Geometry optimization of AC-coupled LGADs for high precision 4D tracking

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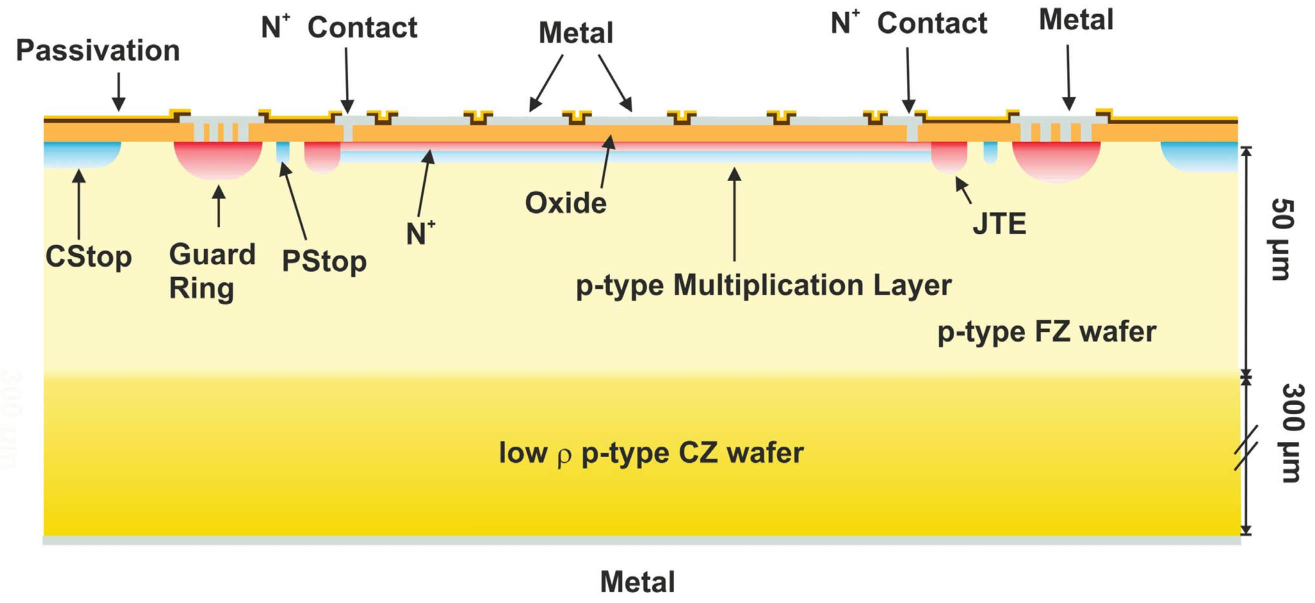
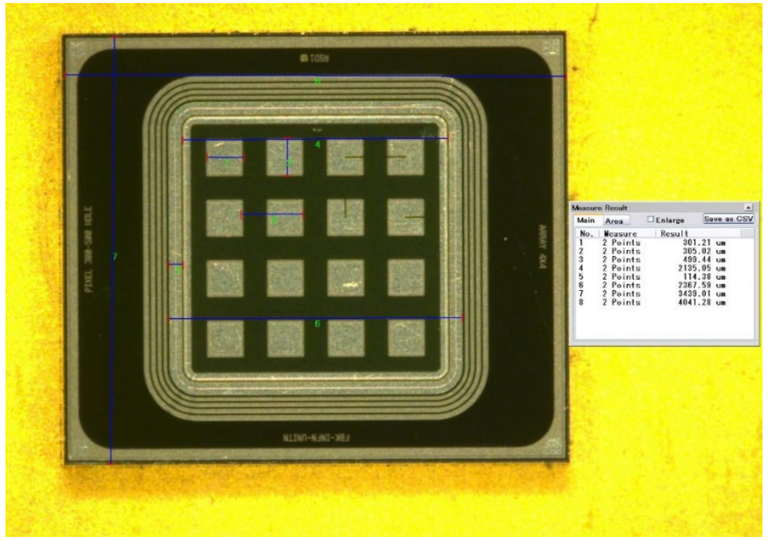
AC-LGADs

- Most advanced prototype of high granularity LGADs are **AC-LGADs**
  - (UCSC - US patent N. 9,613,993 B2, granted Apr. 4, 2017)
- Continuous sheets of multiplication layer and **N+ resistive layer**
  - N+ layer is grounded through side connections
- **Readout pads are AC-coupled** (Insulator layer between N+ and pads)
  - Allows for 100% fill factor and fine segmentation
- Prototypes produced in this study by FBK
- **Many thanks for providing the devices to R. Arcidiacono, N. Cartiglia, M. Ferrero, M.Mandurrino, V. Sola, M. Boscardin, G. Borghi, G. Paternoster, F. Ficorella, M. Centis Vignali, G.F. Dalla Betta, L. Pancheri**
- **Thanks a lot to F. Miserocchi for the help with the CAEN setup**



- **The response of the sensors can be tuned by modifying several parameters**
  - Pad distance
  - Resistivity of N+ layer
  - Oxide thickness
  - Pad geometry and dimension

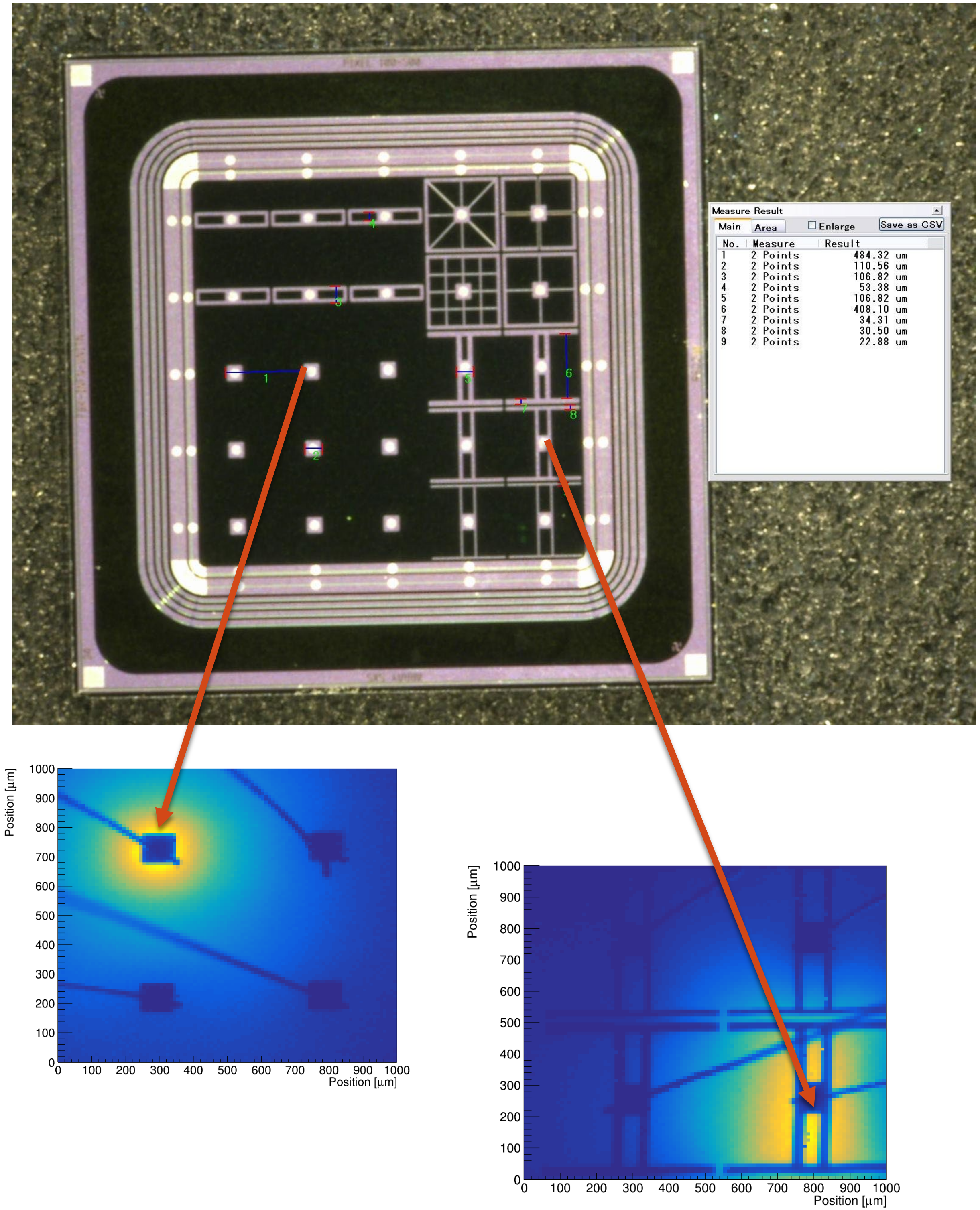


Prototype AC-LGAD from FBK, 500 um pitch, 300 um metal

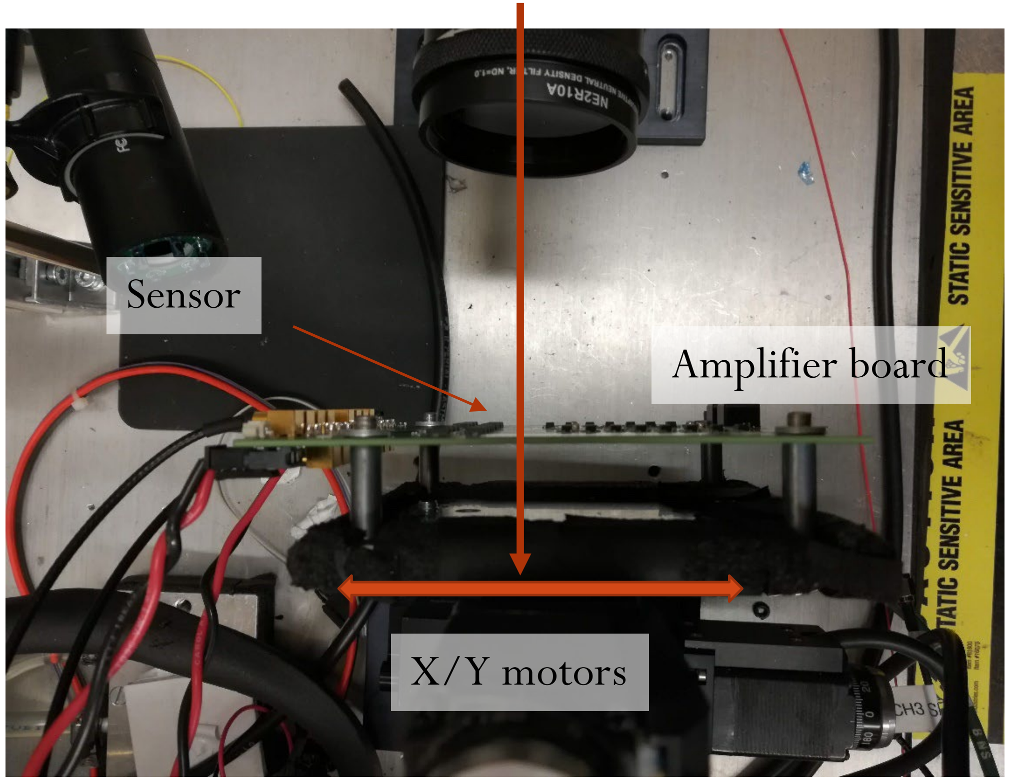
AC-LGAD geometry

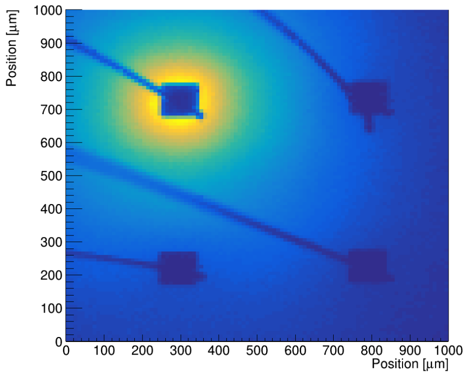
- With AC metal it is possible to create non conventional geometries
  - Simple metal pattern on top, no underlying structures
  - **Allowing to optimize sensor metal shape for the specific application**
- Studies done on a **AC-LGADs** from FBK RSD2 production
  - Pad sensor featuring non conventional geometries, pitch of 500µm
  - FBK RSD2 W13B 8-3 5X5 500 µm
  - Geometries: 100x100um pads, microstrips, H-pads, cages. All have a 100x100um "core" for wire bonding.

- Presented results
  - Capacitance characterization of different pads
  - 2D and 1D response profile (laser TCT)
  - Comparison of waveforms from different pads
  - Rudimentary position reconstruction and Jitter calculation



Sensor testing –Laser TCT setup

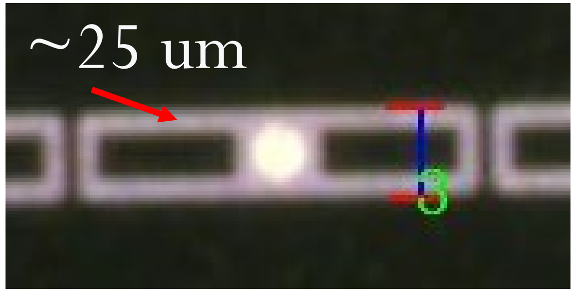


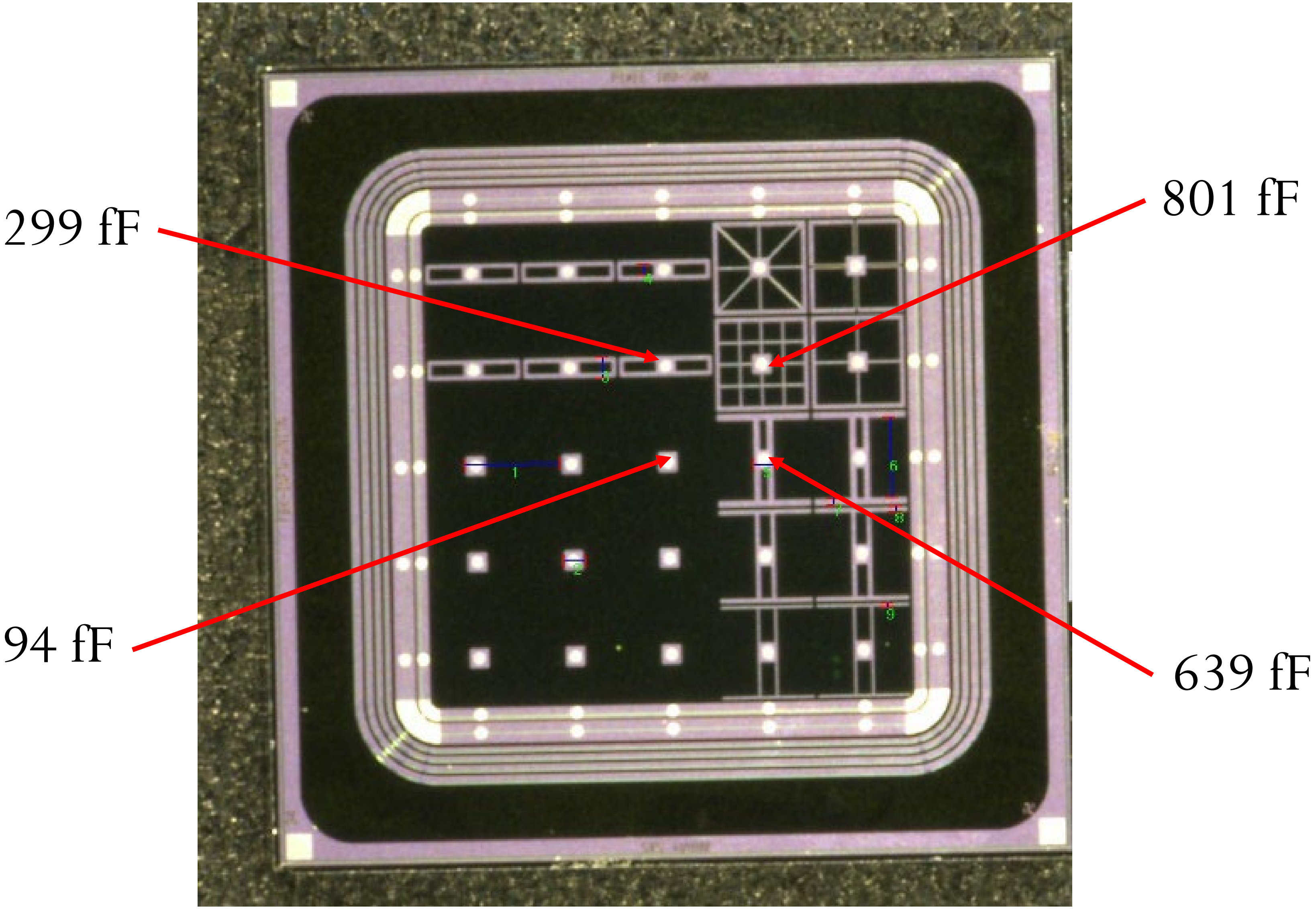


- Sensors are mounted on a multi-channel analog amplifier board with bandwidth ~1 GHz
  - Response is readout by a fast oscilloscope (2 GHz/20 Gs) or a 16ch CAEN digitizer
- **IR laser (1064 nm)** mimics charge deposit of a MIP
  - Focused beam spot width of < 20 um
  - Metal structures of the sensors are not transparent to IR so no response can be seen when laser is on top of metal
- Amplifier board is mounted on X/Y moving stages
  - **Charge injection as a function of position**
- Laser scan of a 100x100um pad: example 2D Pulse maximum (Pmax) map vs X/Y position

AC-LGAD AC-capacitances

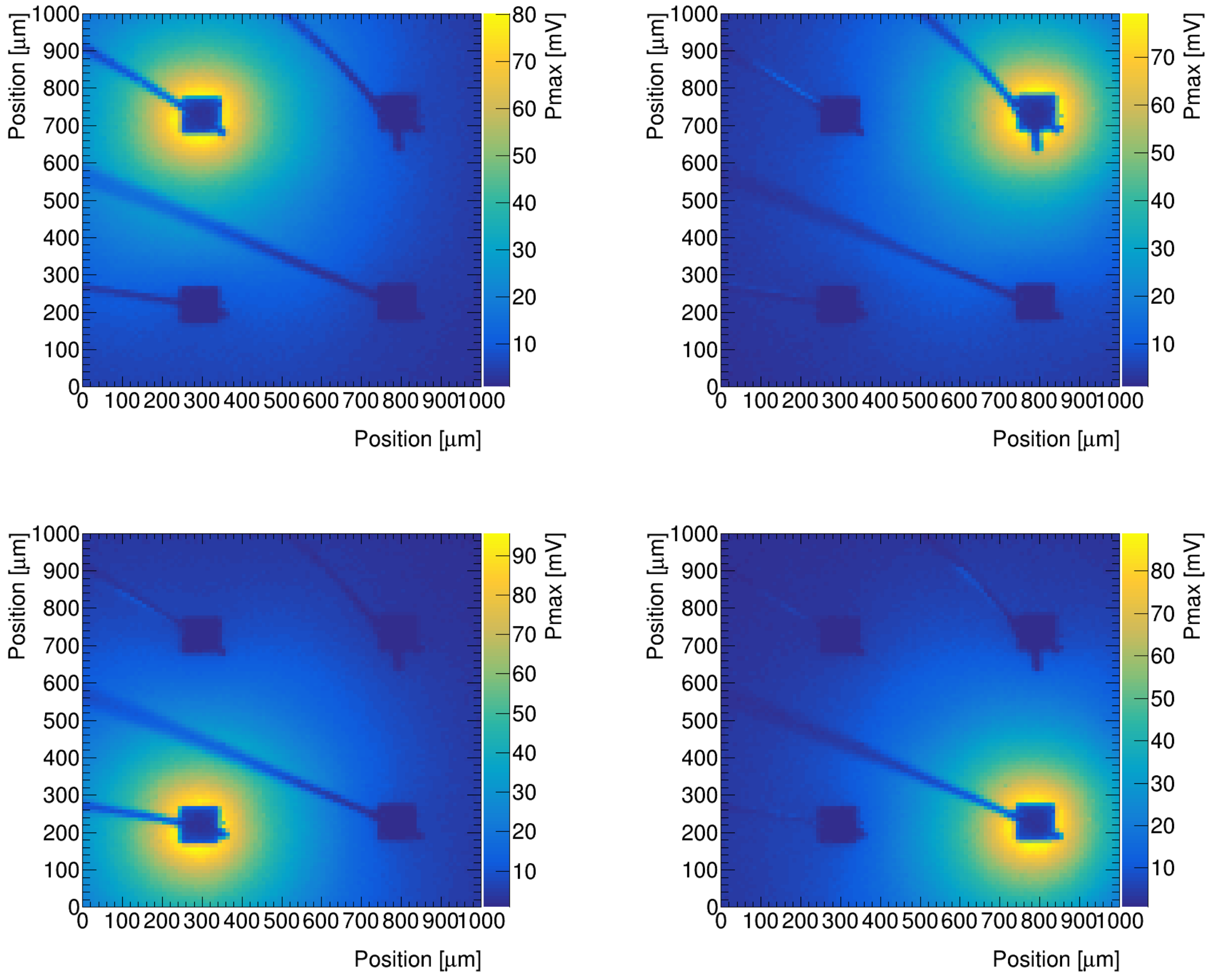
- Measurement of the pad capacitance for each different type of pad
  - HV from the backside, N+ and guard ring grounded, capacimeter connected to top metal
  - The rest of the metal pads around it are floating
- Pad's capacitance scales will amount of metal coverage on top as expected
- **Opening in the metal does reduce the capacitance**
  - Micro-strips are ~100x500 um but the capacitance is not 5 times the one of 100x100 um pads
  - Capacitance is only ~3 times
  - Scales with the (2x) 175x50 um area of the opening
  - H-pad measured has thicker arms so the capacitance is significantly higher

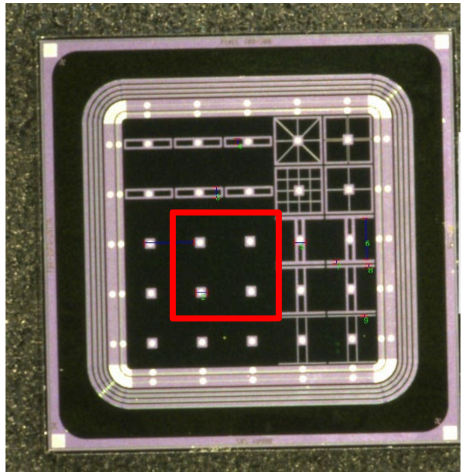




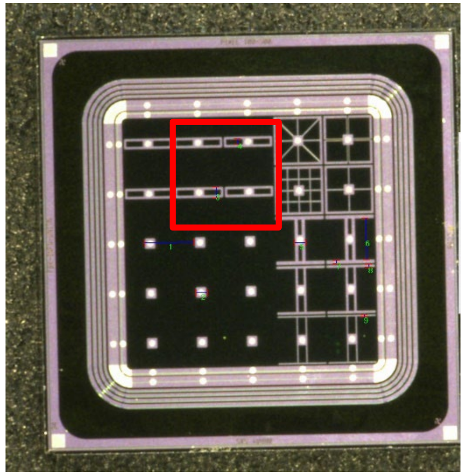
AC-LGAD 100x100 um pads

- Pro
  - Homogeneous in X-Y
  - Likely good reconstruction in the region in between pads
  - Small input capacitance
- Cons
  - Smaller signal

