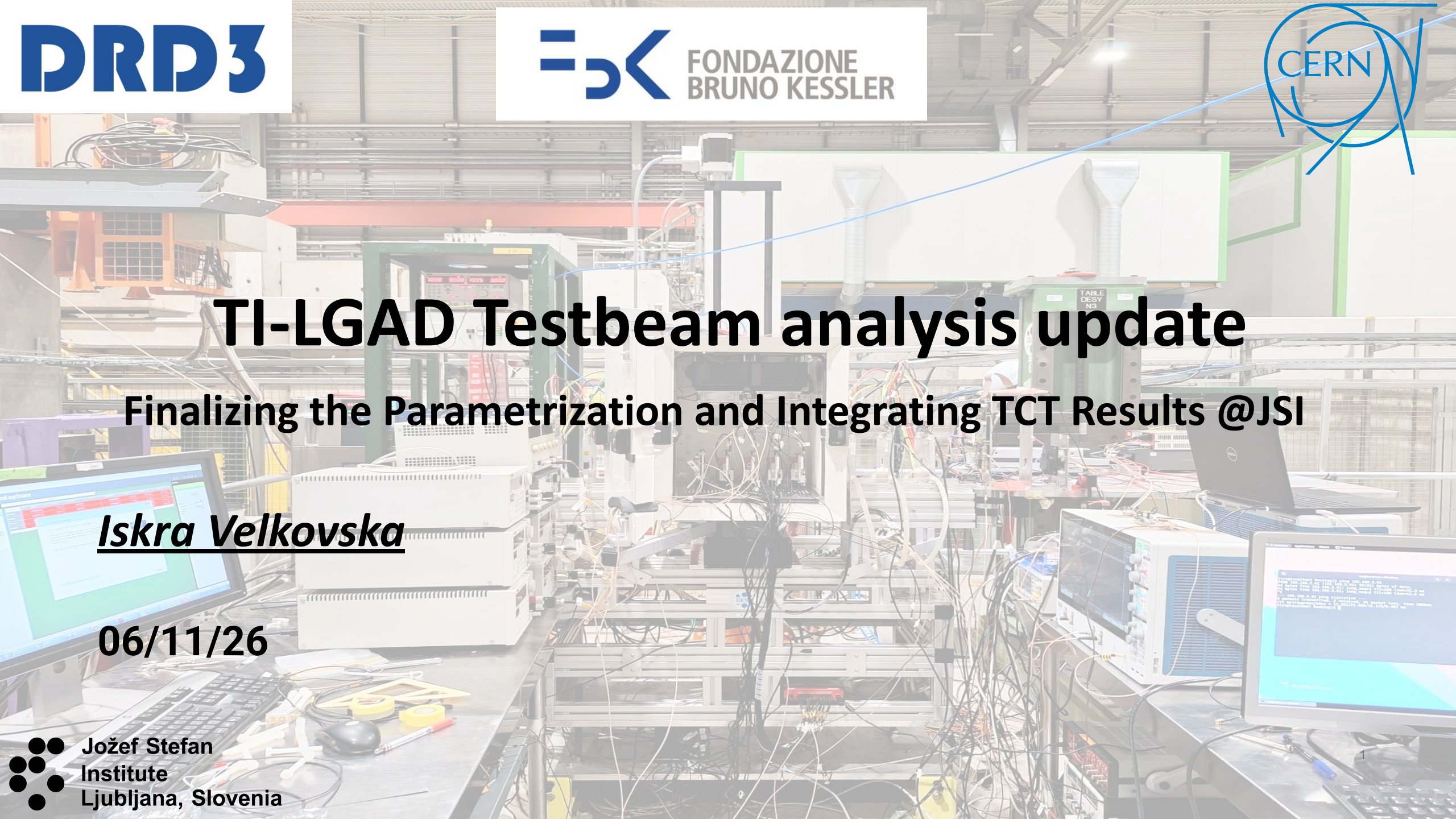


TI-LGAD Testbeam analysis update

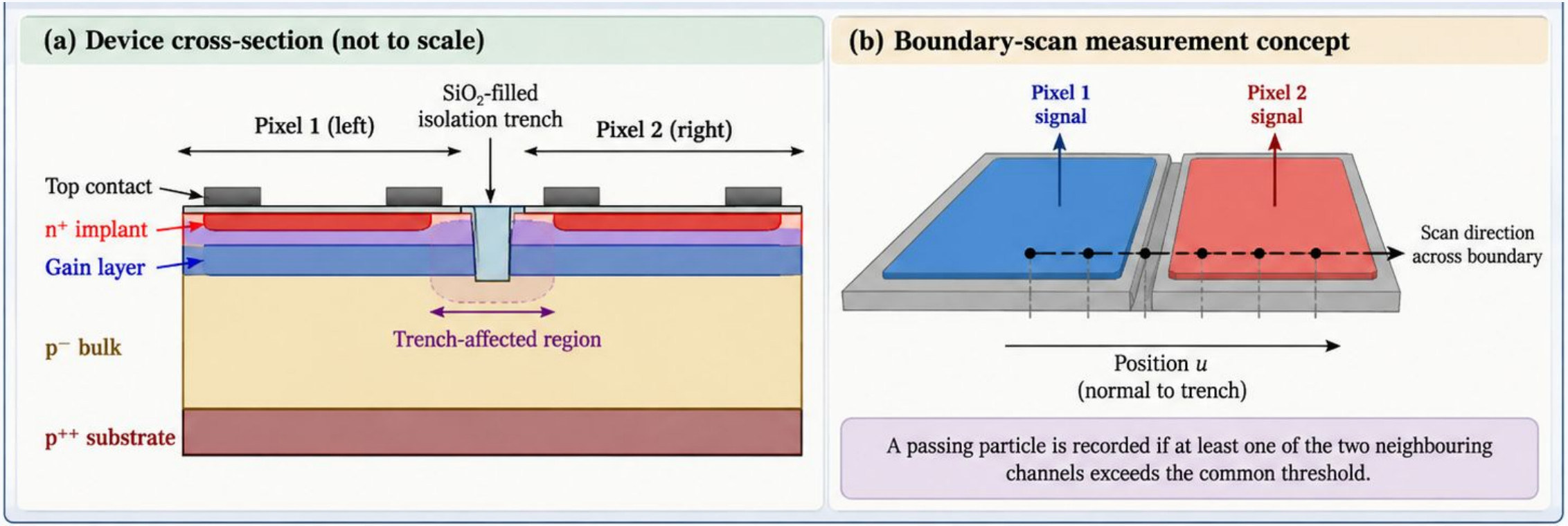
Finalizing the Parametrization and Integrating TCT Results @JSI

Iskra Velkovska

06/11/26

Jožef Stefan Institute
Ljubljana, Slovenia

Reminder: Method for generic TI-LGAD fill factor estimation



TI-LGAD interpad response

From analogue response to operational efficiency

Test-beam parameterization of the IPD region

λ_Q

loss of signal near the interpad region

$W_{\text{share } 10\,\% - 90\,\%}$

width of the signal-sharing transition

$\lambda_\varepsilon(T)$

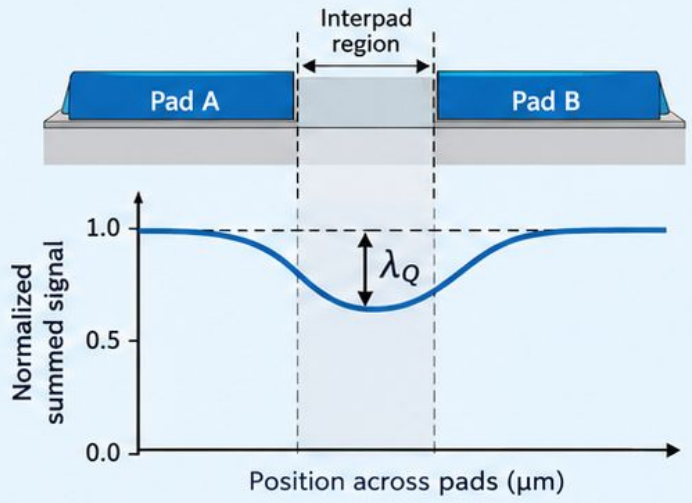
how much efficiency is lost at a given threshold

These three observables separate the response loss, the charge-sharing transition, and the resulting threshold-dependent efficiency loss.

What do these quantities describe?

Analogue response

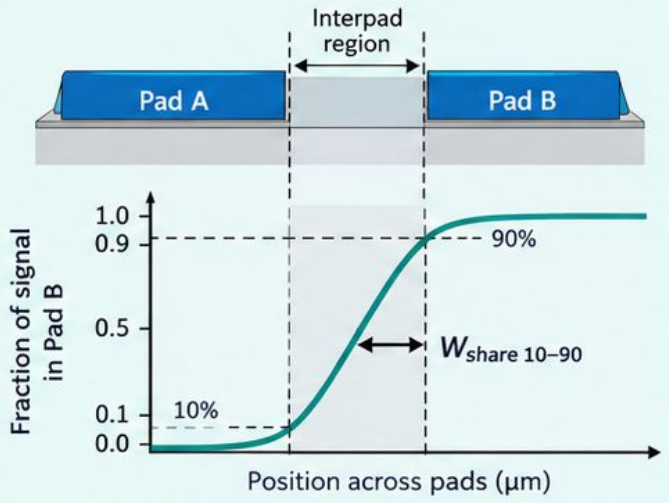
λ_Q



Integrated loss of the normalized summed waveform response.

Charge sharing

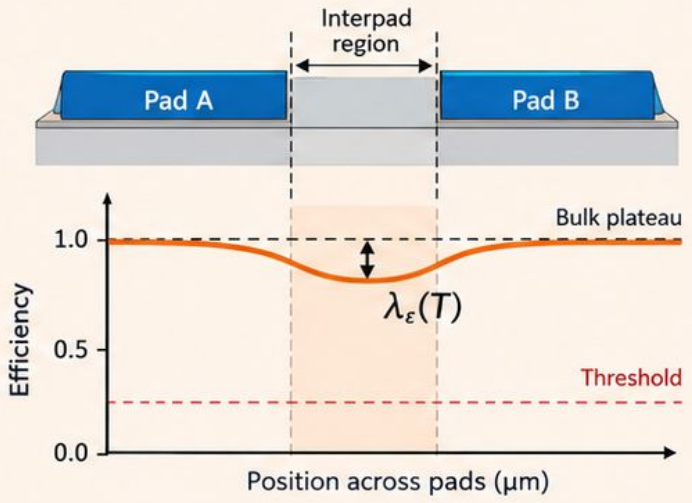
$W_{share\ 10–90}$



Spatial scale over which signal transfers between neighbouring pads.

Efficiency

$\lambda_\varepsilon(T)$



Integrated measured efficiency deficit relative to the bulk plateau.

$\lambda_Q \neq W_{share\ 10–90} \neq \lambda_\varepsilon(T)$

They are related, but they measure different physics.

Summed relative response of the two pads

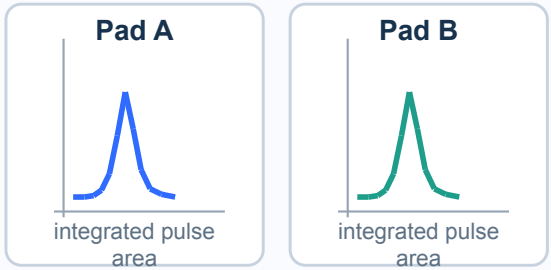
1 Measure both neighbouring pads



track at position u

$$u = x - x_0$$

distance from the trench centre, measured across the two pads



$S_{A(u)}$ $S_{B(u)}$

S = baseline-subtracted waveform integral [V·ns]

2 Normalize each pad to its own bulk signal

Pad A

$$s_A(u) = S_A(u) / S_{A,bulk}$$

Pad B

$$s_B(u) = S_B(u) / S_{B,bulk}$$

S_A,bulk and S_B,bulk are measured far from the trench

"bulk" = reference response measured well inside each pad

In the analysis: 100 < |u| < 230 µm

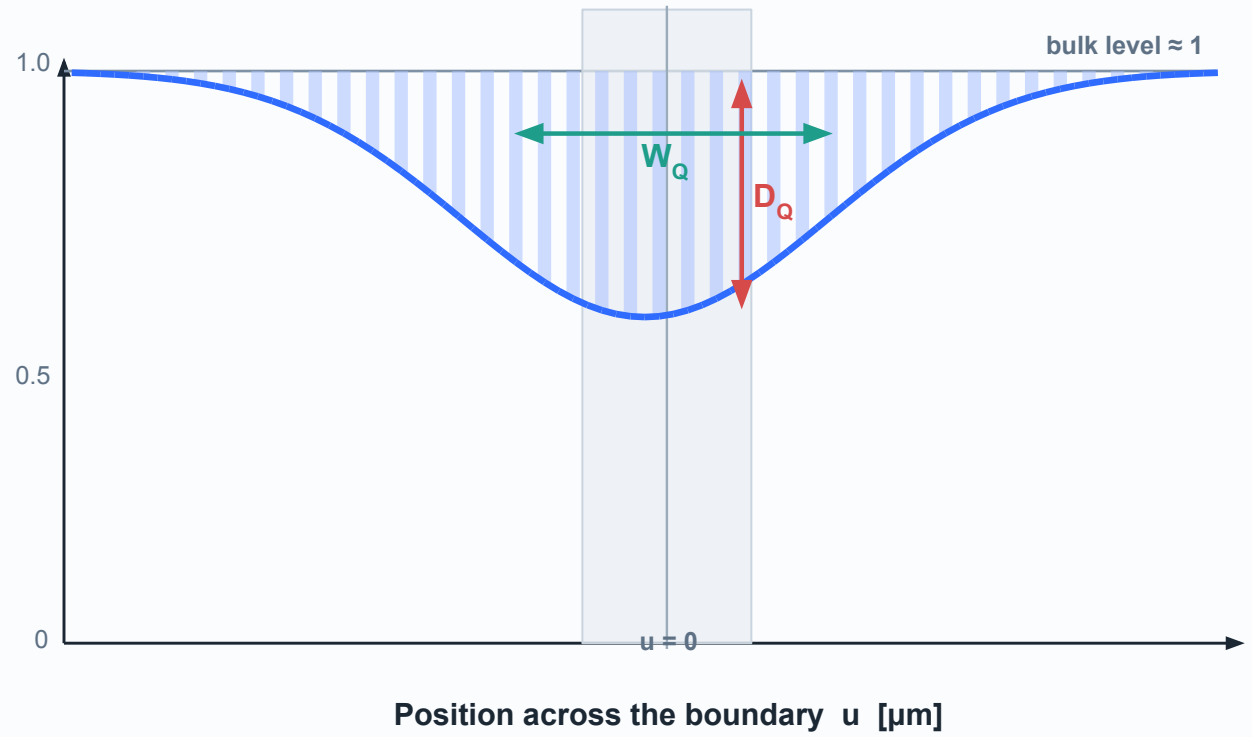
3 Sum of the two normalized signals

$$R\Sigma(u) = s_A(u) + s_B(u)$$



If signal is only shared between pads, the sum stays ≈ 1.
A dip below 1 means the total measured signal is reduced.

Introduction of one number for the size of the summed-signal deficit



How the fit is used

D_Q fractional depth of the signal dip

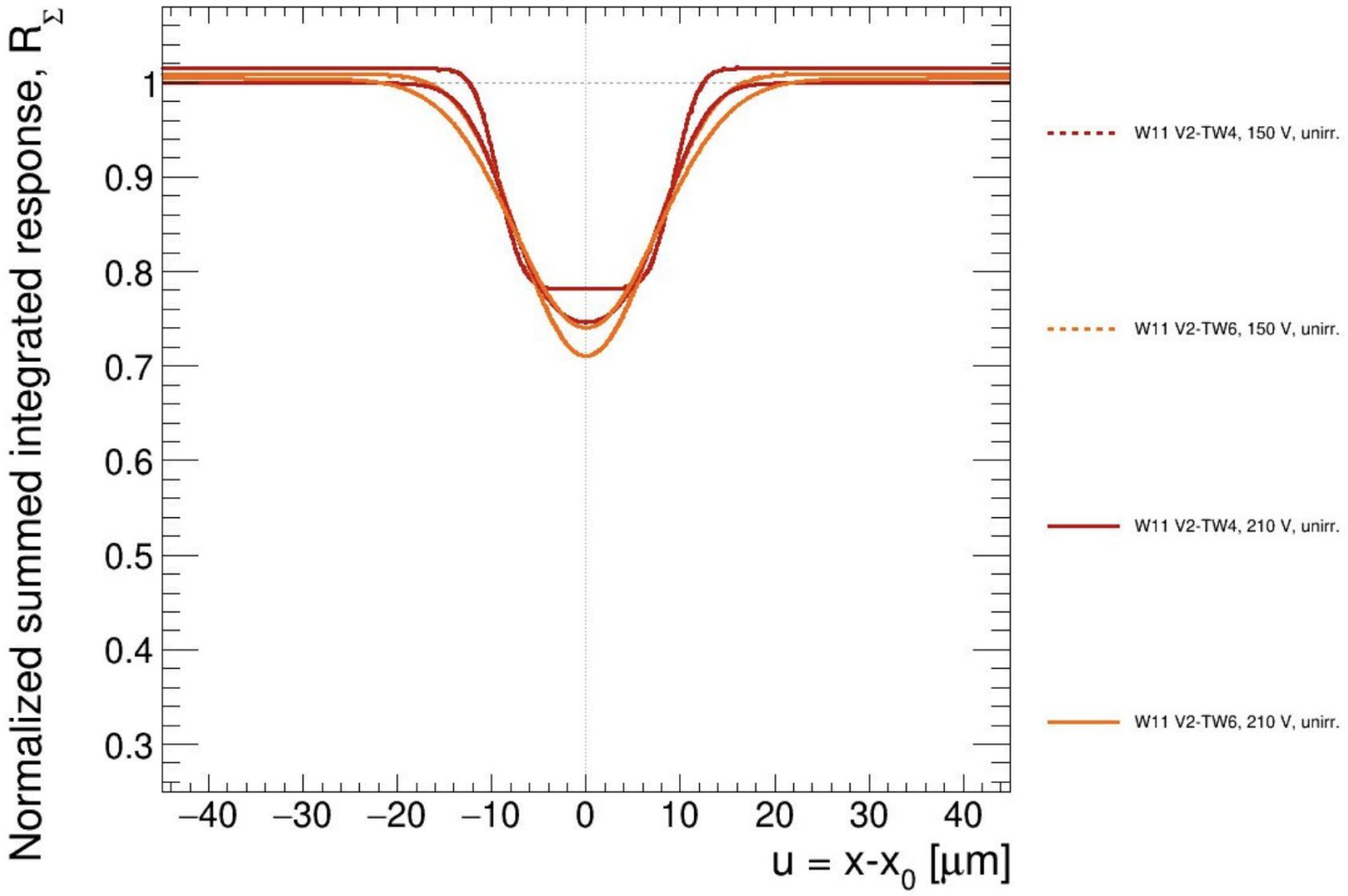
W_Q effective spatial width of the dip

σ edge smearing of the transition

$$\lambda_Q = D_Q \times W_Q$$

λ_Q combines the depth and width into one integrated signal-deficit scale [µm]

Integrated pulse response across the interpixel region



What is extracted?

The dip in RΣ(u) quantifies the summed-signal deficit near u = 0.

