Innovative silicon sensors for future trackers

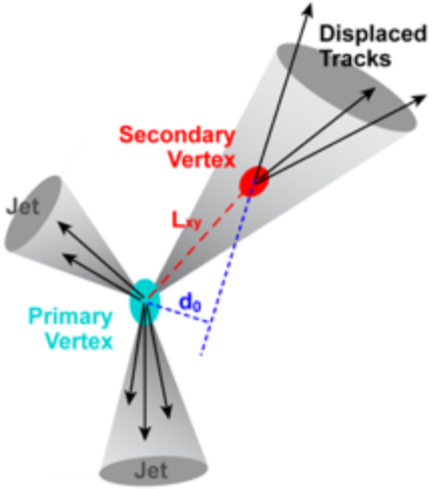
Part II: Principles of operation of RSD

- Single point precision and charge sharing
- Signal formation
- Charge sharing: RSD master formula
- Reconstruction method
- Results: laser, beam test, and application of machine learning
  - ➔ All results obtained using RSD1 from FBK
- Read-out electronics
- Future directions
- RSD timeline, publications, contributors
- Extra topics (not for the presentation)

N. Cartiglia
M. Mandurrino
INFN - Italy

Impact parameter resolution in silicon detector

The capability of distinguishing secondary vertexes is often expressed by the impact parameter resolution $\boldsymbol{\sigma_{d_0}}$



$$\sigma_{d0}^2 = \sigma_{Geom}^2 + \sigma_{MS}^2$$

The geometrical precision $\boldsymbol{\sigma_{Geom}}$ depends on the **single point precision $\boldsymbol{\sigma_i}$** and on the radial positions $\boldsymbol{r_i}$ of the silicon layers

- First layer as close as possible to the beam line
- Last layer as far as possible
- **Best possible $\boldsymbol{\sigma_i}$**

The average multiple scattering $\boldsymbol{\sigma_{MS}}$ depends on the position $\boldsymbol{r_i}$ and amount of material $\boldsymbol{X_0}$

- Low mass beam pipe
- Very thin detectors
- Place services far away

Let's concentrate on $\boldsymbol{\sigma_i}$

Single point resolution σ_i in silicon detector

The read-out of silicon detector can be:

- **Binary**, where the only information is hit/miss (0,1)
- **Analog**, where the amplitude of the signal is recorded

In **binary readout** the single point resolution is $\boldsymbol{\sigma_i = K\, x \frac{pitch}{\sqrt{12}}}$

K ~ 0.5 – 1 depends on the sensor thickness, magnetic field, angle.

$\boldsymbol{\sigma_i = \frac{pitch}{\sqrt{12}}}$, i.e. the standard deviation of a uniform random variable, is commonly used, albeit it is the worst case scenario.

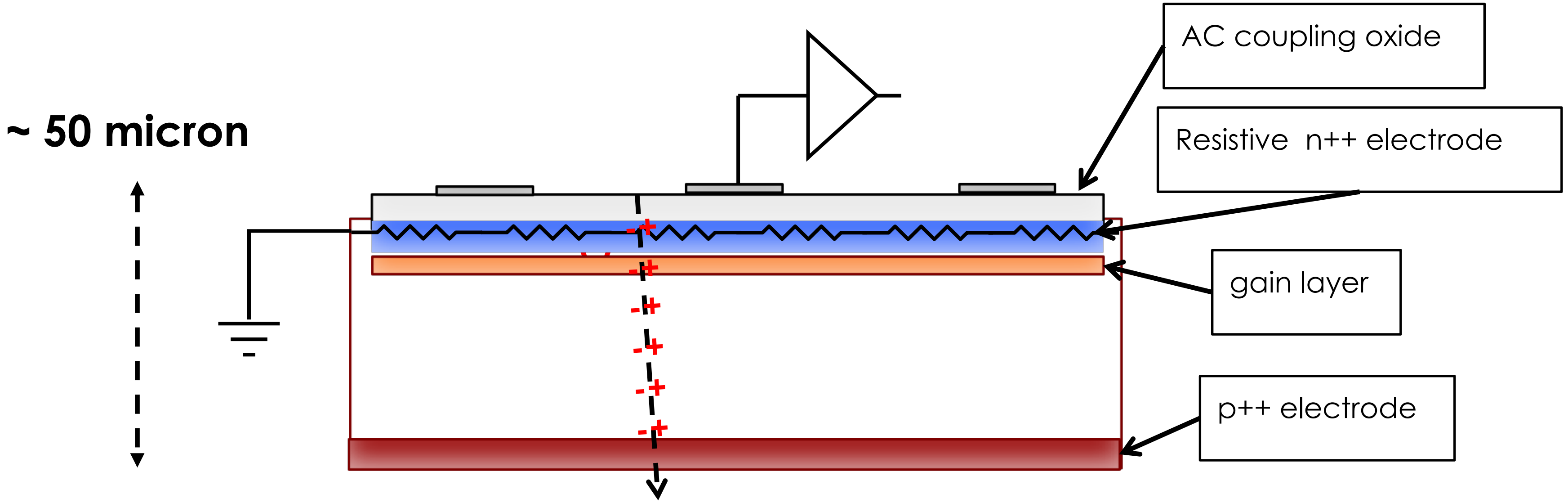
In **analog readout** the single point resolution $\boldsymbol{\sigma_i}$ is obtained by combining the signal amplitudes of 2 (3) channels

However, charge sharing does not come natural in silicon detectors

RSD Signal formation - I

Act 1: the e/h are drifting, producing direct charge induction in the n++ layer (Ramo theorem)

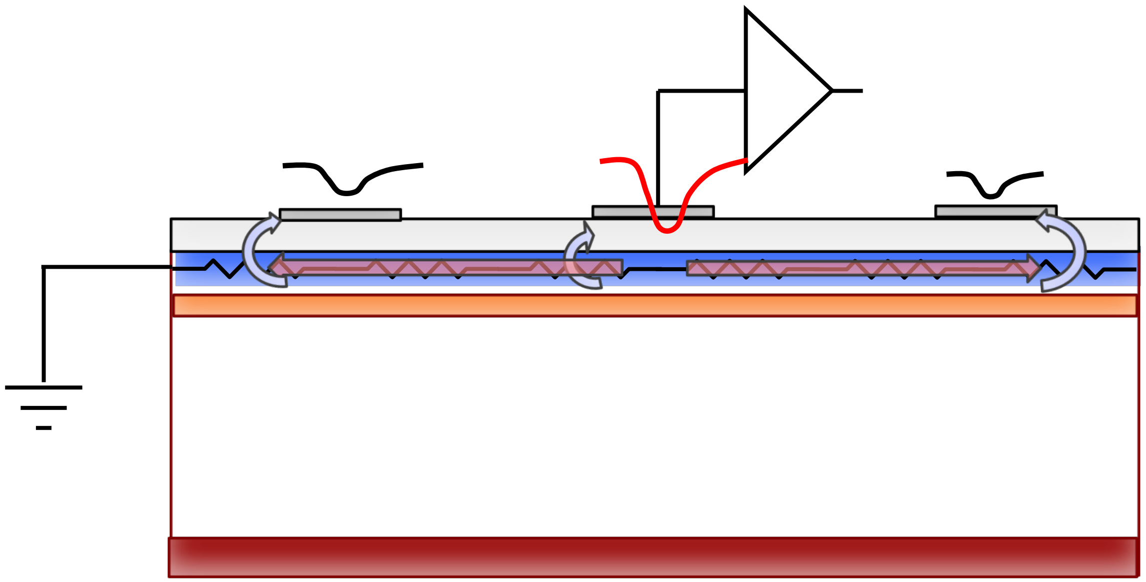
1. The signal is collected on the n++ electrode
2. Large signal (gain 10-20): 5 - 10 fC
3. Very fast collection (1 ns)
4. No lateral spread, very vertical E field and drift

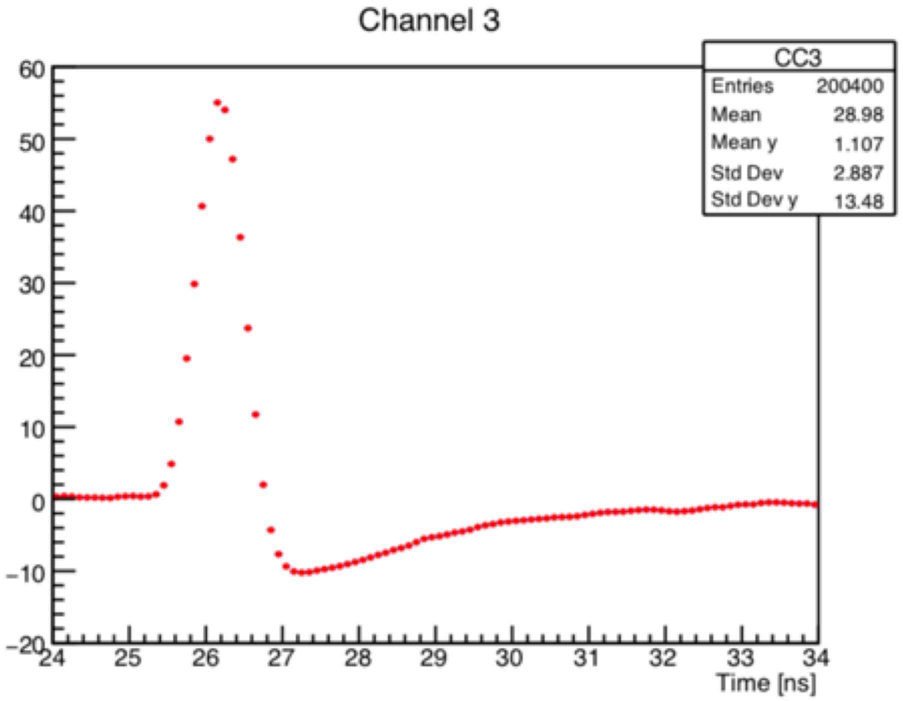


RSD Signal formation - II

Act 2: the signal propagates on the n++, it is integrated on the nearby 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 capacitors, they are charged by the signal
4. Signal gets smaller and delayed with distance





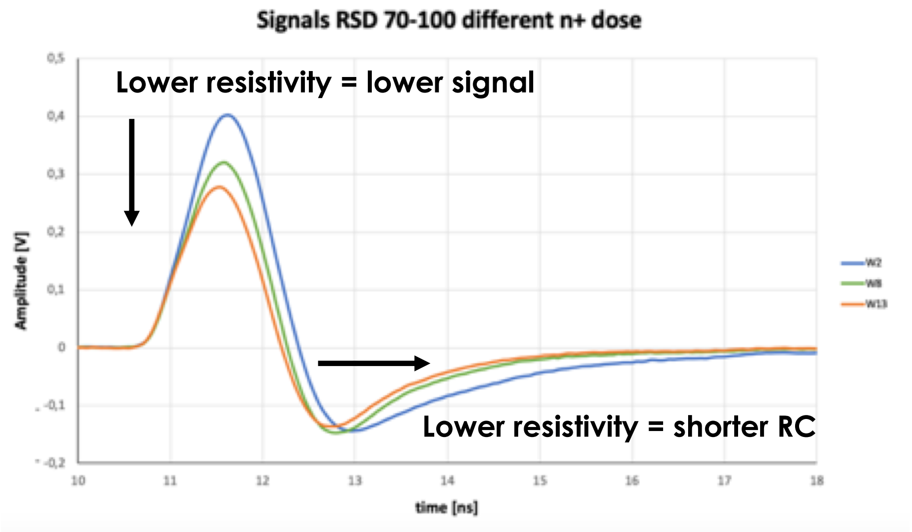
RSD Signal formation - III

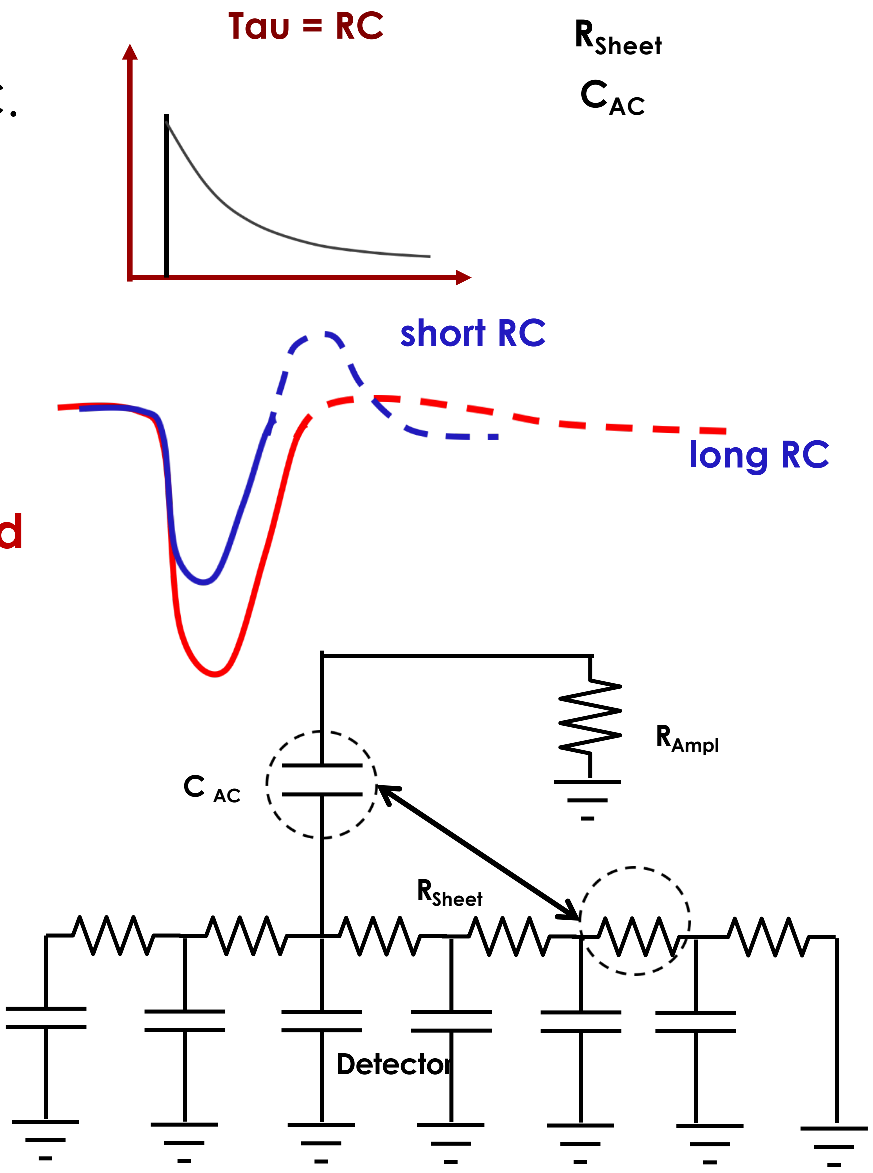
Act 3: the signal discharges, according to the read-out RC.

Warning: **if the RC is too short, the discharging current cancels the incoming signal** (ballistic deficit)

→ Too small RC leads to loss of signal

→ Pad size, dielectric thickness, and n+ resistivity are linked

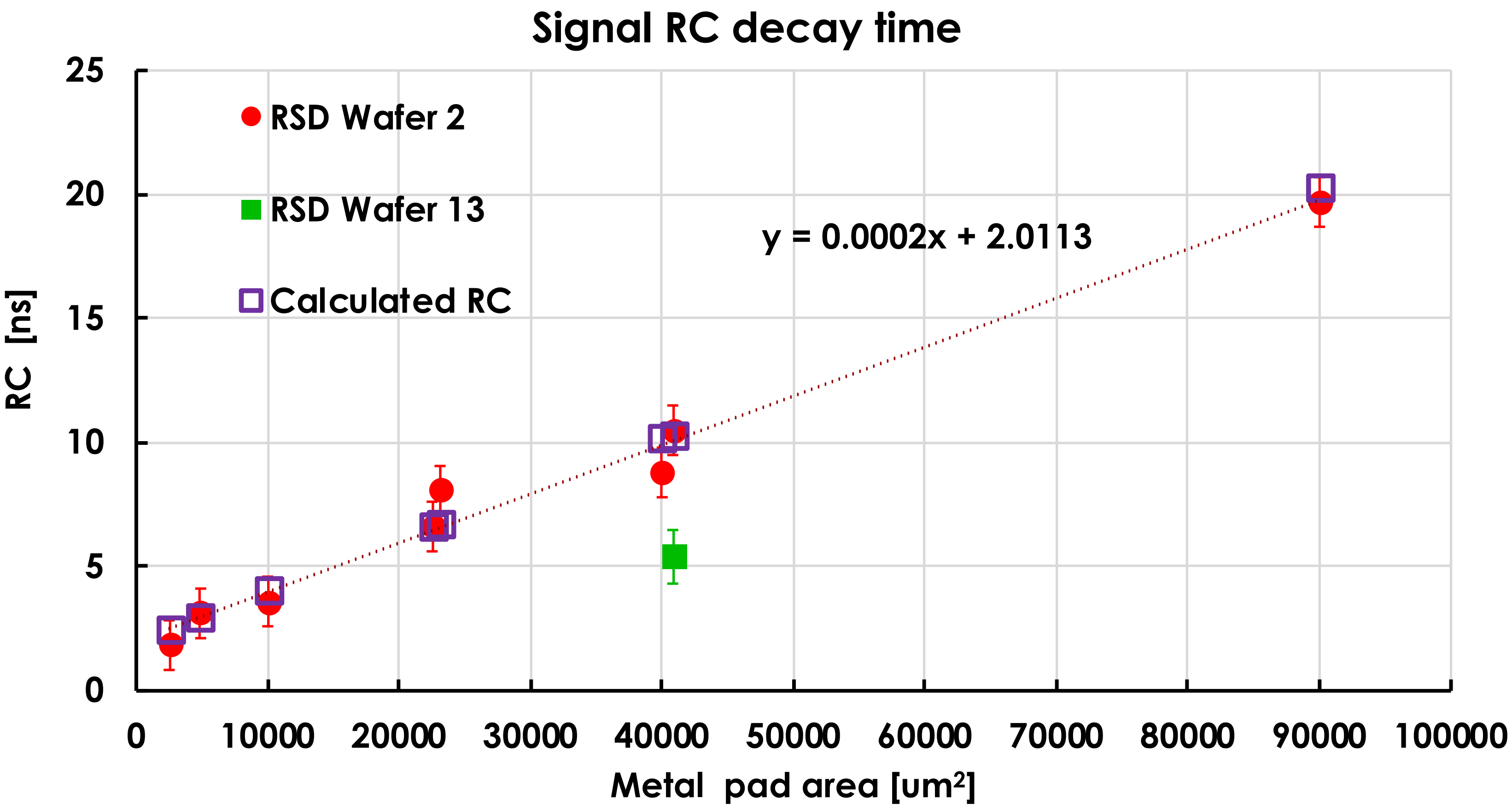




Measurement of the RC time constant

For a given resistivity and dielectric thickness, the RC is function only of the metal size

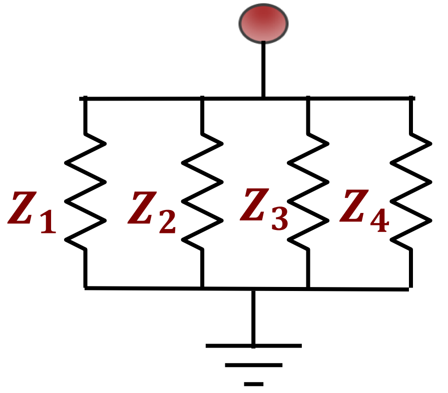
Wafer 13 has smaller resistivity than Wafer 2



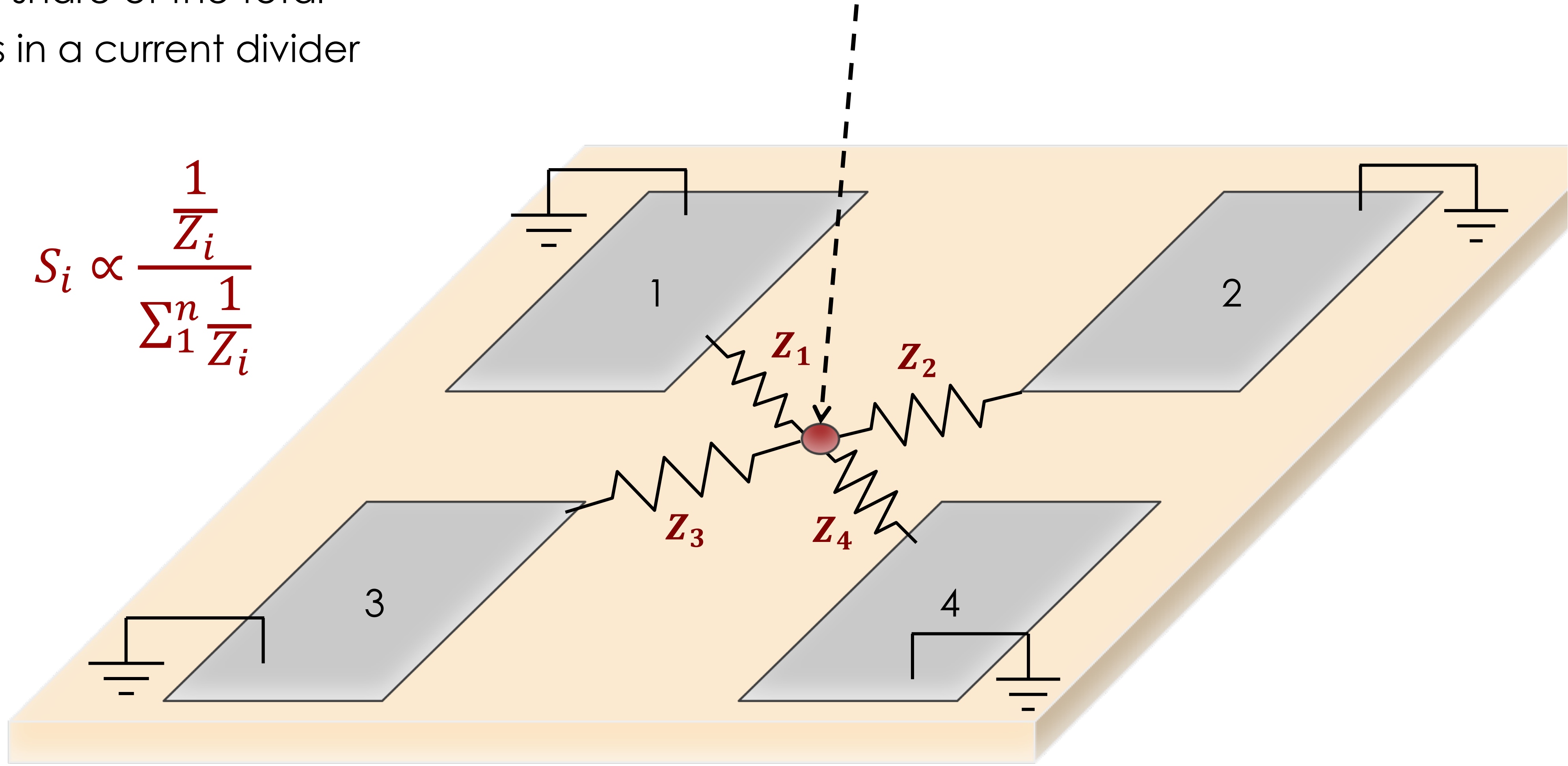
Charge sharing in RSD

The signal sees several impedances in parallel, and it is split according to Ohm's law.