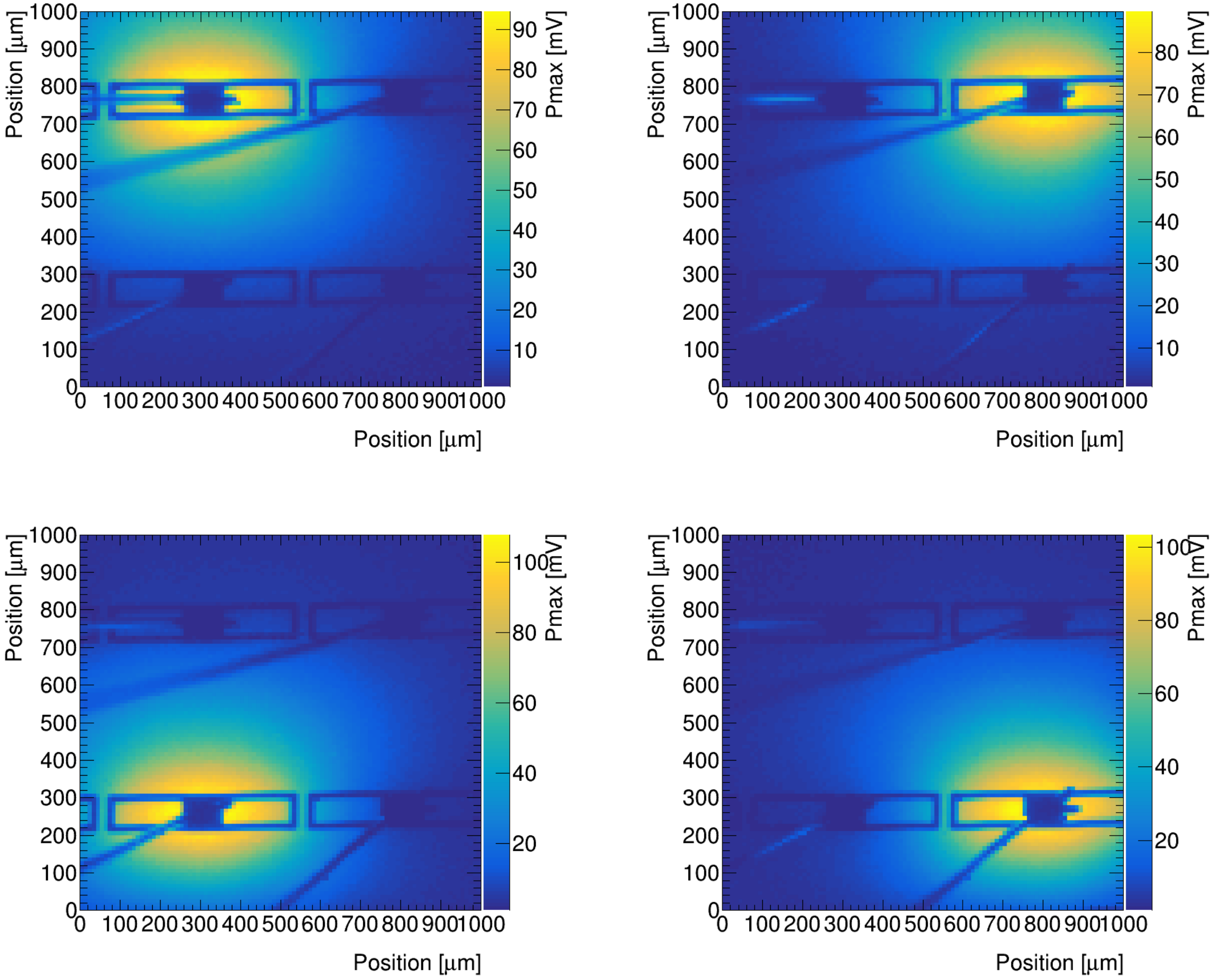




AC-LGAD 100x500 um micro-strips

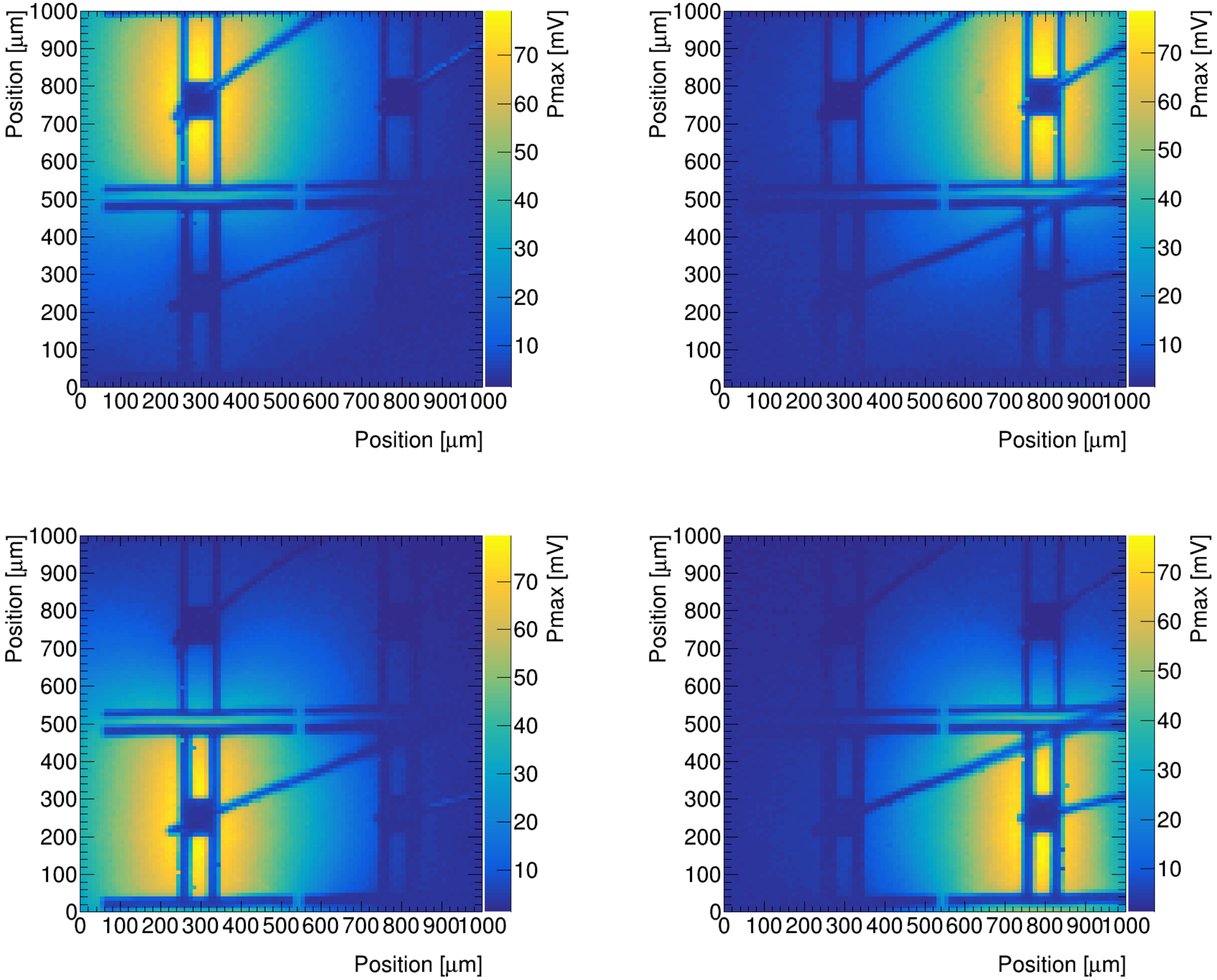


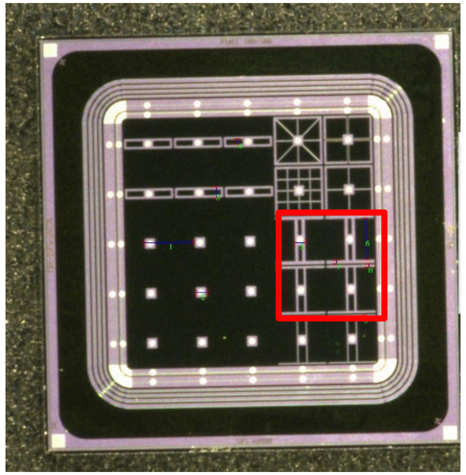
- Pro
  - Bigger signal
  - Better position resolution in Y
- Cons
  - Increased input capacitance
  - Worse position resolution in X



AC-LGAD 500x500 um H-pads

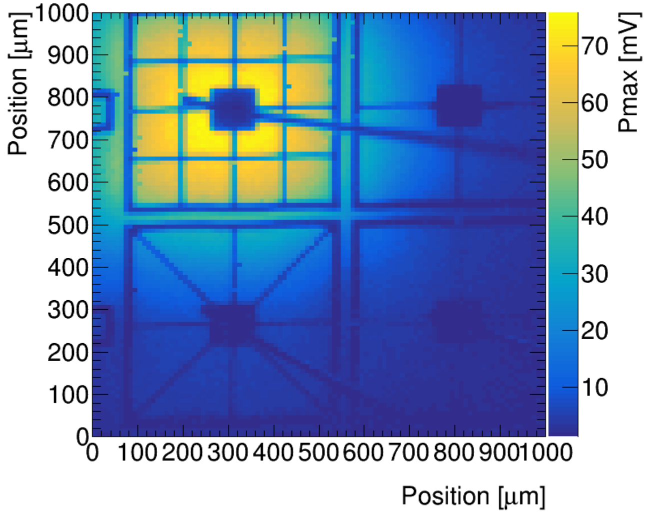
- Pro
  - Bigger signal
  - Better position resolution in X
- Cons
  - Increased input capacitance
  - Worse position resolution in Y

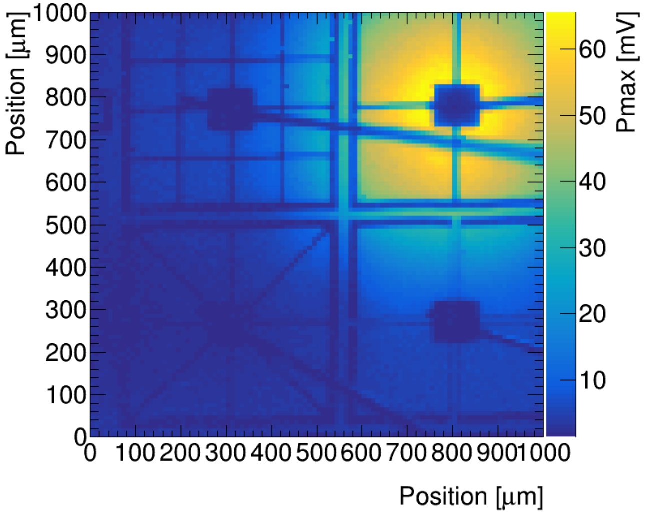


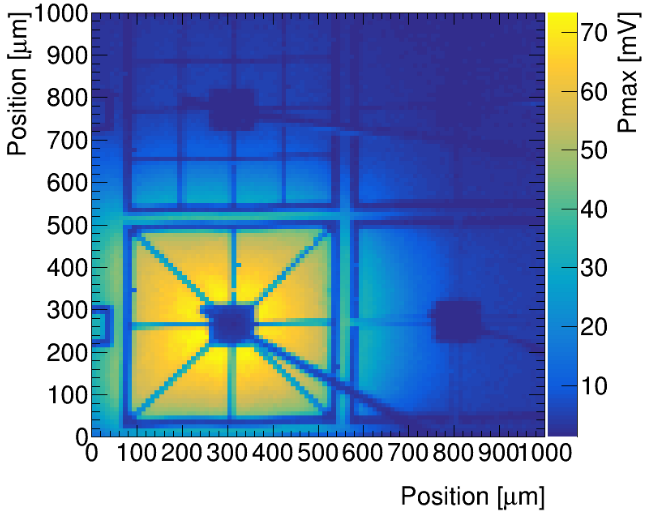


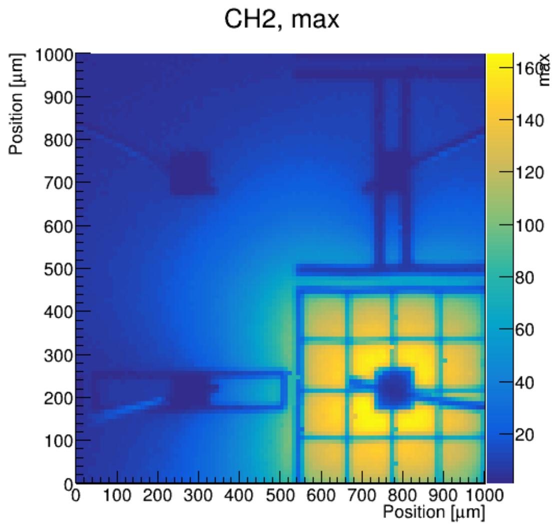
AC-LGAD 500x500 um cages

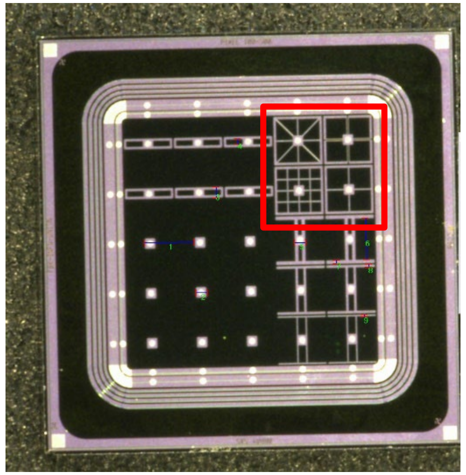
- Pro
  - Bigger signal
- Cons
  - Increased input capacitance
  - Unclear position resolution



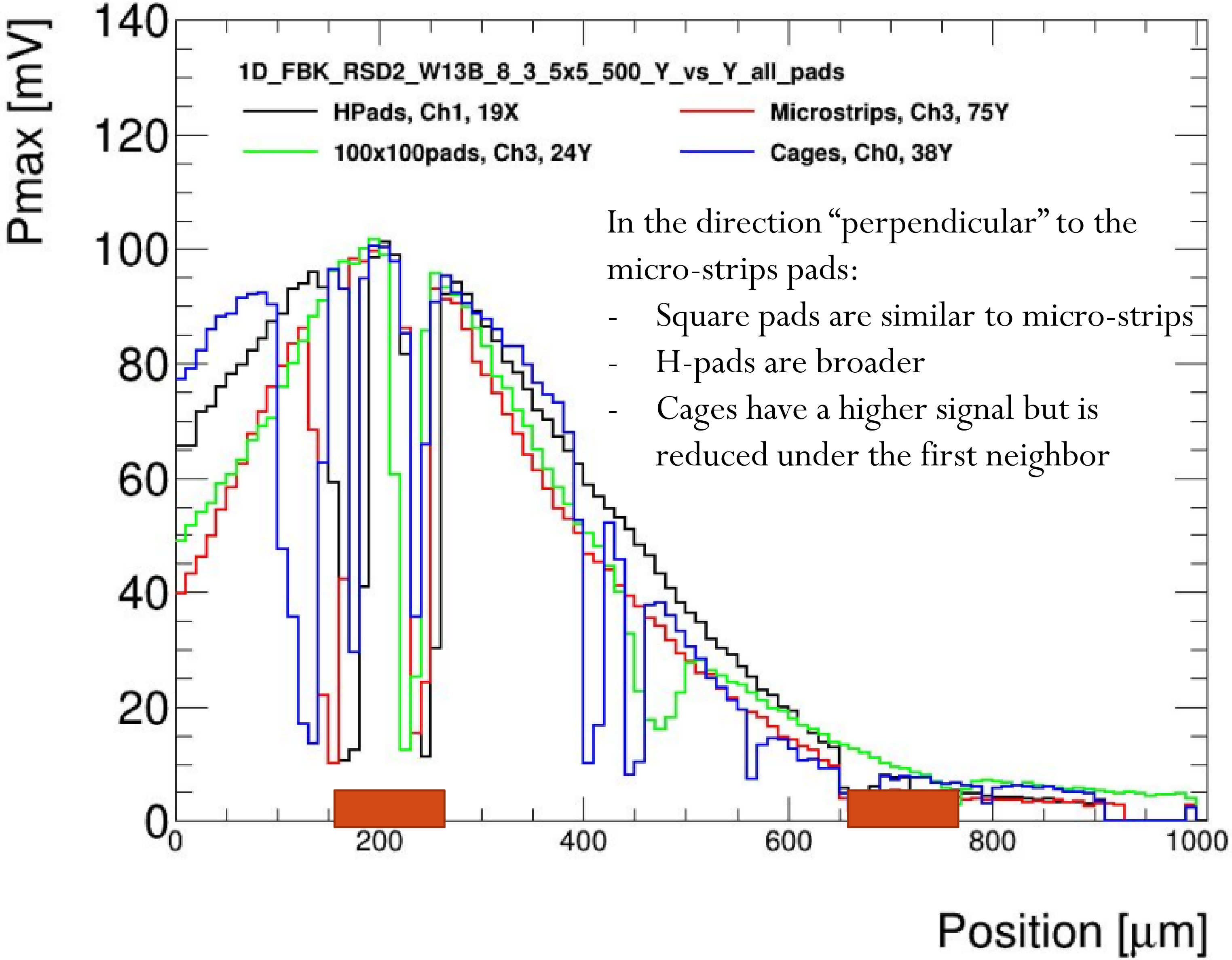






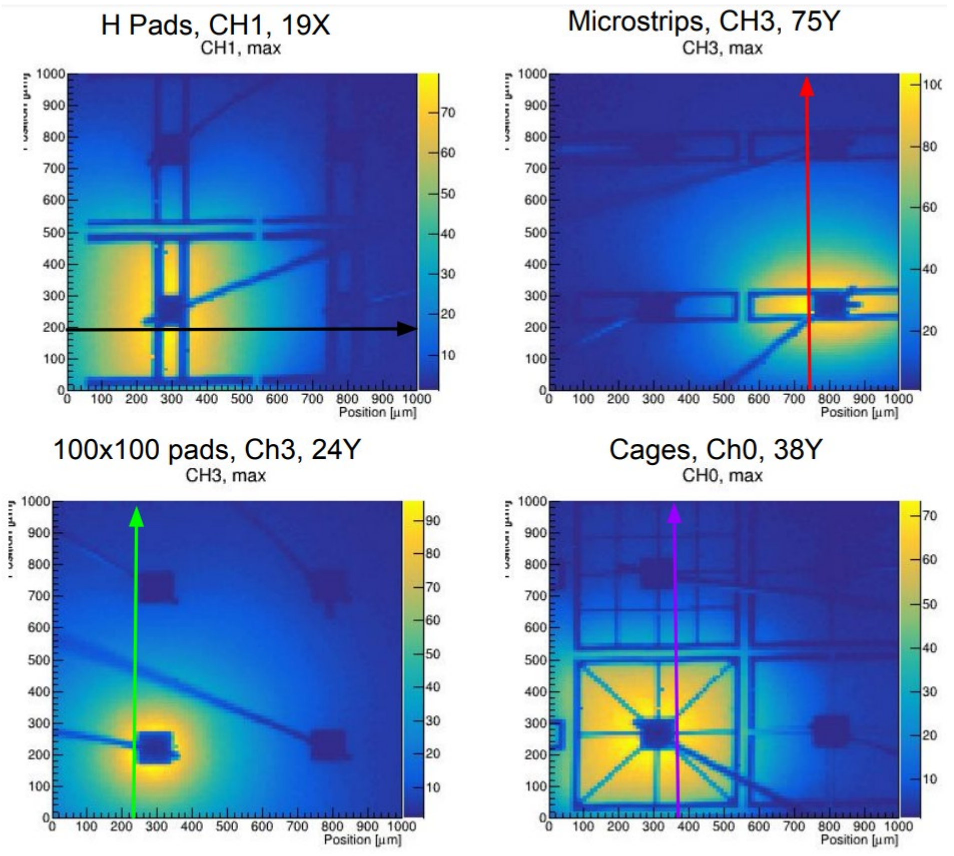


Comparison of 1D profiles, all pads - Y

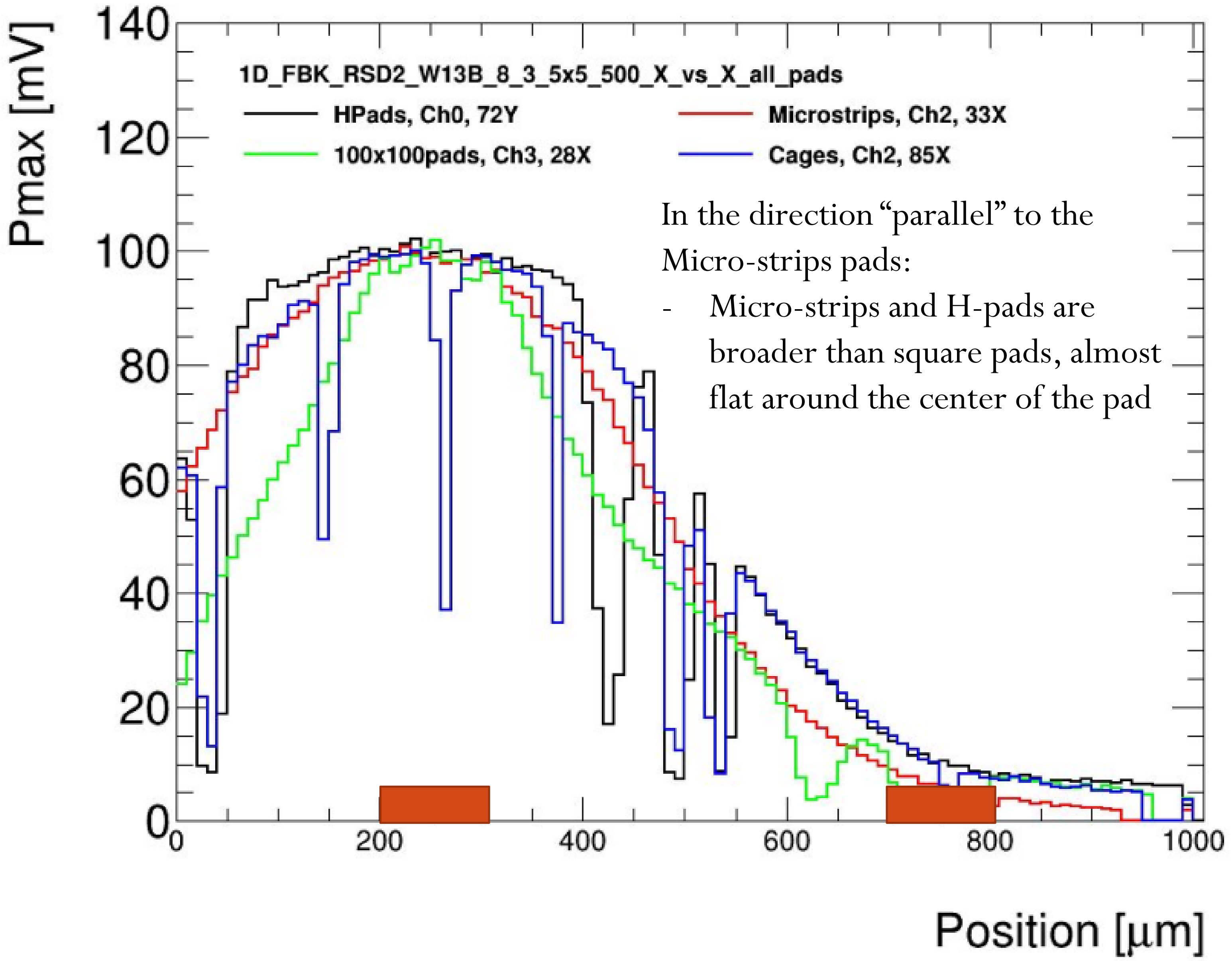


In the direction "perpendicular" to the micro-strips pads:

- Square pads are similar to micro-strips
- H-pads are broader
- Cages have a higher signal but is reduced under the first neighbor

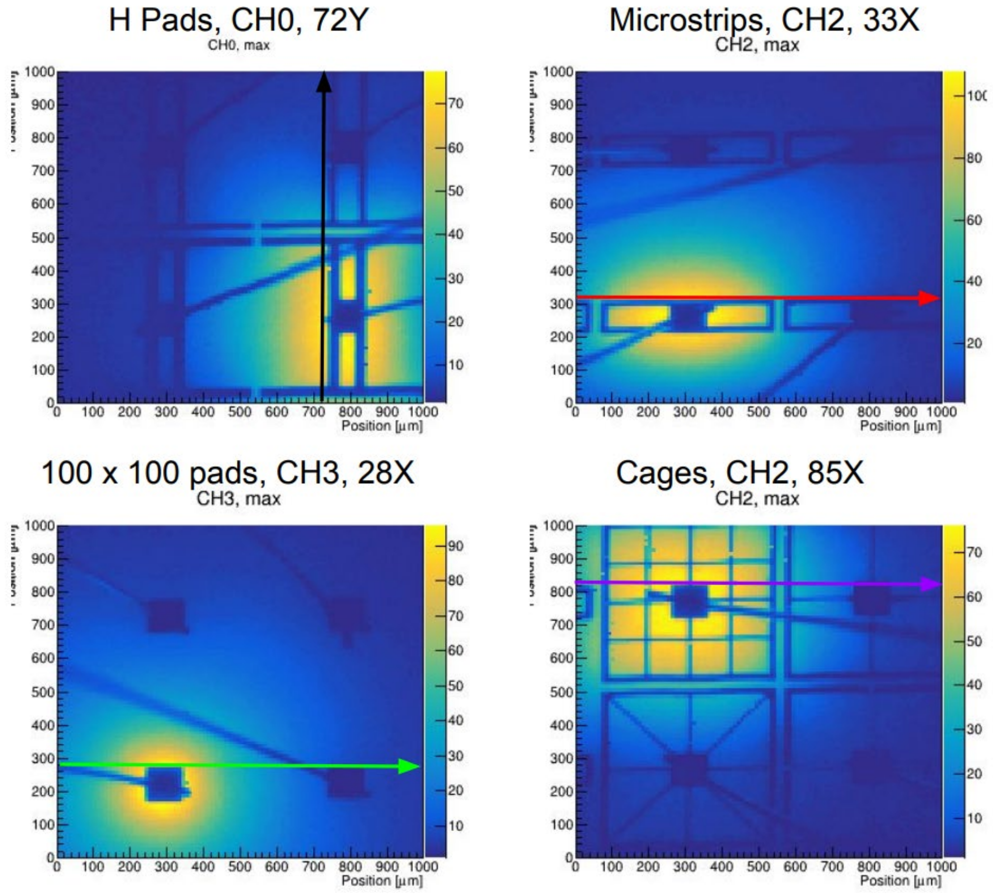


Comparison of 1D profiles, all pads - X



In the direction "parallel" to the Micro-strips pads:

- Micro-strips and H-pads are broader than square pads, almost flat around the center of the pad



