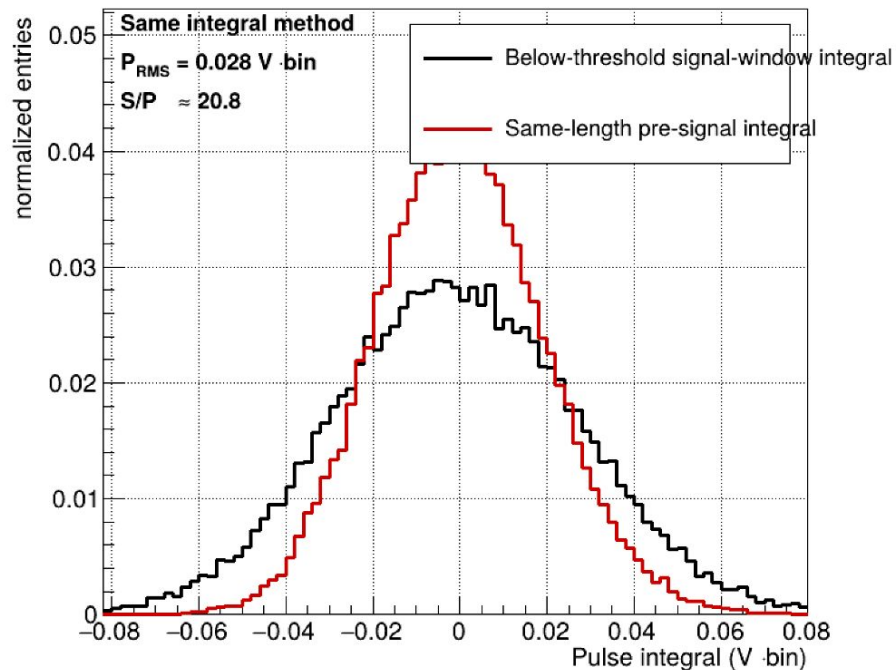
DUT1_0 non-irrad pixel 1

Pedestal-focused comparison



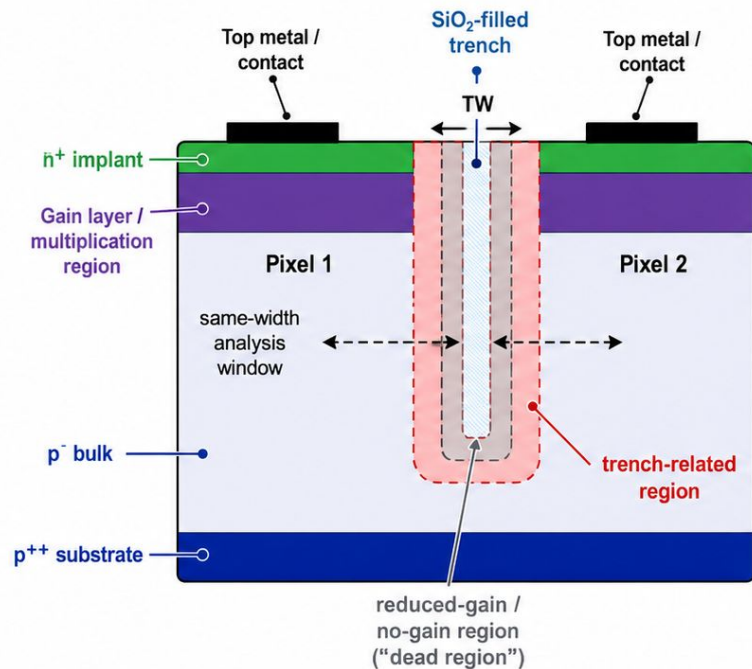
DUT3 1.5e15 pixel 1

Pedestal-focused comparison

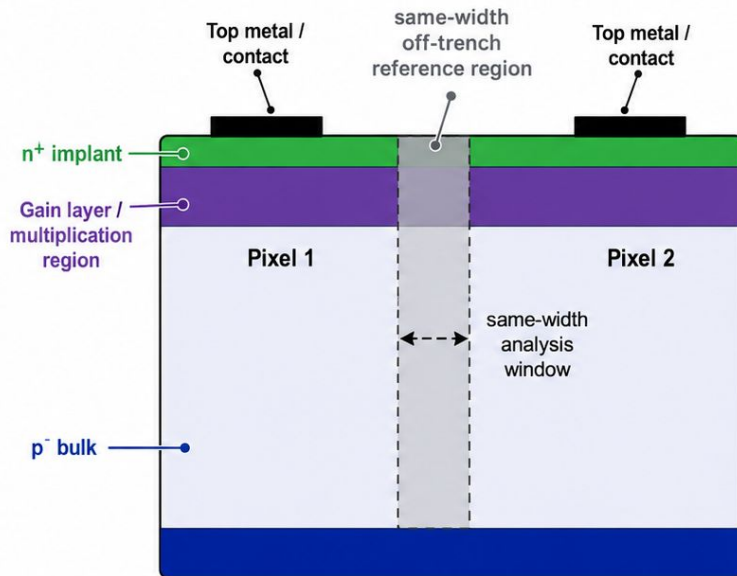


Analysis of trench and off-trench regions with tracks required

Trench region



Off-trench reference region



Red shading:
trench-related region

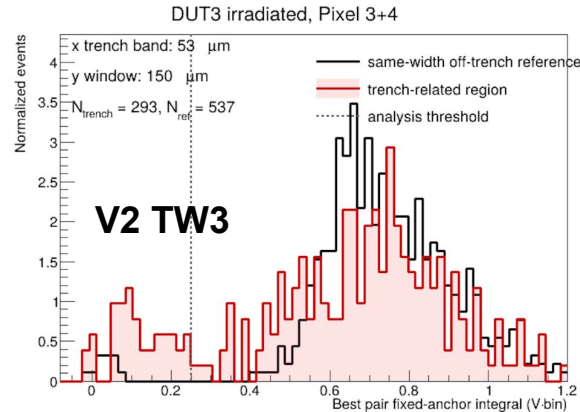
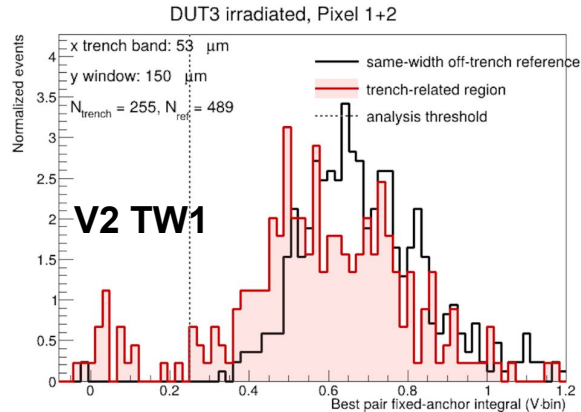
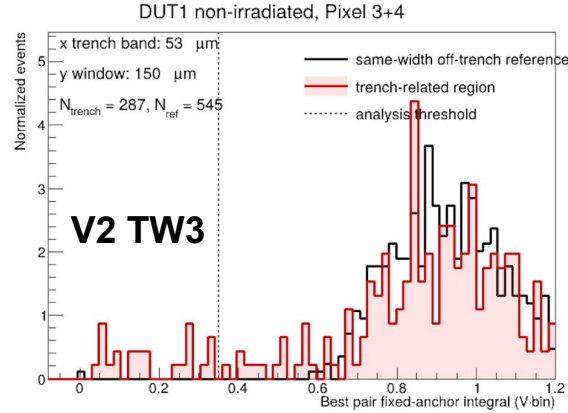
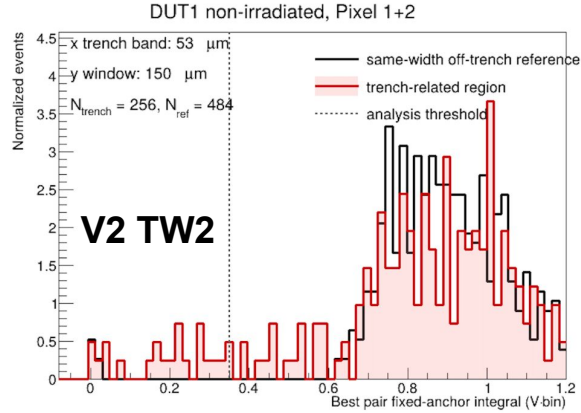


Gray shading:
same-width off-trench