Each pad gets a share of the total signal, exactly as in a current divider



$$S_i \propto \frac{\frac{1}{Z_i}}{\sum_1^n \frac{1}{Z_i}}$$



How to calculate Z_i

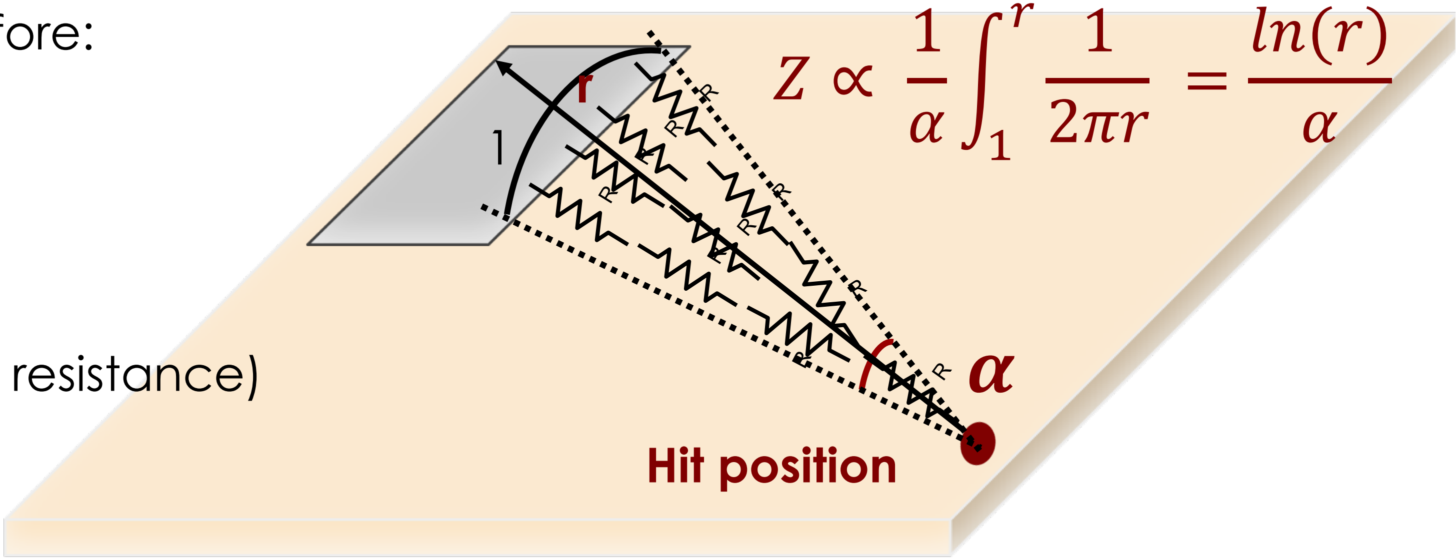
The impedance Z seen by a propagating signal does not increase linearly with the distance r since the signal spreads on a larger area

The resistance R per unit distance decreases as the circumference C becomes larger

$$Z \propto \frac{1}{\alpha C} = \frac{1}{\alpha(2\pi r)}$$

The impedance Z up to radius r is therefore:

$$Z \propto \frac{1}{\alpha}\int_1^r \frac{1}{2\pi r} = \frac{ln(r)}{\alpha}$$

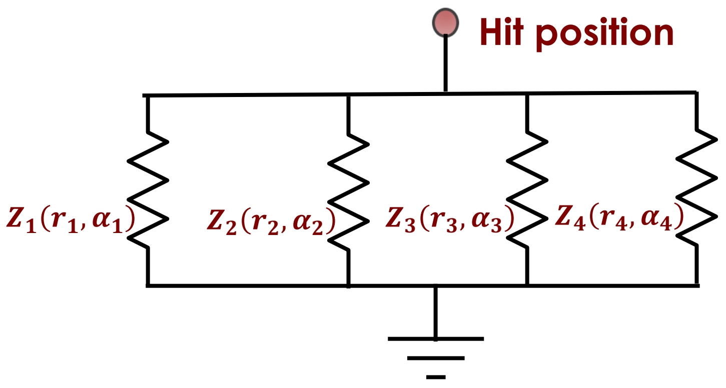


where α is the angle (larger pad, smaller resistance)

RSD master formula

The fraction of signal seen in each pad is:

$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{\ln(r_i)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}}$$

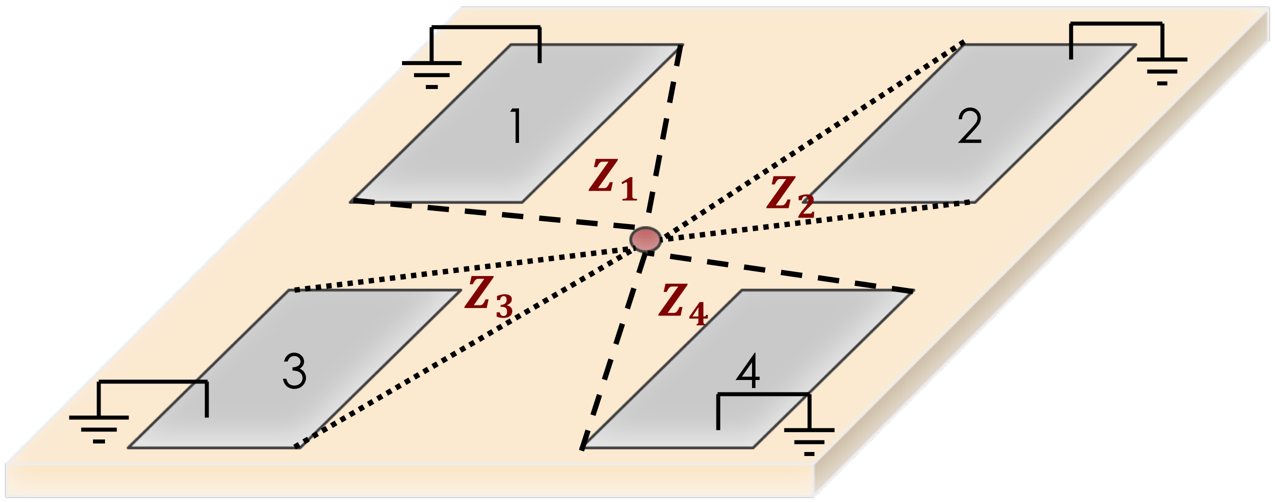


where:

- r_i= distance hit-pad
- α_i= angle of view hit-pad

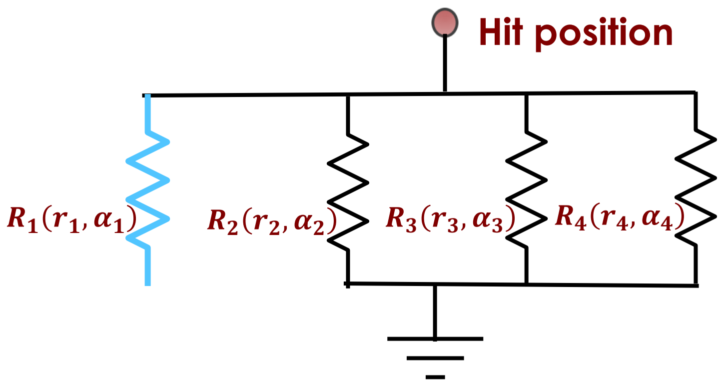
Important points:

- The signal seen in a pad depends upon how many other pads are nearby
- A signal can be seen by 2,3 or 4 pads, depending on the hit location

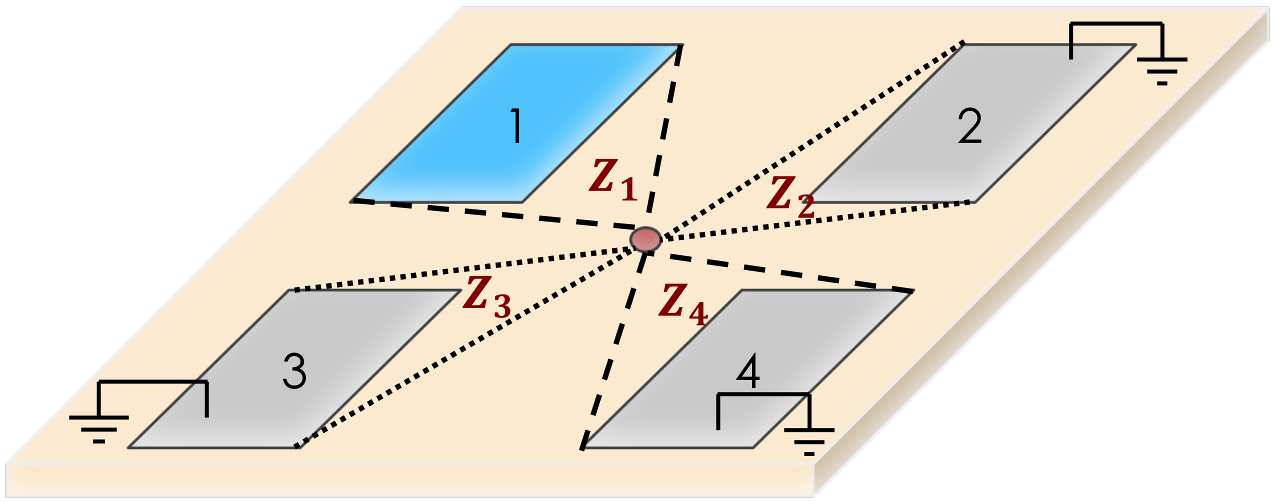


RSD master formula – floating pads

$$S_1(\alpha_1, r_1) = \frac{\frac{\alpha_1}{\ln(r_1)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}} = 0$$

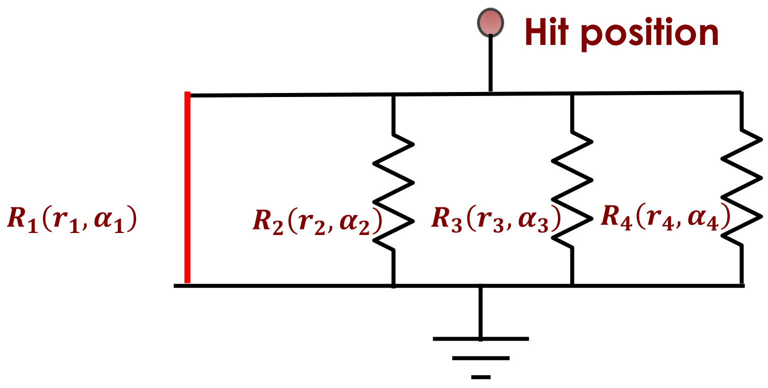


A floating pad does not contribute to the signal sharing, there is no path to ground, i.e., no current flow.

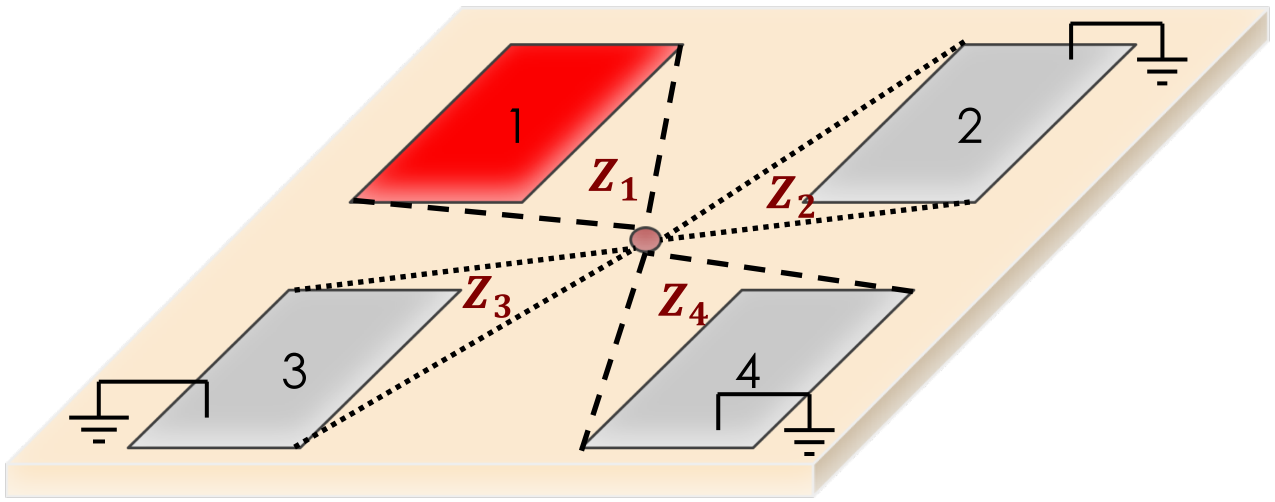


RSD master formula – Hit on metal

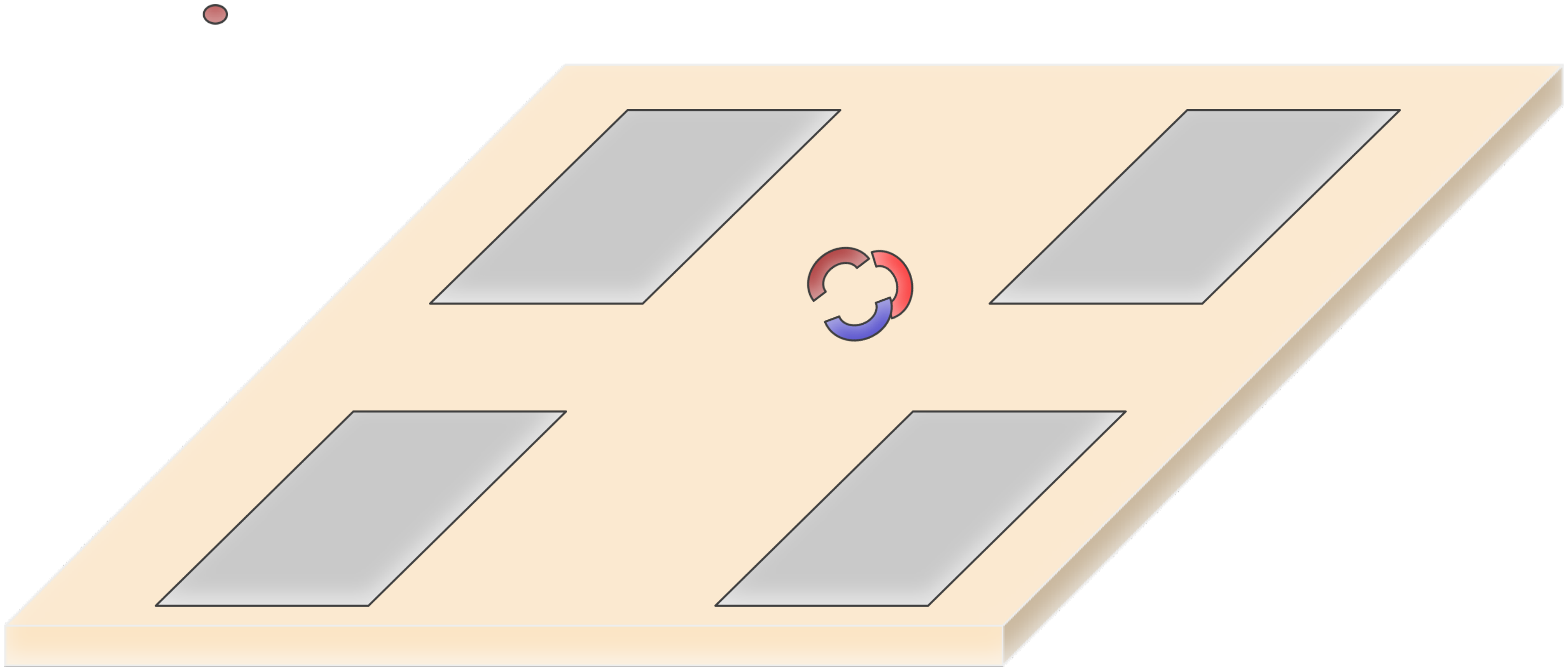
$$S_1(\alpha_1, r_1) = \frac{\frac{\alpha_1}{\ln(r_1)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}} \sim S_{tot}$$



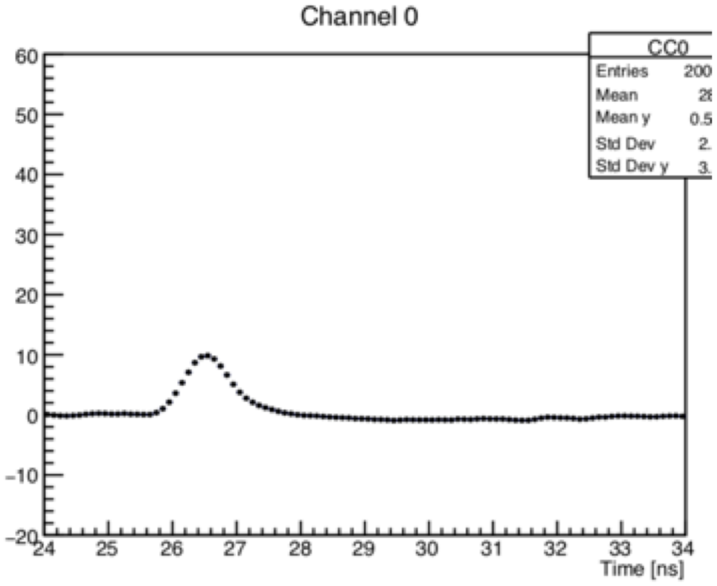
When the hit is on the metal, the impedance to that pad is ~ zero, so the whole signal is in one pas

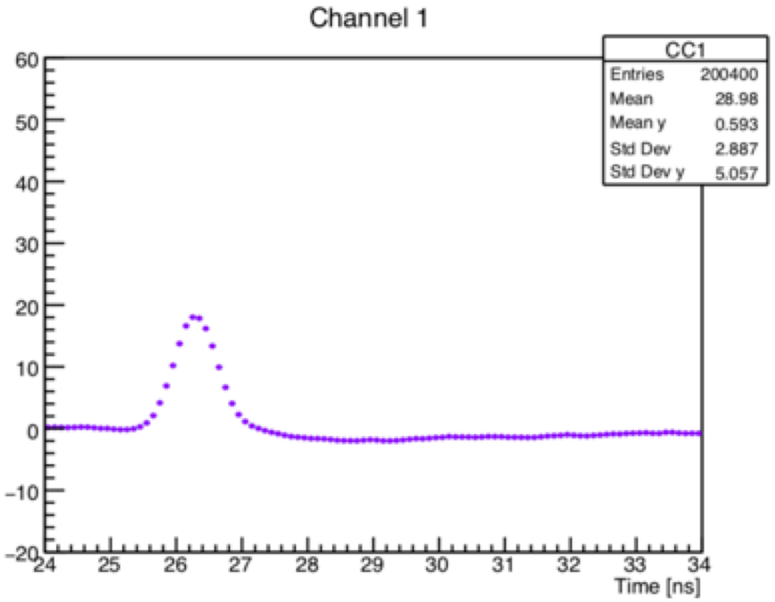


RSD master formula in motion

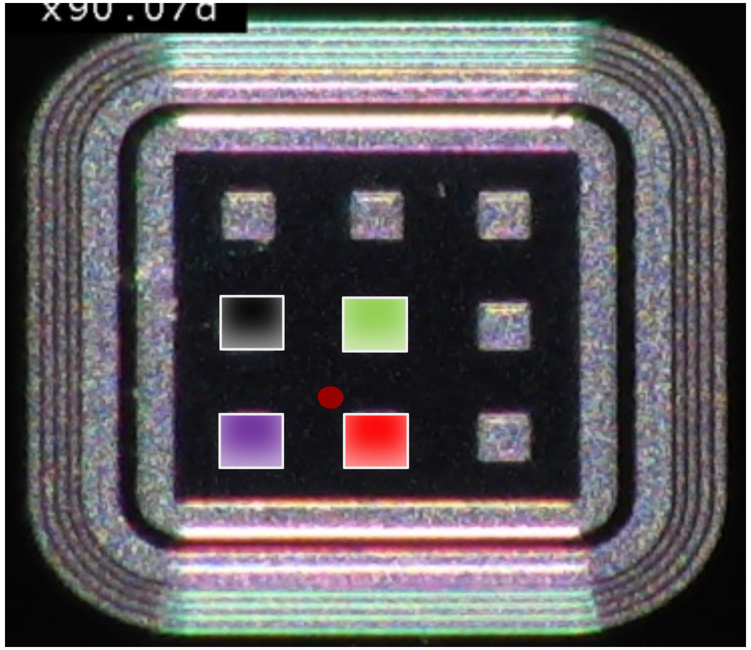


Example of signal sharing

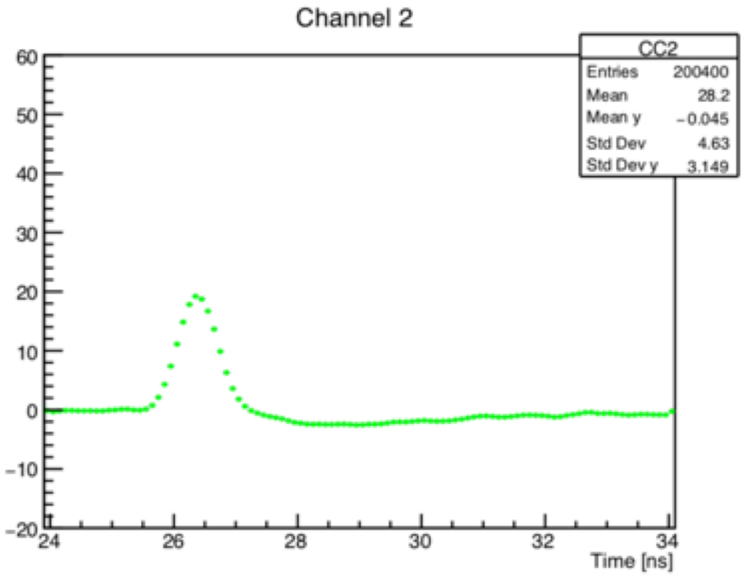


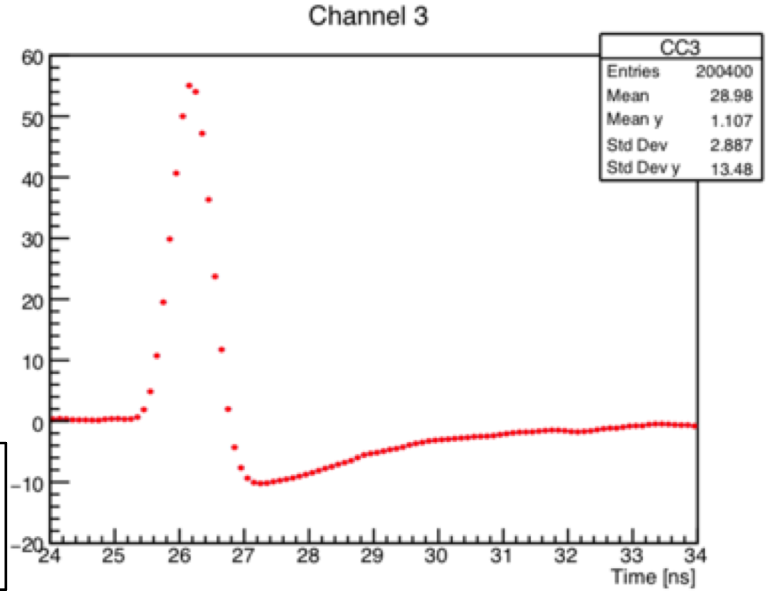


$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{\ln(r_i)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}}$$

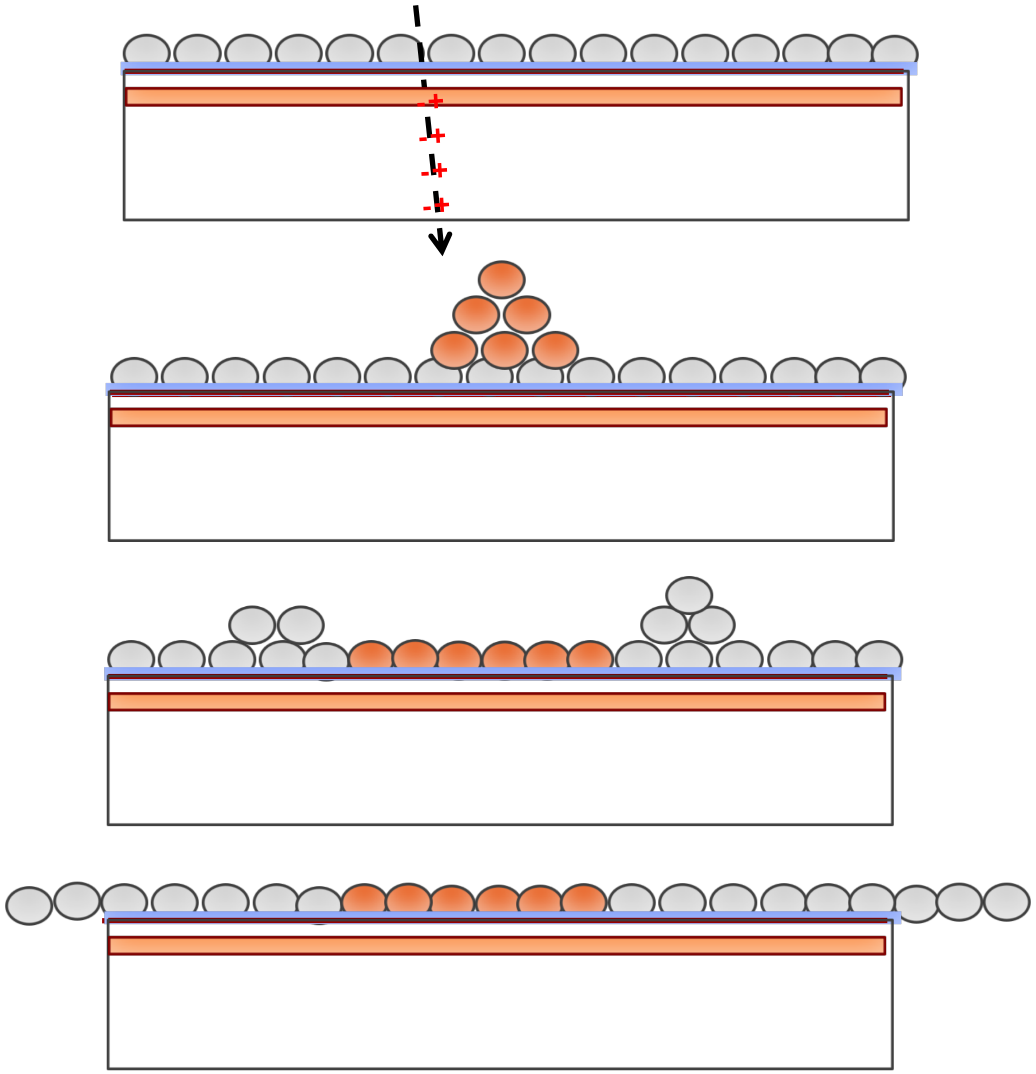


The laser is shot at the position of the red dot: the signal is seen in 4 pads





Current on the DC pad



Calculation of signal sharing

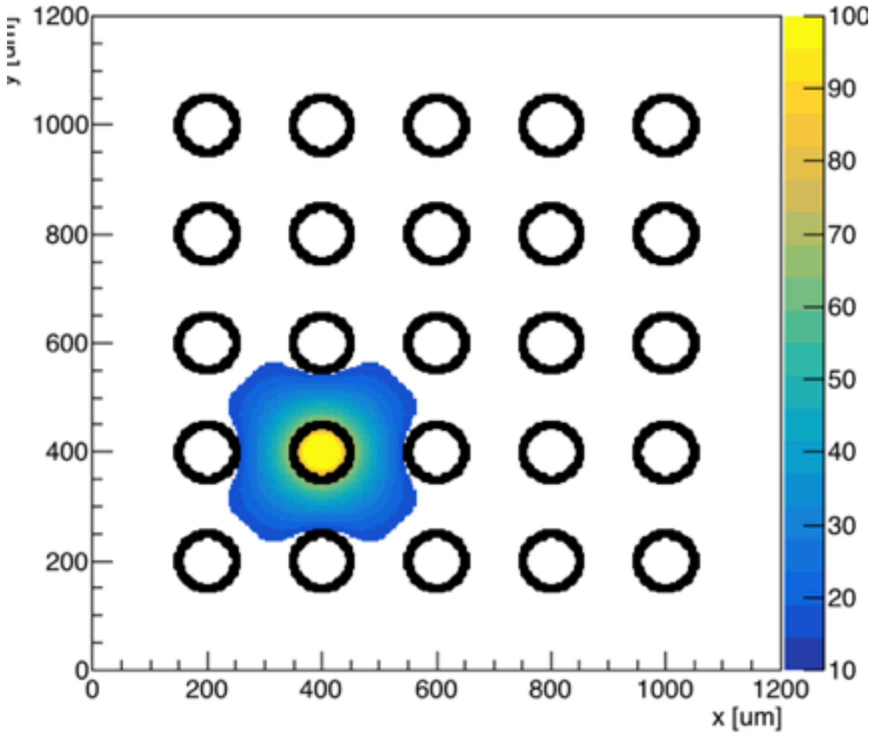
Let's use the RSD master formula to explore the following geometry (analytic calculation):

