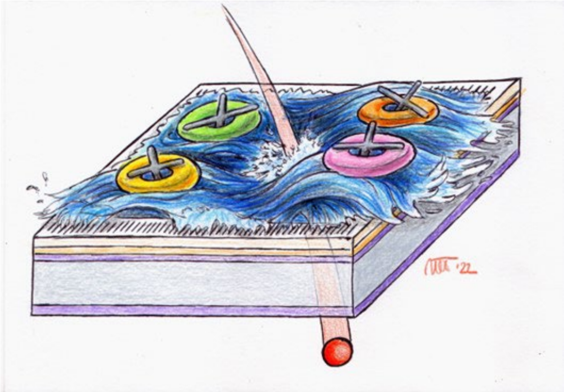


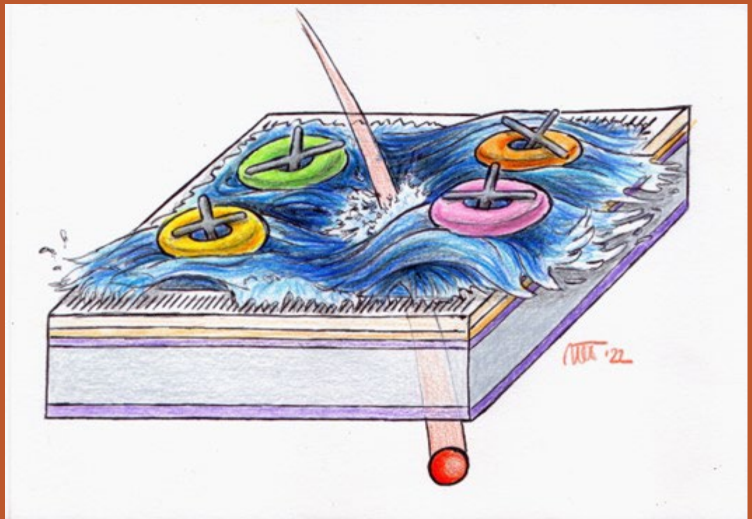
RSD2 performance in the AIDAINNOVA SPS test beam

LUCA MENZIO (INFN TORINO)

ON BEHALF OF THE AIDAINNOVA TESTBEAM TEAM

Contents

Contents



Introduction

- Resistive read-out in silicon detectors

Experimental Set-up

- AIDA test beam setup @ SPS
- Chubut2 acquisition board

Analysis and Results

- Analysis flow
- 1.3 mm-pitch sensor results
- 450 µm-pitch sensor characterization

Conclusions

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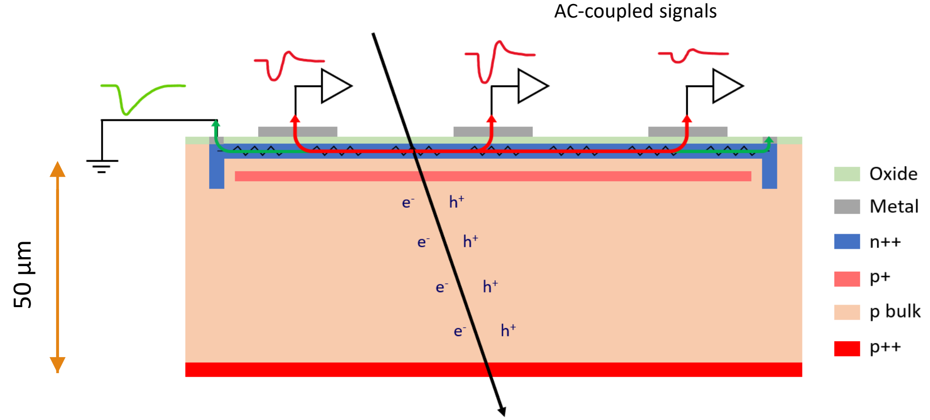
Resistive Read-out

e-h pairs are produced by the impinging particle in the sensor volume



- Electrons are multiplied (LGAD)
- Charge is induced in the n+ layer (resistive layer)
- Nearby electrodes see a fast signal
- Charges in the n+ flow to ground ↳ **Signal sharing**
- AC-coupled electrodes

In normal pixel detectors $\sigma_x = k\frac{pitch}{\sqrt{12}}$ with $\mathrm{k}\sim 0.5 - 1$

Resistive read-out sensors have

- $\sigma_x \ll \mathrm{pitch}$
- Time resolution typical of thin LGADs

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Resistive Read-out

Charge sharing over silicon surface
+
Internal gain (LGAD)

→ Excellent position resolution with large pads

→ Excellent Timing

Pros

- Low channel density
- Thin sensors

⇒

- Low power consumption
- Low material budget

+ **100 %** intrinsic fill factor!

DUTs – RSD devices

Luca Menzio – INFN Toino

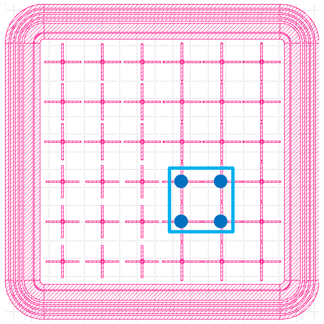
The DUTs come from the second production by FBK of Resistive Silicon Detectors (RSD2)

Two devices tested:

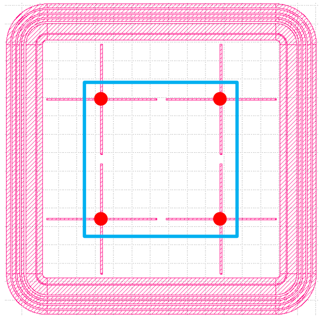
- 450x450 µm^2 from W7
- 1.3x1.3 µm^2 from W13

Same AC-electrodes layout – crosses to help the signal containment

Different n+ layer resistivity



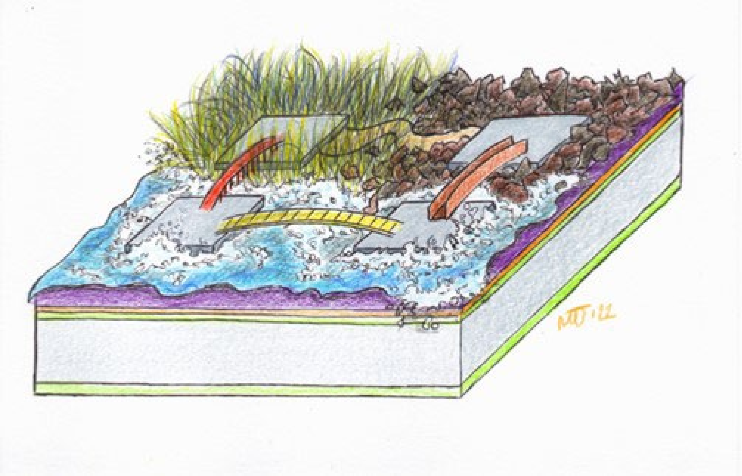
450 x 450 µm^2



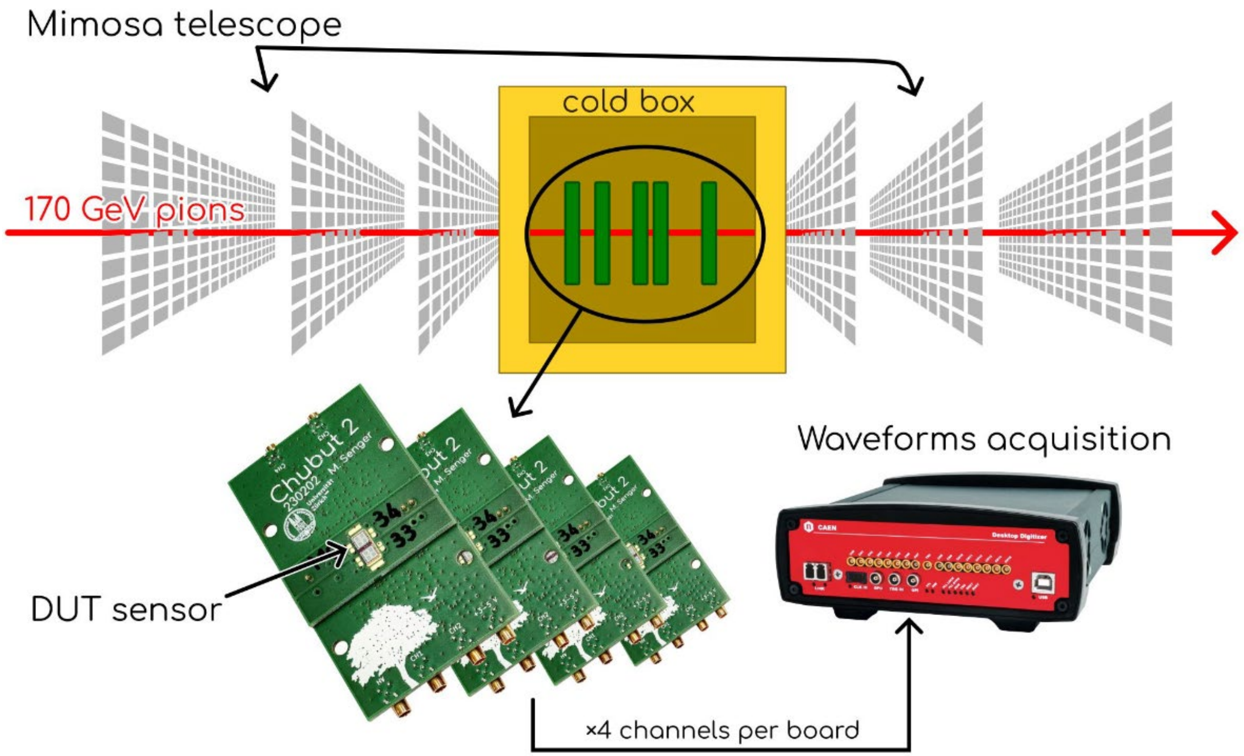
1.3 x 1.3 mm^2

Wafer #	Type	Carbon	n^+ dose	p gain dose
1	Si-Si 55 µm	N	A	0.96
2	Si-Si 55 µm	N	A	0.96
3	Si-Si 55 µm	N	A	0.98
4	Si-Si 55 µm	N	A	1
5	Si-Si 55 µm	N	A	1
6	Epi 45 µm	N	B	1
7	Si-Si 55 µm	N	B	0.98
8	Epi 45 µm	N	B	0.96
9	Epi 45 µm	N	B	0.96
10	Epi 45 µm	Y (1)	B	0.96
11	Epi 45 µm	N	C	0.96
12	Epi 45 µm	Y (0.8)	C	0.96
13	Si-Si 55 µm	N	C	0.98
14	Epi 45 µm	N	C	0.98
15	Si-Si 55 µm	N	C	0.94

