4D-Tracking with DC-coupled Resistive Silicon Detectors (DC-RSDs)

The 14th international "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors

19.11.2025

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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

The 4D-Tracking challenge

Experiments at future colliders will pose unprecedented challenges to tracking systems*

- Spatial resolution O(10 μm)
- Temporal resolution O(10 ps)
- Reduced material budget: < 1% of a radiation length per layer
- Limited power consumption: < 100 mW/cm^2

→ the 4DSHARE project is developing a technology to address the challenge, the DC-RSD

* *Trackers, ToF wrappers for PID*

Outline

- **DC-RSD**
  - Design
  - FBK DC-RSD1 production
- **Devices Under Test and Data taking at DESY**
- **The reconstruction methods**
  - Standard Template
  - ML based: Deep Neural Network
- **Results comparison**
  - Standard Template vs Deep Neural Network
  - Deep Neural Network with different number of samples
- **Resolution of sensors with different pitch and resistivity**
- **Effect of added noise on performance**

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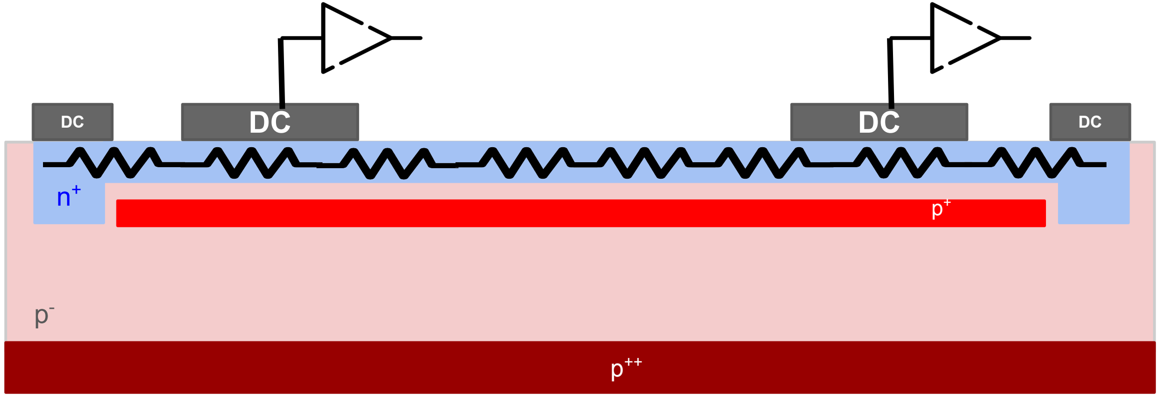
DC-coupled Resistive Silicon Detectors (DC-RSD)



- 55 µm thick Silicon sensor
- based on the **LGAD technology**: fast & large signals
- *n*-layer is made resistive (n^+, **resistive layer**)

First DC-RSD production manufactured by FBK in 2024

FONDAZIONE BRUNO KESSLER

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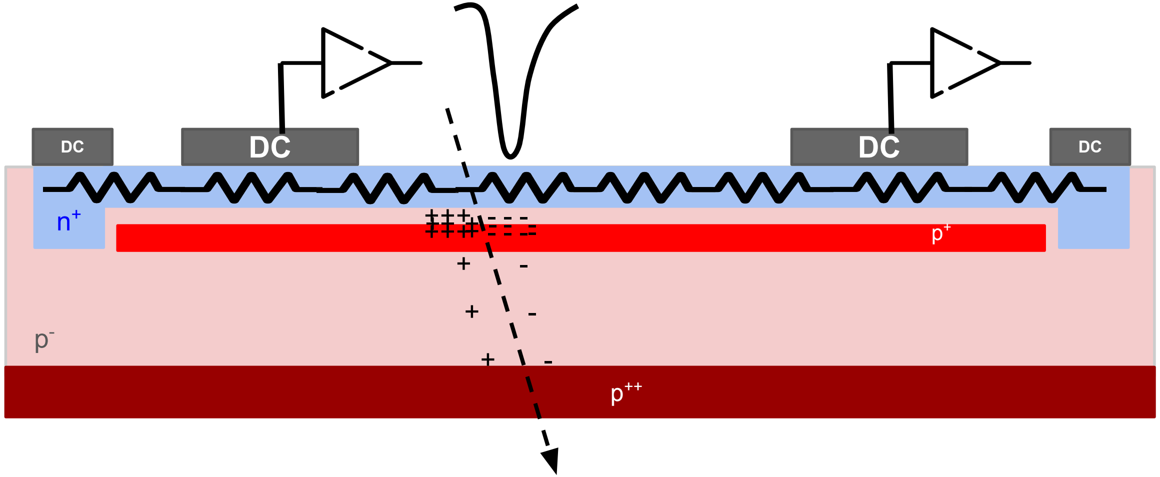

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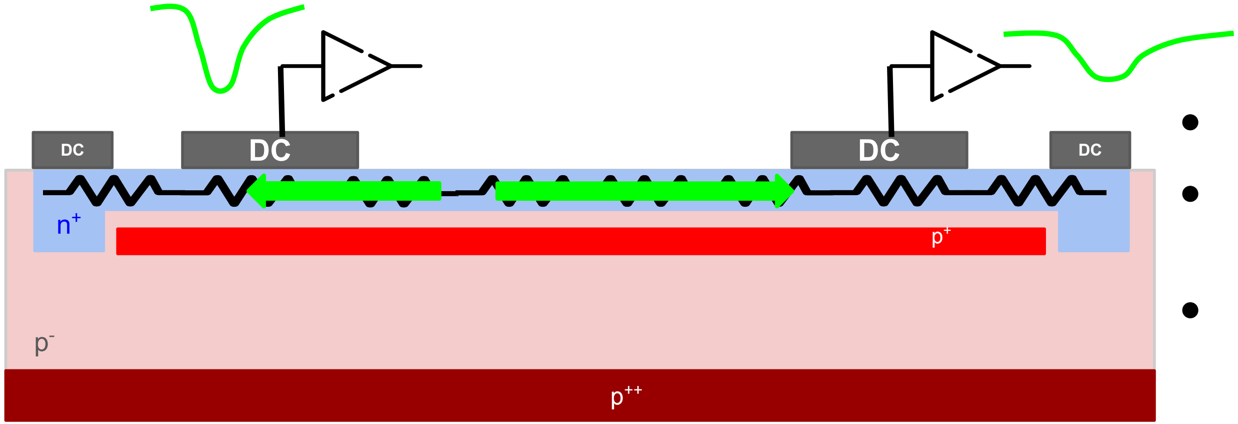

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- Signal spreads on the resistive layer and is collected by metal electrodes DC-coupled to the n^+ → signal sharing

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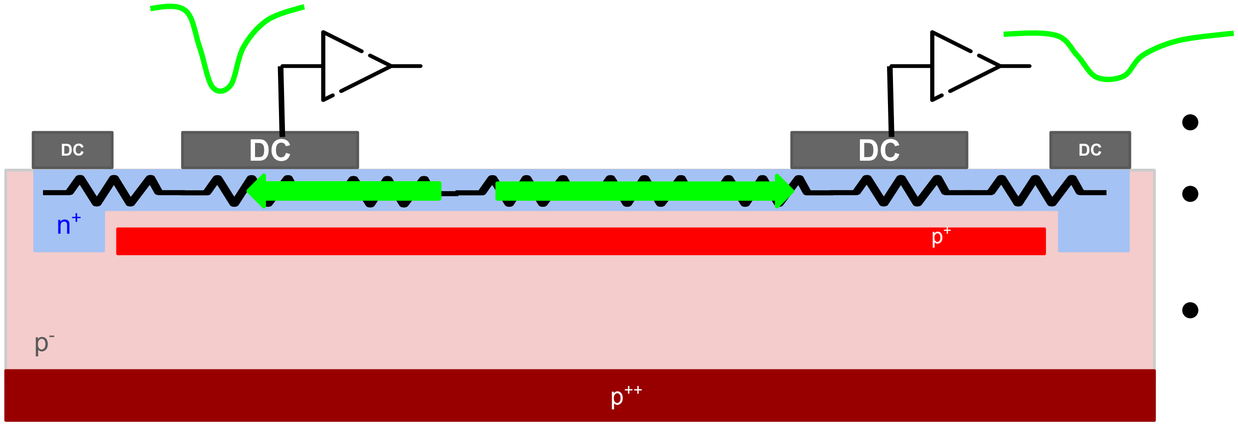

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Each electrode sees a **signal dependent on its distance from the hit position**: further away electrodes see more delayed, smaller, and wider signals → **key to accurately reconstruct the hit position**

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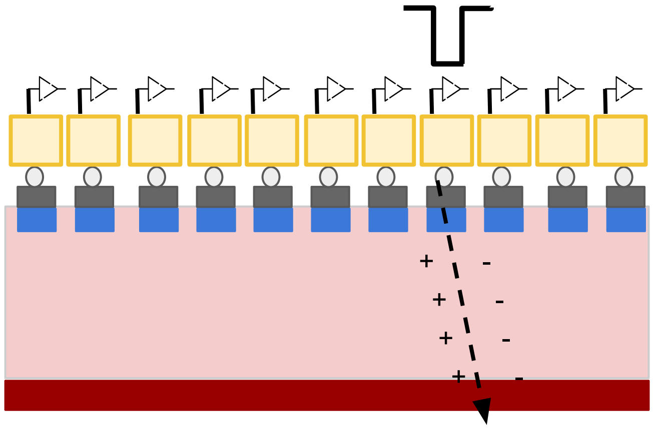
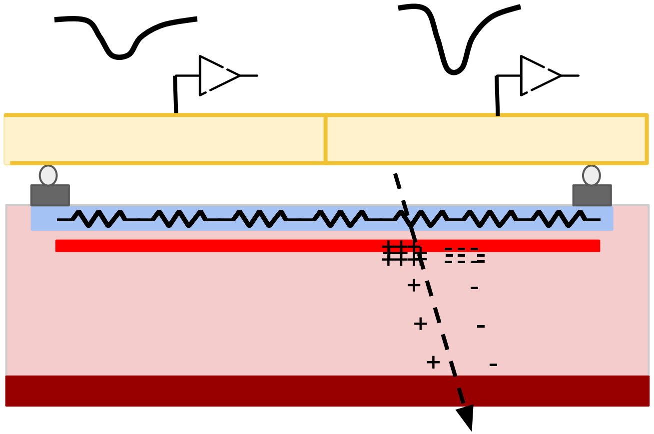


Pixel detector with binary read-out and 50x50 μm² pixels



RSD-based pixel detector with 500x500 μm² pixels

- A traditional tracking detector with binary read-out features many separate *pn* diodes and tiny pixels to accurately reconstruct the hit position
- DC-RSD completely changes the design: accurate tracking is achieved through signal sharing, allowing for large pixels

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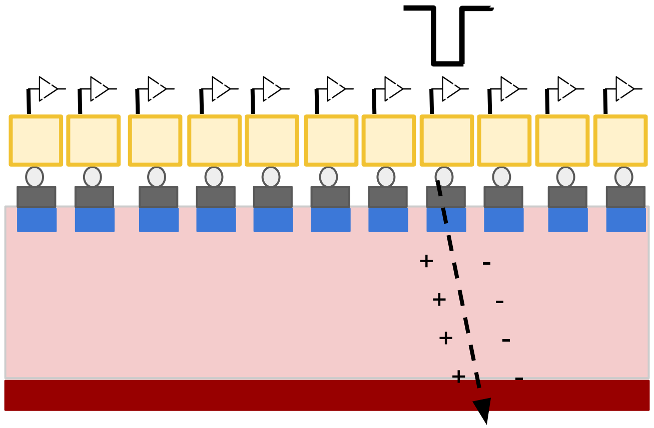

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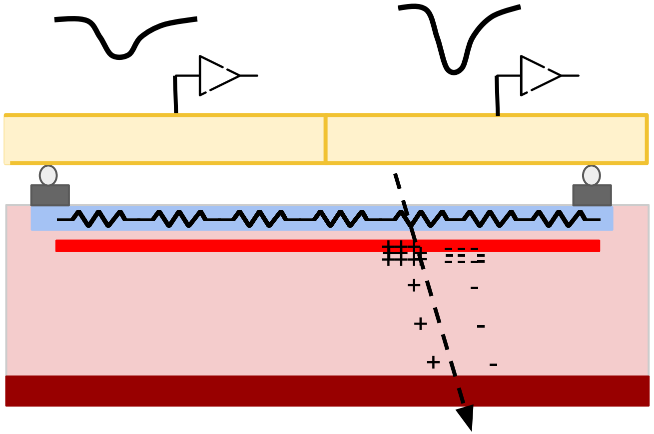

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→ DC-RSDs achieve the same spatial resolution of a traditional pixel detector with ~100 times fewer read-out channels

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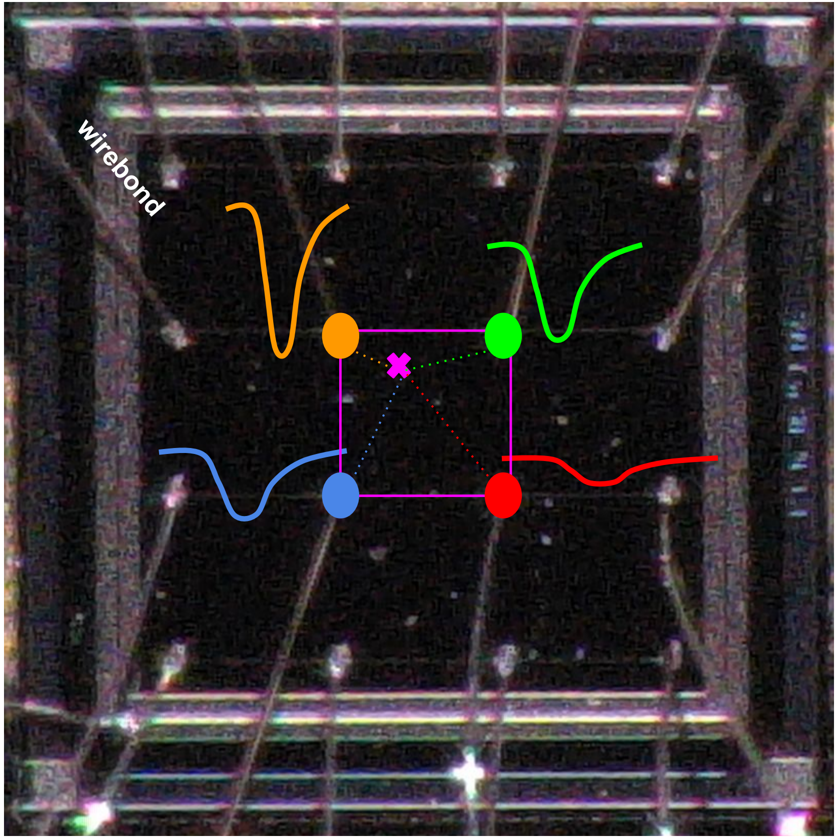
DC-RSDs with isolating trenches



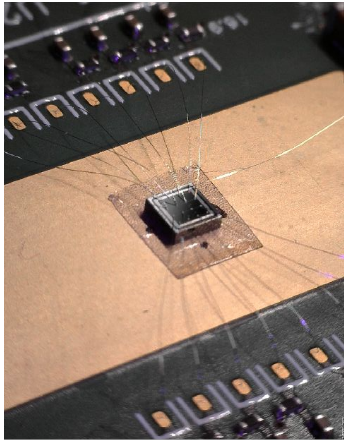
- Square pixels with O(100 μm) pitch, with 4 electrodes at the vertices
- Signal propagates on the resistive layer and is split among the electrodes
- Electrodes are read out through wirebonds
- Signal confined by isolating trenches

❖ DC-RSD gain ranges 10-40

❖ Typical MPV of the sum of the 4 electrode signals is > 100 mV

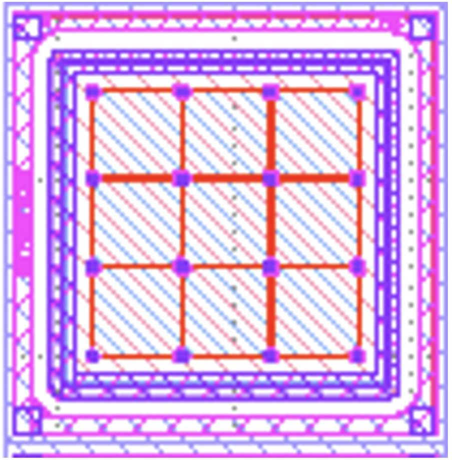
DC-RSDs tested in this work

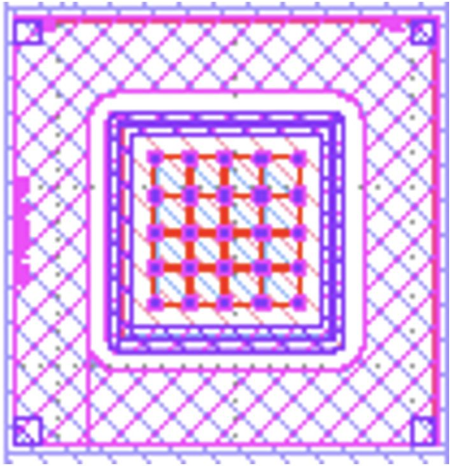
- 2 sensors from Wafer 3 (high n^+ resistivity, ~1.8 kΩ/□):
  - 4x4 pixel matrix, 500 µm pitch
  - 5x5 pixel matrix, 300 µm pitch
- 1 sensor from Wafer 15 (low n^+ resistivity, ~0.75 kΩ/□):
  - 4x4 pixel matrix, 500 µm pitch



