AC-LGAD (RSD): Signal formation and design optimization

- What are AC-LGAD (RSD)
- Signal formation
- Laser study
- Reconstruction method
- Results

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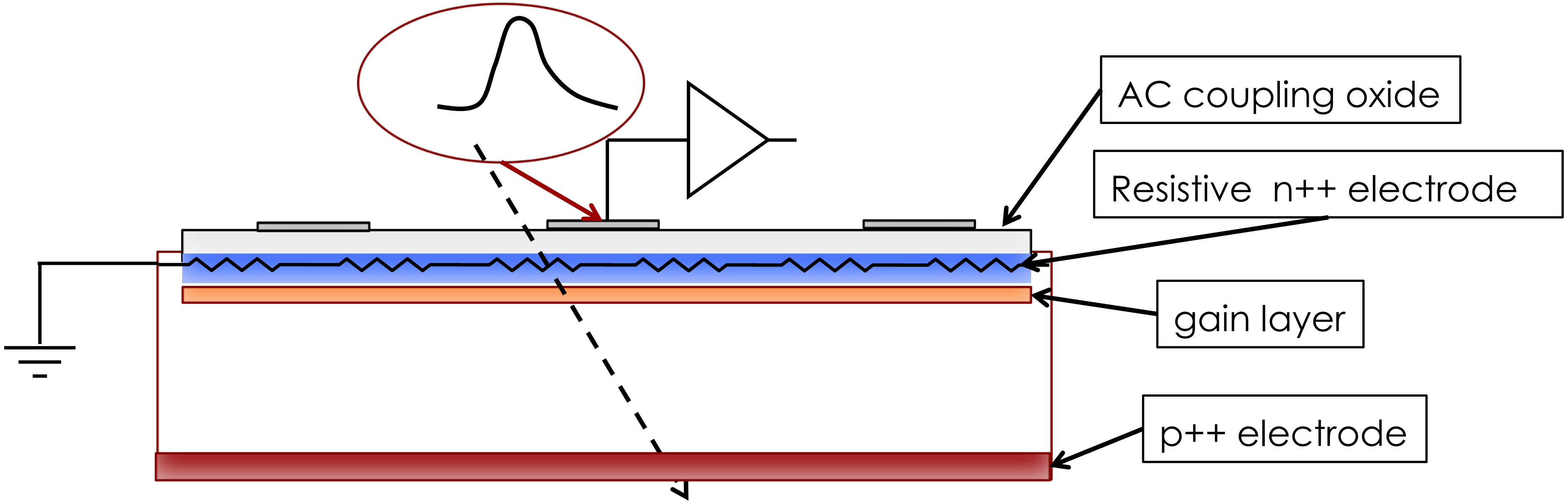
UFSD

15th Trento Workshop
on Advanced Silicon
Radiation Detectors

AC – LGAD: Resistive Silicon Detectors (RSD)



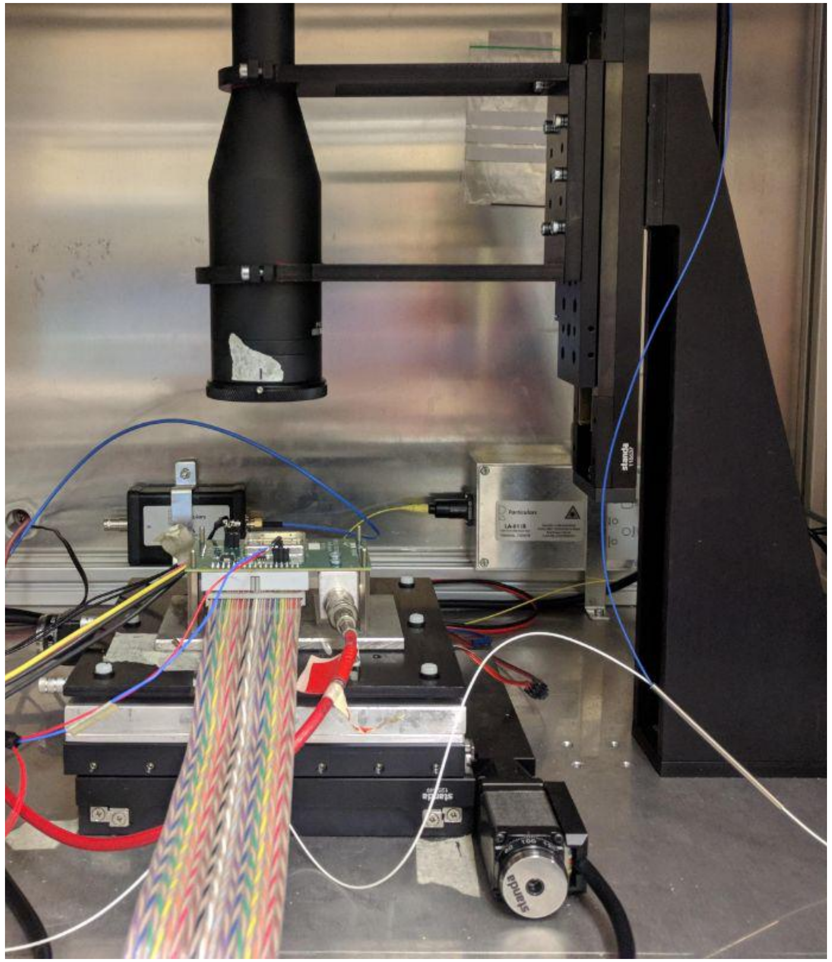
AC-LGAD are a design evolution of LGAD detectors where the gain layer is not segmented, and the signal is read-out via AC coupling (see TREDI 2015 for details).

The **key technological feature** that makes this design work is the **“resistive n++ layer”**, necessary to produce the local AC coupling. For this reason, they are called **“Resistive Silicon Detector”, RSD**.
The sensors presented here are manufactured at FBK within the RSD project (INFN).
➔ CNM produced AC-LGAD sensors in 2017, Sadrozinski’s talk @ HSTD11, BNL in 2019.

Publications:
M. Mandurrino *et al*., "Demonstration of 200-, 100-, and 50- μ m Pitch Resistive AC-Coupled Silicon Detectors (RSD) With 100% Fill-Factor for 4D Particle Tracking," in *IEEE Electron Device Letters*, vol. 40, no. 11, pp. 1780-1783, Nov. 2019.
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

Experimental Set-up

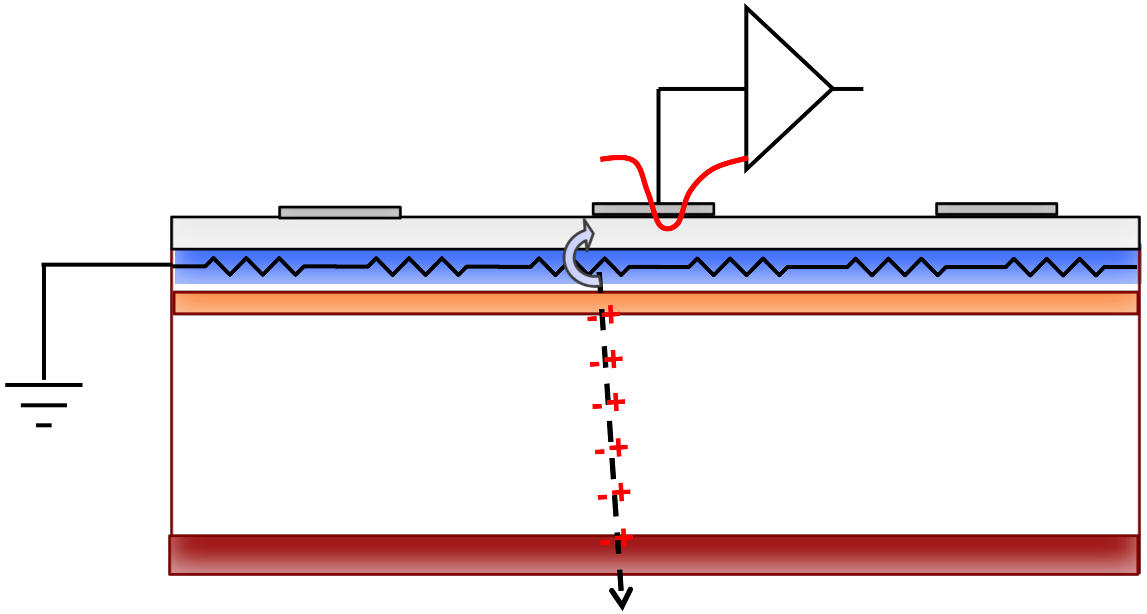
- The study presented here are obtained using a “Particular” laser TCT set-up
- Sensors are glued on a 16-channel read-out board.
- The signal of the 4 pads is recorded using an oscilloscope
- The laser is shot in various position via an x-y-z micrometric stage

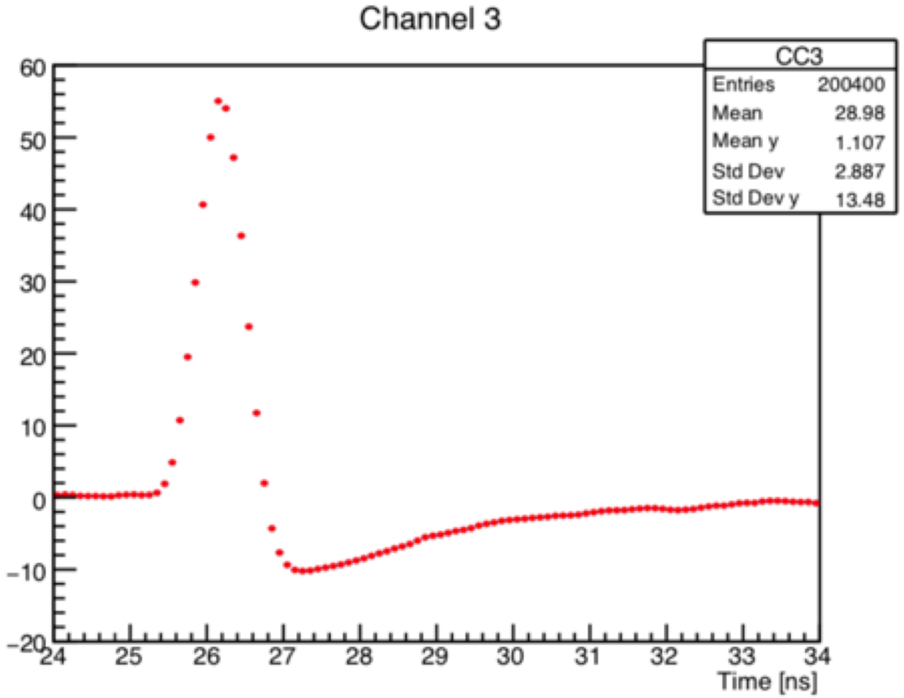


RSD Signal formation - I

Act 1: the e/h are drifting and they produce a direct charge induction in the n++ layer (Ramo theorem)

1. The signal is immediately AC-coupled to the metal pad above (if there is one), its shape identical to an equivalent DC LGAD
2. Large signal (gain 10-20): 5 - 10 fC
3. Very fast collection (1 ns)
4. No lateral spread, very vertical E field and drift

