Towards a Pixel Time Projection Chamber

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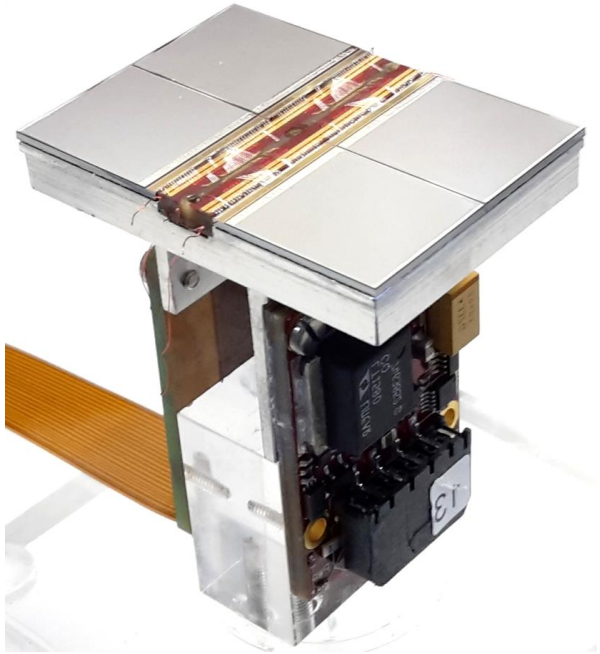
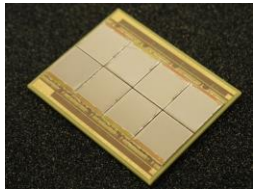
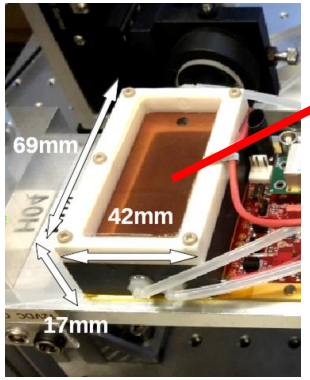


LCWS2019 – Sendai (Japan)

Pixel TPC



(Octopuce)

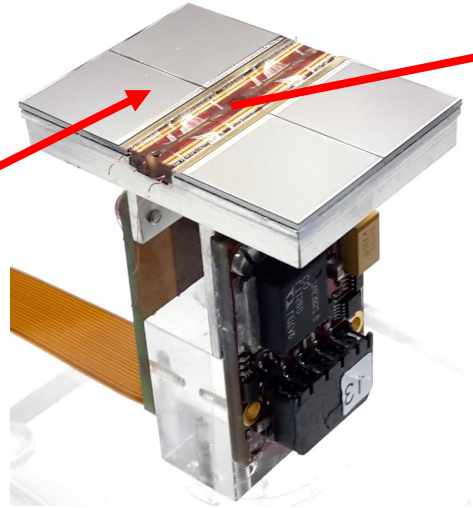


(TimePix1)

(2007-14)

