Recent results with radiation-tolerant TowerJazz 180 nm MALTA Sensors

Vienna Conference of Instrumentation 2022

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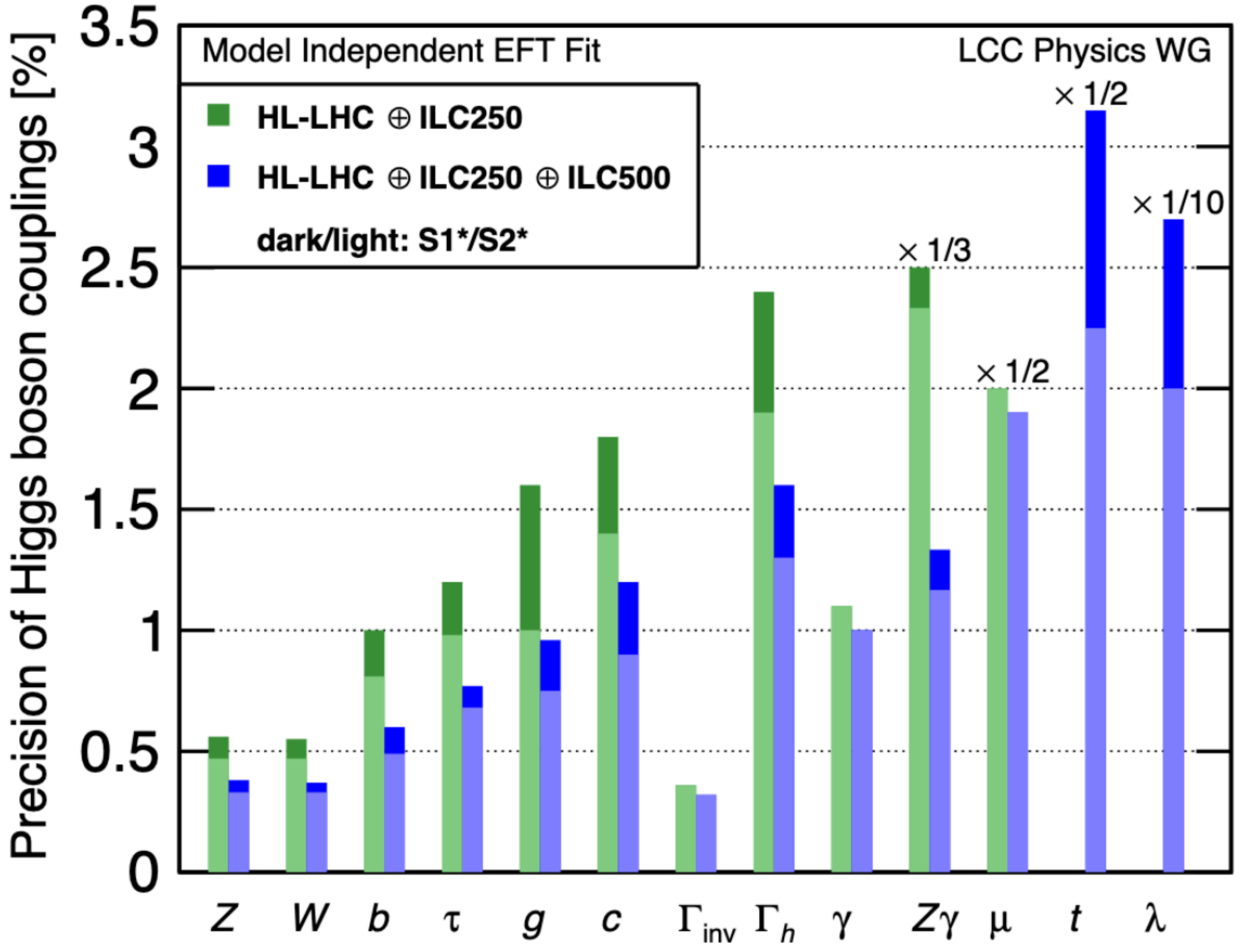
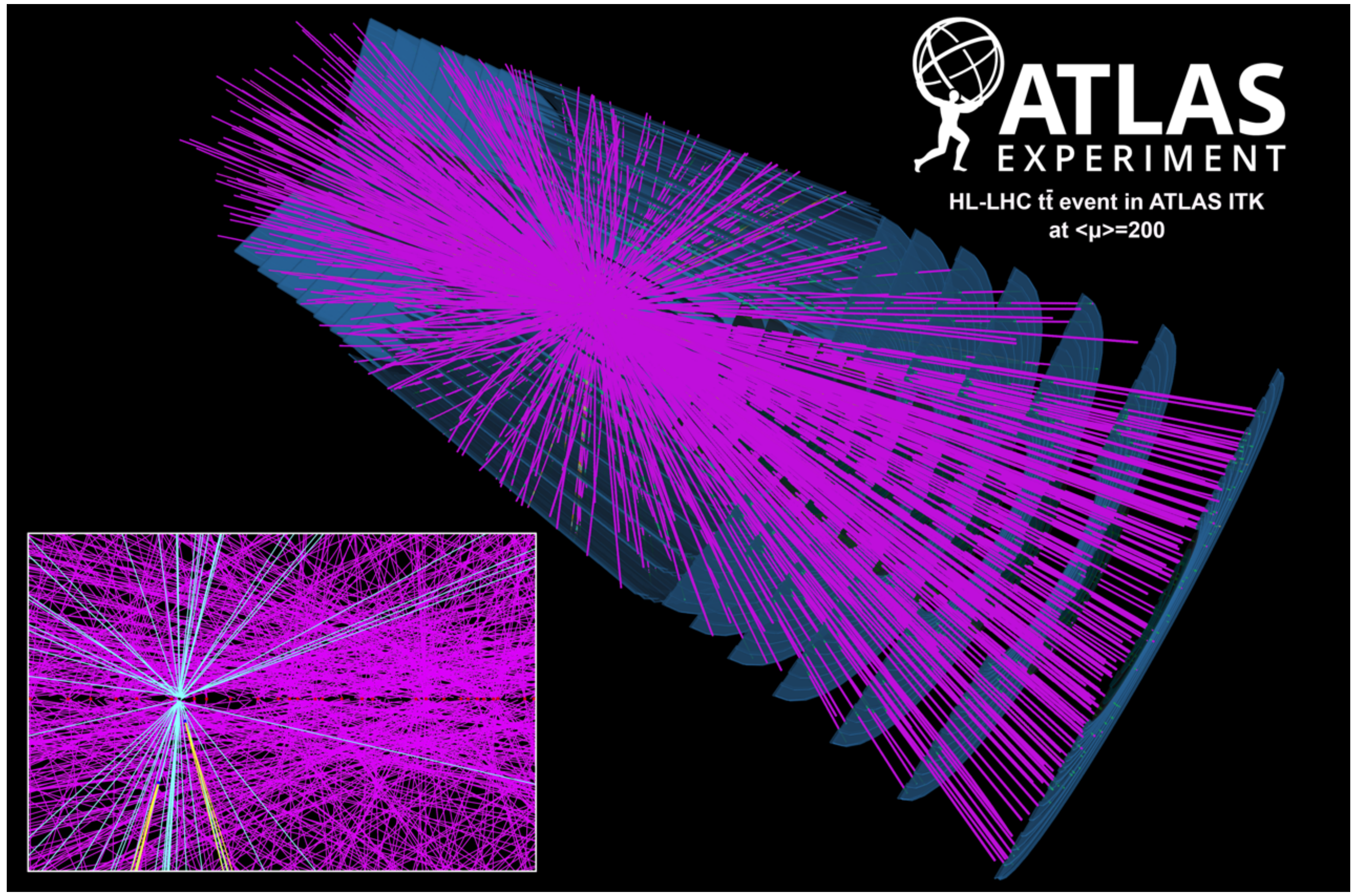
Future physics goals and experimental conditions will challenge us!





Goal: measure major Higgs couplings with ~1% precision!

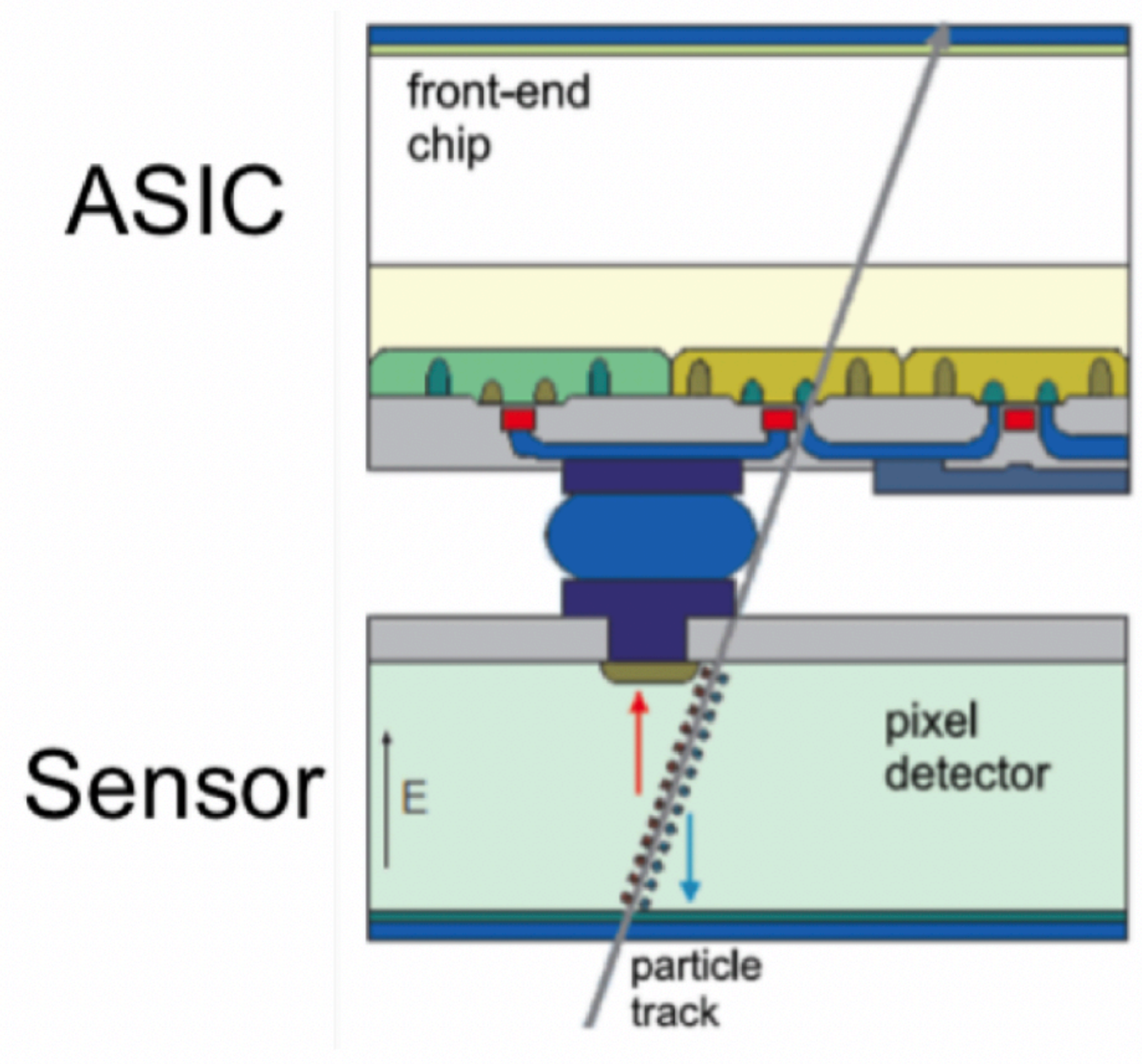
b vs. *c* discrimination, high luminosities, …

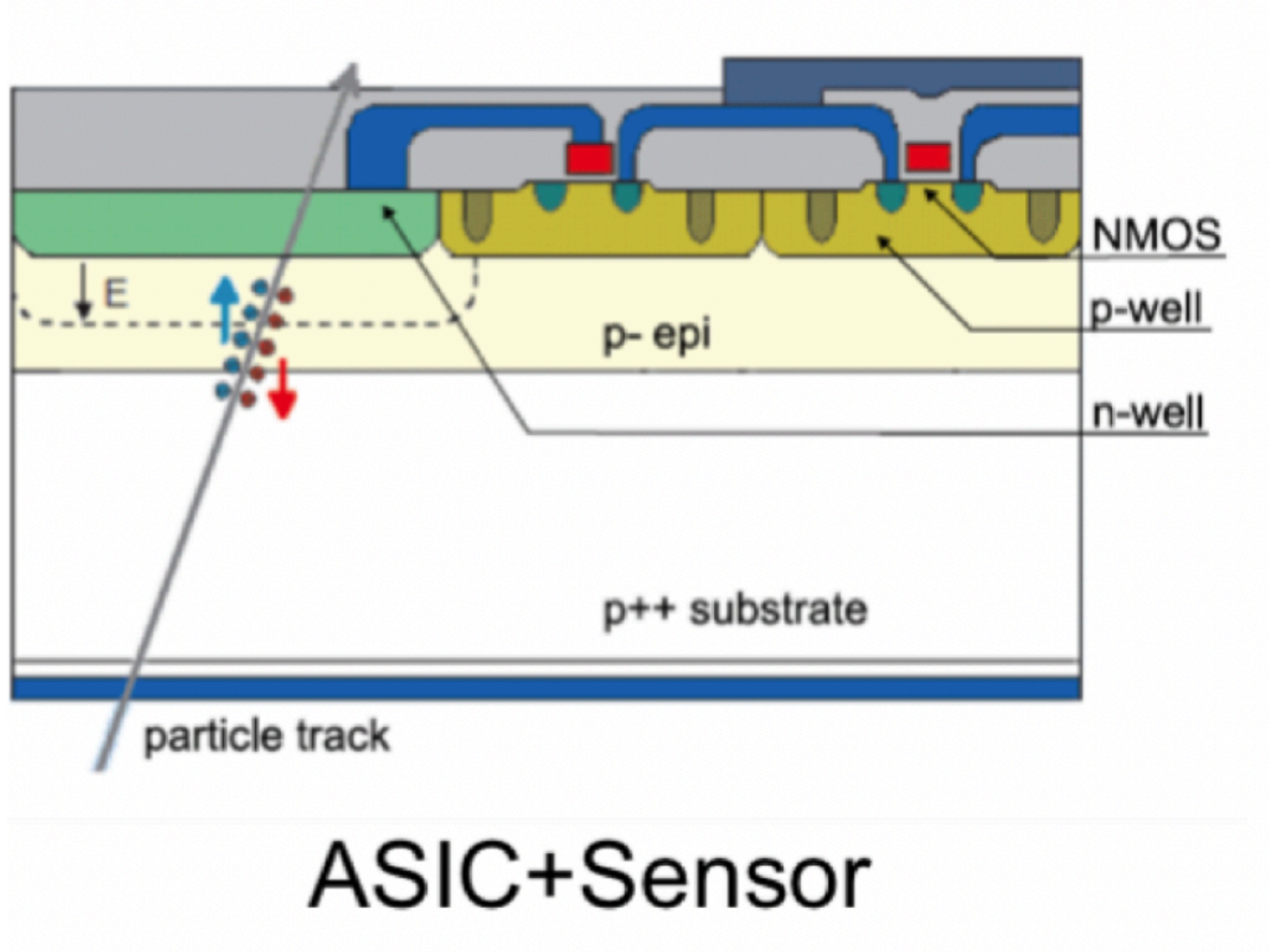
- *High radiation doses,*
- *Low material budget (reduced services / cooling)*
- *Fast readout*
- *Large surface area (13 m², 7x current)*
- *High granularity (200 MHz/cm² hit rate)*
- *Affordability?*

ILC Collaboration, 1903.01629 ATLAS Upgrade Event Displays

MAPS

- Monolithic Active Pixel Sensors (MAPS) present an attractive solution to many experimental challenges.
    - Integration of readout electronics and sensor in a single silicon die eliminates expensive bump-bonding step.
    - Small sensor capacitance (< fF)
      → reduced power consumption
      → reduced services
- Radiation tolerances unproven,
  ATLAS ITk outer layer taken as benchmark:
    - 1E+15 1 MeV n_{eq}/cm^2 Non-Ionising Energy Loss (NIEL)
    - ~100 Mrad Total Ionizing Dose (TID)
- LHC bunch-crossing rate requires
  timing response < 25 ns.
    - Smaller window for future colliders.





Hybrid sensors

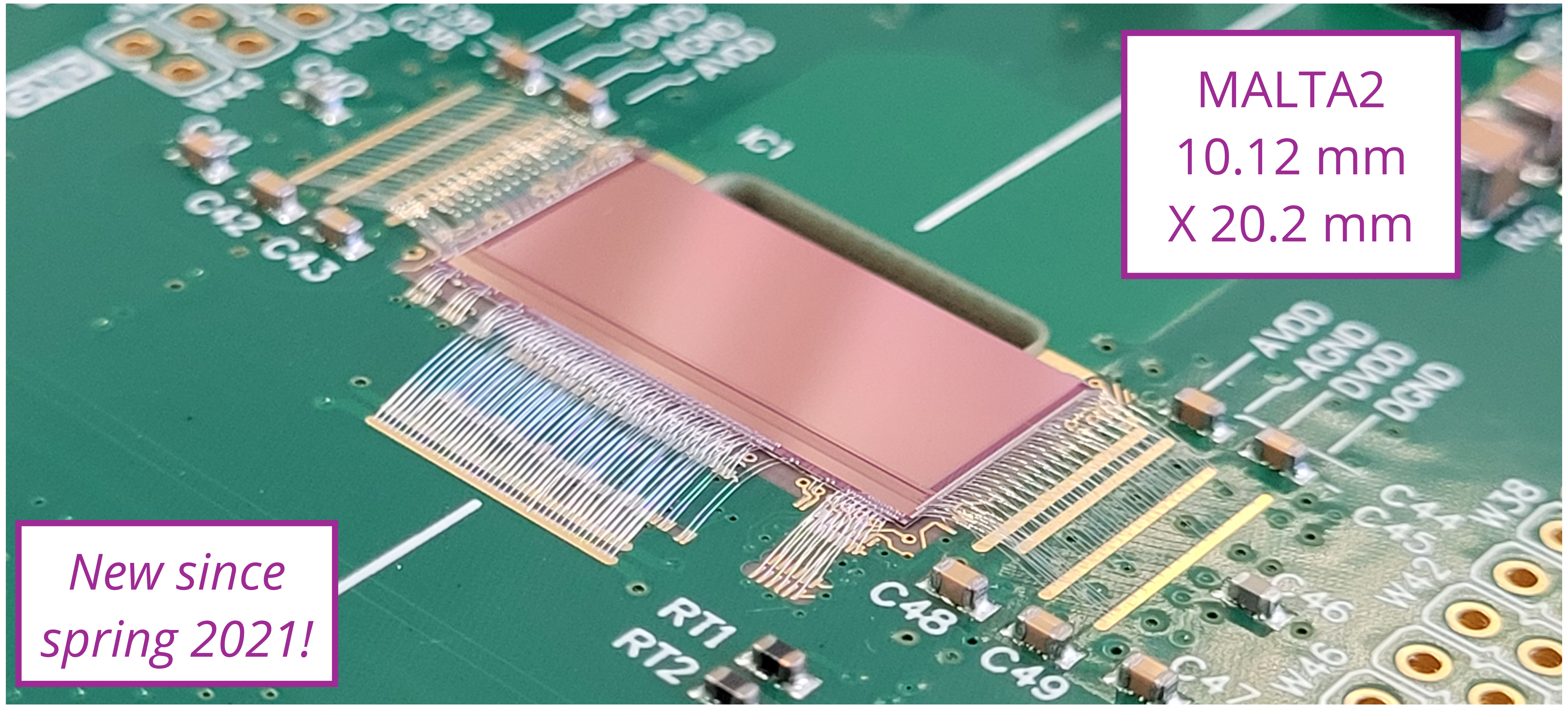
- Current state-of-the-art.
- Expensive bump-bonding.
- Well-understood radiation tolerance

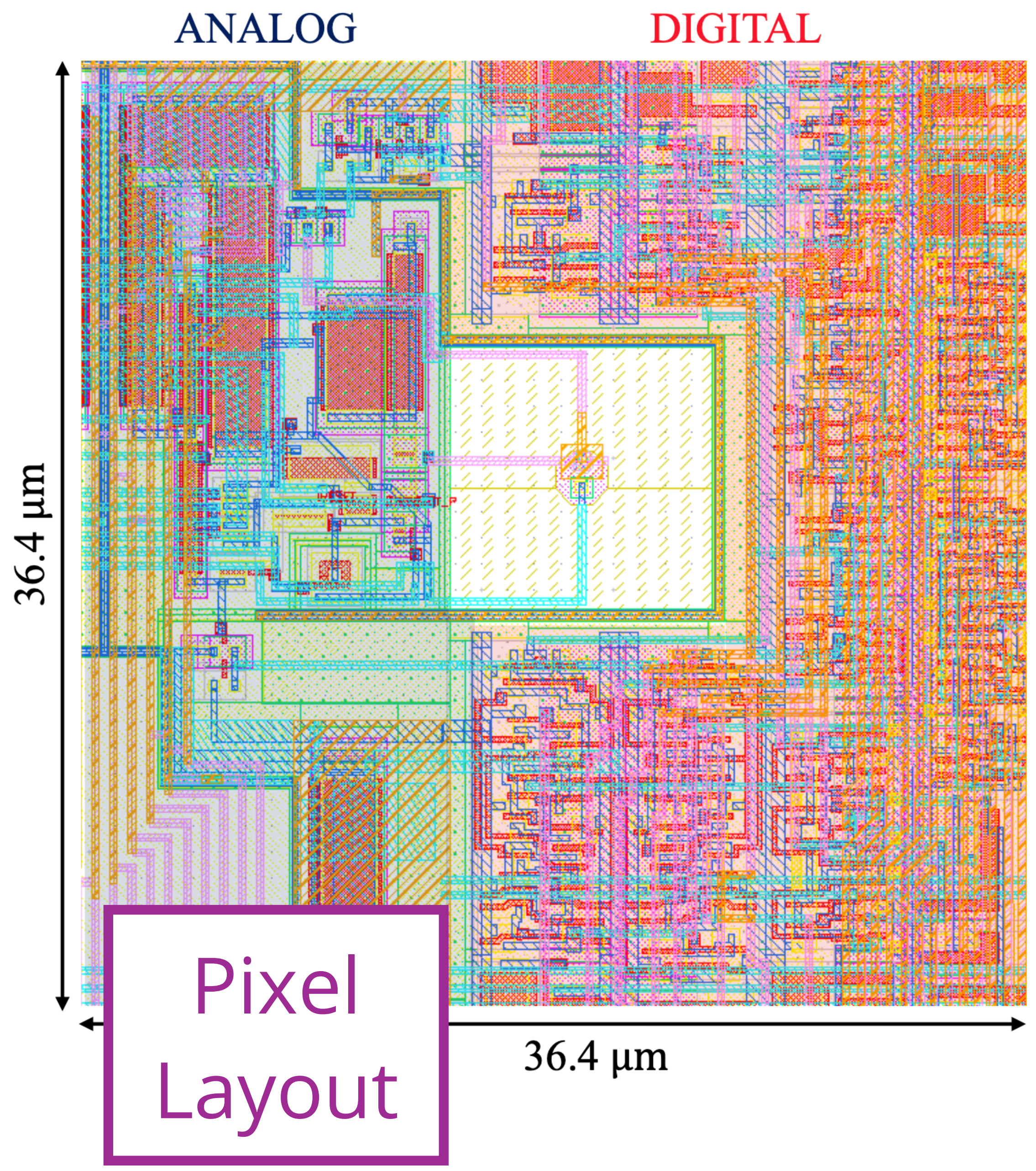
Monolithic Sensors

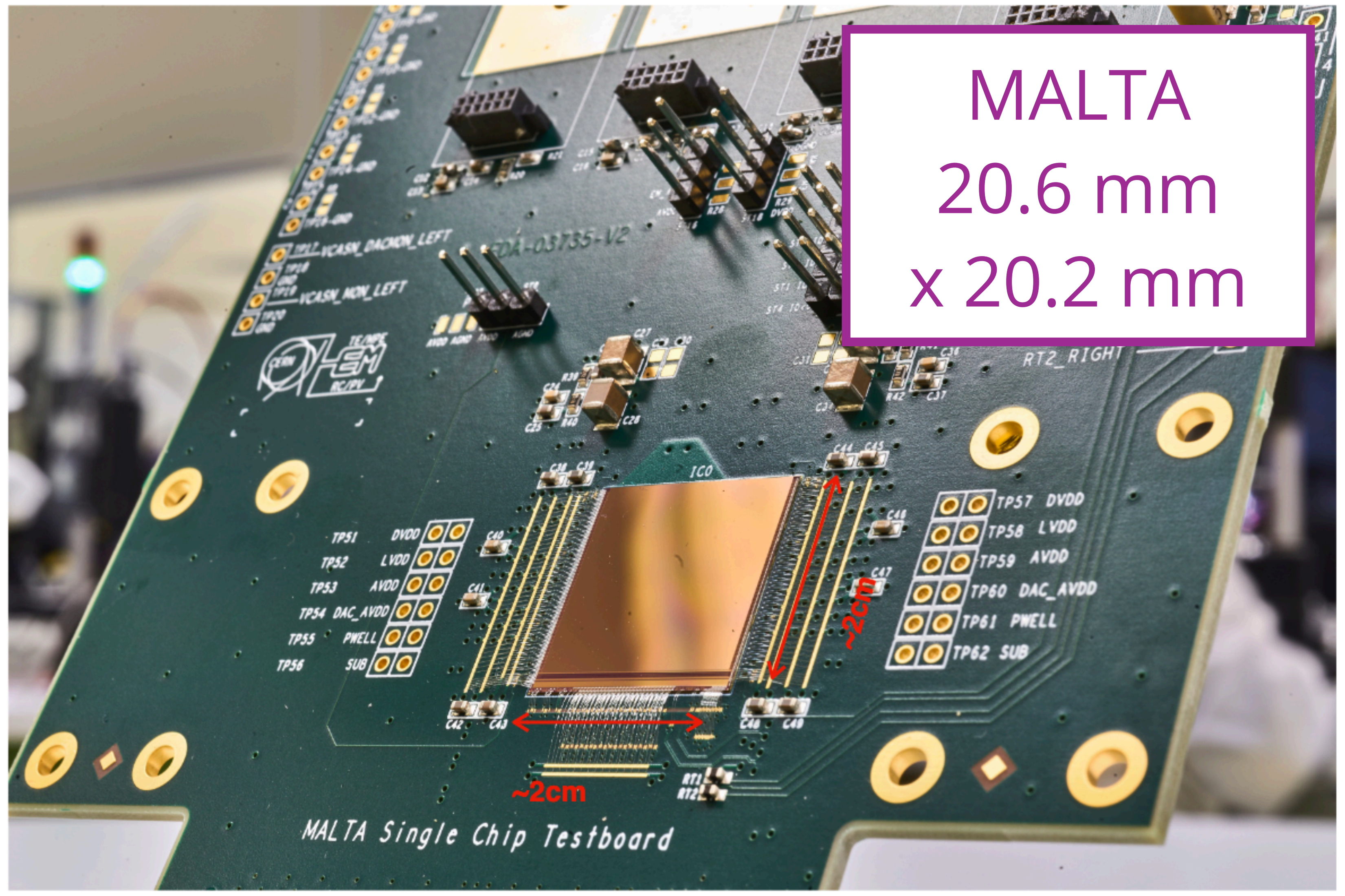
- Commercial process, no flip-chip bonding
- Lower power needs, less material.
- Radiation tolerance still needs to be proven.