reference region



Blue hatched fill:
 SiO_2 -filled trench

How does the trench-region signal spectrum compare to a nearby non-trench region?

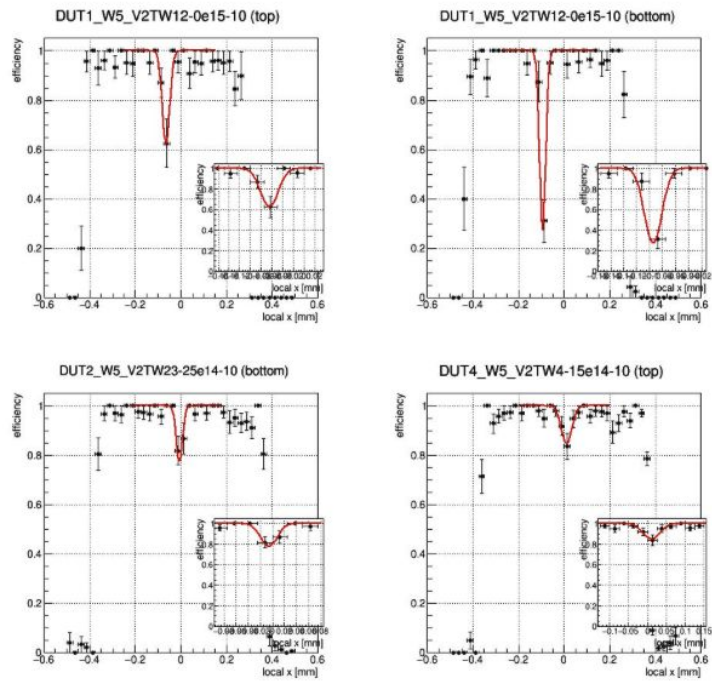


The trench-related region shows a lower-charge population than the off-trench reference region, which is consistent with the local efficiency loss.

x trench band: 53 μm

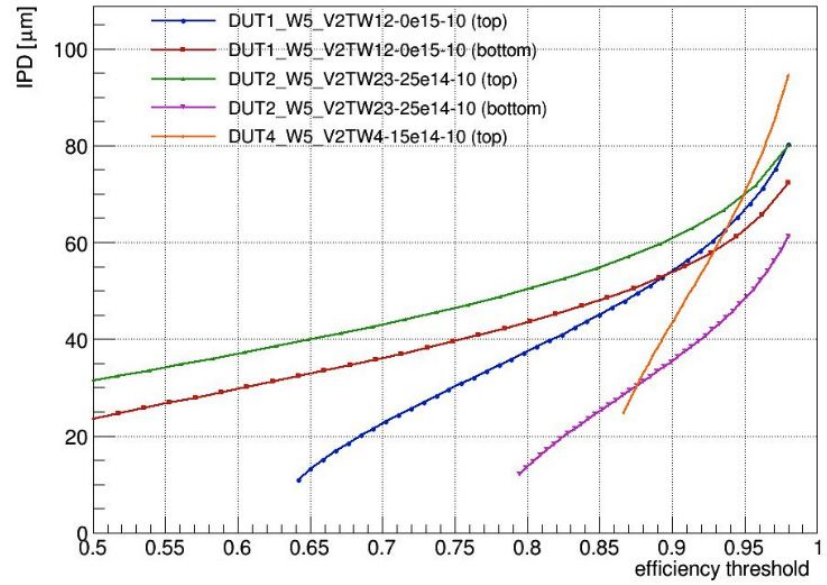
y trench band: 150 μm

Interpad distance evaluation



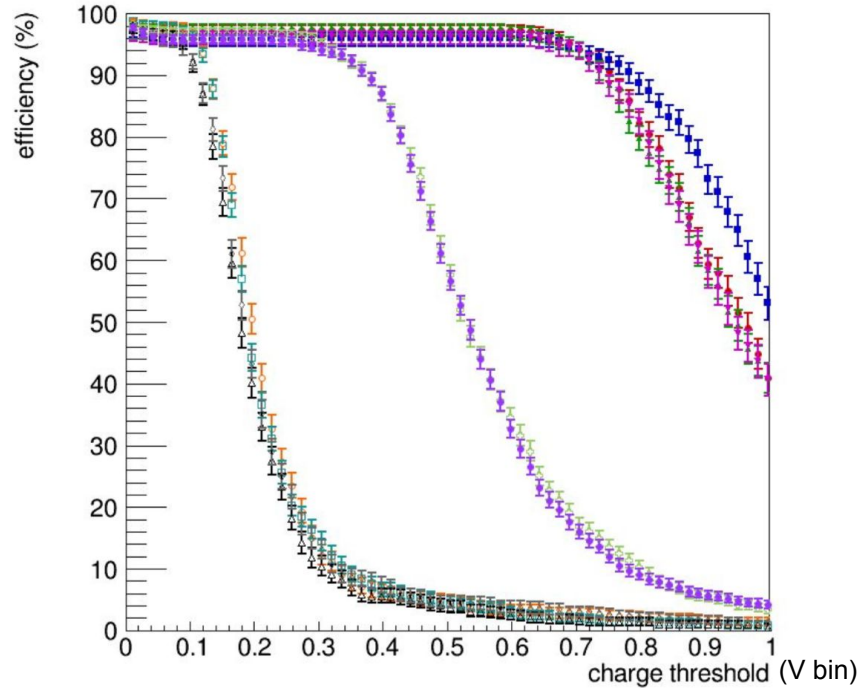
Effective IPD extracted from Gaussian fits to the interpad efficiency dip:

$$\varepsilon(x) = p - A \exp \left[-\frac{1}{2} \left(\frac{x - x_0}{\sigma} \right)^2 \right]$$



Per-pad centralized efficiency versus charge threshold

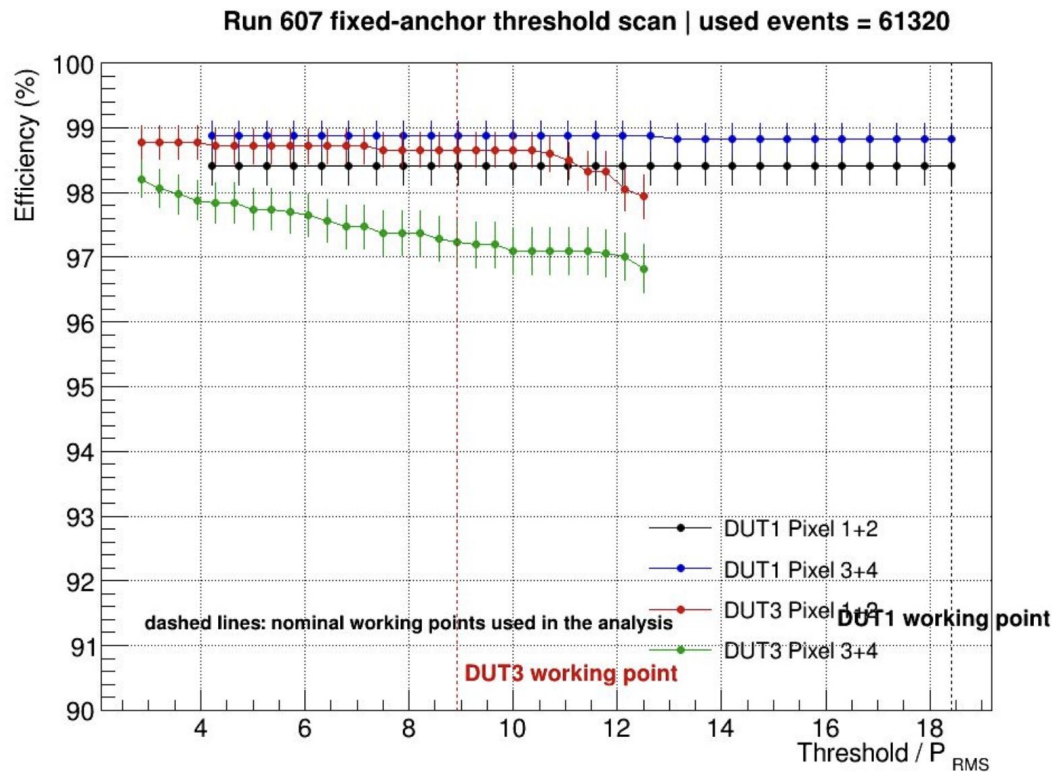
W5 TW2/3 $2.5e15 \text{ n}_{\text{eq}}/\text{cm}^2$ @ 550 V



- CH2: DUT1_W5_V2TW12-0e15-10 (top), thr=0.50
- CH1: DUT1_W5_V2TW12-0e15-10 (top), thr=0.50
- ▲ CH9: DUT1_W5_V2TW12-0e15-10 (bottom), thr=0.50
- ▼ CH10: DUT1_W5_V2TW12-0e15-10 (bottom), thr=0.50
- CH4: DUT2_W5_V2TW23-25e14-10 (top), thr=0.05
- CH3: DUT2_W5_V2TW23-25e14-10 (top), thr=0.05
- △ CH11: DUT2_W5_V2TW23-25e14-10 (bottom), thr=0.05
- ◇ CH12: DUT2_W5_V2TW23-25e14-10 (bottom), thr=0.05
- ◇ CH6: DUT4_W5_V2TW4-15e14-10 (top), thr=0.12
- CH5: DUT4_W5_V2TW4-15e14-10 (top), thr=0.12

