ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

RD50 HV-CMOS Meeting

RD50-MPW4 Allpix^2 Simulations

Bernhard Pilsl

Allpix²

- Monte Carlo Detector Simulation Framework
- Geant4 utilized to build detector geometry and deposit energy in detector due incoming particle beam
- Modular framework
  - Build geometry
  - Apply E-field (simple linear field approximation → advanced fields from TCAD)
  - Deposit charge
  - Propagate charge (drift in E-field and diffusion)
  - Collect at surface / implant
  - Digitize
  - Interpret and output to ROOT files
- Talk by Simon Spannagel at DRD3 week: https://indico.cern.ch/event/1402825/contributions/5998273/

Allpix² Usage

- We need 3 config files (key value pairs, pretty similar to Corryvreckan)

1) Detector model specifies material, thickness, pixel pitch, number of pixels,…
2) Place (several) detectors in world volume in geometry-file
3) Define simulation chain (module by module) in config file

- Allpix² executed via CLI with something like “allpix -c best-simulation-ever.conf”

mpw4 > ⚙ rd50_mpw4.conf

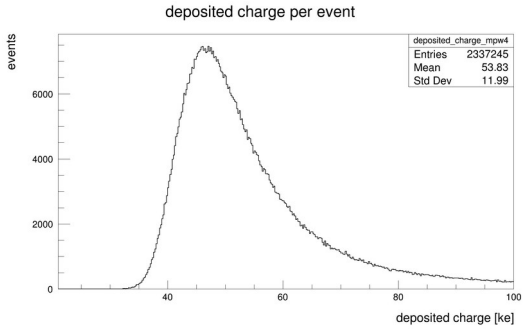
```
type = "monolithic"
geometry = "pixel"

number_of_pixels = 64 64
# Pitch of one individual pixel (column and row pitch)
pixel_size = 62um 62um

# Thickness of the active sensor material
sensor_thickness = 300um
# Excess sensor material outside of the active pixel matrix
# Specifying one value will add the excess to all four sides
#sensor_excess_bottom = 2mm


# [implant]
# type = frontside
# size = 43um 43um 20um

# [support]
# thickness = 1.5mm
# size = 12cm 10cm
# location = sensor
# material = plexiglass
#offset = -4cm 0
#hole_size = 4.2mm 4.2mm
#hole_offset = -4cm 0
```

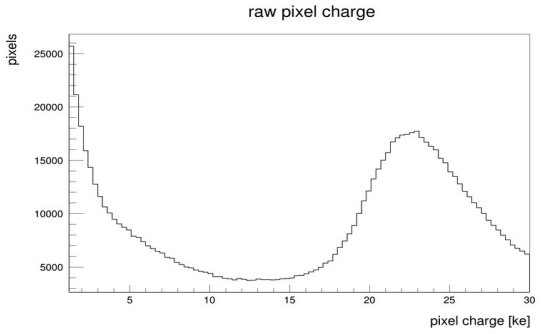
```
[telescope0]
type = "adenium"
position = 0mm 0mm 0mm
orientation_mode = "xyz"
orientation = 0deg 0deg 0deg
alignment_precision_position = 1.5mm 1.5mm 1.5mm
alignment_precision_orientation = 5deg 5deg 5deg

[telescope1]
type = "adenium"
position = 0mm 0mm 26mm
orientation_mode = "xyz"
orientation = 0deg 0deg 0deg
alignment_precision_position = 1.5mm 1.5mm 1.5mm
alignment_precision_orientation = 5deg 5deg 5deg

[telescope2]
type = "adenium"
position = 0mm 0mm 52mm
orientation_mode = "xyz"
orientation = 0deg 0deg 0deg
alignment_precision_position = 1.5mm 1.5mm 1.5mm
alignment_precision_orientation = 5deg 5deg 5deg

[mpw4]
type = "rd50_mpw4"
position =  0 0 137mm
orientation_mode = "xyz"
orientation = 0deg 0deg 0deg
alignment_precision_position = 1.5mm 1.5mm 1.5mm
alignment_precision_orientation = 5deg 5deg 5deg
```

```
[AllPix]
log_level = "WARNING"
log_format = "DEFAULT"
number_of_events = 2000000
# workers = 80
detectors_file = "detectors.conf"
root_file = "sim_investigateNoDiff.root"
output_directory = "/scratch/bpilsl/mpw4_sim"

[GeometryBuilderGeant4]
world_material = "air"

[DepositionGeant4]
physics_list = FTFP_BERT_LIV
particle_type = "e-"
source_energy = 4.2GeV
source_position = 0 0 -20mm
source_type = "beam"
beam_direction = 0 0 1
beam_size = 2.5mm
number_of_particles = 1
output_plots = true

[ElectricFieldReader]
name = "mpw4"
model = "linear"
bias_voltage = -190V
depletion_voltage = -200V
output_plots = true

[GenericPropagation]
name = "mpw4"
temperature = 0.1K
# charge_per_step = 10
output_plots = true
# output_linegraphs = true
# output_linegraphs_collected = true
# output_animations = true

[PulseTransfer]
name = "mpw4"
output_plots = true

#max_depth_distance = 5um

[DefaultDigitizer]
name = "mpw4"
output_plots = true
electronics_noise = 550e
threshold = 2800e
threshold_smearing = 30e
# qdc_resolution = 0
# qdc_offset = -2800e
# qdc_slope = 3200e
```