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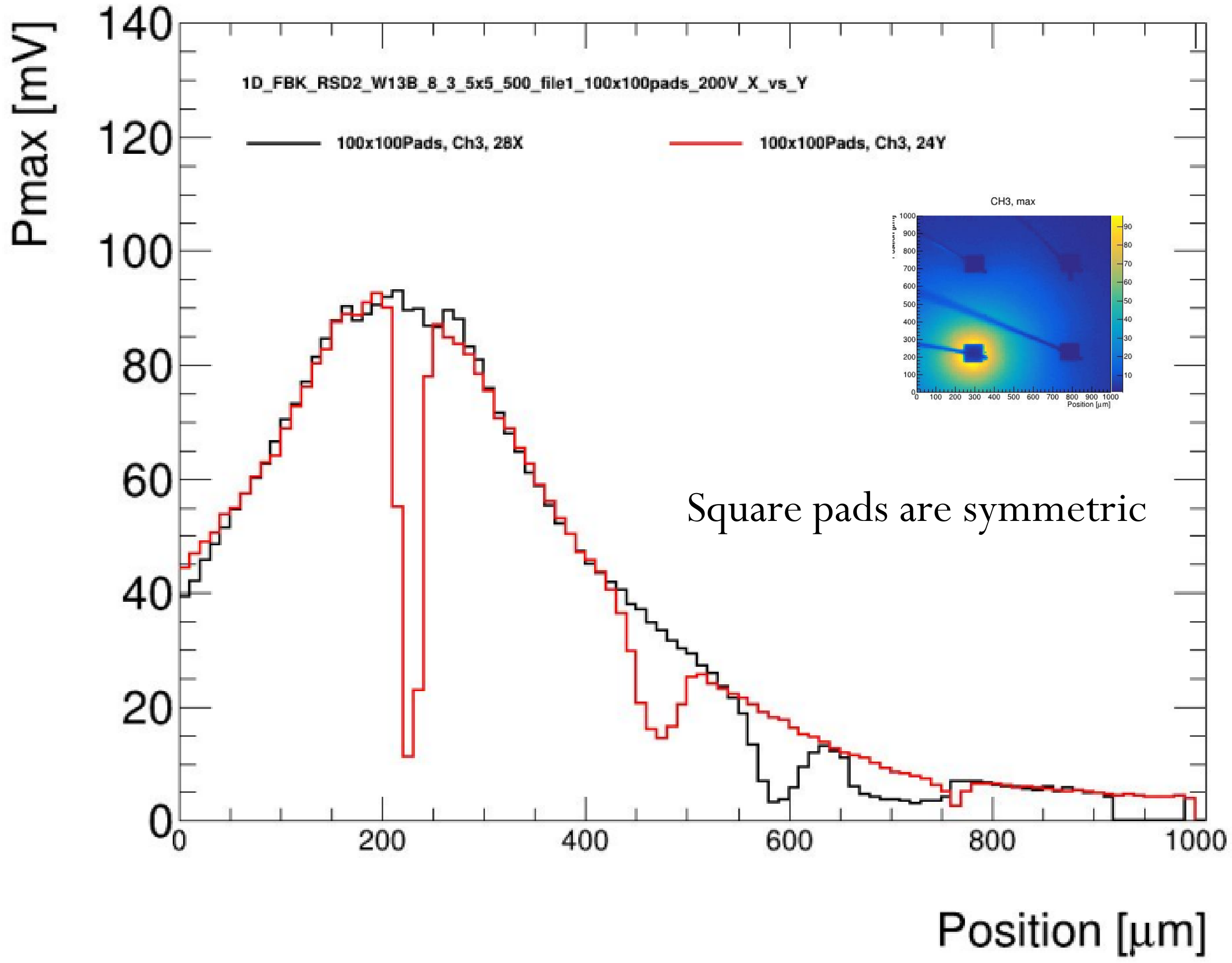
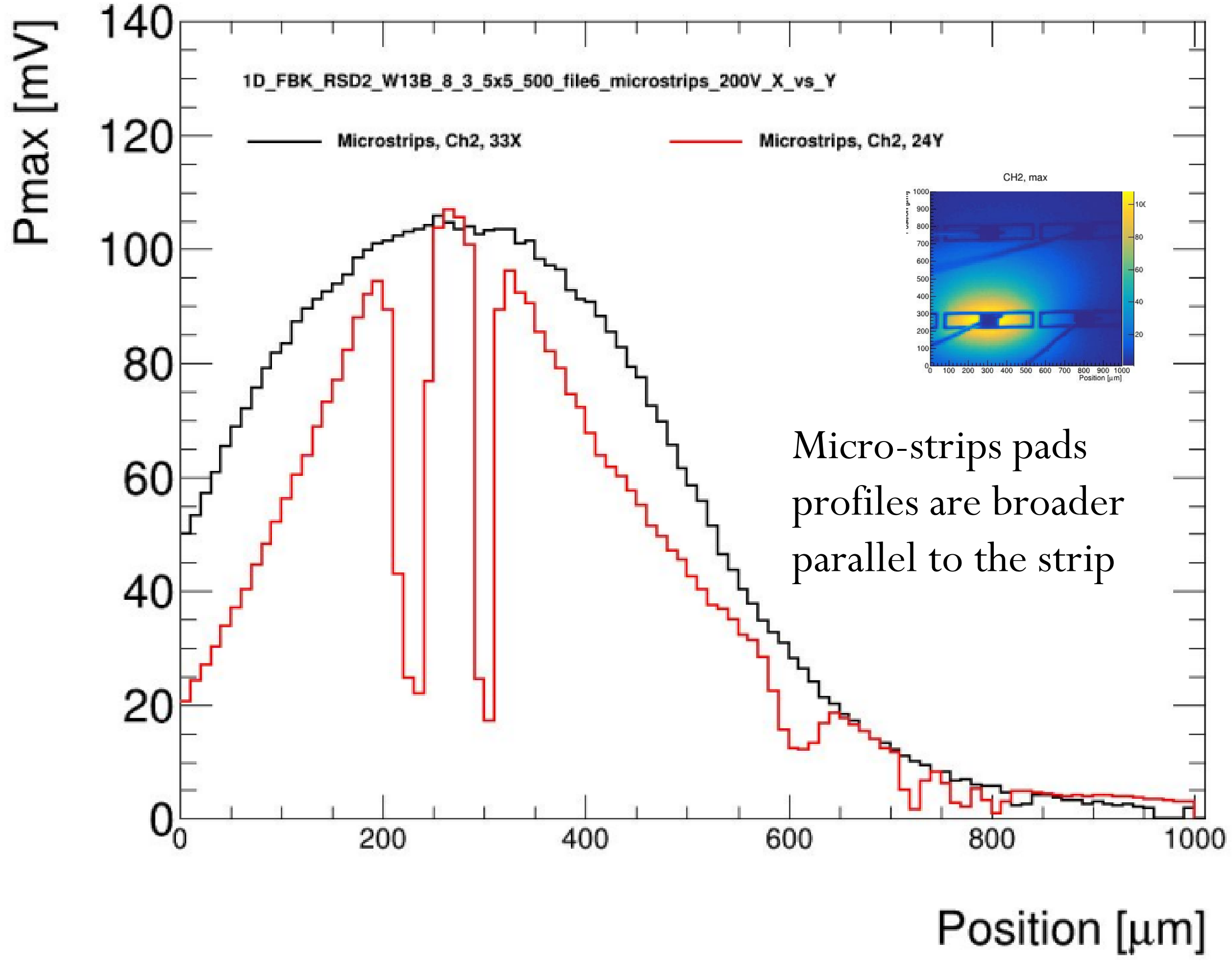
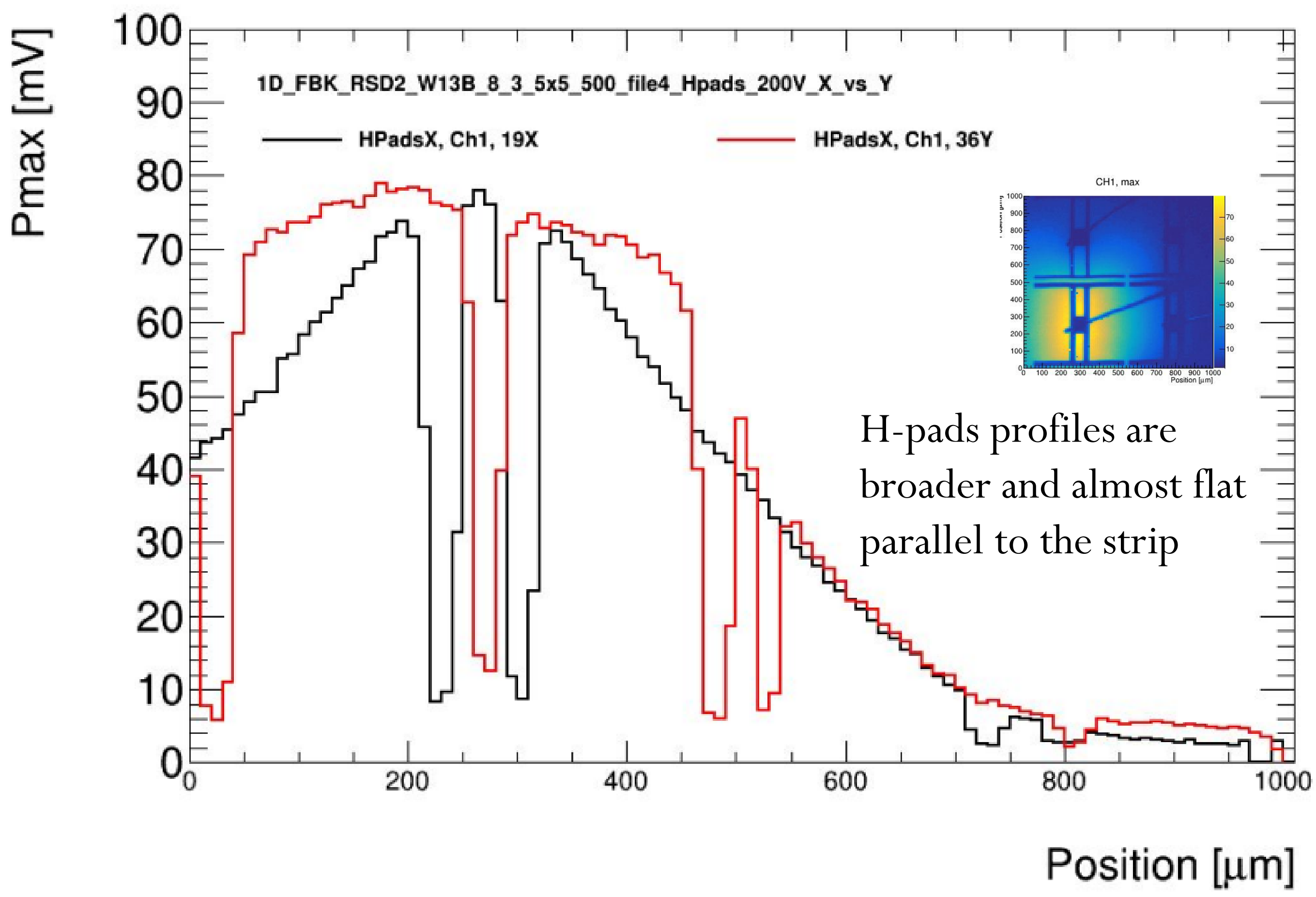
Comparison of 1D profiles, all pads – X vs Y

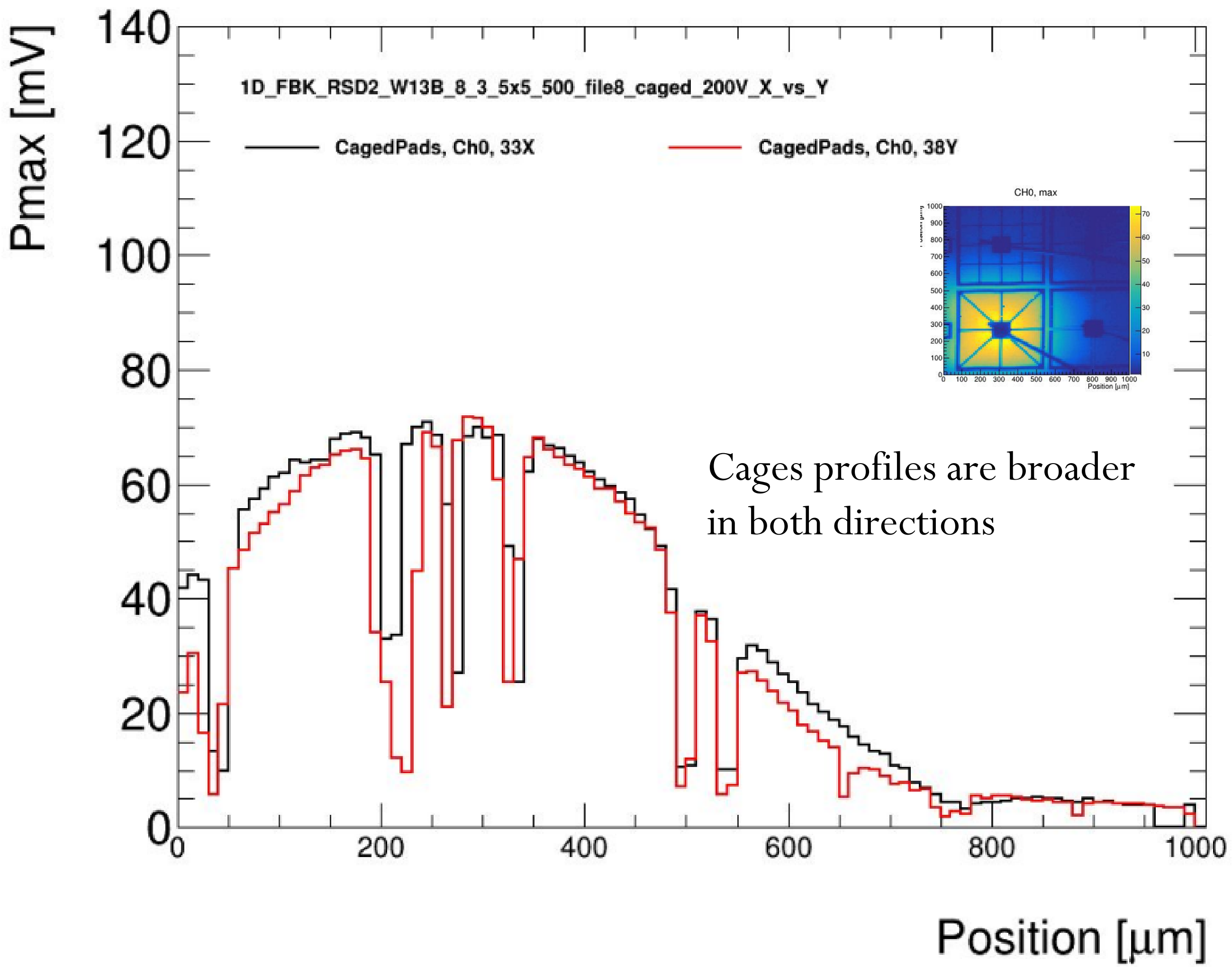




Comparison of 1D profiles, all pads – X vs Y

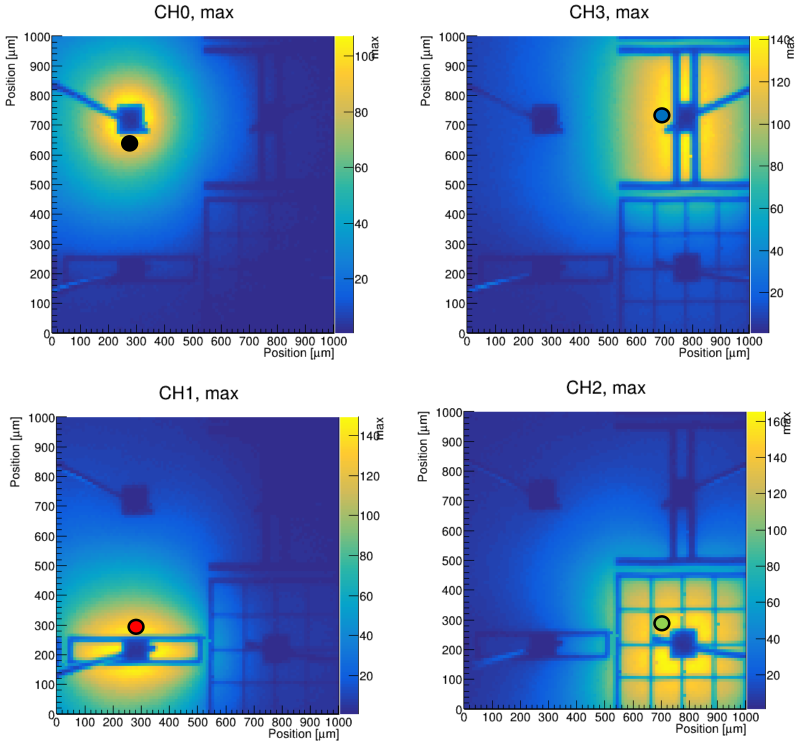


H-pads profiles are broader and almost flat parallel to the strip



Cages profiles are broader in both directions

Signal from all types of pads

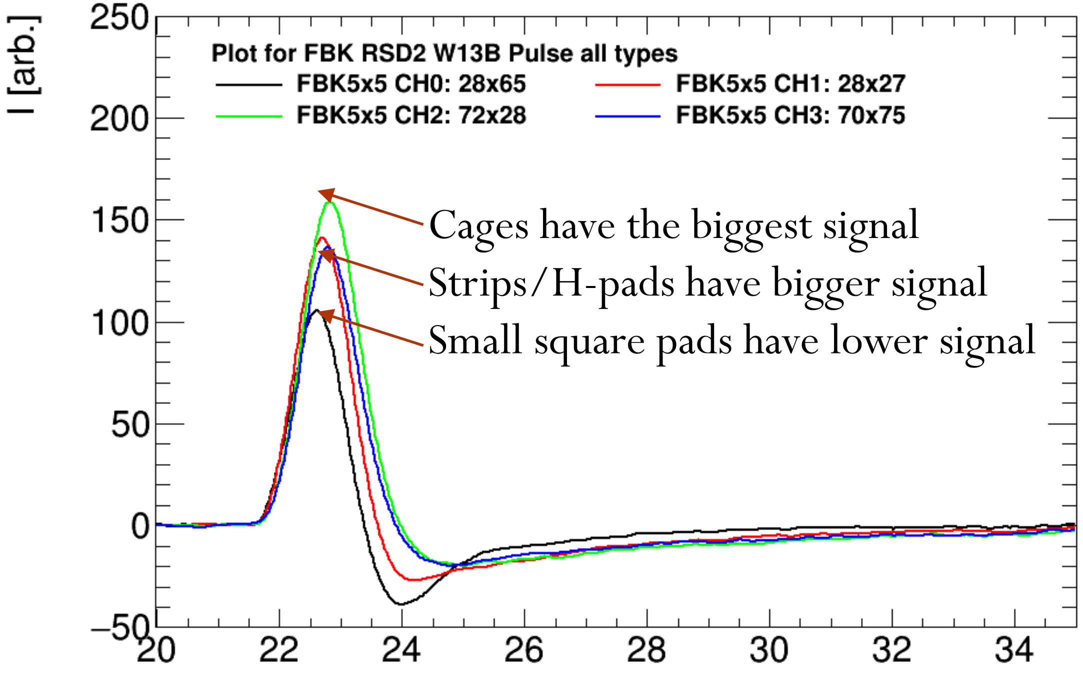


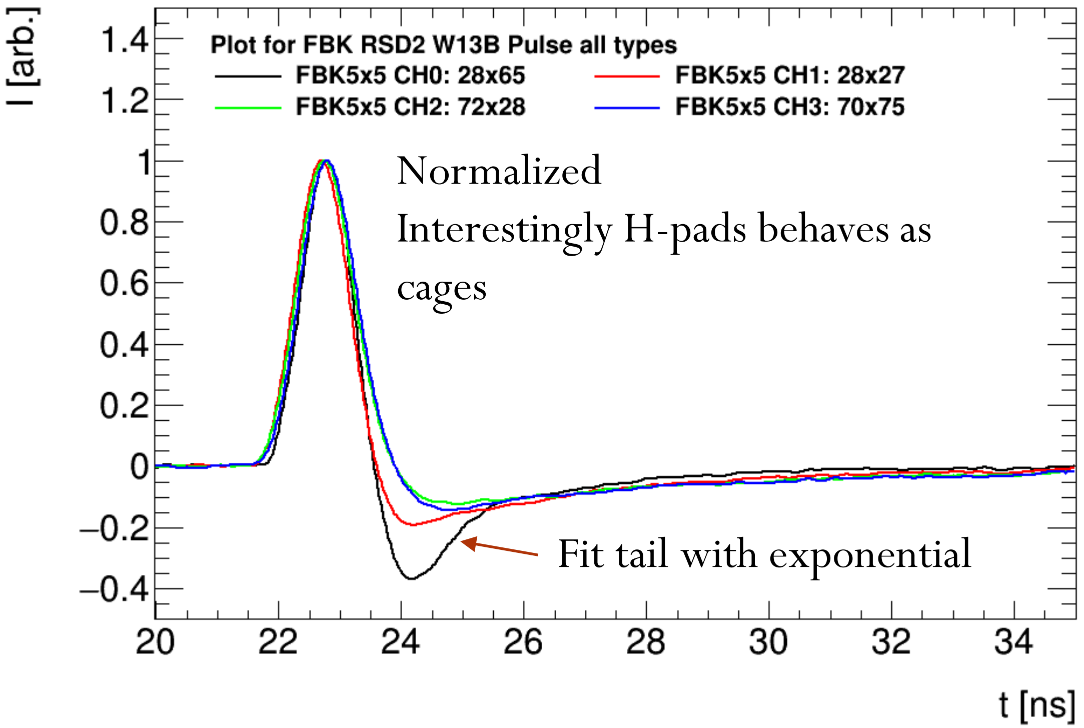
Positive pole of the signal is the same for all pad types

However they have different RC constant and return to baseline

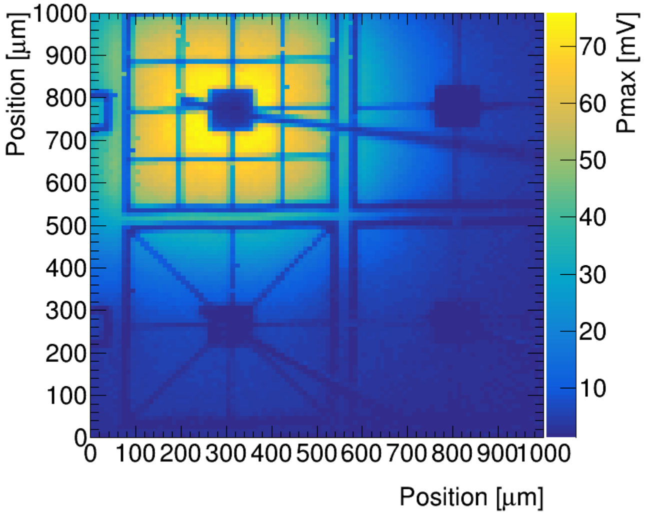
Unclear why it doesn't scale directly with the capacitance of the pad

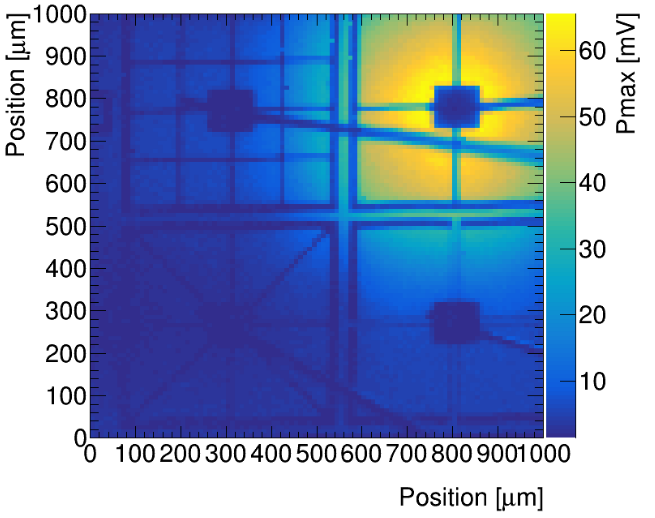
Pad type	Exponential RC constant	Capacitance
Square pads	0.61	94 fF
Micro-strips	0.28	299 fF
H-pads	0.19	639 fF
Cage	0.19	801 fF

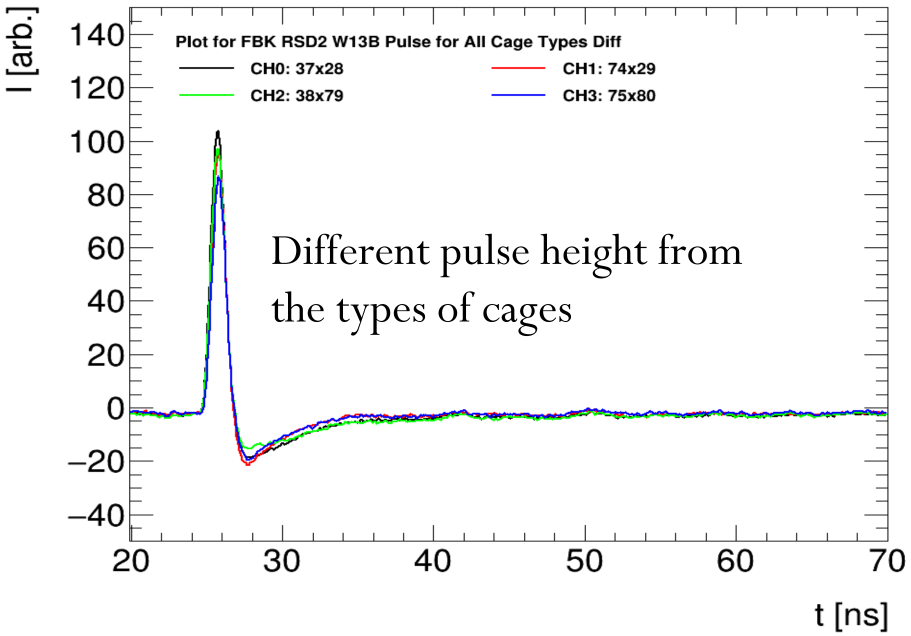




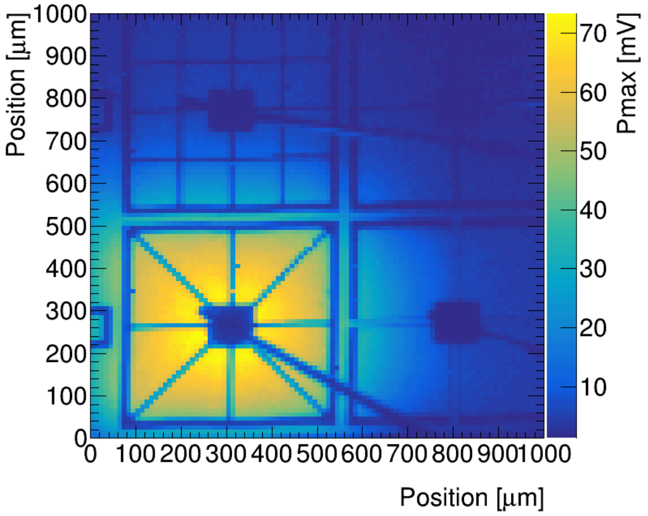
Signal from different types of "cages"