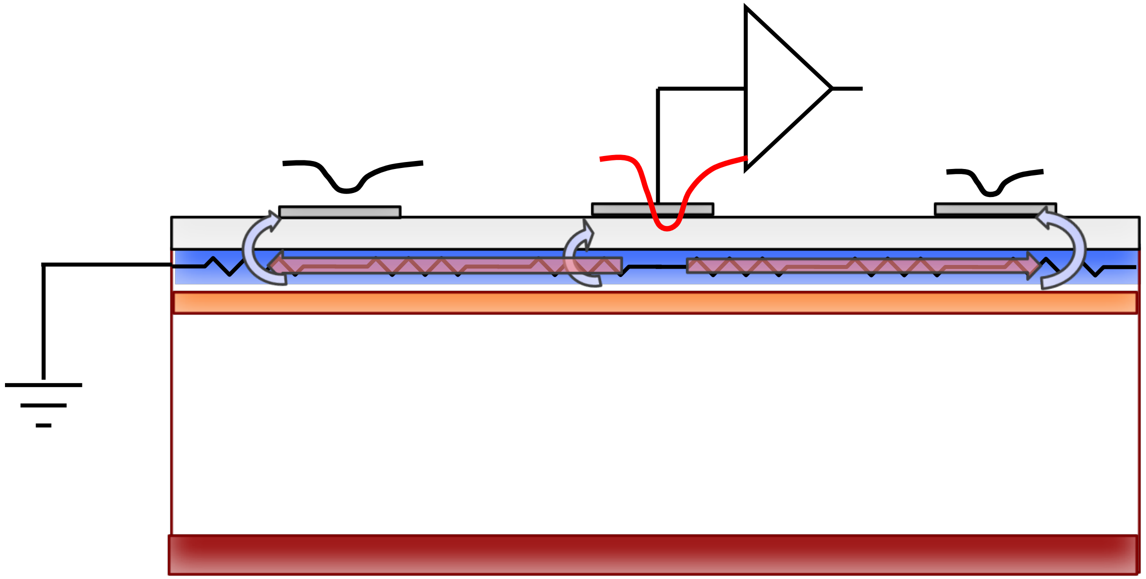




RSD Signal formation - II

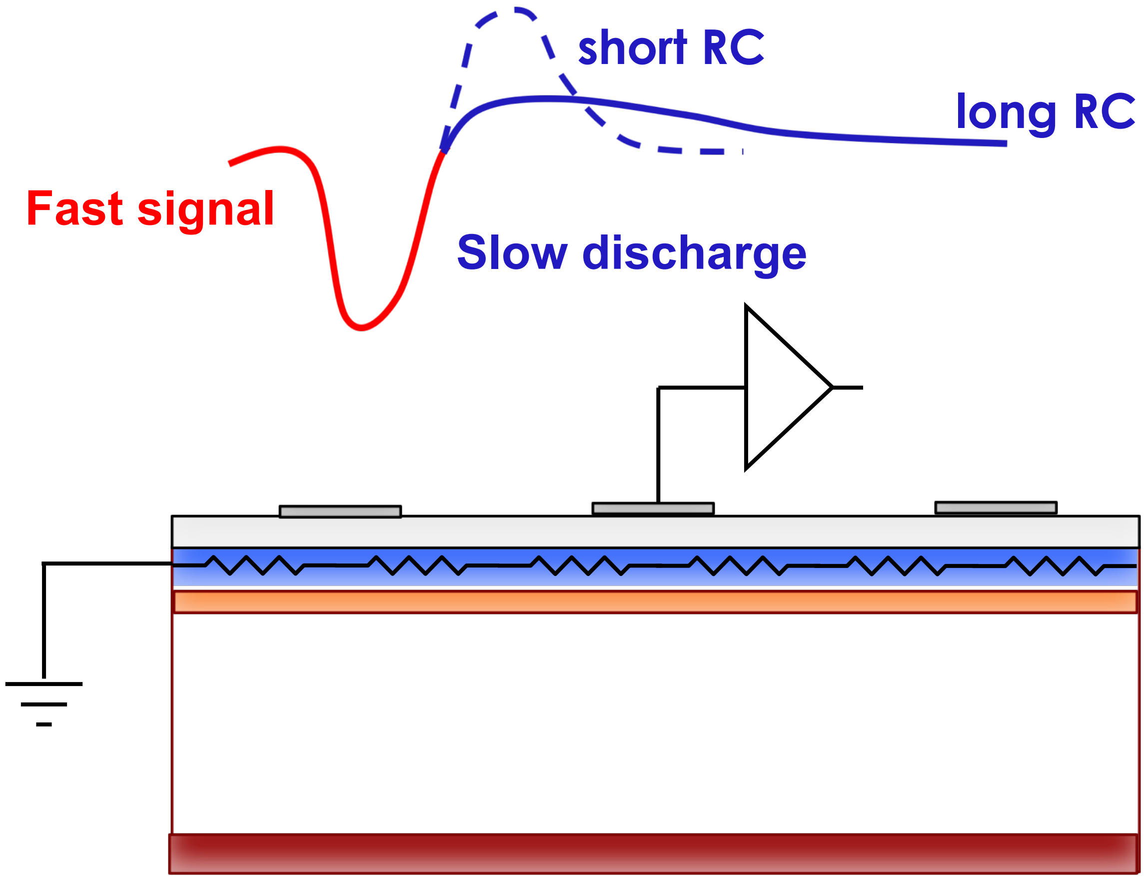
Act 2: the signal propagates on the n++, firing the near-by pads

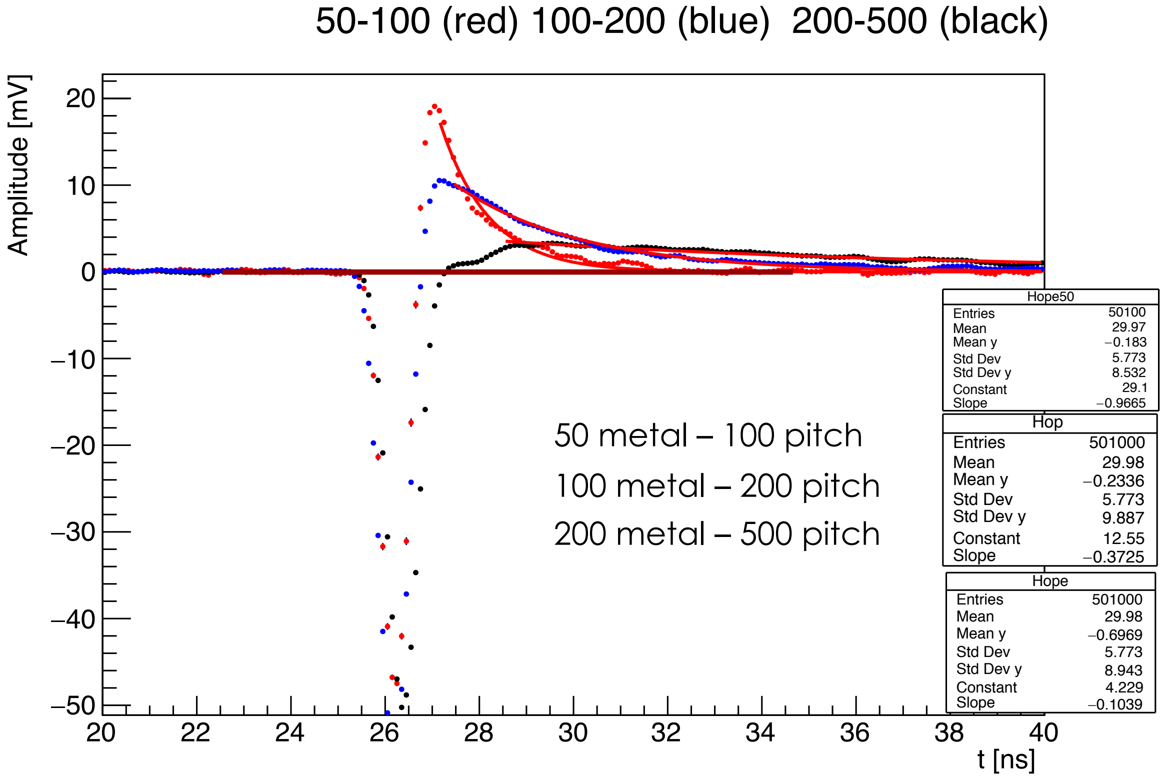
1. The n++ is an almost ideal resistive divider
2. Lateral spread controlled by n++ resistivity, metal pad capacitance, pitch, system inductance.
3. The metal AC pads act as "pick-up" electrodes
4. Signal gets smaller and delayed with distance



RSD Signal formation - III

Act 3: the signal discharges, according to the read-out RC. Small RC have larger and shorter positive lobes (need to discharge the same charge in a shorter time)




50-100 (red) 100-200 (blue) 200-500 (black)

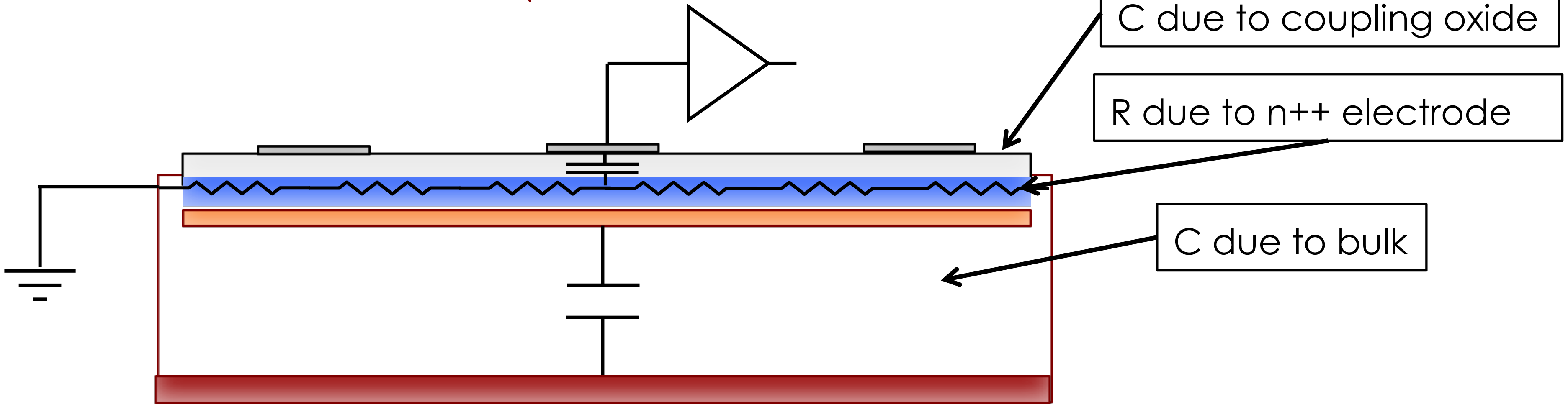
50 metal – 100 pitch

100 metal – 200 pitch

200 metal – 500 pitch

Effect of L,C,R on the signal propagation

The n++ layer of RSD is a lossy transmission line, with R,C and L components. The propagation coefficient is defined as: $\boldsymbol{\gamma = \sqrt{(r + jwL)(G + jwC)} = \alpha + j\beta}$

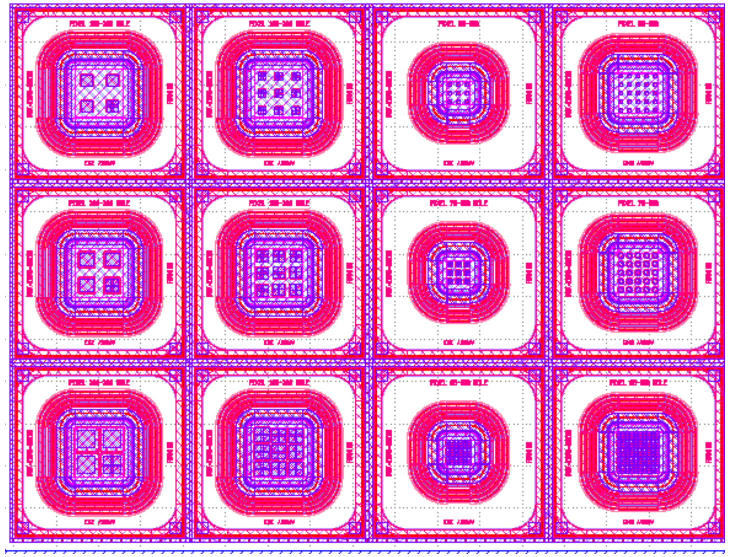


C due to coupling oxide

R due to n++ electrode

C due to bulk

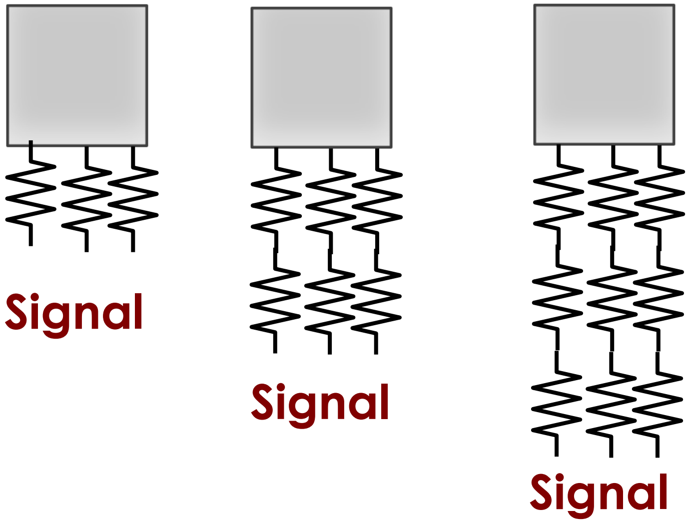
In order to study signal formation, propagation, and attenuation in RSD, sensors with many geometries have been produced (metal-pitch combinations), including strips and large matrices. For example: ➔

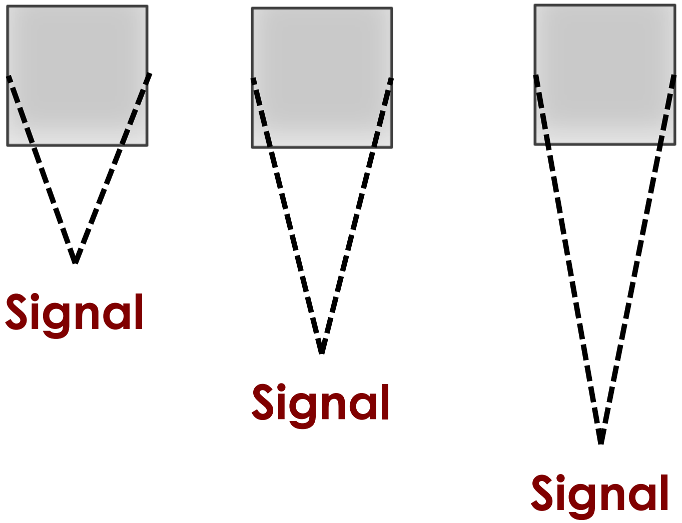


subset of the structures manufactured in the RSD project

Attenuation versus distance

How is the signal attenuated as a function of the distance from the pad?

