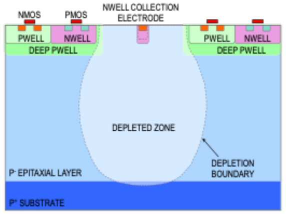
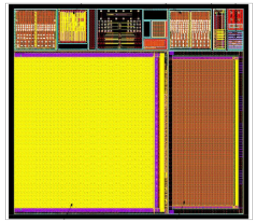
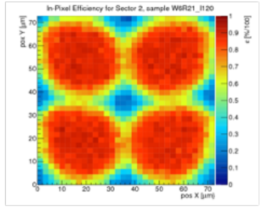
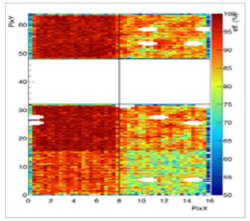
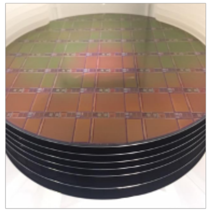
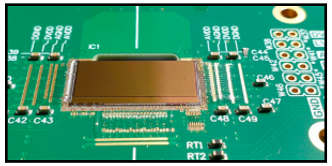
The MALTA tracking sensor as an energy sensitive digital calorimeter

Vlad Berlea on behalf of the MALTA collaboration
Trieste, 10.09.2025

The MALTA collaboration – 180 nm Tower Jazz

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

MALTA

- First large demonstrator (**2x2 cm²**)
- 8 sectors with different pixel flavors
- **Asynchronous readout**
- Target: ATLAS Itk Outter barrel
- Sensor functional. Slow control issues

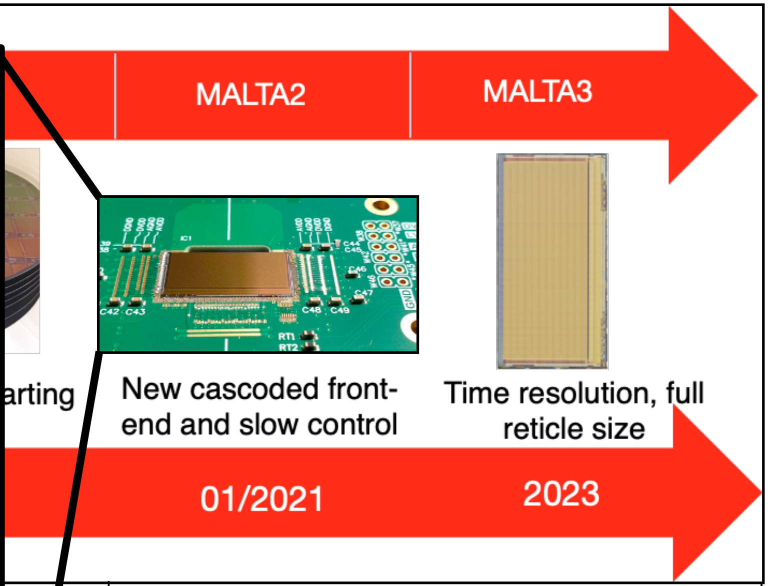
miniMALTA

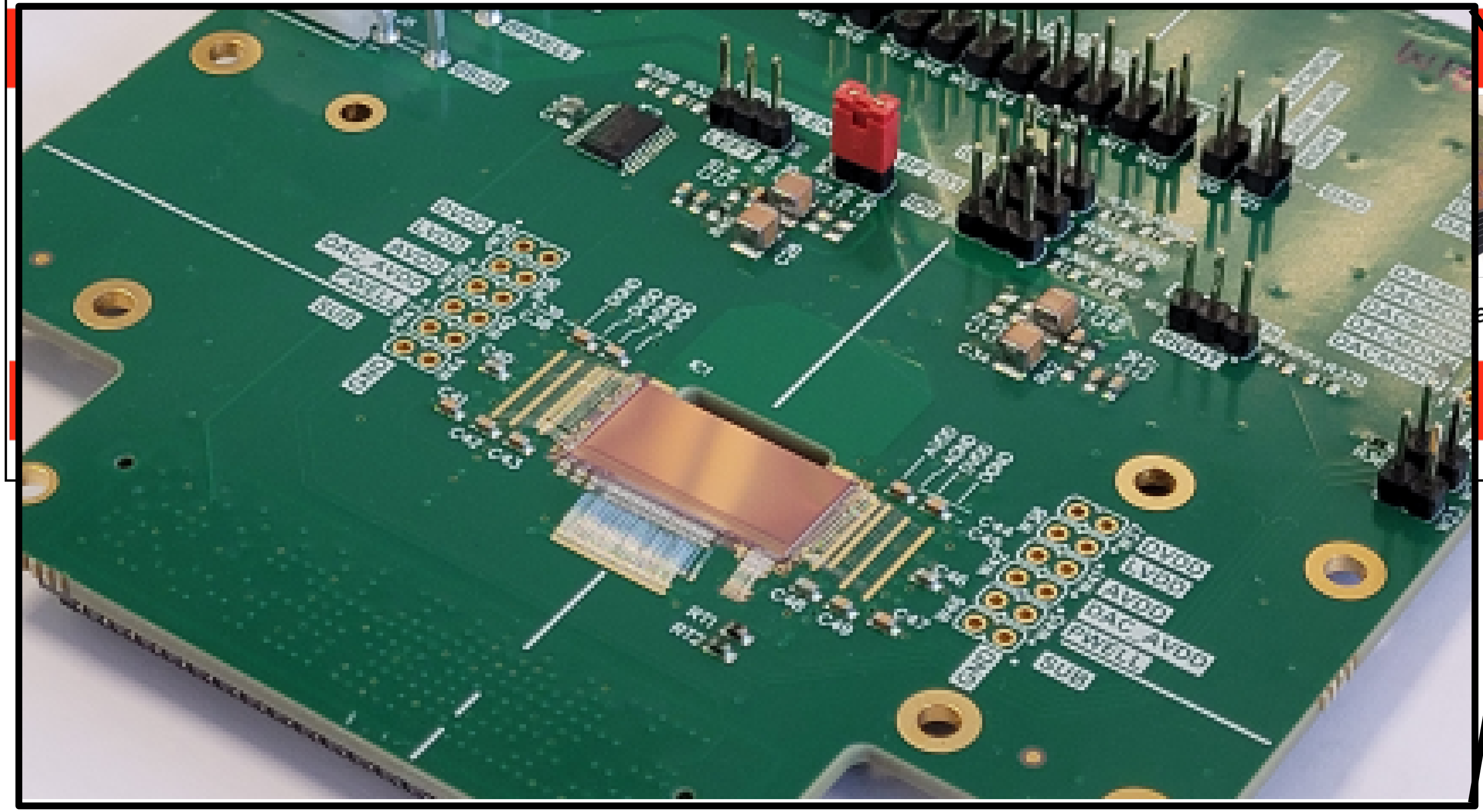
- Small demonstrator (**1.7x0.5 mm²**)
- Serial output
- **Cascoded FE**
- Rad hard, RTS improvements

MALTA2

- Smaller matrix (**2x1 cm²**)
- **New slow control**
- Mini-MALTA FE
- Extensively tested

The MALTA collaboration – 180 nm Tower Jazz





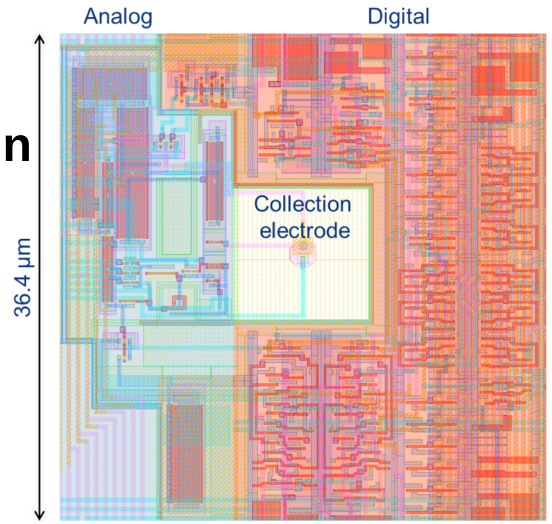
The focus of this presentation!

MALTA2

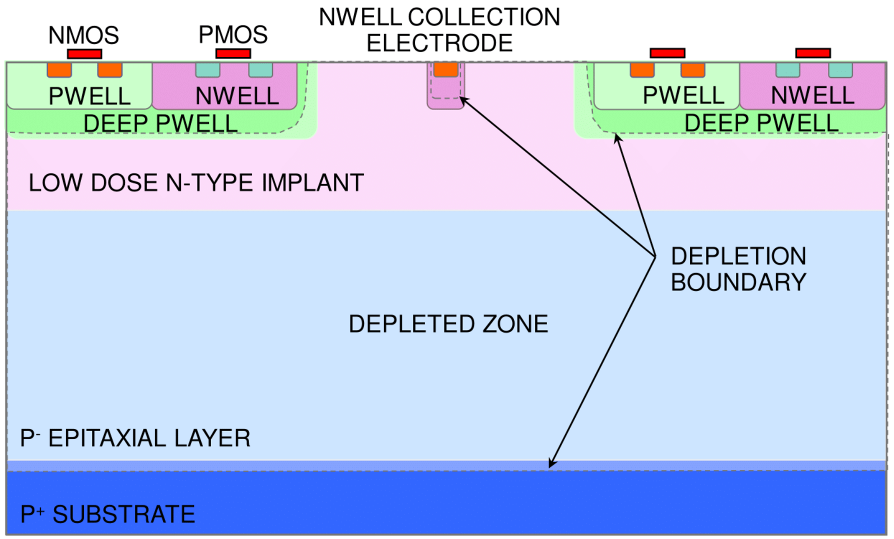
- Smaller matrix (**2x1 cm²**)
- **New slow control**
- Mini-MALTA FE
- Extensively tested

The MALTA2 pixel

Pixel (top view)



Pixel (side view)