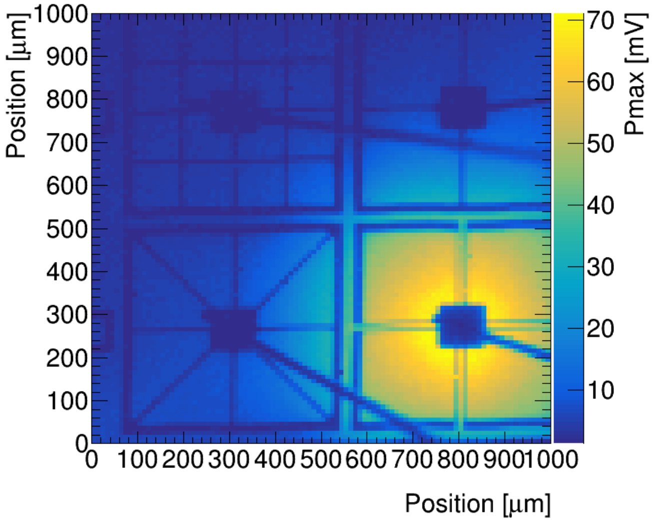


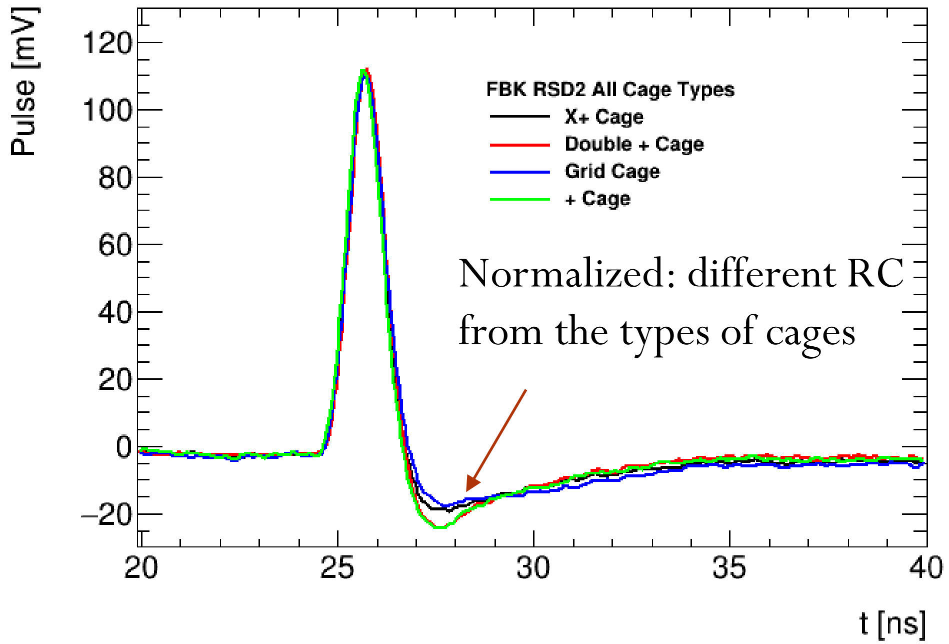




Different pulse height from the types of cages

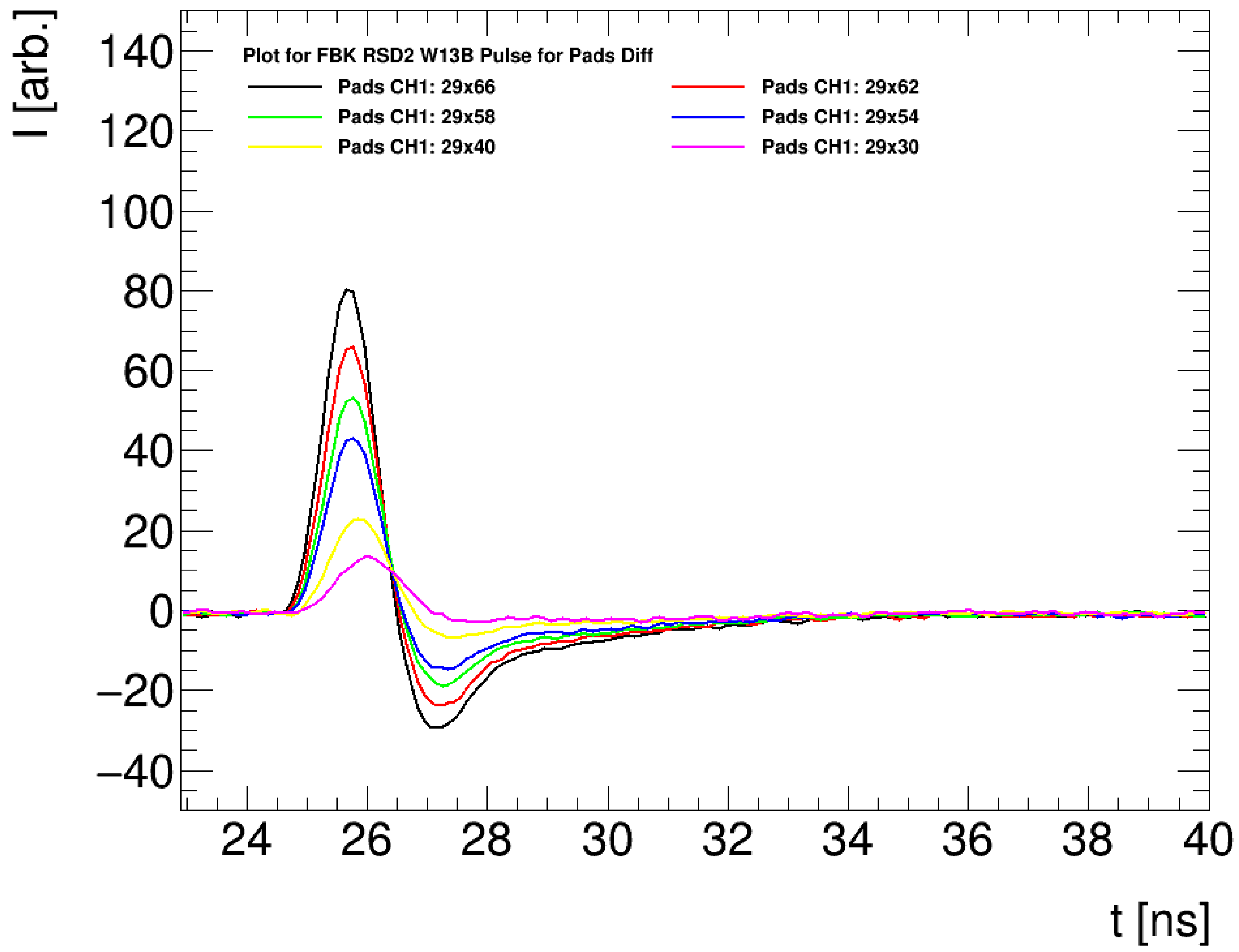


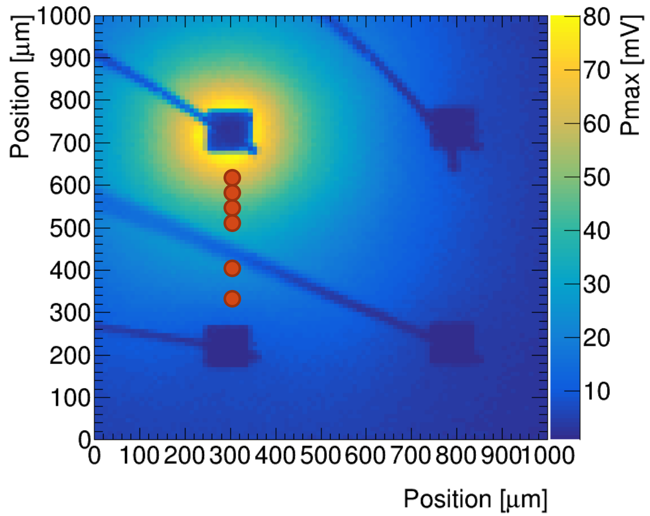


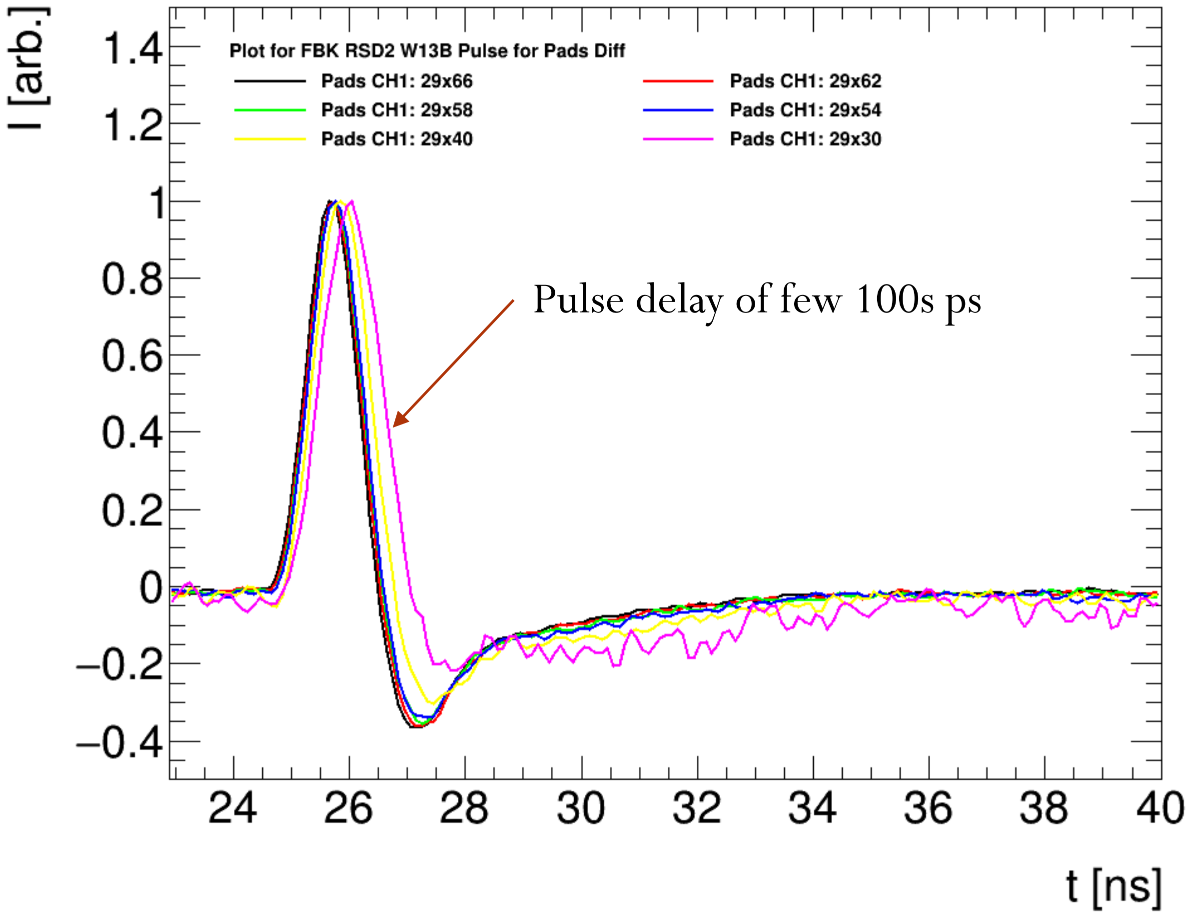


Normalized: different RC from the types of cages

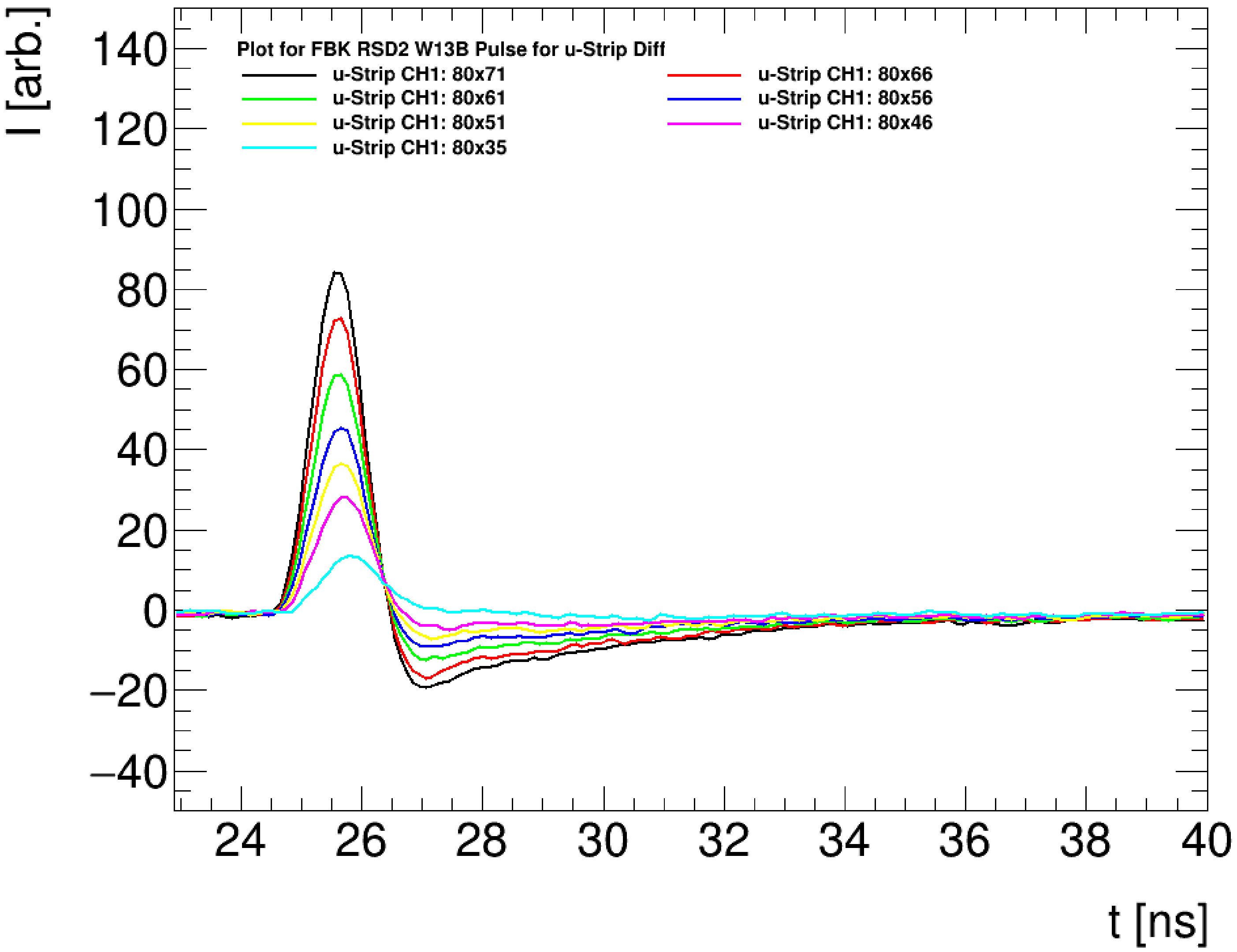
AC-LGAD 100x100 um pads pulses

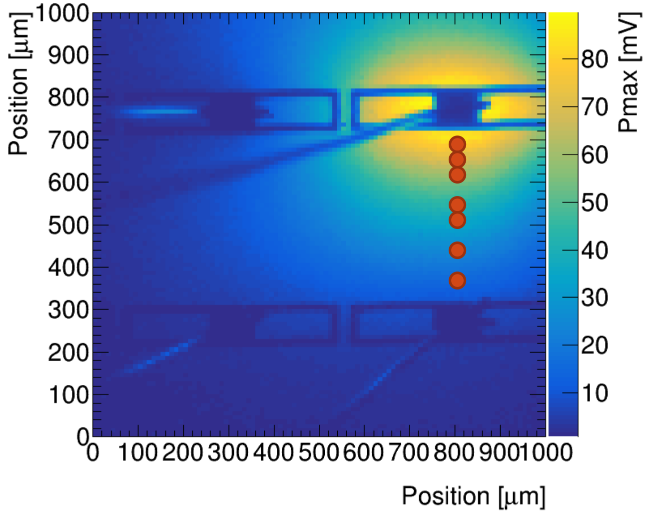


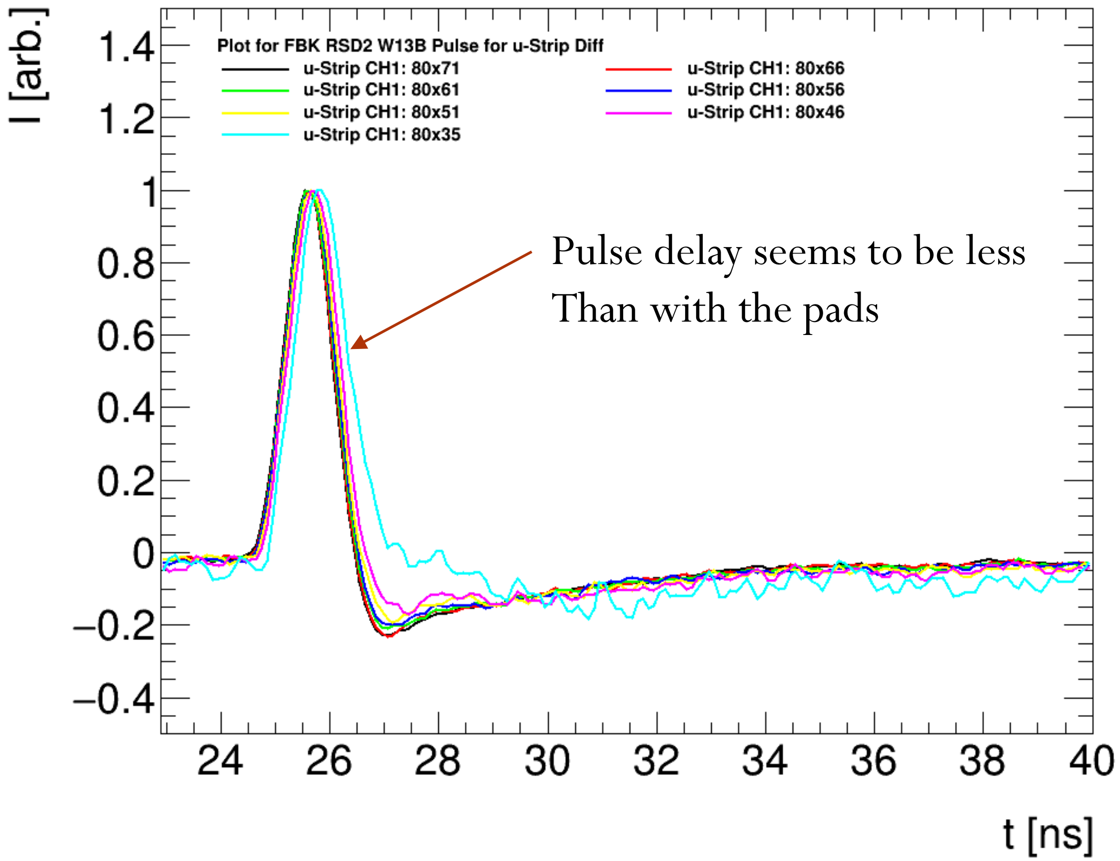




AC-LGAD micro strips pulses

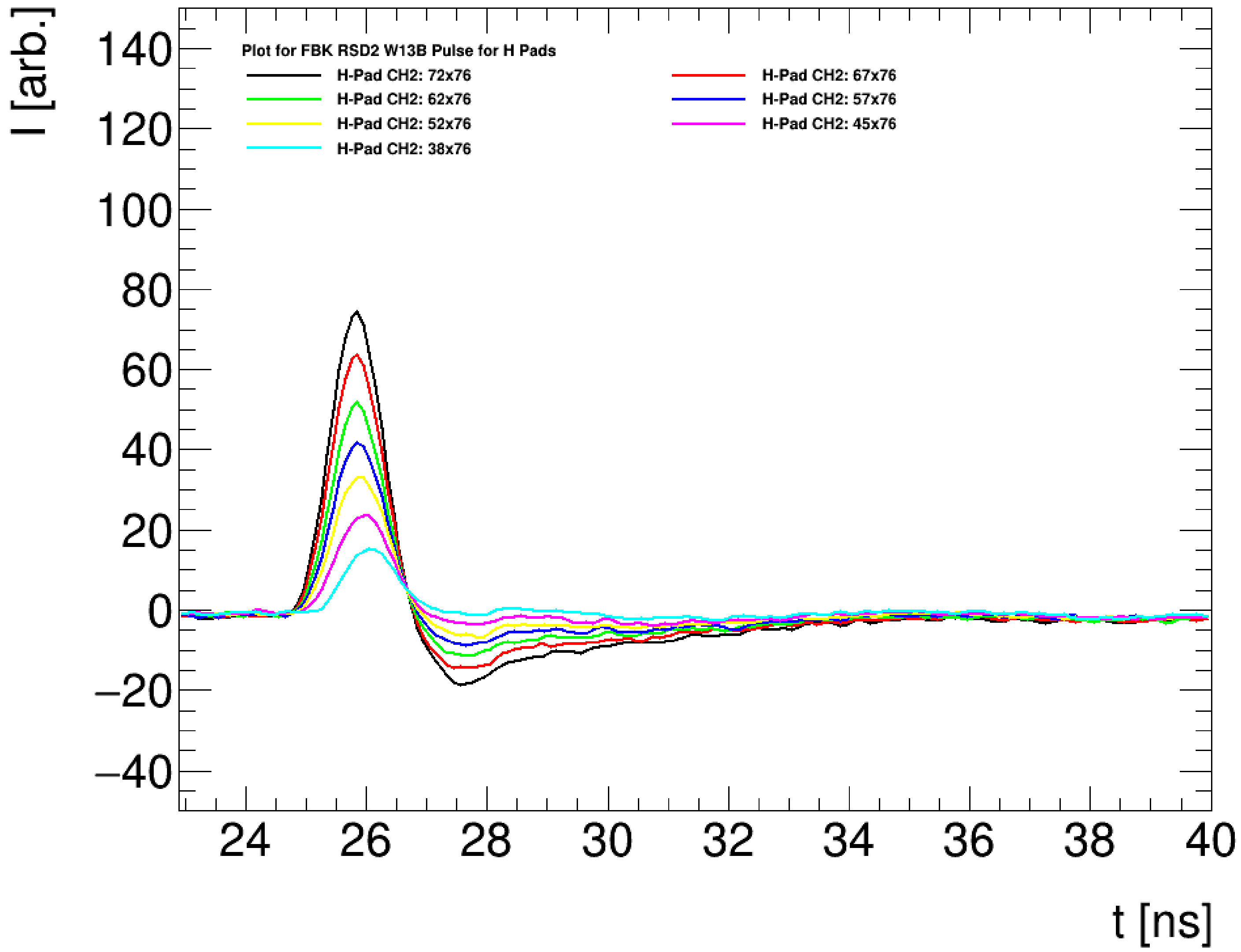


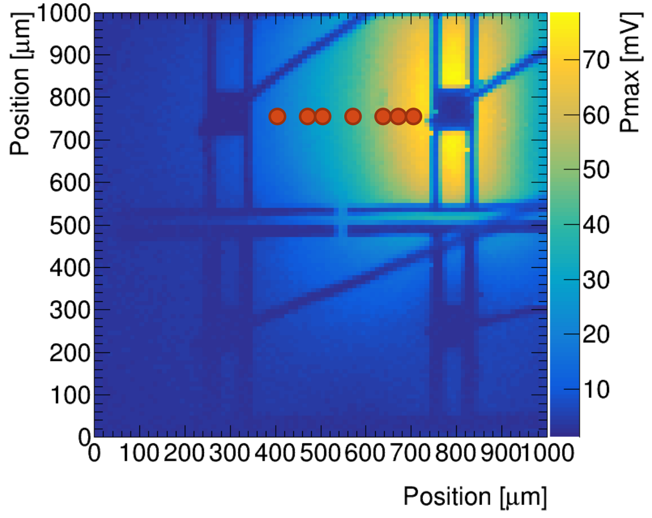


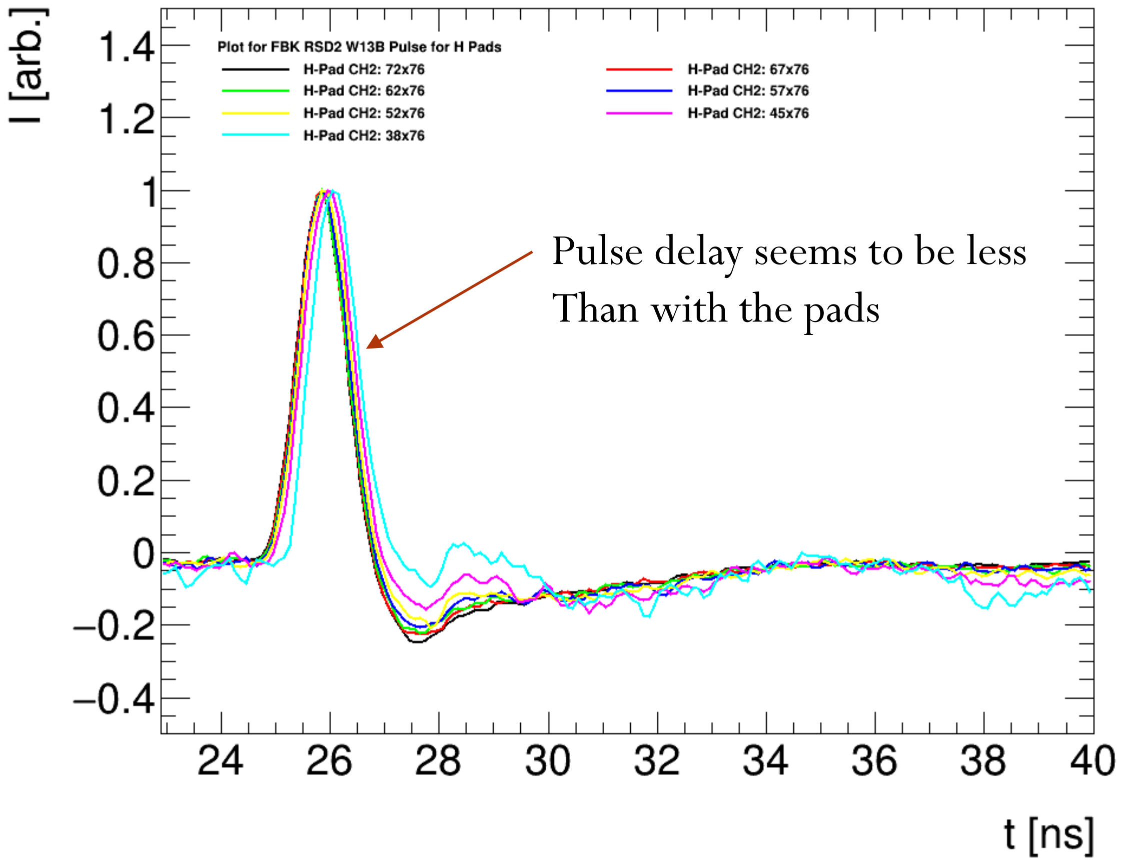


Pulse delay seems to be less
Than with the pads

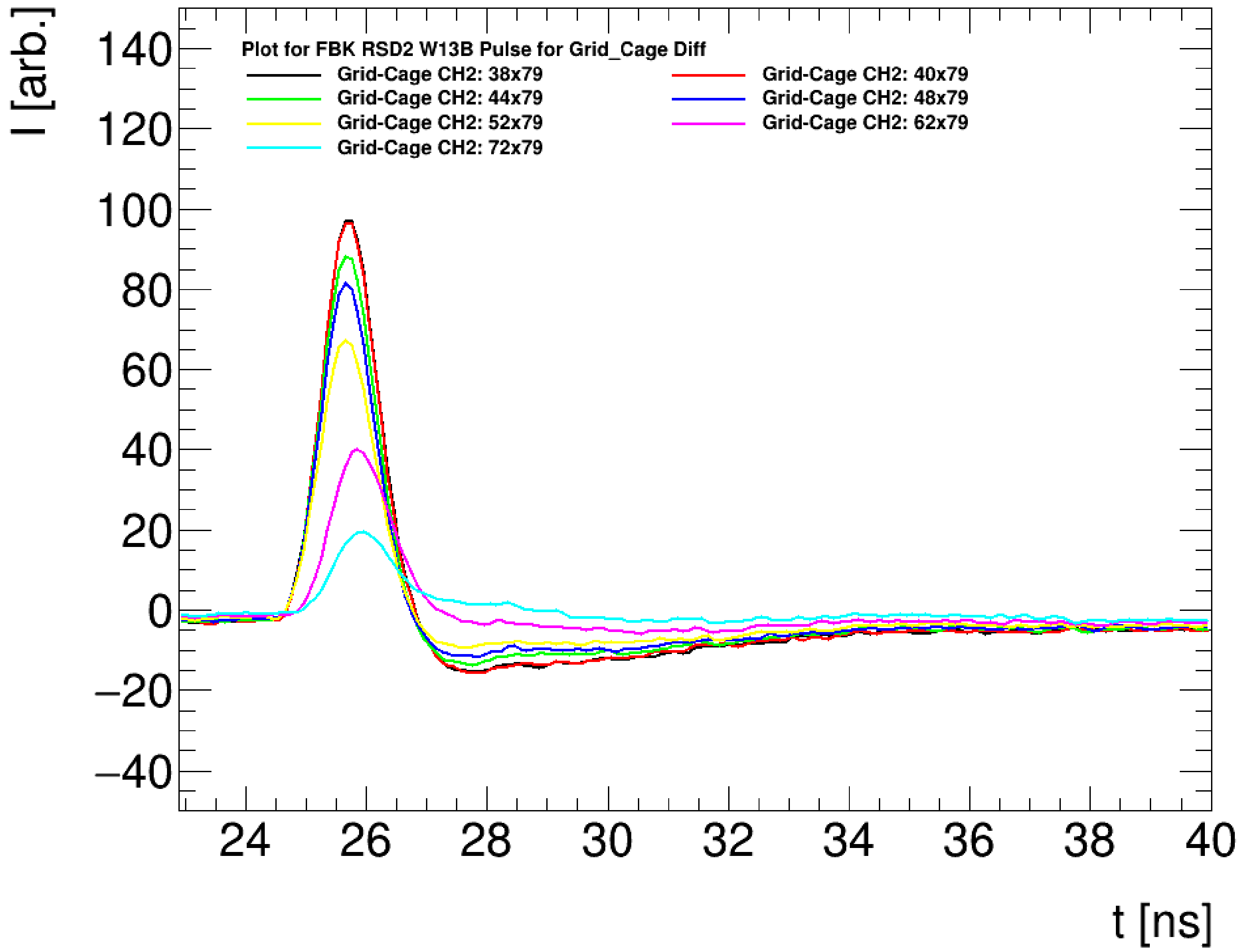
AC-LGAD H pads pulses

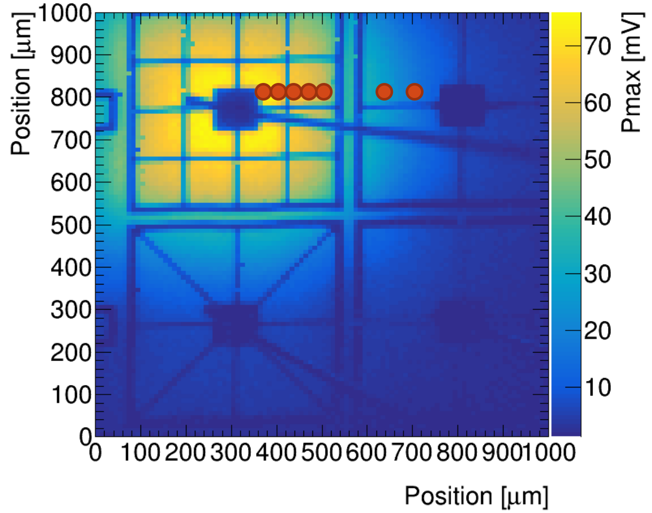


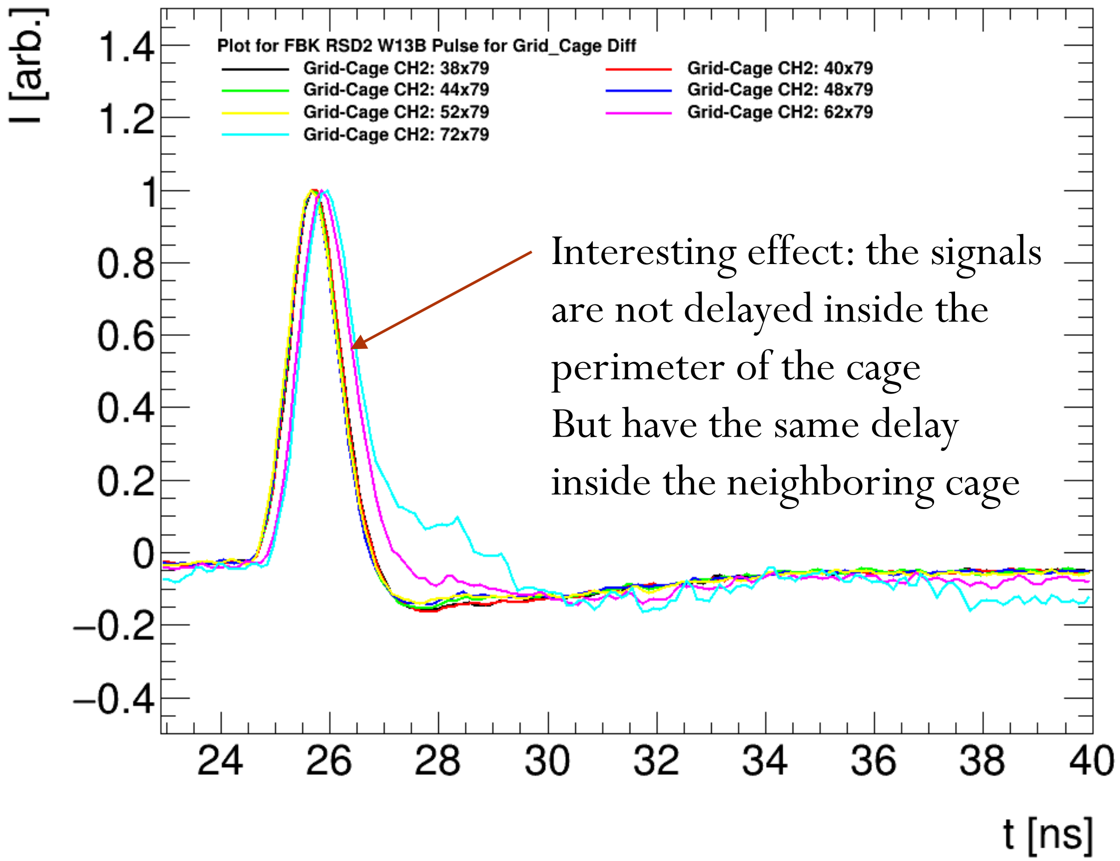




AC-LGAD cages pulses





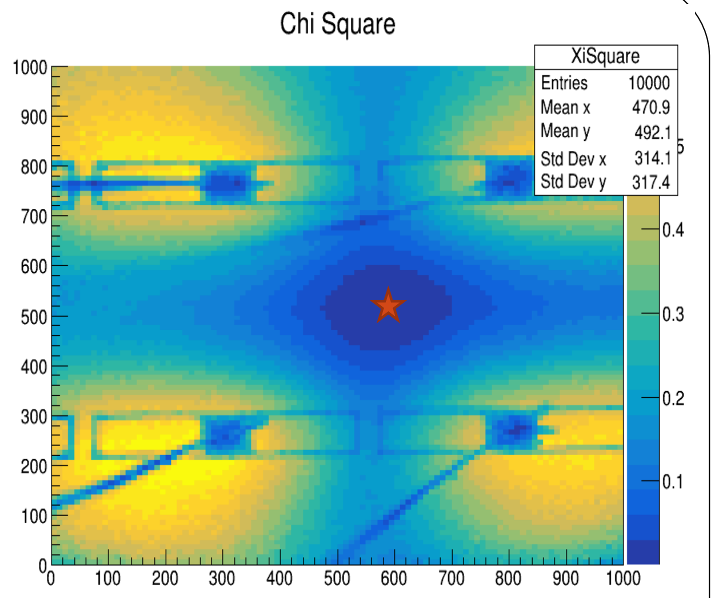


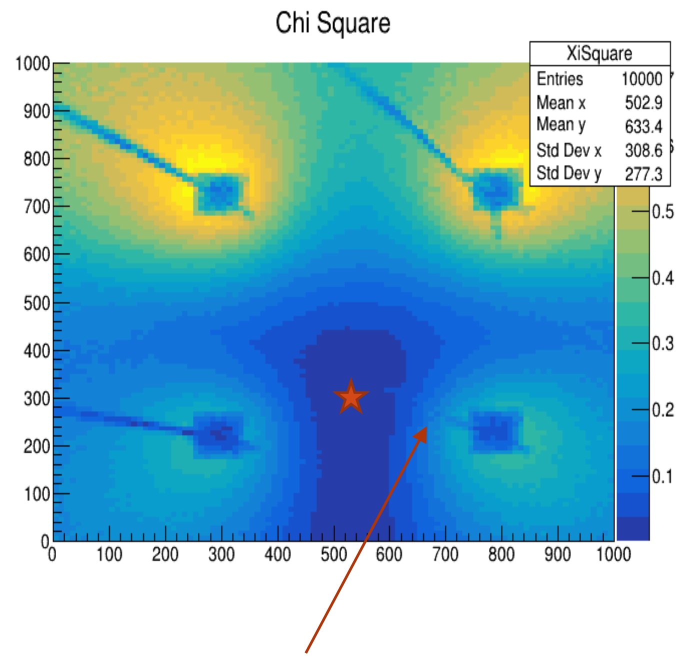
Interesting effect: the signals are not delayed inside the perimeter of the cage
But have the same delay inside the neighboring cage

Position reconstruction technique

- Position reconstruction is made by generating a reference file on the detector itself
  - Fine scan of the area averaging waveforms in each position using the TCT laser (using 2GHz scope)
  - From this reference file a fraction map is calculated for each of the 4 channels
- Then several single events are taken for each of the test positions