- Pixel matrix (round metal for simplicity) with metal – pitch = 100 – 200 micron
- Signal amplitude = 100 mV
- Min amplitude = 15 mV

Blue = 1 active pad: when the hit is on the pad, the signal does not spread much

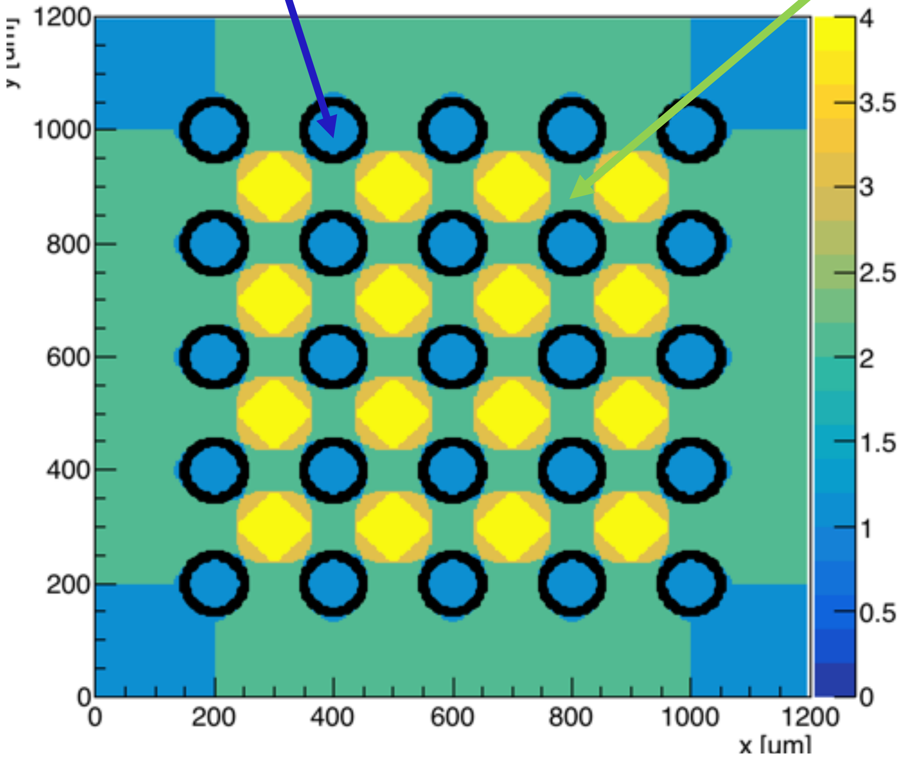
Green = 2 active pads: in between 2 pads

Signal seen by a pad as a function of distance



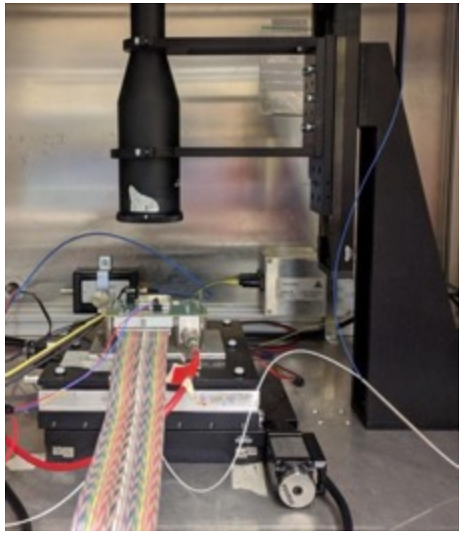
Good localized signal

Number of pads (1,2,3, or 4) with signal > 15 mV



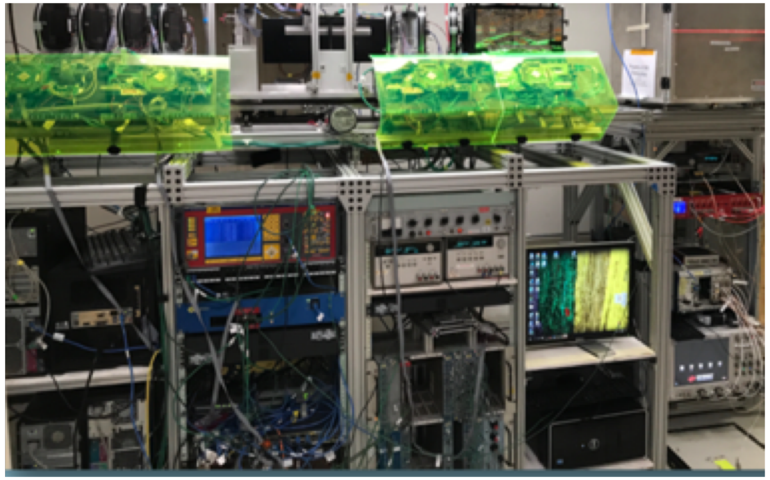
Not very uniform readout pattern

Experimental data: Laser and beam test



The laser studies presented here are obtained using a "Particular" laser TCT set-up

- Sensors are glued on a 16-channel read-out board.
- The laser is shot in various position via an x-y-z micrometric stage



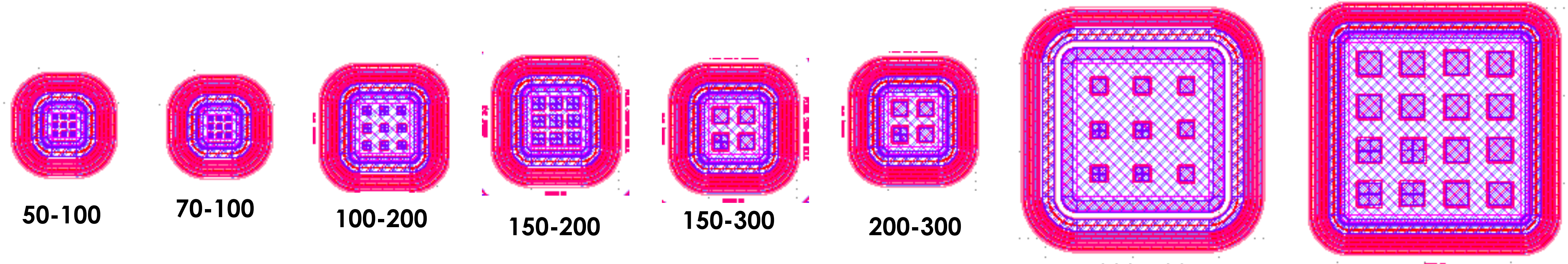
The beam test results have been obtained at FNAL, in collaboration with the FNAL CMS-Timing ETL team

- 120 GeV/c proton beam
- Precise timing determination (~ 10 ps)
- Fairly precise tracking system (~ 35-40 um)

The signals are recorded with a digital oscilloscope (20-40 GS/s, 2-4 GHz BW) for offline analysis

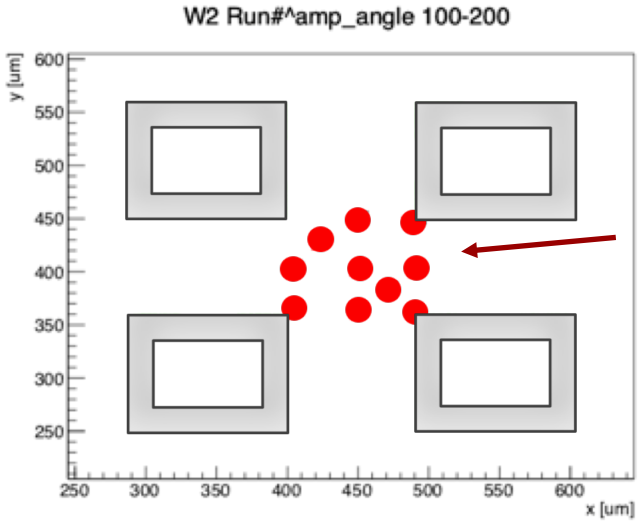
Structures tested (metal-pitch)

The FBK production RSD1 yielded many samples, of several geometries, exploring the interplay of n+ resistivity, dielectric thickness, metal pad, and pitch



50-100 | 70-100 | 100-200 | 150-200 | 150-300 | 200-300 | 200-500 | 300-500

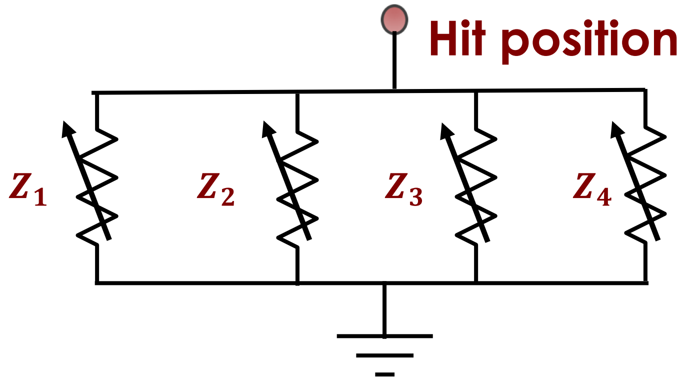
Each sensor was tested with the laser TCT set-up, shining the laser spot (~ 10 um) in several positions and recording the signals seen by the 4 adjacent pads.
The runs were repeated at 3-4 values of gain for each geometry



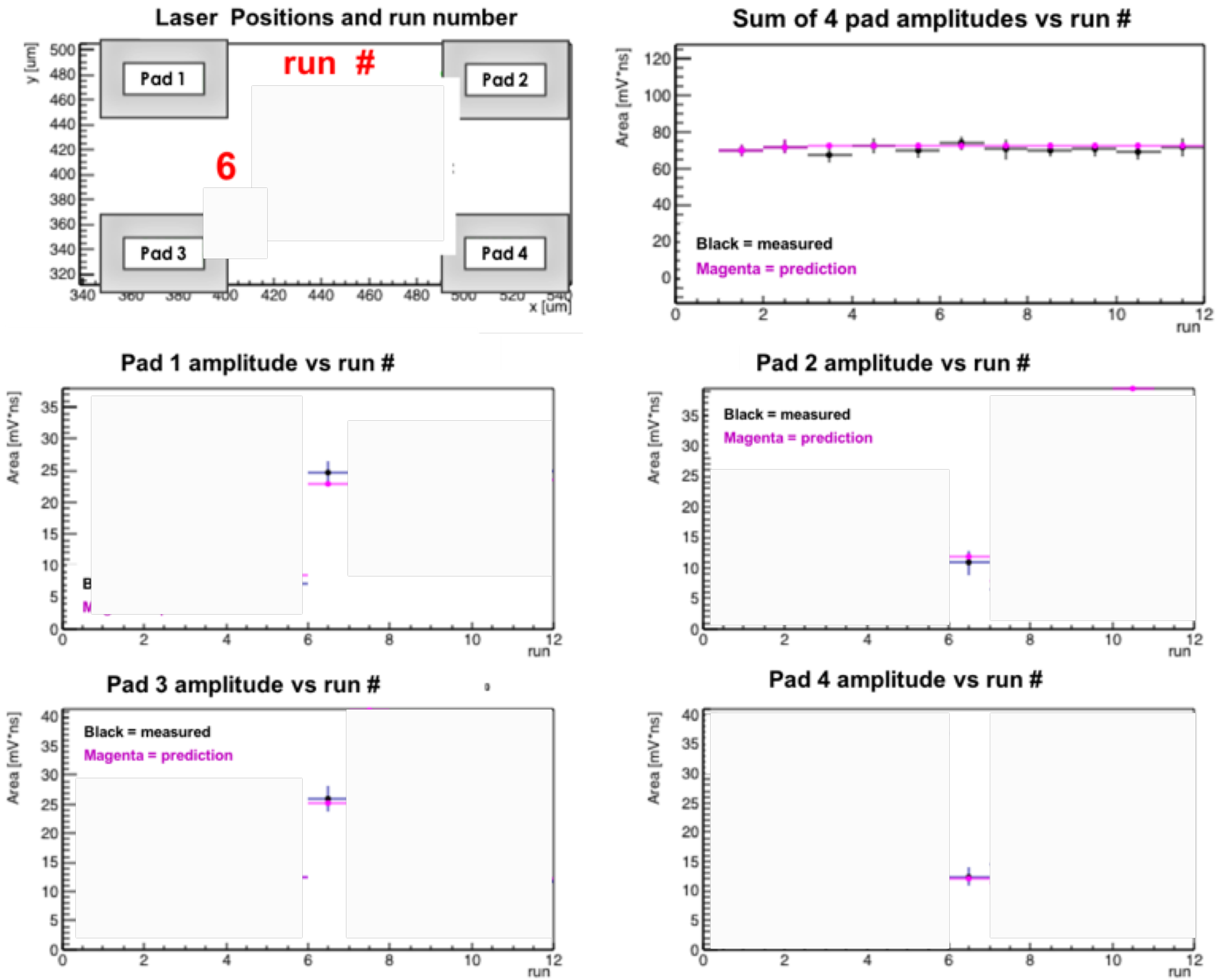
Example of laser positions

Signal amplitudes as a function of positions – 4 pads

The amplitudes in the 4 pads change together, in a "coordinated way", as they should in a current divider.

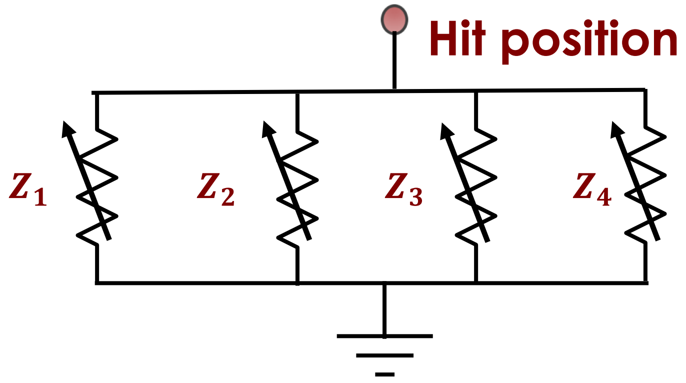


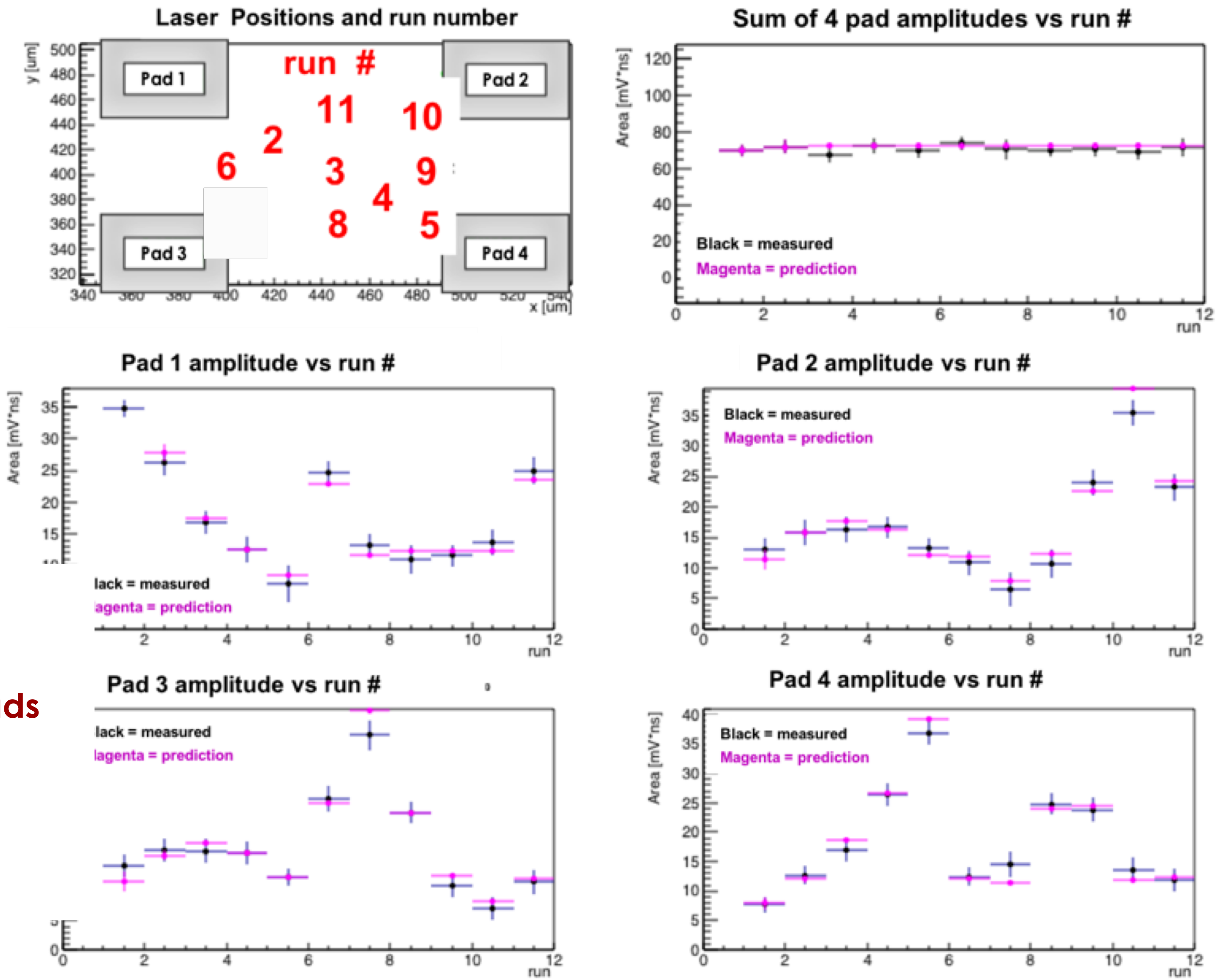
$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{\ln(r_i)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}}$$



Signal amplitudes as a function of positions – 4 pads

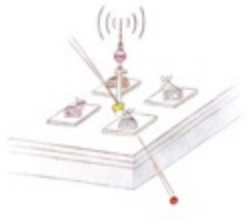
The amplitudes in the 4 pads change together, in a "coordinated way", as they should in a current divider.





Wrap-up:

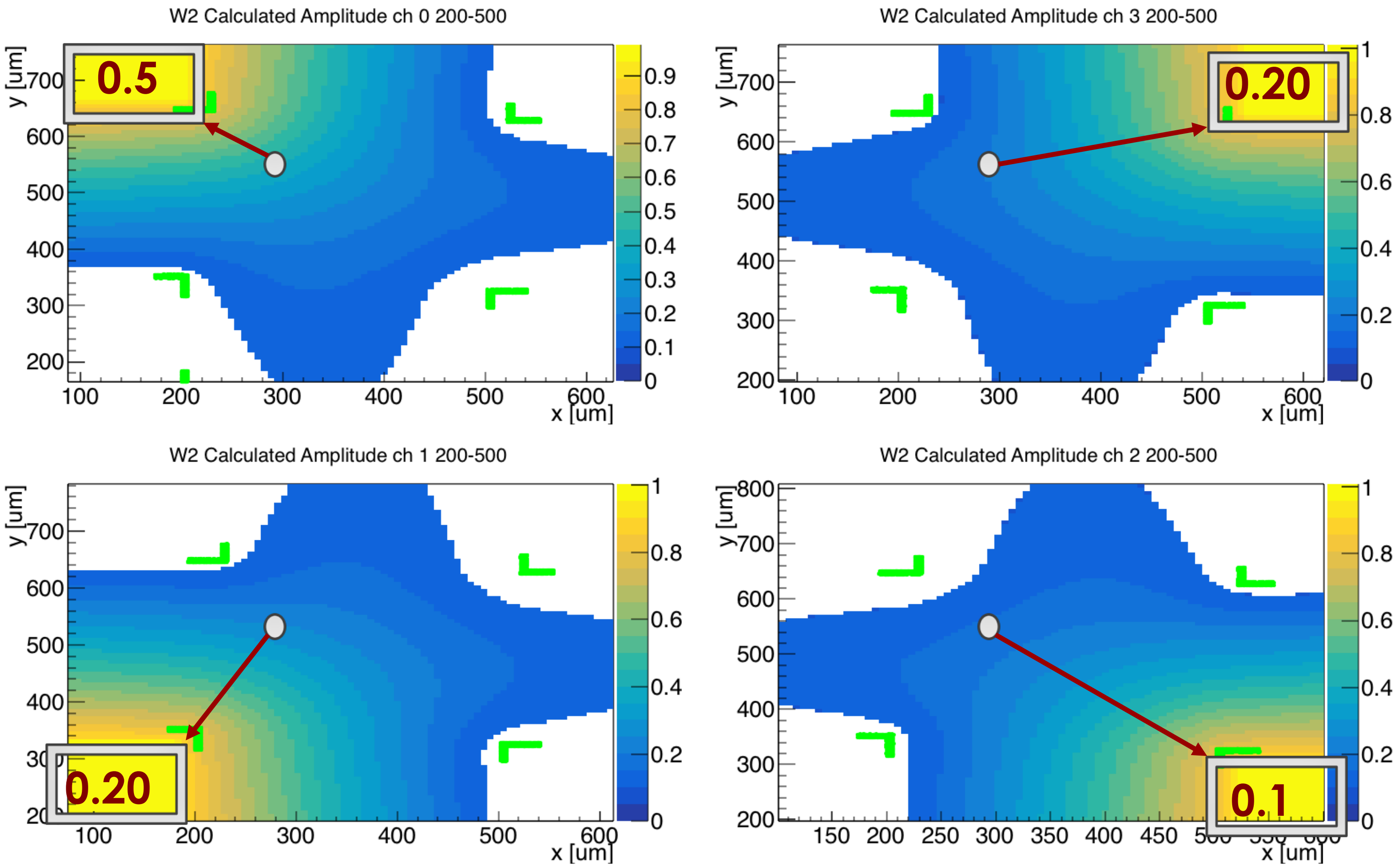
- **RSD works as a current divider**
- **The signal is naturally shared among pads**
- **The RSD master formula works well**
  - ➔ **no free parameters, the magenta points are an absolute prediction**
- **The total amplitude is fairly constant**



Position reconstruction method

Basic principle: the amplitudes seen by the pads define a unique x-y point

The RSD master formula allows computing for each x-y point the 4 amplitudes seen by the pads



A particle hits in a given position, with relative amplitude in the 4 pads **0.5,0.2,0.1,0.2**

How the hit position is determined?

The x-y positions of a measured hit are the **coordinates of the bin that minimize the difference between the measured and calculated amplitudes of the 4 pads.**

Minimize the quantity:

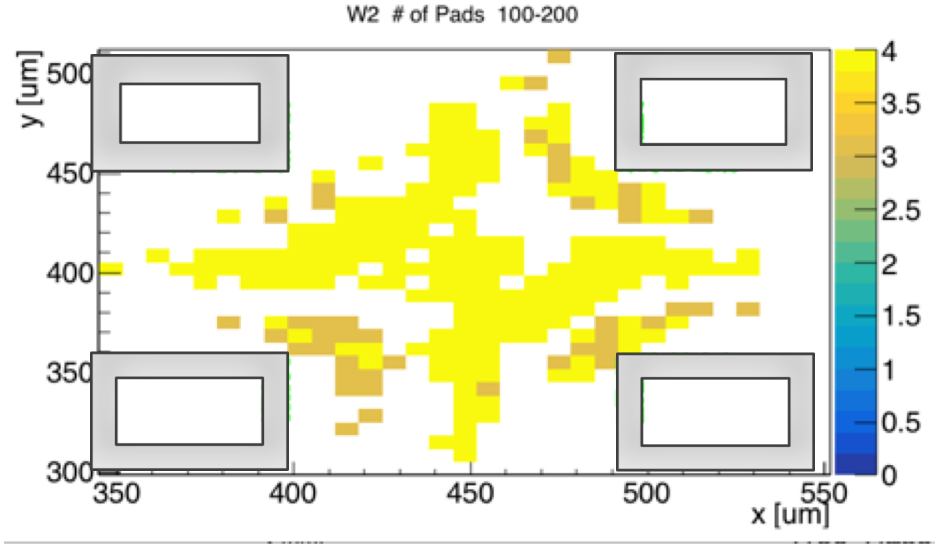
$$\chi^2 = \sum_{1}^{4} \frac{[S_i^{Meas} - S_i^{Calc}]^2}{\sigma}$$

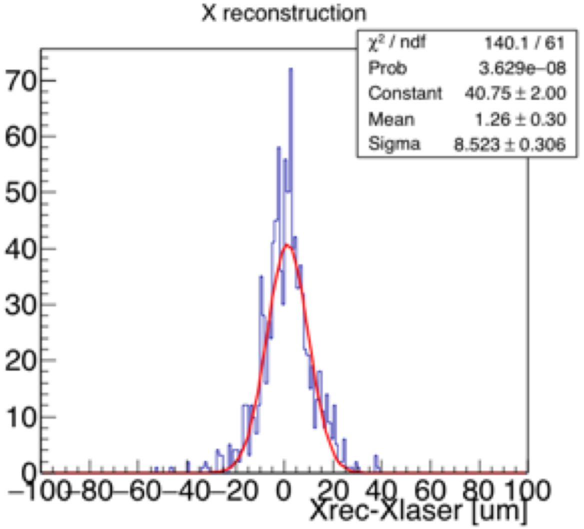
Laser study: position resolution

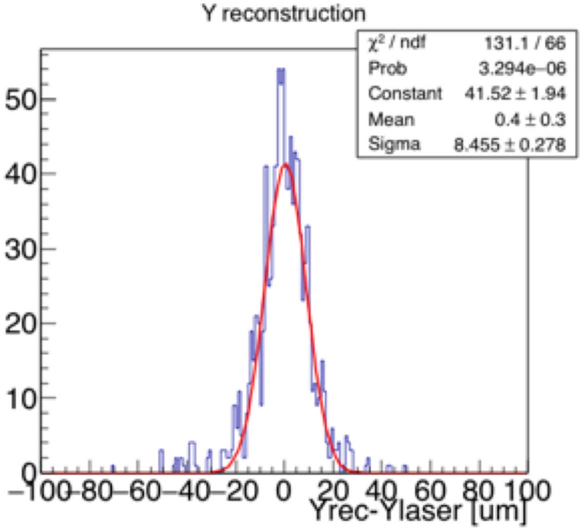
Shooting the laser in many positions, the **spatial precision** can be evaluated. This is done by comparing the position reconstructed using the look-up table to the known laser position.