DC-RSD wire-bonded to a read-out board

4x4 matrix, 500 µm pitch





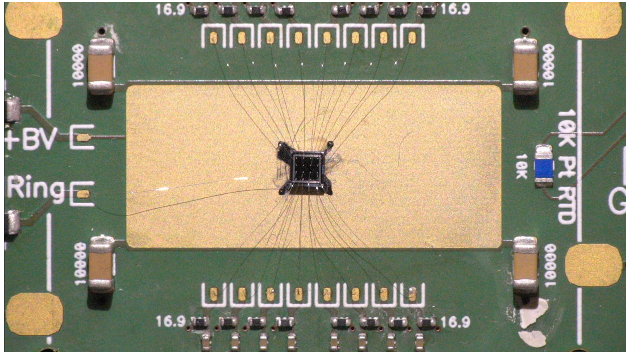
5x5 matrix, 300 µm pitch

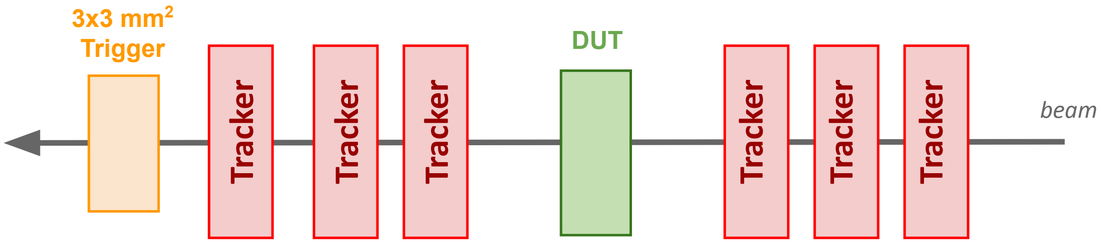
DESY Test Beam Facility

- Data presented in this work have been taken at the DESY test beam facility using 5 GeV electrons
- The reference positions used to evaluate the DUT spatial resolutions are provided by a 6-planes ADENIUM / MIMOSA tracker telescope with $\sigma_{\text{Tracker}} \sim 8\ \mu m$

DESY setup for operation at roomT

DUT mounted on a 16-ch analog board





The DESY II test beam facility *NIMA, Vol. 922, 2019*

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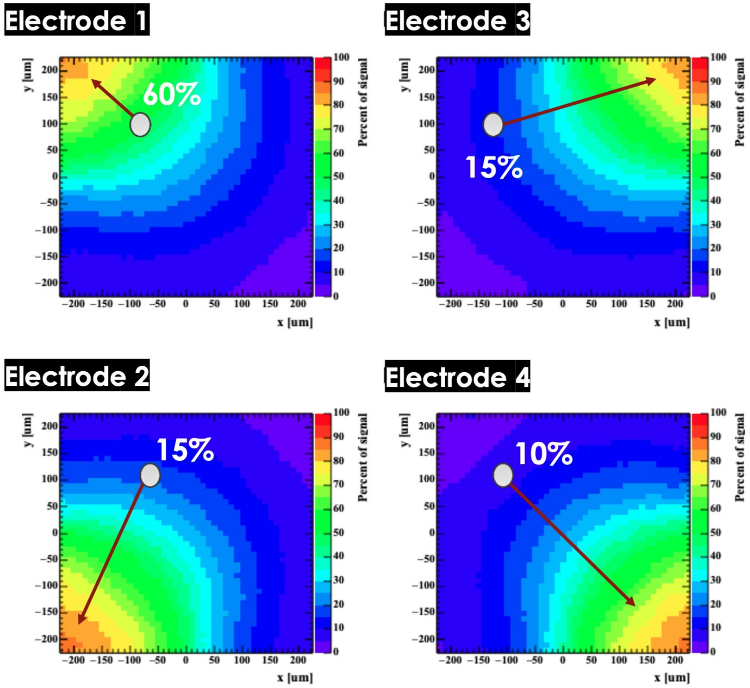
Position reconstruction with DC-RSDs

The standard procedure to reconstruct the hit position with RSDs:

- Produce look-up tables using a subset of test beam data, computing the fraction of signal seen by each electrode for a given hit position (*"Standard Template"* method)
- Each event is then compared to the look-up table to find the location that minimizes a X^2 variable
- This method is based on the amplitude of the 4 signals, extracted with a gaussian fit

Details here:

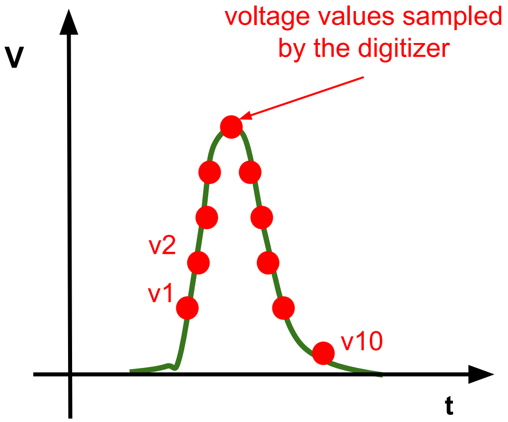
- L.Menzio and F.Siviero, "First test beam measurement of the 4D resolution of an RSD pixel matrix connected to a FAST2 ASIC"
- R.Arcidiacono, "Innovative DC-coupled resistive silicon detector for 4D tracking"



Templates showing the fraction of signal seen by each electrode as a function of the hit position within the pixel

Spatial reconstruction with Machine Learning

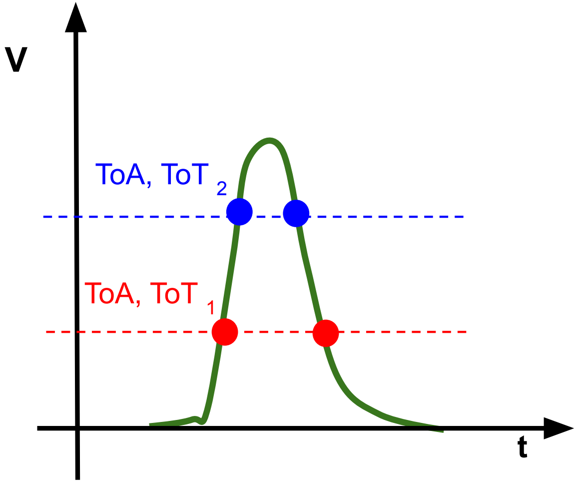
- In this work, we present an **innovative method for position reconstruction with DC-RSDs, based on a Deep Neural Network** (DNN)
- The procedure is straightforward:
  - the electrodes are read out with a 16-ch CAEN digitizer, at a 5 GS/s sampling rate
  - 4 waveforms per event are considered (those recorded by the electrodes of the hit pixel)
  - n samples per waveform are extracted (n = [1,10])
  - each sample is an ADC count measured by the digitizer, converted to mV
- The samples are fed to the DNN as input features: no pre-processing needed, no offline analysis required
- The DNN is trained to predict the x,y coordinates of the hit position, using the coordinates reconstructed by the DESY tracker as reference



ML approach with raw data: the input features are v1,...,v10

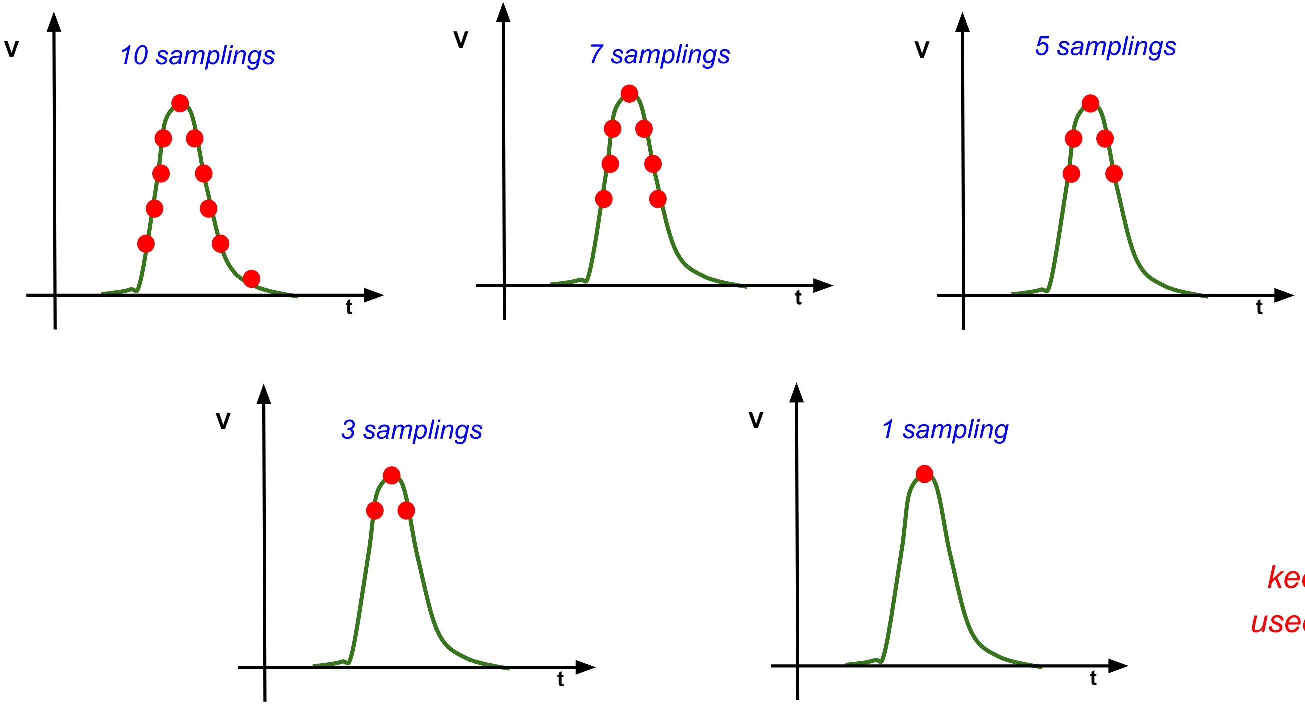
Why pursuing the DNN approach?

- **Presently, state-of-the-art FE electronics** to read out RSD-like sensors (AC-LGAD) is represented by the EICROC chip for the ePIC detector:
  - **2 processing paths** to measure ToA, ToT (timing) and Amplitude/Charge (tracking)
  - The “Standard template” well suited for this architecture
- **DNN allows exploring different architectures, like a double ToA-ToT electronics:**
  - By measuring twice ToA, ToT we sample the signal 4 times → tracking with DNN



DNN varying the number of samplings

To verify the feasibility of tracking with double ToT electronics, we feeded the DNN with a variable number of samplings per waveform to check its performance



keep this in mind, will be used in the following slides

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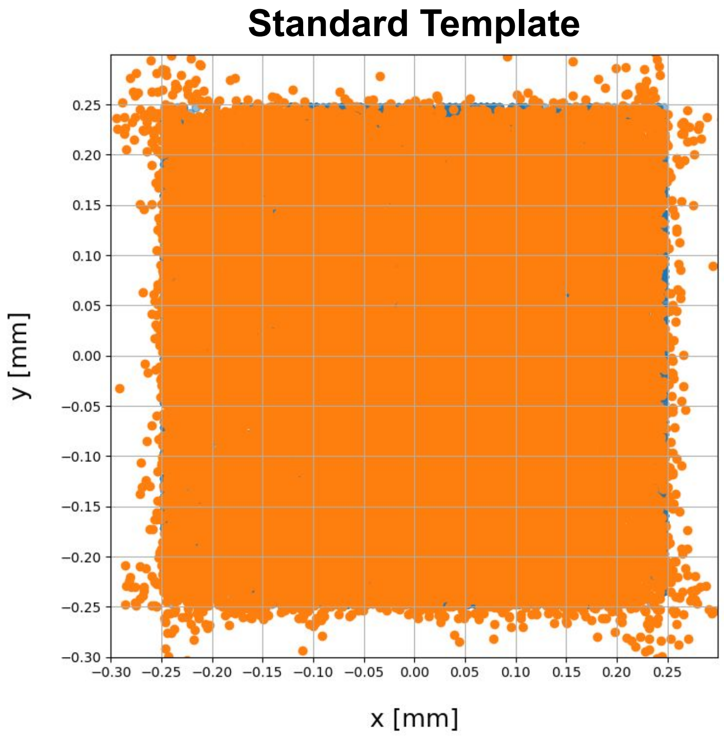
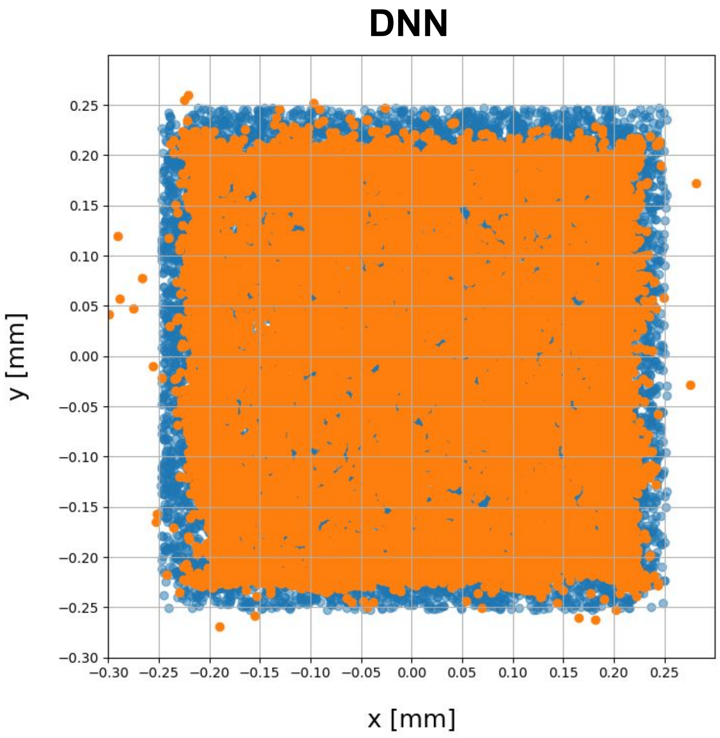
Comparison of predictions

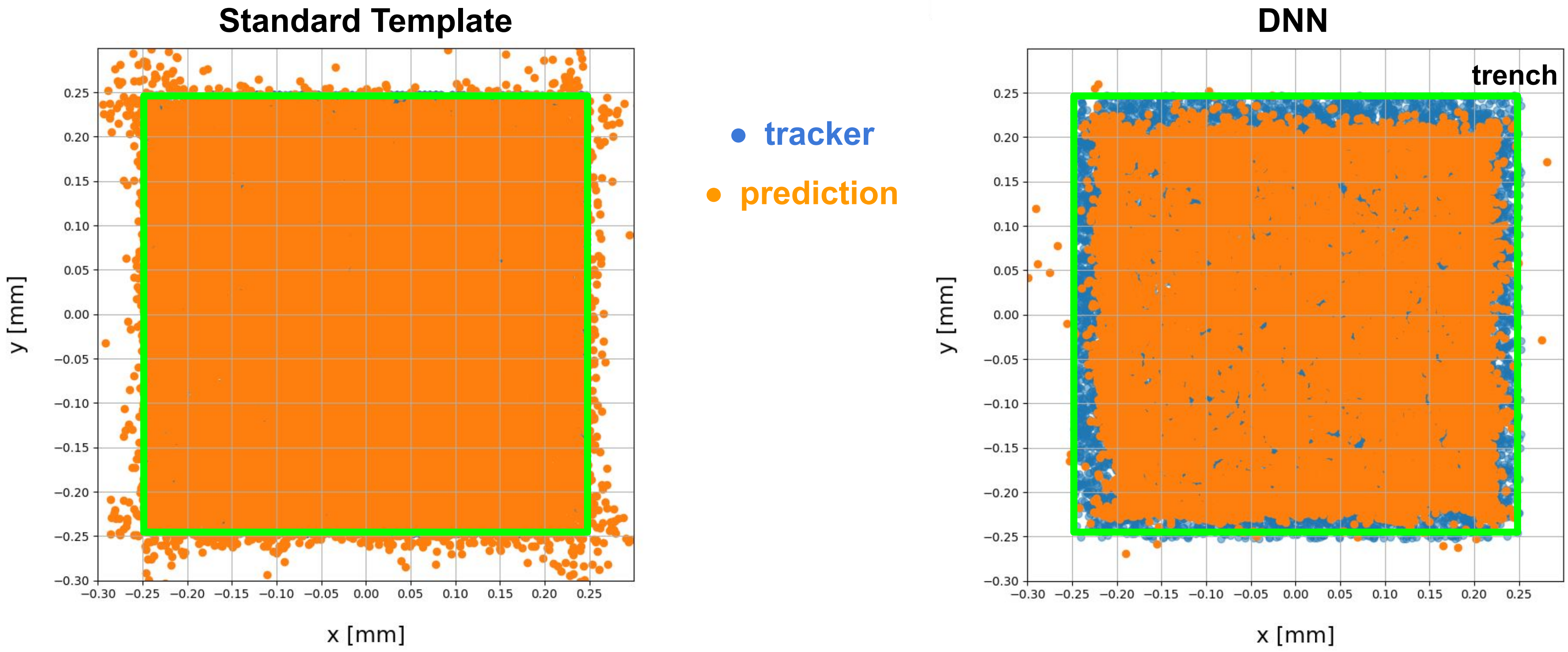




- tracker
- prediction

both maps show the W3 500 μm device measured at the highest gain

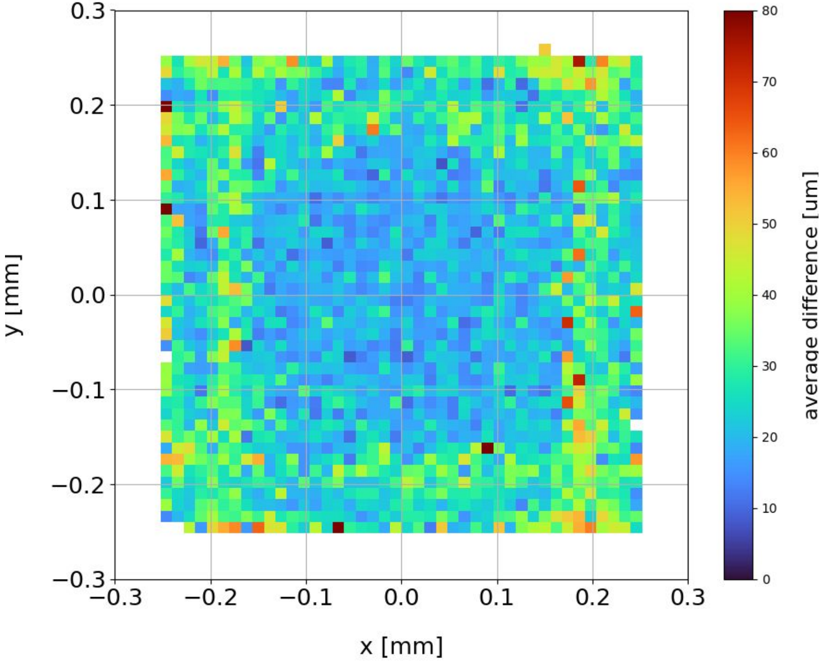
Comparison of predictions



- Standard template predictions cover the whole area with some events at the edges that are reconstructed off pixel
- DNN predictions at the edge tend to systematically “pull” the positions within the pixel, rather than reconstructing off pixel