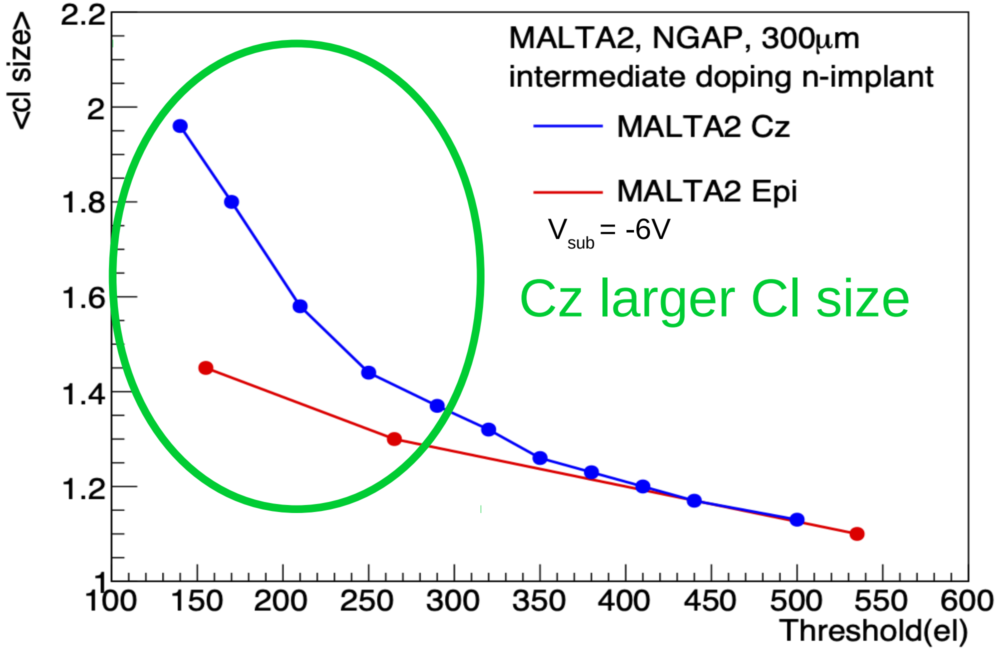


MALTA2 small collection electrode design

- Hexagonal 3x3 µm^2 CE
- < 5 fF input capacitance
- ENC < 15 e$^-$
- Low bias voltage (6 – 55 V)
- Additional low dose N-type implant

MALTA2 samples on multiple substrates

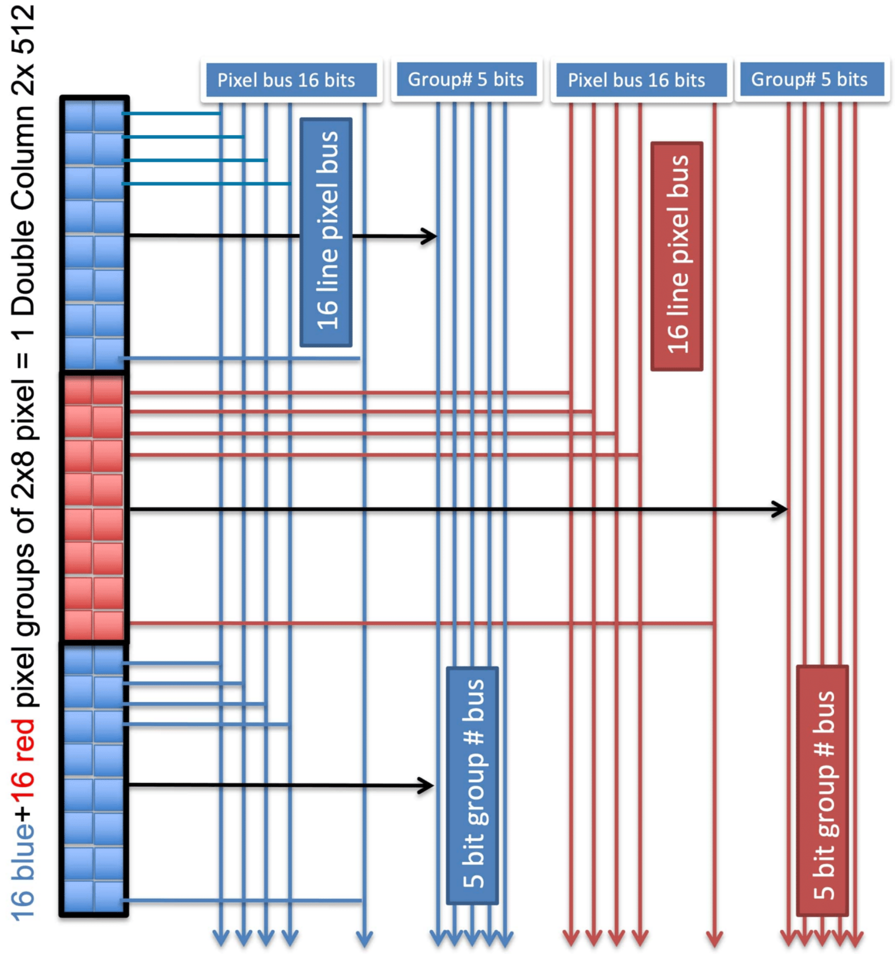
- Epitaxial silicon (Epi): ~30 µm
- Czochralski silicon (Cz): 50 – 300 µm



The MALTA2 sensor

- **224 x 512** pixels (36.4 μm² pitch)
- **Asynchronous readout**
  (No distributed clock across matrix)
- 40 bit MALTA word – **binary tracking**
- **High data rates & Low** power:
  - 1 μW/pixel analog power
  - 70 mW/cm² analog power
  - 10 mW/cm² digital power
- Double column pixel bus (pixel group read-out – 16 pixels)

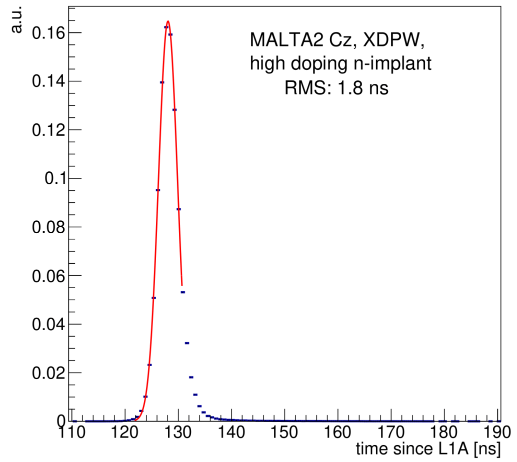
BIT #	ID
0	Reference
1-16	Pixel Address
17-21	Group Address
22	Group Parity
23-25	Delay Count
26-33	Double Column ID
34-35	Bunch Crossing ID
36-39	Chip ID



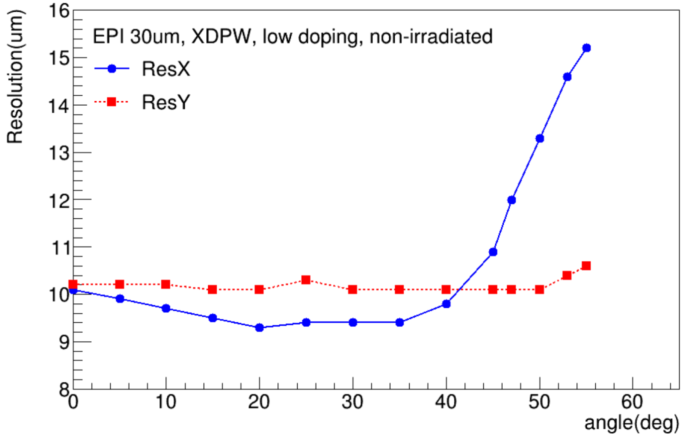
MALTA2. Five years of continuous characterization

- Timing response < 2ns rms — G. Gustavino et al., JINST C03011
- Position resolution ~ 10 µm (improved by inclination) — V. Berlea et al., J.NIMA.2024.169262
- Low threshold (~150 e^-) and noise chip operation — V. Berlea et al., IEEE TNS 2023.3313721
- High data rate (>100 Mhz/cm^2) — F. Piro et al., IEEE TNS 19222311
- Radiation hardness up to 3 x 10^{15} n_{eq}/cm^2 — M. van Rijnbach et al., 2308.13231

