Spatial resolution of FBK RSD2 sensors measured at the DESY beam test facility

18th Trento Workshop, 1.3.2023

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Outline

- Introduction:
  - Sensors tested
  - DESY facility
  - Position reconstruction with RSD
- Results on RSD2 cross 450 um
- Results on RSD2 cross 1300 um

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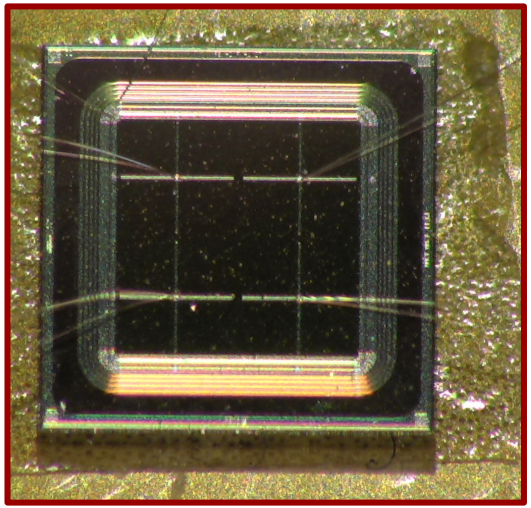
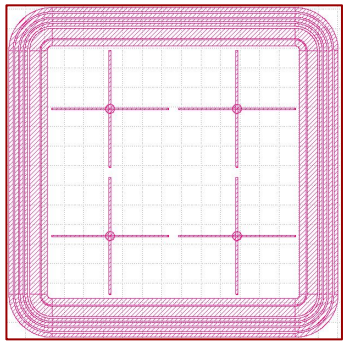
RSD2 sensors tested





- “cross” electrode design
- 55 um active thickness
- 2.6 x 2.6 mm^2 area
- Operated at gain ~ 10
- 1.3 mm pitch

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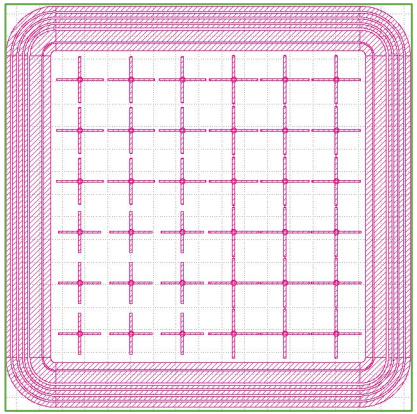
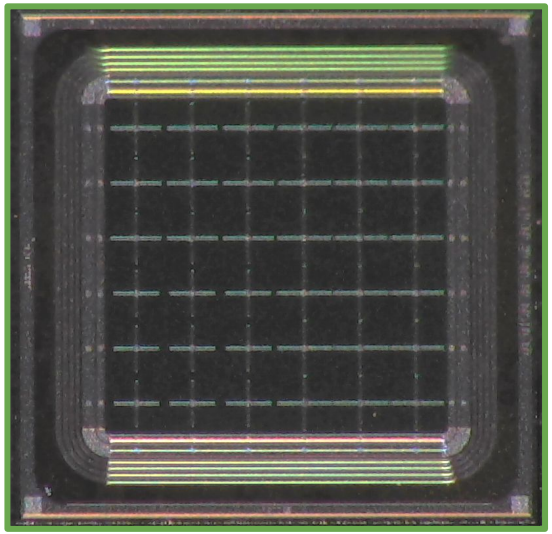
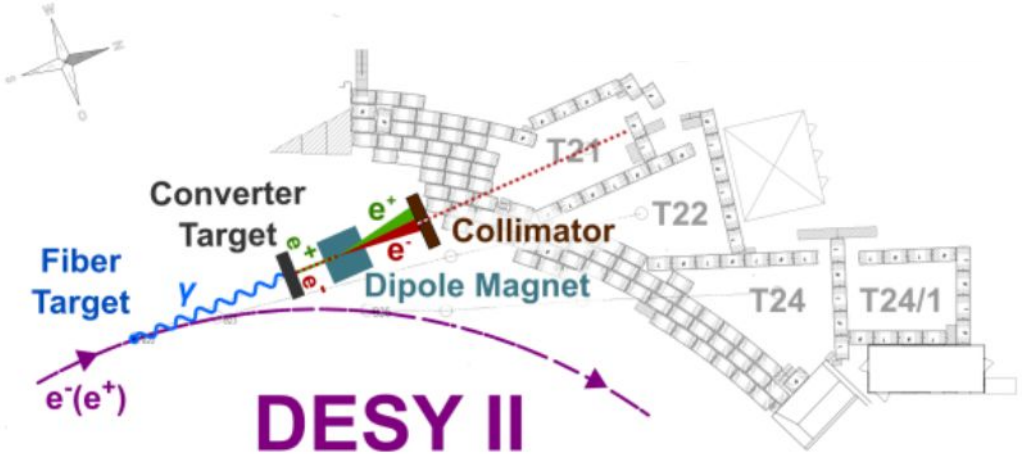




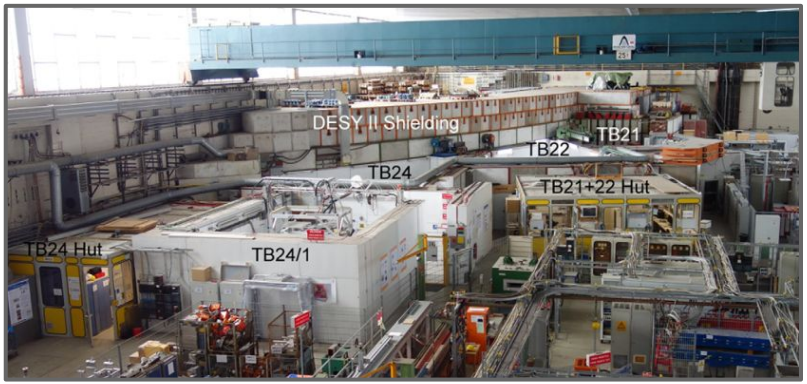
DESY Test Beam Facility

The DESY II test beam facility"
(https://doi.org/10.1016/j.nima.2018.11.133)
NIMA, Vol. 922, 2019

- **1 - 6 GeV electron / positron** beam
- ***O*(10k) particles $s^{-1}cm^{-2}$** rate
- The facility is equipped with EUDET-type **pixel beam telescopes with ~ 2-15 um spatial resolution**