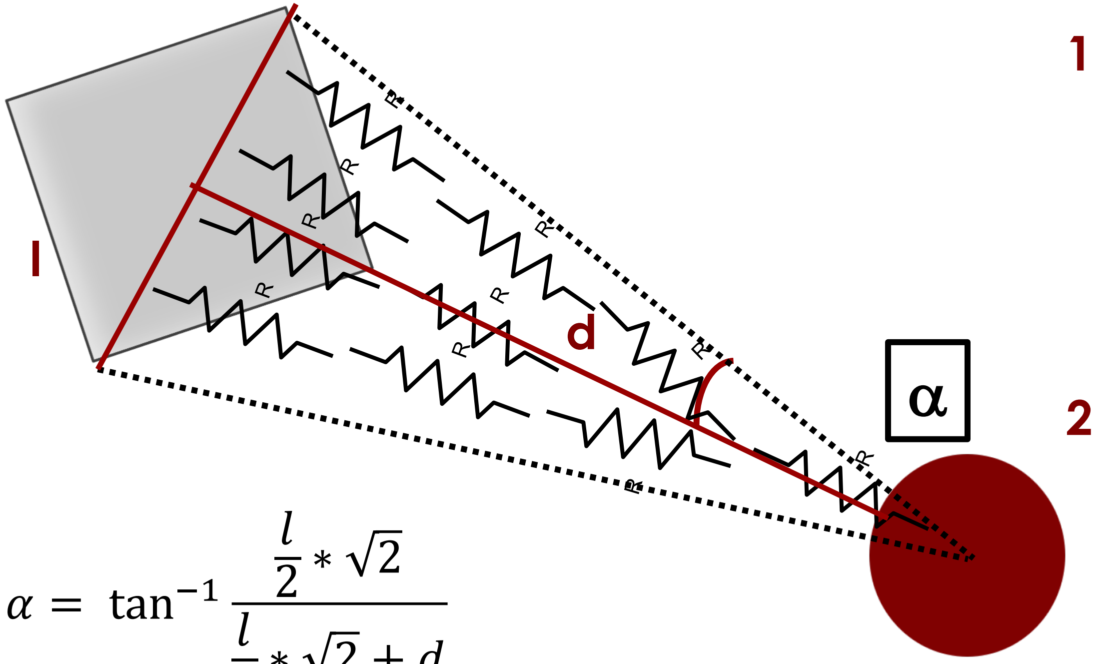




The amplitude decreases linearly with **Increasing distance** due to the resistivity of the n++ layer

The amplitude decreases linearly with **decreasing angle** (angle of view)

Attenuation with distance: resistivity and angle



$$\alpha = \tan^{-1}\frac{\frac{l}{2} * \sqrt{2}}{\frac{l}{2} * \sqrt{2} + d}$$

where

l: side of the pad

d: distance from metal

The 2 sources of attenuation with distance, V(d), can be parametrized as follow:

1) Attenuation due to the resistivity:

$$\mathbf{V}(\boldsymbol{d}) = \boldsymbol{V}(\mathbf{0}) - \boldsymbol{\beta} * \boldsymbol{d}$$

where

$V(0)$: amplitude at distance = 0

d: distance from metal

2) Attenuation due to the angle of view:

$$\boldsymbol{V}(\boldsymbol{d}) = \boldsymbol{V}(\mathbf{0})\frac{\tan^{-1}\frac{\frac{\boldsymbol{l}}{\mathbf{2}} * \sqrt{\mathbf{2}}}{\frac{\boldsymbol{l}}{\mathbf{2}} * \sqrt{\mathbf{2}} + \boldsymbol{d}}}{\tan^{-1}\frac{\frac{\boldsymbol{l}}{\mathbf{2}} * \sqrt{\mathbf{2}}}{\frac{\boldsymbol{l}}{\mathbf{2}} * \sqrt{\mathbf{2}}}}$$

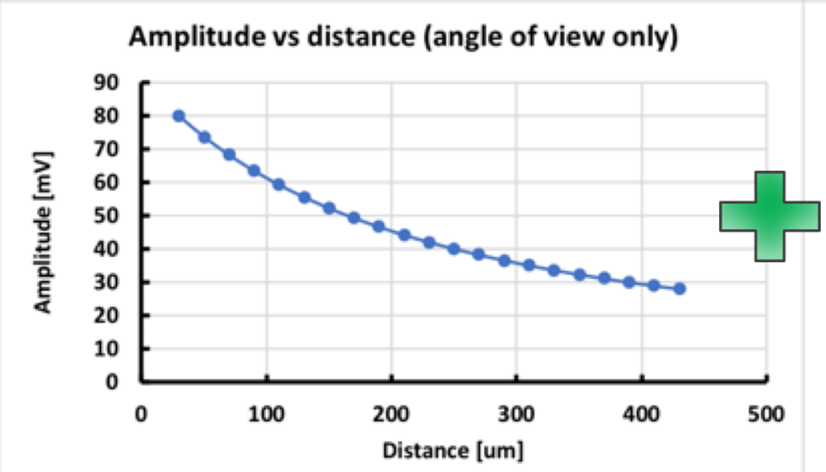
Model of signal attenuation

Using the equations in the previous page, we can make a model of the combination of the two type of attenuations

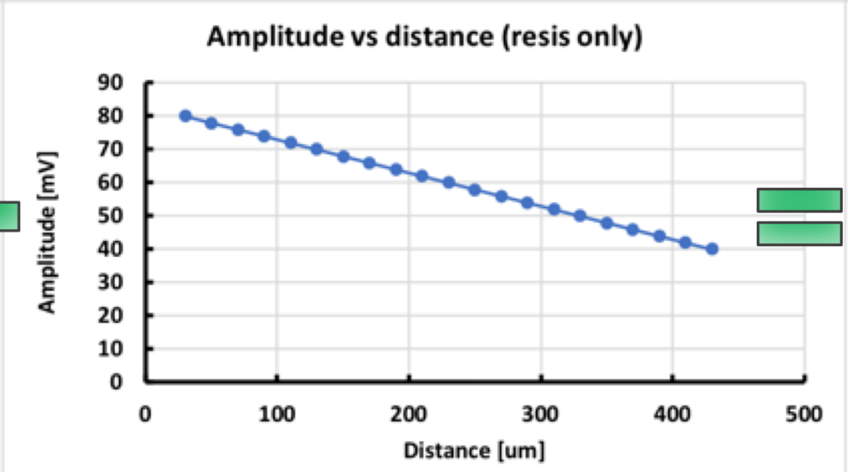
Effect of decreasing angle

Effect of increasing distance

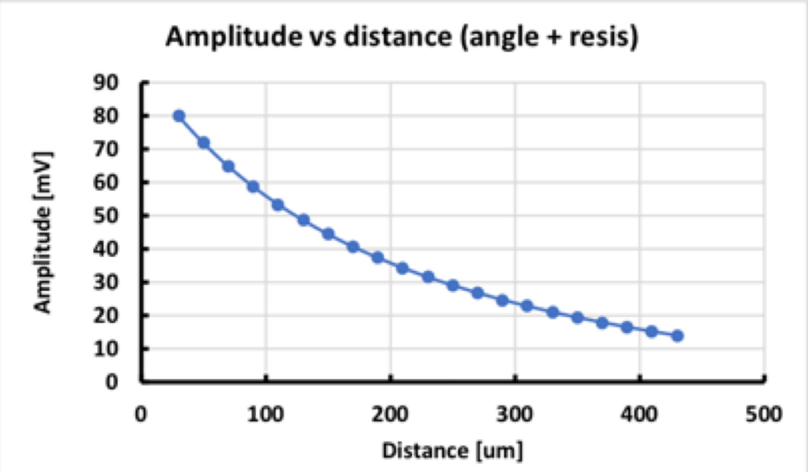
Combined effects of decreasing angle and increasing distance


Amplitude vs distance (angle of view only)

+


Amplitude vs distance (resis only)

=


Amplitude vs distance (angle + resis)

Fitting the data

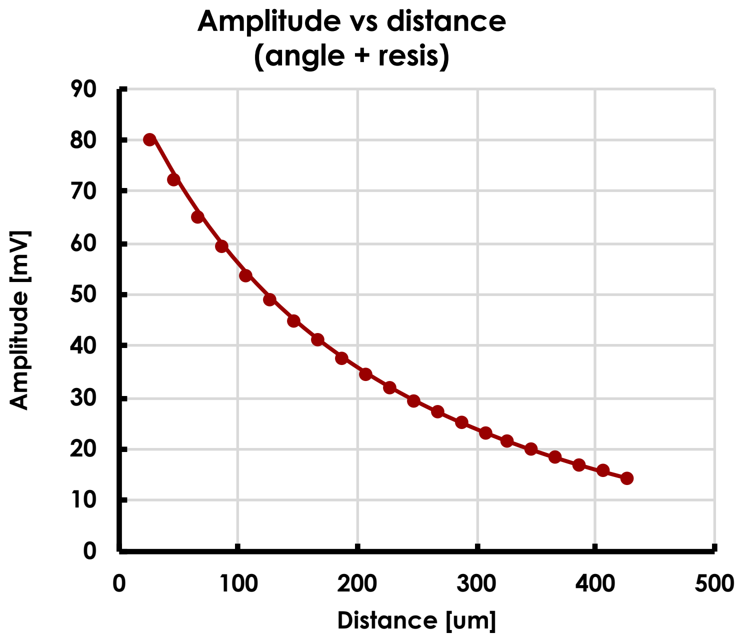
x = distance

[0] = amplitude

[1] = **resistive attenuation with distance**

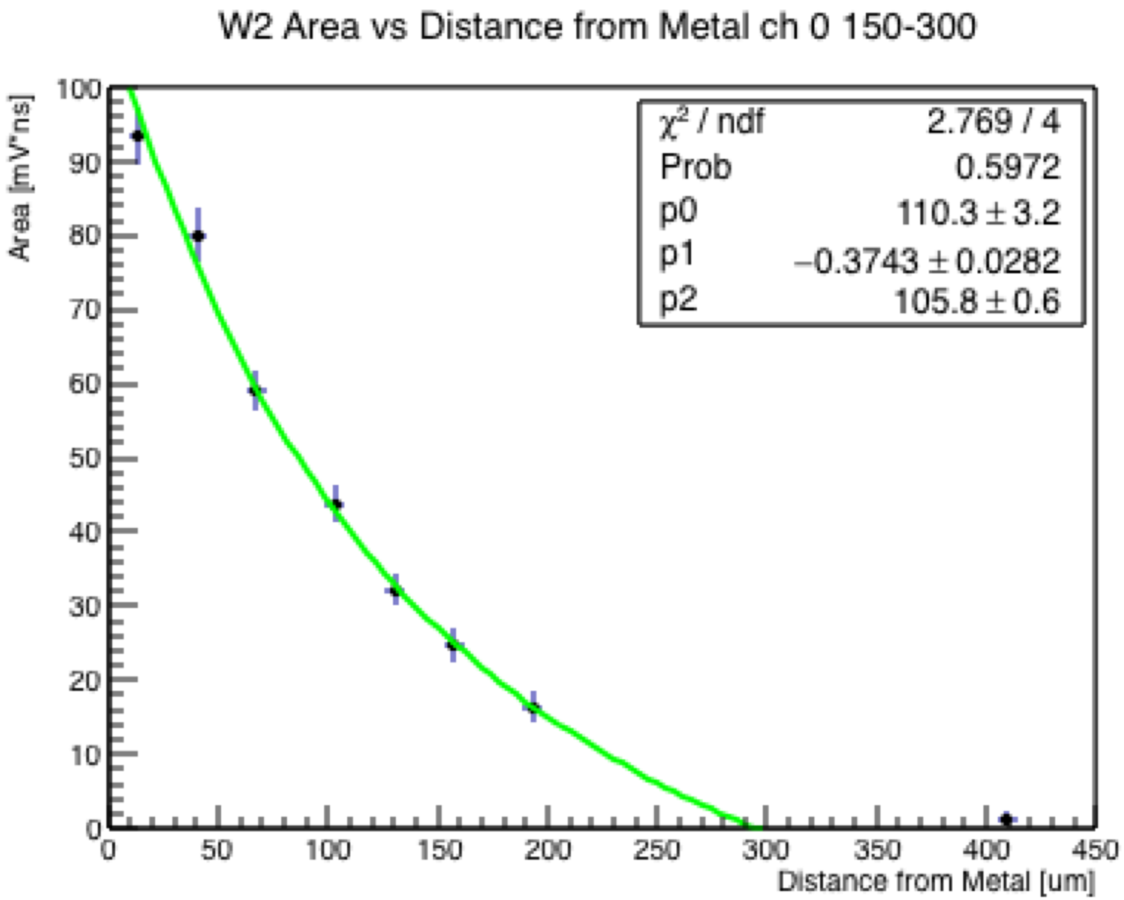
[2] dimension of the pad, fixed to l/sqrt(2)

$$\underbrace{([0]+[1]*x)}_{\text{resistive}}*\underbrace{(atan2([2],[2]+x)/atan2([2],[2])}_{\text{angle}}$$



