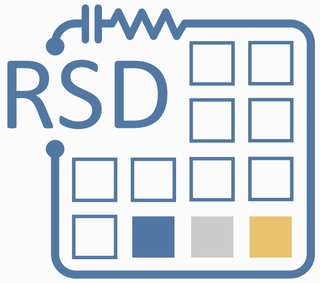
36th RD50 Workshop



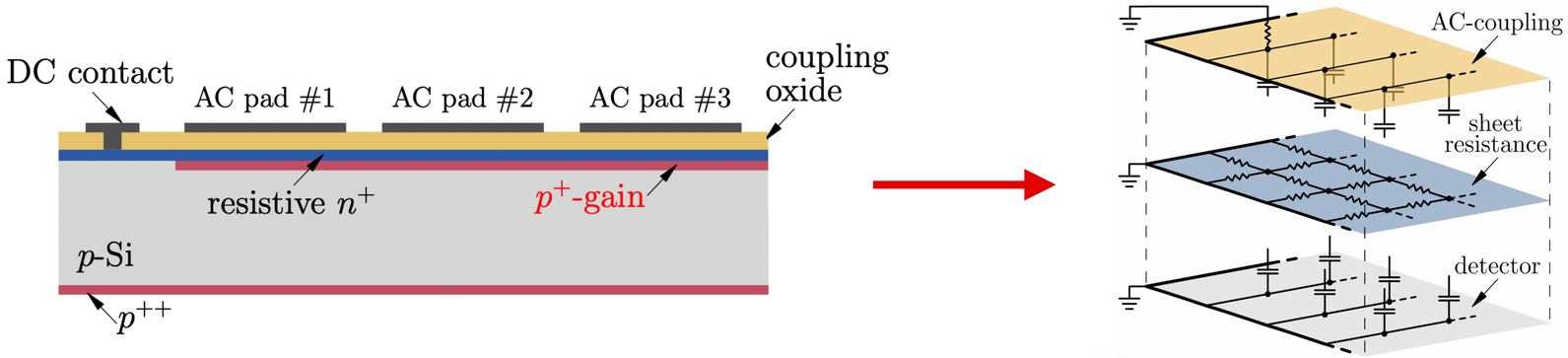
Latest results on Resistive AC-Coupled Silicon Detectors (RSD) spatial and timing resolution

Tornago M., Arcidiacono R., Cartiglia N., Costa M., Ferrero M., Mandurrino M., Siviero F., Sola V. Staiano A., Borghi G., Boscardin M., Centis Vignali M., Dalla Betta G.F., Ficorella F., Pancheri L., Paternoster G., Apresyan A., Di Petrillo K., Heller R., Los S.

RSD PROJECT

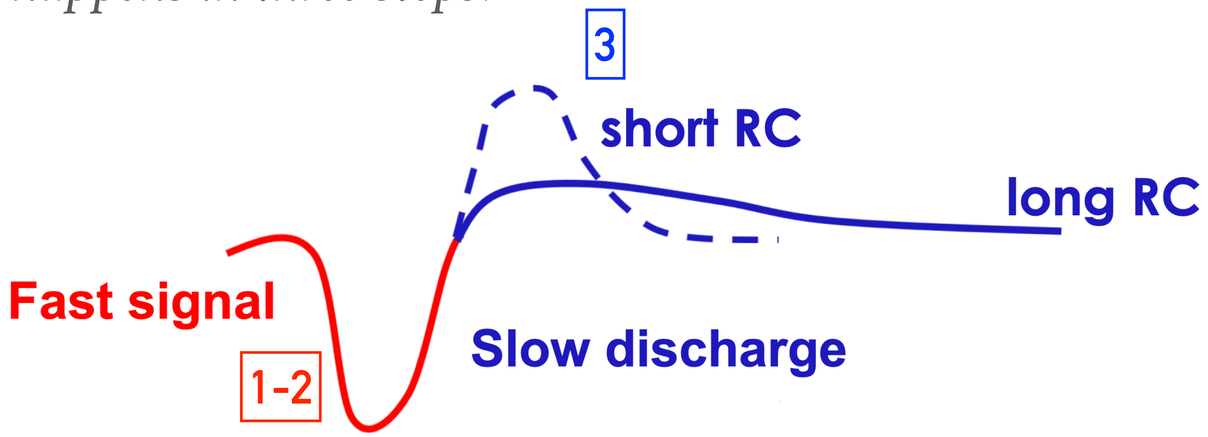
Resistive AC-coupled Silicon Detectors (RSD) *are designed as detectors with 100% fill factor for high precision 4D-tracking*

- *AC coupling occurs through the* ***oxide layer****, allowed by* ***n+ resistive electrode***
- ***One continuous gain layer***
- *Segmentation obtained with* ***read-out pads***
- *Spatial resolution a factor 10 better than binary readout* $bin\ size/\sqrt{12}$ *thanks to charge sharing*
- *Benefit from excellent LGAD timing performances*



RSD SIGNAL FORMATION

Signal formation in RSD happens in three steps:



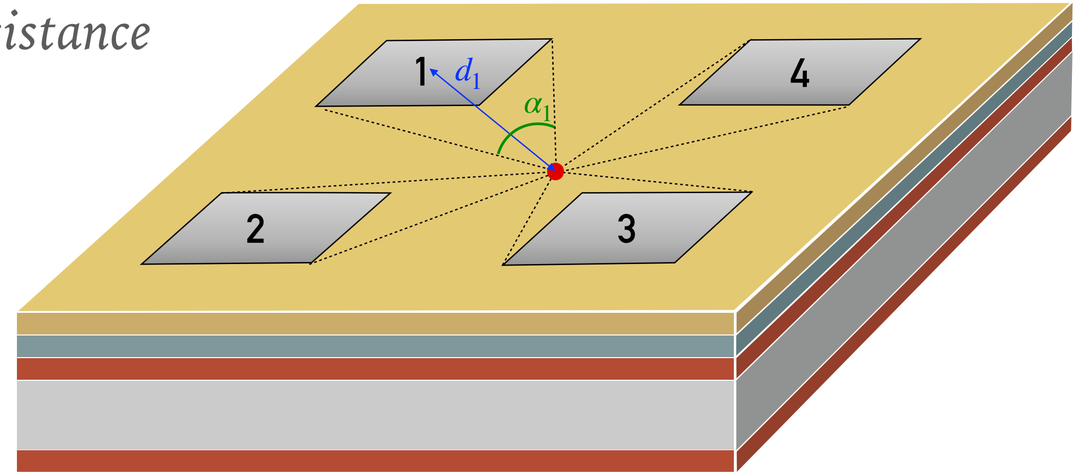
1. *e/h pairs produce a direct charge induction on the n+ electrode, similar to a standard LGAD*
2. *the signal spreads laterally along the n+ layer, the metal pads act as pick-up electrodes and record a signal*
3. *the AC pad discharges, generating a positive lobe whose shape depends on the system RC*

Charge sharing effect

DEVELOPMENT OF AN ANALYTICAL MODEL FOR HIT RECONSTRUCTION

For specific geometries, amplitude can be parametrized using a law that combines the linear attenuation with distance due to sheet resistance and the attenuation with the angle of view

$$A_i(d_i, \alpha_i) = A_0 \frac{[1 - \beta * d_i] * \alpha_i}{\sum_i^n [1 - \beta * d_i] * \alpha_i}$$



d	*distance from the pad centre*
A_0	*amplitude in the pad centre*
β	*attenuation factor*
α	*angle of view*

Signals time of arrival is also delayed as function of distance d:

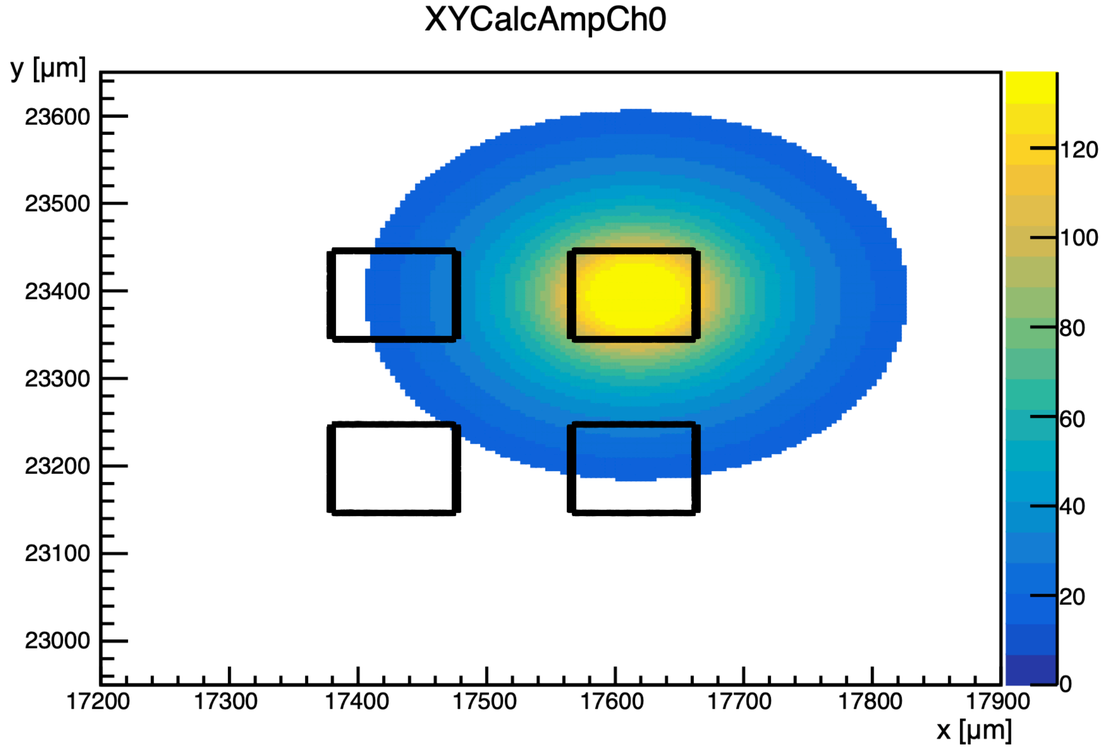
$$t(d) = t_0 + \mathbf{delay} * d$$

t_0 → *time in the pad centre*

DEVELOPMENT OF AN ANALYTICAL MODEL FOR HIT RECONSTRUCTION

We developed an analytical model based on the parametrization of ***amplitude attenuation****:*

given a certain attenuation factor the model allows to generate ***look-up tables*** *with the amplitude seen by each pad in every possible hit position*



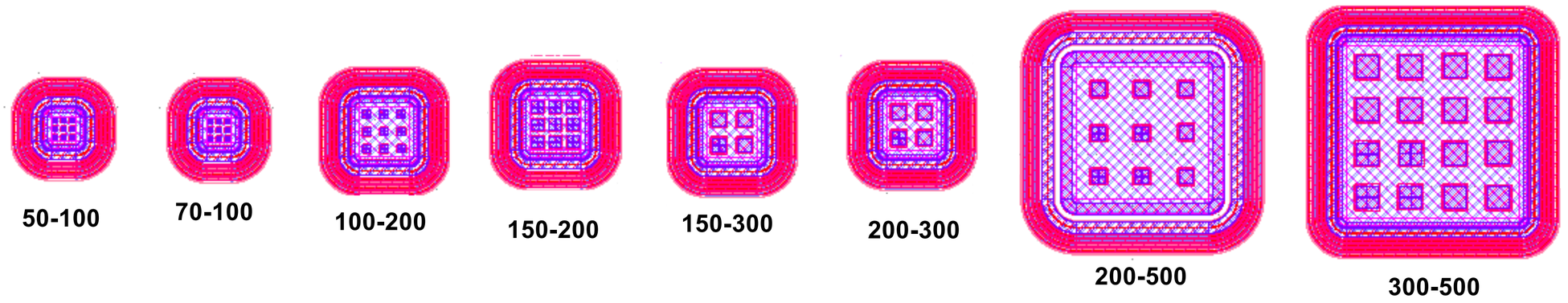
The algorithm compares the amplitude seen by each pad with the look-up tables and finds which x-y point minimizes the chi square:

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

OUTLINE: LABORATORY MEASUREMENTS ON RSD DEVICES

Several RSD matrices with different pad-pitch geometry (but same resistivity) have been measured:

- *at the **Laboratory for Innovative Silicon Sensors** in **Torino** with a Particulars TCT setup, where data have been used to develop the analytical model for hit reconstruction and evaluate spatial resolution and jitter*
- *at the **Fermilab Test Beam Facility** with a 120 GeV/c proton beam, for further studies on RSD signal properties and to measure their timing resolution*

