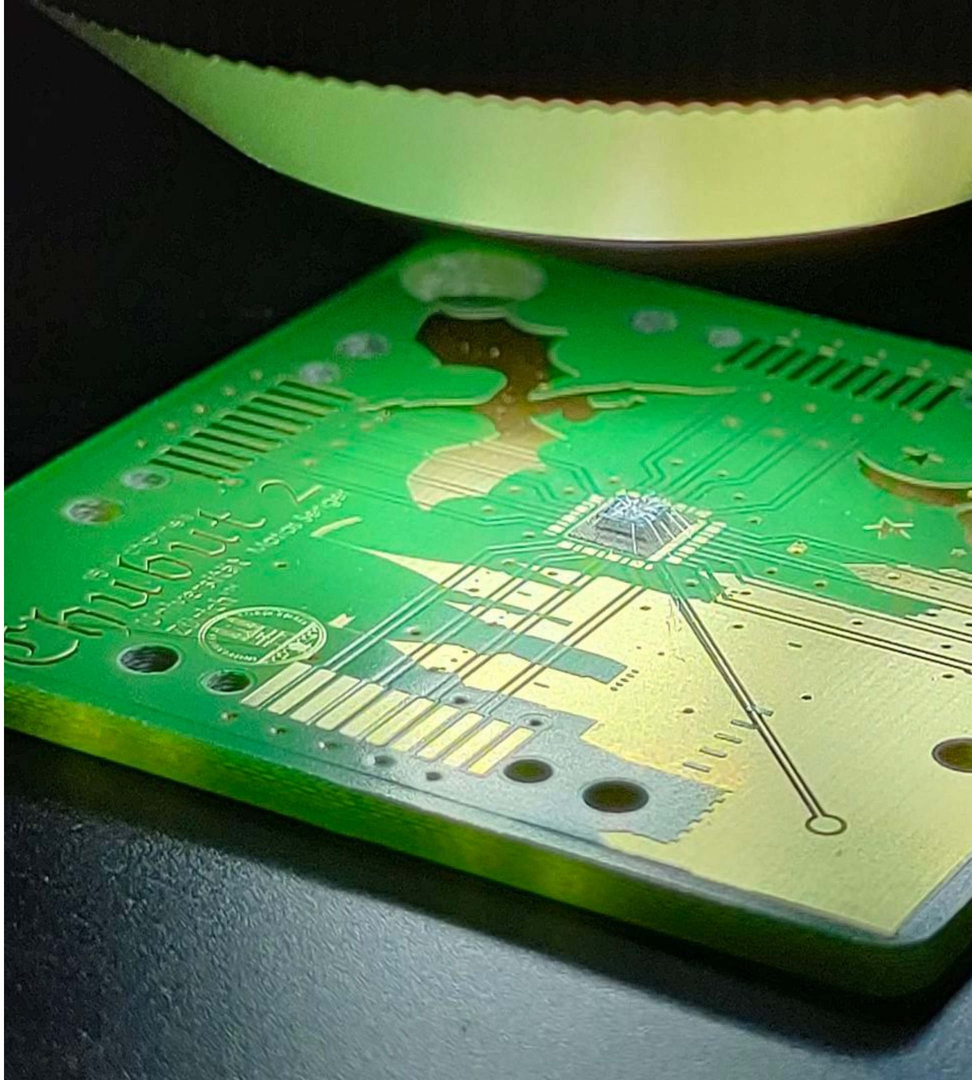
3rd PhD Committee Meeting

Matias Senger

December 11th, 2023



3rd PhD Committee Meeting

- PhD Started in June 2020
  - Defense expected for spring 2024
- Requirements
  - Teaching fulfilled ✅
  - ECTS credits fulfilled ✅
- Publications and presentations in conferences
  - Senger, Matias, Anna Macchiolo, Ben Kilminster, Giovanni Paternoster, Matteo Centis Vignali, and Giacomo Borghi. "A Comprehensive Characterization of the TI-LGAD Technology." Sensors 23, no. 13 (January 2023): 6225. https://doi.org/10.3390/s23136225.
  - Caminada, L., B. Kilminster, A. Macchiolo, B. Meier, M. Senger, and S. Wiederkehr. "Development of a Timing Chip Prototype in 110 Nm CMOS Technology." Journal of Physics: Conference Series 2374, no. 1 (November 2022): 012081. https://doi.org/10.1088/1742-6596/2374/1/012081.
  - Senger, M., A. Bisht, G. Borghi, M. Boscardin, M. Centis Vignali, F. Ficorella, O. Hammad Ali, B. Kilminster, A. Macchiolo, and G. Paternoster. "Characterization of Timing and Spacial Resolution of Novel TI-LGAD Structures before and after Irradiation." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, June 21, 2022, 167030. https://doi.org/10.1016/j.nima.2022.167030.
  - RD50 Workshops 2020, 2021, 2022, 2023

PhD activities

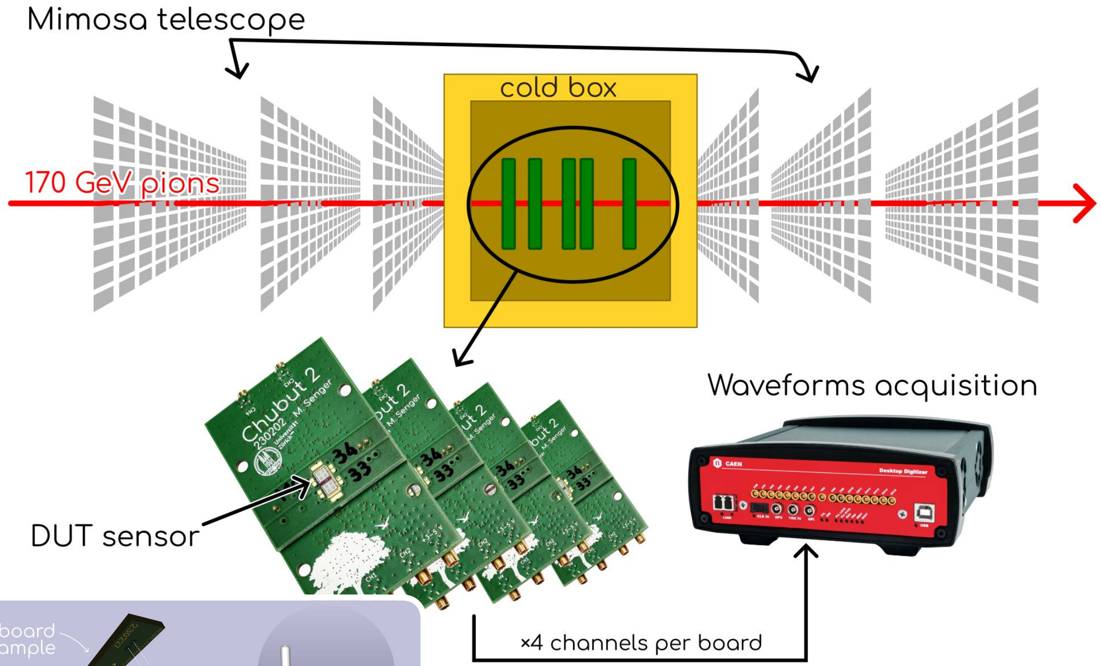
- Up to November 2022, summarized in previous PhD Committee Meeting slides (link)
- Today:
  - 2023 activities
  - Looking forward to my graduation 👨‍🎓

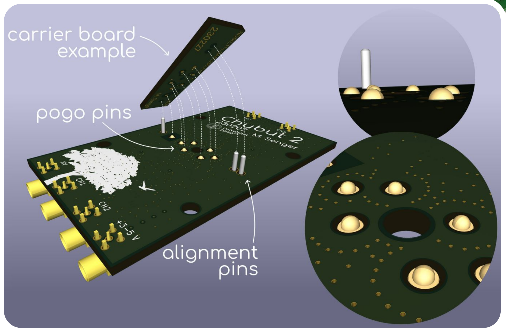
2023 outline

- BNL AC-LGADs
  - TCT scans
  - Reconstruction algorithms
- AIDAinnova test beams
  - Preparations
    - CAEN digitizer
    - Readout boards
  - During test beam
    - 3 weeks in total
  - After test beam
    - Data analysis
      - TI-LGADs
      - BNL AC-LGADs
    - Presentation of results

AIDAinnova test beams

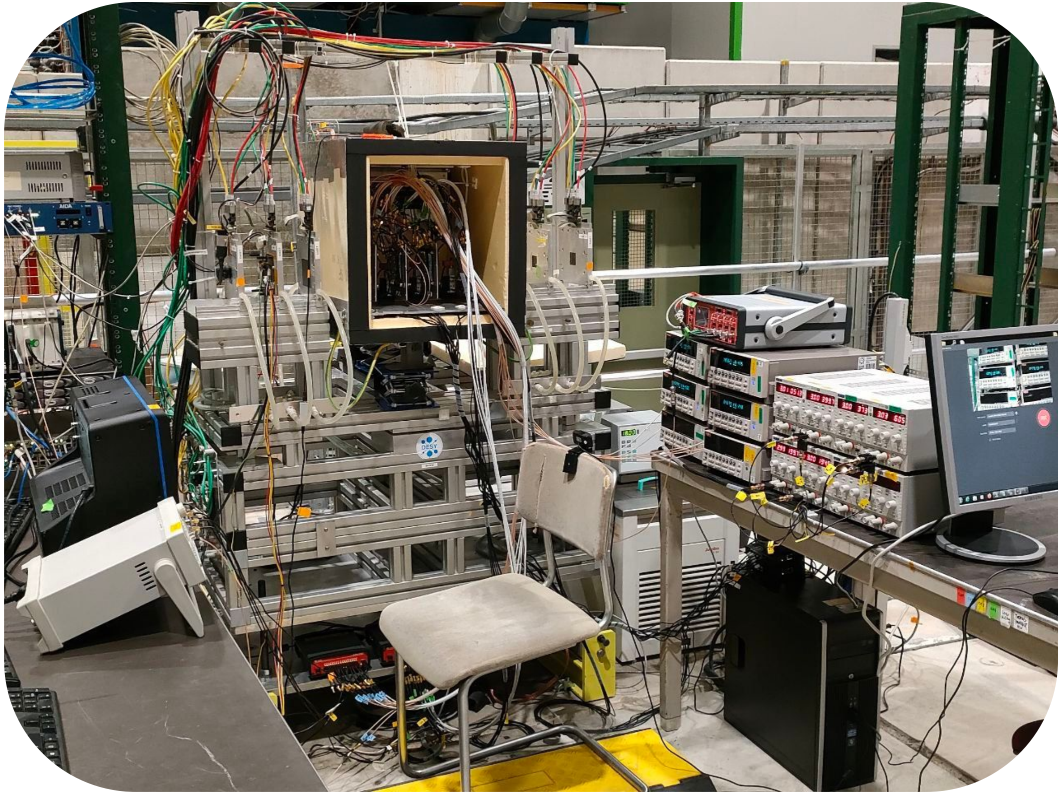
- 2 test beams @ CERN
  - 2 weeks in June
  - 1 week in August
- My contributions:
  - Suggested to go for 16ch digitizer, instead of oscilloscopes
  - Integration of digitizer into EUDAQ
  - Readout boards
  - Commissioning and operation of the setup
  - Data analysis for TI-LGADs and BNL AC-LGADs

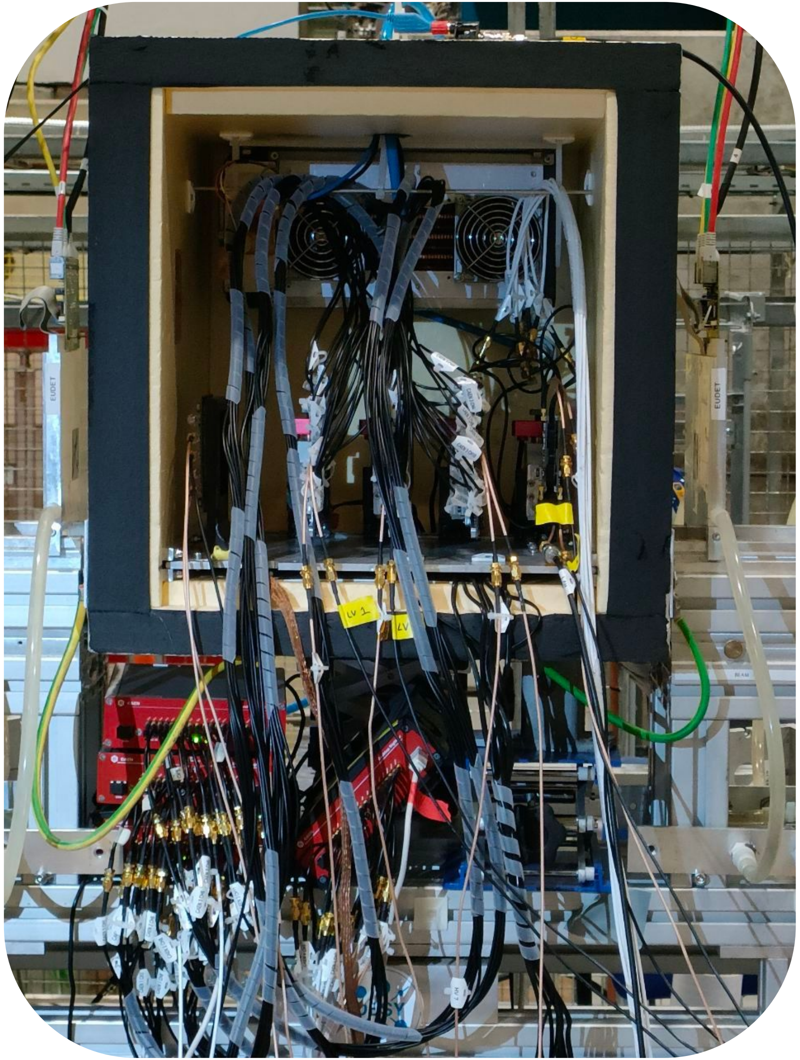




Test beam setup

Some photos:



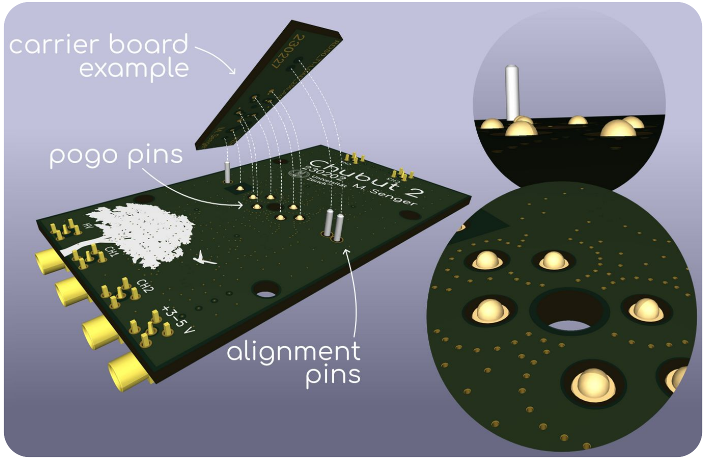


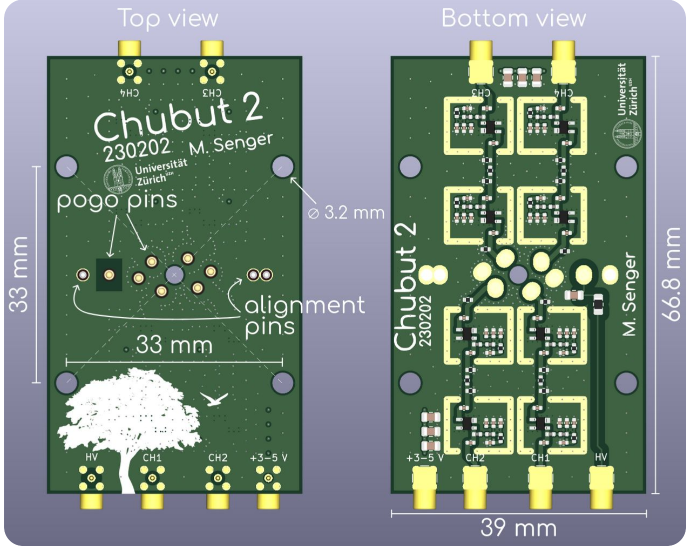
CAEN DT5742b digitizer

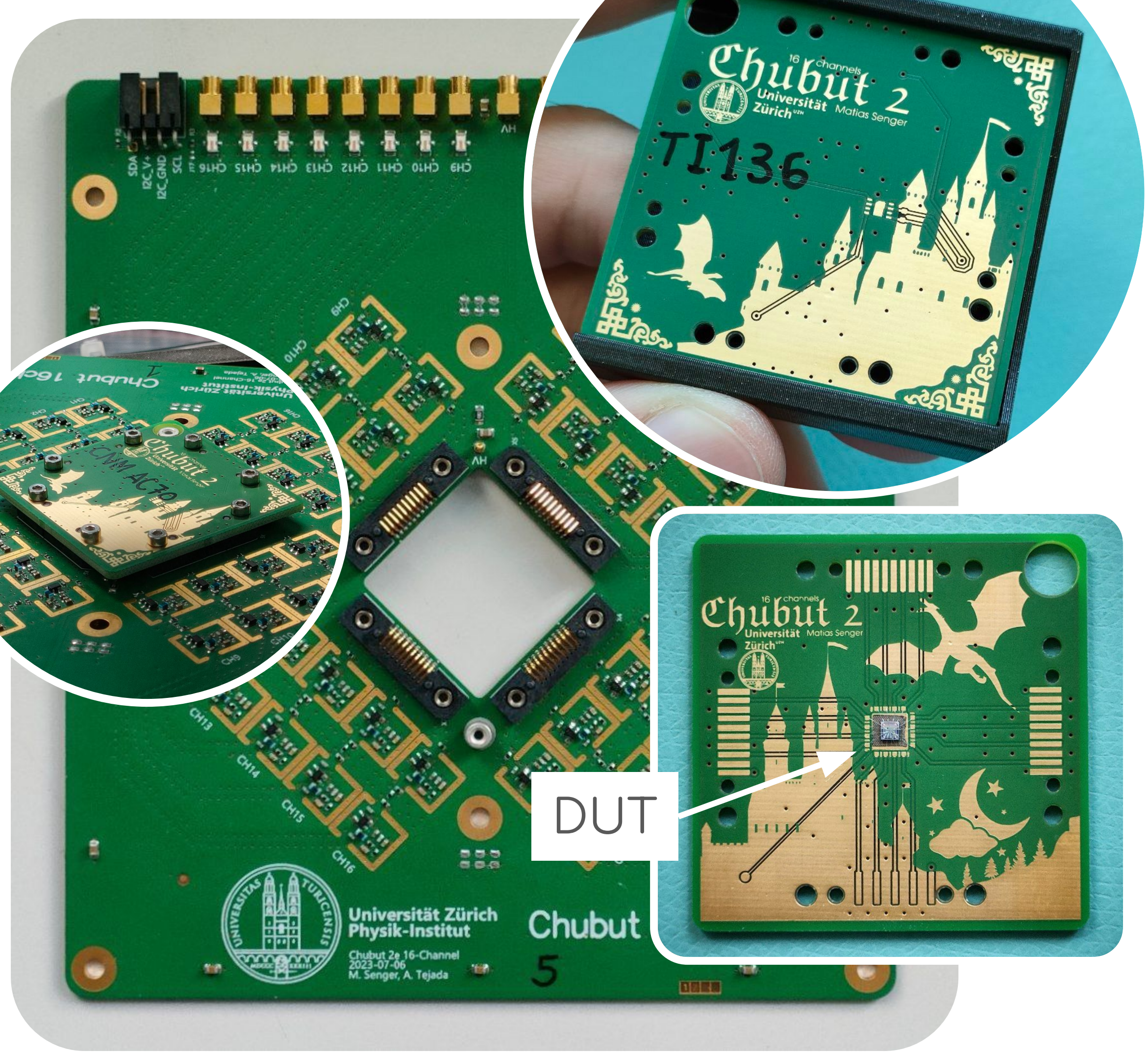
- Why?
  - Not as good as oscilloscopes, but...
  - 16+1 channels per digitizer
  - factor of 10 cheaper
- We put 4 digitizers together
  - 64 readout channels @ 5 Gs/s, 500 MHz
  - Equivalent to 16 oscilloscopes 🤯
- I made some tests to demonstrate the digitizer is a good enough replacement for the oscilloscopes, see slides here
- I wrote the module to integrate it into EUDAQ