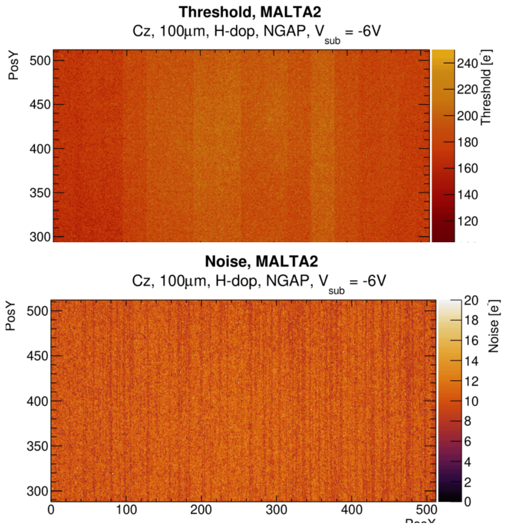
Time resolution



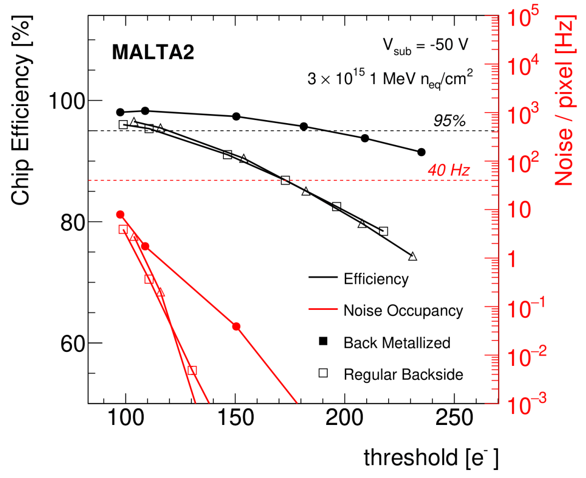
Position resolution



Low noise & threshold

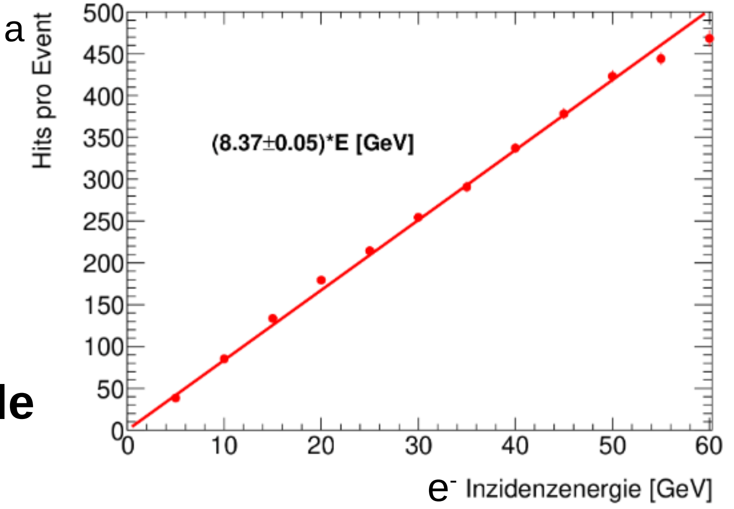


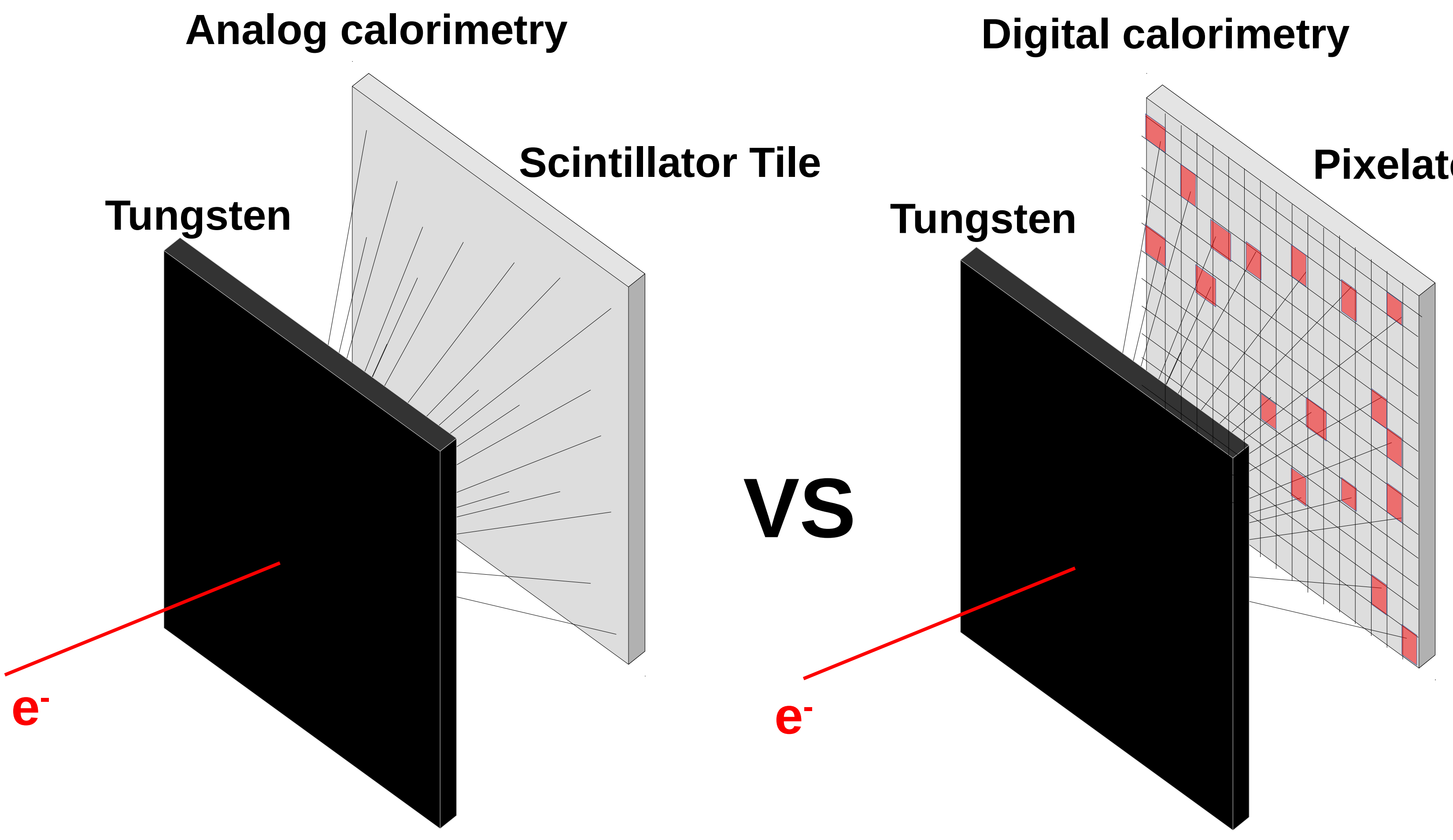
High eff after irradiation



Towards digital EM calorimetry

ALLPIX2 simulation of a single MALTA plane + Tungsten
Colin Zemkus Bsc Thesis





Reconstructed Energy ~
Σ of all absorbed energy

Reconstructed Energy ~
\# of detected hits

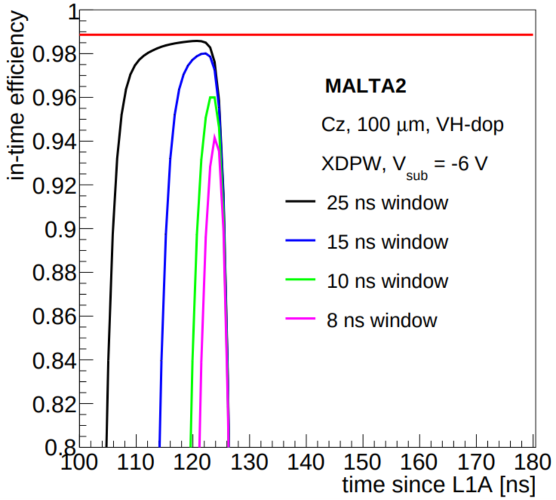
Digital calorimetry:

- No en. deposit fluctuation
- Better energy resolution
- Implementation via MAPS

Digital calorimetry with binary trackers

What we get for free with MAPS

- High granularity (36.4 μm^2 pitch)
- In time efficiency to improve pile-up
- Low threshold, noise operation
- Low power dissipation
- Demonstrated radiation hardness + path to improve
- **Two-in-one solution**: tracking + calorimetry



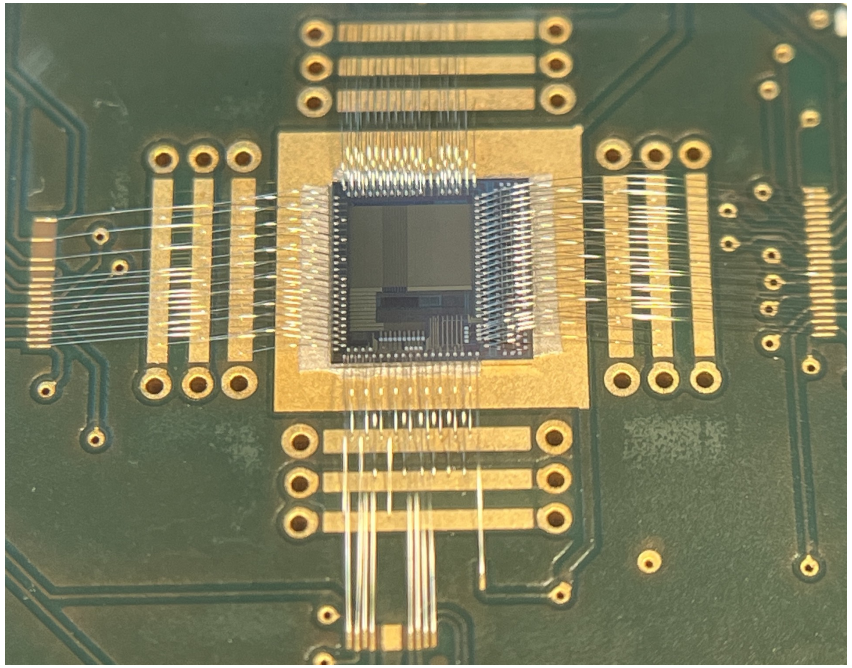
What we need to work on

- Optimized read-out
  - Robust word merging of 1000s of instantaneous shower components
  - On chip time-tagging
- Optimized pixel group size for tracking vs calorimetry optimization
- Data rate
- Expand from binary tracking (e.g. multi thr. sampling)

MALTA (near) future

MALTA3 soon to be tested!

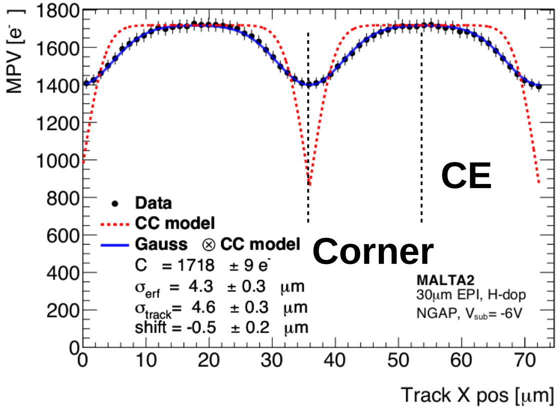
- Introduces on-chip time tagging
- Improved time resolution (expected: ~ 1ns)
- On-chip synchronization memory 1.28 GHz clock
- Improved hit merging

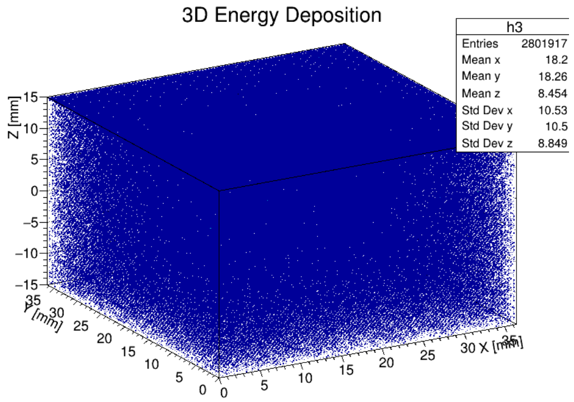


65 nm TPSCo MALTA redesign

- DRD3 proposal key requirements:
  - 1 Ghz/cm^2 readout architecture
  - Chip reconfigurability
  - Low power dissipation
- Tracking and calorimetry applications requirements
- **Simulation work under way**

Data driven parametrization + GEANT4 energy deposition





Thank you

Back up

TCAD usual implementation

Usual MAPS work flow

First principles
TCAD simulations
(doping concentrations
implant sizes
annealing temp ...)