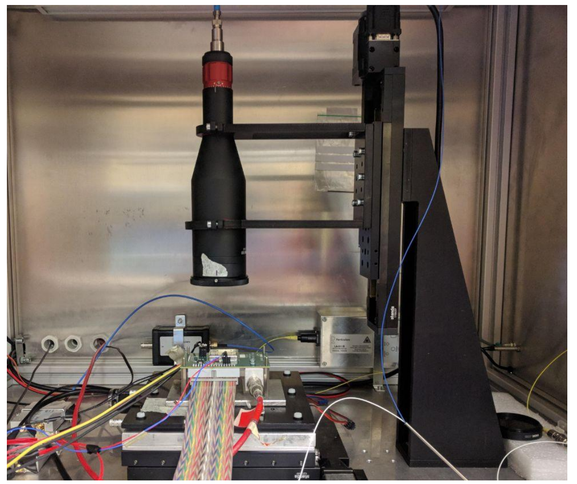


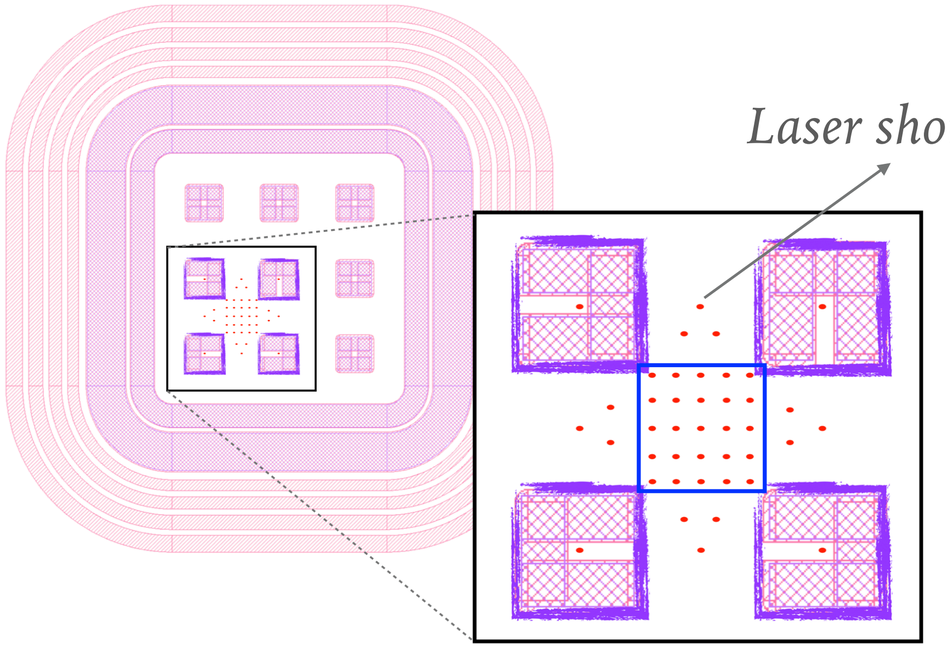
LASER MEASUREMENTS

TCT measurements on several RSD matrices with varying pitch and pad size

Laser 1064 nm 1 kHz, spot ~10 μm, intensity ~ 1 MIP

Acquisition of waveforms from 4 AC pads, ~500 triggers in each point



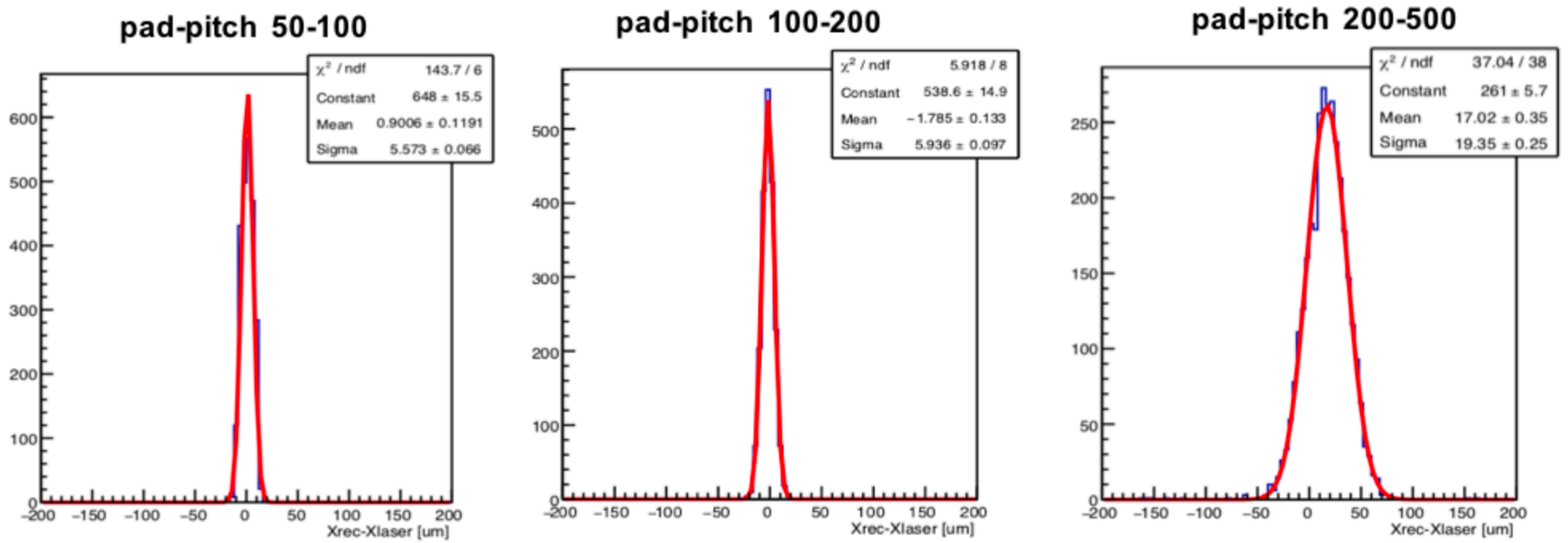


Reconstruction of hit position with an ***amplitude-weighted centroid***

Evaluation of ***spatial and timing resolution*** *considering the points in the most central area (blue square), where you have a good signal from at least 3 pads*

LASER MEASUREMENTS: SPATIAL RESOLUTION

Spatial resolution is obtained as the sigma of the gaussian distribution of $x - x_{reco}$ *and* $y - y_{reco}$

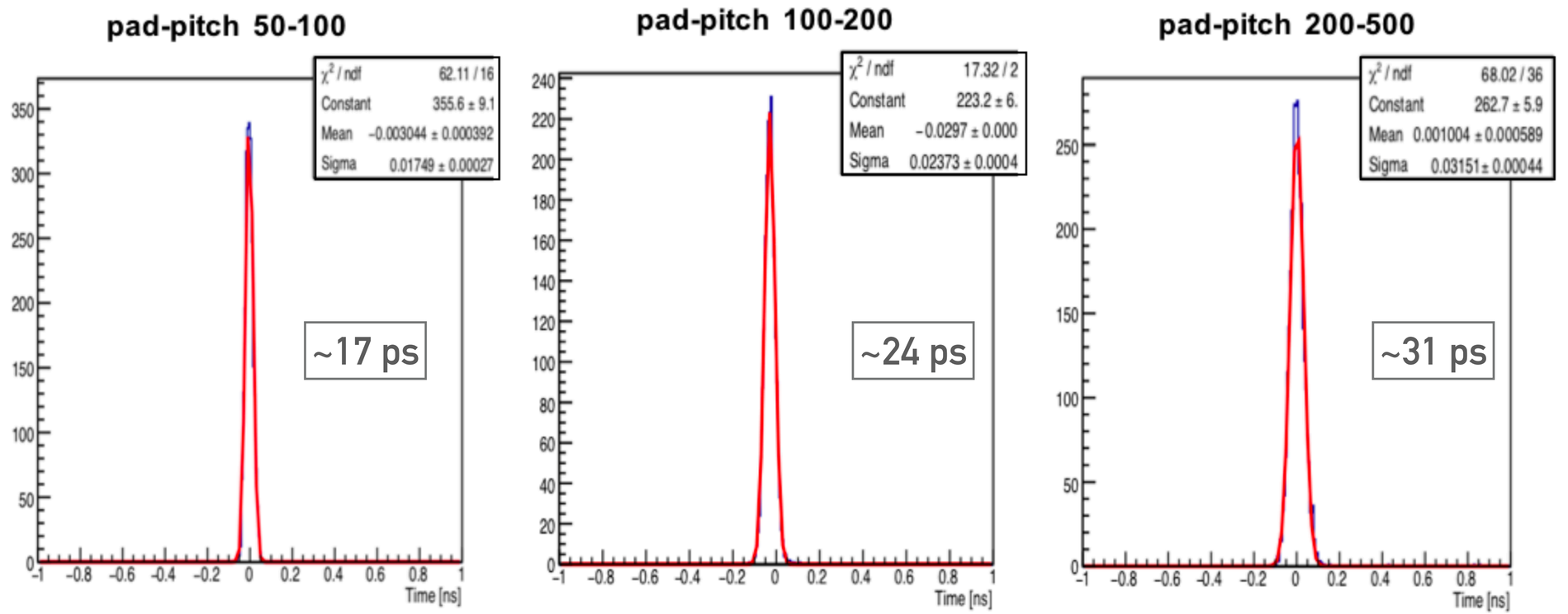


~6 µm binary ~28 µm	~6 µm binary ~58 µm	~20 µm binary ~140 µm

RSD spatial resolution is up to a factor 10 better than the corresponding binary read-out