Readout boards

- 4 channels, 2 stages amplification
- Low cost carrier + main board design
- Easy to adapt to any sensor geometry
- Originally intended for the lab
- Prototyped in 2022, finished in 2023
- Why?
    - No (known) alternative with 4 active channels
    - Ease testing large number of sensors







Chubut 2 16CH

- New version with 16 channels
- Tested in TCT and beta setup ✅ (see here)
- Installed in August test beam for 1 run, unfortunately something went wrong with the beam
- Eager to take data with it in the next test beam
- Why?
  - More channels are always better
  - AC-LGADs require at least 2 adjacent cells to be readout

Data analysis

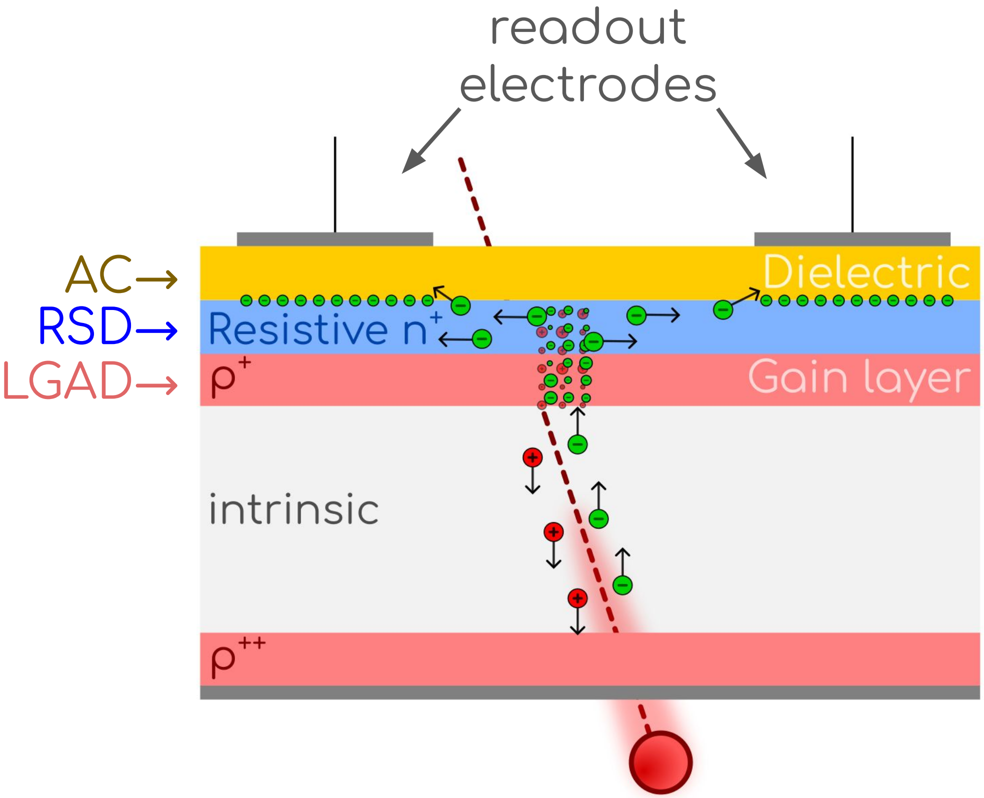
Analyzed data from TI-LGADs and BNL AC-LGADs, presented results in 43rd RD50 Workshop

- 2D pixelated BNL AC-LGADs: From laser TCT to Test Beam characterization
- First characterization of TI-LGAD technology in a test beam setup

AC-LGAD

The AC-LGAD technology

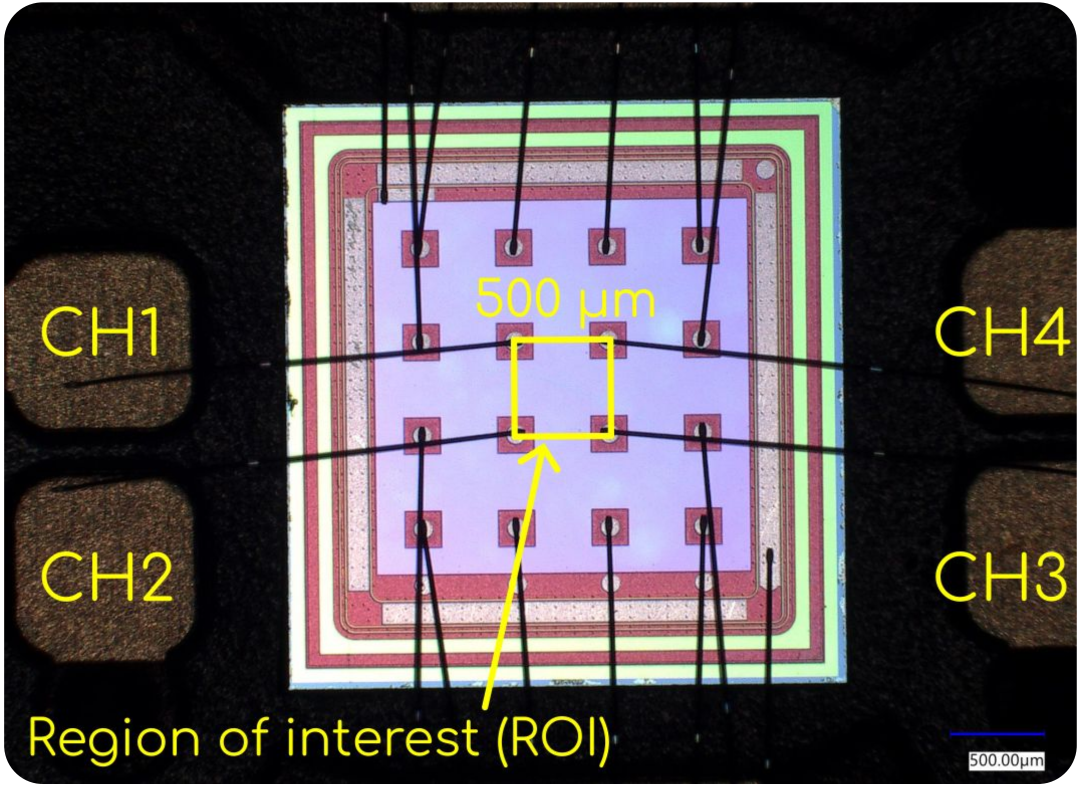
- AC-LGAD*: A single, large LGAD with a resistive and a dielectric layer on top, and small electrodes touching it.
- Fill factor = 100 % by construction. ✅
- Time resolution inherited from LGAD. ✅
- Spatial resolution improved by sharing the charge. 👏



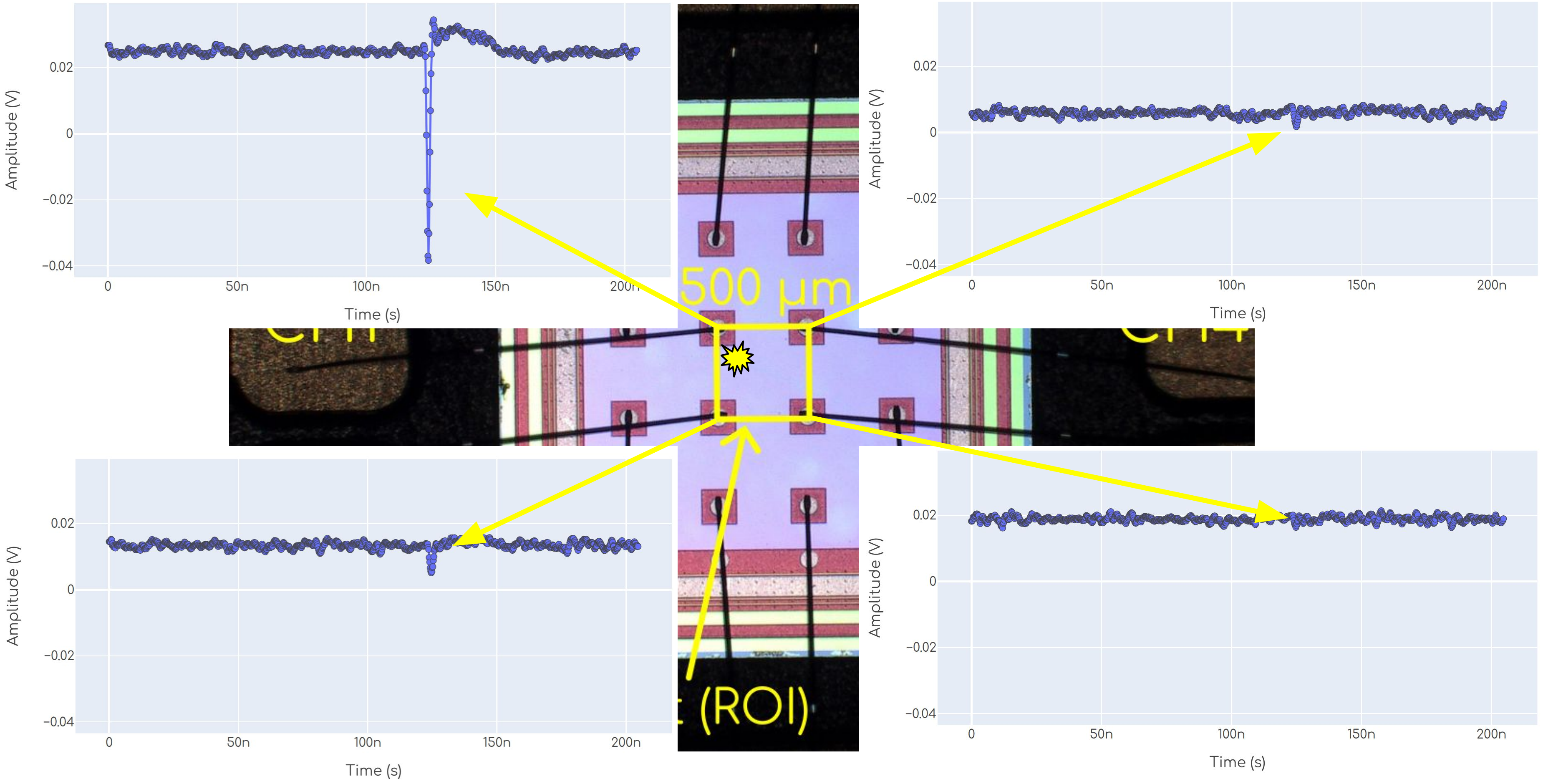
* Maybe a better name would be "AC-RSD-LGAD", see the cartoon.

Characterized devices

- 2 identical devices
- Manufactured at BNL
- Active thickness: 30 µm
- Pad size: 200 µm
- Pitch: 500 µm
- 2×2 pads readout
- Unused pads to GND
- Non irradiated



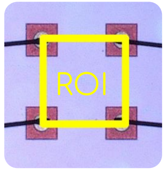
Charge sharing at the heart of this technology



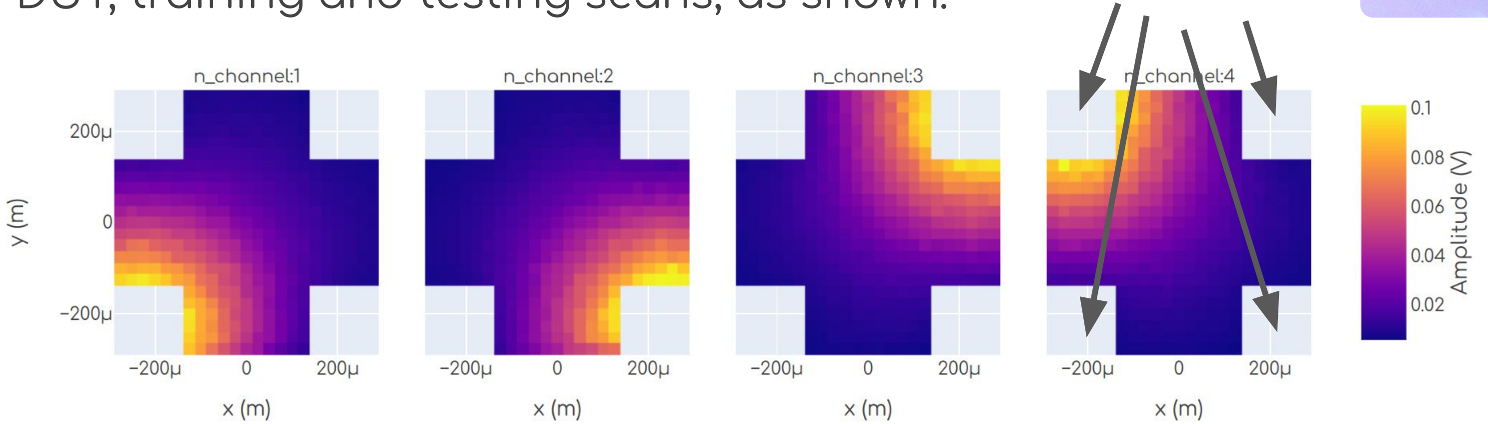
TCT scans

Two scans per DUT, training and testing scans, as shown:

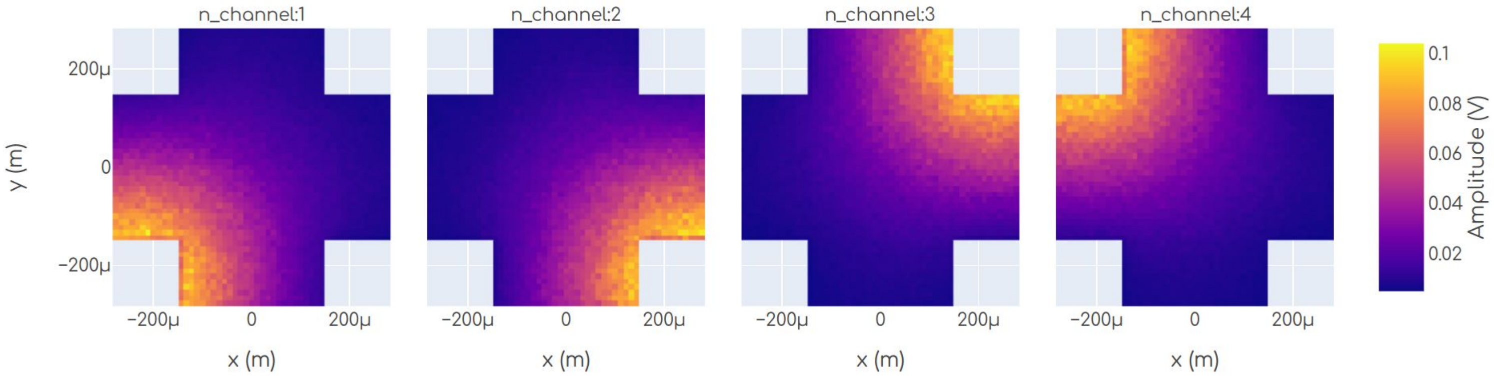
Readout metal pads position



Training scan:
25×25 μm² grid
111 events per position



Testing scan:
11×11 μm² grid
22 events per position



Position reconstruction methods

Two methods were compared:

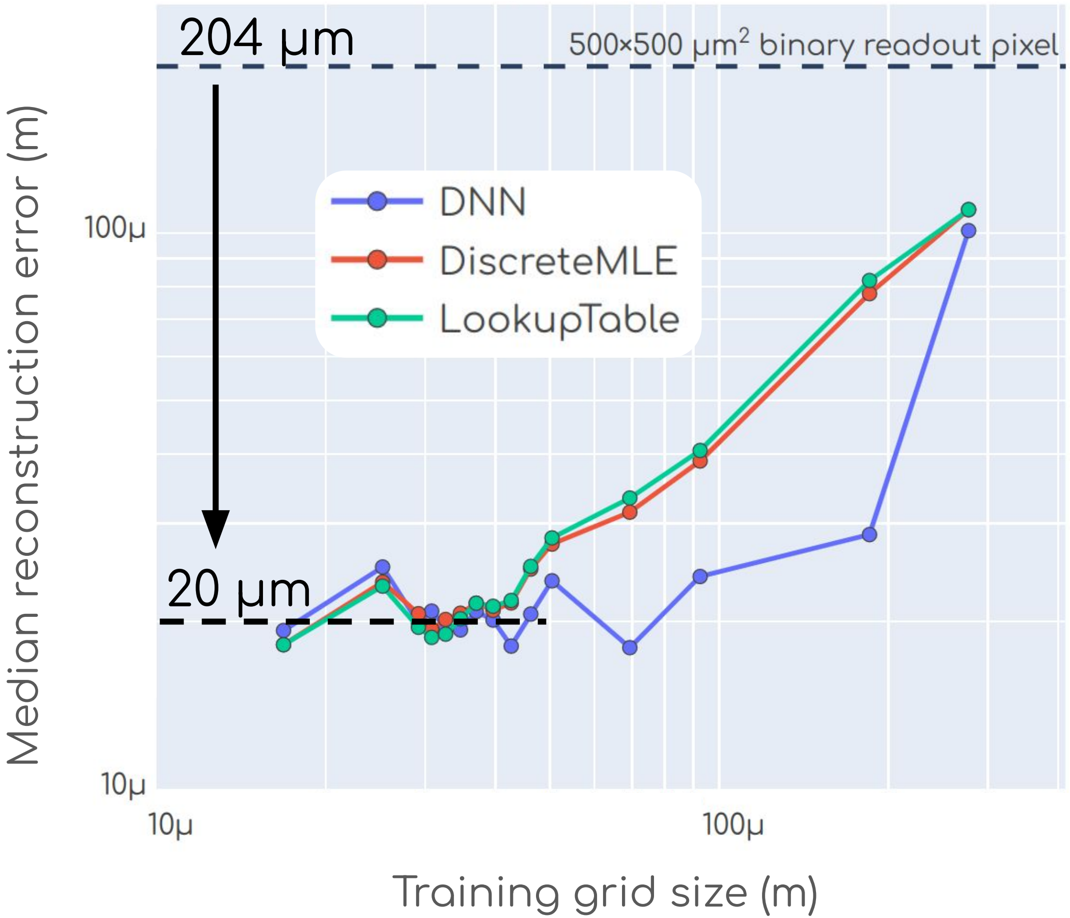
1. Charge imbalance formula.
2. DNN.
   a. Using ASF.
   b. PyTorch library.
3. Discrete MLE
   a. Measure likelihood function at each point and use it to reconstruct hit position

$$\begin{cases} x_{\text{reconstructed}} = \dfrac{\text{pitch}_x}{2} Q_{\text{imbalance } x} \\ y_{\text{reconstructed}} = \dfrac{\text{pitch}_y}{2} Q_{\text{imbalance } y} \end{cases}$$

$$\begin{cases} Q_{\text{imbalance } x} = \dfrac{Q_{11} + Q_{01} - Q_{00} - Q_{10}}{\sum Q_{ij}} \\ Q_{\text{imbalance } y} = \dfrac{Q_{00} + Q_{01} - Q_{11} - Q_{10}}{\sum Q_{ij}} \end{cases}$$

$$\text{ASF}_i = \frac{A_i}{\sum_j A_j}$$

Position reconstruction algorithms comparison (laser TCT)



- DNN outperforms the others for large grids (because it learns to interpolate, even though it was not trained for that)
- For fine enough training grid, all algorithms behave similar.
- Converges to ≈20 µm for smaller and smaller grid sizes.
- Median reconstruction error is ~10 times smaller than for a 500×500 µm² binary readout pixel. 👏

Time reconstruction algorithms

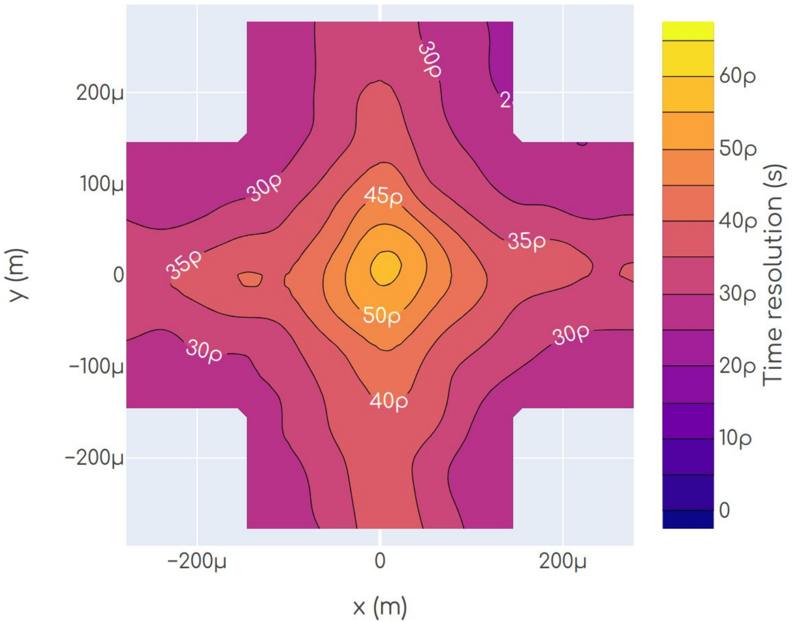
Two methods tested:

1. Single pad approach.
   - For each event just take the time from the leading waveform, ignore other channels.
2. Multiple pad weighted combination:
   - Amplitude weighted average from several pads.
   - No “hit position corrections”.

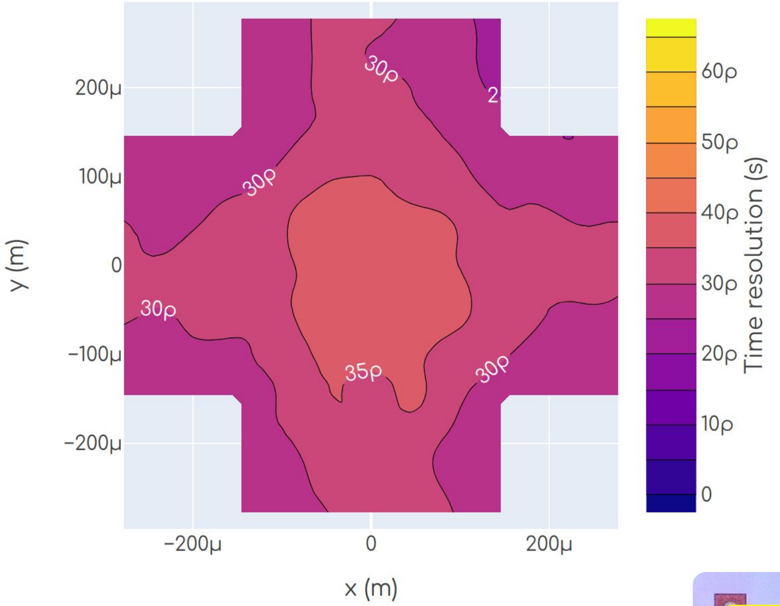
$$t_{\text{reco}} = \frac{\sum_i a_i^2 t_i}{\sum_i a_i^2}$$

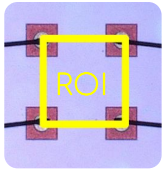
Time reconstruction algorithms (laser TCT)

Single pad algorithm



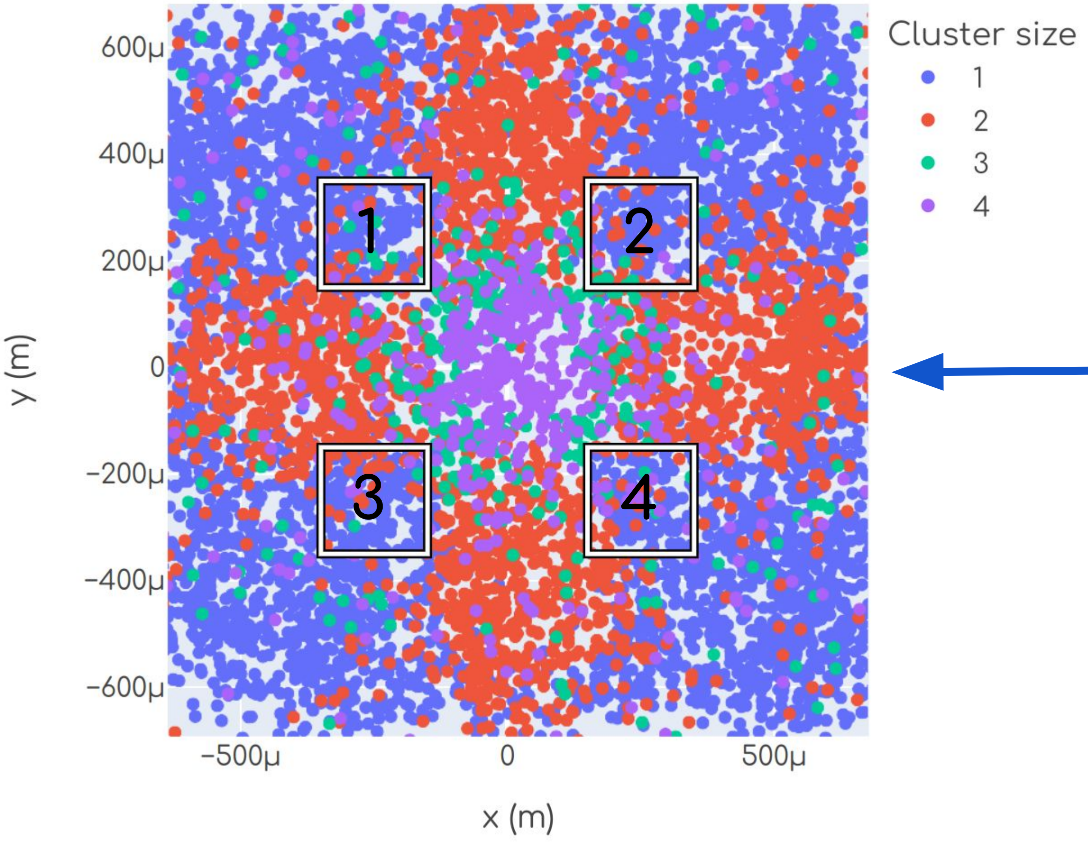
Weighted average algorithm

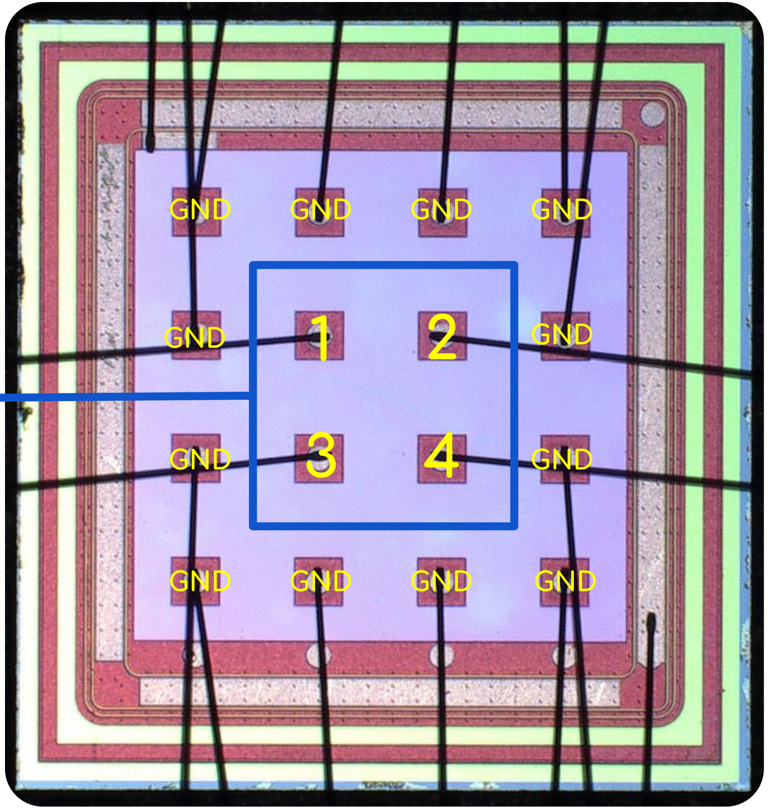




- TDCs from all pads have to be active all the time to get the desired time resolution, one TDC out of 4 is not enough.
- ⚠️ Laser TCT lacks of Landau fluctuations

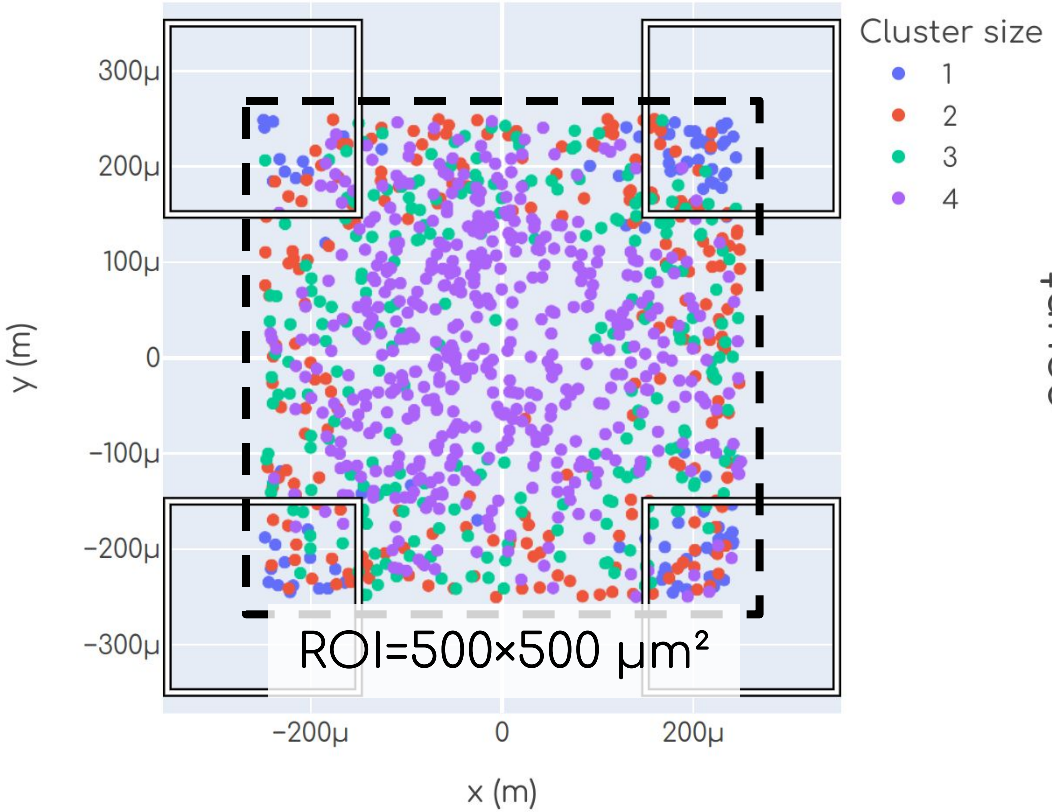
Charge sharing in action (test beam)

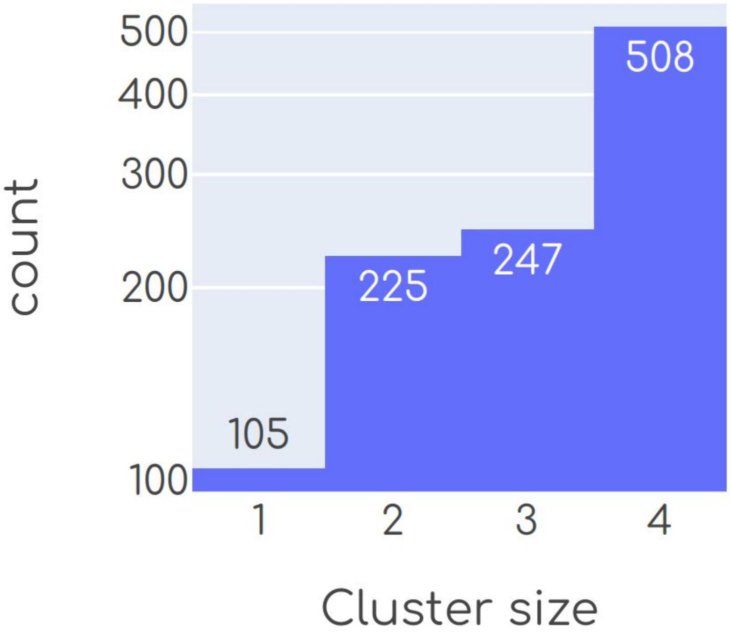




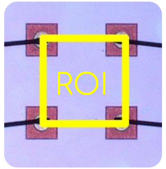
Charge sharing in action (test beam)

Within ROI: Majority of events have large cluster size (desirable in this technology) ✅





Position reconstruction (test beam)

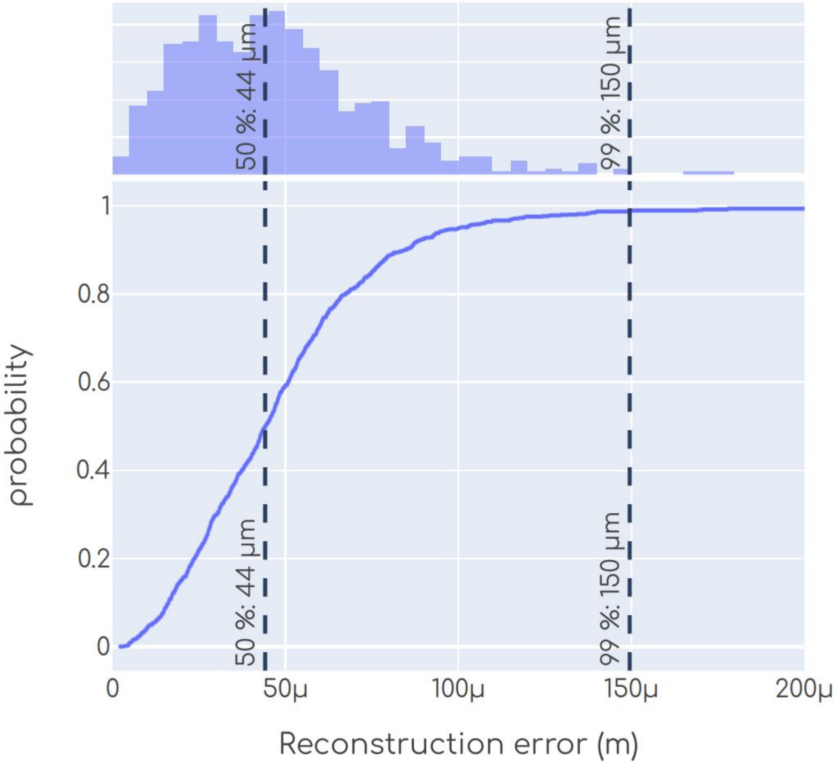


$$\text{reconstruction error} = \sqrt{\sum_{\text{coord}\in\{x,y\}} (\text{reconstructed}_{\text{coord}} - \text{telescope}_{\text{coord}})^2}$$

	Median	99 %
DNN	44 µm	150 µm
Charge imbalance formula	50 µm	173 µm
500×500 µm² SBRP*	204 µm	330 µm

quick comparison

DNN reconstruction error distribution

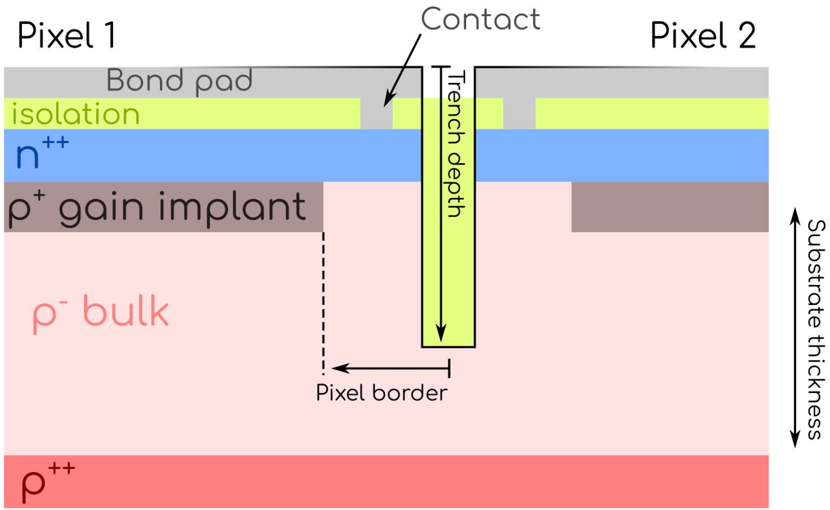


* SBRP = square binary readout pixel, see backup slides.
** Residuals in x and y also available in backup slides.