→ Electric field distribution →

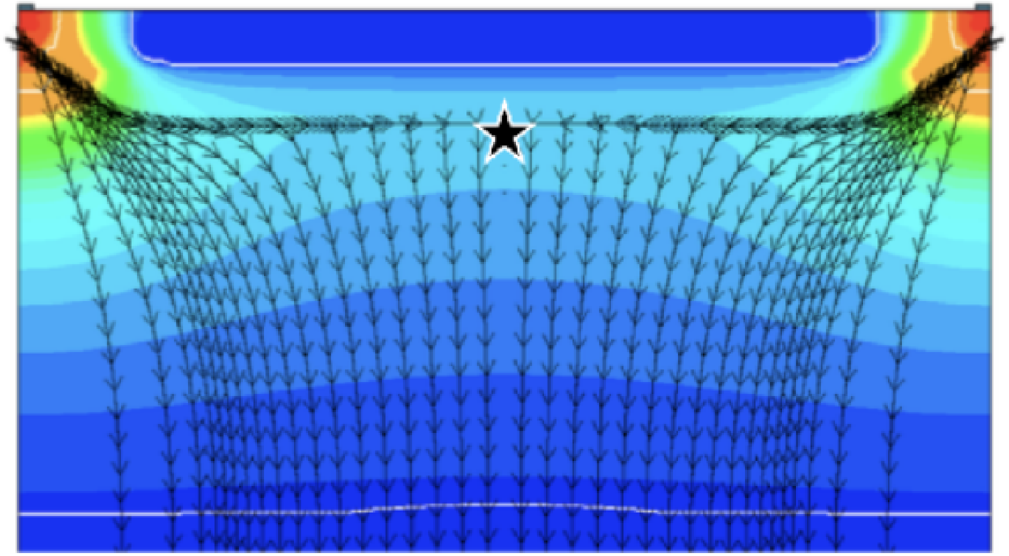
Digitizer
E.g. ALLPIX2
Performs charge propagation

→ Results →

Data
That can be checked against test beam results

Complication of TCAD simulations

- ✖ Unfortunately no access to all manufacture information
- ✖ Very time consuming (implementation + simulation time)
- ✖ Need to find a way around detailed TCAD simulations!
- ✖ MAPS design complexity! Inaccurate to simplify el. fields
- ✔ A wealth of experimental data can aid us in simulation work.

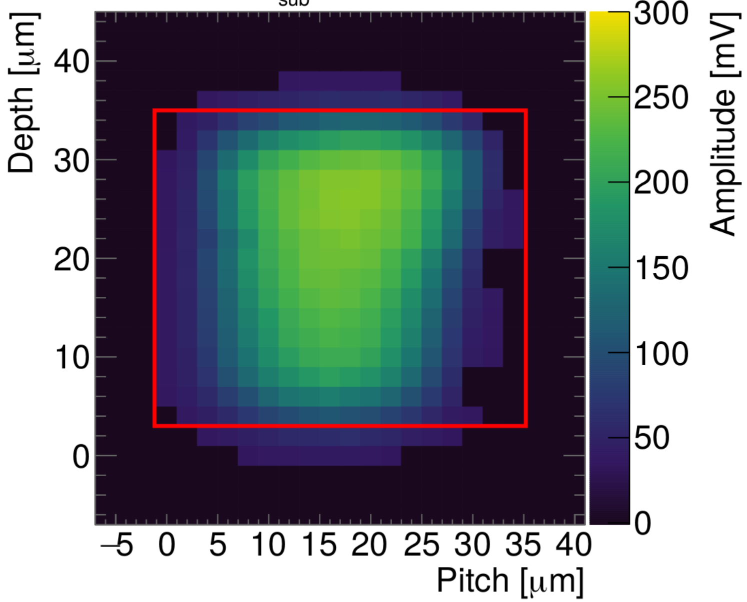


https://repository.cern/records/m44wa-jks69

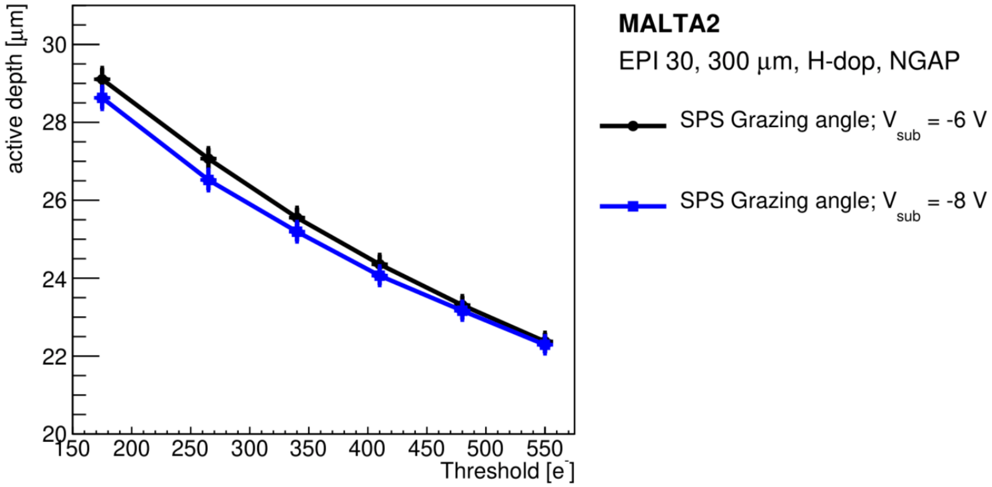
Measurements of in-pixel charge collection

- Fundamental pixel properties characterization has been a focus of the MALTA2 DESY group
- A good understanding of pixel properties proportional to the electric field

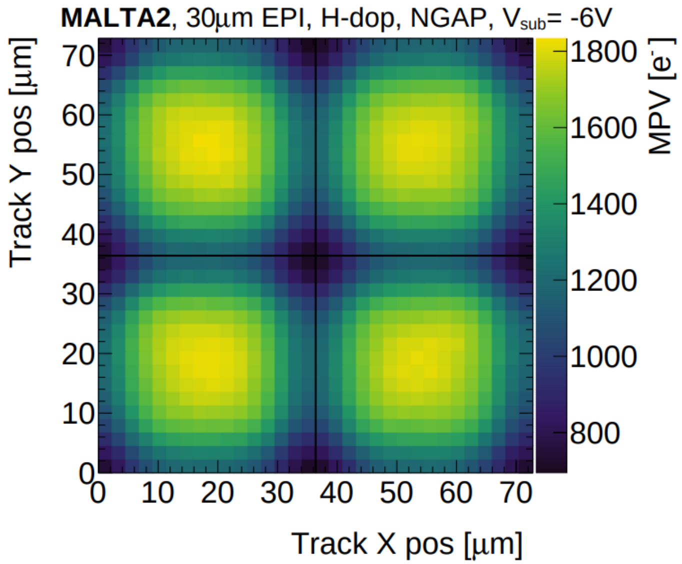
E-TCT (edge view)



Test Beam Grazing angle (averaged depth)



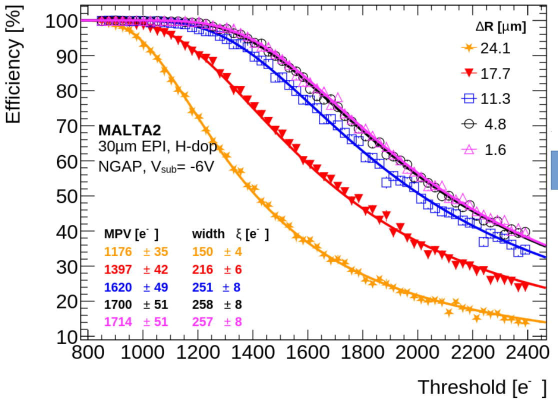
Digital MPV measurements (top view)

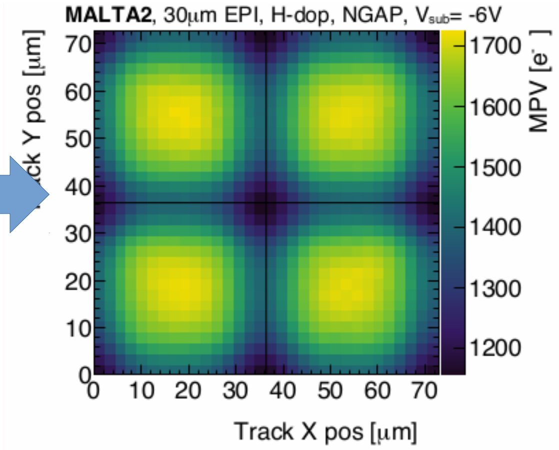


https://doi.org/10.1016/j.nima.2024.169262

Simulation workflow with the MPV data set

1. Derive the MPV





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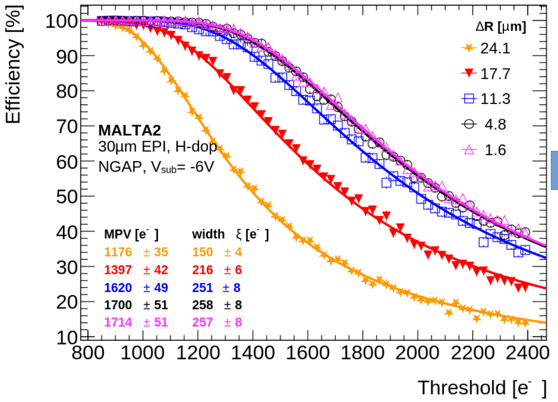
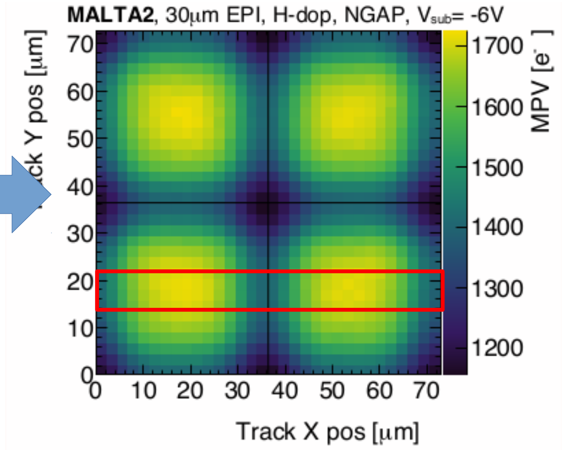
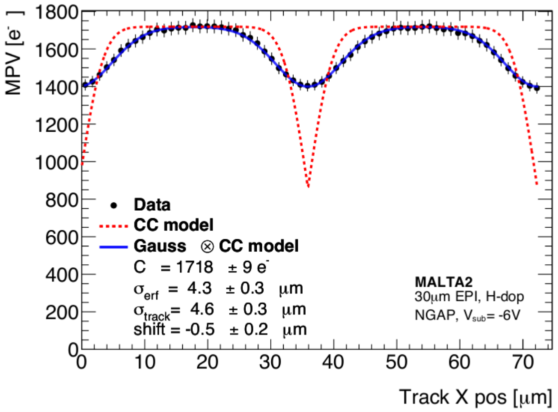
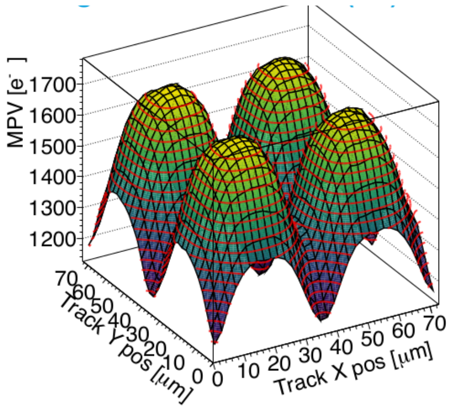