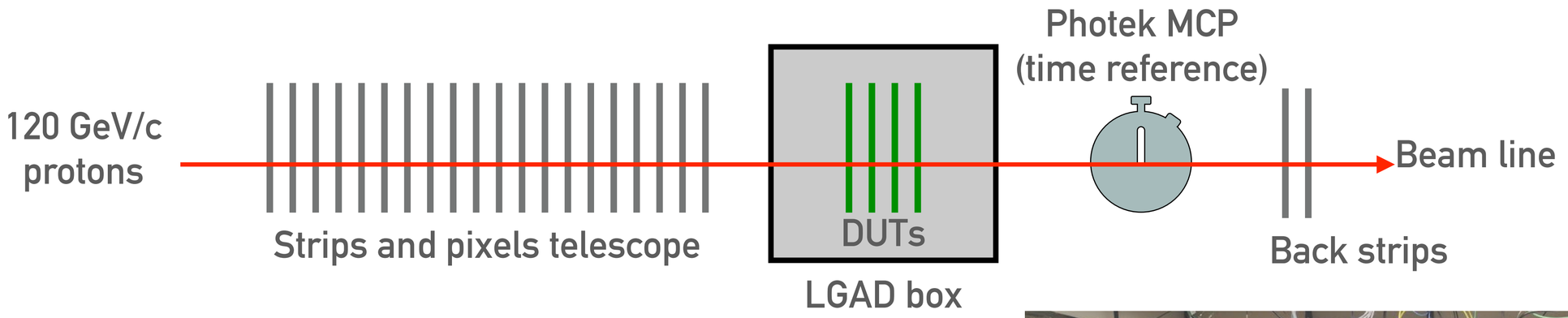
LASER MEASUREMENTS: TIMING RESOLUTION

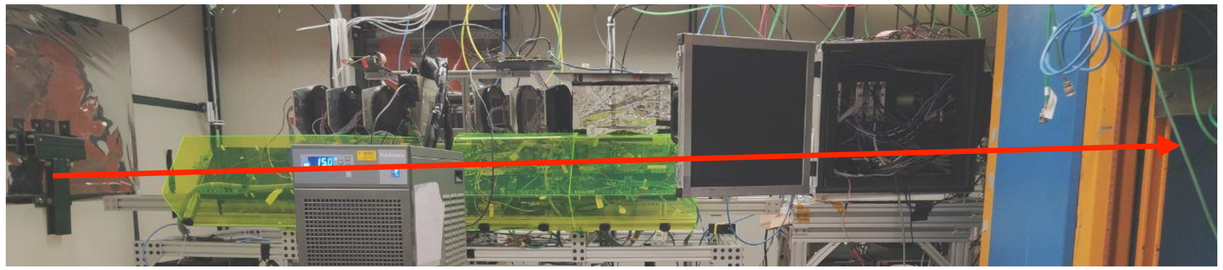
Timing resolution (jitter term) is obtained as the sigma of the gaussian distribution of $t_{trig} - t_{reco}$



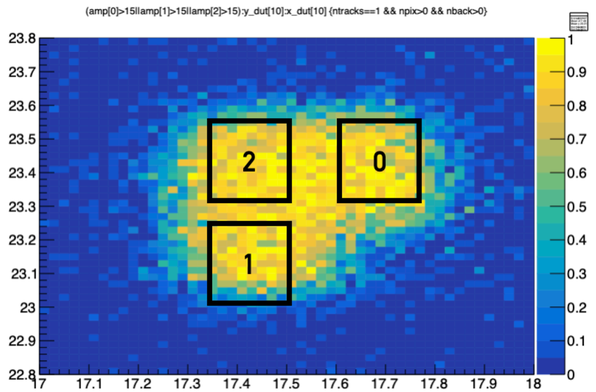
Results obtained combining timing resolutions of the 4 read-out pads

TEST BEAM MEASUREMENTS @FNAL



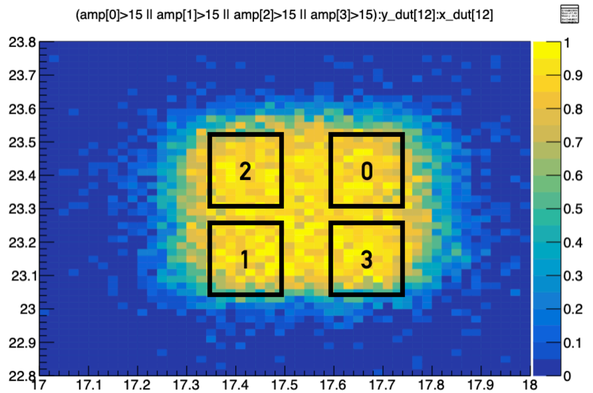


Data taken for RSD 3x3 100-200 and 190-200 pad-pitch geometries using two configurations:

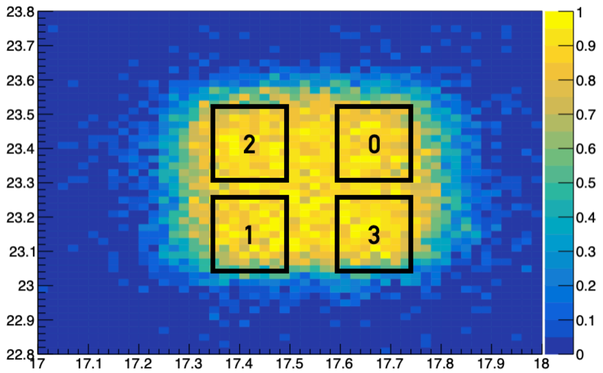


3 AC pads + Photek for timing studies

4 AC pads for position studies



TEST BEAM MEASUREMENTS @FNAL: 100-200 POSITION STUDIES

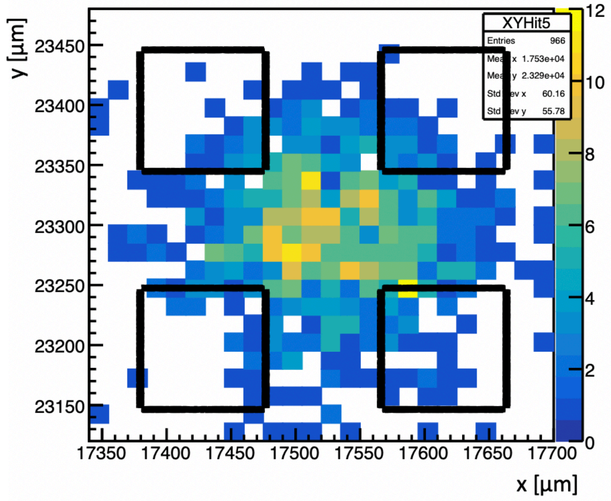


100-200 4 AC pad configuration:

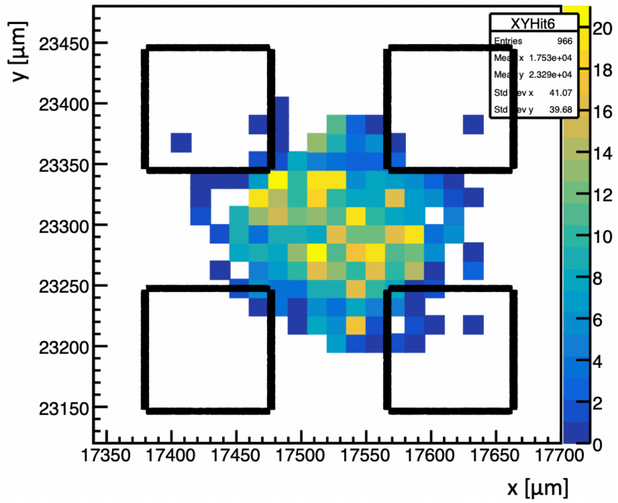
- *Optimization of the reconstruction algorithm, the attenuation factor that better reproduces data is* $\beta = -0.3\,\%/\mu m$
- *Determination of proton hits position with good spatial uniformity*
- *Evaluation of the system spatial resolution as* $x_{tracker} - x_{reco}$*, completely dominated by the tracker resolution (~45 μm)*