Contents



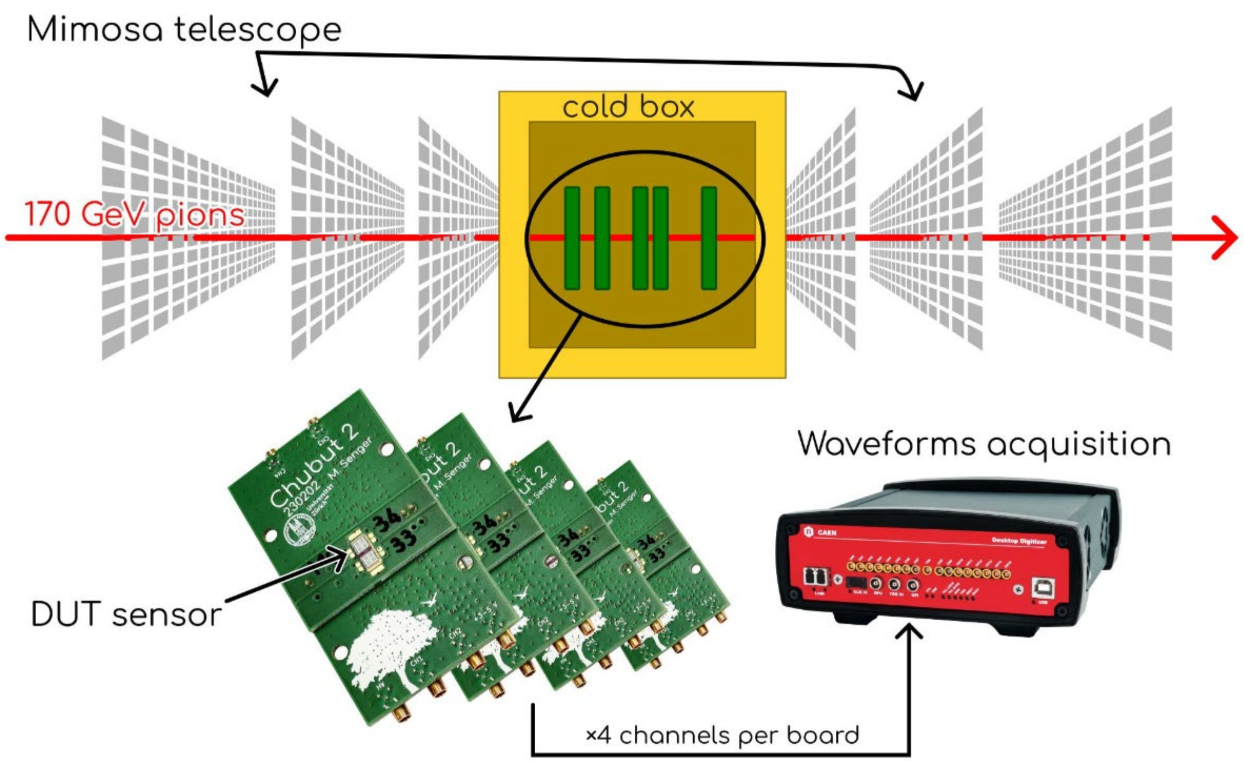
AIDA Test Beam

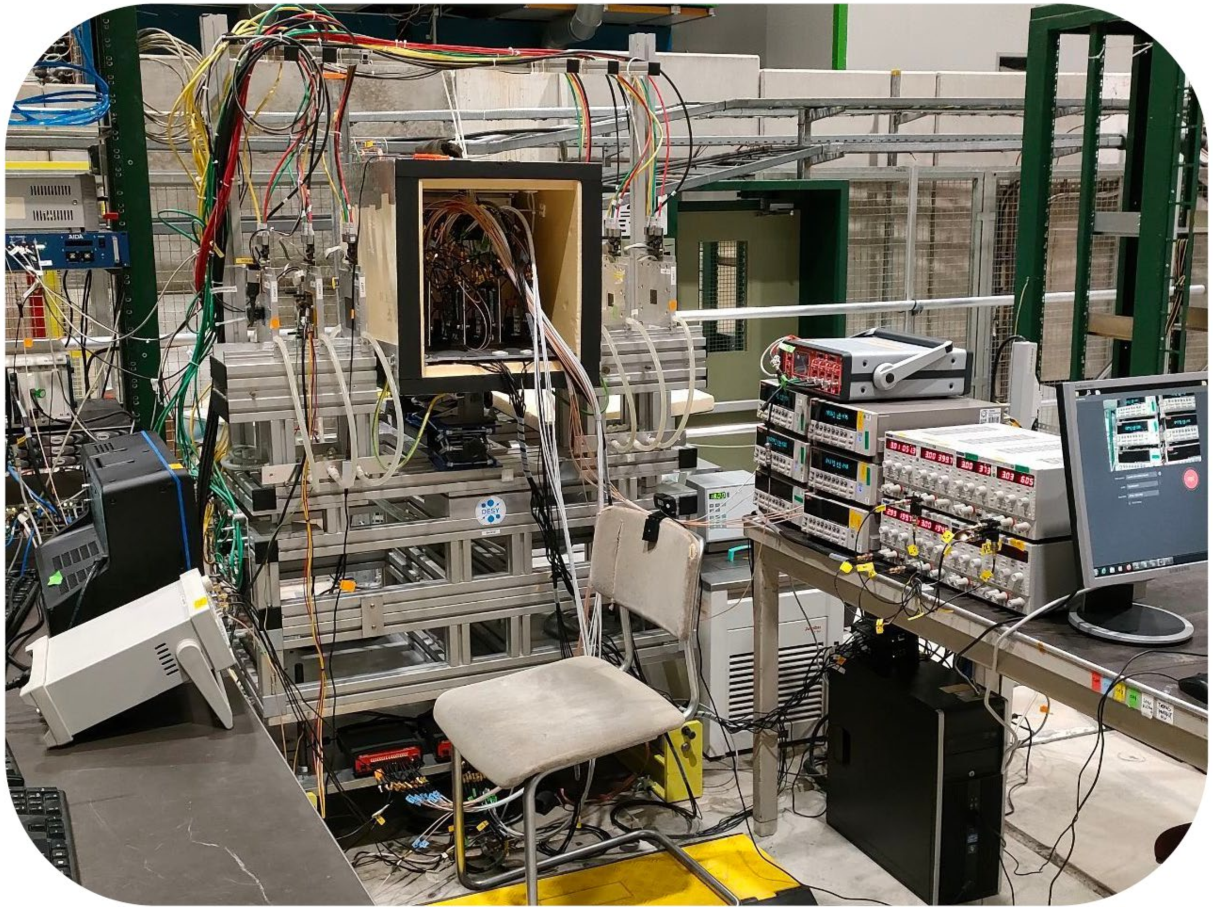


The test beam was performed in the CERN H6 beamline (120 GeV pions/protons)

- MIMOSA telescope
- CAEN DT5742 digitizer, 16 channels @ 5GS/s
- Trigger is a 3x3 mm^2 UFSD1 LGAD
- DUTs on the Chubut2 read-out board
- RSD runs:
  - 2 DUTs, 1.3 mm and 450 µm pitch biased at 240 V and 200 V, respectively
  - **No** time reference

AIDA Test Beam





Chubut2 Acquisition Board

Luca Menzio – INFN Toino

The Chubut2 is a low-noise discrete readout board specifically developed for LGAD testing

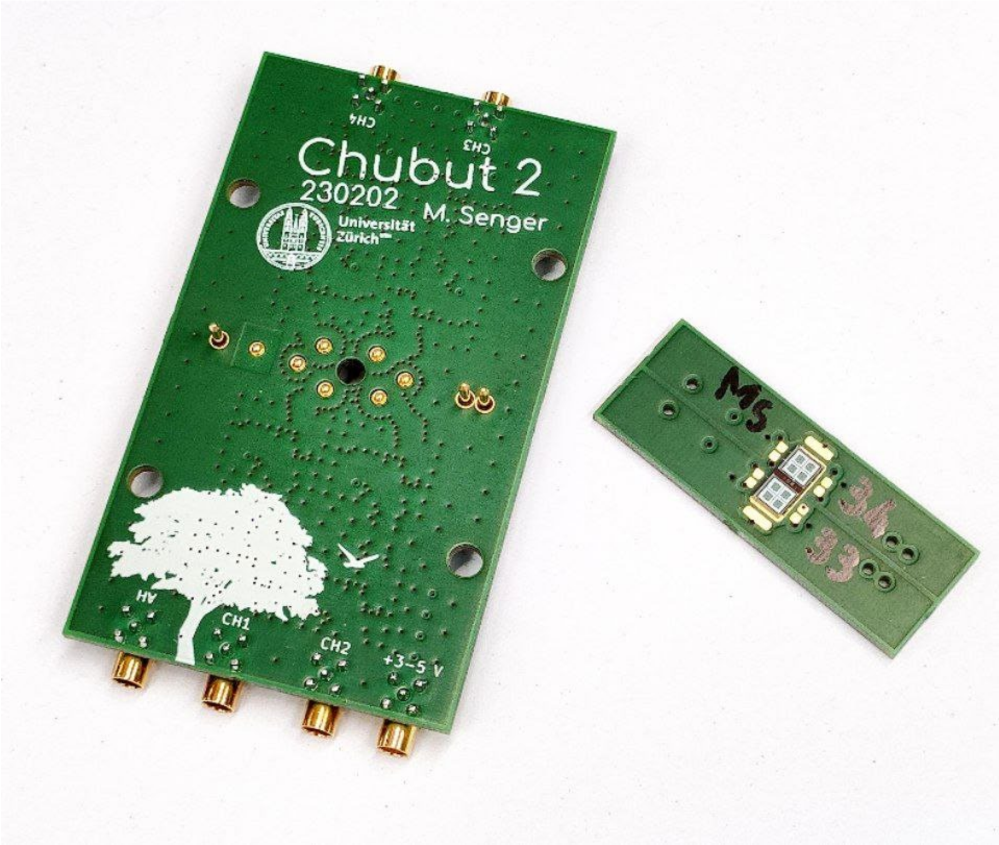
It features a

- Carrier boards that hosts the DUT
- Main board with amplification and power delivery circuitry

The design employed for this test beam has 4 identical channels, each with about 3540 Ω transimpedance on 50 Ω input and output

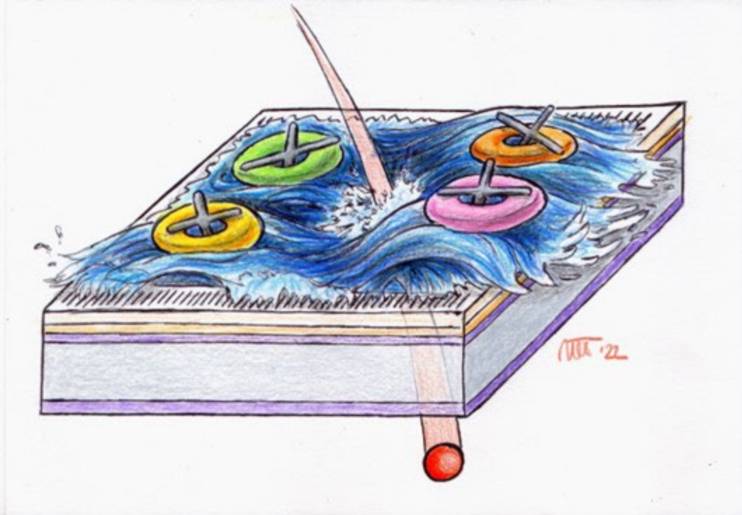
Good S/N with a budget friendly way of switching between sensors (one main board, multiple carrier boards)

Open source project[1]