$\lambda_Q = D_Q \times W_Q$

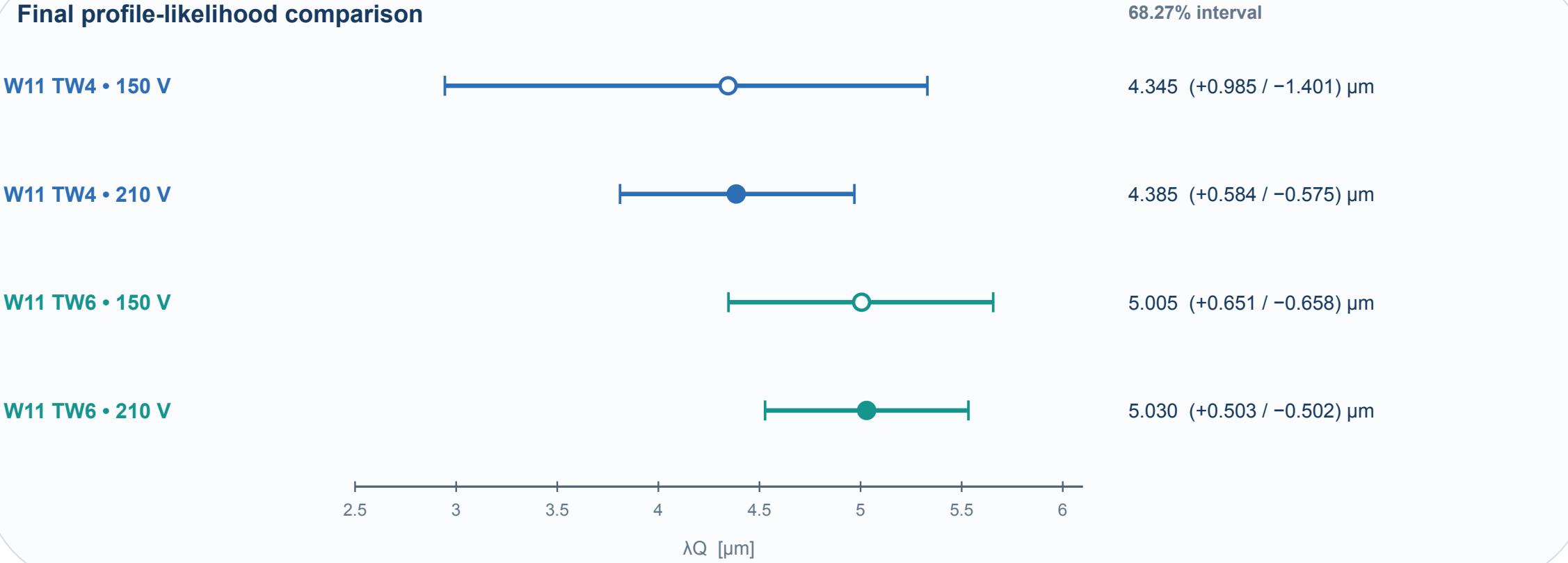
integrated signal-loss scale

Smaller λ_Q

→ smaller summed-signal deficit scale

Summed-response loss scale, λQ

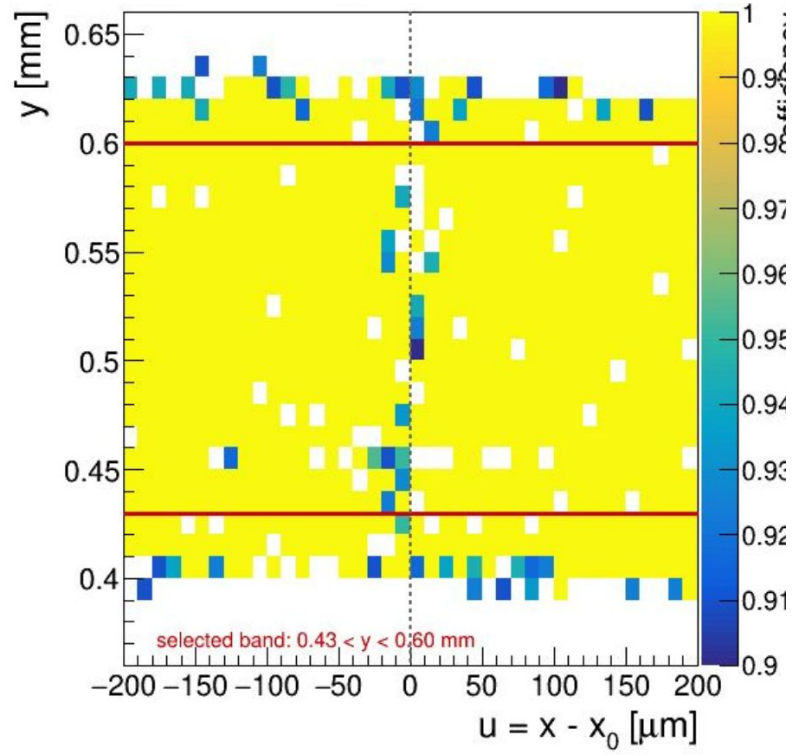
Final profile-likelihood comparison



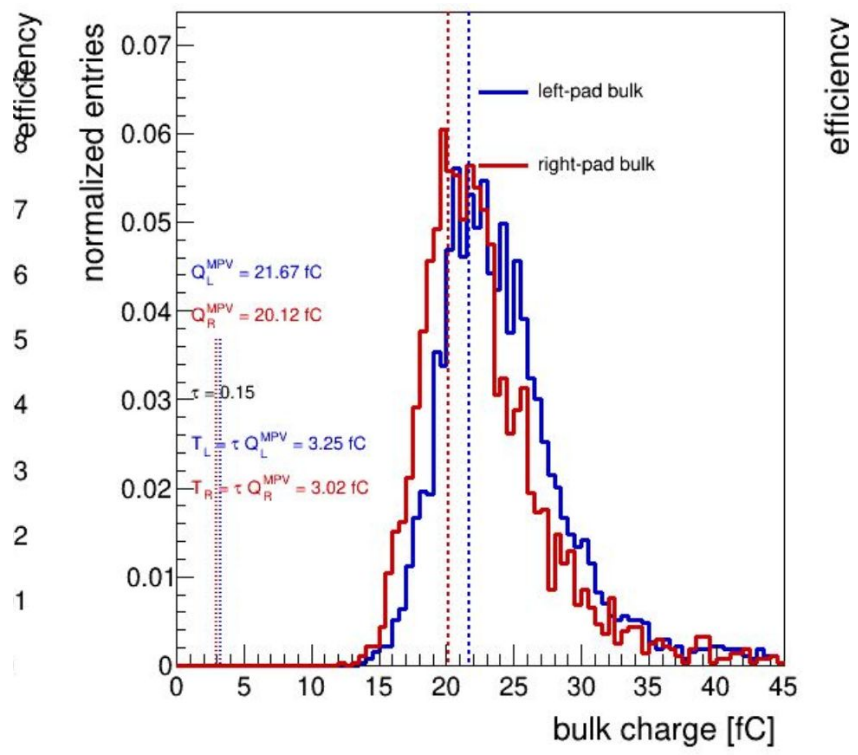
TW4 has a lower central λQ than TW6

Definition of the analysis region and thresholds

1 Select the boundary-crossing y band



2 Determine the bulk charge scale



Selected spatial band
0.43 < y < 0.60 mm

Bulk MPVs
QL,MPV = 21.67 fC • QR,MPV = 20.12 fC

Example at τ = 0.15
TL = 3.25 fC • TR = 3.02 fC

Threshold definitions used in the efficiency analysis

Bulk reference

TW6 at 210 V

Implemented Landau ⊗ Gaussian fit to the bulk charge spectrum of each pad

$Q_{□,MPV} = 21.67$ fC

$Q_{r,MPV} = 20.12$ fC

1 Fixed charge threshold

$$T = 2, 3, 4 \text{ fC}$$

For every event:

$$\text{efficient} \Leftrightarrow \max(Q_{□}, Q_r) > \text{Thr}$$

The same absolute charge threshold is applied to all datasets.

2 Bulk-MPV-normalized threshold

$$T_{□} = \tau\, Q_{□,MPV} \qquad T_r = \tau\, Q_{r,MPV}$$

$\tau = 0.10, 0.15, 0.20$ is a threshold expressed as a fraction of the bulk MIP charge

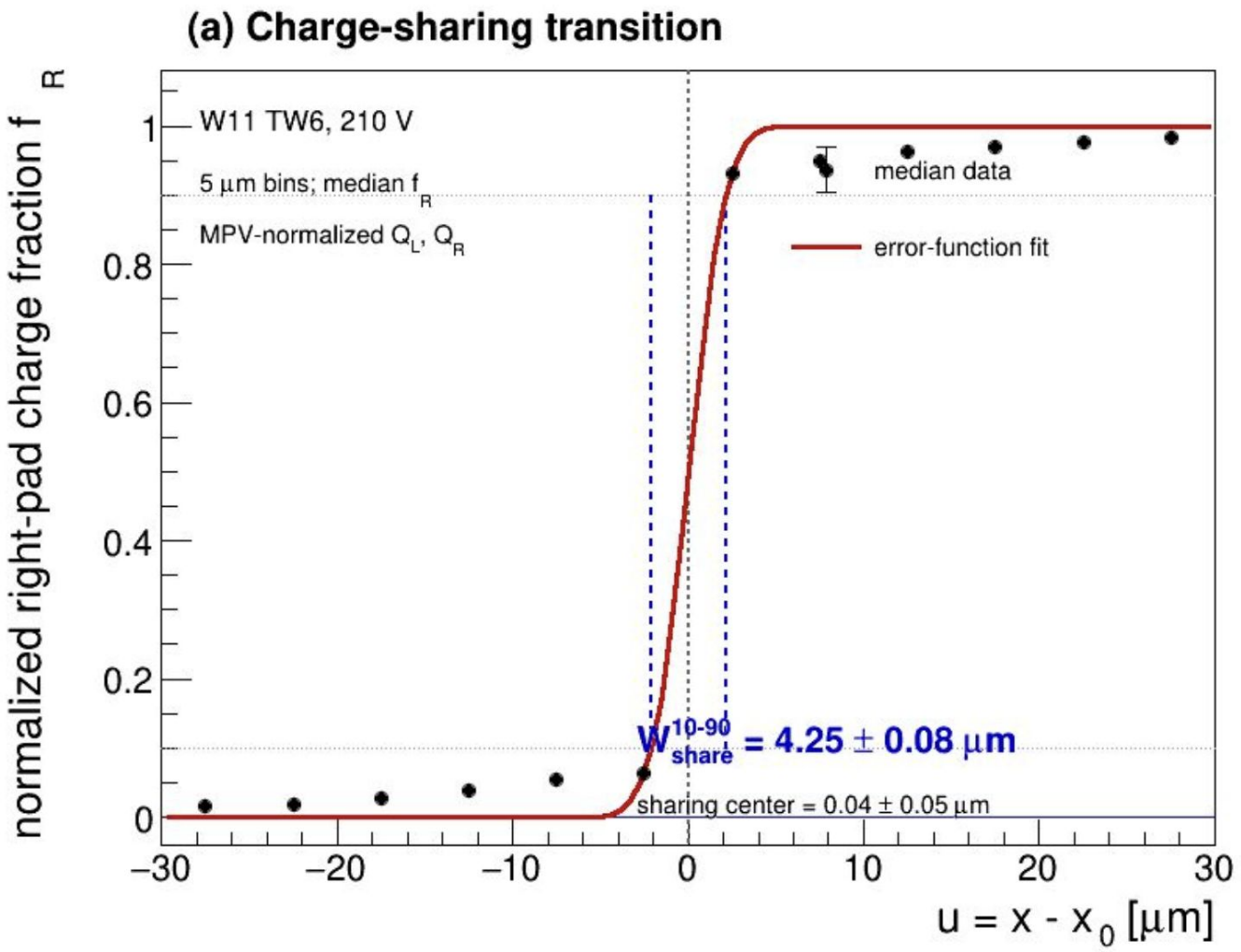
For every event:

$$\text{efficient} \Leftrightarrow Q_{□} > T_{□} \text{ or } Q_r > T_r$$

This compares each dataset at the same fraction of its own bulk MIP signal.

Example for TW6 at 210 V: $\tau = 0.15 \rightarrow T_{□} = 3.25$ fC, $T_r = 3.02$ fC

Charge sharing in beam test



TW6 @ 210 V

$W_{share10\%–90\%}$

4.246 ± 0.084 µm

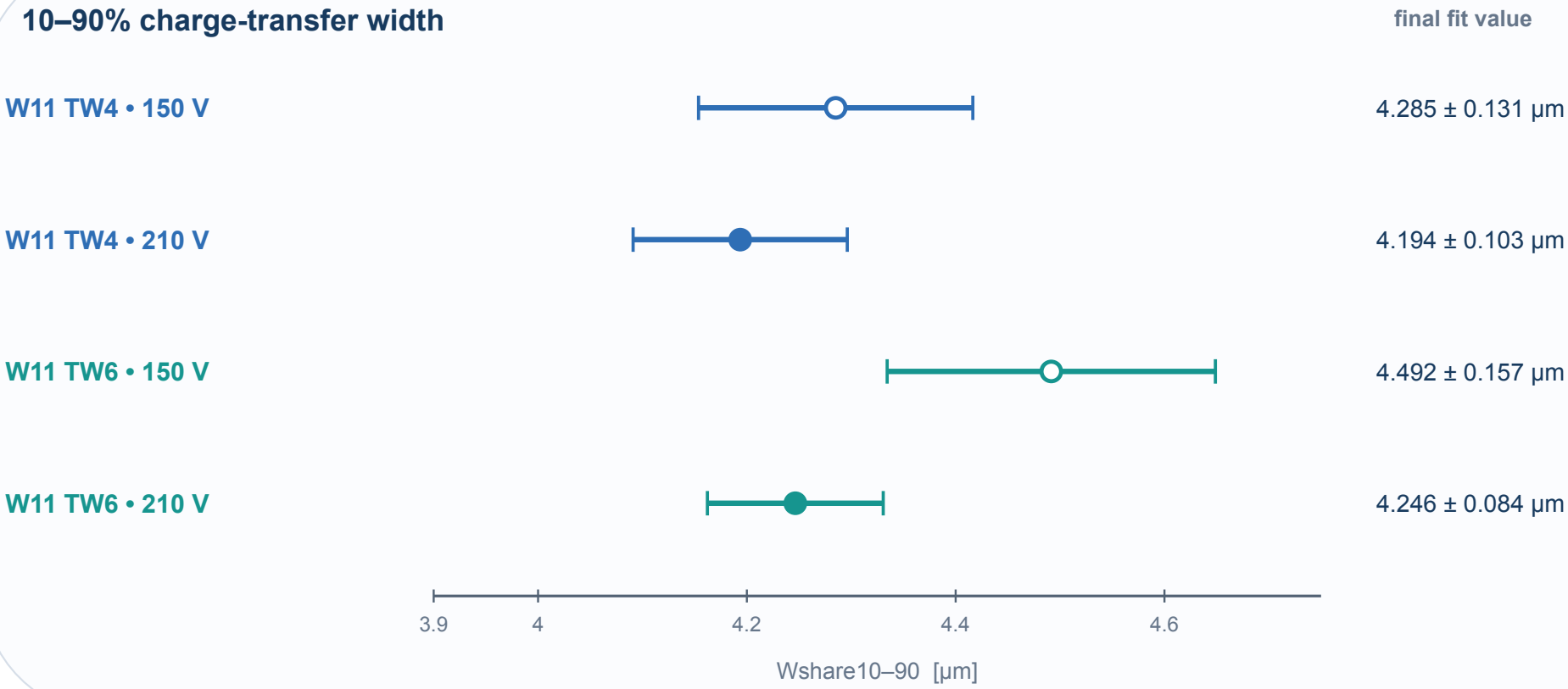
Sharing center

0.038 ± 0.049 µm

Across samples at different V_{bias}: ≈ 4.2–4.4 µm

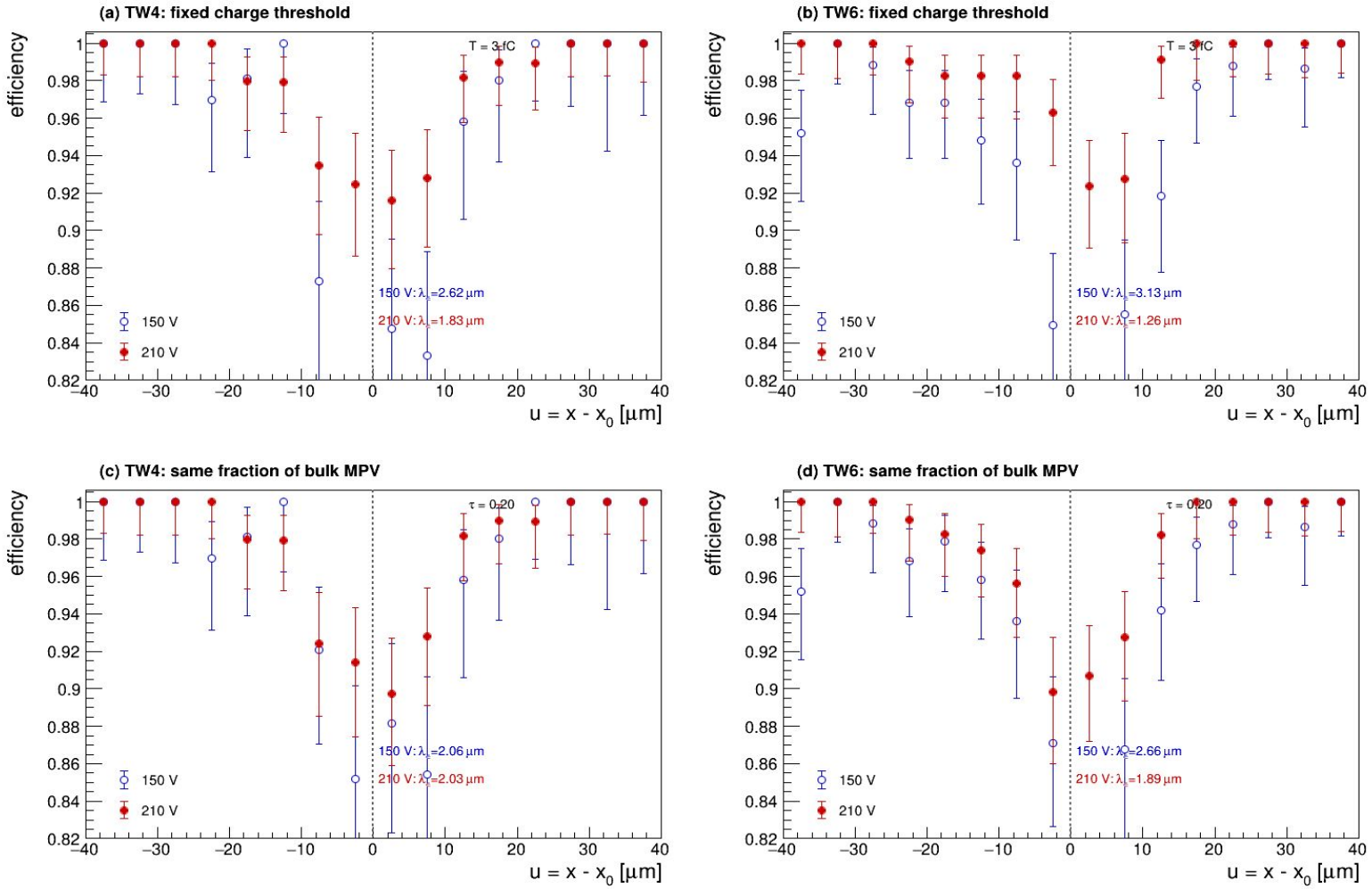
Charge-sharing scale, Wshare 10–90

10–90% charge-transfer width



Bias dependence of the efficiency loss

Measured efficiency profiles at 150 V and 210 V, compared at fixed and bulk-MPV-normalized thresholds.



Efficiency used in the analysis

$$\varepsilon(u) = N_{pass}(u) / N_{tracks}(u)$$

Pass condition

Fixed T: QL > T or QR > T

MPV-normalized:

QL > τQL,MPV or QR > τQR,MPV

$$\lambda_\varepsilon = \int [1 - \varepsilon(u)/\varepsilon_{bulk}]\, du$$

150 V → 210 V

Fixed threshold, T = 3 fC

TW4: 2.62 → 1.83 µm
TW6: 3.13 → 1.26 µm

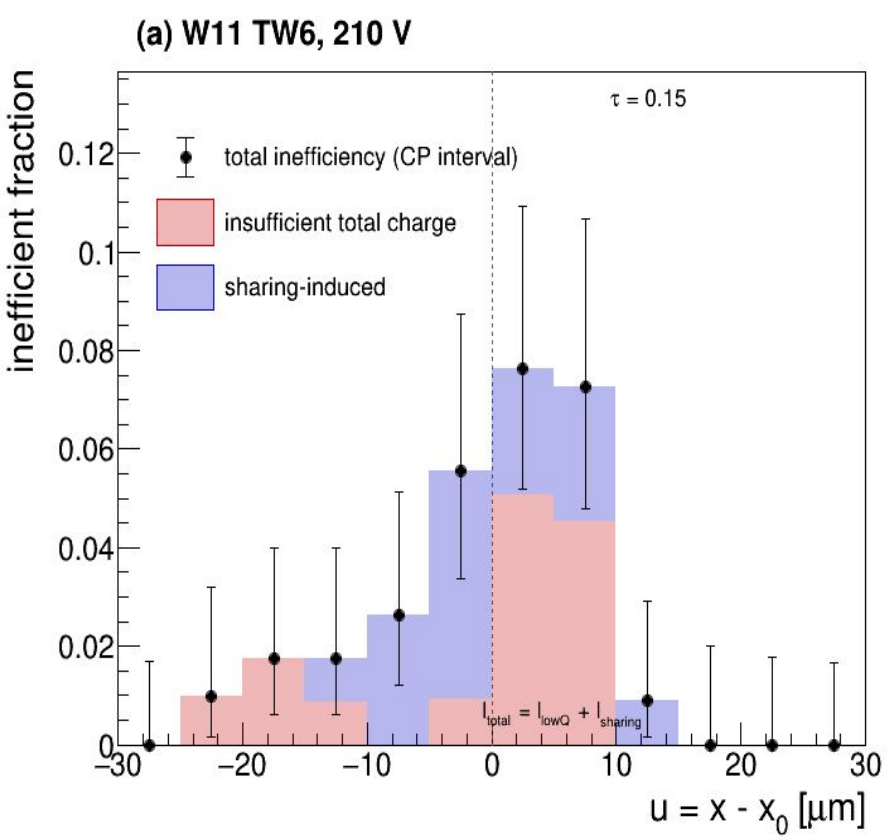
Bulk-MPV-normalized, τ = 0.20

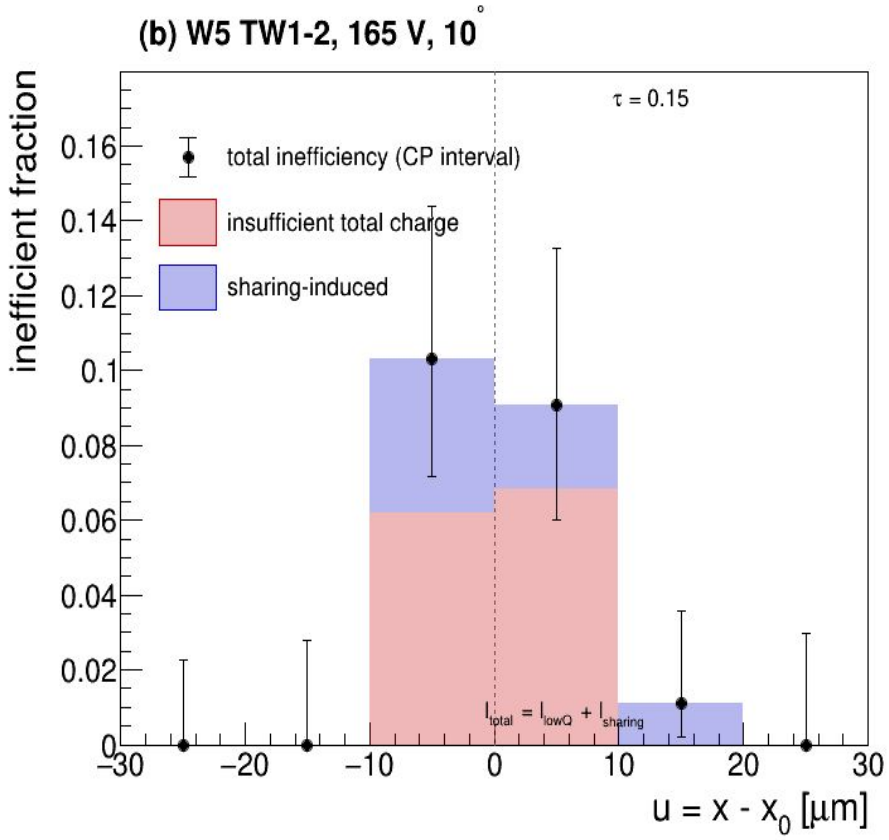
TW4: 2.06 → 2.03 µm
TW6: 2.66 → 1.89 µm

The strong bias dependence seen at fixed T is substantially reduced when the threshold is expressed as the same fraction of the bulk MIP signal.

What causes the inefficiency?

Two event-level mechanisms contribute: low total charge and threshold splitting.

