Simulation and analysis of capacitively coupled pixel detector assemblies

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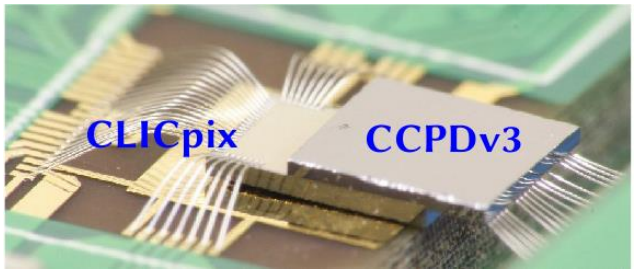
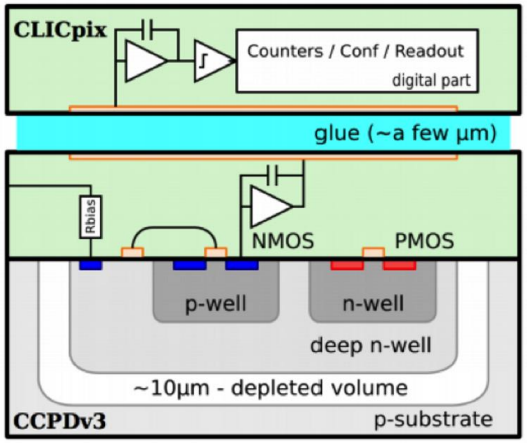
HV-CMOS for CLIC

- High-voltage CMOS (HV-CMOS) has a deep n-well implant which consists of electronics inside
- It shields them from substrate allowing a high bias -> fast signal, larger depletion
- CCPDv3 has 2 stage amplification -> capacitive coupling -> small pitch, no bump-bonding
- Coupled to the CLICpix readout ASIC, 4-bit time over threshold (ToT) counter
- Test beam at the CERN North Area with 120 GeV/c pions
- Angles: 0˚-80˚

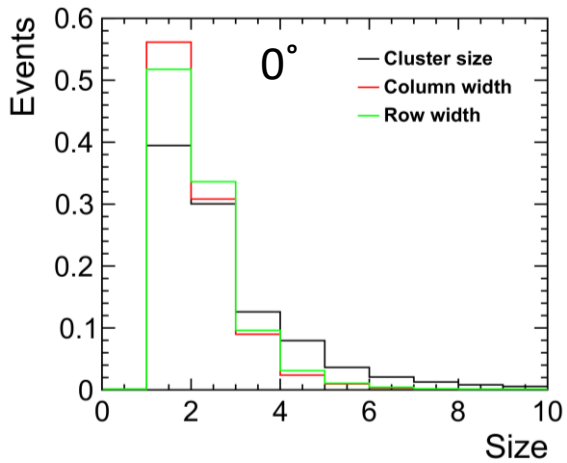


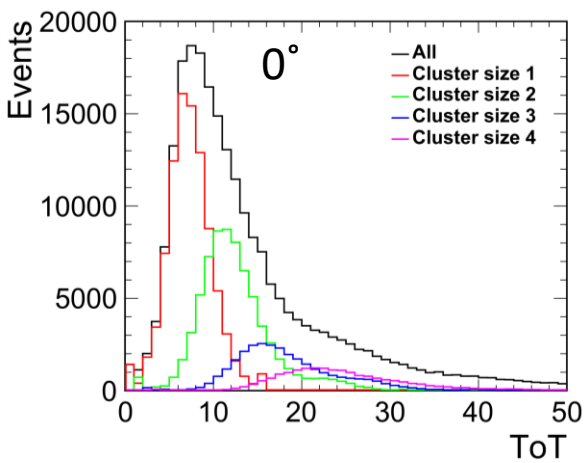


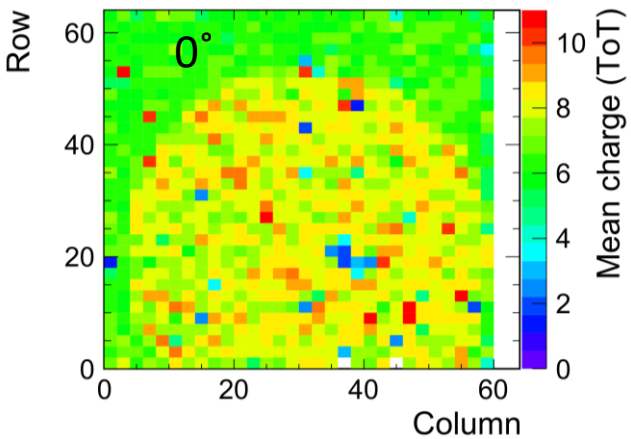
Performance measurements: test beam

Charge collection & signal propagation

- At perpendicular incidence there are mainly 1-2 hit clusters hence the total cluster ToT distribution is dominated by their ToT values
- The mean ToT over the chip shows non planarity, see circle of higher ToT -> stronger coupling due to glue spot
- In real experiment not all tracks are perpendicular
- Need to characterise vs angle to understand performance in final detector…