[1]https://github.com/SengerM/Chubut_2?tab=readme-ov-file

Contents



Waveforms and Tracks Analysis

Luca Menzio – INFN Toino

EUDAQ2 rawfile

WAVEFORMS

Employing the Beta-analysis script

TRACKS

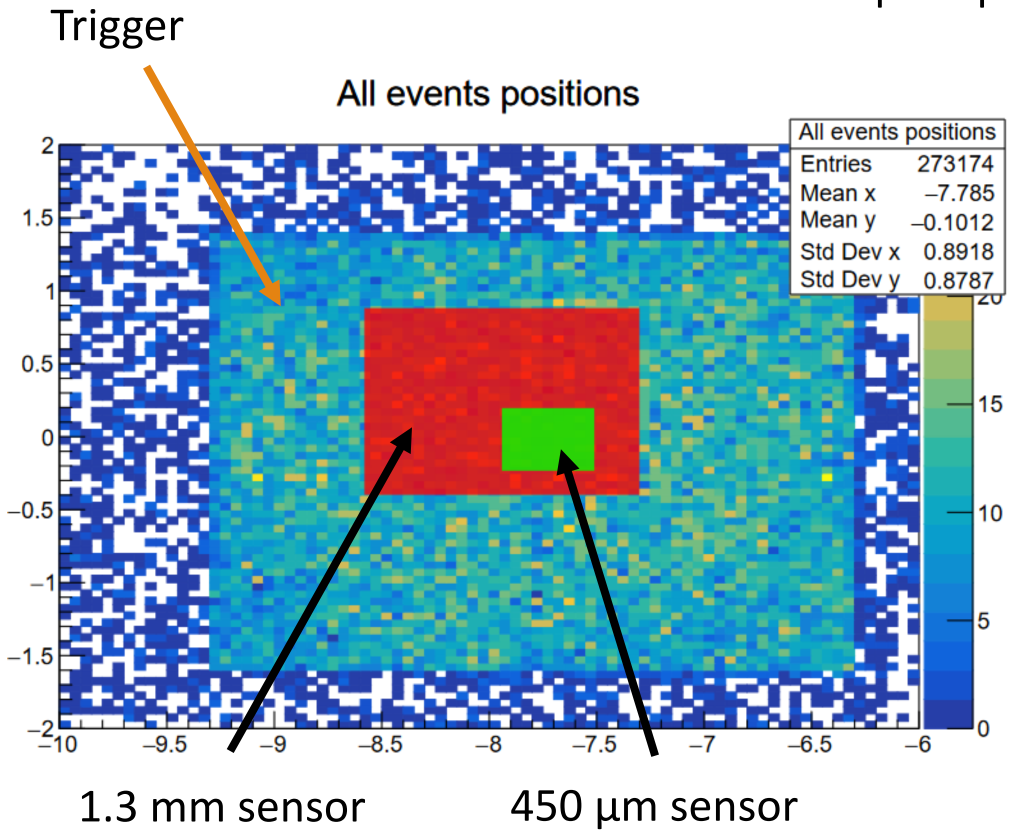
Reconstructed with corryvreckan

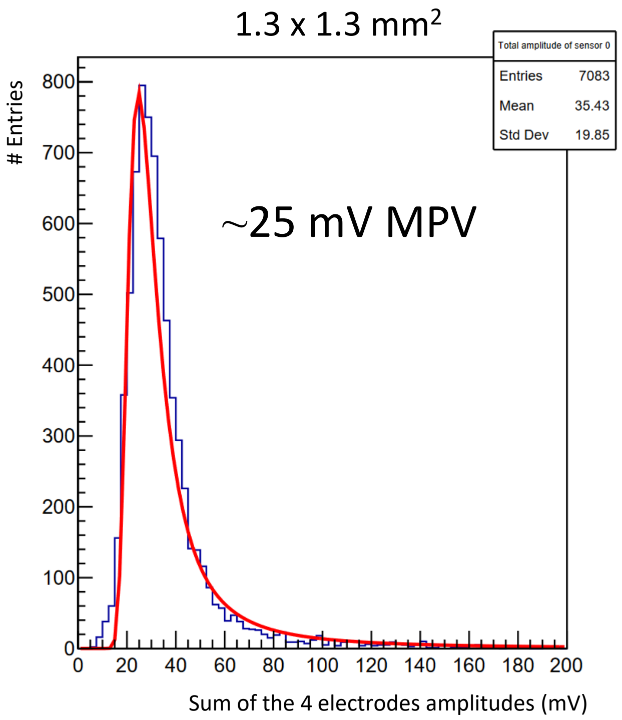
SPS RSD Analysis script

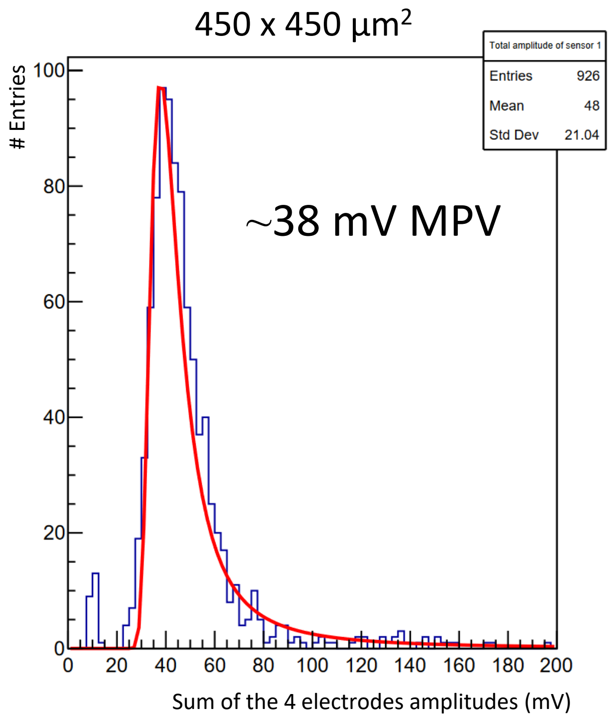
Having a look at the sensors

Luca Menzio – INFN Toino

The sensors overlap in space and have good signals



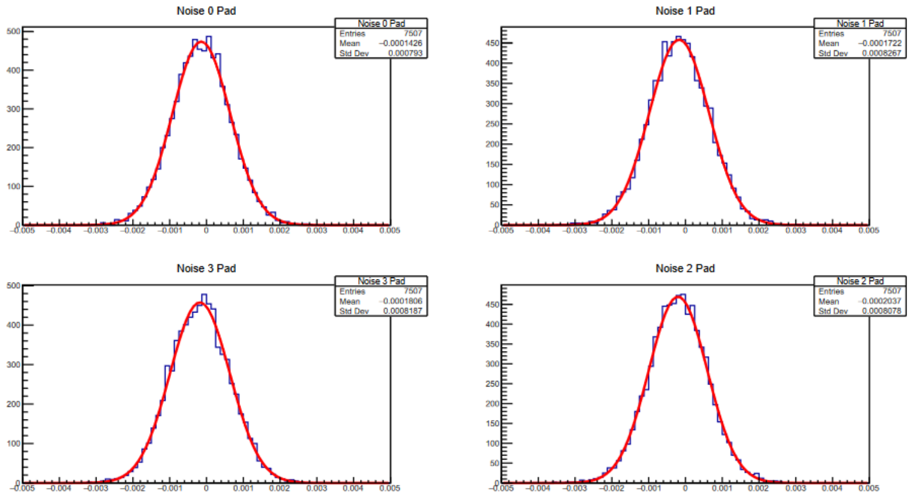




Luca Menzio – INFN Toino

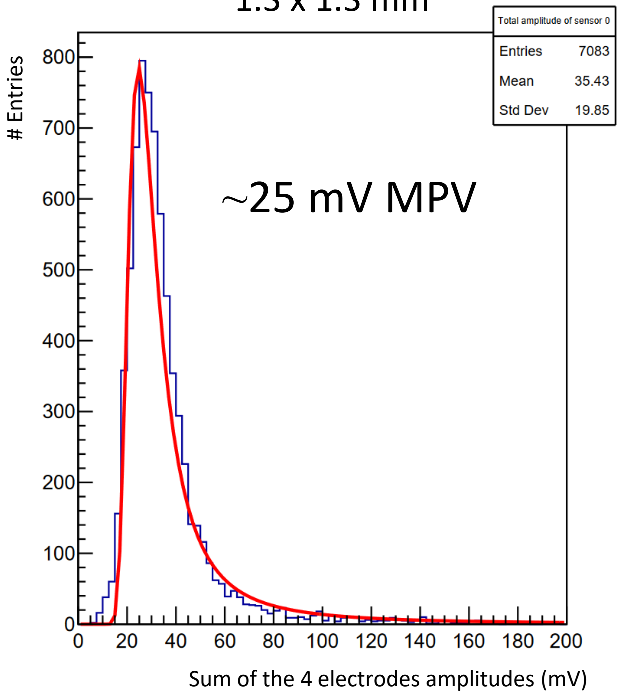
Having a look at the sensors

The sensors overlap in space and have good signals

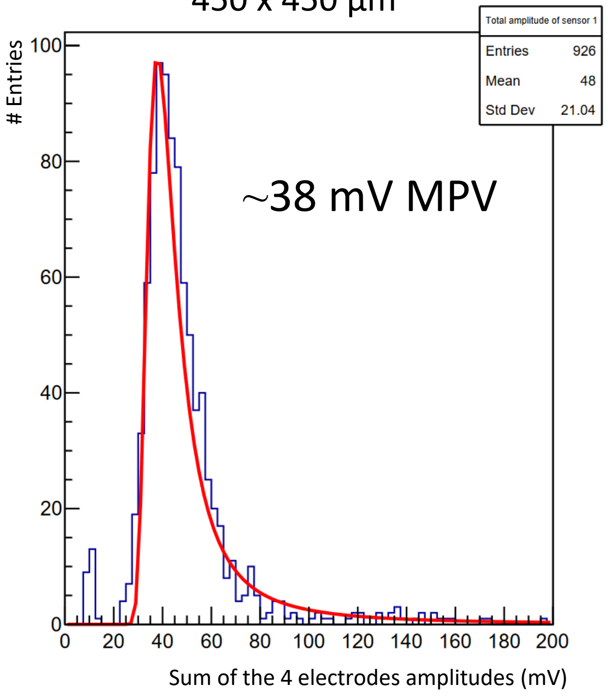


All channels of both sensors have low noise ~0.8 mV

1.3 x 1.3 mm^2



450 x 450 μm^2



W13 1.3 mm – Position Reconstruction

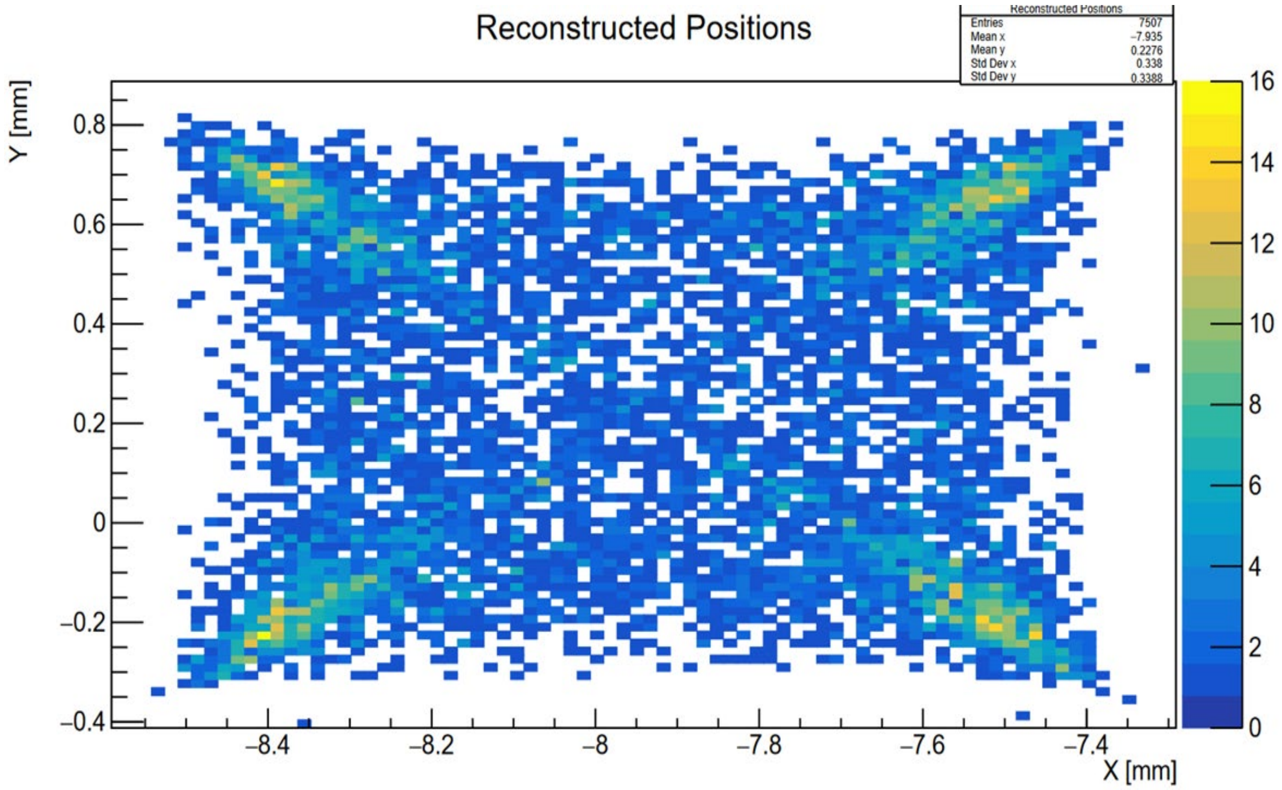
Luca Menzio – INFN Toino

Firstly, the position was reconstructed with the analytical formula based on the charge (amplitude) imbalance

$$x_{rec,i} = x_{centre} + k_x \frac{pitch}{2} \frac{A_3 + A_4 - (A_1 + A_2)}{\sum_{j=0}^{4} A_j}$$

$$y_{rec,i} = y_{centre} + k_y \frac{pitch}{2} \frac{A_1 + A_3 - (A_2 + A_4)}{\sum_{j=0}^{4} A_j}$$

The distortion of the reconstructed positions map is typical of this reconstruction method

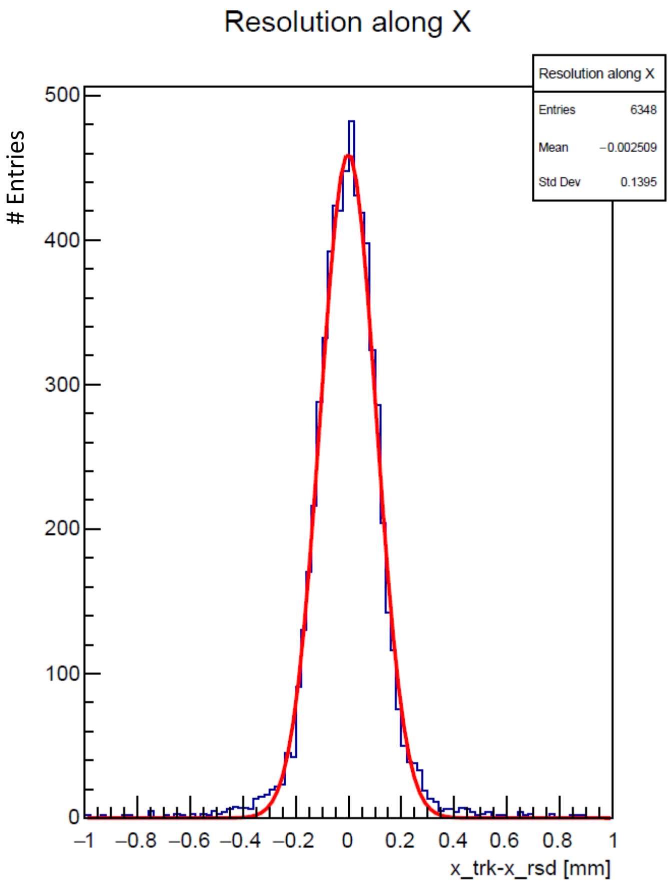


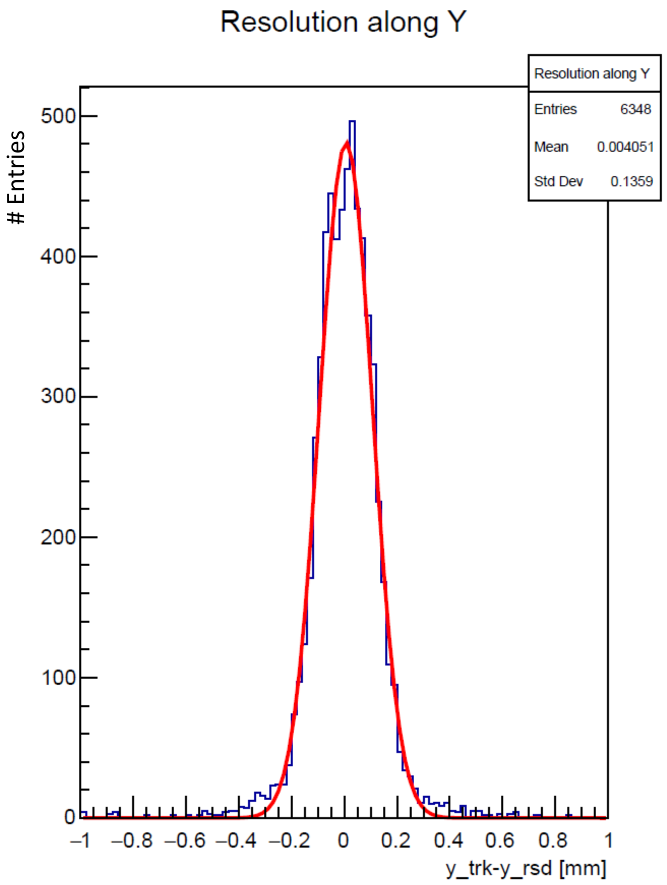
W13 1.3 mm – Position Resolution

Luca Menzio – INFN Toino

About **95** μm on each axis – 13 % of the pitch.
Better than standard binary pixels (29 %)

As already studied and demonstrated using the data collected with the TCT setup, the resolution can be improved applying a correction (distortion mostly due to the reconstruction method):
- use of a "migration matrix"
- use of a template to assign the hit position
- use of machine-learning technique



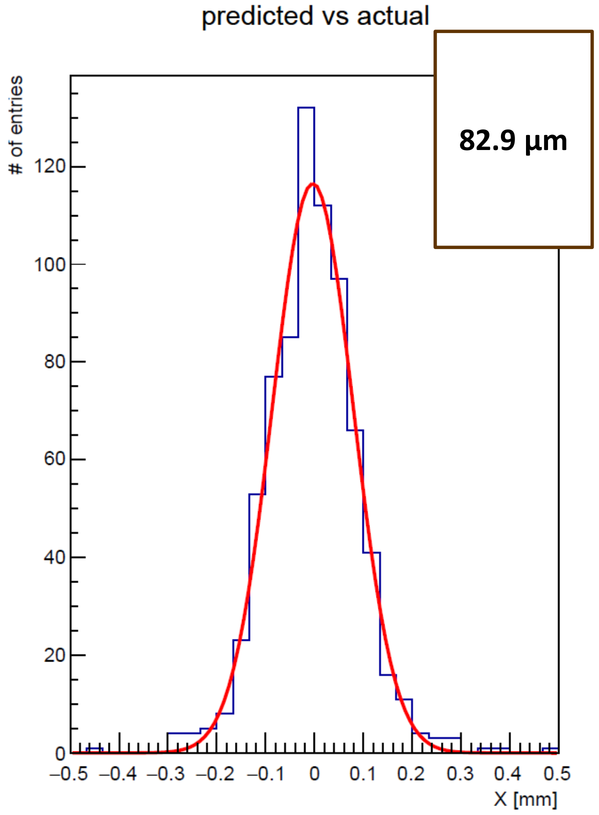


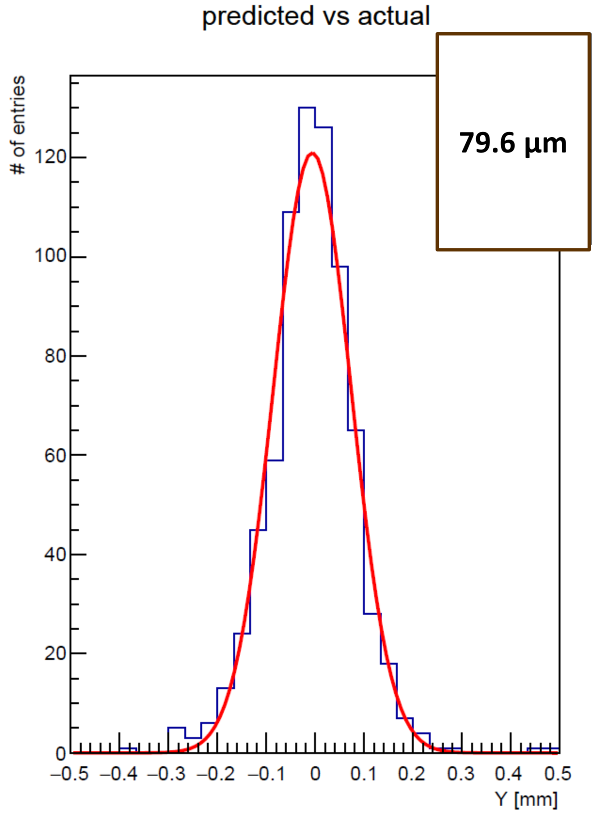
W13 1.3 mm – Machine Learning studies

Luca Menzio – INFN Toino

We tried to implement a Deep Neural Network (presented in the last TREDI)