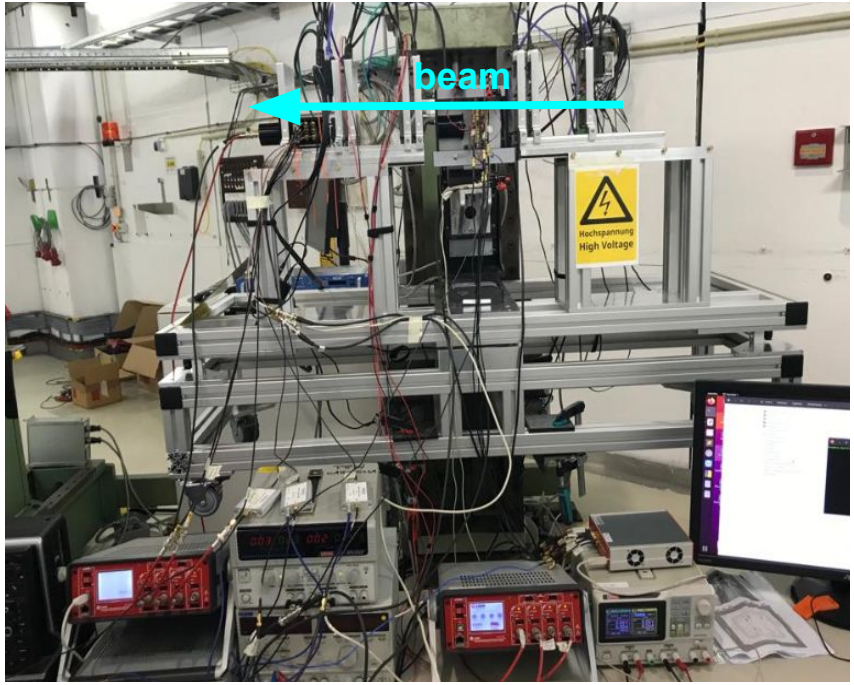


Picture of the test beam facility



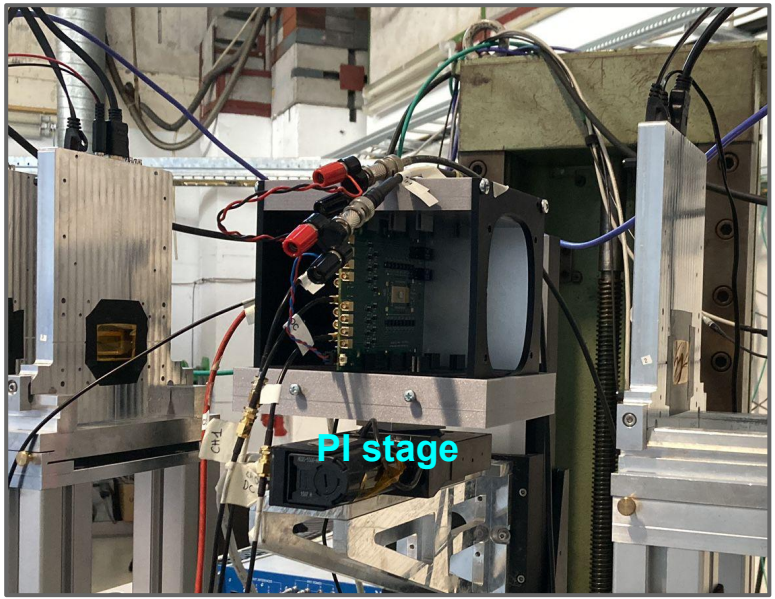
Setup - 1

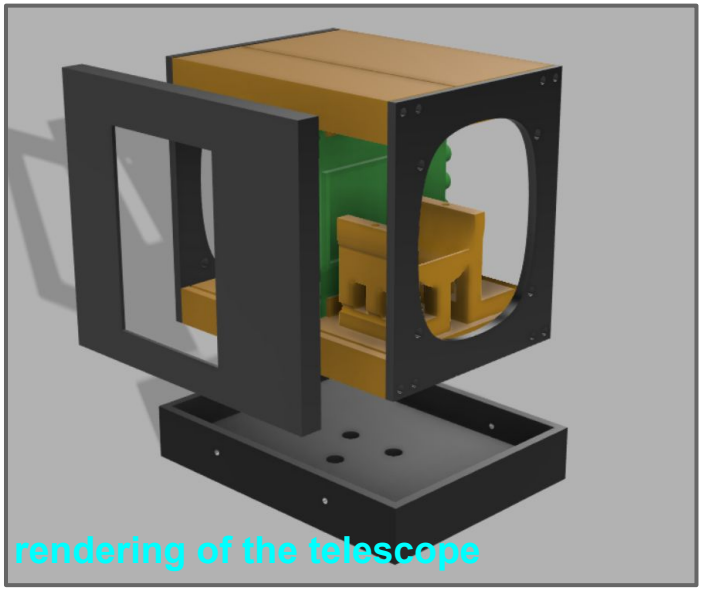
- Energy set to ~4 GeV for RSD tests
- Data acquired for ~5 days
  (@ room T, only pre-rad sensors)
- Collected *O*(100k) trigger per sensor
- A laser system provides the reference beam position
- The setup sits on a dedicated metal rack aligned with the beam



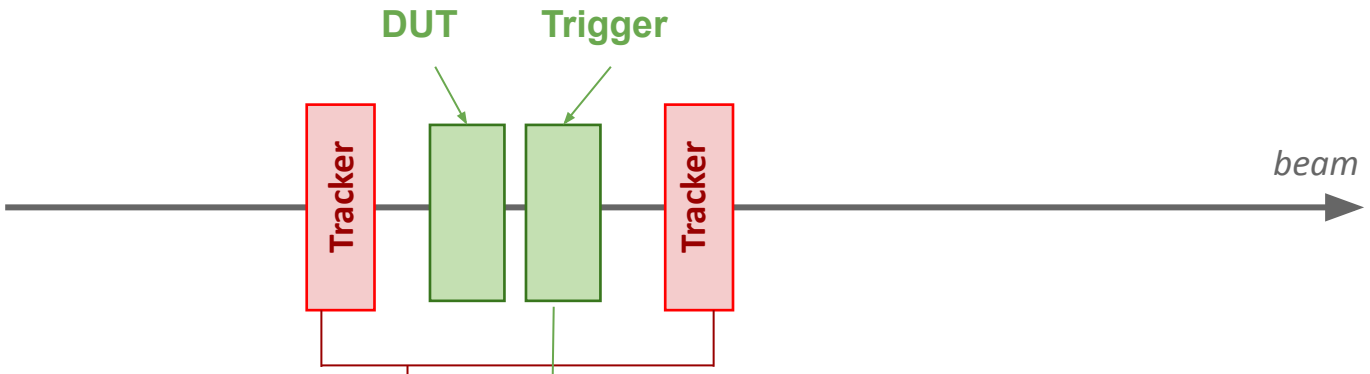
Setup - 2

- Read-out board and digitizer are the same used during lab tests and described in Luca's talk
- Trigger: a RSD2 with same active area of the DUTs, with all AC pads floating and DC-ring read out
- A 3d-printed telescope screwed on a PI stage houses DUT & trigger and ensures they are aligned





Trigger logic



Trigger logic unit sends trigger to the tracker once TTL signal

Trigger sent to digitizer: DUT, trigger signals acquired

Digitizer

Trigger Logic Unit

Once triggered, digitizer sends out TTL signal

Trigger logic possible because of different acquisition windows: 200 ns (Digitizer) vs 230 us (Trigger Logic Unit)

Methods for position reconstruction

- **Analytical law** → "Charge asymmetry" method (see L.Menzio's talk)
  - Not in this talk

$$x_i = x_{center} + k_x \frac{pitch}{2} \frac{A_3 + A_4 - (A_1 + A_2)}{\sum A_j}$$

$$y_i = y_{center} + k_y \frac{pitch}{2} \frac{A_1 + A_3 - (A_2 + A_4)}{\sum A_j}$$

- **Machine learning** proved to be an effective reconstruction method
- Comparison between predictions and tracker positions results in a gaussian distribution → its sigma gives an estimate of total resolution $\sigma_{Total} = \sqrt{(\sigma^2_{RSD} + \sigma^2_{Tracker})}$
- MLPRegressor has been chosen: a neural network providing 2 outputs (the x-y coordinates)

Use signal characteristics and positions provided by tracker to train the model

⇩

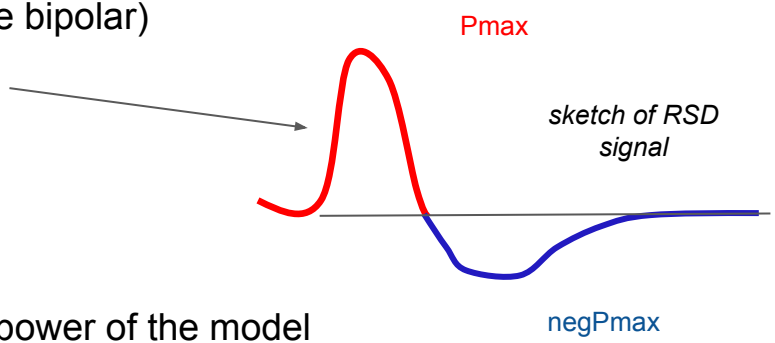
Test the model on a different, independent dataset

⇩

Compare the predicted position with the tracker reference

More on machine learning approach

- We used amplitudes of positive and negative lobes (signals are bipolar) of all read-out pads as input features
- Model training has been performed in 2 different ways:
  - training data come from one of the TB runs
  - training data from lab measurements (using IR laser)
- The purpose of the 2nd method is to check the generalization power of the model and to use a larger dataset for training
  - Lab datasets may have millions of events, in TB are limited (by now) to ~100k
- The test dataset is always one of the TB runs



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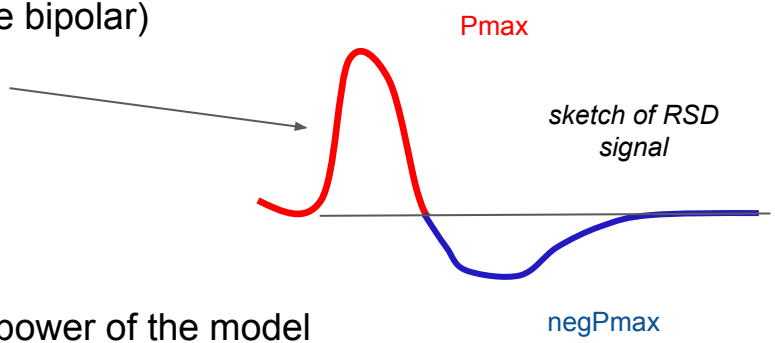

➢ Work in progress to train model with 50-100 input features (presently limited to 8-18) to fully exploit the neural network → looking for parallelizable algorithms

➢ Planning to acquire ~500k events at next TB to increase training dataset

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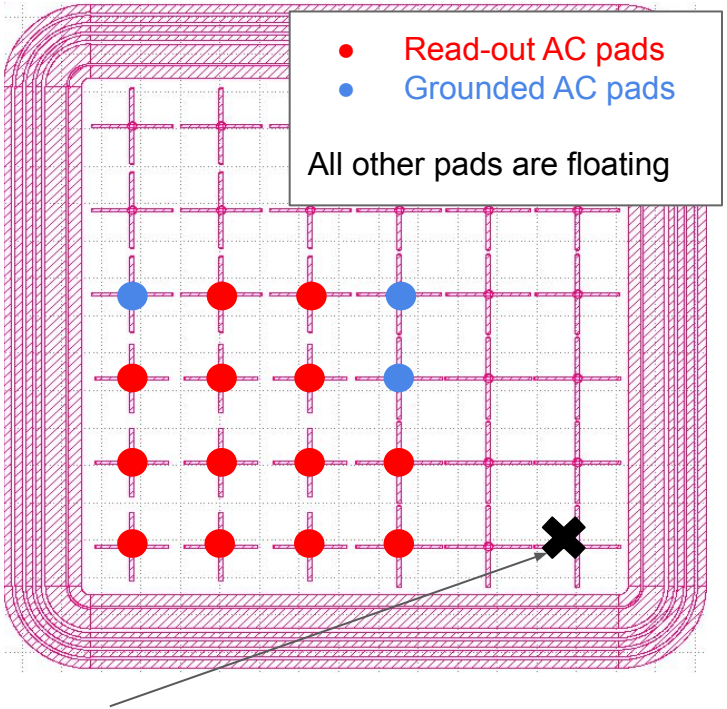
- **Results on RSD2 cross 450 um**
- Results in RSD2 cross 1300 um

cross 450 um

- 13 AC pads + DC ring read out from DUT
  - DC-ring not considered in this work
- Position reconstruction in RSD works using the pads that see a signal above the noise level (i.e. the closest to the hit position)



