APTS Measurements and Results

Setup, Reconstruction and Results

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Vertex Detector Discussion Meeting

DESY, Hamburg, May 2024

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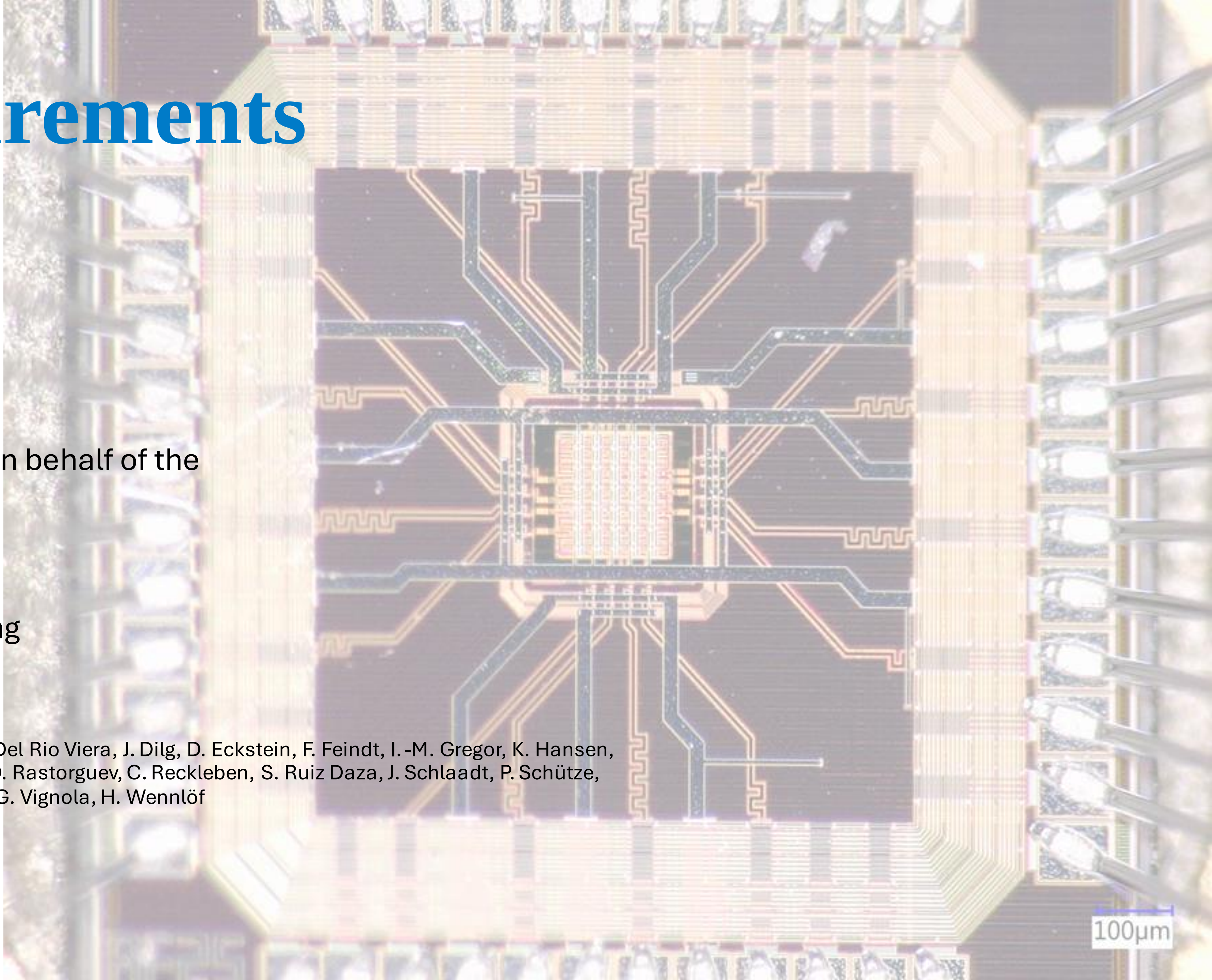
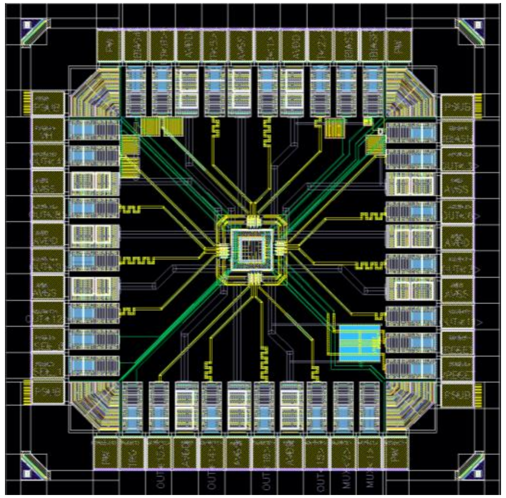


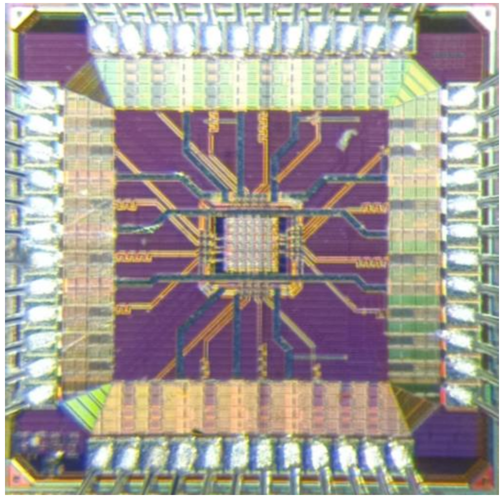
HELMHOLTZ

Sensors in MLR1 production

Analogue Pixel Test Structures (APTS)



ASIC Design



Prototype

- Designed at **CERN** (**DESY** involved in the lab and TB characterization)
- 4x4 pixels structure with analogue output
- Different sensor pitches from 10 µm to **25 µm**
- Different sensor layouts: **Standard**, Modified and **N-Gap**
- Two versions of the output buffer
  - The focus of this talk will be on the **Source Follower** version.

CERN EP R&D ALICE

Objective:

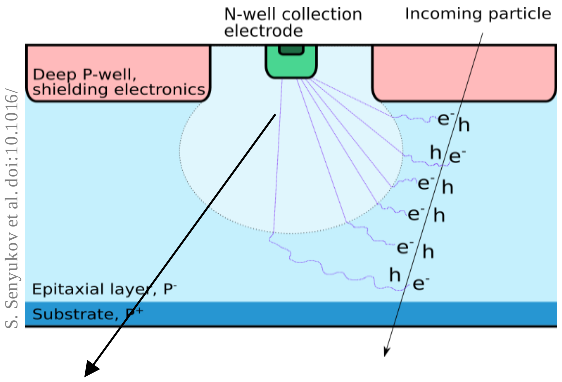
- Study the sensor layout physics
- Obtain data samples during test beam and lab measurements
- Calibration studies so simulations can be compared with data

Electric field in thin silicon sensors

Designs

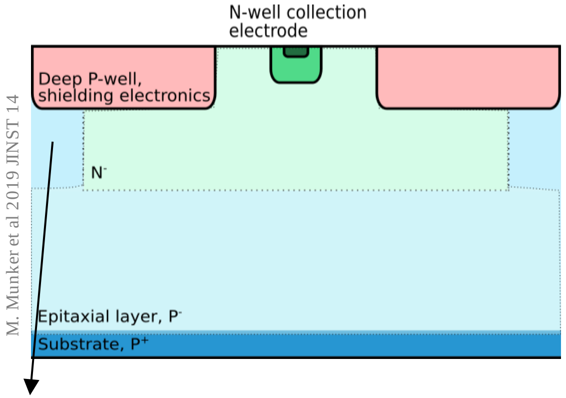
Layout geometry

Standard



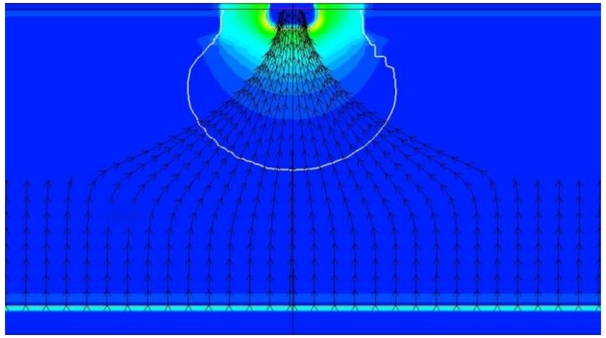
Drift predominates inside depleted region and **diffusion** outside

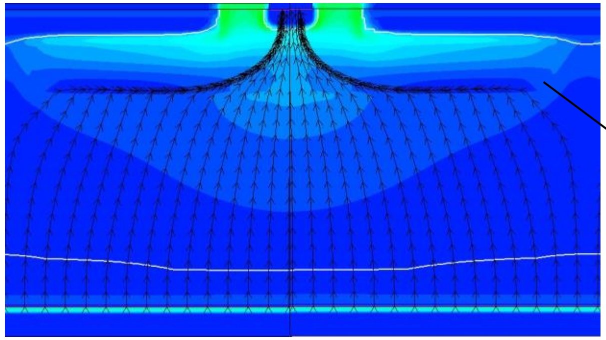
N-Gap



Gap in Continuous N-type Implant
Speed up charge collection

Electric Field lines



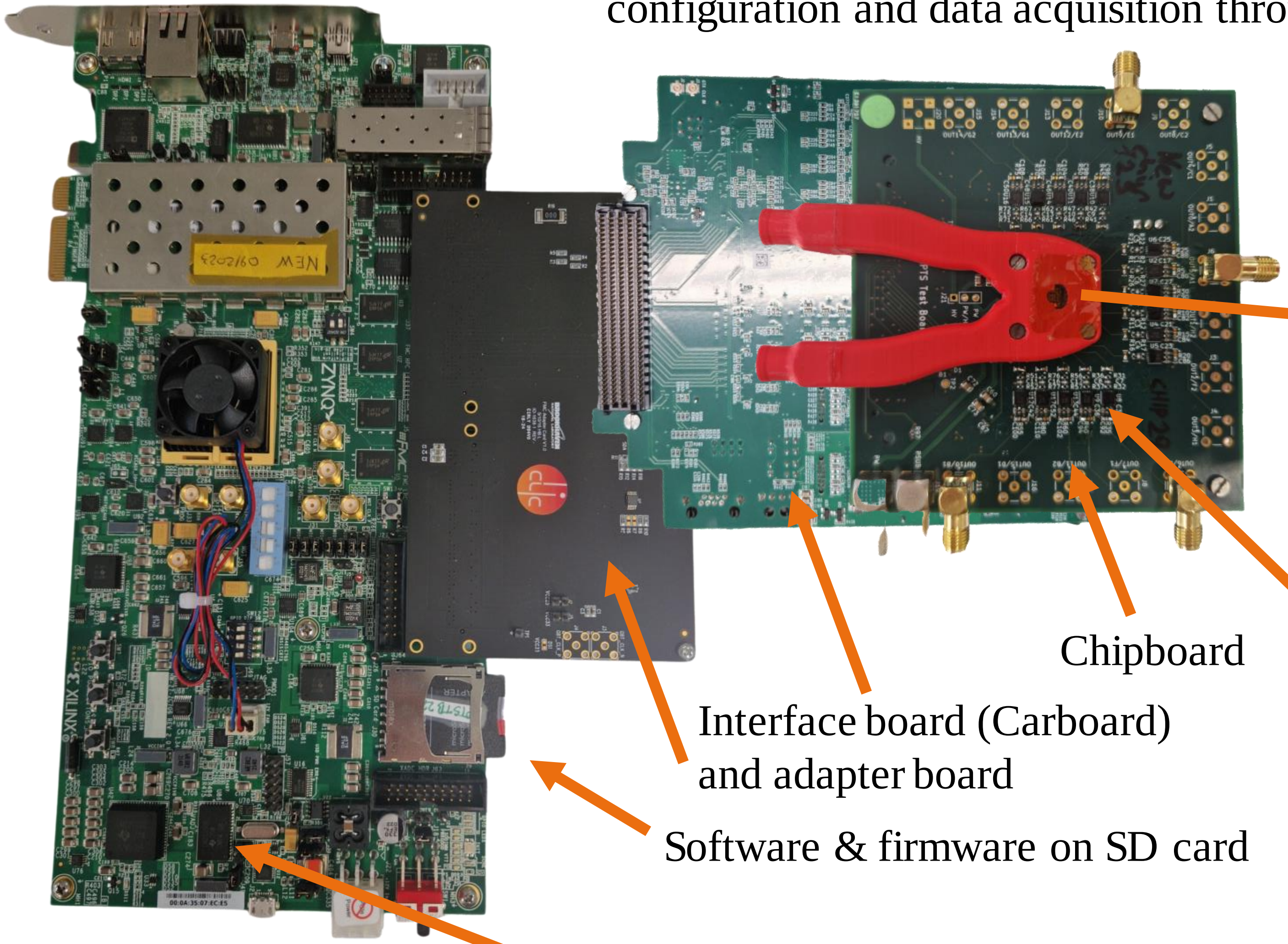


The electrons follow the direction of the **stream lines**

Data Acquisition

Caribou DAQ

The Peary DAQ software framework provides hardware abstraction for periphery components such as voltage regulators and simplifies direct detector configuration and data acquisition through a common interface

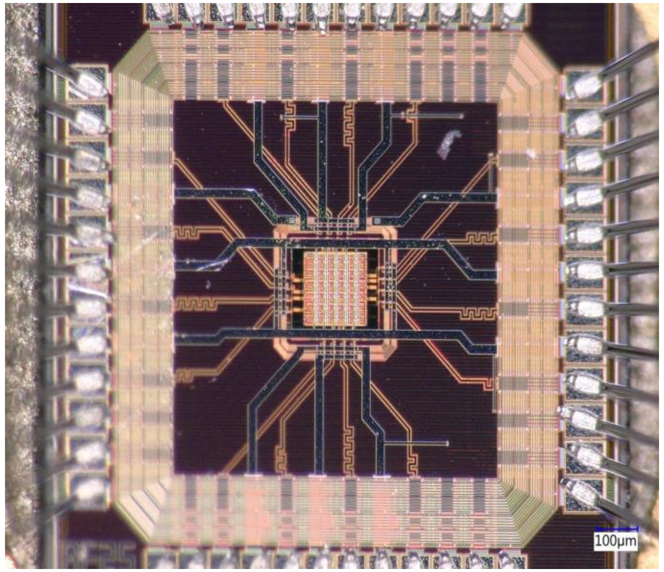


Chipboard

Interface board (Carboard) and adapter board

Software & firmware on SD card

SoC board (ZC706)

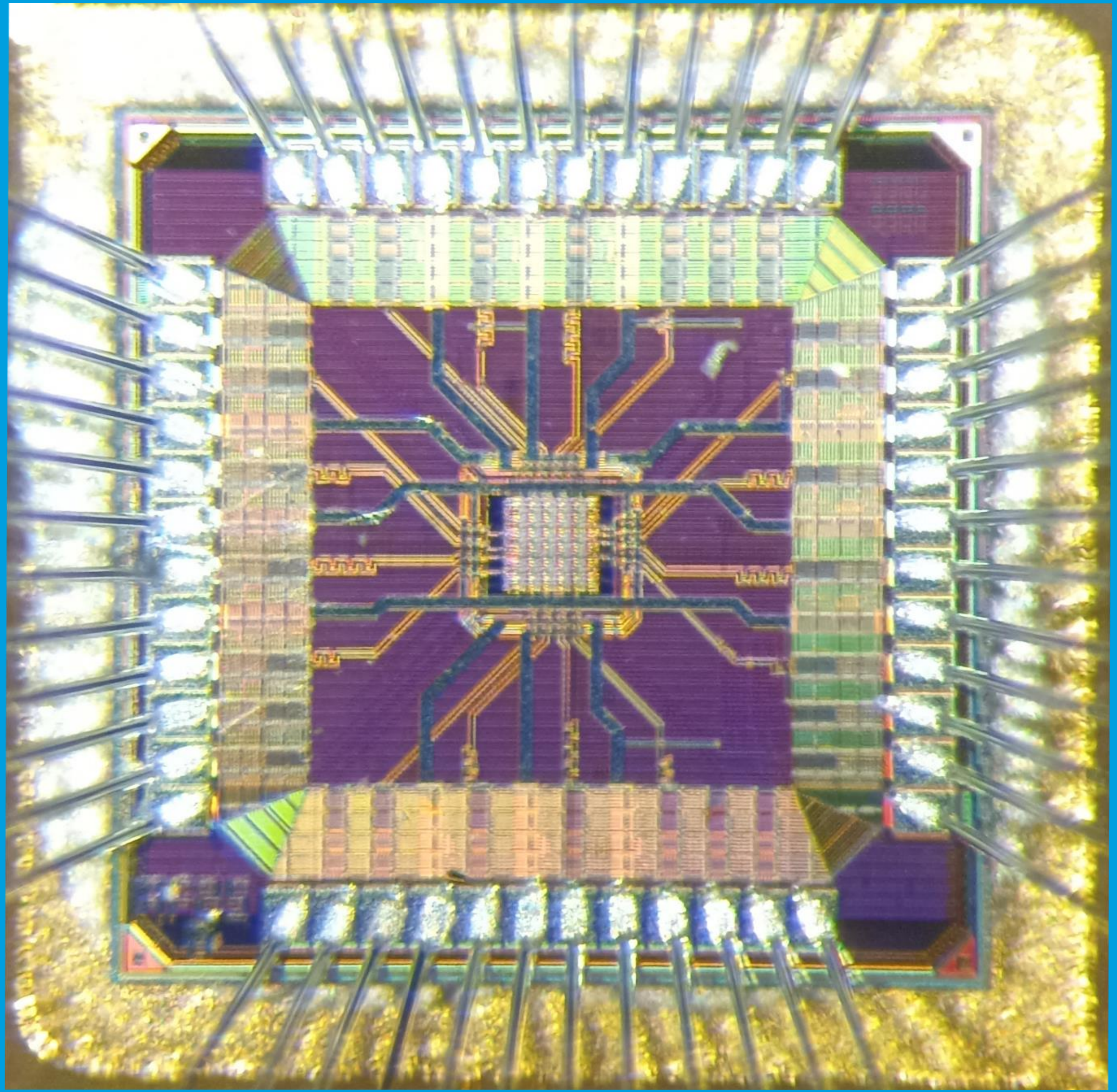


APTS

ADC connected to **each pixel** as output

- Each **pixel** also counts with a **charge injection capacitor** for testing purposes

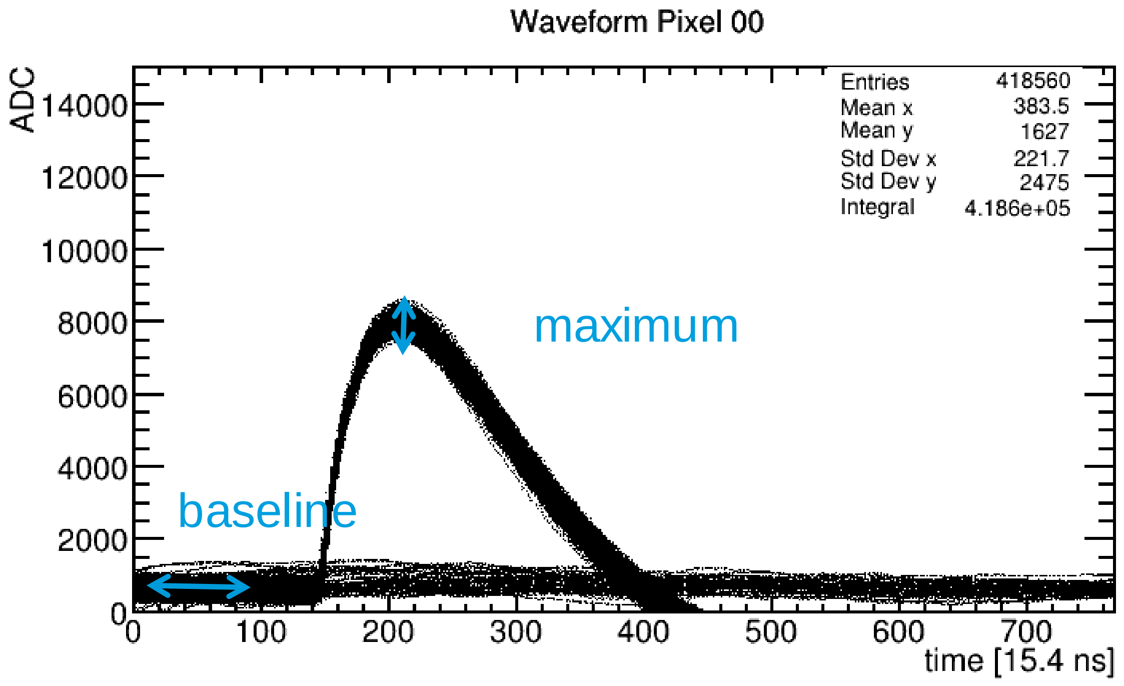
Calibration

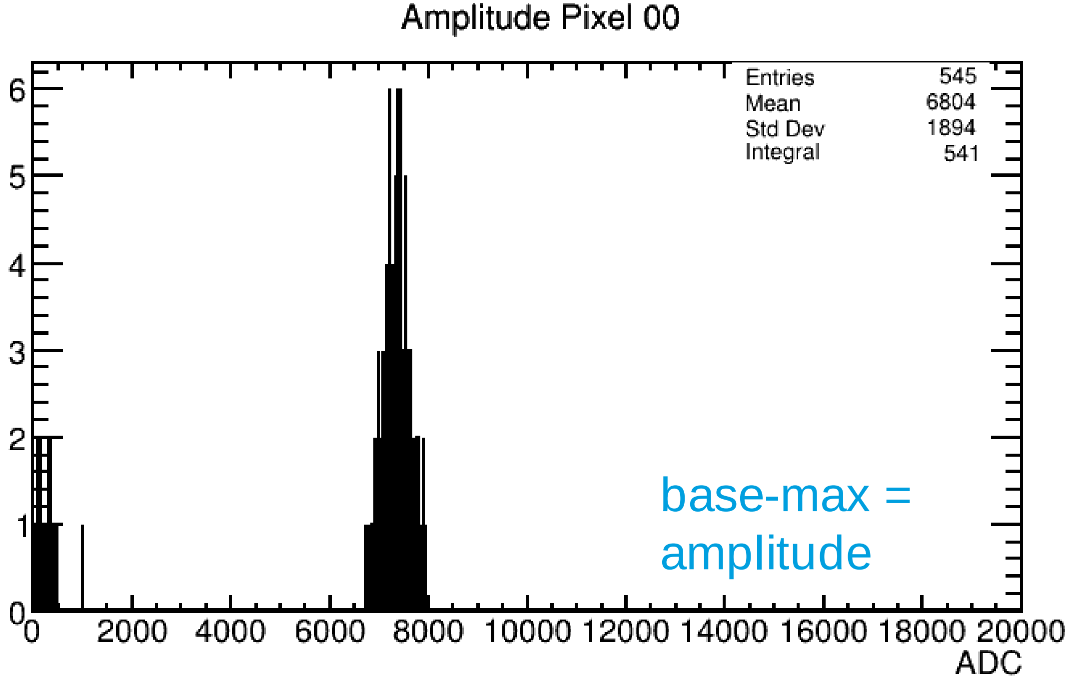


Trigger and Analysis (With amplification)