DATA →

Model ←

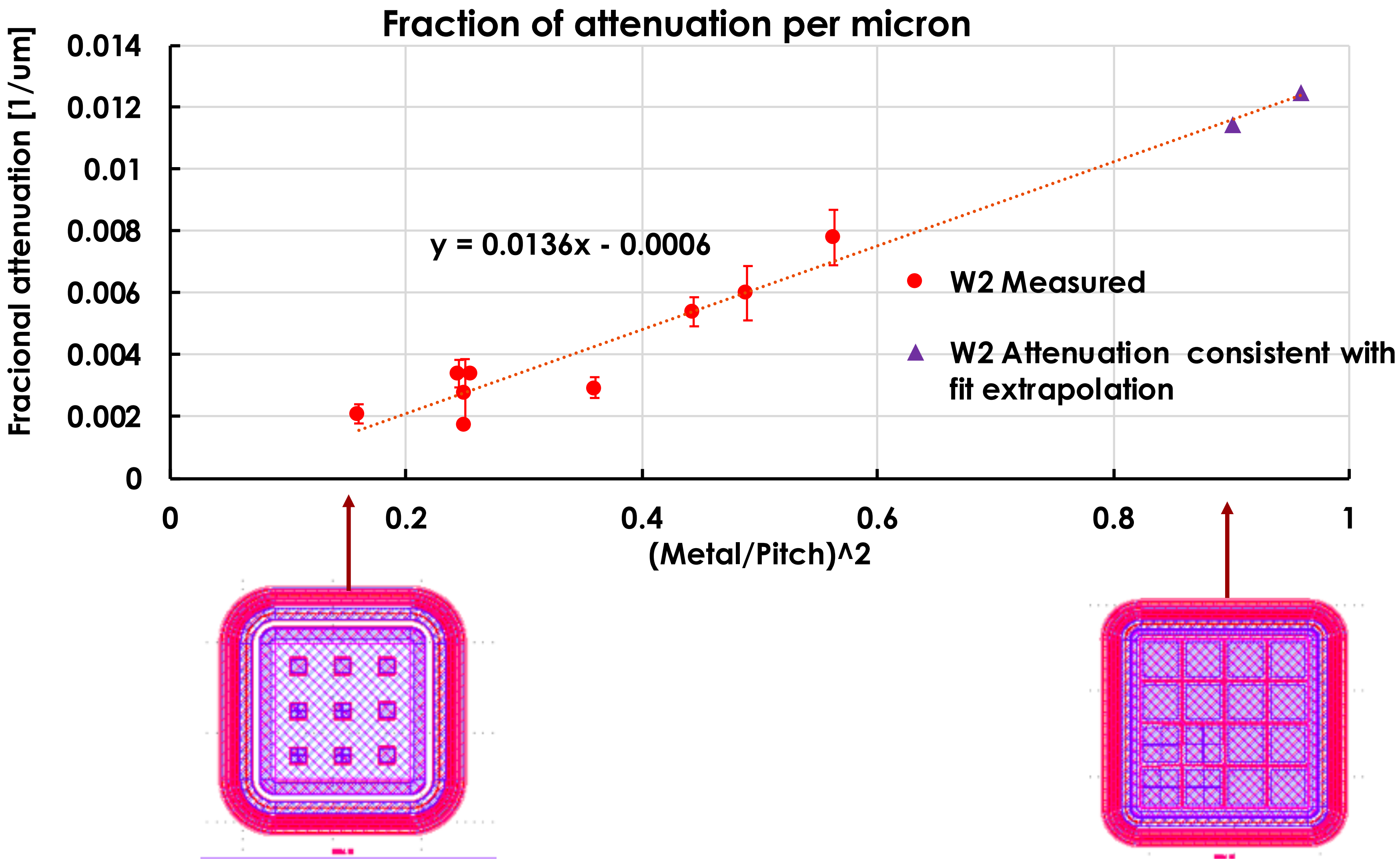


Now we have a analytic model of signal attenuation

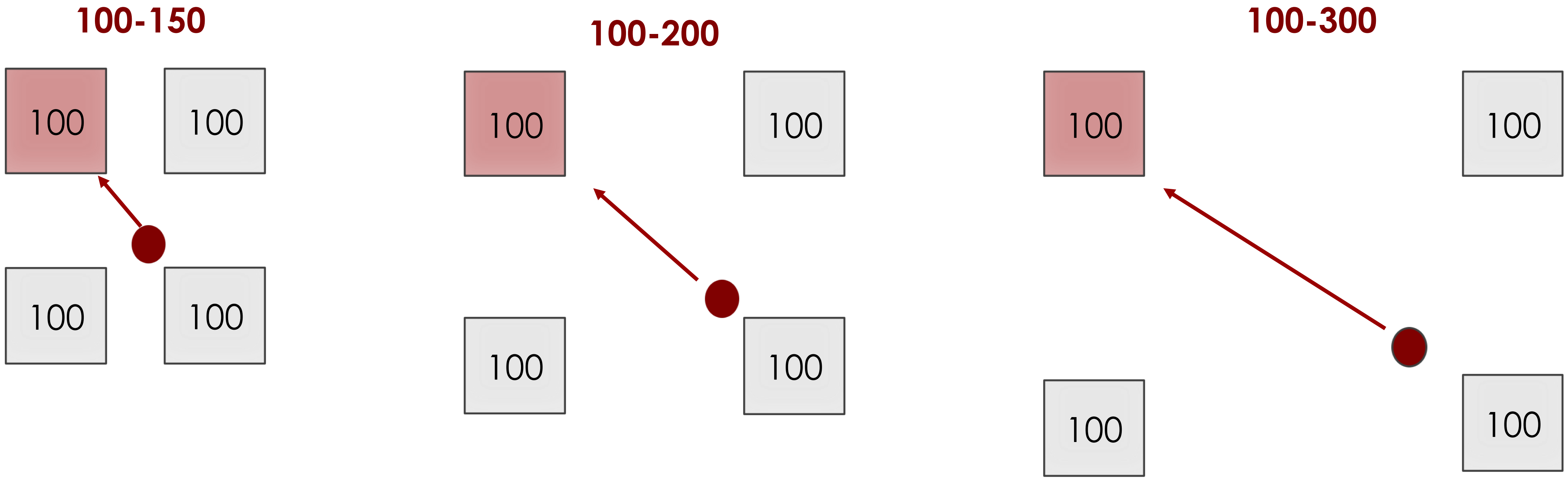
The only unknown is [1], the attenuation with distance

Effect of geometry on attenuation

The attenuation factor was measured for many geometries. **It is dominated by the coupling capacitance: attenuation is higher for sensors where the metal pads cover a large fraction of the area**

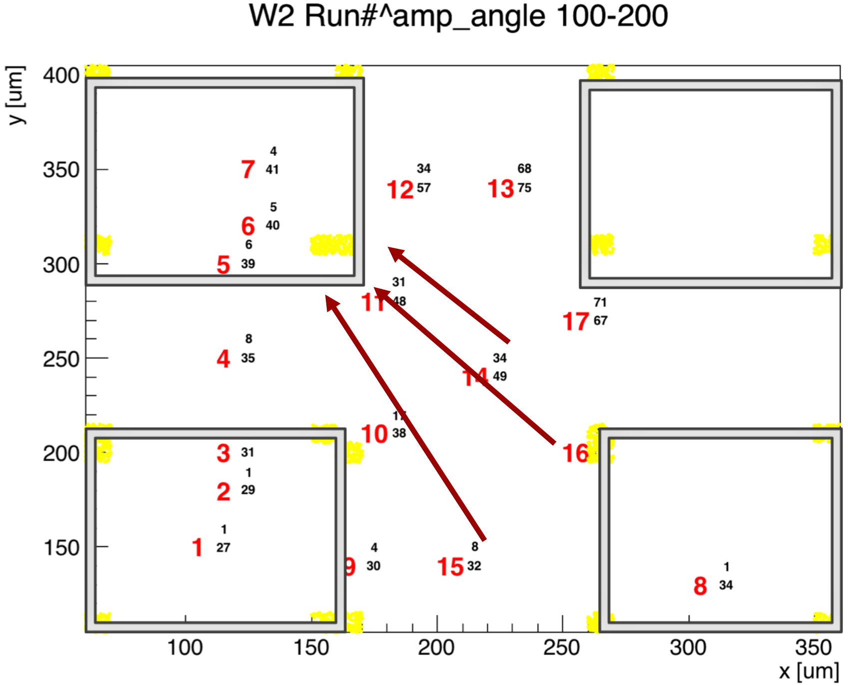


Signal delay

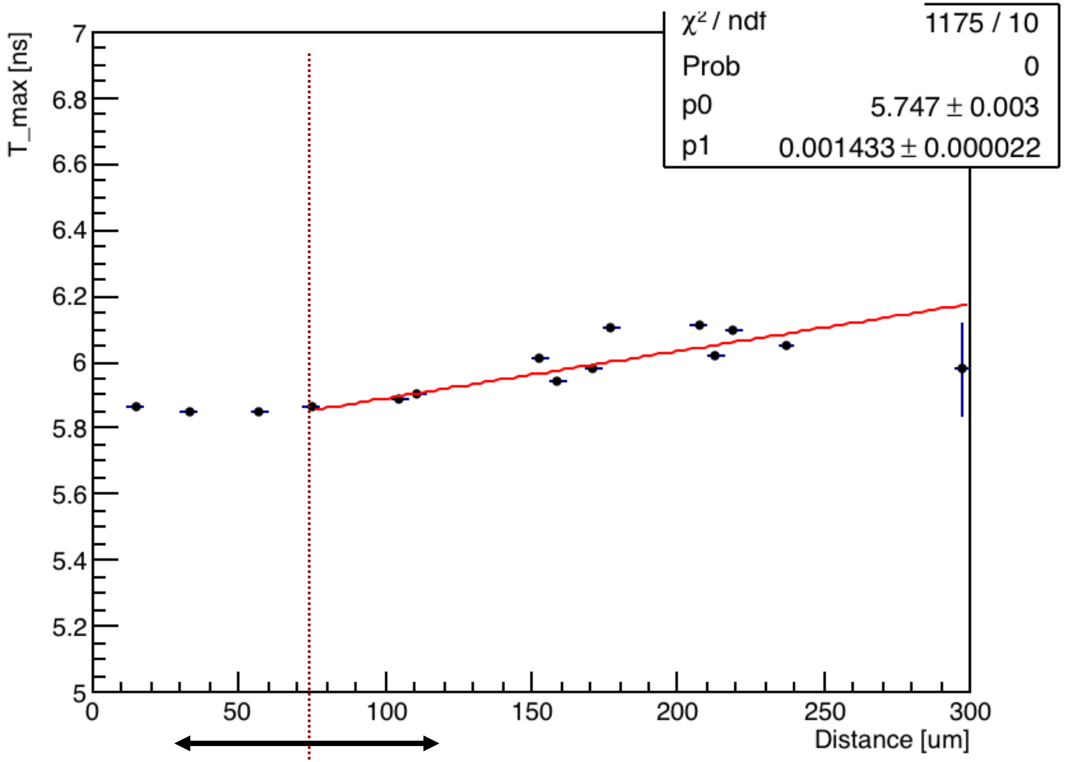


What is the signal delay as a function of distance?

Laser study: signal delay



Signal delay as a function of distance from the pad center



Propagation in metal:
no delay

Propagation in n++"
delay

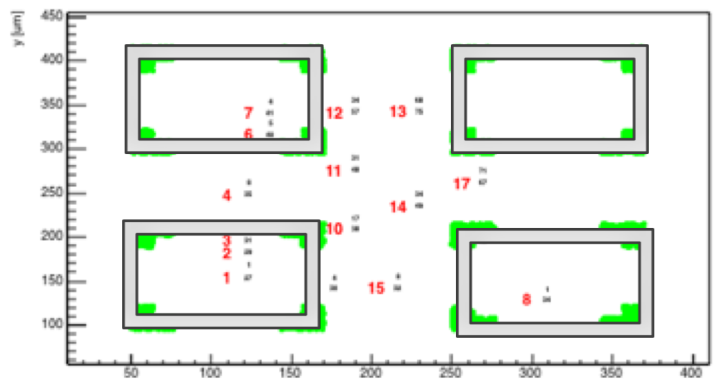
The signal is delayed when it propagates in the n++ and not when it does in the metal