MALTA & MALTA2

- Full-scale demonstrators produced to target specifications for ATLAS ITk outer layer.
    - Pixel pitch 36.4 µm x 36.4 µm.
    - Small collection electrodes: **3 µm**, minimal capacitance.
    - Power requirements: **1 µW/pixel** (<70 mW/cm^2).
        - No propagation of clock to matrix.
    - Fast, asynchronous read-out.
        - No time-over-threshold info, parallel output signal transmission.
- MALTA2 includes larger transistors, additional cascoded transistor to improve speed of front-end w.r.t. MALTA.
    - **Many different chip flavours** (substrate, process modification, thickness, doping concentrations, etc.)
- Extensive characterization campaign consisting of **lab and testbeam** measurements.
    - **Today, we'll be showing new results demonstrating the radiation tolerance of MALTA2's front-end (TID), and its timing performance.**



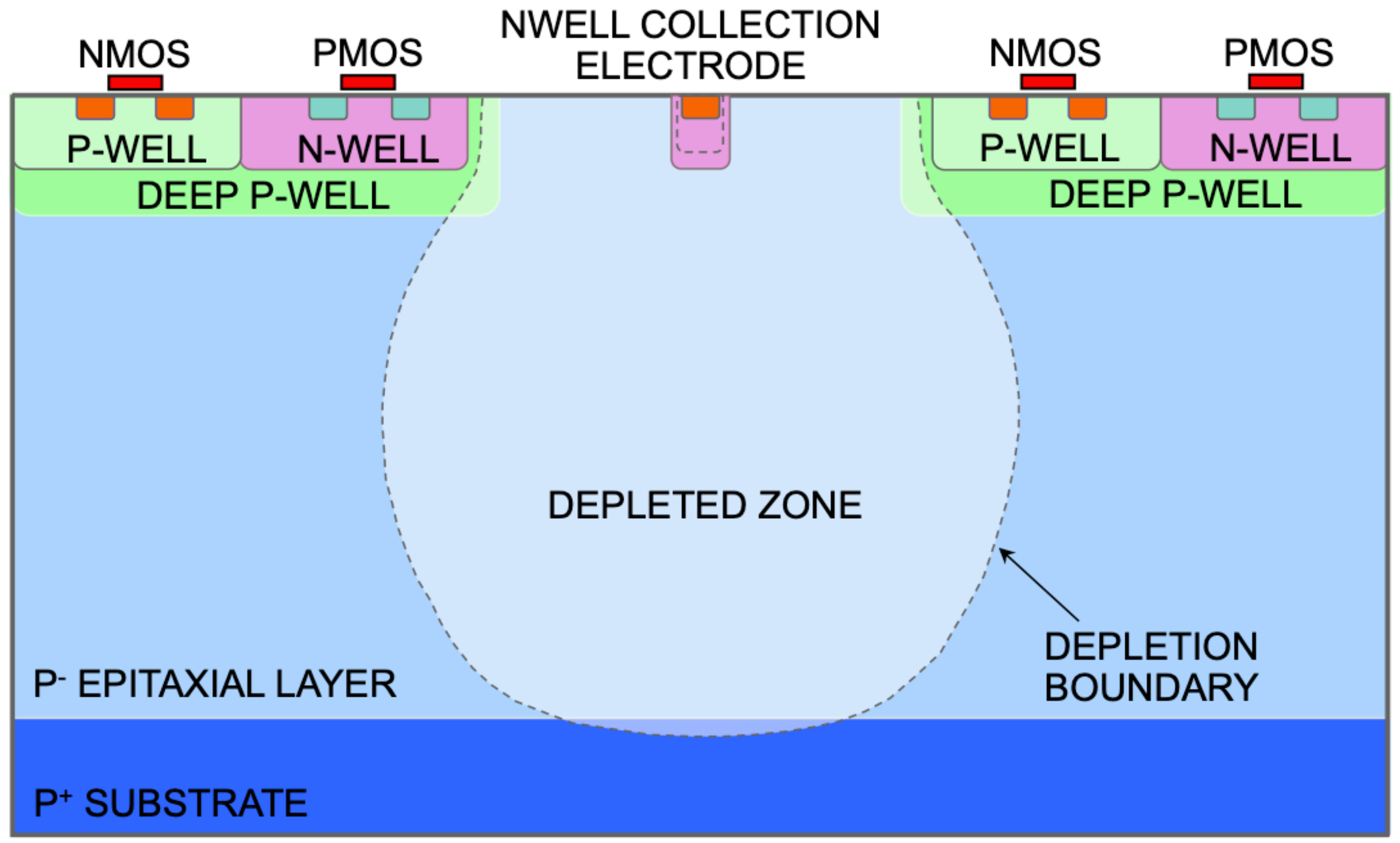




New! F. Piro et al., submitted to IEEE Trans. Nucl. Sci. *H.Pernegger NIM A 986 (2021) 164381* *M. Dyndal,JINST 15 (2020) P02005*

Towerjazz 180 nm Modified Processes

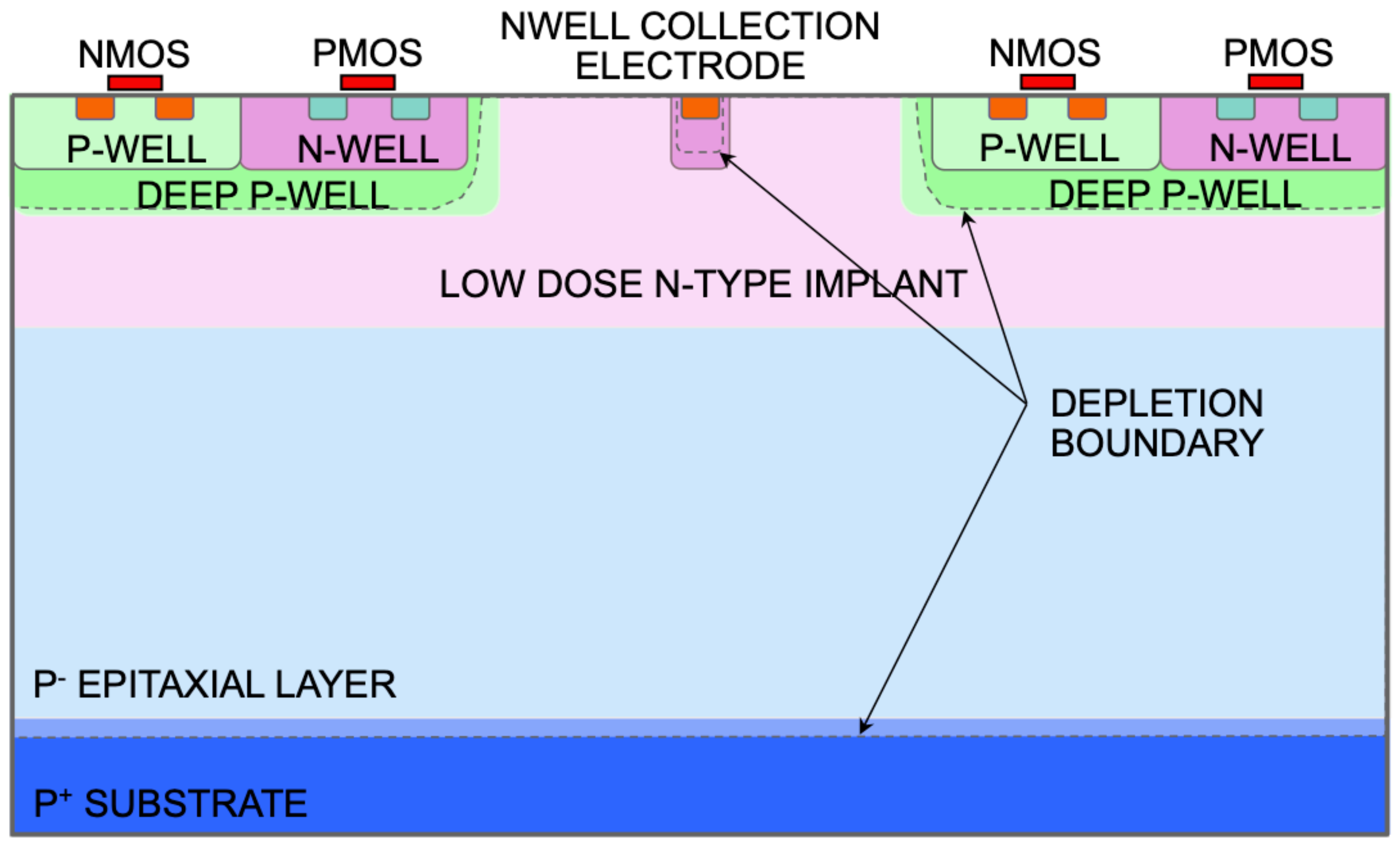
Charge collection time ~100 ns via diffusion, too slow for LHC applications.



Unmodified process

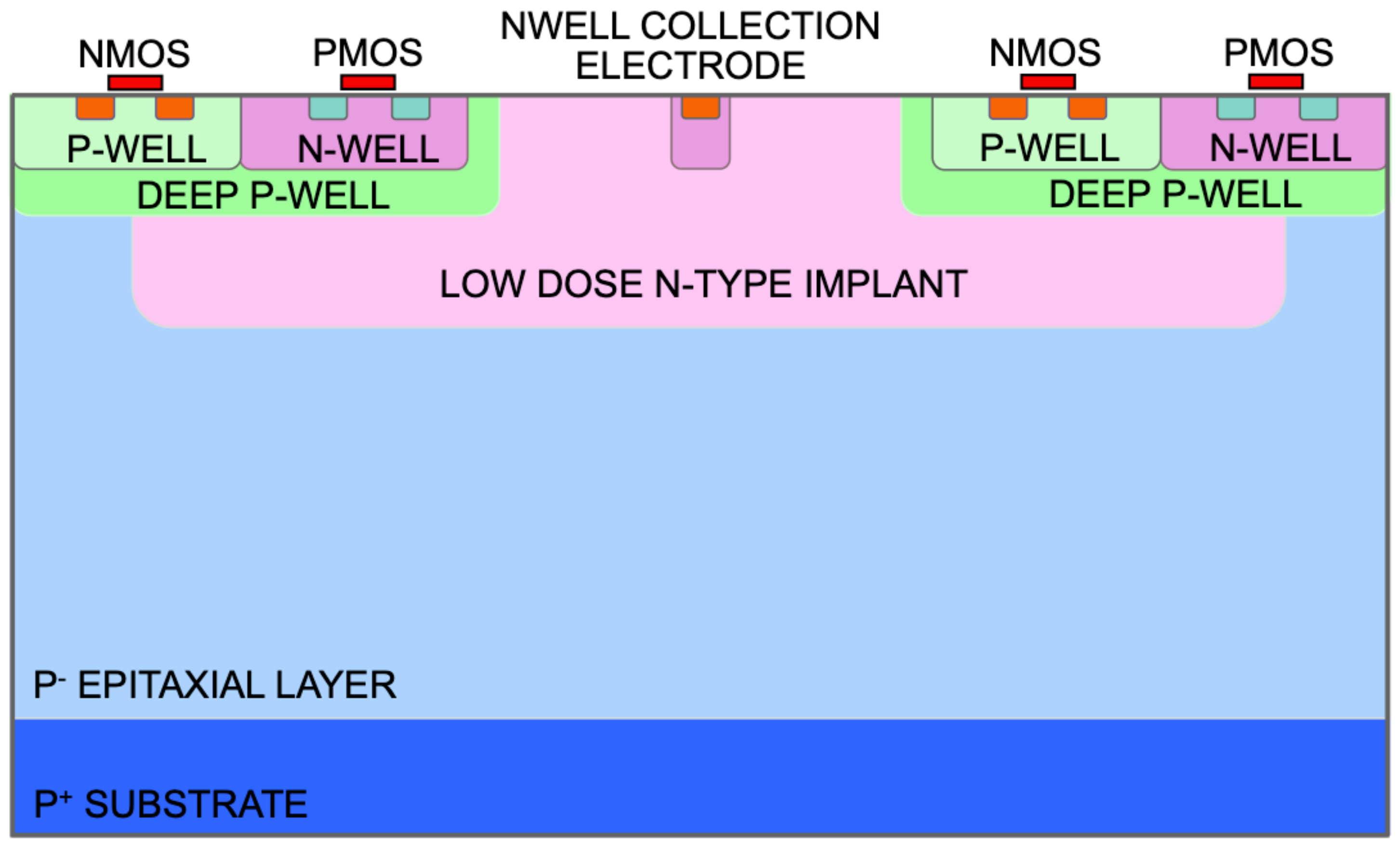
Uniform low-dose n—type implant under p-well fully depletes pixel area, pushing charge-carriers towards collection electrode.

Also reduces charge carrier capture probability, improving sensor tolerance to NIEL.

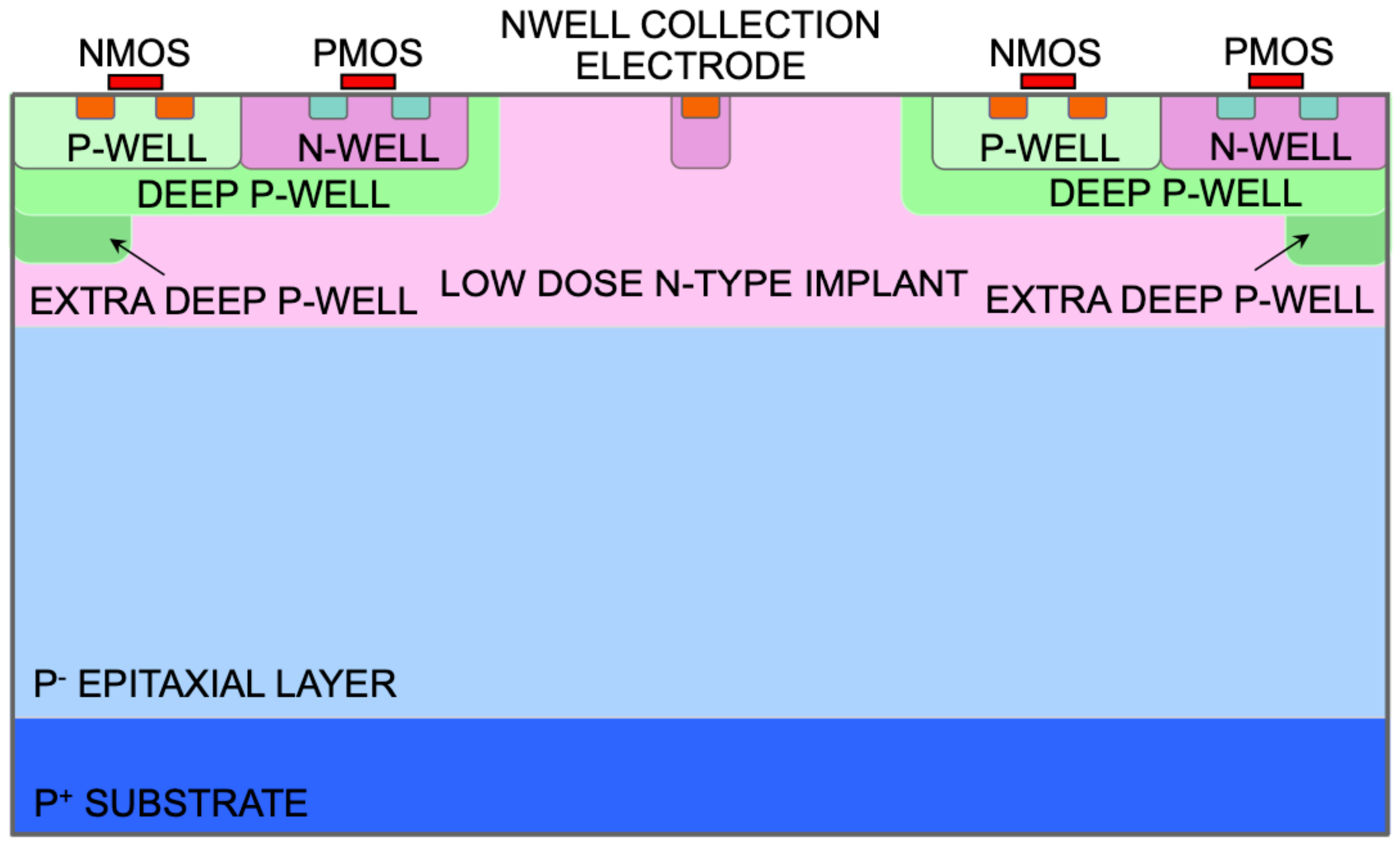


Modified process, low doping

Additional process modifications can increase E-field in pixel corners, further reducing charge collection tails.



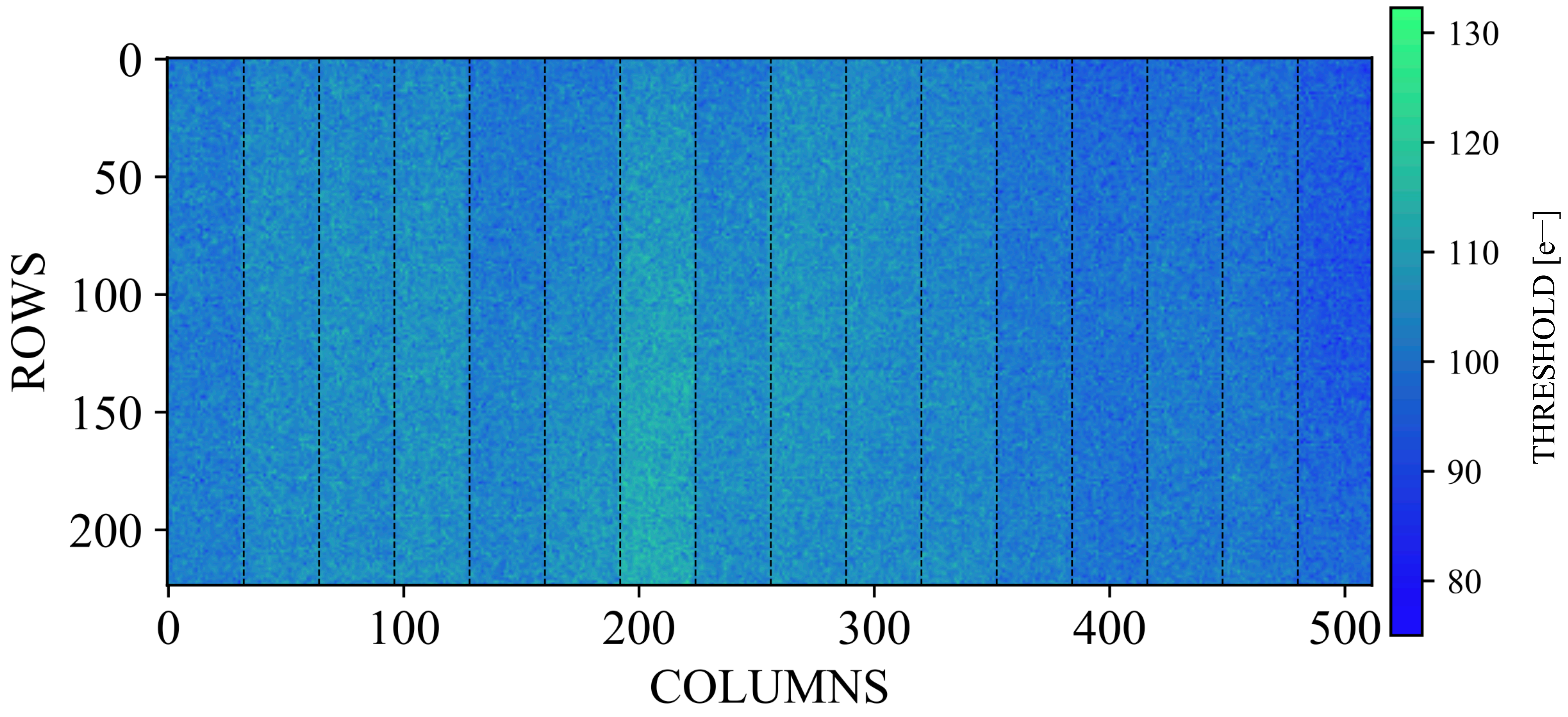
"Gap in the n-layer"

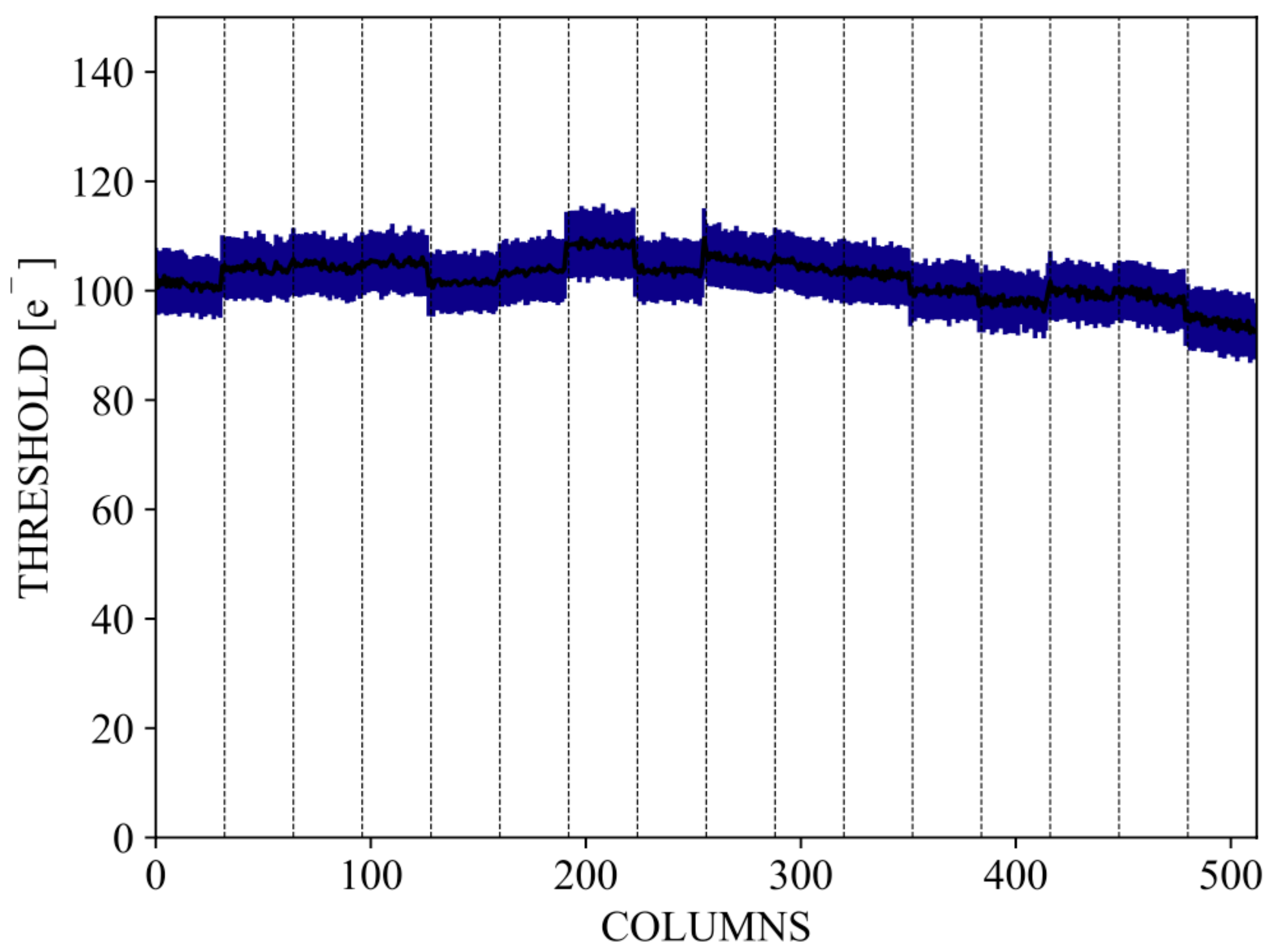


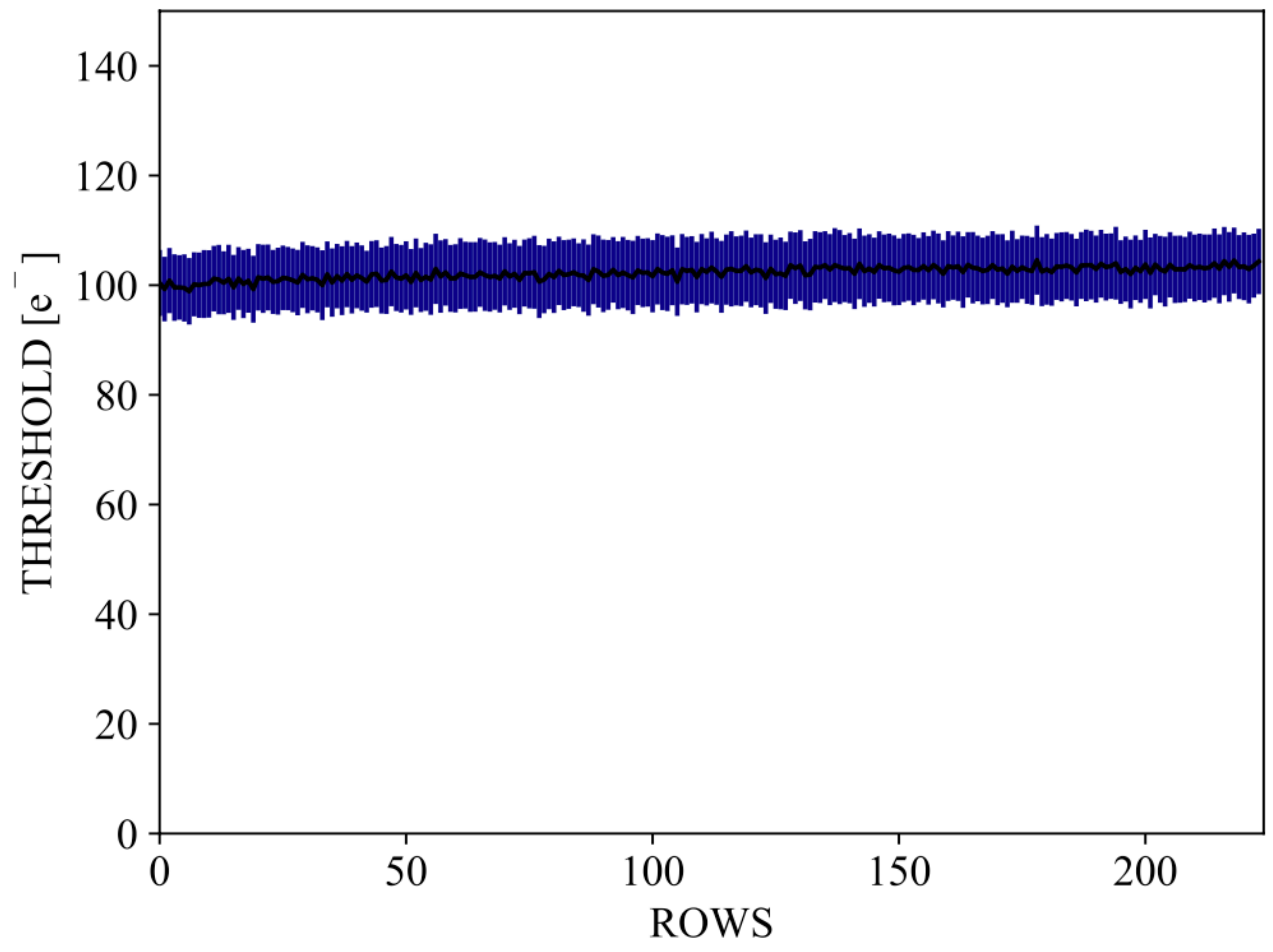
"Extra-deep p-well"

M. Munker et al 2019 JINST 14 C05013

MALTA2 front-end







Threshold scan performed for entire MALTA2 matrix with nominal front-end settings.