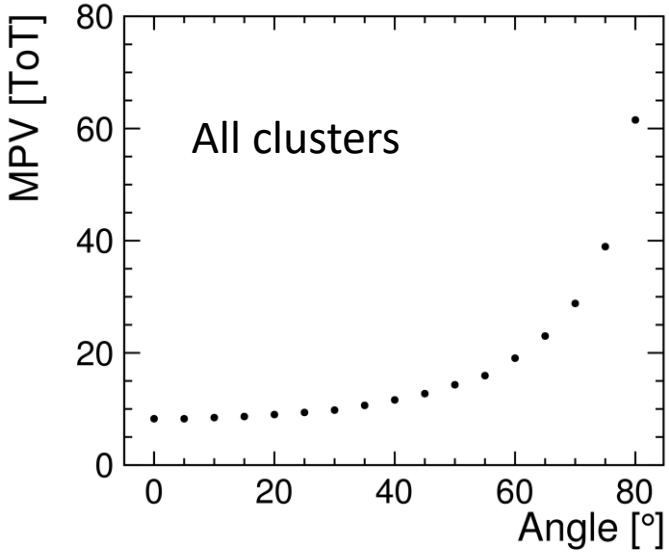


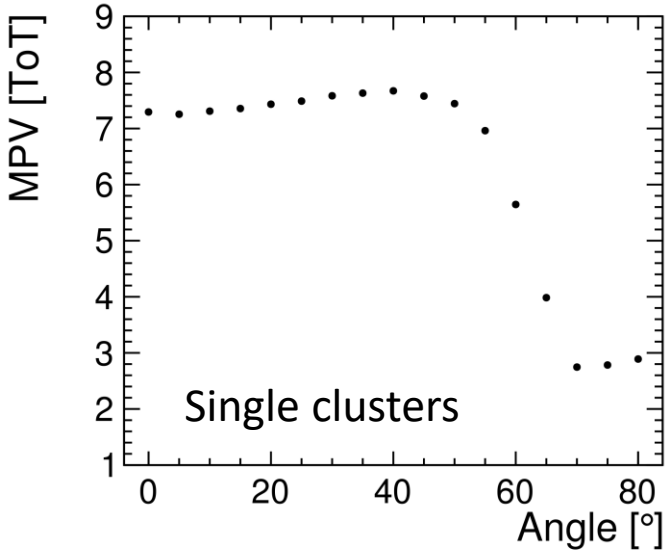




Charge collection & signal propagation

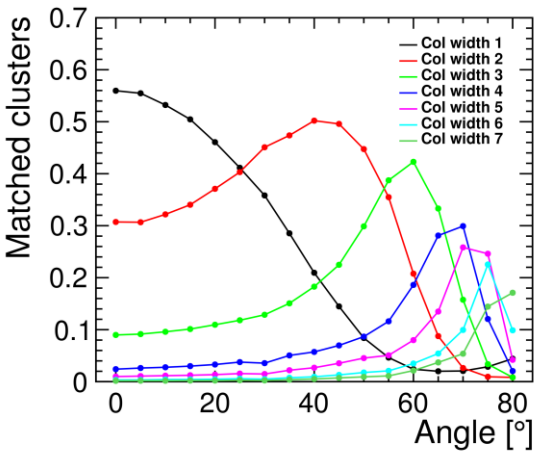
- Looked at the charge collection over the full angular range
- As expected the most probable value for the cluster ToT increase with angle, with a sharp increase at 60˚
- For single pixel clusters there is a sharp drop at 50˚
- Due to number of one hit clusters being low at these large angles
- If they are to happen only a small amount of charge is deposited, not enough to reach the neighbours

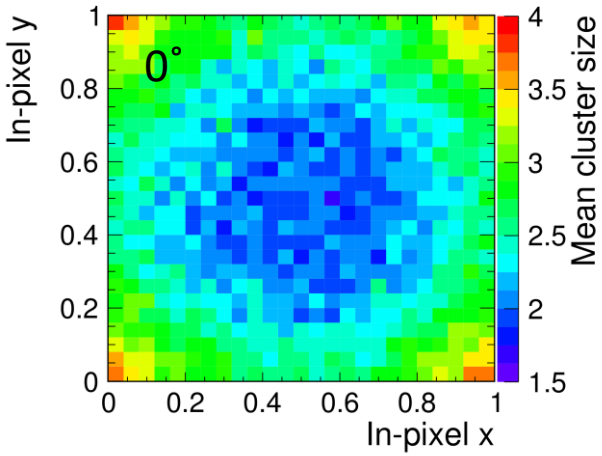


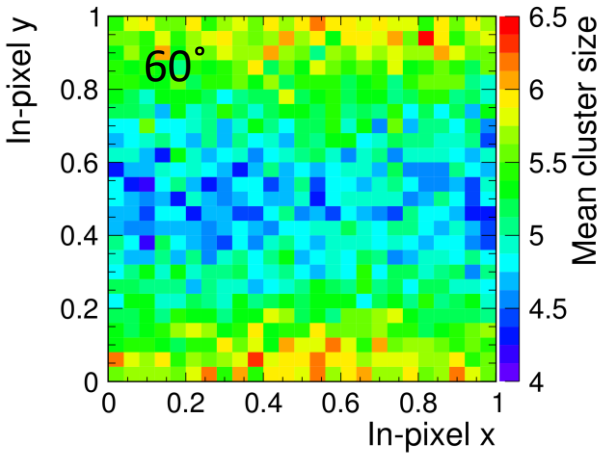


Cluster formation

- Up to 60˚, still dominated by clusters with column width < 4
- This dramatically changes at 80˚ where the dominant width is 7
- The in-pixel cluster size shows mainly 1 hit clusters in the centre and larger clusters at the edges for 0˚
- At 60˚ have a strip through the centre of size 4 along the inclined axis
- Cluster size 5-6 at the top and bottom due to sharing with neighbours in the row direction