Geometry: 100 Metal, 200 pitch

Shooting position and# of pads used in the reconstruction







Resolution ~ 8.5 um

Gain ~ 17

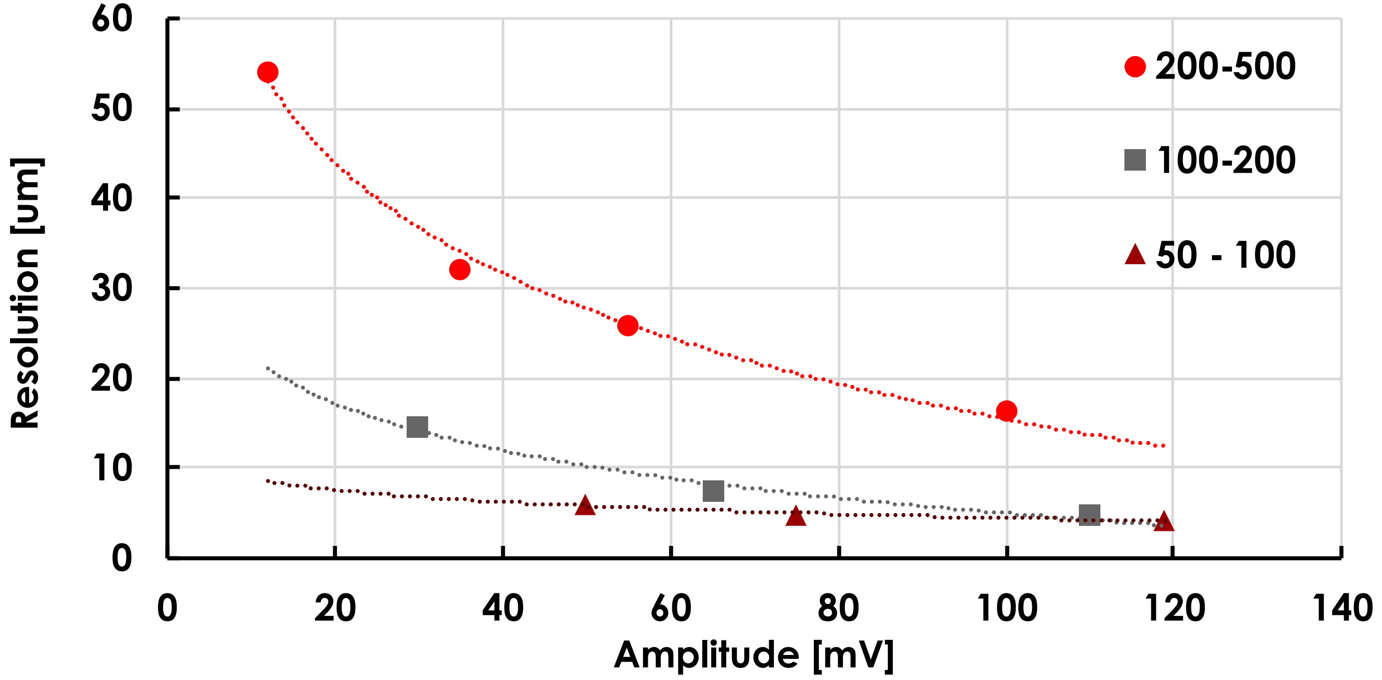
Laser study: position resolution as a function of amplitude

The spatial resolution improves with signal amplitude, plateauing at about 5 um

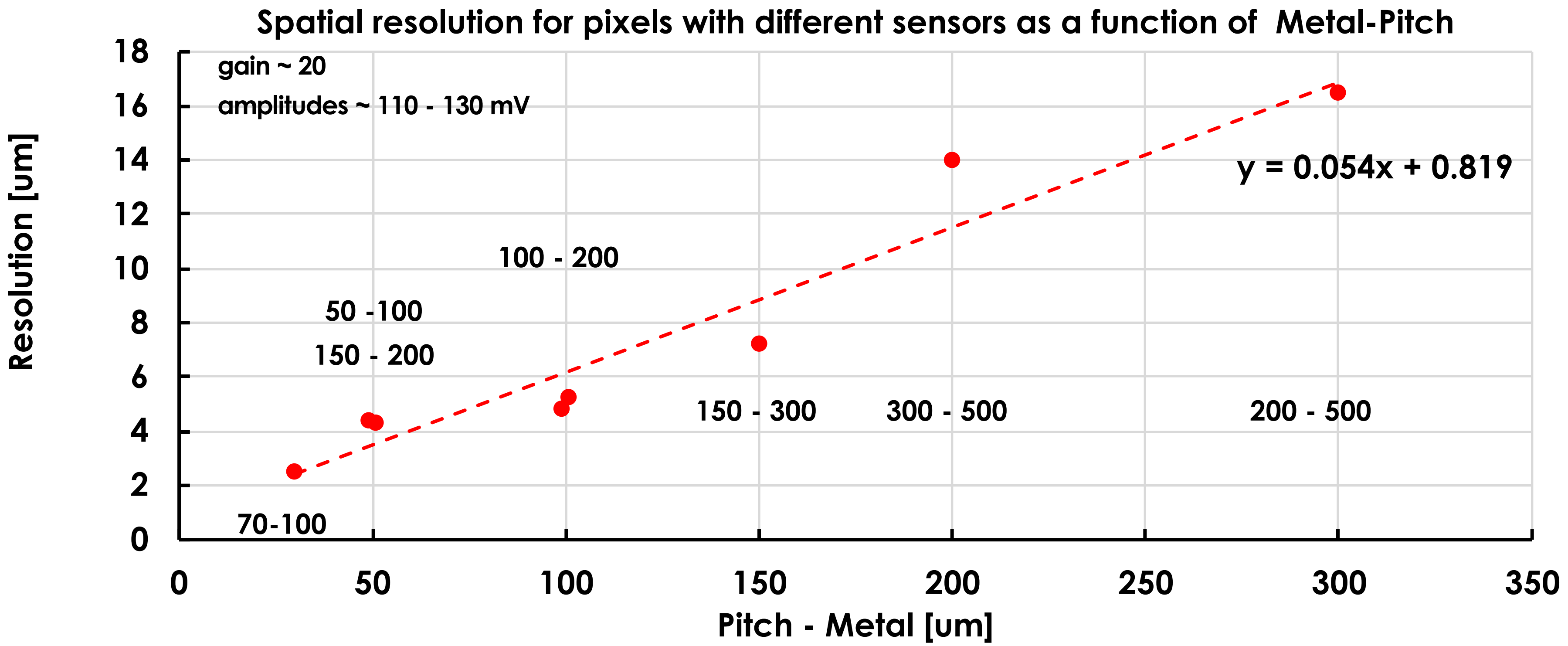
Important points:

- The resolution for 50-100, 100-200 is limited by systematics such as the precision of the amplitude reconstruction, noise, the use of the RSD master formula.
- The resolutions refer to points between pads, not in the metal pads (more on this later).

Spatial resolution for pixels with different Metal-Pitch as a function of signal amplitude



Laser study: position resolution as a function of pixel geometry



The resolution is about 5% of the Pitch-Metal distance

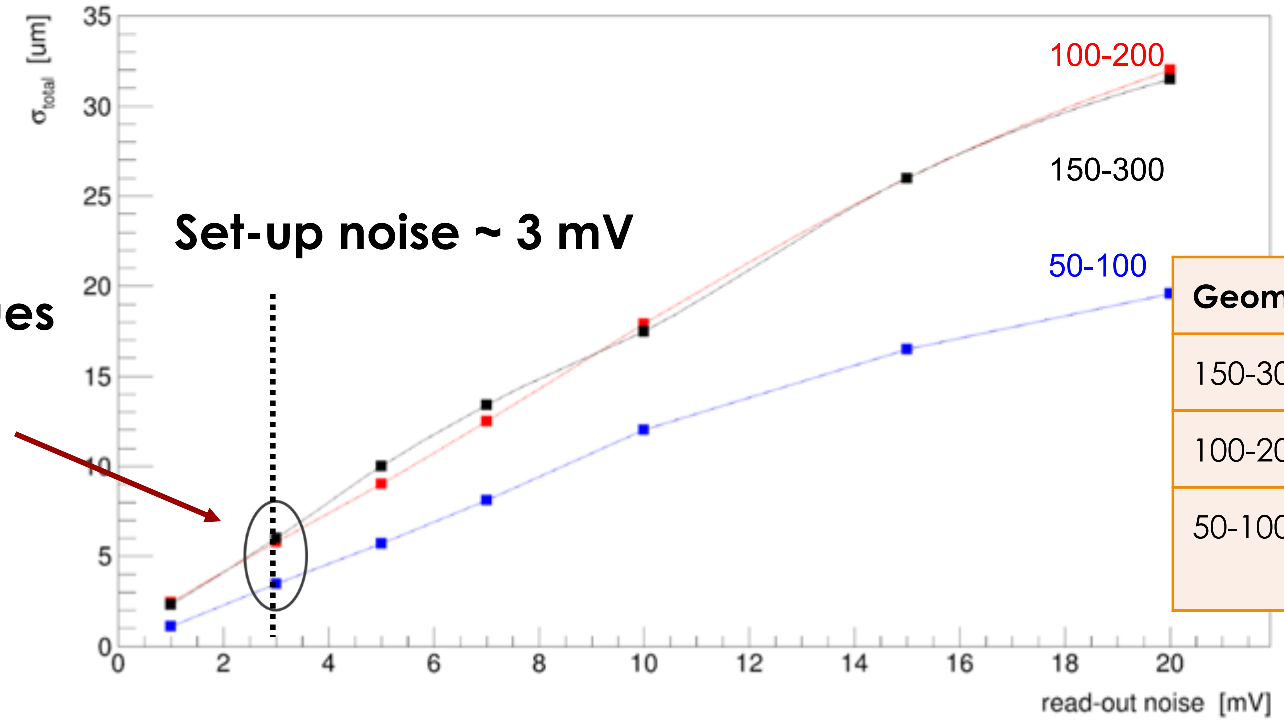
➔ **How small the resolution can be? Why is it not more precise?**

How to obtain a better spatial resolution

- The spatial resolution is controlled by the reconstruction method and by the noise

$$\sigma^2_{tot} = \sigma^2_{Method} + \sigma^2_{Noise}$$

The predicted values matches well the measured values



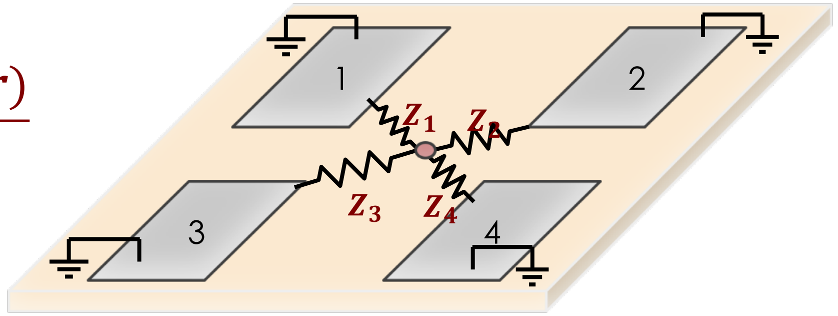
Geometry	Measured Resolution
150-300 um	5.9 ± 0.1 (exp.) ± 3.5 (syst.) um
100-200 um	5.5 ± 0.1 (exp.) ± 3.5 (syst.) um
50-100 um	4 ± 0.1 (exp.) ± 3.5 (syst.) um

This simulation shows that spatial resolutions below 5 micron can be achieved only with very small electronic noise

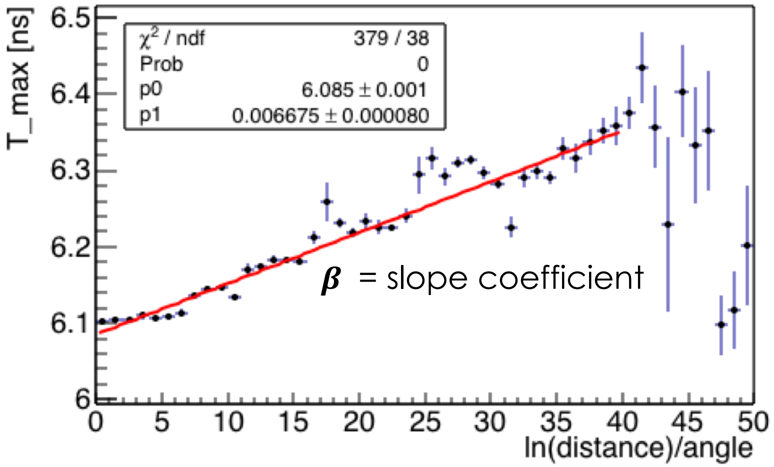
Laser study: signal delay

Each pad sees the signal with a delay proportional to the resistance from the impact point to the pad

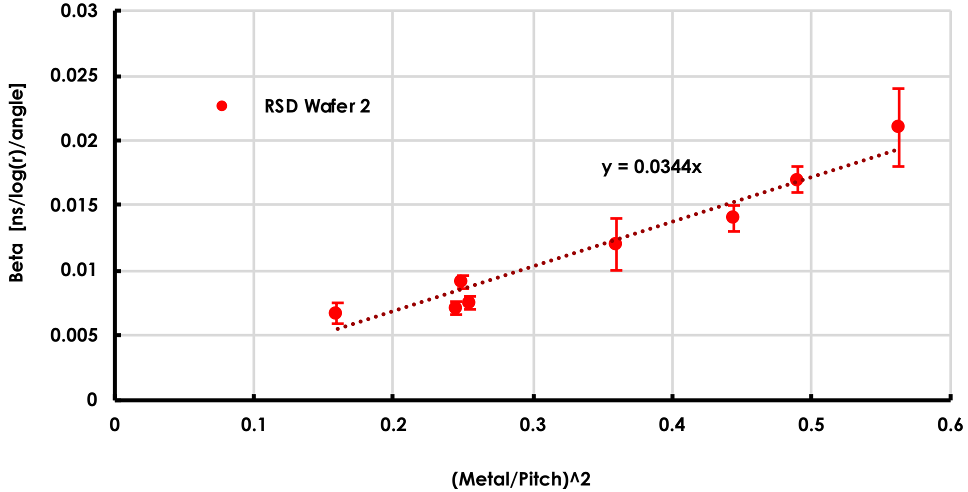
$$delay \propto \frac{ln(r)}{\alpha}$$



T_{max} vs $\frac{ln(r)}{\alpha}$ for the geometry 200-500



Coefficient β for different geometries



The time of each pad is defined as:

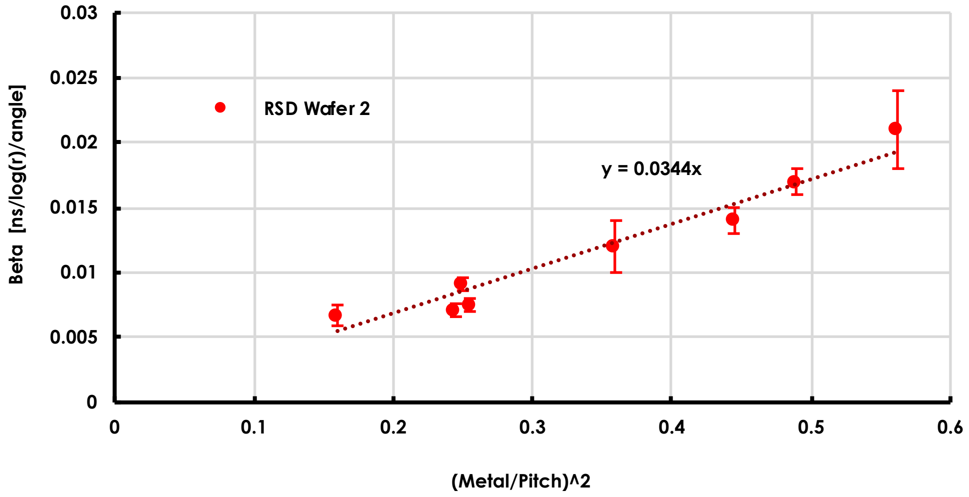
$$t_i^{True} = t_i^{Meas} - \beta \frac{ln(r_i)}{\alpha_i}$$

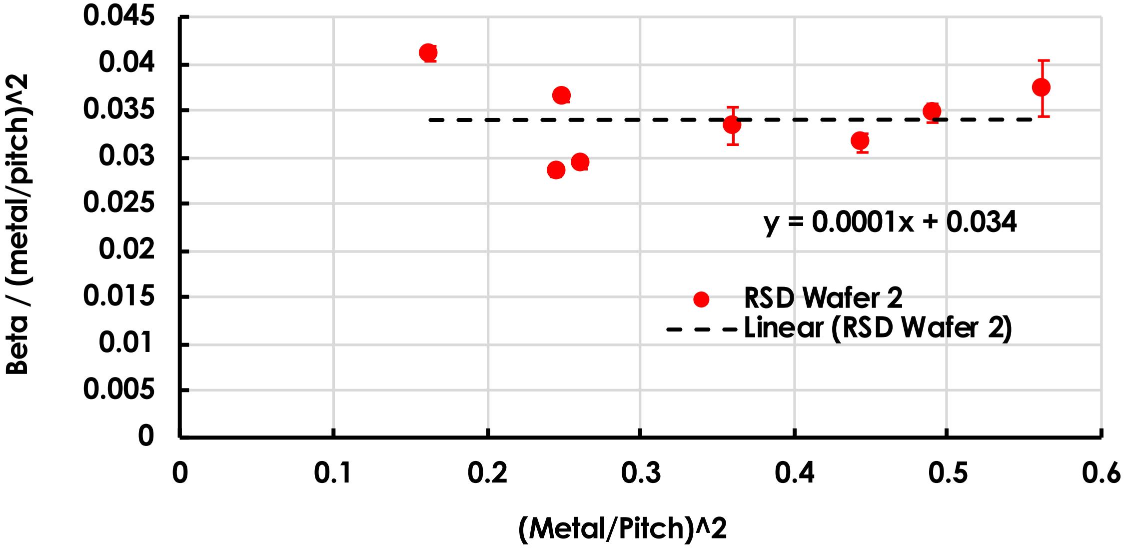
β depends linearly from (metal/pitch)^2

(related to the detector capacitance)

Laser study: signal delay

Coefficient β for different geometries





The time of each pad is defined as:

$$t_i^{True} = t_i^{Meas} - \beta \frac{ln(r_i)}{\alpha_i}$$

β depends linearly from (metal/pitch)^2

(related to the detector capacitance)

$$t_i^{True} = t_i^{Meas} - 0.034 \left(\frac{Metal}{Pitch}\right)^2 \frac{ln(r_i)}{\alpha_i}$$

RSD master formulas

RSD signals are therefore controlled by two equations:

1. the signal sharing among pads

$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{ln(r_i)}}{\sum_1^n \frac{\alpha_i}{ln(r_i)}}$$

2. the signal delay

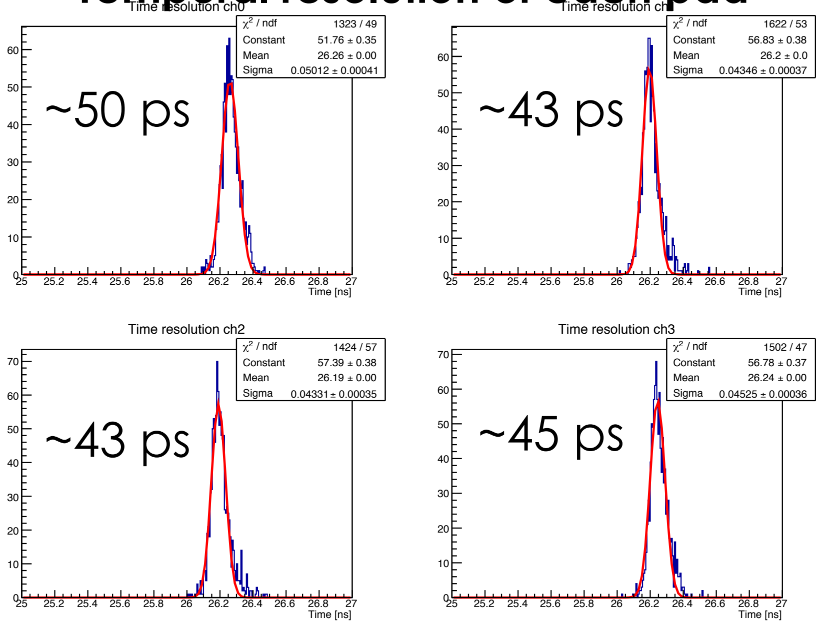
$$t_i^{True} = t_i^{Meas} - \gamma \left(\frac{Metal}{pitch}\right)^2 \frac{ln(r_i)}{\alpha_i}$$

where γ is wafer-specific (n+ resistivity, dielectric thickness)

Laser study: time resolution

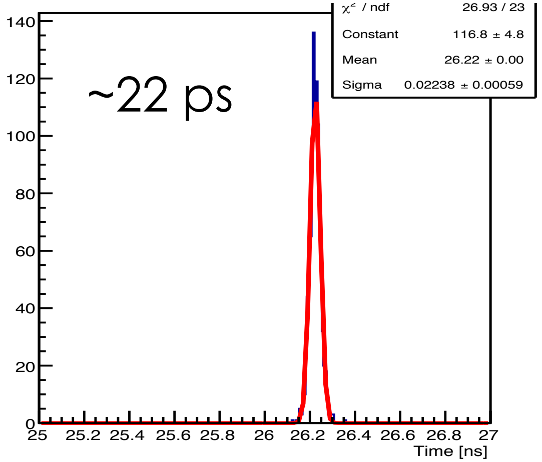
The **hit time** is obtained combining the timing information from each pad, after correcting for delay

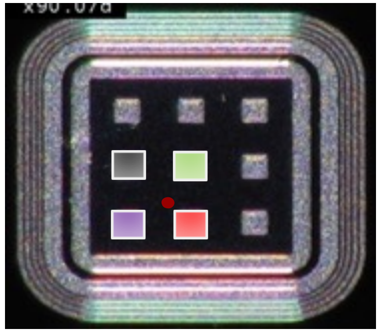
Temporal resolution of each pad



~45ps/√4

4-pads combined temporal resolution





RSD show excellent temporal resolution and the combination of multiple signals yields to $\sim \frac{1}{\sqrt{n}}$ improvements

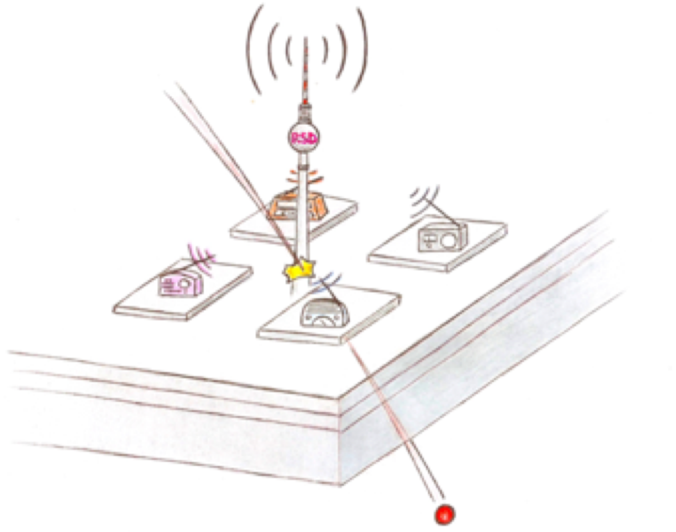
FNAL beam test results

All details in: M. Tornago, 36th RD50 "Latest results on RSD spatial and timing resolution https://indi.to/2cGQy

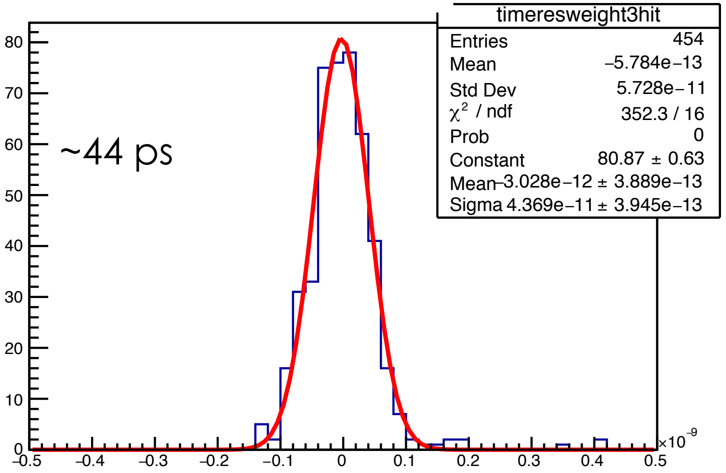
Data taken with RSD 3x3 100-200 and 190-200 geometries

Lesson learnt:

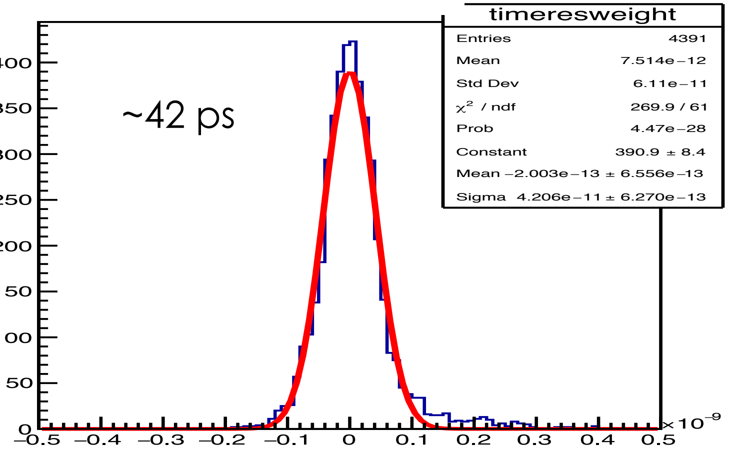
- RSD are ~ 100% efficient
- The RSD x-y hit reconstruction worked very well
- The time resolution is $\sigma_{t\ 100-200} = 44\ ps, \sigma_{t\ 190-200} = 42\ ps$
- The metal size (100 vs 190 um) does not influence the time resolution