The key points

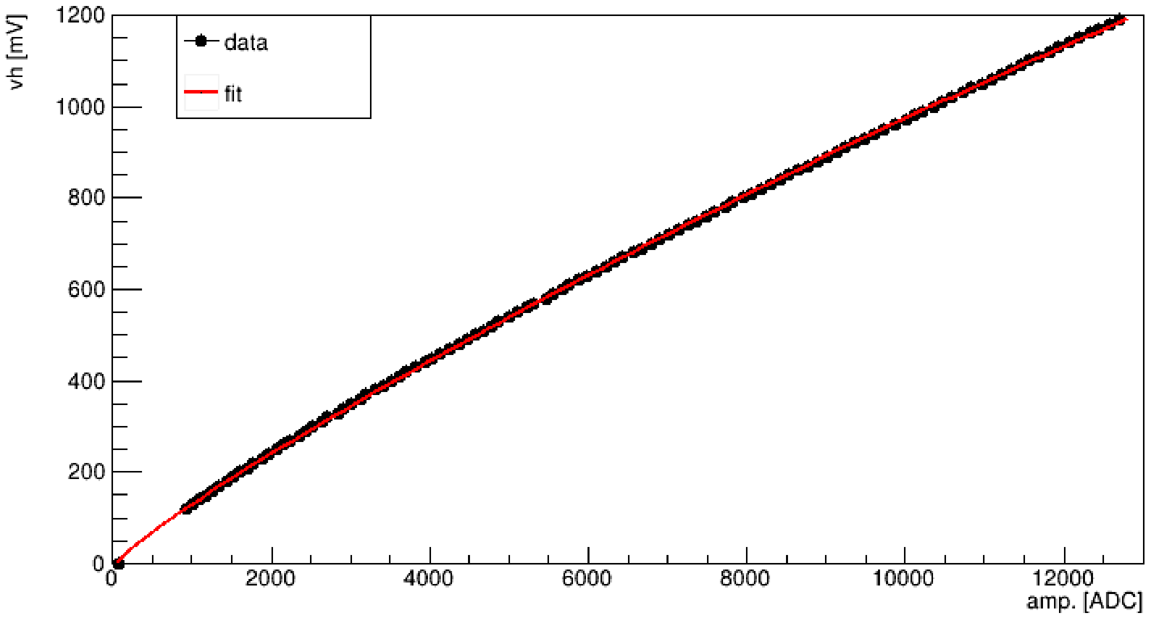
- For each trigger we measure the output waveform of each pixel through the **Caribou ADC**
- **Test beam**: External trigger for efficiency measurements
- **Laboratory**: Self trigger
  - ➢ Needed for source and x-ray measurements
  - ➢ Avoidable for test pulse measurements
- **Pedestal**: Average in the pre-pulse region
- **Pulse height**: Maximum in the peak region
- **Signal amplitude**: Maximum - Pedestal





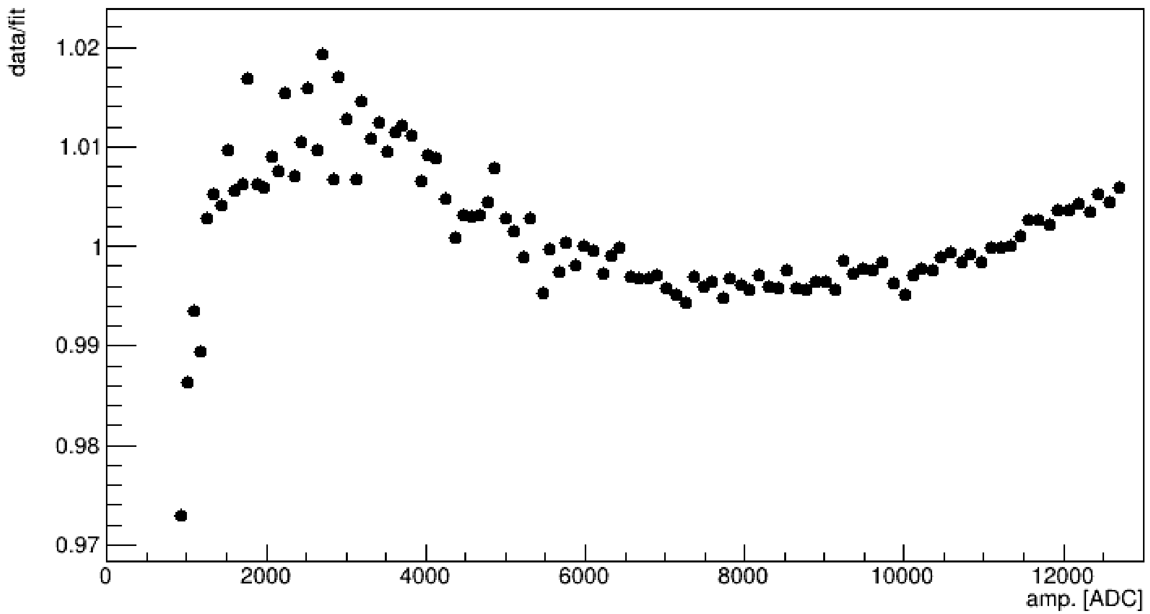
Fitting Gain Curves using test pulses

N-Blanklet, 25x25µm at -3.6 V, pix. [0,0]



- Scan **vh** from 0 to 1200 mV in steps of 10 mV
  - ➢ The parameter **vh** determinates the test pulse **amplitude**
- Triggering on one pixel
- Get amplitude distribution for each vh
- Derive mean in 2σ around peak center
- Fit empiric function

$$\mathbf{vh(x) = (p_0*(x-x_0)+p_1*|x-x_0|^{0.5})*(p_2*x+p_3))}$$

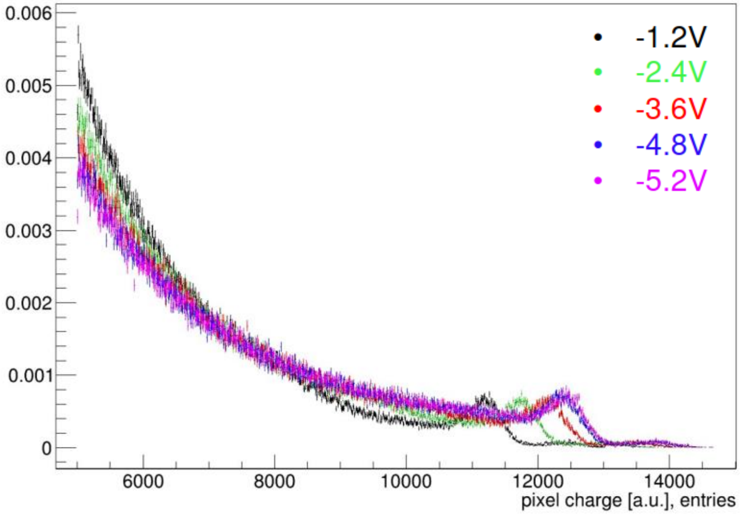


Systematic Measurements with ^{55}Fe

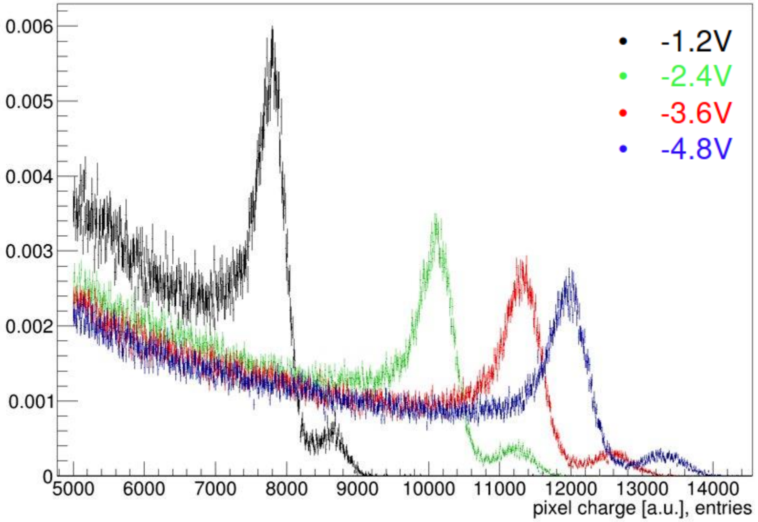
On samples for $V_{sub} = V_{pwell}$

All without calibration, showing only one pixel

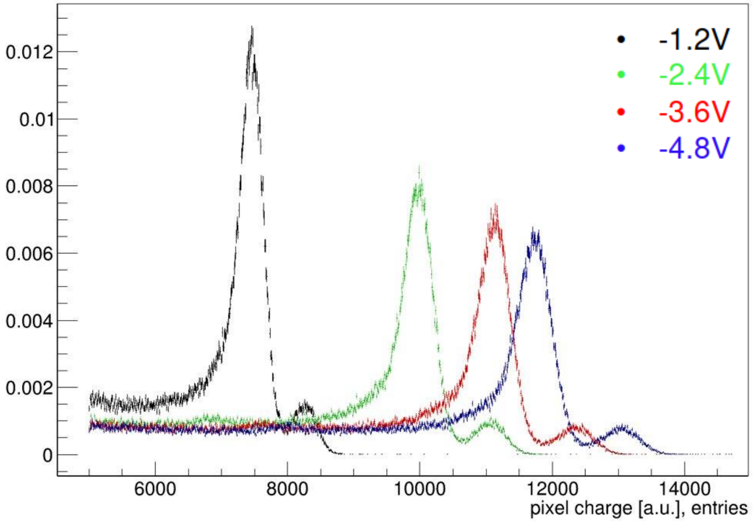
Standard



N-blanket



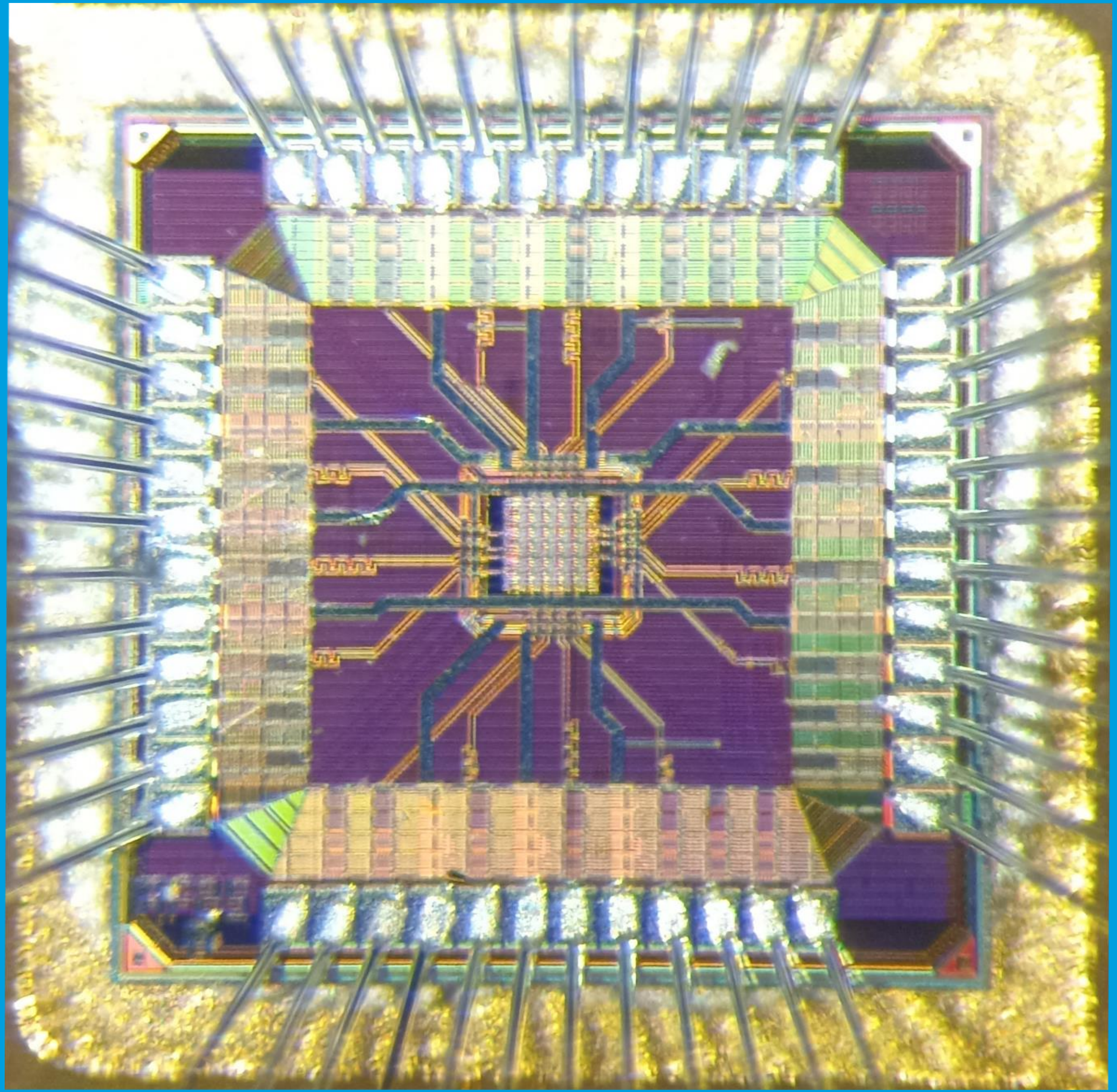
N-gap



- Expecting peak shifts due to change of pixel capacitance.
- Calibration measurements with ^{55}Fe using a Gaussian fit the Kα (~1630e$^-$) and Kβ (~1793e$^-$) peaks

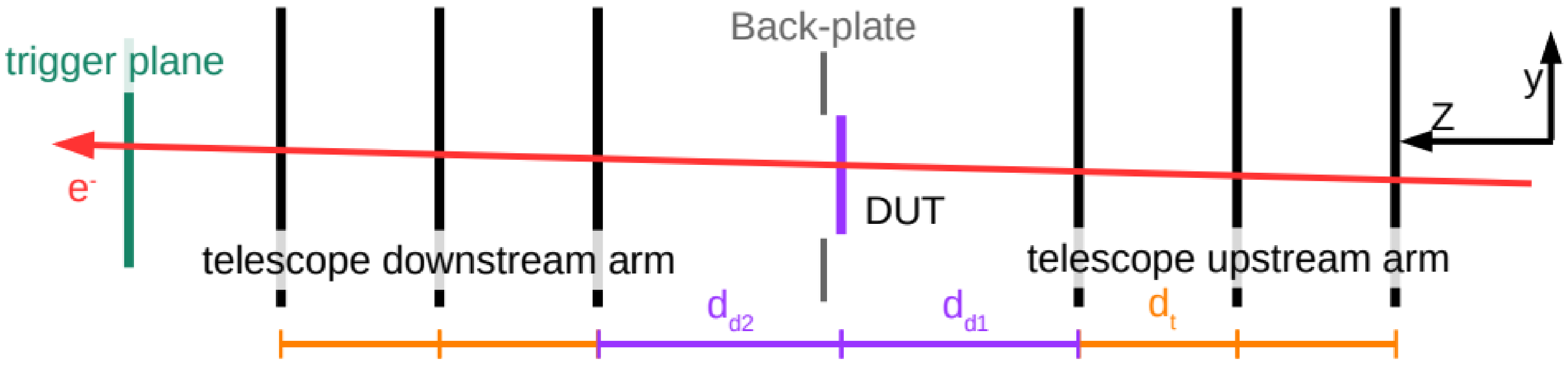
Calibration completed for test beam and simulation comparison

Test Beam Setup



Setup – Overview

Typical Scheme



DESY II Test-Beam Facility

- 6 Weeks, 1 dedicated to pulse-shape studies
- Selected 4 GeV/c as trade-off between rate and momentum (track resolution)

Trigger Plane

- TelePix, trigger area of typically 0.5 x 0.5 mm^2
- Positioned outside of tracking area to minimize negative impact on track resolution

Beam Telescope

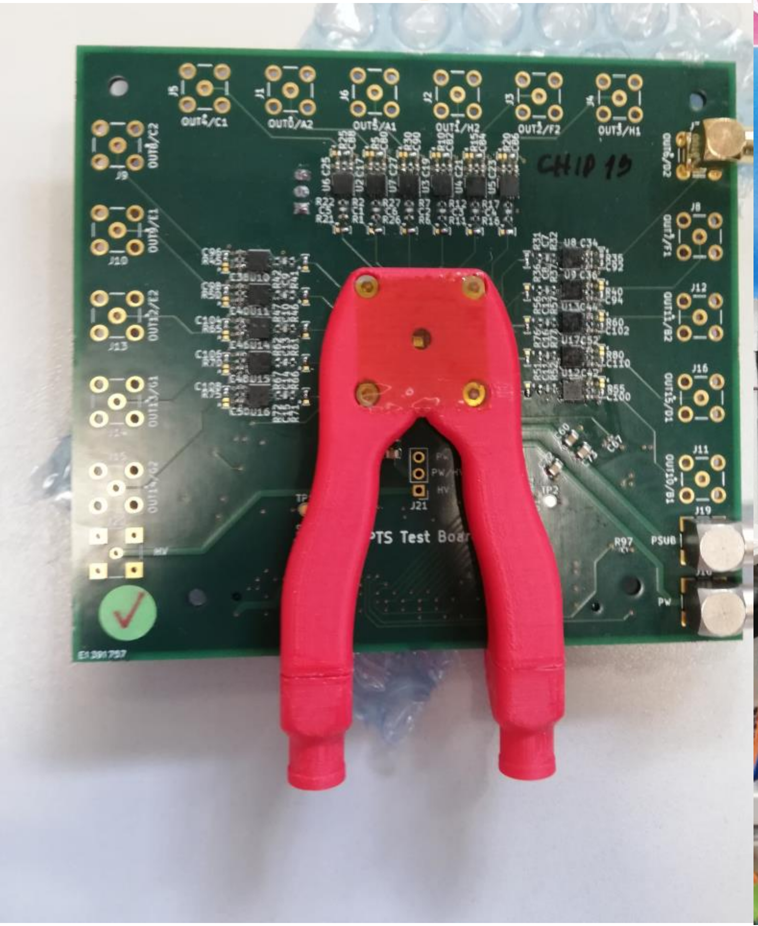
- DATURA/ DURANTA telescope 6 MIMOSA 26 sensors
  - ➢ Spatial resolution 3.24 um per plane (for DATURA)
- Typical Geometry
  - ➢ d_t = 15 to 20 mm, d_{d1}, d_{d2} = 25 to 35mm

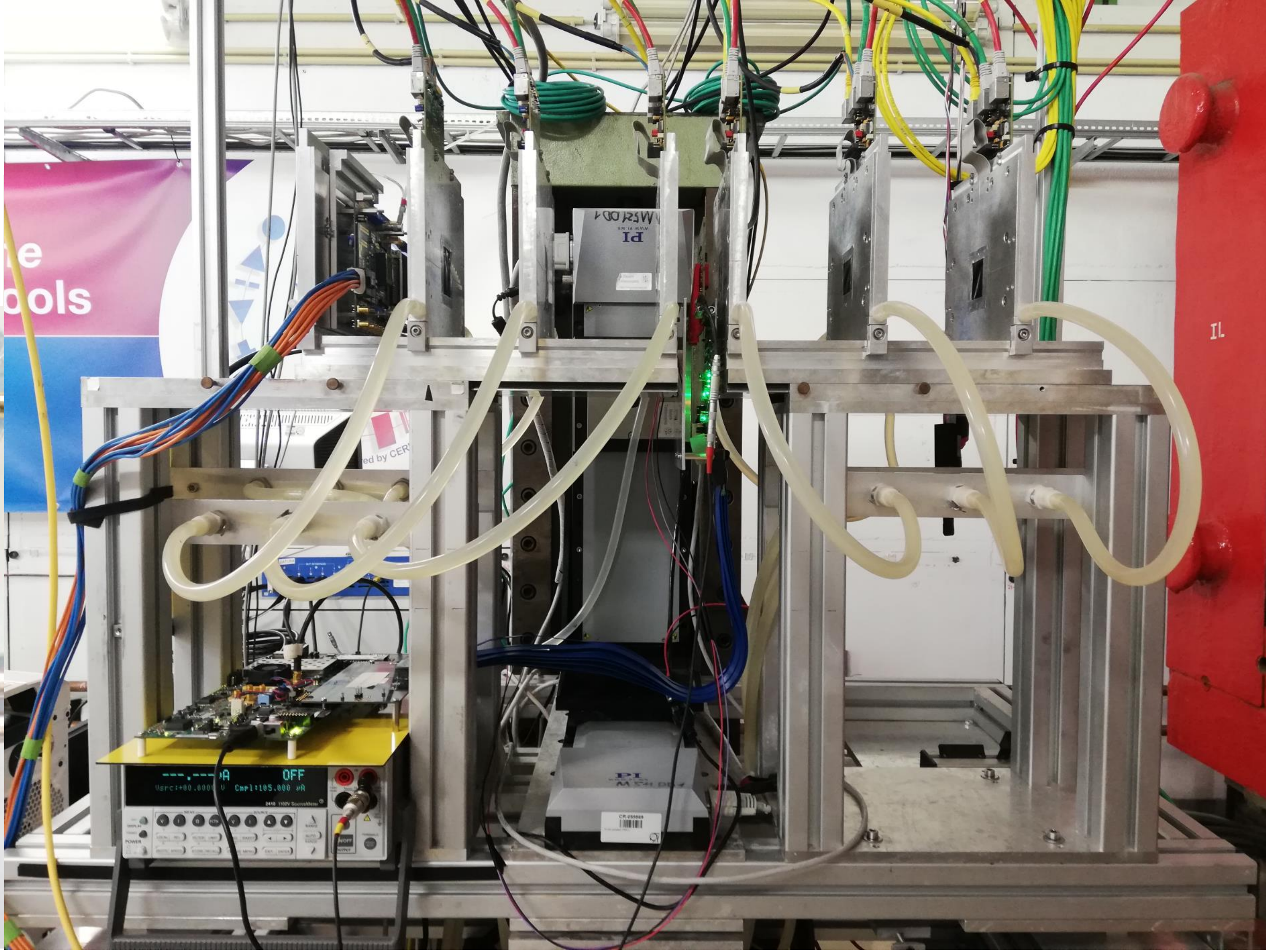
DUT Support

- Simple back-plate with cut out, to mount the carboard and the APTS chipboard
- Versatile, used for many Caribou based test chips