  - The position of each events is calculated by doing a X^2 of the fractions in the event and the fraction maps from the average scan (using a 16ch CAEN digitizer based on DRS4)
  - The minimum X^2 is taken as the reconstructed position (for now limited to the fine scan binning of ~10um, so anything under 5um of precision is not fully accurate)
- **Reconstruction not based on master formula or charge imbalance** since it's not trivial to model these geometries

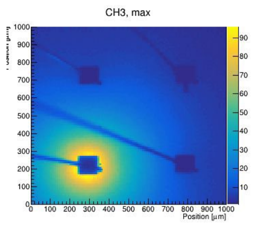
- Jitter is evaluated on the sigma of a Gaussian fit of the distribution of CFD 50% timestamps with the trigger signal
  - The timestamp is calculated using 4 channels weighted with the Pmax^2
  - Jitter seems to be higher than expected, might be because of the low bandwidth of the CAEN digitizer
  - Caveat: the time delay is not taken into account, to have a correct timestamp it needs to be considered. If the position resolution is high the effect should be small.



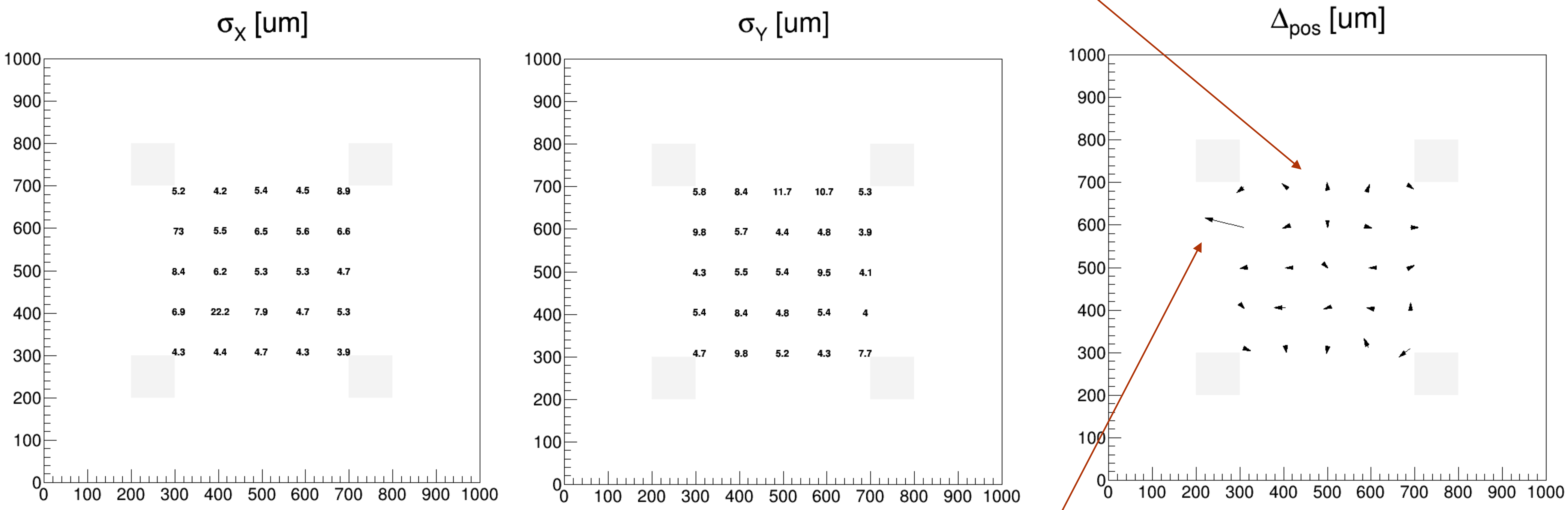


Note: some position are close to the wire bond so the reconstruction might fail

Reconstructed position resolution – small pads

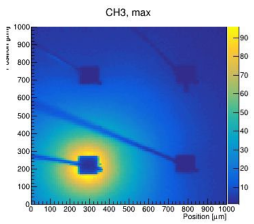


No characteristic 'pincushion' shape since reference is taken from the sensor itself

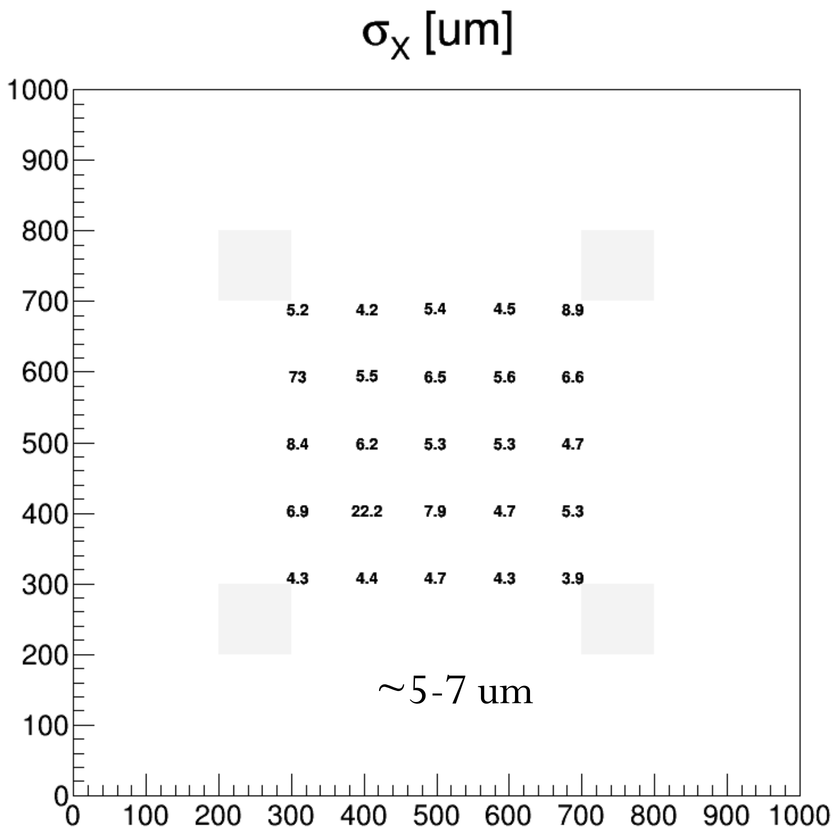


However at the edges the reconstruction can fail!

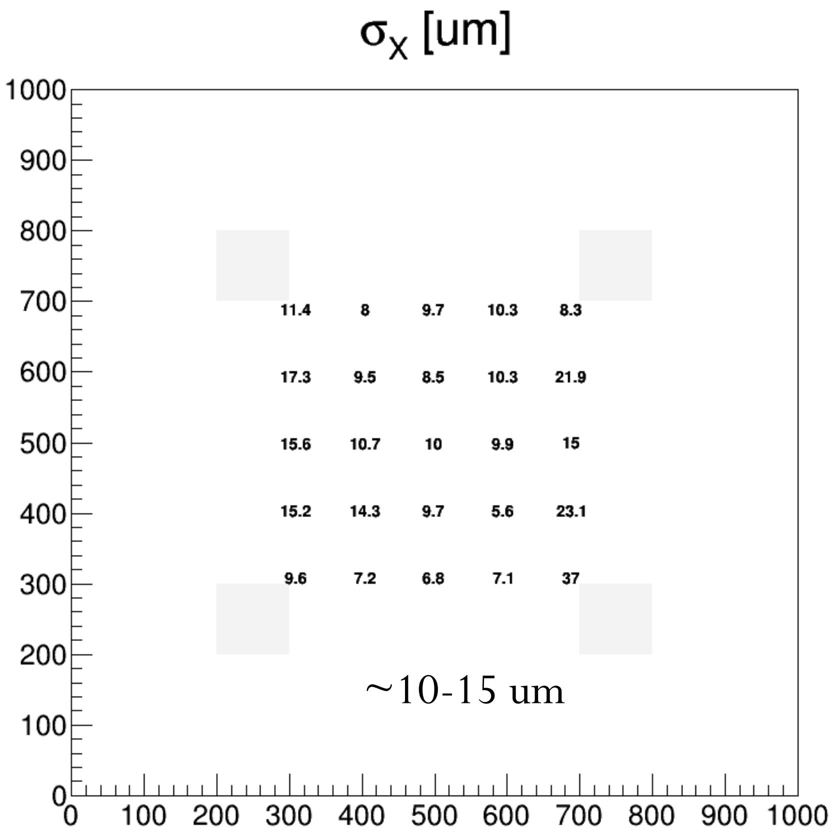
Reconstructed position resolution – small pads