100 - 200



190 - 200

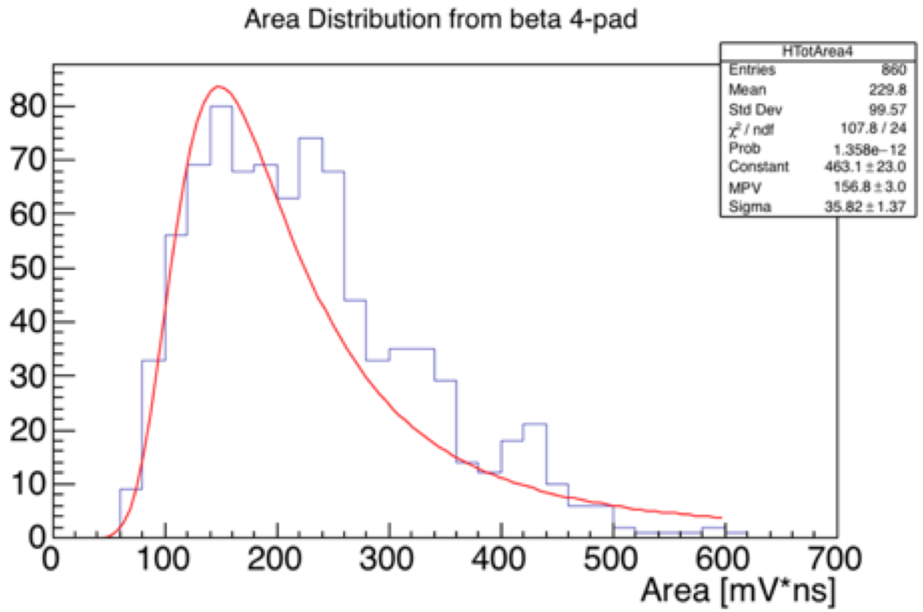


Interesting fact: the combination of n pads does not lead to a $1/\sqrt{n}$ improvement since the effects of non-uniform ionization are fully correlated

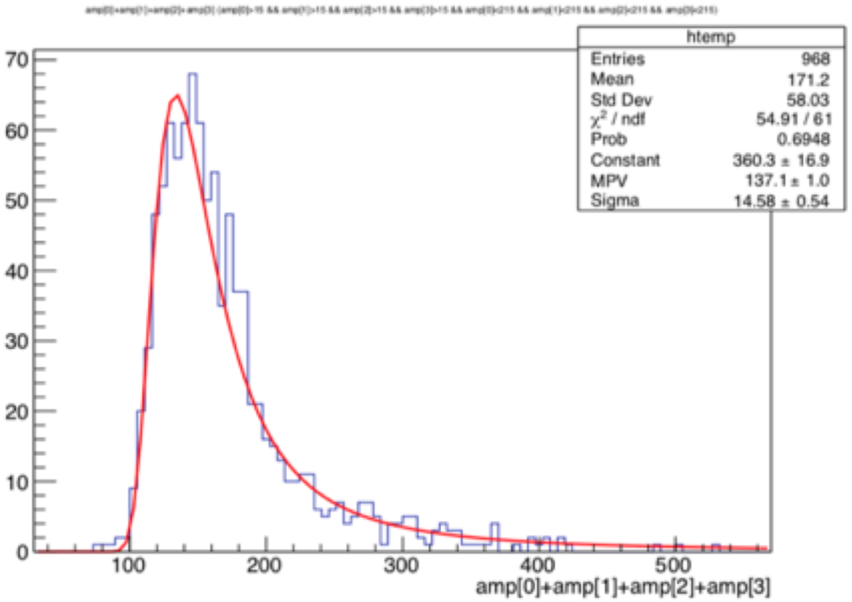
➔ **pads see a copy of the same signal**

Amplitude vs geometry

200-500, Beta, Vbias = 410 V



100-200, 120 GeV protons, Vbias = 410 V



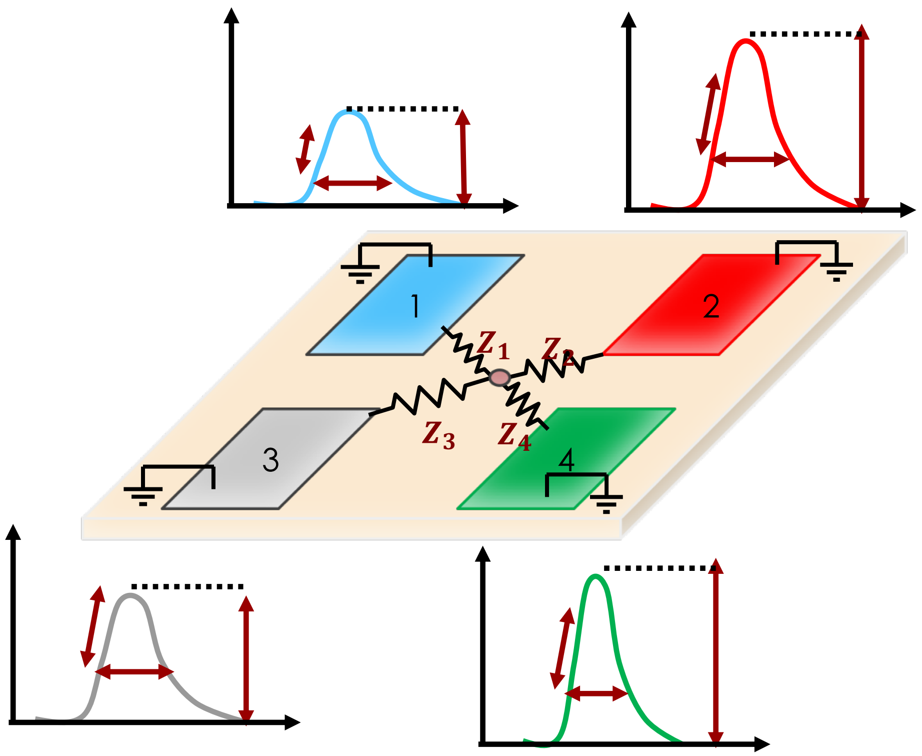
The amplitude obtained summing 4 pads in 200-500 and 100-200 is similar

➔ Need to investigate in which geometries the signal amplitude becomes smaller

Machine Learning applied to RSD

All details in: F. Siviero, 36th RD50 "Position reconstruction using machine learning algorithms applied to Resistive Silicon Detectors (RSD) https://indi.to/vyBcX

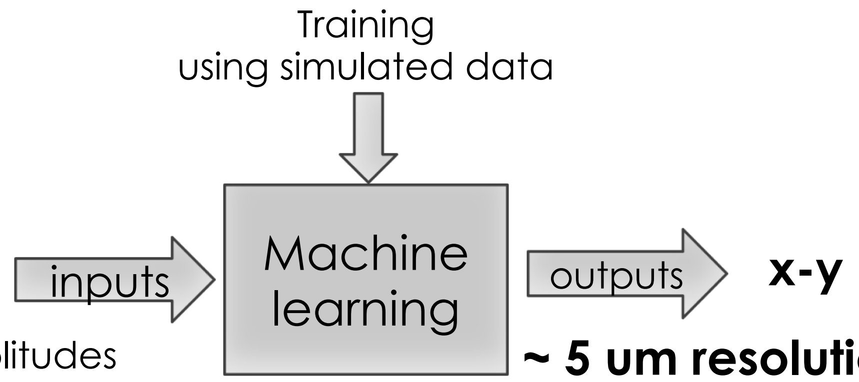
Each of the signals in an RSD event carry a lot of information (amplitude, derivative, width) that can be exploited to perform very accurate x-y-t reconstruction.



Machine learning algorithms are suited to solve regression problems with many inputs and one (or multiple) output.

Present study:

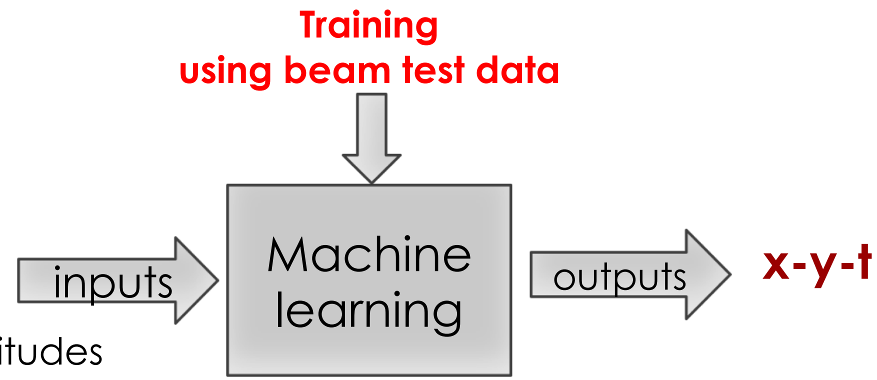
Laser data:
- Amplitude
- Relative amplitudes



~ 5 um resolution

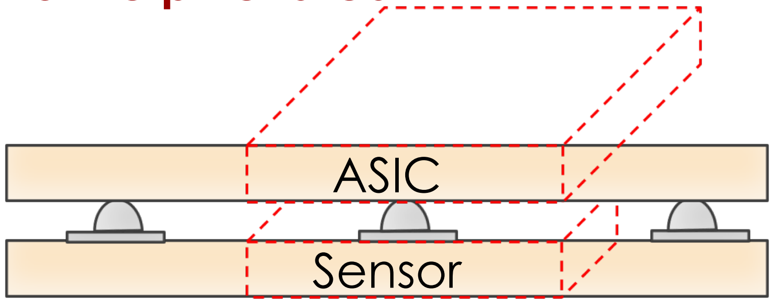
Future:

Beam test data:
- Amplitude
- Relative amplitudes
- Width
- Time
- Rise time



ASIC for RSD

Very important point: in hybrid technology (sensor bump-bonded to the ASIC),
the area available for each read-out channel is identical to the pixel area

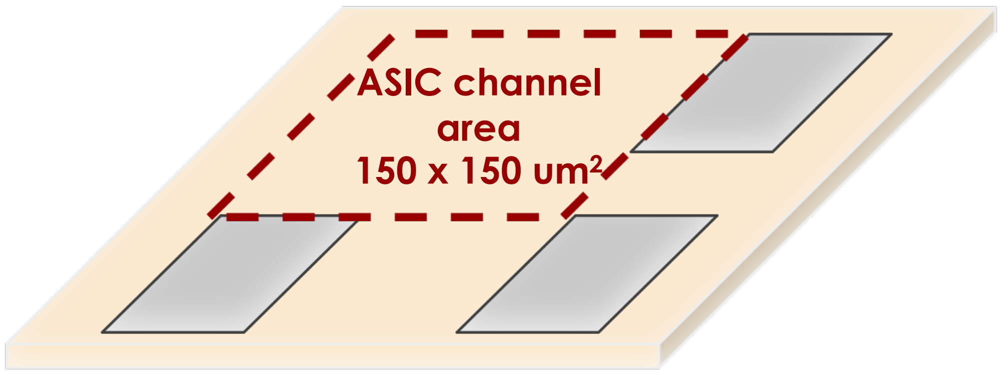


Assuming a goal of ~ 5 um spatial resolution,
the RSD pitch can be 100-150 um

➔ At least a factor of 10-20 more space than using binary readout

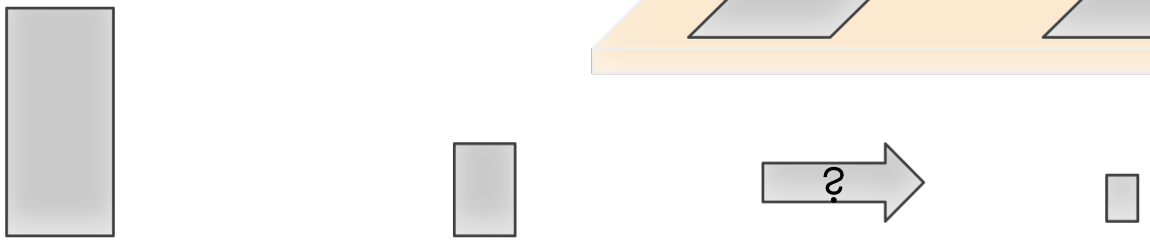
➔ Can concentrate the power available for that area into a single channel

➔ The needed circuits for timing might actually fit



Example:

TDC evolution



130 nm:
70 x 150 micron

65 nm:
40 x 60 micron

28 nm:
~20 x 30 micron

RSD Read-out scheme - II

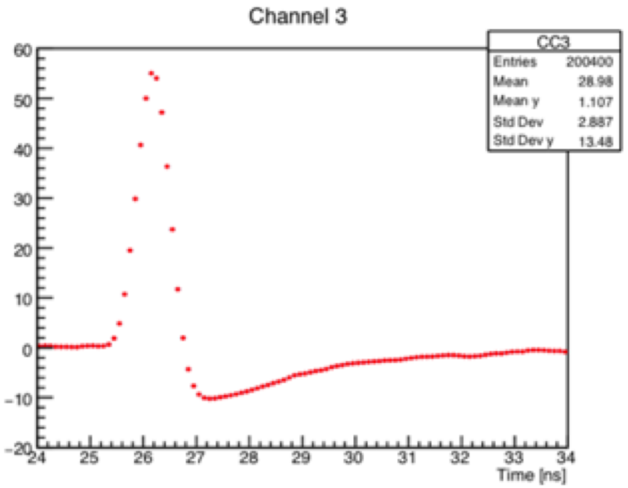
Signal characteristics:

- Short and fast, very similar to standard UFSD
- Bipolar (do not integrate)

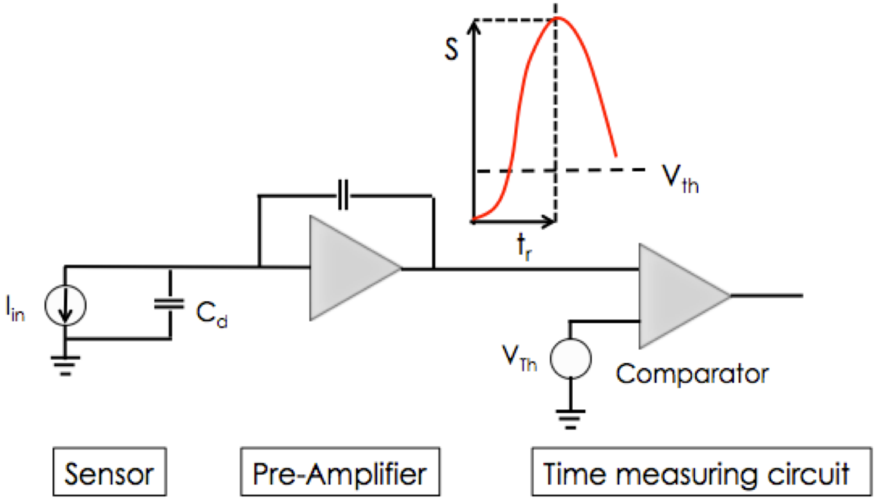
Read-out characteristics:

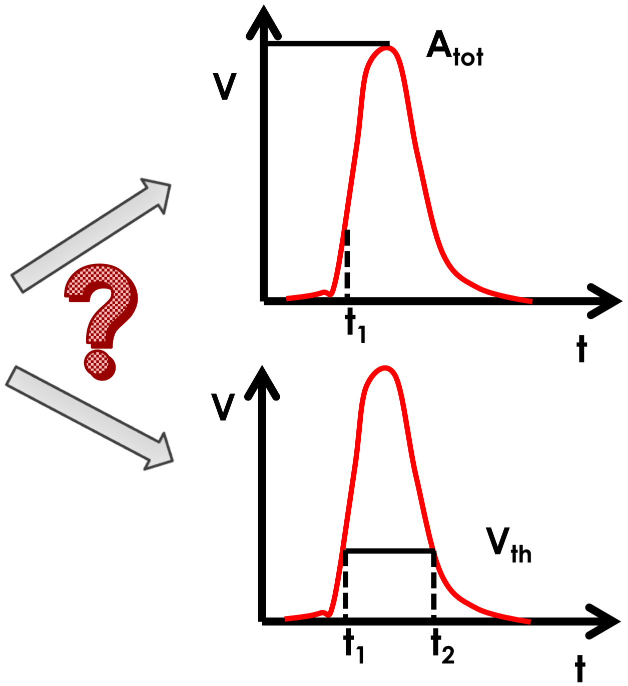
- Record signal amplitude with good precision
- Timing capabilities: keep the jitter below the Landau floor

BW ~ 500 MHz, $Q_{in} \sim 5 - 10\, fC$



➔ A Leading edge discriminator with linear Time-over-Threshold information or/and a DAC for amplitude measurement





Time of Arrival and Amplitude:

t_1, A_{tot}

TDC for t_1,

ADC for A_{tot}

Time over Threshold:

$ToT = t_2 - t_1$

Need TDC for t_1, t_2

Future directions

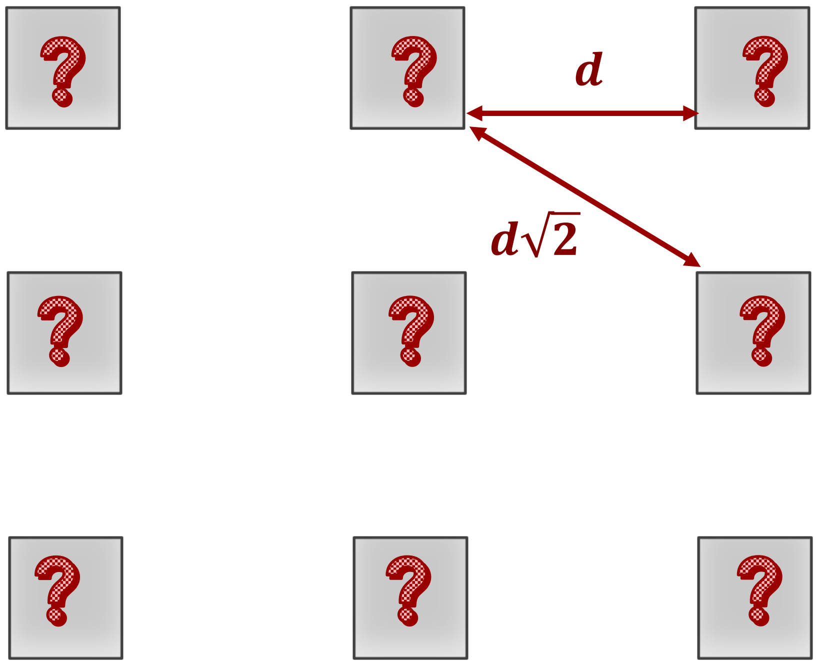
- **Position resolution**: design optimization
- **Temporal resolution**: thinner active area
- **Material budget**: thinner handle wafer
- **RSD strip detector**: design optimization
- **RSD simulator**: evolution of UFSD simulator Weightfield2
- **Far out designs**: where the wild things are
- **RSD field of applications**

RSD design evolution

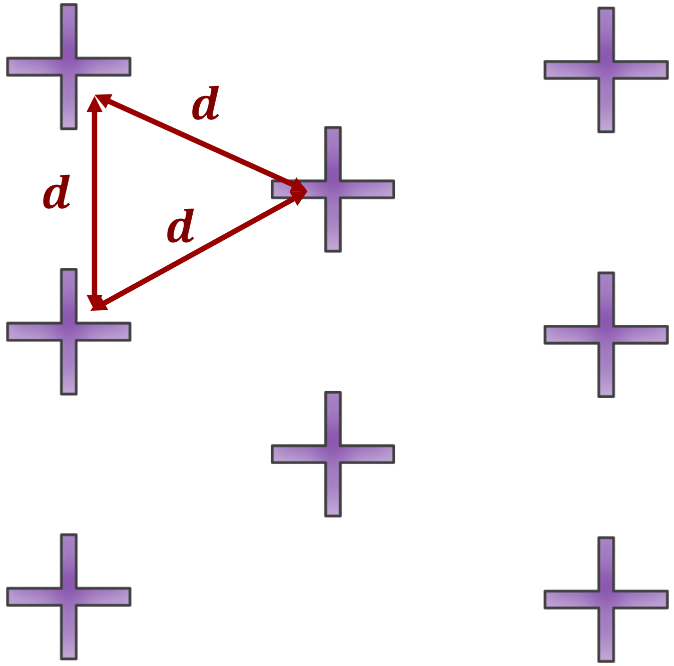
Lessons learnt:

- Very good position resolution (~ 3-5 um) even with large pixels (~100 – 200 um) can be achieved exploiting charge sharing
- The traditional "squared geometry" leads to a position-dependent space resolution
- Large metal pads prevent good hit localization
- **Uniform read-out is obtained when the distance between neighboring pad is the same**
- **The metal pads should be redesigned, using less metal**

Present design



Better design



RSD intrinsic time resolution

The AC readout scheme does not change the basic timing properties of UFSD:

$$\sigma_t^2 = \left(\frac{Noise}{dV/dt}\right)^2 + (\Delta ionization)^2$$

"Jitter" term

Here enters everything that is "Noise" and the steepness of the signal

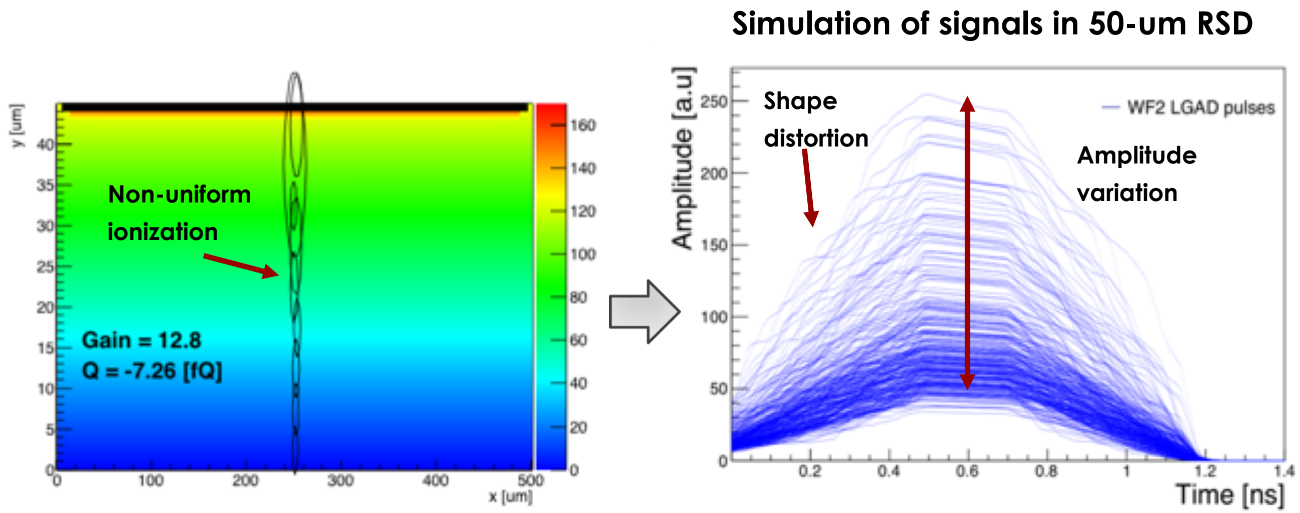
Non uniform ionization:

1) Amplitude variation:

variation in the total charge

2) Shape distortion:

Signal Shape distortion ➔Minimum time resolution

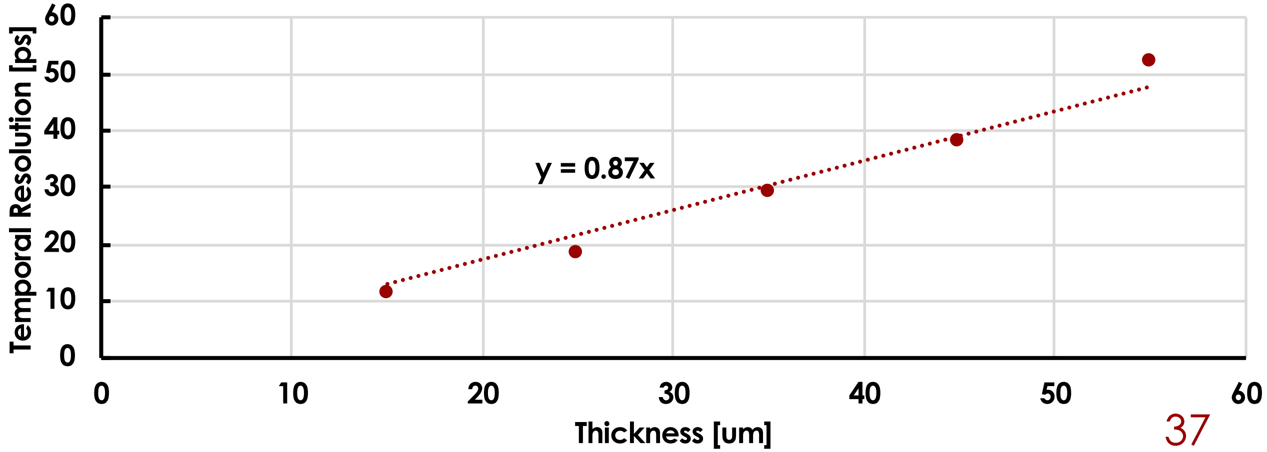


RSD minimum temporal resolution improves for thinner sensors:

40 ps @ 45 um ➔ 20 ps @ 25 um

However, the total charge is less (10fC➔5 fC) and the electronics might not be able to exploit this improvement

WF2 Simulation
Minimum temporal resolution vs sensor thickness using CDF = 50%

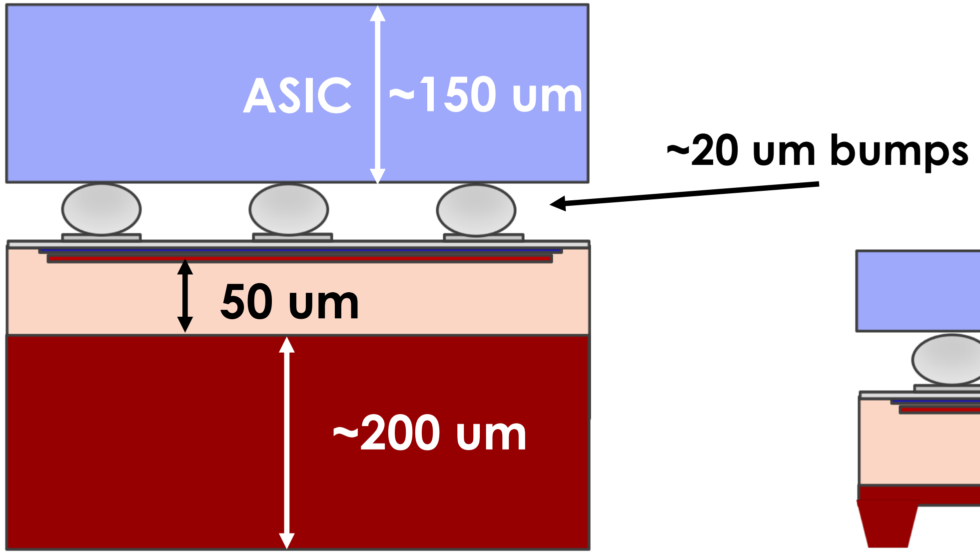


RSD material budget and time resolution

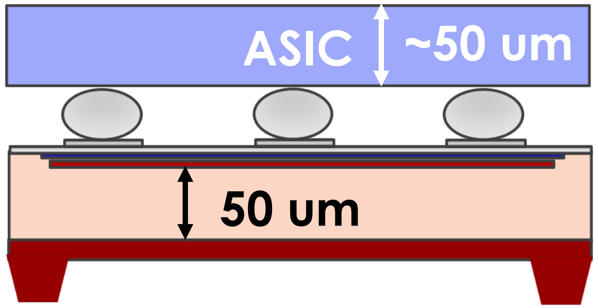
The active thickness of RSD sensor is rather small ~ 50 um.