Laser study: total charge vs position

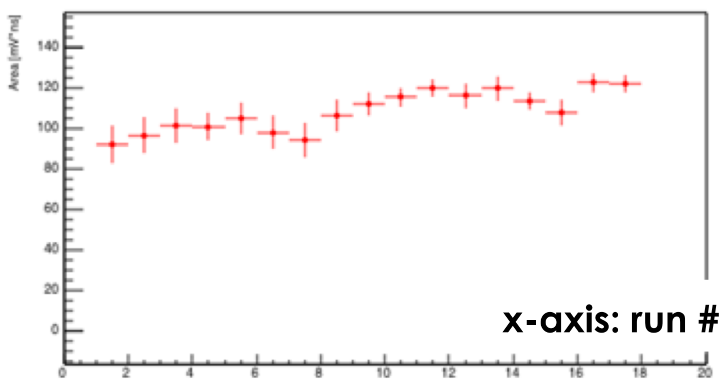
For all geometries, **the sum of the signals on the 4 pads is almost constant**, weakly dependent on the hit position

$$A_{tot} = \sum_{1}^{n} A[i] = const$$

W2 Run#^amp_angle 100-200

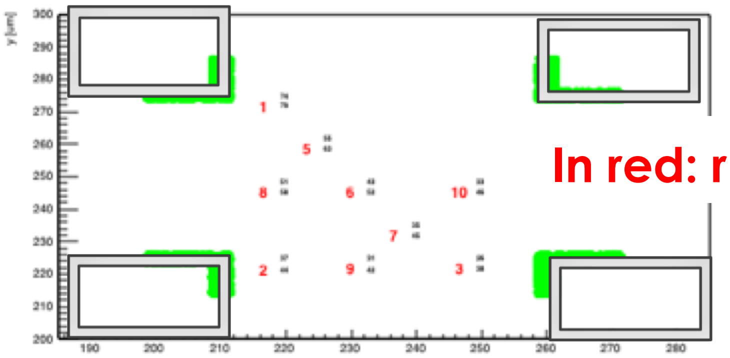


W2 Sum of all Angles (blue) and areas (red). vs run # 100-200



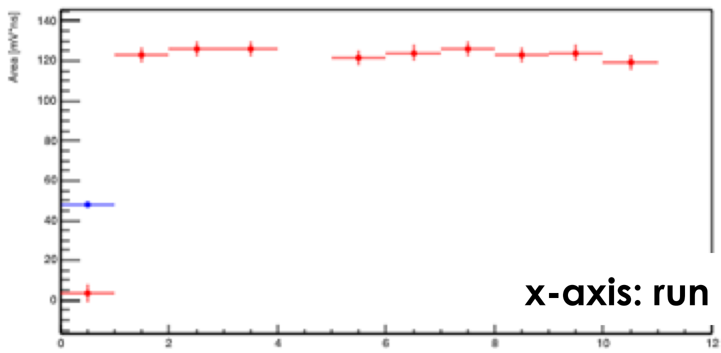
x-axis: run #

W2 Run#^amp_angle 50-100



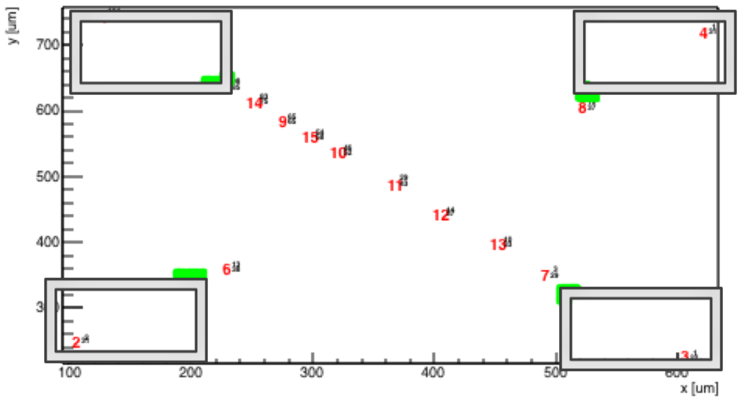
In red: run #

W2 Sum of all Angles (blue) and areas (red). vs run # 50-100

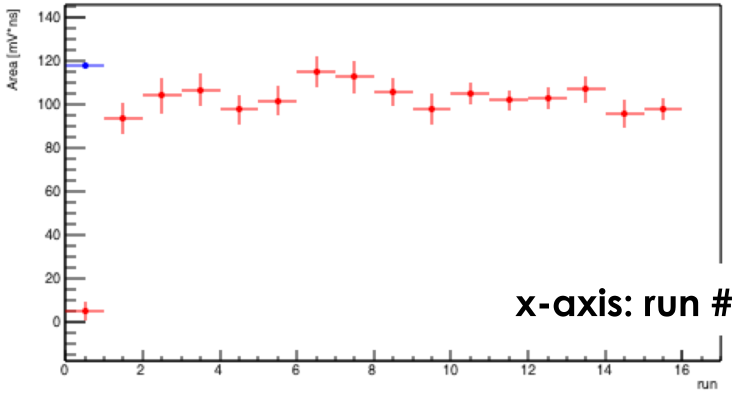


x-axis: run #

W2 Run#^amp_angle 200-500



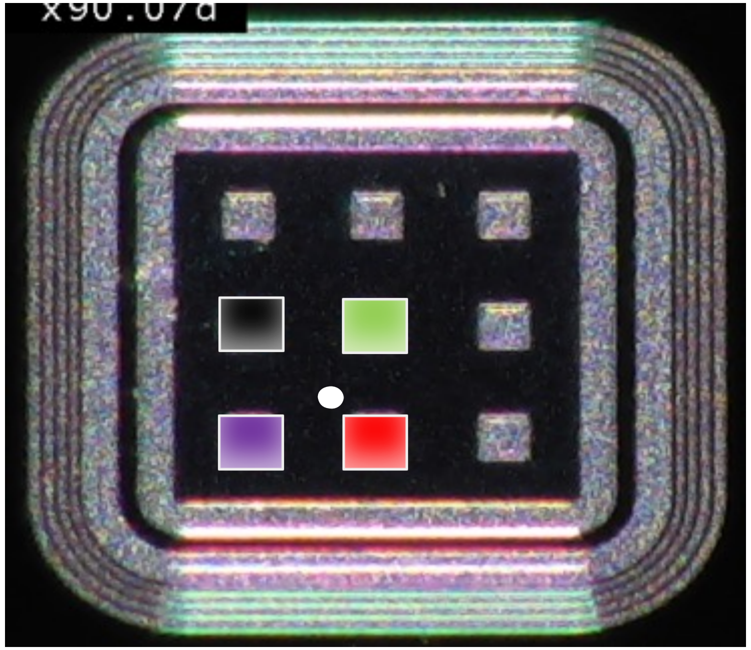
W2 Sum of all Angles (blue) and areas (red). vs run # 200-500



x-axis: run #

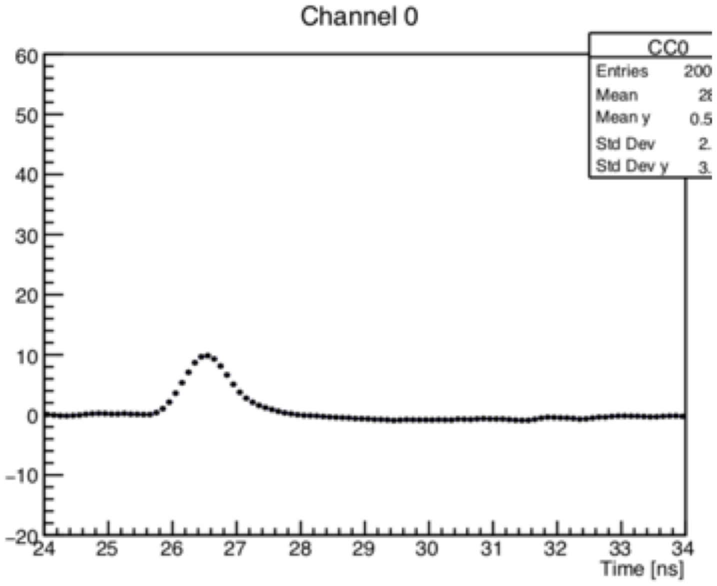
Position reconstruction method - I

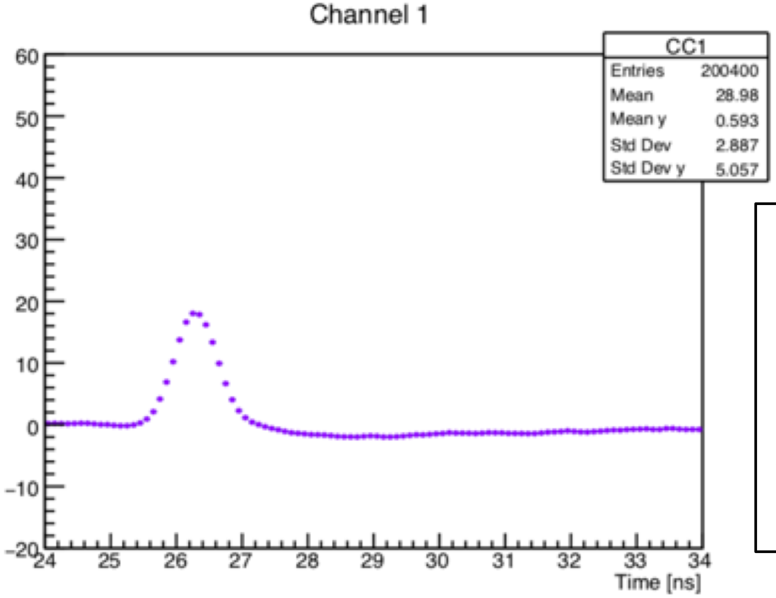
Each hit position is characterized by a specific set of amplitudes in the pads

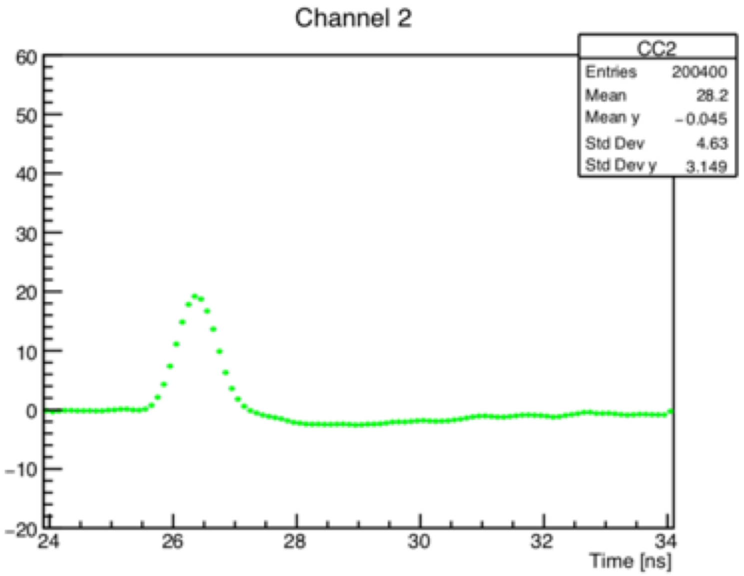


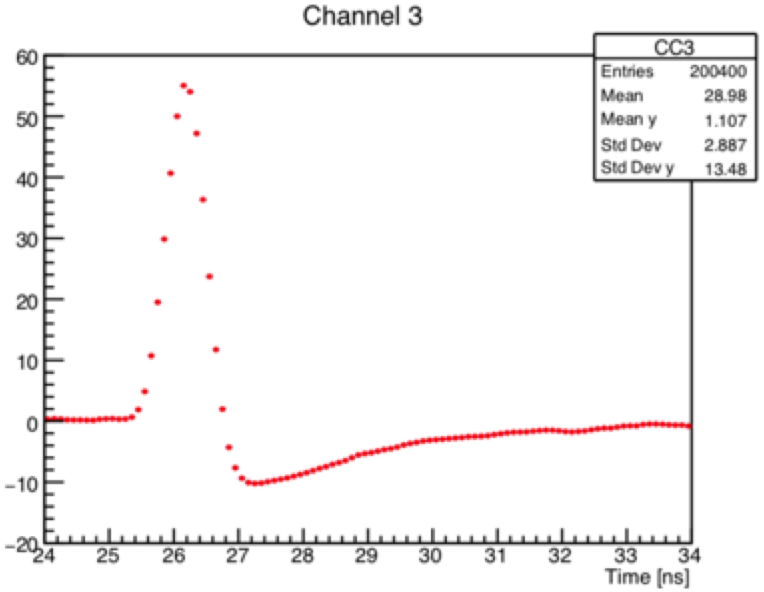
It is possible to associate to each x-y point the relative importance of the signal in each pad: **A[0]/Atot, A[1]/Atot, A[2]/Atot,A[3]/Atot,**

In this case (0.09, 0.18, 0.18, 0.55)