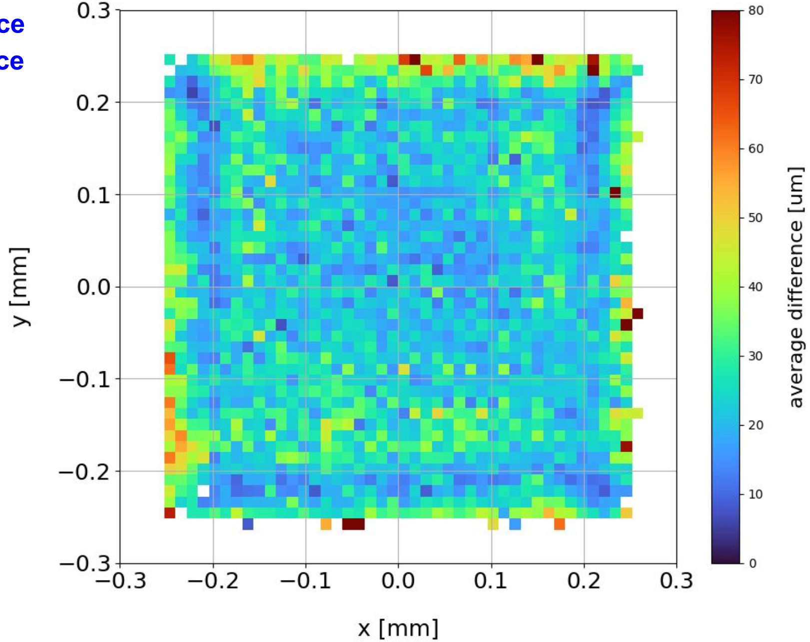
Comparison of predictions

Standard Template



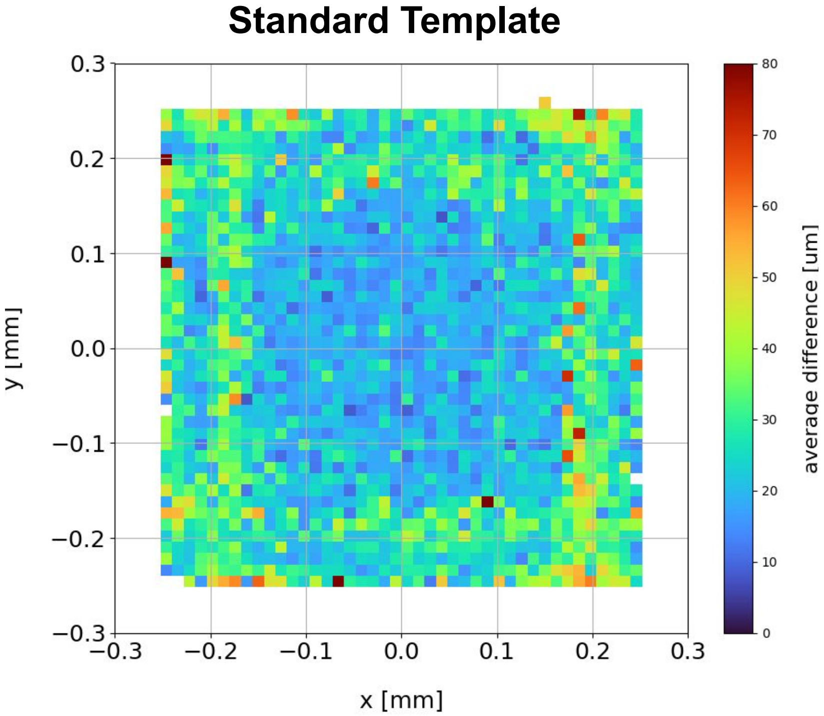
average difference between reference and prediction
$\sqrt{(\Delta x^2 + \Delta y^2)}$

DNN

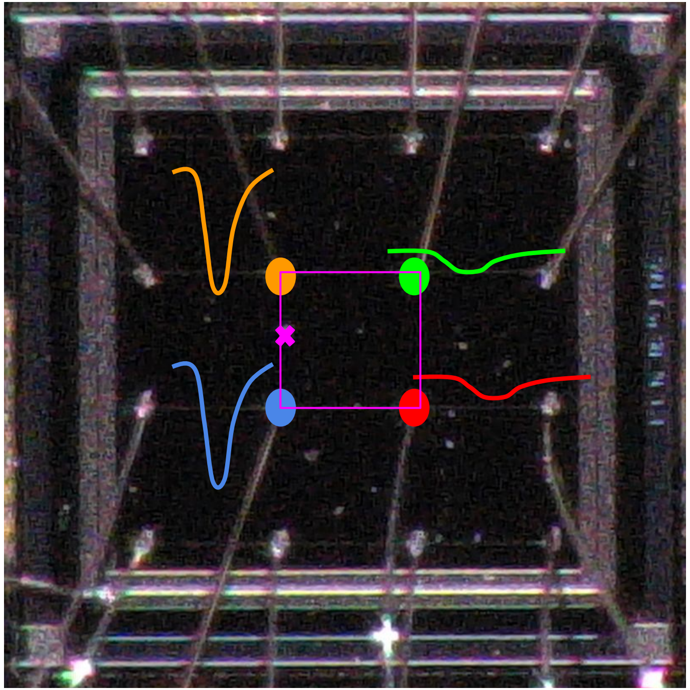


- Overall, similar performance, with the DNN slightly worse at the edges
- Better reconstruction in the center → even split of the signal between the 4 electrodes
- Worse at the edges → only 2 electrodes see large signals

Comparison of predictions



average difference between reference and prediction $\sqrt{(\Delta x^2 + \Delta y^2)}$



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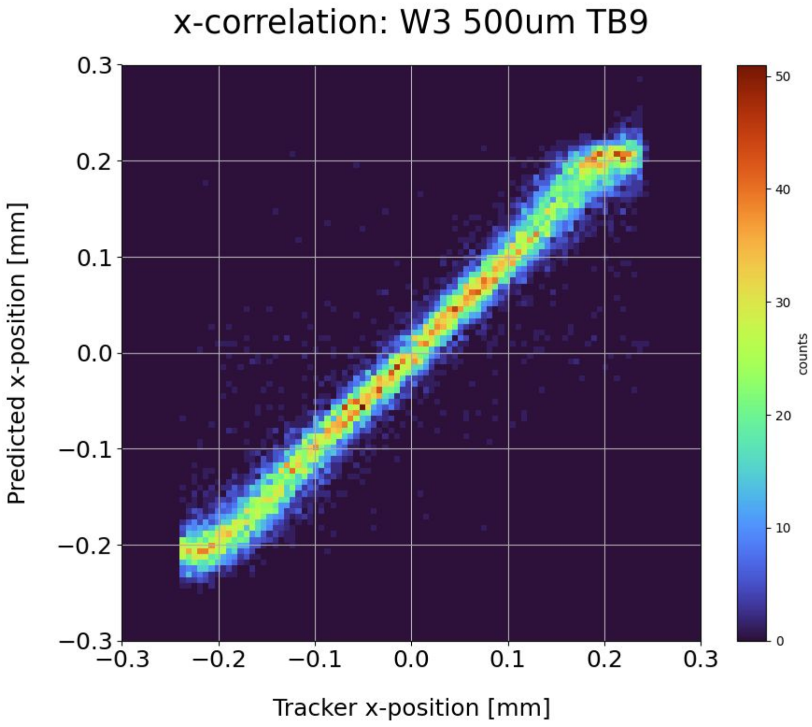
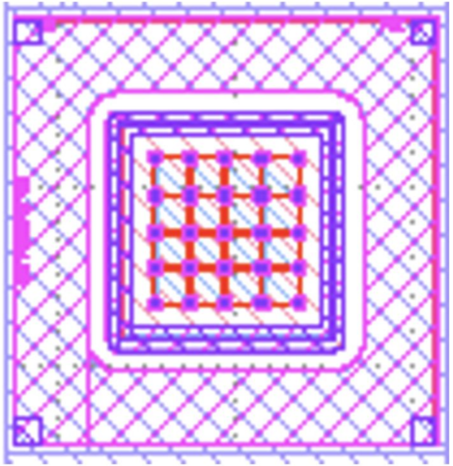
Correlations (DNN)



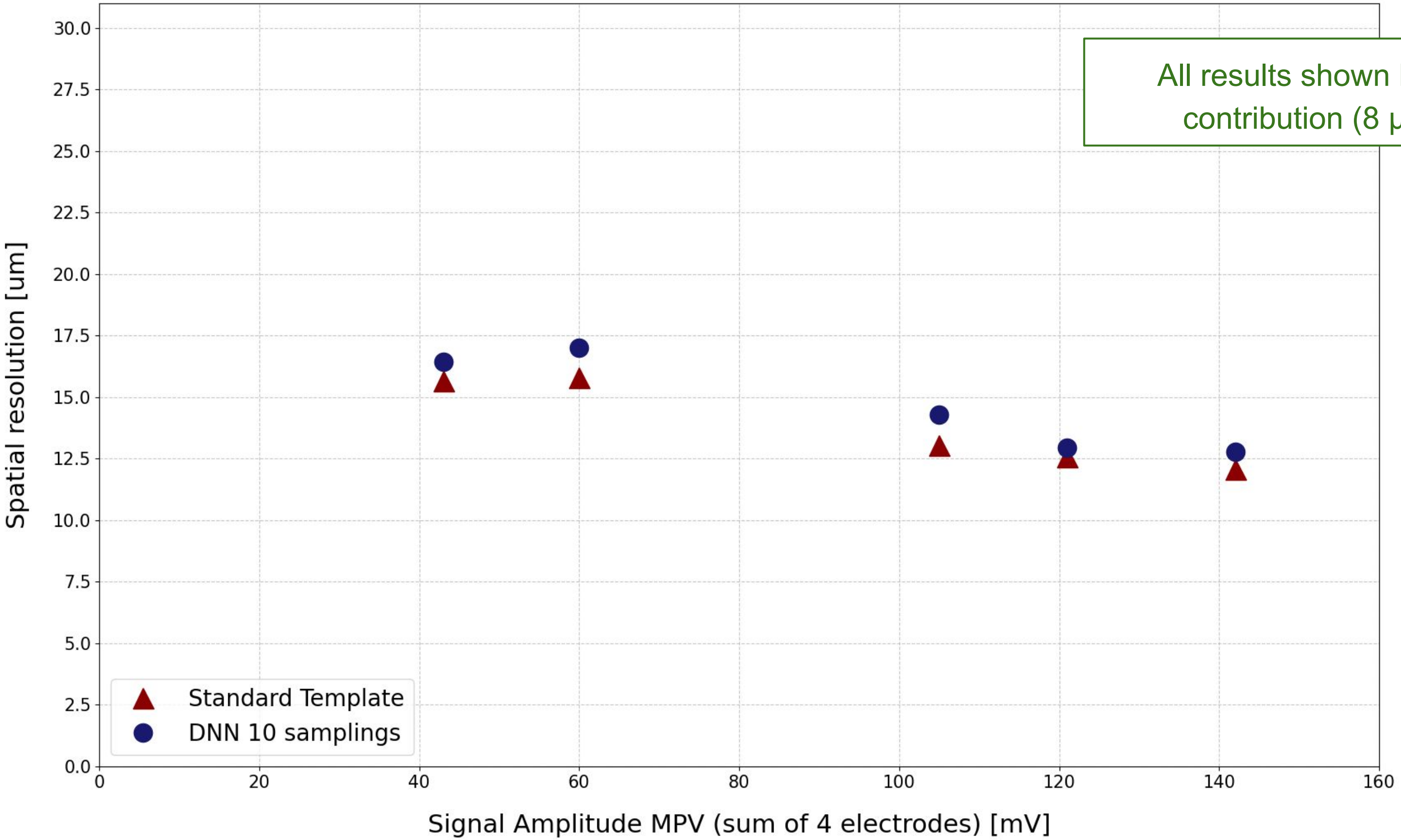
correlation reference-prediction (x-axis)