Although the statistics is very poor for Machine Learning, the results are very promising and present a **15% improvement** compared to the non-corrected results





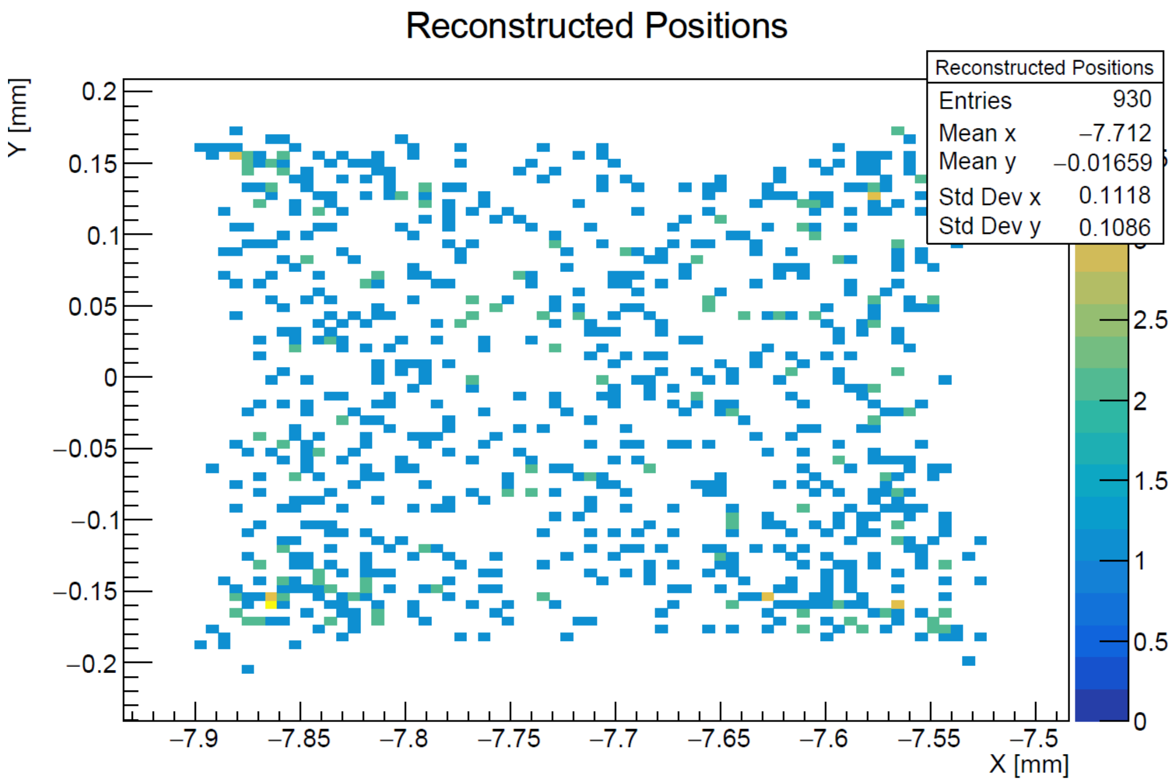
W7 450 µm – Analytical Method

Luca Menzio – INFN Toino

The results of the 450 µm-pitch sensor benefit from the better signal-to-noise ratio

$$x_{rec,i} = x_{centre} + k_x \frac{pitch}{2} \frac{A_3 + A_4 - (A_1 + A_2)}{\sum_{j=0}^{4} A_j}$$

$$y_{rec,i} = y_{centre} + k_y \frac{pitch}{2} \frac{A_1 + A_3 - (A_2 + A_4)}{\sum_{j=0}^{4} A_j}$$



W7 450 µm – Analytical Method

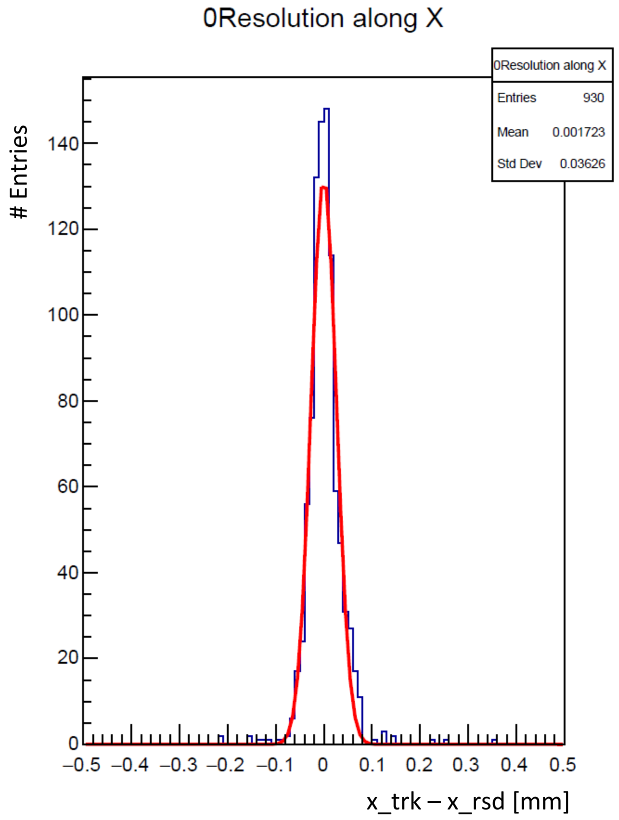
Luca Menzio – INFN Toino

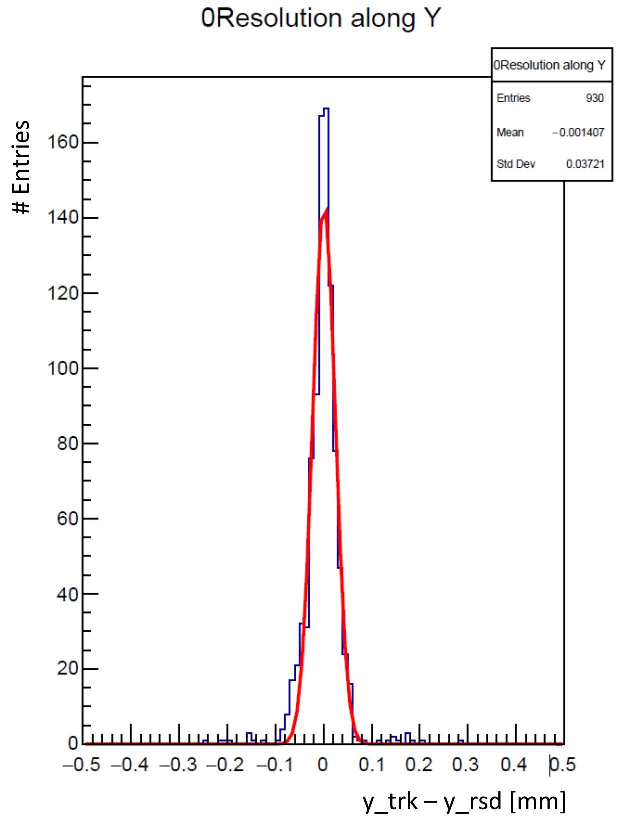
The results of the 450 µm-pitch sensor benefit from the better signal-to-noise ratio

$$x_{rec,i} = x_{centre} + k_x \frac{pitch}{2} \frac{A_3 + A_4 - (A_1 + A_2)}{\sum_{j=0}^{4} A_j}$$

$$y_{rec,i} = y_{centre} + k_y \frac{pitch}{2} \frac{A_1 + A_3 - (A_2 + A_4)}{\sum_{j=0}^{4} A_j}$$

Reconstruction with the charge imbalance formula leads to a resolution of about 25 µm on each axis
→ 5% of the pitch





W7 450 um – Template Method

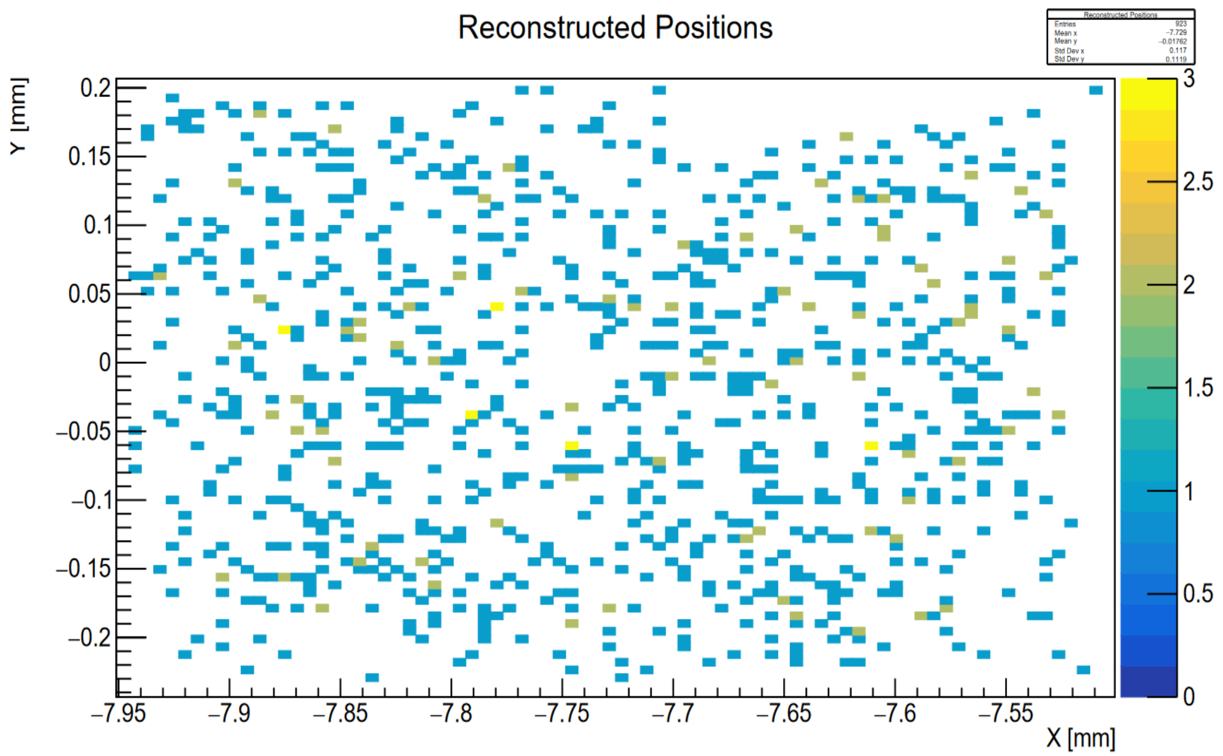
Luca Menzio – INFN Toino

Positions were also reconstructed using the "**template method**".