Allpix^2 Possibilities

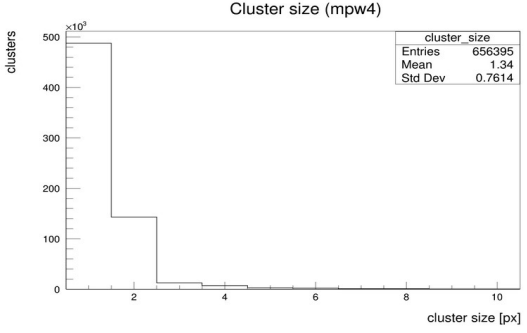
Deposited charge (e- / hole pairs) per incident particle

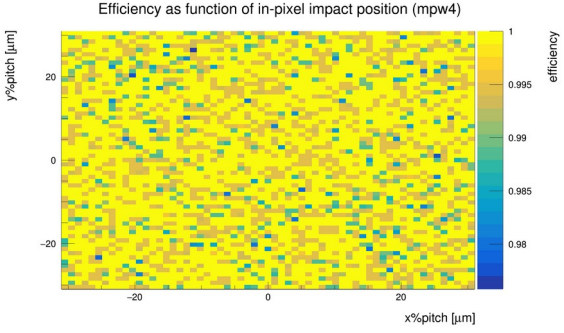




Charge propagated to pixel

Cluster size





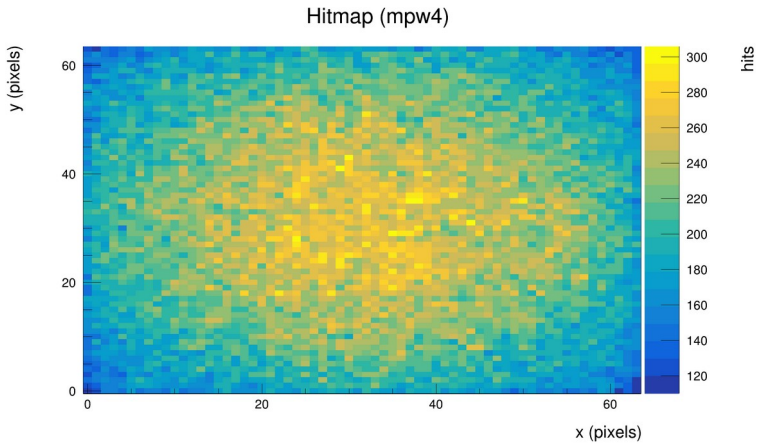
Efficiency
- In-Pixel
- Full Chip

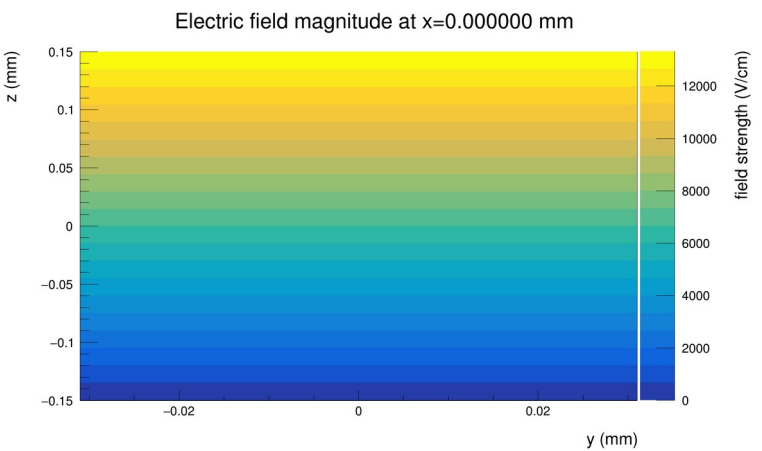
Simulation Goals

- Do we understand our sensor properly?
  - Depletion
  - Threshold
  - …
- Benchmark simulation with test-beam results
- Tune simulation parameters → Improve characteristics of MPW4
  - Spatial resolution (charge sharing, cluster position calculation)