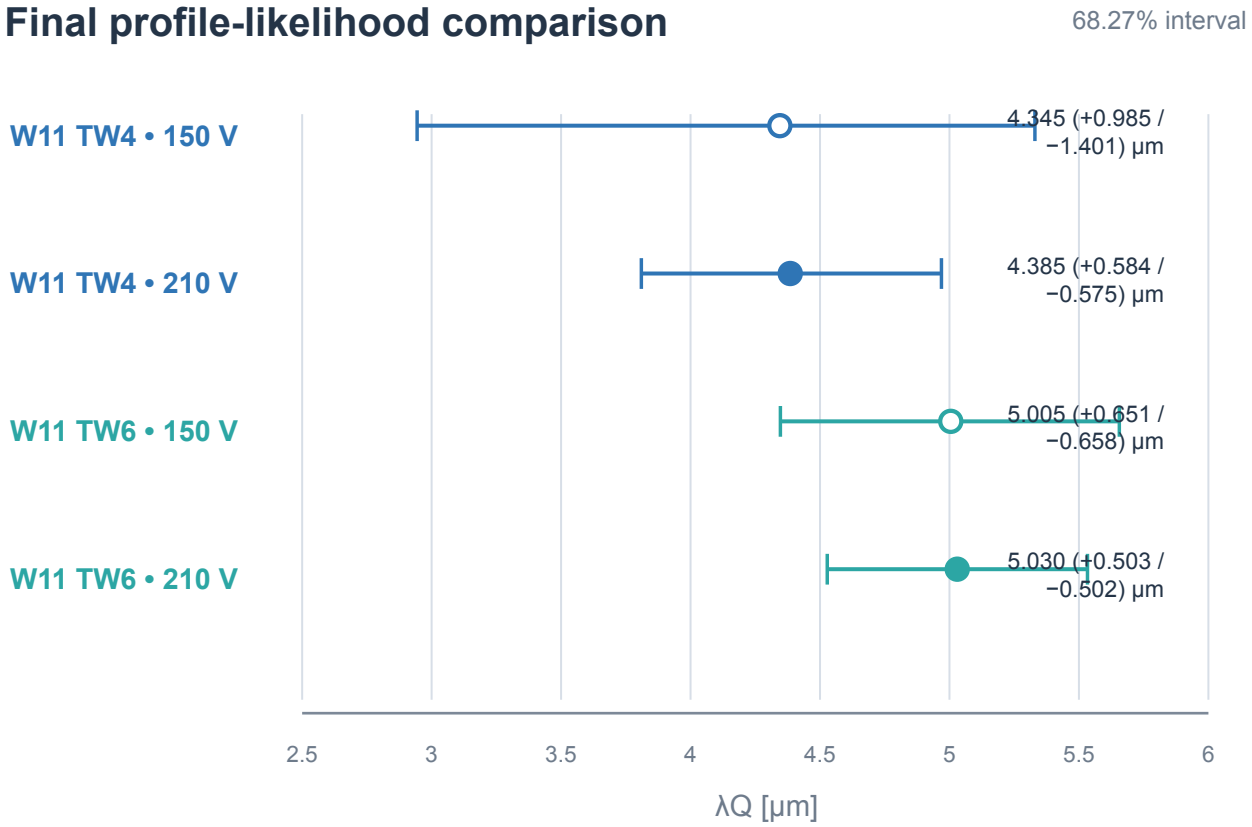




Two mechanisms contribute to inefficiency:
insufficient total charge and charge splitting between neighbouring pads.

Interpretation of the final summed-signal loss scale, λQ

Final profile-likelihood comparison



What should we conclude?

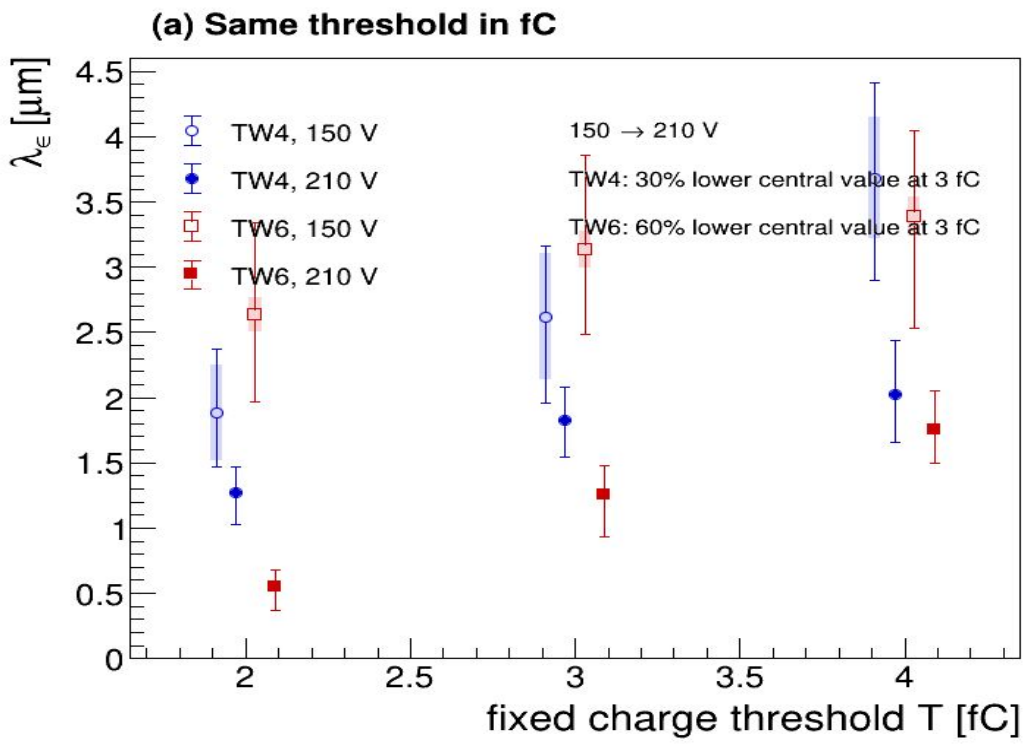
1. **No meaningful bias dependence**
   Within uncertainties, λQ is essentially unchanged from 150 V to 210 V for both TW4 and TW6.

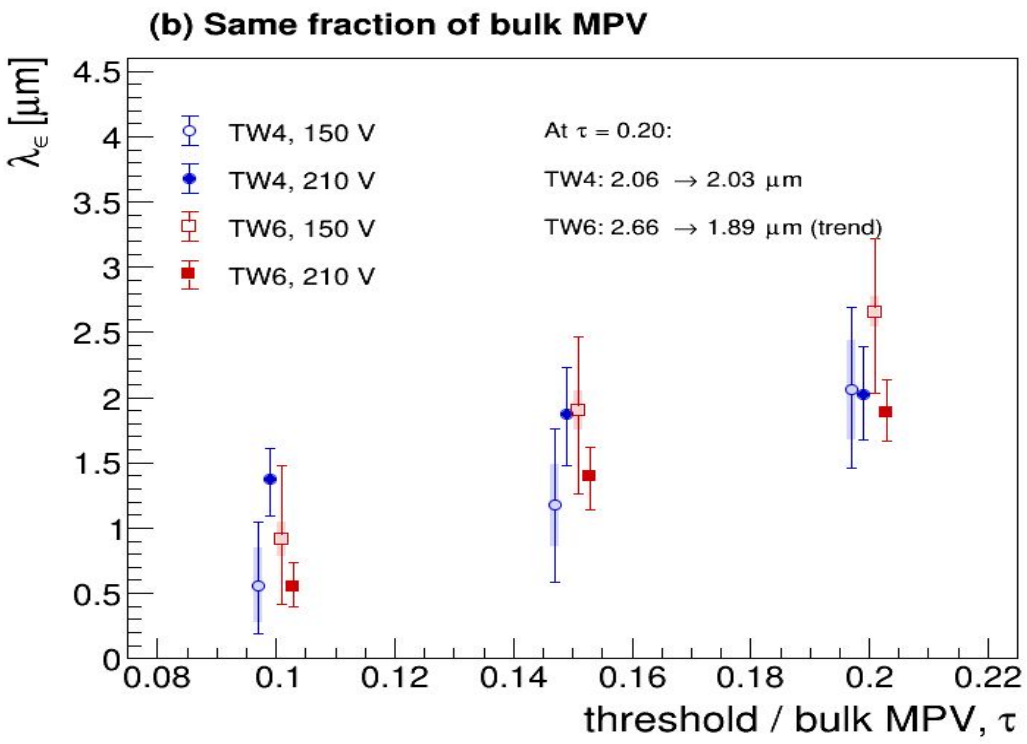
2. **TW4 central values are lower**

3. **λQ is a response-loss scale**
   It combines the depth and width of the summed-signal deficit; it is not a geometric trench width.

Summary of λ_ε across operating points

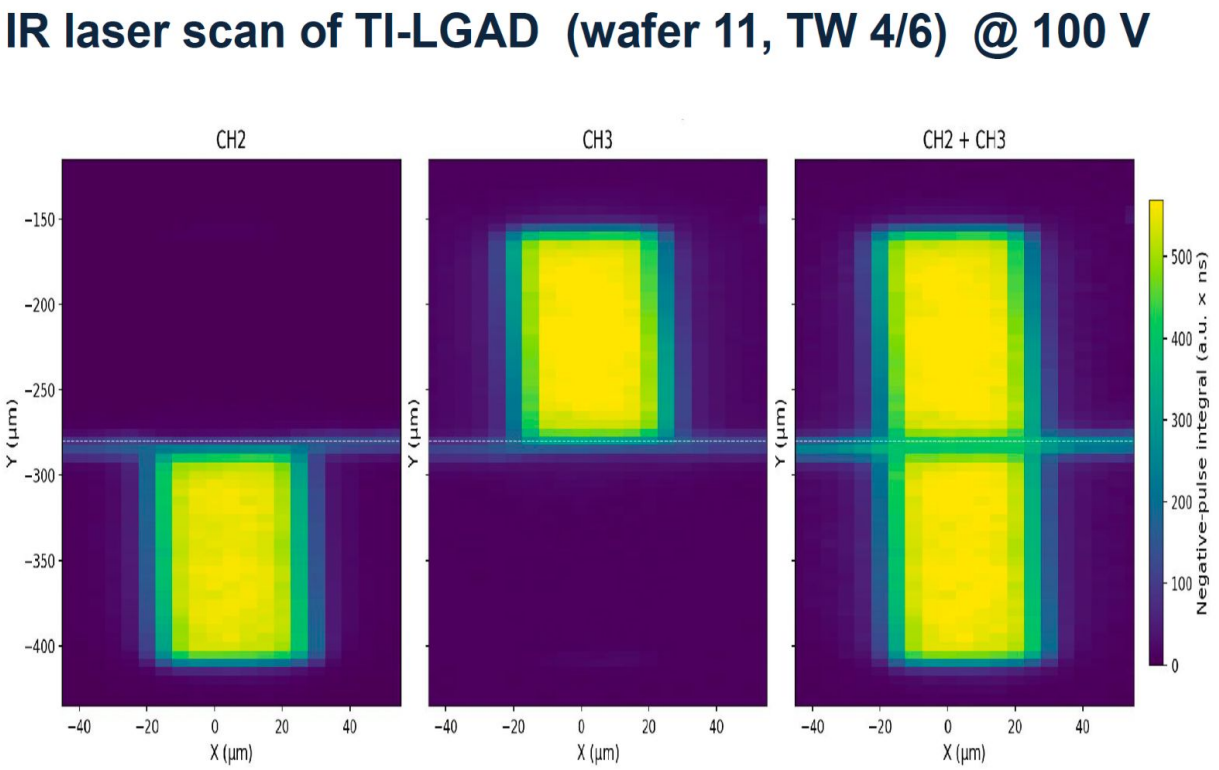
The operational loss is threshold- and operating-point dependent, not geometry-only.



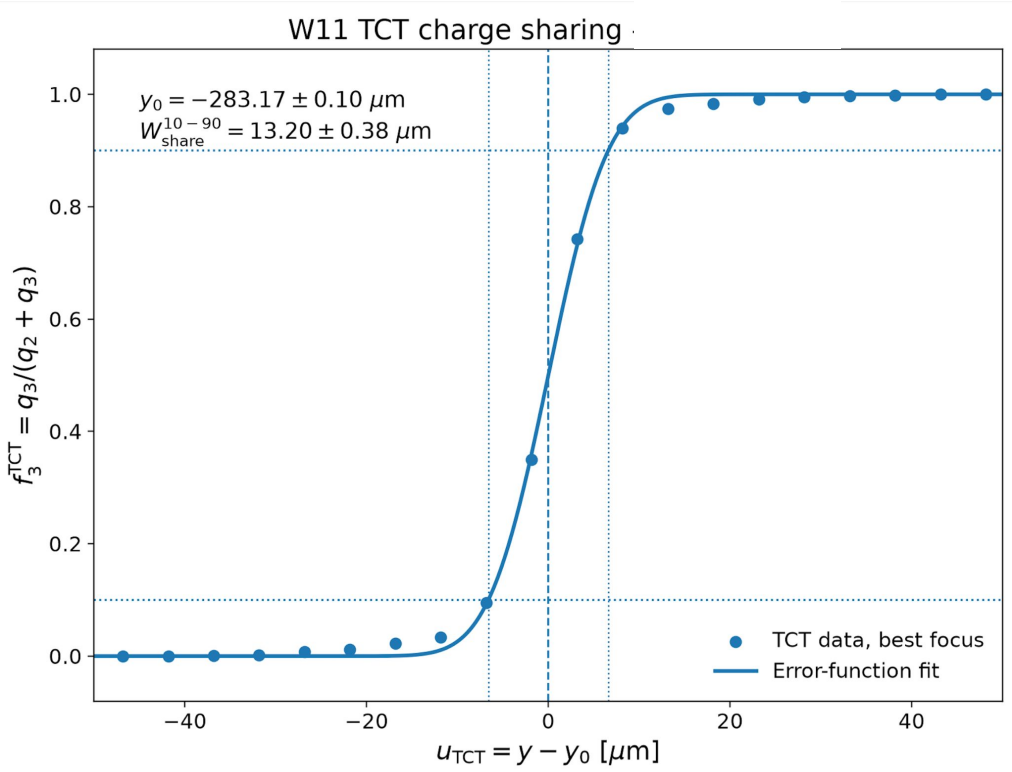


TCT comparison with 1064 nm IR laser

The same boundary is visible in IR-TCT, but the measured sharing transition is resolution-convolved.



A Gaussian deconvolution gives width of about 7 µm.



TCT sharing width **13.20 ± 0.38 µm**

Beam sharing width **4.246 ± 0.084 µm**

TCT is broadened by the finite laser spot / optical response; the beam result is the primary MIP charge-sharing scale.

W11 conclusions

λQ • summed-response loss

TW4: 4.345 → 4.385 µm

TW6: 5.005 → 5.030 µm

150 V 210 V

TW4 central values are lower, but no significant design separation is established.

Wshare10–90 • charge sharing

TW4: 4.285 → 4.194 µm

TW6: 4.492 → 4.246 µm

150 V 210 V

All values ≈ 4.2–4.5 µm.

The MIP charge-transfer scale is stable across the studied operating points.

λε(T) • operational efficiency

Fixed T = 3 fC:

TW4: 2.62 → 1.83 µm

TW6: 3.13 → 1.26 µm

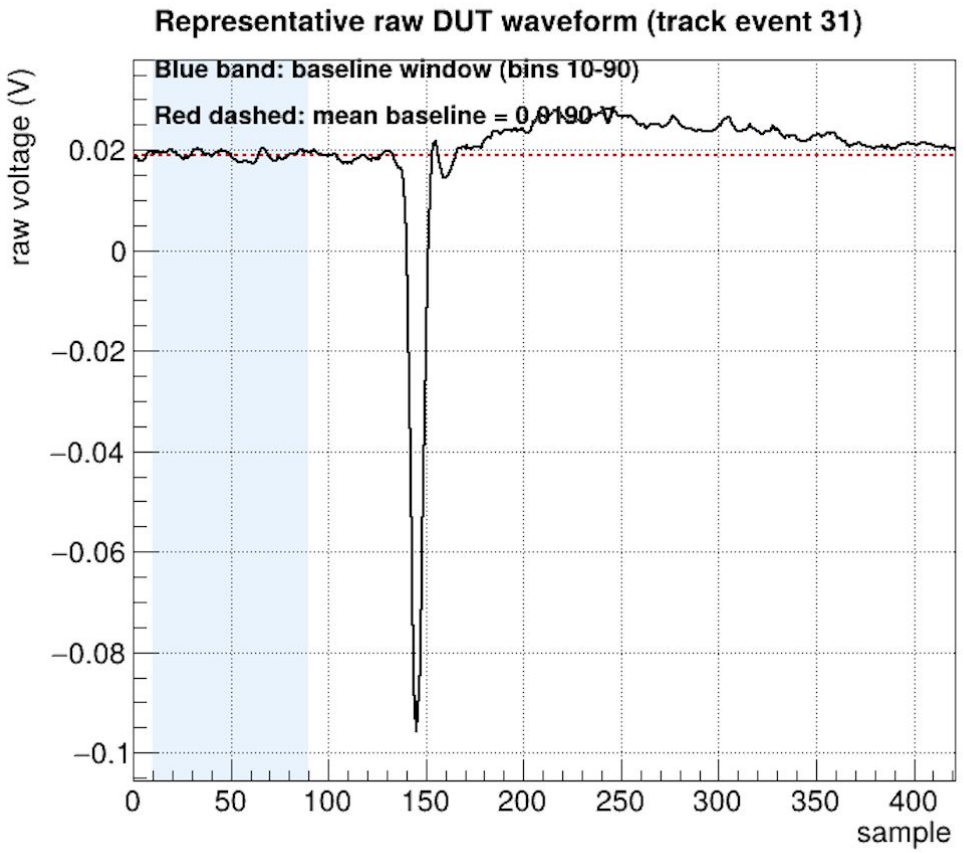
At τ = 0.20:

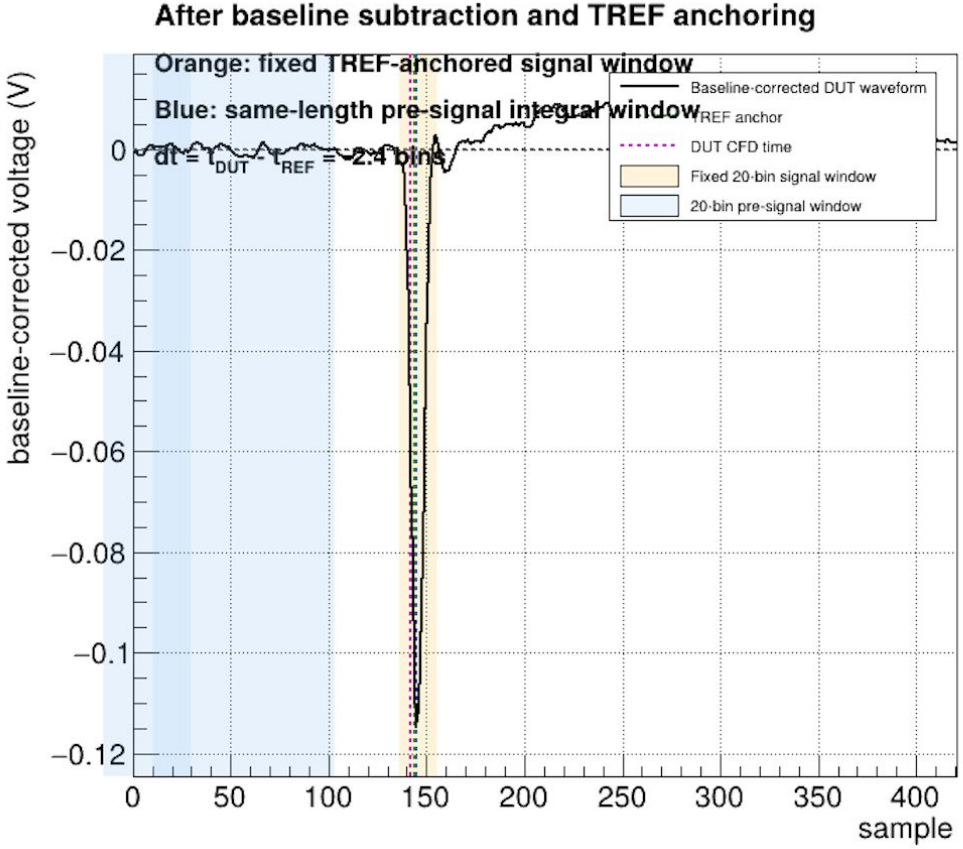
TW4: 2.06 → 2.03 µm

TW6: 2.66 → 1.89 µm

Backup slides

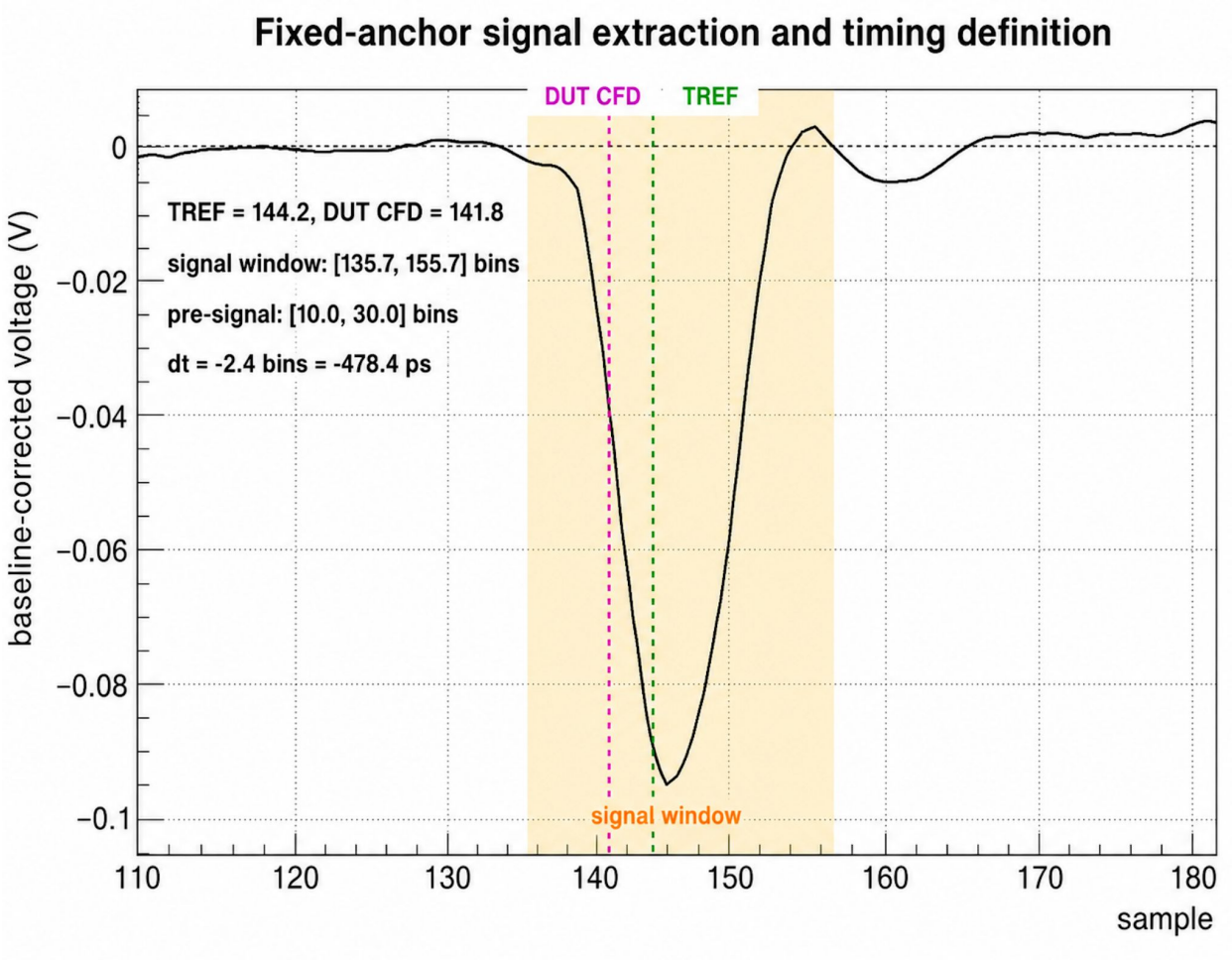
- DUT signal is integrated in a fixed 20-bin window relative to that anchor.
- A same-length pre-signal window is used for the baseline reference.
- dt is the time difference between DUT and reference.