TI-LGAD

The TI-LGAD technology

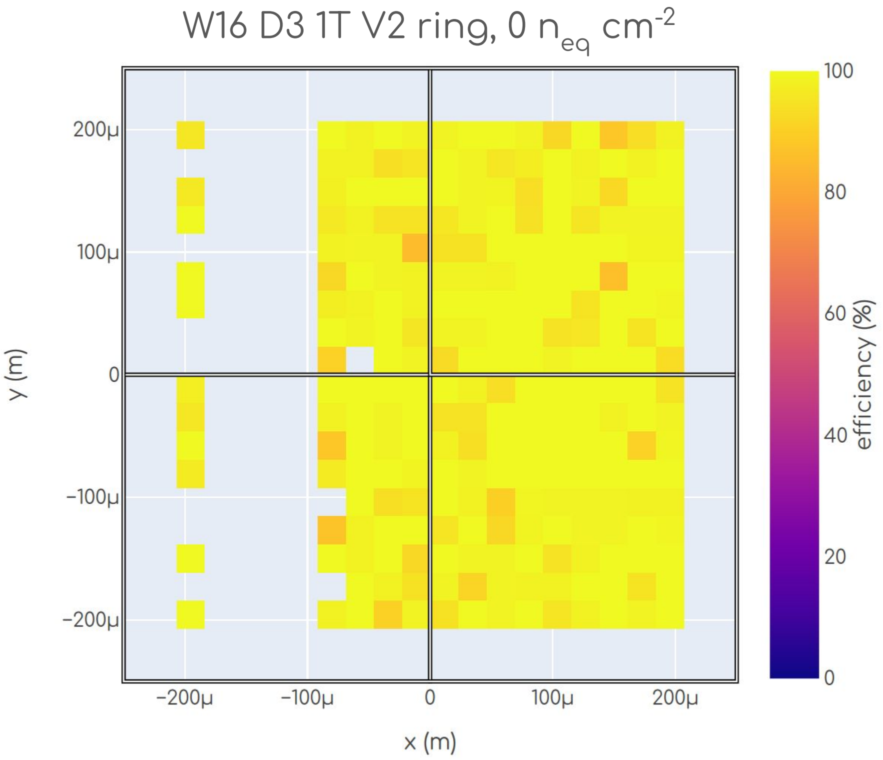
- Natural evolution of the LGAD technology
- Binary readout pixels (yes/no hit)
- Device segmentation using small trenches
- Share all same characteristics with regular LGADs, but much better inter-pixel distance
  - Time resolution ✅
  - Radiation hardness ✅
  - Small pixels with high fill factor plausible ✅

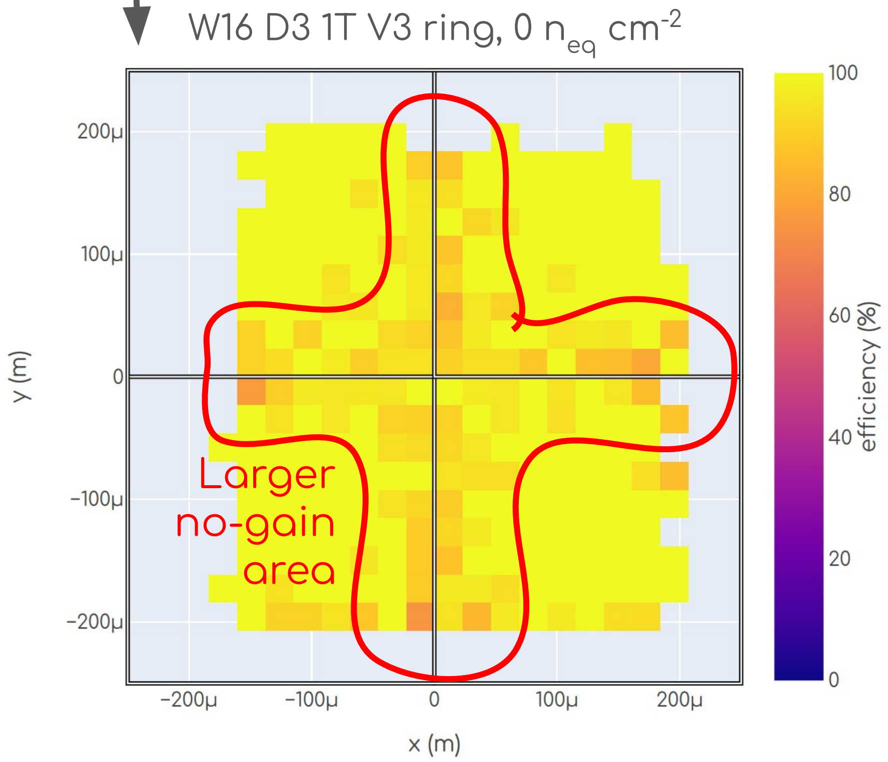


Efficiency vs position

$$\text{Efficiency} = \frac{\text{Number of detected particles}}{\text{Number of particles that went through}}$$

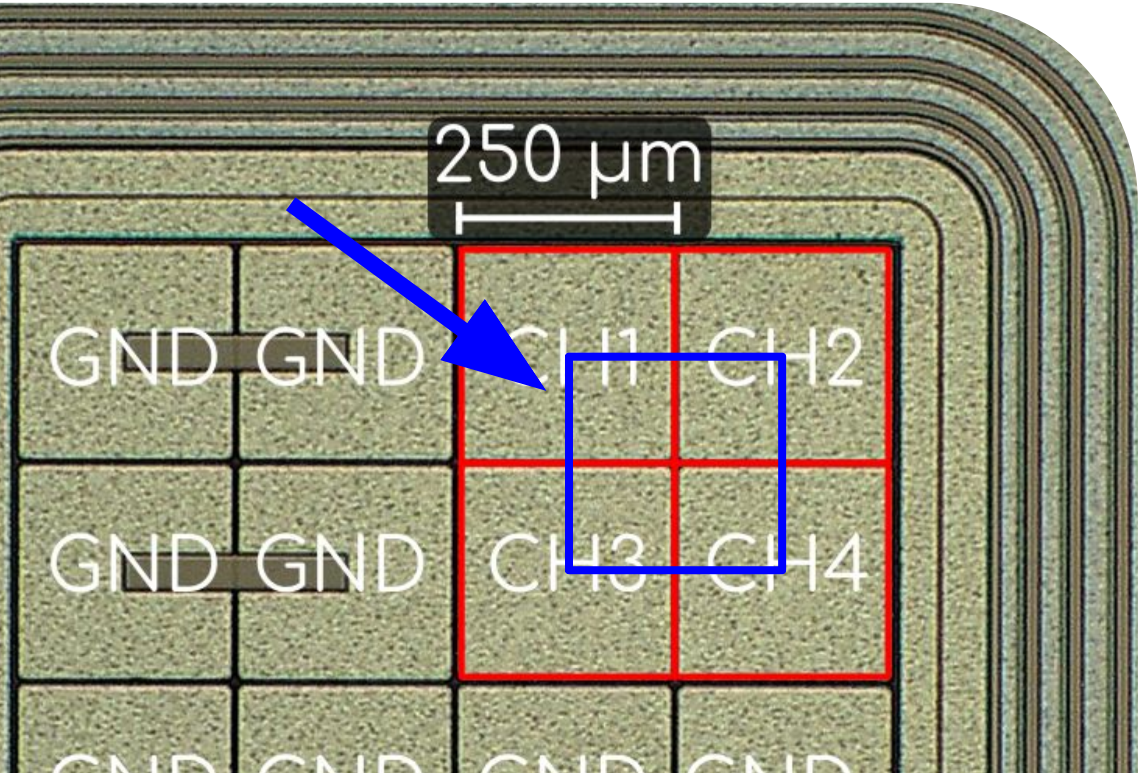
This DUT was measured as a control DUT, knowing it has a larger inter-pixel distance. Here we can see it ✅





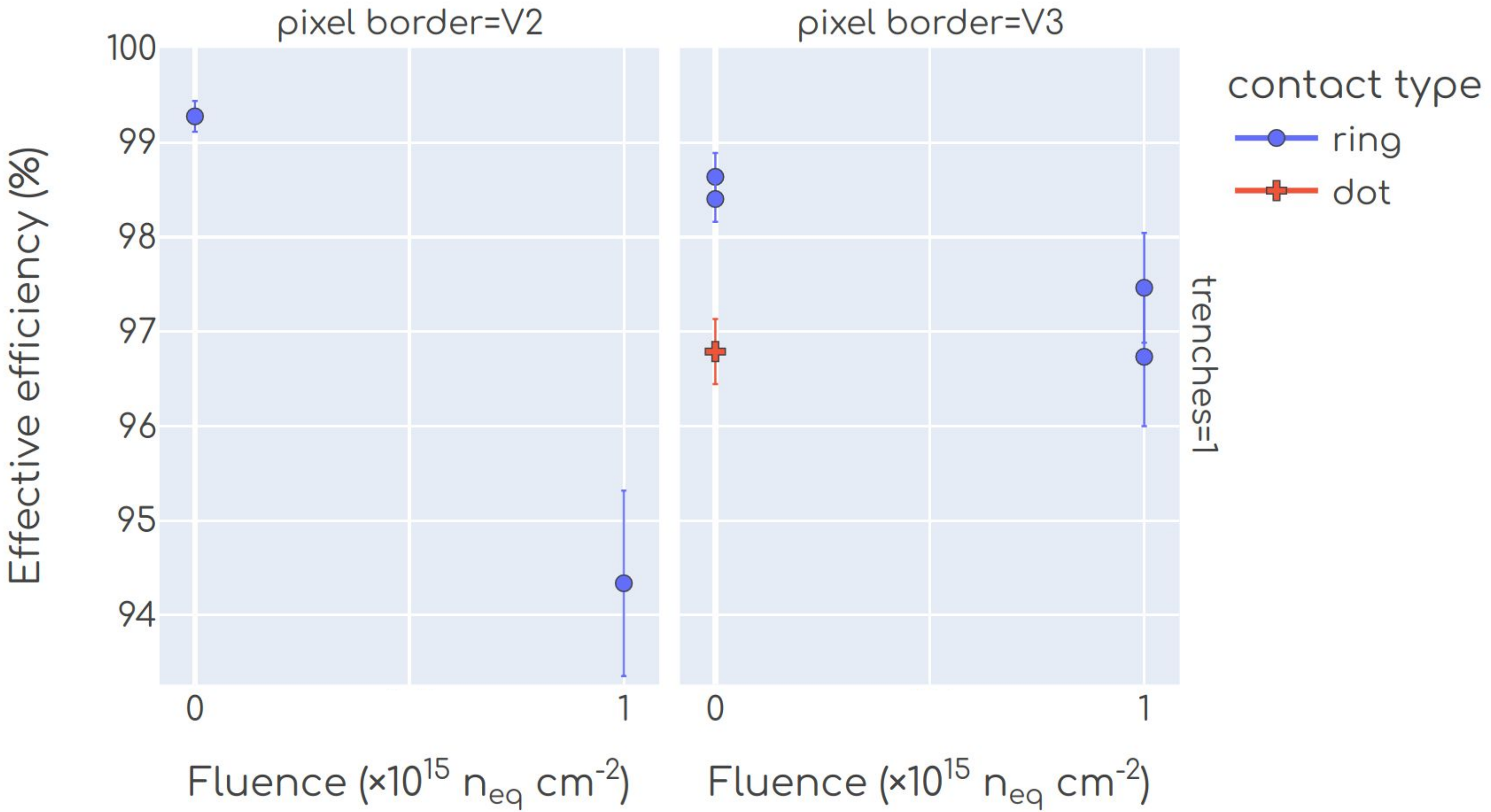
Effective efficiency

Efficiency measured in an area of the same size as a pixel. To avoid edge effects, take it close to the center:



- Global efficiency that a large area sensor would have
- Thanks to DUT symmetry, it is translation invariant
- Higher statistics

Effective efficiency



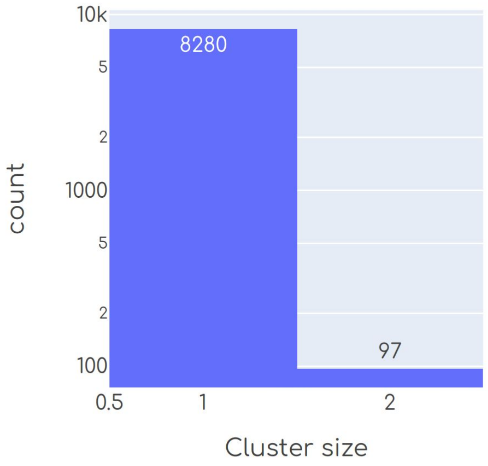
TI-LGAD vs AC-LGAD

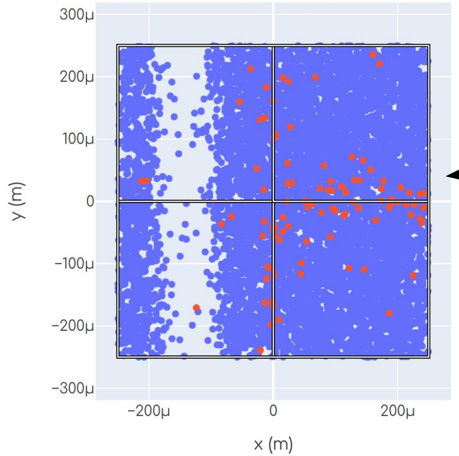
Both technologies do what they promise

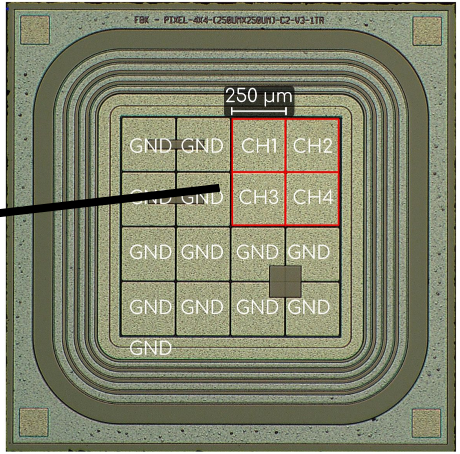
From my tests, both technologies are good... So how do we choose?

Charge sharing is the difference!