2. Derive analytical data parametrization





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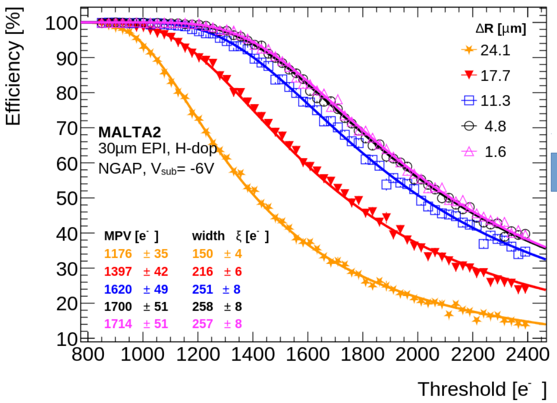

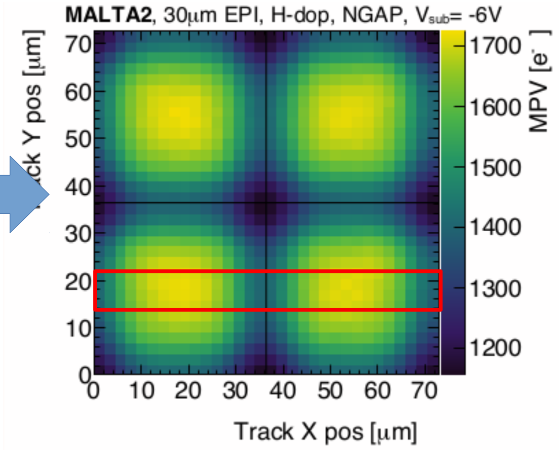

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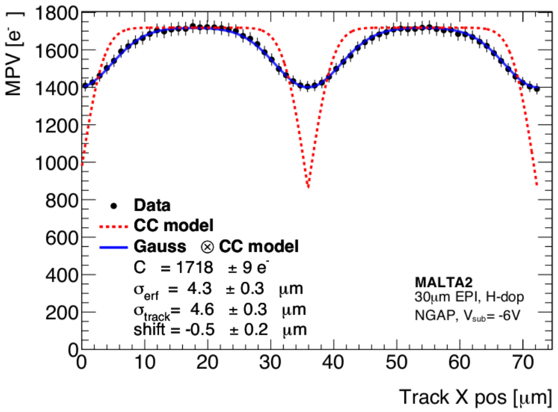
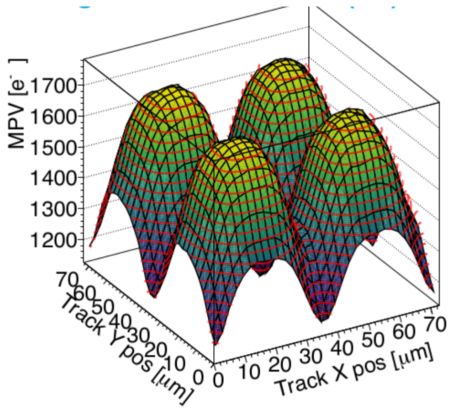
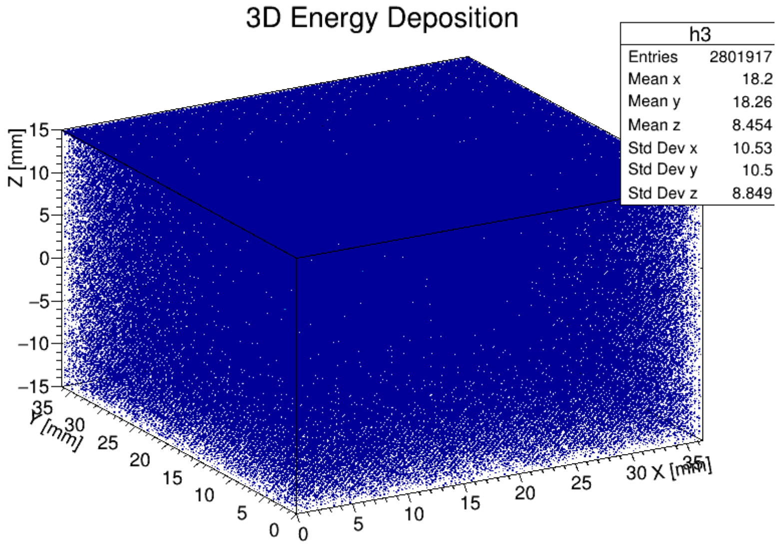




3. GEANT4 Si energy deposition



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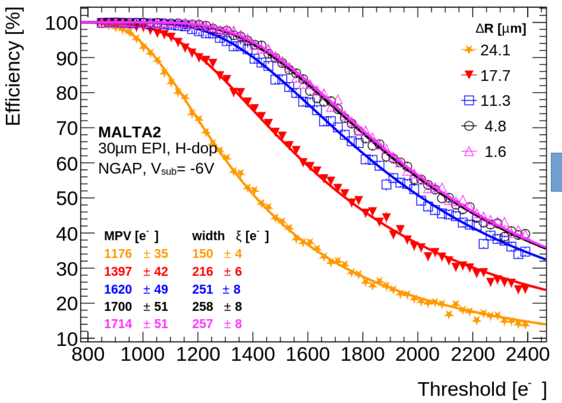
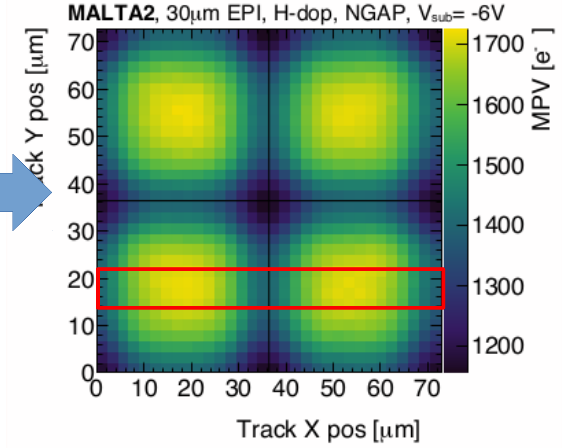
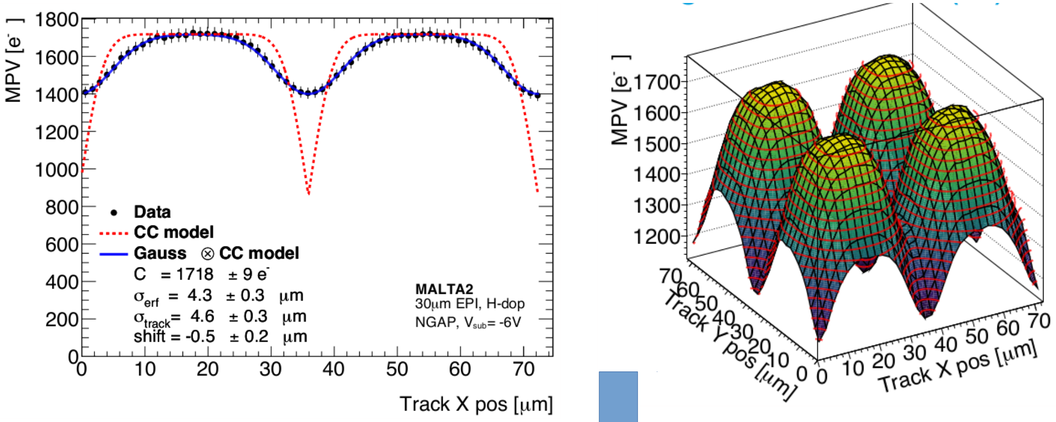