In the present prototypes, the active part is attached to a thick "handle wafer"

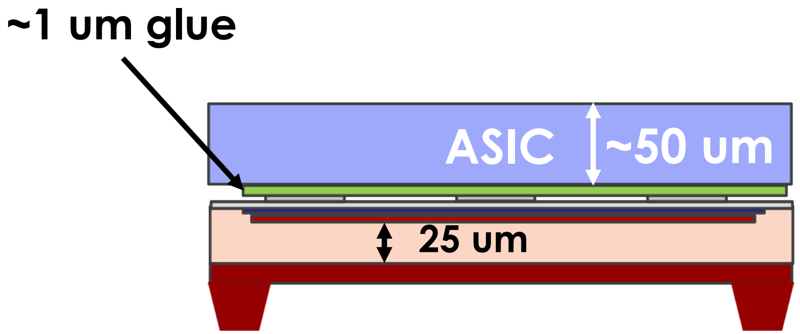
It is rather easy to thin the handle wafer and/or to leave a minimum support structure (similar to BELLE II)



Present design: no material budget optimization



- Thinned handle wafer:
  500 um ➔ 10-20 um
- Thinned ASIC

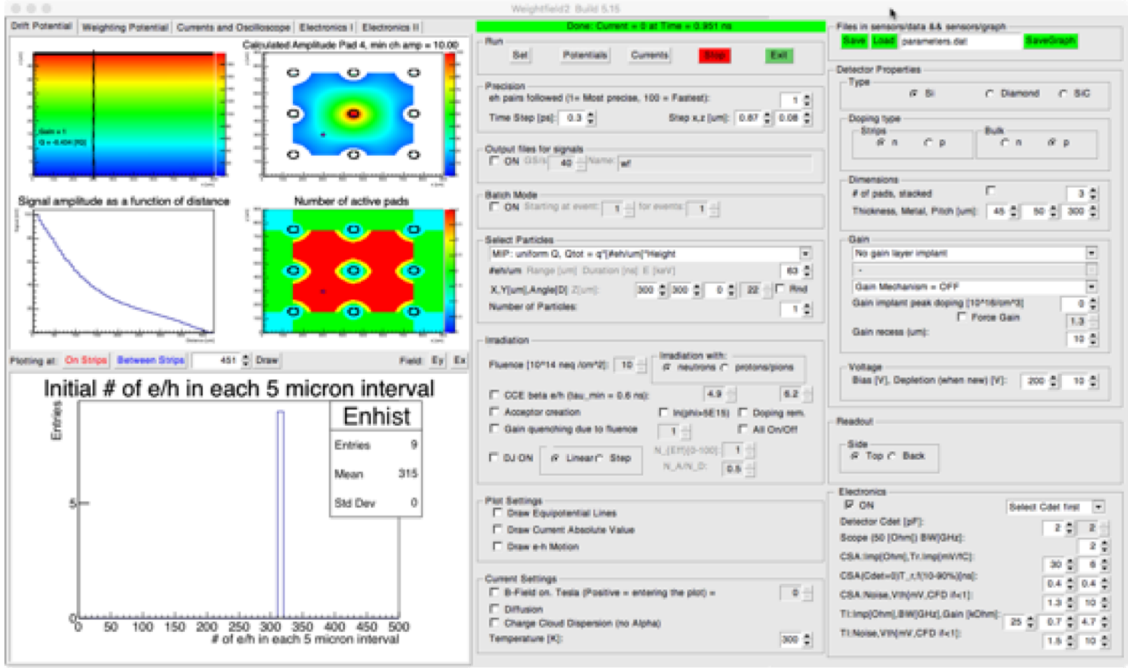


- Thinned active area:
  50 um ➔ 25 um
  50 ps ➔ 25 ps
- Remove bumps, use glue

RSD Simulator: $WF2_{RSD}$

In the development of Ultra Fast Silicon Detectors we have written and extensively used a simulator, Weightfield2.

- http://personalpages.to.infn.it/~cartigli/Weightfield2/Main.html
- WF2 emulates the current signals produced in a UFSD.
- It includes non-uniform ionization, radiation damage, B field, temperature
- It requires Root build from source, it is for Linux and Mac.
- It will not replace TCAD, but it helps in understanding the sensors response

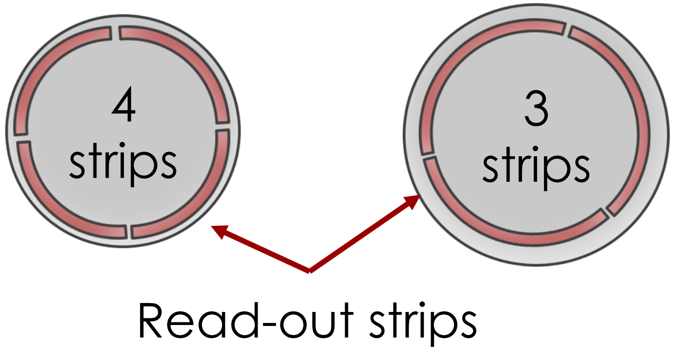


We are in the process of extending WF2 to include RSD, incorporating the RSD master formula and the signal sharing among pads placed with any array geometry.

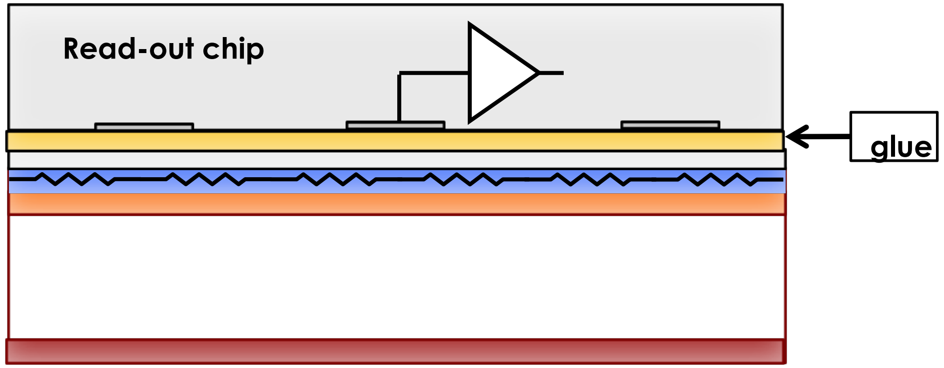
$WF2_{RSD}$ will emulate the charge sharing among pads and provide the current signals from each pad.

Where the wild things are

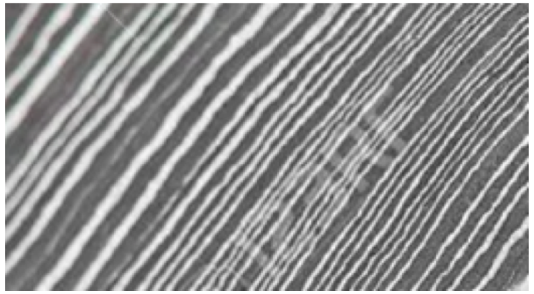
A circular RSD with 3 or 4 electrodes should be very accurate providing with a few channels excellent position (~ 5 um) and time (~ 35 ps) resolution. Looks promising for beam test apparatuses



Universal RSD: no metal pad, glued to the ASIC.
In RSD the signal is large, 5-10 fC, so it can be seen across a thin layer of glue.
The metal pads are provided by the read-out chip, no need to deposit metal pad on the RSD side.



Any metal pattern: as there is no implant underneath, the AC metal can be shaped into any pattern



RSD possible applications

Presently, very precise spatial resolution calls for small pixel size

CLIC: 5 – 10 um resolution, pixel size ~25 x 25 um^2

EIC = ~ 5 um resolution, pixel size ~20 x 20 um^2

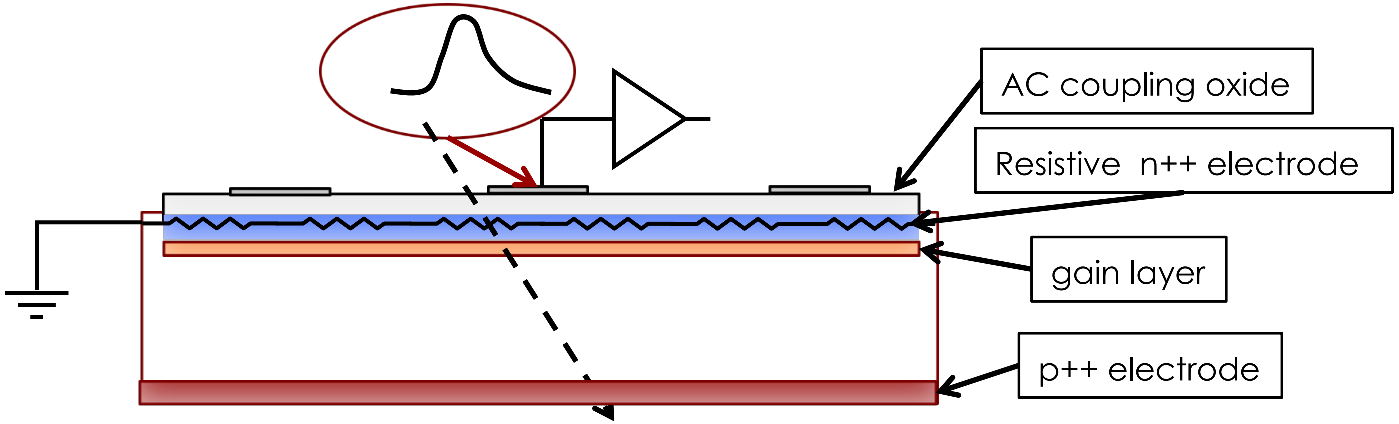
We showed that RSD sensors with large pixels (100 – 200 um) provide excellent position (~3-5 um) and temporal (15-20 ps) resolutions

RSD are well suited for applications with:

- No multiple hits in a 3x3 pixel area (low occupancy)
- Low noise (low leakage current)

These requirements suggest possible RSD use in environments such as e+e-, EIC, mu-mu colliders, and in non HEP fields where particles rate and fluence are low.

AC – LGAD / RSD - Timeline



AC-LGAD /RSD sensors enjoy a double name: the **key technological feature** is the **"resistive n++ layer"**, necessary to produce the local AC coupling. For this reason AC-LGAD, are called **"Resistive Silicon Detector", RSD**.

- AC-LGAD were proposed at the TREDI 2015 conference [1].
- The sensors presented here are manufactured at FBK within the RSD project (INFN) [2],[3].
- CNM produced AC-LGAD sensors in 2017 [4]
- BNL produced AC-LGAD in 2019 [5].
- Results shown from beamtest are from [6]
- The application of Machine Learning is [7]
- First results on AC-LGAD strips at beam test [8]

RD50 is very active in this development (internal R&D project, 3 talks yesterday at the RD50 workshop)

It takes a village

Very special thanks to the UFSD group, for enduring endless weeks of measurements in the lab and many many meetings

R. Arcidiacono[ab] , G-F Dalla Betta[ae], G. Borghi[fa], M. Boscardin[fa], M. Costa[ac], F. Fausti[ac], F. Ficorella[fa], M. Ferrero[ab], M. Mandurrino[a], J. Olave[a], L. Pancheri[ae], F. Siviero[a], V. Sola[a], M. Tornago[ac], ,G. Paternoster[f], H. Sadrozinski[d], A. Seiden[d], M. Centis Vignali[fa]

[a] INFN, [b] Università del Piemonte Orientale, [c] Università di Torino,
[d] University of California, Santa Cruz , [e] Università di Trento, [f] FBK

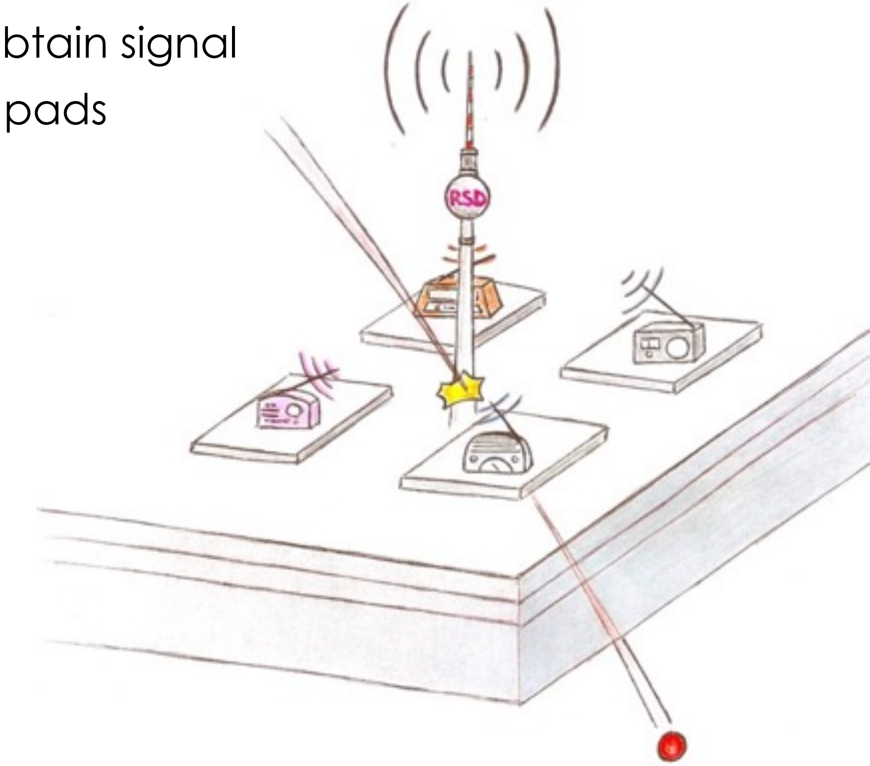
Fermilab beam test team: A. Apreysan, R. Heller, K. Di Petrillo, S. Los.

Acknowledgement

We kindly acknowledge the following funding agencies, collaborations:

- INFN - Gruppo V, UFSD and RSD projects
- INFN – FBK agreement on sensor production (convenzione INFN-FBK)
- Horizon 2020, grant UFSD669529
- U.S. Department of Energy grant number DE-SC0010107
- Dipartimenti di Eccellenza, Univ. of Torino (ex L. 232/2016, art. 1, cc. 314, 337)

Thank you for your attention



RSD are a novel n-in-p silicon device that evolves the LGAD design to obtain signal amplification with 100% fill factor and very strong signal sharing among pads

The RSD design maintains the excellent temporal resolution of UFSD sensors,: **$\sigma_t \sim 45\ ps$ for $50\ \mu m$ thick sensors at gain ~ 15.**

RSD exploits the resistive n+ layer to achieve charge sharing among pads. The spatial resolution is about 5% of the interpad distance:

Geometry	50 -100	100-200	150 - 300	200-500
σ_x [um]	4	5.5	5.9	15

The multiple signals that belong to a single RSD are well suited for reconstruction algorithms based on machine learning. We expect that this technique will provide the ultimate spatial and temporal resolution

The extended signal sharing in RSD is a drawback in environment with high density of tracks and high irradiation. Most likely RSD and FCC-hh don't go together

Bibliography

[1] N. Cartiglia, Tredi 2015,"Topics in LGAD Design" https://indico.cern.ch/event/351695/contributions/828366/attachments/695875/955507/TREDI_Cartiglia.pdf

[2] M. Mandurrino *et al.*, "Demonstration of 200-, 100-, and 50- micron 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.

[3] 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

[4] H. Sadrozinski, HSTD11, "Time resolution of Ultra-Fast Silicon Detectors", https://indico.cern.ch/event/577879/contributions/2740418/attachments/1575077/2487327/HSTD1--HFWS1.pdf

[5] G. Giacomini, W. Chen, G. D'Amen, A. Tricoli, Fabrication and performance of AC-coupled LGADs, JINST 14 (09) (2019)

[6] M. Tornago et al, "First combined laser and beam test analysis of Resistive AC-coupled LGAD", paper in preparation

[7] F. Siviero et al, "Application of machine learning algorithms to the position reconstruction of Resistive Silicon Detectors", paper in preparation

[8] A. Apresyan, "Measurements of an AC-LGAD strip sensor with a 120 GeV proton beam", https://arxiv.org/abs/2006.01999

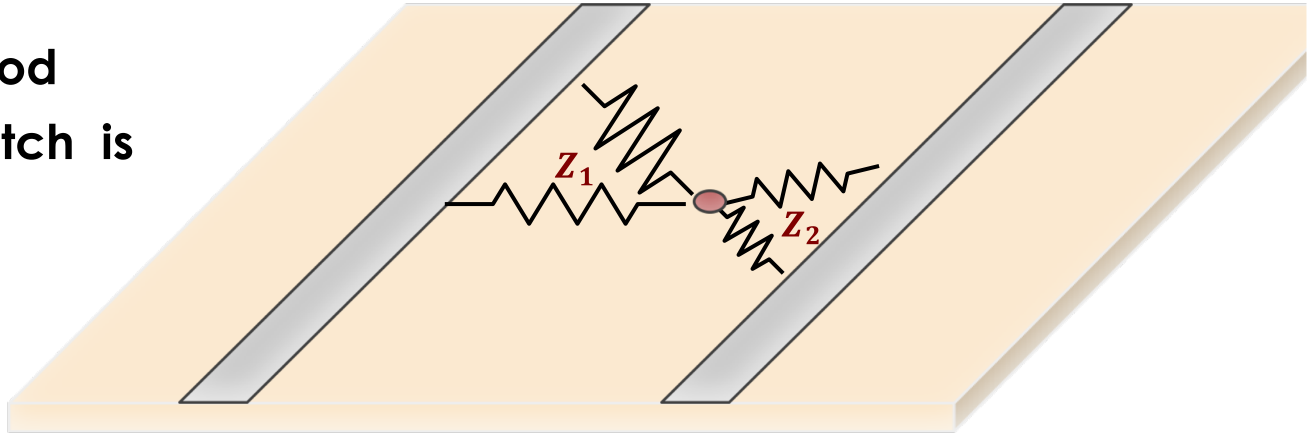
Extra topics

RSD strip detectors

The FBK RSD1 sensor production included 2 type of strip designs.
We tested them with the TCT laser and they work fine.
This first design did no exploit completely the charge sharing capability

In the next productions, several strip pitch and metal width will be explored, using thin metal strips (~ 20-30 um) at increasing distance (50,100, 200, 500 um).

Given the very favorable geometry, very good position resolution (~ 5 – 10 um) with large pitch is expected



RSD strips should have small metal and large intergapd

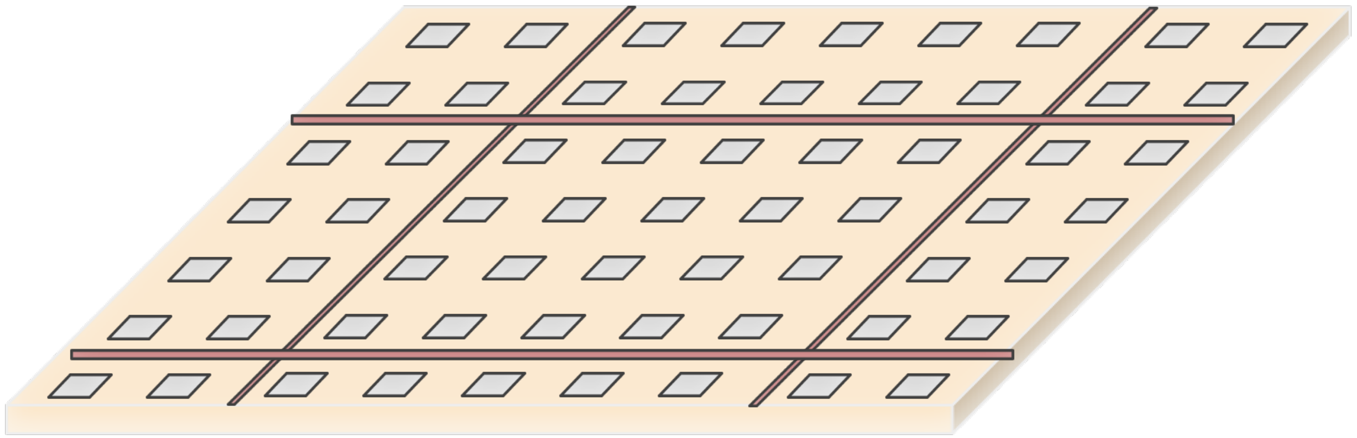
Results on AC-LGAD strips manufactured by BNL was shown here: K. Di Petrillo,
https://indico.cern.ch/event/918298/contributions/3880513/attachments/2050888/3437589/2020.06.04.kdp.ACstrips_RD50.pdf

RSD large sensors

Pixellated RSD sensor have a single n-in-p diode.

This can be a problem in large detectors (in 6" wafers they can be~ 10x10 cm^2)

Possible solution: insert a macro grid of ground contacts connected to the guard ring.



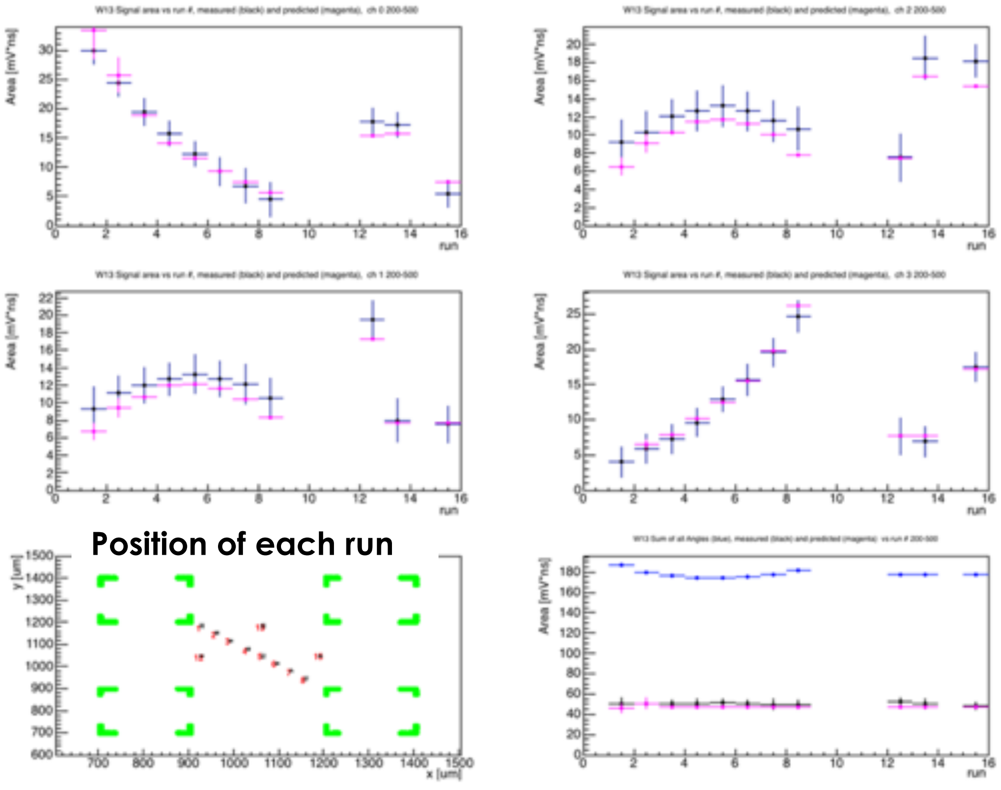
This grid isolates the macro area from each other, making the detector look like a sequence of smaller units

The RSD master formula vs n+ resistivity

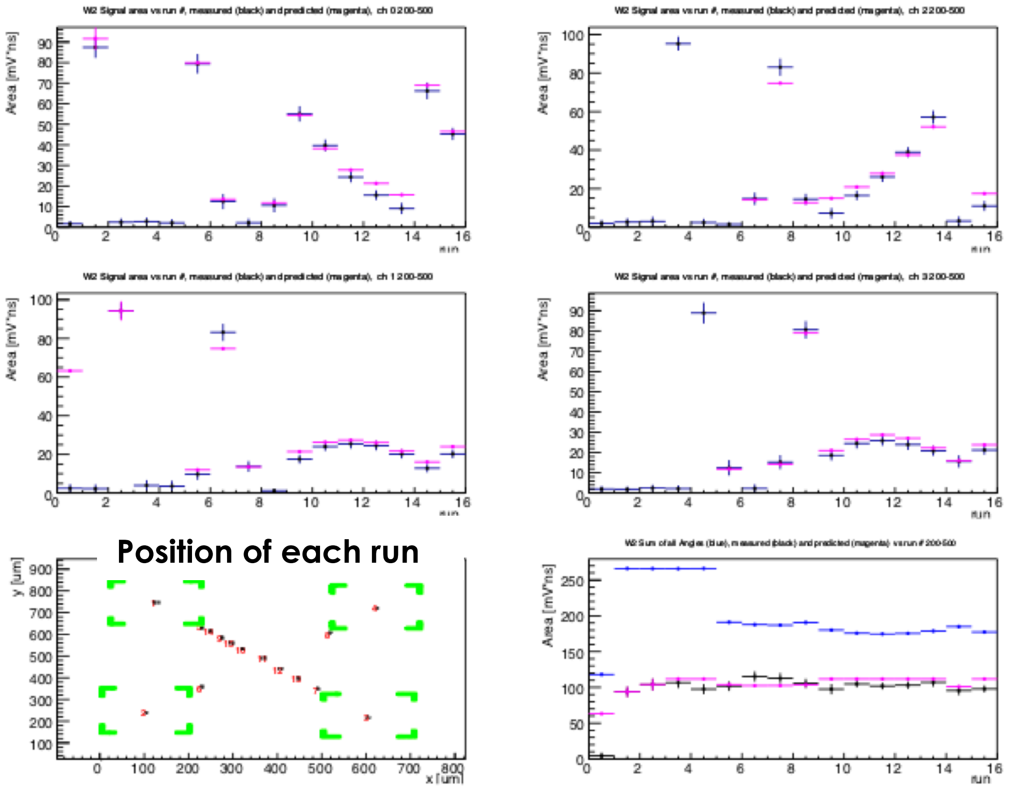
The RSD master formula does not depend on the n+ resistivity since **it predicts the relative split** of signals among the pads.