Reconstruction of events in which all the 4 pads see a signal

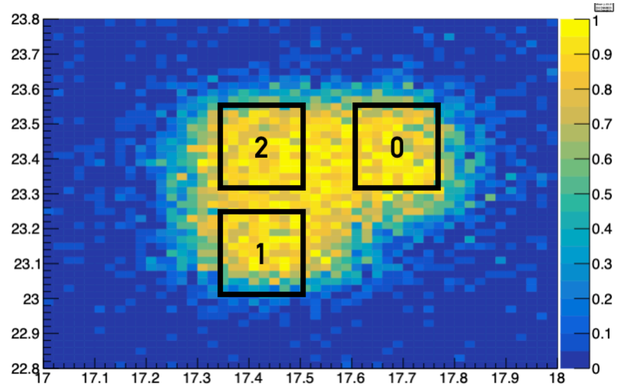
Tracker coordinates



RSD coordinates

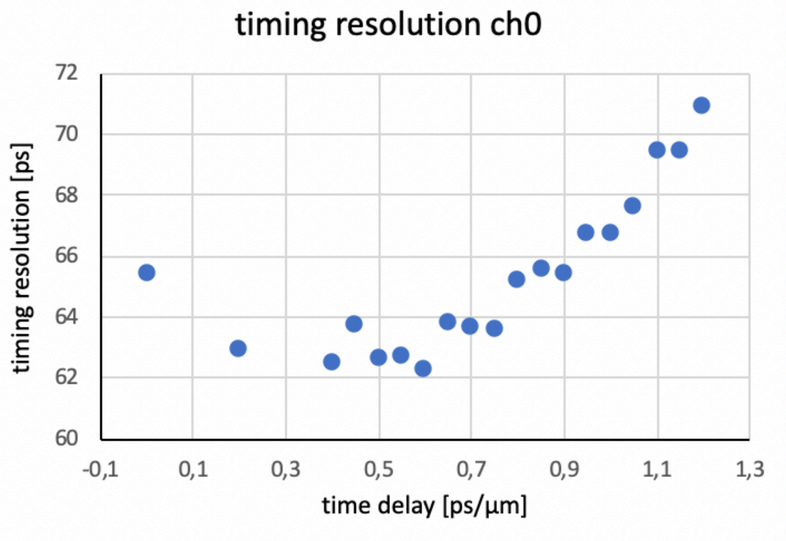


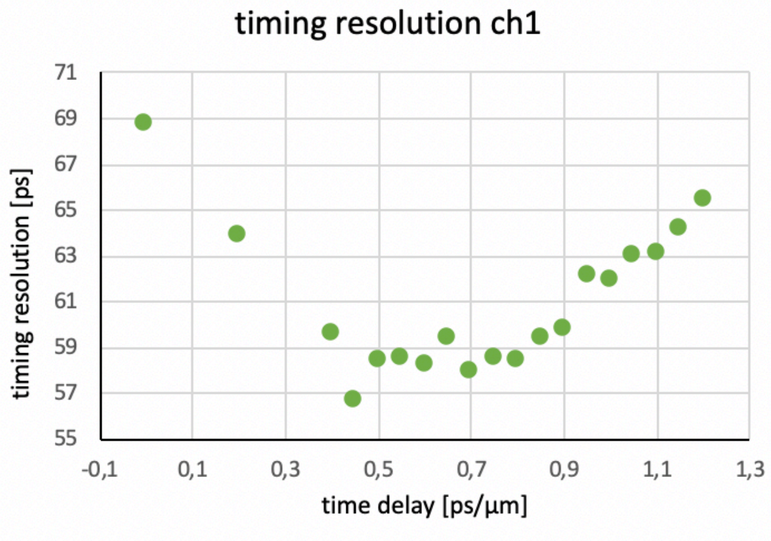
TEST BEAM MEASUREMENTS @FNAL: 100-200 TIMING STUDIES

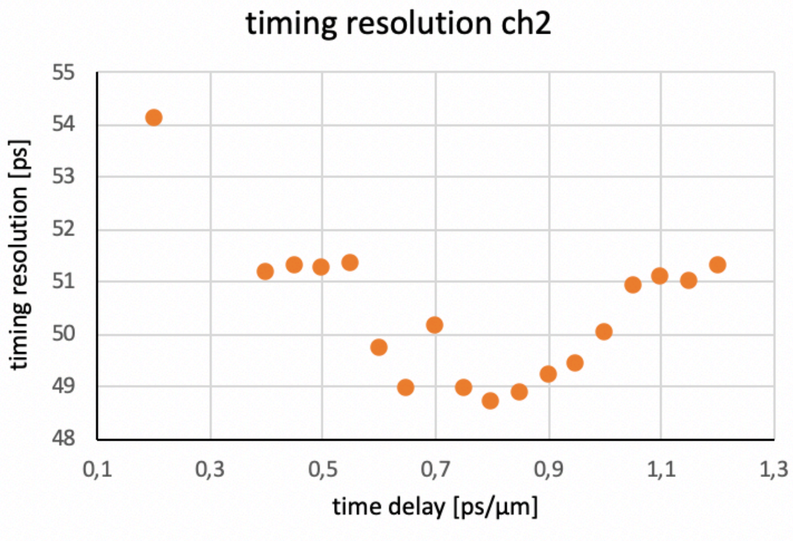


100-200 3 AC pad+Photek configuration:

- *The best time delay with is* $t_{delay} = 0.6\ ps/\mu m$
- *Evaluation of the RSD timing resolution as* $t_{photek} - t_{reco}$ *, considering negligible the Photek contribution*

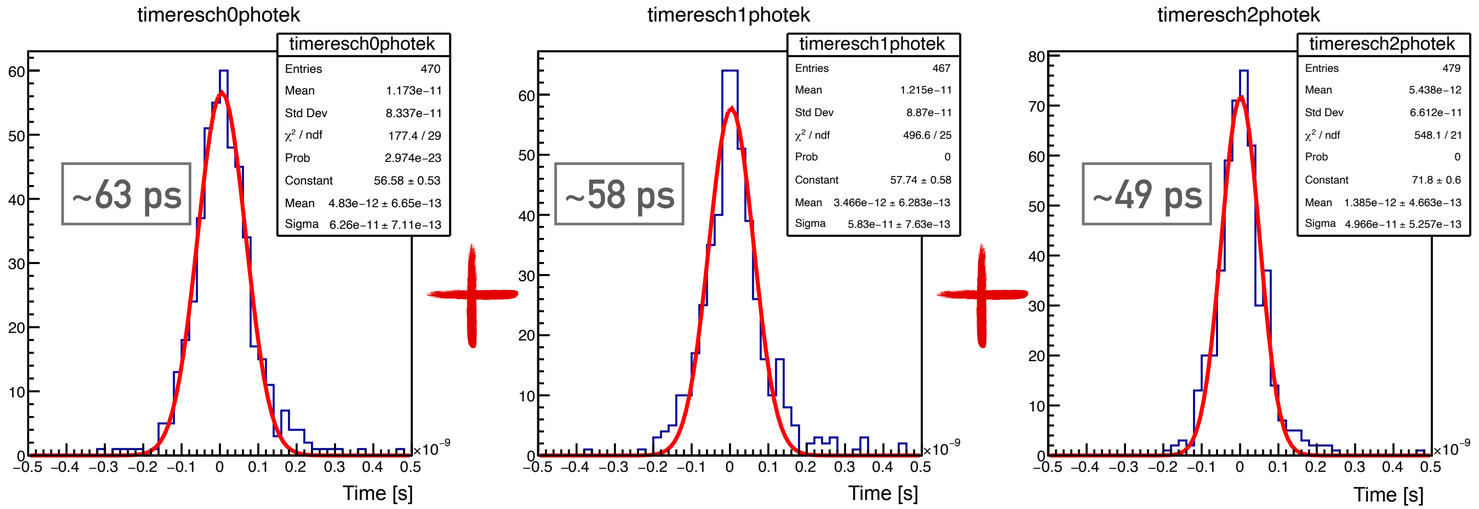




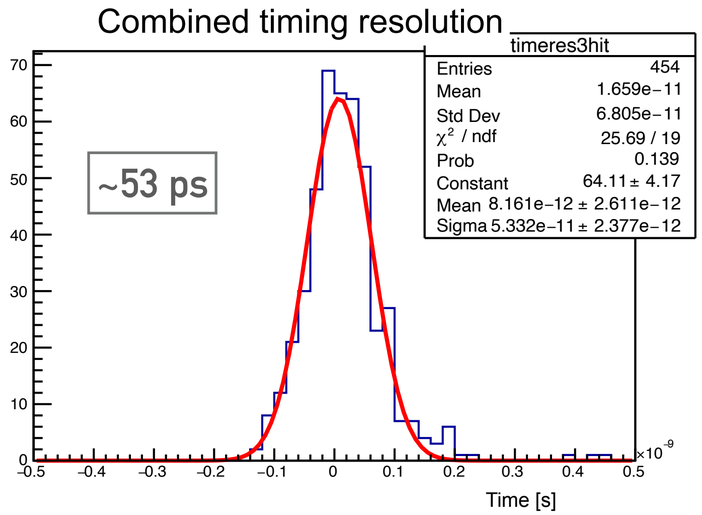


TEST BEAM MEASUREMENTS @FNAL: 100-200 TIMING STUDIES

Combining the time resolution for the 3 pads we obtain a timing resolution higher than the one expected from calculations