W3 = high resistivity n^+

Results on W3 300 µm pitch

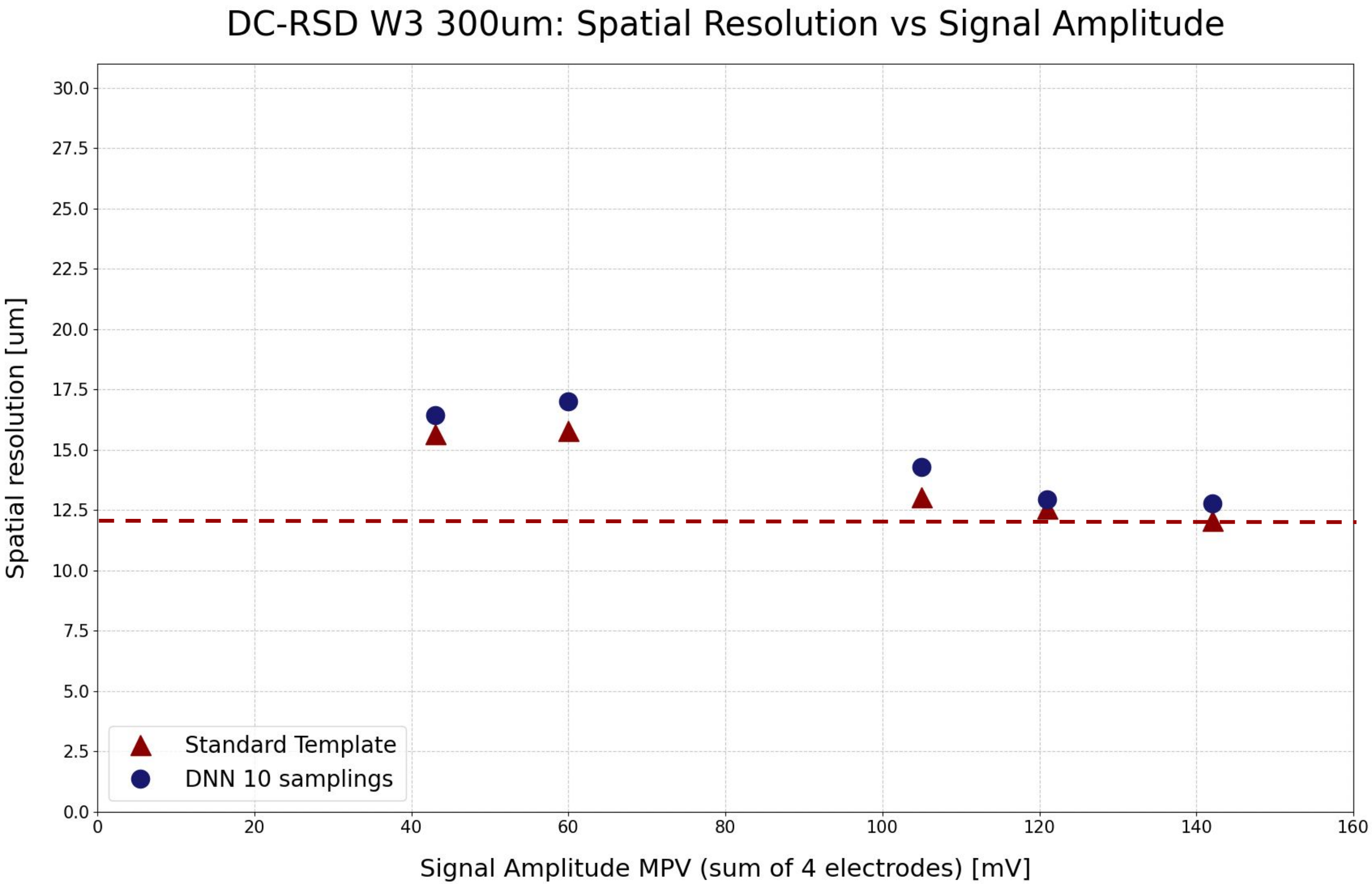


DC-RSD W3 300um: Spatial Resolution vs Signal Amplitude



All results shown have the tracker contribution (8 μm) subtracted

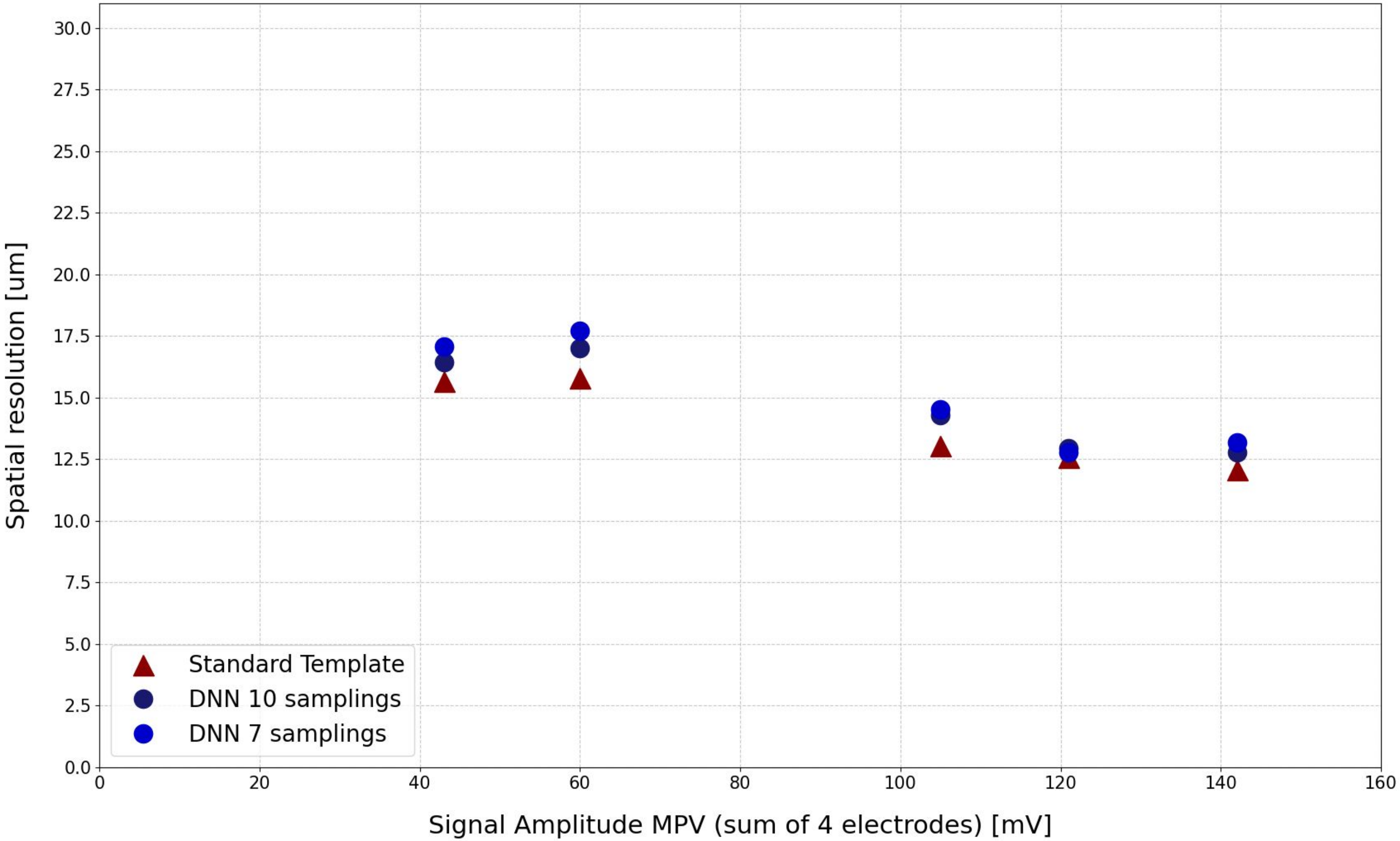
measured at +15°C



Template:
12 µm
(4% pitch)

measured at +15°C

DC-RSD W3 300um: Spatial Resolution vs Signal Amplitude



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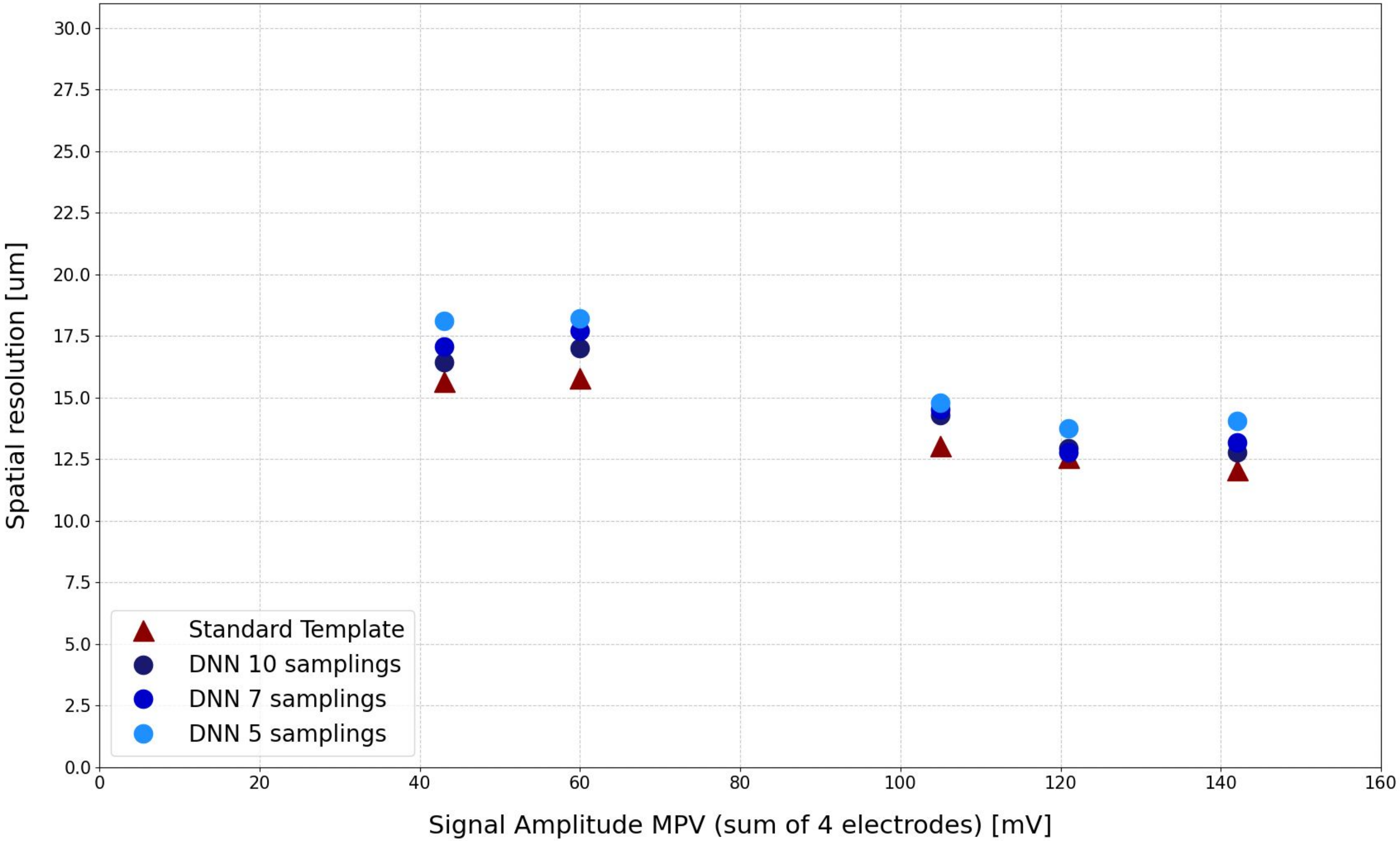

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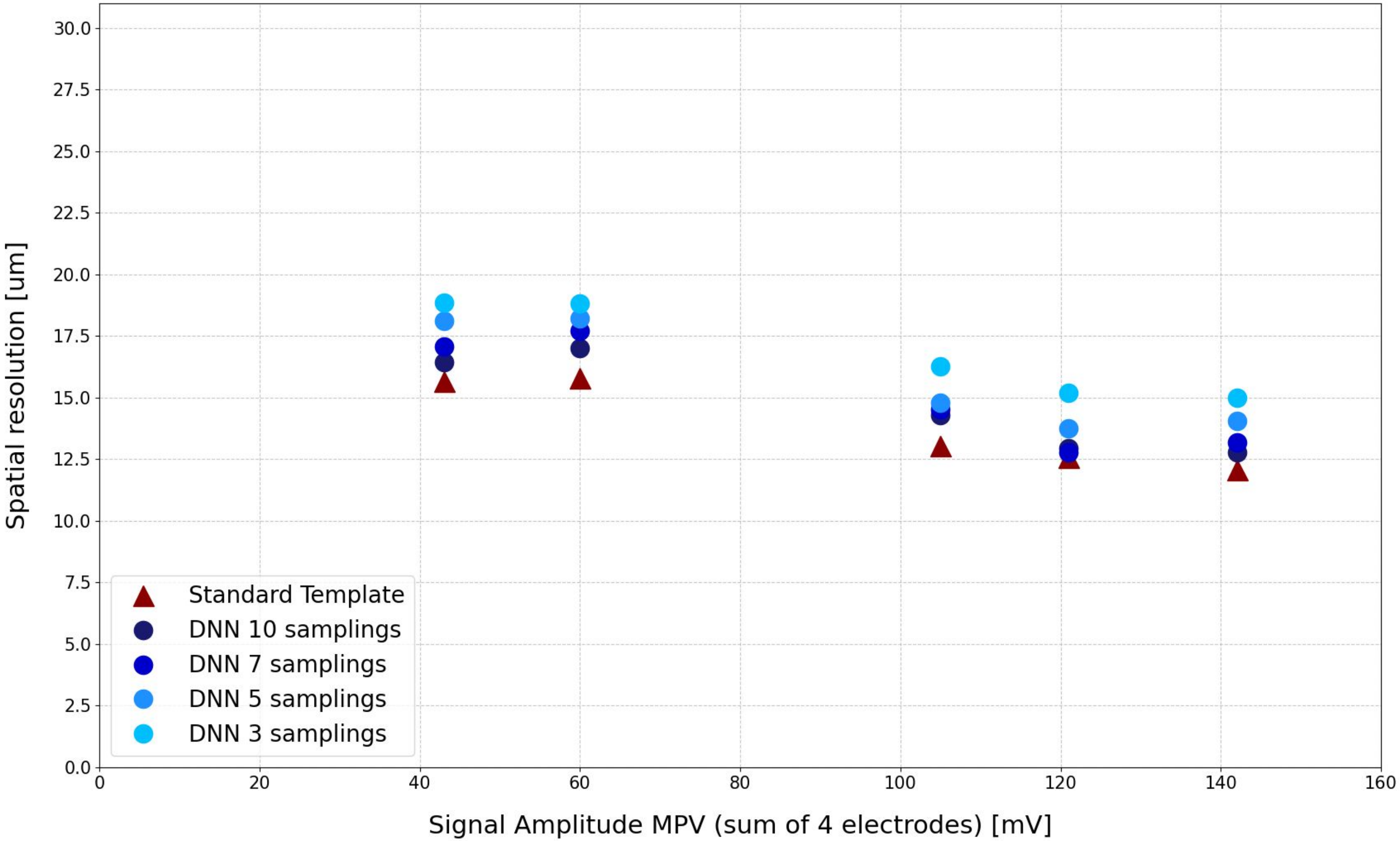

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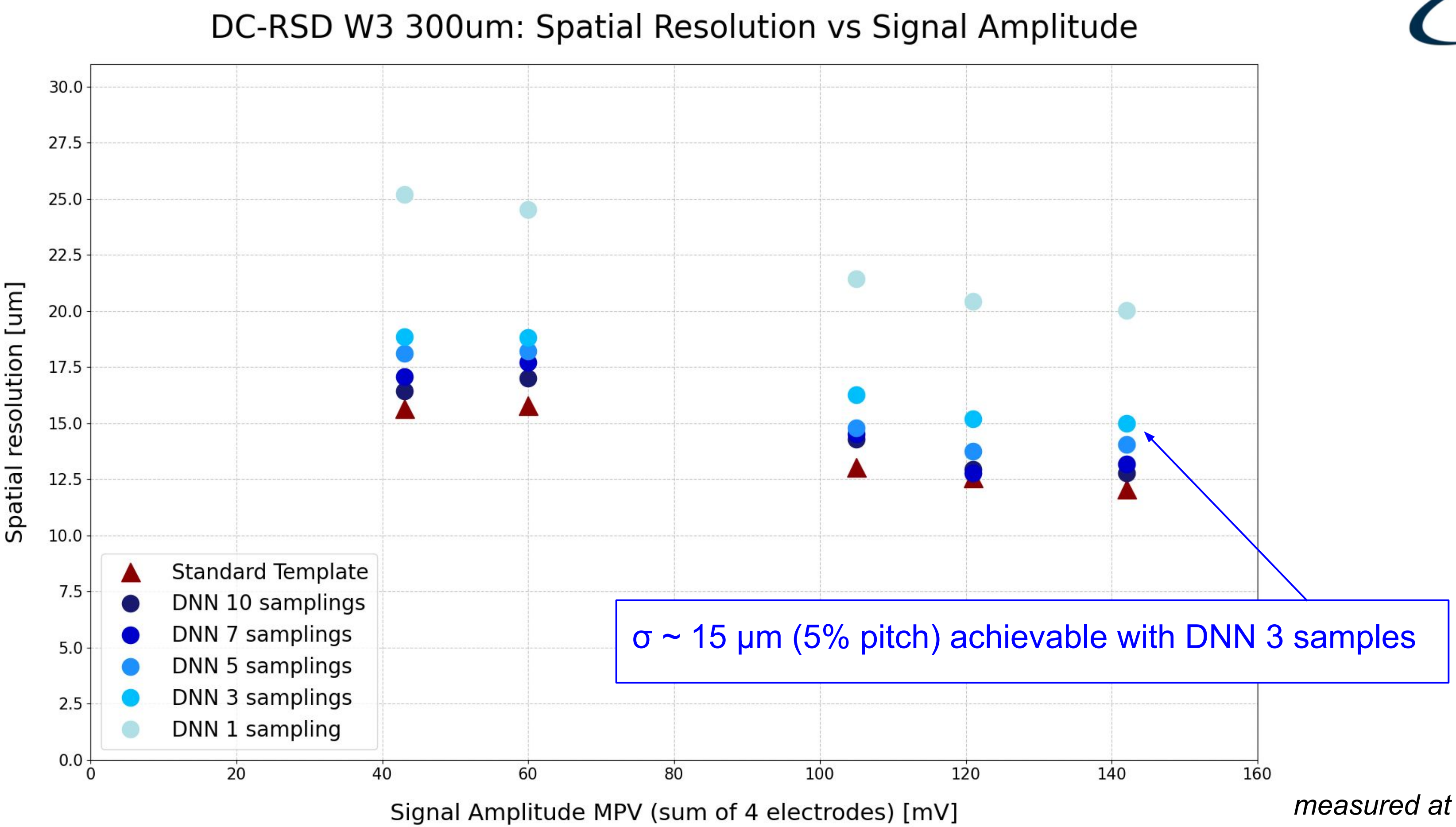
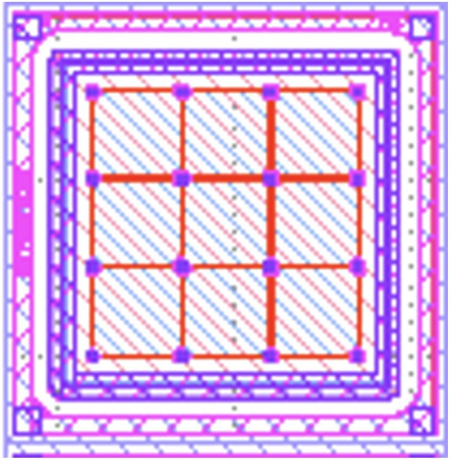