Average threshold is ~100 *e*⁻, with ~6 *e*⁻ variation.
Variation across vertical 32-pixel columns of matrix attributed to front-end biasing scheme, will be refined in future MALTA prototypes.

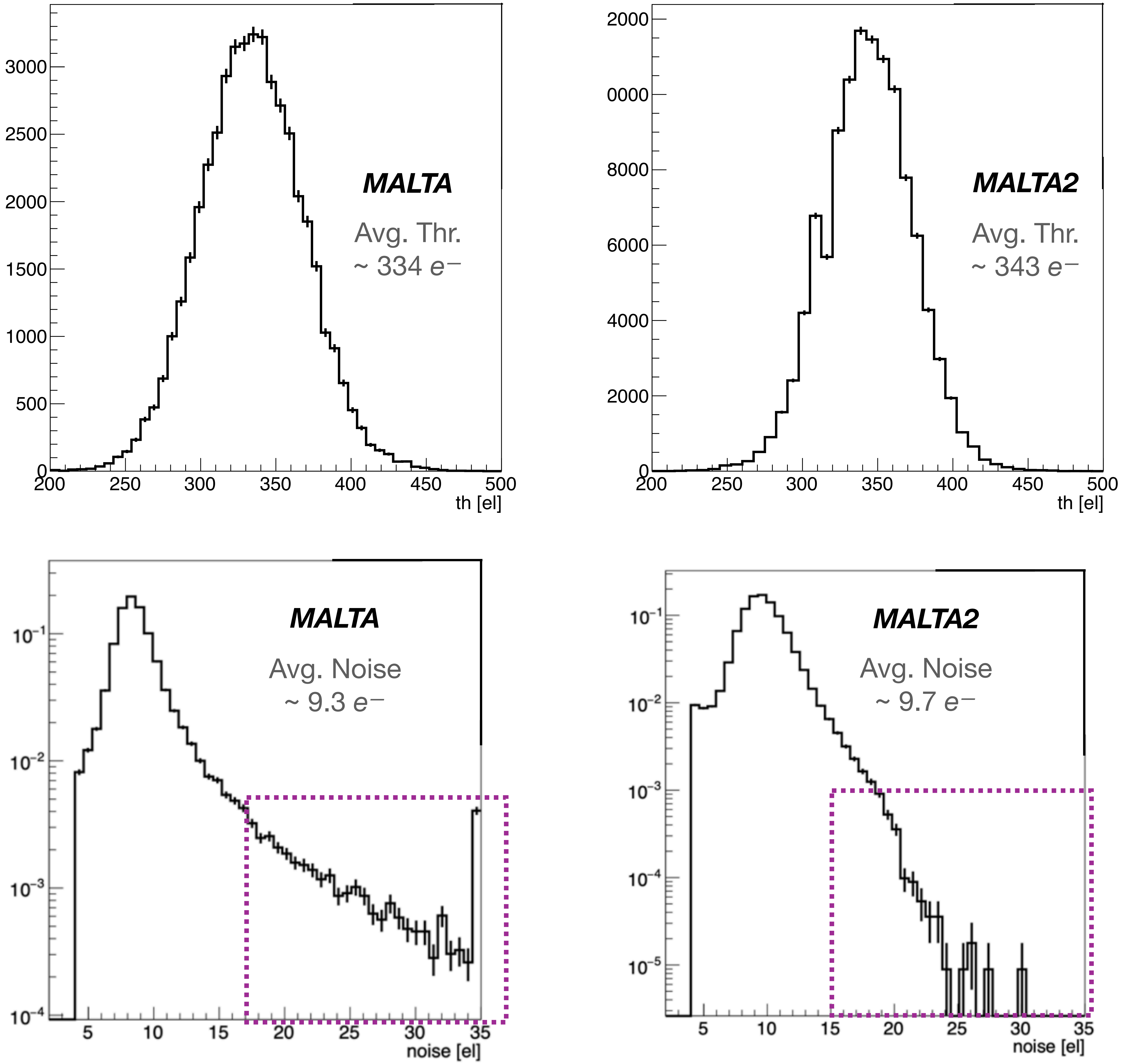
No systematic trends observed for pixel noise as a function of the matrix.

Threshold variation within a single biasing group is ~5.1*e*⁻.

New! F. Piro et al., submitted to IEEE Trans. Nucl. Sci.

MALTA vs. MALTA2

- Comparison of MALTA & MALTA2 at compatible threshold (~340 e—).
  - ***Significant reduction of non-Gaussian tails in noise distribution.***
  - Attributed to improved MALTA2 front-end.
- Both chips are epi. w/ gap in n-layer
  - High doping of n-layer
  - 300 μm thickness
  - Unirradiated

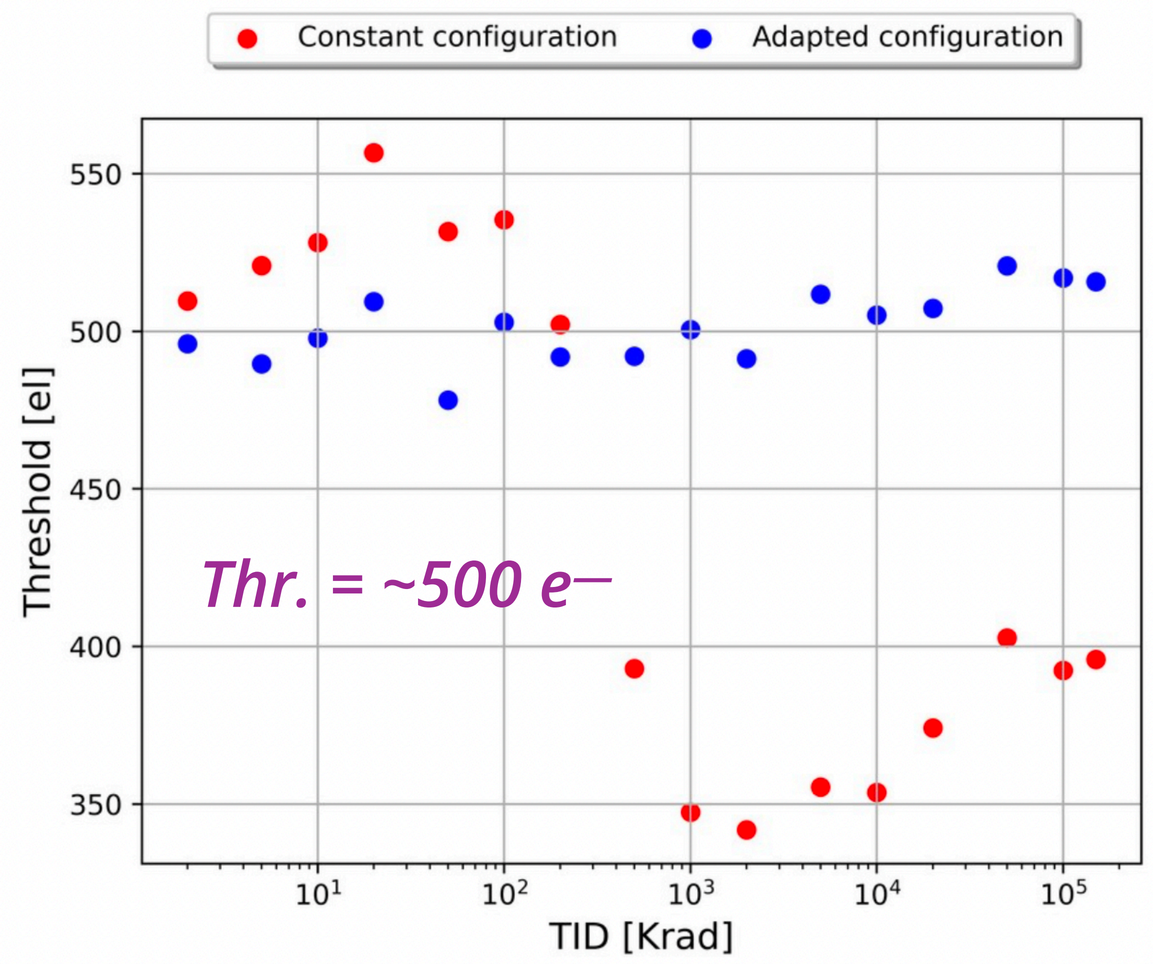


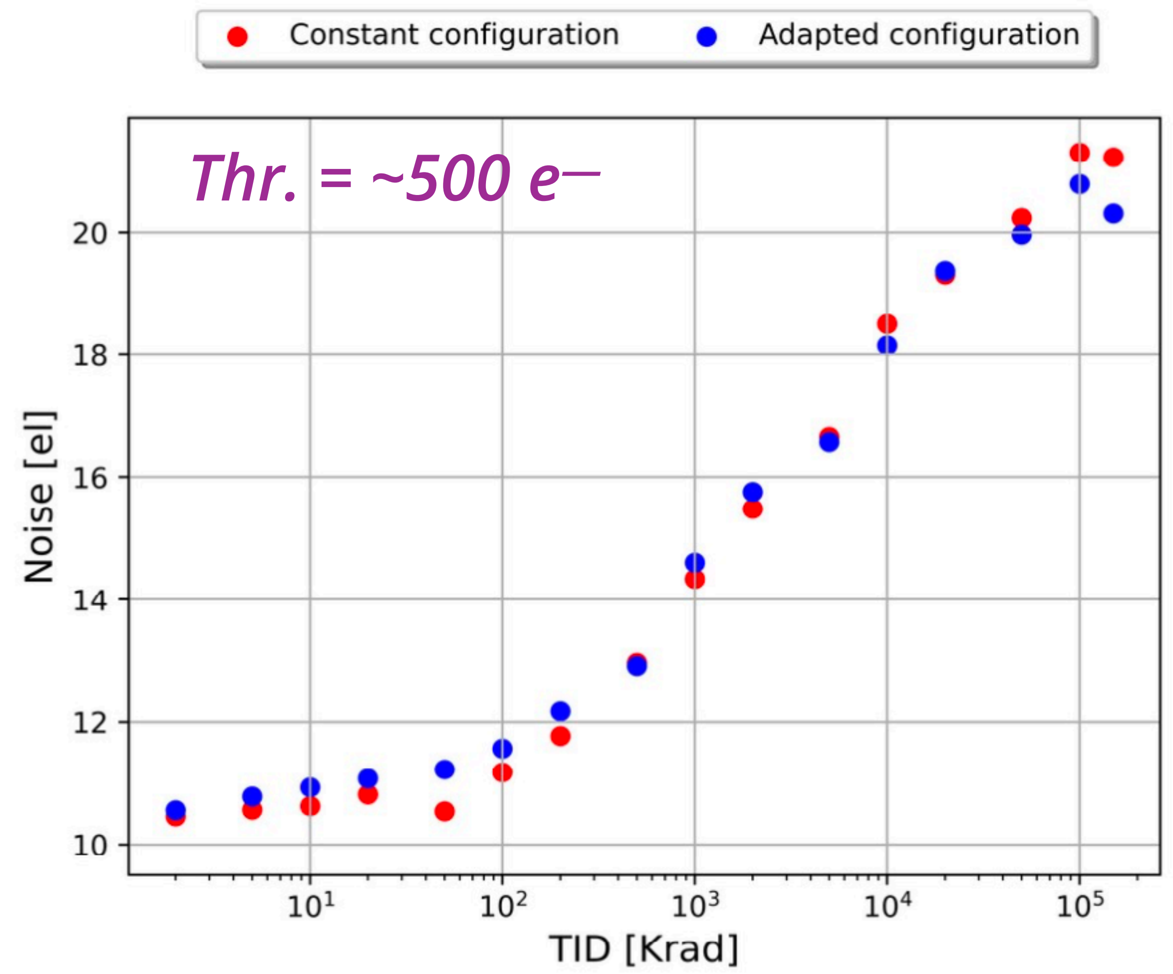
New! *MALTA Preliminary Results*

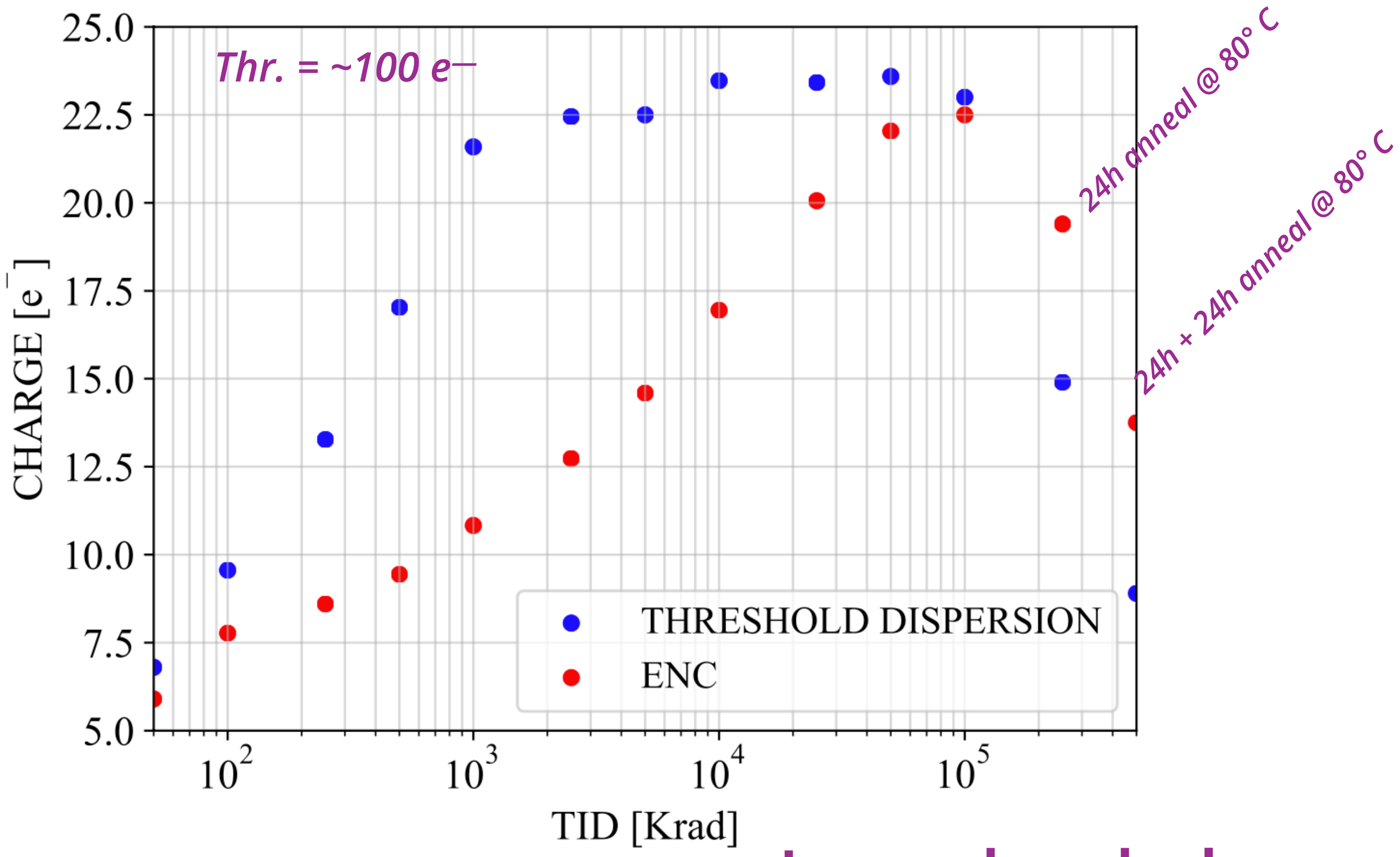
MALTA2 Front-End : Stability after irradiation

- Two additional studies of front-end **performance at higher TIDs, up to 150 MRad,** by irradiating sensors with X-ray laser.
- Constant thresholds at 100 *e*–, 500 *e*– were maintained by **manually re-adjusting front-end settings** between steps of irradiation.
    - **Sensors remained fully functional** throughout irradiation.
    - **Noise found to increase monotonically with TID** in both studies.
    - For study at thr.~100 *e*–, **24h annealing at 80° C was performed after each of the final two steps.**
        - Noise and threshold dispersion performance found to recover after procedure!

Higher-doped n-layer





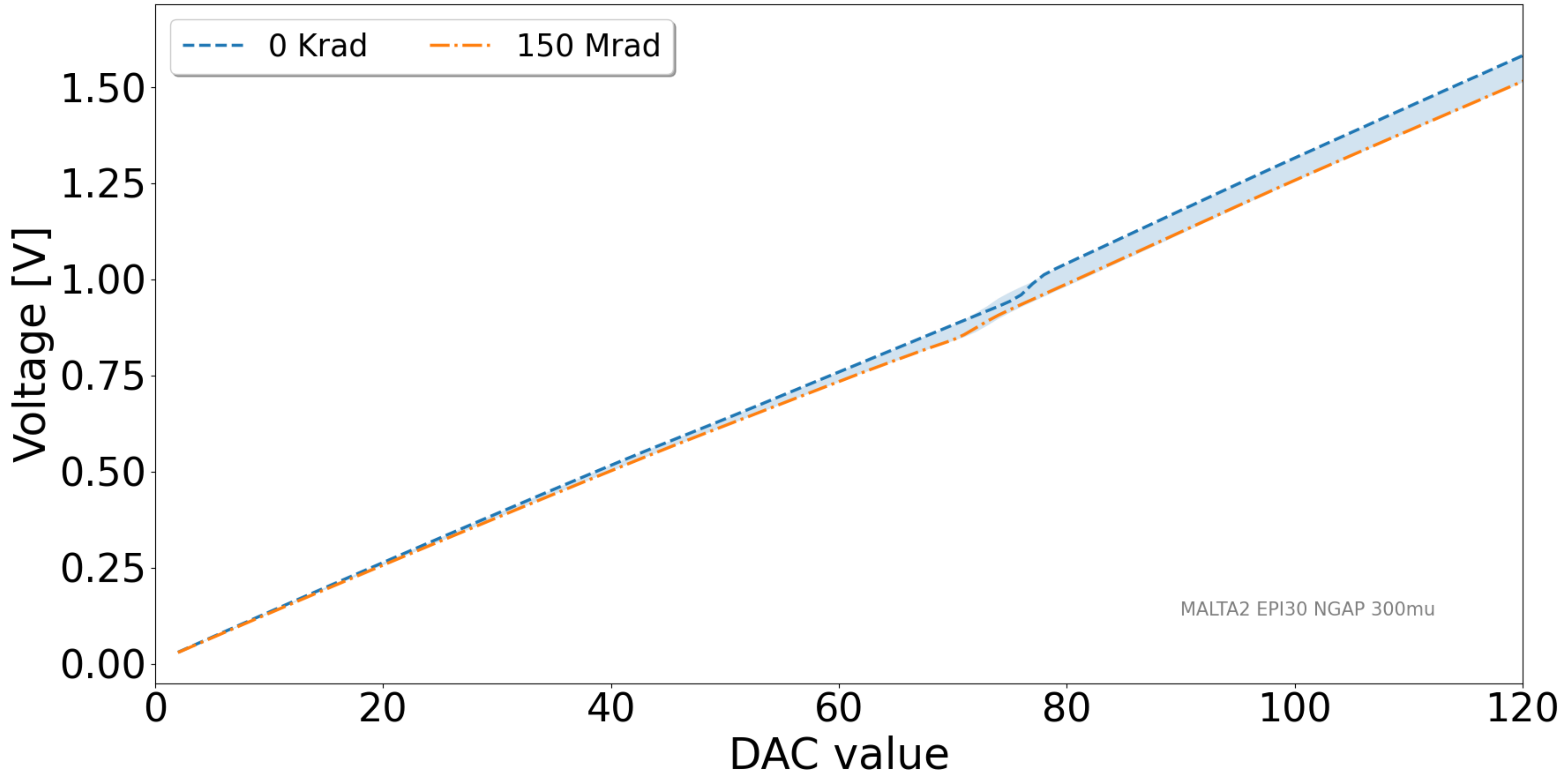


Lower-doped n-layer

New! F. Piro et al., submitted to IEEE Trans. Nucl. Sci.

MALTA2 Front-End : Stability after irradiation

- Two additional studies of front-end **performance at higher TIDs, up to 150 MRad,** by irradiating sensors with X-ray laser.
- Constant thresholds at 100 e^-, 500 e^- were maintained by **manually re-adjusting front-end settings** between steps of irradiation.
  - **Sensors remained fully functional** throughout irradiation.
  - **Noise found to increase monotonically with TID** in both studies.
  - For study at thr.~100 e^-, **24h annealing at 80° C was performed after each of the final two steps.**
    - Noise and threshold dispersion performance found to recover after procedure!
  - Linearity of front-end response (digital-to-analogue converters) vs. TID also verified.
    - Slight non-linearity related to the DAC under study, has no impact on front-end operation.