2. Derive analytical data parametrisation



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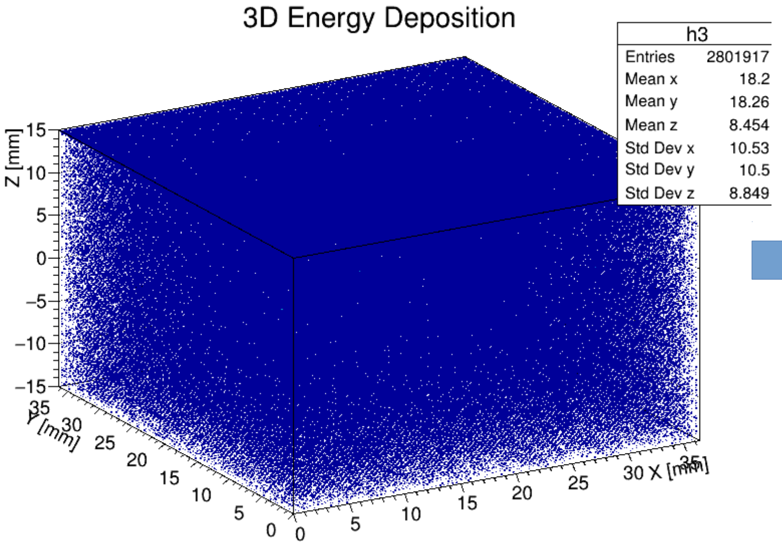
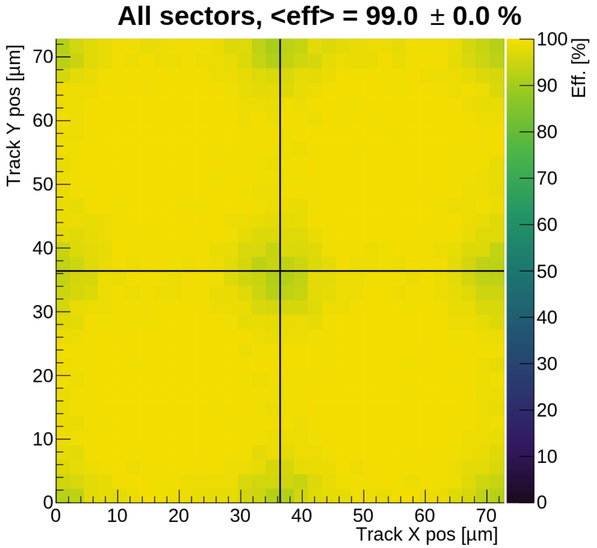
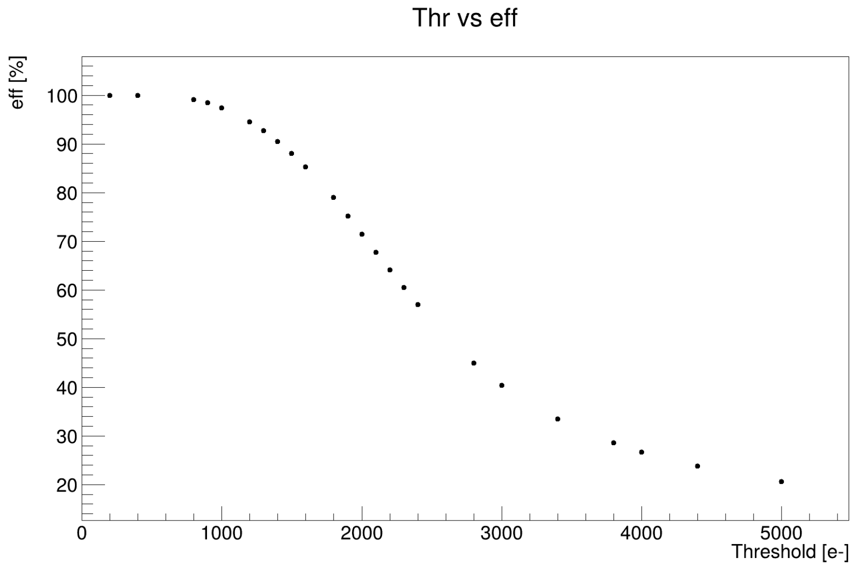


4. Validation against data



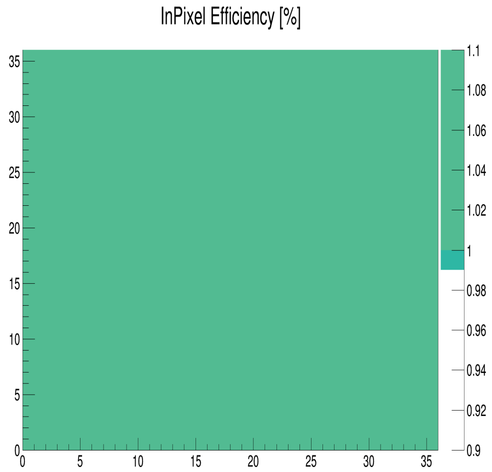
Preliminary reconstructed in-pixel efficiency

- Qualitative match between data and simulation
- Still to be implemented:
  - Digital FE simulation
  - Realistic tracking smearing
  - Stochastic charge trapping

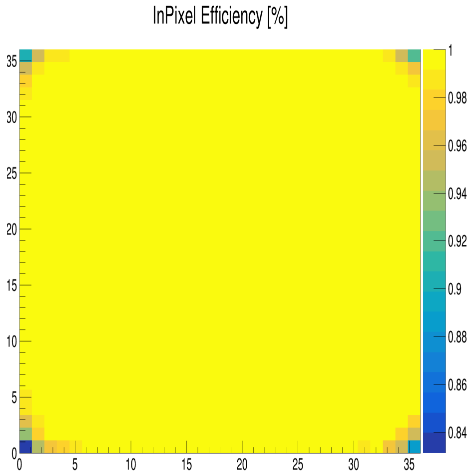


Work in Progress. Preliminary Results!

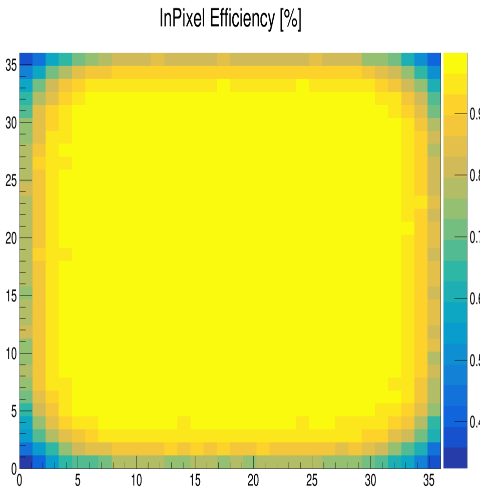
200 el threshold



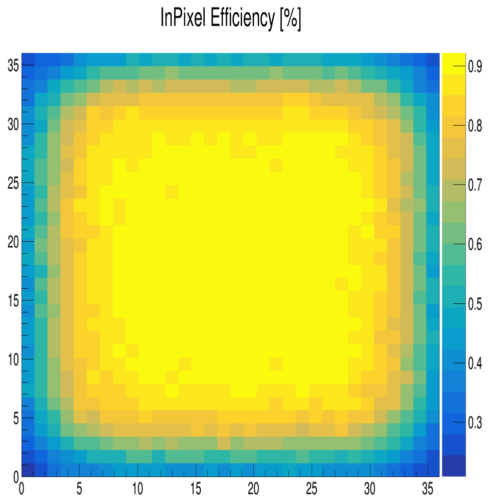
600 el threshold



1200 el threshold



1800 el threshold



Conclusions and outlook

Next steps

- Continue working on the realism of the simulation
- Quantitative data – simulation comparison
- Introduce more data sets for further validation
- Goal: calorimetry simulation → optimization of sensor properties

Physics case

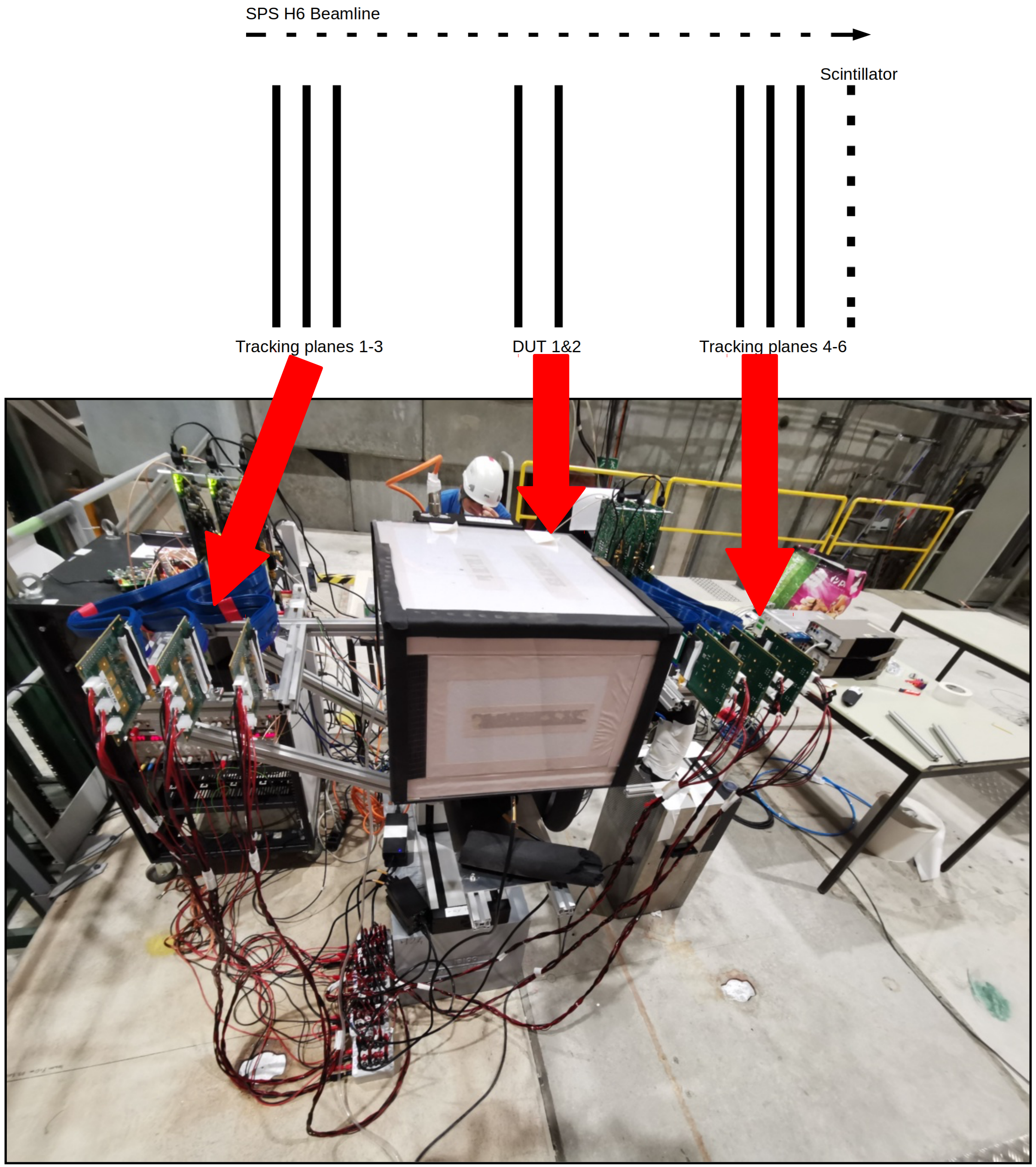
- Investigating possible physics cases
- Forward physics applications (compact, lightweight LHC experiments)
- Low energy applications: LUXE
- Looking for possible collaborations!

MALTA SPS Telescope

- **Malta Telescope** operated the whole of 2021 at CERN SPS H6 beamline. So far so good for 2022!