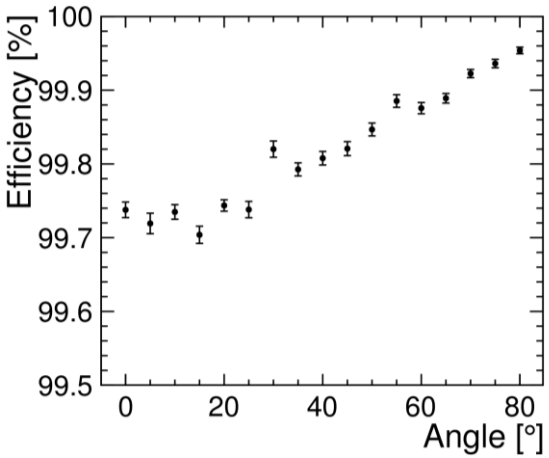


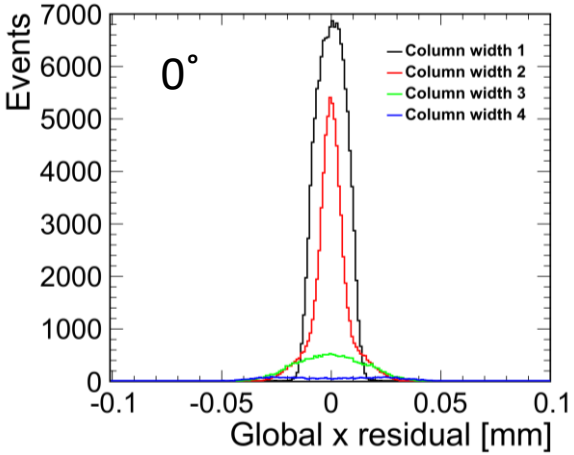


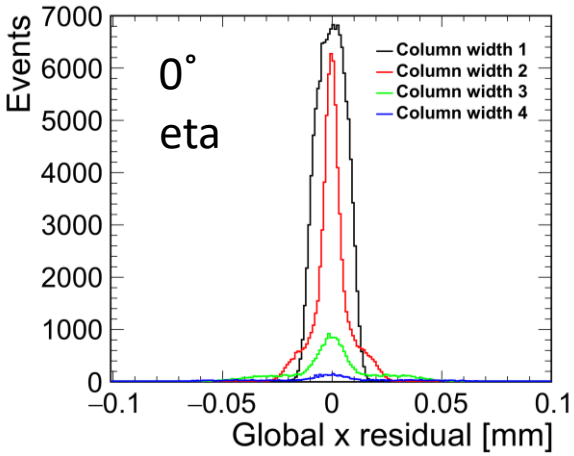


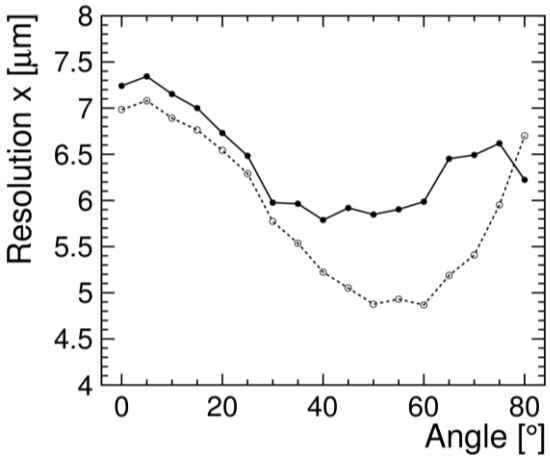
Tracking performance

- Vertex detector needs good efficiency (>99%) and spatial resolution (3µm)
- Very high efficiency over whole angle range
- Resolution is not at target, improve this with eta correction
- Residuals are limited by fake multi-pixel hits from cross-coupling…



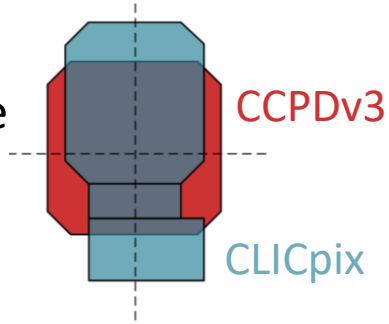


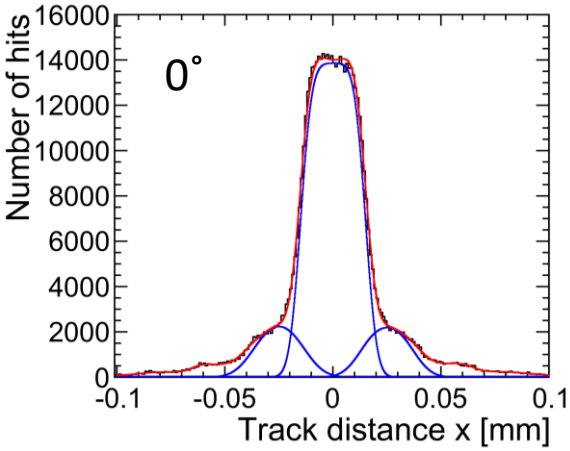


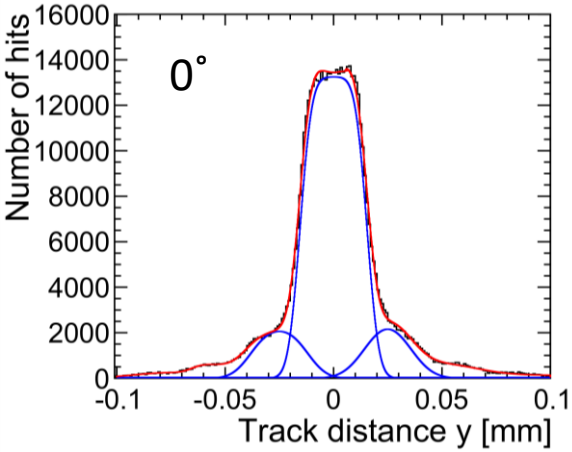


Cross-coupling

- The signal is capacitively transferred and the capacitance to neighbours could be non-zero
- Signal on one HV-CMOS pixel could be transferred to multiple readout side (cross-coupling)
- CCPDv3 and CLICpix metal pads are in “ideal” alignment
- Scan beam along matrix see when pixel responds, produce central peak from “real” charge collection and additional peaks from cross-coupling
- Symmetric in both column and row direction at 0˚