$$N_{\text{tracks}} = 383262$$

Detector efficiency at different threshold in units of Pedestal Noise RMS

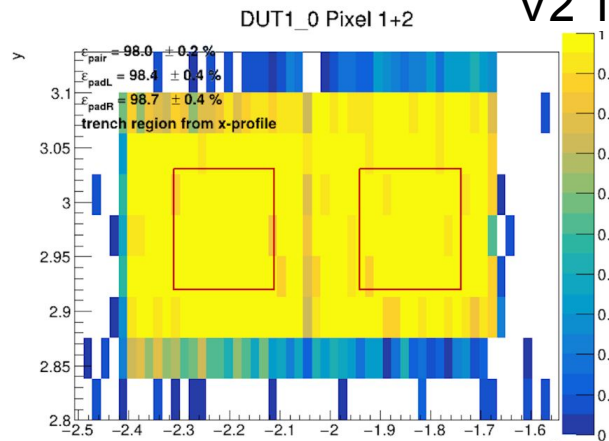


DUT1: W2 V2 TW 2/3 $0e15 n_{eq}/cm^2$

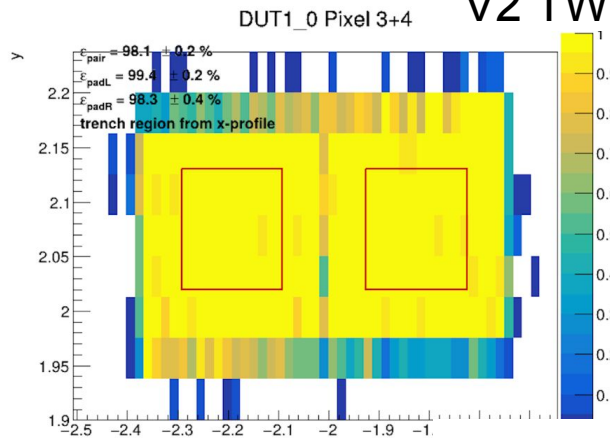
DUT3: W2 V2 TW 1/3 $1.5e15 n_{eq}/cm^2$

Efficiencies

V2 TW2



V2 TW3

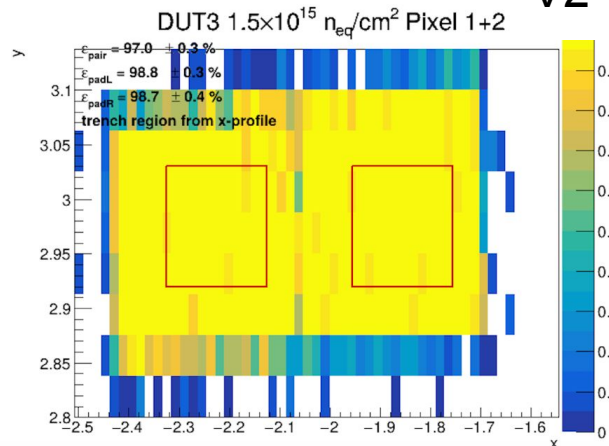


@ 165 V

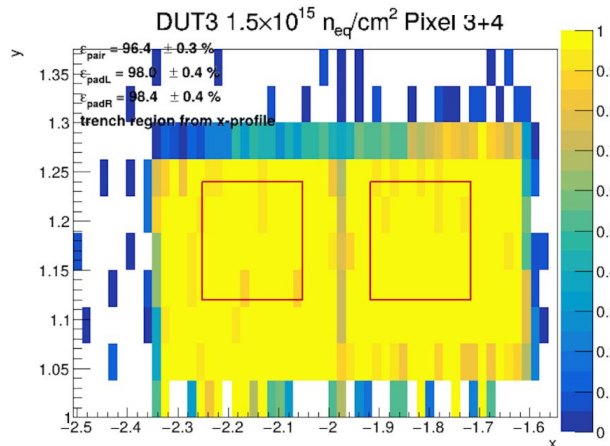
Temperature of -23.72 °C

- Pad-only ROIs exclude the trench
Left and right pad efficiencies
quoted separately
- Pair inefficiency is partly driven by
the trench region

V2 TW1



V2 TW3

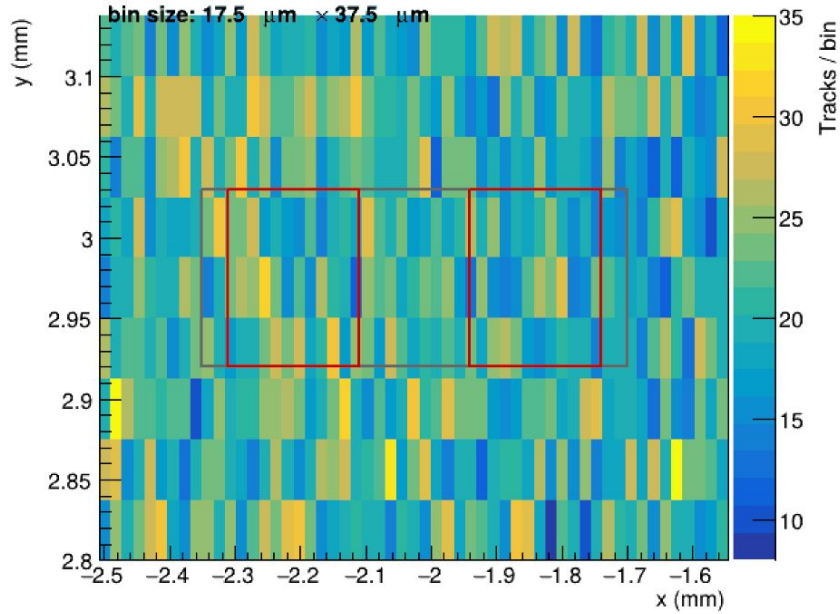


@ 495 V

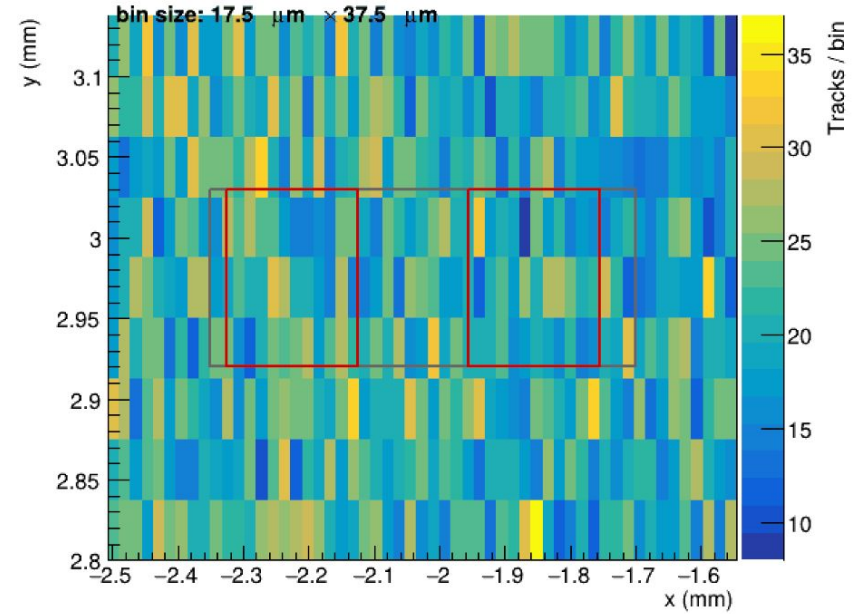
276,813 waveform events
61,311 used (after track matching +
TREF anchor)