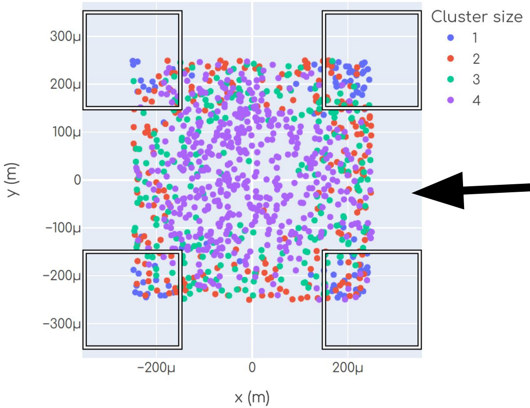
TI-LGAD →

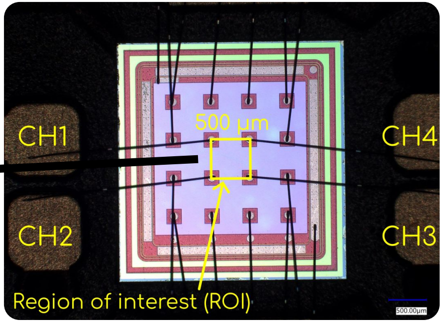






AC-LGAD →





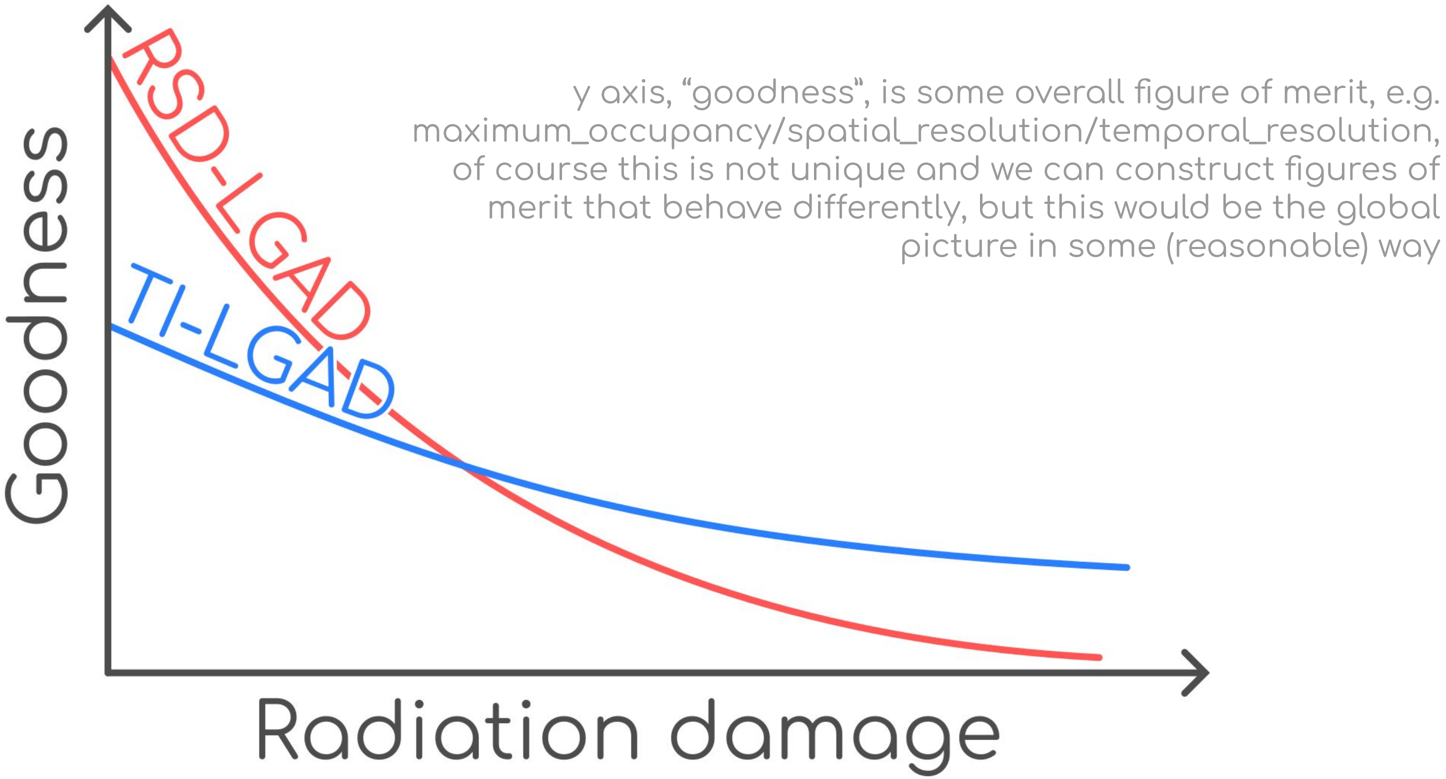
Charge sharing is the difference!

- TI-LGAD: Almost no charge sharing
- RSD-LGAD: A lot of charge sharing (desired, by design)

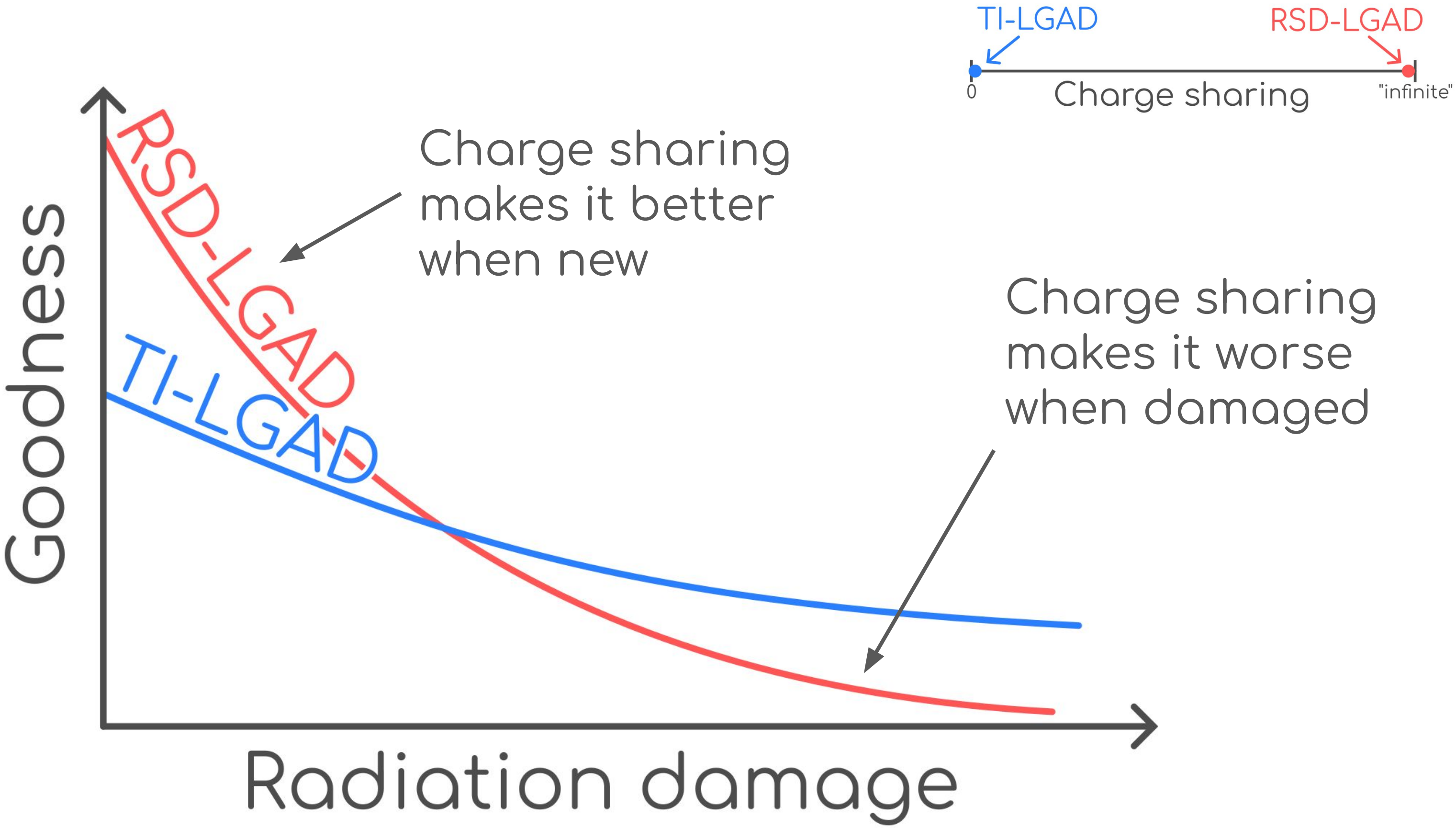
My conclusion from
my experience
+
current understanding

How do the two technologies coexist?

Given my current understanding, we can expect this (not verified yet!):



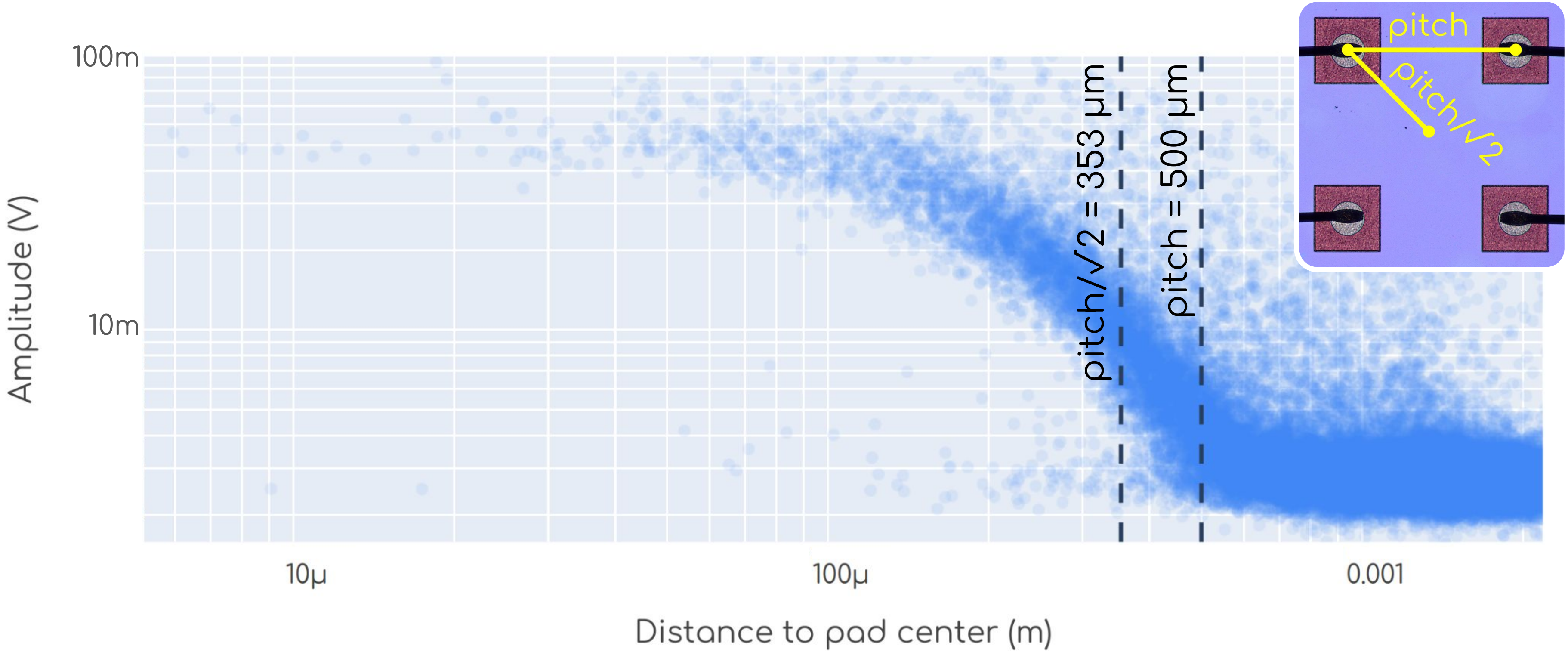
How do the two technologies coexist?



Why?

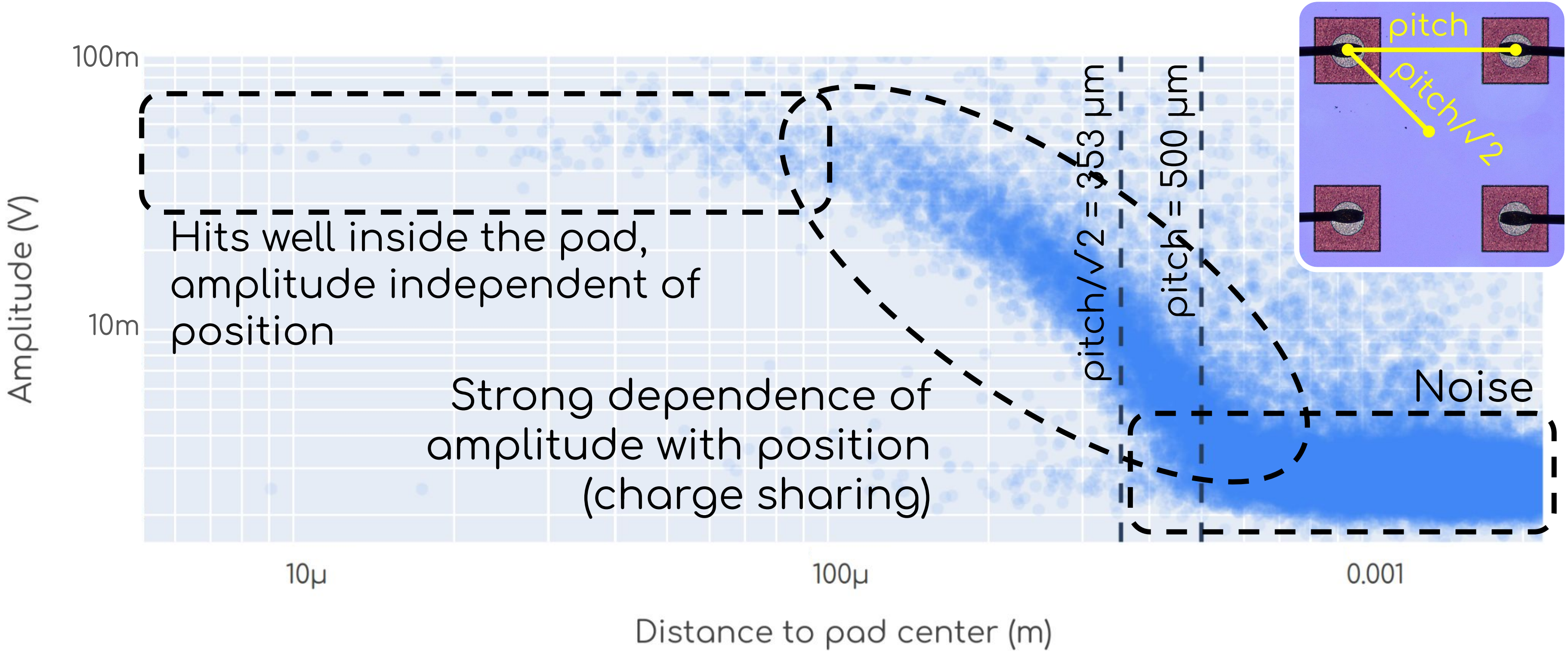
How much gain loss can we afford in AC-LGADs?

Let's look at this plot, amplitude vs distance to pad center (this is test beam data, each point is one waveform):



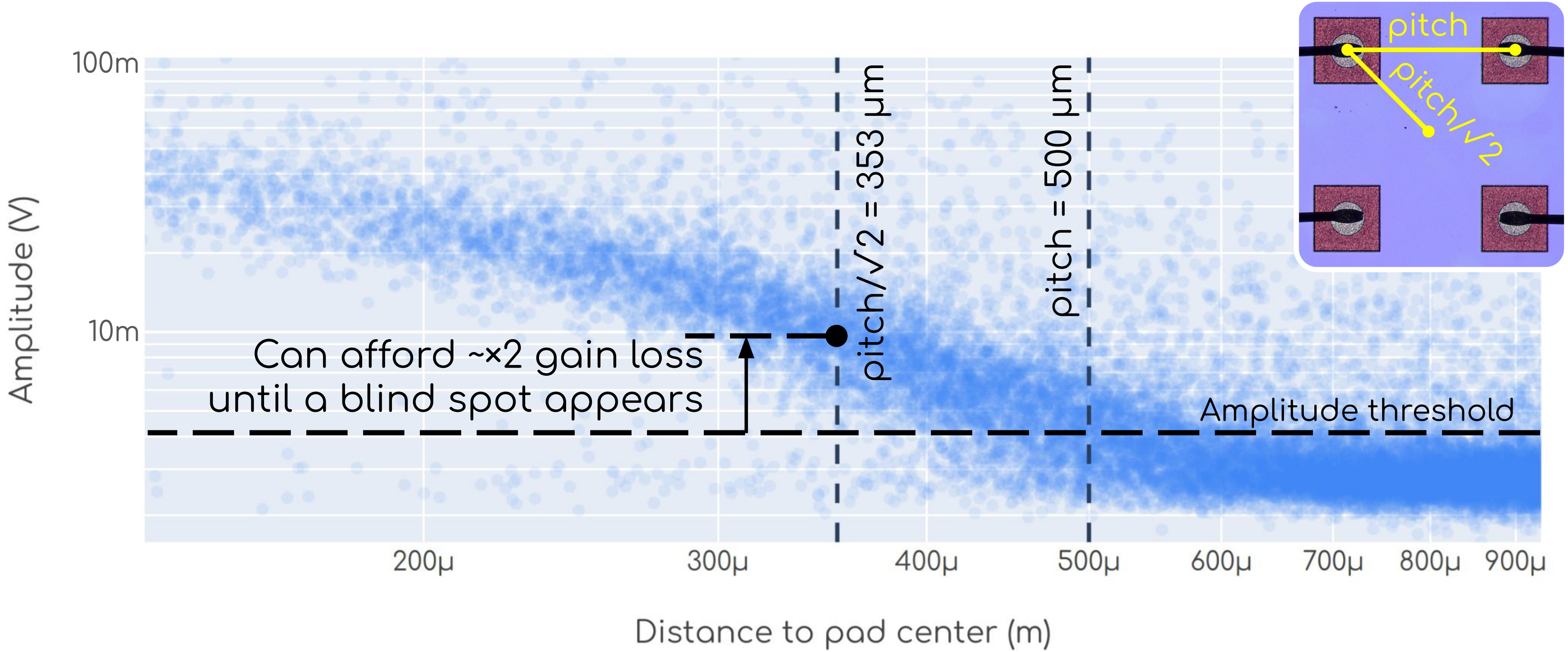
How much gain loss can we afford in AC-LGADs?

We can recognize these 3 different regimes (note log scales):



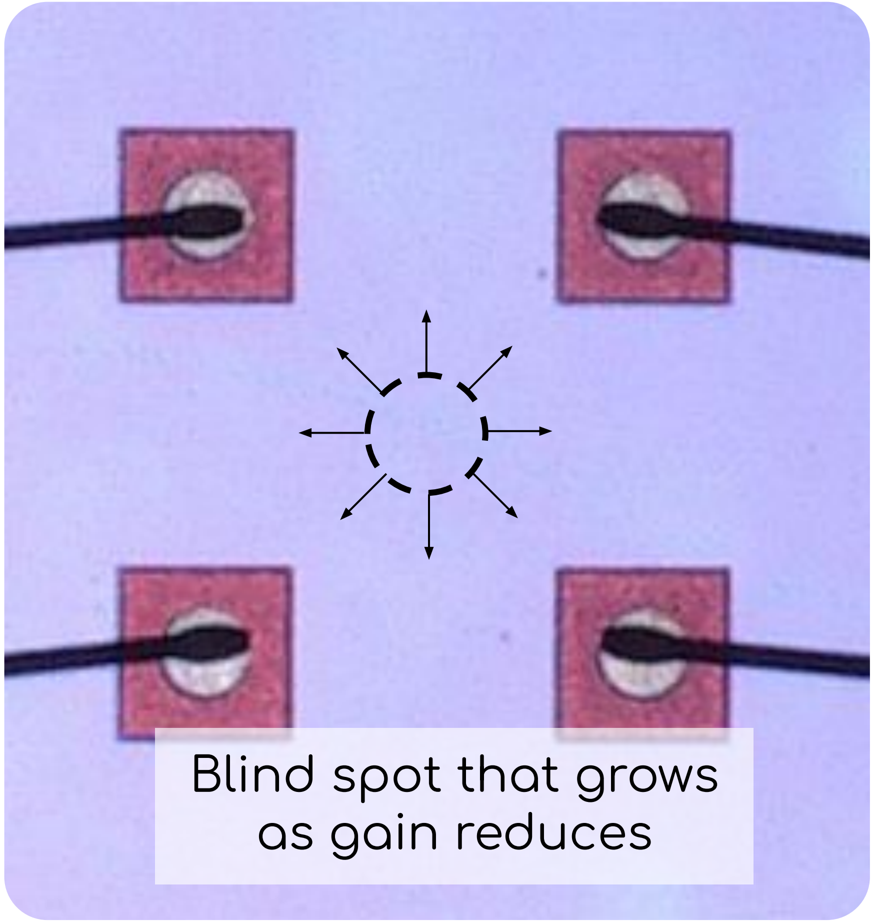
How much gain loss can we afford in AC-LGADs?