We cannot use this configuration of read-out pads to reconstruct this position → events in this region will not be considered

cross 450 um

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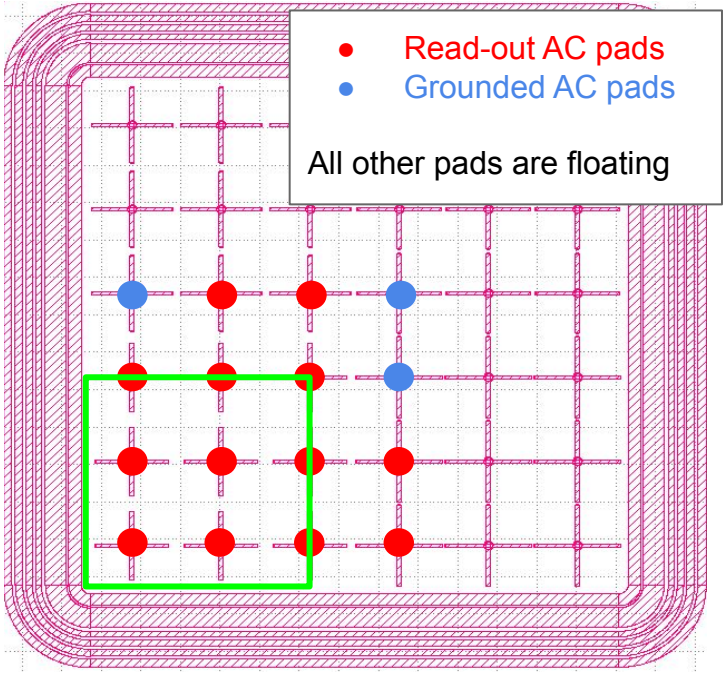
- The 3x3 matrix is the “elementary unit” for position reconstruction → hit positions in this work are reconstructed in the framed area only, as position outside would require using pads not read out



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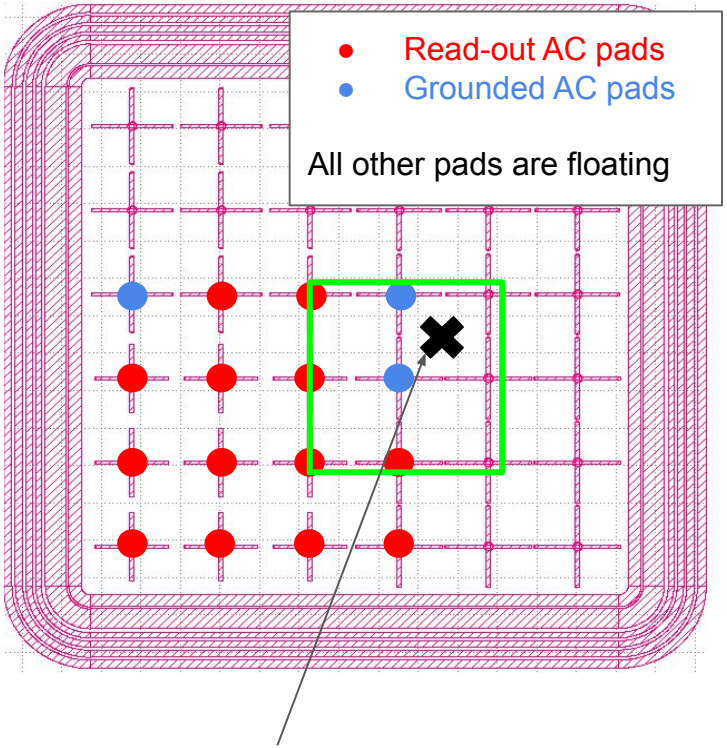
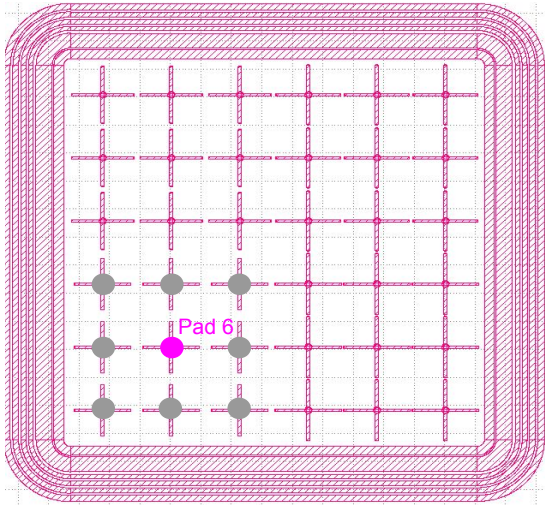


cross 450 um : Machine Learning

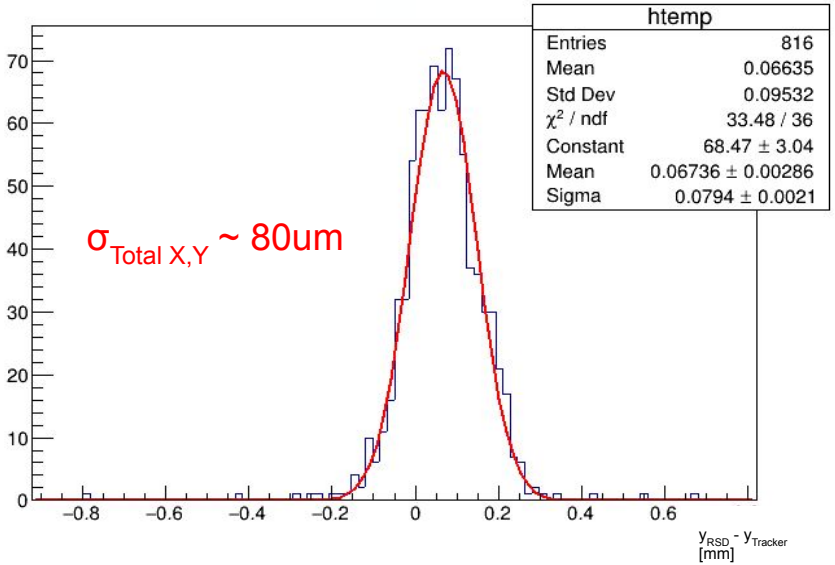
Requirements:

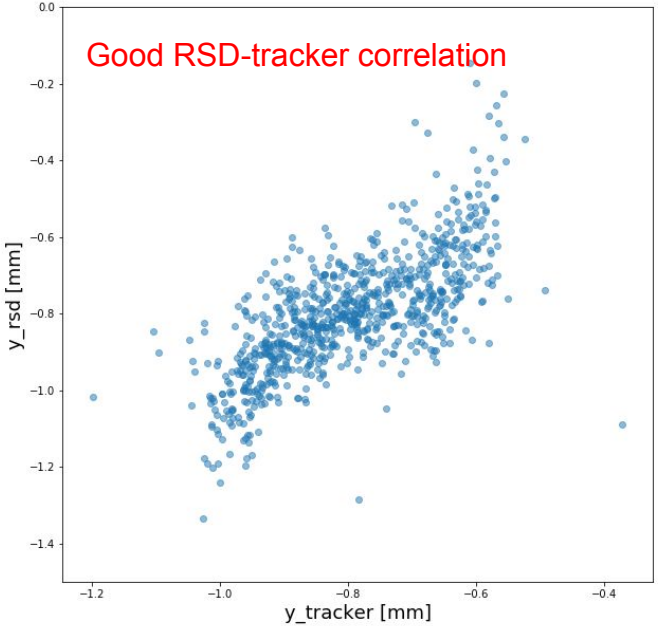
- Pad 6 signal amplitude > 7 mV (cut most noise events)
- Pad 6 sees the highest signal among all pads