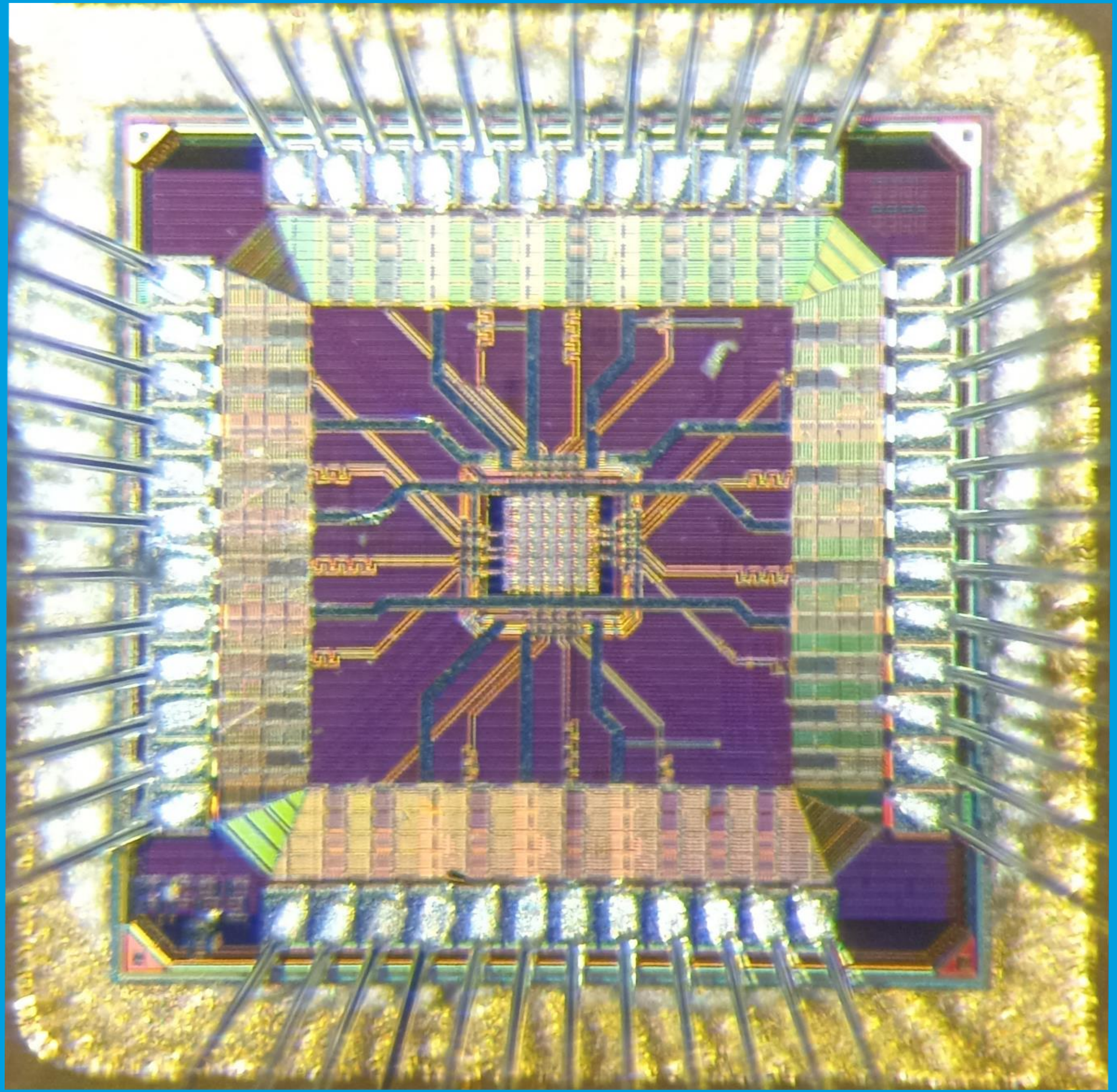
Setup – Pictures

At Beam Line 21



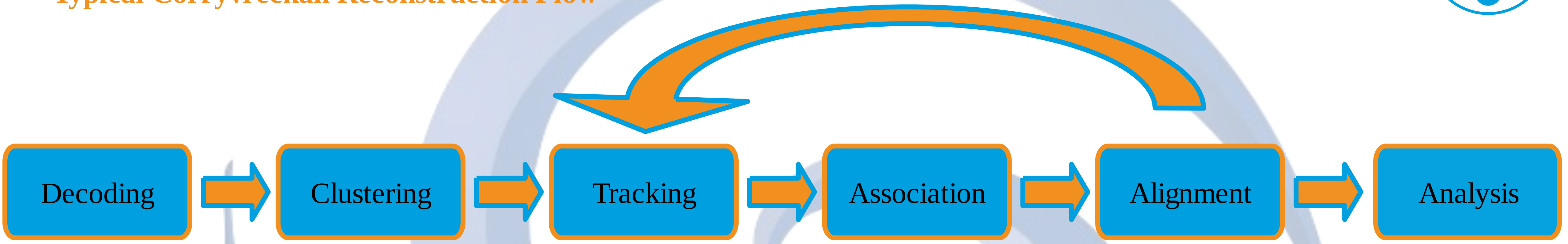


Reconstruction



Reconstruction – The Chain

Typical Corryvreckan Reconstruction Flow



Decoding
- Read waveforms and time stamps
- Find maximum and baseline
- Apply calibration

Clustering
- Apply threshold
- Define neighbors
- Group neighbors
- Seeding

Tracking
- Track finding
- Track model GBL
- Track fitting

APTS are small sensors which require excellent alignment
- Physical Alignment
- Time Alignment
- Fake Rate

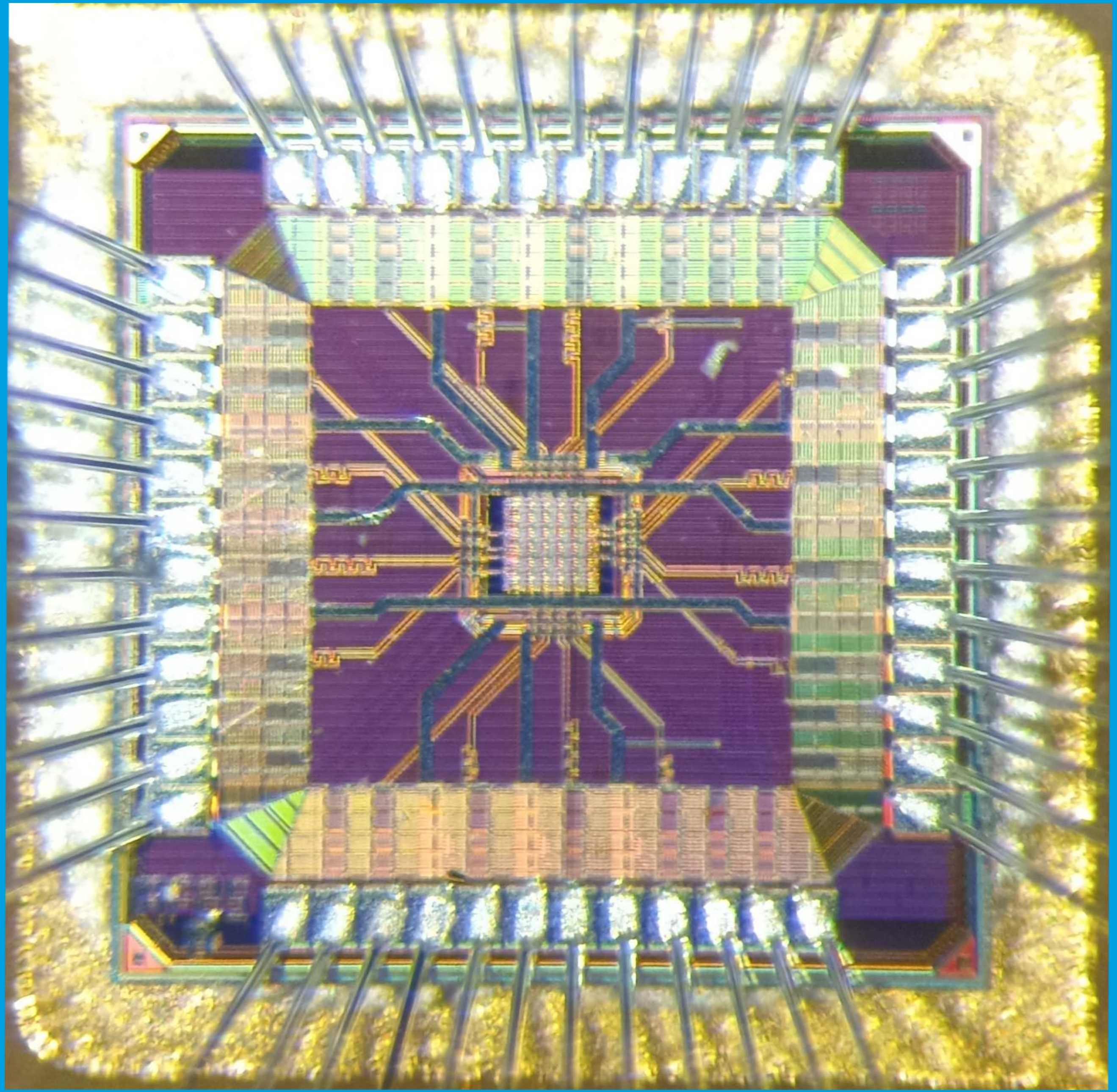
Association
- Match tracks and DUT hits in space and time

Alignment
- Telescope
- DUT
- Time dependence
- Iterate, then skip

Analysis
- Spatial and time resolutions
- Efficiency
- Cluster Size and charge
- Fake rate

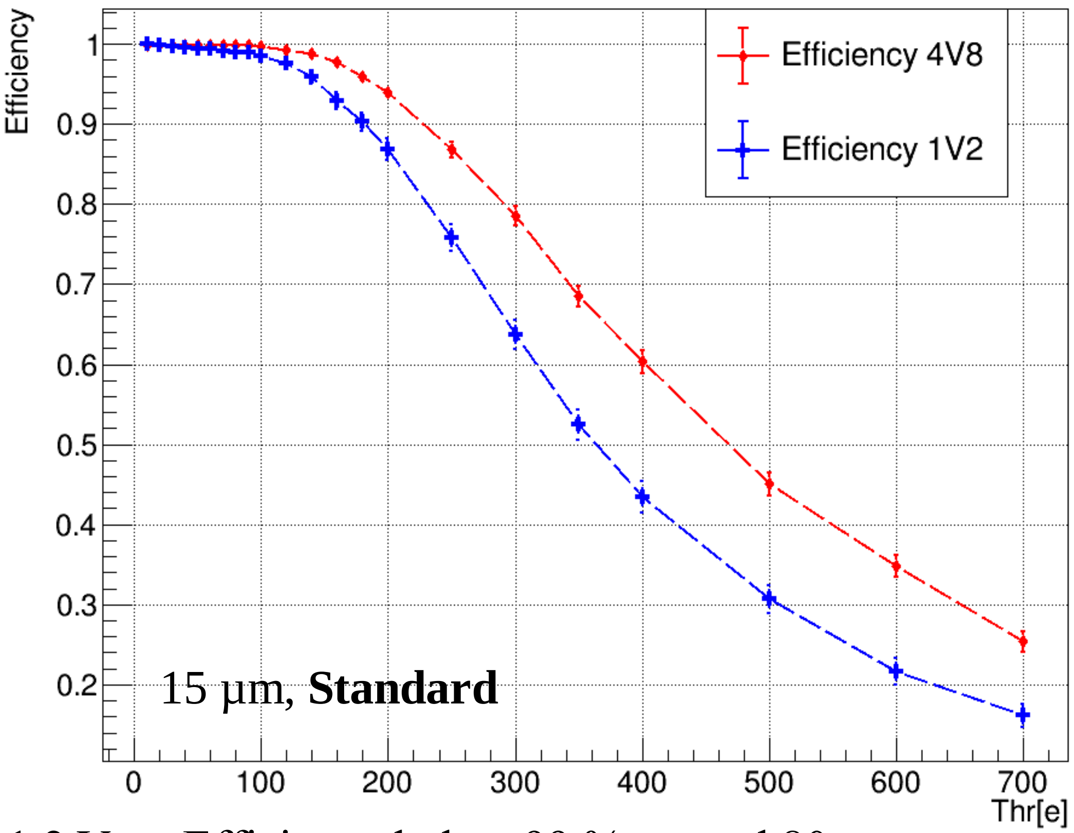
Corryvreckan web page

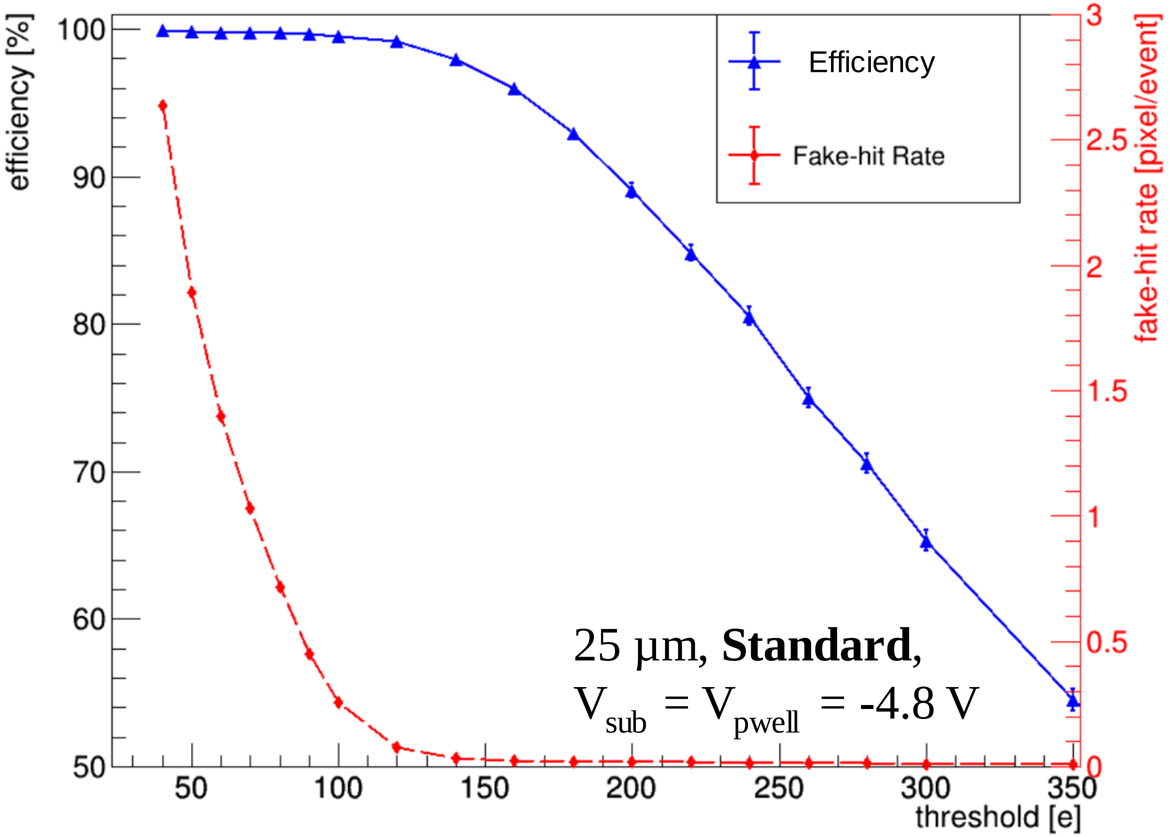
Results



Results – Efficiency for Standard Layout

As a function of threshold





- -1.2 V → Efficiency below 99 % around 80 e
- -4.8 V → Efficiency below 99 % around 140 e

- Efficiency below 99 % around 120 e
- Fake rate diverges below 100 e, RMS O(30 e) all samples

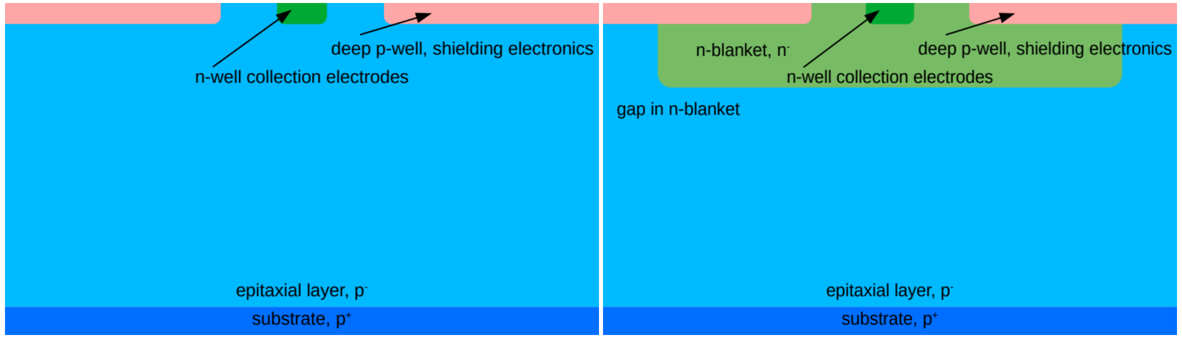
Reducing the pitch and increasing the bias, increases efficiency for the standard layout

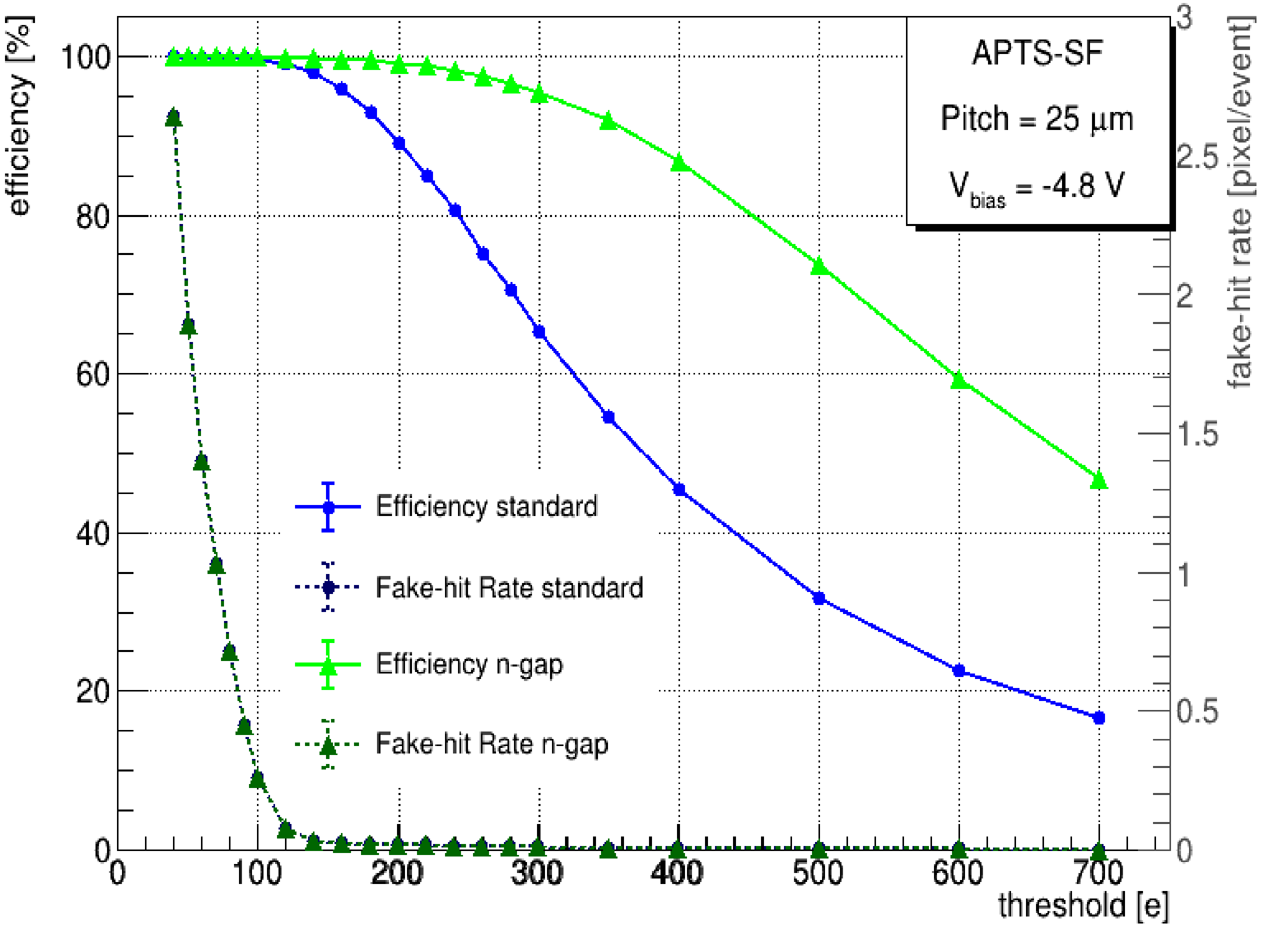
Results – Efficiency

Comparing Standard and N-Gap Layout

- N-gap design shows significantly higher efficiency
  - Drops below 99 % at about 200 e at similar noise level

Efficiency better for n-gap layout





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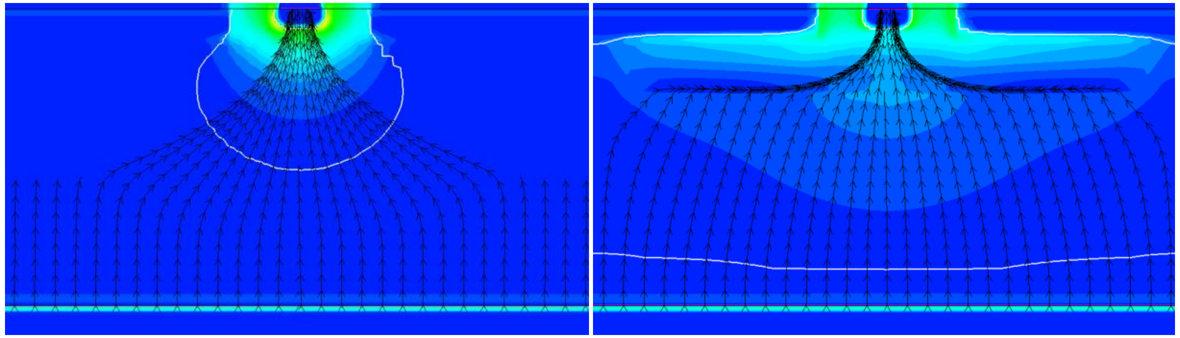
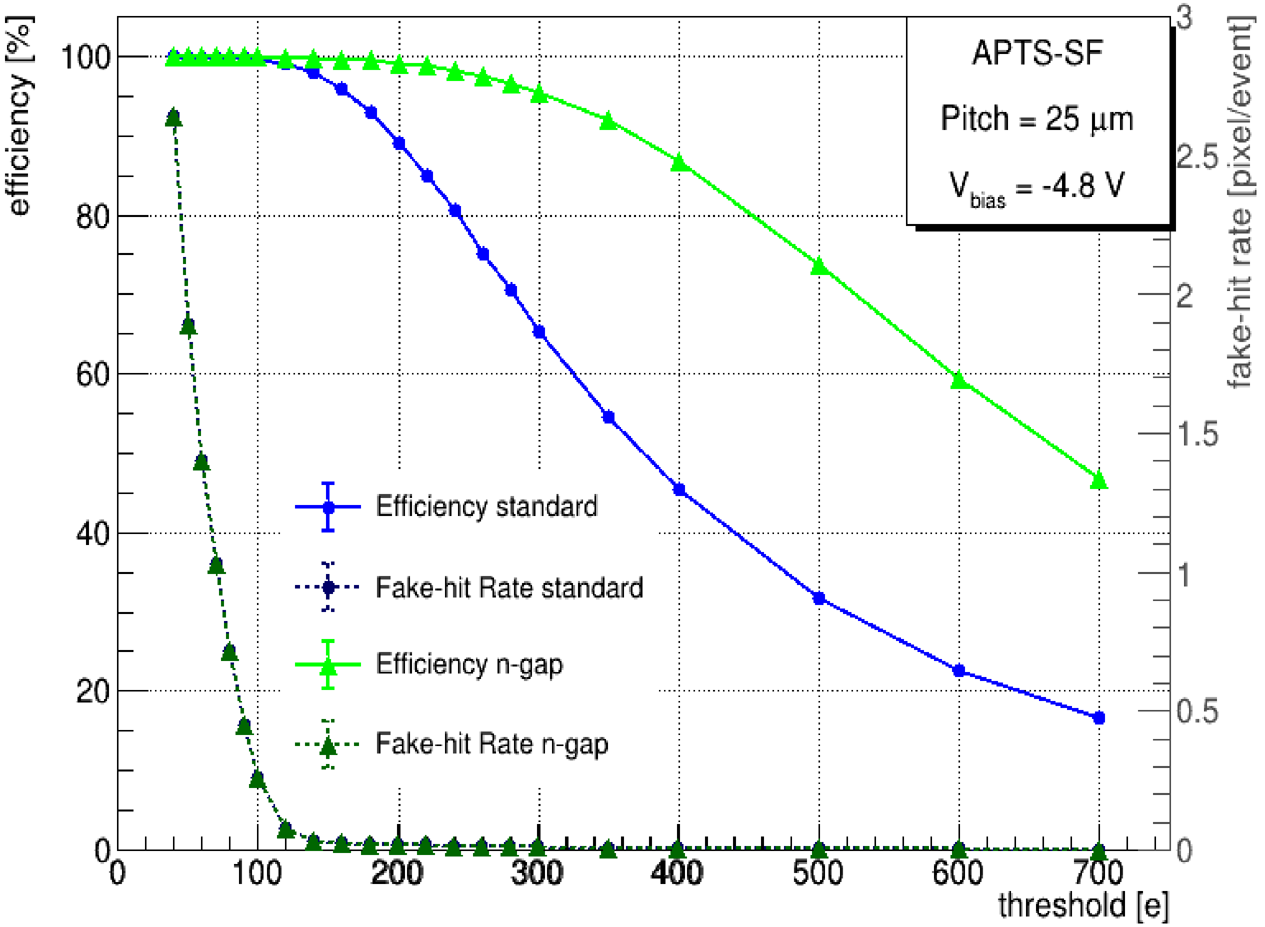