As long as the amplitude at the epicenter of the pads is higher than the noise, we can expect 100 % efficiency in all the surface, i.e. 100 % fill factor.



What happens after that?

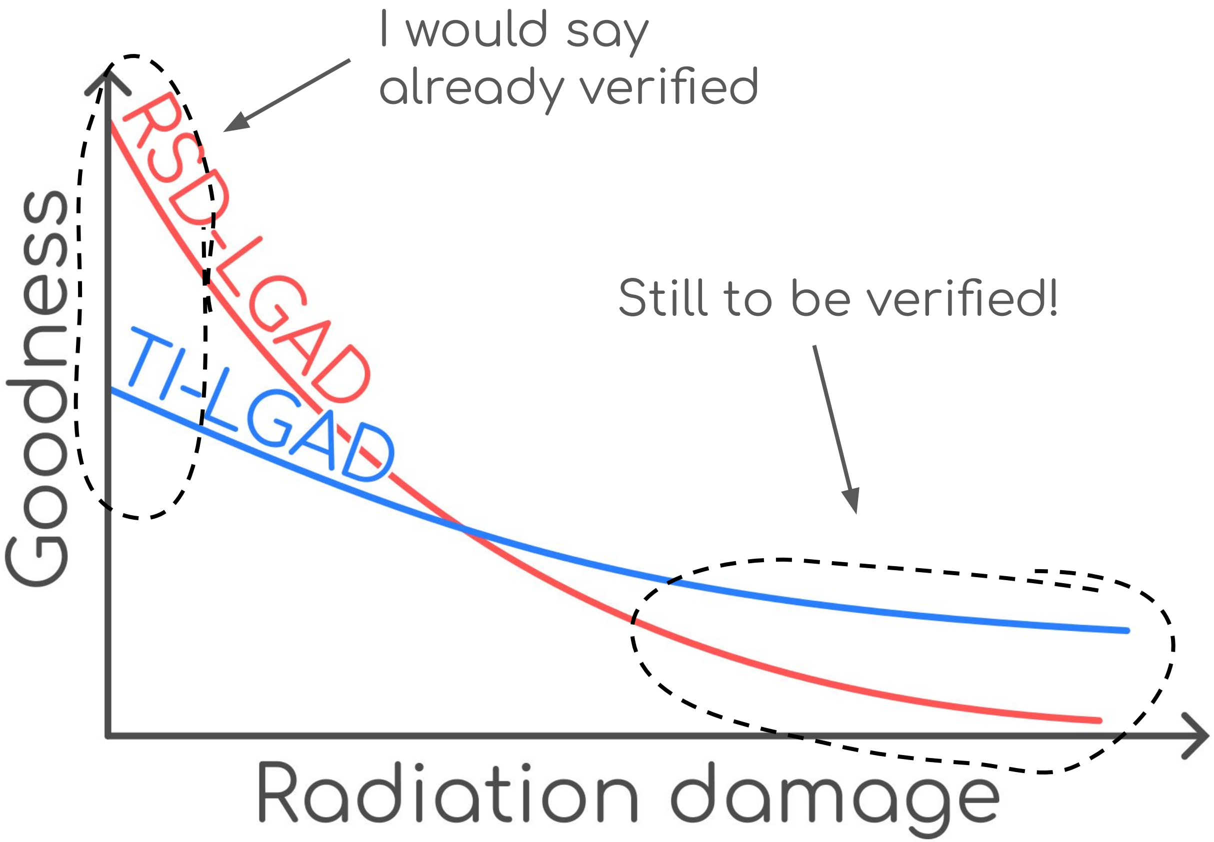
After gain loss goes beyond the "critical gain loss", a blind spot will appear in the center and grow in size as gain further reduced, thus degrading the fill factor.



Comparison of my results

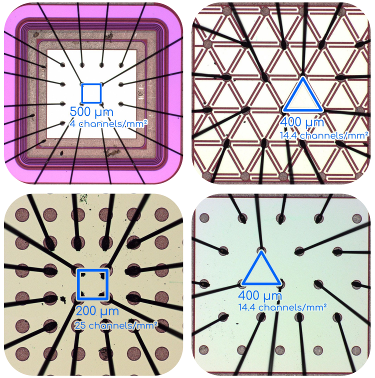
	TI-LGAD	AC-LGAD
Effective efficiency when new	>99.2±0.2 % efficiency, consistent with 0.9 ±0.2 μm effective inter-pixel distance (measured in 250×250 μm² DUTs)	100 % (measured in 500×500 μm² DUTs)
Effective efficiency after 1 n_{eq} cm^{-2} irradiation	97±1 % (measured in 250×250 μm² DUTs)	⚠️ Unknown
Spatial resolution (xy residuals)	std: pitch/√12 68 %: pitch*0.340	68 %: ±40 μm (measured in 500×500 μm² DUTs)
Spatial resolution after irradiation	Same as before irrad	⚠️ Unknown
Temporal resolution	Same as regular LGAD (measured)	Same as LGAD when 4 pads are readout, else strong position dependence (measured in 500×500 μm² DUTs)
Maximum occupancy	Calculate it as for a normal pixel of same size	Factor of 9 worse than a normal pixel with same pitch (for square pad arrangement)

How do the two technologies coexist?

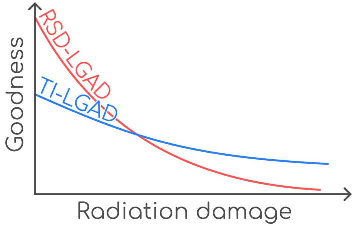


Future plans

Future plans

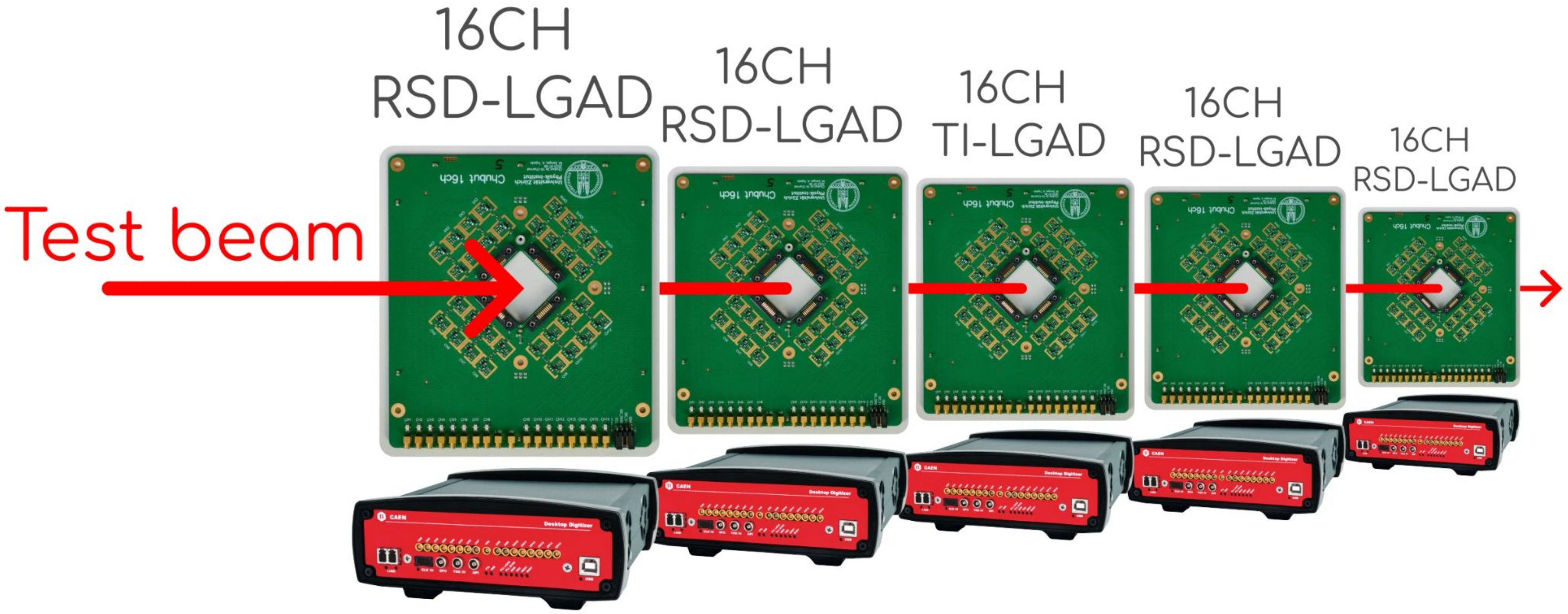


- PhD 4 years mark: June 2024
  - Graduation before then!
- Test beam at DESY (February)
  - Take more data with TI-LGADs
    - New AIDAinnova production with carbon co-implantation for radiation hardness
  - Test AC-LGADs with 16 channels
    - Non irrad + <u>irrad</u>
    - New geometries
- Try to quantify a bit this plot



- Some other minor things (e.g. spatial reconstruction in RSD-LGAD using only time variables, and using charge&time variables together)

I would love to do this



- Suggested by Nicolò in the previous PhD Committee Meeting
- We (ADIAinnova WP6 TB team) have ALL what is needed, except maybe the beam 😅 (CERN? Can be done at DESY?)

Conclusions

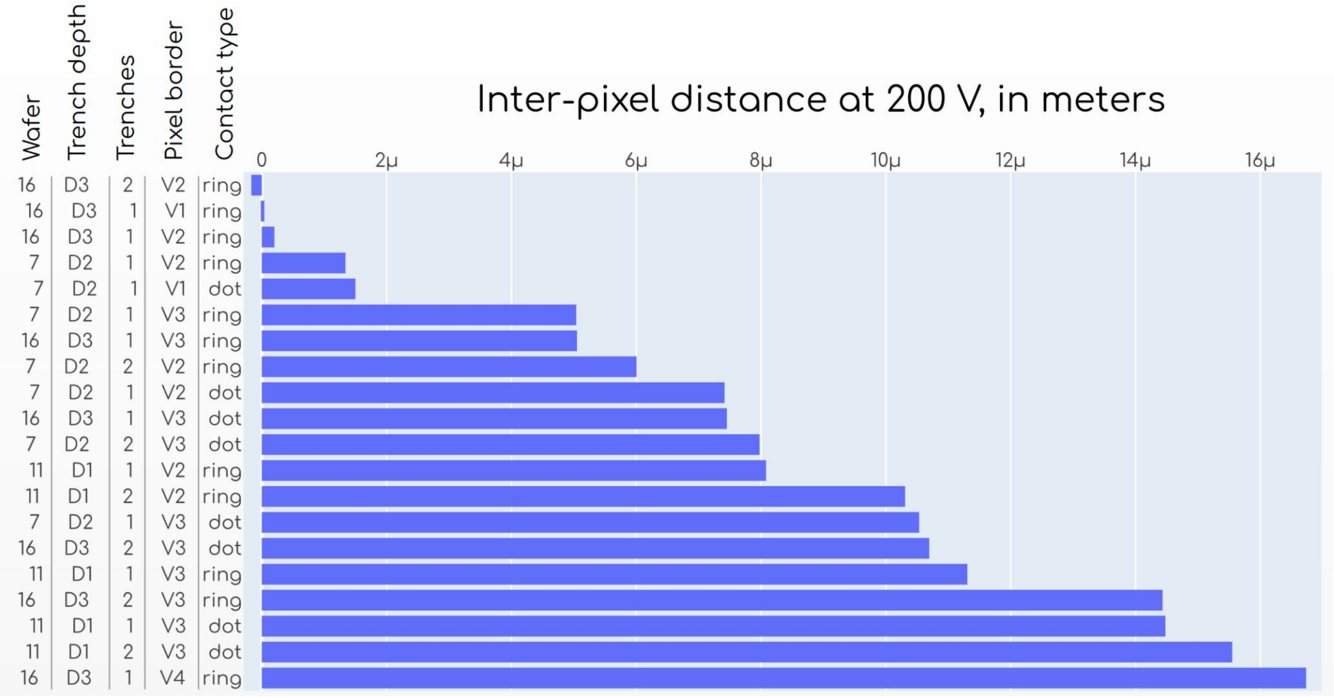
- A lot of work with TI-LGADs and AC-LGADs
  - Laboratory
  - Test beam
- Comparison of the two technologies (ongoing)
  - So far I would say: One is not better than the other, depends on the application
- Still some things to be done
  - DESY test beam
- All in all, I think I am on track for my PhD, but please you tell me 🙂


Thank you for your attention
"That's all Folks!"

Backup slides

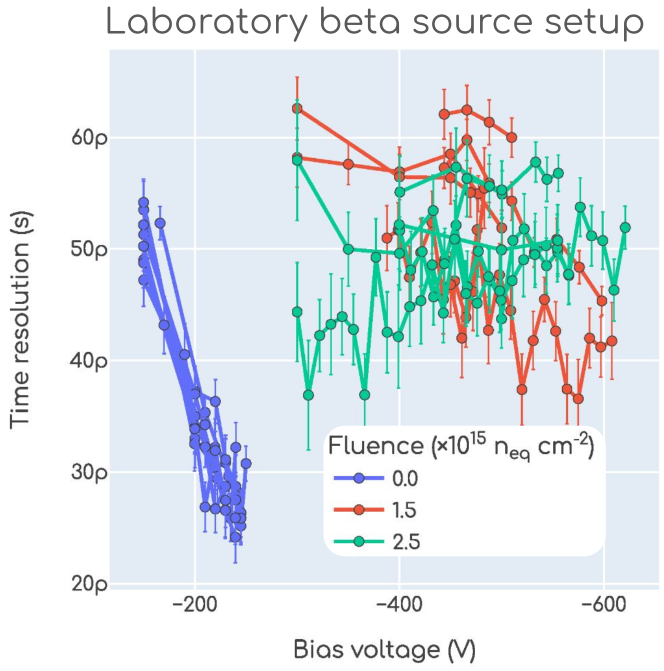
TCT characterization (TI-LGAD)

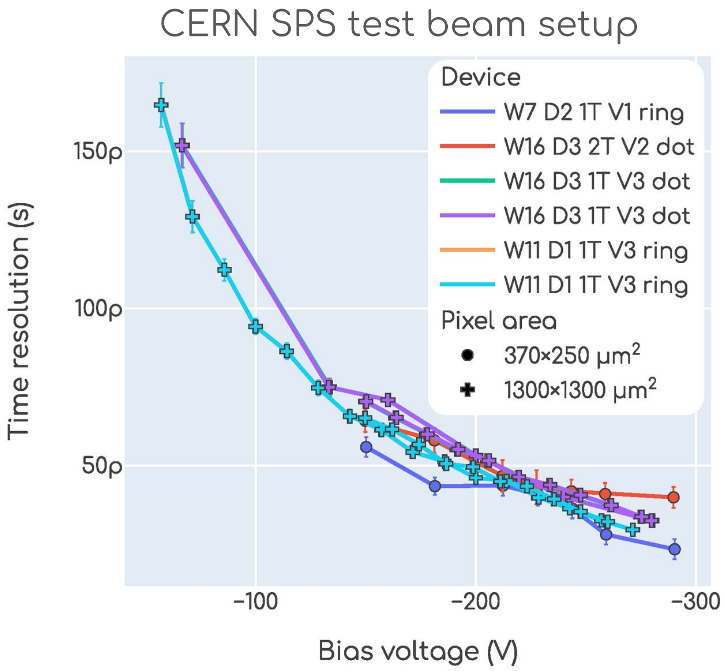
Almost all design patterns from the FBK RD50 TI-LGAD production were ranked according to their inter-pixel distance as measured with laser TCT, more details in https://doi.org/10.3390/s23136225.



Time resolution (TI-LGAD)

Measured in laboratory beta source setup as well as in test beam setup, see https://doi.org/10.3390/s23136225 for more details.

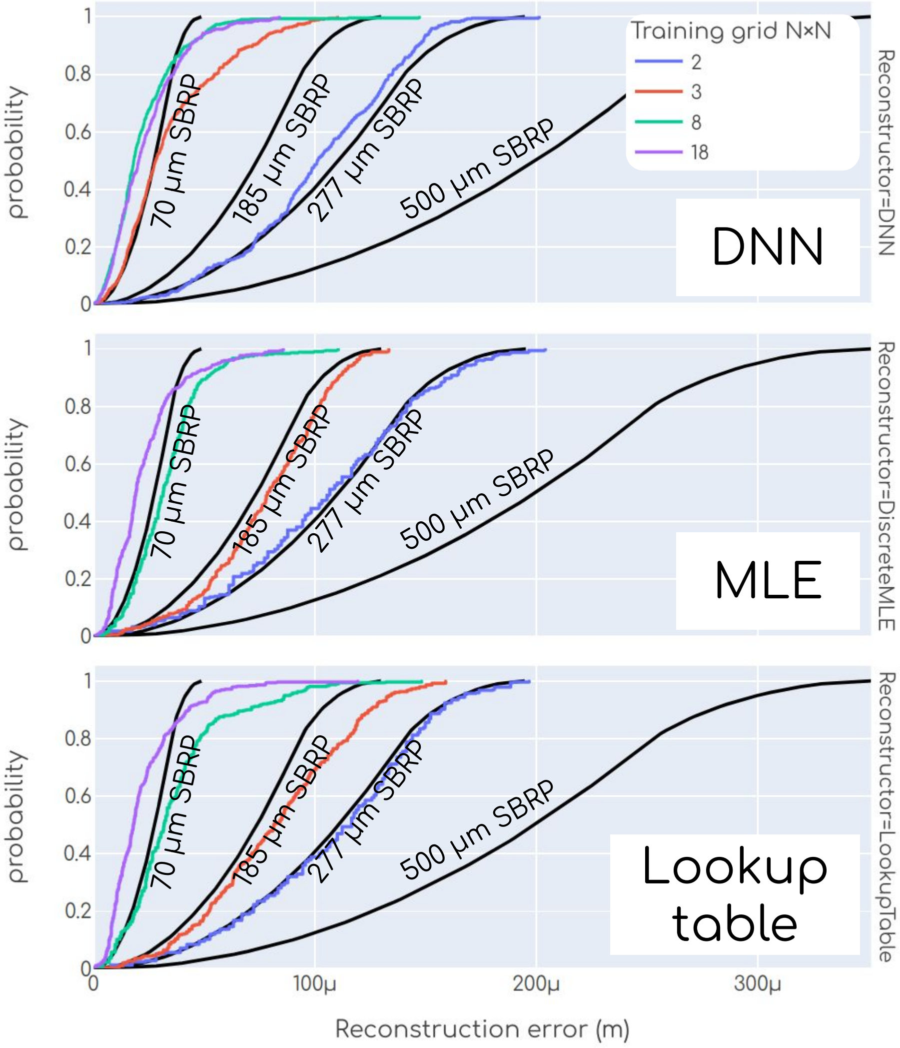




Algorithms detailed comparison (TCT data)

Plots show reconstruction error distribution (ECDF plots, the integral of histograms without bins).