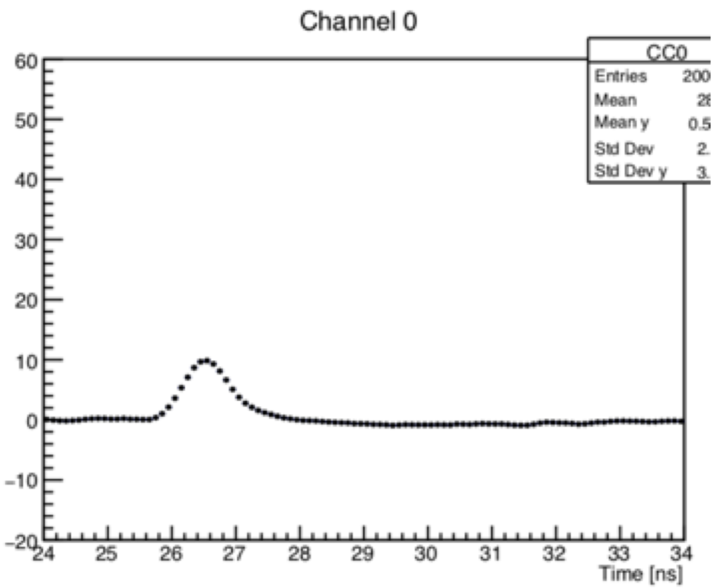

Channel 0

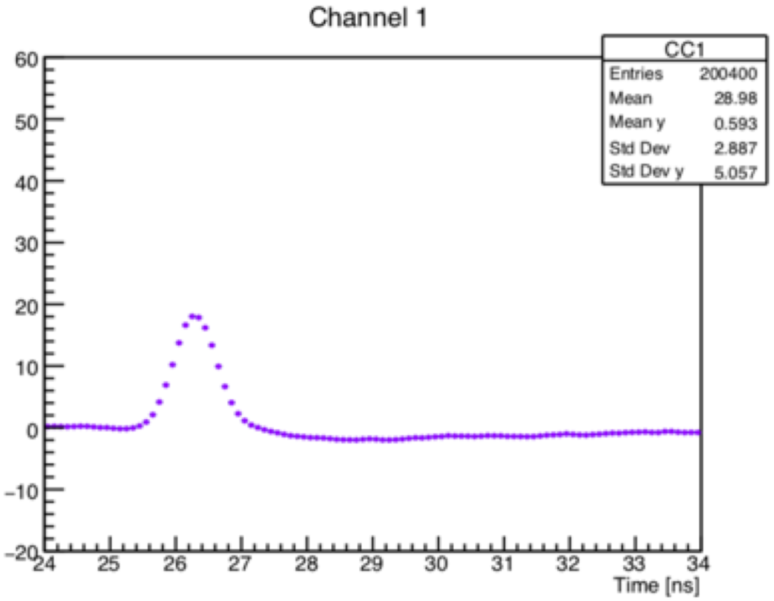

Channel 1

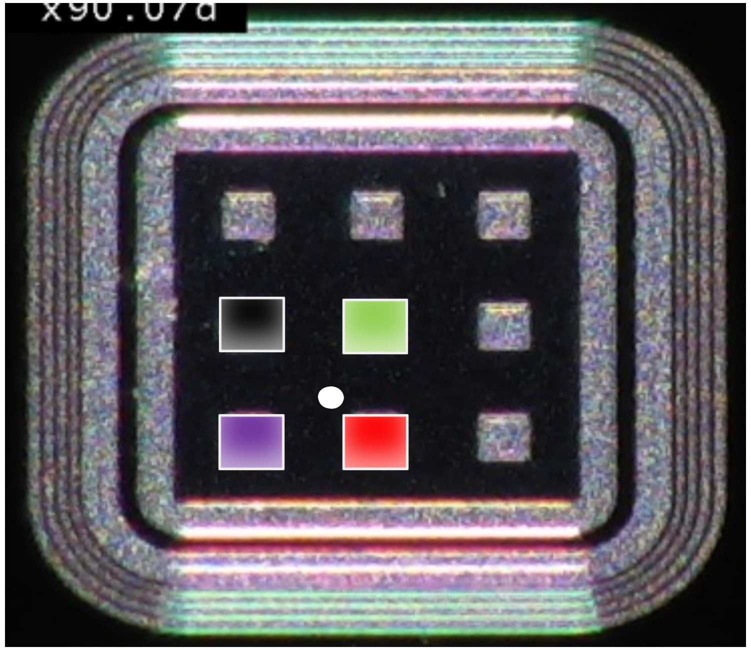

Channel 2

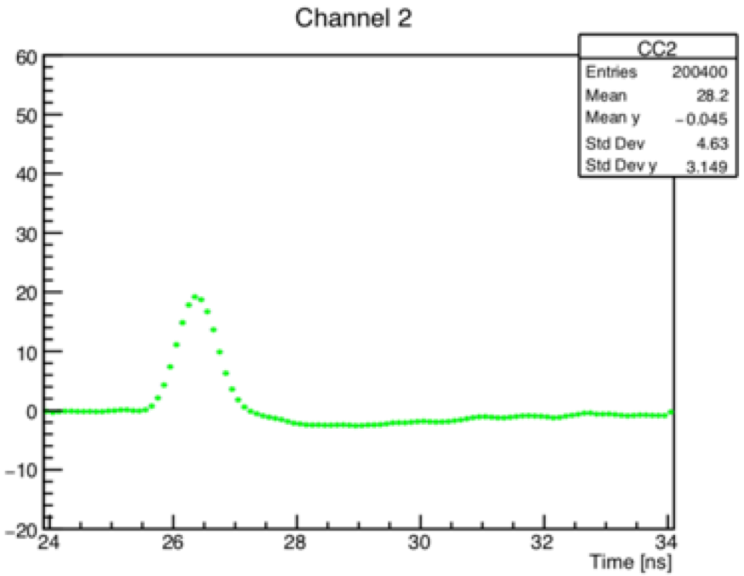

Channel 3

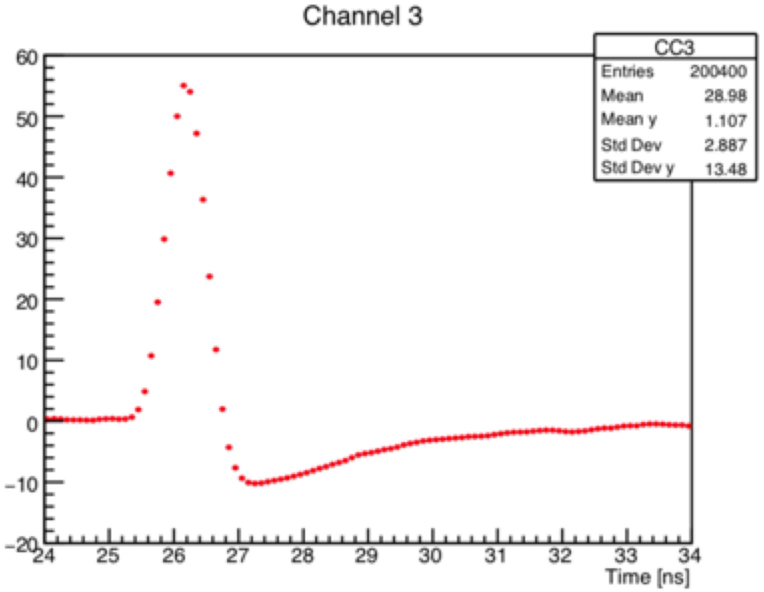
Position reconstruction method - I









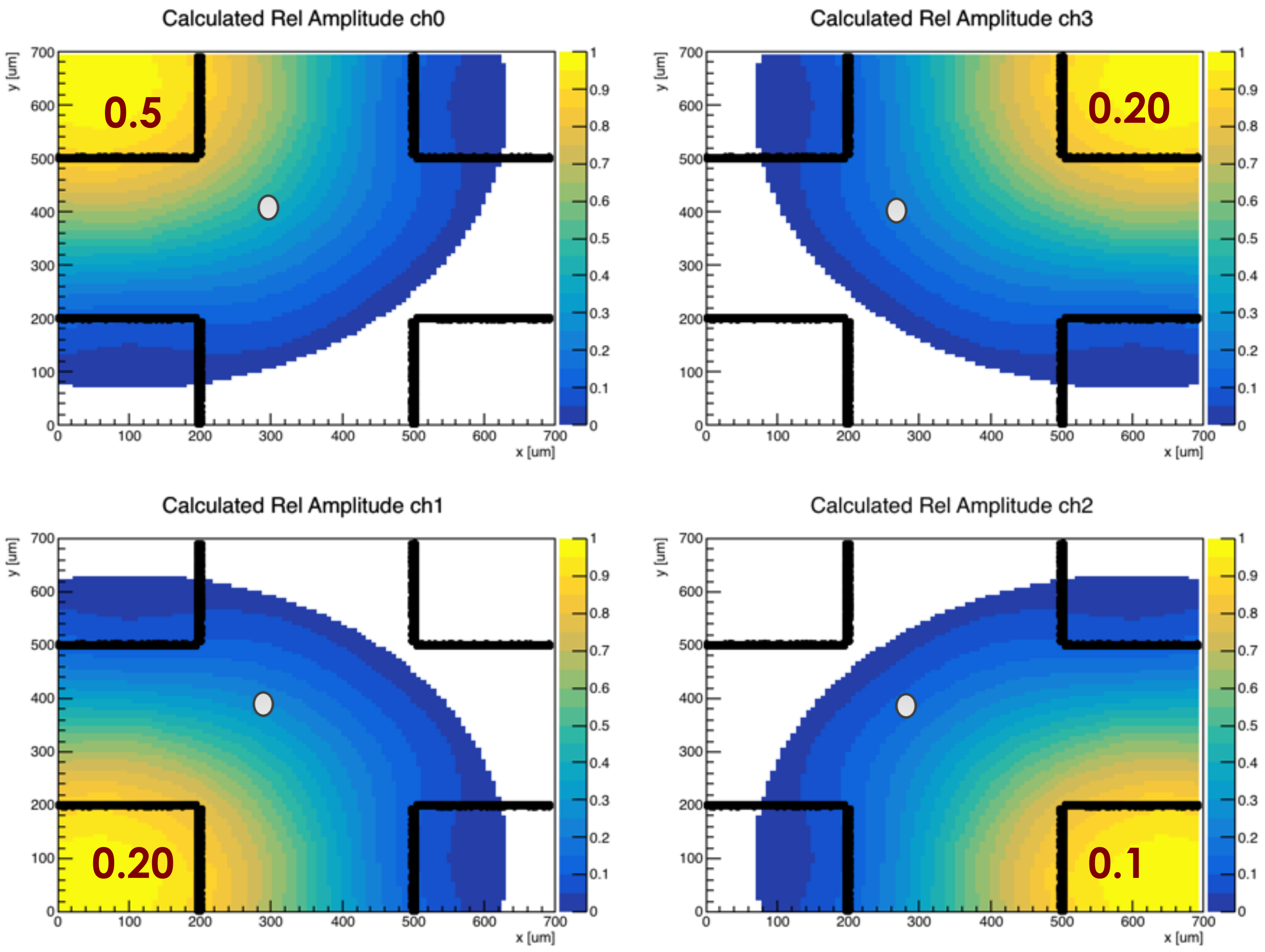


Position reconstruction method - II

Using the attenuation model, the fraction of the total amplitude seen in each pad for every x-y point can be calculated

In this example, 4 values: (0.5,0.2,0.1,0.2) are associated to the x-y point

The analytic model allows computing a look-up table containing for each x-y point the relative signal amplitude of every pad.



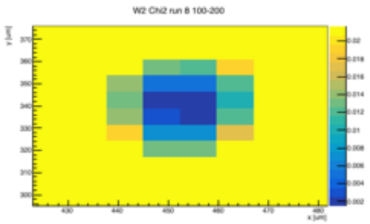
Position reconstruction method: the recipe

Recipe:

- For each hit, calculate the total amplitude summing all pads: $A_{tot} = \sum A[i]$
- Calculate the relative amplitudes $\left(\frac{A[i]}{A_{tot}}\right)_{Meas}$ seen in each pad.
- Use the look-up table to find which x-y bin minimize the quantity:

$$\chi^2 = \sum_{1}^{4} \left[\left(\frac{A[i]}{A_{tot}}\right)_{Meas} - \left(\frac{A[i]}{A_{tot}}\right)_{Calc} \right]^2$$

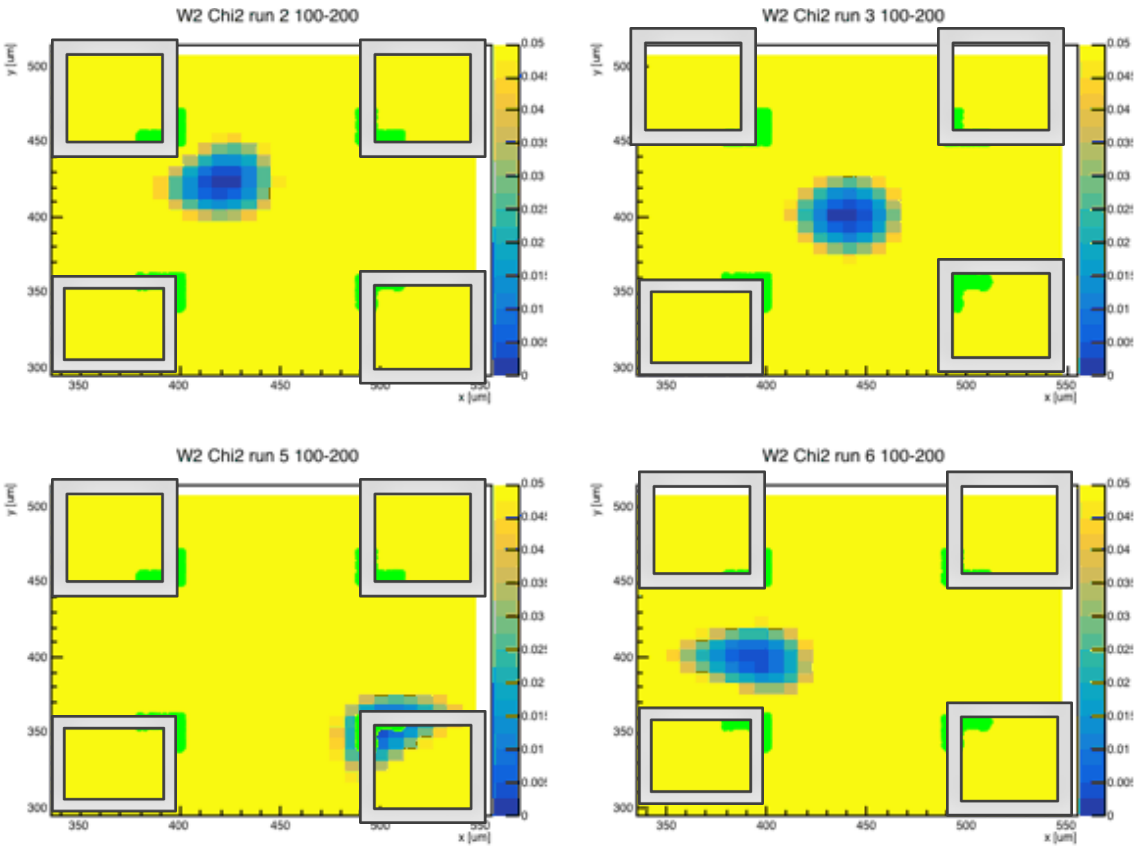
- Perform a local interpolation around the minimum.