- Find crucial parameters as „design goals“ for possible next iteration

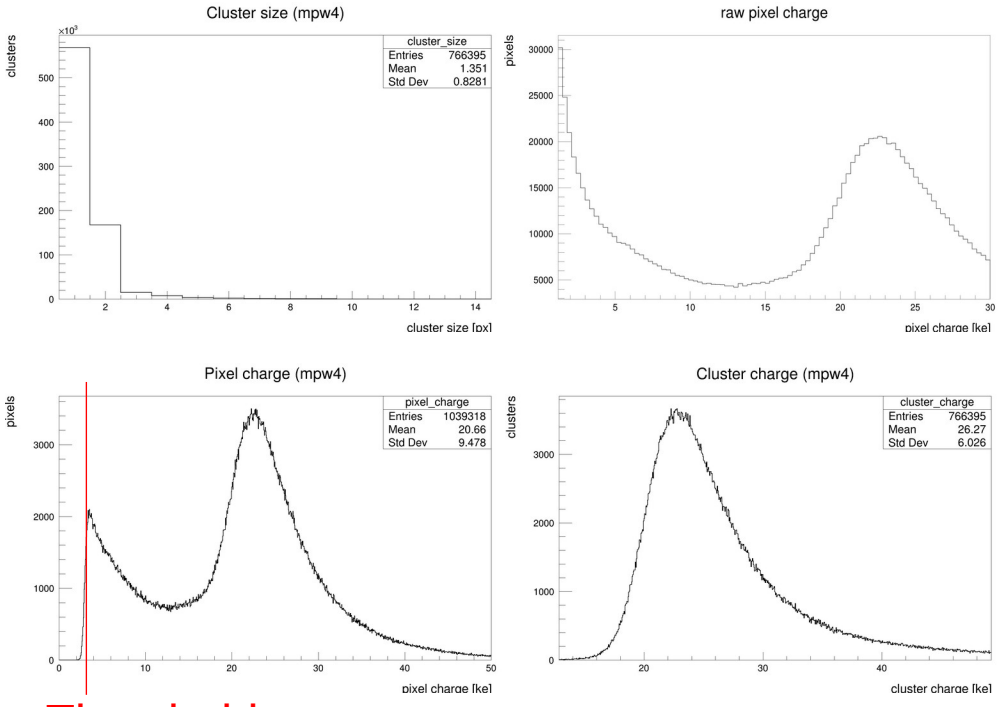
Current Setup

- DESY beam
  - 4.2 GeV electrons in air
- Linear electric field
  - Depletion voltage = -200V
  - Bias voltage = -200V
  - Only in z-direction; No lateral component
- Charge collection full pixel surface
  - No deep N-Well implant
- Threshold: 3000e-
  - V_{Thr} ~ 30 – 40mV
- No telescope only MPW4 in 2cm distance from particle source
  - Faster than using actual test-beam distance (less scattering in air needs to be simulated)