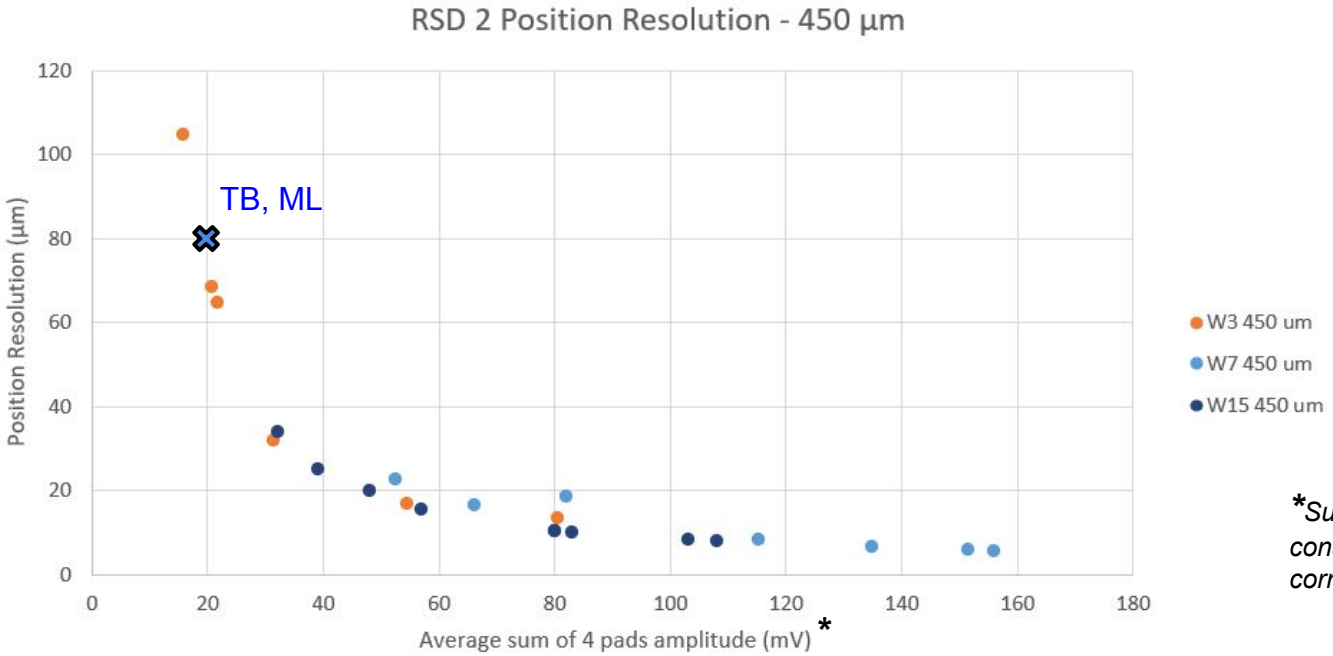
cross 450 um : Machine Learning

- Best performance when training the algorithm with the laser dataset from lab measurements
  - Resolution when training w TB dataset is ~ 5um worse





Cross 450um: Comparison with lab tests



**Sum of the 4 amplitudes of the "pixel" considered for the event, highest signals correspond to laser set to several MIPs*

- Plot summarizing RSD2 cross 450 um resolution, as measured with the TCT setup (link)
- **Resolutions measured during test beam well agree with expected trend**

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cross 1300 um

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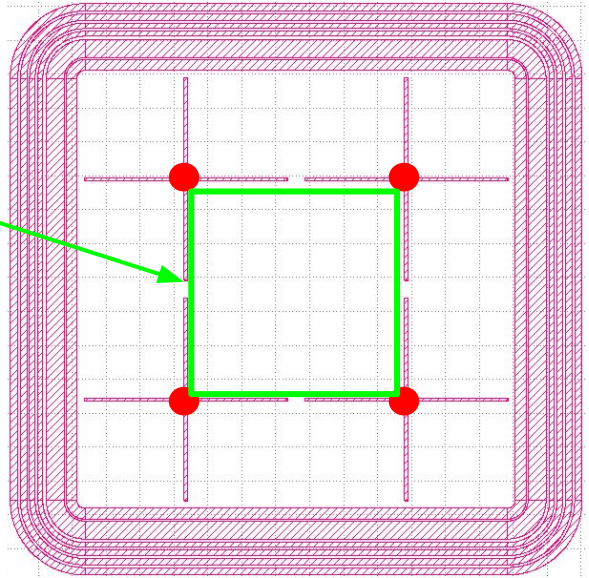
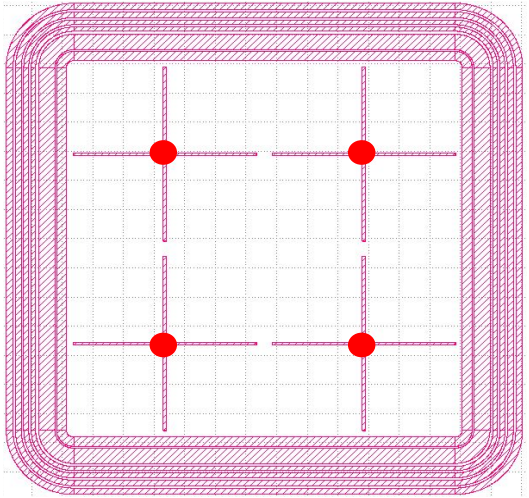
- Events reconstructed only within the active area
- Events outside active area are mis-reconstructed, as only 1-2 pads are involved





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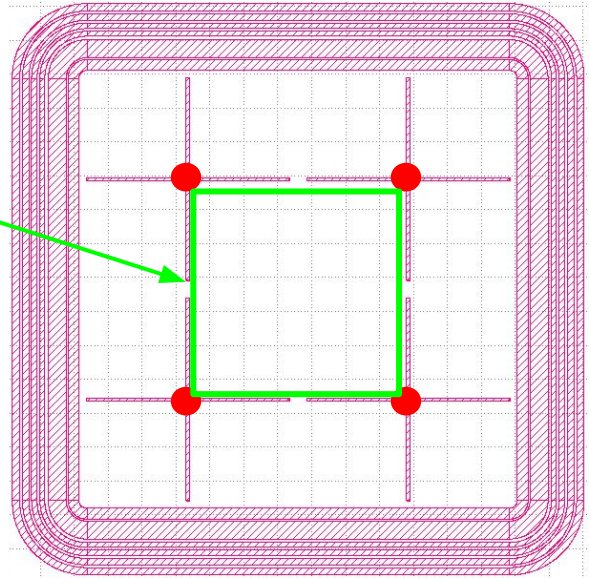
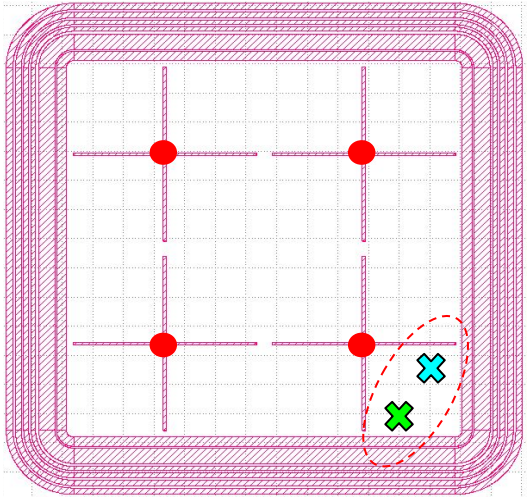
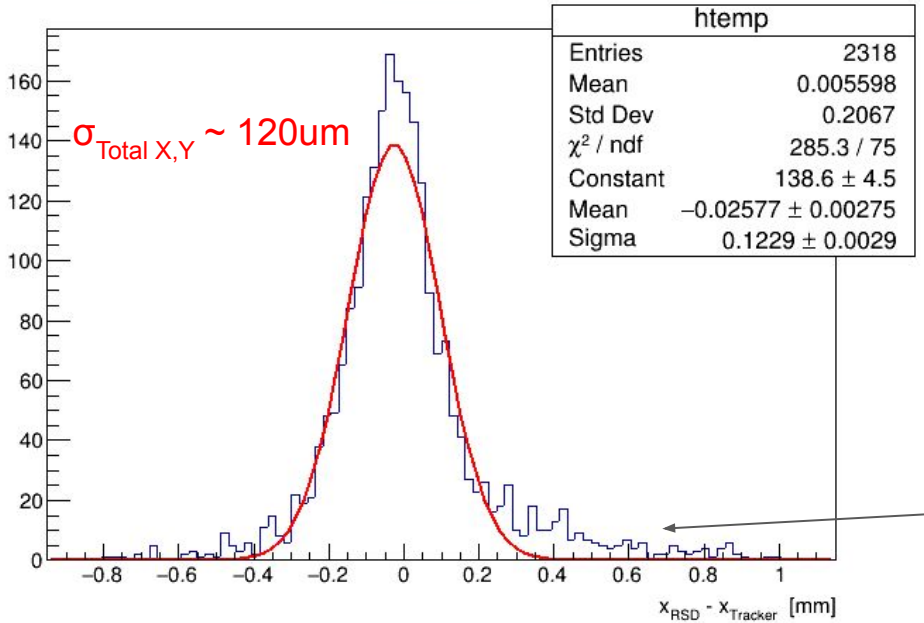