measured at +15°C

W3 = high resistivity n^+

Results on W3 500 µm pitch



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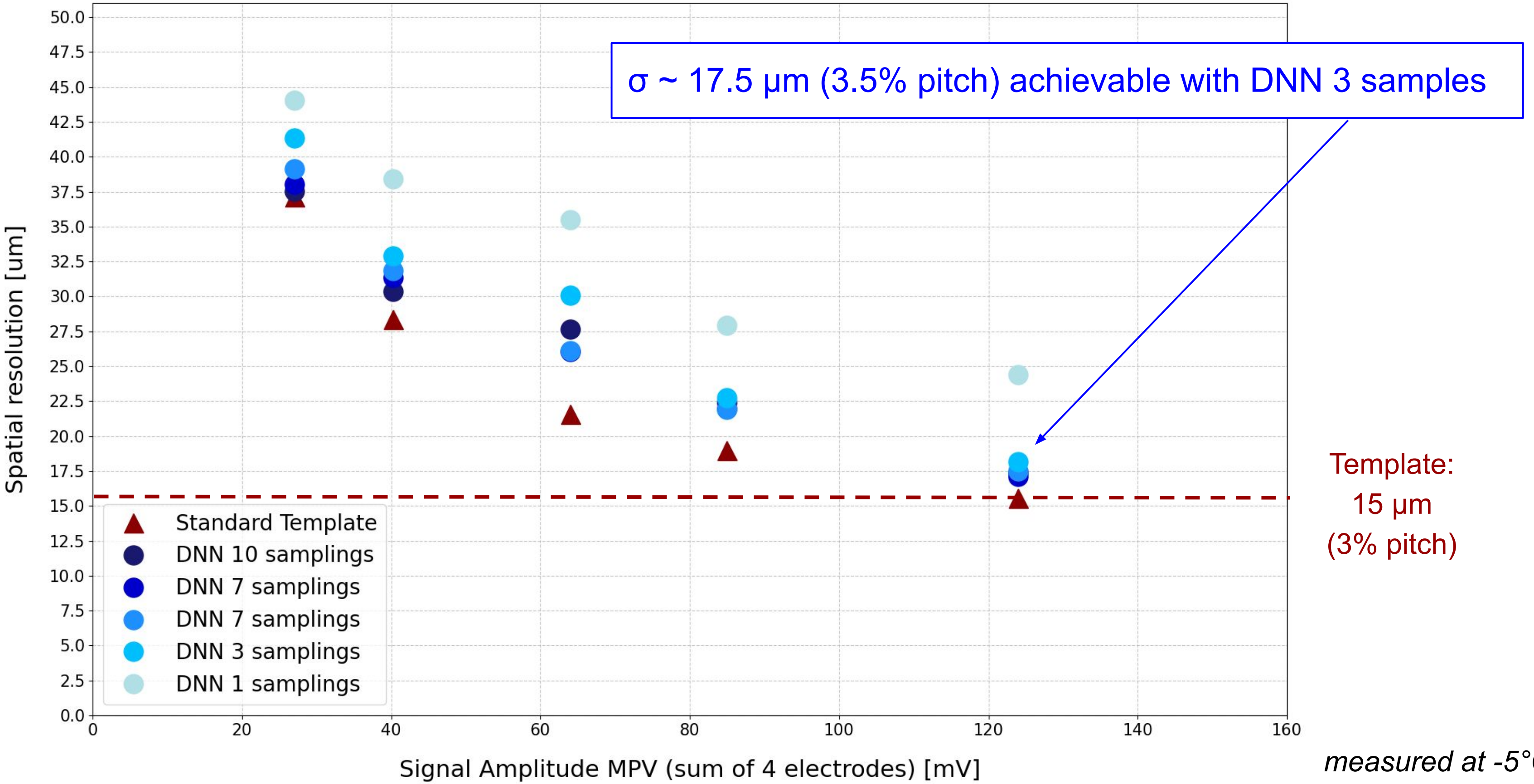
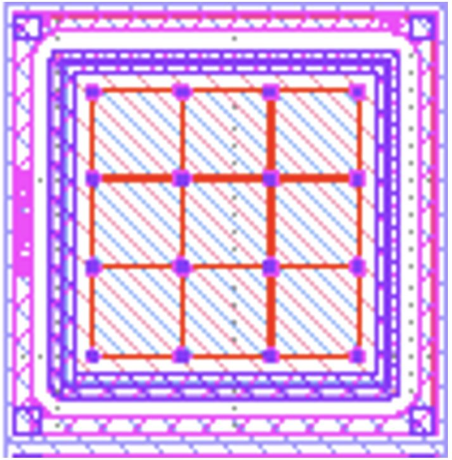


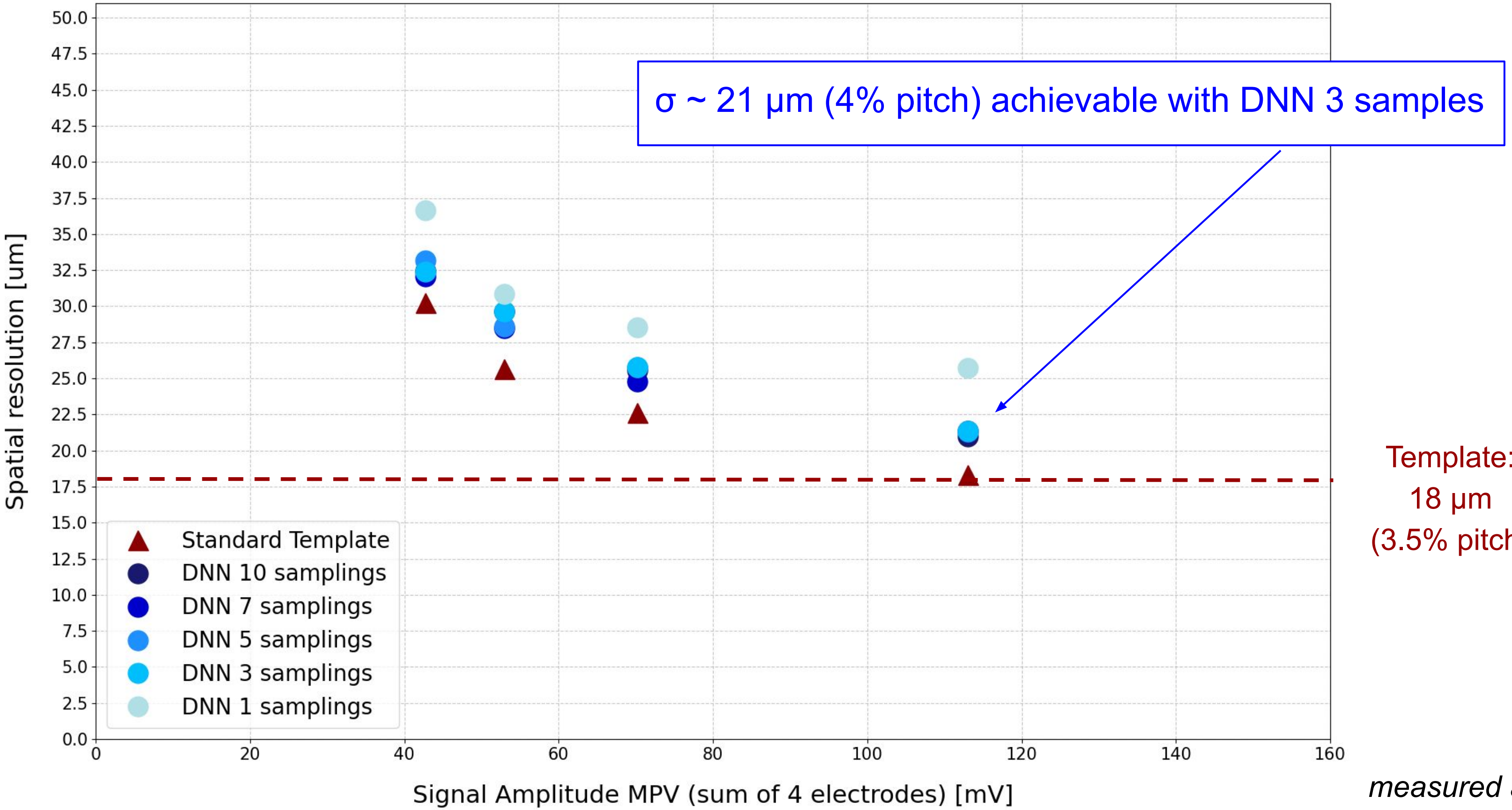
measured at -5°C

W15 = low resistivity n^+

Results on W15 500 µm pitch



DC-RSD W15 500um: Spatial Resolution vs Signal Amplitude



Template:
18 µm
(3.5% pitch)

measured at +15°C

Take-home messages

- **DC-RSDs can achieve a spatial resolution equal to 3-4 % of their pitch**
    - 300 µm pitch → 12 µm
    - 500 µm pitch → 15-20 µm
- **Standard Template and DNN provide similar results**, with Standard Template being slightly better
- Decreasing the number of samplings used for DNN training does not change much the performance
  - DNN trained with 3 samples → resolution ≤ 5% of the sensor pitch
  - **Using a double ToA-ToT electronics to perform 4D-tracking with RSDs might be possible**

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Do we expect these results?

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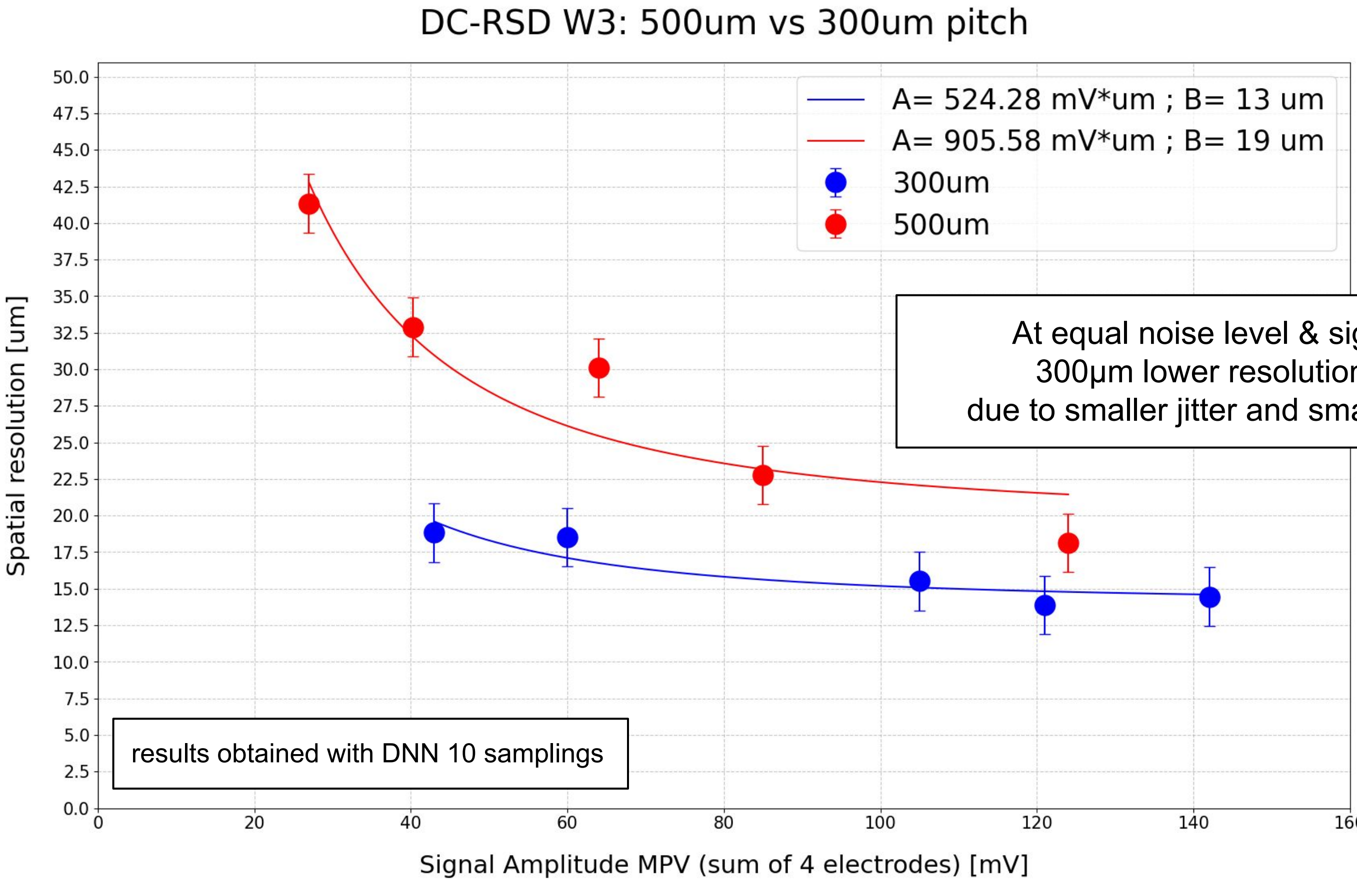
The DC-RSD spatial resolution

$$\sigma_{RSD} = \sqrt{\boxed{\sigma^2_{jitter}} + \boxed{\sigma^2_{constant}}} = \sqrt{(\frac{noise}{dV/dx})^2 + \sigma^2_{constant}} = \sqrt{\boxed{(\frac{noise \cdot pitch}{Signal})^2} + \sigma^2_{constant}}$$

- Noise constant at ~1.3 mV (electronics noise) → for a given signal amplitude (and same n$^+$ resistivity), jitter determined by the sensor pitch
- Constant term depends upon: accuracy of reconstruction method, resistive layer non-uniformity, slightly different amplifiers gain

RSD sweet spot: Signal high enough to minimize jitter → resolution determined by constant term

Pitch comparison (W3)

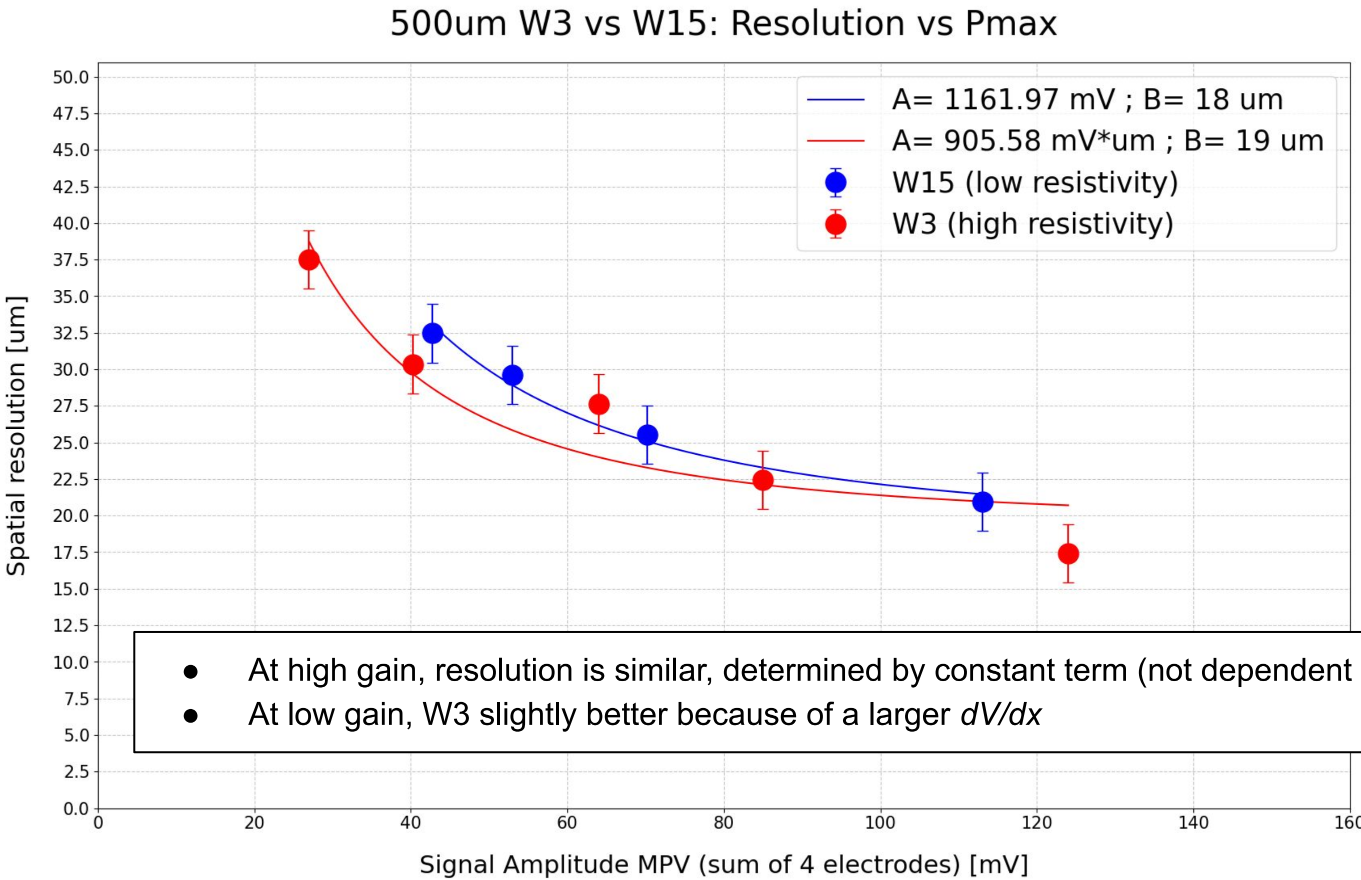


fitted to :

$$\sqrt{\left(\frac{A}{Signal}\right)^2 + B^2}$$

At equal noise level & signal amplitude,
300µm lower resolution than 500µm
due to smaller jitter and smaller constant term

Resistivity comparison (500um)



fitted to :

$$\sqrt{\left(\frac{A}{Signal}\right)^2 + B^2}$$

- At high gain, resolution is similar, determined by constant term (not dependent on resistivity)
- At low gain, W3 slightly better because of a larger *dV/dx*