χ^2 values for 4 different laser shots

(sensor geometry:100-metal 200-pitch)

The reconstructed position is the bin with the minimum χ^2 value



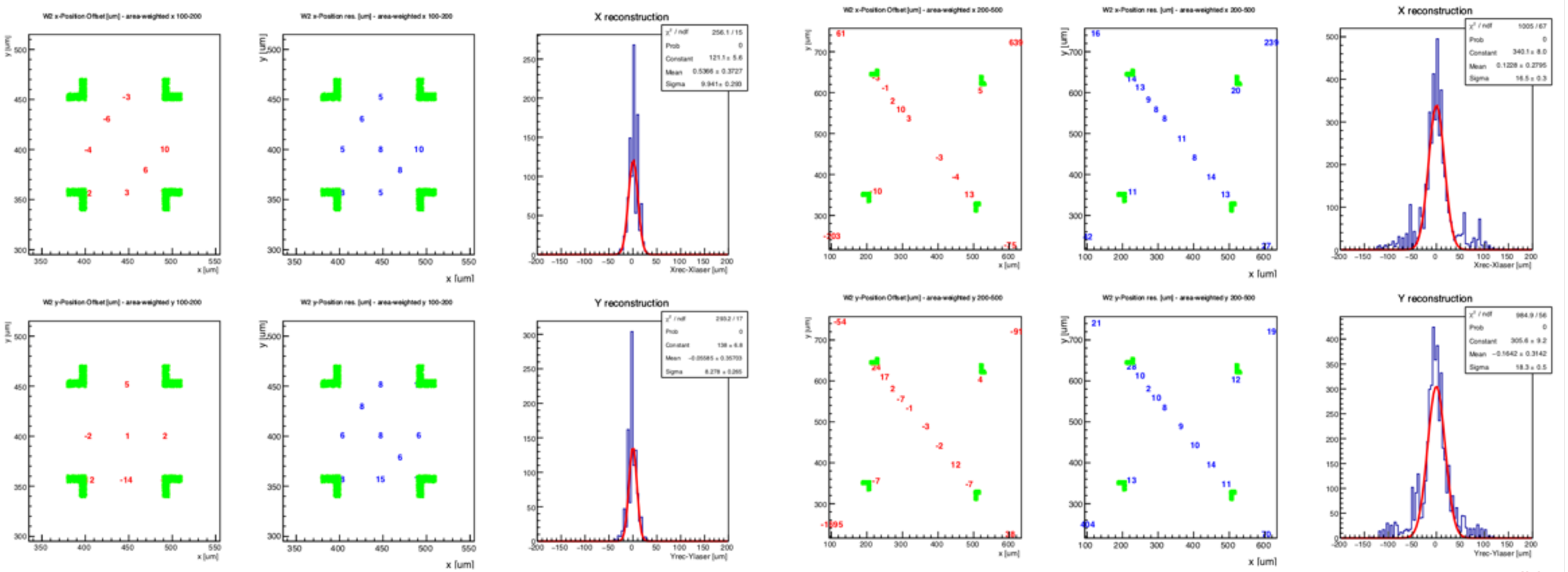
Laser study: position resolution

Shooting the laser in many positions, the **"single point precision"** and the **"overall precision"** can be evaluated.

This is done by comparing the position reconstructed using the look-up table to the known laser position.

Two examples:

Geometry:	**100 Metal, 200 pitch**	**200 Metal, 500 pitch**
Single point precision:	6 micron	10 micron
Global precision:	10 micron	18 micron

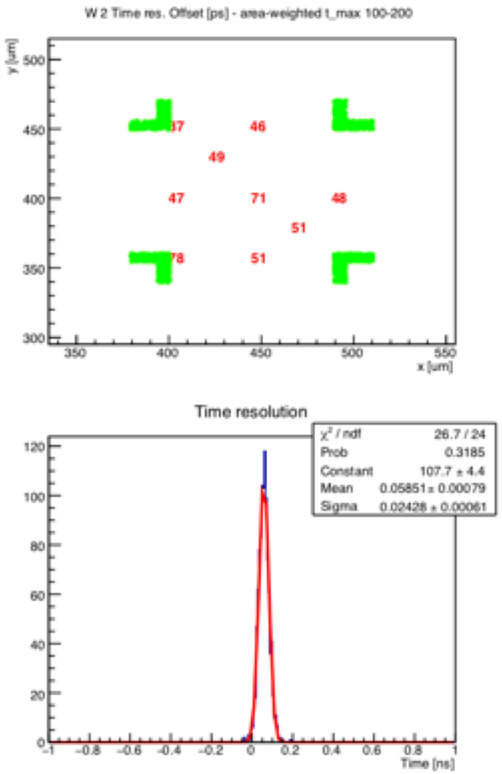


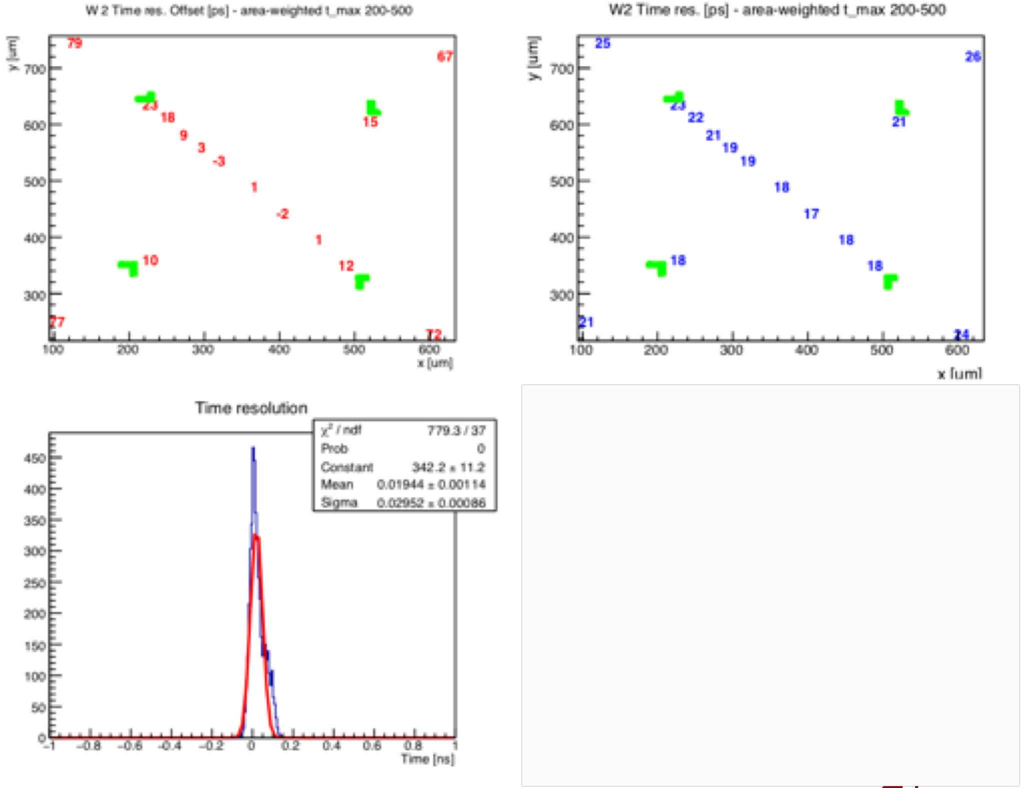
Laser study: time resolution

An estimate of the RSD time resolution is obtained in the following way:

1) Determine the hit position using the look-up table
2) Correct for the propagation delay between the hit position and each pad
3) Compute the amplitude weighted time centroid (assume no jitter on the laser shot)

Geometry:	**100 Metal, 200 pitch**	**200 Metal, 500 pitch**
Single point precision:	20 ps	20 ps
Global precision:	24 ps	30 ps





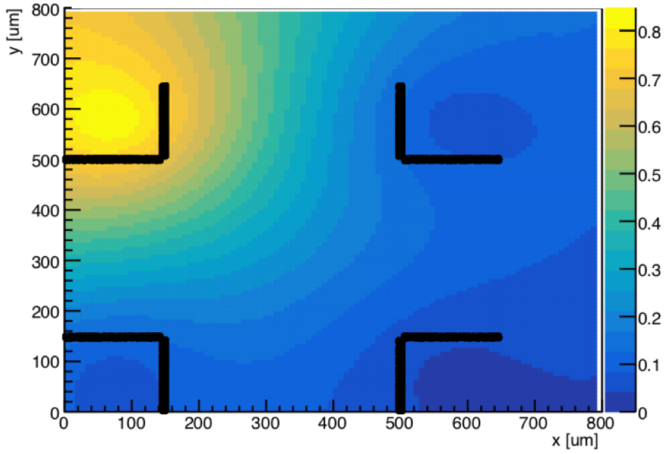
N. Cartiglia, INFN Torino, TREDI, Wien, 18/02/2020

Design optimization

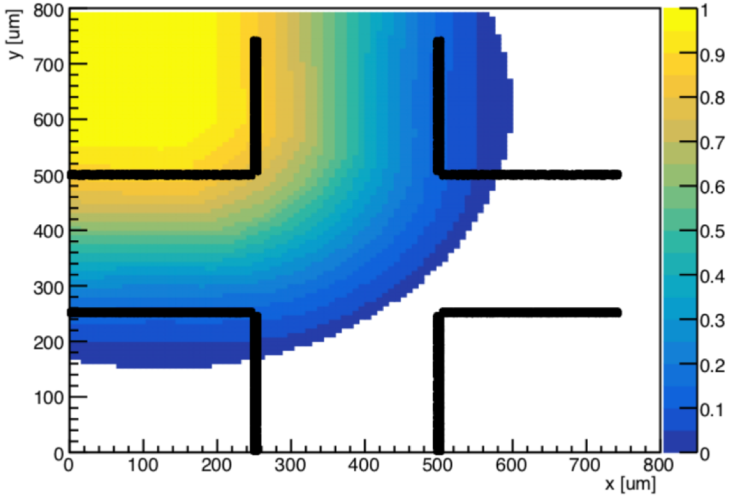
Position and time resolutions are optimized when several pads see a signal

Let's examine signal sharing in 3 designs with equal pitch (500 micron)

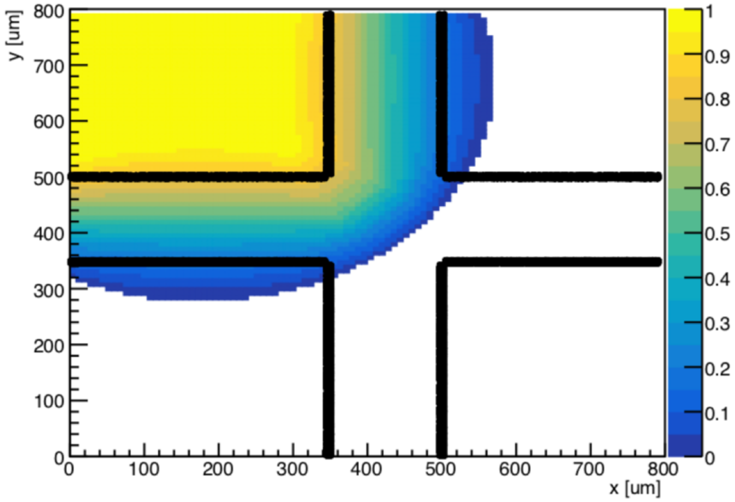
150 metal – 500 pitch



250 metal – 500 pitch



350 metal – 500 pitch



For small metal pads, the signal is shared among many pads, however the amplitude seen by each pad is small

For large metal pads, the signal is very attenuated and sharing is limited.

Best performance is obtained when at least 4 pads see an amplitude well above the noise level.

Conclusions

- AC-LGADs (RSD) are silicon sensors working on the principle of charge sharing
- Charge sharing is obtained using a delayline-like lossy system (and not drift lines)
- RSDs employ the LGAD mechanism for charge multiplication
- They have a uniform response, no dead area between pads. This design is well suited for very small pitch.