The hit position is extracted starting from the amplitudes read out by the four electrodes, using the template computed with the test beam data @DESY (see Nicolò's talk)

The template was computed using the same sensor type, but different sensor die, n+ resistivity, and electronics

The template works well!
No position distortion pattern is visible



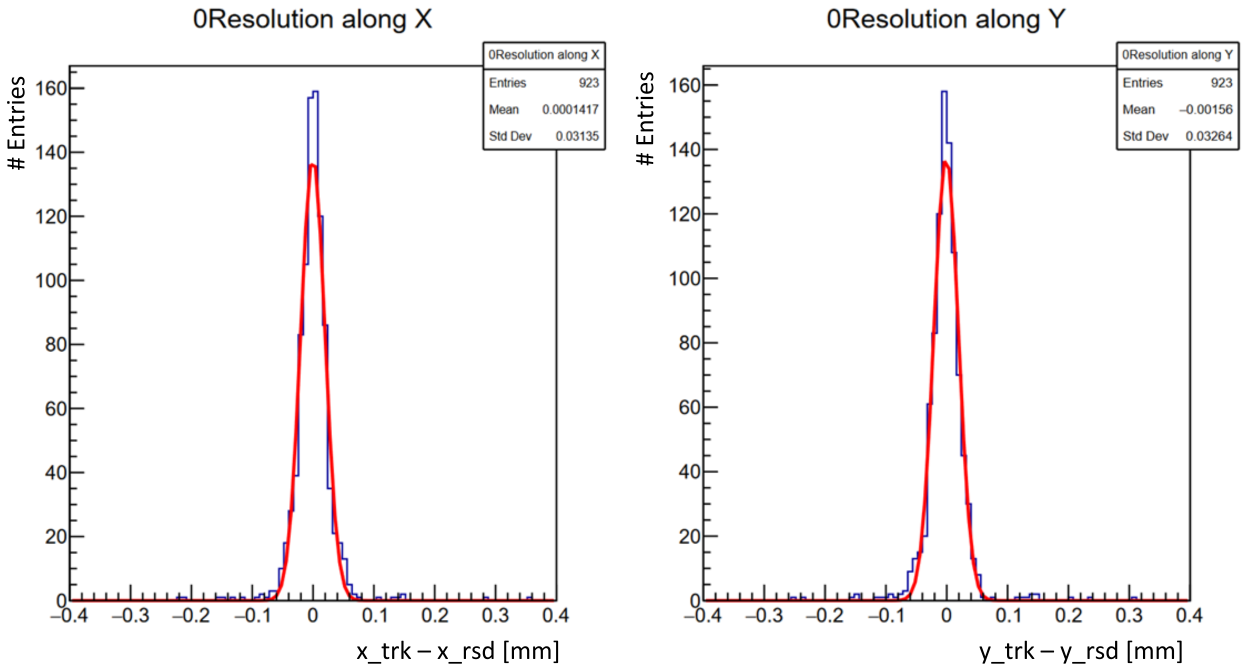
W7 450 um – Template Method

Luca Menzio – INFN Toino

Secondly, positions were reconstructed thanks to a **template method.**

About **20** µm on each axis with the template reconstruction (19.5 µm) – **4% of the pitch**

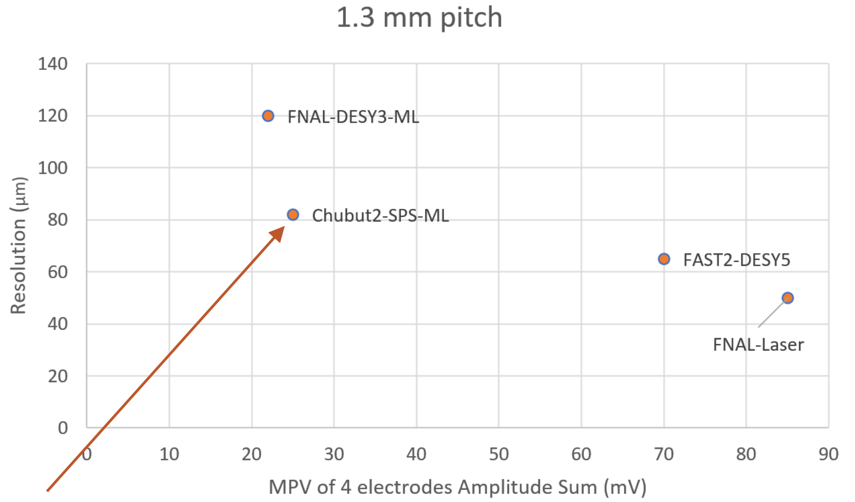
The reconstruction with the template computed in a different experimental setup is viable

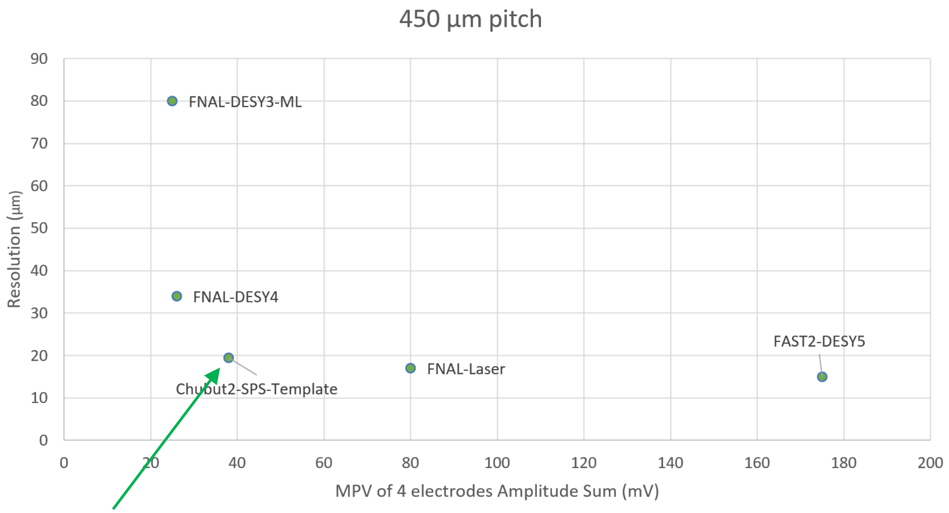


Comparison with other test beams

Luca Menzio – INFN Toino

Comparing with the best results achieved in other test beams





Suffering from low signals and low statistics. It would benefit from a dedicated template/Machine Learning training dataset

Performance is very good thanks to the template model created on another test beam facility and on another electronics!

Good results with low signals

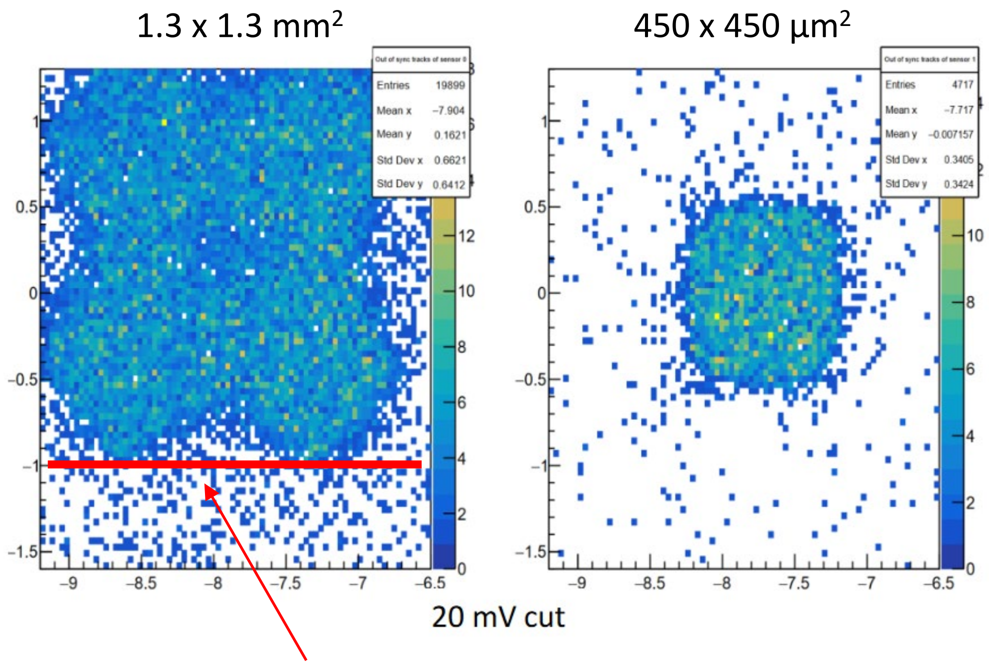
Very good results with low signals

Luca Menzio – INFN Toino

Efficiency

We defined a hit on a sensor as the combination of three conditions

- *time:* the RSD hit timestamp must be compatible with the tracks in the tracker
- *amplitude:* sum of the four signals amplitudes must be above a certain threshold (~3x sigma noise)
- *track:* there is a reconstructed track pointing inside the sensor area
  - **But** some tracks are reconstructed in the wrong positions!



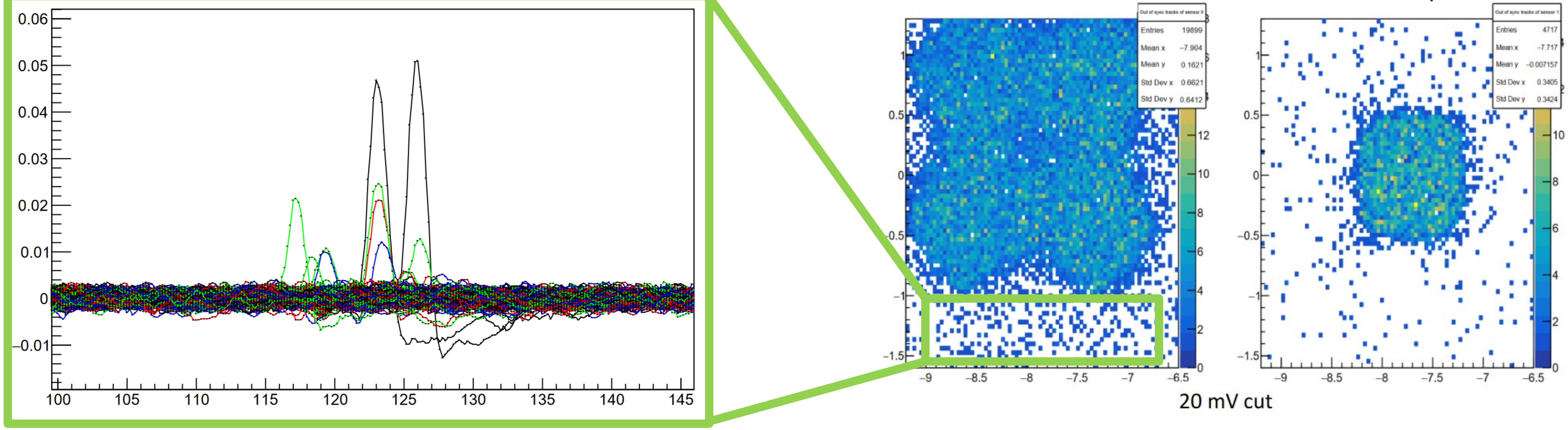
The silicon physically ends here

Efficiency

Luca Menzio – INFN Toino

1.3 x 1.3 mm^2

450 x 450 µm^2



20 mV cut

Efficiency

Because of the tracks small mis-reconstruction, one has to use the signals on one of the two sensors to infer the efficiency of the other

→ only the efficiency of the smaller sensor can be computed

$$Eff_{450\mu m} = \frac{\#tracks(hit_{450\mu m} \wedge hit_{1.3mm})}{\#tracks(track_{450\mu m} \wedge hit_{1.3mm})}$$

Luca Menzio – INFN Toino

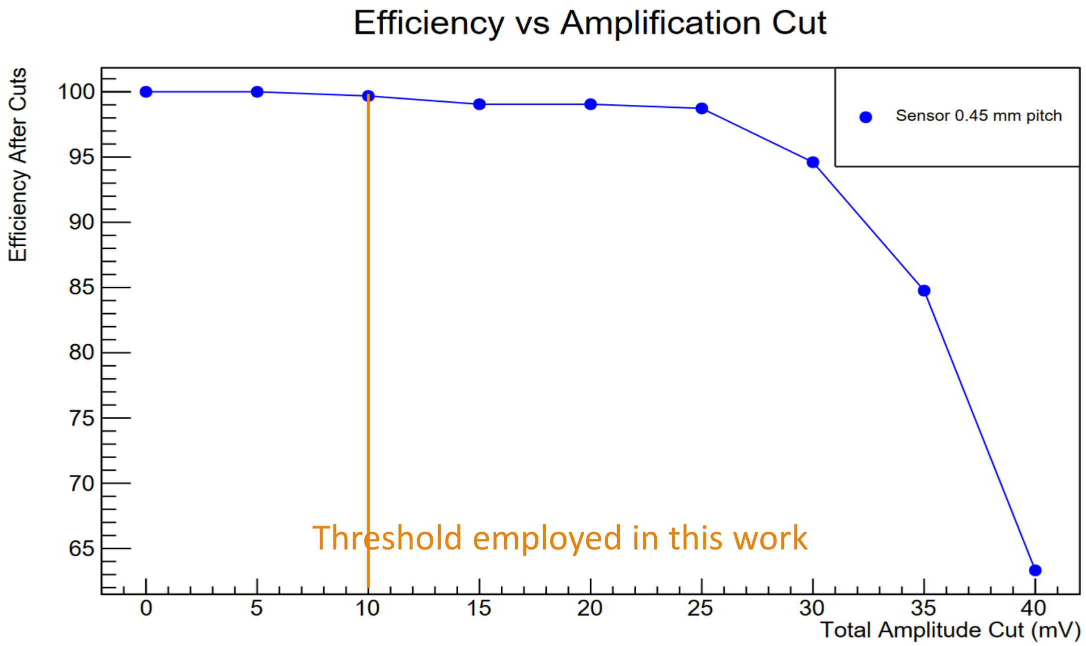
Efficiency

Because of the tracks small mis-reconstruction, one has to use the signals on one of the two sensors to infer the efficiency of the other

→ only the efficiency of the smaller sensor can be computed (completely inside the bigger one)

$$Eff_{450\mu m} = \frac{\#tracks(hit_{450\mu m} \wedge hit_{1.3mm})}{\#tracks(track_{450\mu m} \wedge hit_{1.3mm})}$$

Values of efficiency typical of silicon are maintained, **> 99%**



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Conclusions

The performance of two RSD2 sensors, 1.3mm pitch and 450 µm pitch, were measured during the second AIDAinnova 2023 test beam at SPS.

The devices were bonded to a novel low-noise and open-source electronics: the Chubut2 board

The best spatial resolutions achieved are:

1. $\sigma_{1.3\ mm} \sim$ **81 µm** employing a Machine Learning approach (6% of the pitch)
2. $\sigma_{450\ \mu m} \sim$**19.5 µm** with the template method (4.3% of the pitch)

Both designs achieve significantly better results than those of standard pixel detectors (15-30%) with a low number of channels.