Binning: 17.5 μm $\times$ 37.5 μm

DUT1_0 Pixel 1+2 track statistics



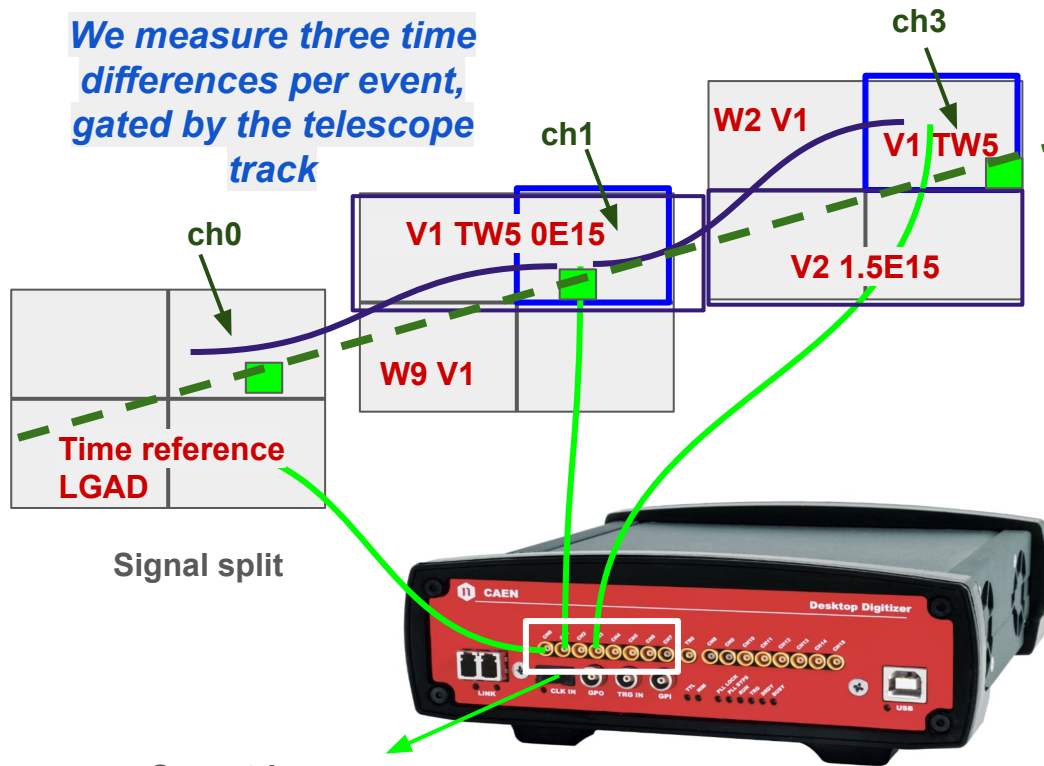
DUT3 $1.5 \times 10^{15} n_{\text{eq}}/\text{cm}^2$ Pixel 1+2 track statistics



- Track-statistics map shown to indicate local entries per bin-> Typical local statistics: about 17 tracks/bin

Tracking-Gated¹ Timing Results Explanation

We measure three time differences per event, gated by the telescope track



For each event, the track is interpolated across the three sensors, and the time differences between their signals are calculated.

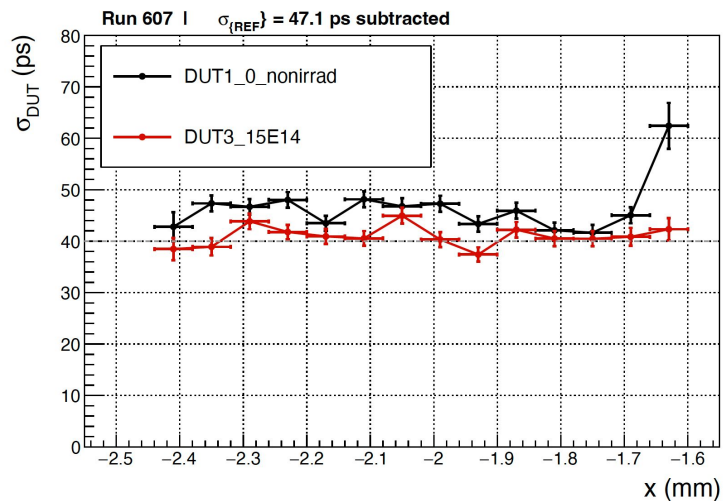
- $A = t(\text{ch1}) - t(\text{ch0})$ (non-irradiated DUT - REF)
- $B = t(\text{ch3}) - t(\text{ch0})$ (irradiated DUT - REF)
- $C = t(\text{ch1}) - t(\text{ch3})$ (DUT - DUT, REF-independent)

Triplet system equations:

$$A^2 = \sigma_1^2 + \sigma_R^2, \quad B^2 = \sigma_3^2 + \sigma_R^2, \quad C^2 = \sigma_1^2 + \sigma_3^2$$

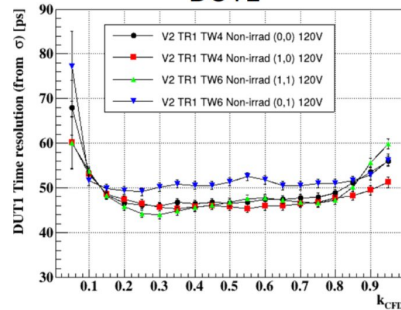
¹ Track gating is the process of keeping only data associated with valid particle tracks and rejecting unrelated or noisy events

Timing tracking-anchored results

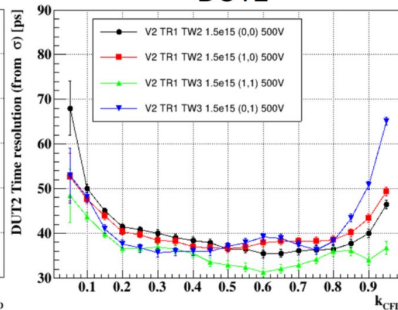


Batch 3: $\sigma_{\text{REF}} = 47.1$ ps (triplet method)

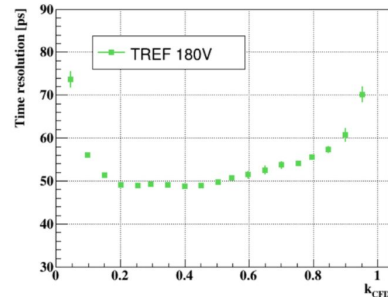
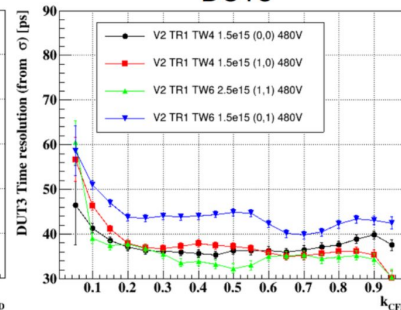
DUT1



DUT2



DUT3



Cuts:
NPeaks=1
RiseTime>0.6
(to get rid of digitizer fast noise)