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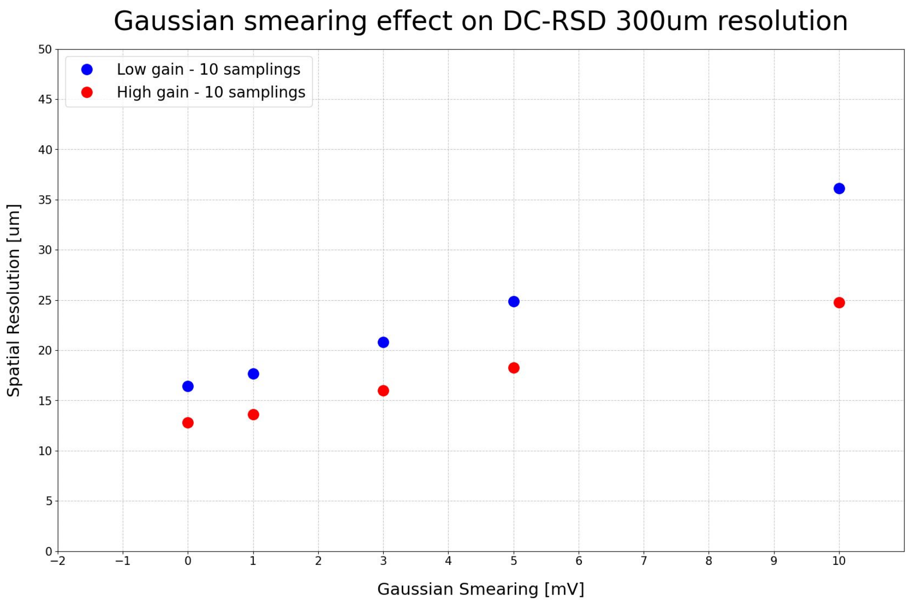
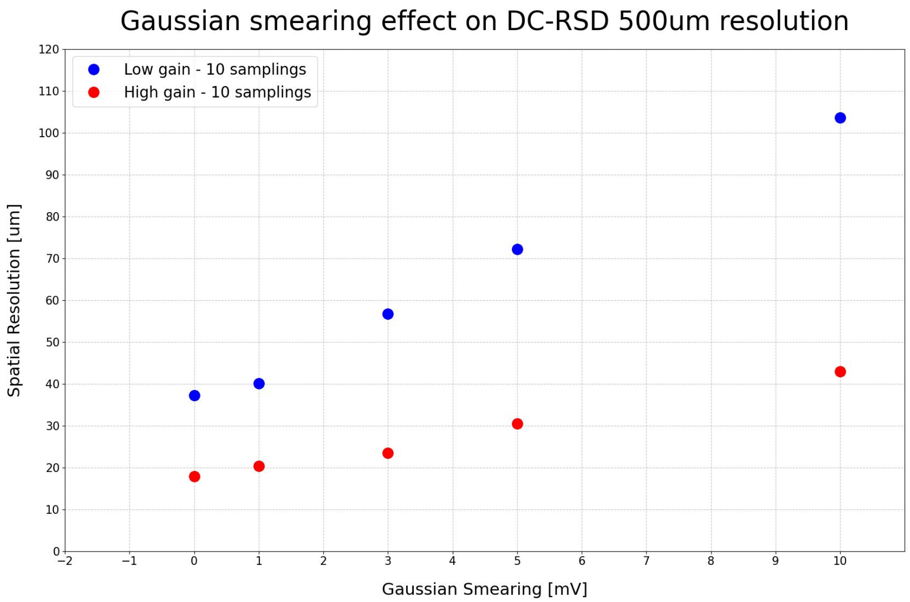
low gain ~ 10

high gain ~ 30

Gaussian smearing

We studied the effect of adding noise to the samples used to train the DNN (simulate the presence of noisy channels in an experiment)

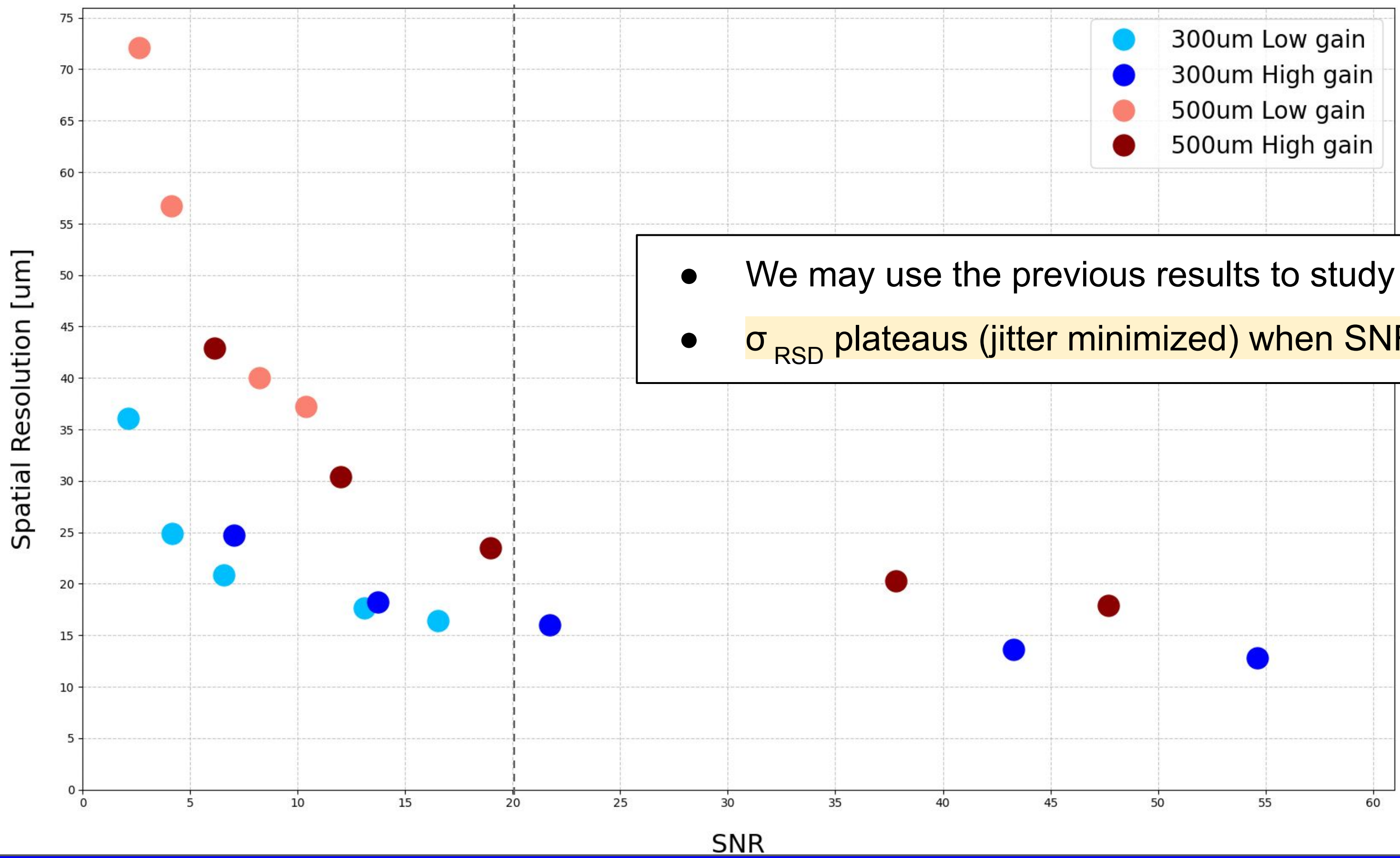




- Low gain more affected as the jitter component (noise dependent) is the leading contribution to σ_{RSD}
- At high gain, a 3 mV noise (x3 electronics noise) leads to less than 50% increase in σ_{RSD}

→ DC-RSD not particularly sensitive to high noise

Spatial resolution vs Signal-to-Noise Ratio



- We may use the previous results to study σ_{RSD} vs SNR
- σ_{RSD} plateaus (jitter minimized) when SNR > 20

note: noise in the 4 read-out channels are independent → total noise obtained by summing the single channels noise in quadrature

Timing with DC-RSD

- RSDs are characterized by intrinsic timing capabilities, typical of the LGAD design: they are able to reach a timing resolution of ~ 40 ps, see for instance:
    - L.Menzio and F.Siviero, "First test beam measurement of the 4D resolution of an RSD pixel matrix connected to a FAST2 ASIC"
    - M. Tornago et al, "Resistive AC-Coupled Silicon Detectors principles of operation and first results from a combined analysis of beam test and laser data"
- Analysis of timing resolution with DC-RSD using recent TB data is ongoing, both with analytical laws and with machine learning
    - Preliminary results with analytical laws very promising, confirming previous results
    - Timing with ML is challenging, we are working to develop strategies to achieve predictions as accurate as the analytical law ones…more news coming soon!

Summary

- **DC-RSDs**, developed within the 4DSHARE project, are thin **silicon sensors combining the LGAD technology and resistive read-out to achieve excellent 4D-tracking** performance with reduced material budget and a very low density of read-out channels

- **In this work**, we studied the spatial resolution of DC-RSDs measured with 5 GeV electrons at the DESY TB facility, **comparing the performance of an analytical model and a DNN** that takes the raw digitized data to make a prediction on the hit position

- We found that:
    - **DC-RSDs can achieve a spatial resolution equal to 3-4 % of their pitch**
        - DC-RSD 300 μm pitch → 12 μm
        - DC-RSD 500 μm pitch → 15-20 μm
    - **Analytical model and DNN provides similar results** when ~10 samples per signals are used for the DNN training
    - When DNN is trained with 3 samples the resolution increases to ≲ 5% of the sensor pitch → **using a double ToA-ToT electronics to perform 4D-tracking with RSDs might be possible**, this opens up a new R&D path towards the production of a front end electronics to be coupled to RSDs in future experiments

Thank You!

Acknowledgements

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- We acknowledge the fruitful discussions with the RD50 and DRD3 collaborations, CERN

- Measurements leading to these results have been performed at the test-beam facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF).

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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

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BACKUP

The 4D-Tracking challenge

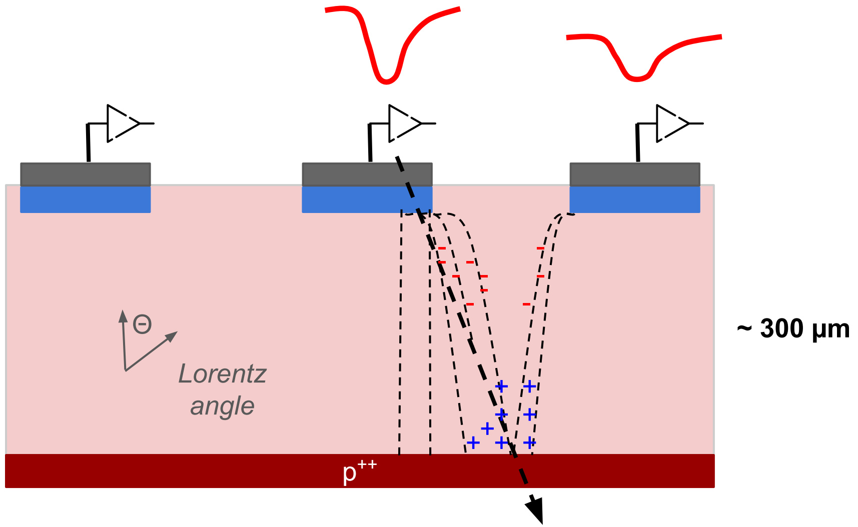
Experiments at future colliders will pose unprecedented challenges to tracking systems*

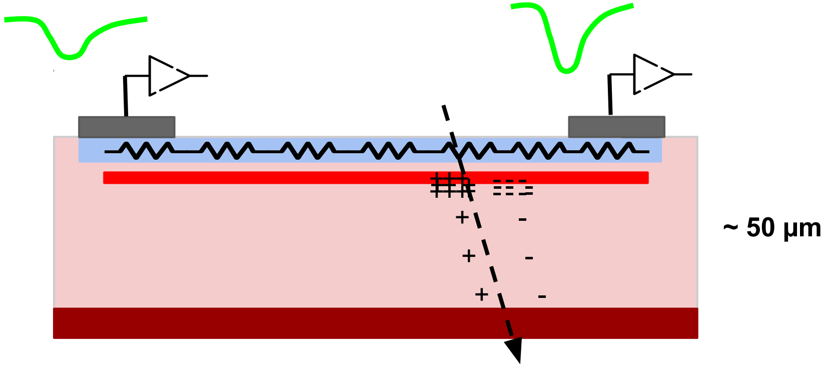
- Spatial resolution O(10 μm)
- Temporal resolution O(10 ps)
- Reduced material budget: < 1% of a radiation length per layer
- Limited power consumption: < 100 mW/cm^2

→ the 4DSHARE project is developing a technology to address the challenge, the DC-RSD

* *Trackers, ToF wrappers for PID*

DC-coupled Resistive Silicon Detectors (DC-RSD)

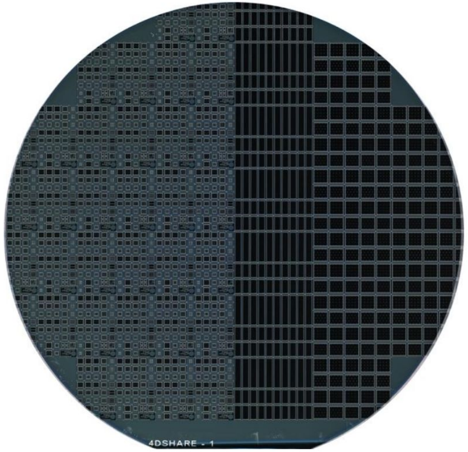




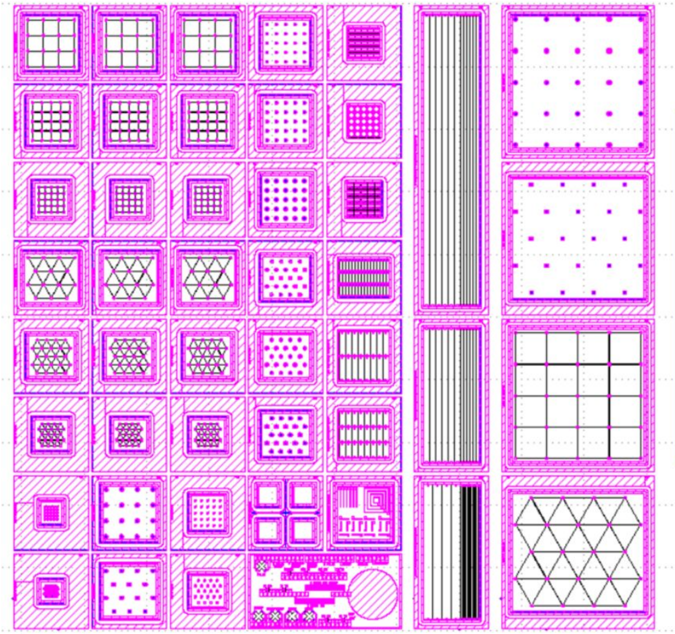
- Traditional pixel detector with multi-pixel read-out may have larger pixel, though they require strong B-field and need to be thick to exploit charge sharing
- In DC-RSD, sharing happens on the resistive layer and the initial signal is boosted in the gain region, so they do not need B-field and may be thin (reduced material budget)

The FBK DC-RSD1 production

- The first production of DC-RSD has been manufactured by FBK in 2024
- 15 wafers with different n^+ and p^+ doses (resistive layer, gain implant)
- Wafer layout with different electrode patterns and pitch



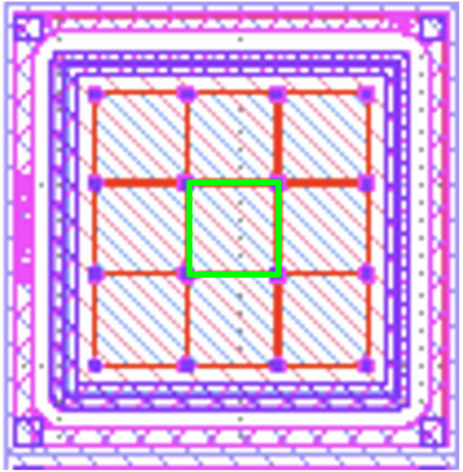
DC-RSD1 wafer

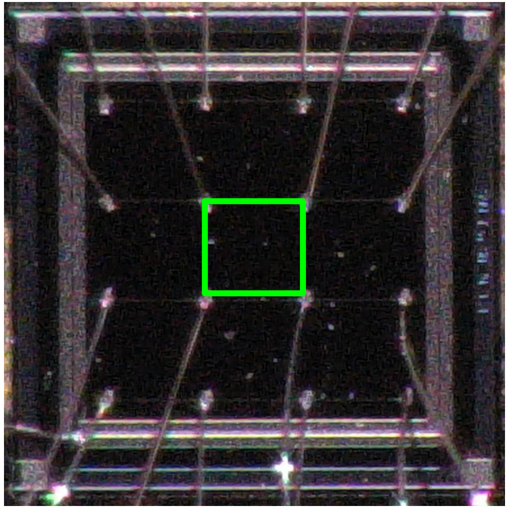


DC-RSD1 reticle

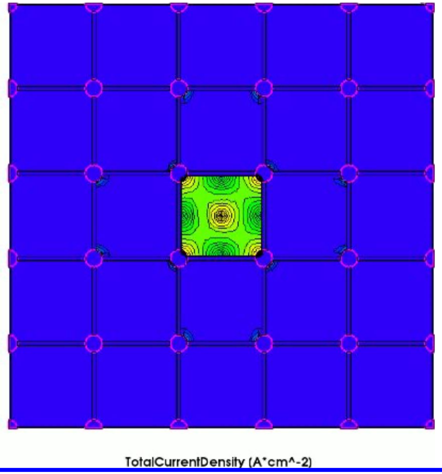
M. C. Vignali et al., Development and wafer-level characterization of the First Production of DC-RSD Sensors at FBK

DC-RSDs with isolating trenches





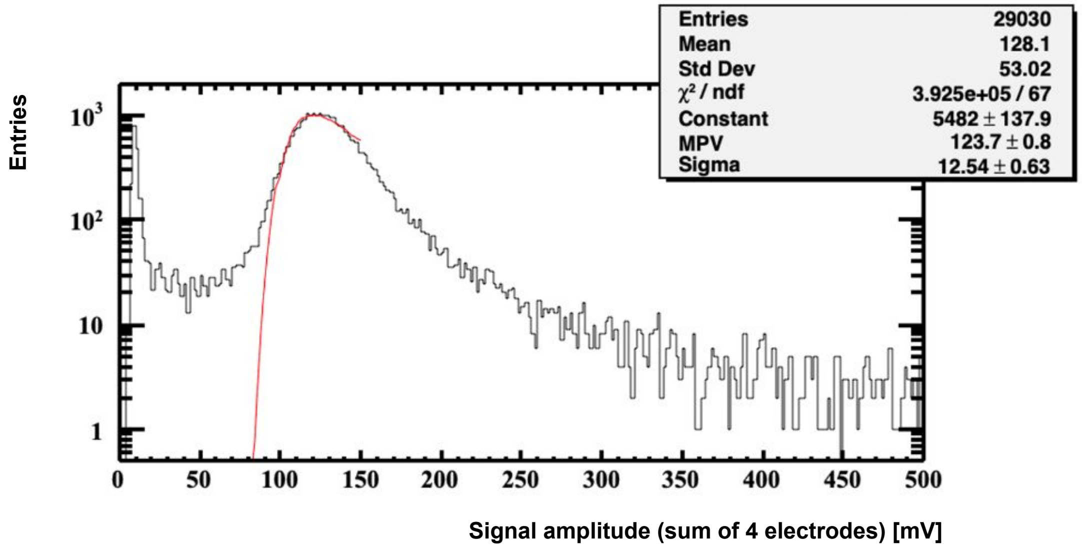
Signal confinement studied with TCAD (see ref.)