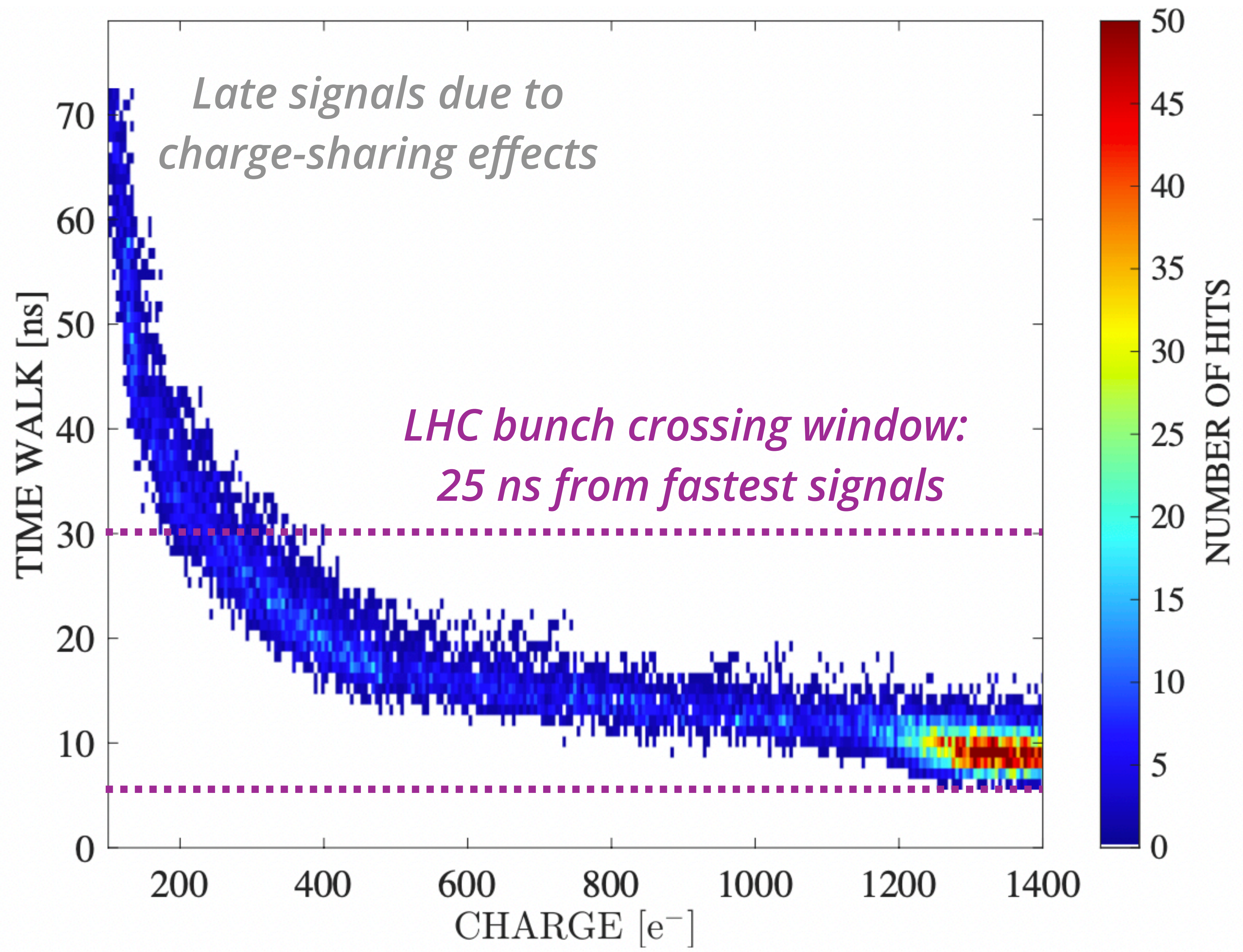


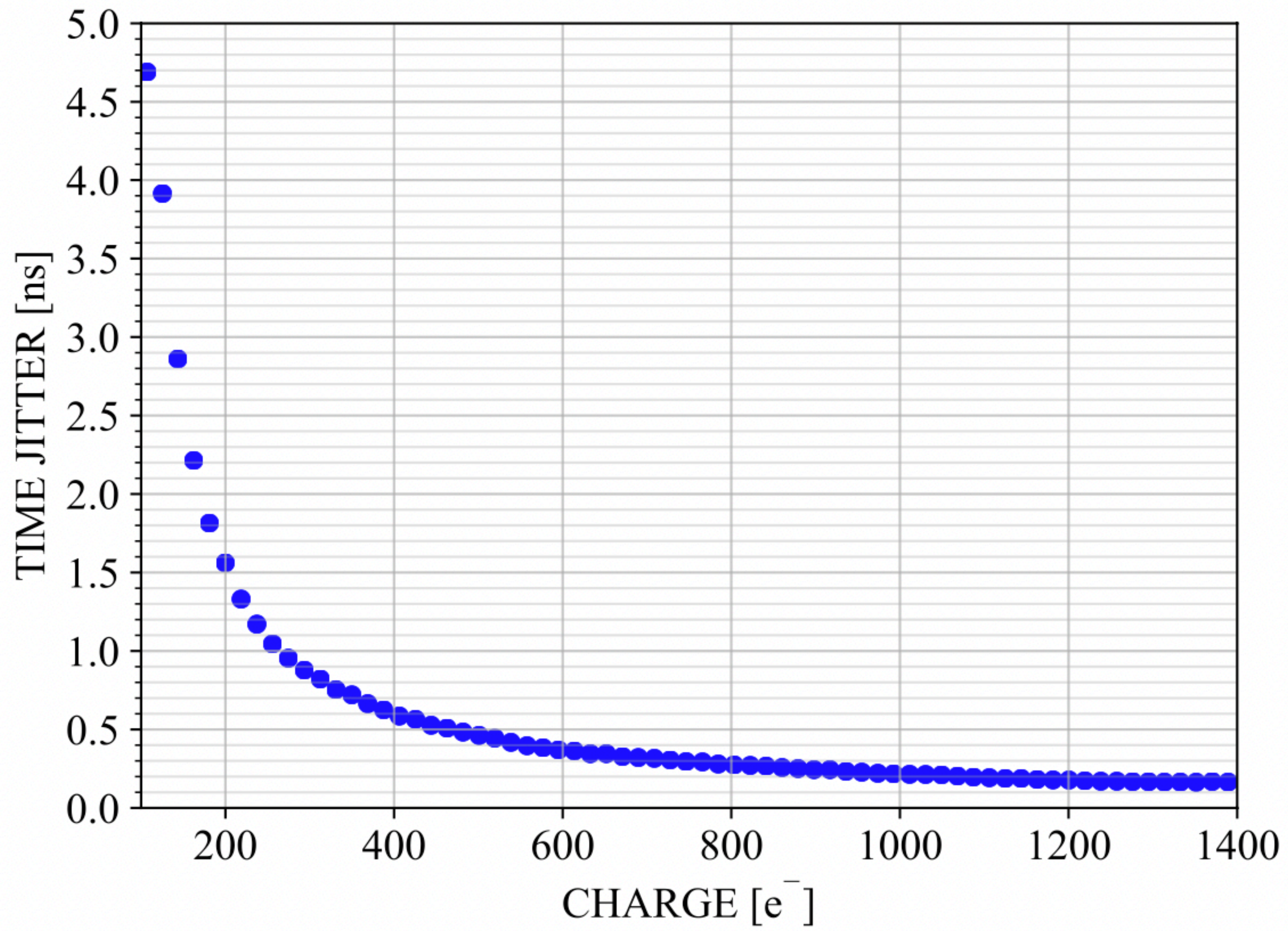
Blue envelope represents spread of scans at intermediate irradiation steps

New! *MALTA Preliminary Results*

MALTA2 Front-End : Timing

- Time-walk of front-end measured using special pixels with analogue output monitoring.
  - Time for amplifier output to reach discriminator threshold, depends on charge deposition.
  - Sensor exposed to **^{90}Sr source in lab**
    → MIP-like signals, avg. deposition ~1800 *e*⁻.
    - 90% of hits arrive within 25 ns window.
    - For largest deposited charges, time-walk ~10 ns.
    - Contributions with small charge deposition attributed to charge-sharing effects (expect small signals from pixel corners to arrive later).
- Can also measure time jitter of front-end by injecting charge in pixel matrix and triggering on signal using CERN-developed PicoTDC ASIC.
  - Time jitter dominated by front-end, which varies from 4.7 ns to 0.17 ns as injected charge increases.

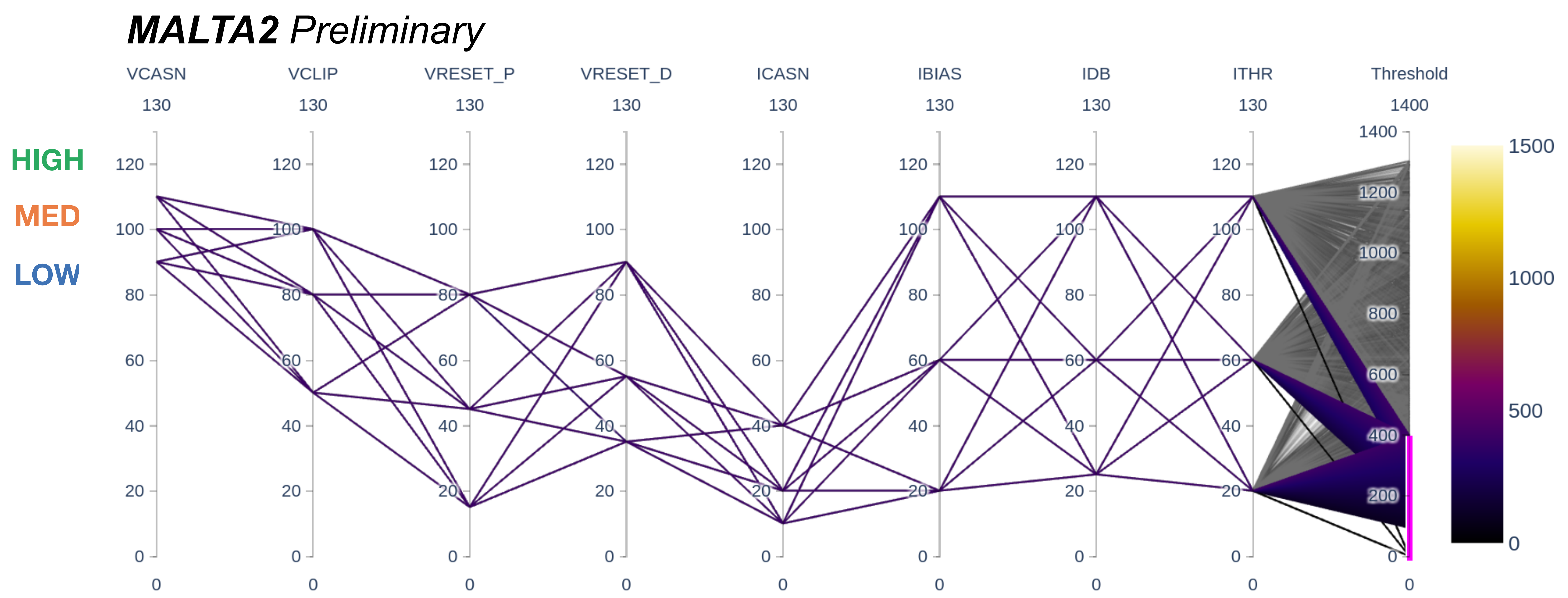


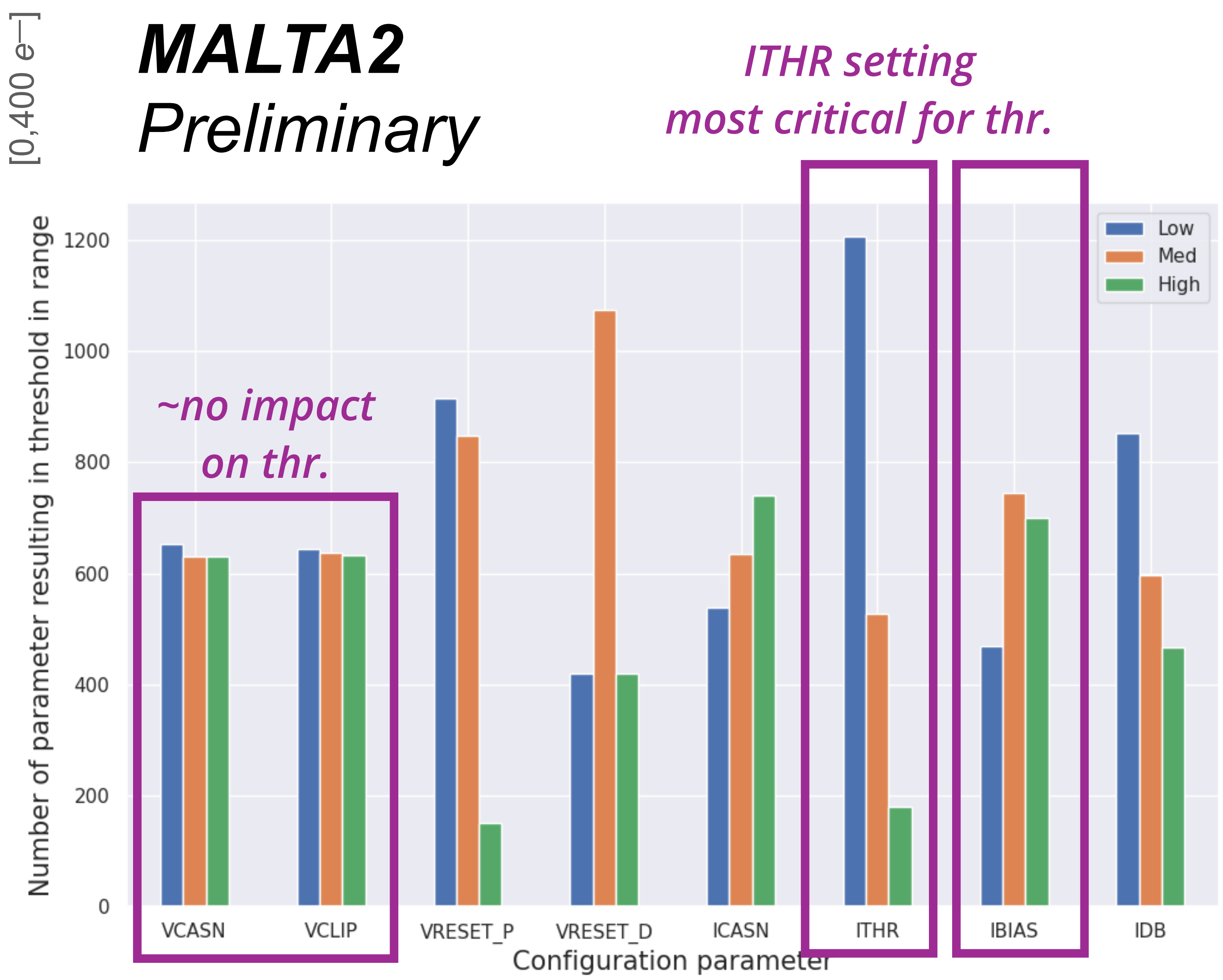


New! *F. Piro et al., submitted to IEEE Trans. Nucl. Sci.*

PicoTDC: L Perktold et al. JINST 9 (2014) C01060

MALTA2 Front-End : DAC correlations





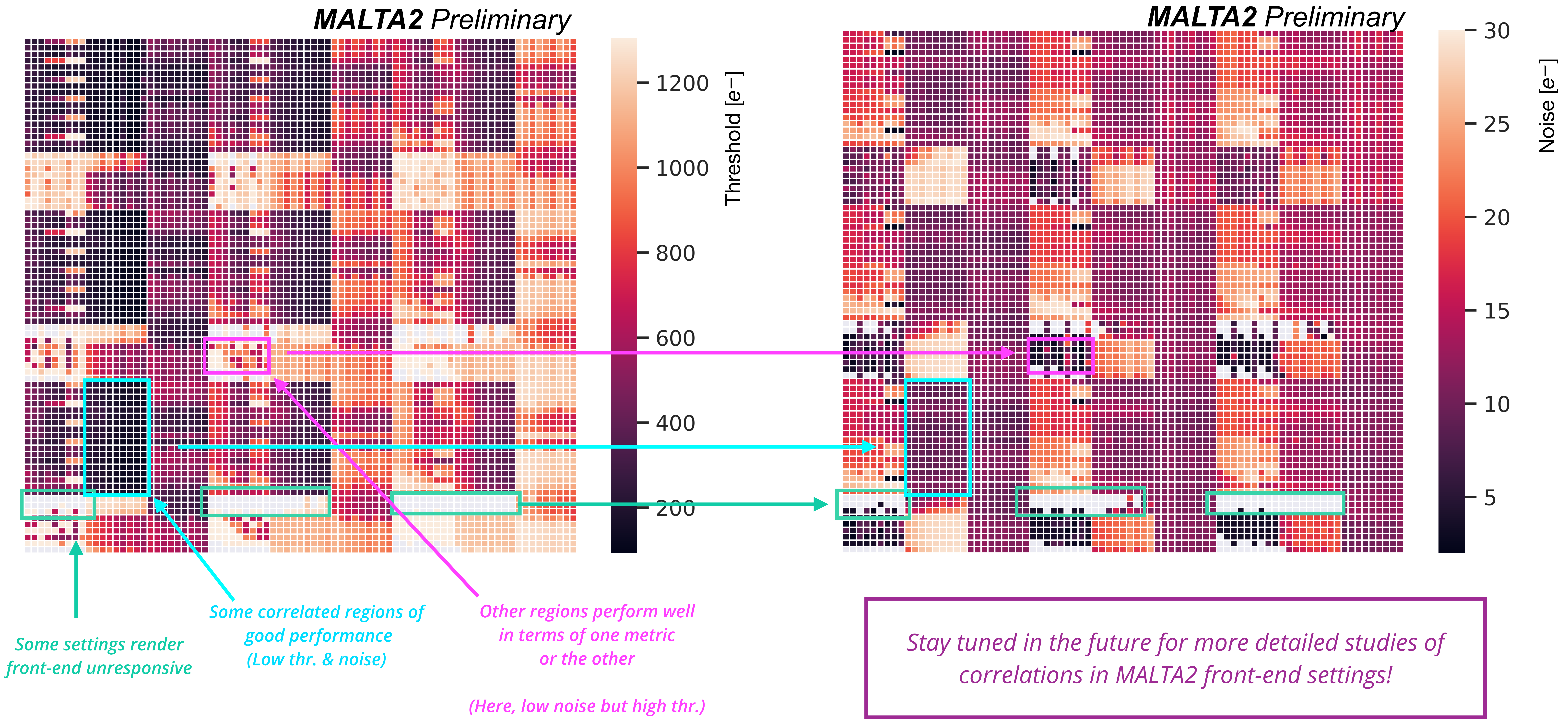
What are A,B,C,?
They must correspond to DACs

… but others can play a role!

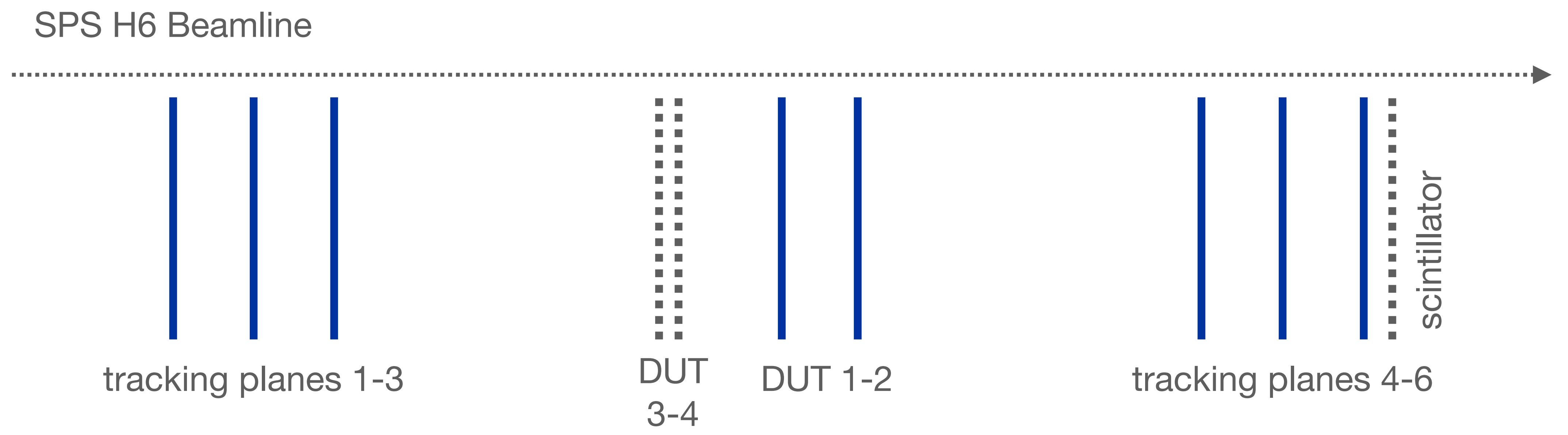
- More detailed studies of the front-end behaviour are underway — in this study, many combinations of front-end settings are evaluated in terms of the resultant **threshold** (pictured), **noise** & **number of inactive pixels**.
- DACs are designed to be linearly independent — but in practice, some nonlinear codependencies exist.
  How many different configurations yield comparable front-end performance? Does this picture change with TID?
- Pushing some settings to the margins of design range in order to probe a large parameter space.

New! *MALTA Preliminary Results*

MALTA2 Front-End : DAC correlations

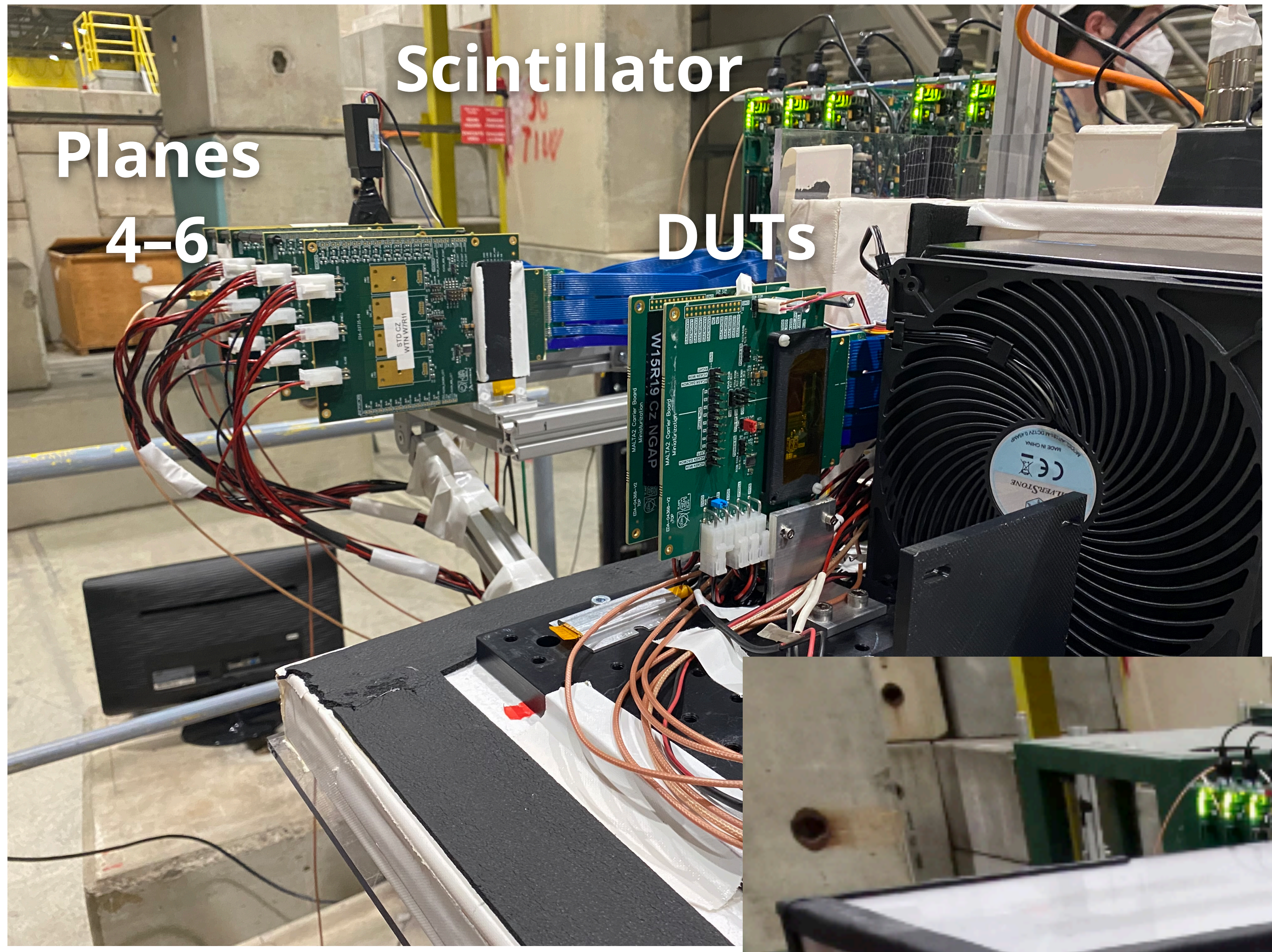


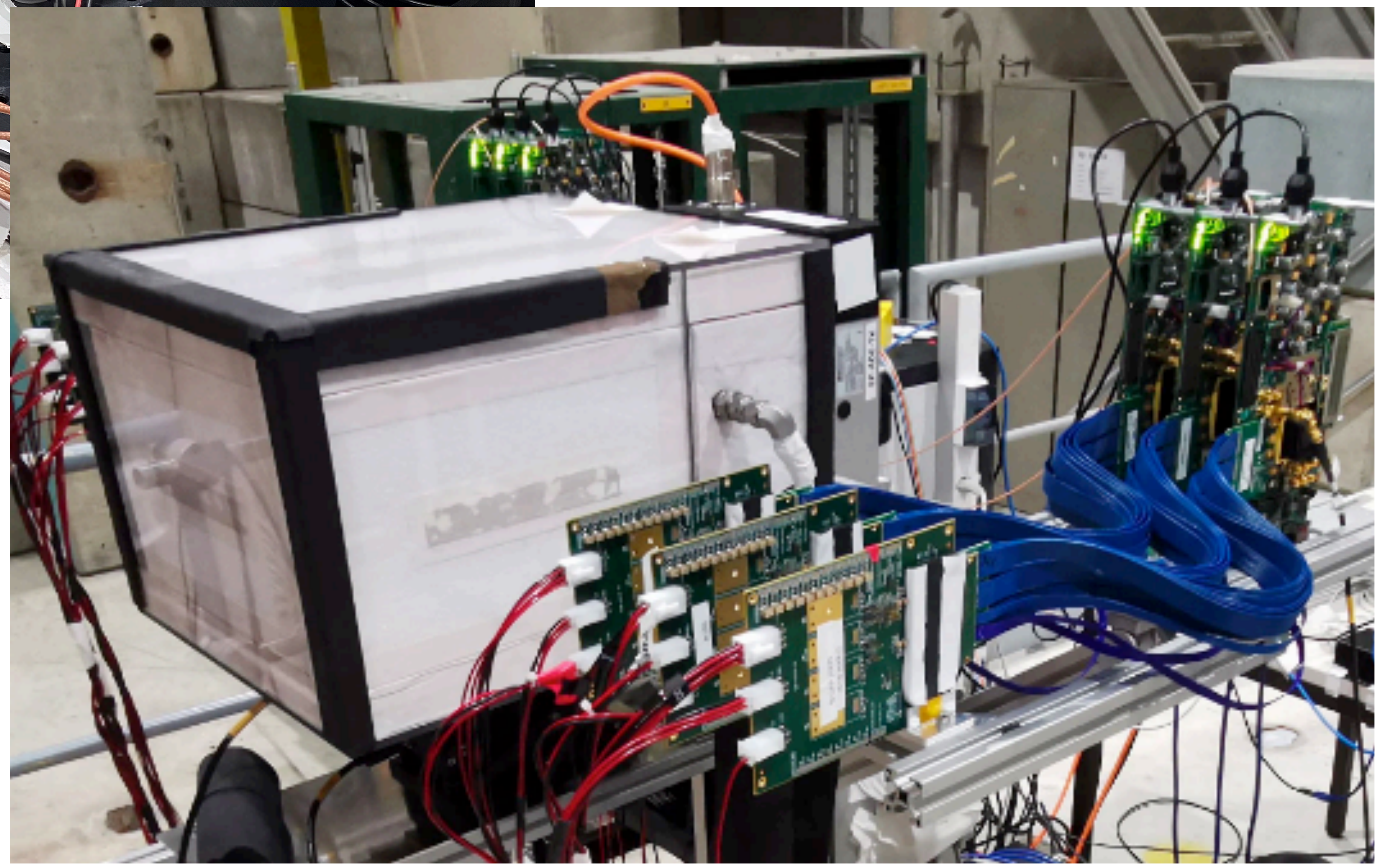
Stay tuned in the future for more detailed studies of correlations in MALTA2 front-end settings!



MALTA Telescope @ SPS

- Operating an eight-plane telescope in **CERN's SPS H6 beamline**.
  - 180 GeV proton beam.
  - Continuous data-taking from summer 2021 until end-of-year.
- **Six tracking / triggering planes** (MALTA, 2xCz, 4xEpi), and **up to two MALTA2 Devices Under Test** (DUTs).
  - Use of MALTA with high-resistivity **Czochralski (Cz)** substrate for tracking planes **produces increased cluster size,** improves spatial resolution of telescope.
- Campaign to demonstrate ***MALTA2* performance** in terms of **radiation tolerance** and **timing performance**.