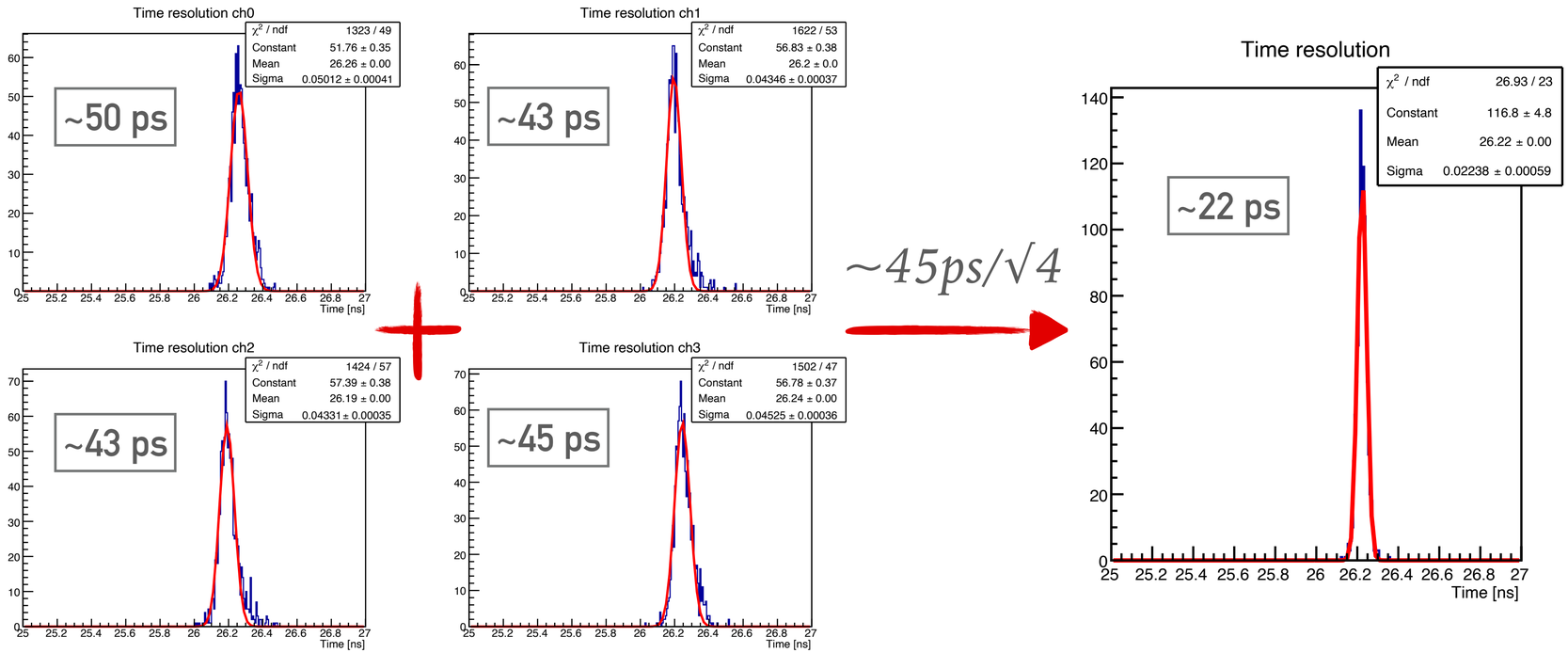
Expected resolution from 3 uncorrelated pads ~33ps



- *correlated noise is present in these data due to non uniform ionization*
- *to check this hypothesis we compare the results with the ones obtained with laser data*

LASER MEASUREMENTS: CORRELATED NOISE

If we consider laser data, the result obtained combining 4 pads is close to a situation without correlated noise



The only contribution to laser data timing resolution is represented by the jitter term, arising from the electronics noise

$$\sigma_t^2 = \cancel{\sigma_{Landau}^2} + \sigma_{Jitter}^2$$

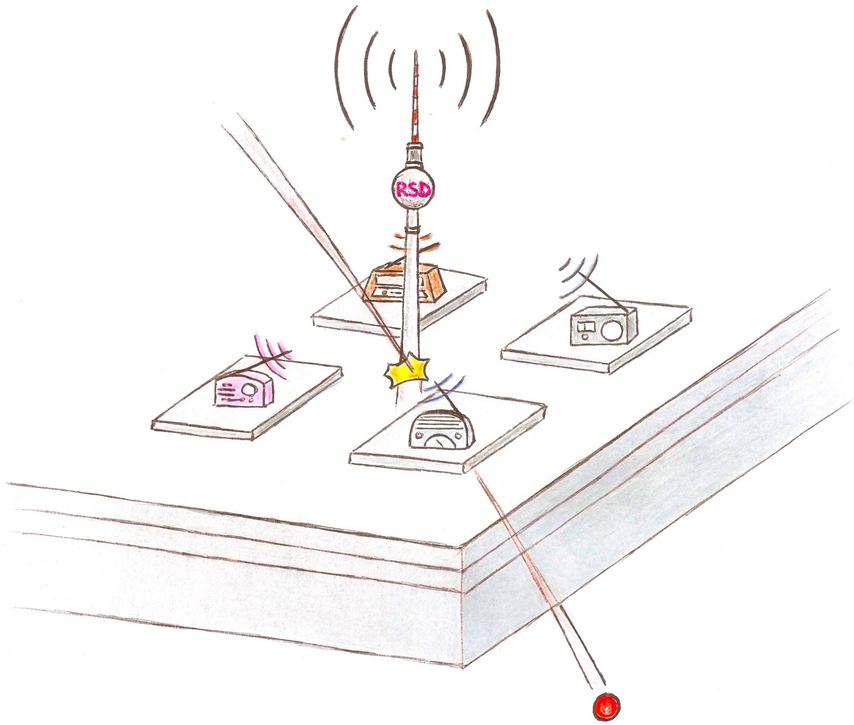
TEST BEAM MEASUREMENTS @FNAL: CORRELATED NOISE

Where does correlated noise come from?

After an impinging particle creates a concentration of charges at the point of impact, the signal is "broadcasted" from this point to the AC pads and each of them ***see a copy of the same signal***

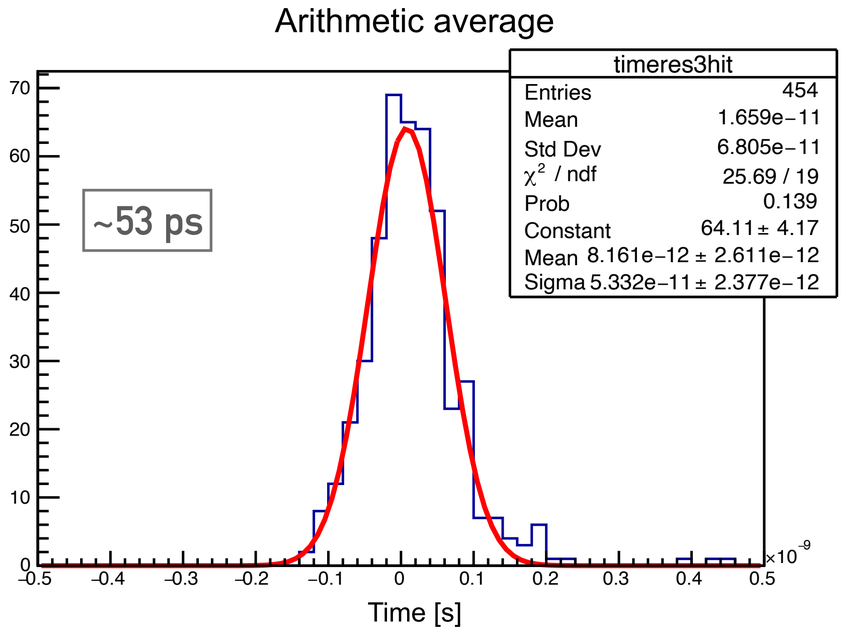
→ *combining signals from multiple pads, jitter term improves as it is uncorrelated, while* ***Landau term doesn't improve*** *since its fluctuation is correlated in the read-out pads*