From Waveform to Charge

- Baseline -> mean of the first 100 samples (also gives the noise RMS).
- Charge = signed sum of (baseline − V) over a fixed window, converted to fC via the 0.2 ns/sample period at 5 GS/s.
- The window is not gated on the DUT's own CFD success -> every track gets a charge, including faint inter-pad events.
- Nominal window: 5 bins before + 15 after center = 4.2 ns. Short (4+11) / long (7+18) variants are recorded only as a stability cross-check, never for event selection.



In general:

- TREF CFD defines the event time anchor
- Same-length pre-signal window used for baseline reference
- dt = t_{DUT} - t_{REF}
- The DUT charge is integrated in a fixed 20-bin window placed relative to the TREF CFD anchor, to avoid the pedestal bias of peak-centering while retaining the main part of the DUT pulse for the selected events in this run

$$\text{threshold} = k_CFD \times A_peak$$

timestamp = linear interpolation of the crossing between the two samples straddling threshold

A pulse is only accepted if its peak clears 5σ of that channel's own baseline

Calibrating TREF: the Triplet Method

$$\sigma_{TREF}^{\,2} = \tfrac{1}{2}(\sigma_{1R}^{\,2} + \sigma_{2R}^{\,2} - \sigma_{12}^{\,2})$$

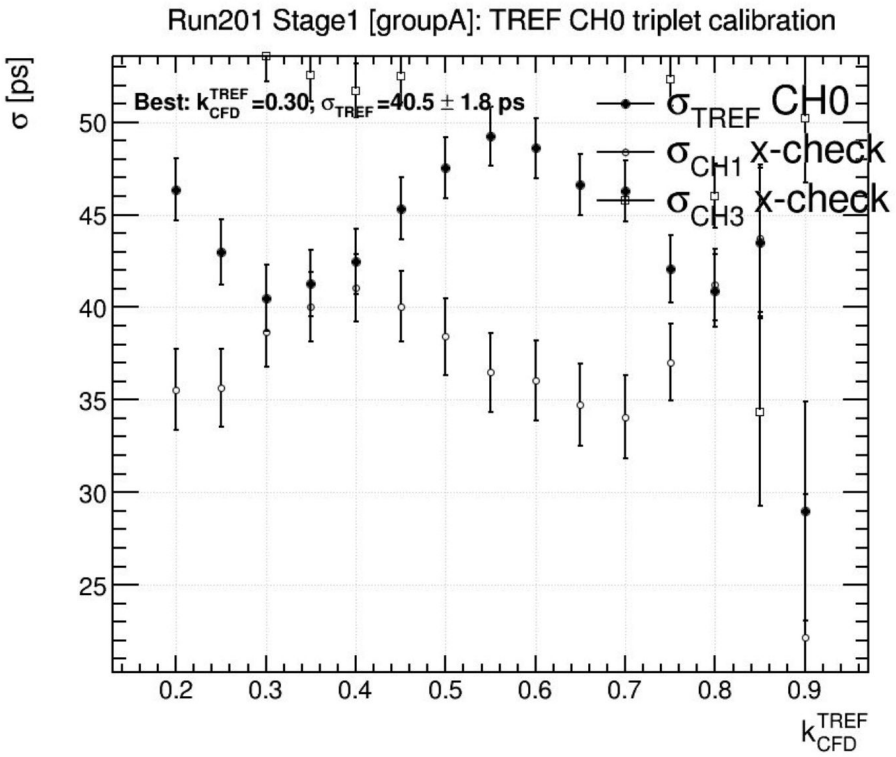
three pairwise timing widths (TREF-DUT1, TREF-DUT2, DUT1-DUT2) solve algebraically for each individual channel's own resolution

- TREF's own resolution is extracted from three pairwise widths among TREF and two calibration DUTs, using the same three-channel variance decomposition throughout this analysis.
- k_{TREF} is scanned, both calibration DUTs are held at a fixed, standard fraction so only TREF's own operating point moves.
- A scan point is only eligible as “best” if it clears BOTH a relative-error floor and a minimum-statistics floor
- Result: one k_{TREF} and one σ_{REF}, per group, and used as the fixed reference for every subtraction in every later stage.

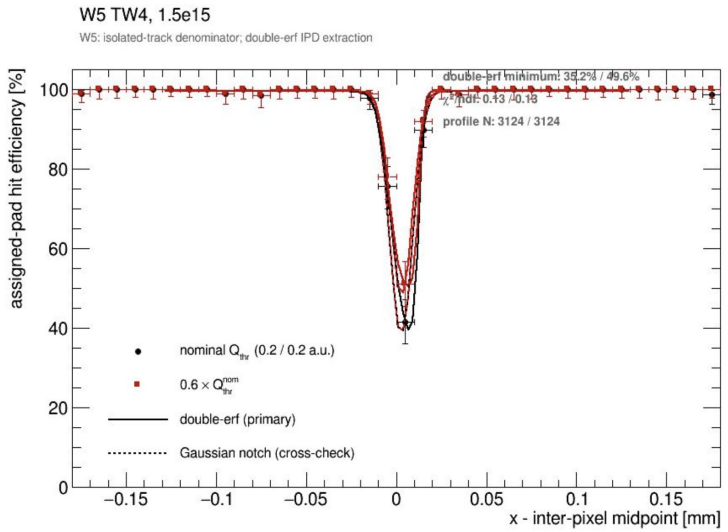
with tracking included $\sigma_{TREF} = 40.5 \pm 1.8$ ps

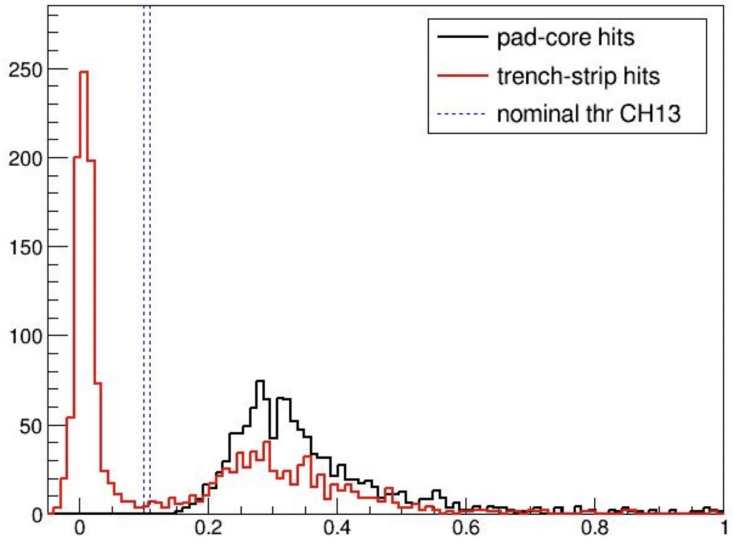
Frozen once, reused everywhere

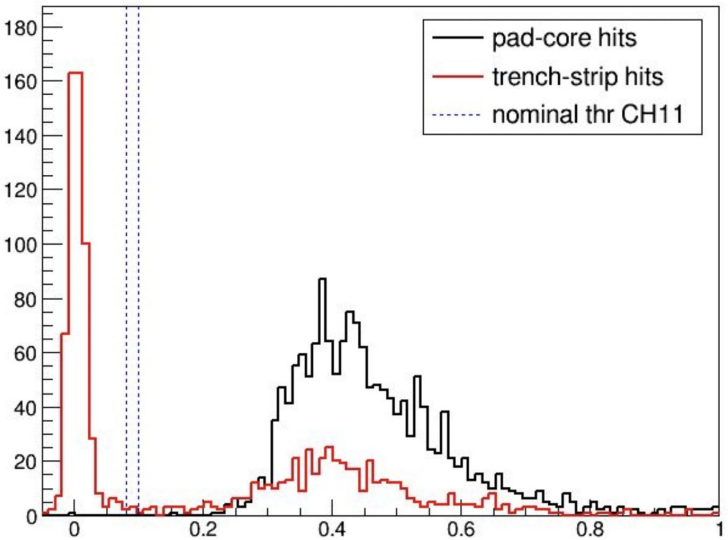
- This is the ONE place σ_{TREF} is measured in the entire macro.
- Later resolves an independent “anchor triplet” using the frozen k's, purely as a cross-check
- Every quoted σ_{DUT} (the bulk ROI, the 1D profile, the 2D map) subtracts the same σ_{TREF}, in quadrature

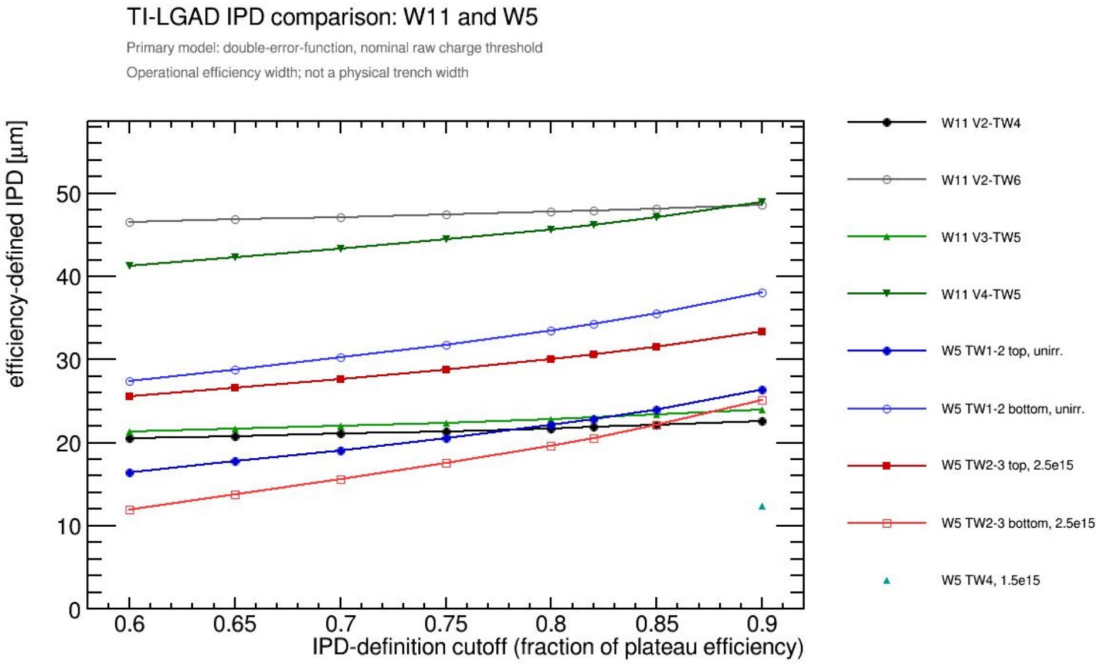


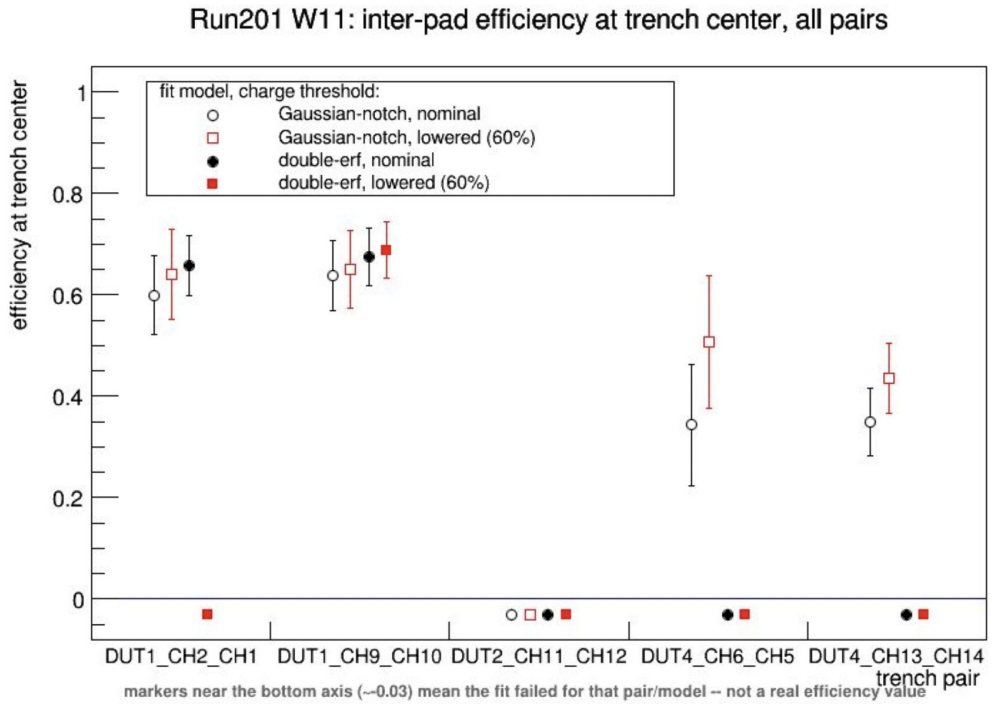
IPD results for wafer 11 V2 and V3/4



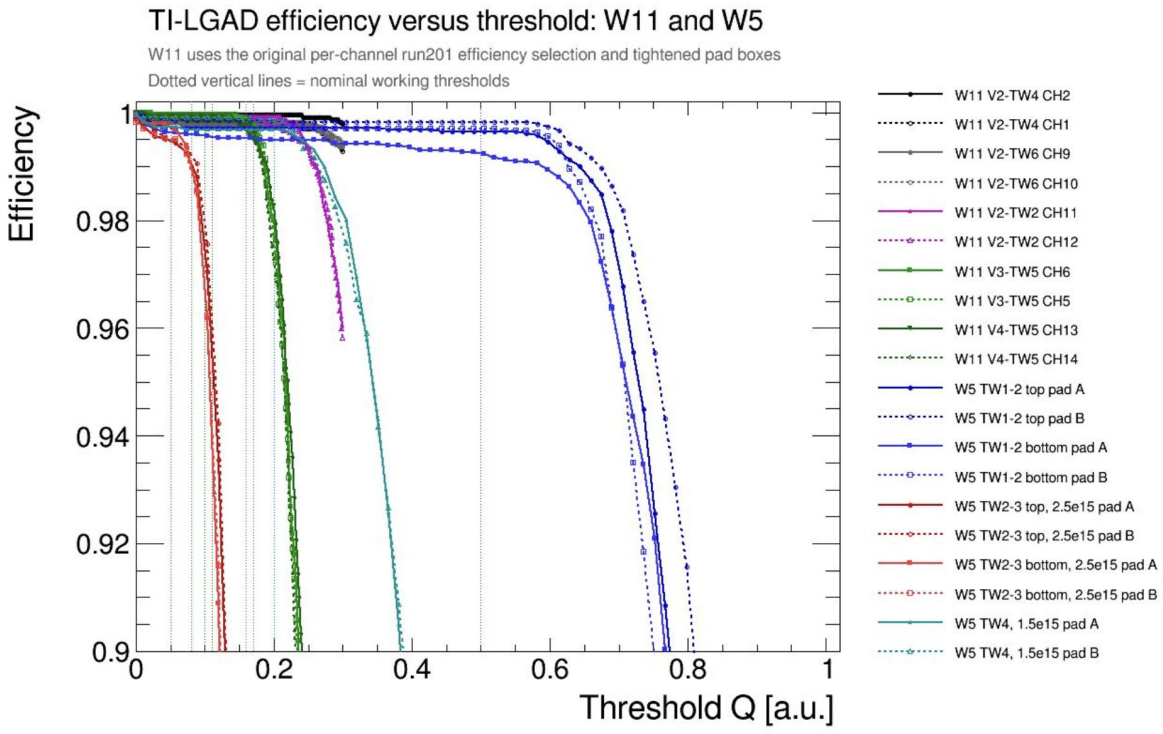


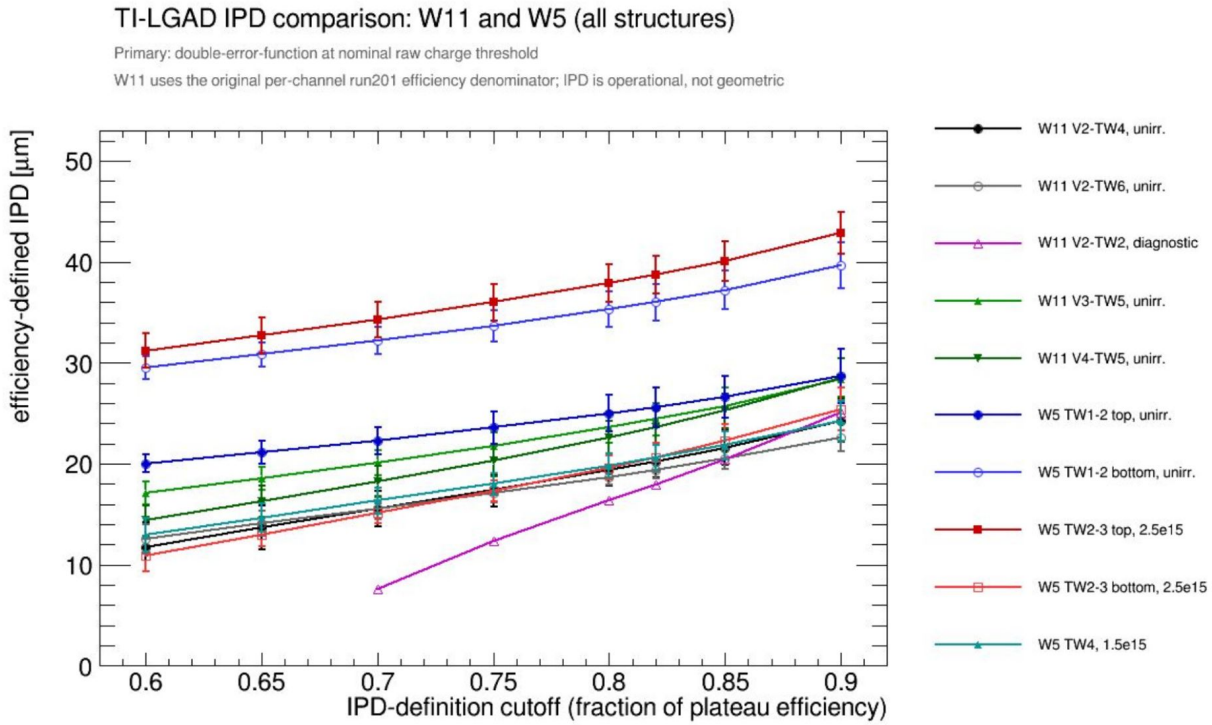




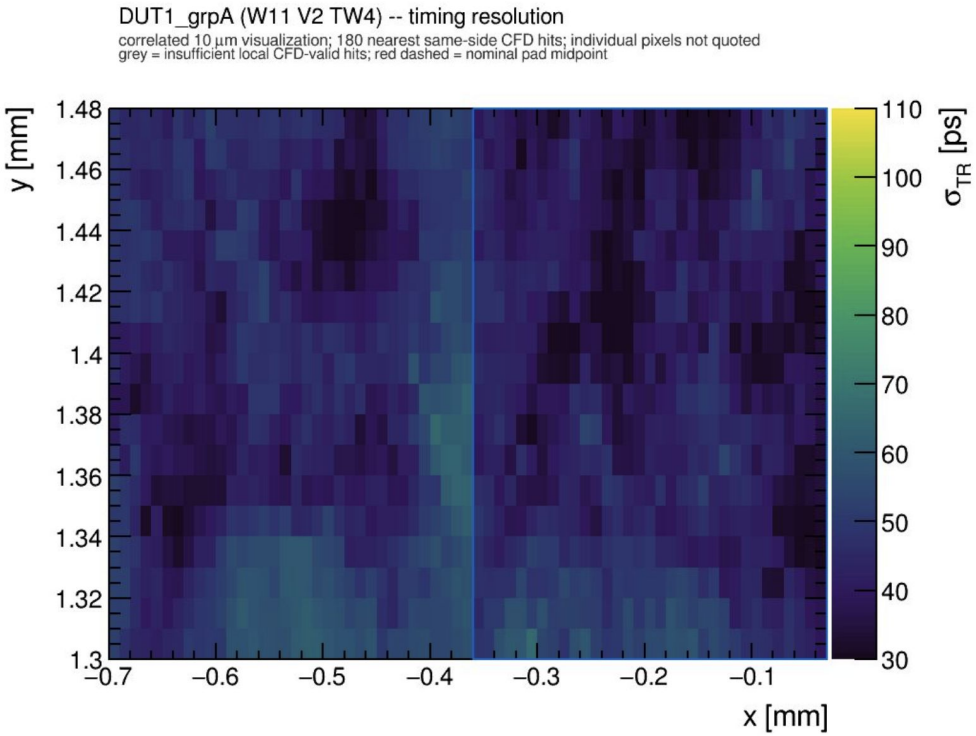


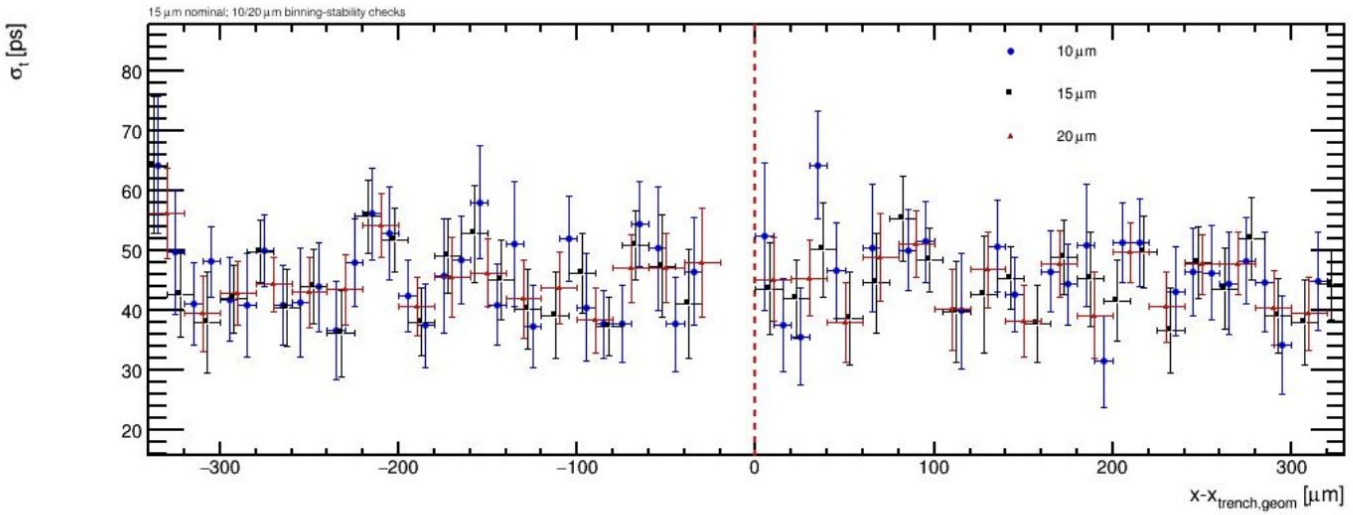
Efficiency vs threshold and IPD for TI-LGAD from wafer 5 and 11