See also M. Van Rijnbach @ TWEPP21 for more info about Cz MALTA sensors

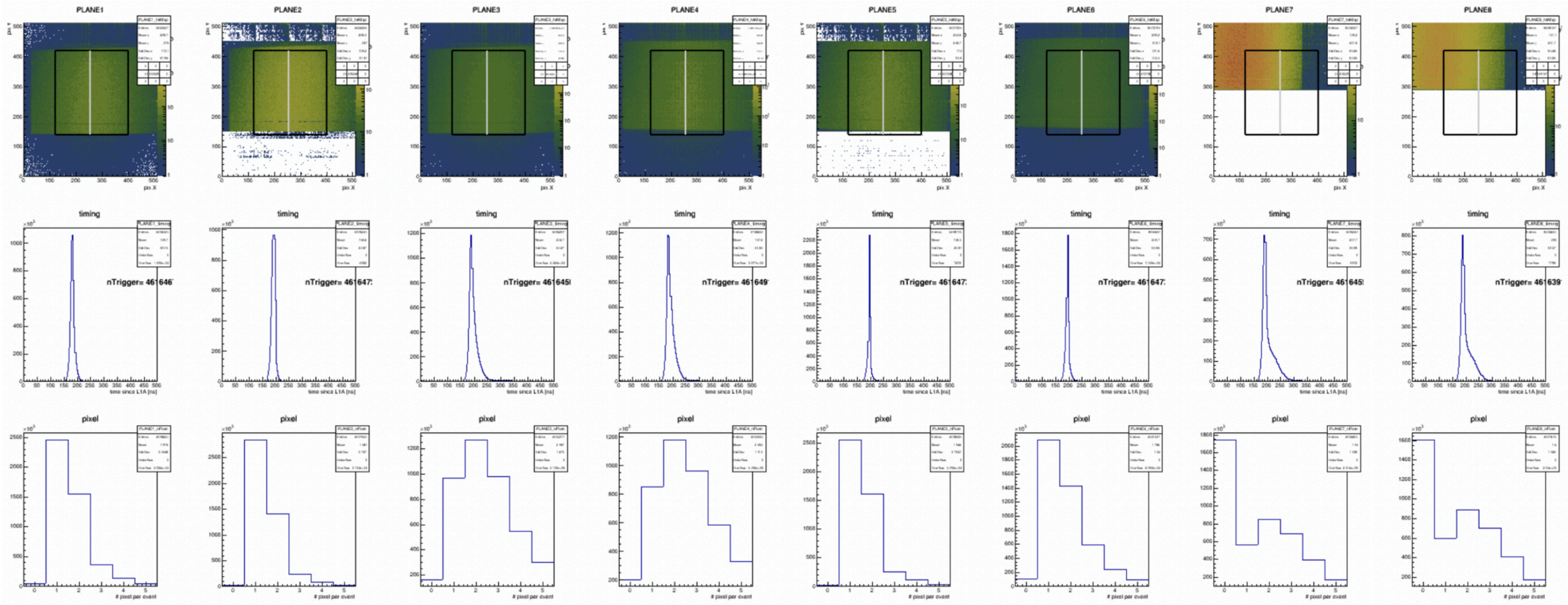
SPS Testbeam Monitoring Plots

DUT1 DUT2

Hitmap

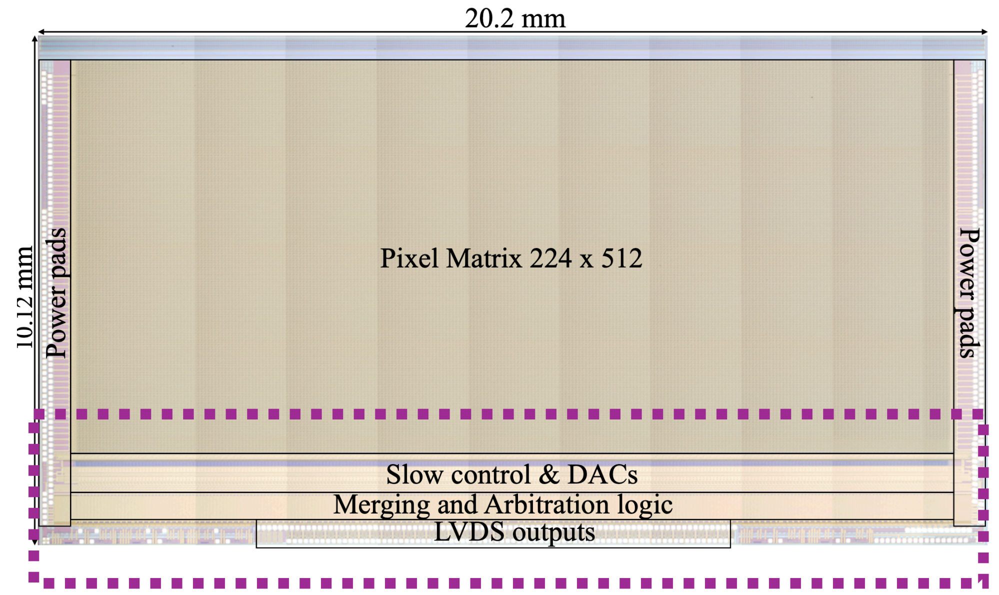
Time since L1A

#pixel /event



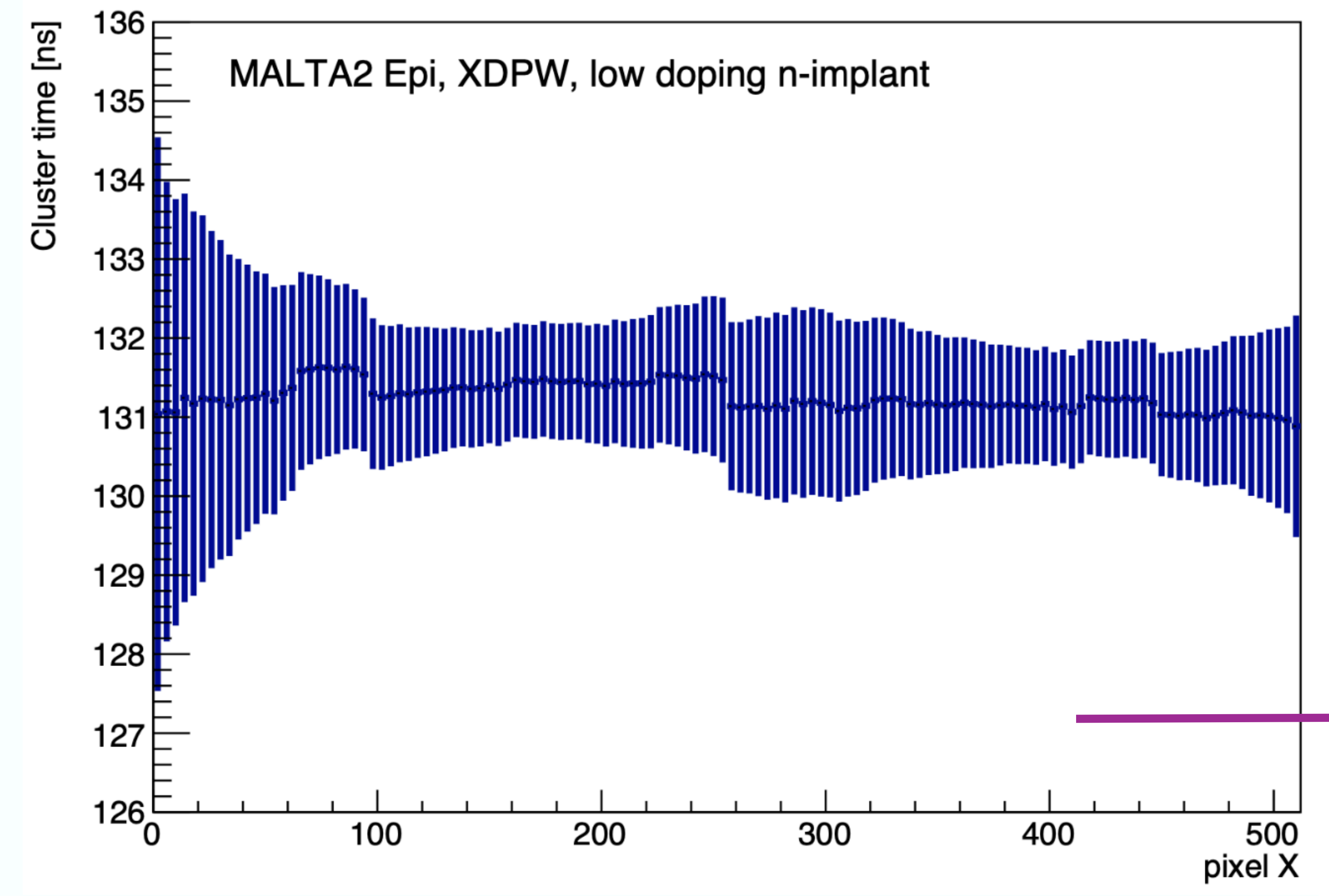
- Realtime monitoring with hitmap, time distribution and number of hits per-event.
- Low noise / occupancy of MALTA allows for fast track reconstruction (~1.2 hits/plane/event).

MALTA2 Timing

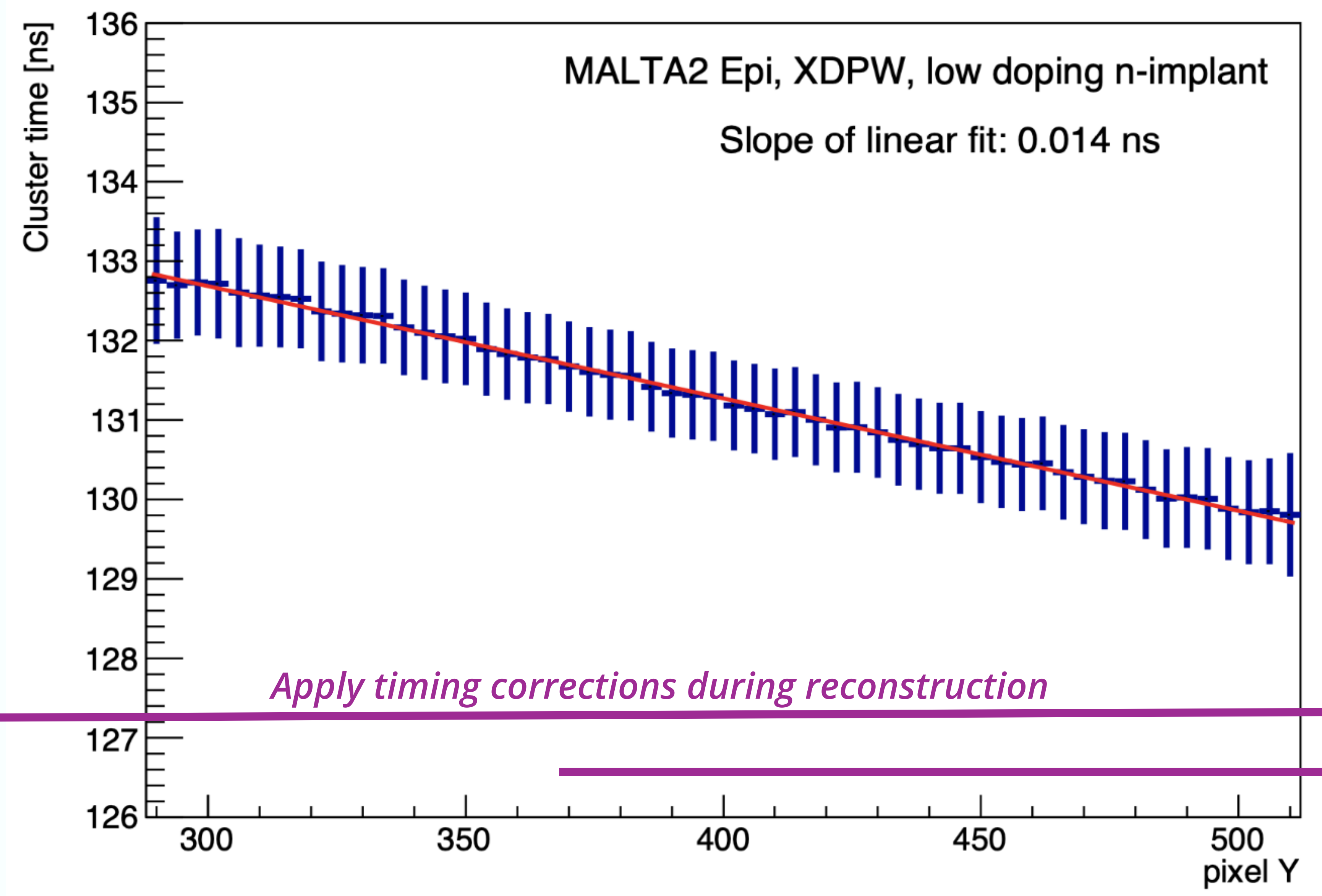


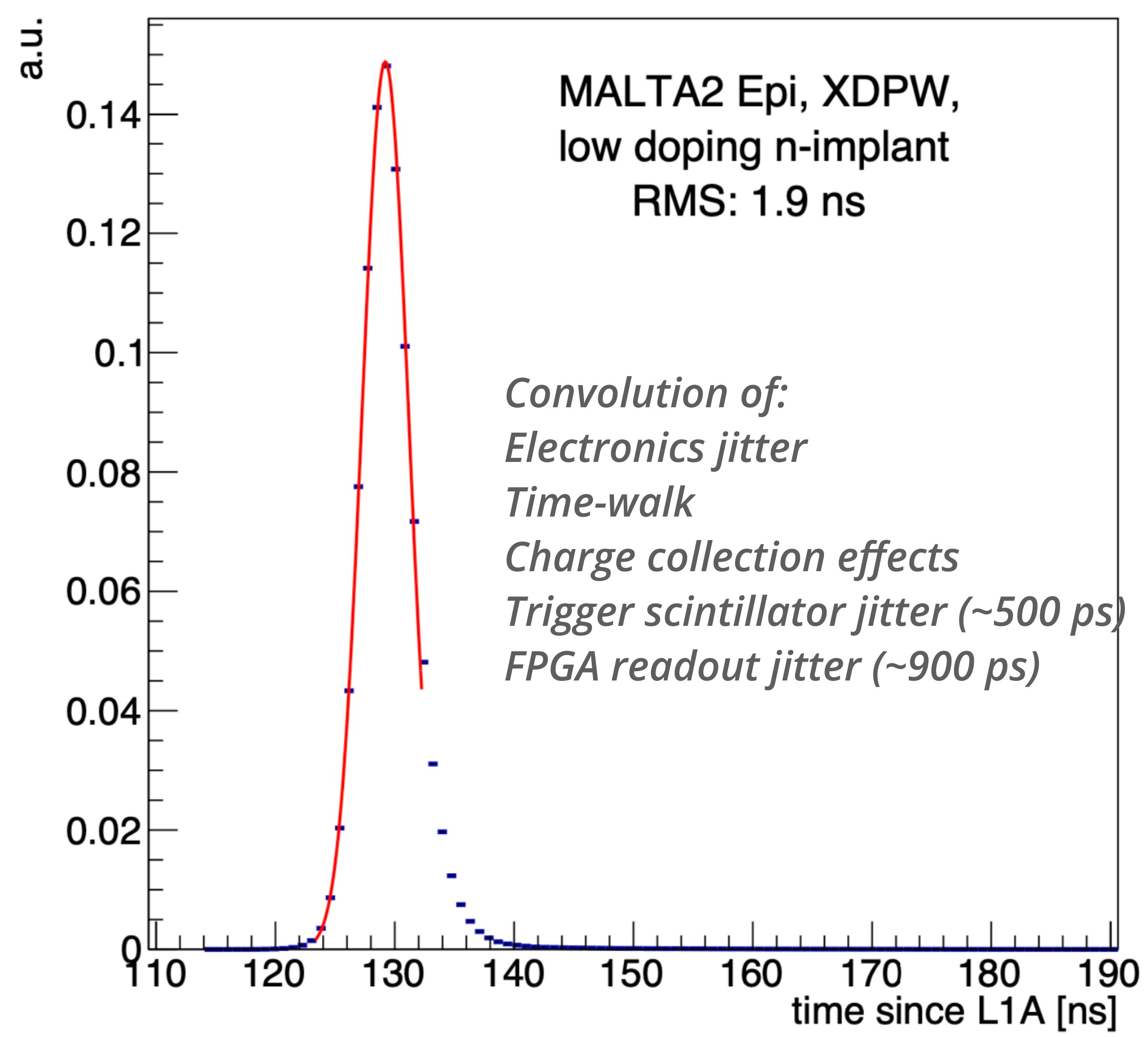
Corrected time of arrival for clusters matched to a track.

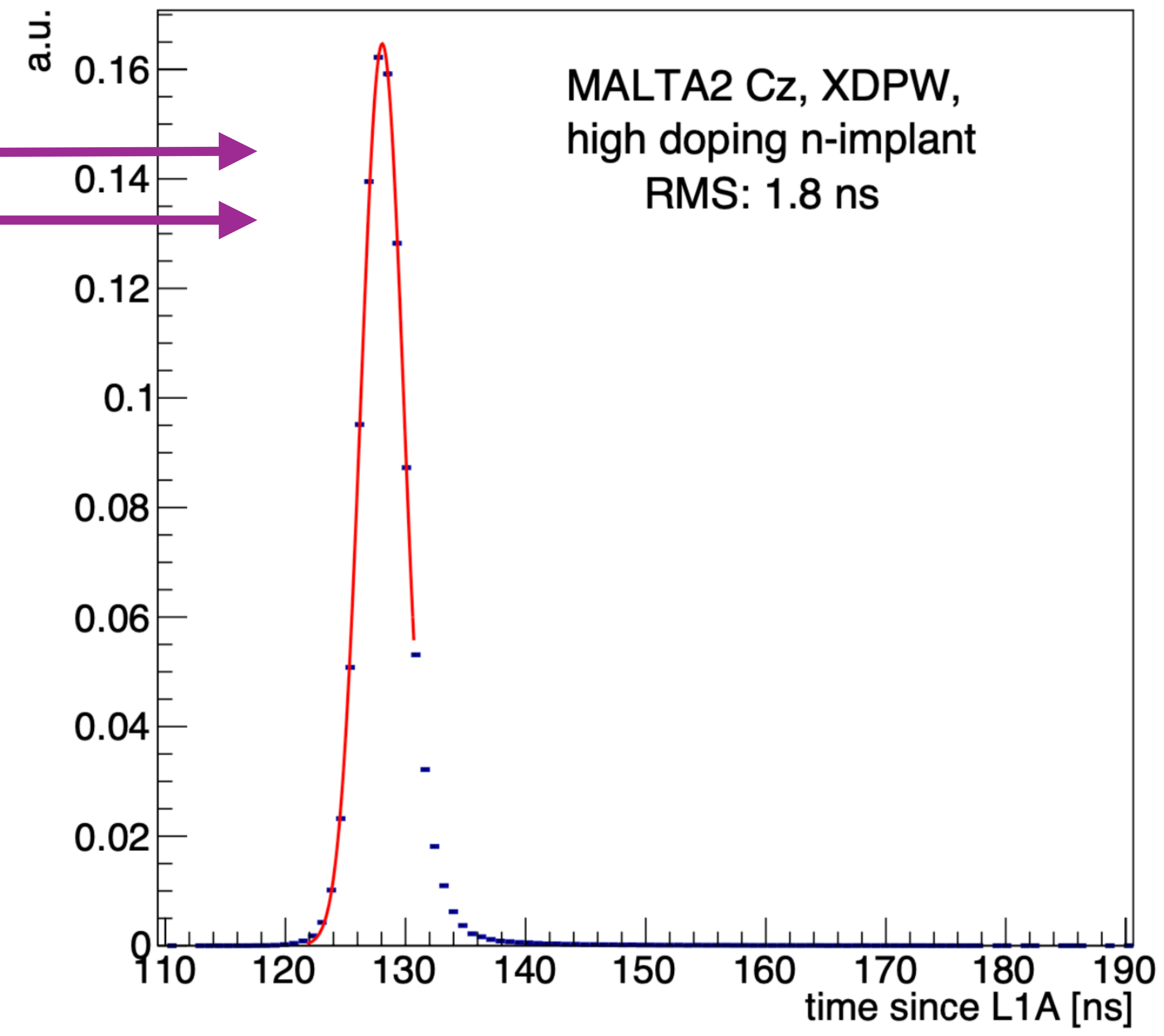
Bias groups visible



Far side of sensor *Read-out*



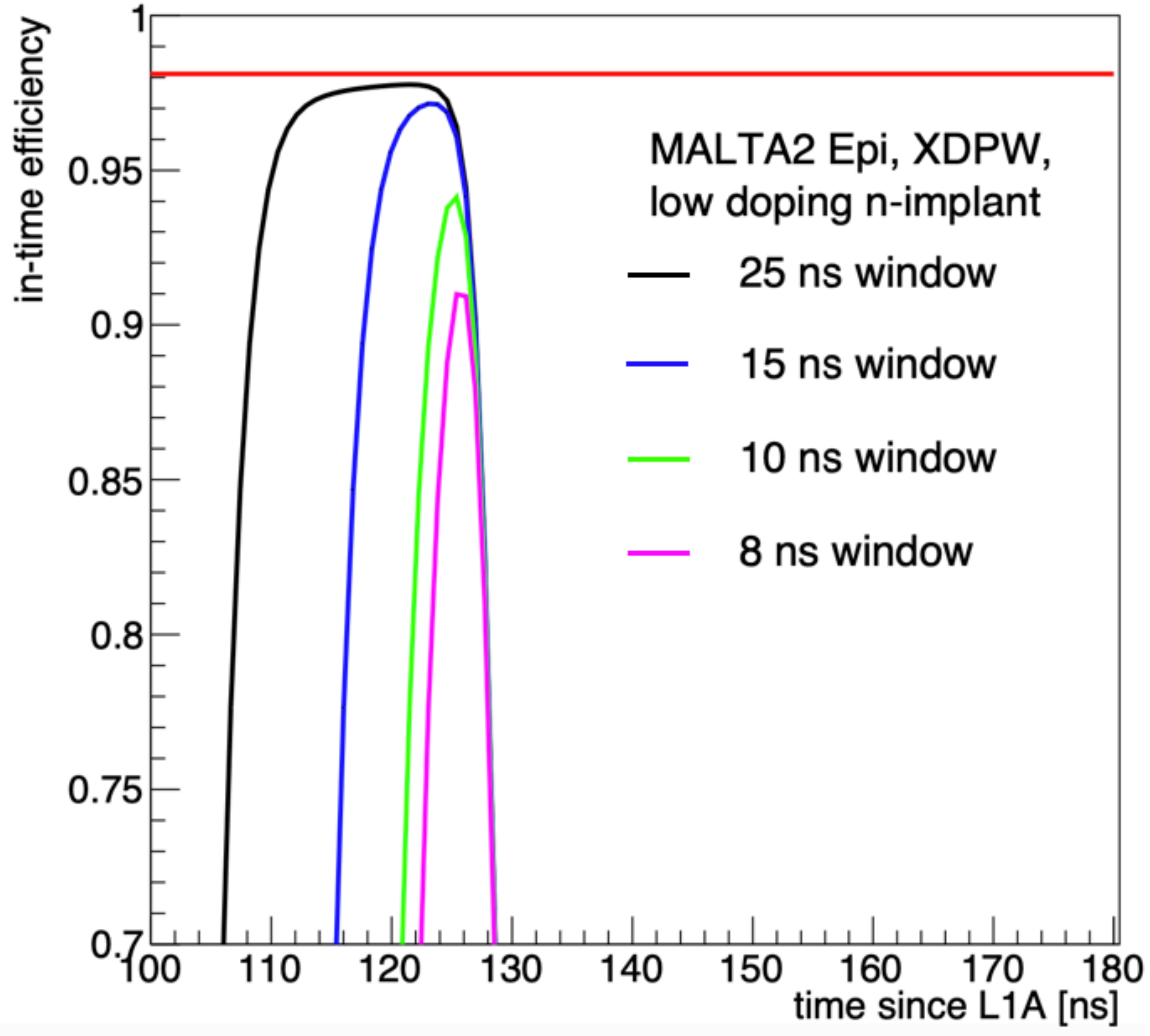


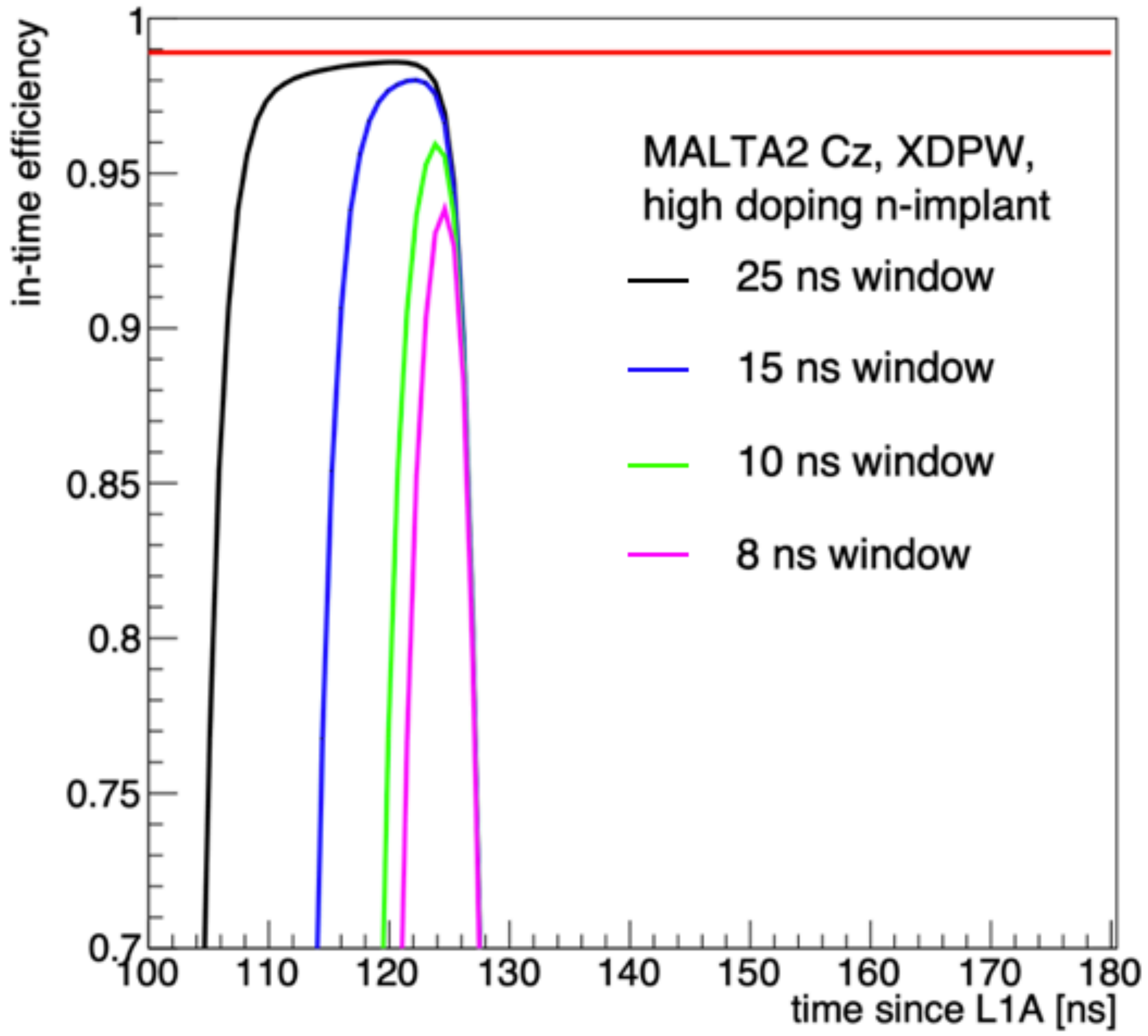


- **Time of arrival of the fastest hit in a cluster,** as a function of the matrix X/Y coordinate.
  - There is some propagation time of signals from top-to-bottom of columns, different bias groups also exhibit slightly different arrival times.
  - After correcting for the arrival-time offset, we find that the average time between triggering and receiving a signal is ~1.8—1.9 ns, for **MALTA2** with **extra-deep p-well (XDPW),** with both high-resistivity **epitaxially grown** and **Czochralski (Cz)** substrates, and **different n-implant doping** concentrations.
- *n.b. — only the difference between min & max cluster time values is relevant. Pipeline results in arrival of signal after ~130 ns.*

New! MALTA Preliminary Results   See also M. Van Rijnbach @ TWEPP21 for more info about Cz MALTA sensors

MALTA2 Timing, *suite.*





>98% of MALTA2 signals arrive within LHC 25 ns bunch spacing window!