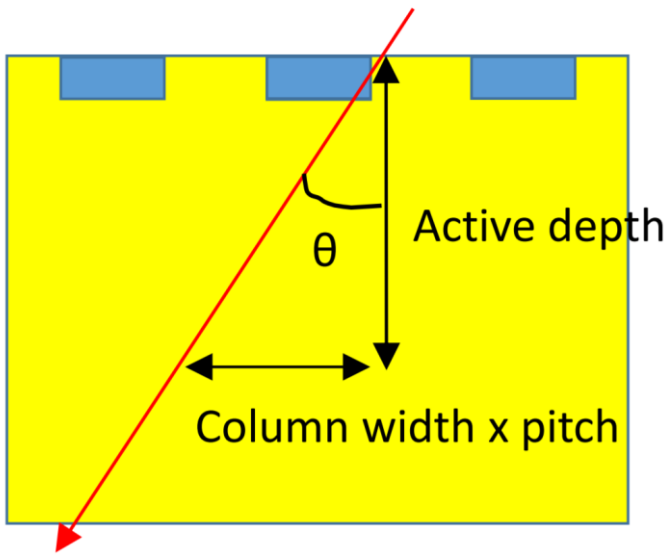


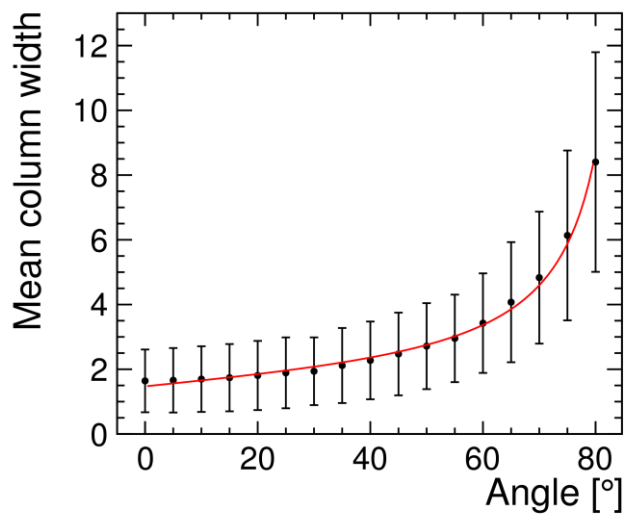




Active depth

- How deep into the sensor charge contributes to the signal
- Estimate using a geometric approximation making use of known parameters
- Fit: column width $= \tan(\theta + \Delta\theta)\frac{d}{p} + c$, where d=active depth, p=pitch, $\Delta\theta$= angular offset and c=intercept
- Active depth of $\approx 26\mu m$, over 2 times larger than estimate of 10µm for the depletion depth -> some diffusion