0,1	1,1
0,0	1,0

Comparison with Marcos' results 33

Batch 2 run509

Batch 3 run607

DUT1 non-irrad

~47 ps @ 120V

43 ps @ 165V

DUT3 1.5×10^{14}

~38 ps @ 500V

38 ps @ 495V

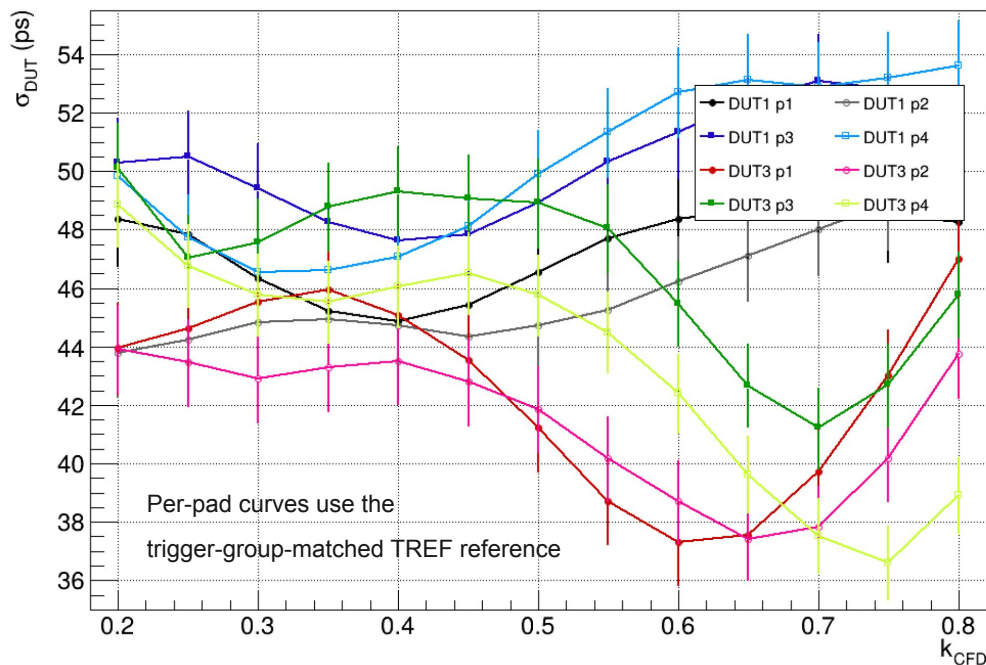
TREF 180V

~49 ps

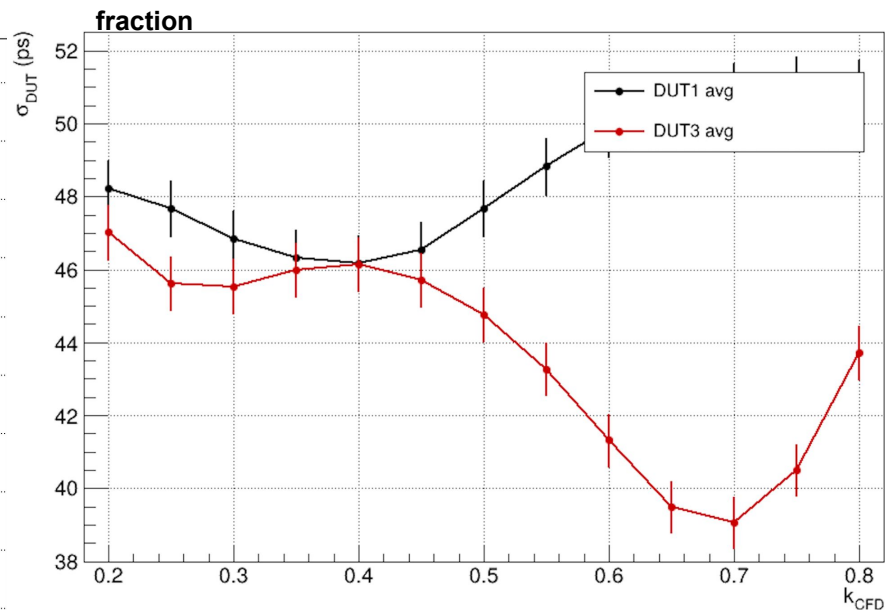
47 ps ✓

Threshold and CFD scans with track-based TREF-anchor selection

Per-pad timing vs CFD | $\sigma_{\text{ref}} = 47.1$ ps

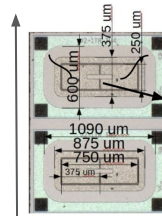
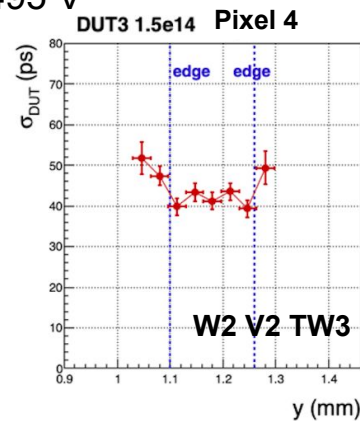
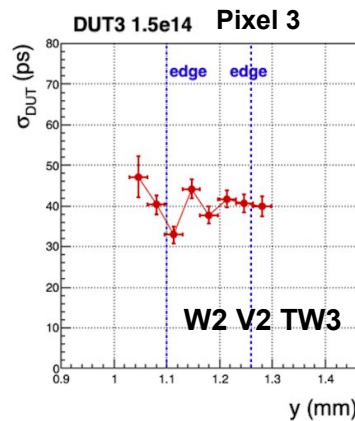
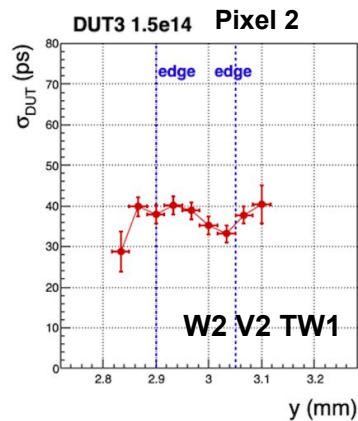
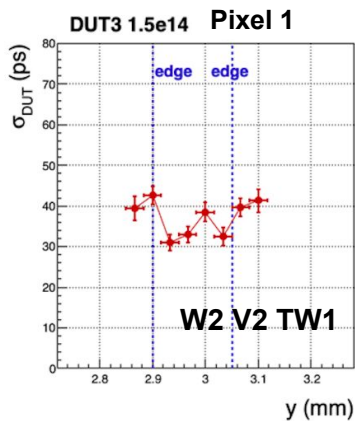
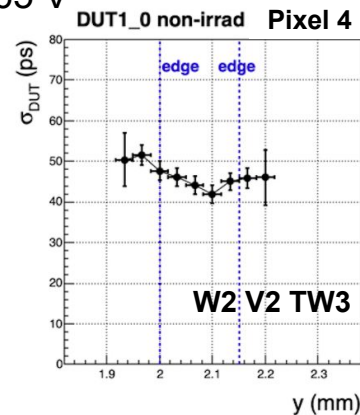
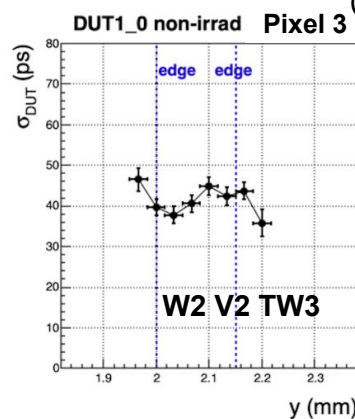
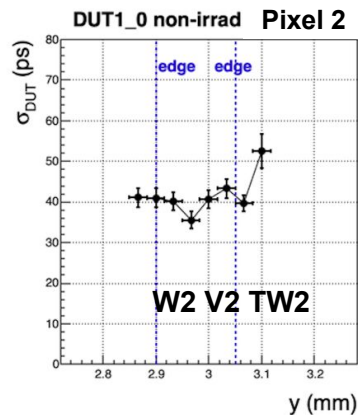
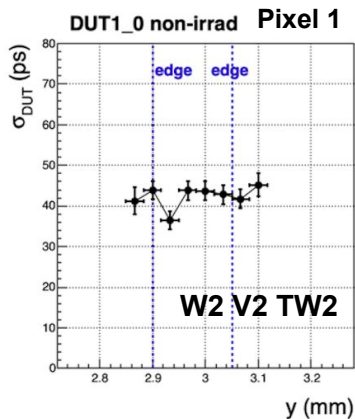