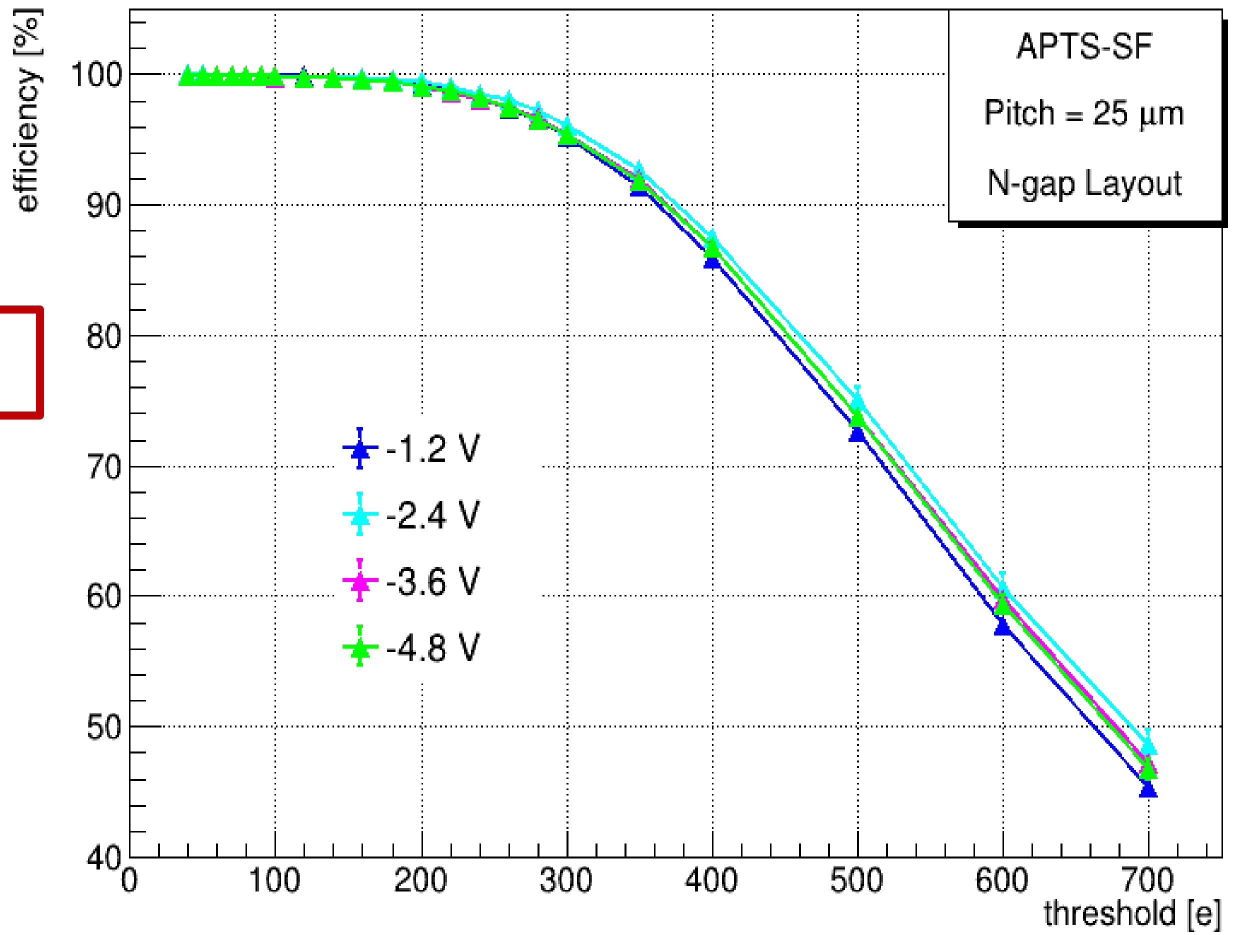


Results – Efficiency for N-Gap Layout

As a Function of the Bias Voltage

- Expected from simulation studies
- Although there are marginal variations in both

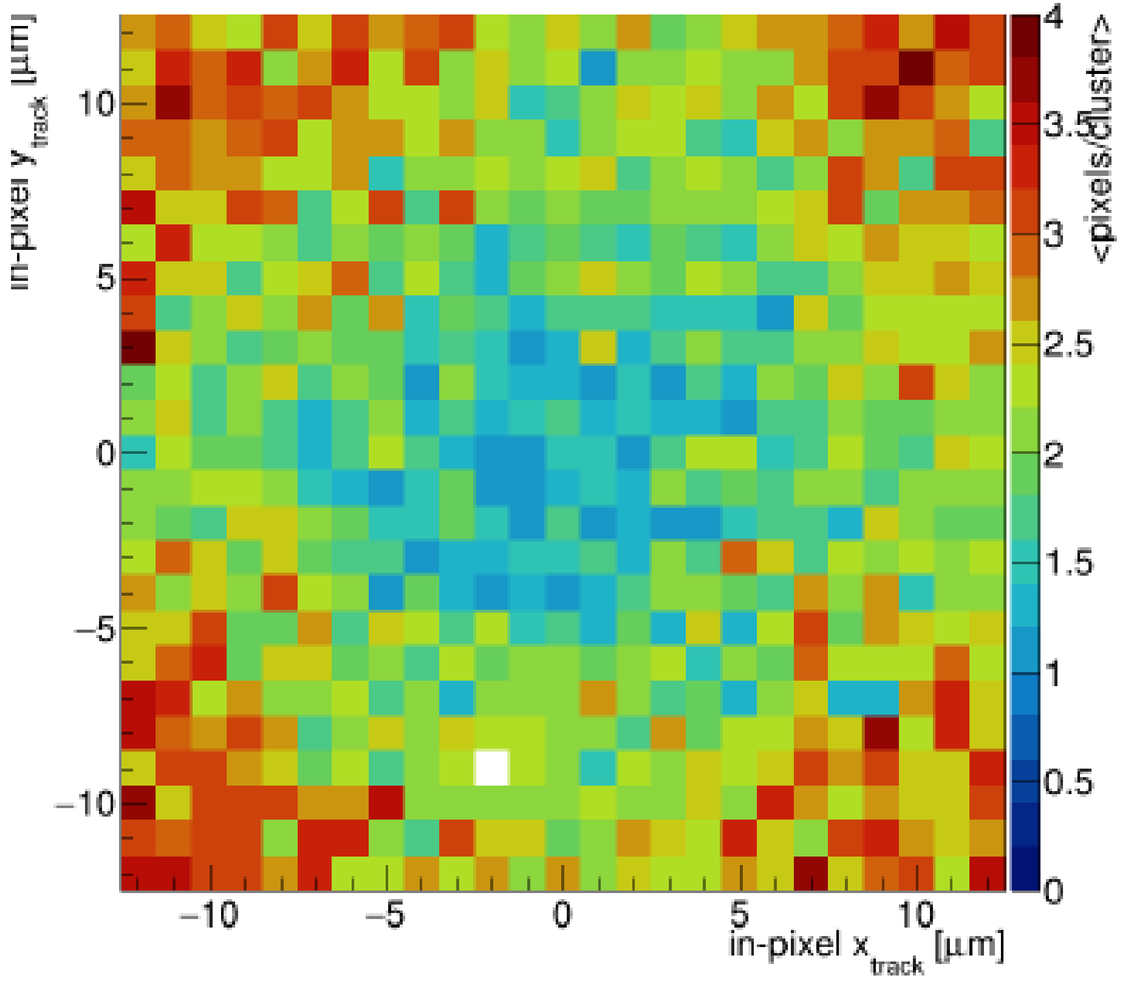
Essentially independent of the bias



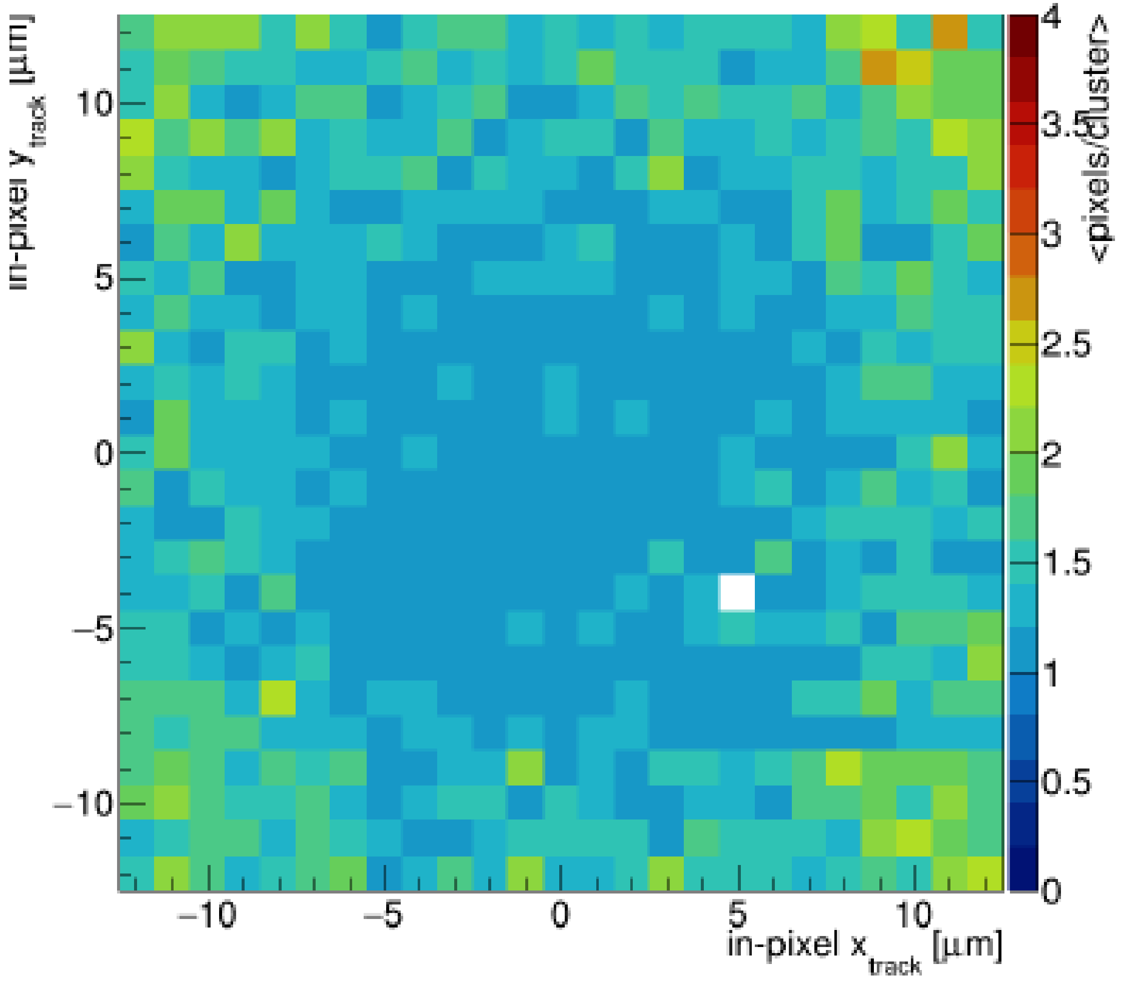
Results – In-Pixel Cluster Size Comparison

Higher efficiency comes with a reduction in cluster size

25 um, **Standard**, $V_{sub} = V_{pwell} = -4.8$ V, th = 120 e



25 um, **N-gap**, $V_{sub} = V_{pwell} = -4.8$ V, th = 120 e

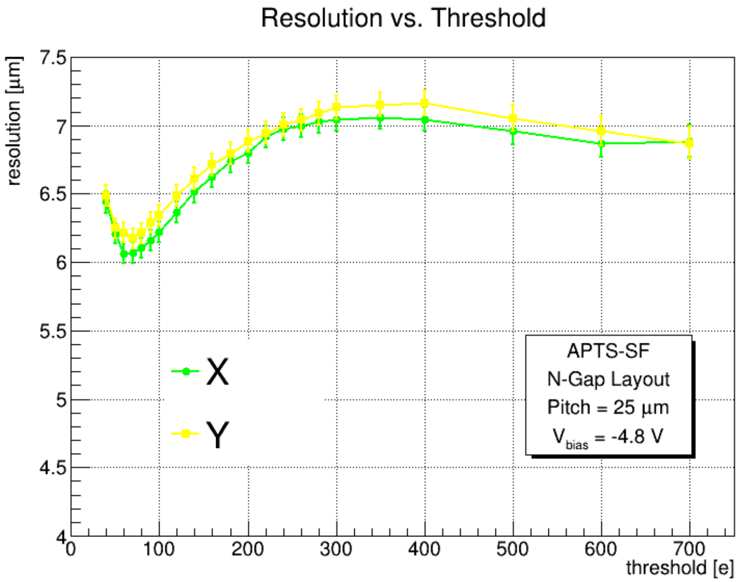


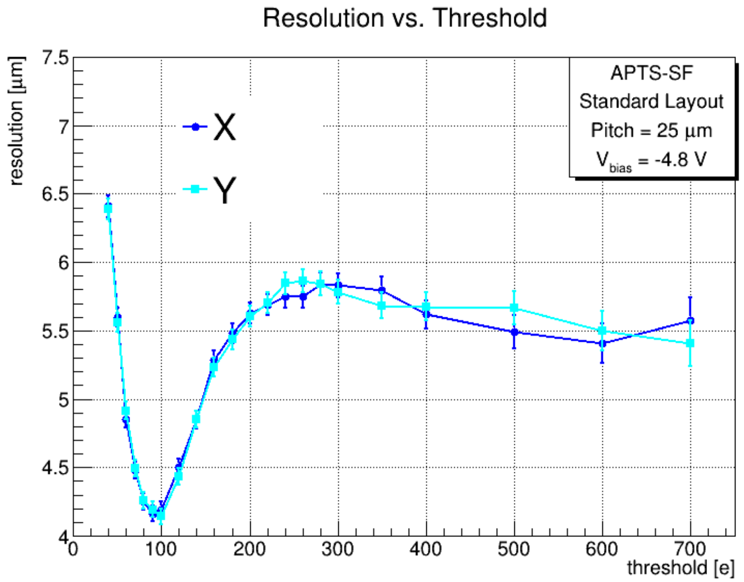
Results – Cluster Size and Resolution

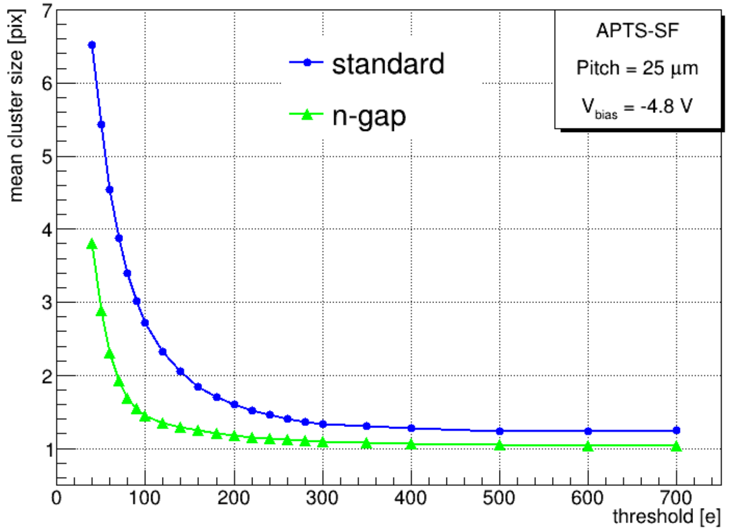
Comparing Standard and N-Gap Layout

- Low thresholds: noise rate increases drastically (below ~ 100 electrons)
- High thresholds: efficiency drops (layout dependent, 200 to 300 electrons)