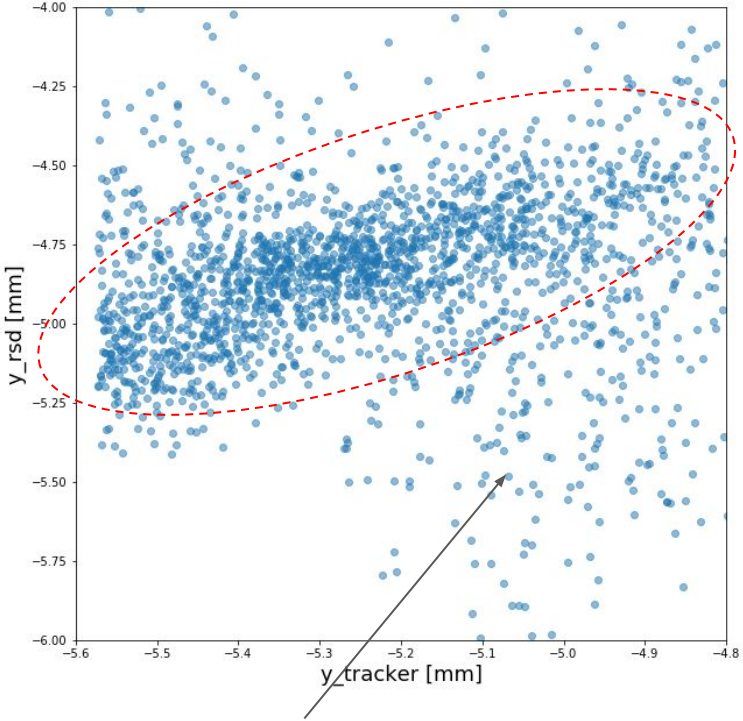


Same radial distance from pad → ambiguous reconstruction

cross 1300 um : Machine Learning

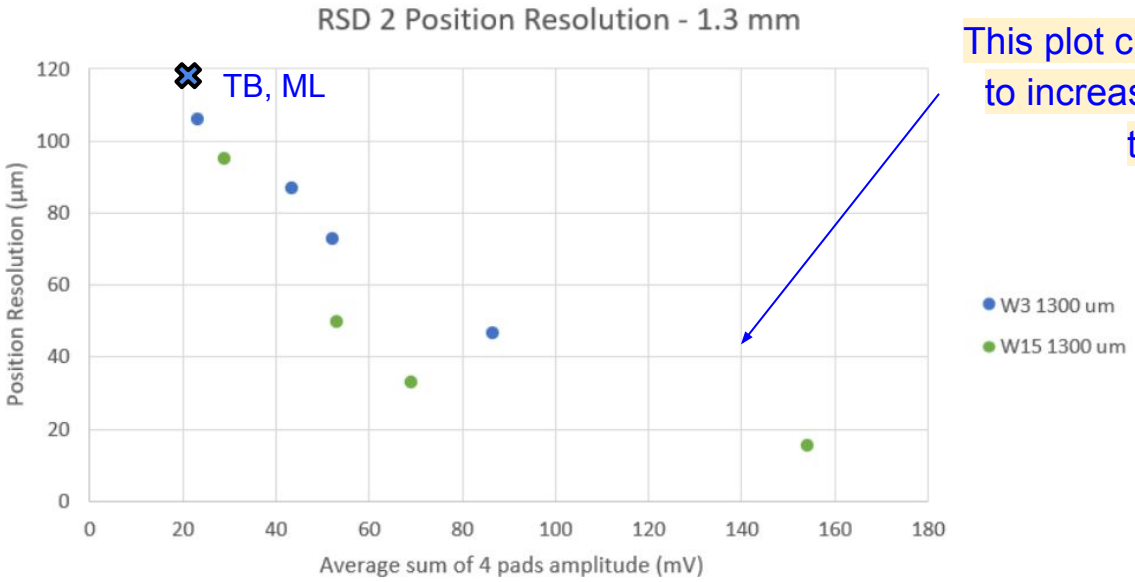
- Selected events where at least 3 pads see signals > 3 mV
- Laser dataset for training not available, training done with TB data





Correlation is quite good, though non correlated events present (tails in distribution)

Cross 1300 um: Comparison with lab tests



This plot clearly shows that we need to increase the signals to improve the performance

- Plot summarizing RSD2 cross 1300 um resolution, as measured with the TCT setup
- Performance are ~ as expected

Summary & next steps

- We tested two RSD2 sensors at the DESY test beam facility to measure their spatial resolution, using an accurate tracker as reference
- **First device** features cross-shaped electrodes with 450 um pitch:
  - **σ_{ML} ~ 80 um**
  - Traditional pixel detector with same pitch: σ_{Pixel} = 450 um / √12 ~ 130 um
- **Second device** features cross-shaped electrodes with 1.3 mm pitch:
  - **σ_{ML} ~ 120 um**
  - Traditional pixel detector with same pitch: σ_{Pixel} = 1300 um / √12 ~ 375 um
- We demonstrated that large-pitch **RSD2 sensors tested on beam can reconstruct the hit position with very good accuracy**

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Next steps

- collect more data (next test beam at end of March), use single-output algorithms (much more options compared to multi-output models), move to designs with higher gain
- RSD2 sensors are designed to be future 4D-trackers candidates → including timing is our next milestone!

Thank You!

Acknowledgements

- The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association (HGF)
- We kindly acknowledge the following funding agencies and collaborations:
  - INFN–CSN5, RSD Project
  - FBK-INFN collaboration framework
  - MUR PRIN project 4DInSiDe
  - Dipartimenti di Eccellenza, Torino University (ex L.232/2016, art. 1, cc. 314, 337)

The research leading to these results has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101057511

References

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- M. Mandurrino *et al.* "Analysis and numerical design of Resistive AC-Coupled Silicon Detectors (RSD) for 4D particle tracking" https://doi.org/10.1016/j.nima.2020.163479

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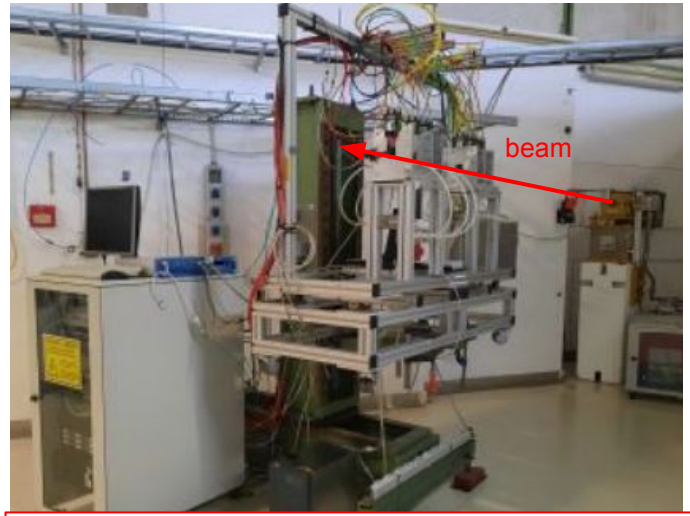
- M.Mandurrino *et al., "The second production of RSD (AC-LGAD) at FBK"*, arxiv.org/abs/2111.14235

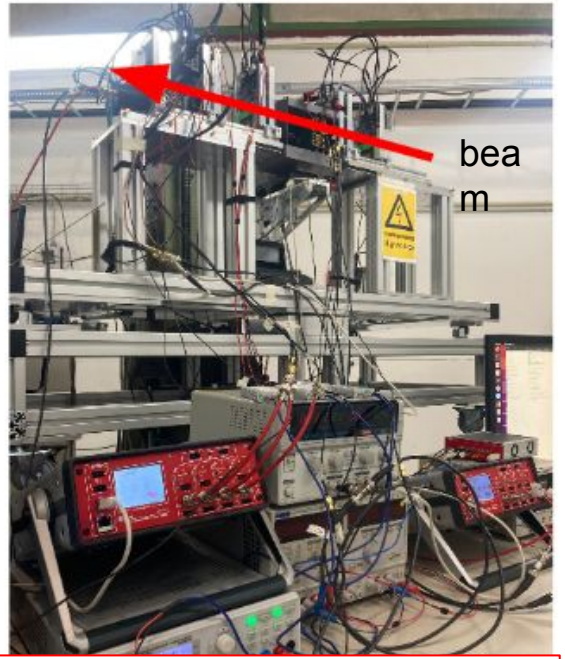
- F.Siviero *et al, "First experimental results of the spatial resolution of RSD pad arrays read out with a 16-ch board"*, https://doi.org/10.1016/j.nima.2022.167313

BACKUP

Setup - 1

- Energy set to ~4 GeV for RSD tests
- Data acquired for ~5 days (@ room T, only pre-rad sensors)
- Collected *O*(100k) trigger per sensor





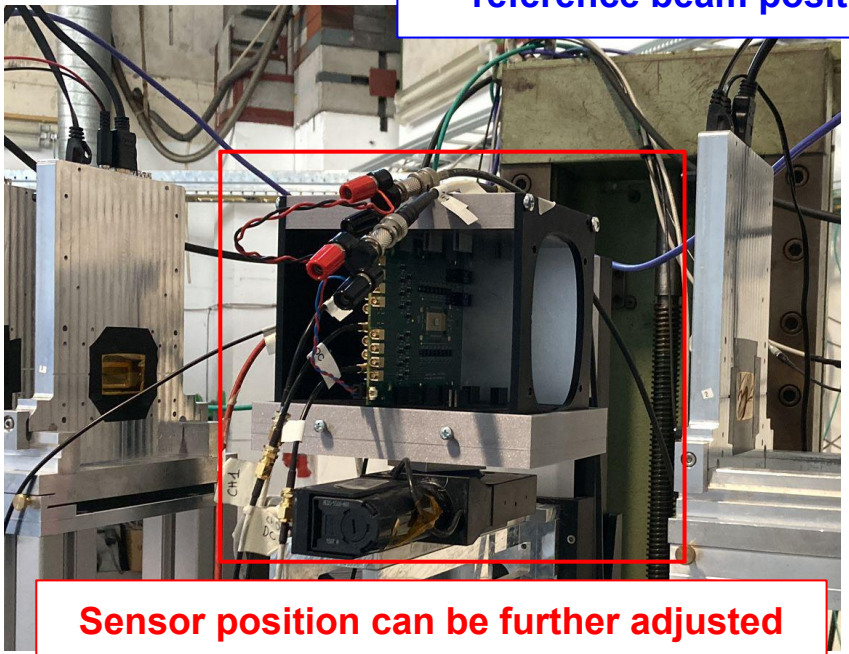
Setup sits on a dedicated metal rack aligned with the beam