- As the training grid gets finer, the results get better (as expected).
- Because of the discrete training grid, reconstruction error resembles that from a BRP of the same size.
- The DNN learns to interpolate, that's why it is better for e.g. training grid 3×3 (red).
- All cases are better than a 500 µm SBRP.
- For small enough training grid (N×N=18 in the plots), all algorithms behave roughly as a 70 µm SBRP.



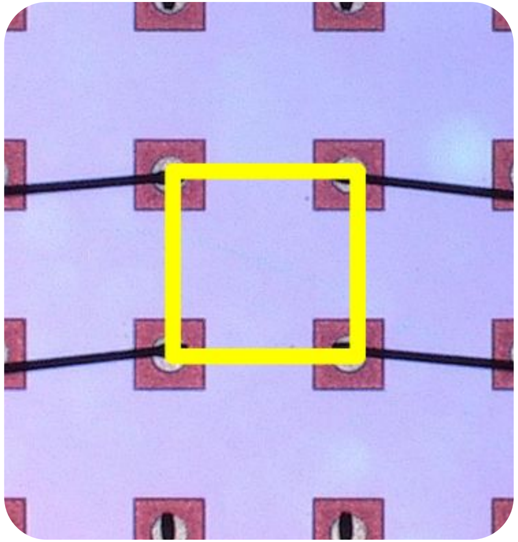
* SBRP = square binary readout pixel

Position reconstruction using charge imbalance

$$\begin{cases} x_{\text{reconstructed}} = \dfrac{\text{pitch}_x}{2} Q_{\text{imbalance } x} \\ y_{\text{reconstructed}} = \dfrac{\text{pitch}_y}{2} Q_{\text{imbalance } y} \end{cases}$$

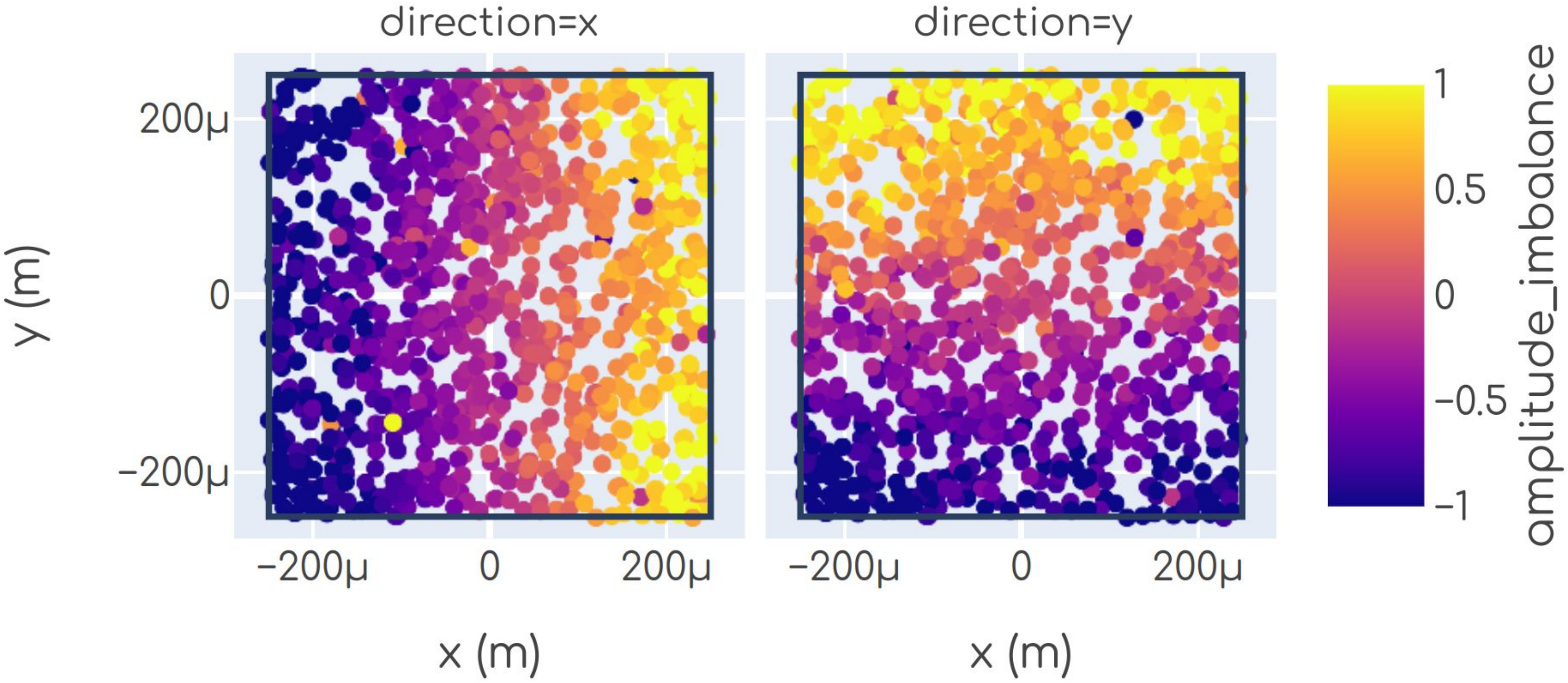
$$\begin{cases} Q_{\text{imbalance } x} = \dfrac{Q_{11} + Q_{01} - Q_{00} - Q_{10}}{\sum Q_{ij}} \\ Q_{\text{imbalance } y} = \dfrac{Q_{00} + Q_{01} - Q_{11} - Q_{10}}{\sum Q_{ij}} \end{cases}$$

- Pros
  - Easy
- Cons
  - Only applicable to very symmetric geometries (like this one 👍)
  - No special reason why this simple formula should be right one



Charge (amplitude) imbalance (test beam data)

$$\begin{cases} Q_{\text{imbalance } x} = \dfrac{Q_{11} + Q_{01} - Q_{00} - Q_{10}}{\sum Q_{ij}} \\ Q_{\text{imbalance } y} = \dfrac{Q_{00} + Q_{01} - Q_{11} - Q_{10}}{\sum Q_{ij}} \end{cases}$$



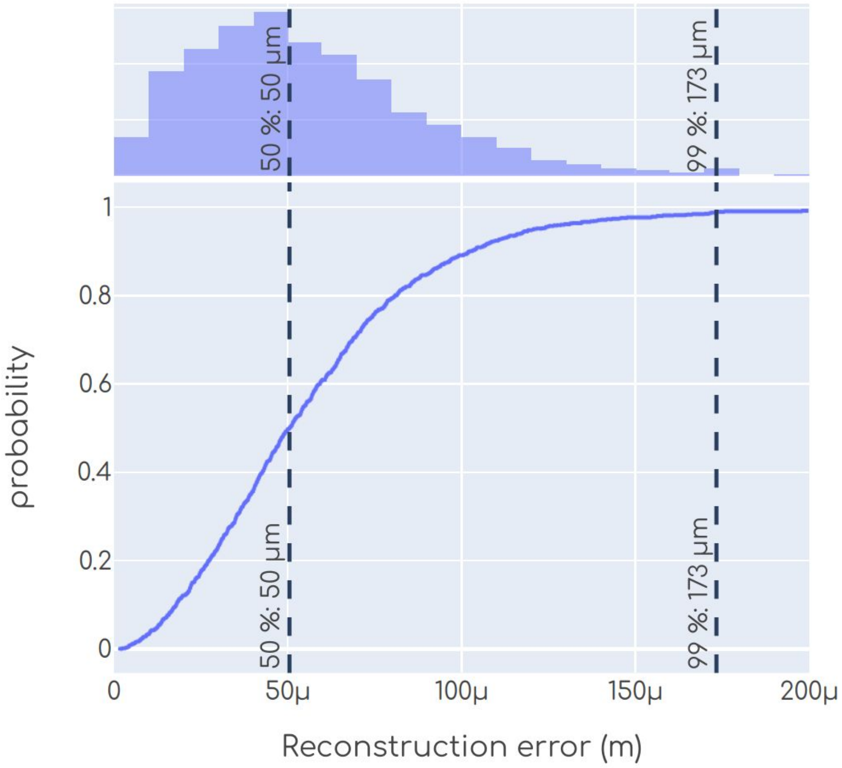
Charge imbalance reconstruction results (test beam)

$$\text{Reconstruction error} \stackrel{\text{def}}{=} \sqrt{\sum_{\text{coord}\in\{x,y\}} (\text{coord}_{\text{reconstructed}} - \text{coord}_{\text{original}})^2}$$

- Median: 50 µm
- 99 %: 173 µm

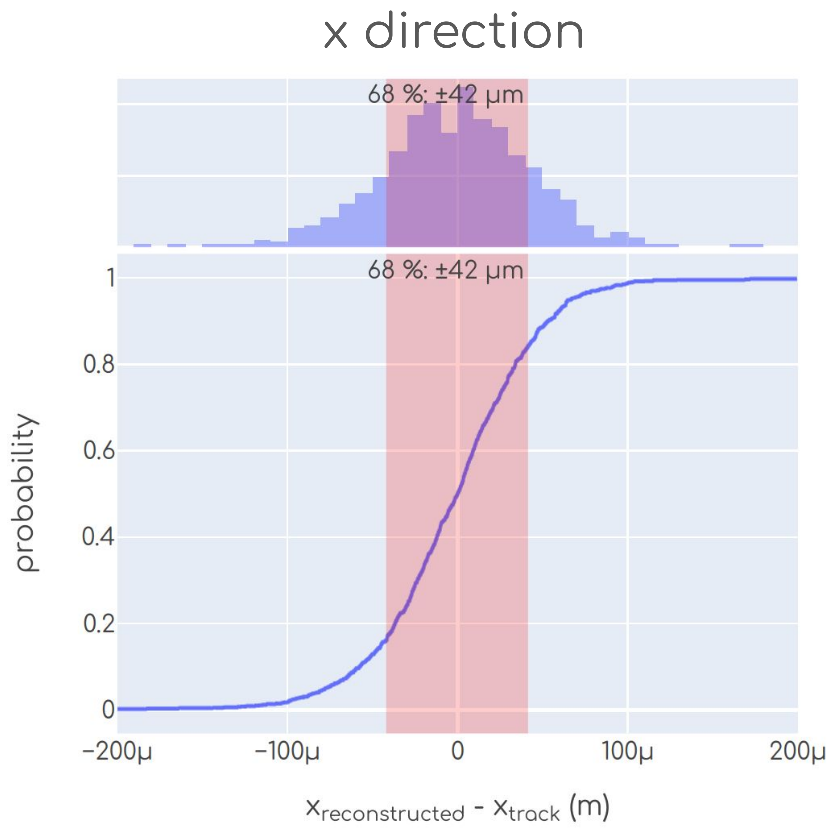
For a 500×500 µm² SBRP*:

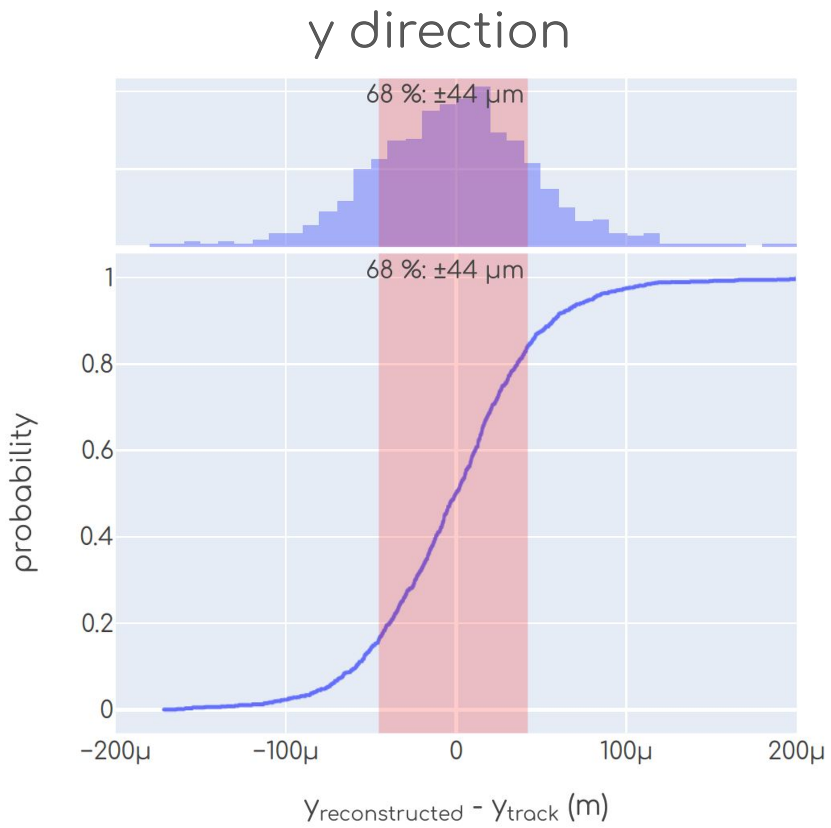
- Median ≈ 200 µm
- 99 % ≈ 330 µm



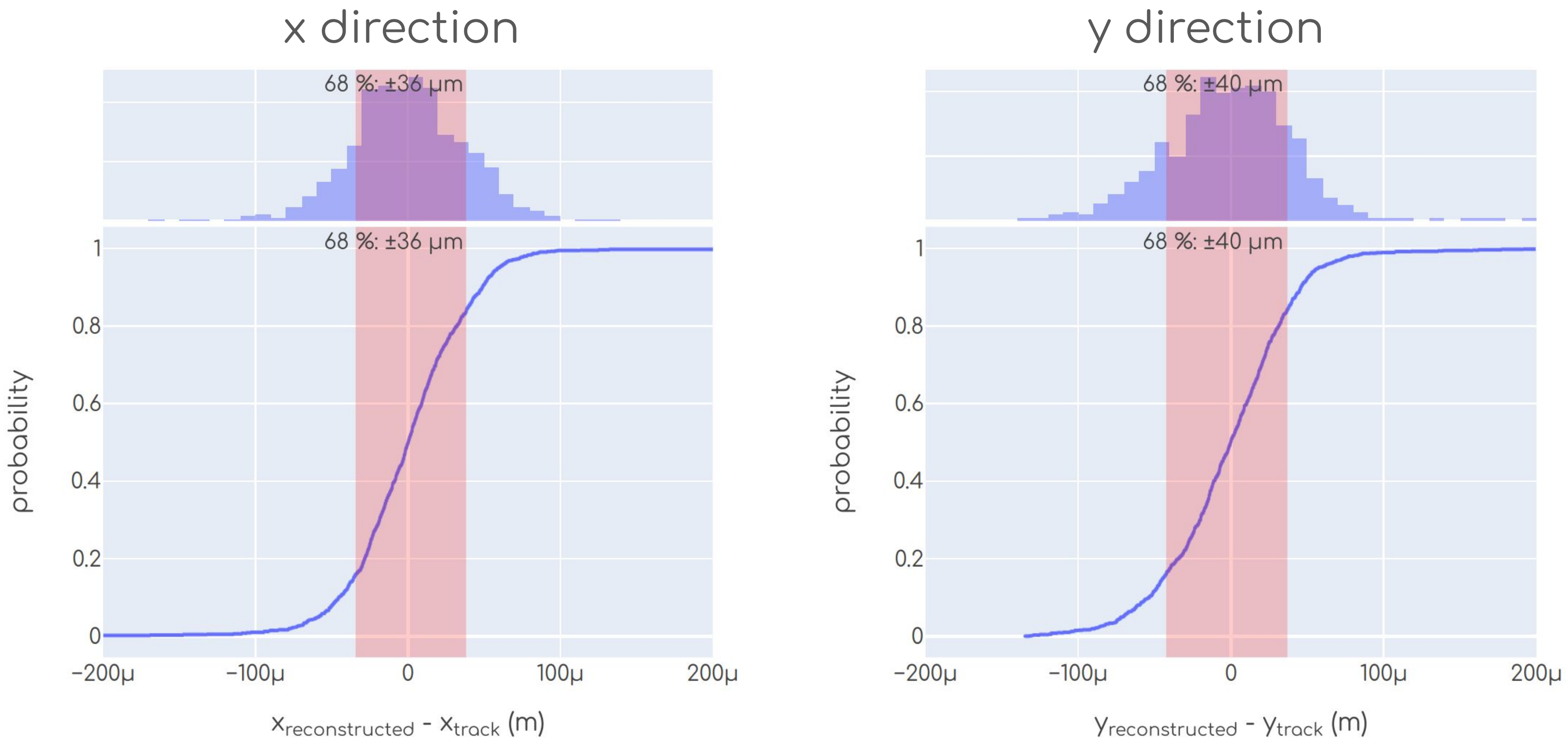
* SBRP = square binary readout pixel.
** Residuals in x and y also available in backup slides.