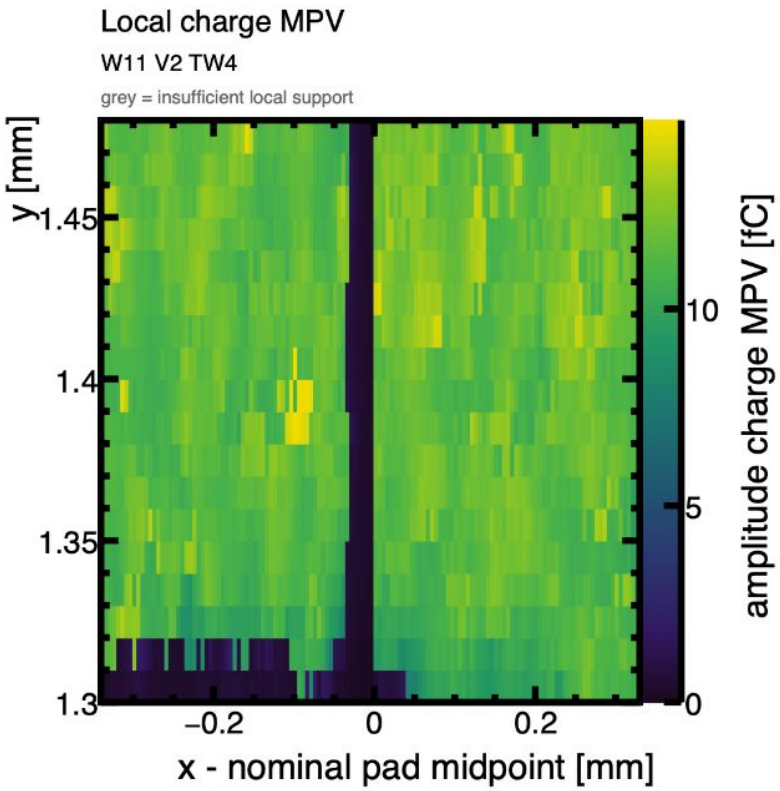
Spatial timing performance — W11 V2–TW4, unirradiated, 150 V

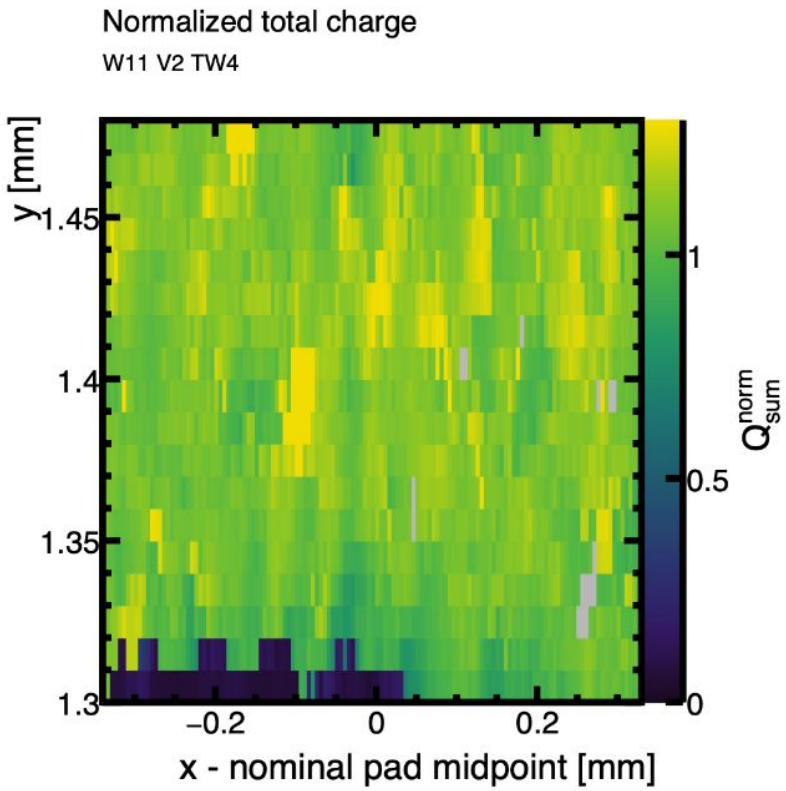


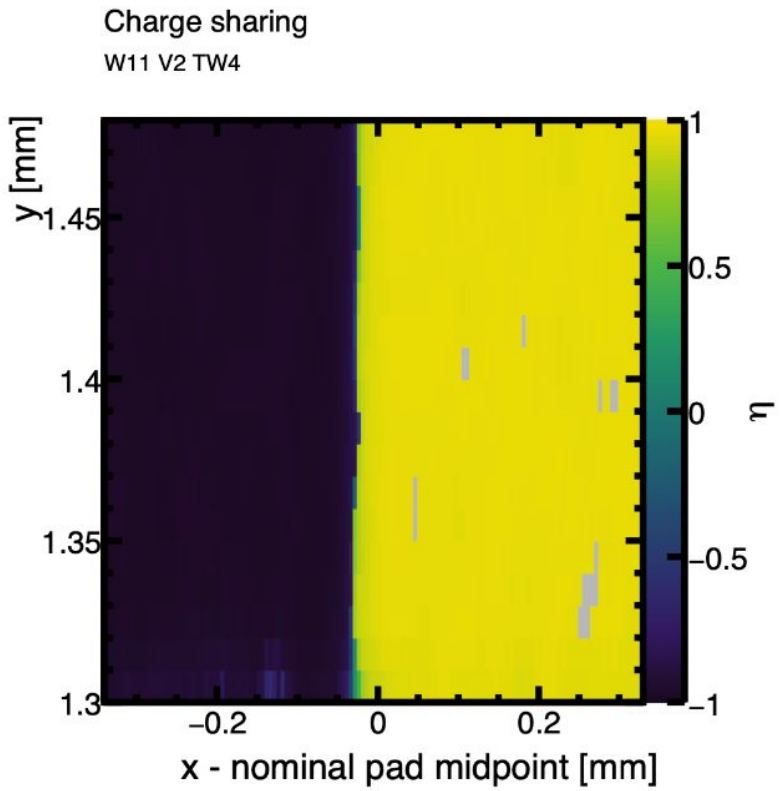


- **Bulk timing resolution: ~40–42 ps.**
- **CFD efficiency decreases locally in the inter-pixel region, accompanied by a degradation of σ_t.**
- **Away from the inter-pixel region, timing recovers to the clean-bulk level.**

2D charge response and charge sharing — W11 V2–TW4, 150 V

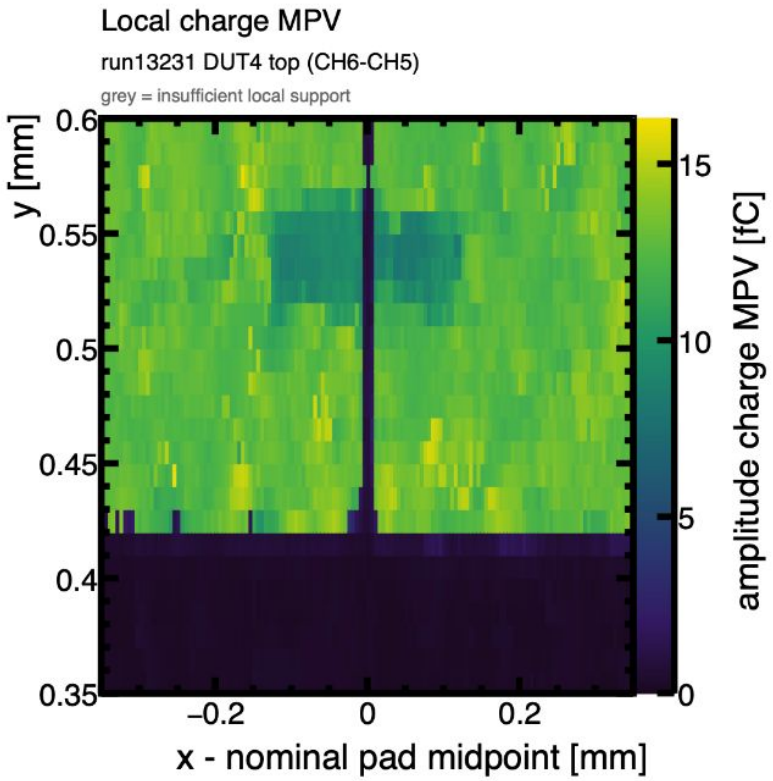


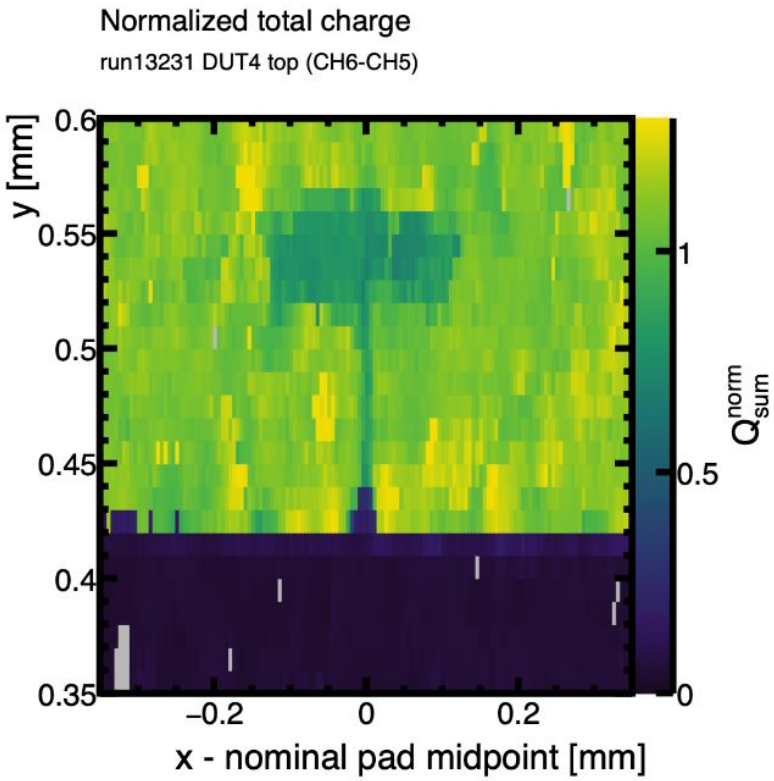


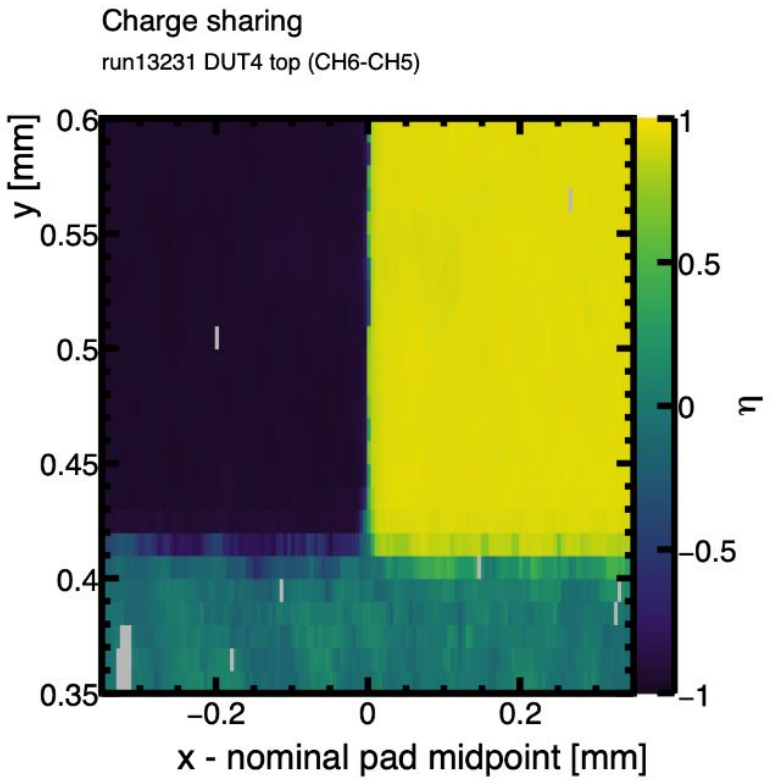


- **The inter-pixel structure is localized in 2D.**
- **The summed response and sharing observable show the same spatial transition.**
- **The 2D result is consistent with the 1D charge-sharing profile.**

Spatial charge response after irradiation — W5 V2 TW4, $1.5\times10^{15}\,n_{eq}/cm^2$

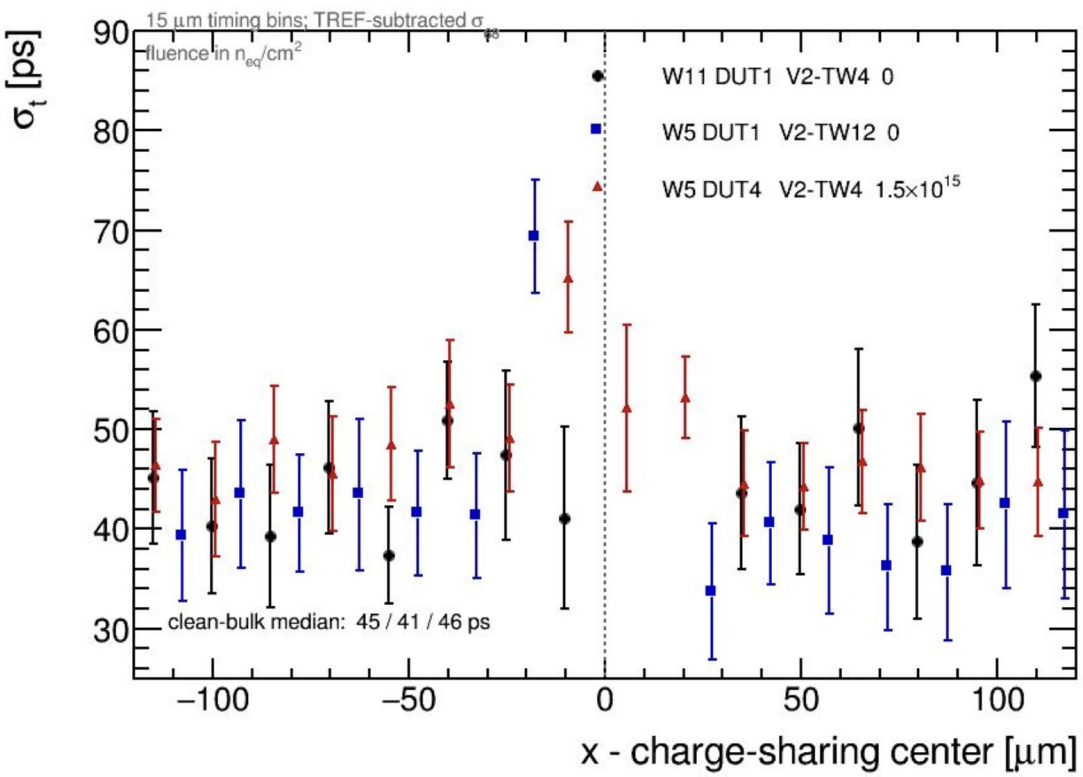


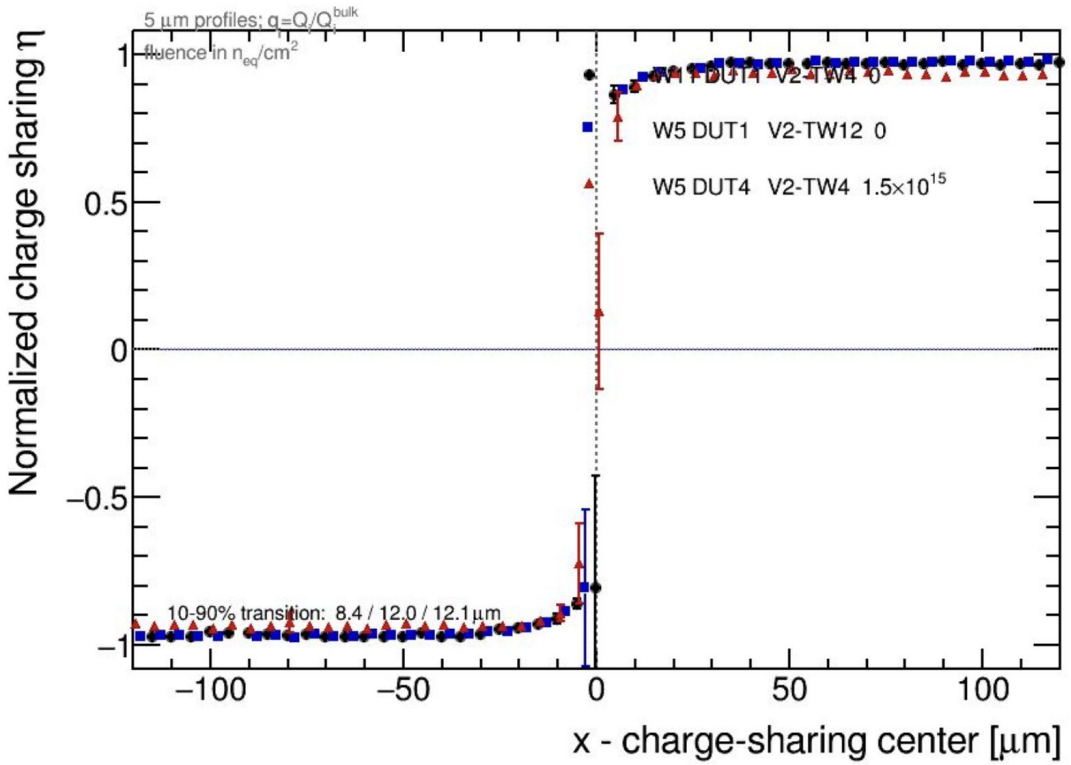




- **A clear charge-sharing transition remains visible after irradiation.**
- **The signal transfers between the two neighboring pads across the inter-pixel region.**
- **The normalized total response and sharing observable remain spatially localized around the transition.**

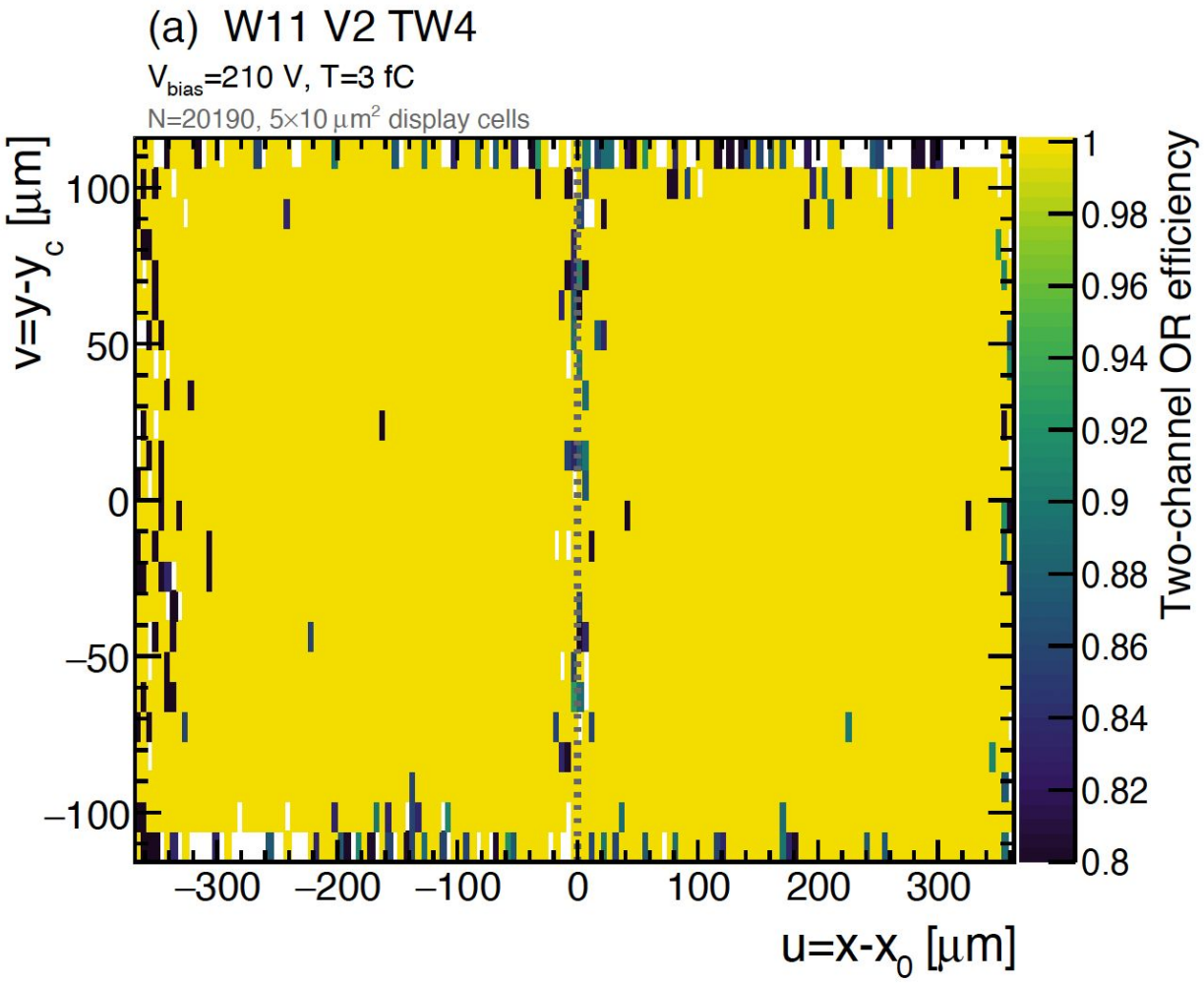
Inter-pixel timing and charge sharing in W11 and W5 TI-LGADs





- **A narrow charge-sharing transition is observed in all three devices**
- **The timing degradation is localized around the charge-sharing region; away from it, the bulk timing is recovered.**
- **The irradiated W5 DUT4 retains a sharp inter-pixel transition and ~46 ps bulk timing at 1.5 $\times 10^{15}$ n_{eq}/cm^2.**

TB efficiency



All selected tracks enter ε (u,T).
No DUT-response requirement is imposed in the denominator.