Setup - 1

- Energy set to ~4 GeV for RSD tests
- Data acquired for ~5 days (@ room T, only pre-rad sensors)
- Collected *O*(100k) trigger per sensor

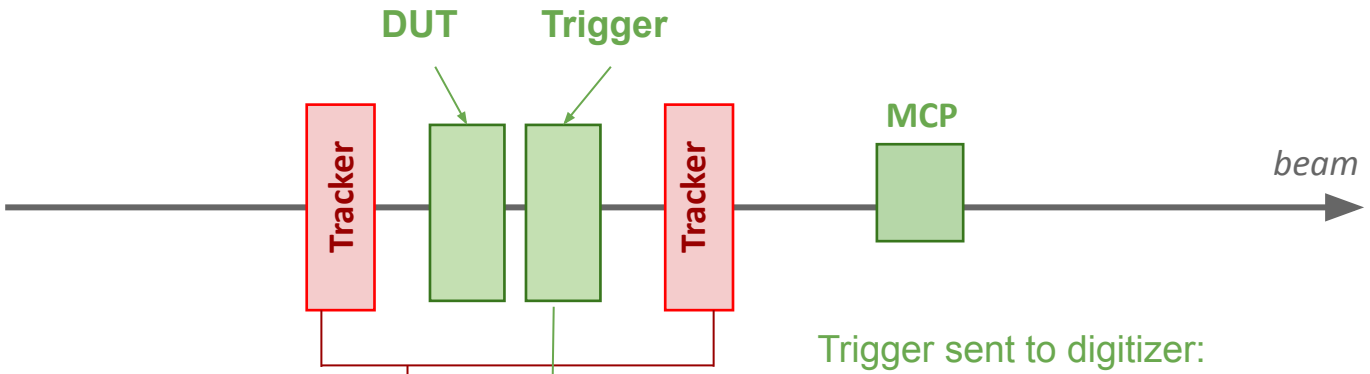
A lifter with ~100 um steps can move the rack up/down

A laser system provides the reference beam position



Sensor position can be further adjusted with a micrometric PI stage

Trigger logic



Trigger logic unit sends trigger to the tracker once TTL signal

Trigger sent to digitizer: DUT, trigger and MCP signals acquired

Digitizer

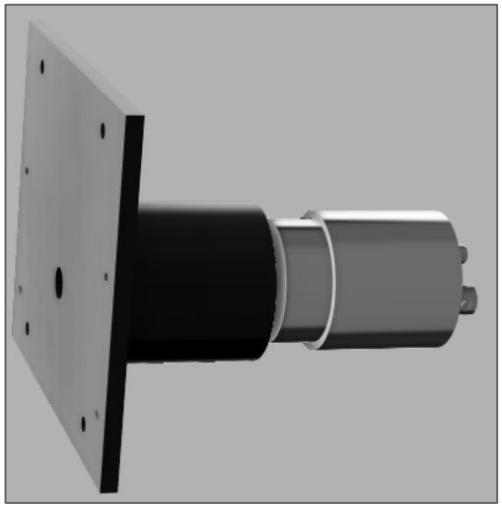
Trigger Logic Unit

Once triggered, digitizer sends out TTL signal

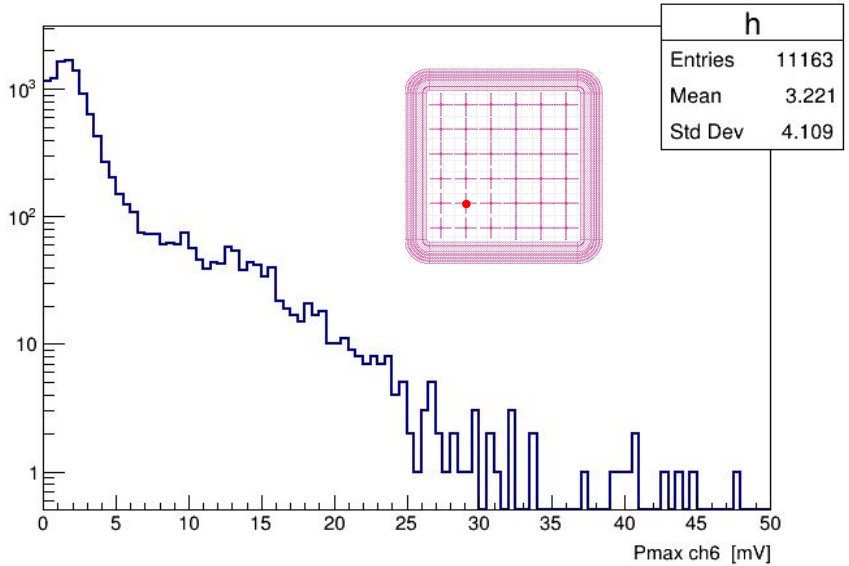
Trigger logic possible because of different acquisition windows: 200 ns (Digitizer) vs 230 us (Trigger Logic Unit)

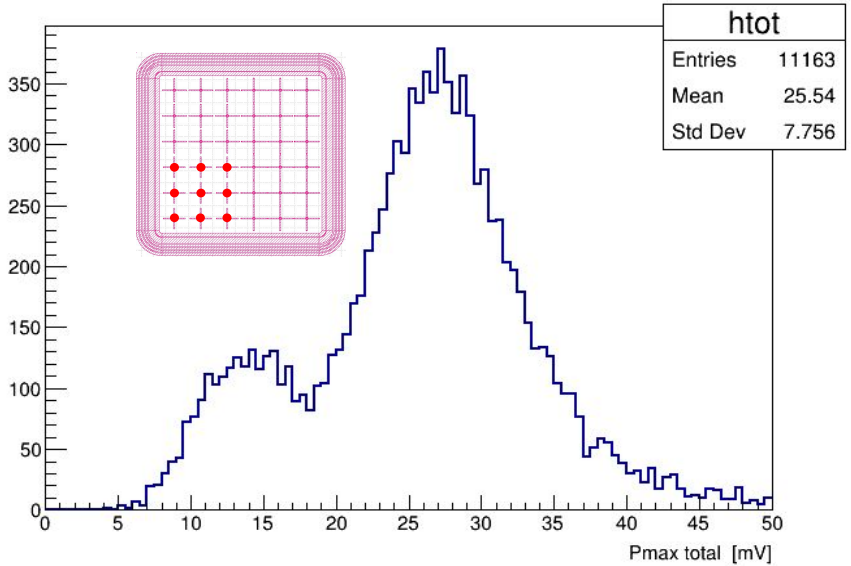
MCP

- A **Photonis MCP** is placed downstream to the telescope and provides the **event timestamp** with 15-20 ps resolution → it is mounted on a 3d printed carrier attached to a metal plate aligned with the beam