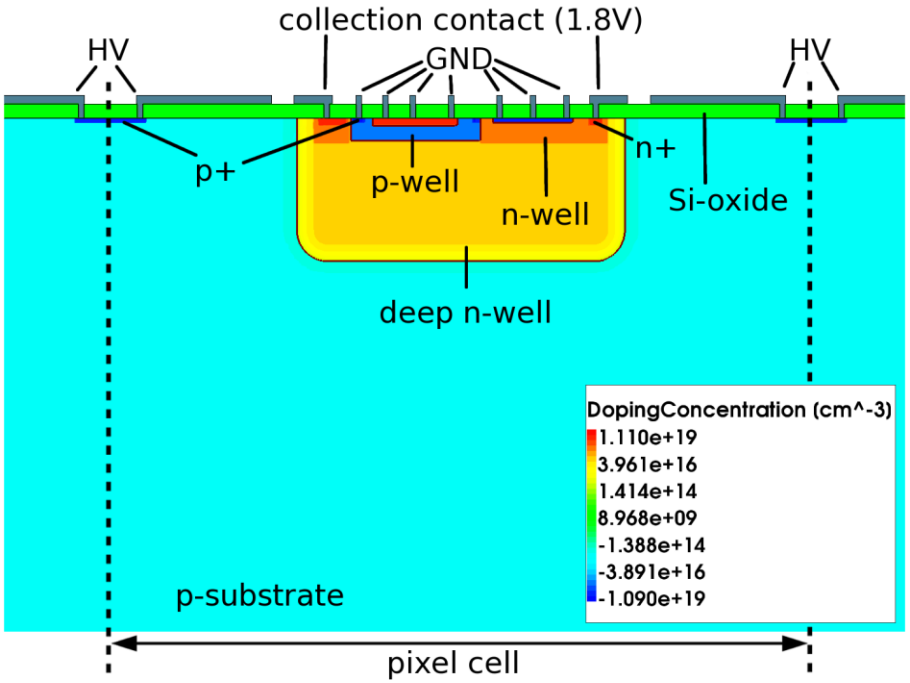




Interpreting the results: simulations

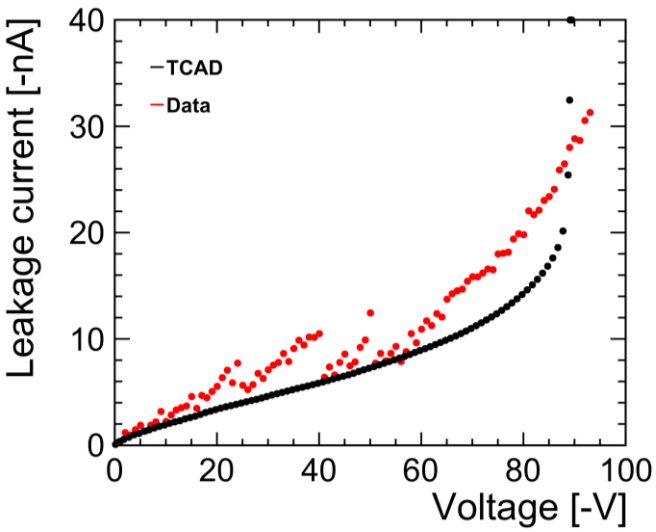
TCAD simulations

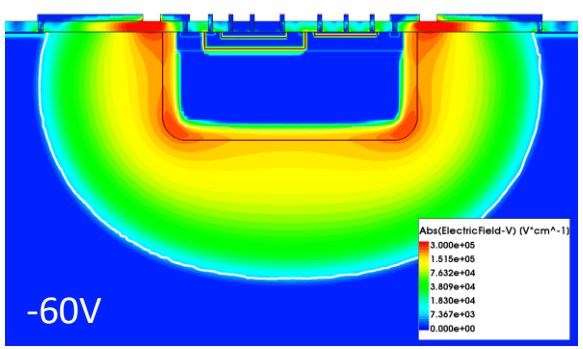
- Using the design file of the chip can produce structures in TCAD
- 2D simulations
- Simulations can help to understand features of the sensor:
  - Depletion region
  - Breakdown
  - Signal collection

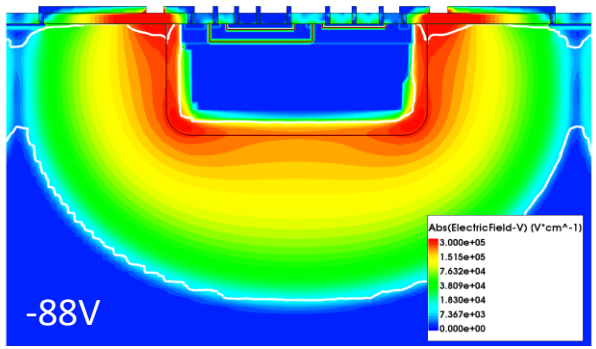


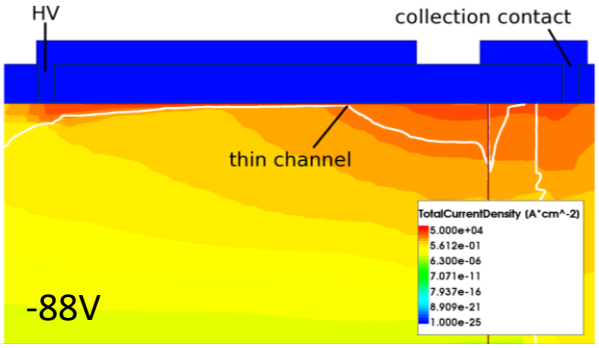
Current-voltage and electric field

- Both current and breakdown reproduced well in simulations
- Breakdown: data -93V, TCAD -88V
- Large electric field near deep n-well
- Depletion region extends from deep n-well, gives fast charge collection across pixel
- At high enough bias distortion of depletion region, allows thin channel to short HV and deep n-well