- Charge sharing allows reaching the same spatial precision of traditional silicon detector using a factor of 5-10 larger pitch (in bump-bonding design, this allows a lot of space for electronics):
  - ➔ $\sigma_{position} = 10\ \mu m$ for 200-micron pitch, $\sigma_{position} = 20\ \mu m$ for 500-micron pitch
- Time resolution, obtained using information from multiple pads, is at the level of (or better) traditional LGAD sensors: $\sigma_{time} = 25 - 30\ ps$
- Signal delay happens only in n++, not in metal: for best results use round and not square metal pads

➔ First ever polka dot detector

Next steps:

- More testing of other geometries, strips…
- Beam test
- Irradiated samples have been received last week, need to check the stability of the sensors' parameter

Acknowledgement

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- INFN - Gruppo V
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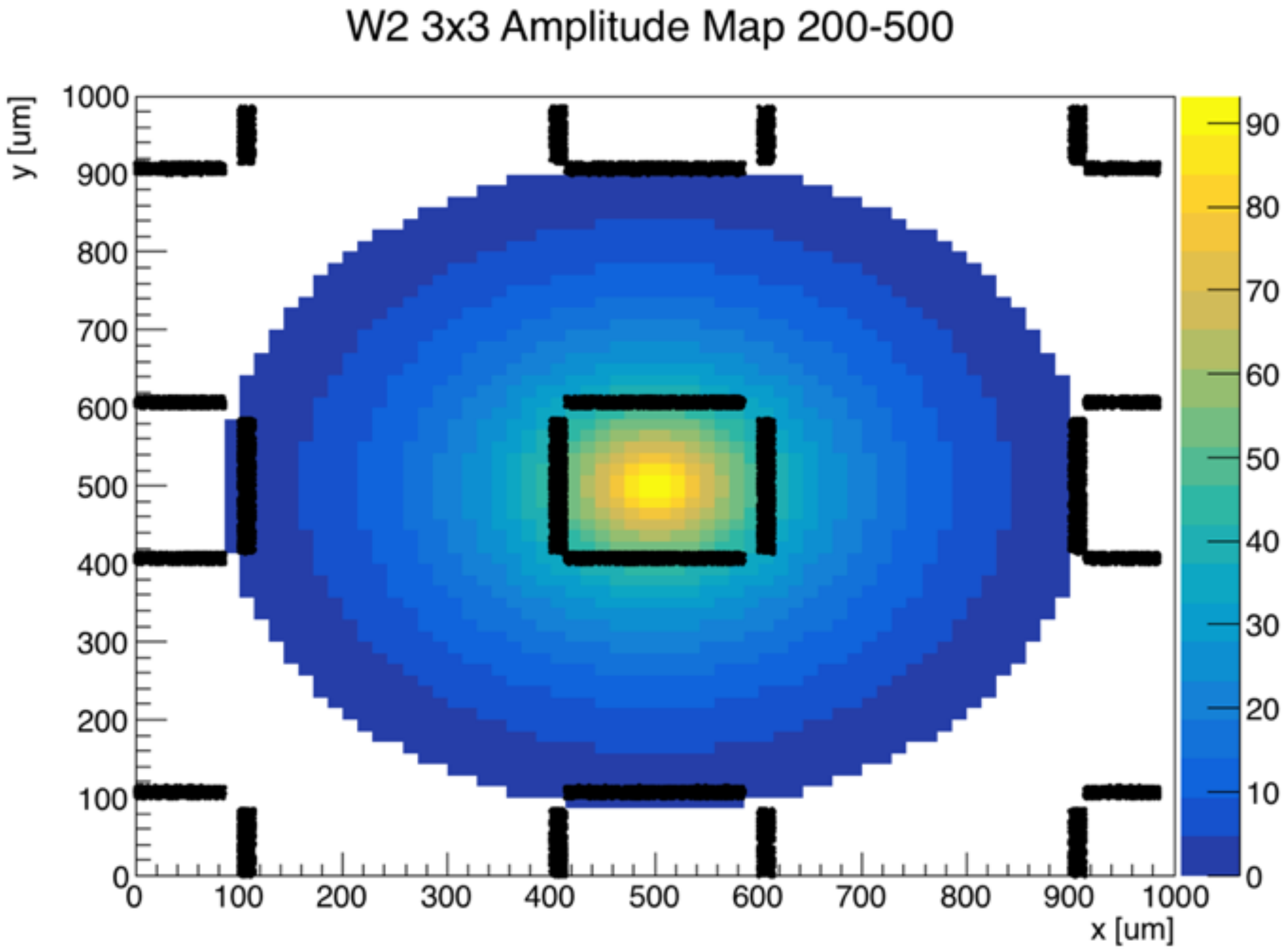
- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE,   R165xr8frt_fare

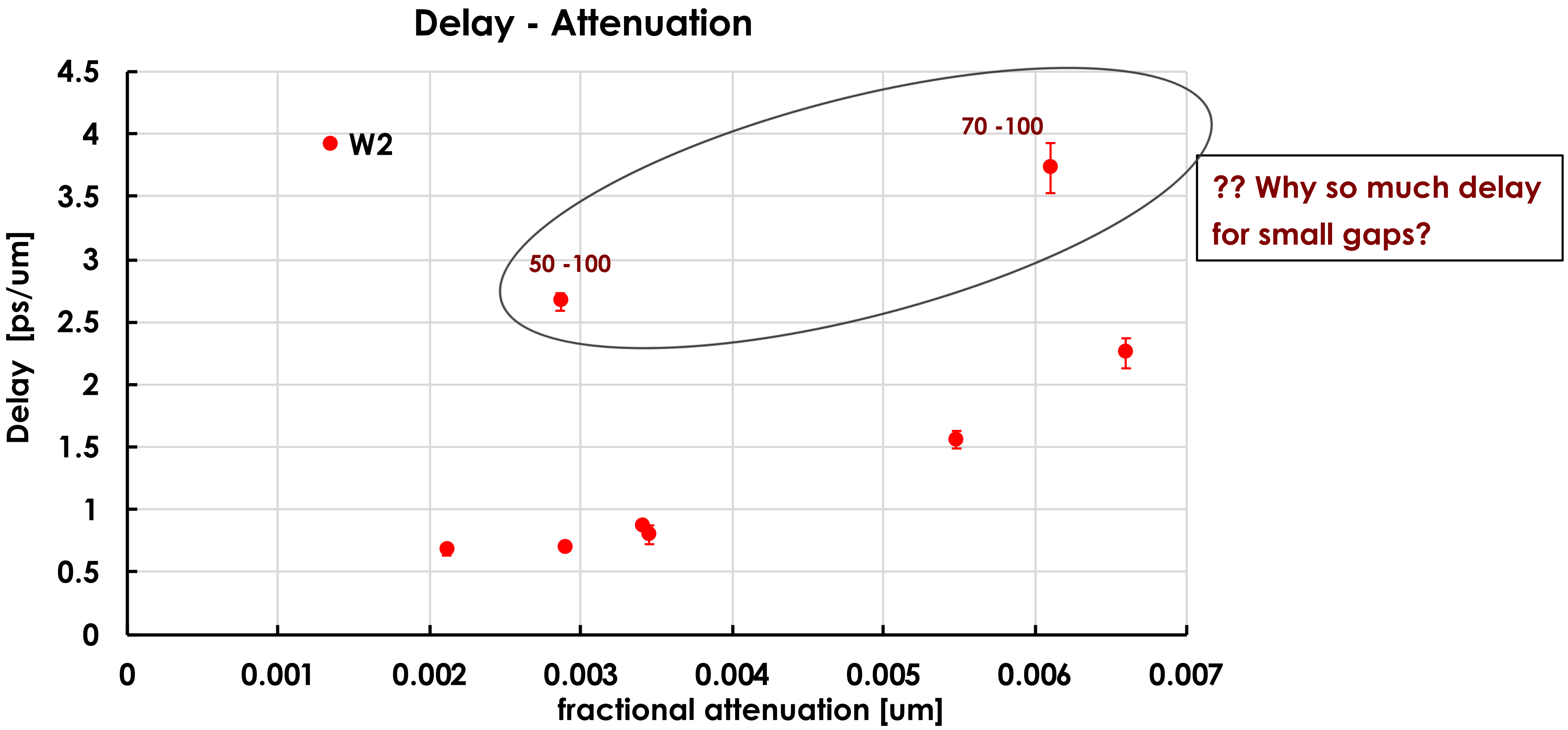
extra

Example of the analytic prediction of the signal attenuation

$$\boldsymbol{A\,(d) = (A(0) - \beta * d)\,\frac{\tan^{-1}\dfrac{\frac{l}{2} * \sqrt{2}}{\frac{l}{2} * \sqrt{2} + d}}{\tan^{-1}\dfrac{\frac{l}{2} * \sqrt{2}}{\frac{l}{2} * \sqrt{2}}}}$$



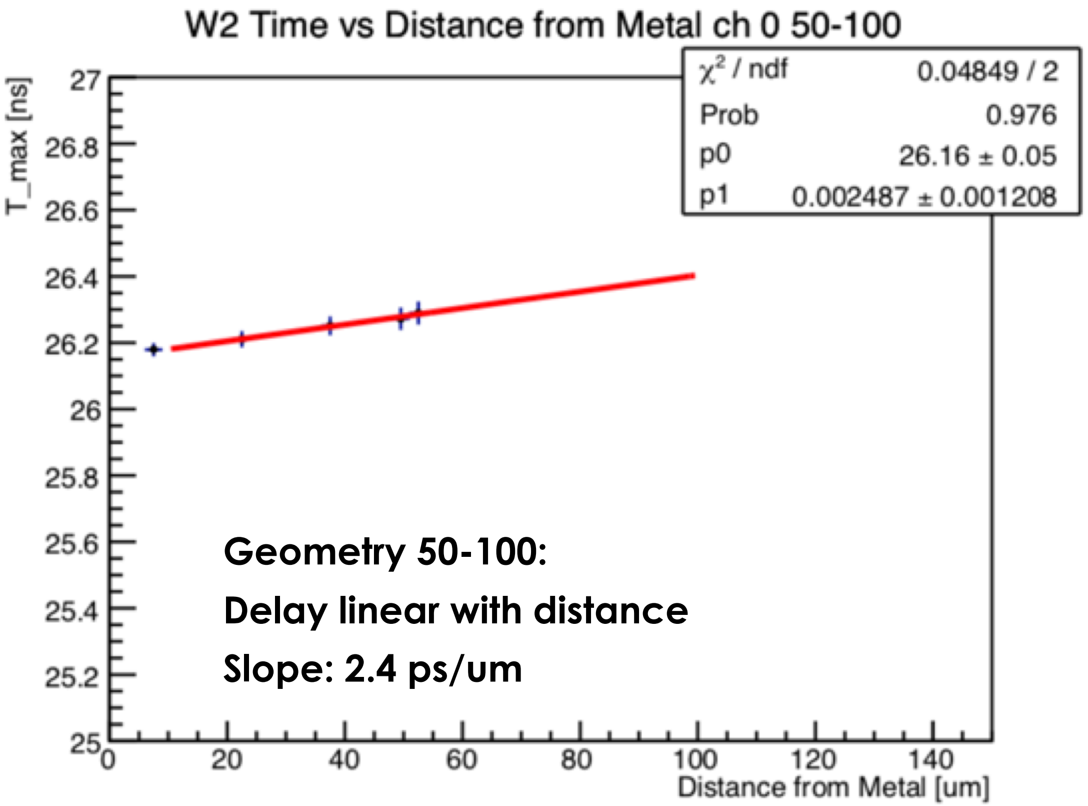
Attenuation vs delay



Delay and attenuation are connected in the dispersion relationship: higher attenuation is coupled to higher delay

➔ The two smallest geometries are somewhat different.

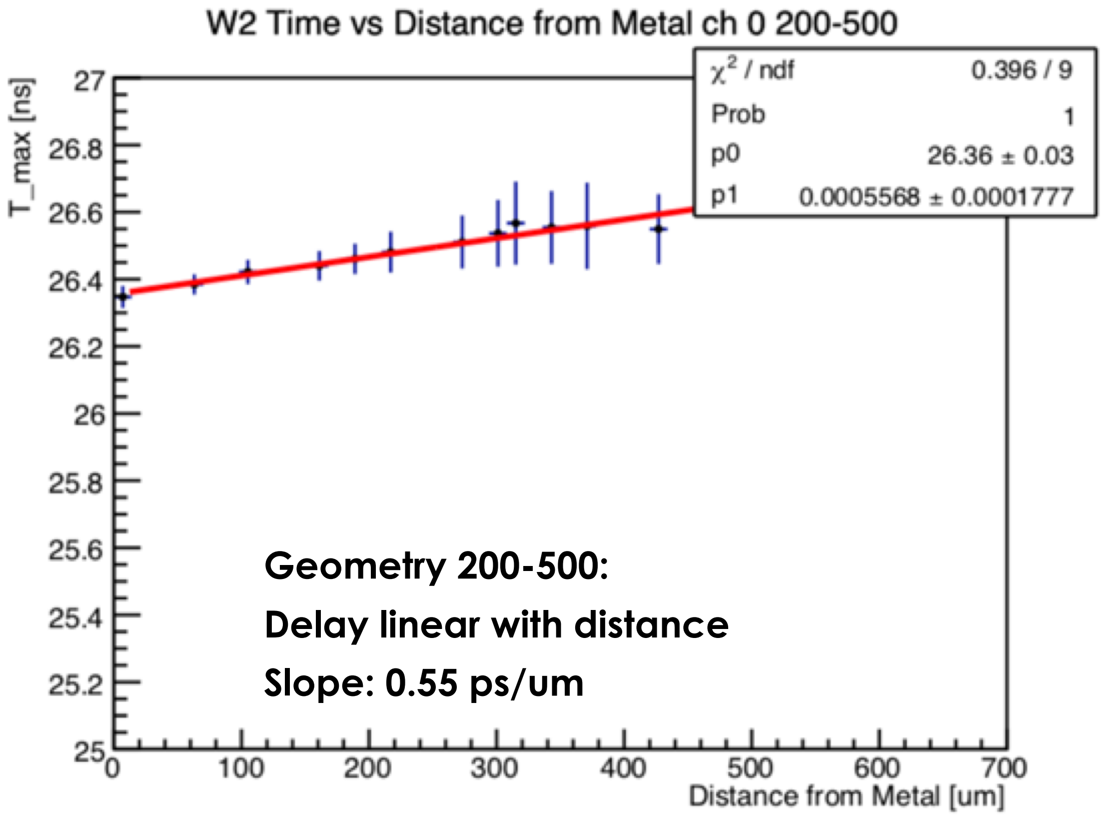
Laser study: signal delay



Geometry 50-100:

Delay linear with distance

Slope: 2.4 ps/um



Geometry 200-500:

Delay linear with distance

Slope: 0.55 ps/um

The delay slope is computed for every geometry