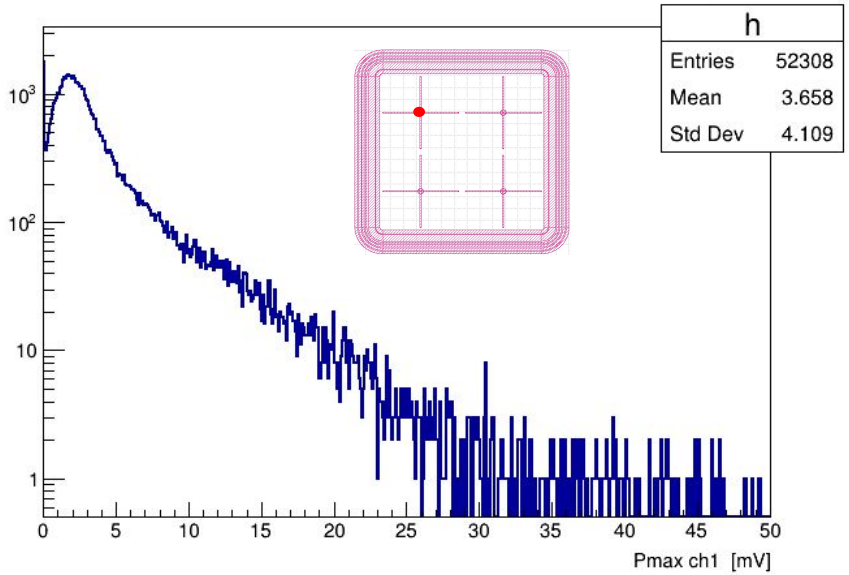
cross 450 um @ 285V

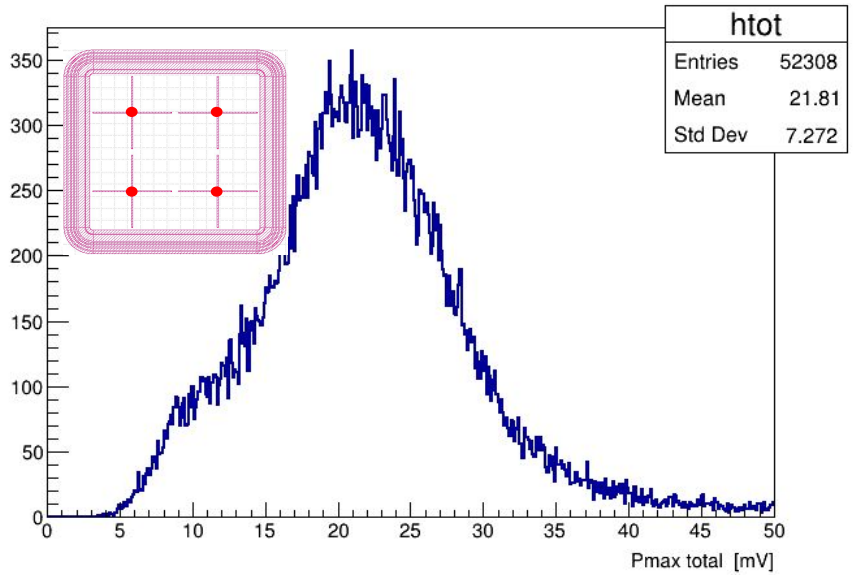




- Pmax of a single AC pad: noise and signal overlapped (7-8 mV to cut most of the noise), signals are position-dependent (no Landau distribution visible)
- Sum of Pmax of pads in the 3x3 matrix: noise and signal are well separated, average signal of ~25 mV → from lab measurements, that corresponds to **gain ~10**

cross 1300um @ 300V

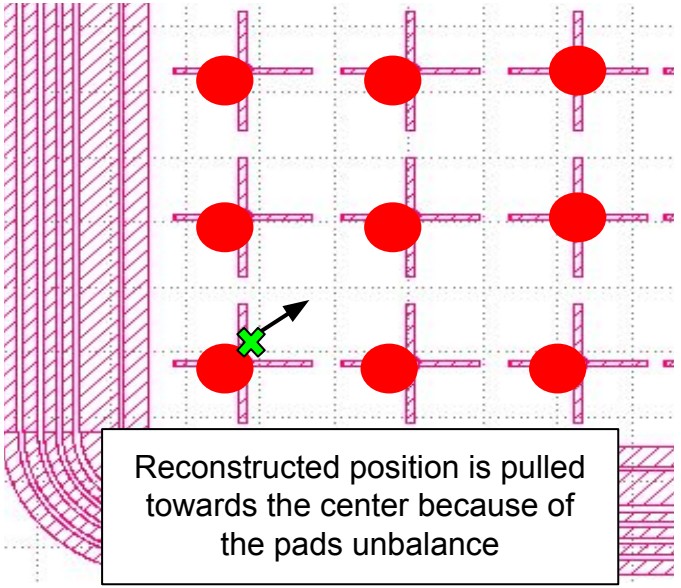




- Pmax of a single AC pad: no Landau distribution visible as signals are position-dependent
- Sum of Pmax of 4 pads: small noise peak between 5-15 mV, typical sum of signals in the 20-25 mV range → from lab measurements, that corresponds to **gain 10-12**

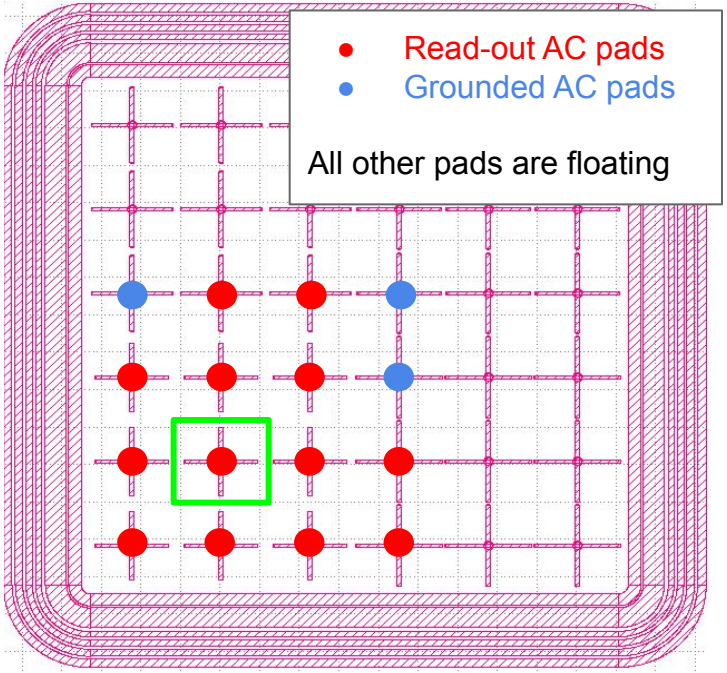
cross 450um: ML

- Positions in corners are always biased as the reconstruction requires a symmetric distribution of pads around the hit position



cross 450um: ML

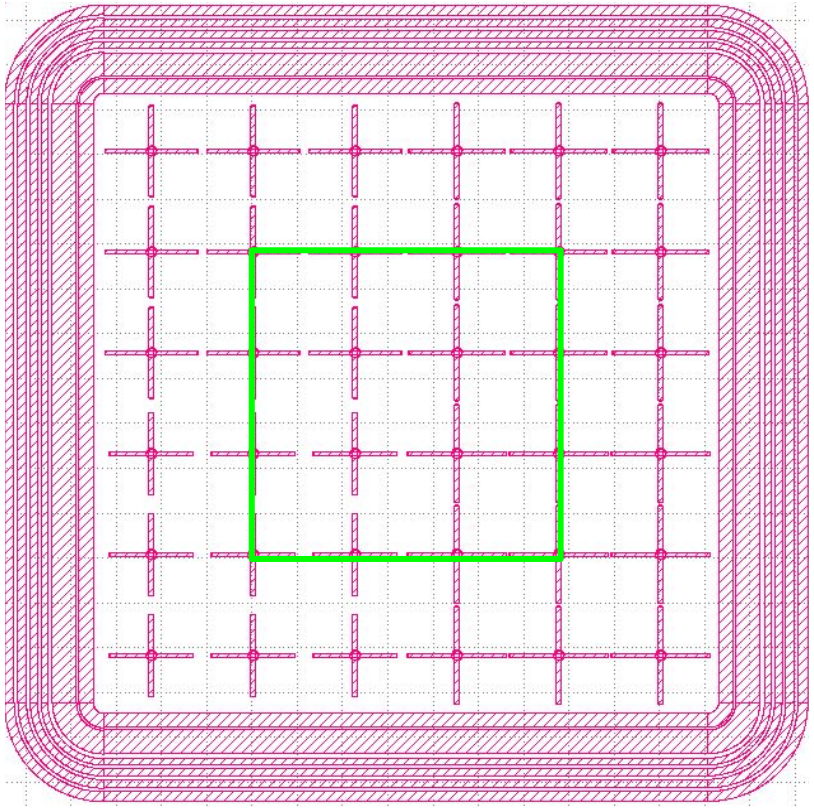
- Positions in corners are always biased as the reconstruction requires a symmetric distribution of pads around the hit position → we use only events where the pad seeing the maximum signal is the central one, avoiding in this way corners



cross 450um: a side note

Given our current understanding of position reconstruction in RSD, in a real detector all pads of the 6x6 matrix would be bonded, but only in the 4x4 matrix position may be reconstructed unbiased → in this way, it is always possible to define a 3x3 matrix around the hit position and use those 9 pads for the reconstruction

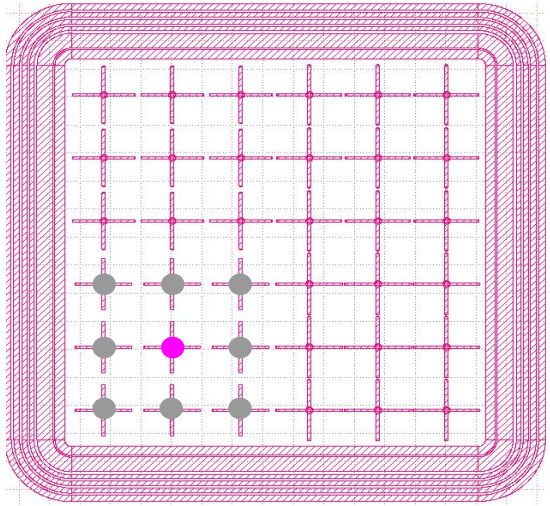
Such effect calls for large-size matrices, to minimize the inactive region