N-gap; higher efficiency, but lower cluster size hence worse resolution





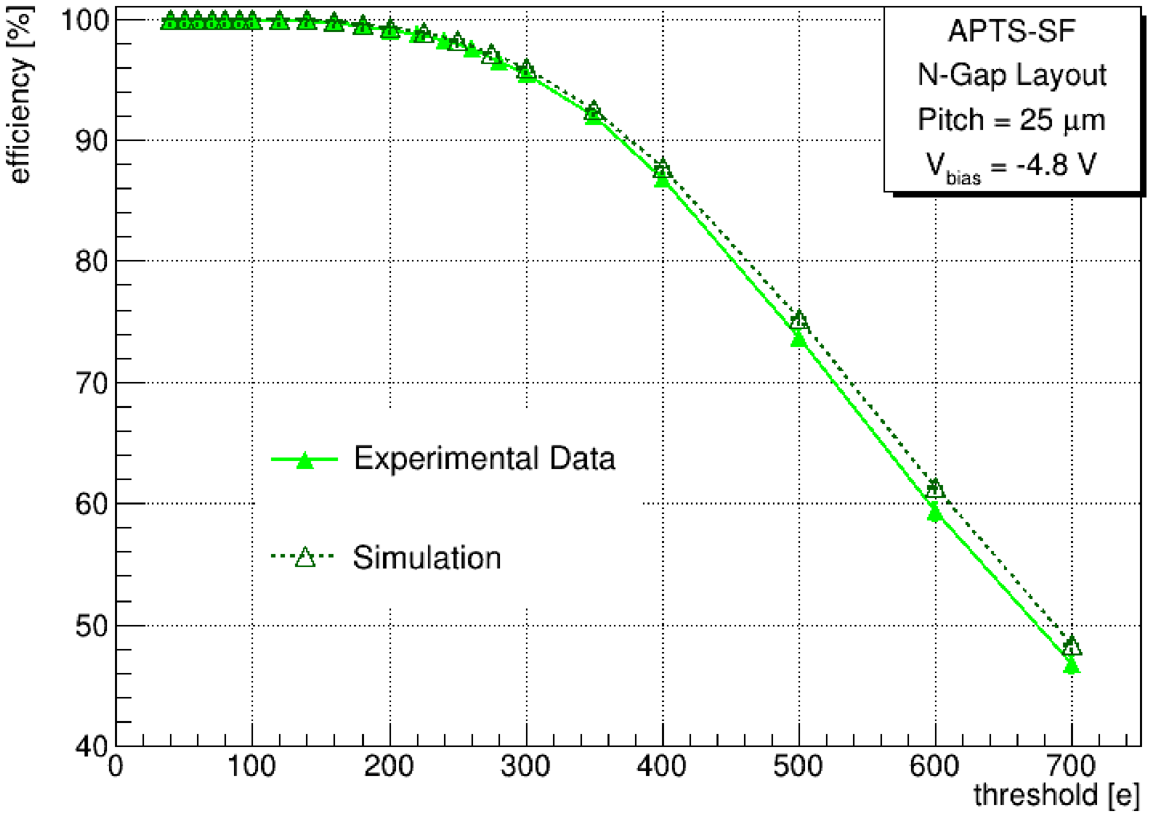


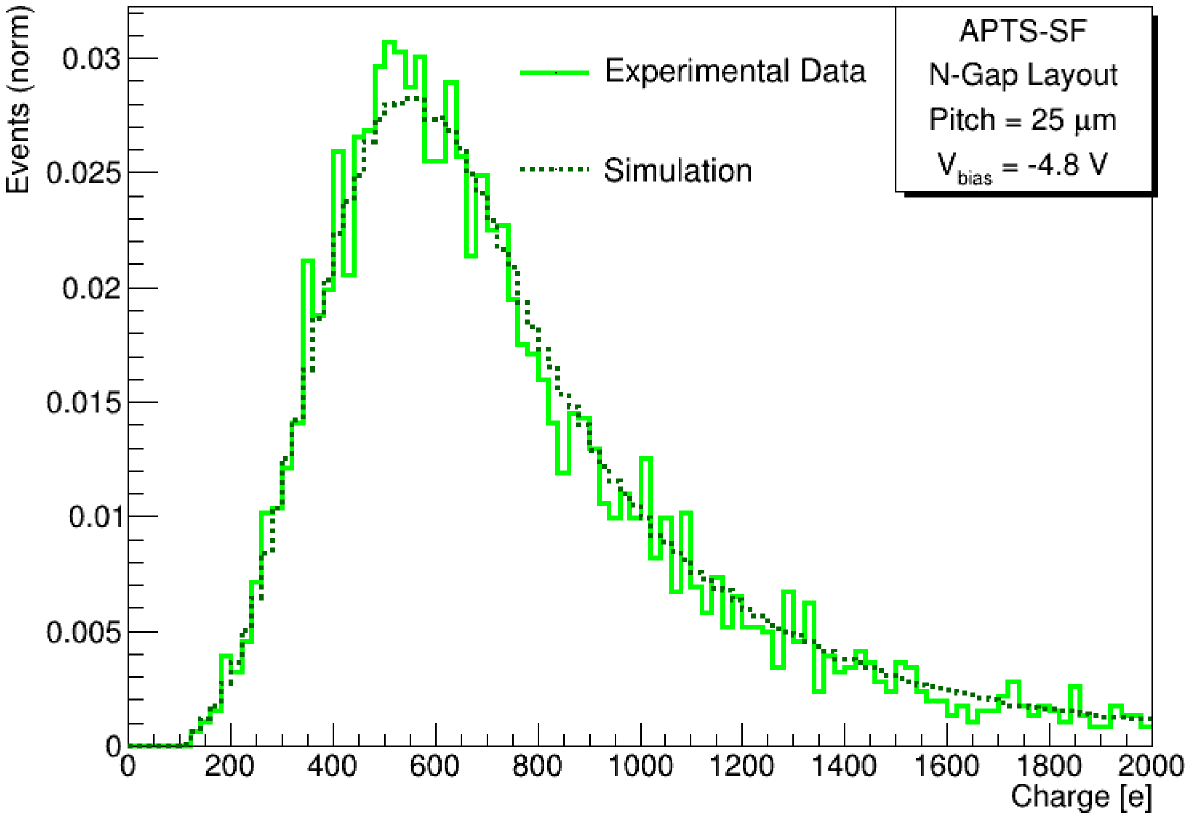
All 25 μm, at -4.8 V

Comparing to Simulation

Efficiency and Cluster Charge

25 µm, N-gap at -4.8 V



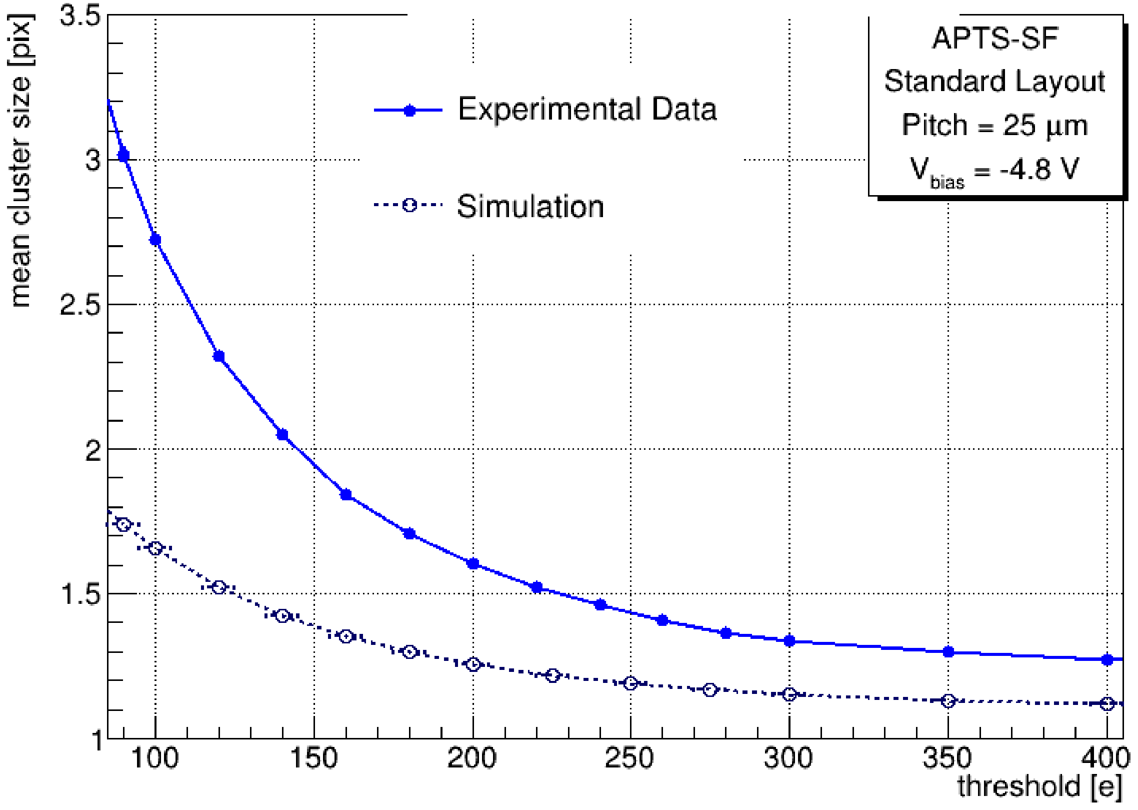


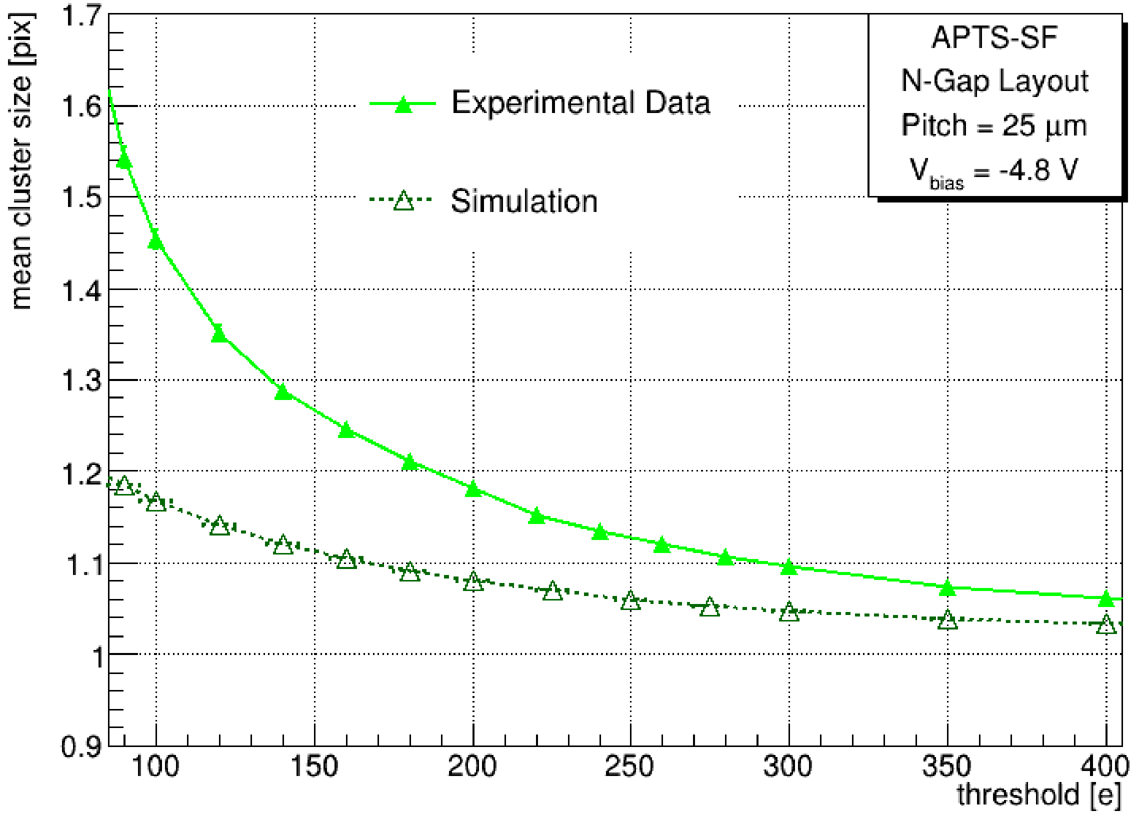
Good agreement between simulation and data

Comparing to Simulation (II)

Mean Cluster Size

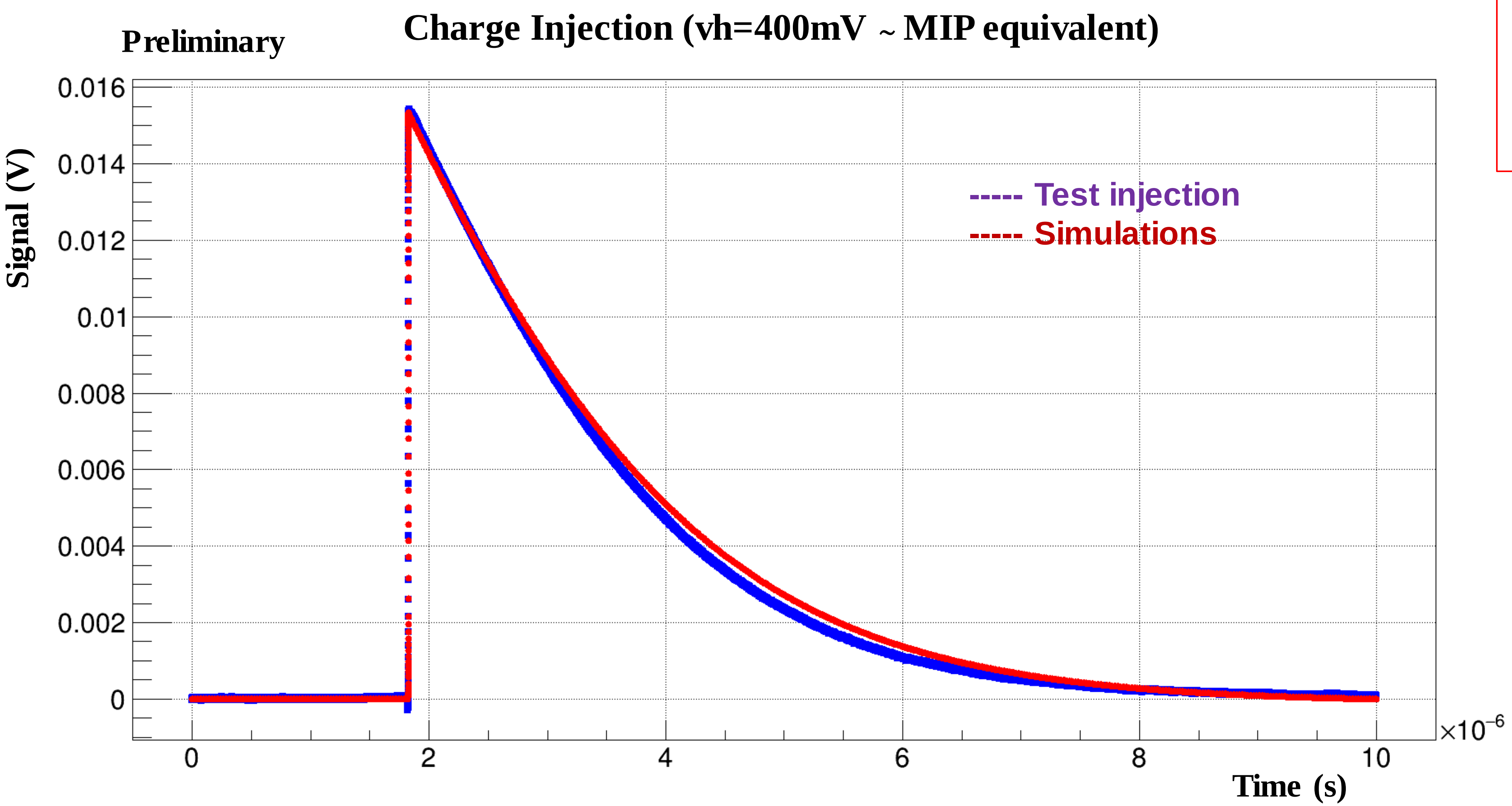
All 25 µm, at -4.8 V





Large phase space (layouts, conditions, observable) to fine tune simulations

Comparison with SPICE simulation (without amplification)



Average pulse obtained through charge injection.

Chip settings

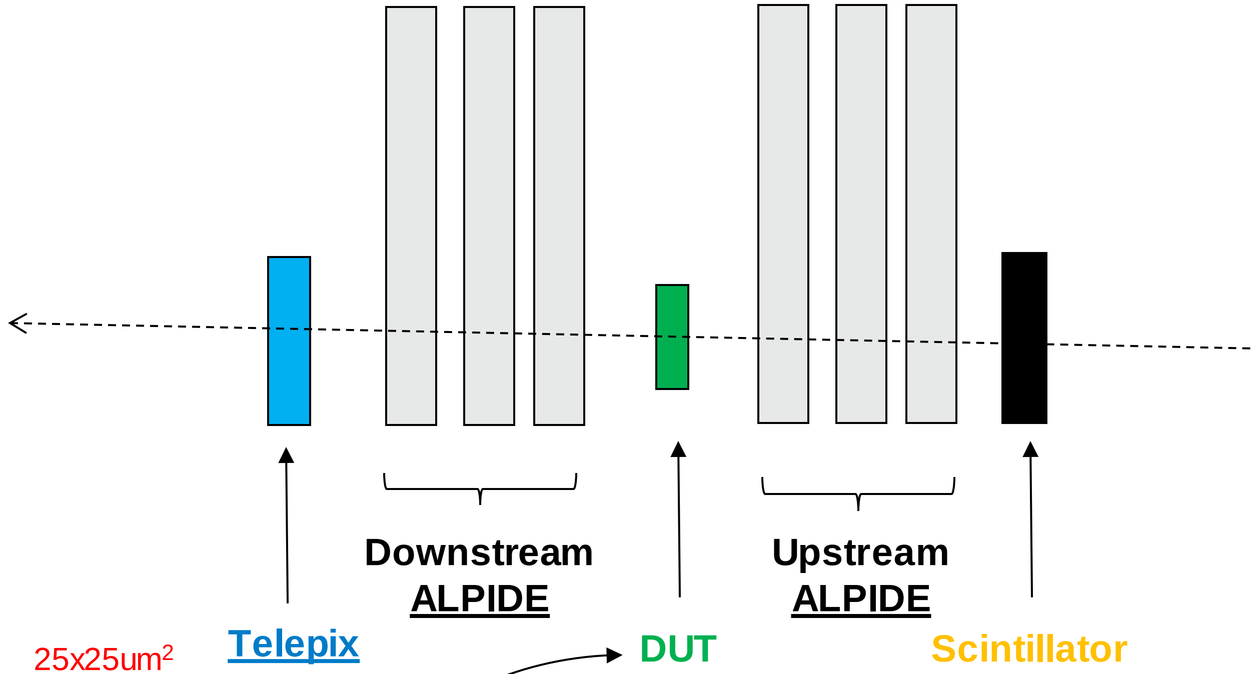
IBIASN 400 uA
IBIASP 40 uA
IBIAS3 500 uA
IBIAS4 6 mA
IRESET 1 uA
VRESET 0.48 V
PWell/PSub -1.2 V

Used in the simulations as well

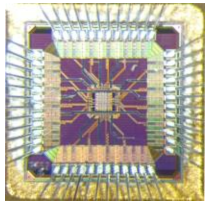
$25x25um^2$
Standard

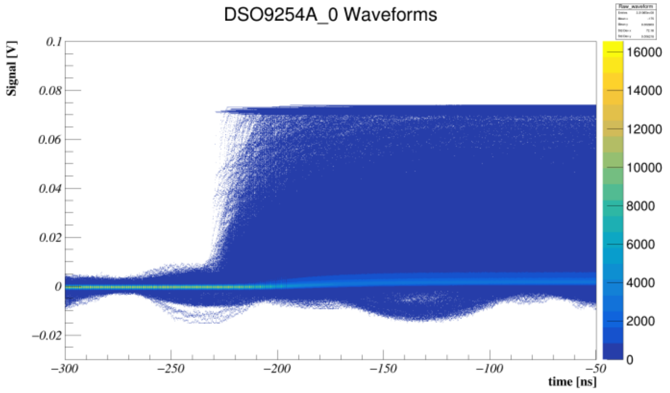
Test Beam Setup (June & December 2023)

DESY II Test Beam Facility



25x25um^2
Standard and N-Gap

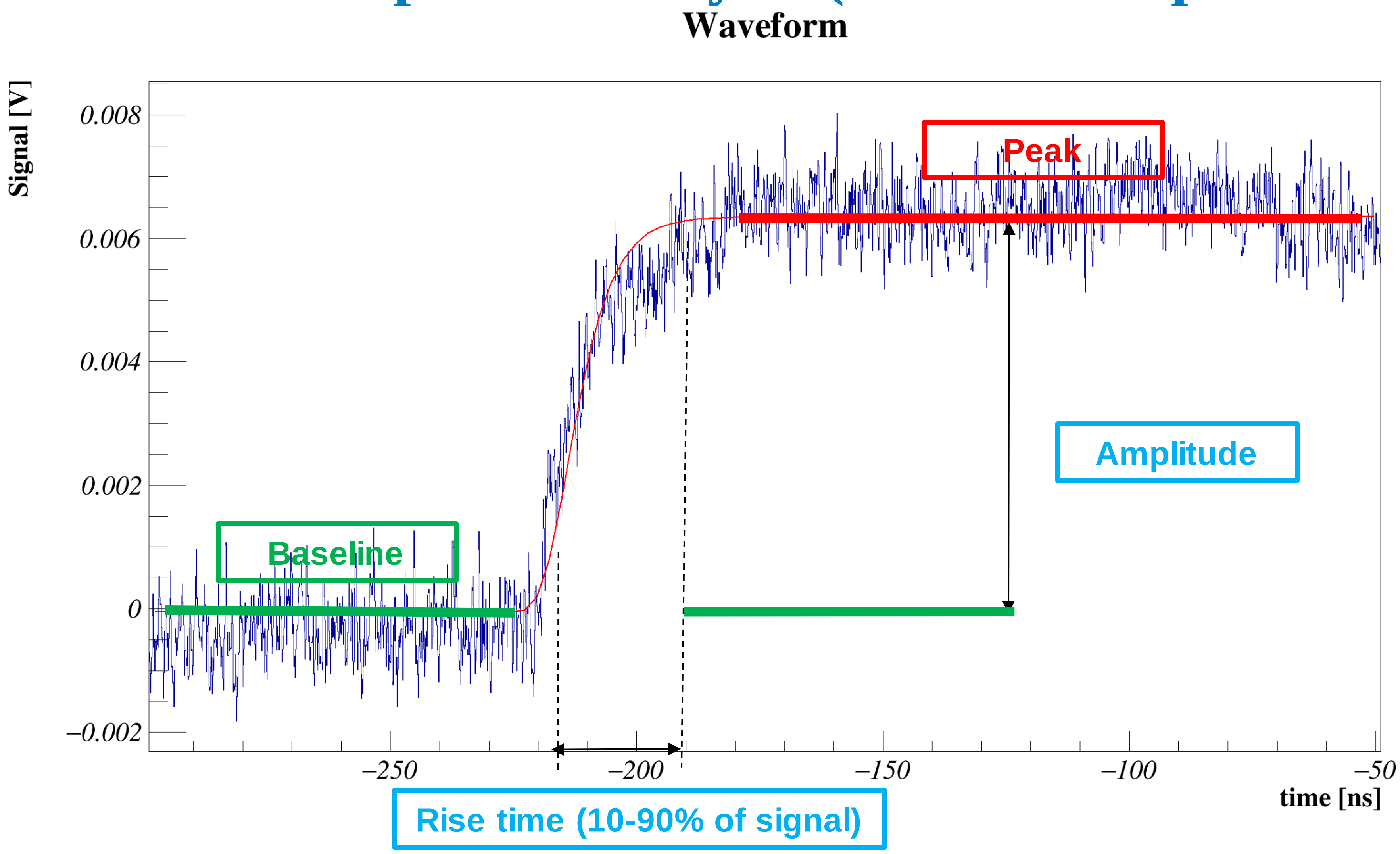




- Telepix and scintillator used in coincidence as trigger, and the former as **time reference**
- Telepix **masked** used to reduce trigger area
- NIM logic used along with TLU to introduce a BUSY signal while the oscilloscope records data

Motivation: Obtain waveforms associated with a track and a rise time

Waveform Simplified Analysis (Without amplification)



The rise time* is an intrinsic quantity of the electronics response due to the signal induced in the detector. This can be directly compared to simulations

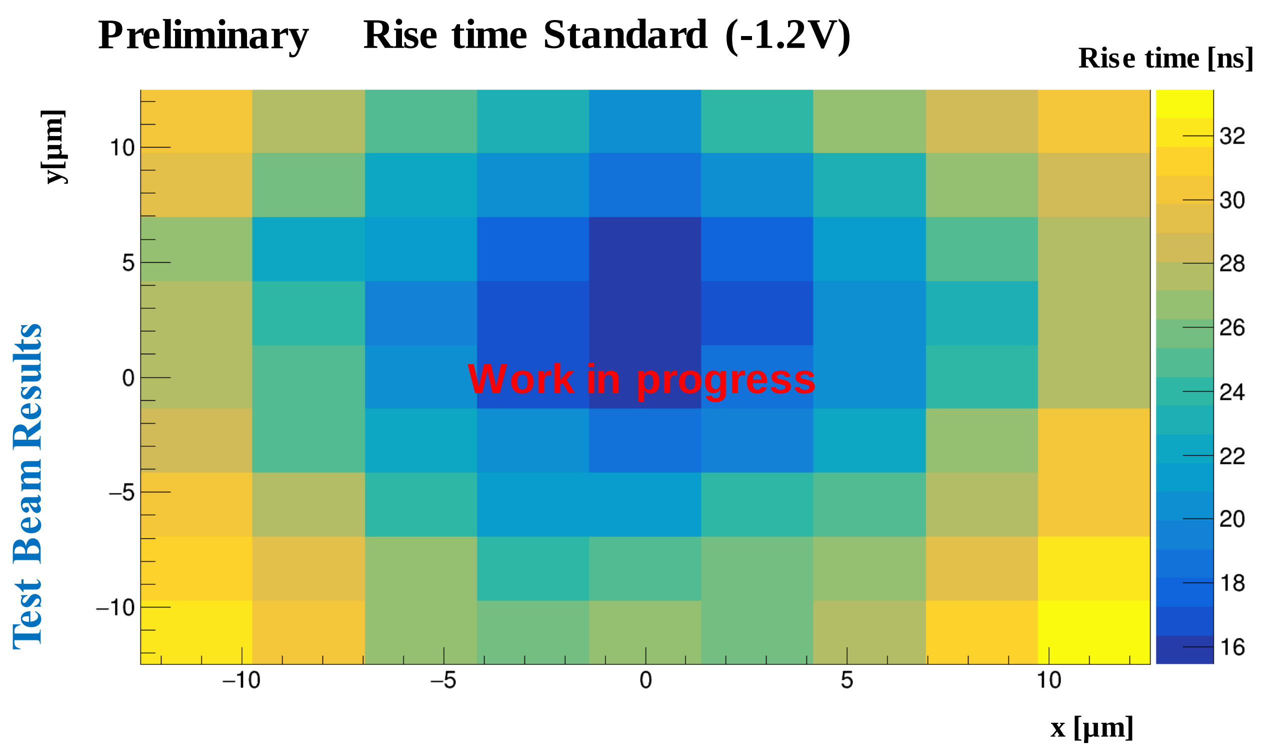
Chip settings

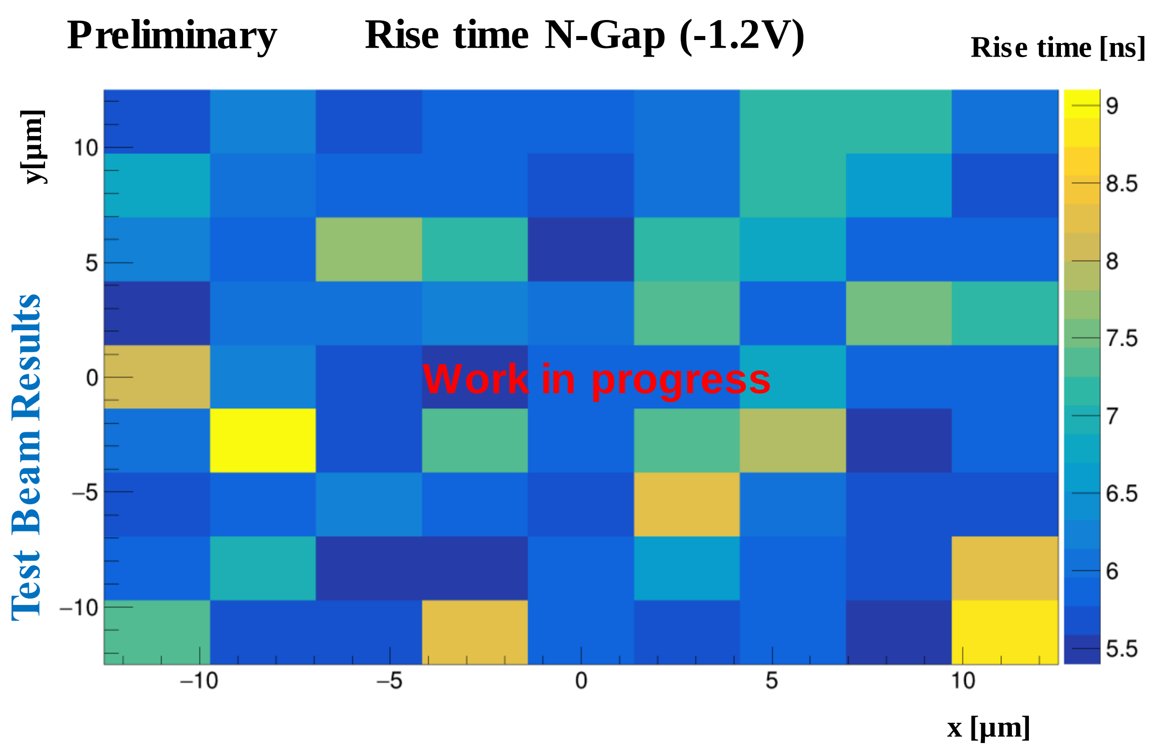
IBIASN 400 uA
IBIASP 40 uA
IBIAS3 500 uA
IBIAS4 6 mA
IRESET 1 uA
VRESET 0.48 V
PWell/PSub -1.2 V

$25x25um^2$
Standard

*Dominated by the electronics, but consist in a convolution of the electronics response and transient from the detector.