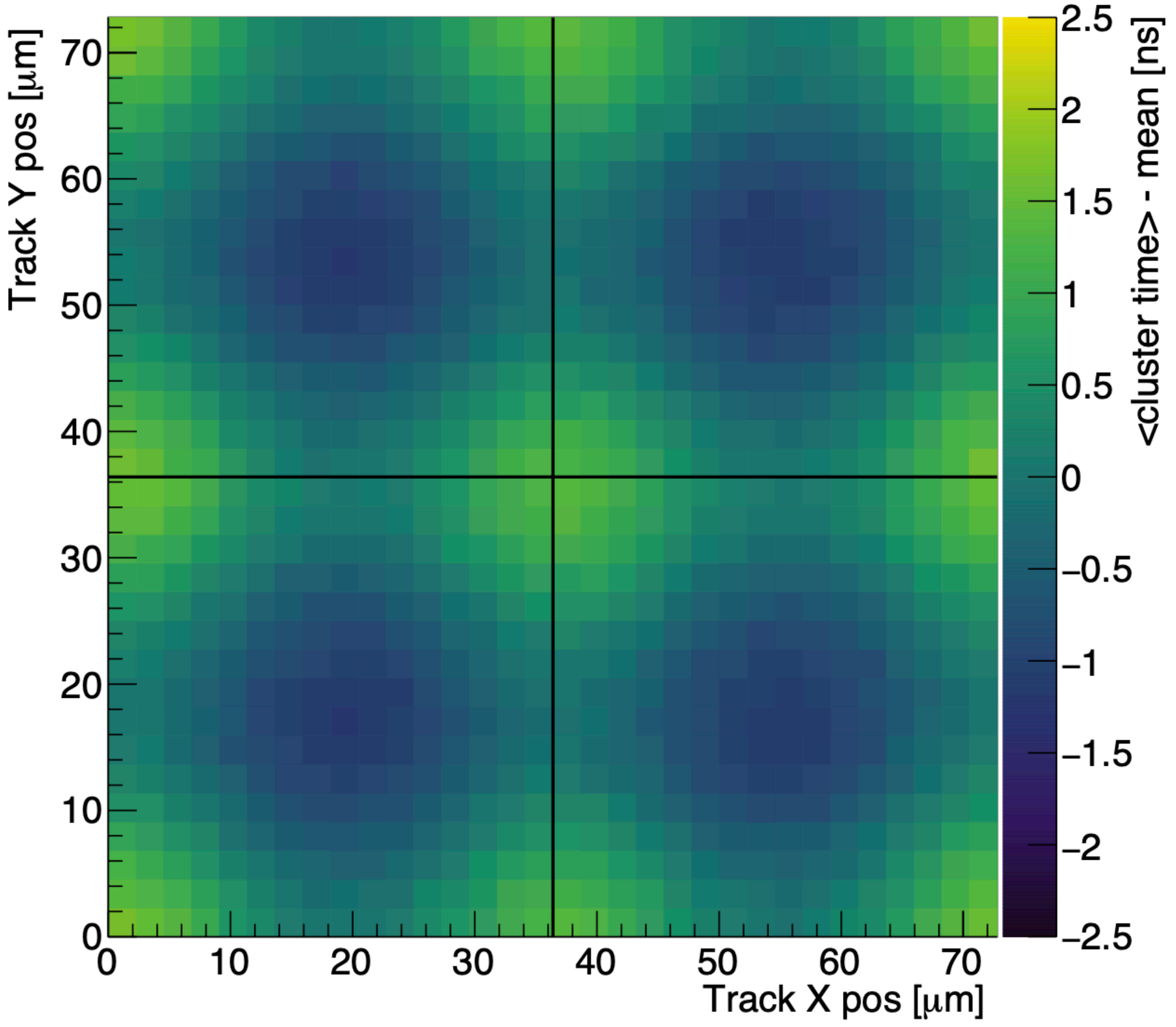
*Able to achieve >90% in-time efficiency for smaller windows (based on currently-discussed **ILC**, **FCC-ee** specifications).*

New! *MALTA Preliminary Results* *See also M. Van Rijnbach @ TWEPP21 for more info about Cz MALTA sensors*

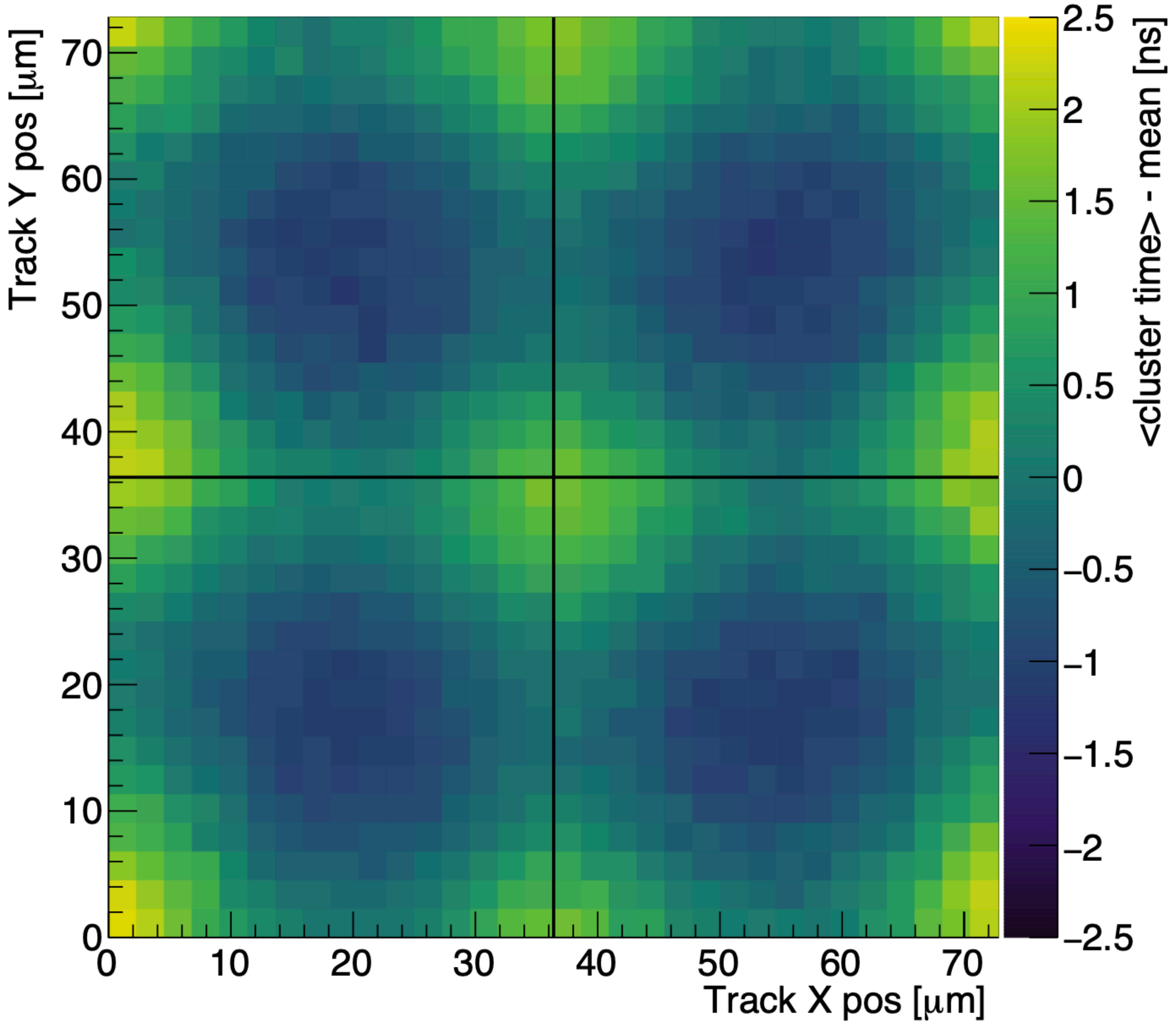
MALTA2 Timing, *suite.*

(Thr. = 170 e^-, substrate bias voltage -6 V.)

MALTA2 Epi. XDPW 100 µm, low doping of n-implant



MALTA2 Cz. XDPW 100 µm, low doping of n-implant



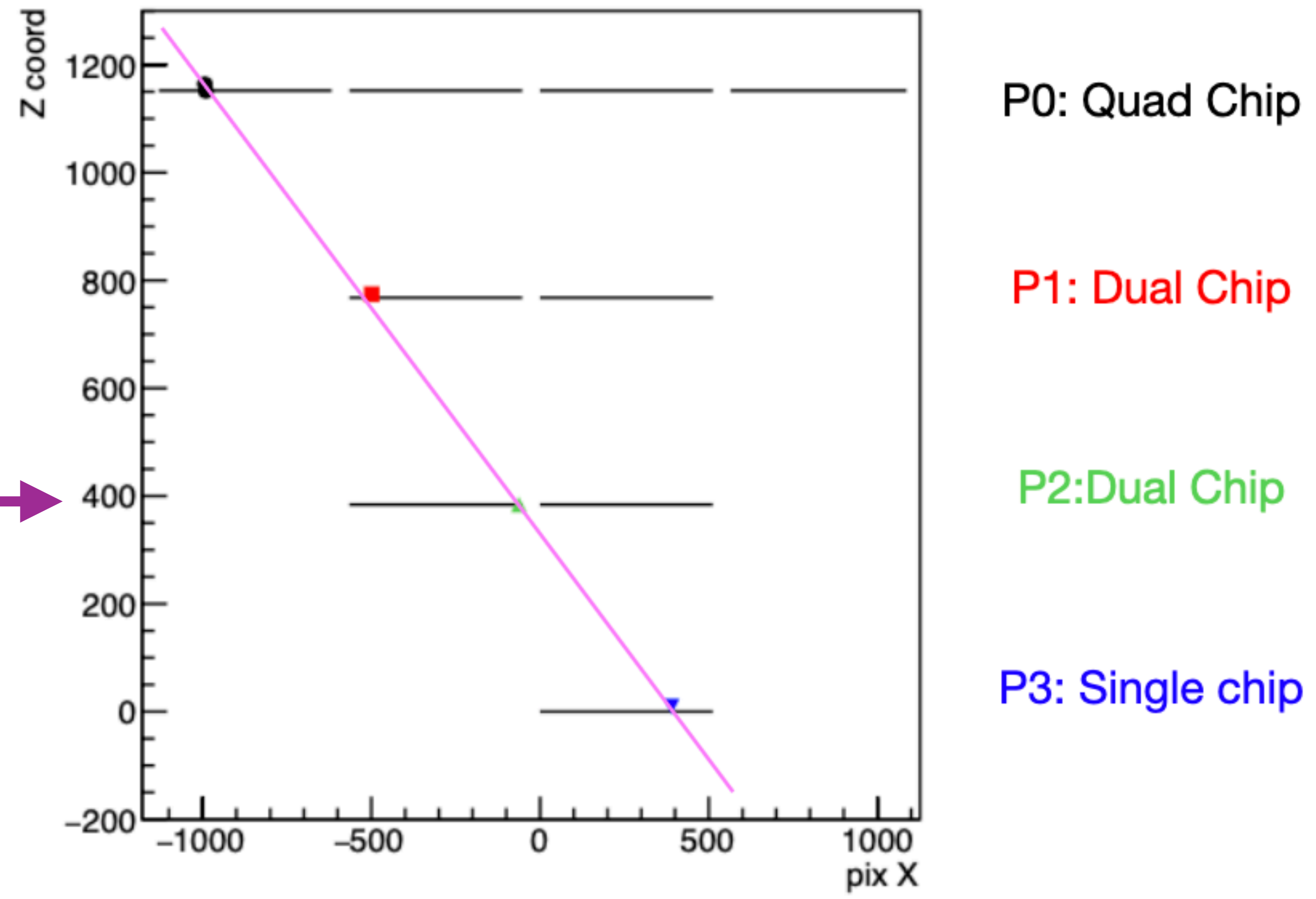
Study of in-pixel timing projected over 2x2 pixel matrix indicates that **late-arriving signals originate from pixel corners**: in these cases, charge-sharing effects result in a **lower charge deposition per-pixel** and **increased time-walk**.

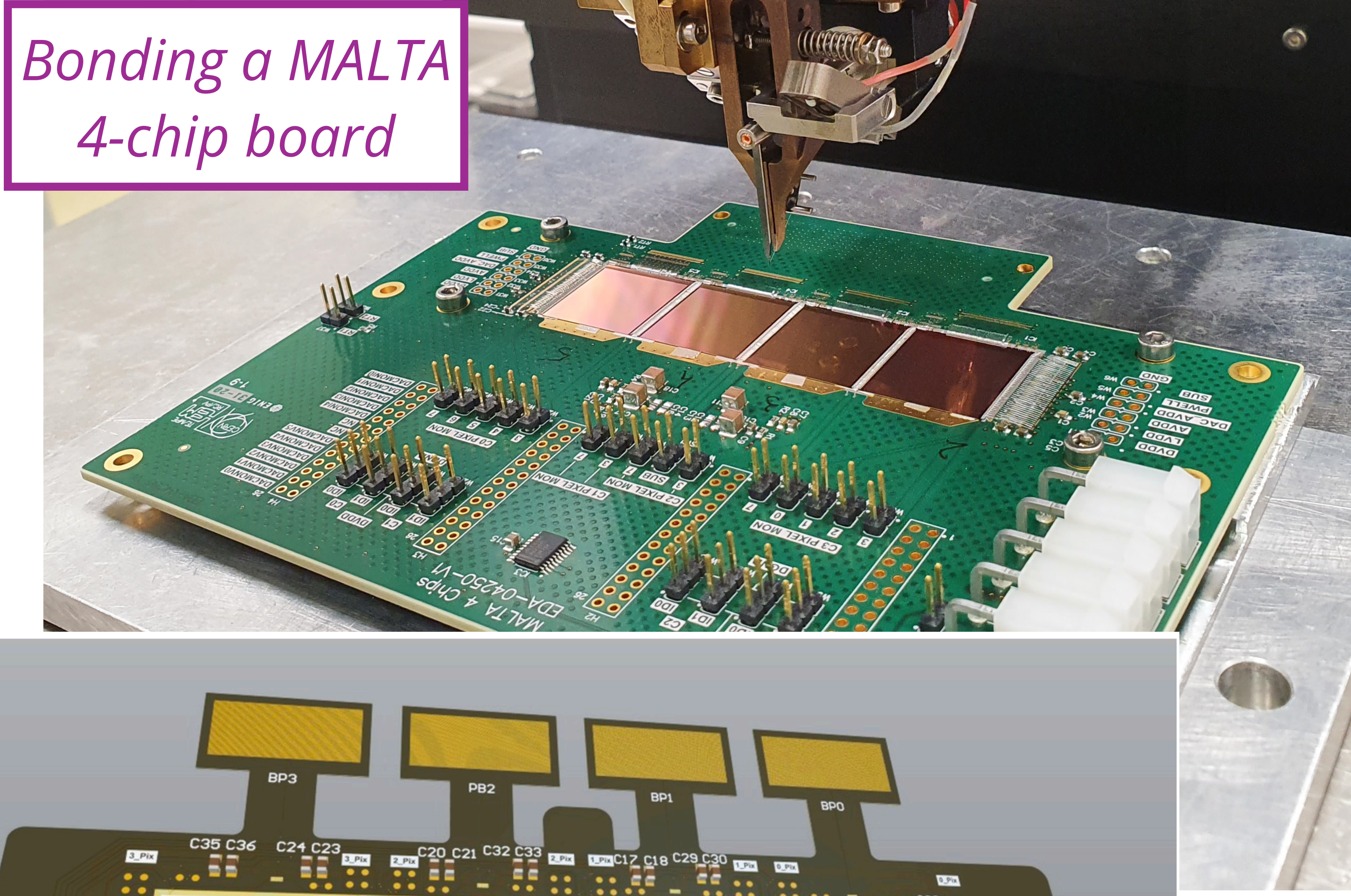
More detailed simulations of charge collection times are currently being pursued.

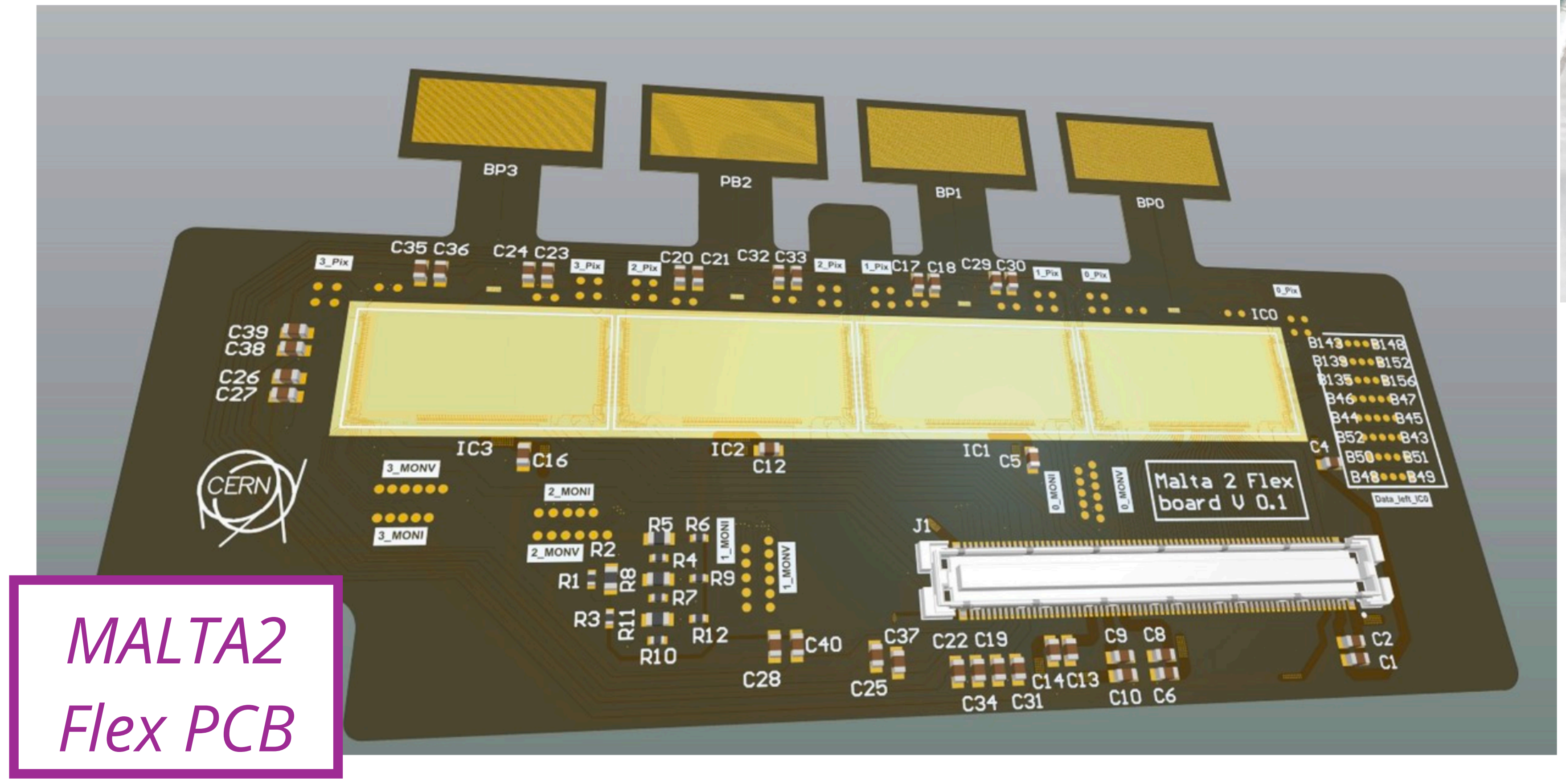
New! *MALTA Preliminary Results* *See also M. Van Rijnbach @ TWEPP21 for more info about Cz MALTA sensors*

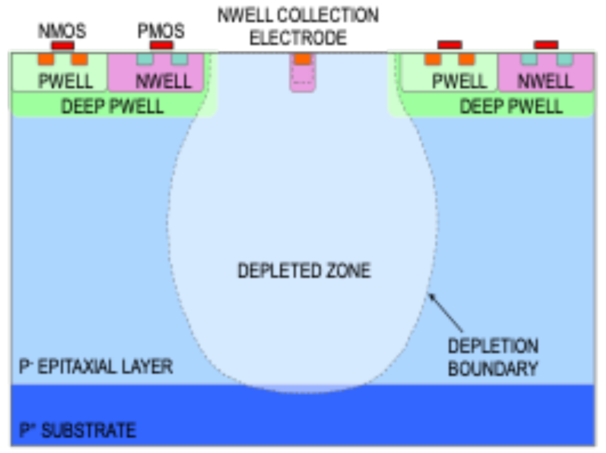
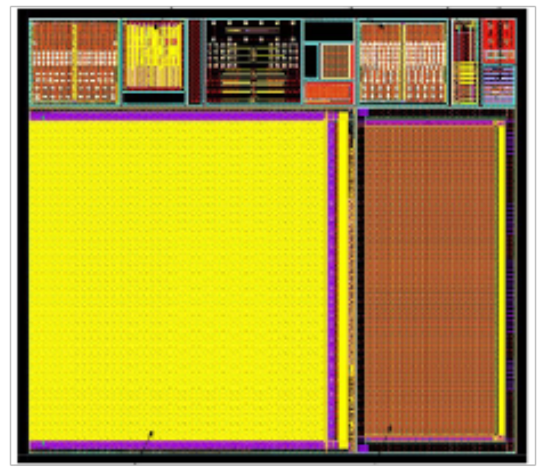
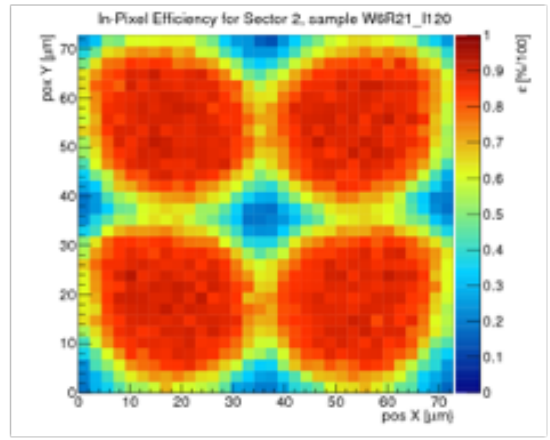
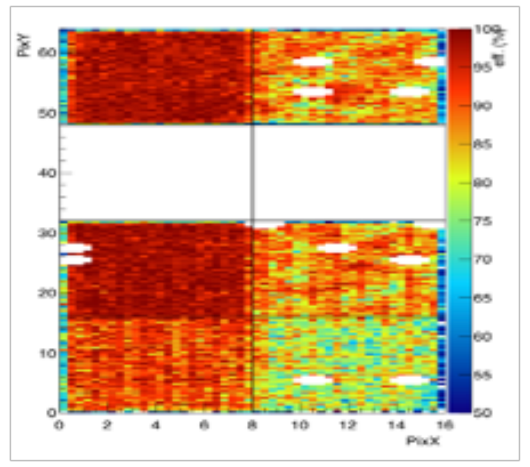
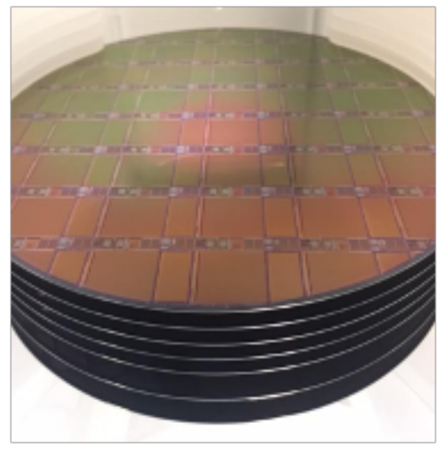
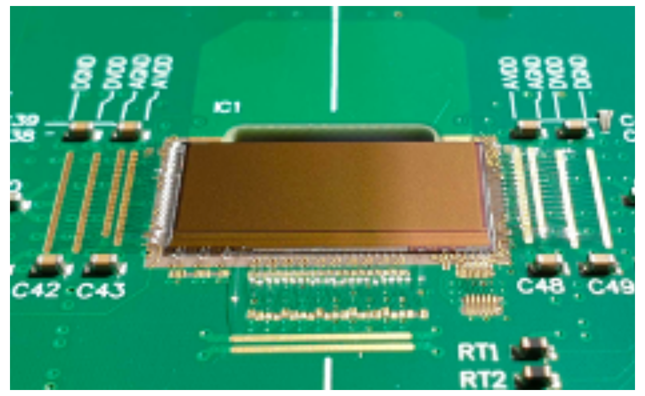
Four-chip board and flex

- Process of building multi-chip modules is ongoing for MALTA 1 & 2.
- **4-chip MALTA board functionality recently demonstrated.**
  - Quad-chip plane already installed in MALTA “mini-telescope” for cosmic data-taking!
- **4-chip MALTA2 flex PCB** in planning stages.
- ***Serialization improvements planned for next versions of MALTA prototypes.***







Standard Modified process	MALTA and Monopix designs	Sensor characterization	Further improvements miniMALTA	MALTA-C	MALTA2	MALTA3
						
First promising measurements	First engineering run with large designs	Efficiency/charge loss at the corner of pixels	Pixel modifications and RTS improvements	Epi and CZ starting material	New cascoded front-end and slow control	Time resolution, full reticle size
2014	07/2017	01/2018	09/2018	09/2019	01/2021	2023

New! MALTA Preliminary Results

Concluding remarks

- Detailed studies of the MALTA2 sensor performance continue.
  - Characterization of MALTA2 performance after irradiation.
    - Device is fully-functional after irradiation.
  - Measurements of MALTA2 timing performance.
- Planning more testbeam measurements throughout this year at the CERN SPS!
- Stay tuned for more from MALTA in the near-future!