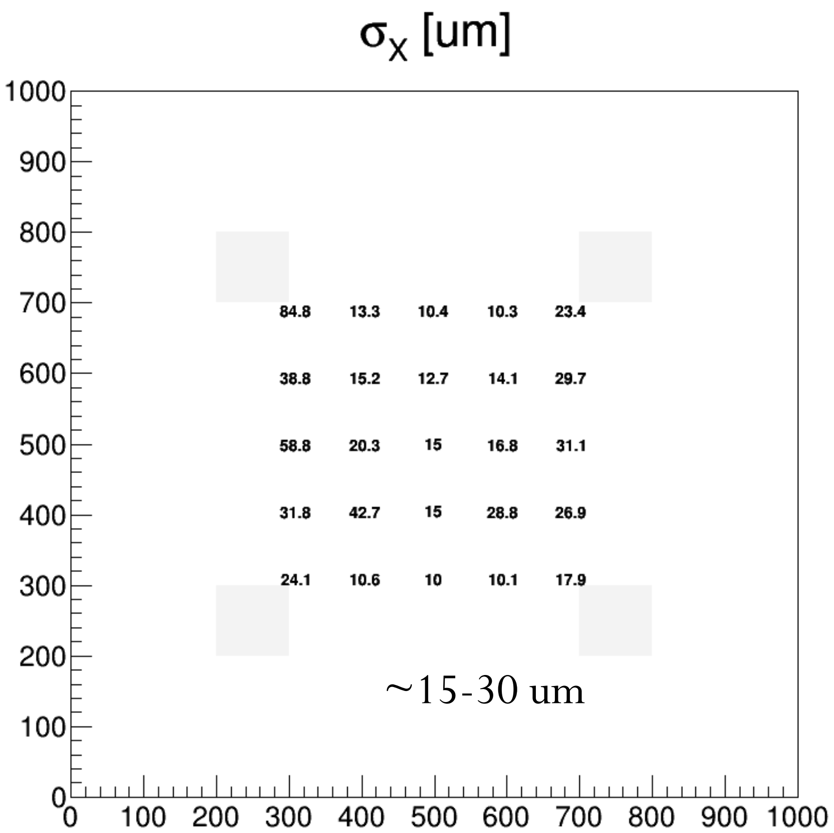
250V



200V

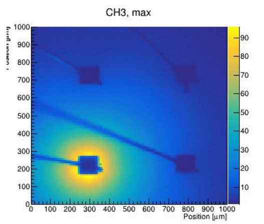


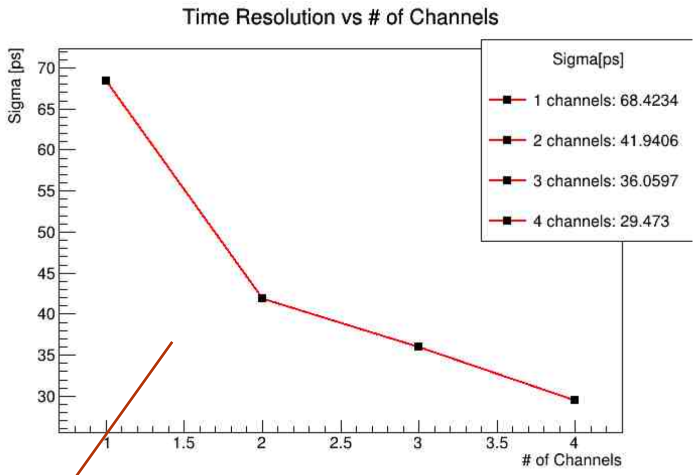
150V



As expected the resolution is worse at lower gain

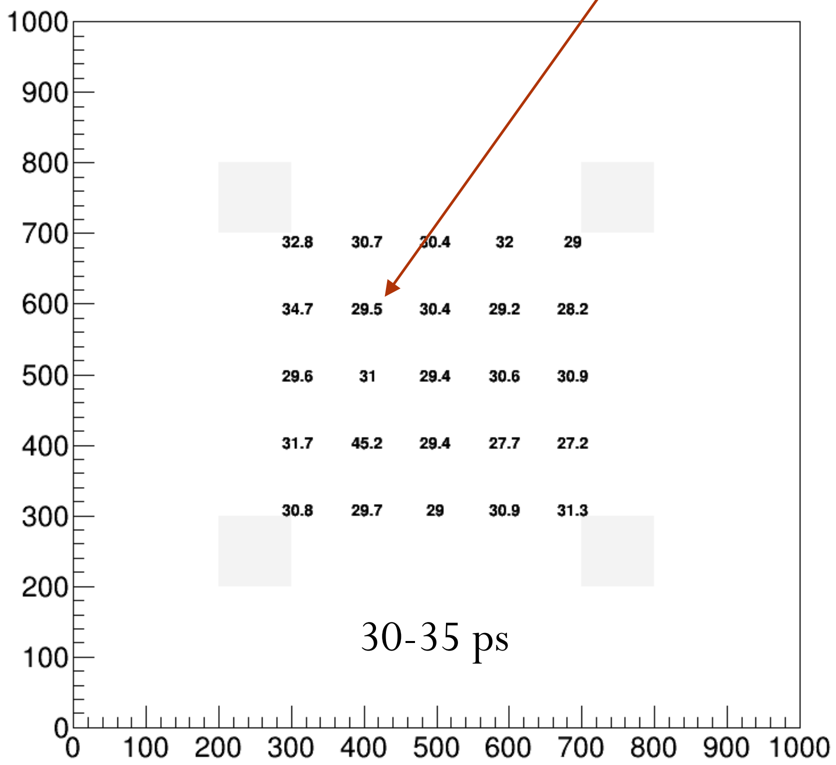
Jitter – small pads





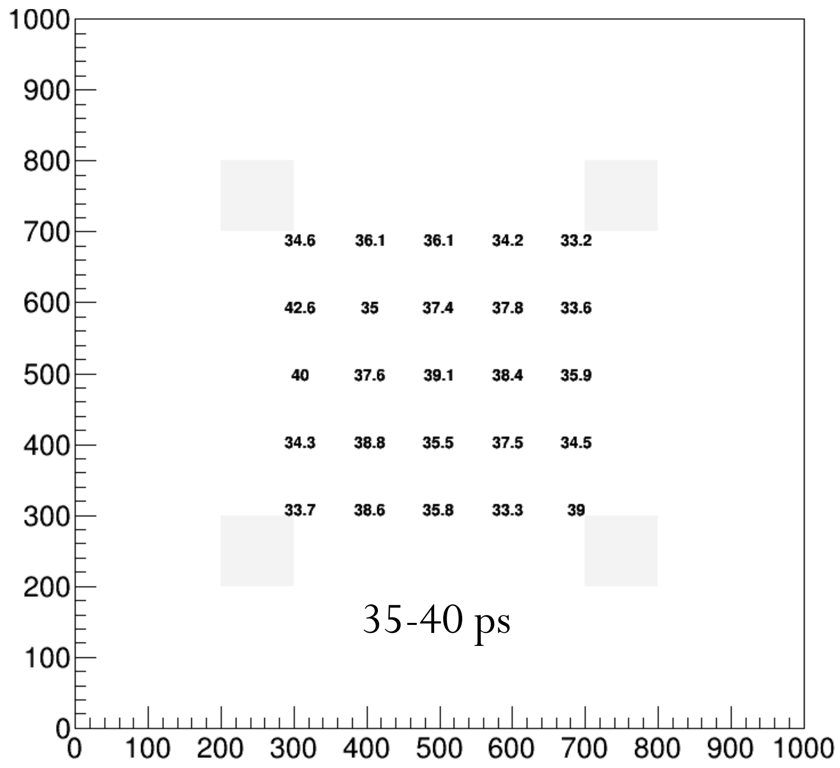
250V

σ_T [ps]



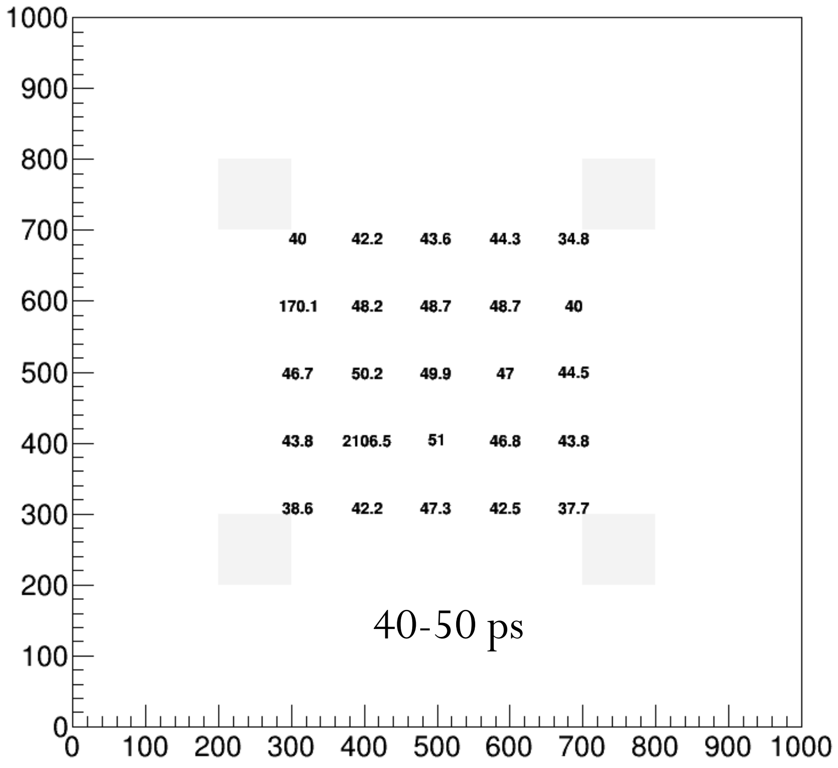
200V

σ_T [ps]



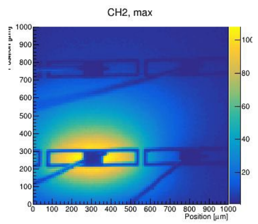
150V

σ_T [ps]

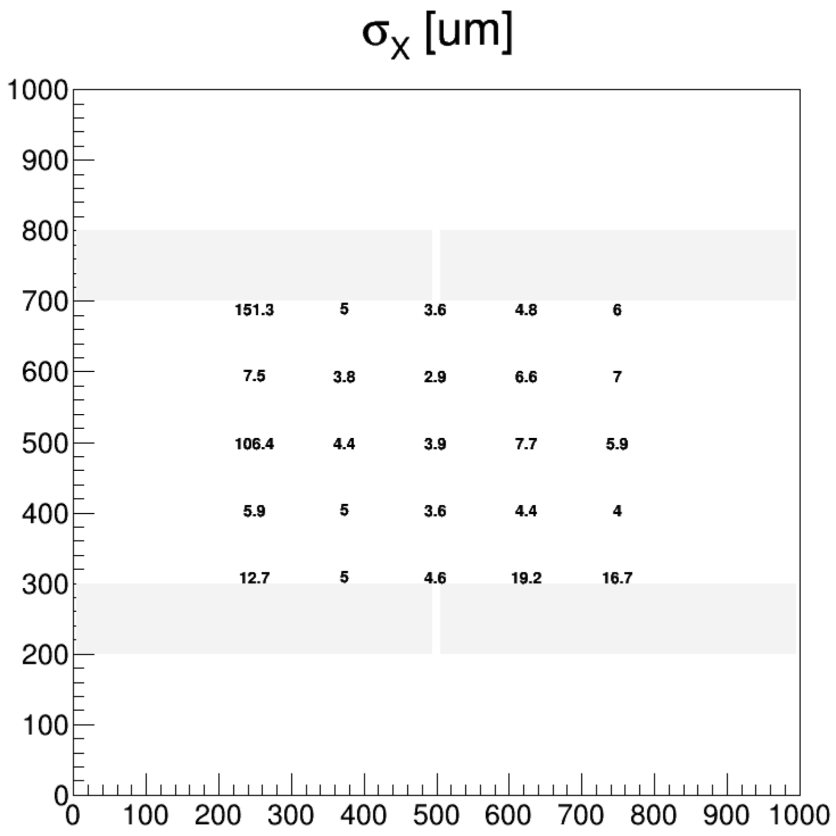


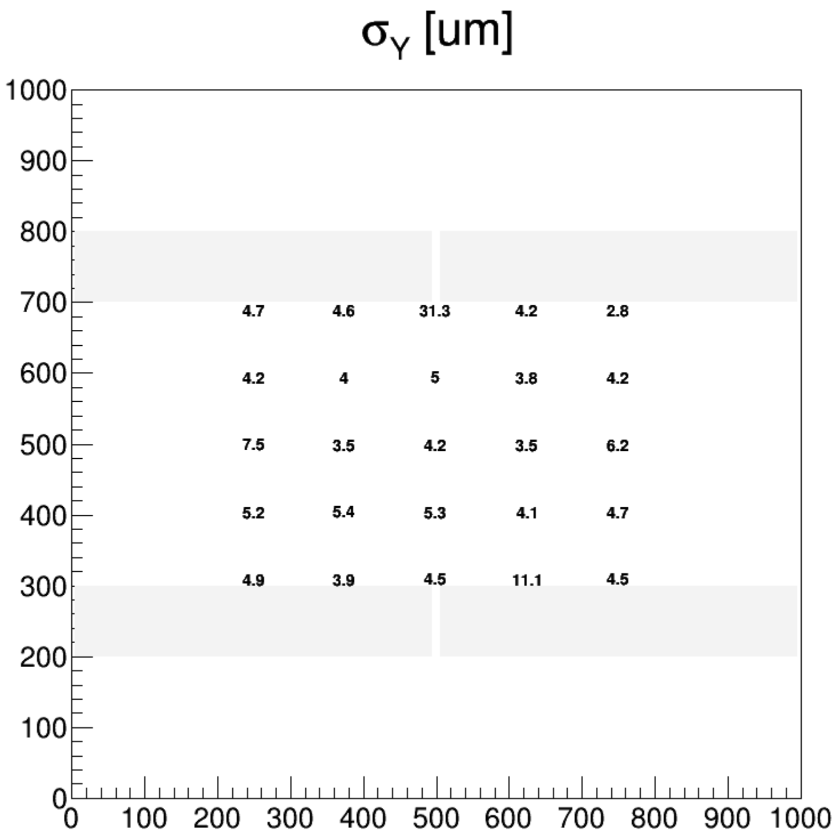
Jitter using the 4 channel combination is fairly constant in the region in between pads

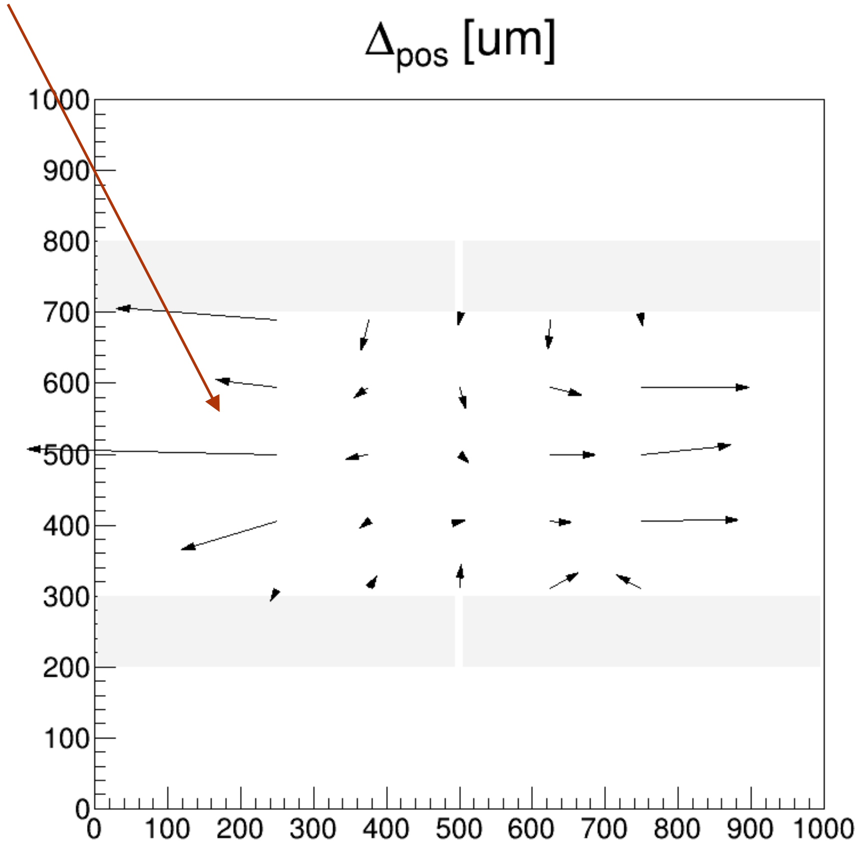
Reconstructed position resolution – microstrips



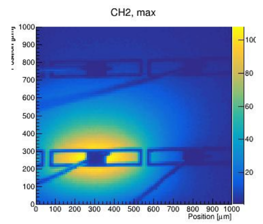
As expected better reconstruction in Y than in X, especially at the edges



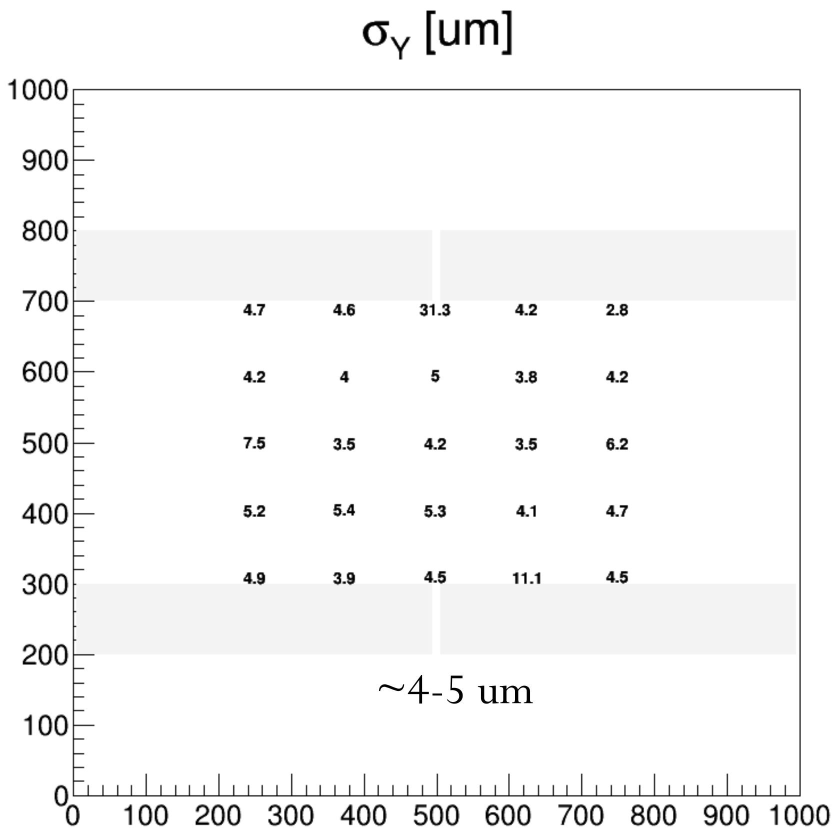




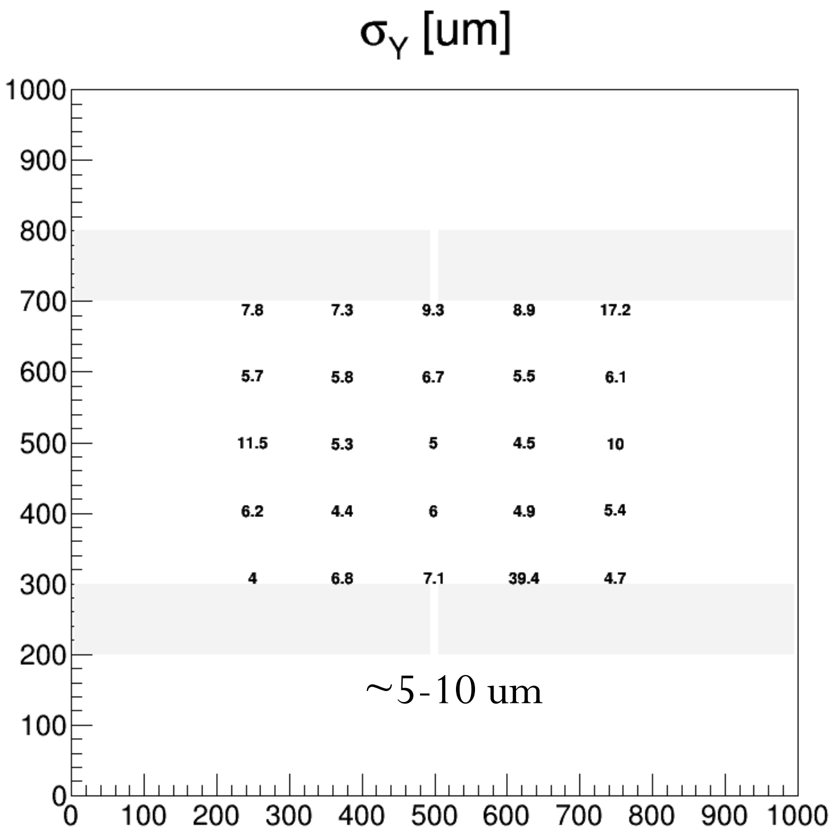
Reconstructed position resolution – microstrips