Detector-averaged timing shown as a function of CFD



DUT 1: W2 V2 TW2/3 pixel 1/2 (p1/2) @ 165 V

DUT3: W2 V2 TW1/3 pixel 1/2 (p1/2) @ 550 V

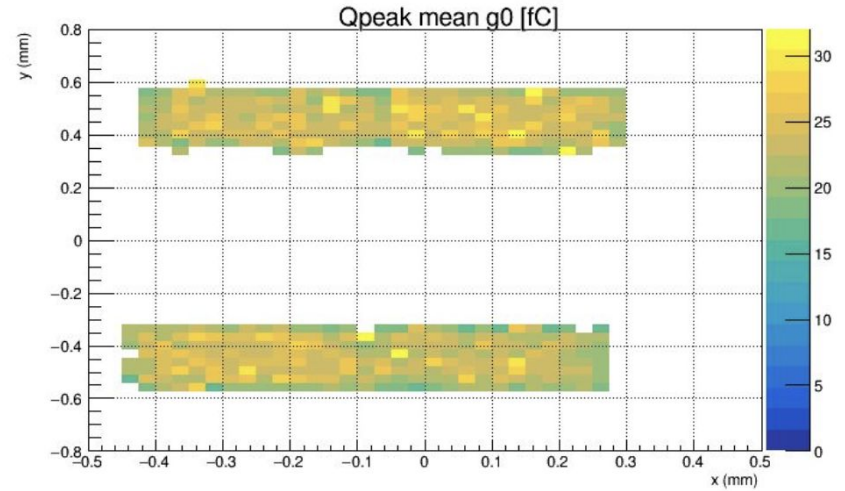
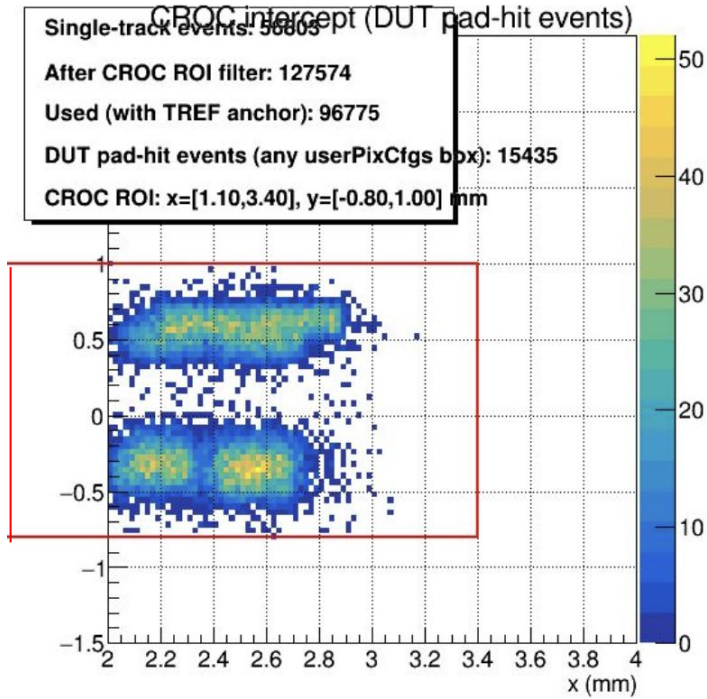