For more on *MALTA*:

https://ade-pixel-group.web.cern.ch/Welcome/

https://twiki.cern.ch/twiki/bin/viewauth/Atlas/MaltaApprovedPlots

https://ade-pixel-group.web.cern.ch/TowerJazz/

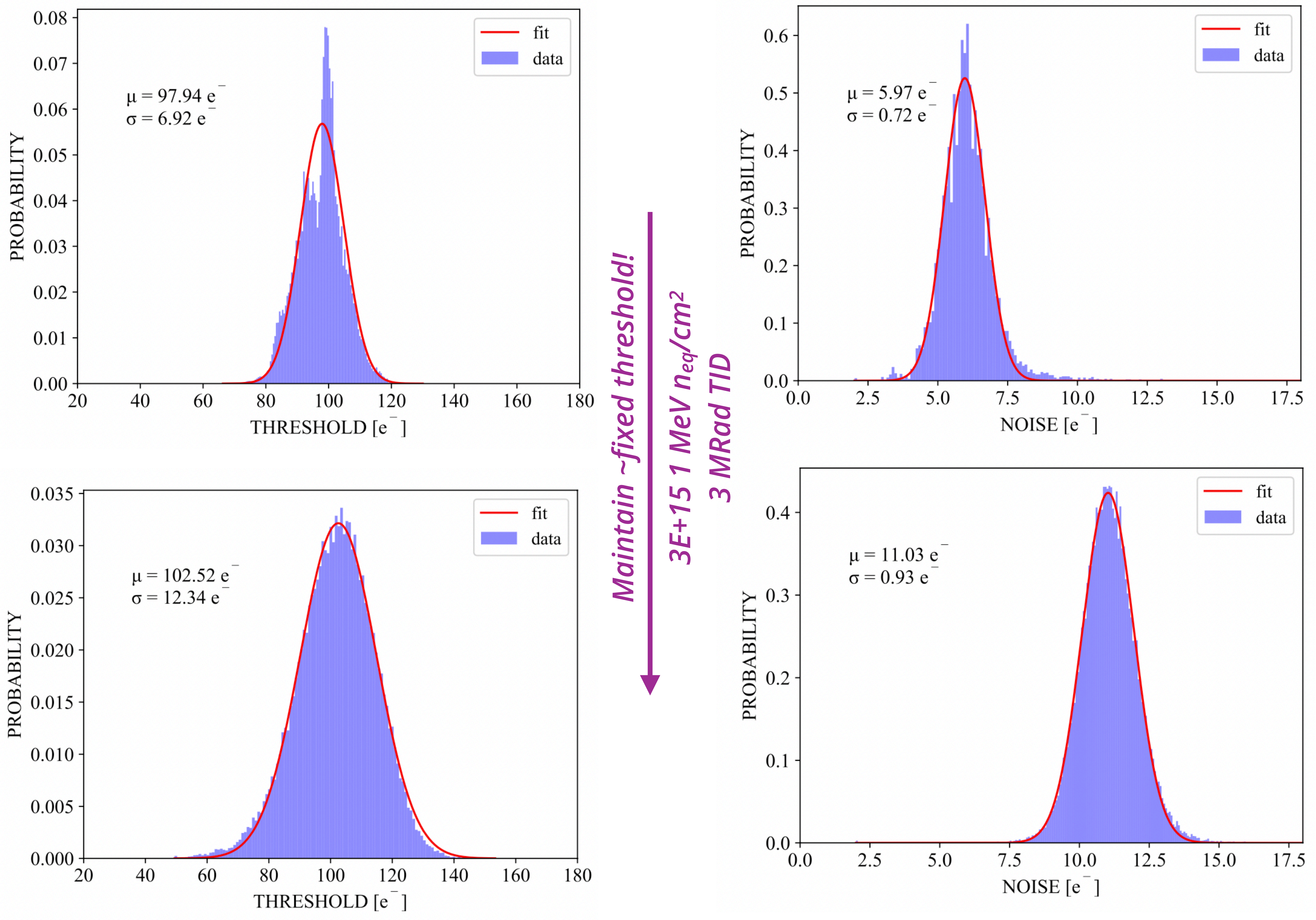
https://ade-pixel-group.web.cern.ch/Publications/

CERN

Auxiliary material.

MALTA2 Front-End : Irradiation

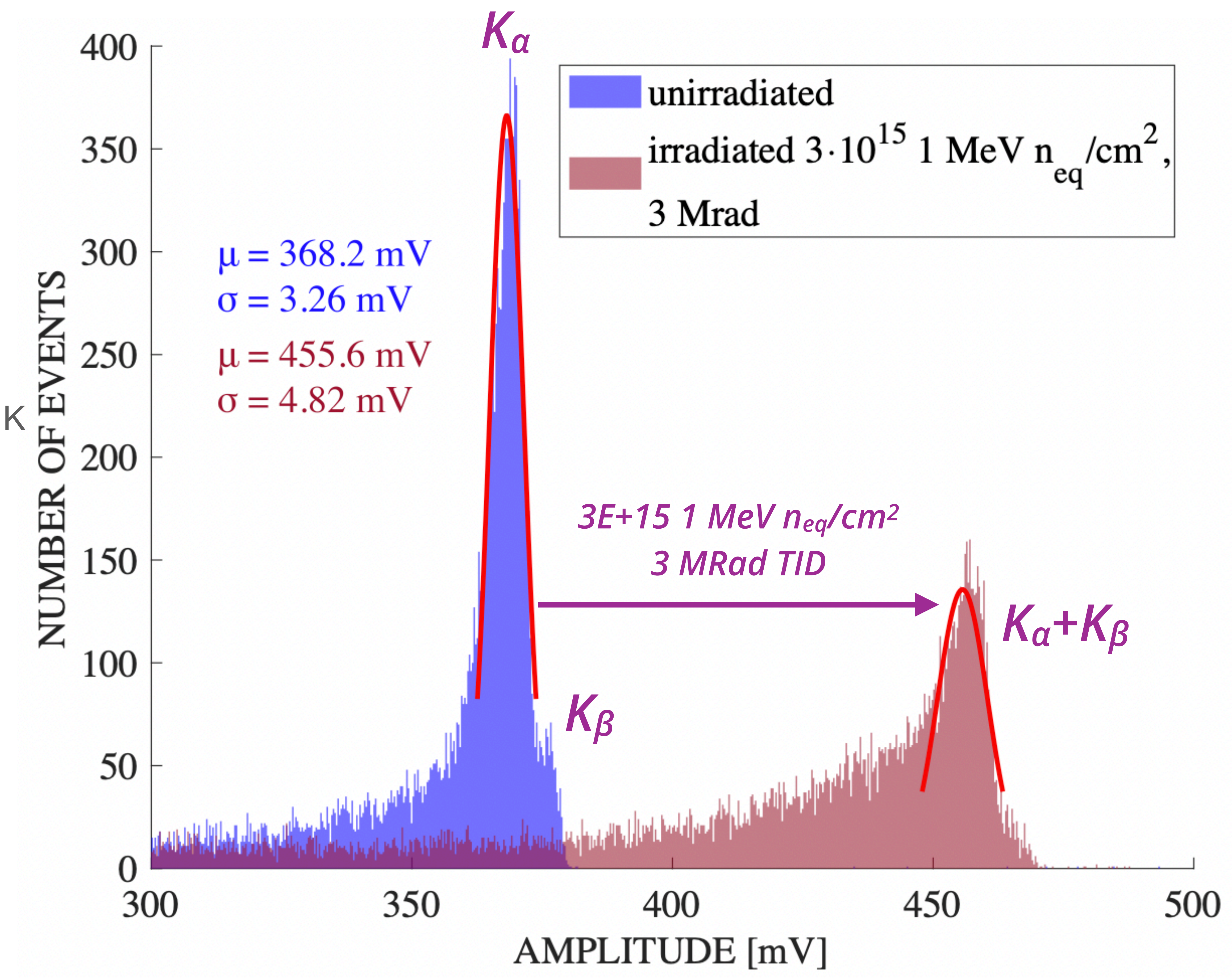
- MALTA2 sensors irradiated at TRIGA reactor in Lubljana.
  - Up to 3E+15 1 MeV n_{eq}/cm^2
  - Background TID of 1 Mrad per 1E+15 1 MeV neq/cm2
- **Sensors are fully functional following irradiation.**
- **Threshold dispersion and noise increase.**
  - For a 100 *e*— threshold, pixel-to-pixel variation in threshold increases from ~7 *e*— to ~12.5 *e*—.



New! F. Piro et al., submitted to IEEE Trans. Nucl. Sci.

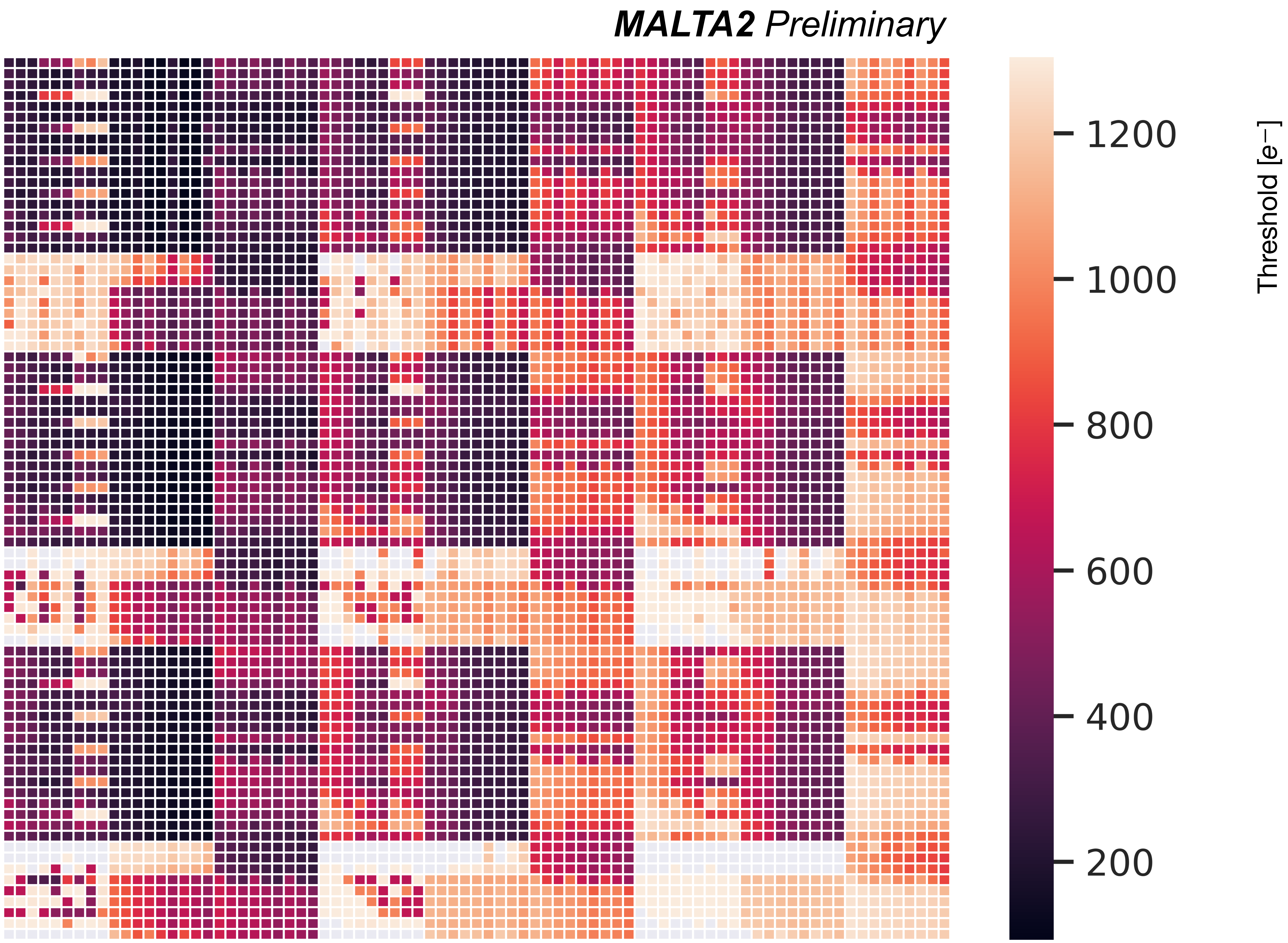
MALTA2 Front-End : Irradiation, suite.

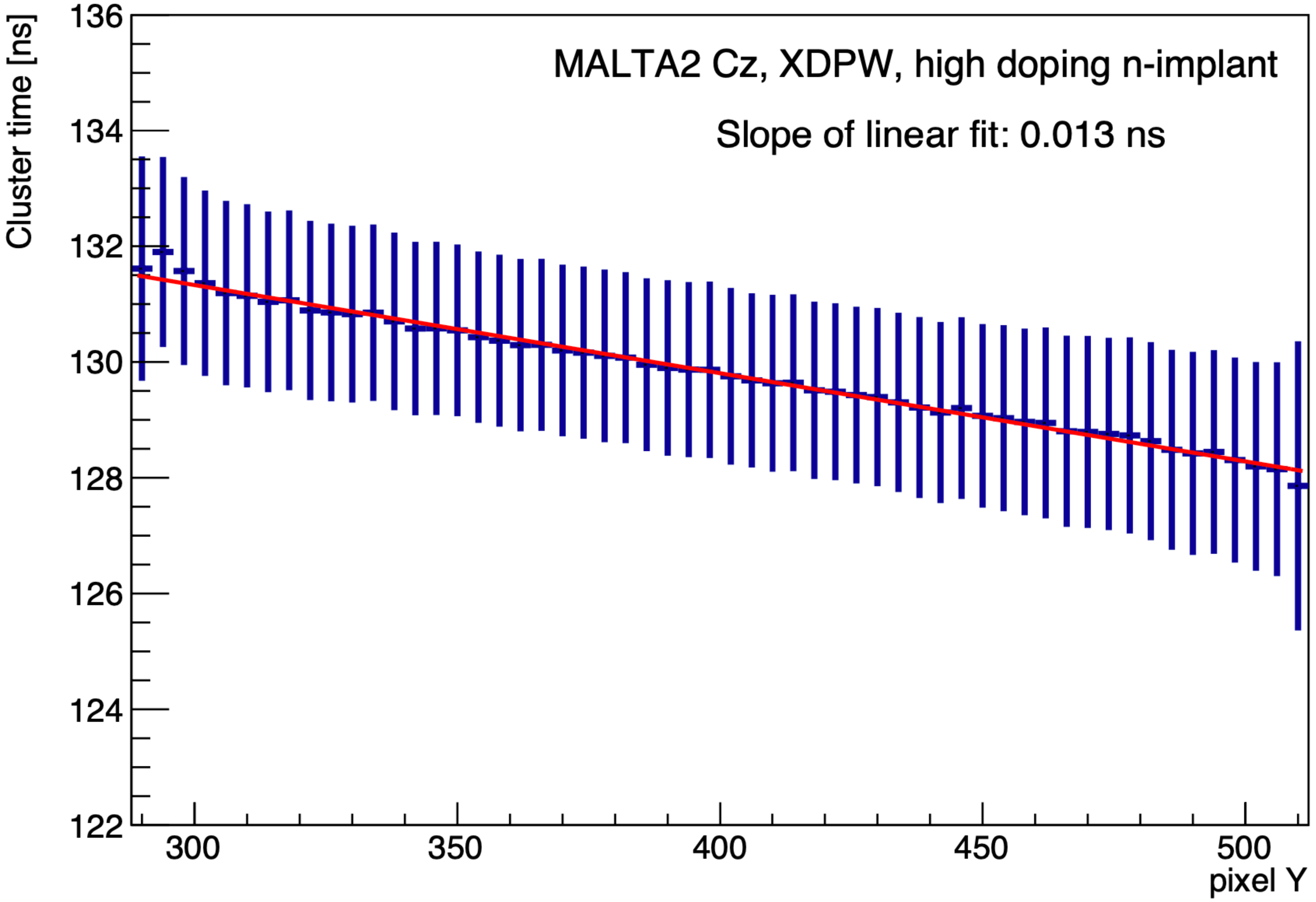
- MALTA2 sensors irradiated at TRIGA reactor in Lubljana.
  - Up to 3E+15 1 MeV n_{eq}/cm^2
  - Background TID of 1 Mrad per 1E+15 1 MeV neq/cm2
- Effect of irradiation on sensor energy resolution studied using ^{55}Fe source.
  - Kα peak amplitude increases ~23.7% after irradiation.
    - Kβ peak no longer distinct!
  - Noise increase from ~6.8 e⁻ → ~11.7 e⁻
  - Behaviour expected from previous MALTA studies, likely related to NIEL decreasing effective doping of n — layer (lower capacitance → higher amplitude).



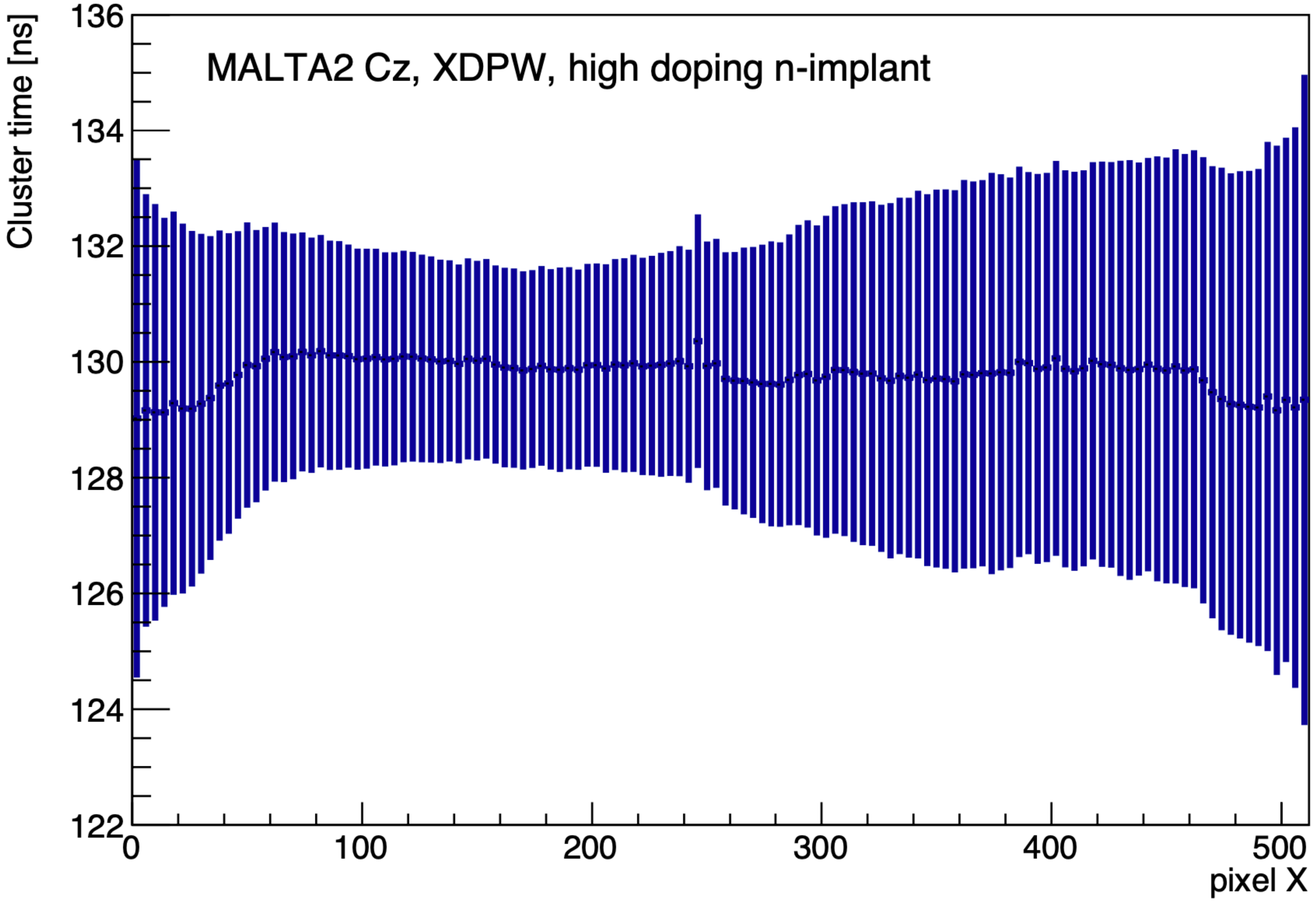
New! F. Piro et al., submitted to IEEE Trans. Nucl. Sci.

MALTA2 Front-End : DAC Interdependencies (no annotations)





MALTA2 Cz, XDPW, high doping n-implant
Slope of linear fit: 0.013 ns
Cluster time [ns]
pixel Y
136
134
132
130
128
126
124
122
300
350
400
450
500

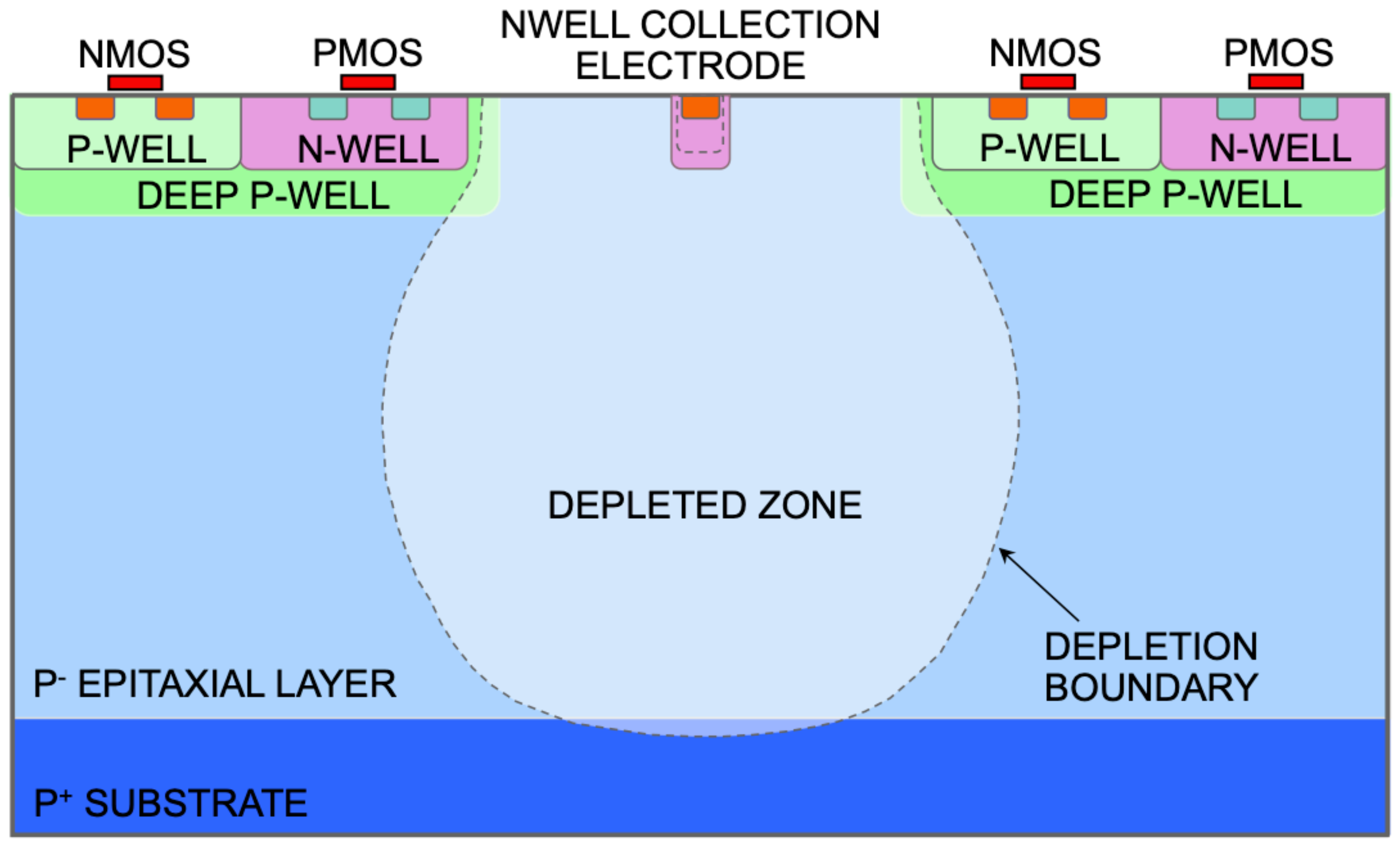


MALTA2 Cz, XDPW, high doping n-implant
Cluster time [ns]
pixel X
136
134
132
130
128
126
124
122
0
100
200
300
400
500

Towerjazz 180 nm Modified Processes

Charge collection time ~100 ns via diffusion, too slow for LHC applications.

Not in today's talk!