Coordinate

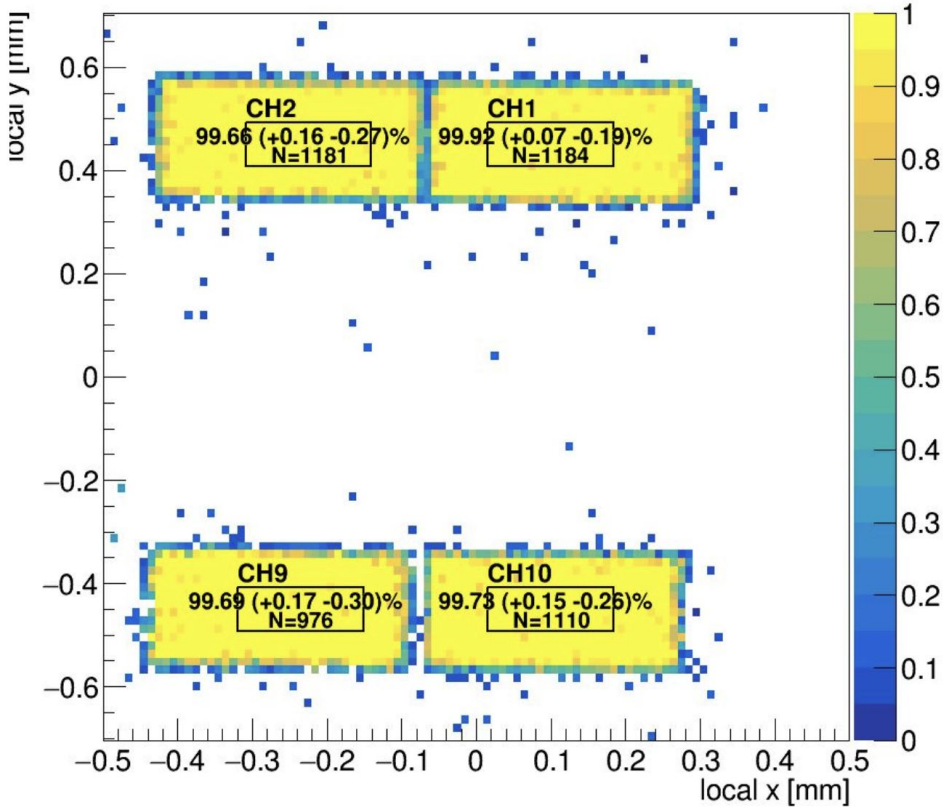
$u = x - x_0$

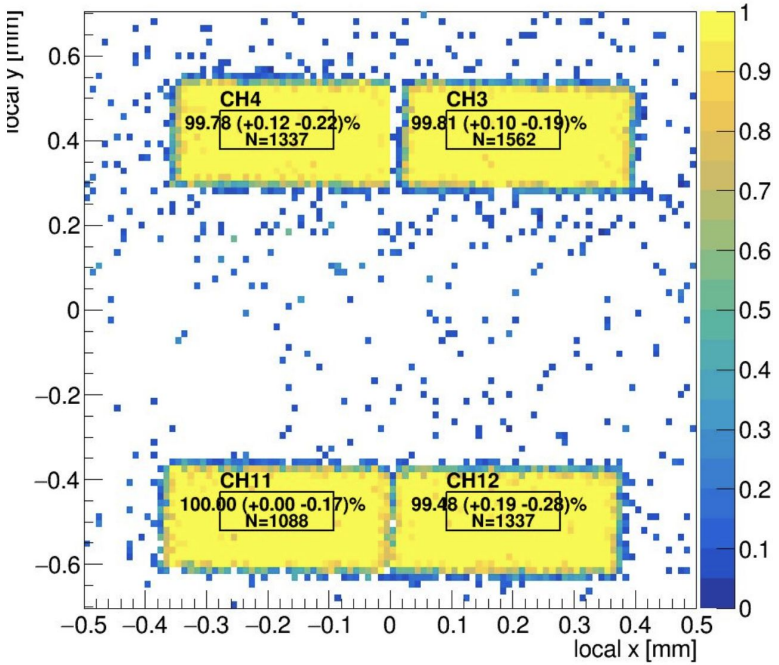
Bulk reference

100 < |u| < 230 μm

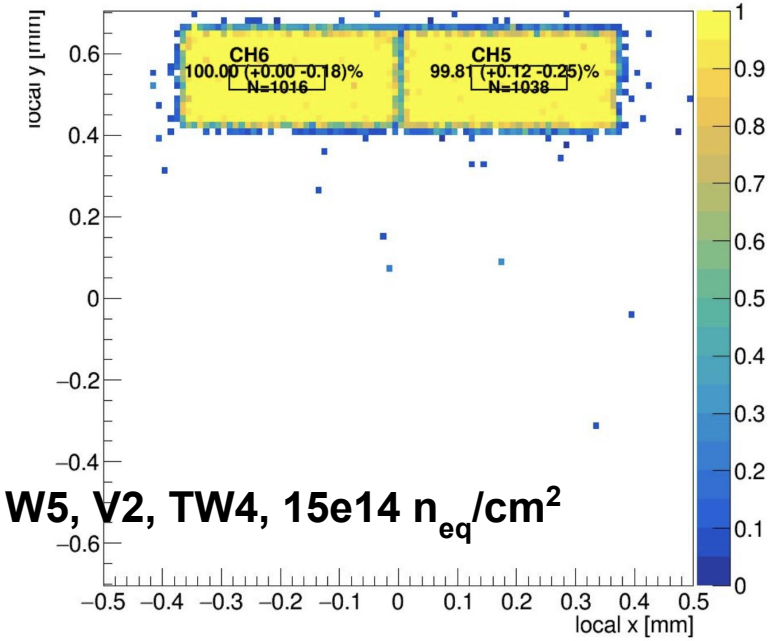
εbulk is measured, not forced to 1.

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



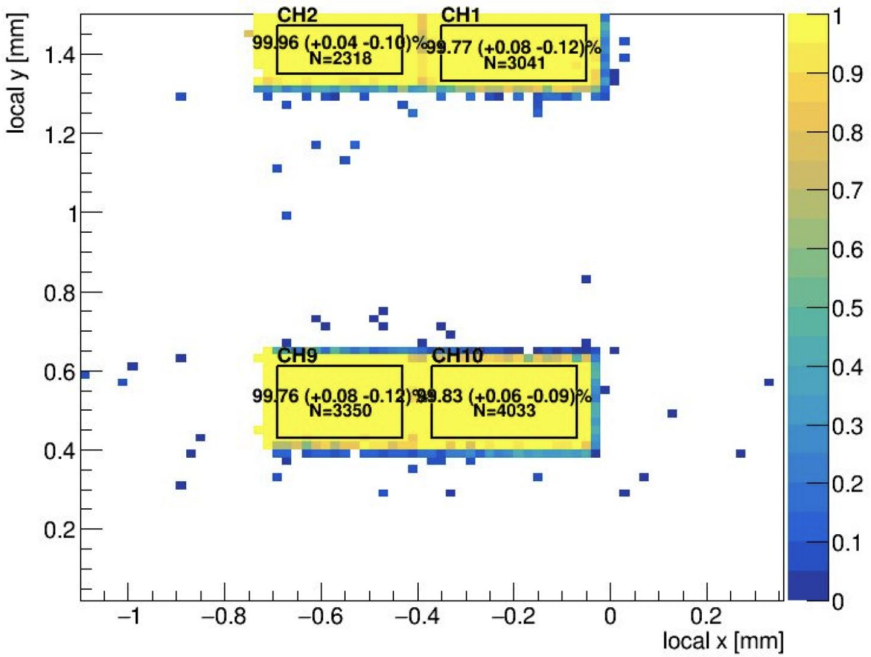


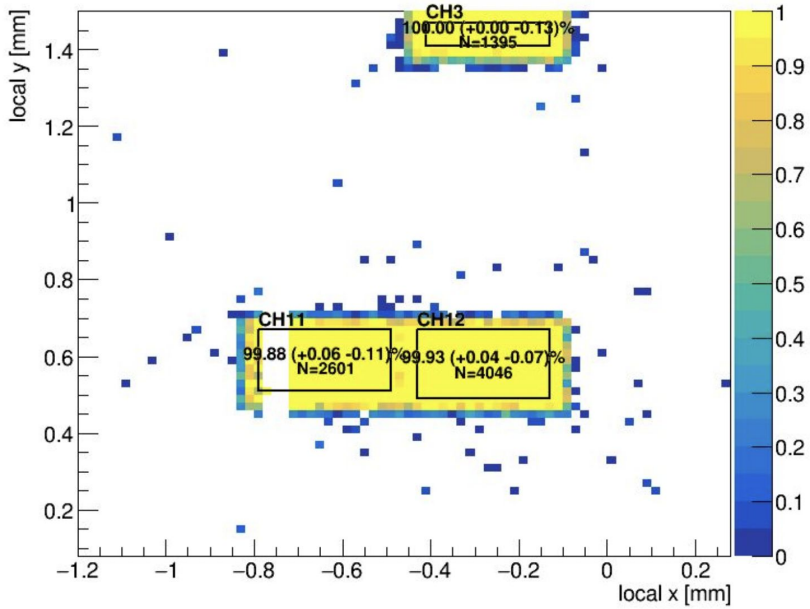
W5, V2, TW2-3, 25e14 n_{eq}/cm^2



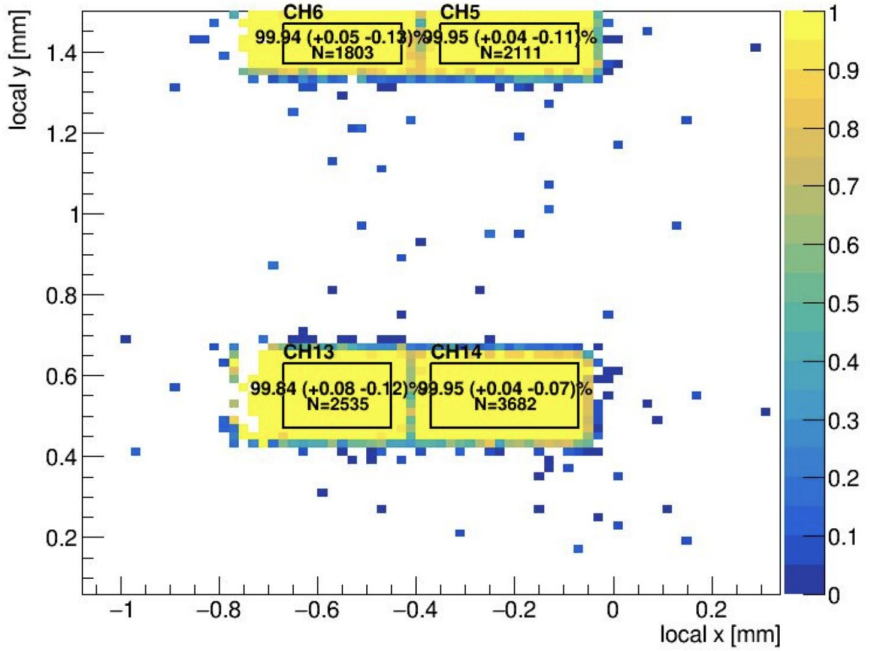
W5, V2, TW4, 15e14 n_{eq}/cm^2

W11, V2, TW 4/6, 0e14 n_{eq}/cm^2





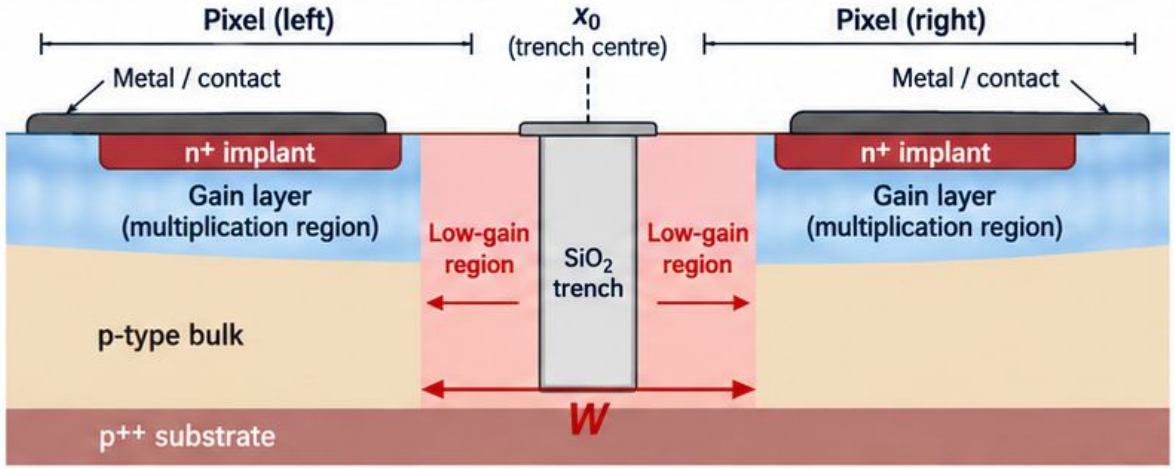
W11, V2, TW 1/2, 0e14 n_{eq}/cm^2



W11, V3/4, TW5, 0e14 n_{eq}/cm^2

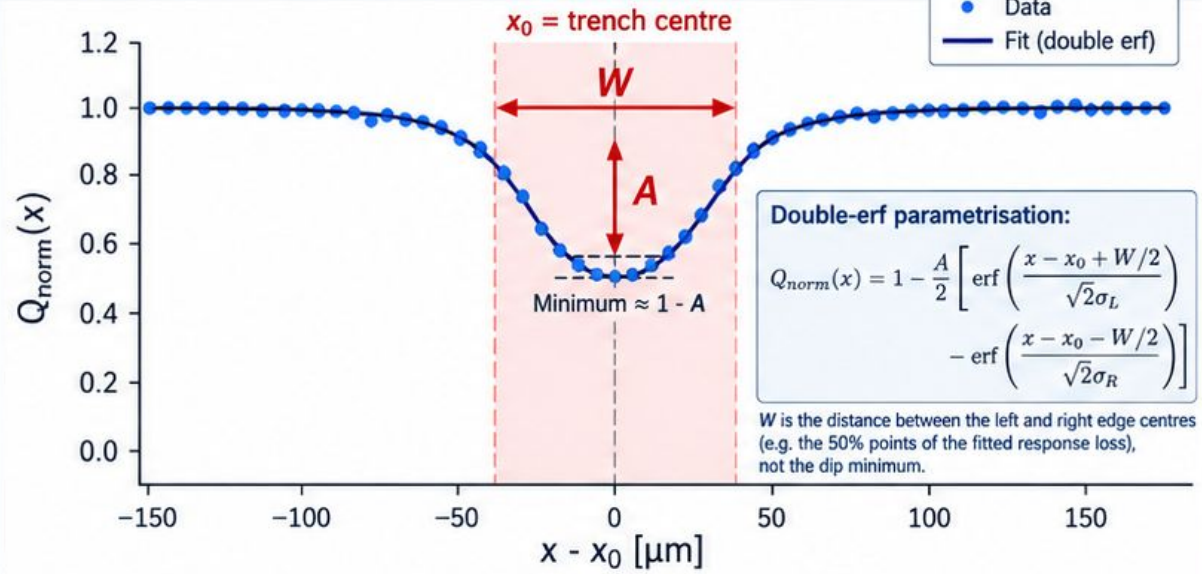
Conceptual parametrisation of TI-LGAD trench response

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

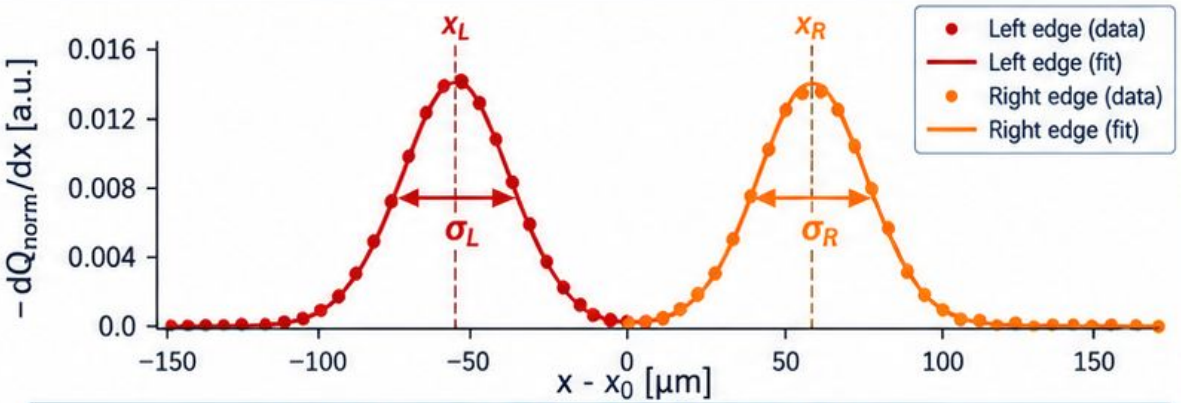


W is not the physical etched trench width only,
but the effective response-loss width extracted from the signal profile.

B Normalised collected charge across the trench

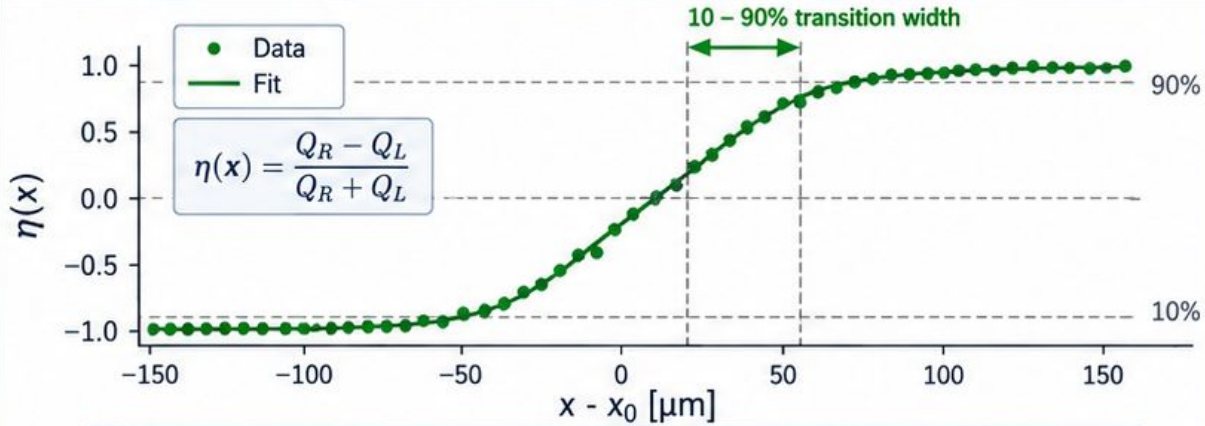


C Edge response and extraction of σ



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



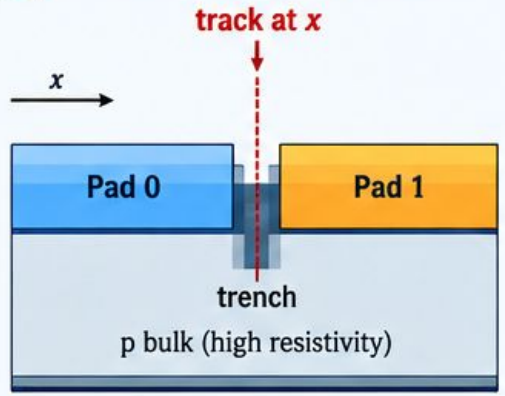
η provides an independent charge-sharing observable complementarty to $Q_{norm}(x)$.