$$S_i(\alpha_i, r_i) = \frac{\frac{\alpha_i}{\ln(r_i)}}{\sum_1^n \frac{\alpha_i}{\ln(r_i)}}$$

Signal split among pads as a function of run number (black = measured, magenta = predicted)

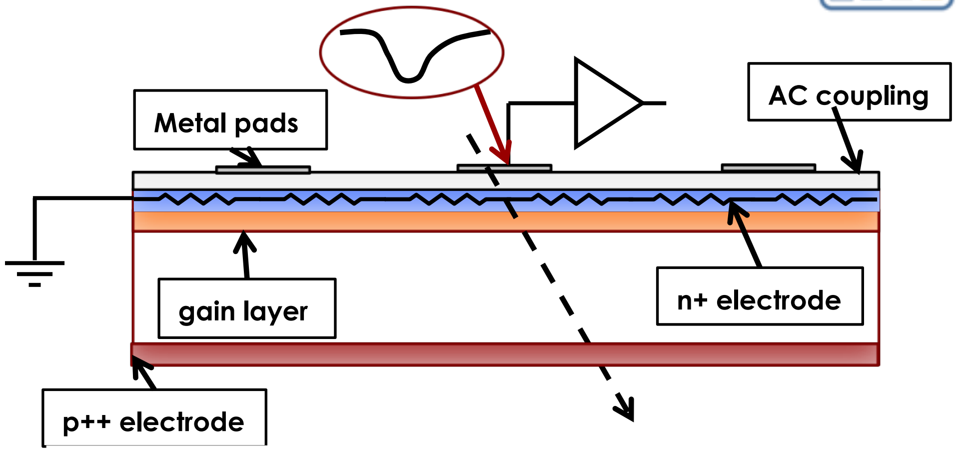


RSD1 W13: low resistivity n+ implant



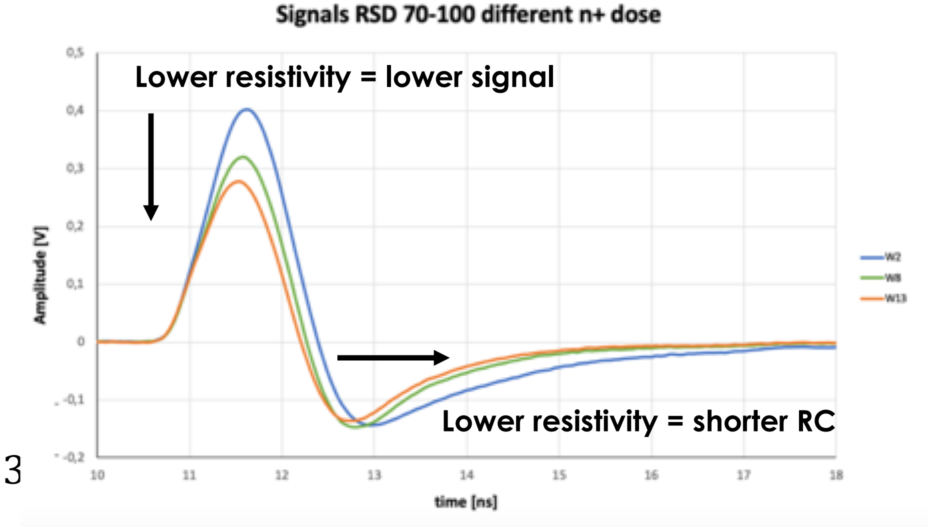
RSD1 W2: high resistivity n+ implant

The effect of n+ resistivity



What are the effects of n+ resistivity on the signal?

The signal is formed on the n+ layer, and it is coupled to the AC metal pad.
If the n+ is too conductive, it will not couple the charges to the AC metal pad

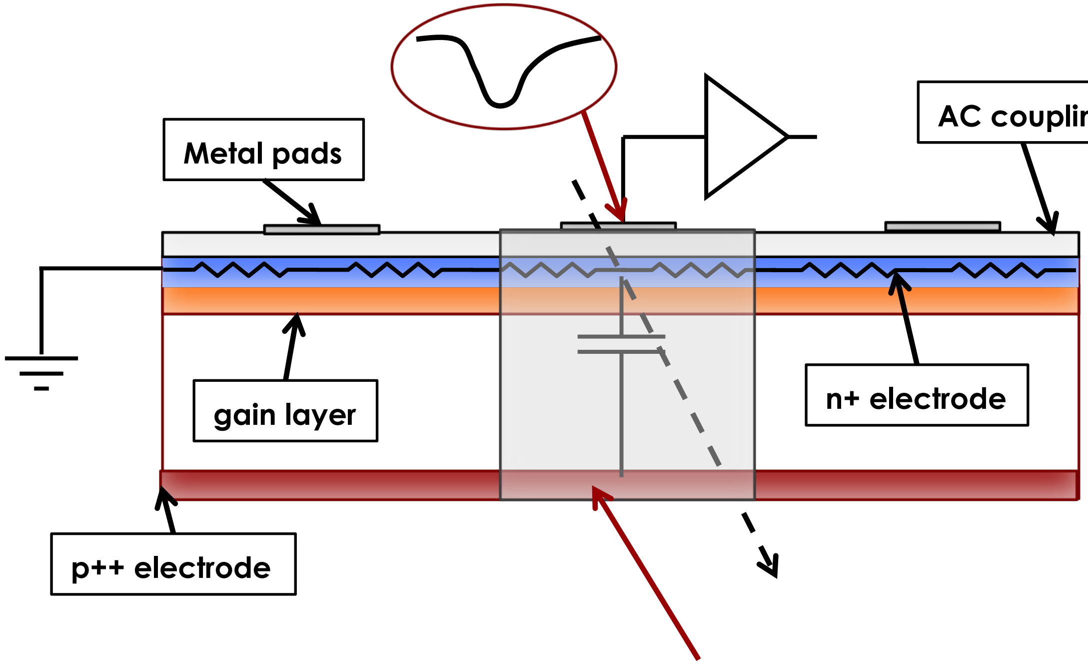


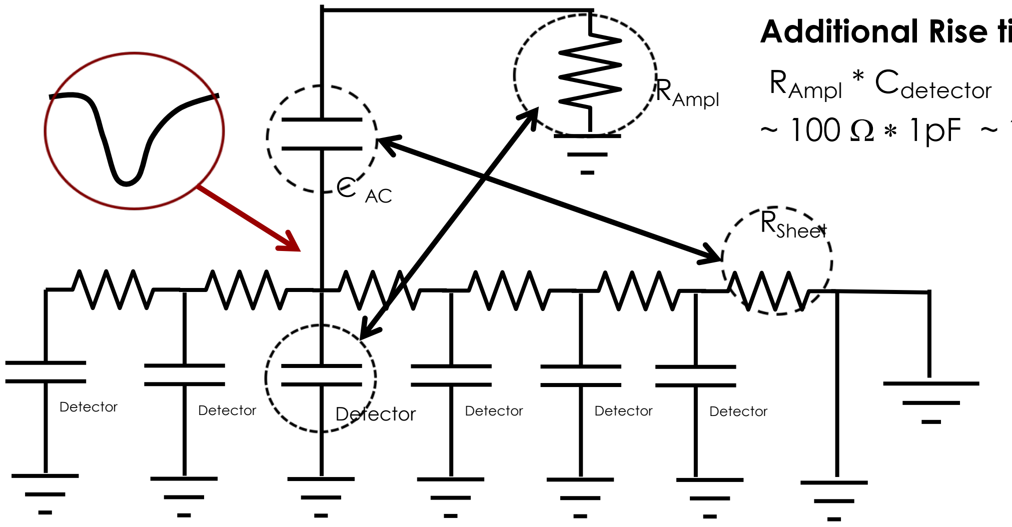
➔ the AC amplitude decreases with increasing n+ doping.
In the limit of very conductive n+, there is no AC signal.

➔ Additional effects, studied on RSD1 wafers (W13, W2) with $\frac{Doping\ W13}{Doping\ W2} \sim 3$

- RC discharge time is shorter at lower resistivity, $(\frac{\tau_{W13}}{\tau_{W2}} \sim 0.5)$
- The β $[\mathrm{ns}/\frac{ln(r)}{\alpha}]$ coefficient, the delay, decreases at lower resistivity $(\frac{\beta_{W13}}{\beta_{W2}} \sim 0.8)$

RSD Read-out scheme: input capacitance





Additional Rise time

$R_{Ampl} * C_{detector}$

~ 100 Ω ∗ 1pF ~ **100 ps**

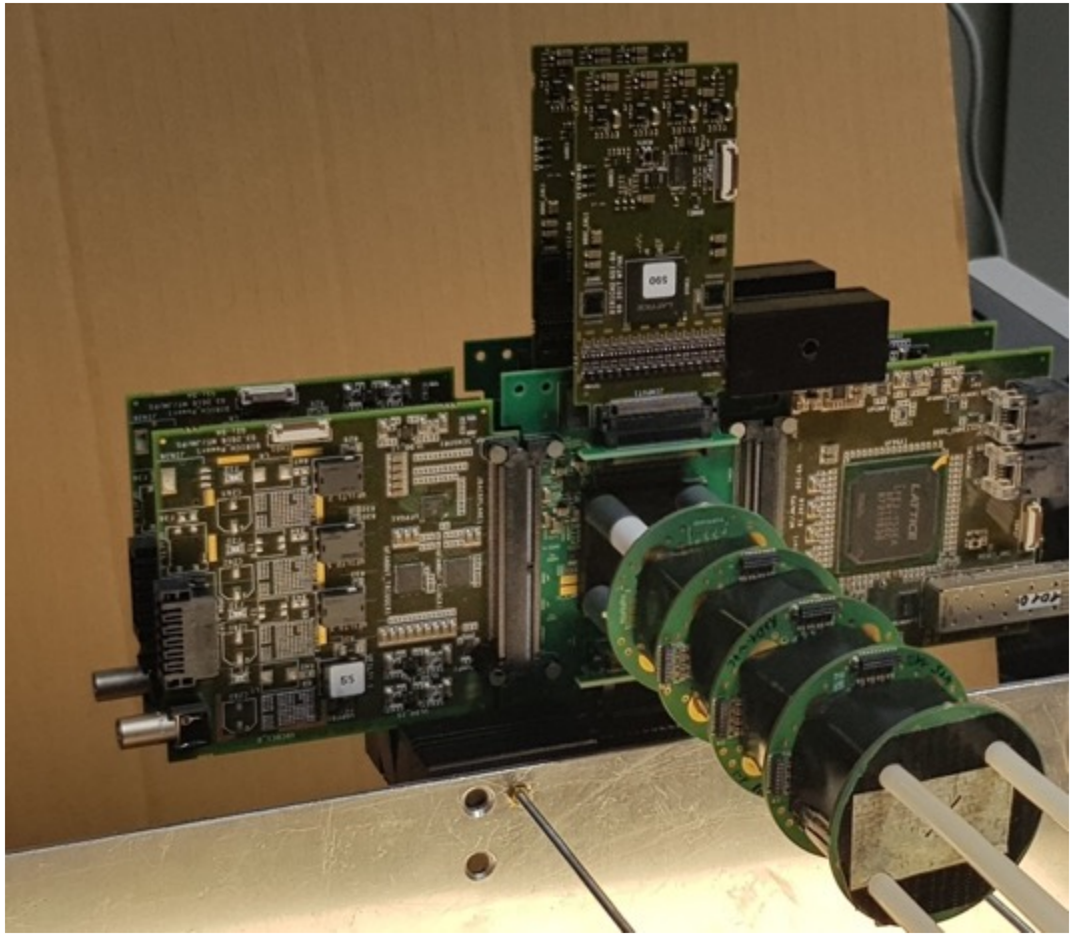
The resistive n+ electrode limits the geometrical volume seen by the read-out: given the high frequencies involved, the capacitive path to ground is more favorable than the resistive path

- Rather small capacitance: $\frac{1}{C_{Tot}} = \frac{1}{C_{AC}} + \frac{1}{C_{Det}} \sim \frac{1}{C_{Det}}$
- The AC pad discharge time is: $R_{Sheet} * C_{AC}$~ 2 kΩ ∗ 3 pF ~ 4 ns
- The signal rise time is increased by: $R_{Ampl} * C_{Det}$~ 100 Ω ∗ 1pF ~ 100 ps

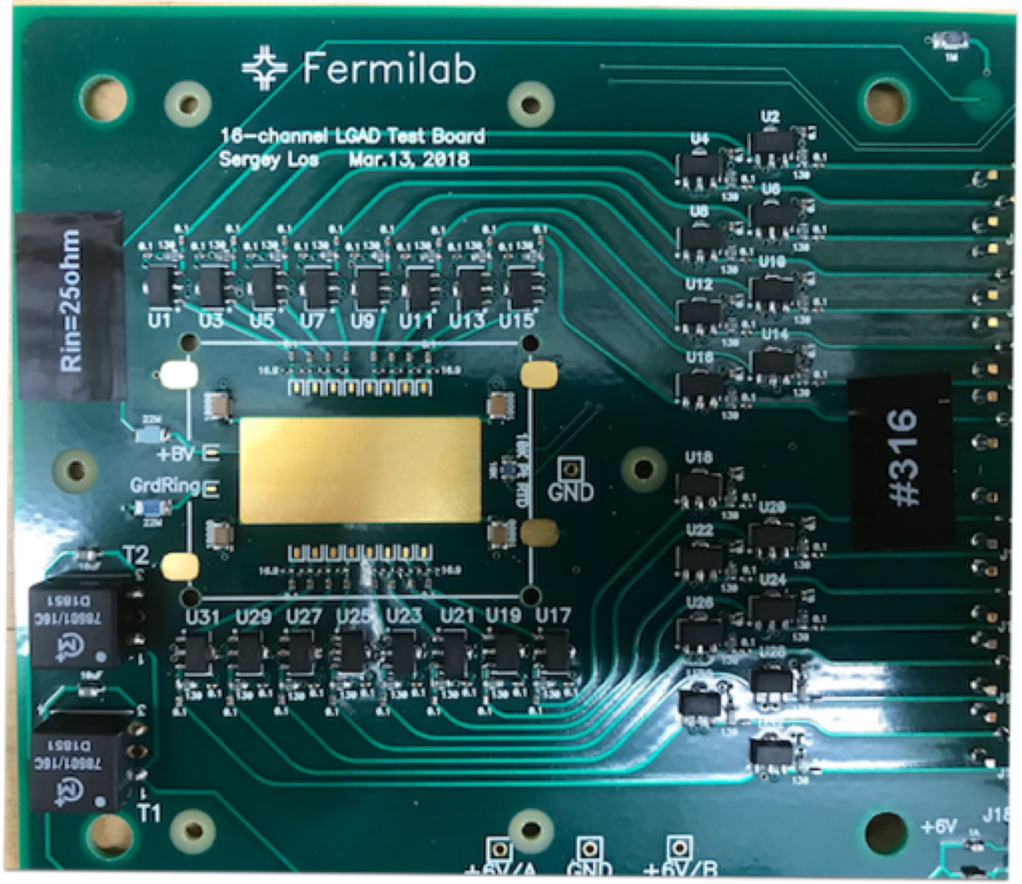
RSD use in HADES

The HADES collaboration (GSI) has completed a beam test with a combination of UFSD and RSD strips.

2.5 GeV/c protons, 1.2 MHz/ strip, results in the near future



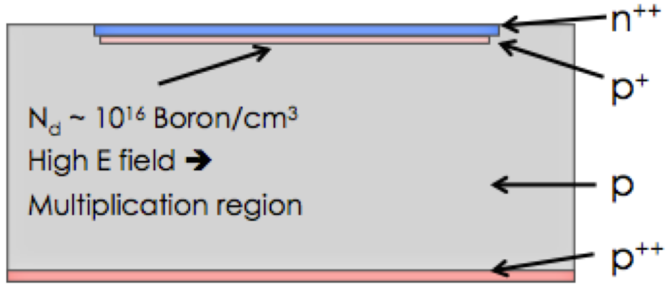
FNAL 16-ch board



RSD radiation resistance

The effect of irradiation on RSD is similar to that of the other LGAD-based devices:

- Decrease of charge collection efficiency due to trapping
- Doping creation/removal
- Increased leakage current, shot noise



Most important fact: irradiation de-activate the gain layer
➔ the electric field decreases, and the multiplication stops.

RSD has been irradiated, albeit not yet tested after irradiation.

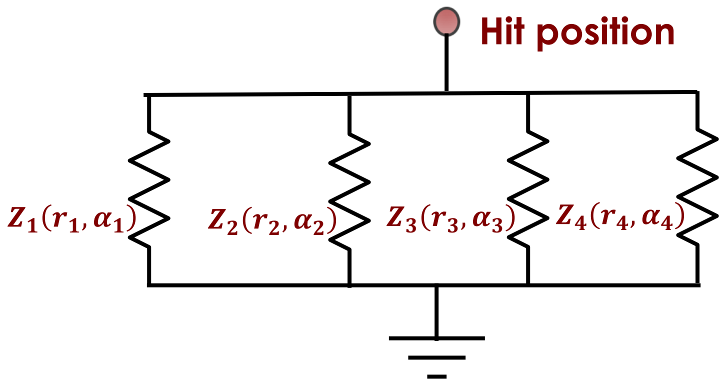
Possible outcome: RSD will behave as the other LGAD-based devices, working well up to fluences of about ~ 1E15 n_{eq}/cm^2

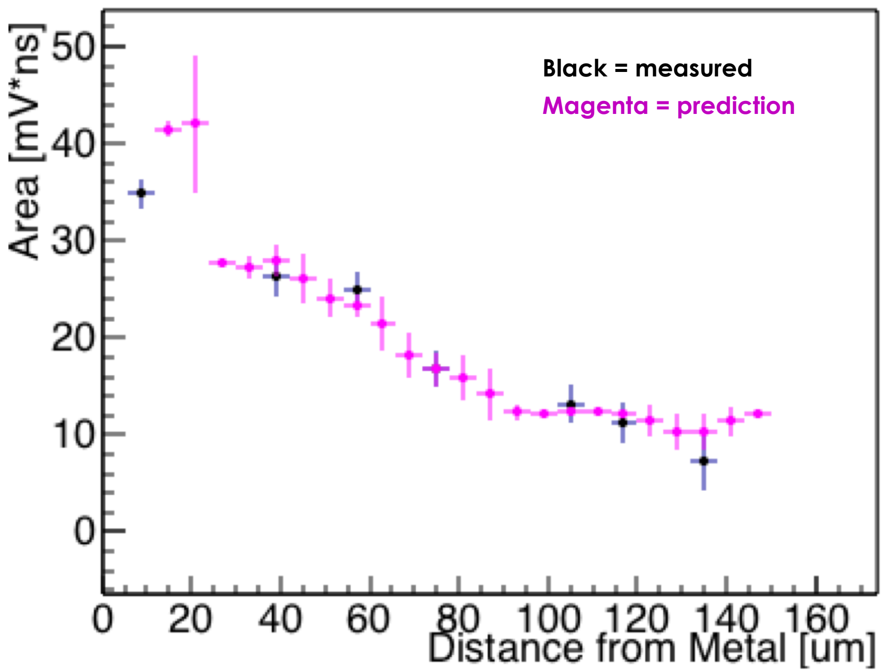
Unknown: effect of enhanced oxide charges due to radiation to the AC coupling mechanism

Signal amplitude as a function of position – one pad

How does the signal change as a function of position?

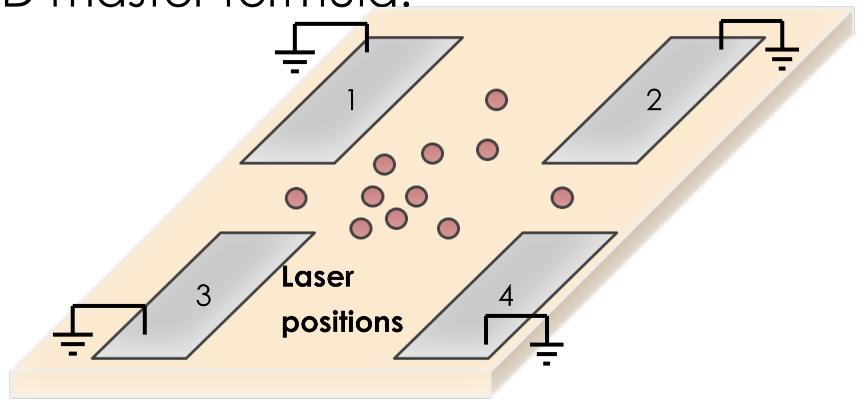
Moving the spot position changes the impedance to all 4 pads, all 4 signals changes together.





➔ Prediction obtained using RSD master formula:

$$S_i(\alpha_i, r_i) = \frac{\dfrac{\alpha_i}{\ln(\beta * r_i)}}{\sum_1^n \dfrac{\alpha_i}{\ln(\beta * r_i)}}$$



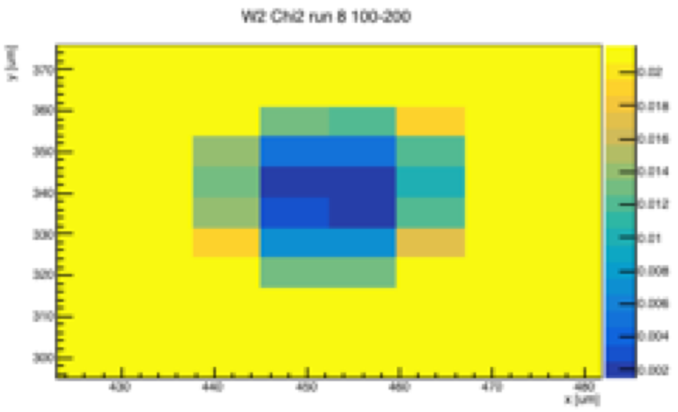
Position reconstruction method: the recipe

Recipe:

- For each position, using the RSD master formula, calculate S_i^{Calc}
- Find which x-y bin minimize the quantity:

$$\chi^2 = \sum_{1}^{4} \frac{\left[S_i^{Meas} - S_i^{Calc}\right]^2}{\sigma}$$

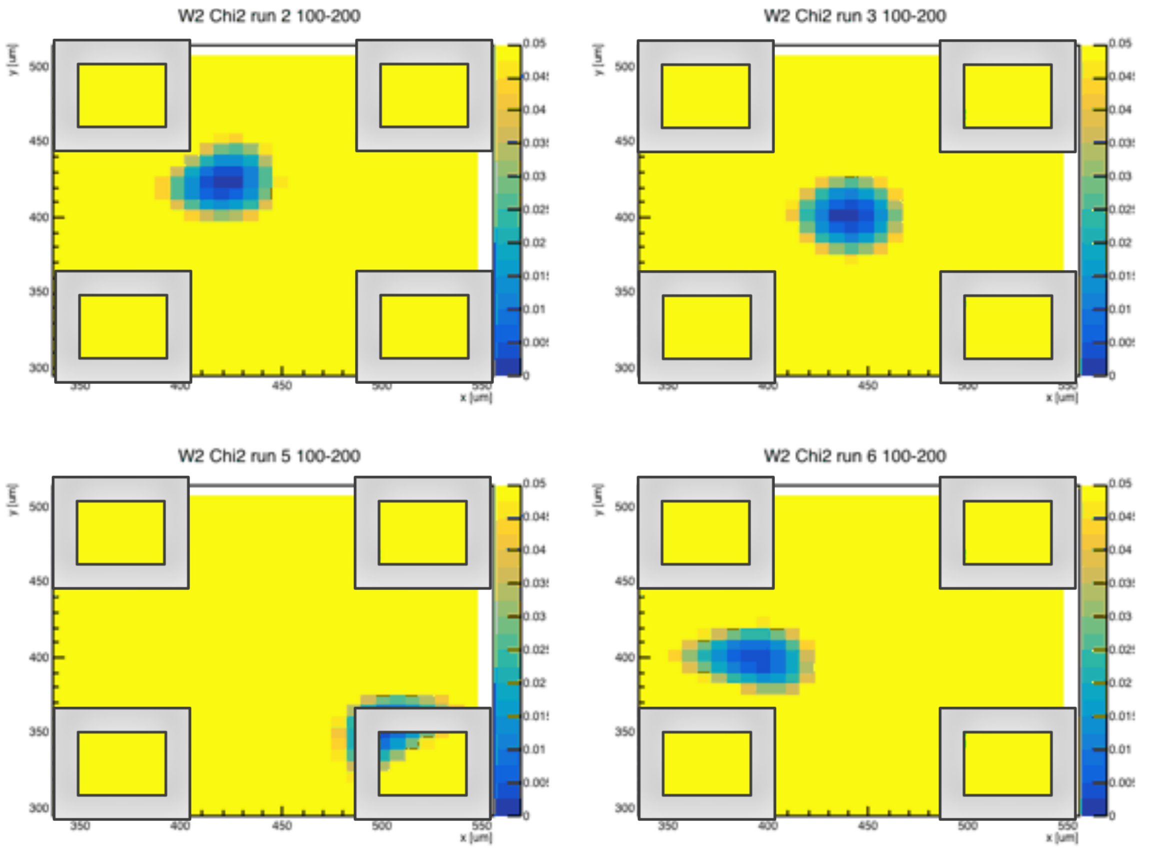
- Perform a local interpolation around the minimum.