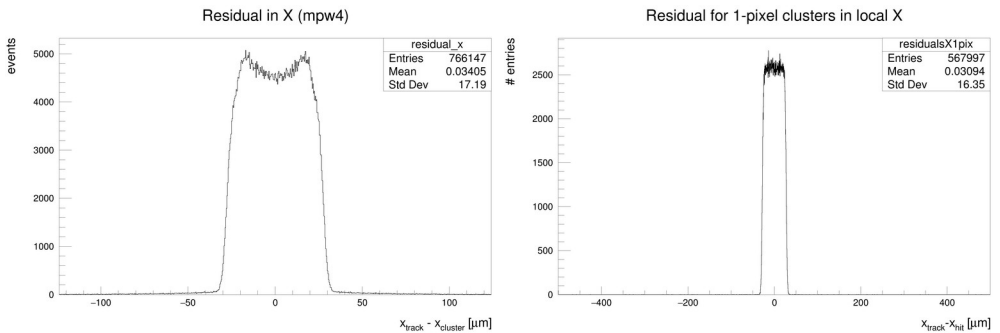


Results Overview



- Average Cluster-size ~1.3 pixel / cluster
  - Testbeam result: 1.324 pixel / cluster
- Mean charge of 20.6 ke^- collected at pixels
  - First peak at ~3.5ke^- due to charge sharing
  - Cluster charge shows only 1 single peak

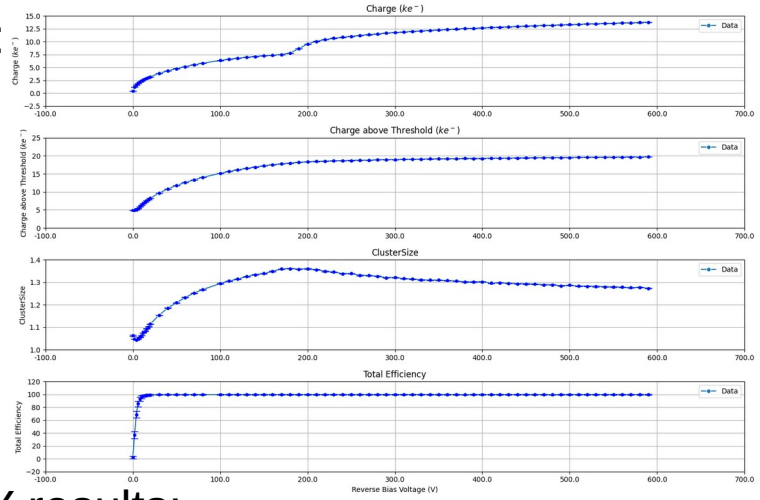
Spatial resolution



- Residuals show spatial resolution of
  - Total: 17.19um
  - 1 Pix cluster: 16.35um
  - 2 Pix cluster: 15.58um
    - Significant double peak
  - 3 Pix cluster: 21.8um
    - Significant double peak
- Double peak due to high threshold?
  - Shared charge not detected
- “Significant” differences to test-beam
  - We are using actual charge in e^- not ToT for center of gravity impact position

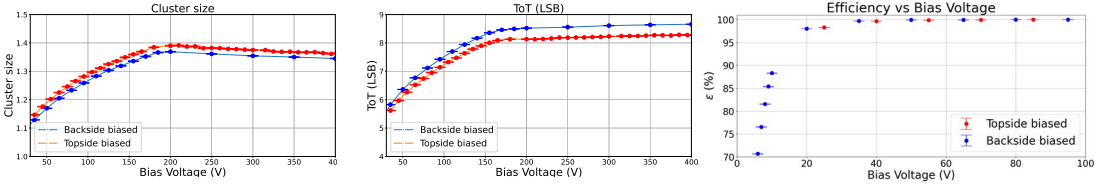
Bias scan

Allpix²:



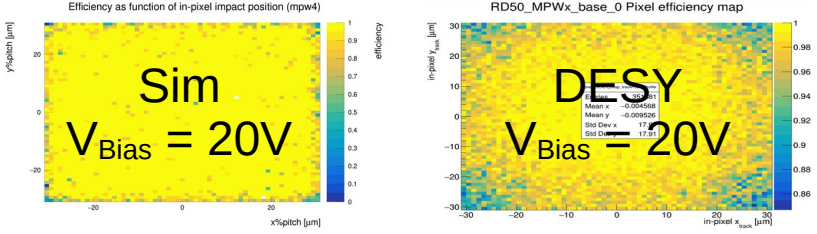
- Saturation of charge observed at V_{Bias} → depletion voltage (V_{Depl} simulated with 200V)
- Cluster-size decreases at $V_{Bias} > V_{depl}$
- Both in good agreement with testbeam results

DESY results:



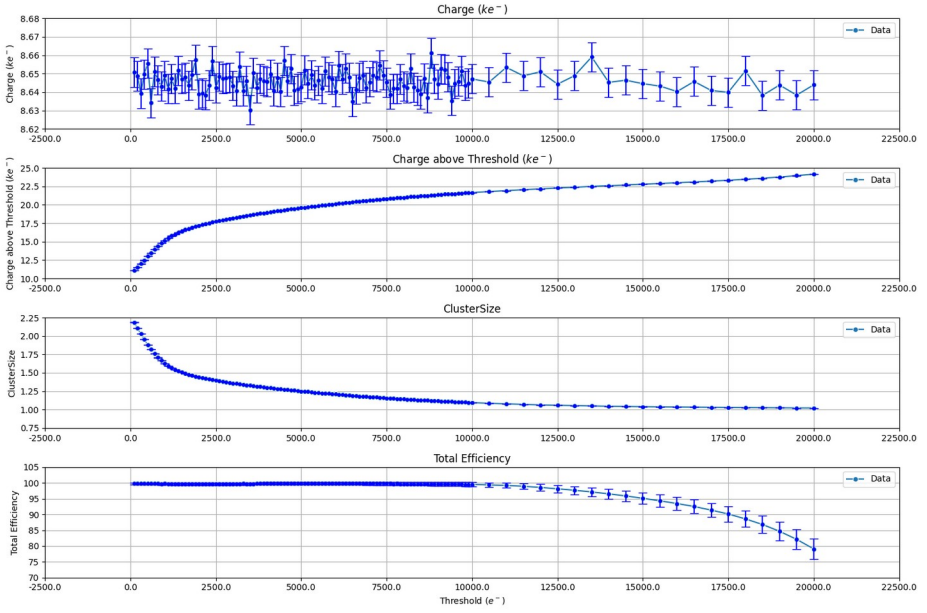
- Simulation full efficient down to V_{Bias} ~ 10V
- Test-beam shows degradation „already“ at V_{Bias} ~ 20V
  - Linear approximation of E-field no longer valid
  - Test-beam results show strong corner effects

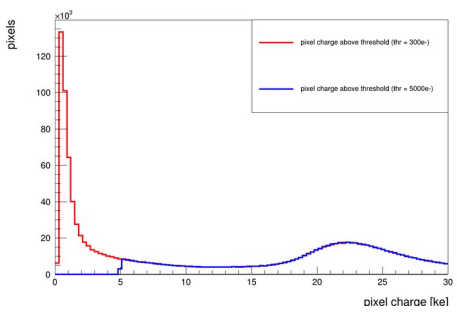
In-pixel efficiency:

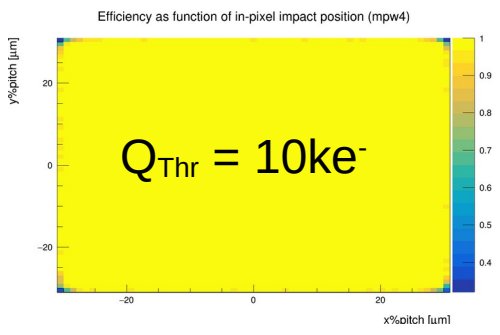


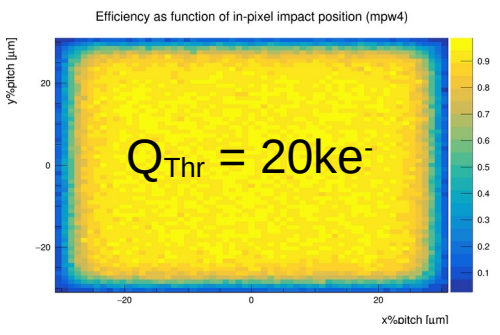
Threshold scan

- Charge mostly unaffected
- Mean charge above threshold increases due to cut off of low charge signals
- Efficiency decreases only at ~10ke$^-$
  - Test-beam shows decrease at ~ 5000e$^-$
  - Again less severe corner effects in in-pixel-efficiency observed



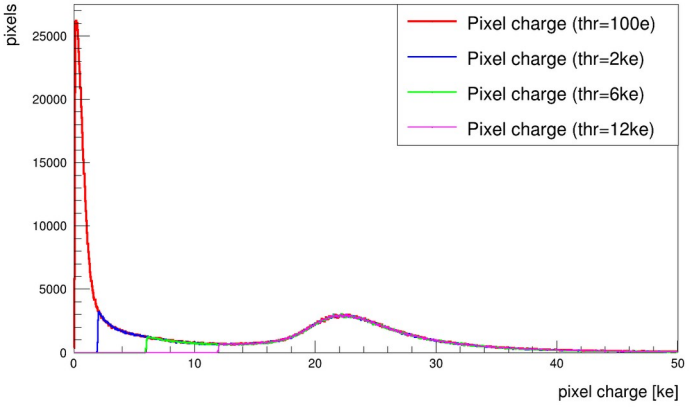


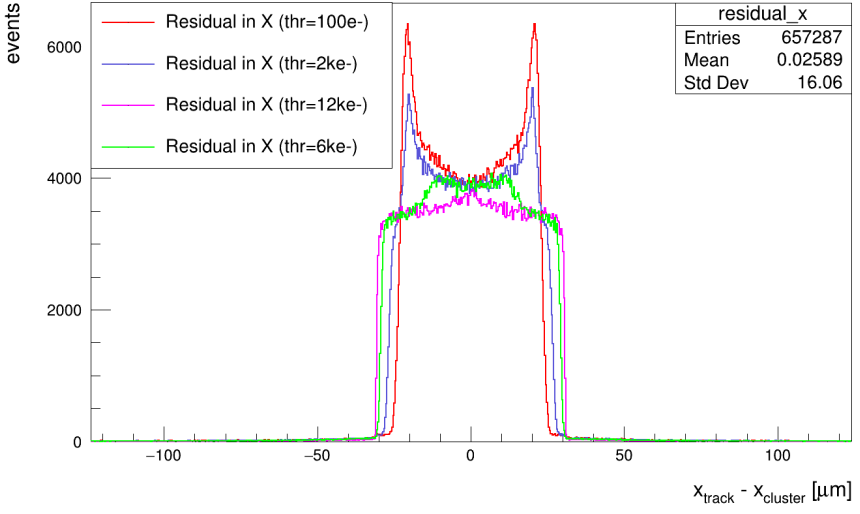




Threshold scan – Residuals

- Double peak characteristic less pronounced at higher thresholds
  - Less charge sharing