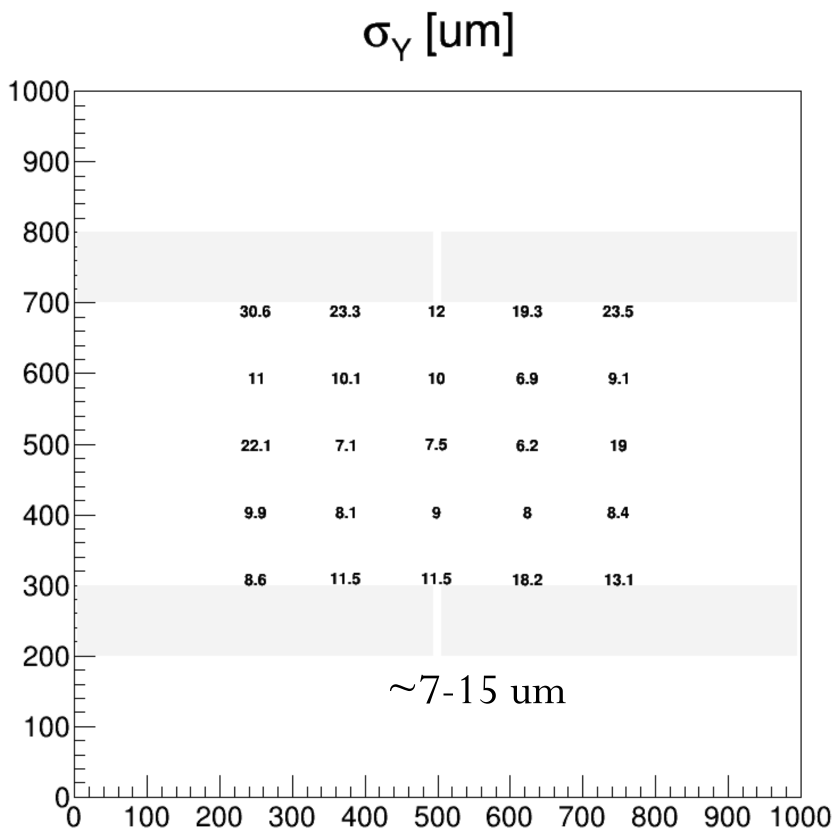
250V



200V

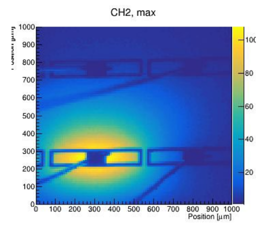


150V

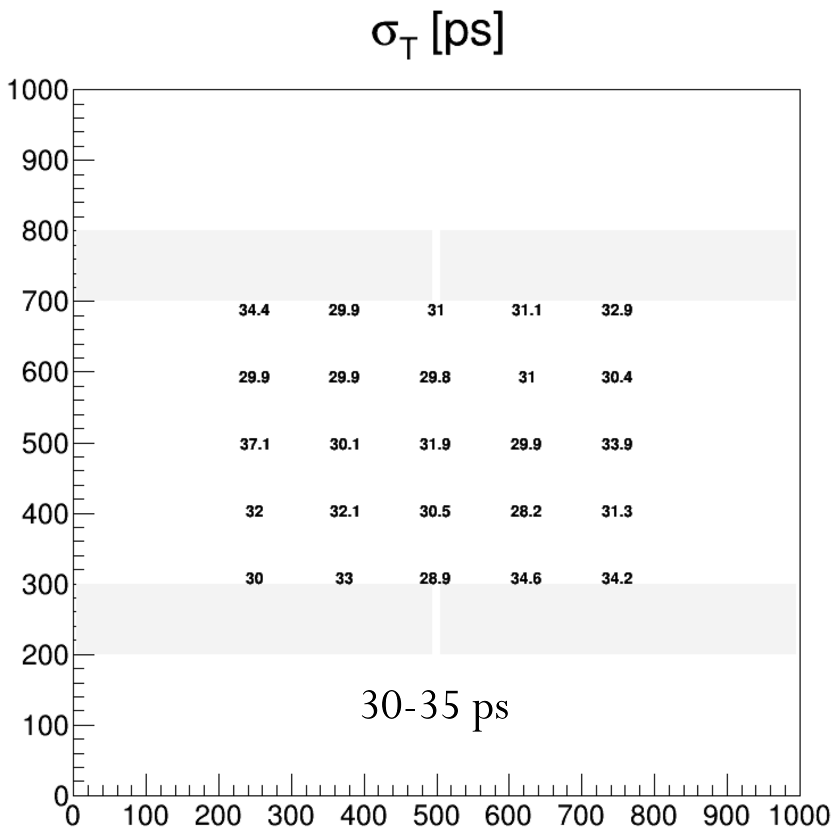


Resolution is worse at lower gain, but better than in the small pads case

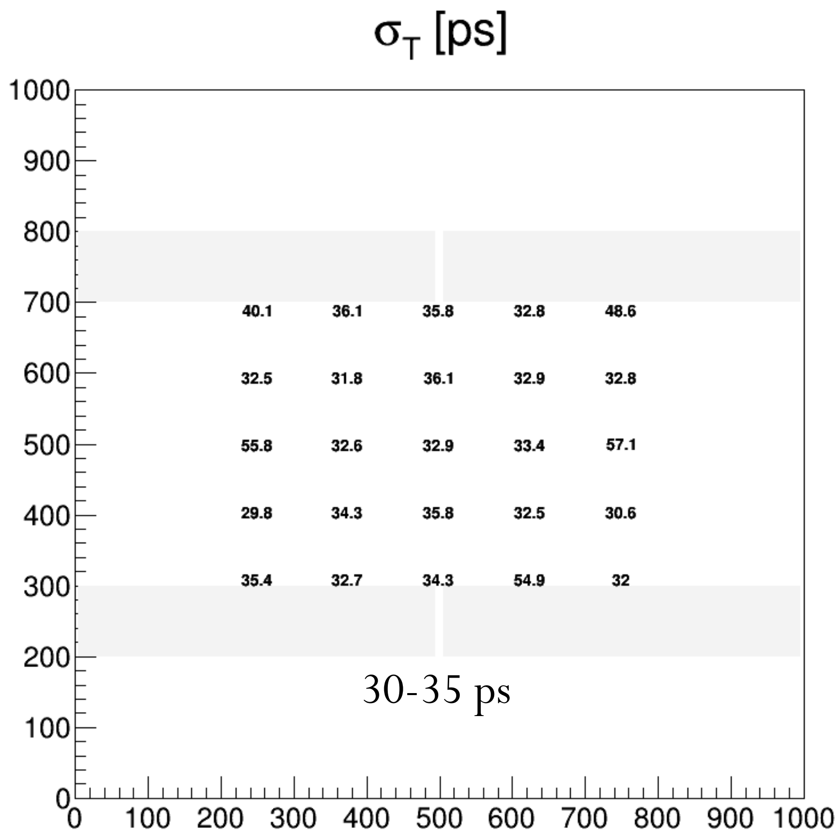
Jitter – microstrips



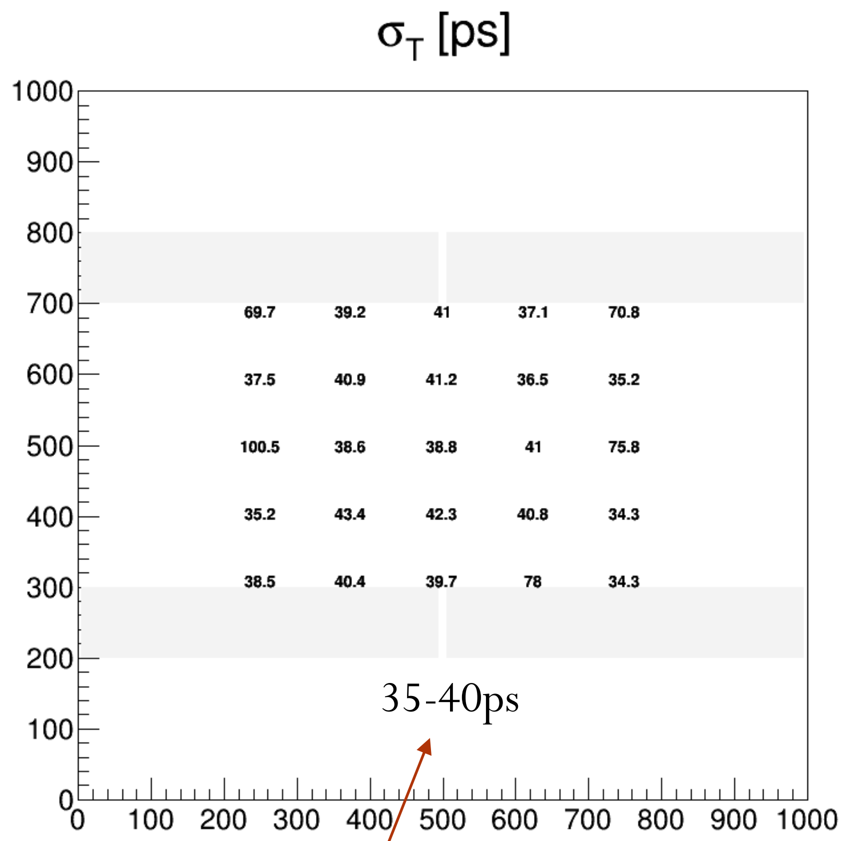
250V



200V



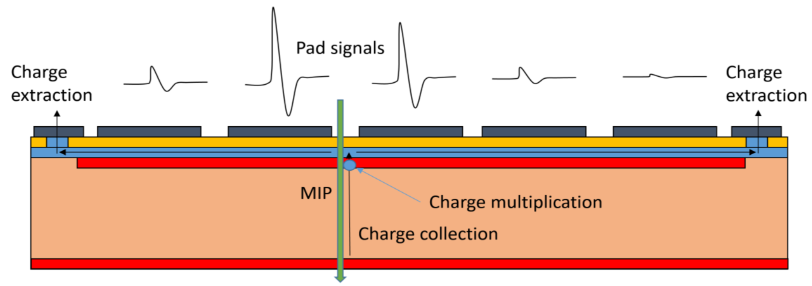
150V



Better time resolution than with pads, related to higher S/N

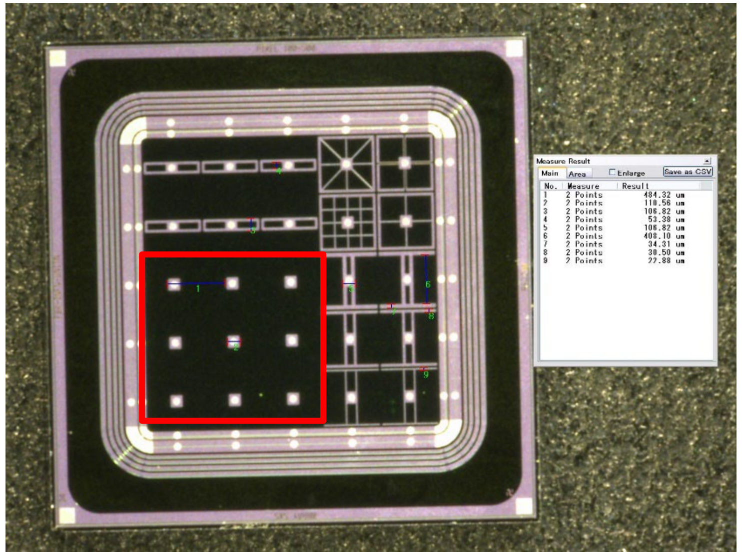
Conclusions – AC-LGAD geometries

- AC-LGADs need fine tuning of parameters for each application
  - The effect of different metal shapes have been studied for this contribution



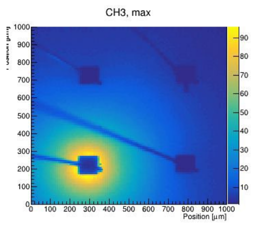
Some questions answered:

- Does the metal structure influence the capacitance to the amplifier? **Yes**, it scales pretty well with the metal area
- Does the metal structure influence the charge sharing profile in X and Y? **Yes**, it depends on the metal shape
  - It also influence the amount of signal picked up, a larger metal structure has a higher signal
  - The the signal is also delayed in a different way
  - **Signal induction on the metal pad is not trivial to understand**
- Is there a difference in position resolution of the reconstructed events? **Yes**, but it's not as clear to understand.
  - The Jitter is lower for bigger metal structures, likely due to the increased S/N
- Reconstruction technique used is rudimental but it seems effective, **next step** is to make it more robust
  - Fully map the position resolution and Jitter for all types of pads
  - Also increase the number of channels used in the reconstruction (e.g. all 3x3 small pads)

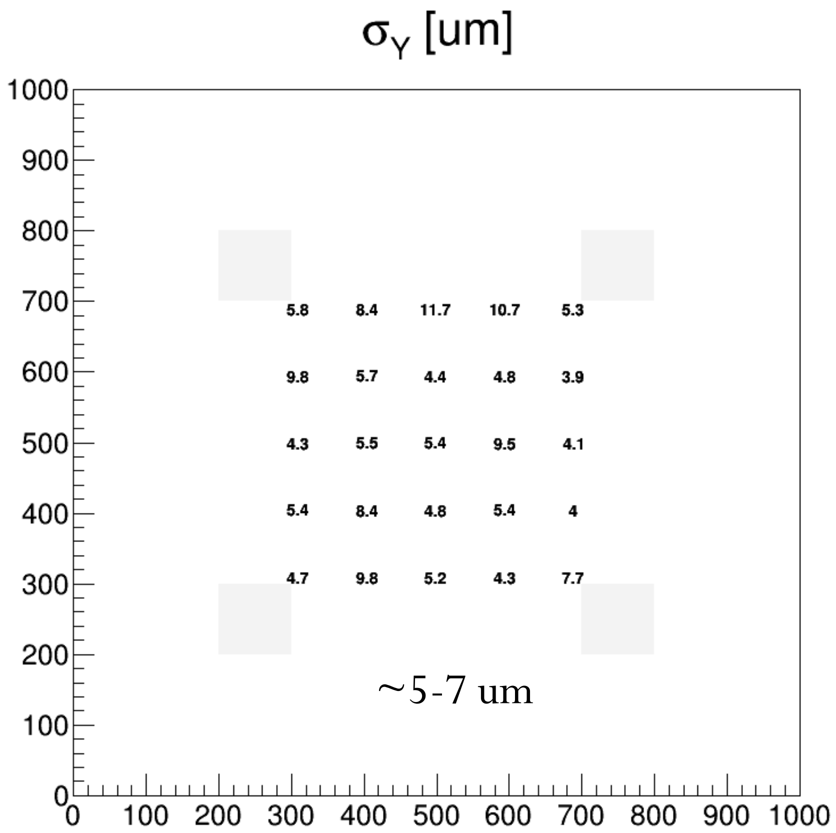


Thanks for the attention

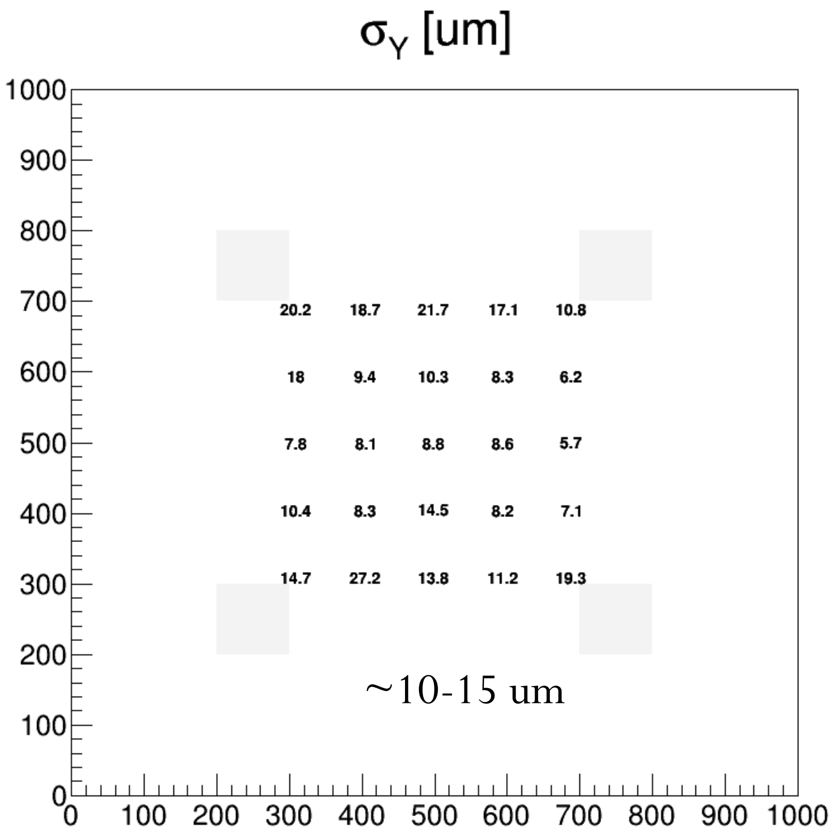
Reconstructed position resolution – small pads



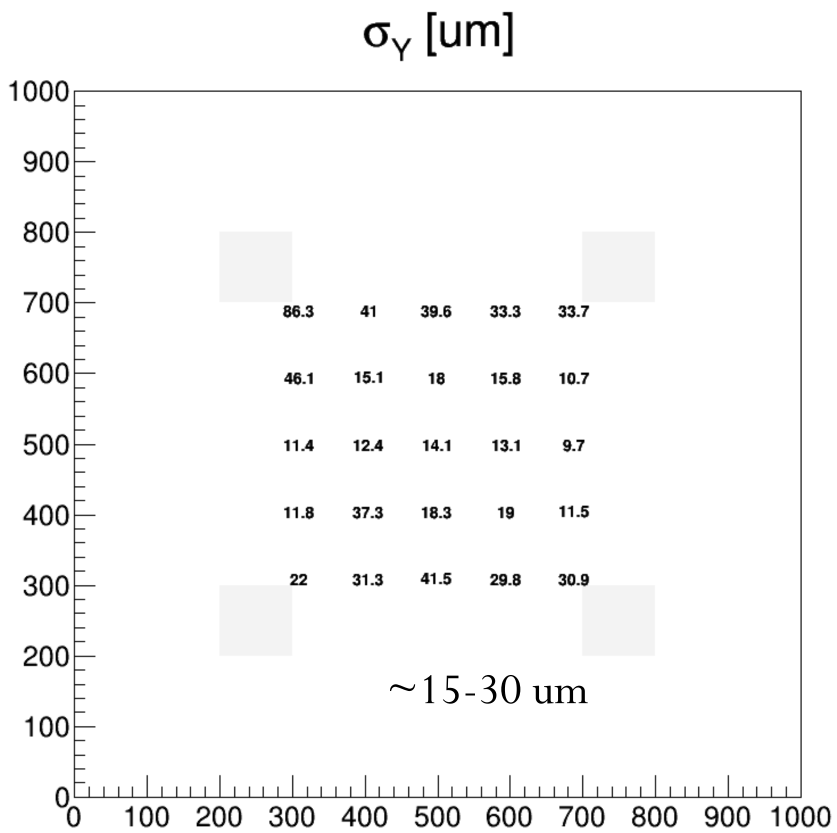
250V



200V

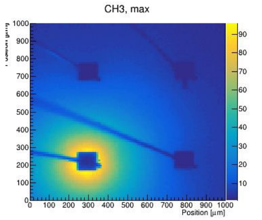


150V

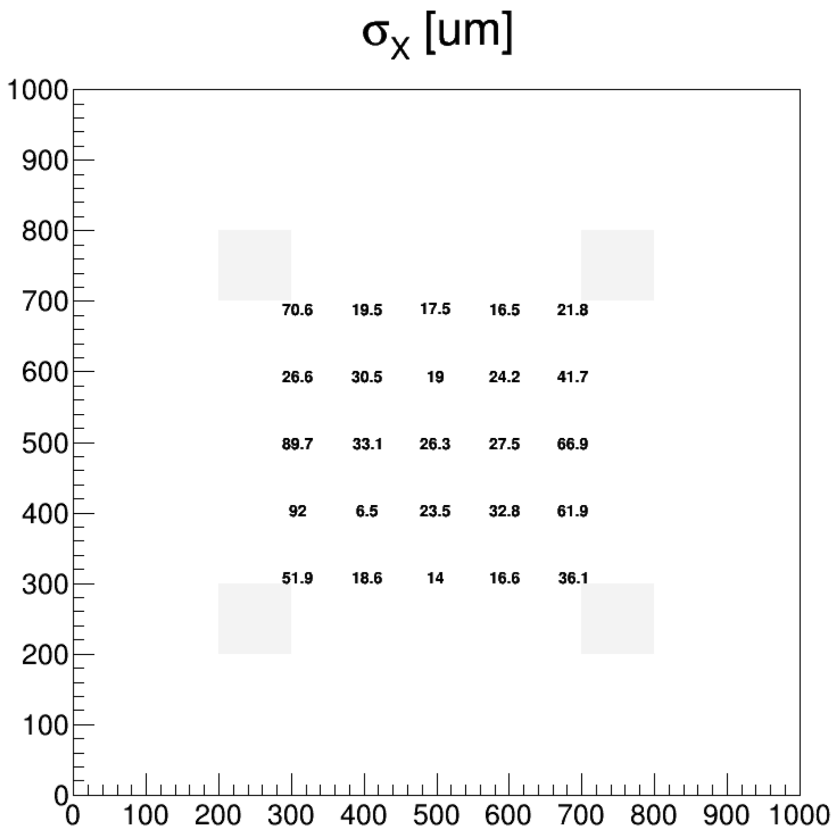


As expected the resolution is worse at lower gain

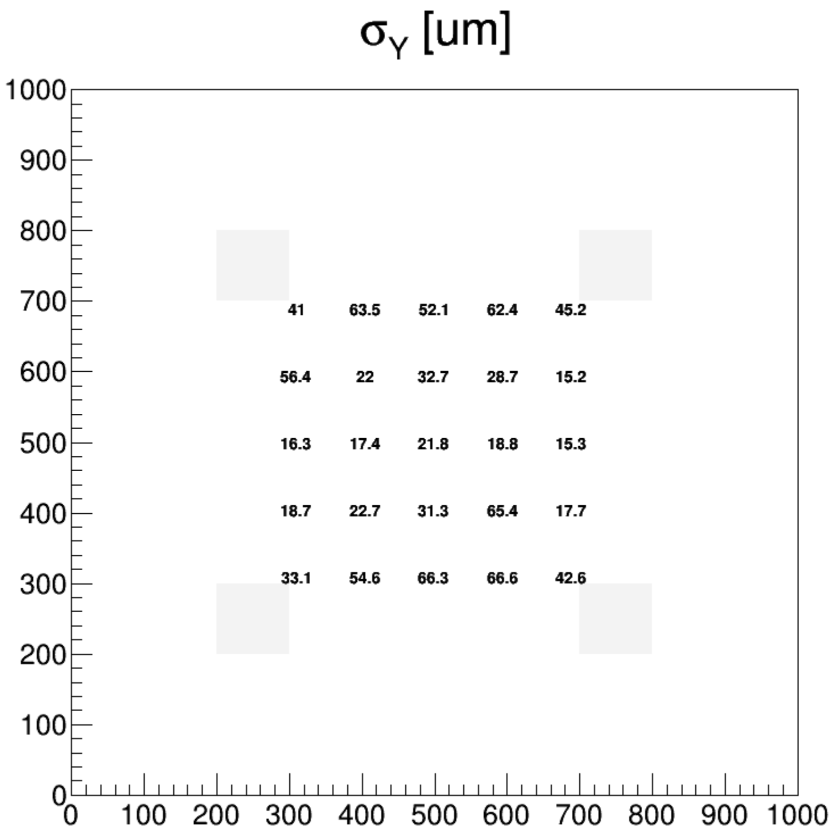
Reconstructed position resolution – small pads



100V

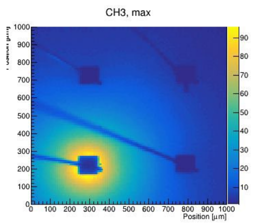


100V

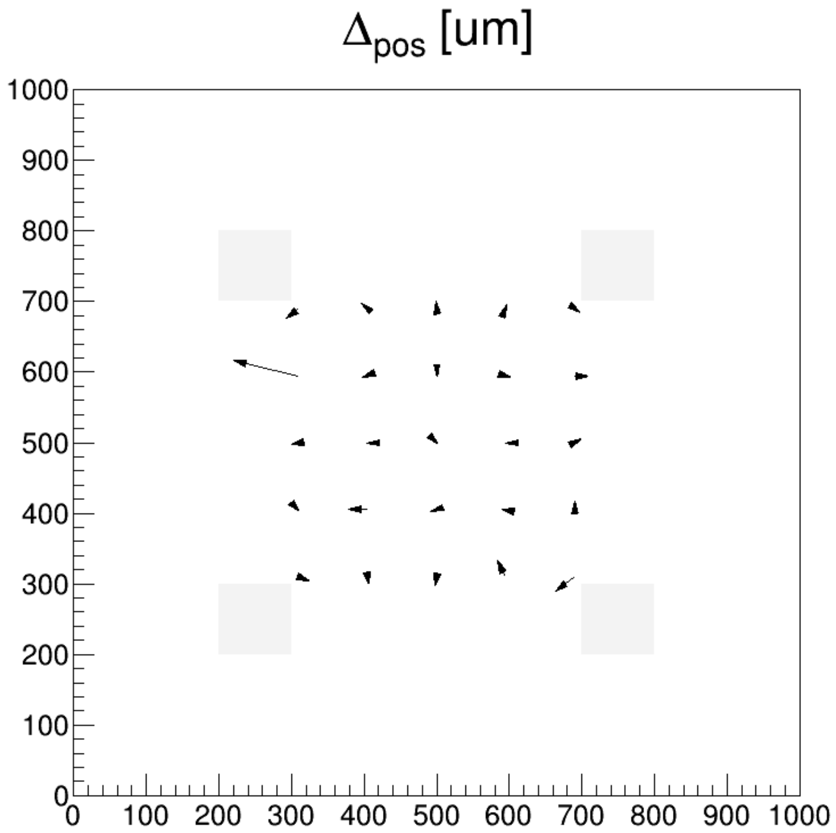


As expected the resolution is worse at lower gain

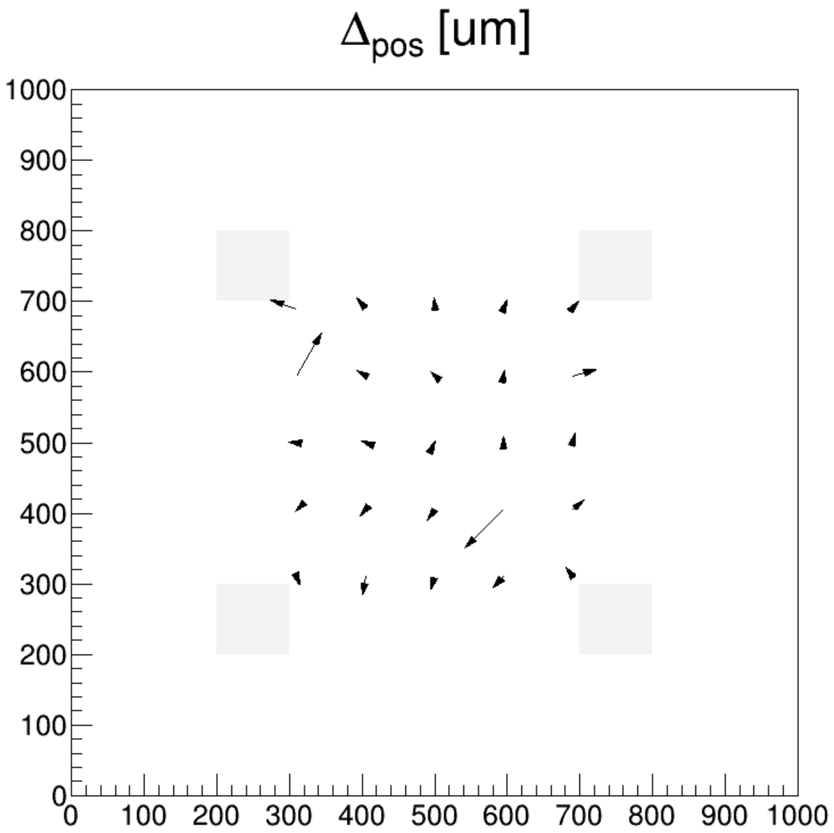
Reconstructed position resolution – small pads