Hit pixels read out by 4 electrodes placed at the vertices, contacted through wirebonds

- The DC-RSDs presented in this work feature isolating trenches used to confine the signal within square pixels of O(100 μm) x O(100 μm) area
- Trenches ensure that the hit position is always reconstructed by the same number of electrodes, and prevent the signal from spreading across the whole active surface (reduce occupancy)

DUT gain

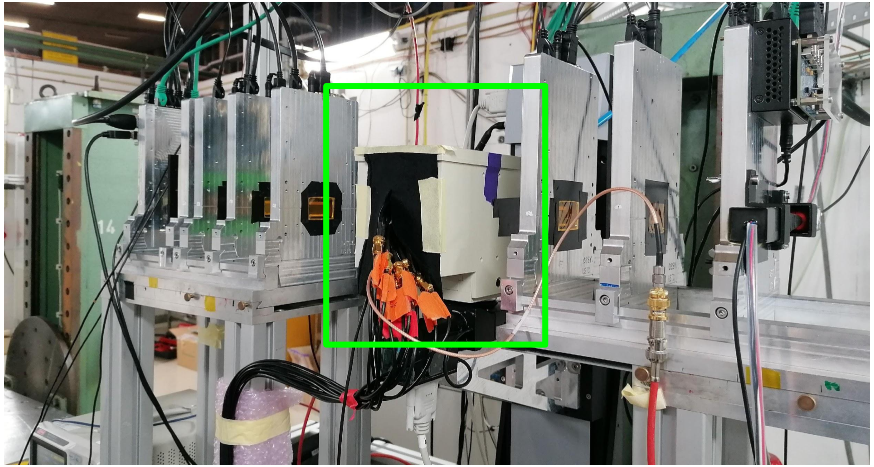


Requiring signal amplitude > 30 mV is enough to separate noise from signals

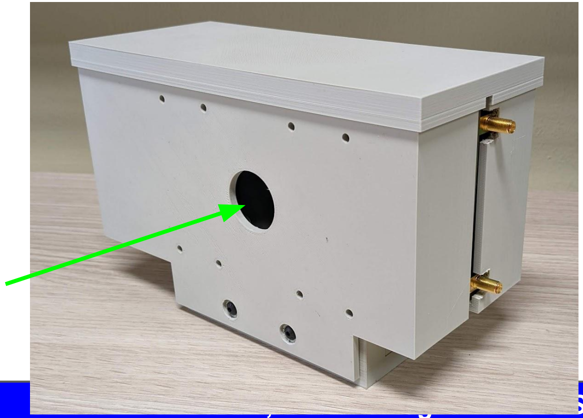
- All tested DC-RSDs can provide large initial signals, as proven by the distribution of the sum of the 4 signal amplitudes in the read out pixel
- At high gain (~30) the MPV is >120 mV, a value comparable with that of a standard LGAD

DESY Test Beam Facility

- Data presented in this work have been taken at the DESY test beam facility using 5 GeV electrons
- The reference positions used to evaluate the DUT spatial resolutions are provided by a 6-planes ADENIUM / MIMOSA tracker telescope with $\sigma_{\text{Tracker}} \sim 8\ \mu m$
- Trigger is a standard 3x3 mm^2 LGAD



DESY setup for operation at roomT

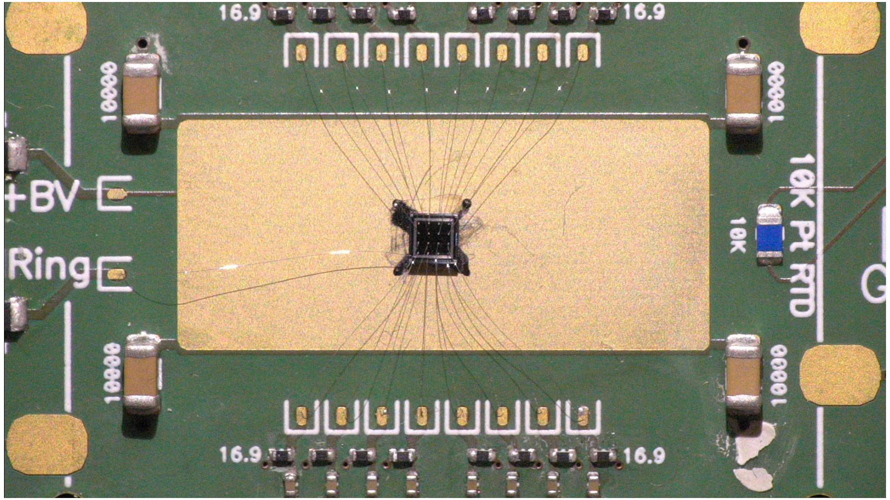


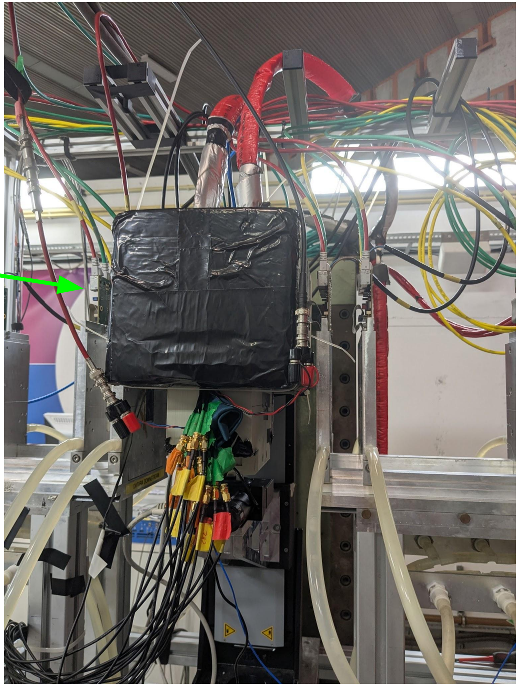
DUT placed within a 3d-printed dark box sitting on a x,y,Θ PI stage

The DESY II test beam facility *NIMA, Vol. 922, 2019*

DESY Test Beam Facility

- Sensors are read out through a 16-ch fast analog board designed at FNAL
- W3 300 µm, W15 500 µm operated at +15°C
- W3 500 µm operated at -5°C within a custom-made cold box
- Dry air always fluxed for 10-20% relative humidity

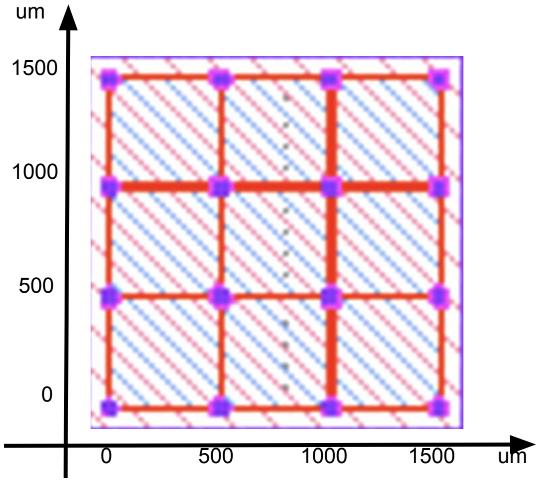


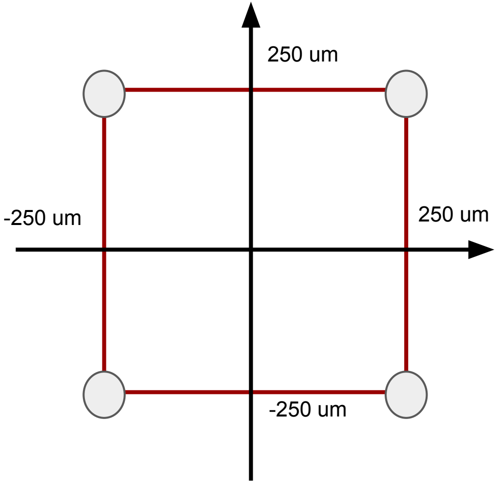


DUT mounted on 16-ch FNAL board

DUTs pixel pattern

- Because of signal confinement, position reconstruction always involves only 4 electrodes → each pixel is independent from the others
- It is then convenient to “fold” the DUT matrix, shifting each pixel so that it is centered in the origin



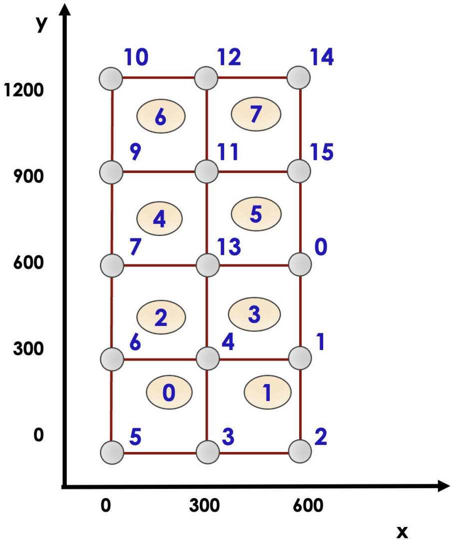


9 overlapped pixels

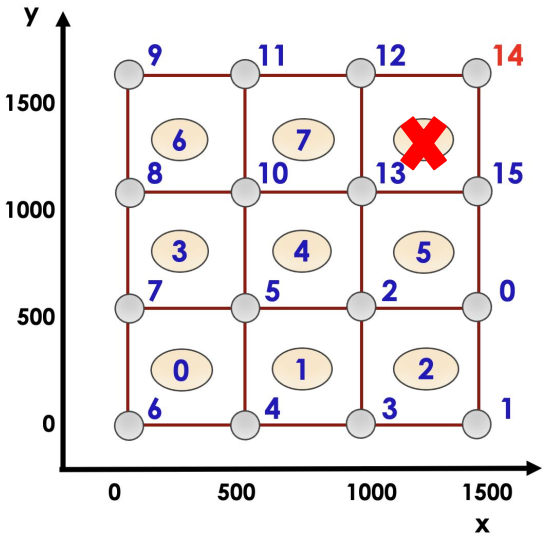
DUTs pixel pattern

- It was not possible to read all DUT electrodes during data taking:
  - we used a 16-ch CAEN digitizer
  - sometimes wirebonds detach, or a channel on the board fails
- Below are the patterns used for the different DUTs

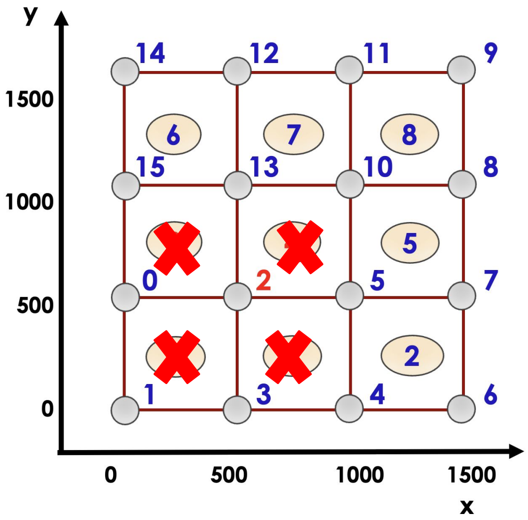
we use tracker information to select the active pixels



W3 300 µm: 15ch, 8 pixels



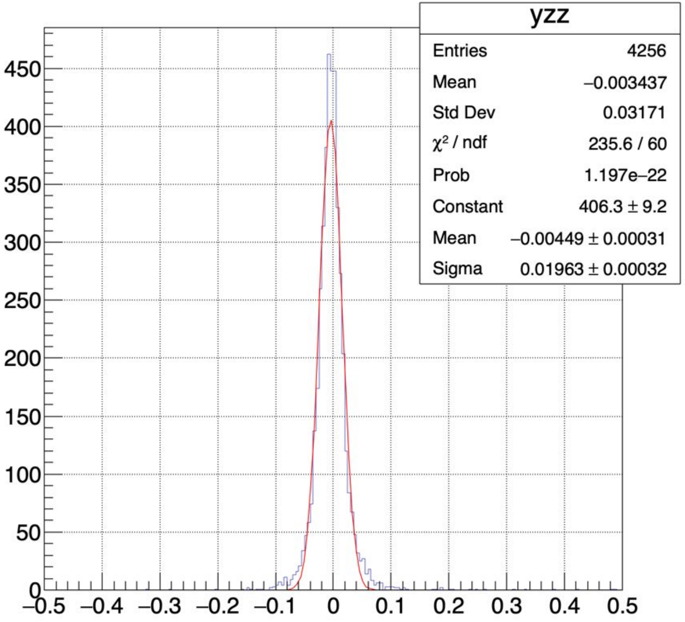
W15 500 µm: 15ch, 8 pixels



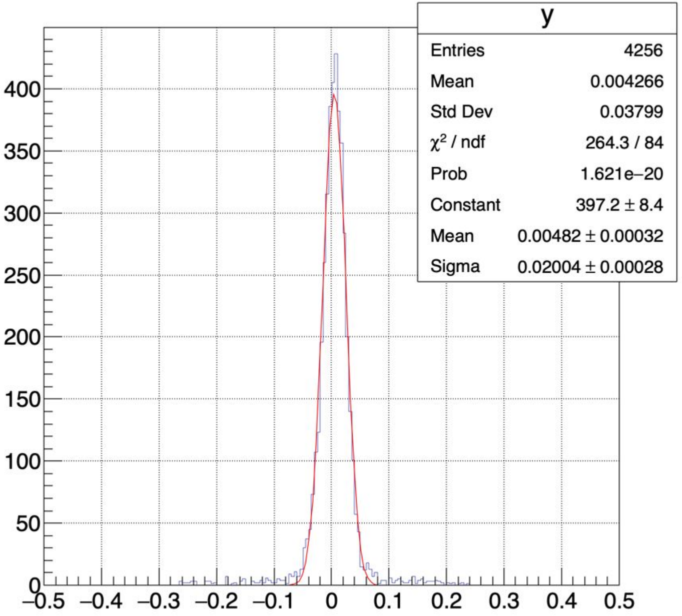
W3 500 µm: 15ch, 5 pixels

Comparison of predictions

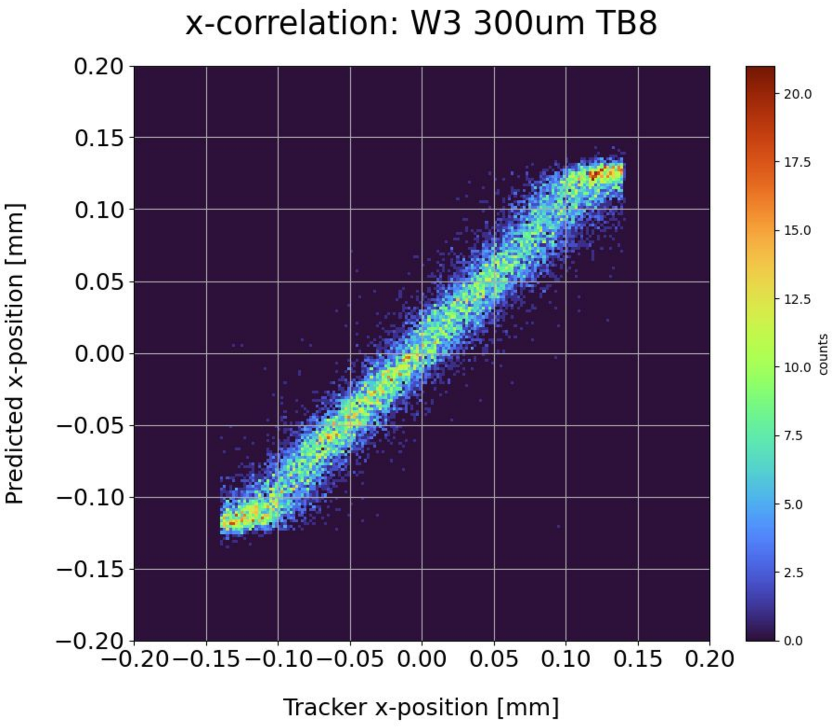
Standard Template



DNN

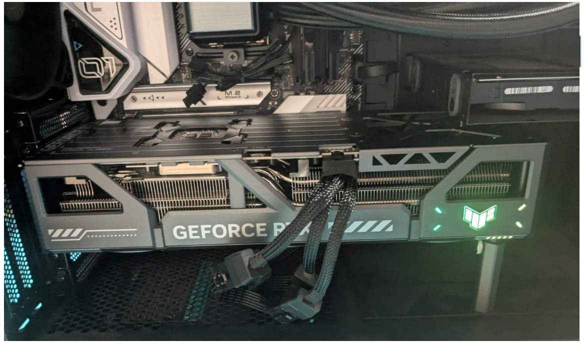


Correlations (DNN)



correlation reference-prediction (x-axis)