The detection efficiency of a 450 µm pitch RSD2 was evaluated to be **>99%**

AIDAinnova WP6 Test Beam group

- CNM-Barcelona (AIDAinnova): Oscar David Ferrer Naval
- IFCA (AIDAinnova + ETL): Ivan Vila Alvarez, Andres Molina
- Ribagorda, Jordi Duarte Campderros, Efren Navarrete Ramos,
- Marcos Fernandez Garcia, Ruben Lopez Ruiz
- IJS (AIDAinnova): Gregor Kramberger, Jernej Debevc
- The UFSD group (University of Torino / INFN): Roberta Arcidiacono, Nicolò Cartiglia, Marco Ferrero, Leonardo Lanteri, Luca Menzio, Roberto Mulargia, Federico Siviero, Valentina Sola
- INFN Genova: Claudia Gemme
- UZH (AIDAinnova): Anna Macchiolo, Matias Senger
- Korea: D. Lee, W. Jun, T. Kim
- CERN: A. Rummler, V. Gkougkousis

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Luca Menzio – INFN Toino

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- INFN – FBK agreement on sensor production (convenzione INFN-FBK)
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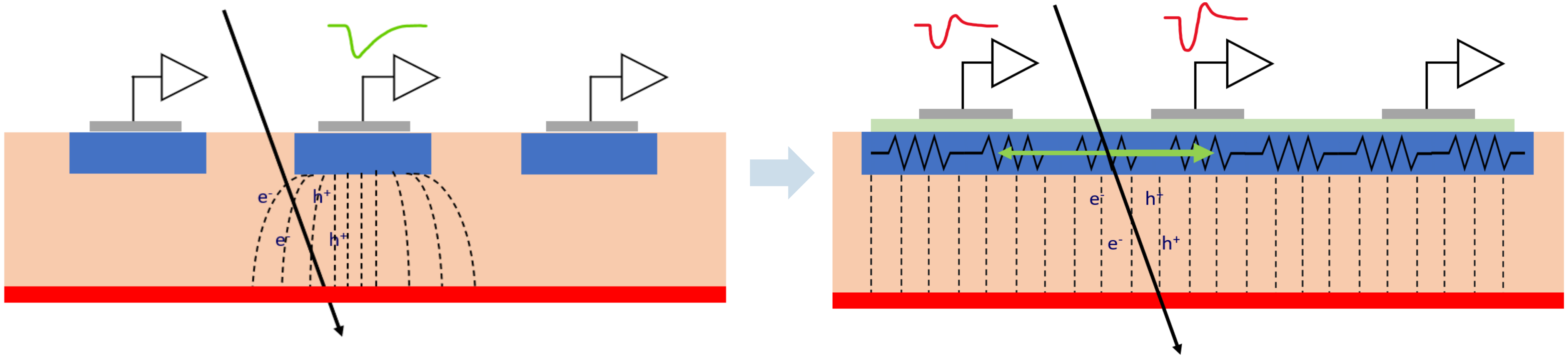
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare

Resistive Read-out



- In resistive read-out, instead of many p-n diodes, there is a single diode.
- The n-doped implant is resistive and acts as a signal divider
- Very uniform electric and weighing fields, perfect geometry for timing

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Runs

Two test beam performed: June and August

Practically, only August has good runs (Mimosa problems, not much time for RSDs runs)

41	Data run, EVERYTHING LOOKS GOOD 🎉 🍻 🥳	87470
42	Data run, EVERYTHING LOOKS GOOD 🎉 🍻 🥳	273174
43	Data run, EVERYTHING LOOKS GOOD 🎉 🍻 🥳	27989
44	Data run, EVERYTHING LOOKS GOOD 🎉 🍻 🥳 CAENGECO2020.log	127551
50	Data run, EVERYTHING LOOKS GOOD 🎉 🍻 🥳	
51	🎉 🍻 🥳	409414
52	🎉 🍻 🥳	39820

Runs 50–52: With trigger signals
But corrupted 6th mimosa plane

4 sensors:

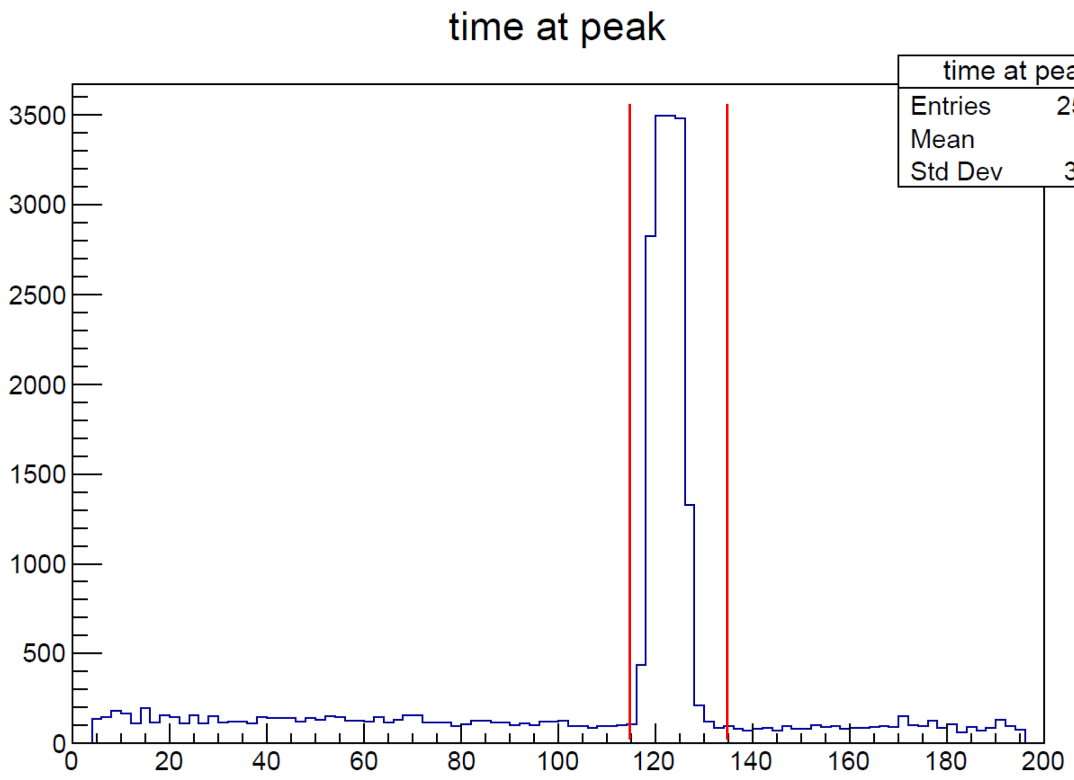
- W13 1.3 mm-pitch
- 2x W7 450 um-pitch
- W3 450 um (low bias due to high current)

2-3 bias points per sensor

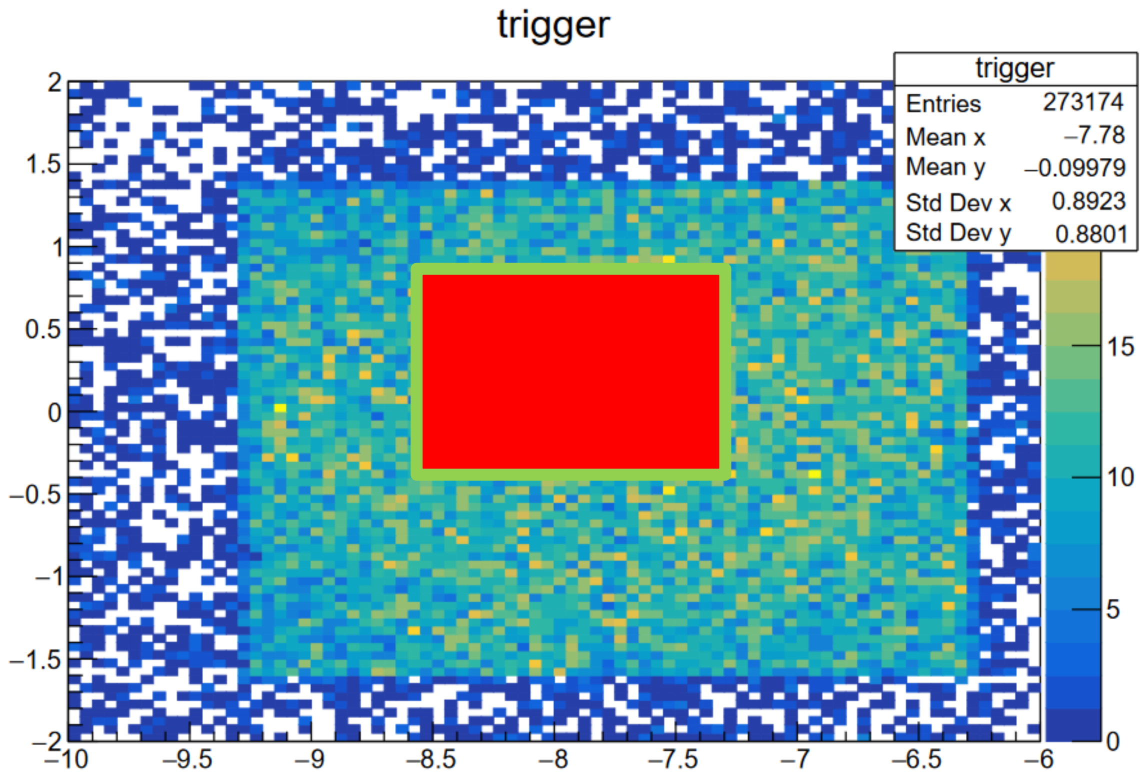
Given the nature of the readout board, 4 electrodes were read.

The analysis is restricted to one pixel of the matrix

Cuts



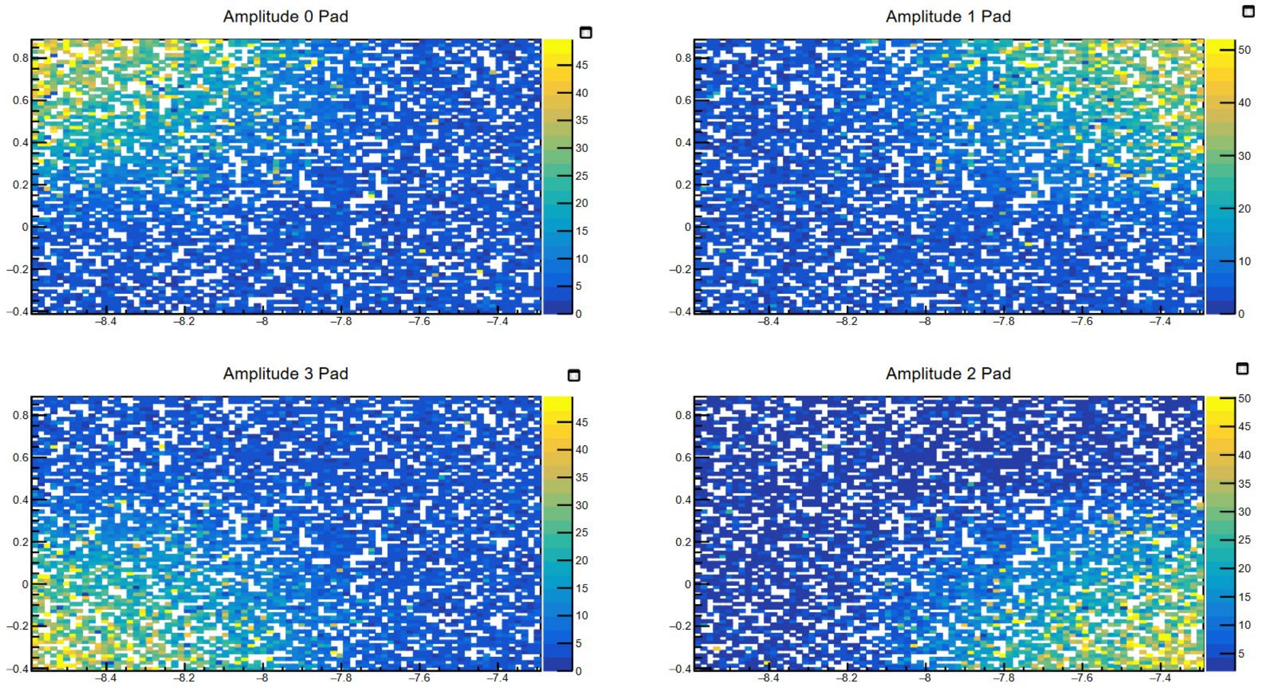
1) Tracks within time window



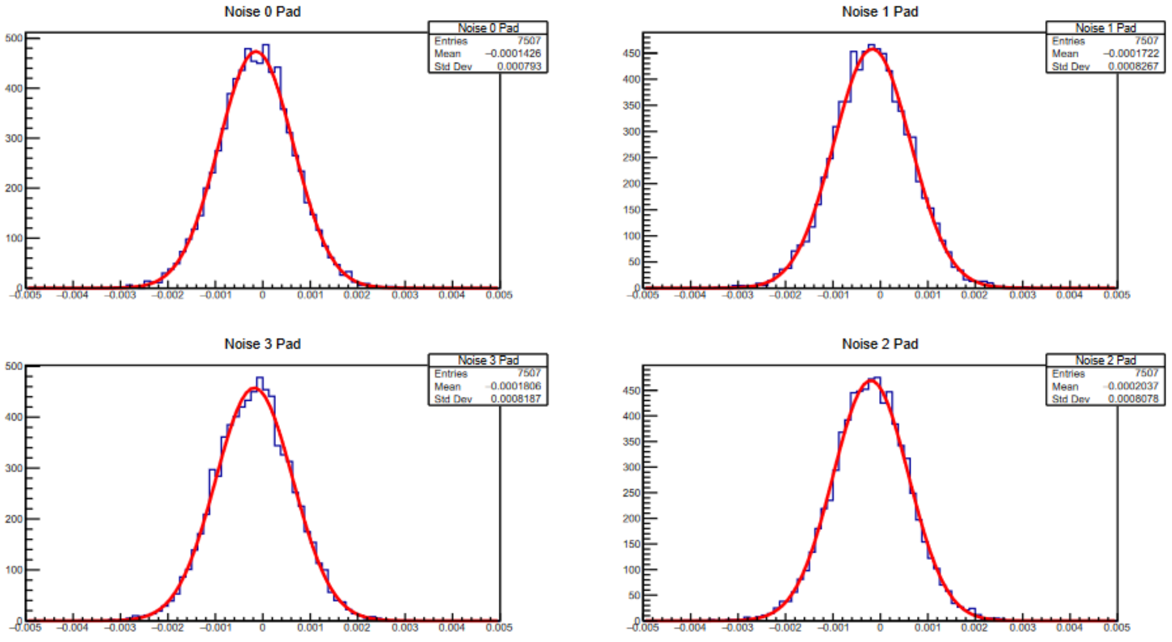
2) Tracks inside the pixel

First sensor - W13 1.3mm

Quite small MPV for the amplitude (as expected) 30 mV



Very low noise <1 mV



S/N for the single pad is good

Taking a look at the data

Luca Menzio – INFN Toino

1. **W13 1.3** mm has smaller signals
   - Although not ideal, it can be used for the reconstruction (rotated by 2.5 degrees)
2. The data from the **first 450 um W7** is good (rotated by 1.7 degrees)
   - High-enough signals and
   - Another data acquisition was performed in DESY with a similar sensor
3. The second **450 um W7** has really small signals, even if the bias is almost the same as the first sensor
4. The fourth sensor (**450 um W3**) had issues and its signals are very low cannot be used for reconstruction