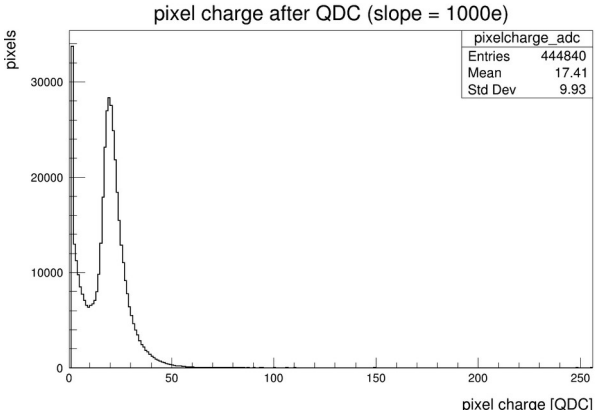


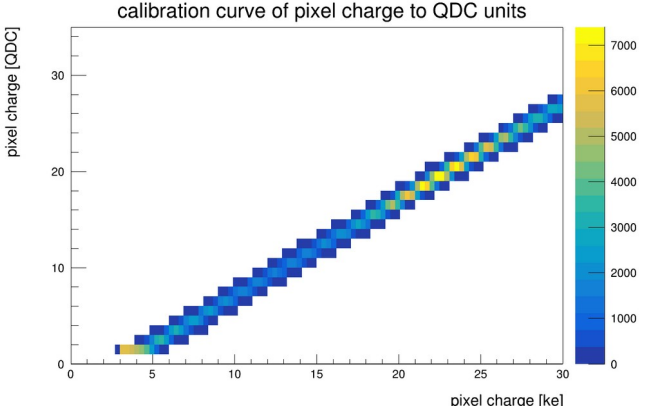


Q_{thr} [e-]	Spatial resolution [µm]
100	16.06
2k	16.82
6k	17.39
12k	17.75

Introducing QDC → ToT

- In MPW4 data we have no actual charge but ToT
- What effect does this have on the observables? Also “easy access” benchmark
- Easiest way to simulate in Allpix²: introduce a QDC (charge to digital converter)
  - Number of bits (in our case 8)
  - QDC slope as slope of linear relation between Charge → ToT
- First peak at low QDC values again due to charge sharing