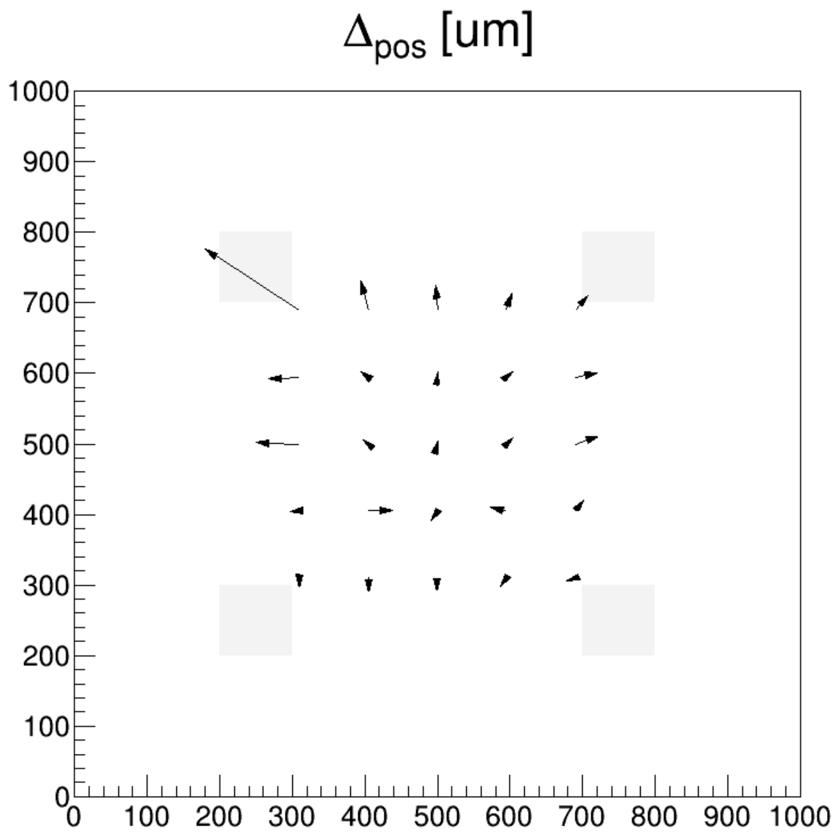
250V



200V

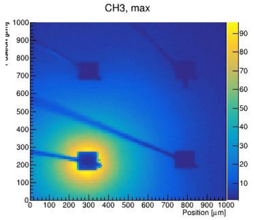


150V

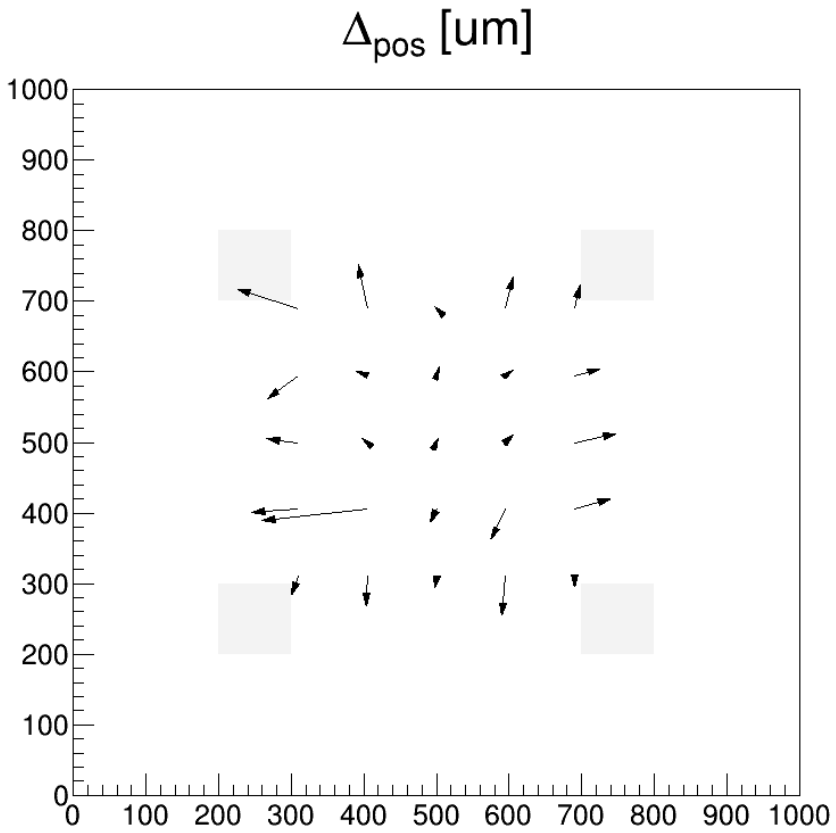


As expected the resolution is worse at lower gain

Reconstructed position resolution – small pads

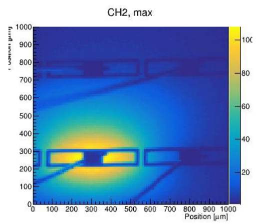


100V

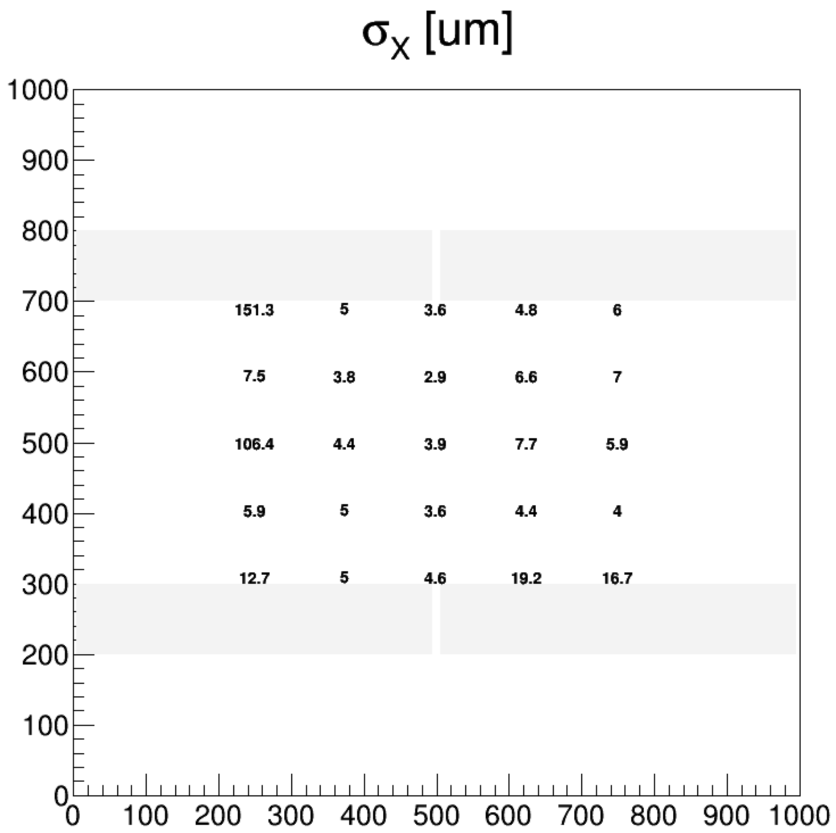


As expected the resolution is worse at lower gain

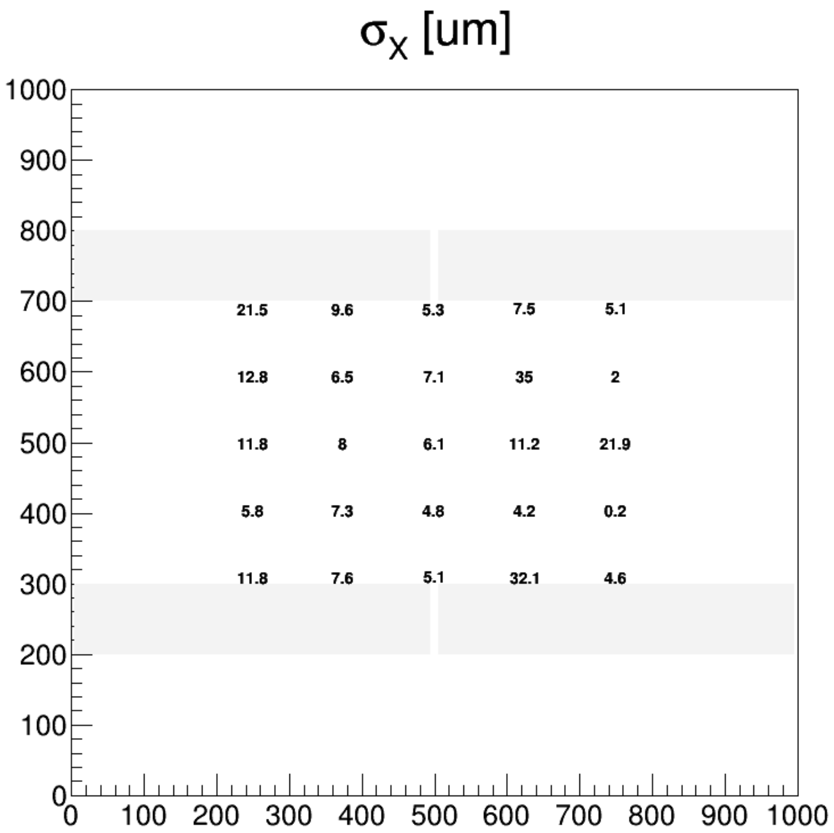
Reconstructed position resolution – microstrips



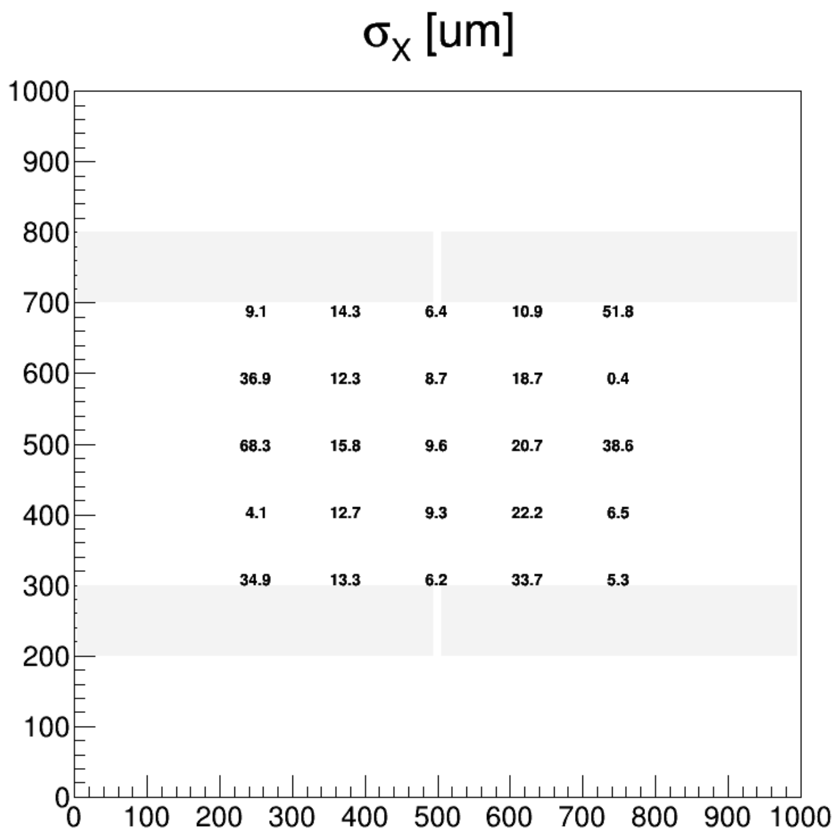
250V



200V

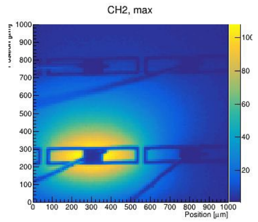


150V

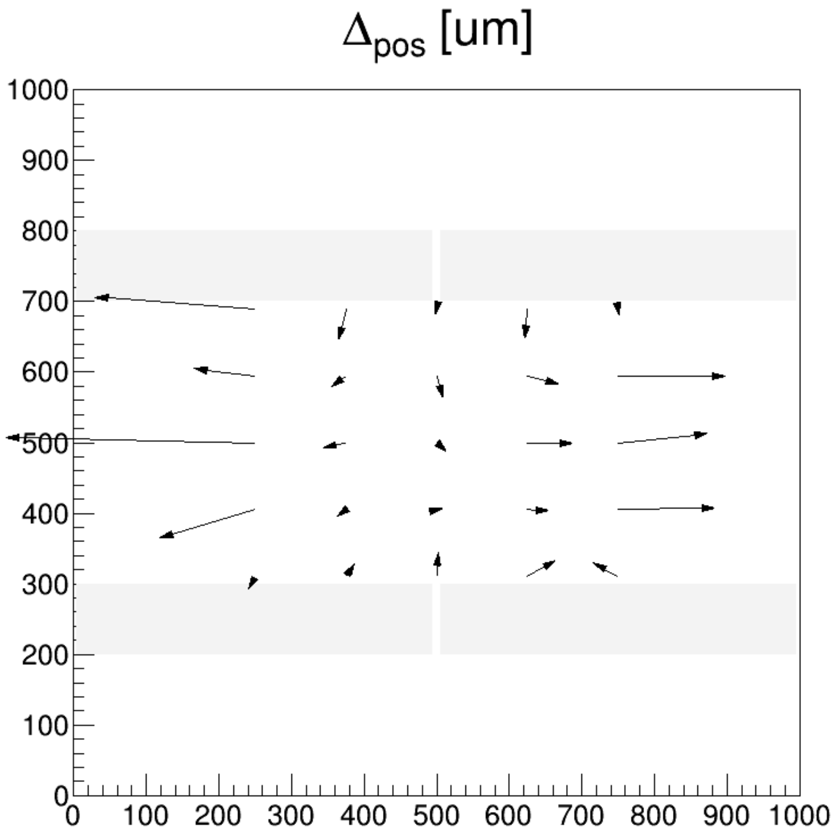


Resolution is worse at lower gain, but better than in the small pads case

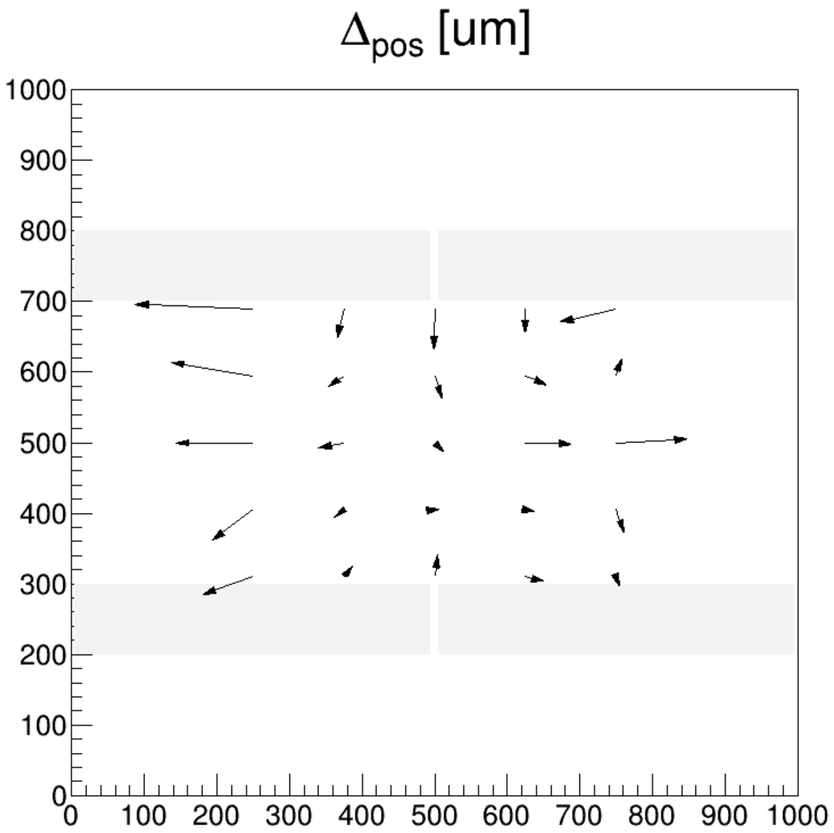
Reconstructed position resolution – microstrips



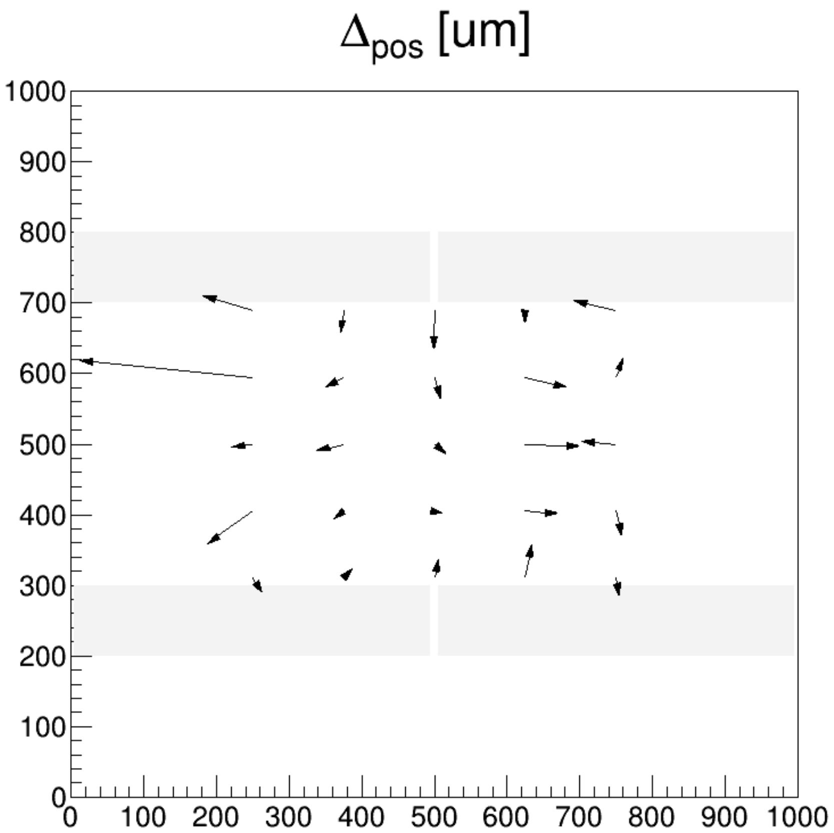
250V



200V

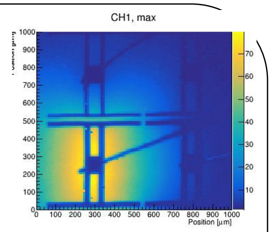


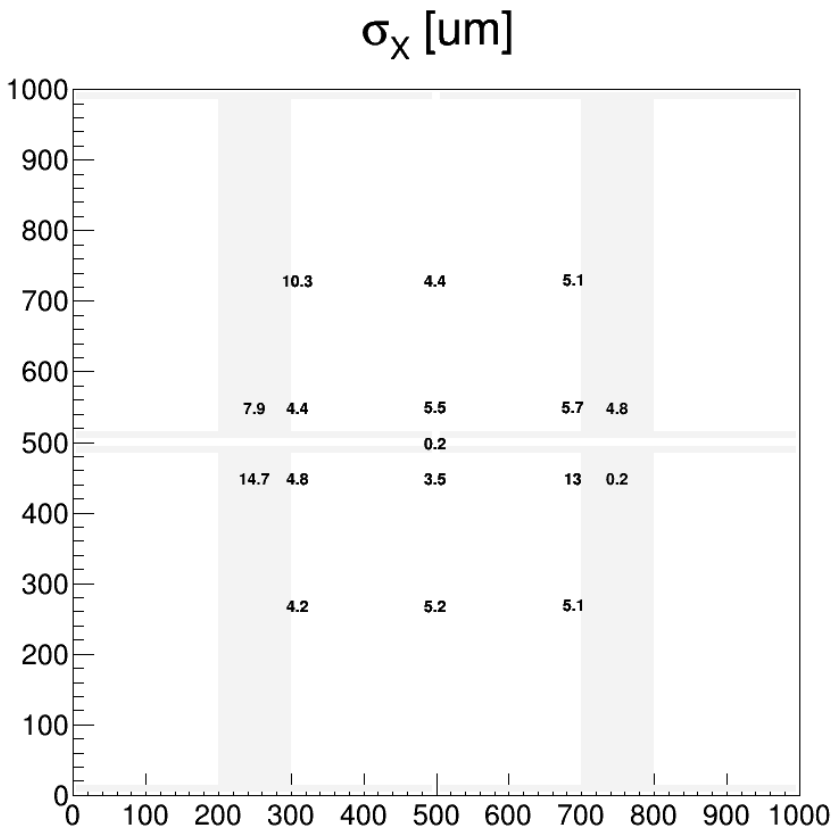
150V

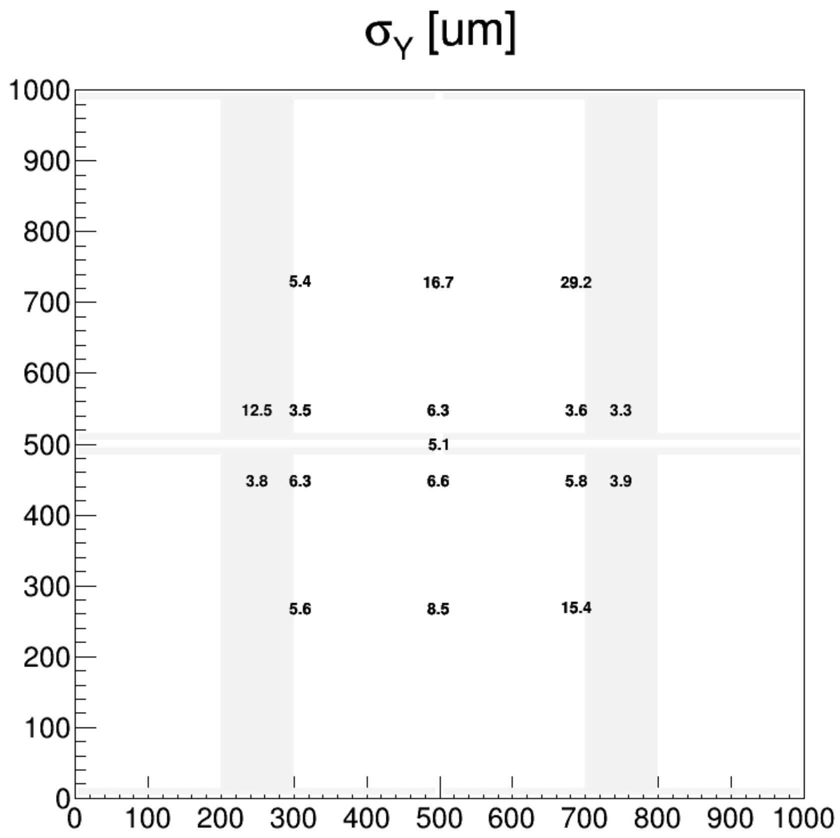


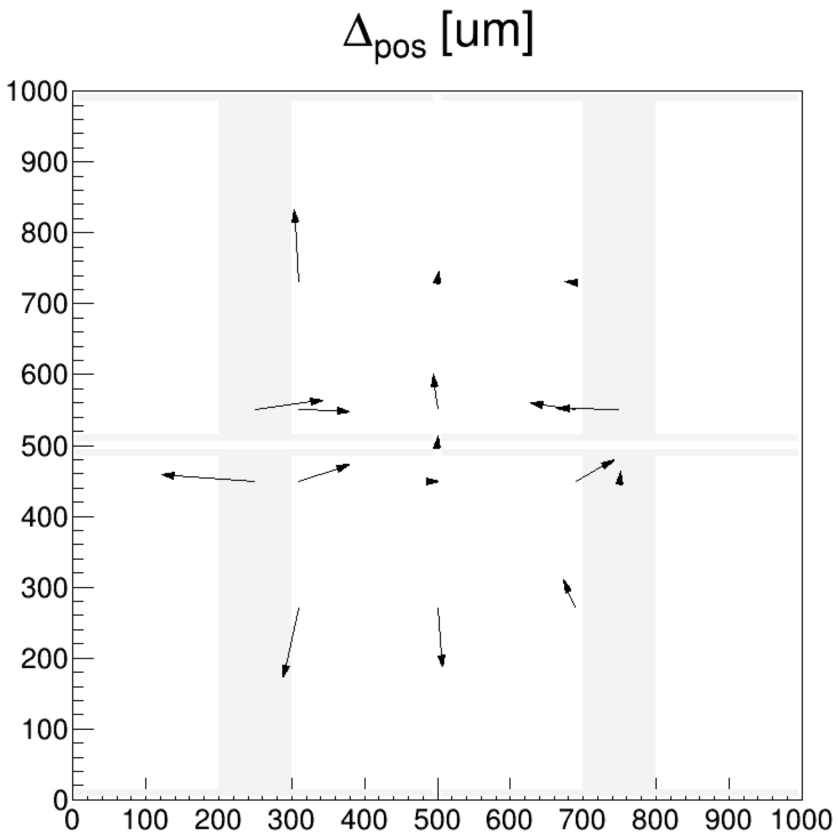
Resolution is worse at lower gain, but better than in the small pads case

Reconstructed position resolution – H pads









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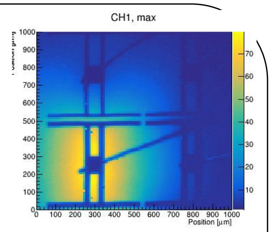
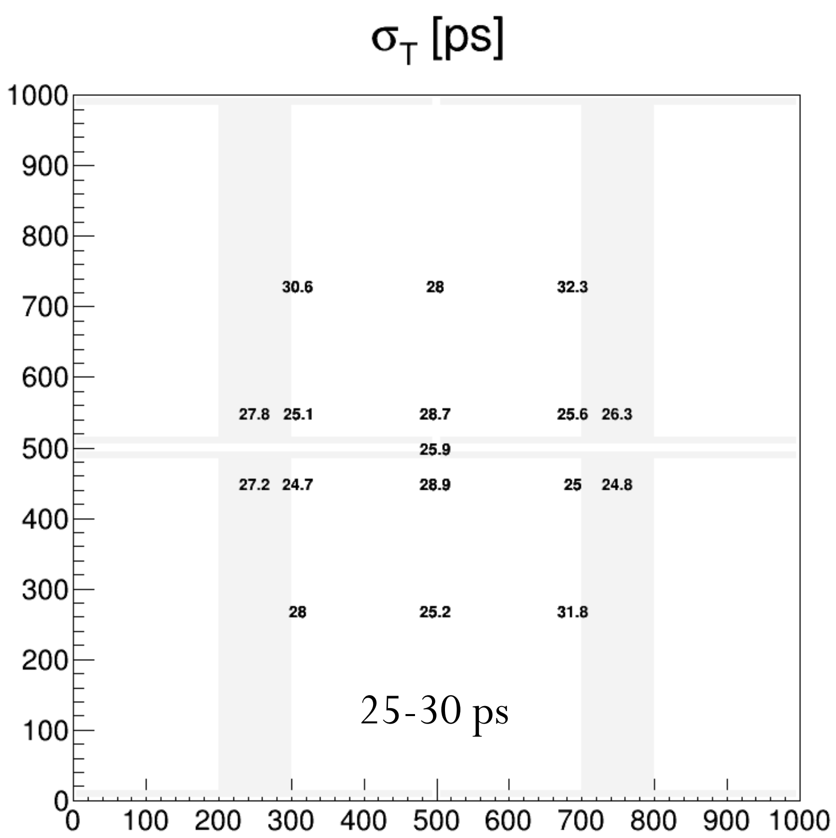
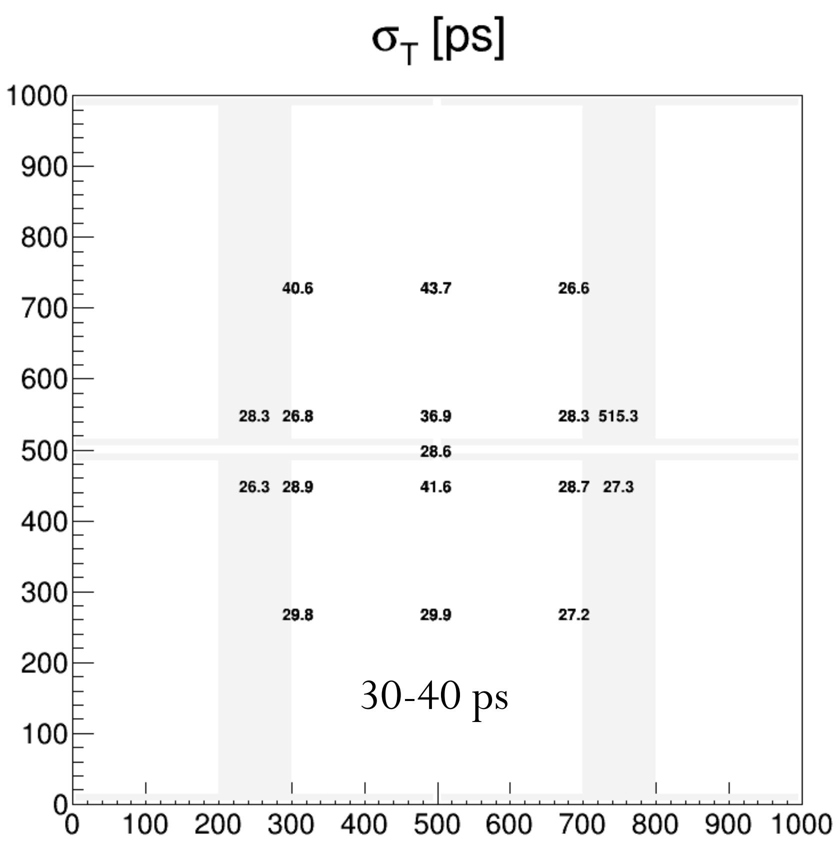
Jitter – H pads



250V



200V



150V