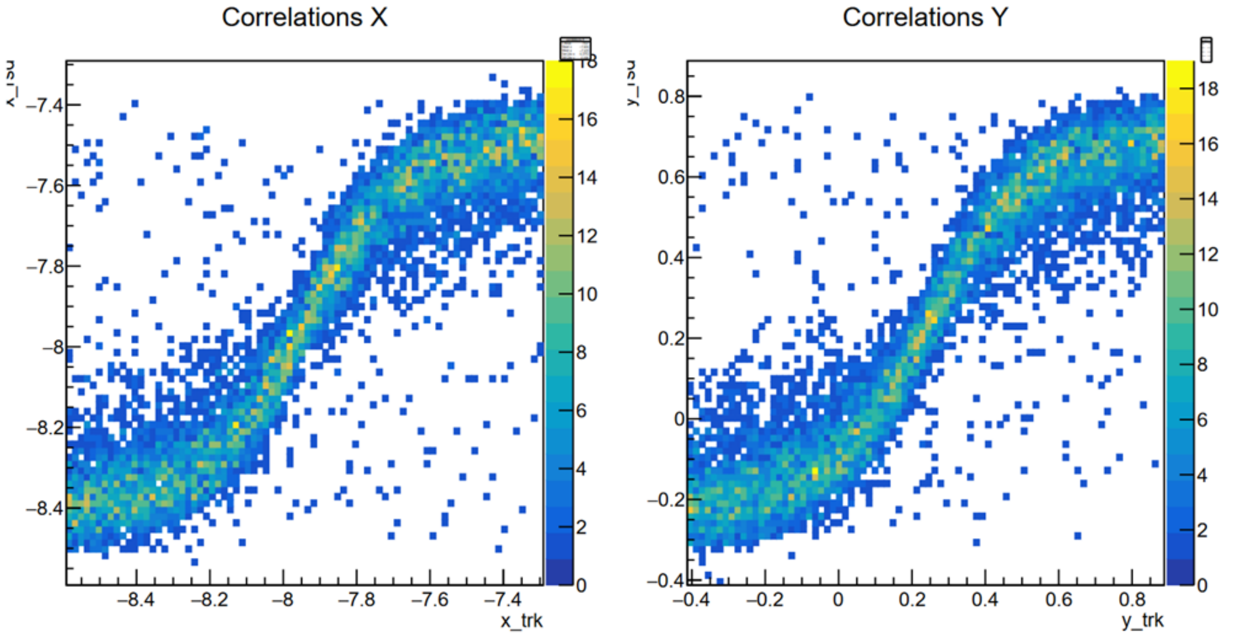
Taken into consideration in this work

W13 1.3 mm – Position Reconstruction

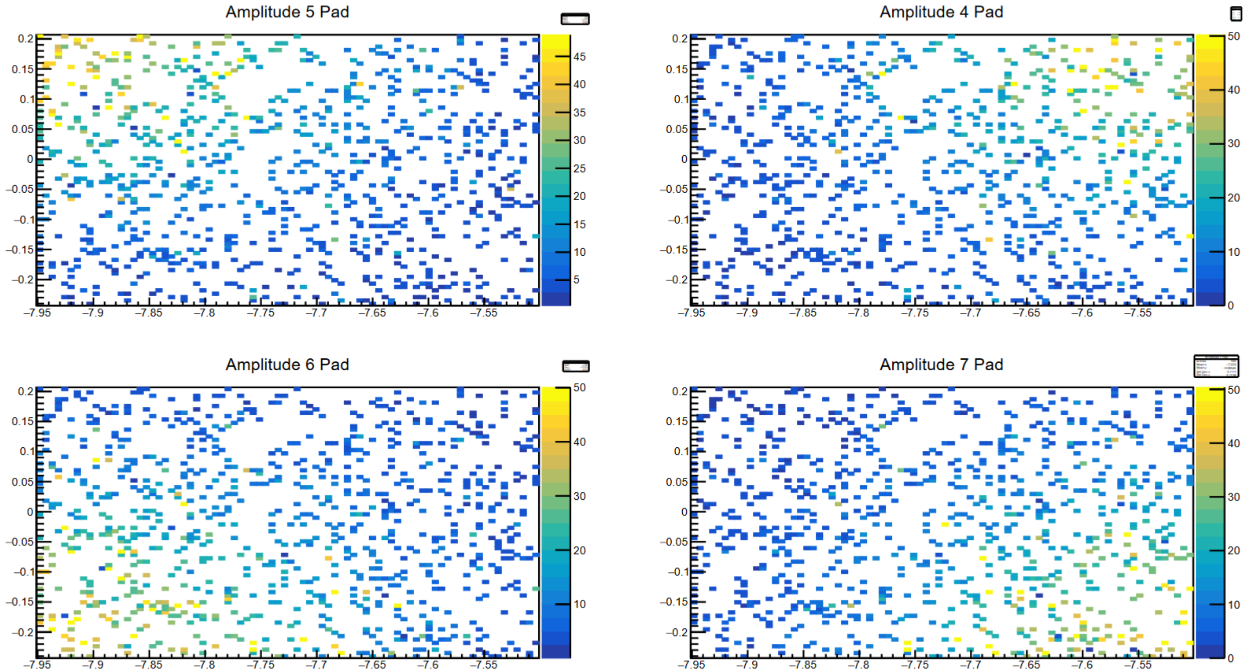
Reconstruction with charge imbalance

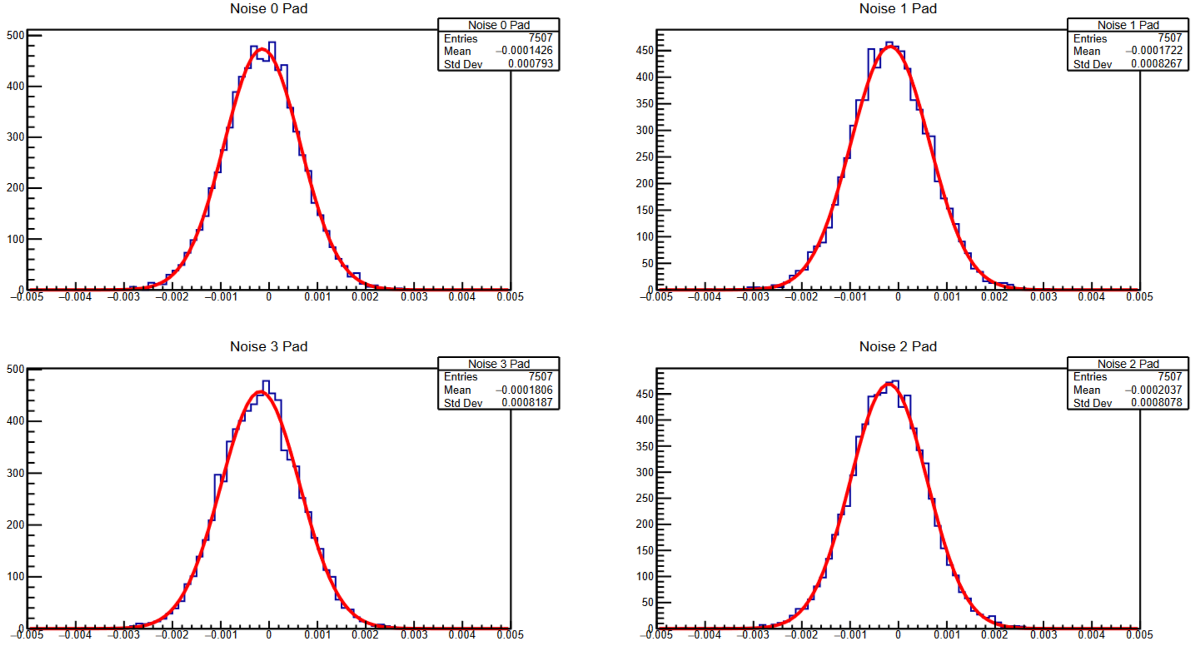
$$x_{rec,i} = x_{centre} + k_x \frac{pitch}{2} \frac{A_3 + A_4 - (A_1 + A_2)}{\sum_{j=0}^{4} A_j}$$

$$y_{rec,i} = y_{centre} + k_y \frac{pitch}{2} \frac{A_1 + A_3 - (A_2 + A_4)}{\sum_{j=0}^{4} A_j}$$