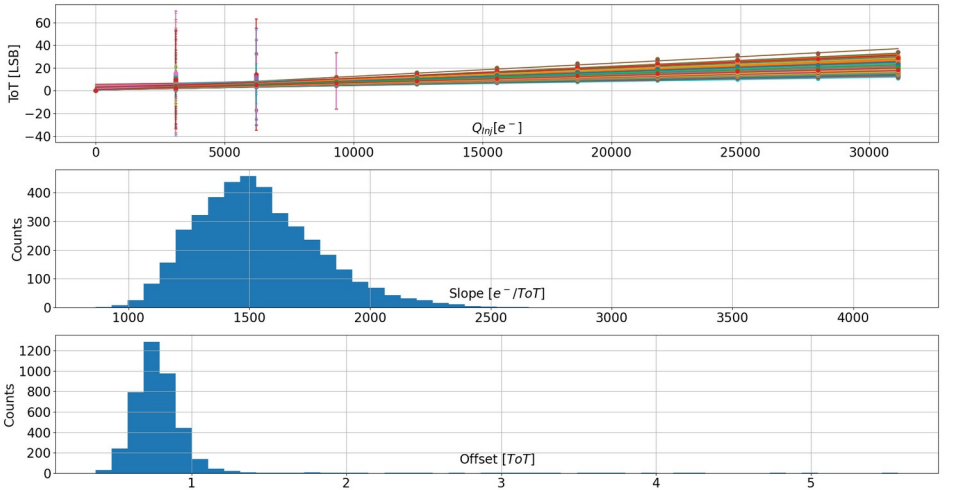


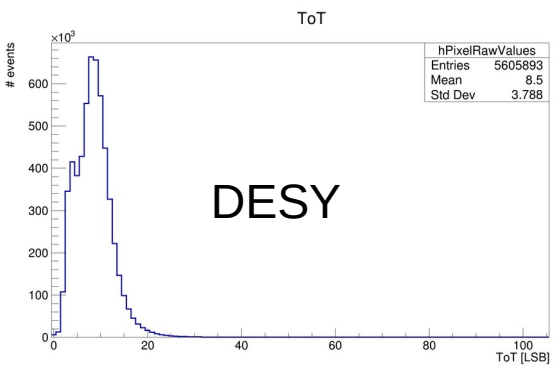


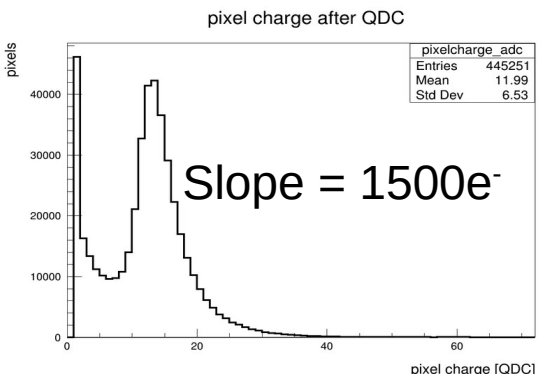
Get QDC slope right

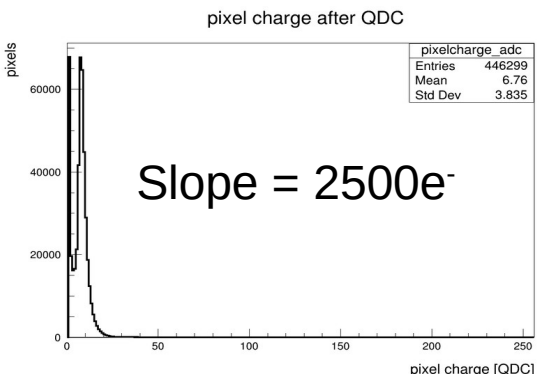
- How to get QDC slope right?
  - Lab evaluation inject into all pixels → fit to linear function → extract mean slope
    - Shows slope of ~ 1530e$^-$
    - Ranging from 1000 – 2500e$^-$
  - Benchmark to test-beam results
    - Show average ToT of ~8.5LSB at Q_{Thr} ~ 3000e-

Injection Scan



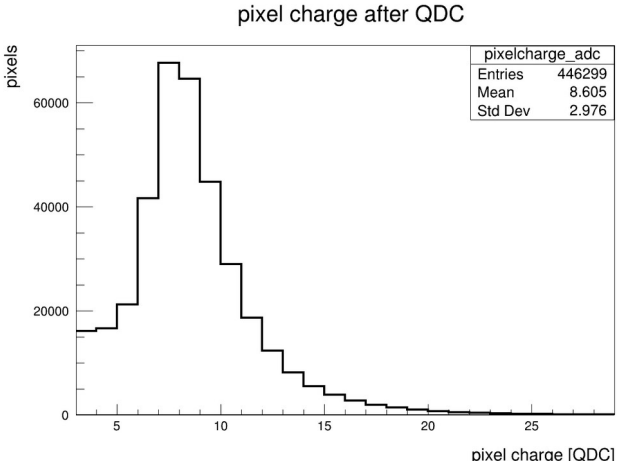


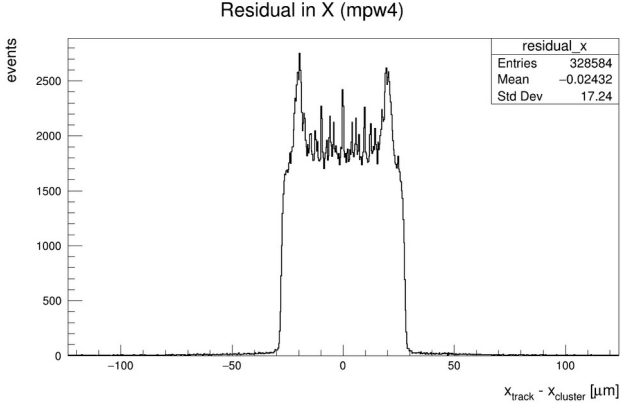




QDC results

- QDC slope of 2500e^- and cut first peak resembles ToT of test-beam result pretty good
- Residuals show only slightly worse spatial resolution compared to calculation with actual charge
  - Double peak more pronounced compared to simulation without QDC





Summary / Outlook

- Most results of test-beam (at least right ball park) were reproduced in simple simulations
- Residuals show unexpected „shape“
  - Cut pixels with low charge
  - Disable diffusion
  - Increase track position uncertainty at DUT
  - Collect charges not on sensor surface but with actual (Deep N-well) implant
    - Requires E-field with lateral components → TCAD
- First (low ToT) peak not observed in DESY results
  - Is our threshold larger than we think?