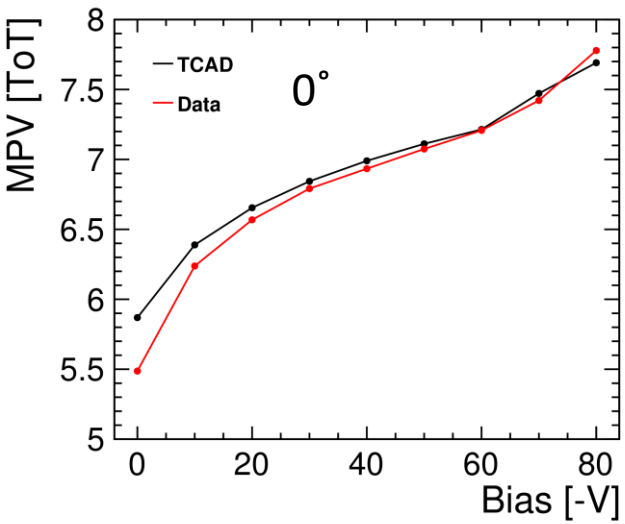


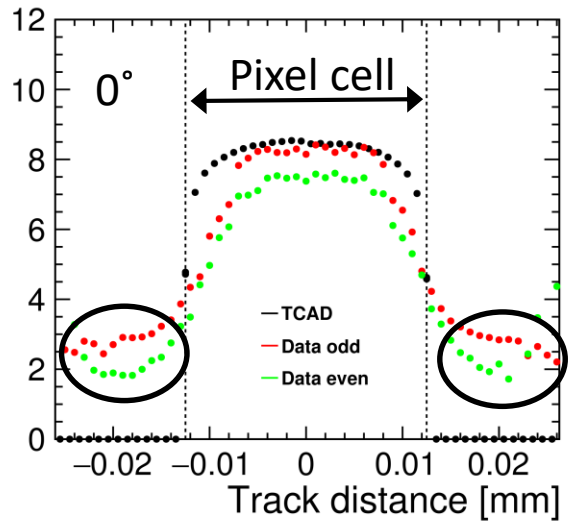


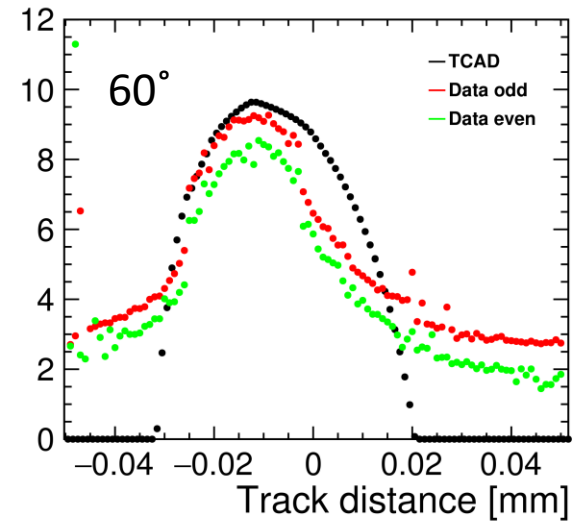


Charge collection simulations

- Calibrations of the device are used to convert TCAD output to ToT
- Bias scan at 0˚, showing the MPV ToT of the single pixel clusters
- Increase in gradient at -70V and -80V due to avalanche multiplication
- Good agreement at 0˚ but response width is too large at 60˚ for TCAD
- See ToT of ≈3 at sides due to cross-coupling, not put into simulation

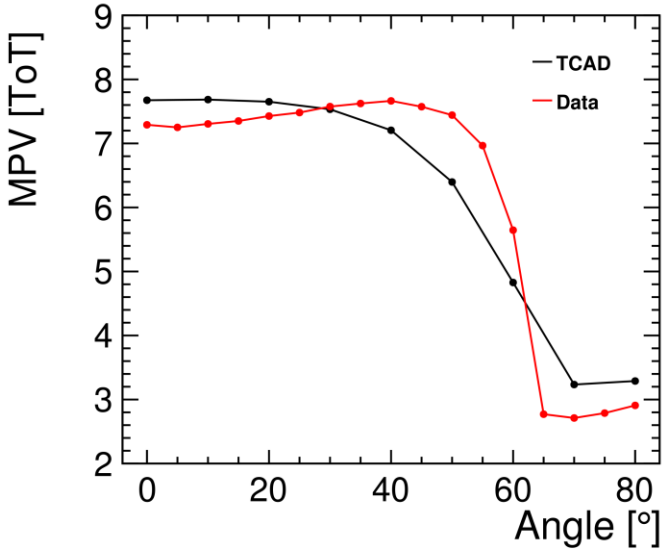


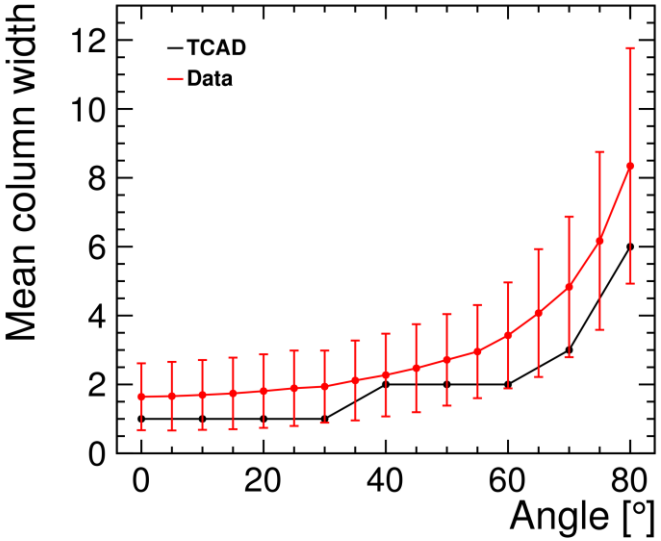




Charge collection simulations

- MPV ToT of single pixel clusters and mean column width as a function of angle
- TCAD results are similar to data, many effects produce variation:
  - No Landau deposition of charge considered in simulation
  - Variations in calibration
  - Variations in integration time for electronics