W7 450 um

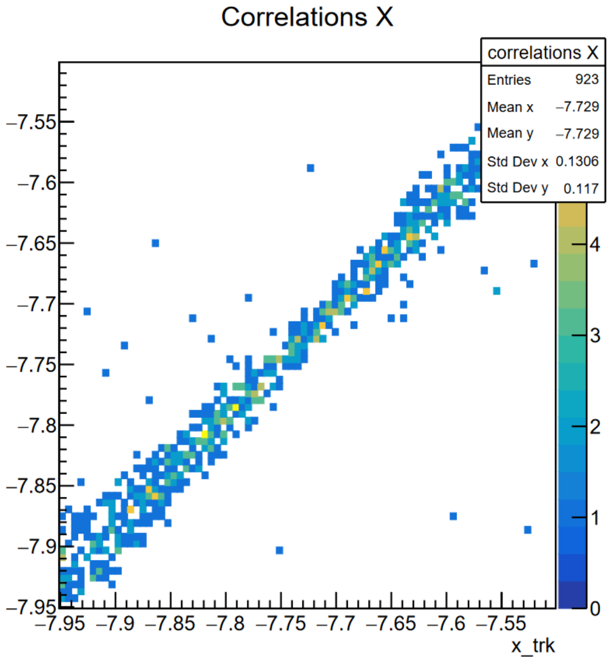


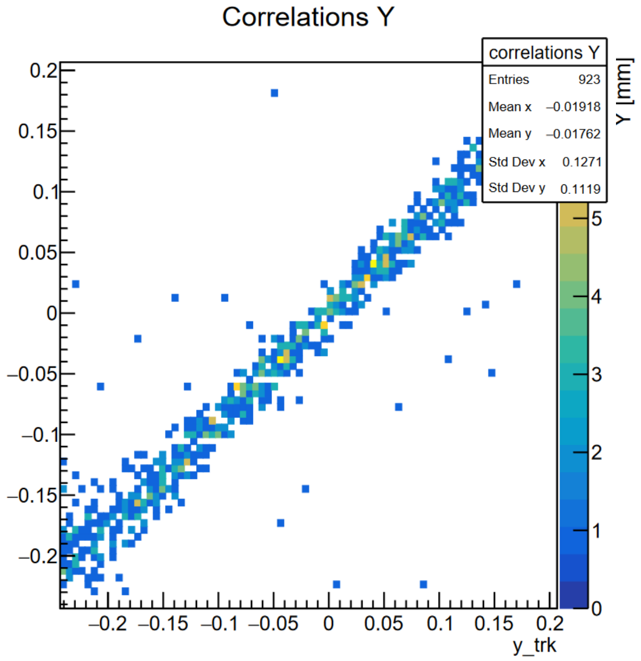


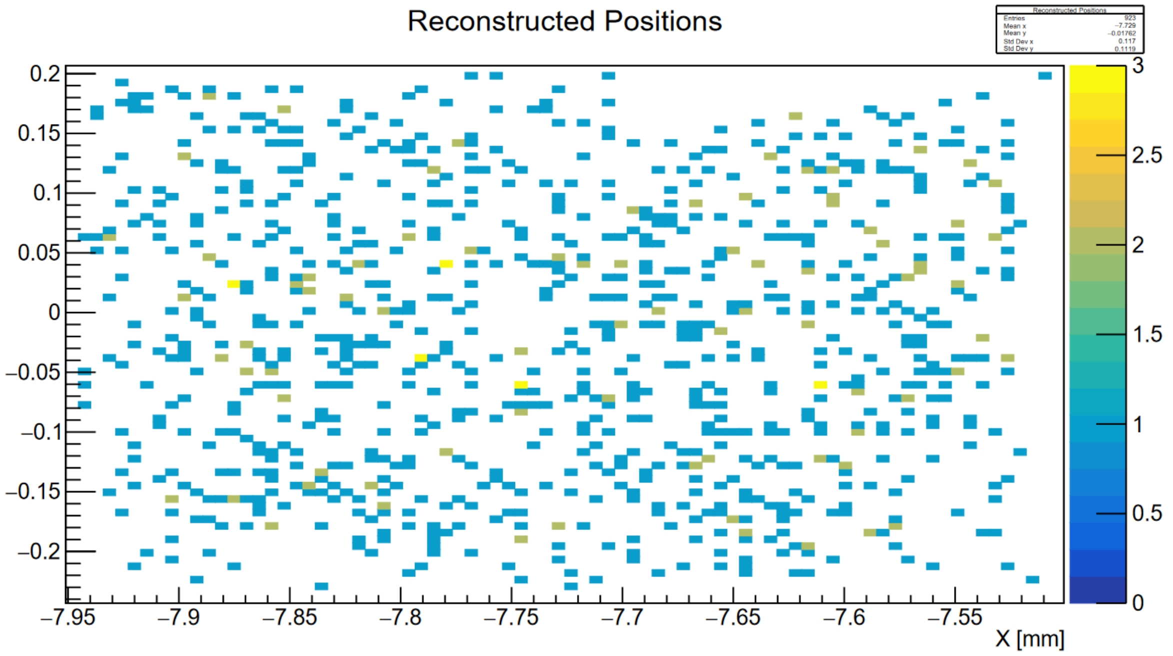
Same as before, slightly better S/N

W7 450 um

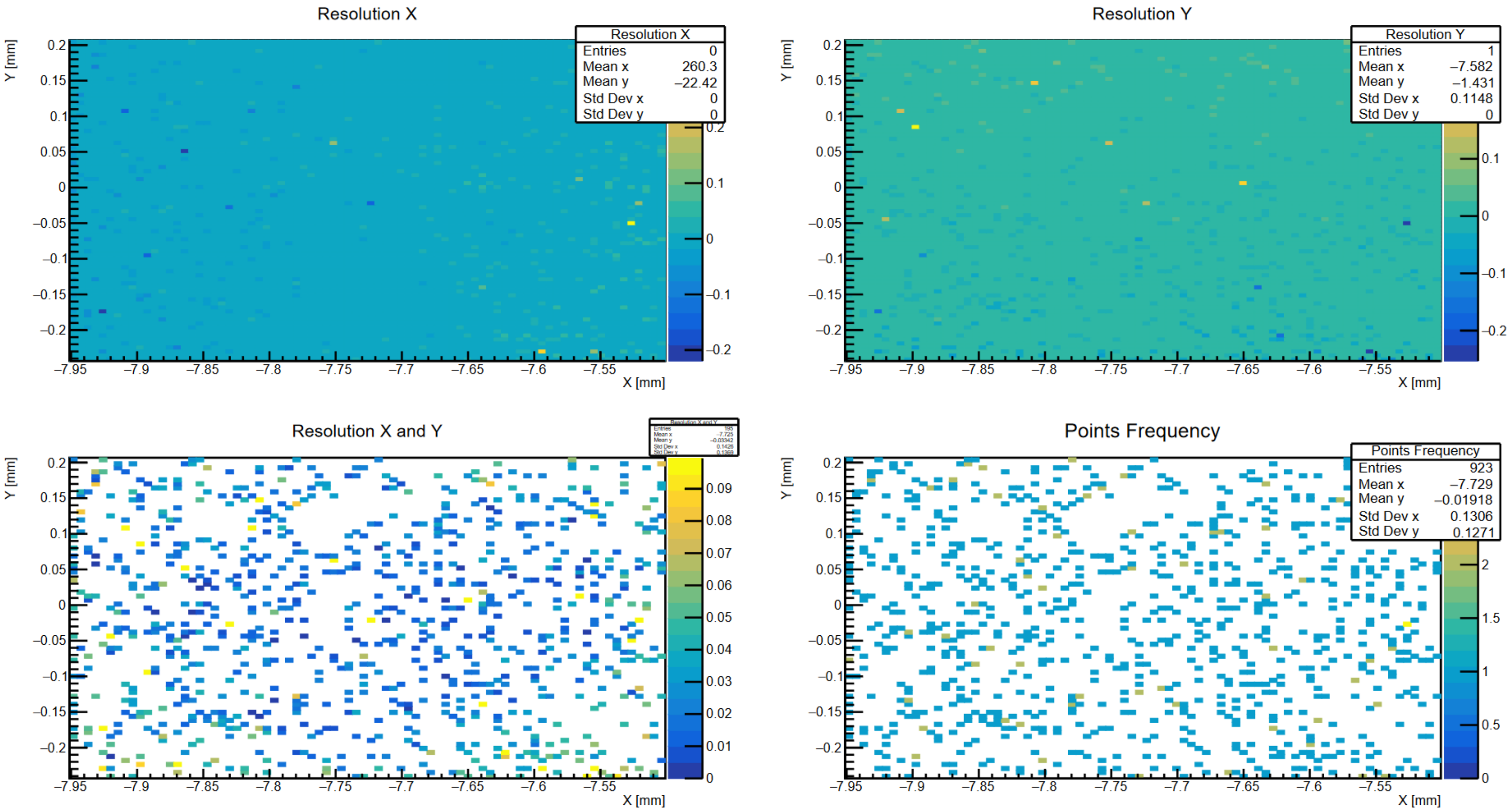
Secondly, positions were reconstructed thanks to the information gathered at another test beam in DESY with a similar sensor. SPS positions are extracted by comparing the pads amplitudes with the ones registered in the DESY data (template)







W7 450 um – first plane

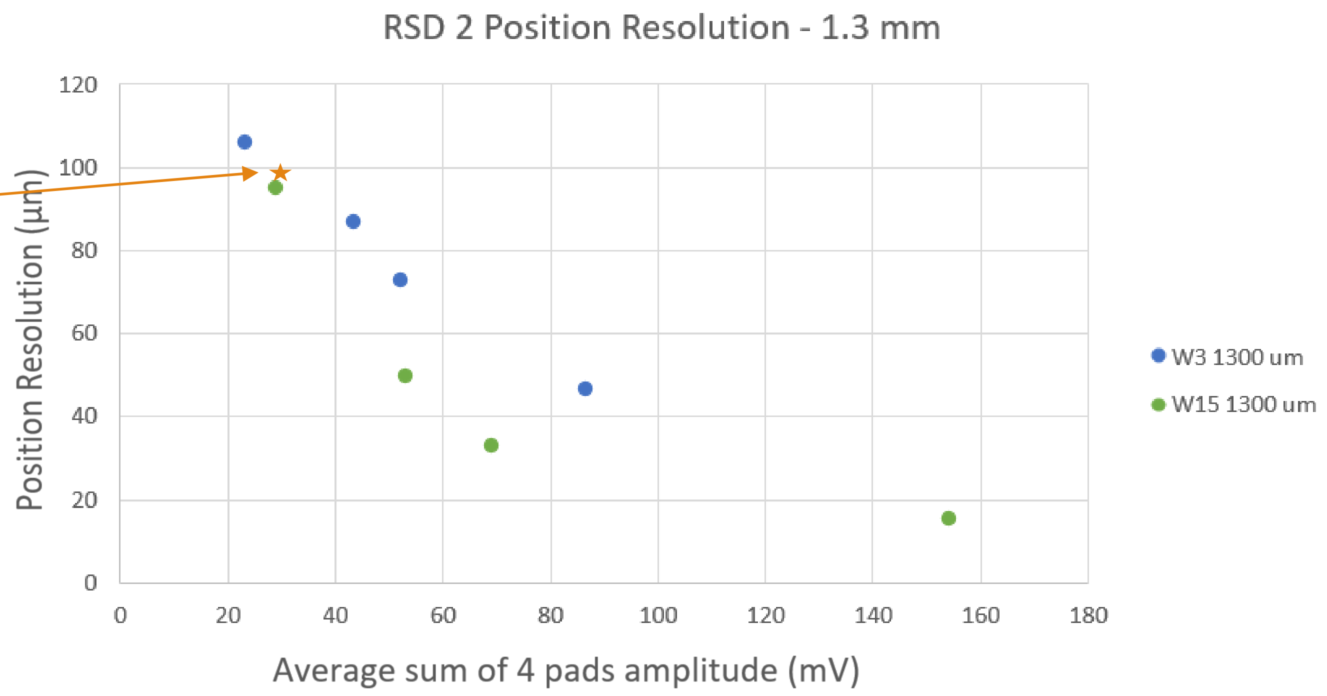


Resolution is uniform over the whole pixel

Comparison with TCT – 1.3 mm

TCT data was corrected, but the results are still comparable

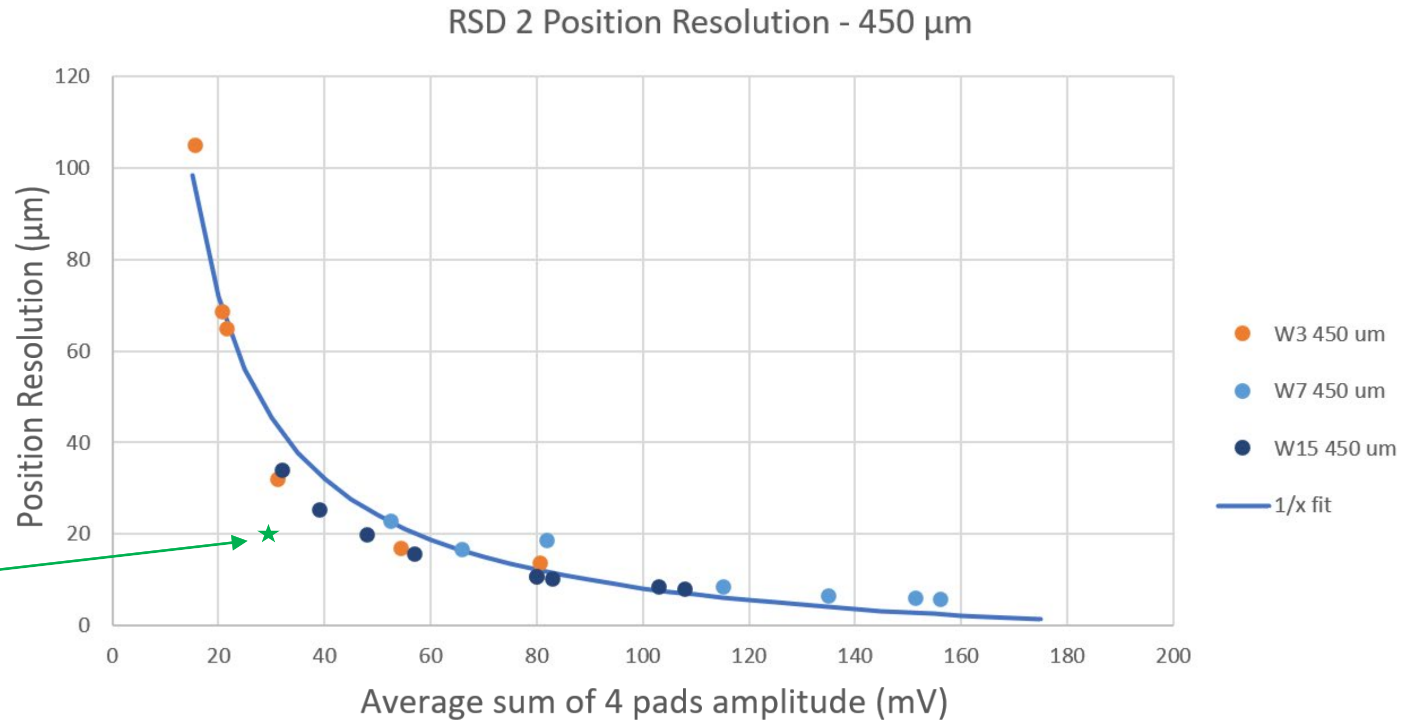
This analysis



For sake of completeness, the S/N ratio is different and this point should be further on the right. A correction is needed

Comparison with TCT – 450 um

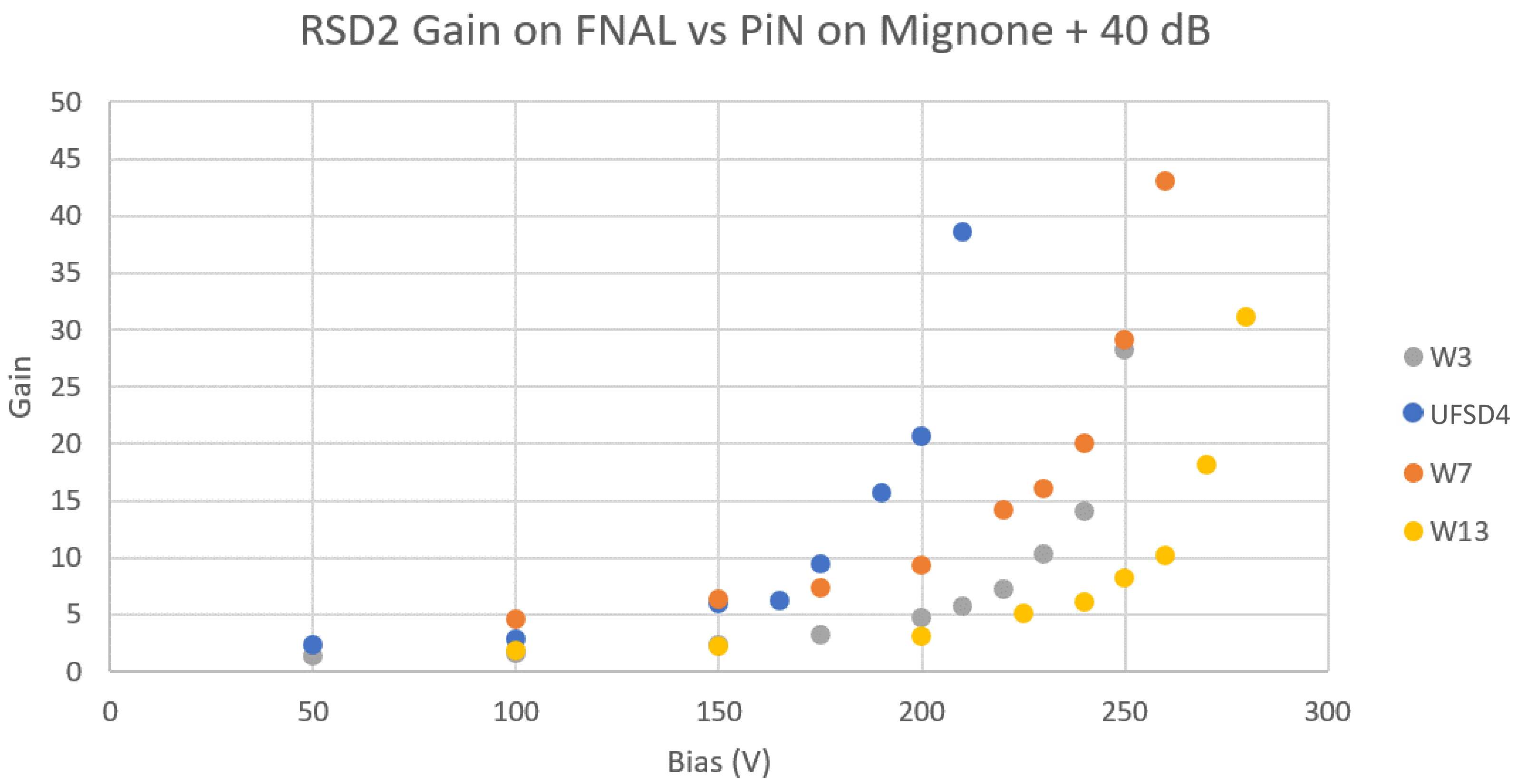
TCT data was corrected, but the results are still comparable



This analysis

The difference is more visible in this plot

RSD2 Gain


RSD2 Gain on FNAL vs PiN on Mignone + 40 dB
Gain
0
5
10
15
20
25
30
35
40
45
50
0
50
100
150
200
250
300
Bias (V)
W3
UFSD4
W7
W13