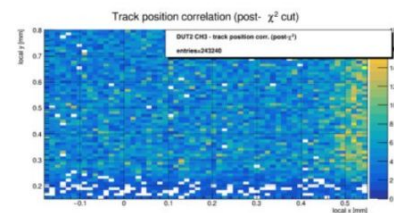
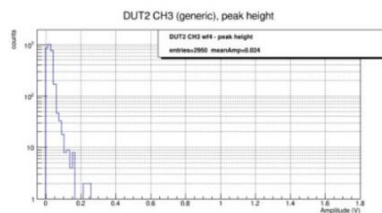
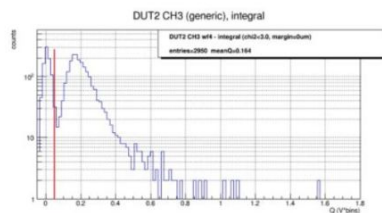
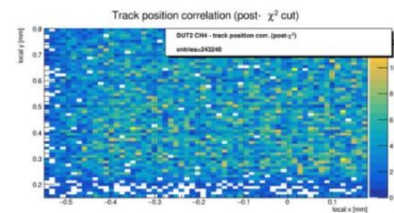
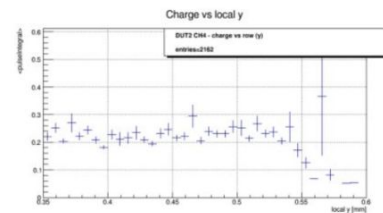
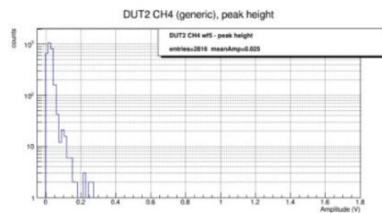
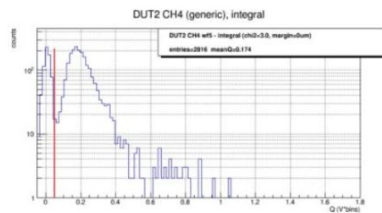
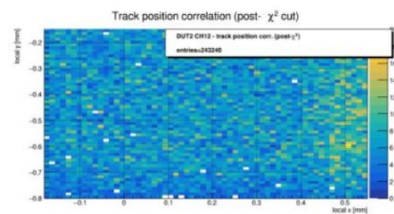
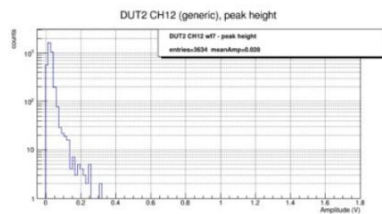
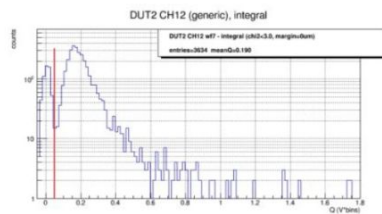
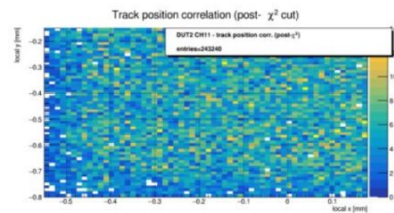
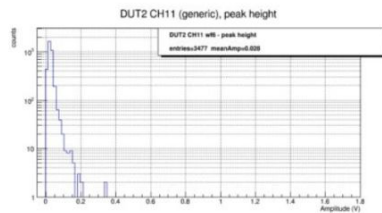
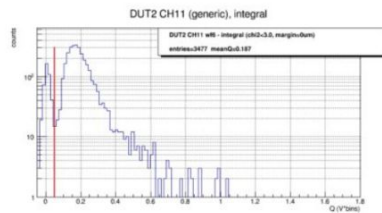
Time resolution as a function of position across the pixel width for DUT1_0 (black) and DUT3 at $1.5 \times 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ (red). Blue dashed lines indicate pixel boundaries. Resolution is uniform within the active area with no degradation at the LGAD edges — direct evidence of the TI-LGAD full fill factor

Note: ~30-50 events per y-bin

Error bars represent the statistical uncertainty on the measured time-difference RMS, $\sigma_{\Delta t}/2N$; horizontal bars indicate half the position-bin width.

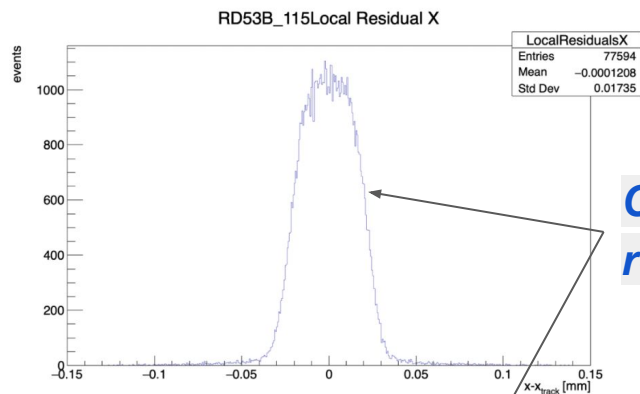
Non irradiated W5 V2TW12 angle 10



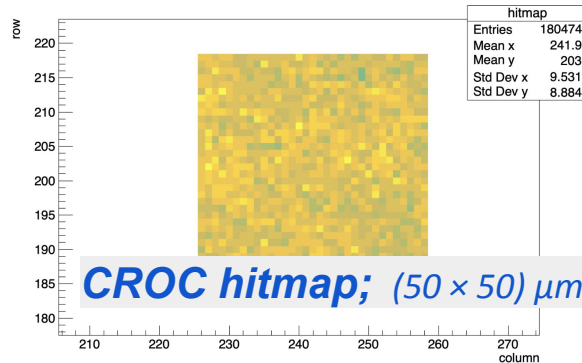
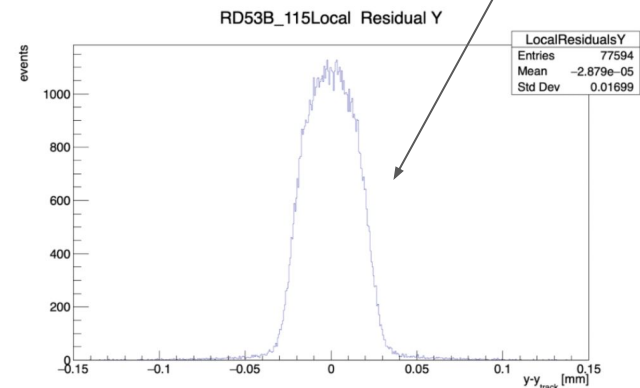


CMS Readout Chip: $\sigma_x=17.3\text{ }\mu\text{m}$, $\sigma_y=17.0\text{ }\mu\text{m}$

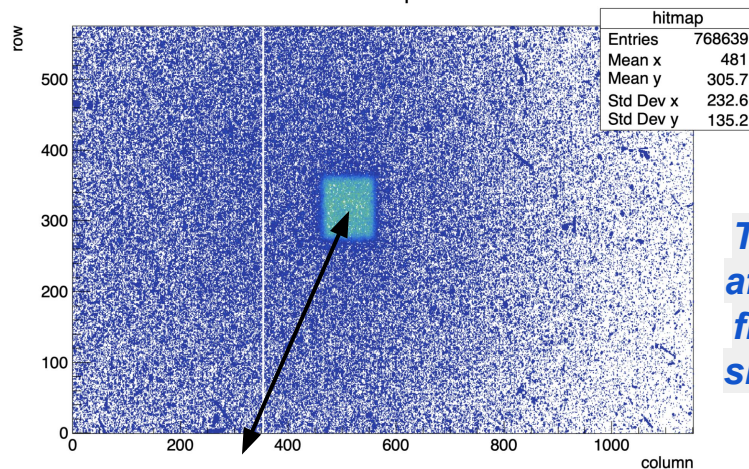
DRD3



CROC
residuals



CROC hitmap; (50 × 50) μm pixel size



**Triggering on CROC,
after having defined a
fiducial area with the
shadowing procedure**

Triggering on CROC