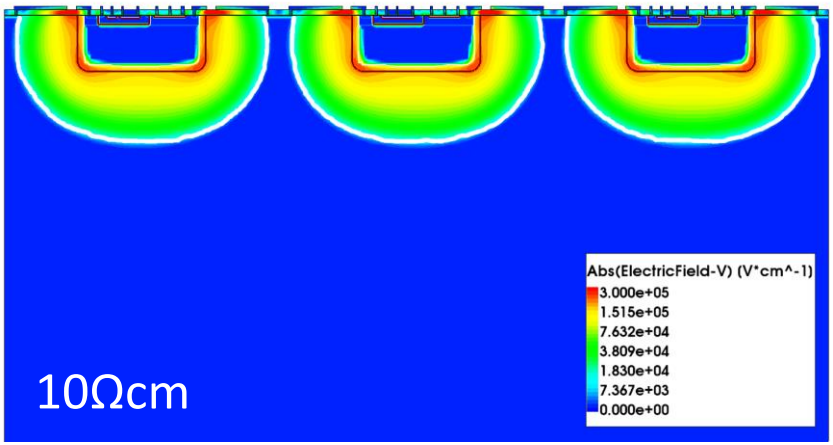


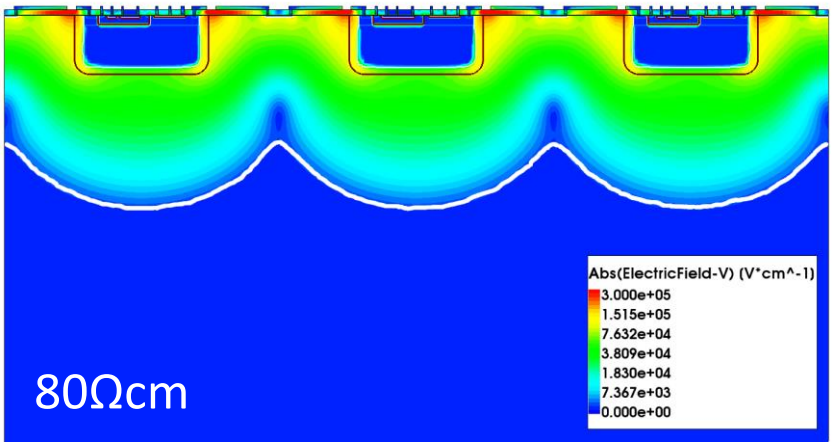


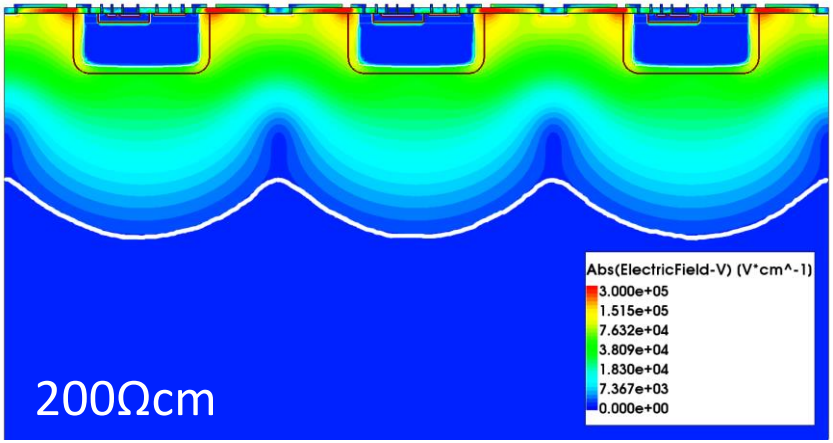
Prospects for improved performance

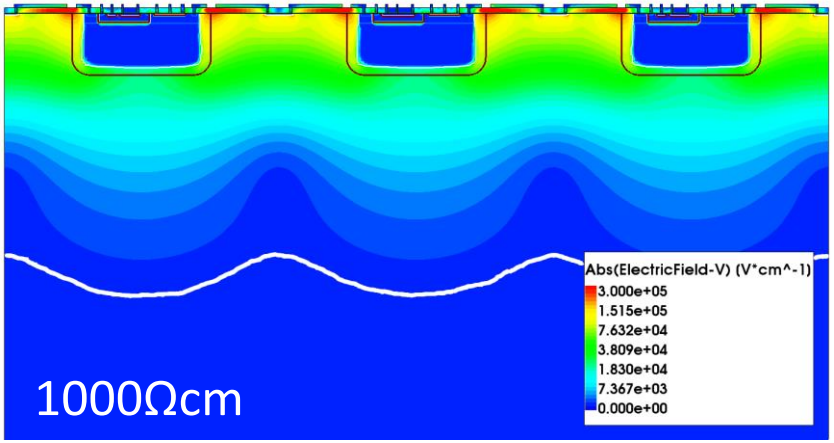
Electric field and depletion depth

- Increase in electric field depth and depletion depth with resistivity
- Field strength around deep n-well decreases