In pixel rise time distribution (Qualitative trend values)



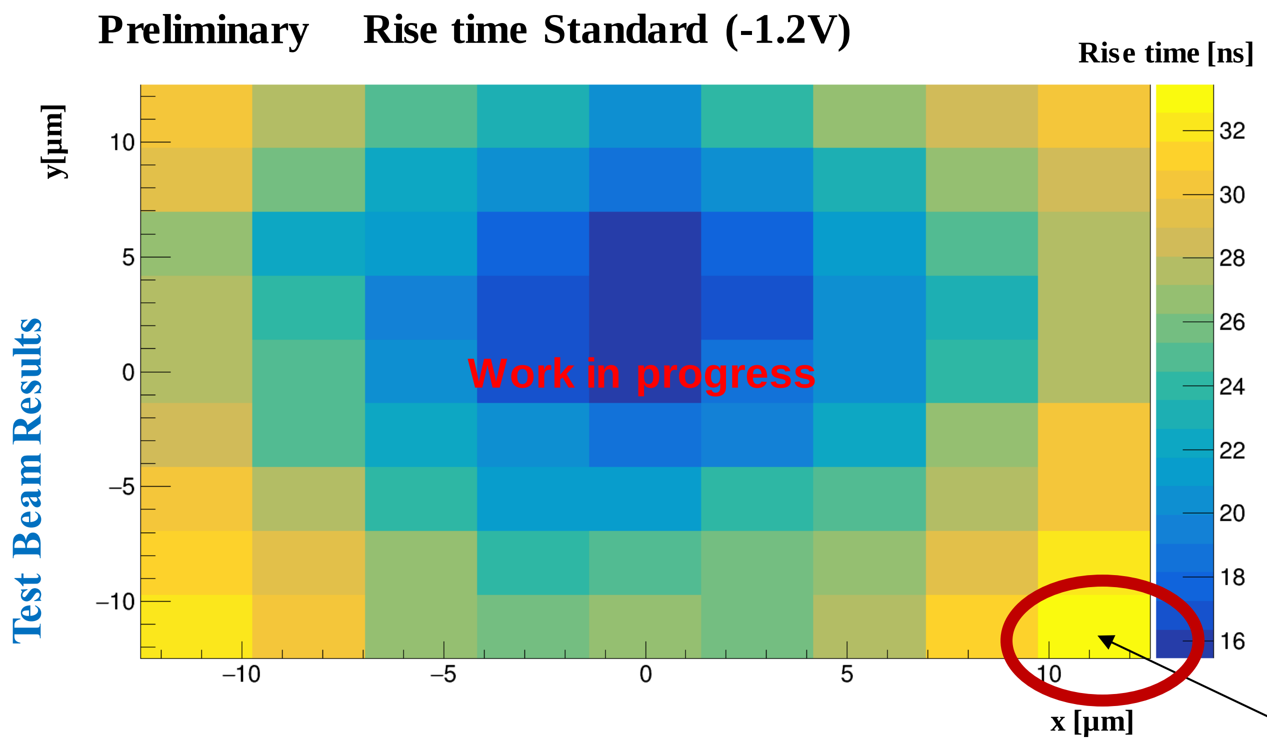


- Clear dependence of particle incident position and rise time

- Uniform rise time distribution regardless of incident position

<u>Note that the spatial resolution for ADENIUM telescope for 4 GeV ~ 3-4 μm</u>

In pixel rise time distribution (Qualitative trend values)



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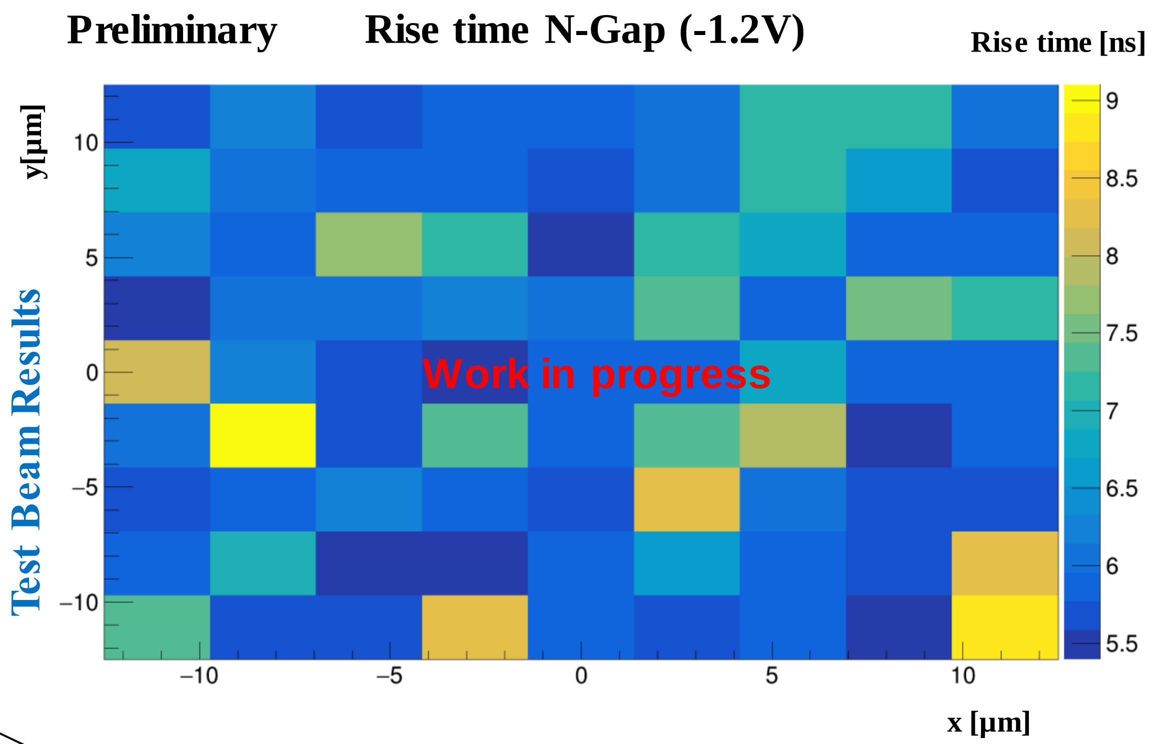

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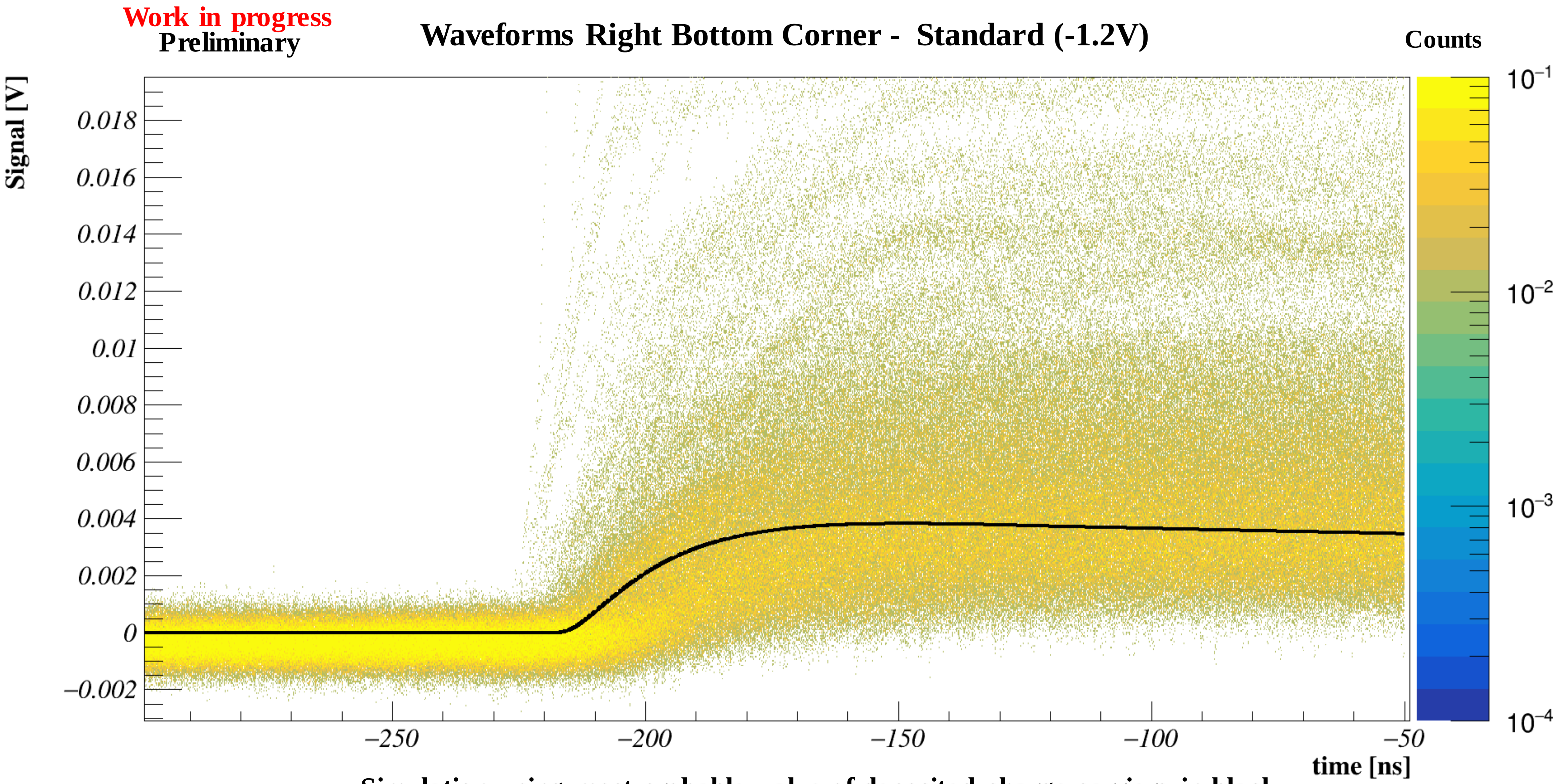
<u>Note that the spatial resolution for ADENIUM telescope for 4 GeV ~ 3-4 µm</u>

Waveforms in the corner of the pixel – Standard Layout



Simulation using most probable value of deposited charge carriers in black

Conclusion and Outlook

Promising Results and More to Come

Big step forward in integration and testing of 65 nm CMOS imaging sensors at DESY

- *The results underline our expectations and predictions from simulations*
  - N-gap layout performs **best in terms of efficiency** and offers the most promising **timing** capabilities
  - Standard layout shows larger cluster size and better spatial resolution
- *Comparison between simulations and data*
  - Decent description of **charge distribution** and **efficiency** for N-gap
  - Mean cluster size is trickier to match
  - Good agreement between analog signals and simulation
- *In the end, this data set is a valuable asset:*
  - Qualifying the technology, quantifying and comparing sensor performance for different layouts
  - A **solid test bench** for our simulation procedure

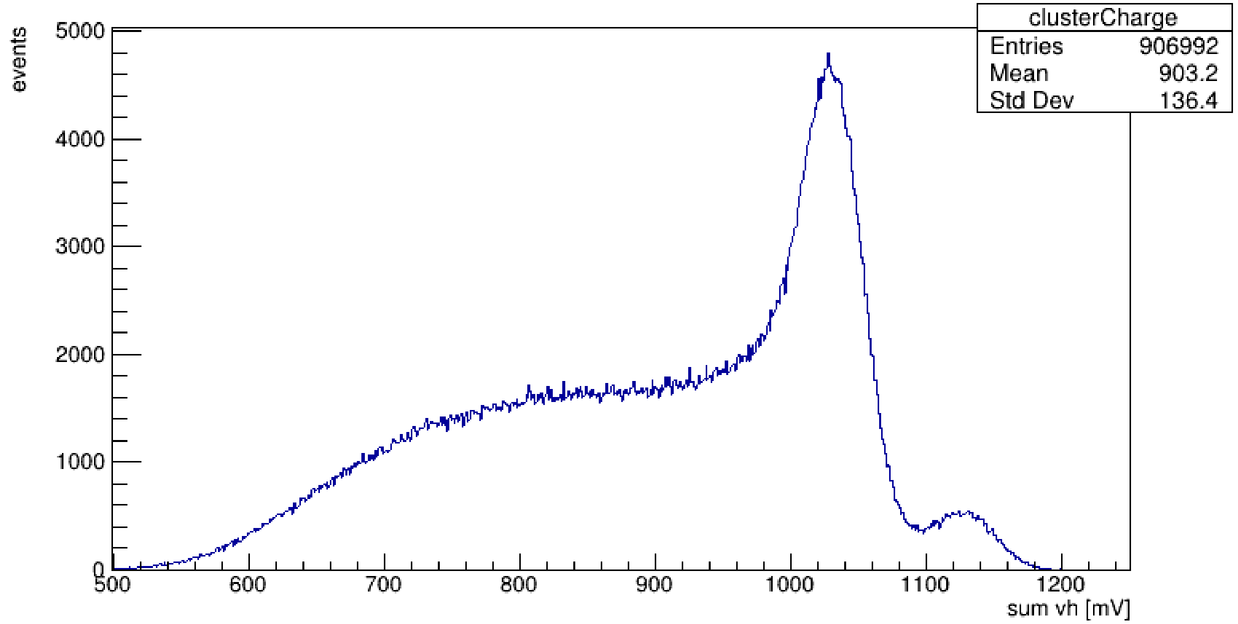
Thank you

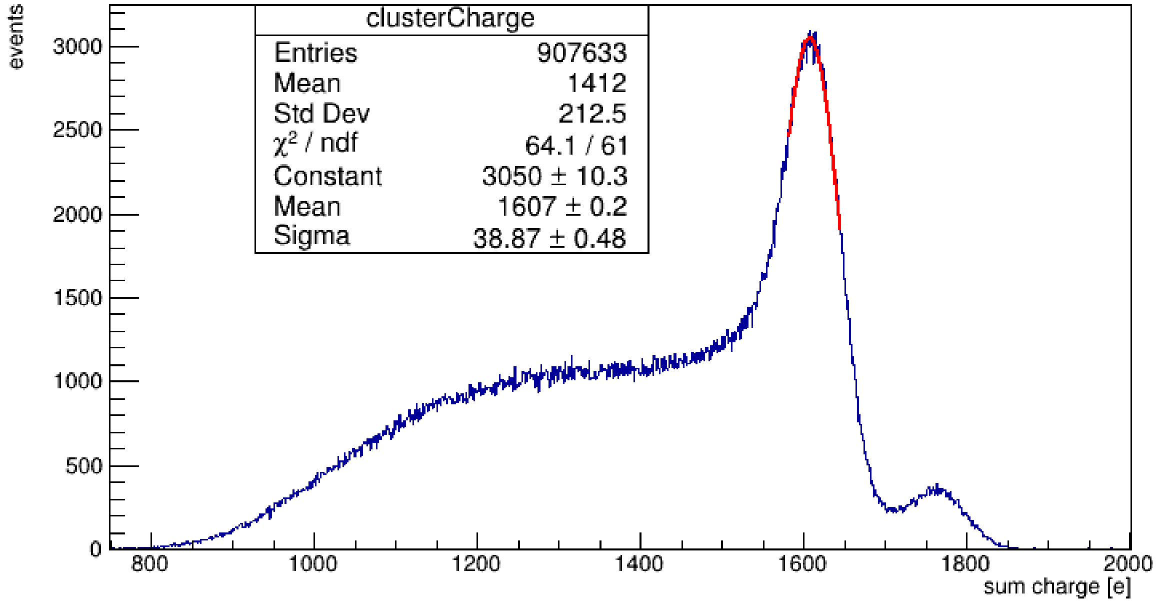
Back up

^{55}Fe Measurements

For Absolute Charge Calibration

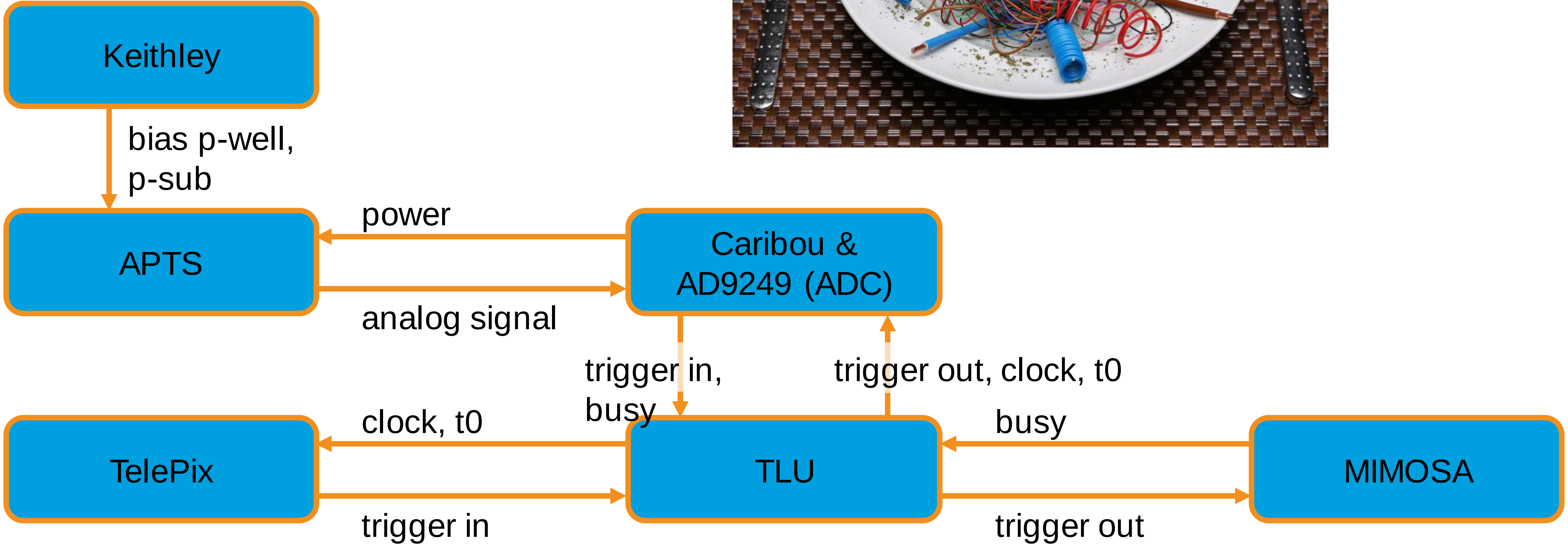
- Sample 24 (AF25B), -3.6 V
- Applying the gain curves from test pulse measurements
- Fitting the ^{55}Fe Kα to get overall charge calibration
  - Kα line (1.606 ke) visible
  - Kβ line (1.769 ke) visible
- Fitting a Gaussian
  - Mean 1.607 ke (by construction)
  - Width 39 e, ratio 2.4 %
  - Depends on background estimate
- At test-pulse amp. of about 650 e (expected MPV)
  - Width 28 e





Setup – Trigger Schematic

Self and Externally Triggered



Setup – External Trigger

Small Acceptance is Key

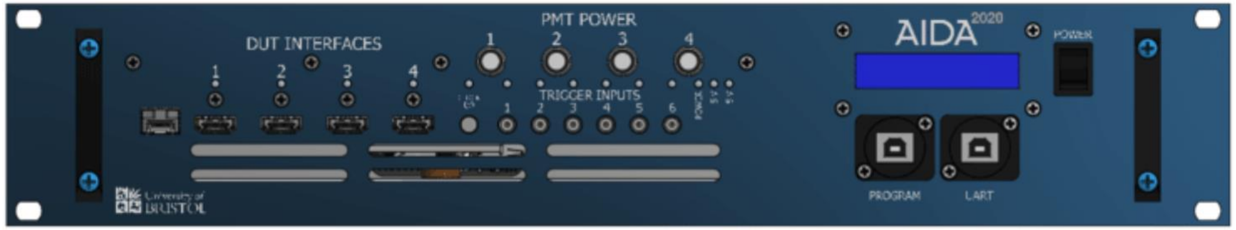
TelePix

- Placed downstream of the telescope setup
- Configurable trigger area to match the active area of the DUT
- Selected 0.5 x 0.5 mm^2 as trade-off between rate and yield
- Time resolution of about 2.4 ns
- Excellent hit efficiency
- Possible to time-tag tracks

Reference

AIDA Trigger Logic Unit (TLU)

- Enables synchronous operation of the involved detector systems
- Select trigger input from TelePix
- Distributes trigger signal to DUT (Caribou) and DATURA DAQ
- Accepts busy signals from DUT and DATURA to veto further triggers to be issued
- Provides clock and run-start signals



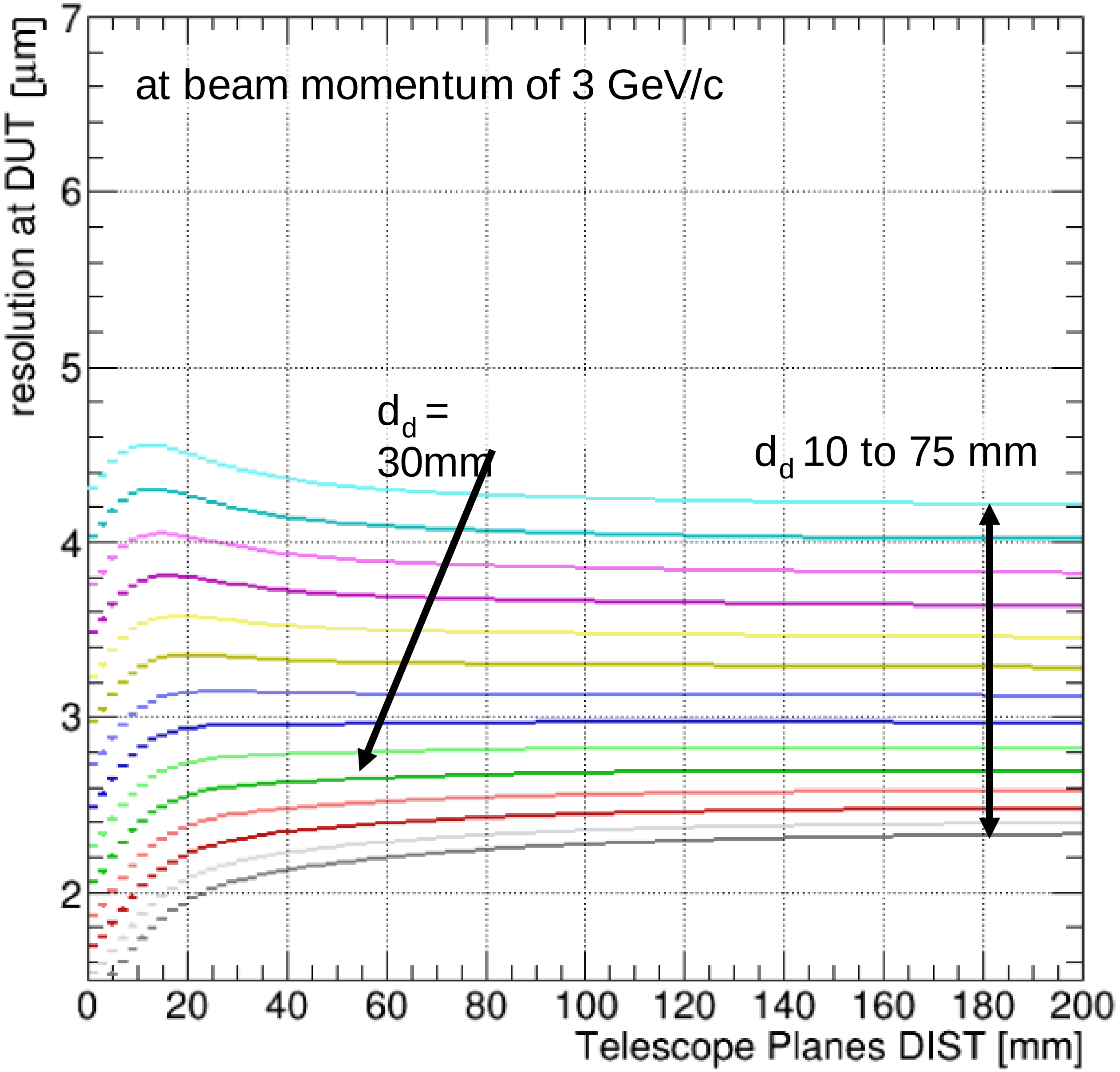
https://github.com/simonspa/resolution-simulator
Using the General Broken Lines formalism