Details on the DNN

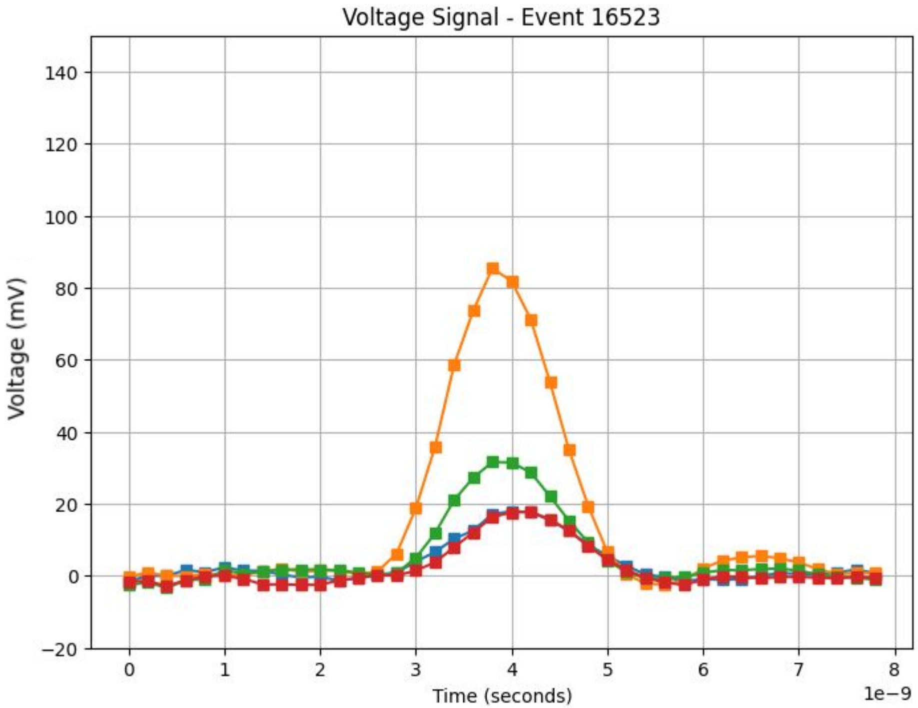


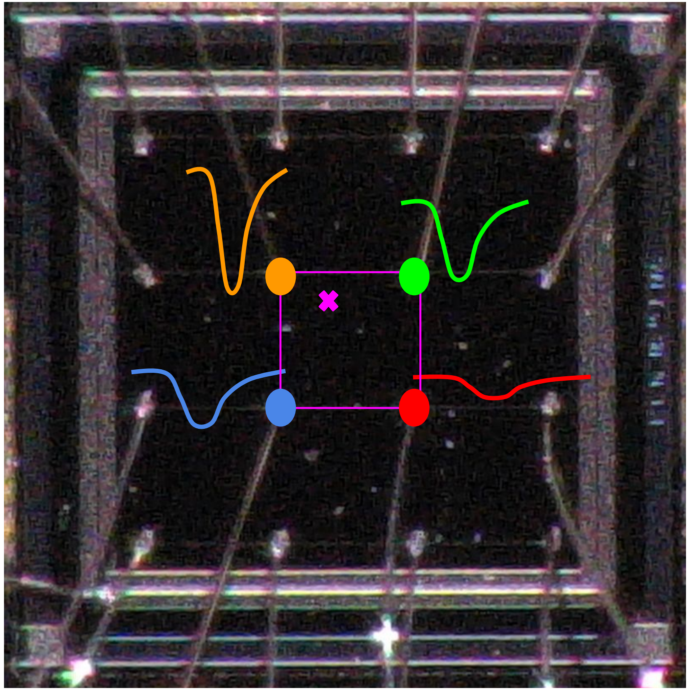
GPU installed in our workstation

- Developed using tensorflow
  - 6 hidden layers, input features range 40 to 4 depending on the number samplings per waveform
  - 20% dropout layer after the first dense layer
  - Adam optimizer
  - *tanh* as activation function, input features are normalized in the [-1, 1] range
- Training pipeline: raw data from the digitizer are saved as root file, used to produce sets of csv files containing the input features and the target (x-y coordinates of the hit position) that are fed to the DNN
  - 80% of data for training, 20% for test

All these studies are possible thanks to a powerful GPU (NVIDIA GeForce RTX 5090) recently purchased by the project → we have just started exploring this innovative approach!

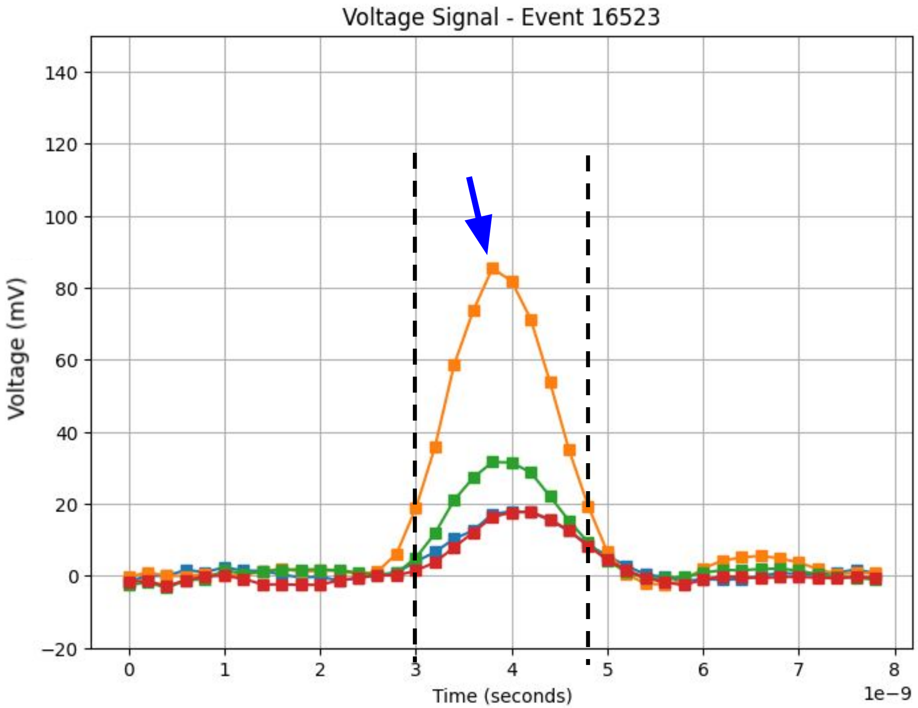
Spatial reconstruction with Machine Learning

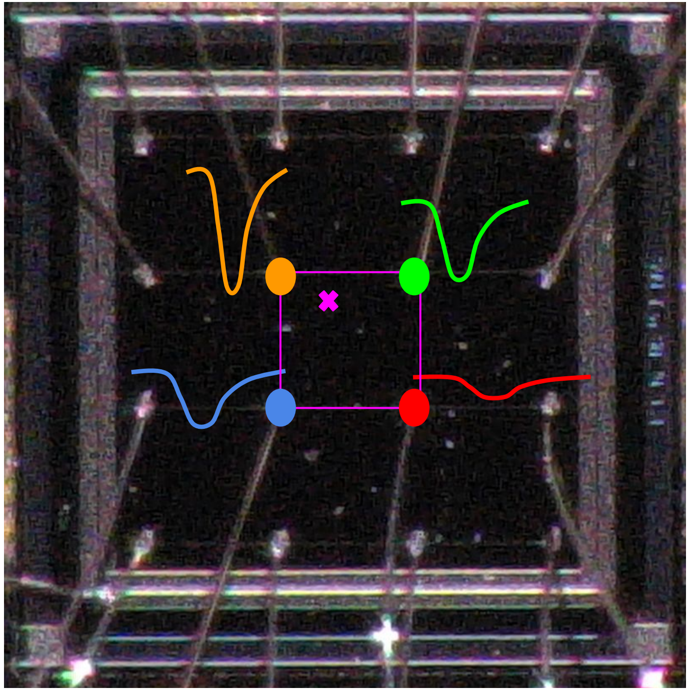




The 4 read-out signals in a typical event

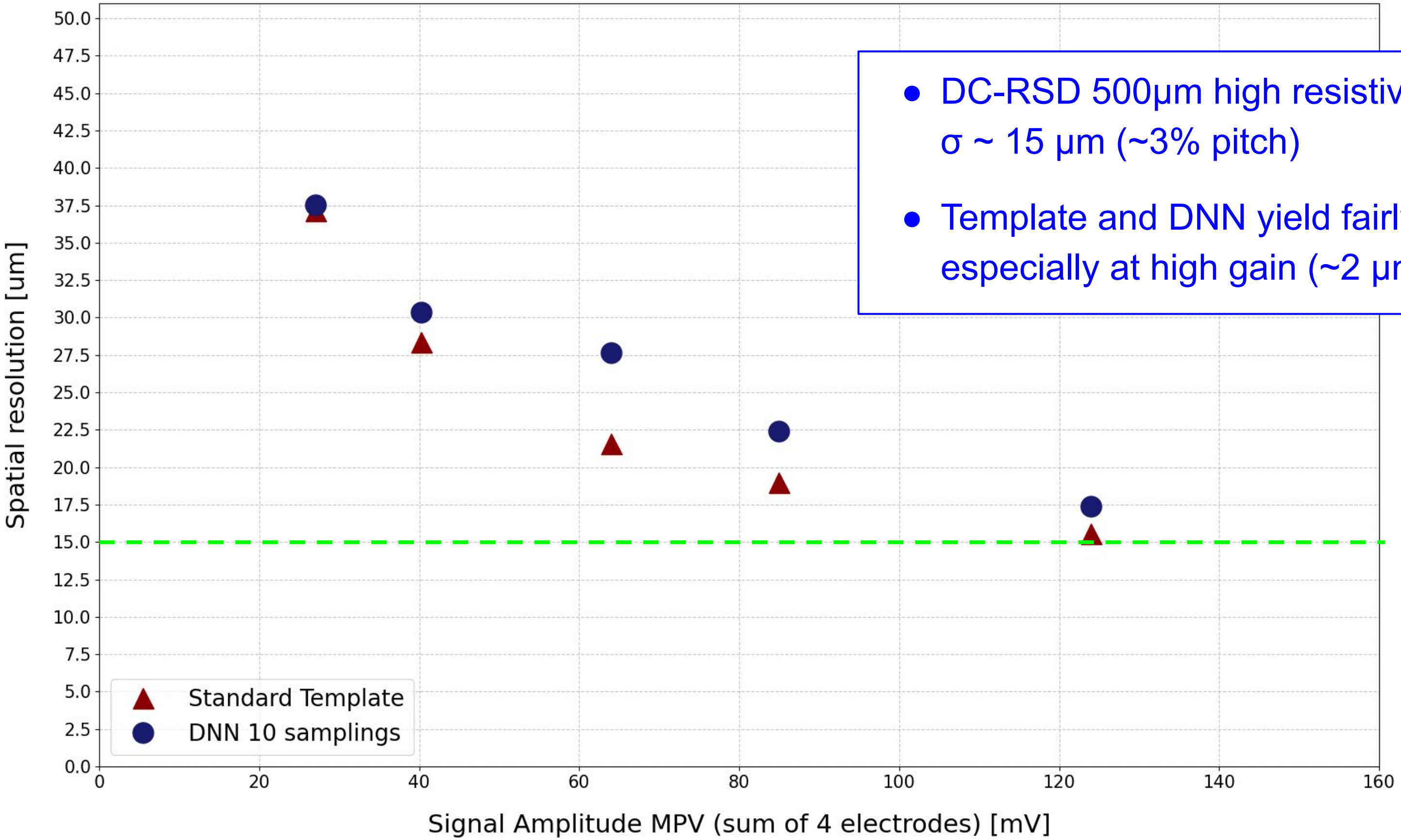
Spatial reconstruction with Machine Learning





- Digitization clock provided by the digitizer common to all read-out channels
- **Time window** where the samples for the analysis are extracted is determined by the **highest sample** of the highest signal (10 samples per waveform in this example)

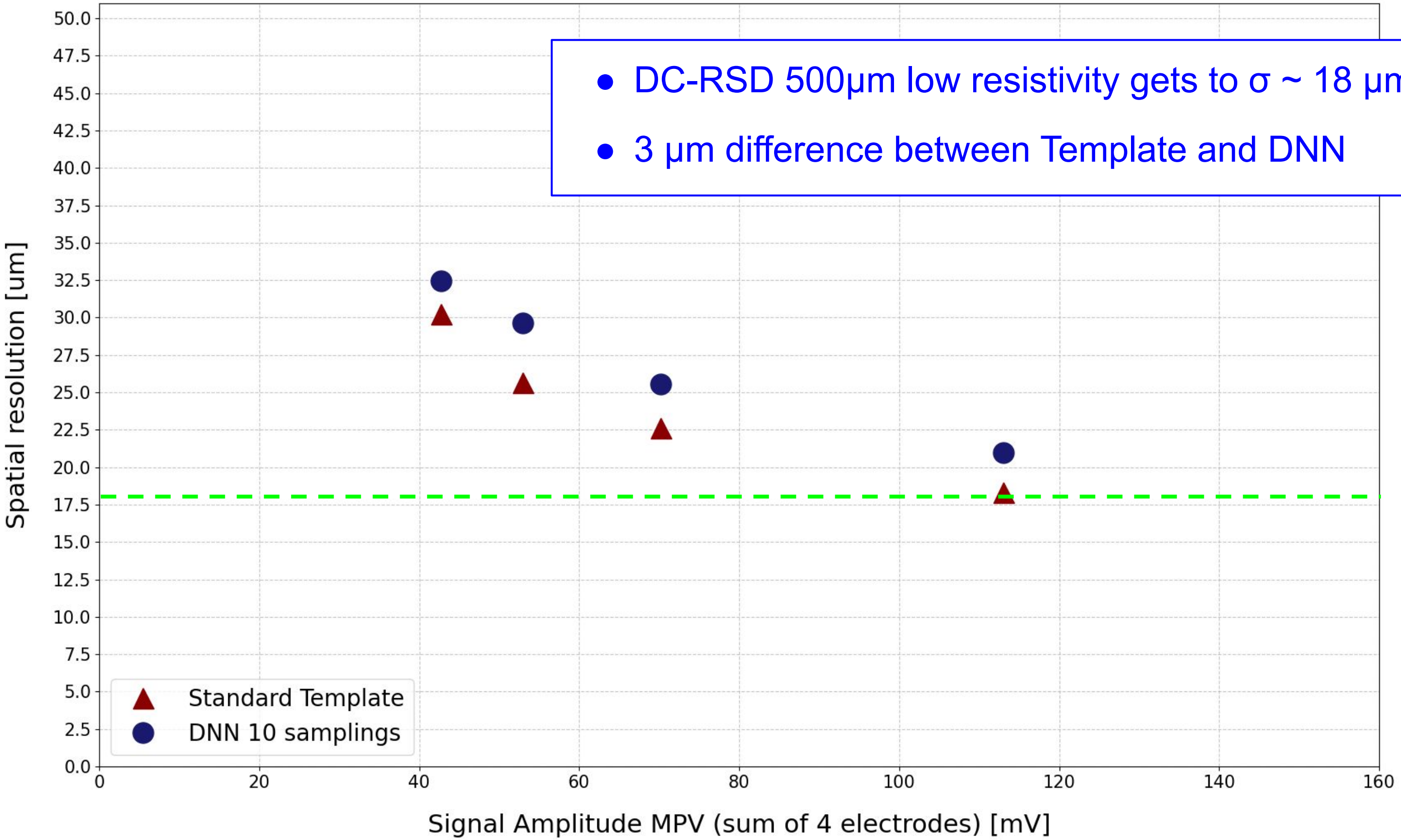
DC-RSD W3 500um: Spatial Resolution vs Signal Amplitude



- DC-RSD 500µm high resistivity gets to σ ~ 15 µm (~3% pitch)
- Template and DNN yield fairly similar results, especially at high gain (~2 µm difference)

measured at -5°C

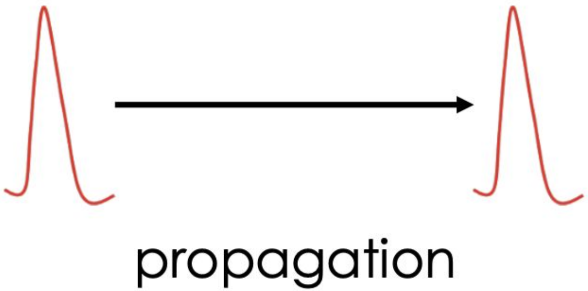
DC-RSD W15 500um: Spatial Resolution vs Signal Amplitude

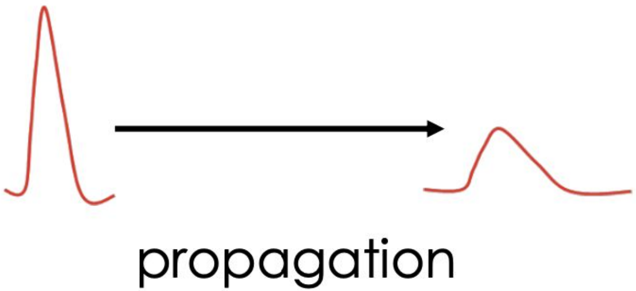


- DC-RSD 500µm low resistivity gets to σ ~ 18 µm (~3.5% pitch)
- 3 µm difference between Template and DNN

measured at +15°C

Effect of different n^+ resistivity





Low resistivity → small *dV/dx*

High resistivity → large *dV/dx*