- **2021/22 SPS Test beam** Goals for MALTA2:
  - MALTA 2 performance
  - Radiation tolerance
  - Timing performance

- **Six MALTA tracking planes** (2x Cz, 4 Epi), Scintillator and Cold Box with capacity for up to 2 DUTs



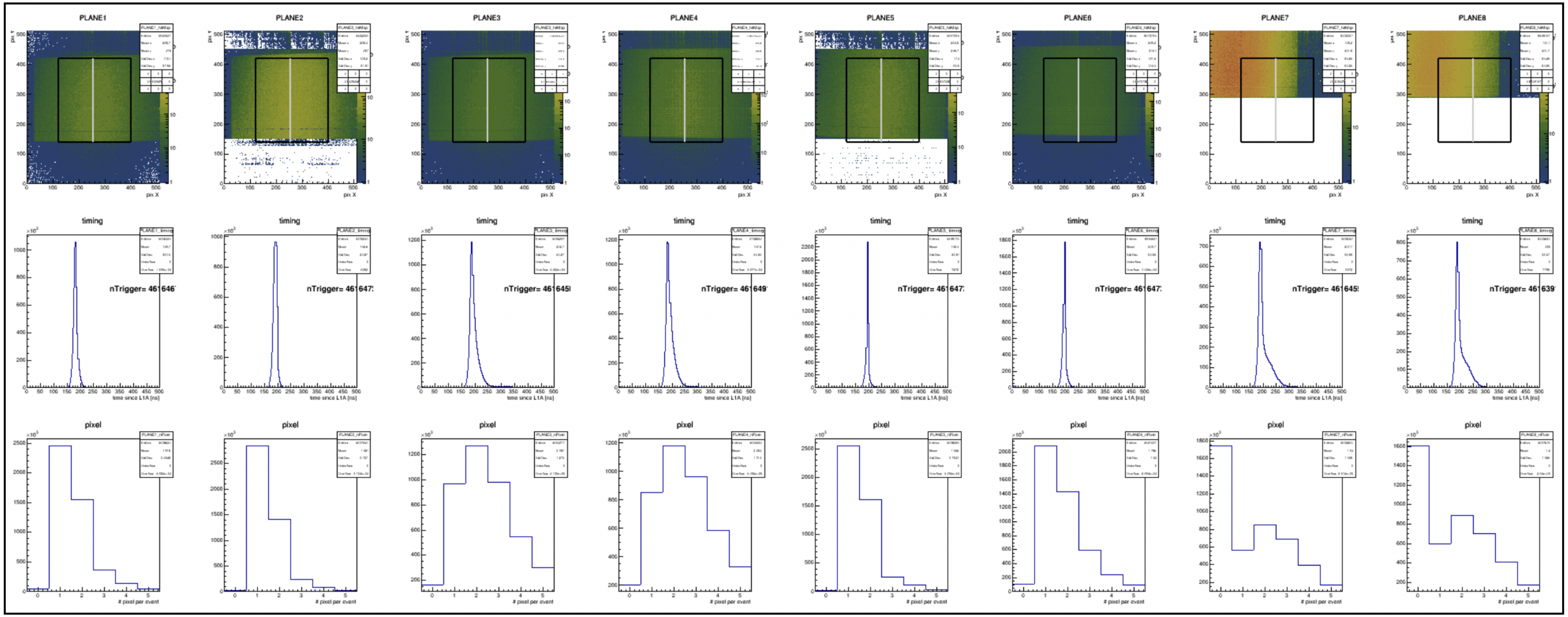
SPS Testbeam Monitoring plots

DUT 1 DUT 2

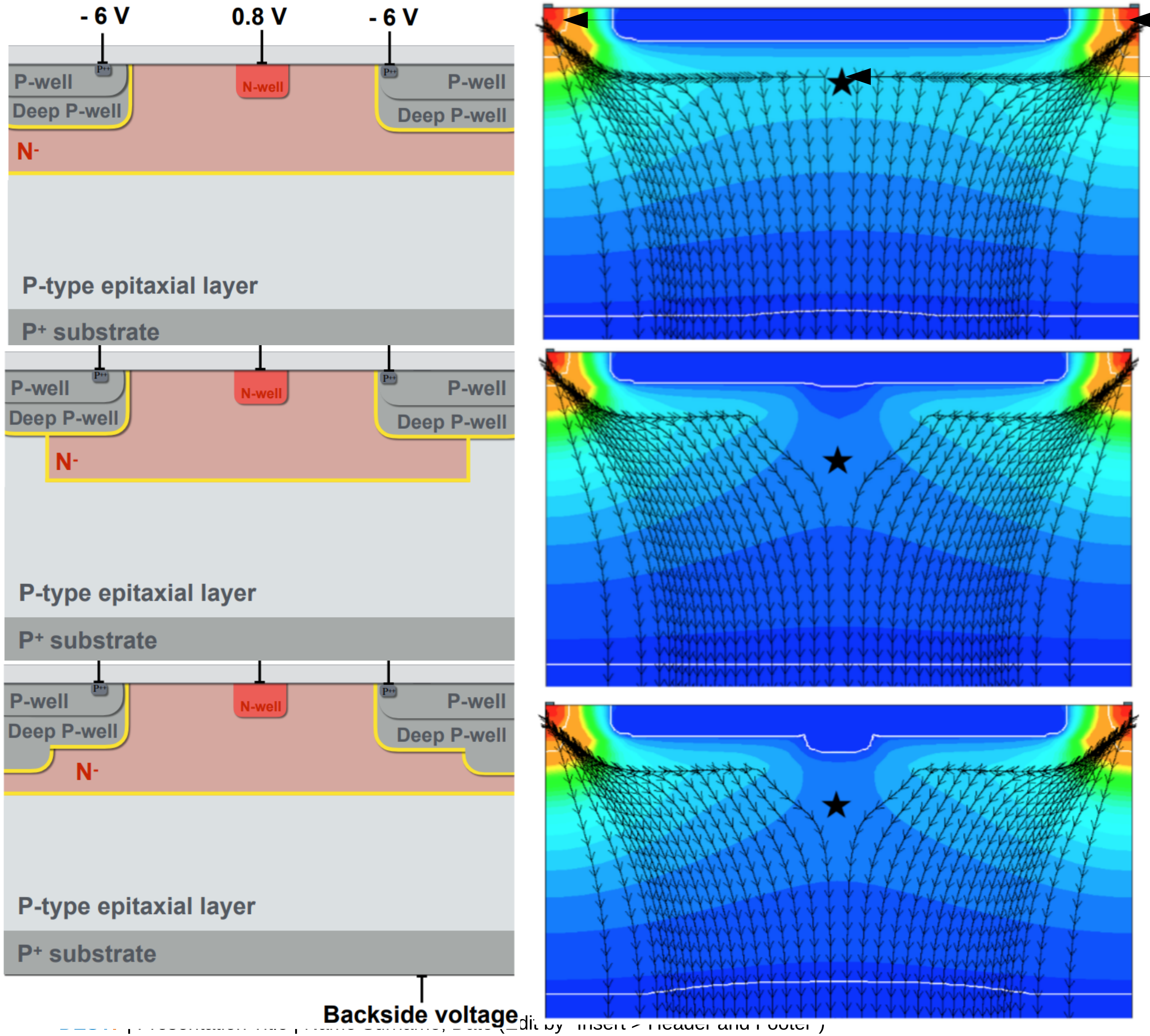
Hitmap

Time since L1A

#pixel/ event



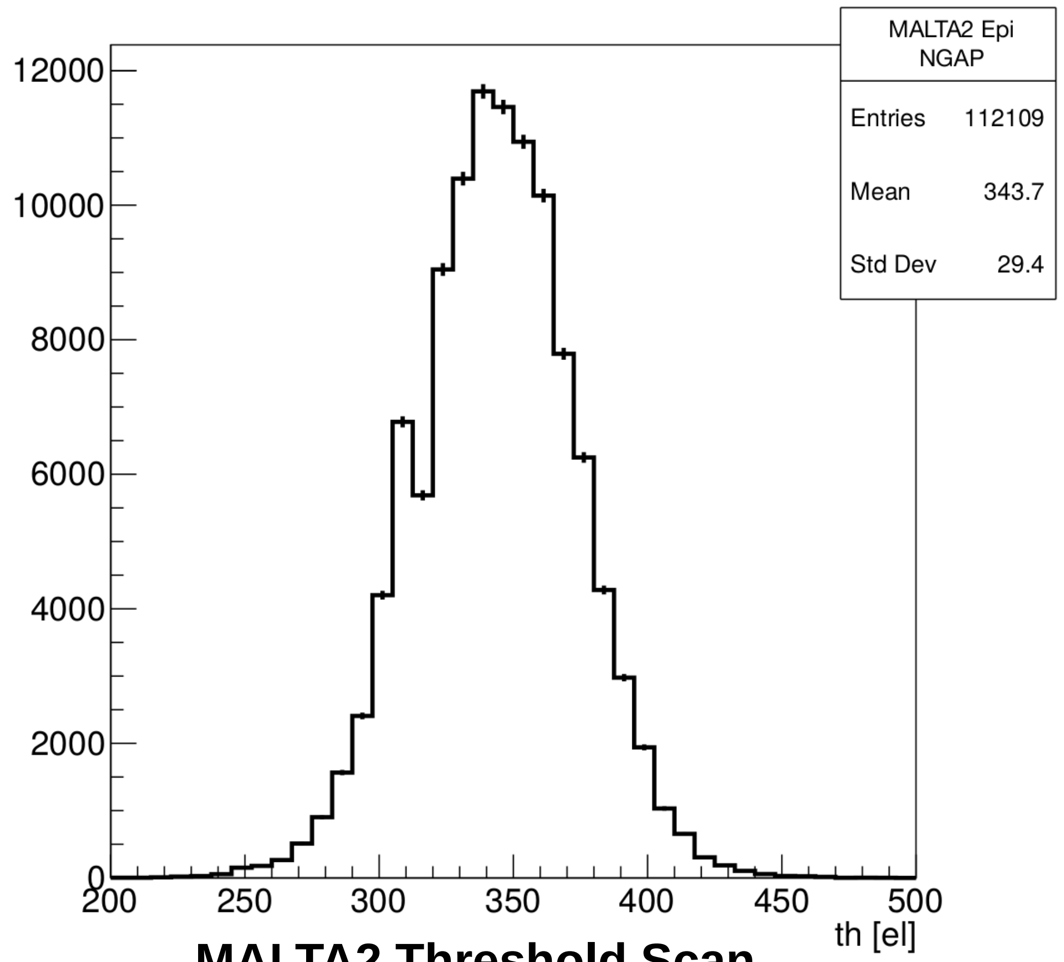
- **DAQ** with **online monitoring** (hit map, time distribution, number of hits per-event)
- **Fast track reconstruction** due to low noise/ occupancy (~1.2 hits/plane/event)