Setup – Geometry

Resolution Dependence on Setup Geometry

Optimizing the track resolution

- Depends on:
  - Electron momentum
  - Material budged of the DUT (and support)
  - Distance d_d between DUT and closest telescope planes
- There is a break even point
  - For large d_d wide plane spacing is better
    - Better lever arm for track angle measurement
  - For small d_d close plane spacing is better
    - Smaller scattering effects
- For us, closer is better... but marginally

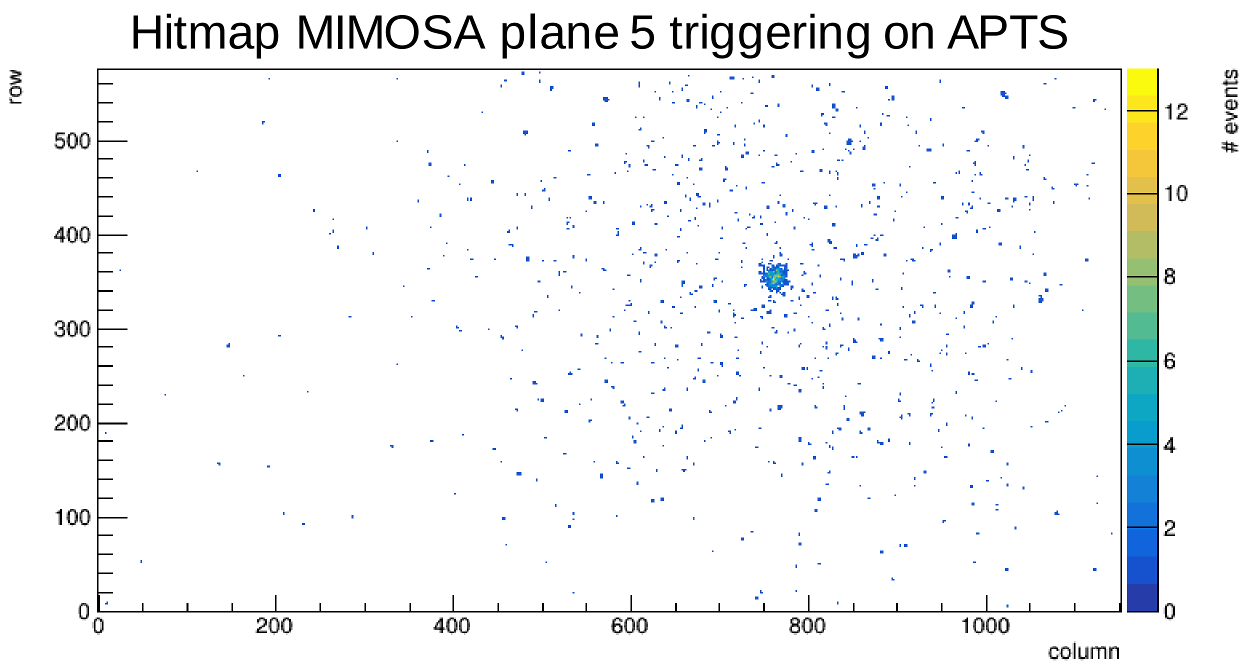


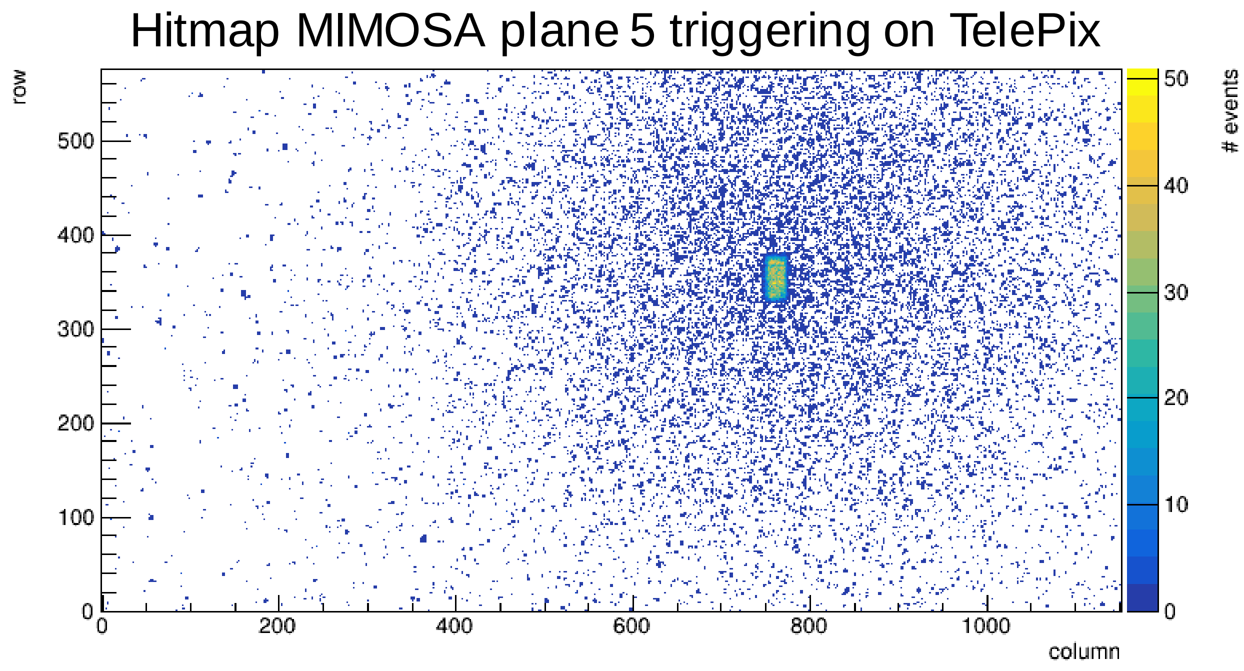
Setup – Physical Alignment

Half a Millimeter Matters

- **Use APTS trigger signal**
  - Check the hitmap of the last MIMOSA plane
  - APTS position at approx. column 765 and row 355
  - Spot width of about 165 um due to scattering
- **Use TelePix trigger signal**
  - Again check the hitmap of the last MIMOSA plane
  - Configure the trigger area of TelePix to match the width and position determined above
  - Physically move APTS, if it is outside of the TelePix acceptance
  - Confirm correct position (lower figure)

APTS are small sensors which require excellent alignment



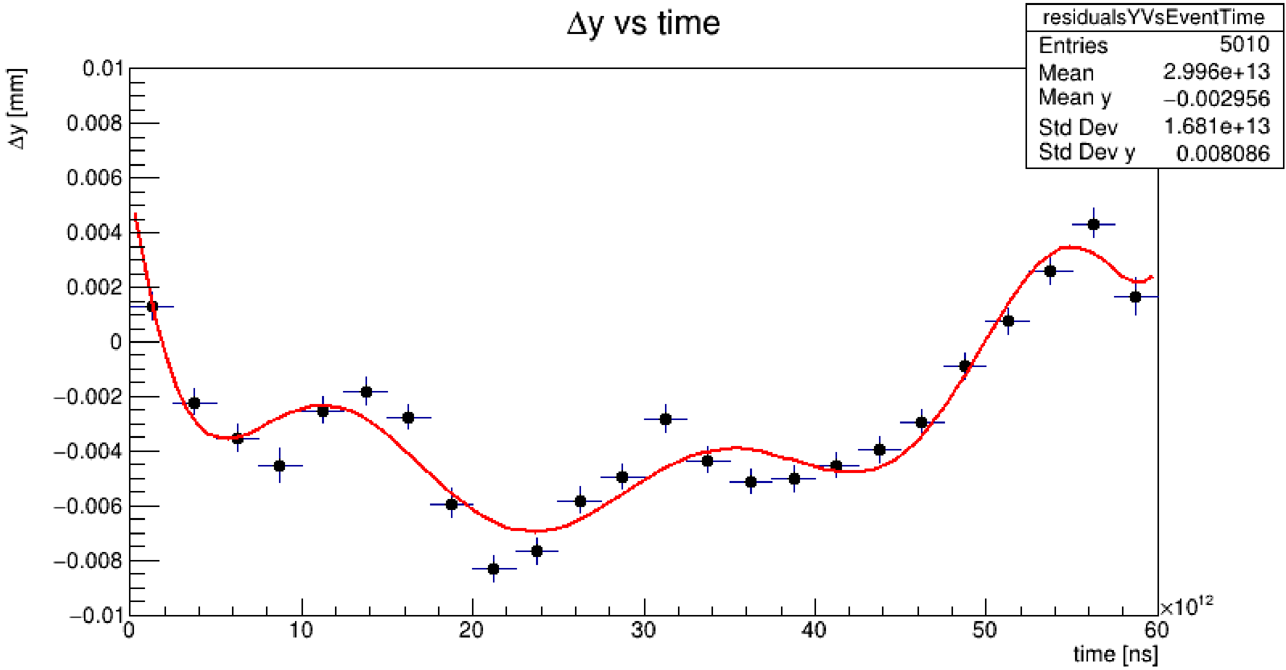


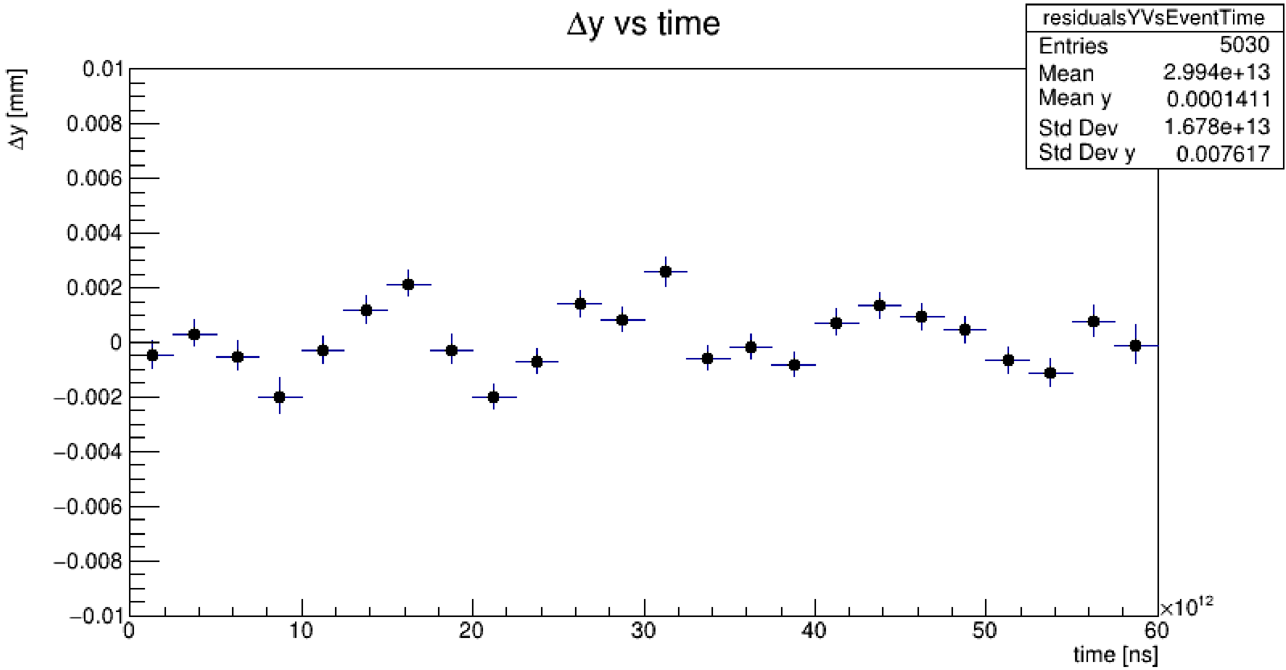
Reconstruction – Time Alignment

Required for Long Measurements

- DUT residual is not a constant function of time
  - Correlated with temperature variations in the area
  - Due to thermal expansion in general
- **Solution**
  - Fit arbitrary function (here 9thorder polynomial)
  - Add function parameters to Corryvreckan geometry definition
- **Caveats**
  - Might bias residual width (in both directions)

APTS are small sensors which require excellent alignment over time

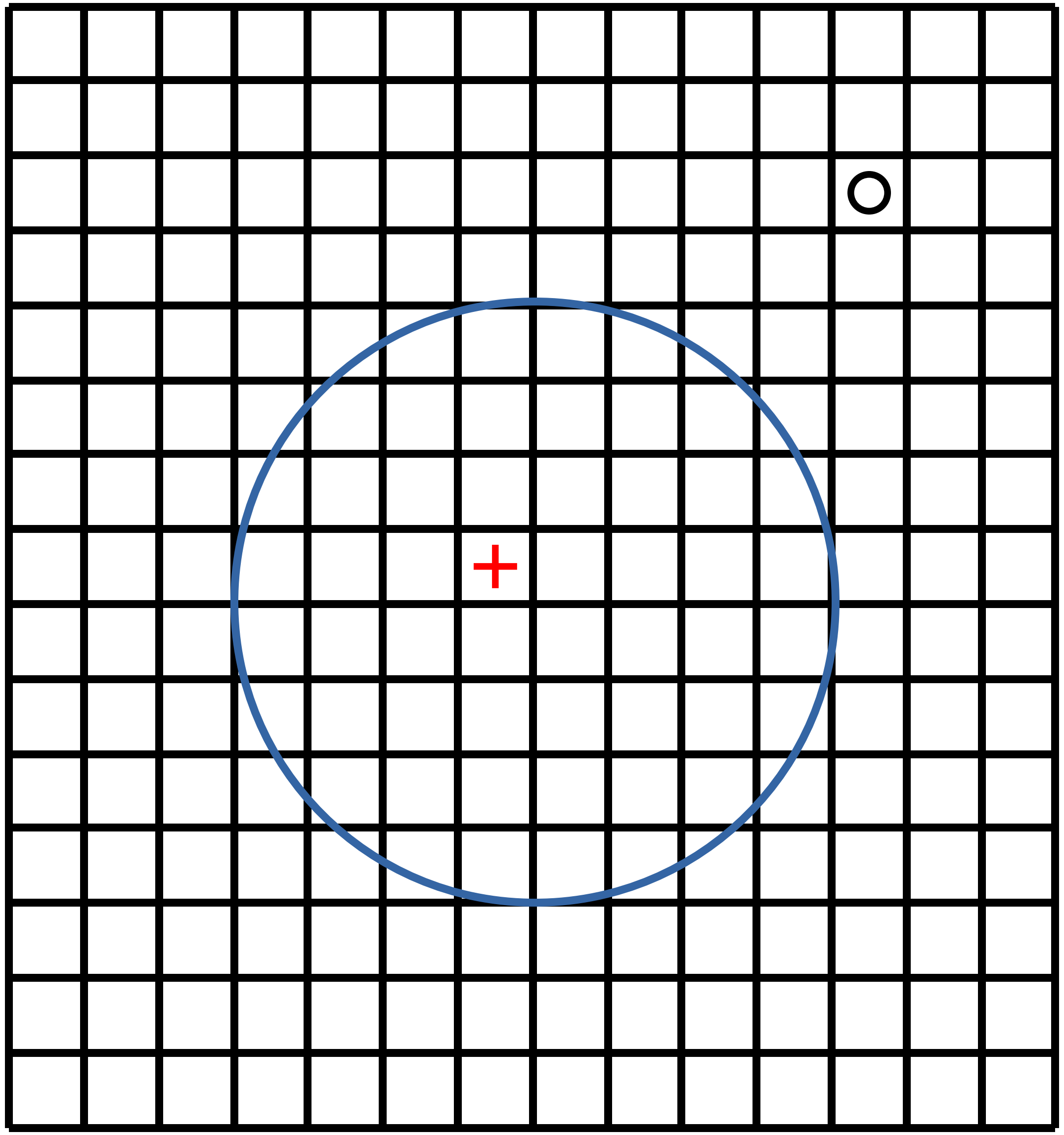




Reconstruction – Fake Rate

Interesting in Combination with Efficiency vs. threshold

- **Radius Method; for large sensors**
  - Veto a circular region around reconstructed tracks
  - Every hit outside the vetoed region is considered fake
- **Edge Method; for small sensors**
  - Define an active region (larger than the sensor)
  - Find events with not tracks crossing the active region
  - Every hit in these events is considered fake
- **Caveats**
  - This depends on tracking efficiency
  - Definition of area is tricky for the edge method
- Still this clearly shows a trend in threshold scans



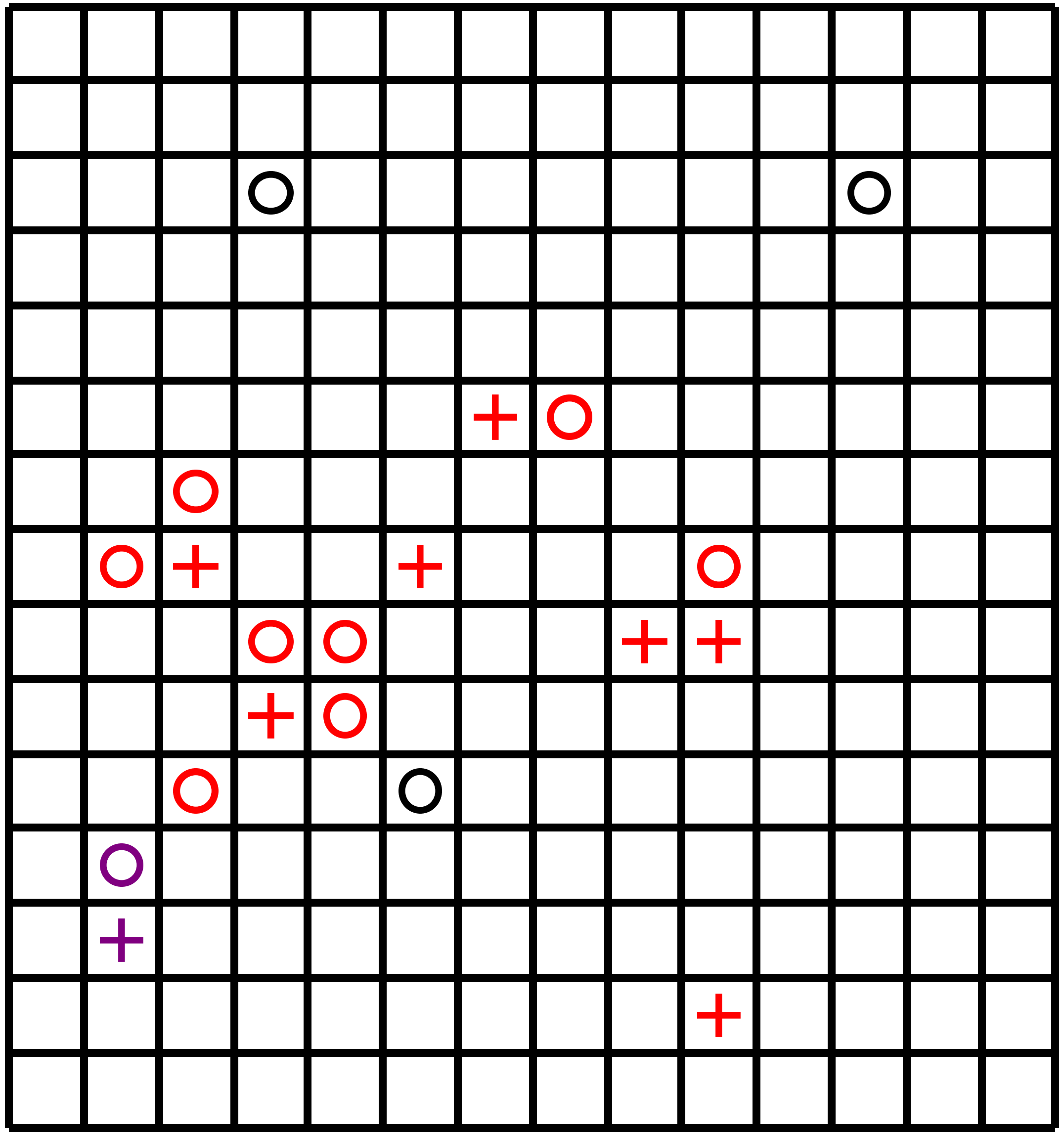
Reconstruction – ClusteringAnalog

Versatile Clustering Module

1) Define Seed Threshold
   - Find pixels above (Seeds)
2) Define Neighbor Threshold
   - Check pixels around seeds (distance in column and row direction ≤ 1) (Neighbors)
3) Define Iteration Threshold
   - Check pixels around Neighbors (Second Neighbors)
   - Iteratively search their neighbors (step 2)

- All these are part of the cluster
- Cluster topology depends on how you set the three thresholds

Iter. = Seed > Neigh.