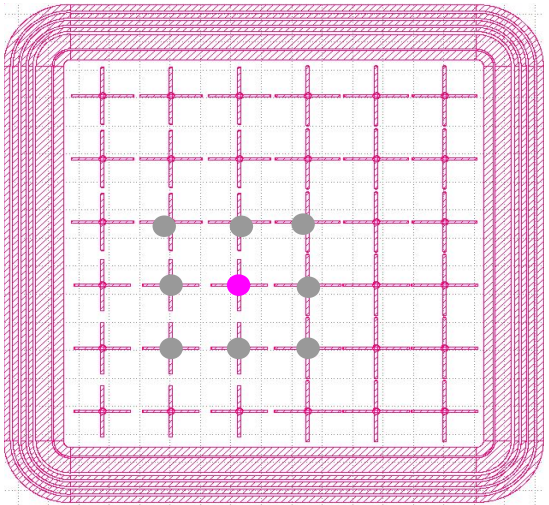


cross 450 um : Machine Learning

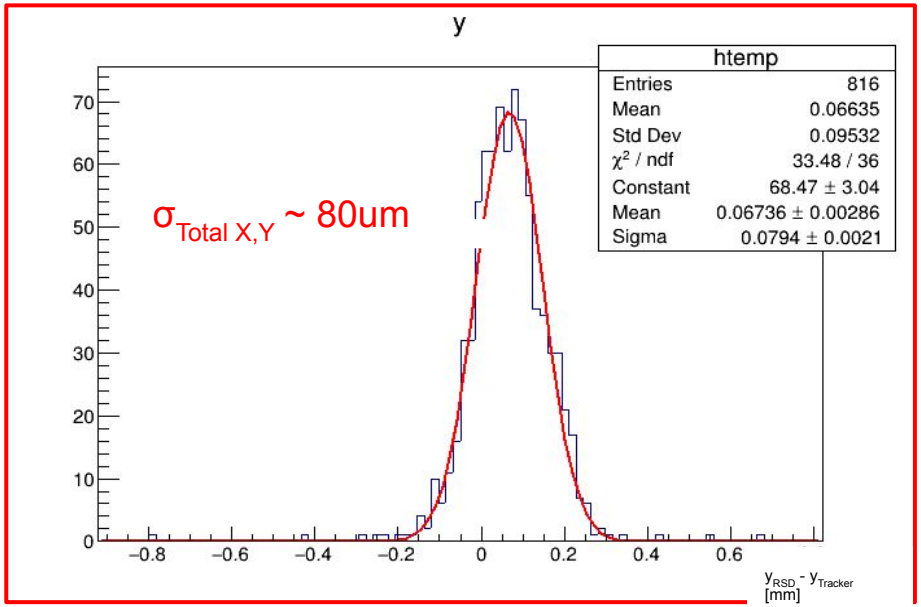
Requirements:

- Pad 6 signal amplitude > 7 mV (cut most noise events)
- Pad 6 sees the highest signal among all pads → if another pad would see the highest signal, a different 3x3 matrix should be used





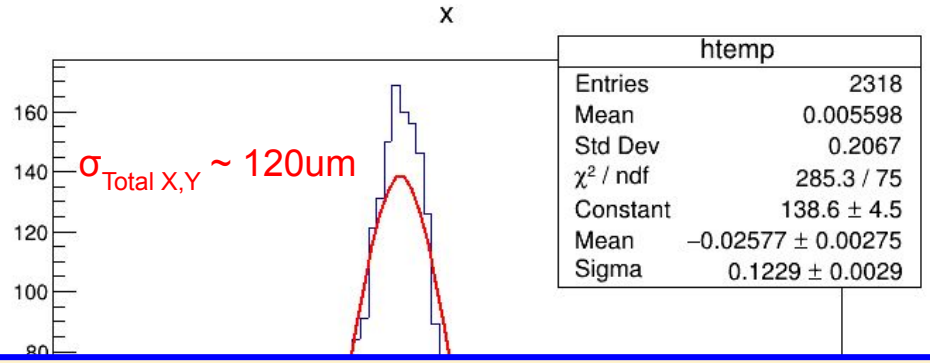
cross 450 um : Machine Learning

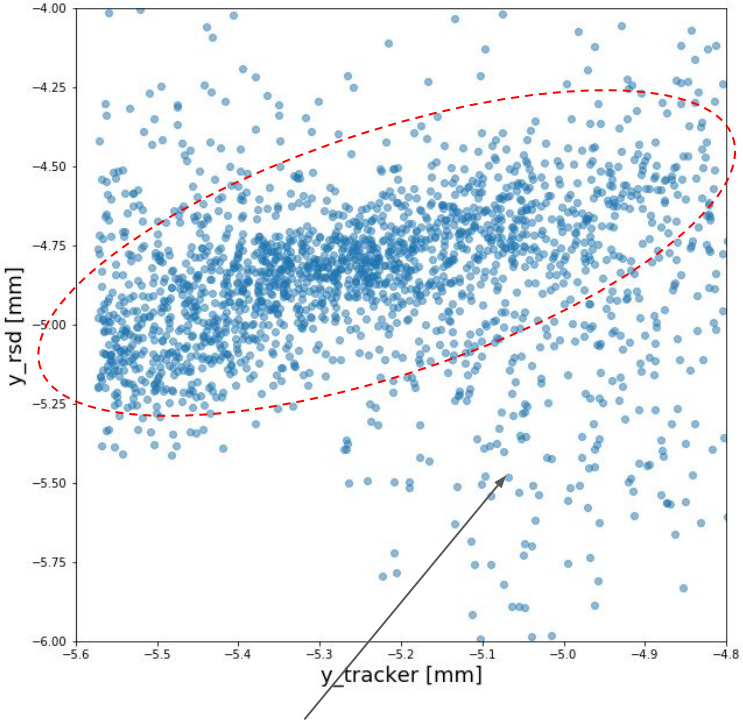


- Remarkably, if we 90-10 split the laser dataset and predict the 10% fraction (validation dataset) with the trained algorithm, the resulting σ is ~ 80 um
- This highlights the generalization power of the algorithm → we can train the model in the lab and then use it at test beams

cross 1300 um : Machine Learning

- Tracker is present (not same run of previous slide)
- Selected events where at least 3 pads see signals > 3 mV
- Laser dataset for training not available, training done with TB data

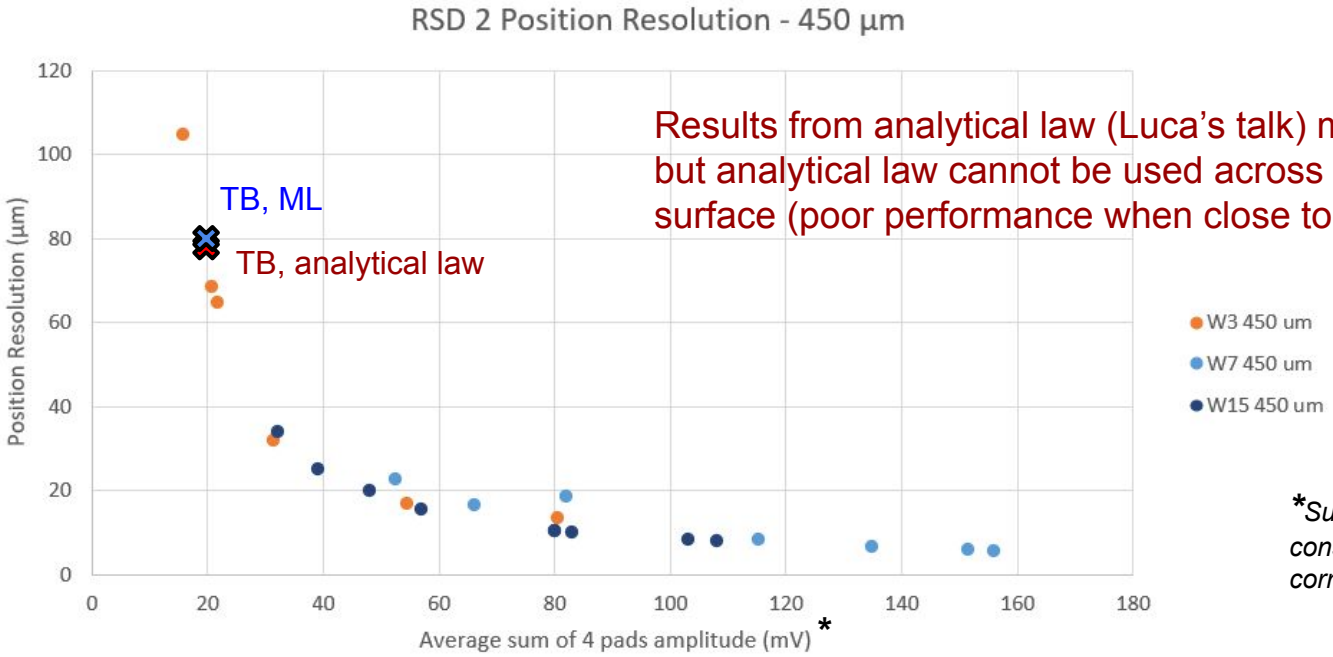




Correlation is quite good, though non correlated events present (tails in distribution)

Using ML techniques with the “3 planes” configuration and no tracker is challenging, as the reference positions used for training are not provided by an independent source (tracker) → any bias or mis-reconstruction in training dataset is propagated to the test dataset

Cross 450um: Comparison with lab tests



Results from analytical law (Luca's talk) matches ML results, but analytical law cannot be used across the whole active surface (poor performance when close to the electrodes)

**Sum of the 4 amplitudes of the "pixel" considered for the event, highest signals correspond to laser set to several MIPs*

- Plot summarizing RSD2 cross 450 um resolution, as measured with the TCT setup (link)
- **Resolutions measured during test beam well agree with expected trend**

Cross 1300 um: Comparison with lab tests

analytical law range

This plot clearly shows that we need to increase the signals to improve the performance

- Plot summarizing RSD2 cross 1300 um resolution, as measured with the TCT setup (link to our paper)
- Performance are ~ as expected