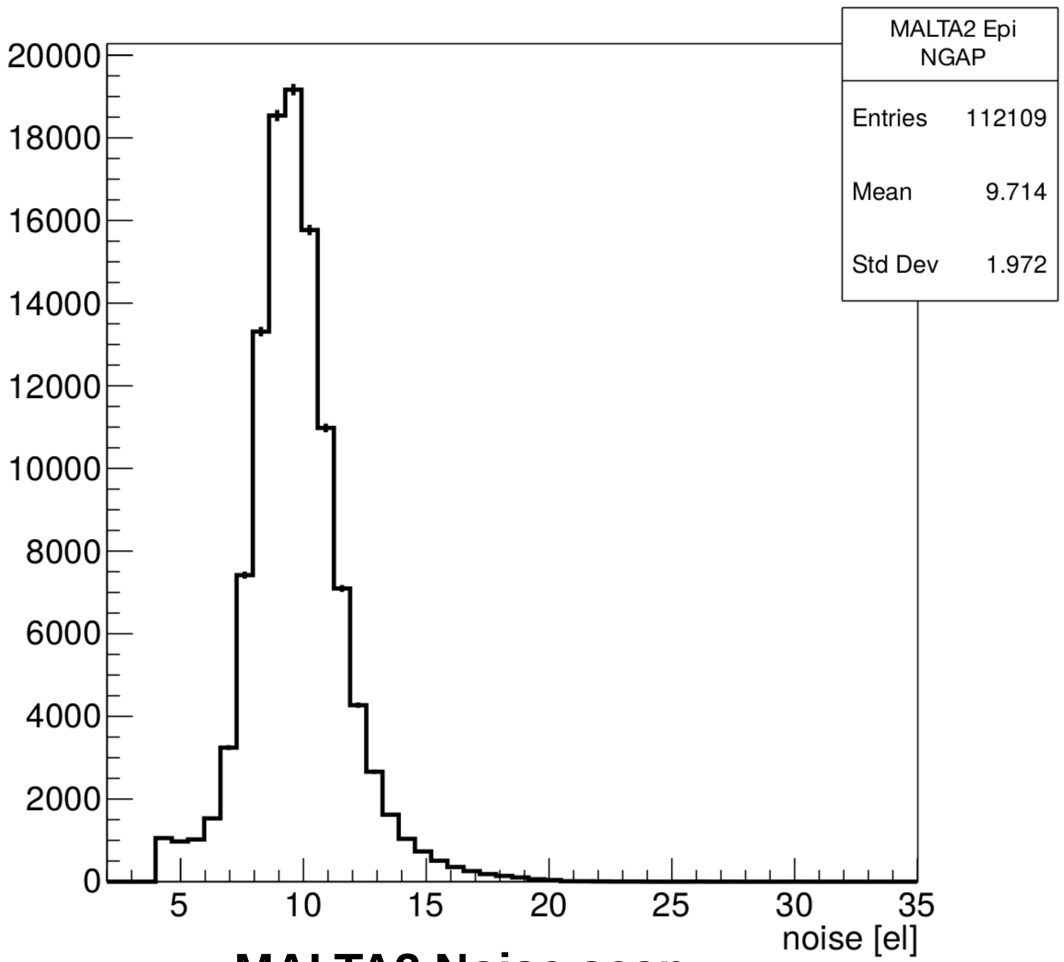
Electrostatic potential + el. field lines

- Electric field minimum achieved at the pixel corners → charge collection eff. drop expected in the corners
- Lateral electric field causes charge to be pushed towards the electric field minimum
- Purpose of process modification towards NGAP and XDPW → enhanced lateral field, moving charge away from the field minimum at the pixel corner → higher collection eff.

MALTA2 threshold and noise scans

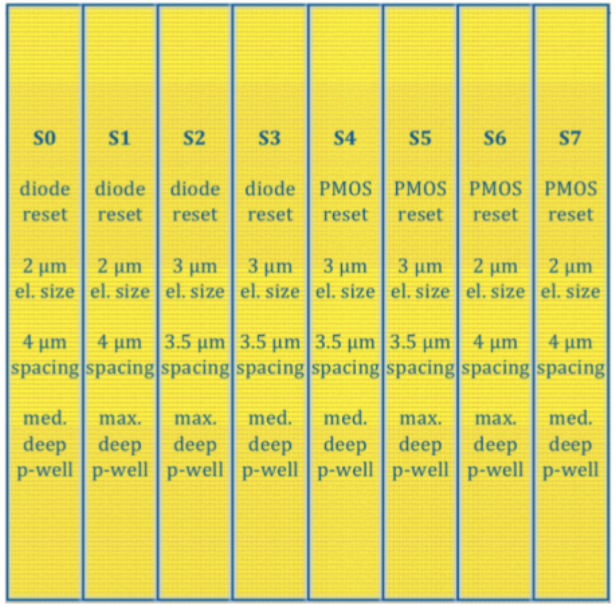


MALTA2 Threshold Scan



MALTA2 Noise scan

- Threshold dispersion ~10% of the mean
- Low noise (+very low noise tail)



MALTA sectors

Sector	Reset	Electrode size [um]	Spacing	P-well depth
0	Diode	2	4	medium
1	Diode	2	4	maximum
2	Diode	3	3.5	maximum
3	Diode	3	3.5	medium
4	PMOS	3	3.5	medium
5	PMOS	3	3.5	maximum
6	PMOS	2	4	maximum
7	PMOS	2	4	medium

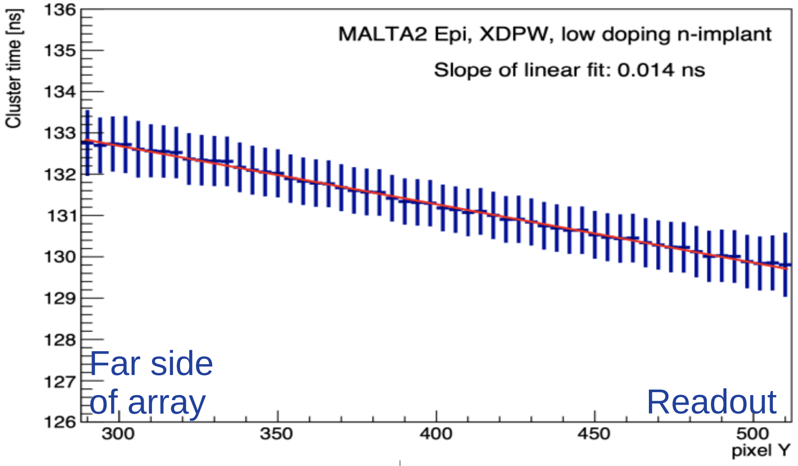
MALTA sectors

MALTA2 Timing

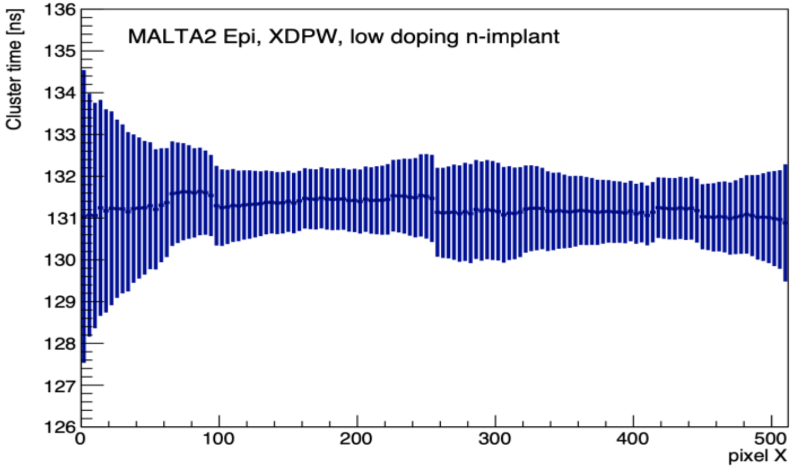
Time of arrival of the fastest hit in a matched cluster w.r.t scintillator reference, as a function of the matrix X/Y coordinate

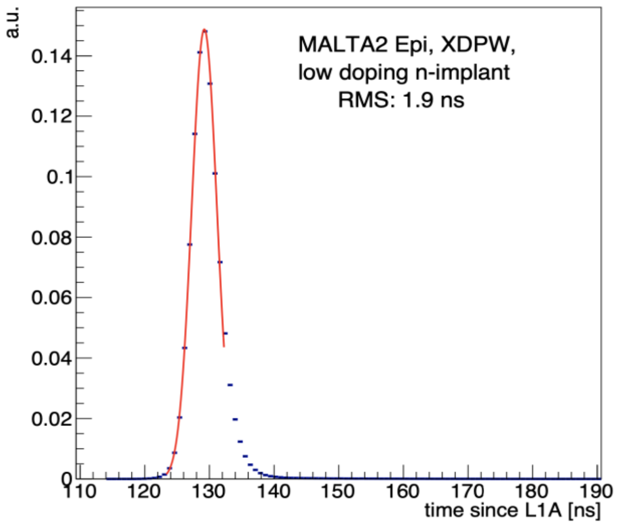
- **Timing corrections**:
  - **(Y)** Linear due to column time propagation (**top**)
  - **(X)** Non-uniform chip response in the row direction (**bottom**)

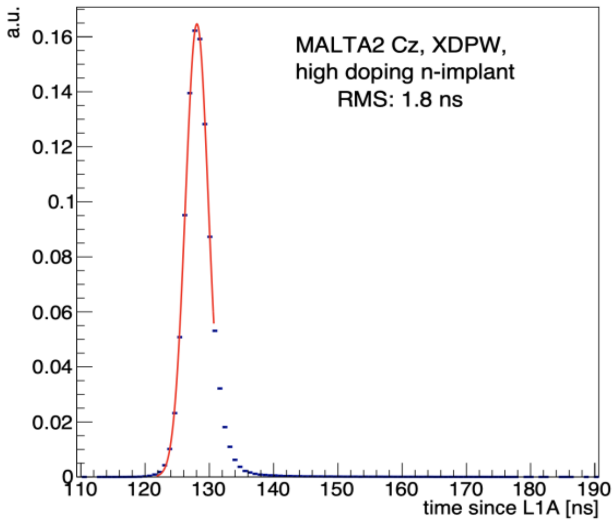
- The **timing plots** are a convolution of:
  - Electronics jitter
  - Time-walk
  - Charge collection effects
  - Scintillator jitter (500ps)
  - FPGA readout jitter (900ps)



Apply corrections







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