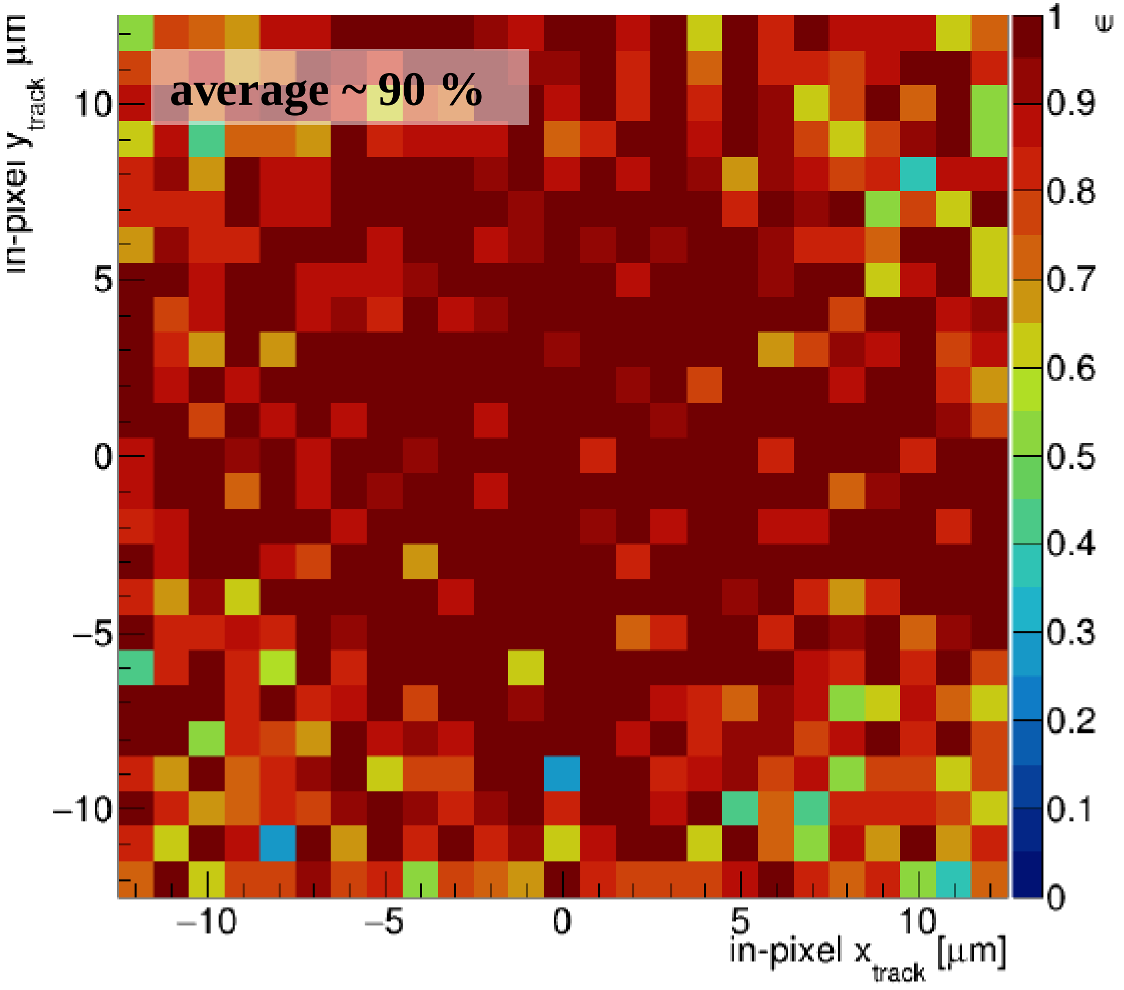


+ > Seed ○ > Neighbor

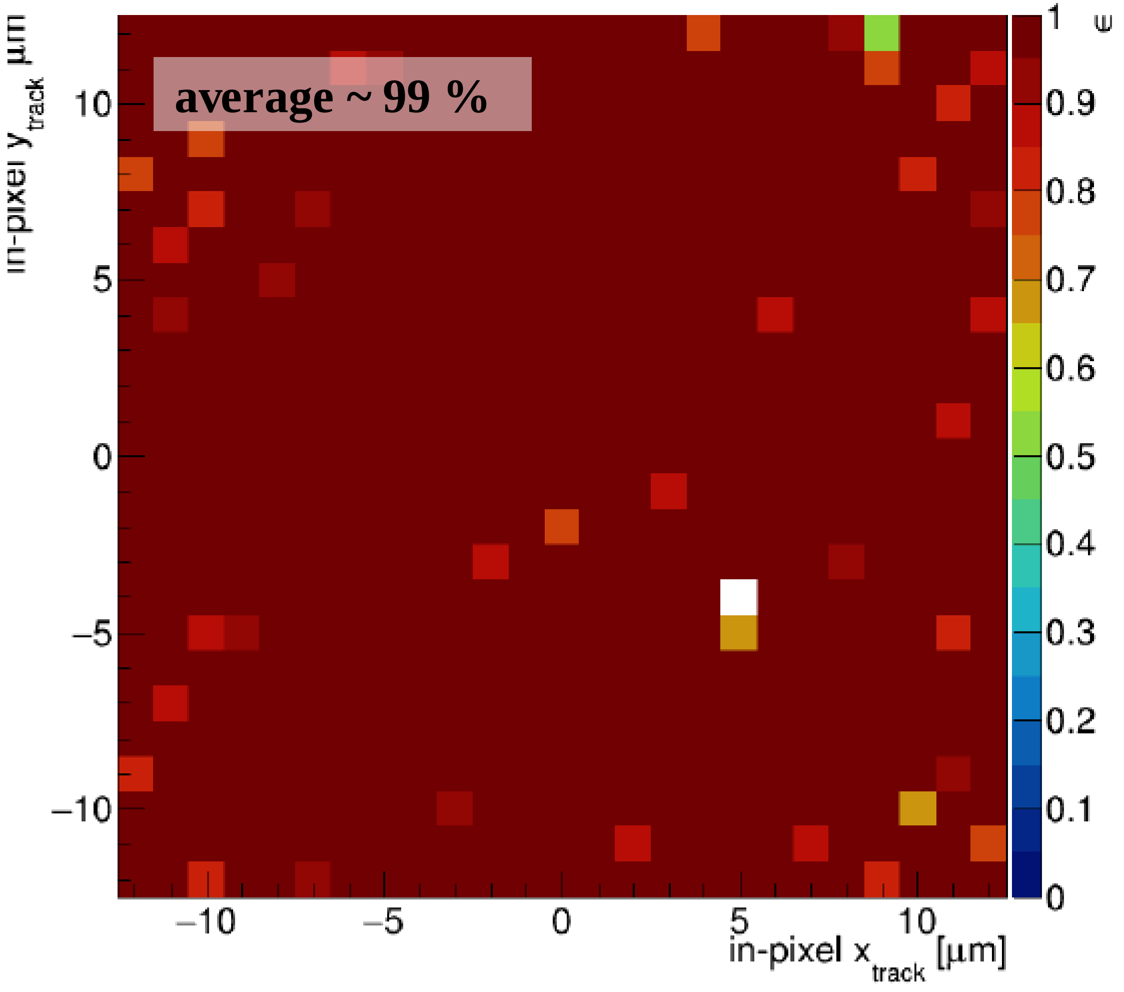
Results – In-Pixel Efficiency Comparison

Efficiency losses can be associated with the corners and edges of the pixel

25 µm, Standard, $V_{sub} = V_{pwell}$ = -4.8 V, th = 120 e^-



25 µm, N-gap, $V_{sub} = V_{pwell}$ = -4.8 V, th = 120 e^-

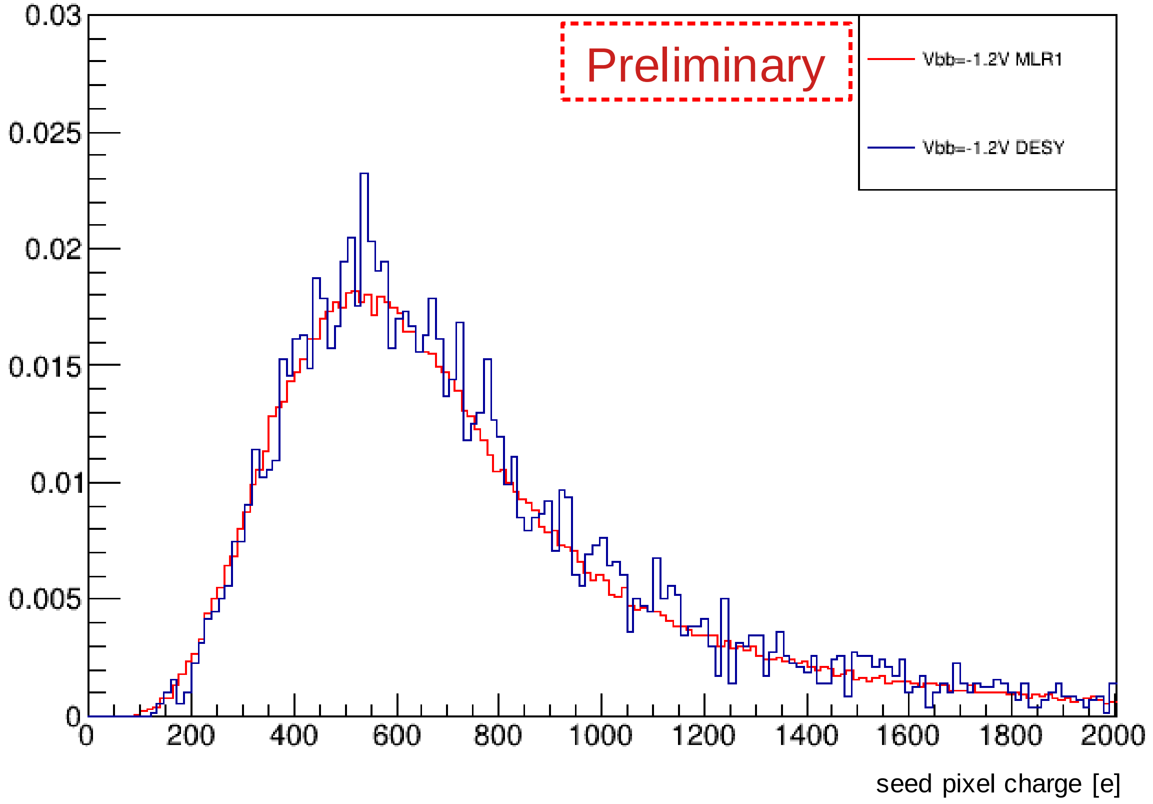


Results – Cluster Charge Distribution

Comparing with ALICE

- Studies with Caribou readout system are complementary
- ALICE collaboration is working on publishing their results
- Studies were performed with different
  - Beam lines
  - Front-end operation points
  - Analysis and calibration procedures
- Excellent agreement given systematic differences

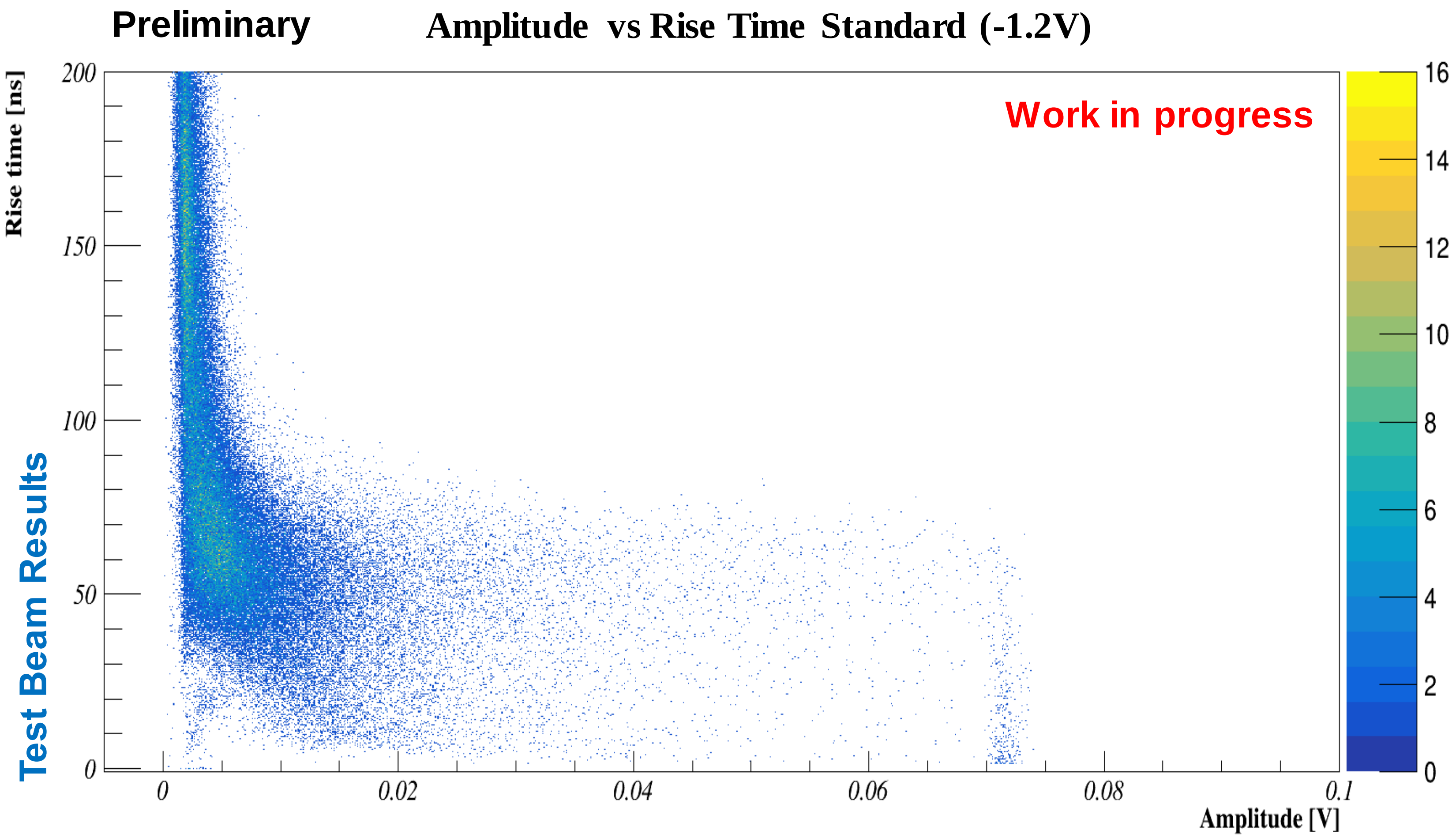
25 um, n-gap, -1.2 V



Conclusion: We are not alone!

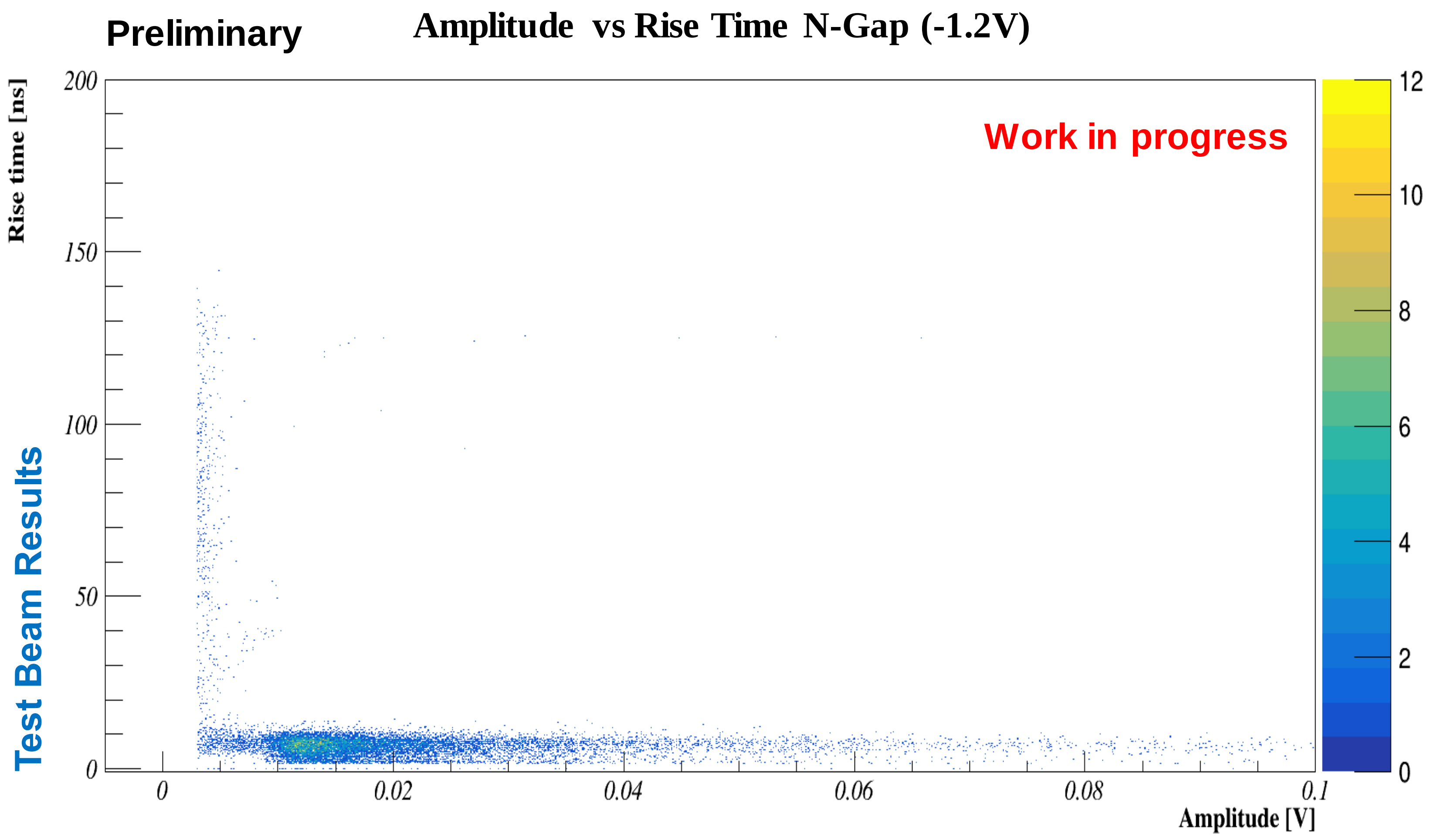
Amplitude vs Rise time distribution

Test Beam Results



- Fast rise time values achieved for larger values of the amplitude.
- Wide range of rise time distribution.

Amplitude vs Rise time distribution

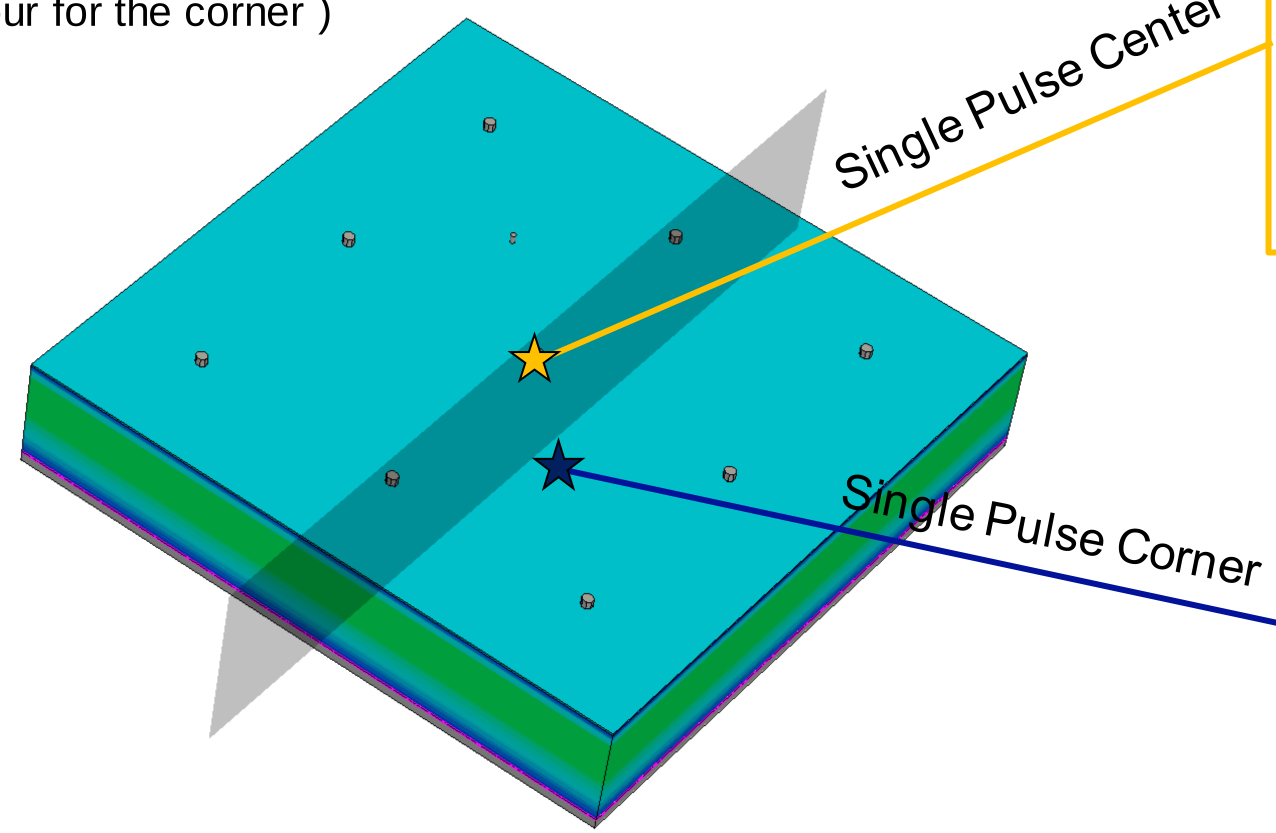


- Clear trend where regardless of signal amplitude, a fast rise time is achieved.
- Only for small signals, large values of rise time appear.

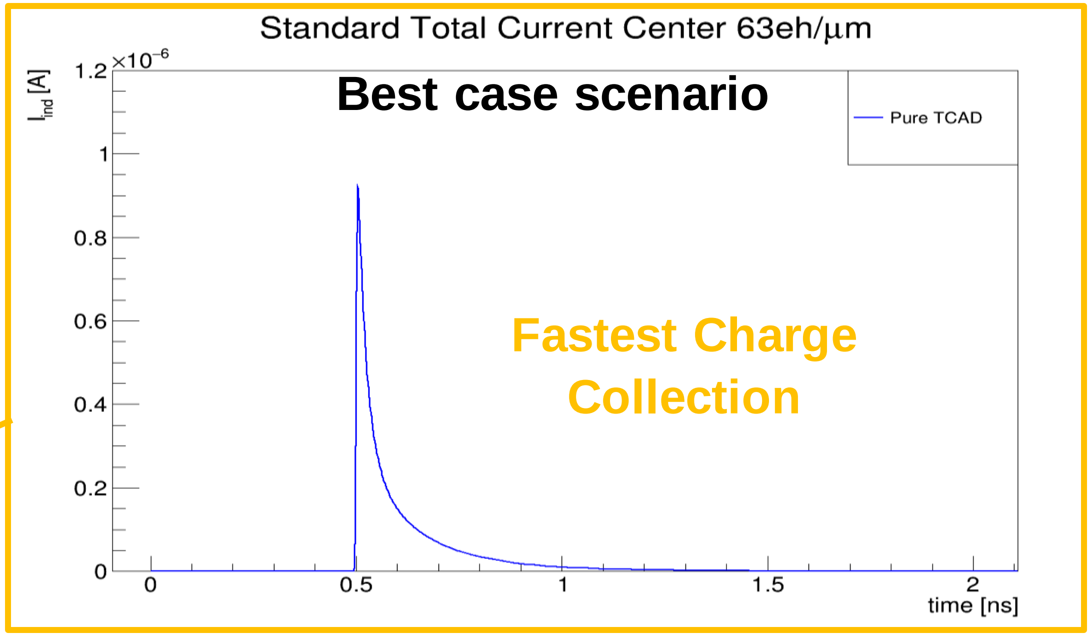
TCAD + Allpix^2 Simulations

Two extreme cases under study – Standard Layout

- Charge carriers injected alongside the pixel **corner** or **center**
- Fixed amount of charge carriers **63 eh/µm**
- Average of pixels over threshold calculated (One for center and four for the corner)



3x3-cell model in TCAD



Not same time scale!