Parameter summary

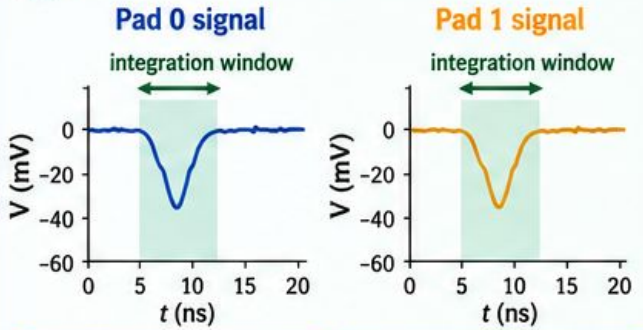
x_0 : trench centre from the fit / symmetry point | *W* : effective trench-affected width | *A* : relative charge-loss amplitude
σ_L, σ_R : edge-transition widths | $\eta(x)$: charge-sharing observable | **Applicable to both test beam and TCT scans**

A From detector signals to normalised total response

1 Geometry and track position



2 Signals from both pads



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

3 Normalisation and total response

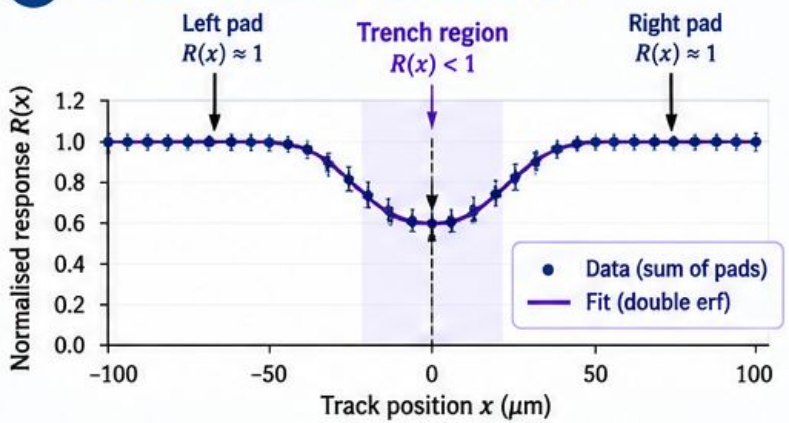
Each pad is normalised to its own bulk response (far from the trench):

$$q_L(x) = \frac{Q_L(x)}{Q_{L,\text{bulk}}} \qquad q_R(x) = \frac{Q_R(x)}{Q_{R,\text{bulk}}}$$

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

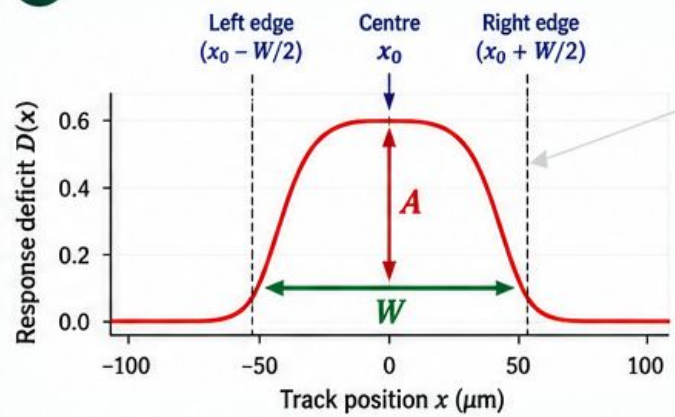
The response deficit $D(x)$ is described by a double error function:

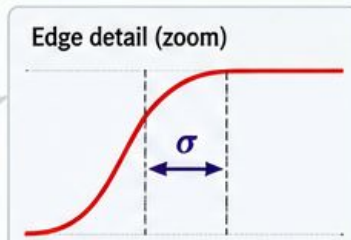
$$D(x) = 1 - R(x) = \frac{A}{2}\left[\operatorname{erf}\left(\frac{x-(x_0 - W/2)}{\sqrt{2}\sigma}\right) - \operatorname{erf}\left(\frac{x-(x_0 + W/2)}{\sqrt{2}\sigma}\right)\right]$$

2 Meaning of the parameters

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

3 Visual meaning of W and σ





σ determines how quickly the response changes at the edge.

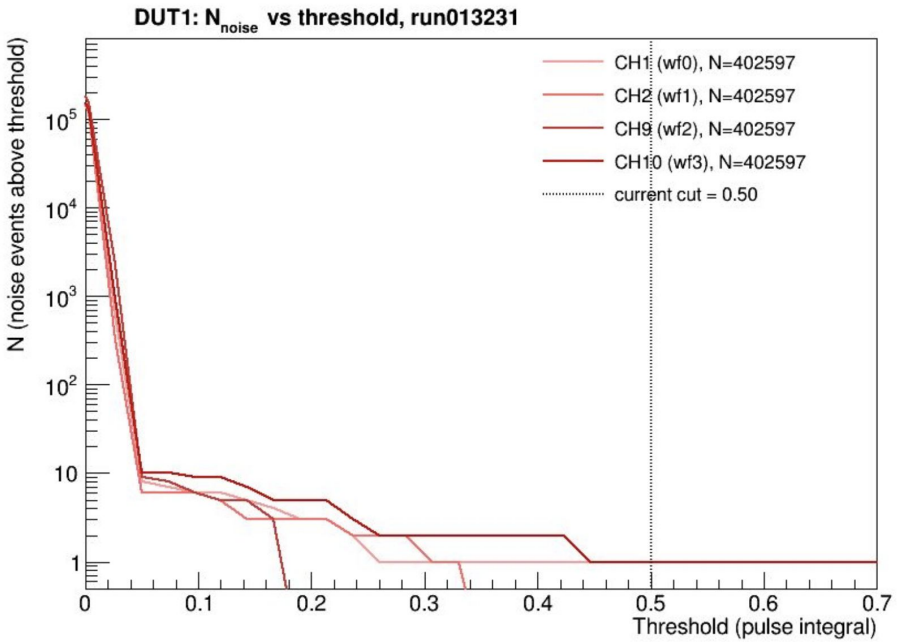
4 Figure of merit

Integrated response loss (area of the deficit):

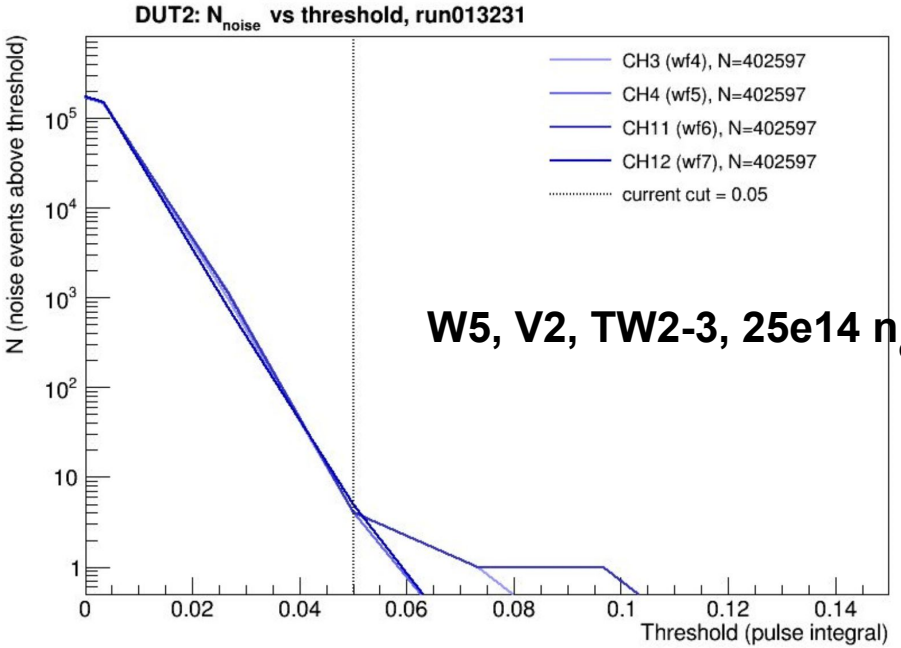
$$F = A \cdot W$$

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

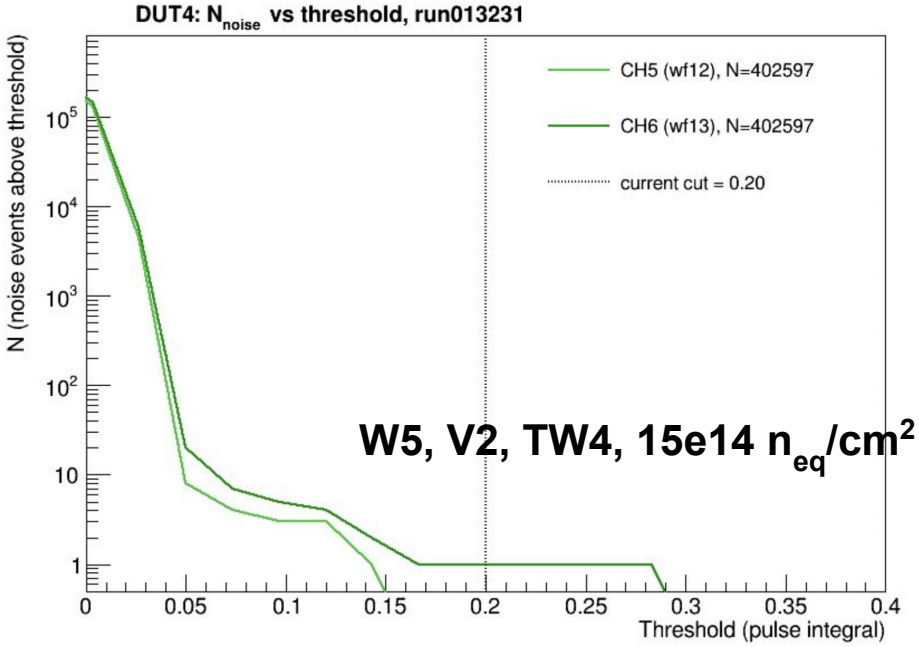
Wafer 5 analysis



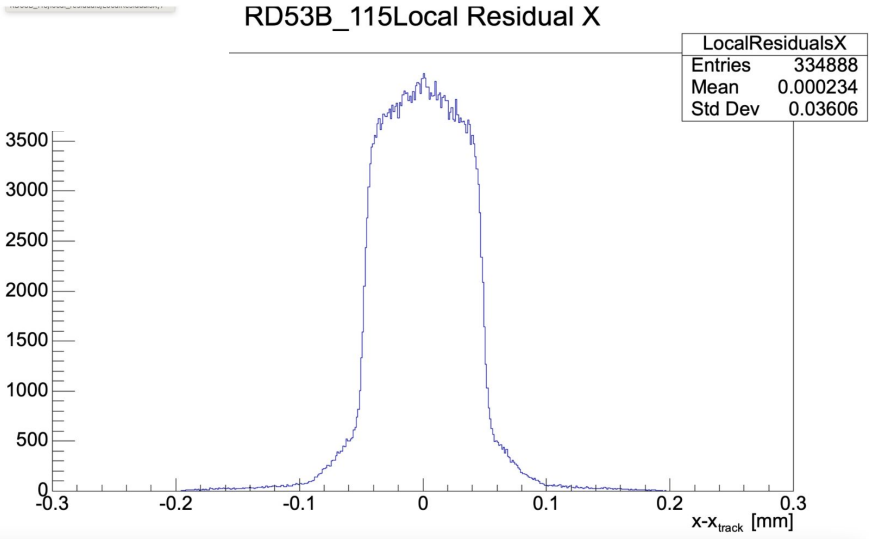
W5, V2, TW1-2, 0e14 n_{eq}/cm^2, angled at 10˚

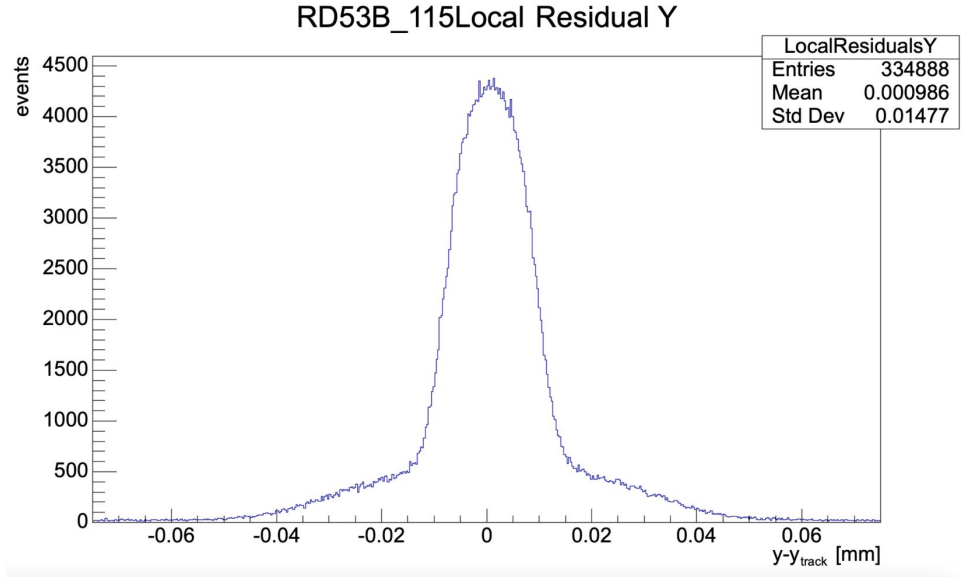


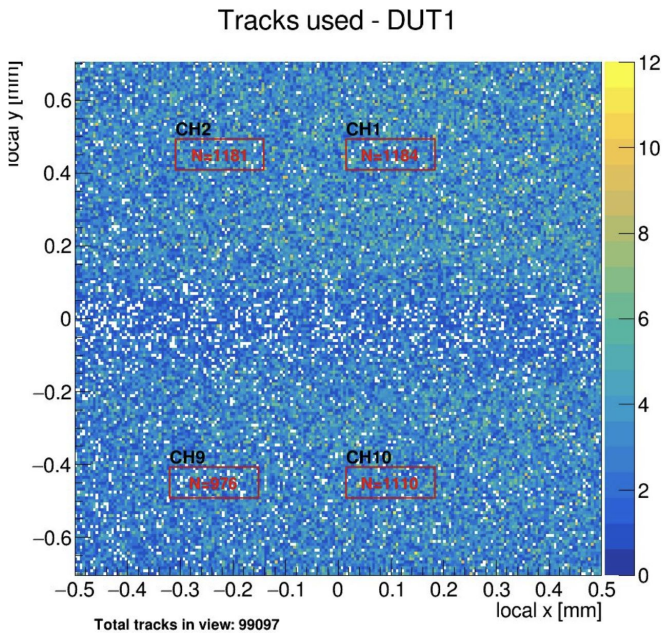
W5, V2, TW2-3, 25e14 n_{eq}/cm^2

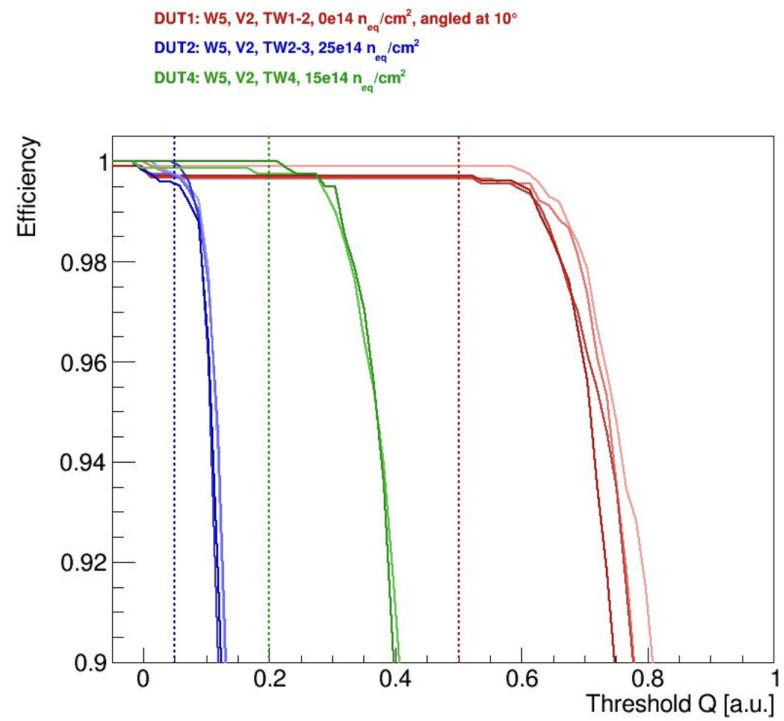


W5, V2, TW4, 15e14 n_{eq}/cm^2

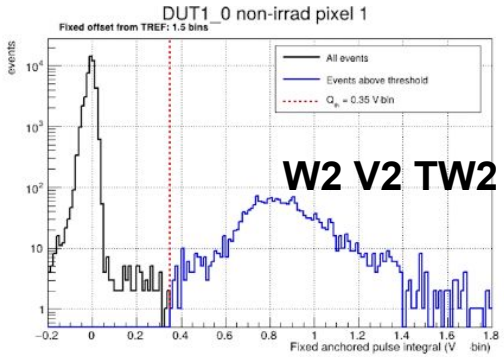

RD53B_115Local Residual X
LocalResidualsX
Entries 334888
Mean 0.000234
Std Dev 0.03606
x-x_track [mm]

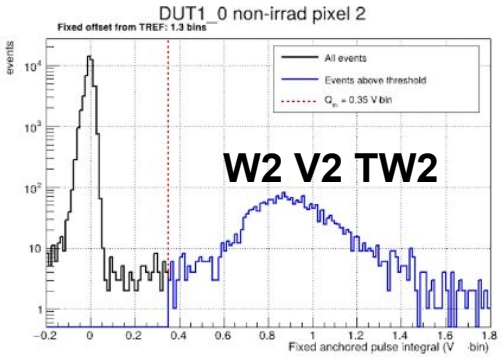

RD53B_115Local Residual Y
LocalResidualsY
Entries 334888
Mean 0.000986
Std Dev 0.01477
events
y-y_track [mm]

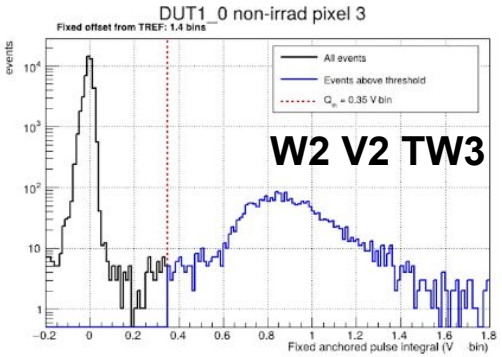

Tracks used - DUT1
CH2
N=1181
CH1
N=1164
CH9
N=979
CH10
N=1110
local x [mm]
Total tracks in view: 99097

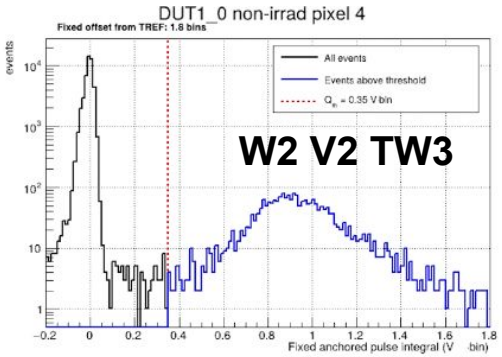

DUT1: W5, V2, TW1-2, 0e14 n_eq/cm², angled at 10°
DUT2: W5, V2, TW2-3, 25e14 n_eq/cm²
DUT4: W5, V2, TW4, 15e14 n_eq/cm²
Efficiency
Threshold Q [a.u.]