χ^2 values for 4 different laser shots

(sensor geometry:100-metal 200-pitch)

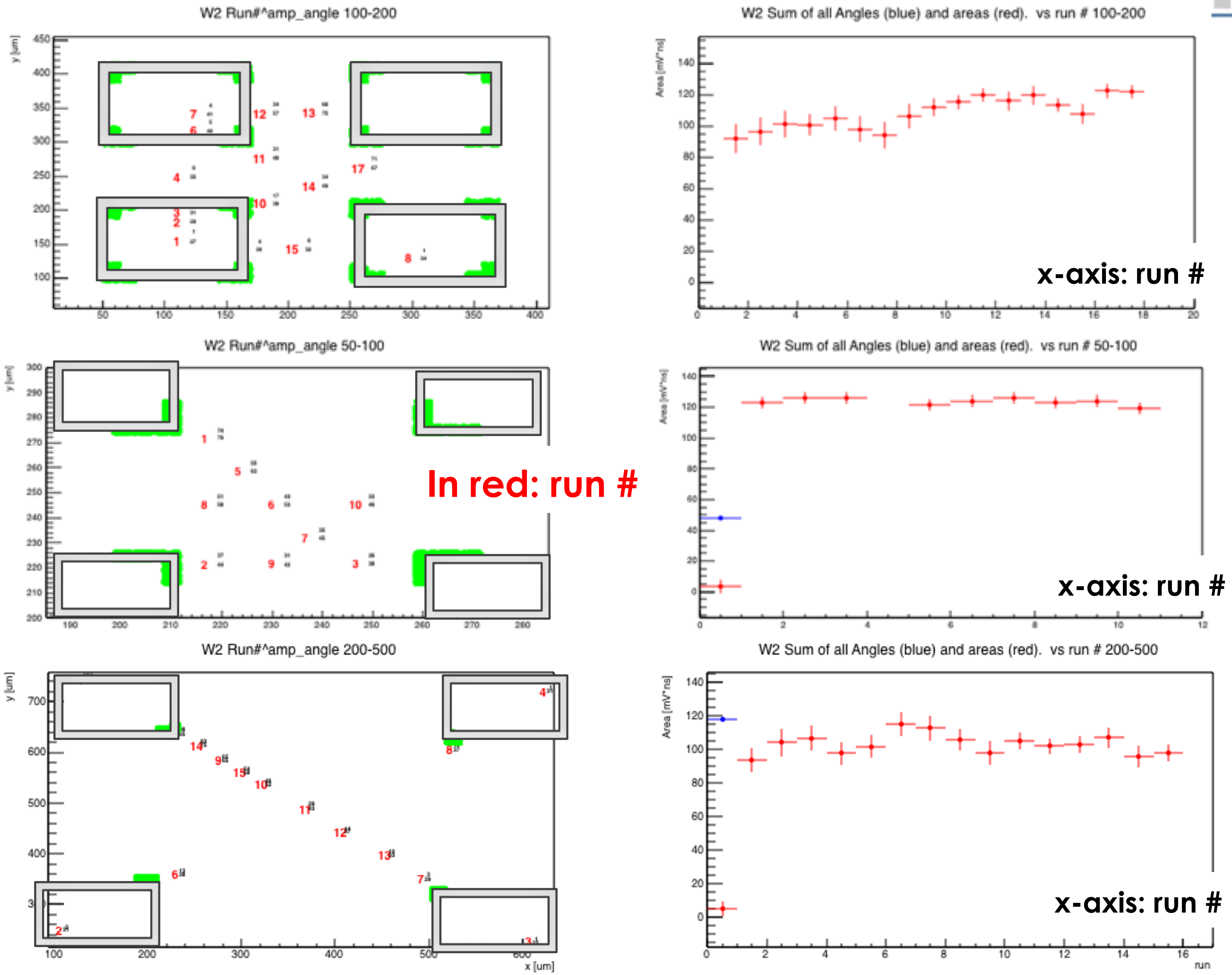
The reconstructed position is the bin with the minimum χ^2 value



Laser study: 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

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

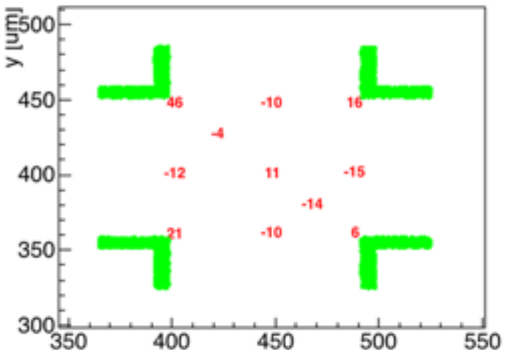


Laser study: time resolution

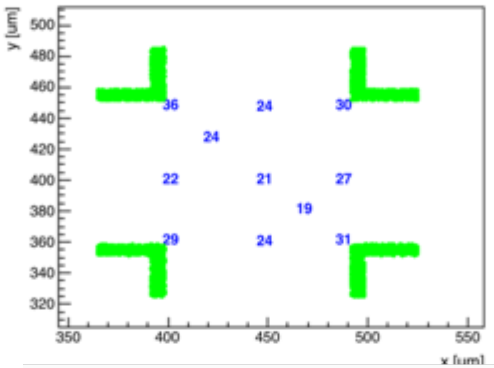
The **hit time** is obtained combining the timing information from each pad, after correcting for delay

Geometry:	**100 Metal, 200 pitch**	**200 Metal, 500 pitch**
Temporal precision:	**28 ps**	**35 ps**

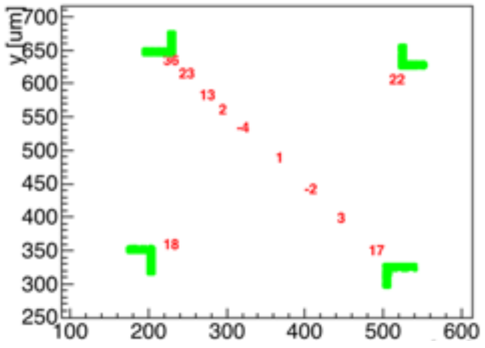
Offset at each point



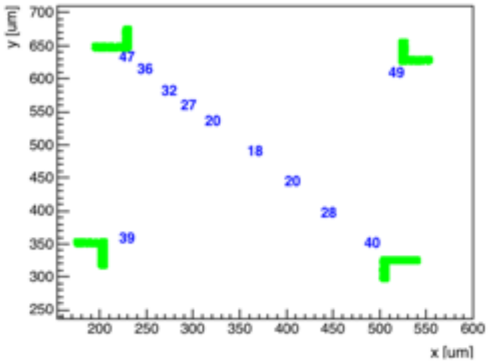
Resolution at each point



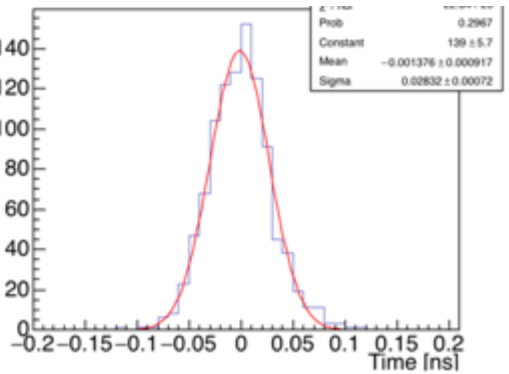
Offset at each point



Resolution at each point

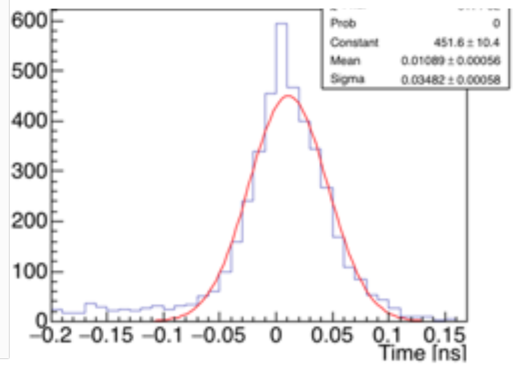


Total resolution



RSD maintain the "usual" excellent temporal resolution of standard UFSD

Total resolution



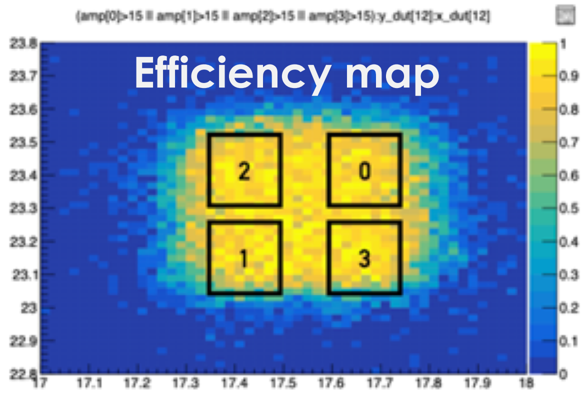
Fermilab beam test results

All details in: M. Tornago, 36th RD50 "Latest results on RSD spatial and timing resolution https://indi.to/2cGQy

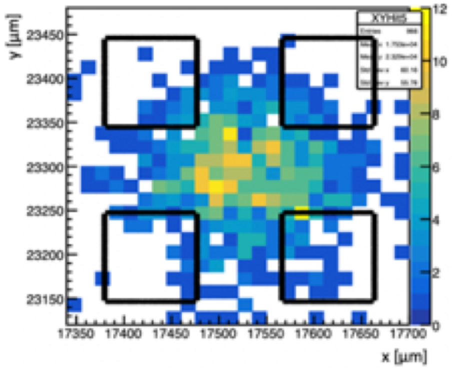
Data taken with RSD 3x3 100-200 and 190-200 geometries

Lesson learnt:

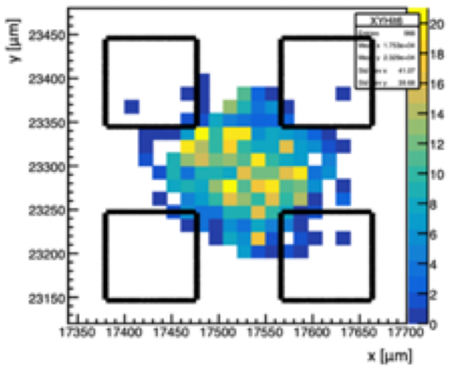
- RSD are ~ 100% efficient
- The RSD x-y hit reconstruction worked very well
- The time resolution is $\sigma_{t\ 100-200} = 44\ ps, \sigma_{t\ 190-200} = 42\ ps$ similar to UFSD results, limited by non-uniform ionization
- The metal size (100 vs 190 um) does not influence the time resolution



	single pad	3 pad	4 pad
100-200 laser	45 ps	Improves as $1/\sqrt{n}$ →	22 ps
100-200 test beam	50 ps →	44 ps	-
190-200 test beam	35 ps → ($\cancel{1/\sqrt{n}}$)	42 ps	-



x-y tracker reconstruction



x-y RSD reconstruction

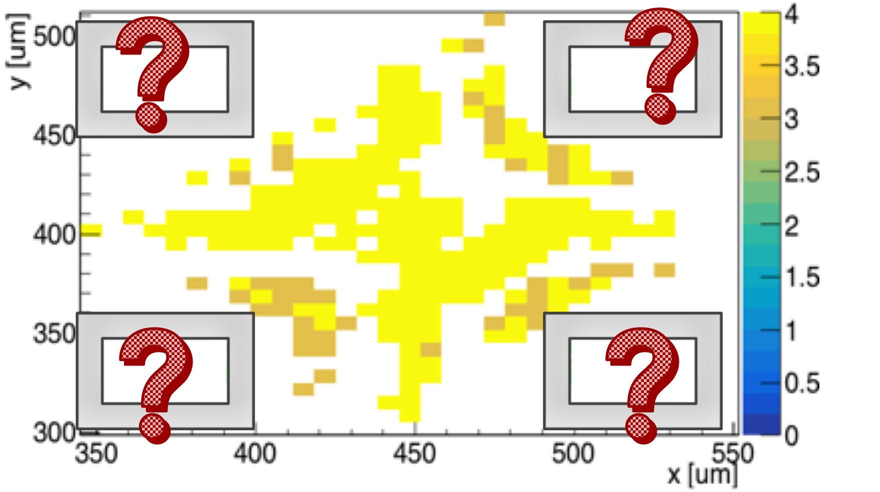
Small improvement combining pads in beam test:
resolution limited by the effects of non-uniform ionization that are fully correlated

Position resolution: the metal problem

The results shown so far are obtained by **shooting the laser between pads**.

What does it happen when the particle hits a metal pad?

100 – 200 Number of pads used in reconstruction

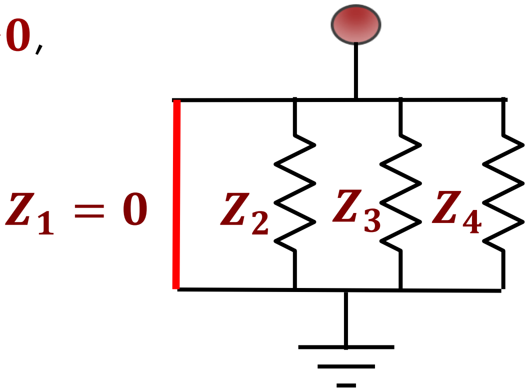


The impedance for that pad is very small $Z_i \sim 0$,

➔ The whole signal is seen by just one pad:

➔ No charge sharing

➔ Position resolution = $metal/\sqrt{12}$

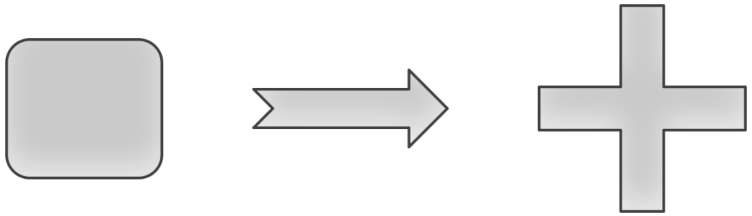


$$S_1 \propto \frac{\frac{1}{Z_1}}{\sum_1^n \frac{1}{Z_i}} \sim 1$$

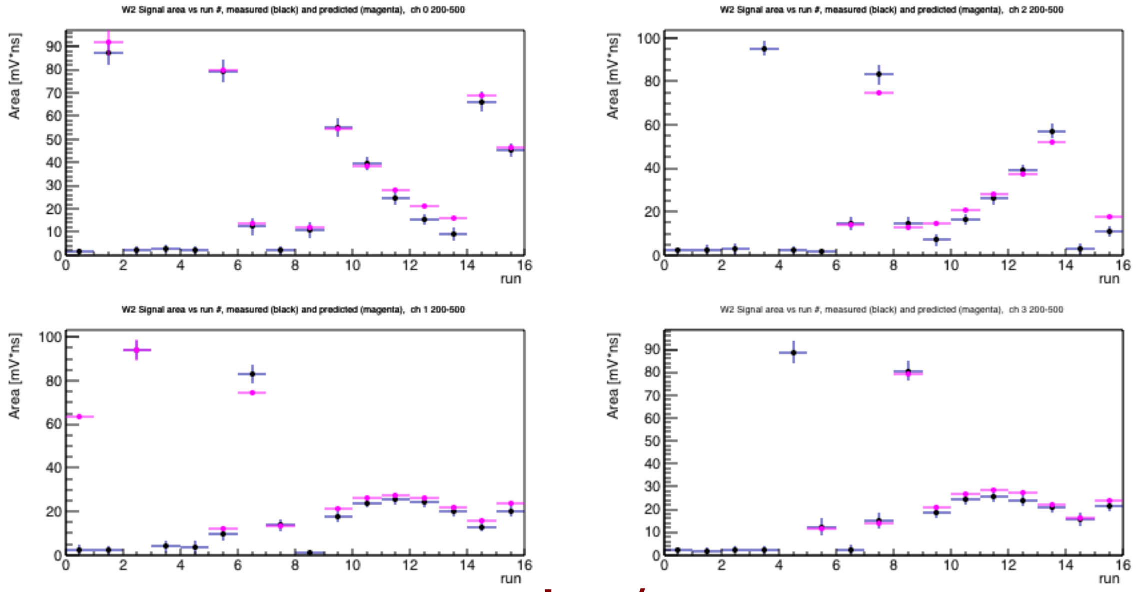
Solution:

➔ do not use "solid" metal pad

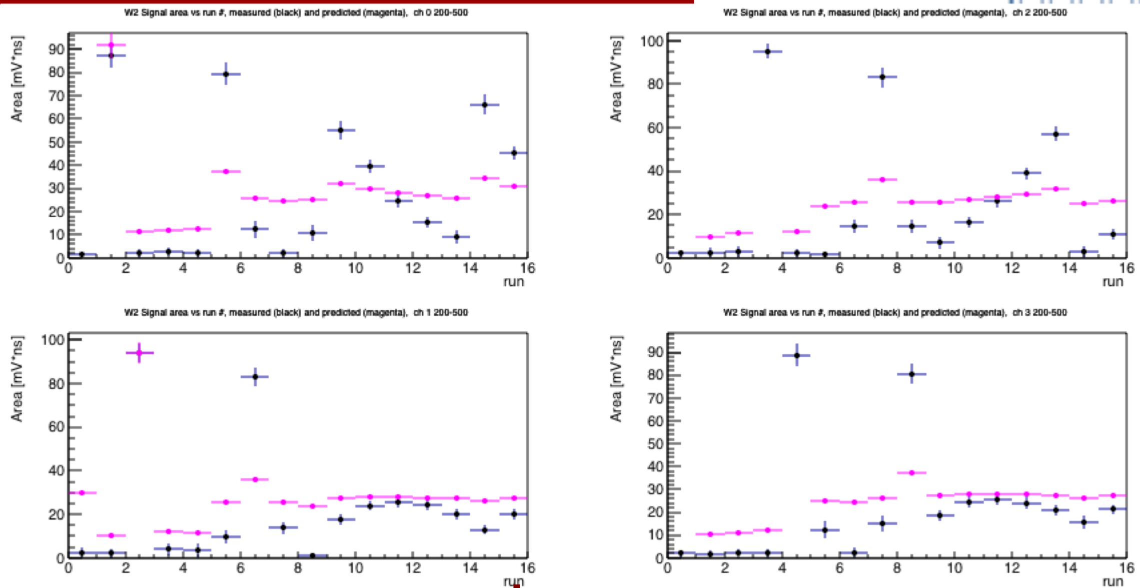
➔ Use geometries that do not absorb the whole signal



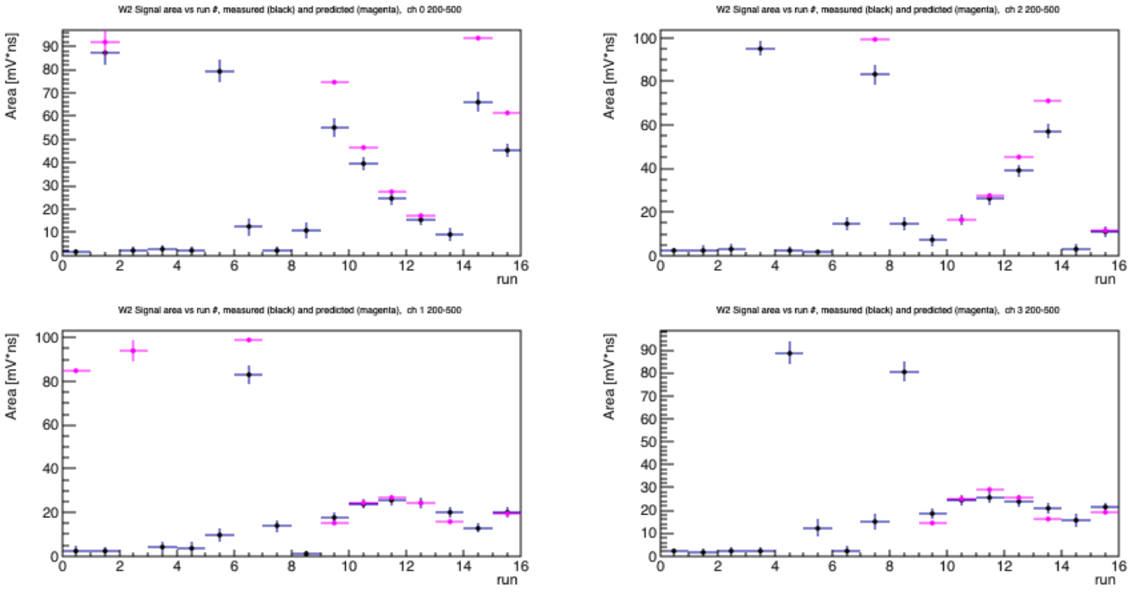
Different sharing laws



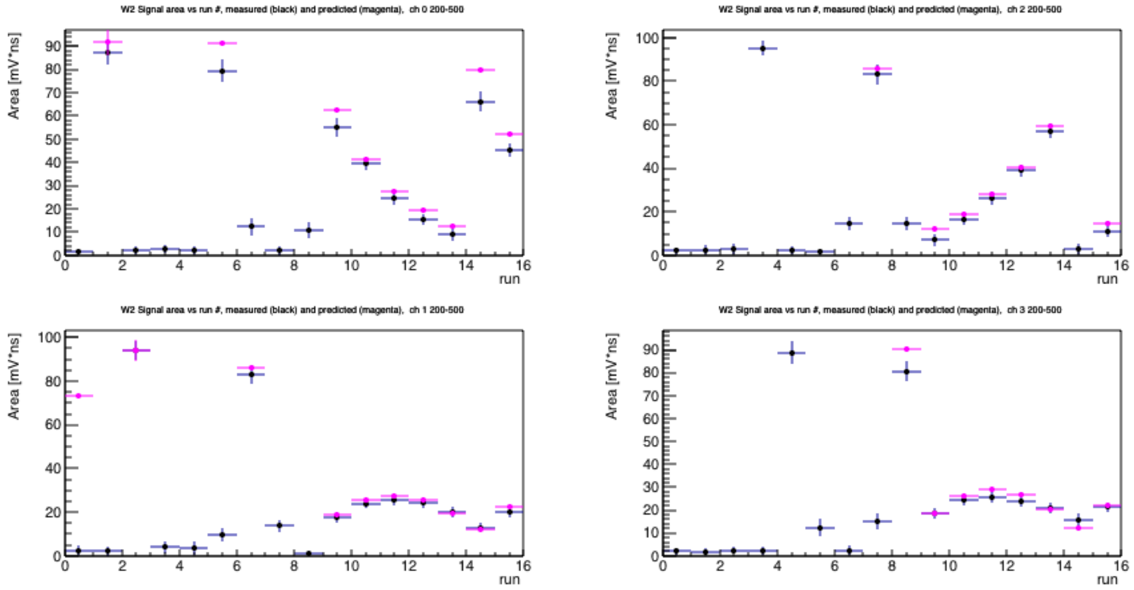
Log/ang



Log



Lin/ang

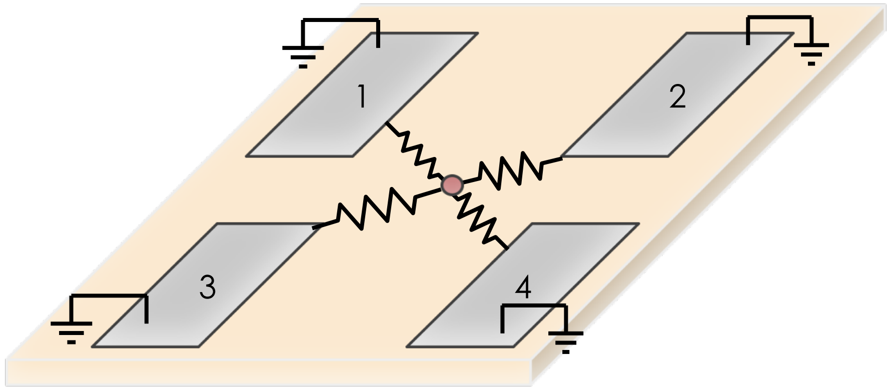


sqrt/ang

Laser study: signal delay

There is one more interesting point.

Let's compute the time of the event as the average time seen by the 4 pads:



$$RSD_{Time} = \frac{1}{4}\sum_{1}^{4} t_i^{True} = \frac{1}{4}\sum_{1}^{4} t_i^{Meas} - \beta\frac{1}{4}\sum_{1}^{4}\frac{ln(r_i)}{\alpha_i}$$

The sum of the resistivity, $\sum_1^4 \frac{ln(r_i)}{\alpha_i}$**, is actually a constant** (it is equivalent of the signal amplitude) for every point of the sensor, **so it does not contribute to the time resolution**, it is just an offset ➔ **no need to know accurately the delay**

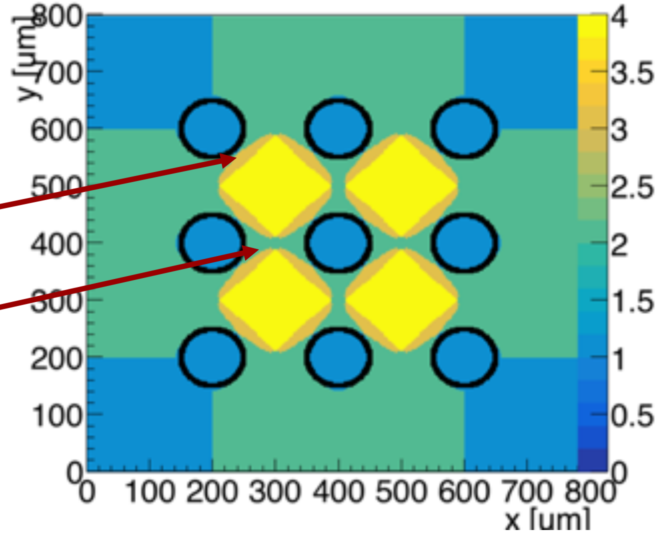
$$\sigma_{tot}^2 = \sigma_{Trigger}^2 + \sigma_{RSD}^2 = \sigma_{Trigger}^2 + \frac{1}{4}\sqrt{\sum_{1}^{4}\sigma_{t_i^{Meas}}^2}$$

Position resolution: the geometry problem

In a squared pixel geometry, **4 pads are necessary to obtain optimal resolution**

- **When only 3 pads are used**, the reconstructed position is "pulled away" from the missing pad
- **When 2 pads are used**, the hit position cannot be determined

100 – 200 Number of pads used in reconstruction
Amplitude = 120 mV, min amplitude = 15 mV



Solution:

➔ Use triangular geometry, with equidistant pads

➔ In triangular geometry, **3 pads are necessary to obtain optimal resolution**

➔ **No region with 2 pads**

100 – 200 Number of pads used in reconstruction
Amplitude = 120 mV, min amplitude = 15 mV