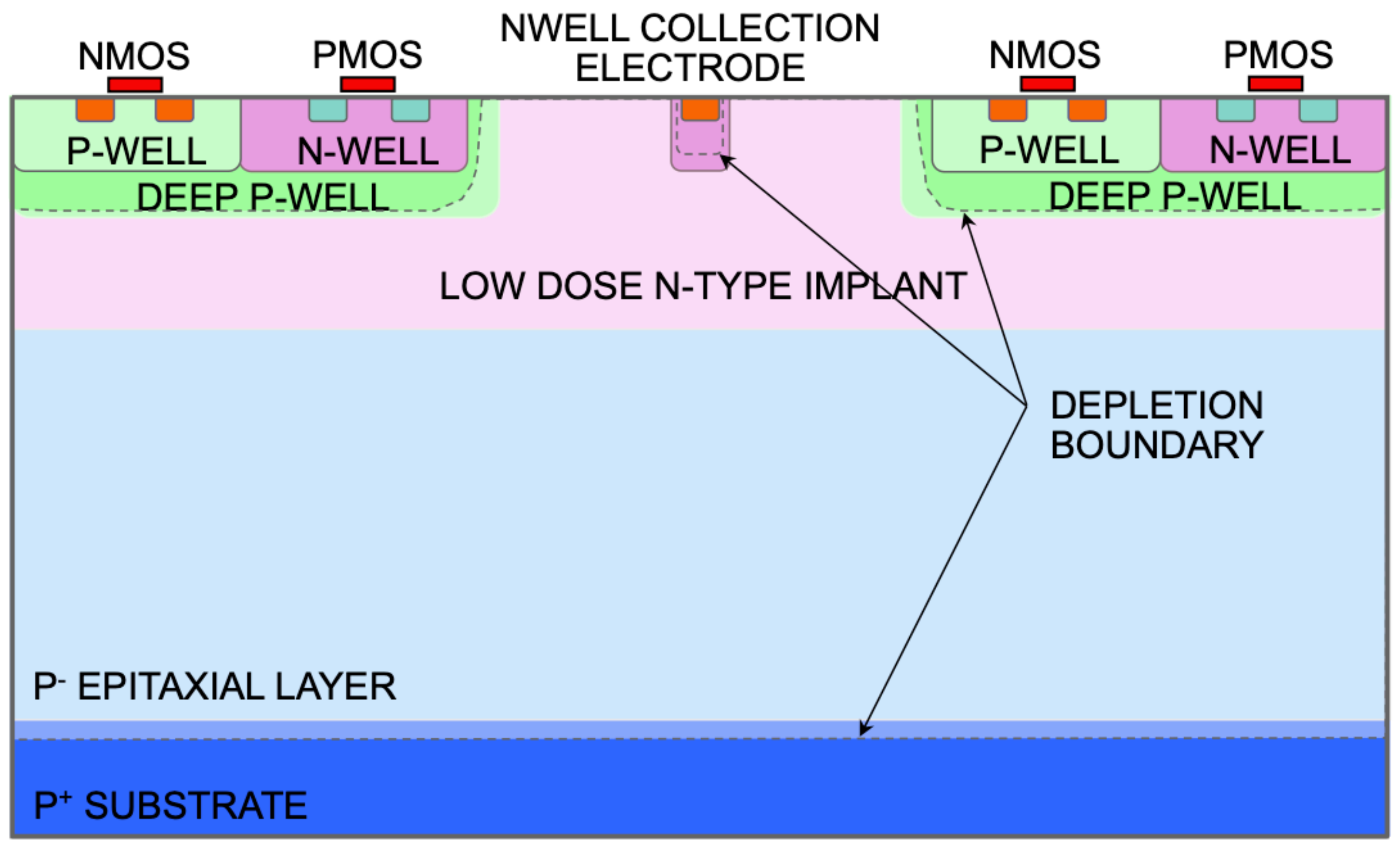


Unmodified process

Uniform low-dose n— layer under p-well fully depletes pixel area, pushing charge-carriers towards collection electrode.

Also reduces charge carrier capture probability, improving sensor tolerance to NIEL.

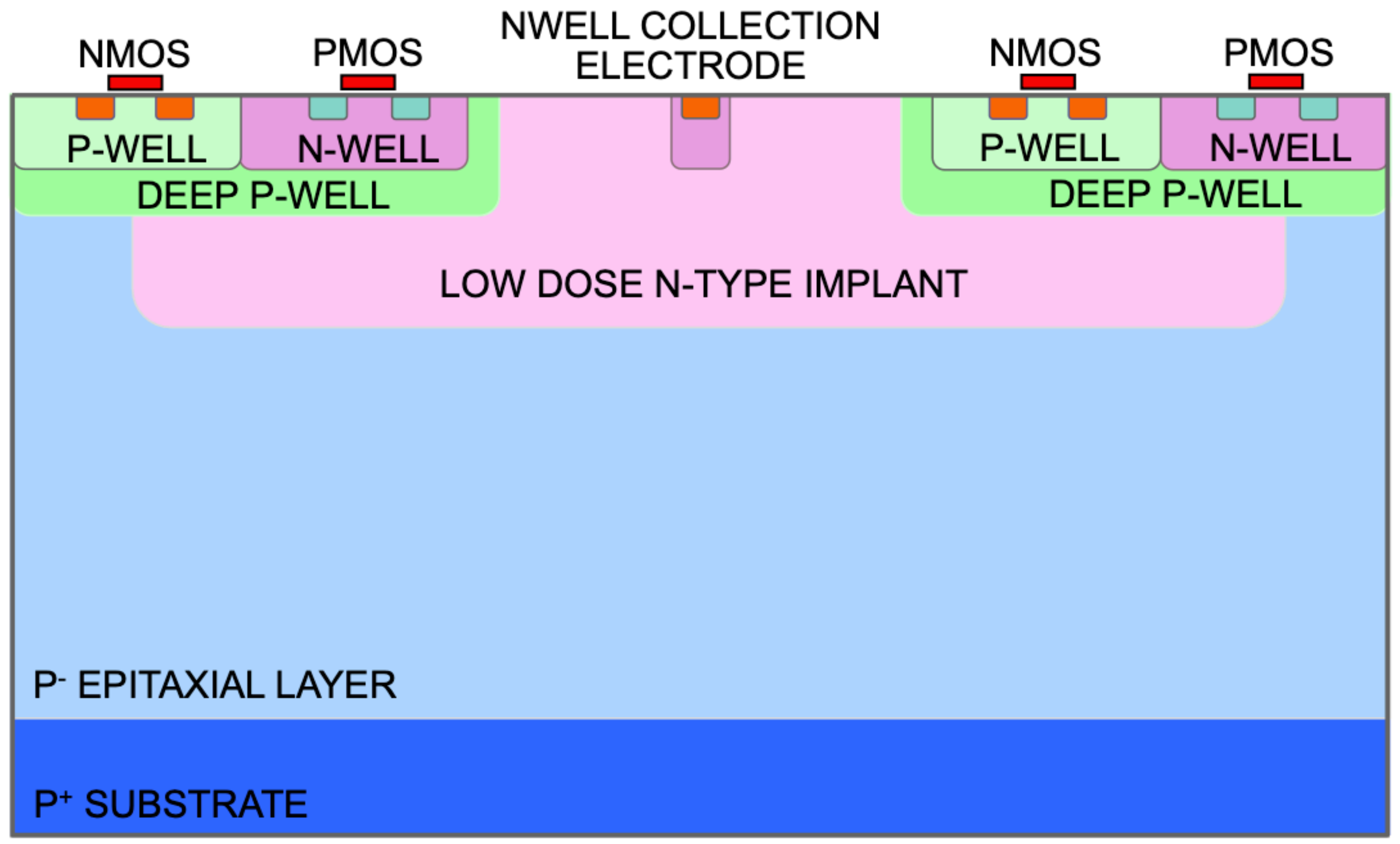
In today’s talk!



Modified process, low doping

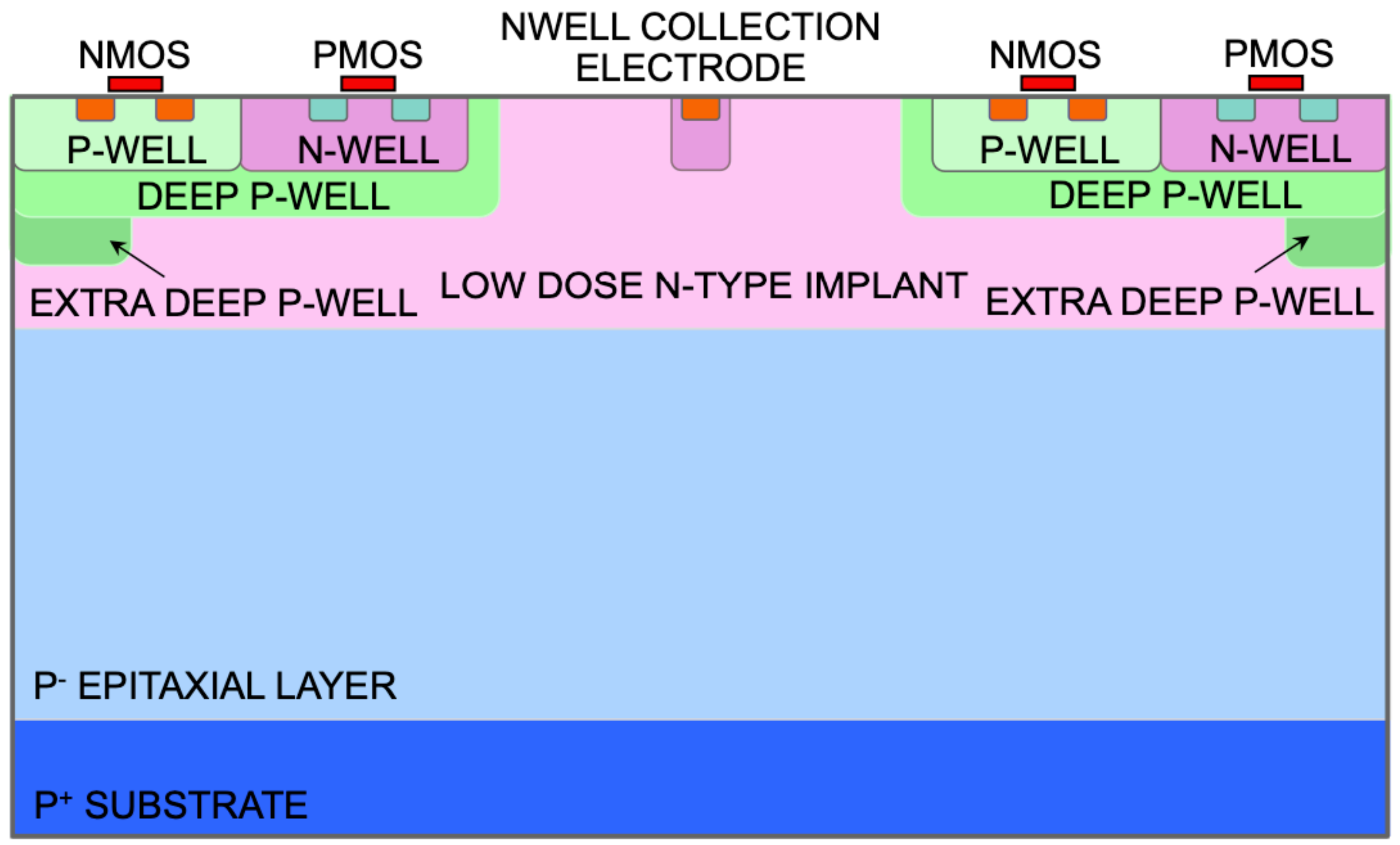
In today’s talk!

Additional process modifications can increase E-field in pixel corners, further reducing charge collection tails.

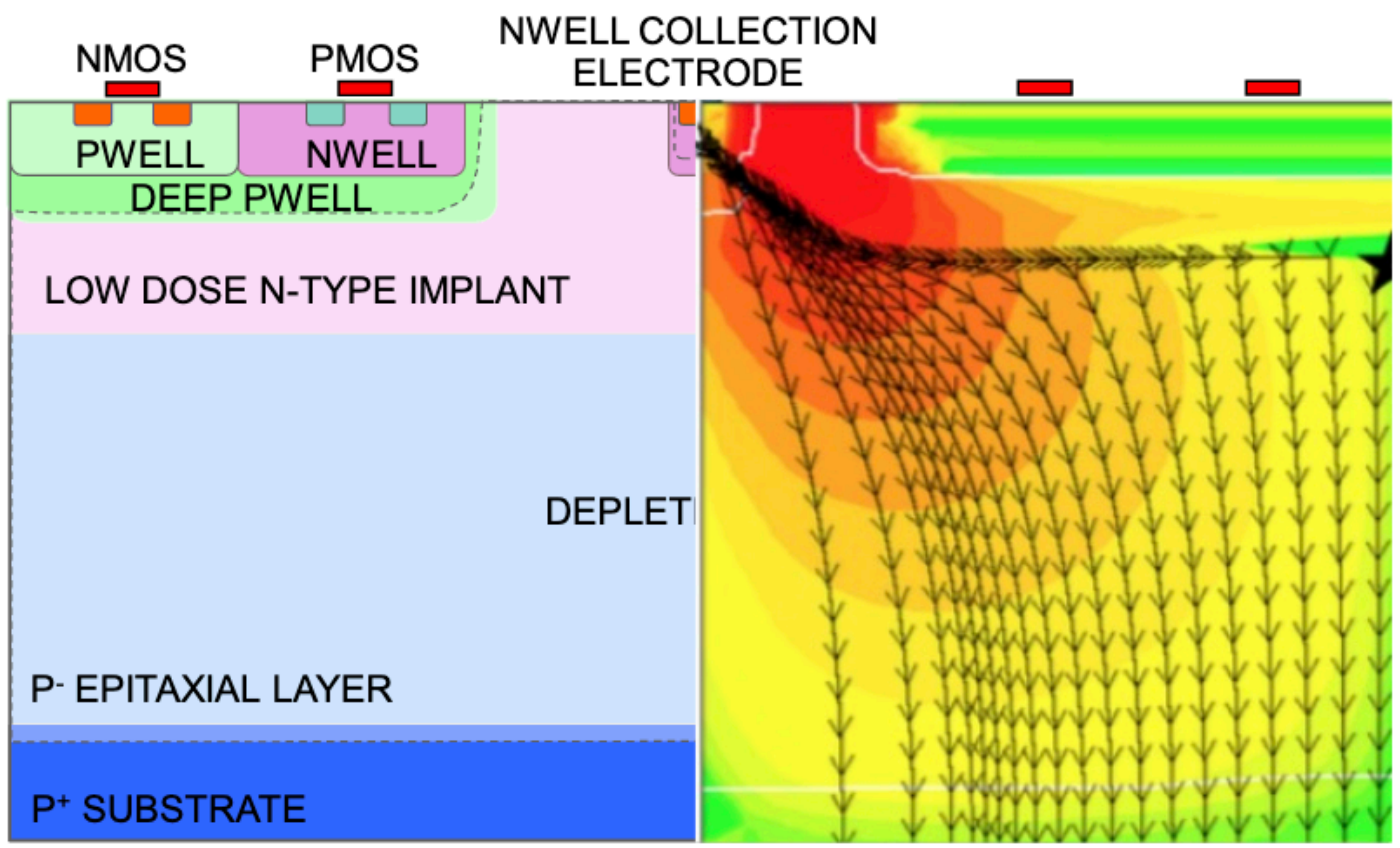


Gap in the n-layer

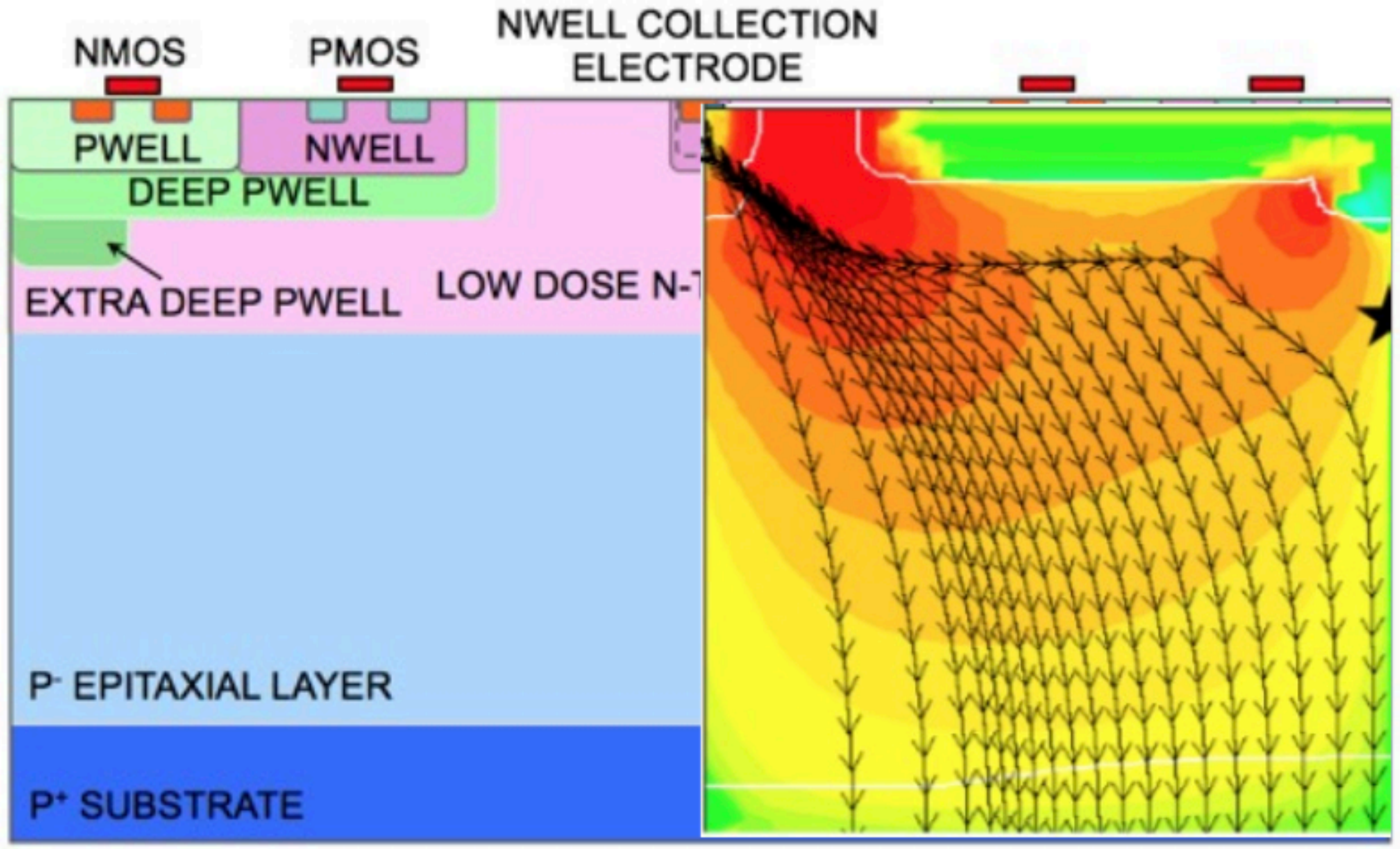
Not in today's talk!



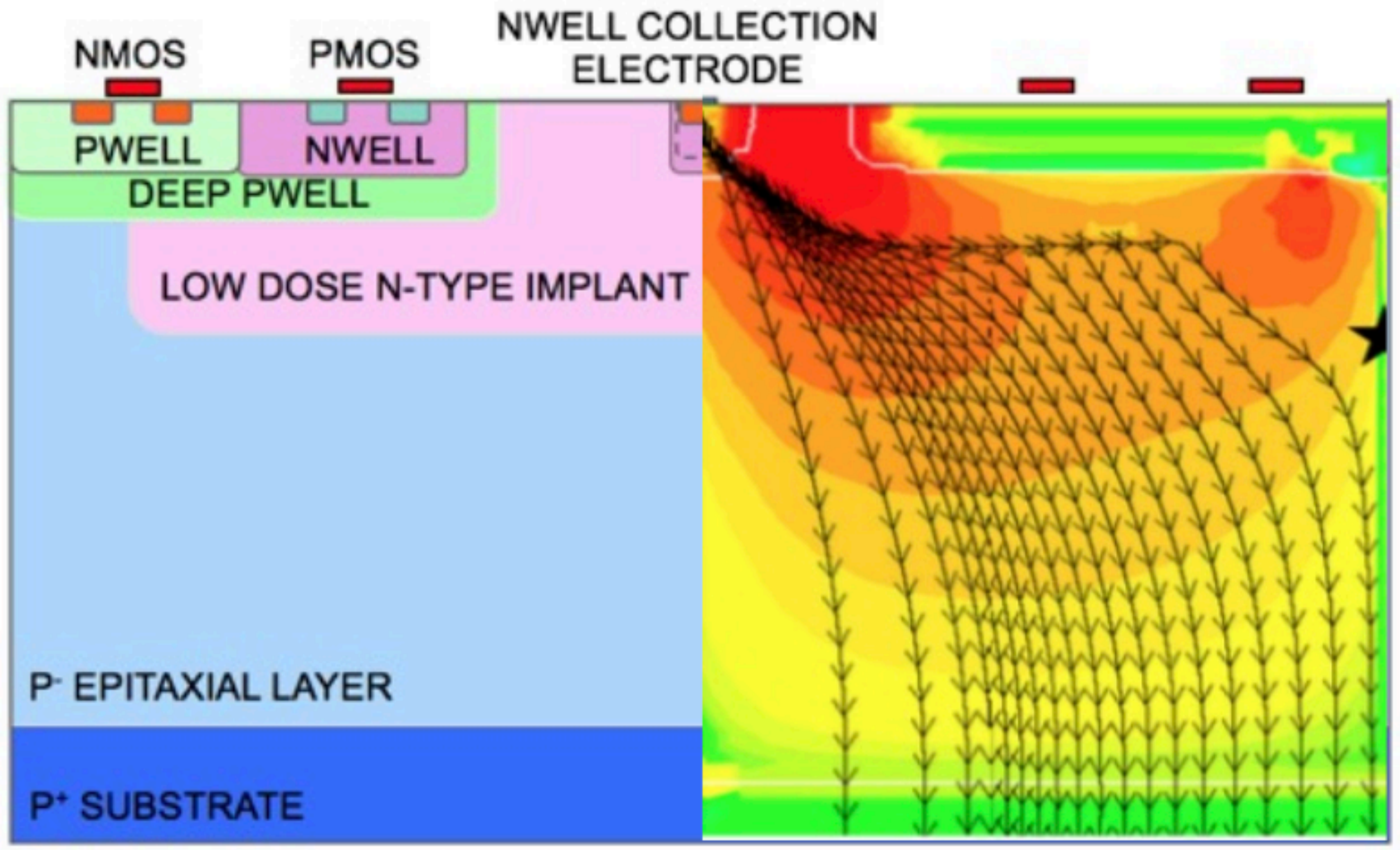
Extra-deep p-well



Standard modified process



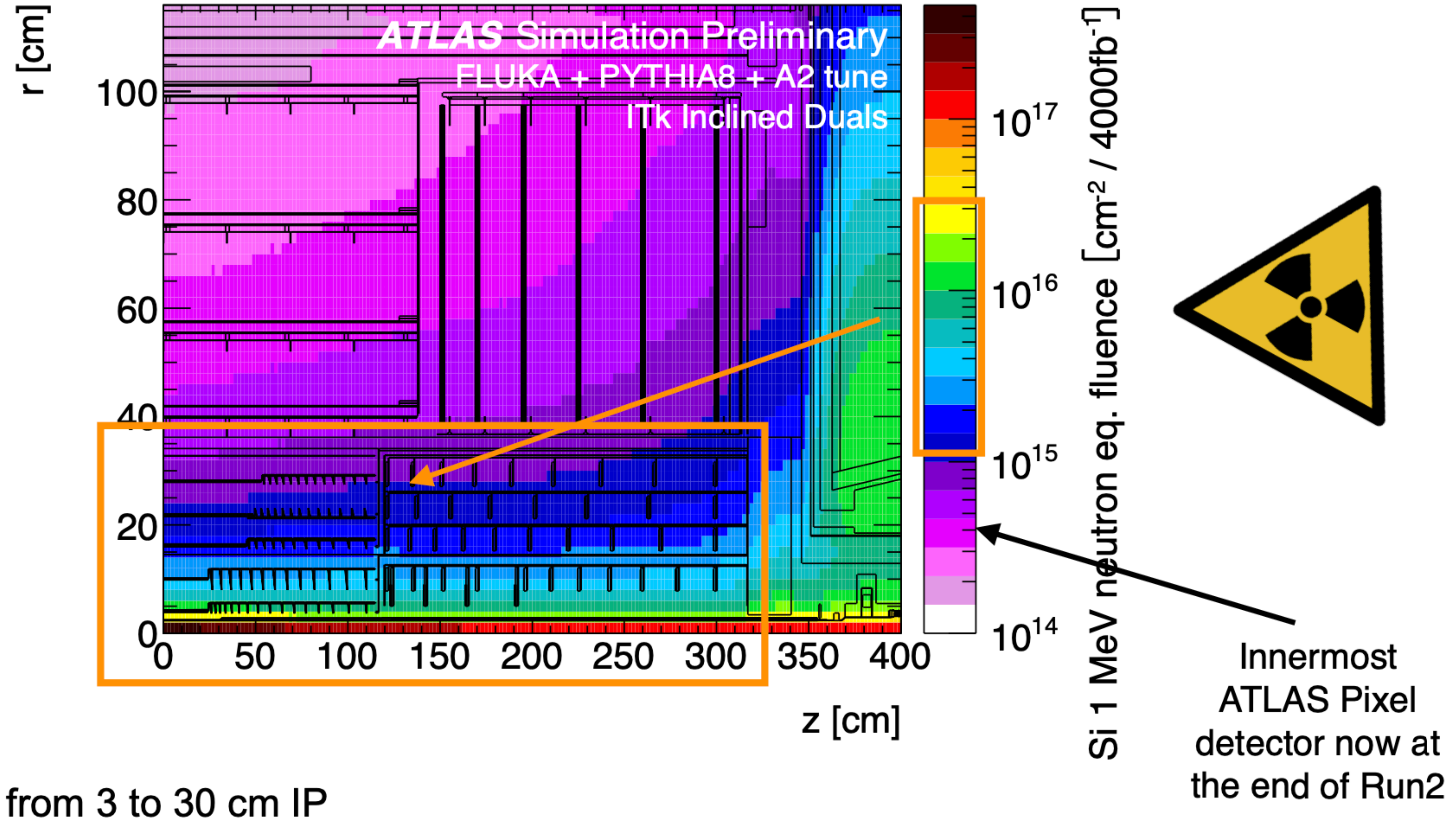
Extra deep p-well (EDPW)



Gap in the n- layer (NGAP)

(one of) the next challenges for pixel detectors

- ***Large hit rate***: 200 MHz/cm^2
- ***'As thin as possible'***
- ***Resist to very large radiation dose***:
  - HL-LHC pixel detector:
    2 10^{16} - 10^{15} n_{eq}/cm^2 NIEL



- **ATLAS Itk**:
  - 5 pixel layers from 3 to 30 cm IP