Charge imbalance reconstruction residuals (test beam)

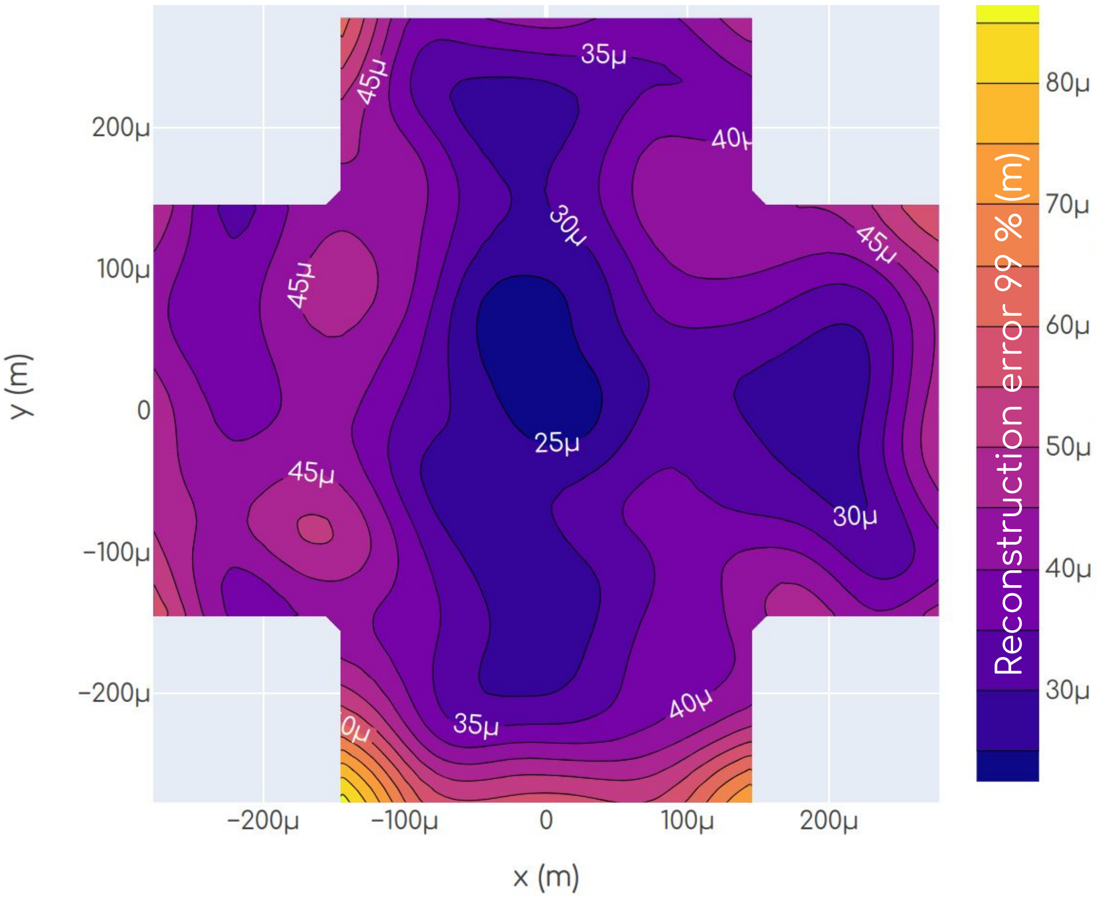




DNN reconstruction residuals (test beam)



Reconstruction error vs position (TCT)



- TCT data
- DNN reconstruction
- Color is quantile 0.99, i.e. at each position, 99 % of hits got lower reconstruction error than shown

On the statistics used to measure the spatial resolution

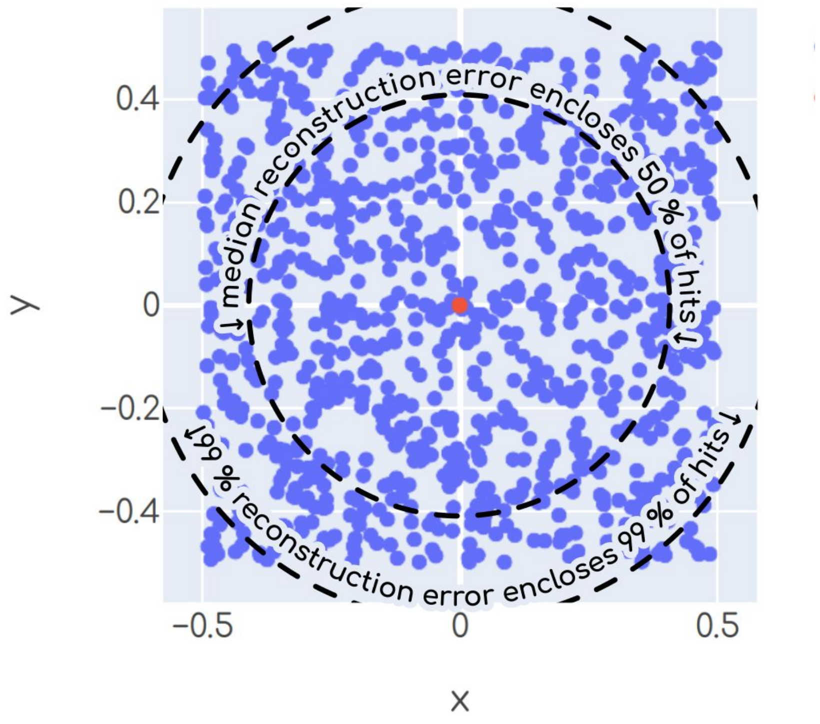
Spatial resolution statistics table

Quantity	Formula in SBRP*	Meaning	Comment
Median reconstruction error	≈ pitch × √(2/12)	≡ 50 % of reconstructed hits will be closer than this to the actual hit	It is the radius of a circle in the xy plane around the reconstructed position
std of residuals in x,y, i.e. std of "$x_{reconstructed}-x_{real}$" and "$y_{reconstructed}-y_{real}$"	≡ pitch / √12	• Depends on the distribution • In a square SBRP*: ≈ 58 % of reconstructed hits will have x,y coordinates within ± this quantity (yes, 58, not 68)	• Not easy to interpret in a 2D arbitrary case (see slide with pathological example) • Beautiful interpretation for Gaussian distributions, but not for arbitrary distributions
99 % of reconstruction error	≡ pitch*0.66	≡ 99 % of reconstructed hits will be closer than this to the actual hit	Useful to account for plausible tails and measure "the worse case scenario"

* SBRP = square binary readout pixel

Median reconstruction error interpretation

Simulated hits and reconstruction
Square binary readout pixel of size 1

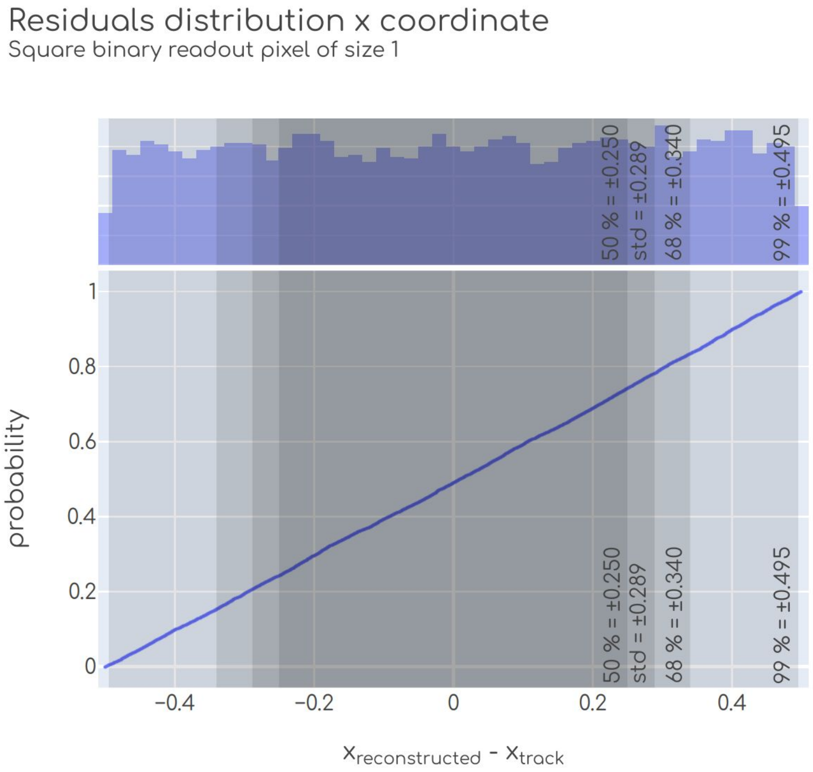


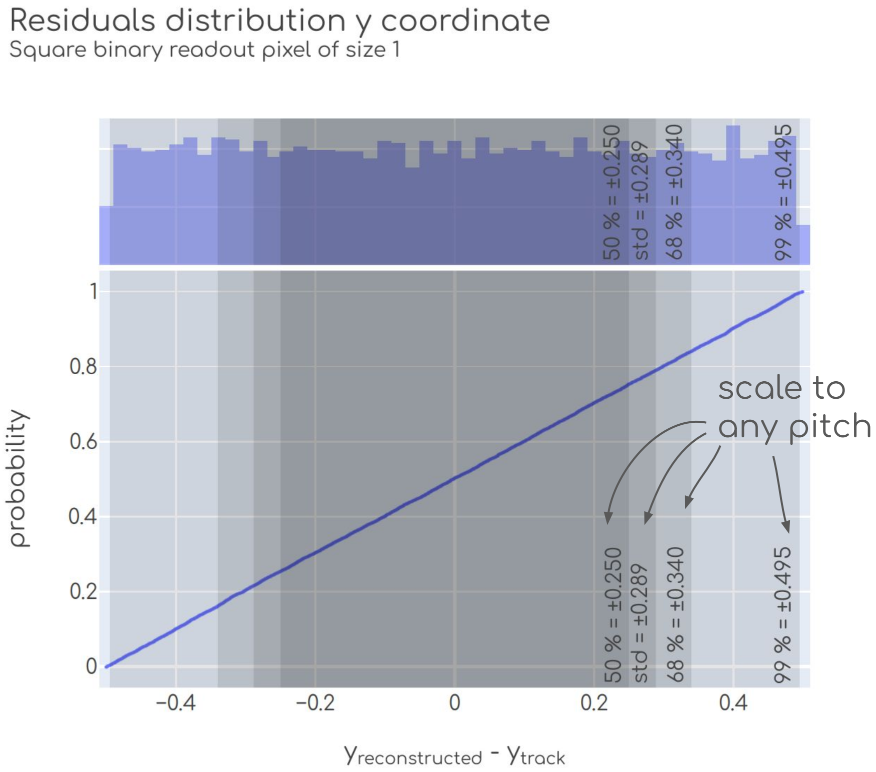
- ✅ The meaning of the statistics shown in the plot is independent of distribution (i.e. valid for binary readout pixels, AC-LGADs, whatever)
- ⚠️ pitch/√12 ≡ std ONLY for binary readout pixels
- ⚠️ Interpretation of std is different for different distributions (for sure it is different for AC-LGADs and binary readout pixels)
- In my opinion, the most meaningful statistics when comparing binary readout pixels and non-binary readout pixels (e.g. AC-LGAD) are the quantiles of the reconstruction error, since the meaning is the same in both cases

Residuals in a square binary readout pixel (BRP)

$$\frac{\text{pitch}}{\sqrt{12}} \equiv \text{std of square BRP} \approx 58\ \%\ \text{of hits}$$

← The “magical formula” is the standard deviation of a uniform distribution (by definition), which is NOT the 68 % centered interval!!! (see plots) (It is so for a Gaussian, but this is not even close to a Gaussian)

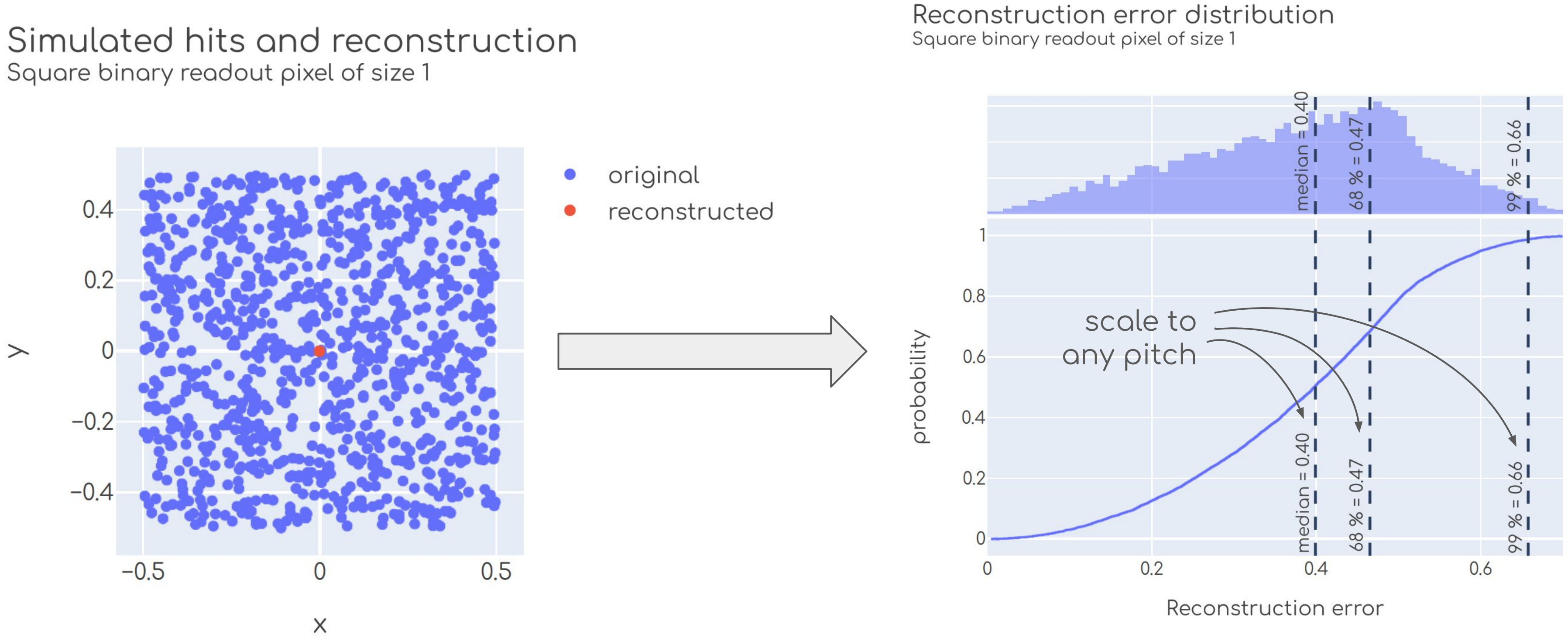




Reconstruction error in a square binary readout pixel

$$\text{Reconstruction error} \stackrel{\text{def}}{=} \sqrt{\sum_{\text{coord}\in\{x,y\}} (\text{coord}_{\text{reconstructed}} - \text{coord}_{\text{original}})^2}$$

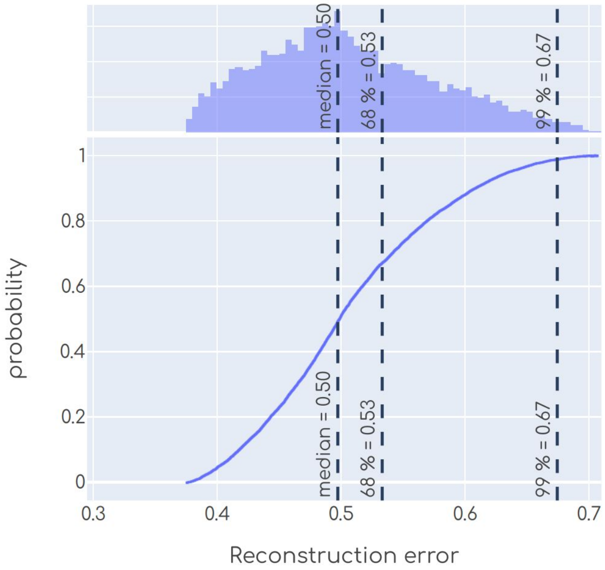
$$\begin{matrix}\text{Median reconstruction error} \\ \text{in a square binary readout pixel}\end{matrix} \approx \text{pitch}\sqrt{\frac{2}{12}}$$



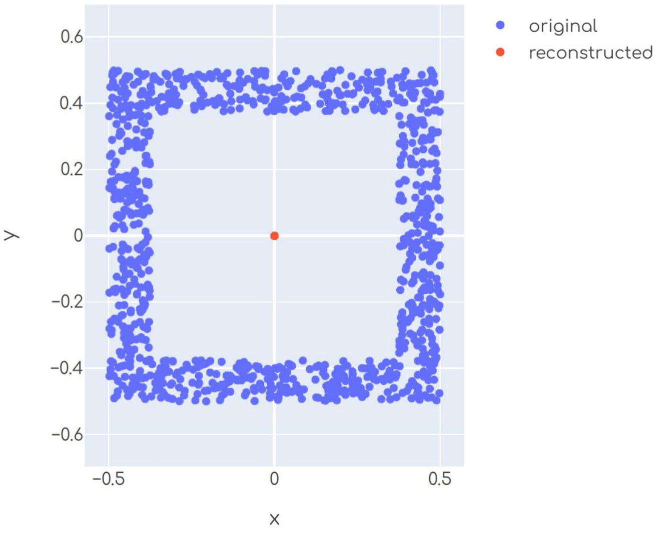
Pathological example

Consider this weird, still plausible pixel. Looking at the residuals in x,y we may be led to believe that ≈ 50 % of events are closer than 0.361 to the center. However, the minimum reconstruction error is actually 0.36. The reconstruction error quantiles, instead, never fail.

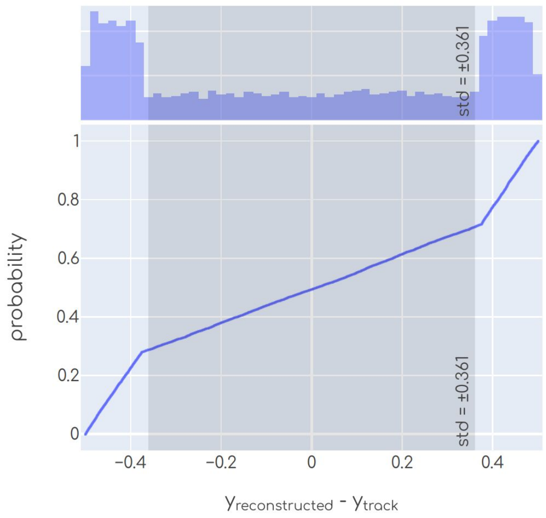
Reconstruction error distribution



Simulated hits and reconstruction



Residuals distribution y coordinate



Residuals distribution x coordinate