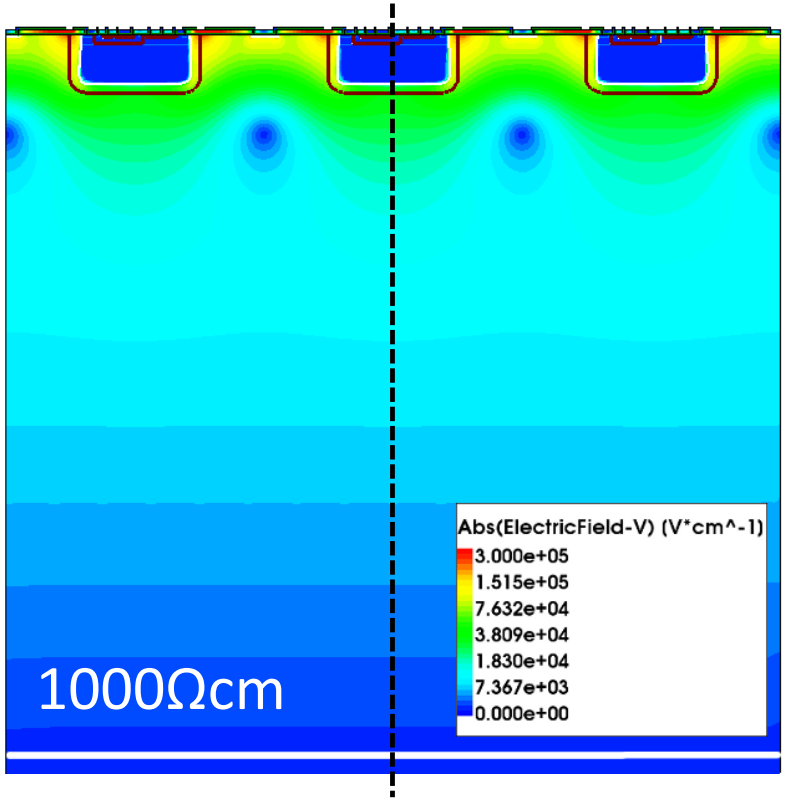


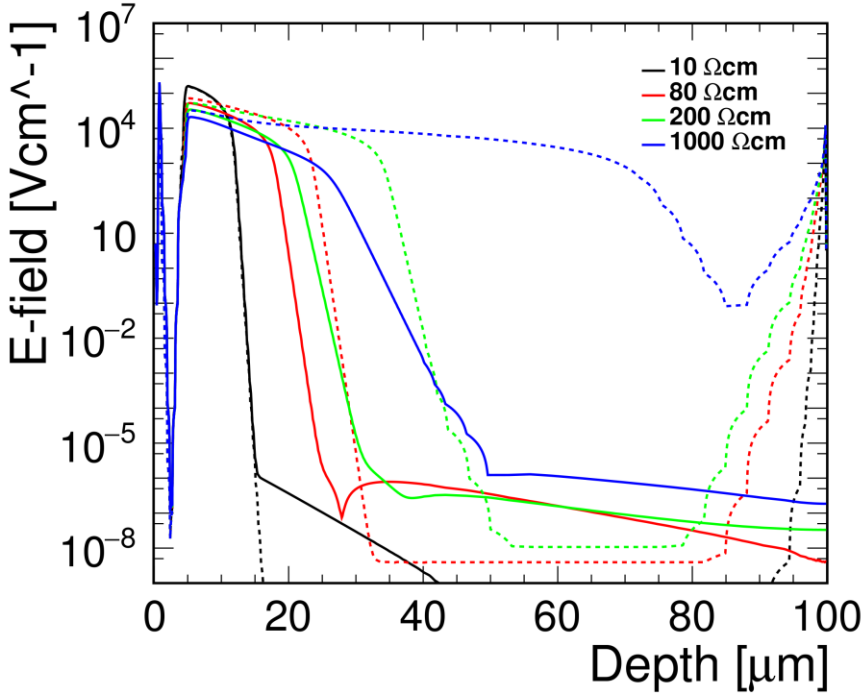




Electric field and depletion depth

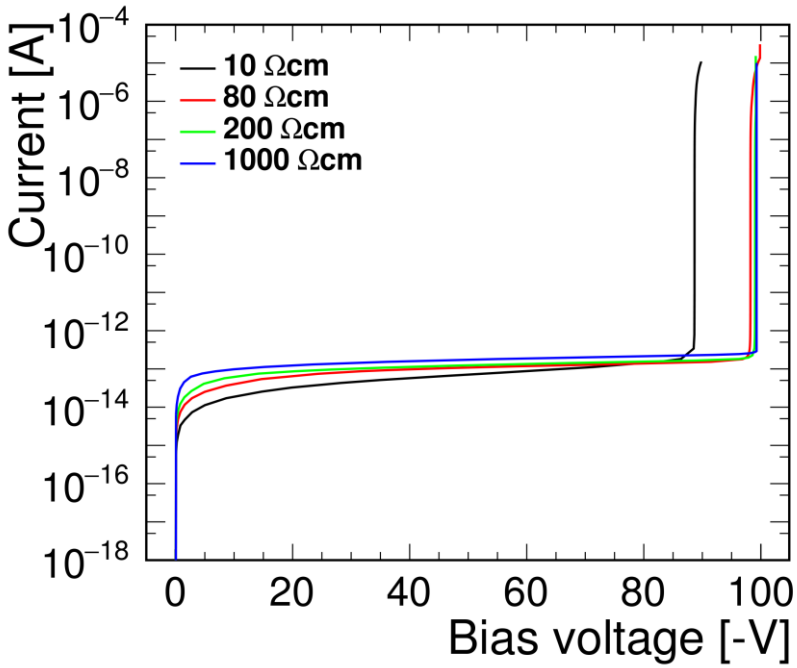
- Biasing from the back increases the electric field depth and depletion depth
- No difference at 10Ωcm
- The largest improvement comes from the higher resistivities
- The most pronounced is at 1000Ωcm

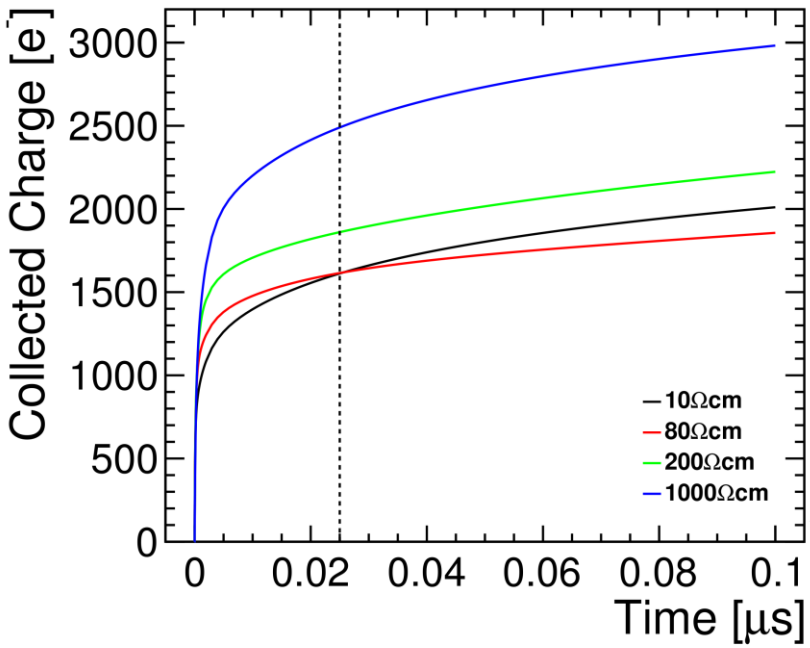




Current-voltage and charge collection

- Higher resistivities produce:
  - Larger breakdown voltage
  - Faster and more charge collection
- Again 1000Ωcm produces largest improvement





Summary

- Measurements of HV-CMOS assemblies for the CLIC vertex detector have shown excellent tracking performance across the full detector acceptance
- TCAD simulations have been used to estimate sensor properties and compare well to measurements
- Using a higher resistivity should see larger breakdown and faster charge collection