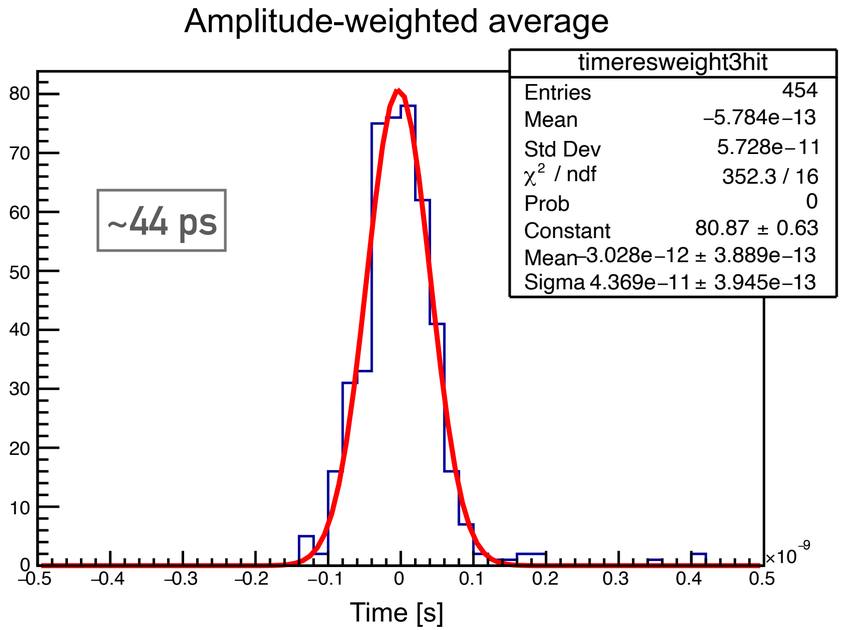
→ *Hits position can be accurately reconstructed by using the signals relative amplitudes, while time of arrival doesn't improve using multiple pads as signal shapes are 100% correlated*



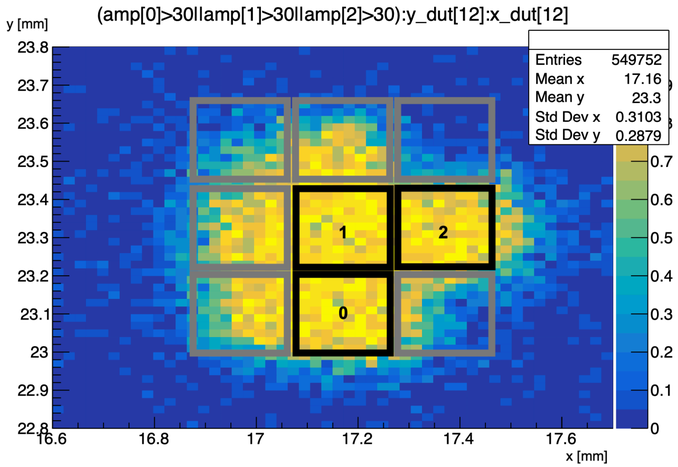
TEST BEAM MEASUREMENTS @FNAL: TIMING RESOLUTION

At test beam, it's possible to optimize timing resolution results considering the amplitude-weighted average of the time of arrival for the three pads, in order to give more importance to larger signals





TEST BEAM MEASUREMENTS @FNAL: 190-200 TIMING STUDIES



190-200 3 AC pad+Photek configuration:

With 190-200 geometry ***charge sharing is much reduced*** *with respect to 100-200 since the signal does not spread towards neighboring pads and it's mostly absorbed by the large metal pads*

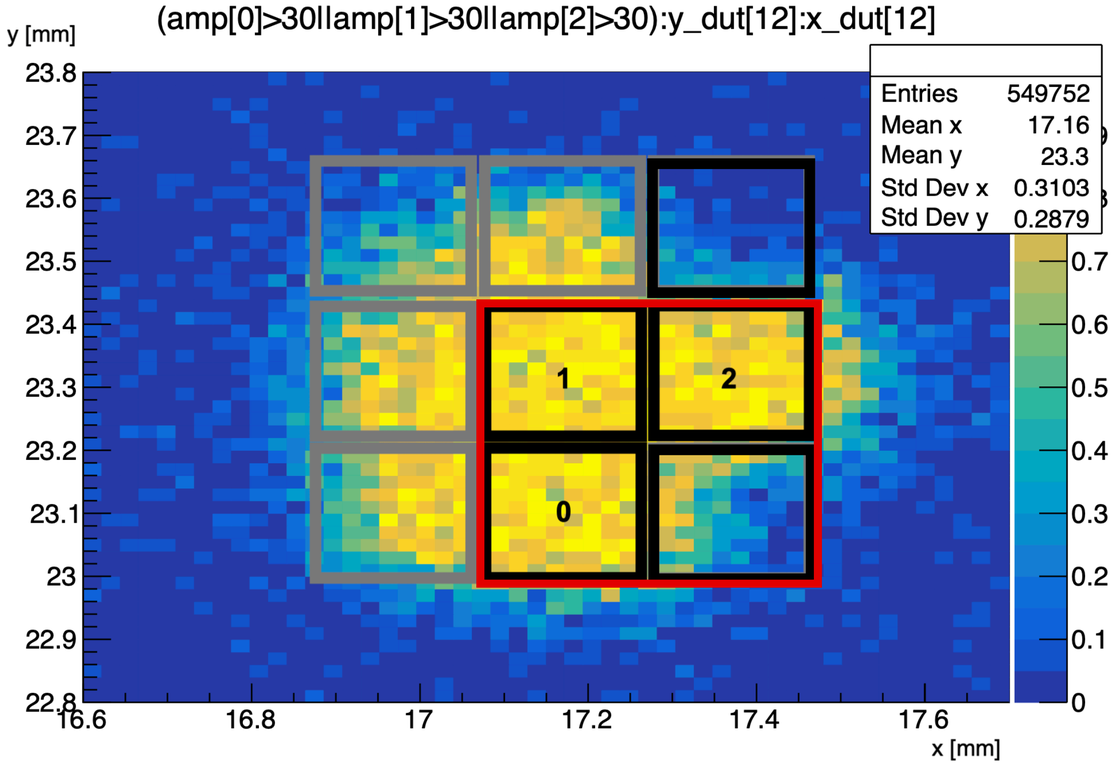
→ *large majority of 1-pad events, spatial precision becomes the same we would obtain in binary read-out, pixel size/√12 ⟶ 190μm/√12*