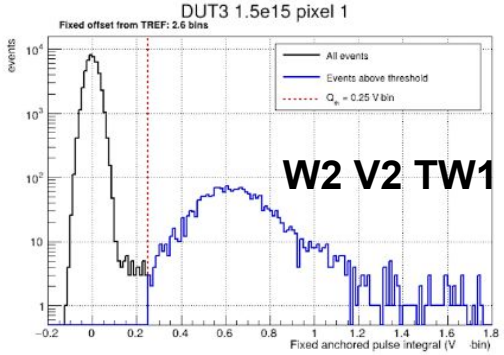
Pulse-integral distributions for TI-LGAD pixels before and after irradiation

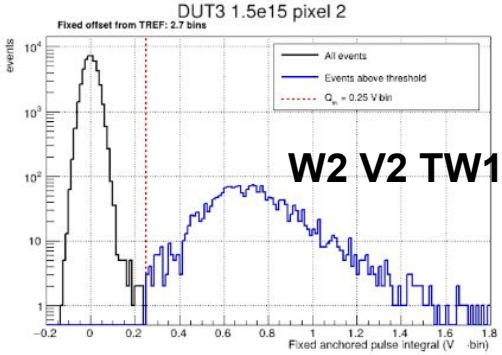


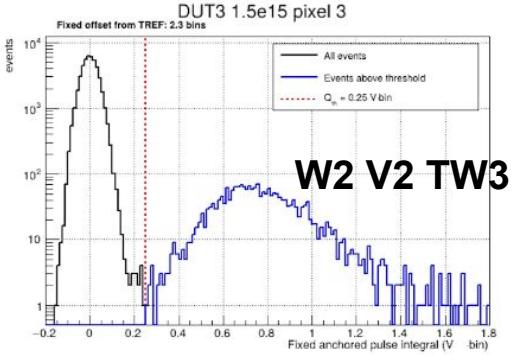


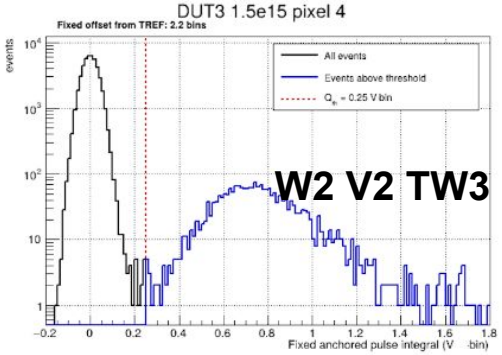








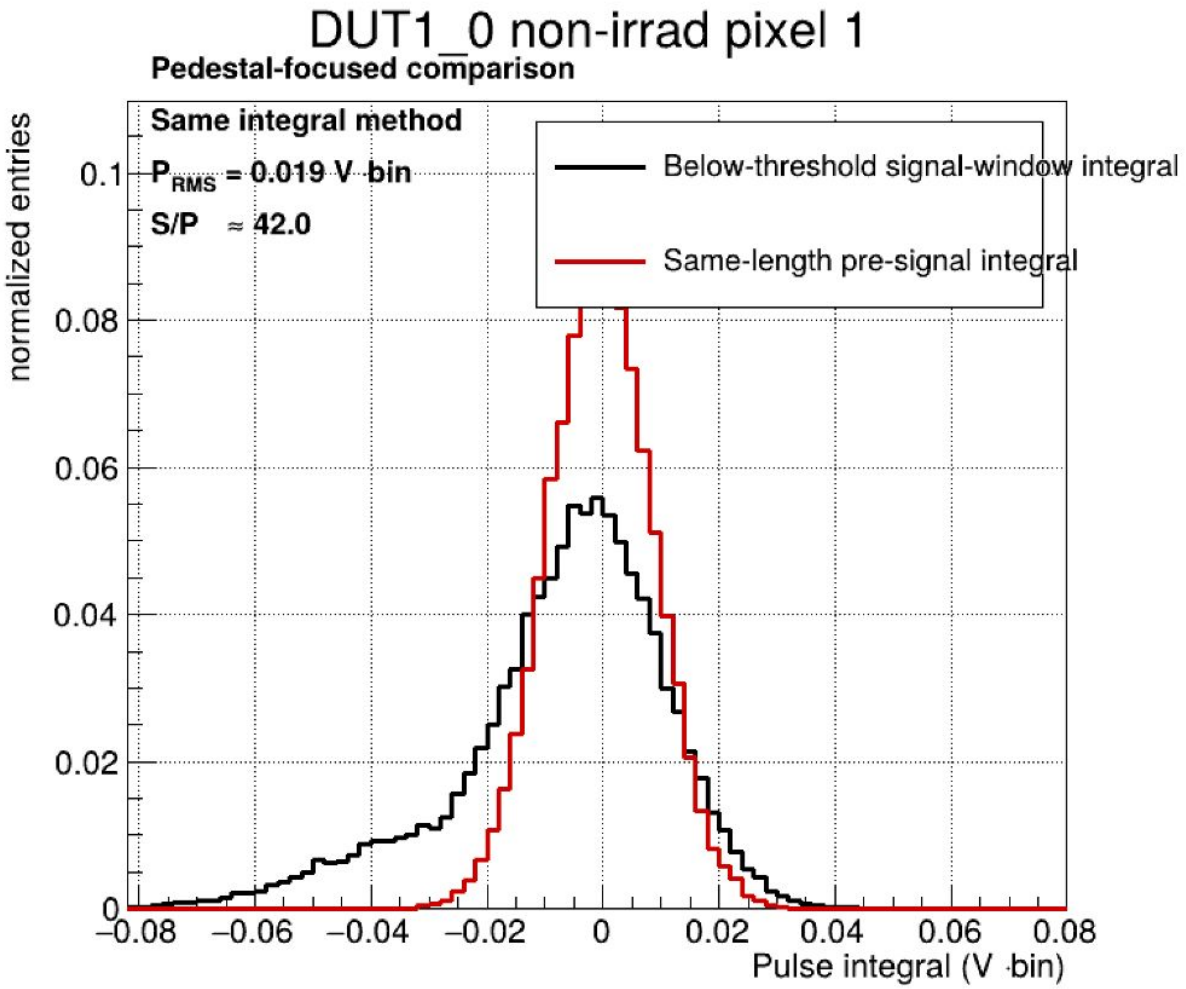


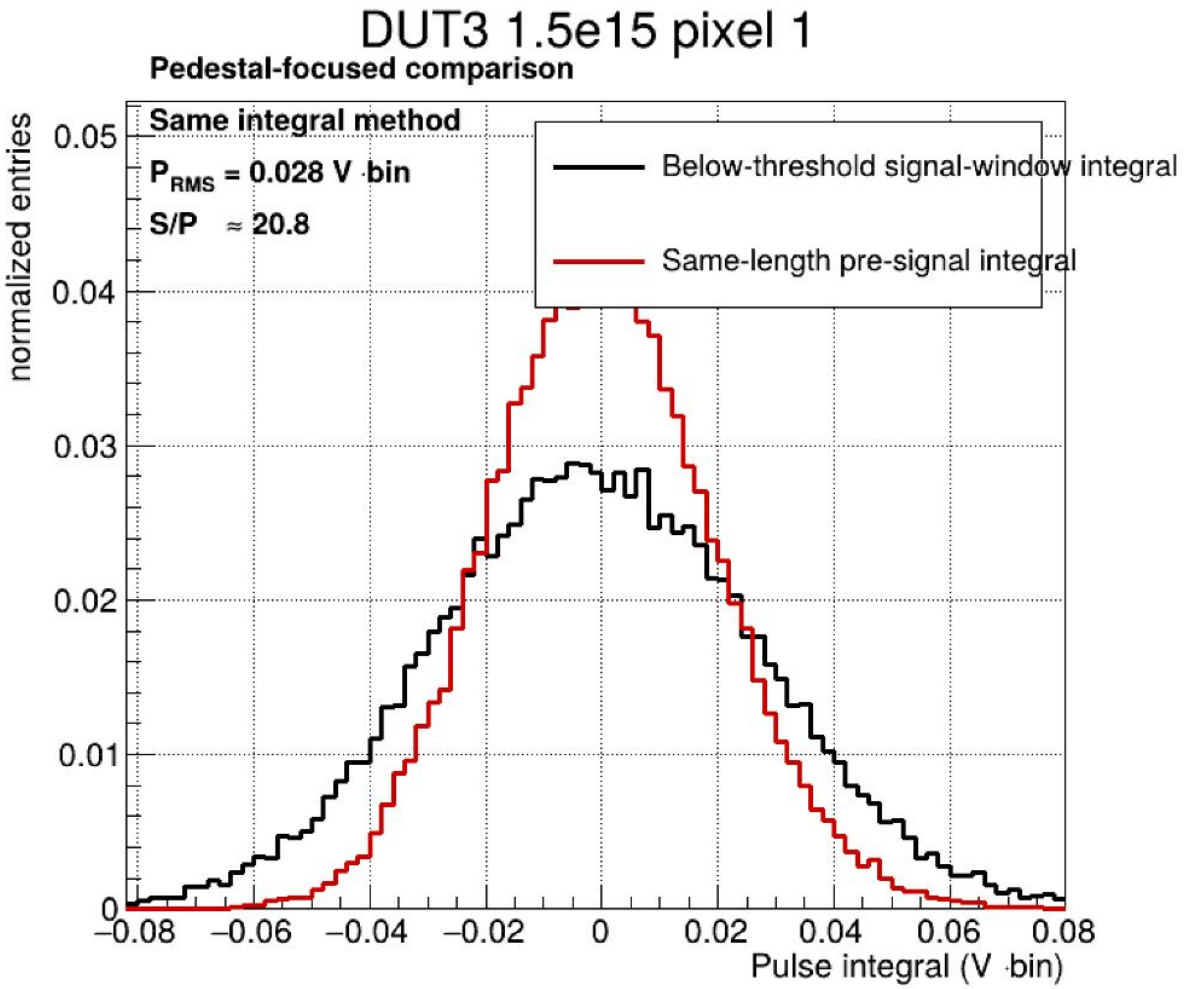


Top: non-irradiated DUT
Bottom: DUT irradiated to 1.5×10^{15} n_{eq}/cm^2

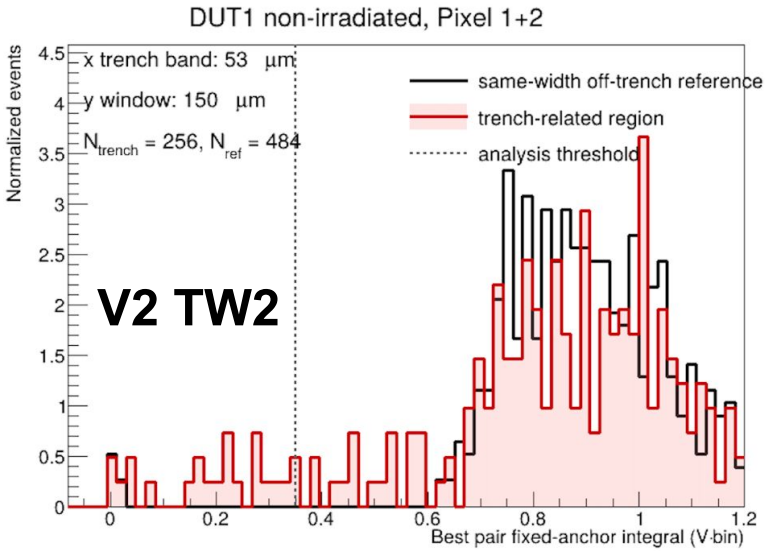
Black distributions contain all events, blue distributions show events passing the pulse-integral threshold

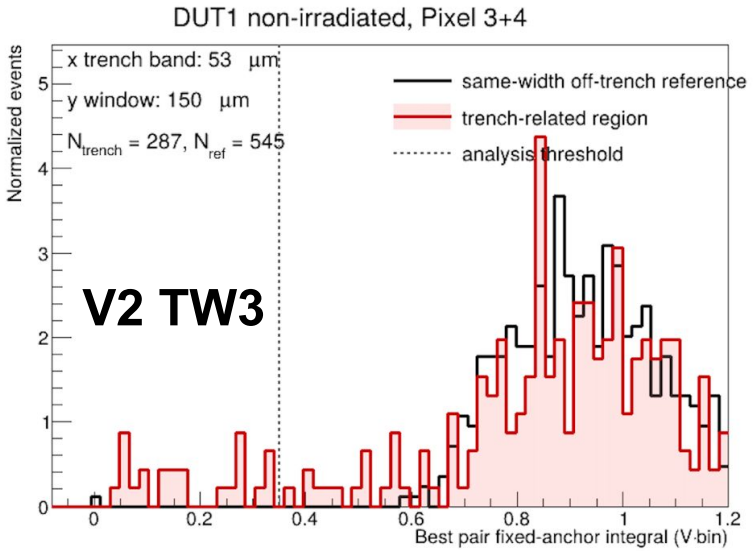
Pedestal Noise Comparison Before and After Irradiation

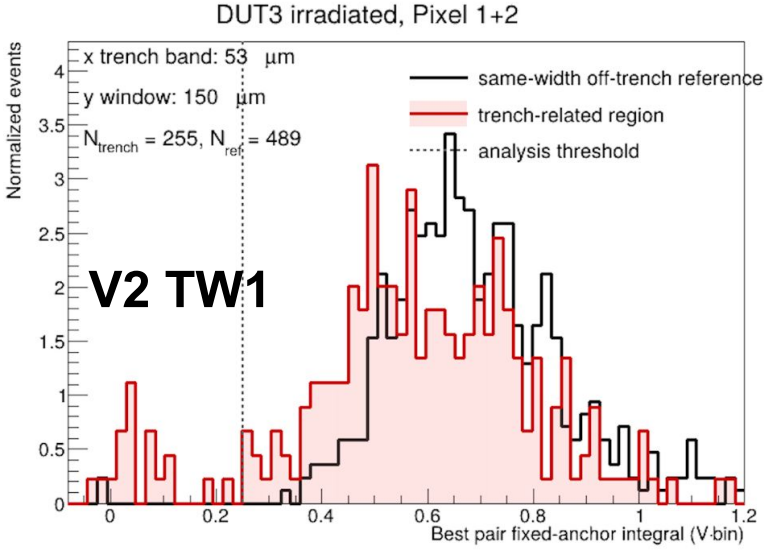


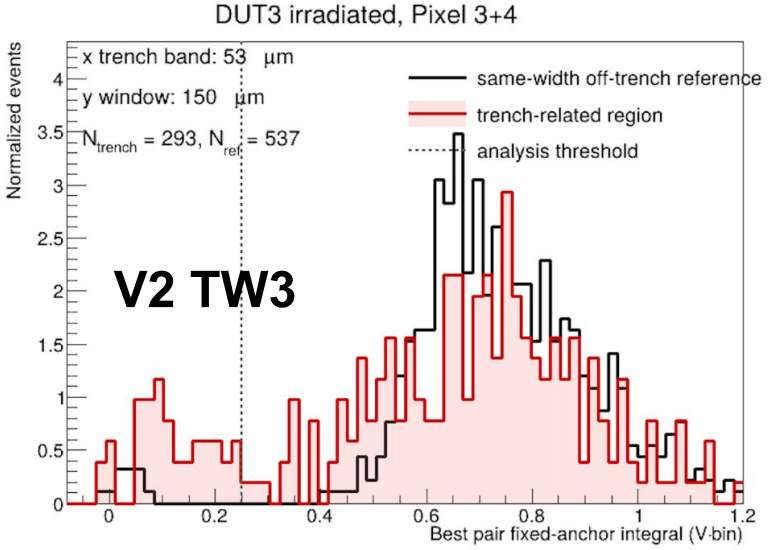


How does the trench-region signal spectrum compare to a nearby non-trench region?









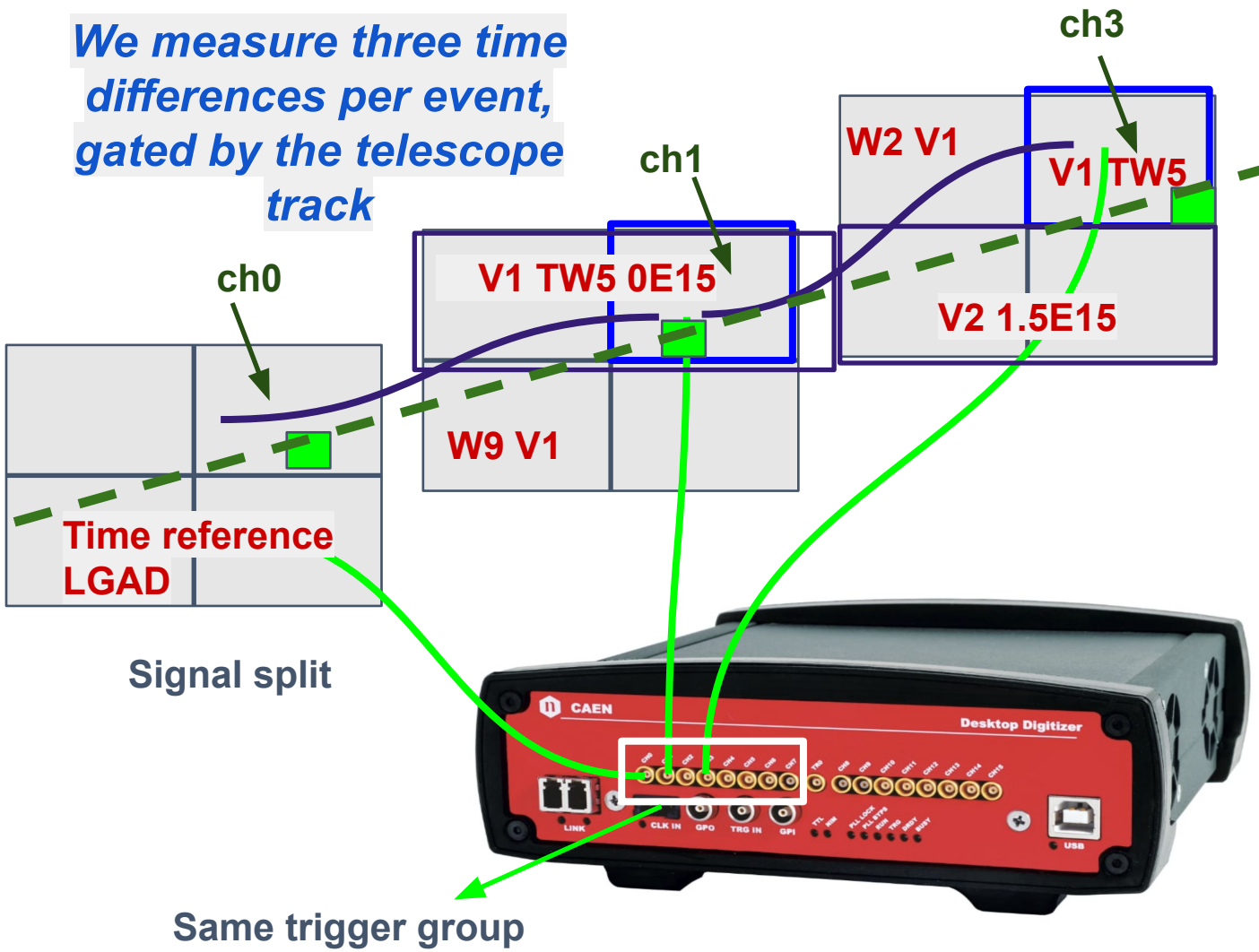
The trench-related region shows a lower-charge population than the off-trench reference region, which is consistent with the local efficiency loss.

x trench band: 53 µm

y trench band: 150 µm

Tracking-Gated[1] 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.

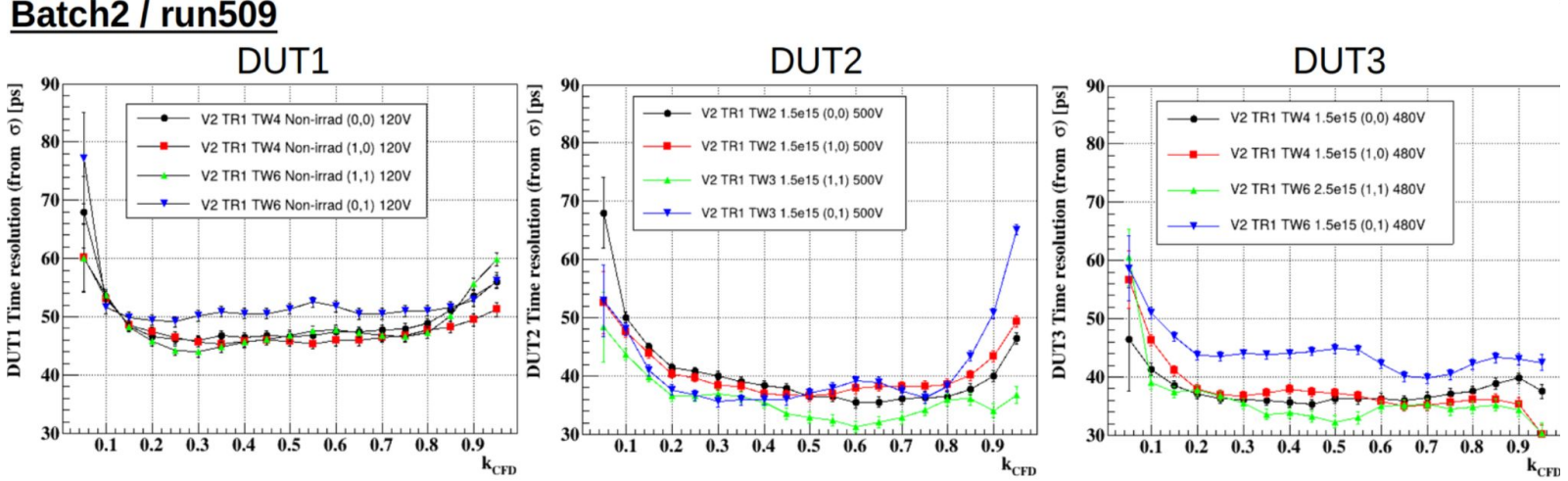
- **A** = *t*(ch1) – *t*(ch0) (non-irradiated DUT − REF)
- **B** = *t*(ch3) – *t*(ch0) (irradiated DUT − REF)
- **C** = *t*(ch1) – *t*(ch3) (DUT − DUT, REF-independent)

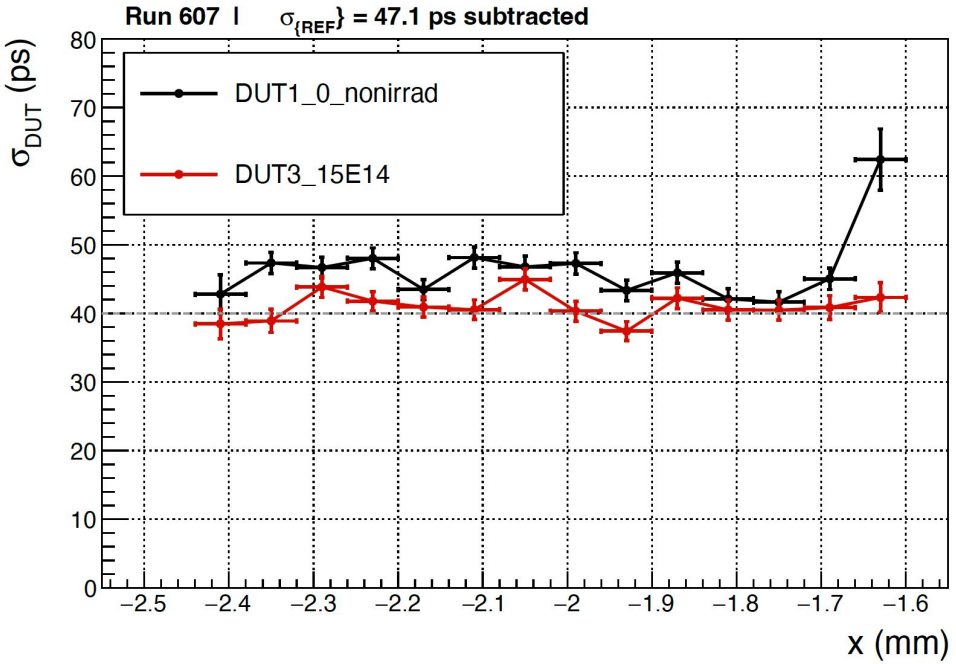
Triplet system equations:

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

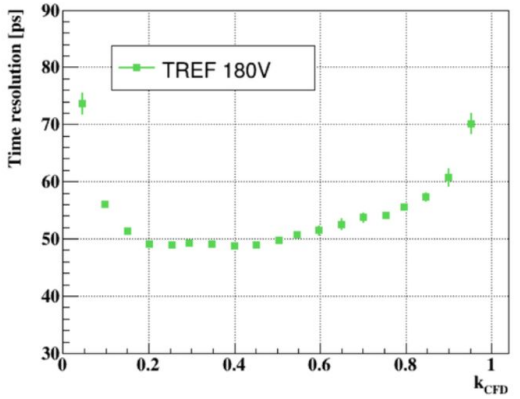
[1] Track gating is the process of keeping only data associated with valid particle tracks and rejecting unrelated or noisy events

Timing tracking-anchored results





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

	Batch 2 run509	Batch 3 run607
DUT1 non-irrad	~47 ps @ 120V	**43 ps @ 165V**
DUT3 1.5×10¹⁴	~38 ps @ 500V	**38 ps @ 495V**
TREF 180V	~49 ps	47 ps ✓

Batch 3: σ_{REF}= 47.1 ps (triplet method)