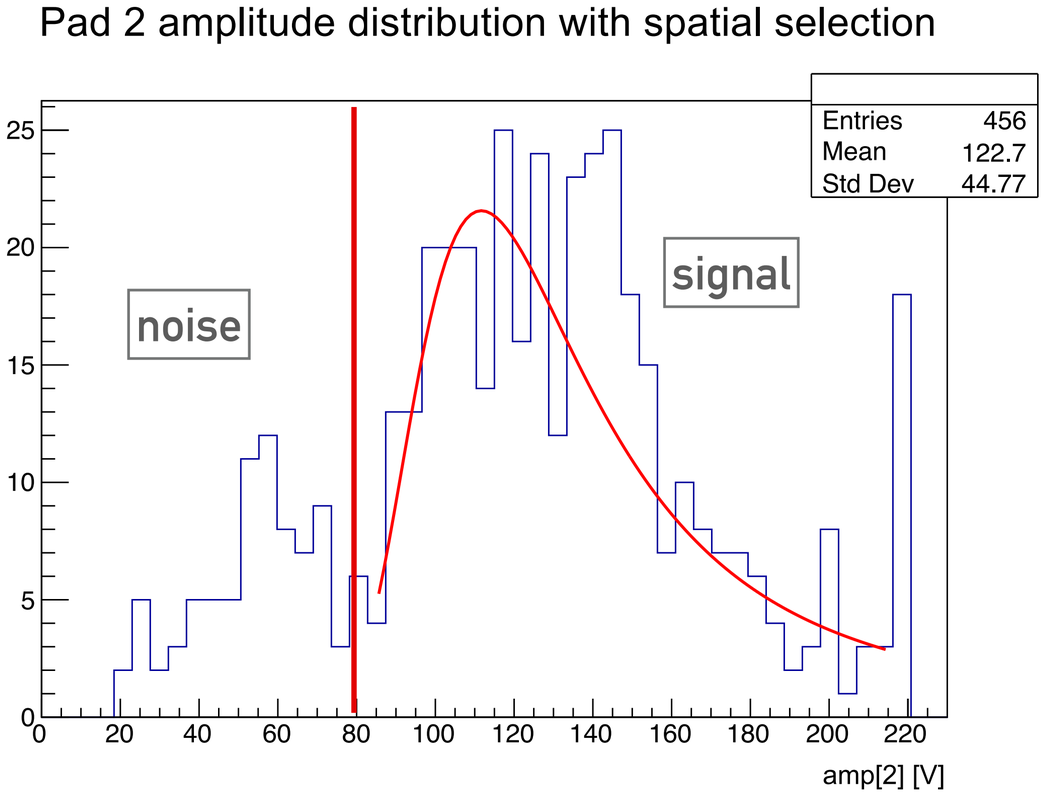
→ *some 2-pads events, charge sharing is limited to 20-30 μm near the metal edge, good precision in only one coordinate*

→ *very few 3-pads events*

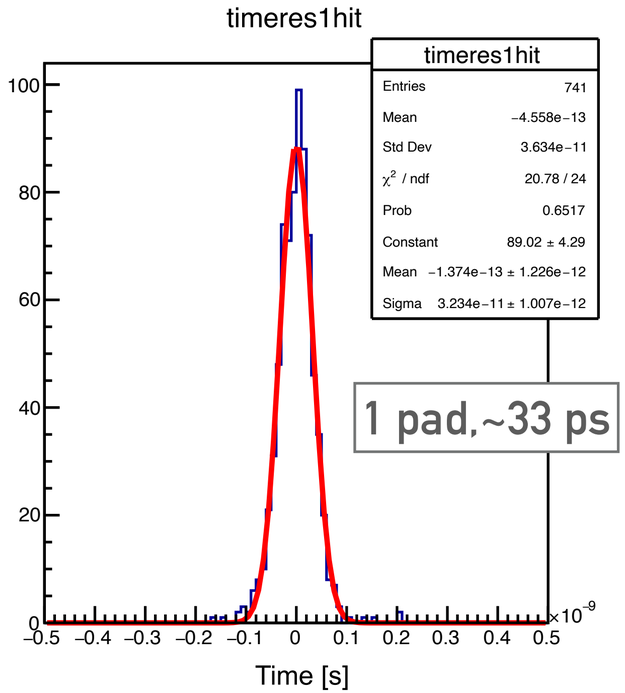
TEST BEAM MEASUREMENTS @FNAL: 190-200 TIMING STUDIES

Timing resolution for 1-pad events is obtained applying spatial selection cuts to exclude events underneath floating pads and asking for amp>80





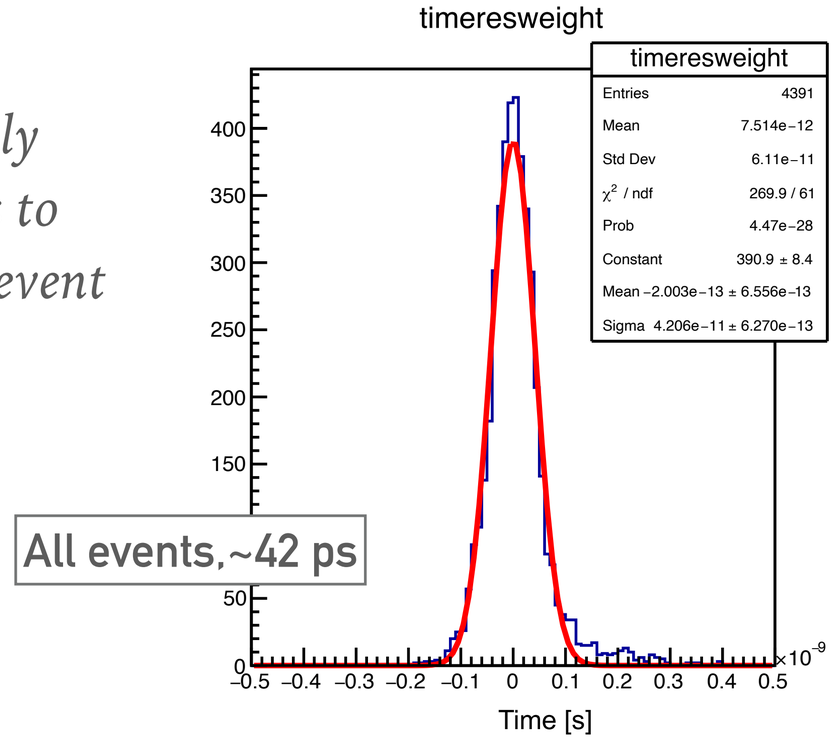
TEST BEAM MEASUREMENTS @FNAL: 190-200 TIMING STUDIES



Timing resolution for 1-pad events is obtained applying spatial selection cuts to exclude events underneath floating pads and asking for amp>80

For 2, 3-pads hits we don't need to apply further cuts, since asking for more pads to see a signal with amp>15 in the same event already allows to select good events

Combining all the events we get 42 ps timing resolution



SUMMARY OF RSD TIMING RESOLUTION RESULTS

Time resolution results are compatible with the best LGAD performances obtained at the same gain

	single pad	3 pad	4 pad	
100-200 laser	45 ps	-	22 ps	$\sigma_t^2 = \sigma_{Jitter}^2$
100-200 test beam	50 ps	44 ps	-	$\sigma_t^2 = \sigma_{Landau}^2 + \sigma_{Jitter}^2$
190-200 test beam	35 ps	42 ps	-	

CONCLUSIONS AND FUTURE PLANS

Resistive AC-Coupled Silicon Detectors *are a new type of n-in-p devices designed for high-precision 4D tracking*

- *Their charge sharing properties allow to define a parametric description of signals amplitude, that has been used to develop an* ***analytical model for hit reconstruction***
- *Laser measurements show that RSD can reach a* ***very good spatial resolution****, up to a factor 10 better than the corresponding binary read-out precision*
- *From beam test results we obtain a* ***time resolution compatible with the best LGAD performances*** *obtained at the same gain*
- *First* ***demonstration of 100% fill-factor*** *LGAD at beam test*
- *Beam test analysis almost completed (paper in preparation)*

Future plans*: study of wafers with different resistivity, analytical model optimization*

ACKNOWLEDGEMENTS

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- ***INFN - Gruppo V***
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- *U.S. Department of Energy* ***Grant number DE-SC0010107***
- ***Dipartimenti di Eccellenza****, University of Torino (ex L. 232/2016, art. 1, cc. 314, 337)*
- *Ministero della Ricerca, Italia , PRIN 2017,* ***progetto 2017L2XKTJ – 4DinSiDe***
- *Ministero della Ricerca, Italia, FARE,* ***R165xr8frt_fare***