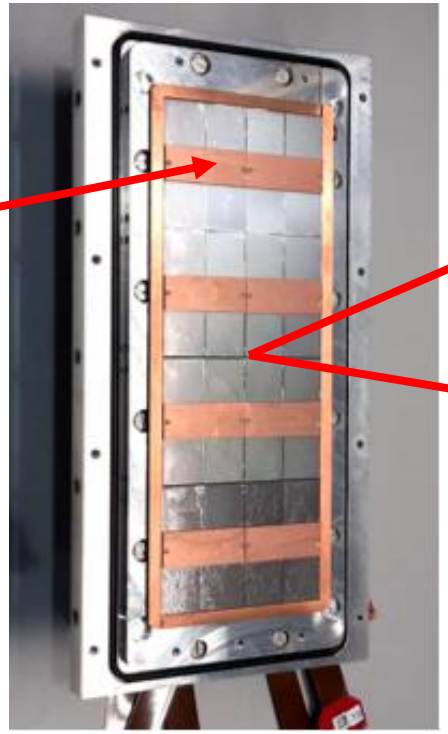
TPX3 chip

2017



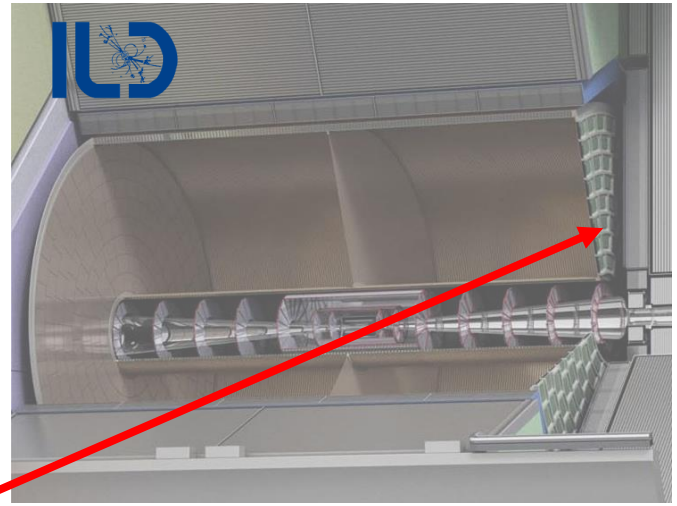
Quad

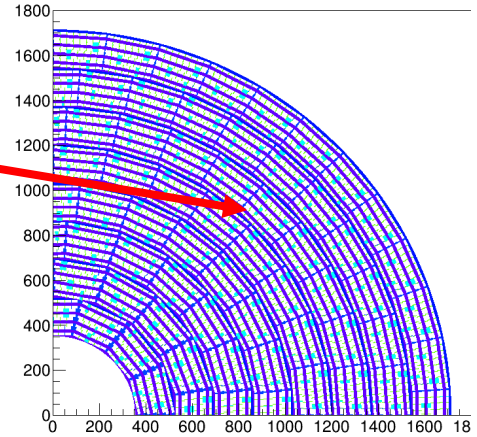
2018



Module

2019

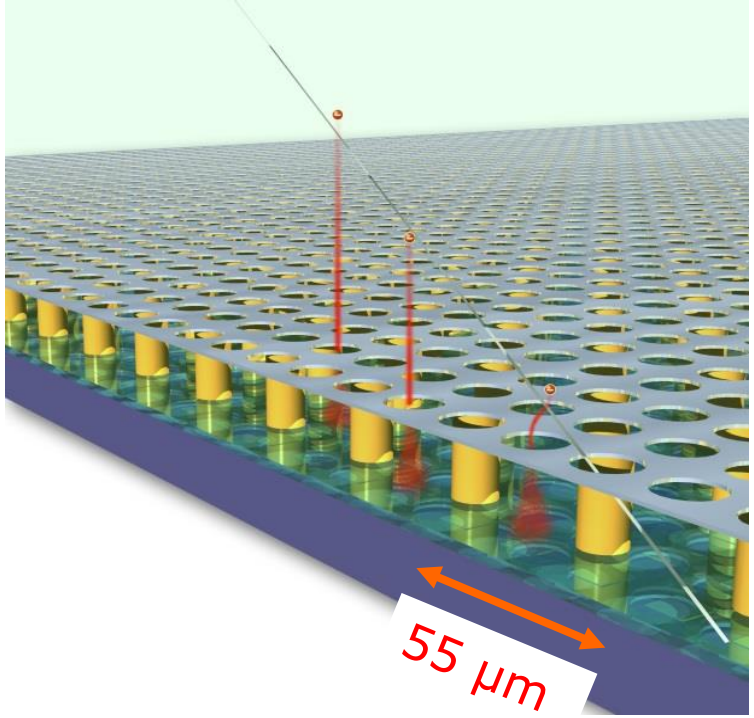


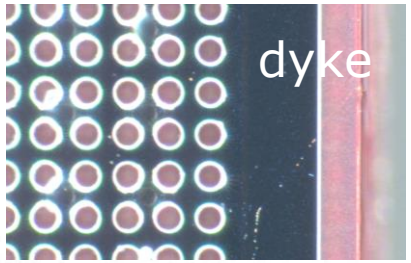


TPC plane

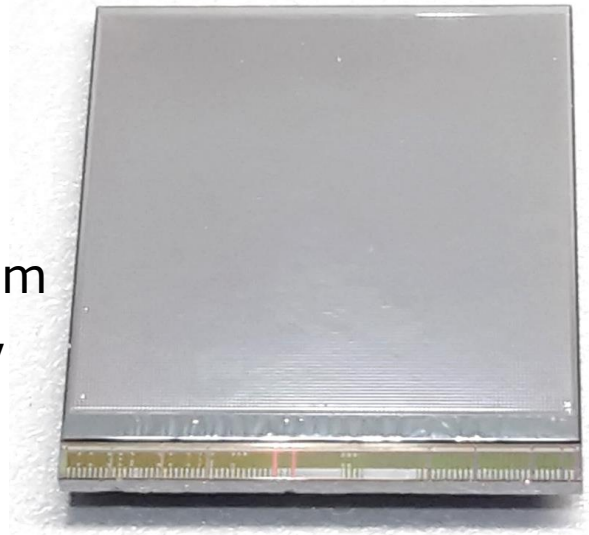
GridPix technology

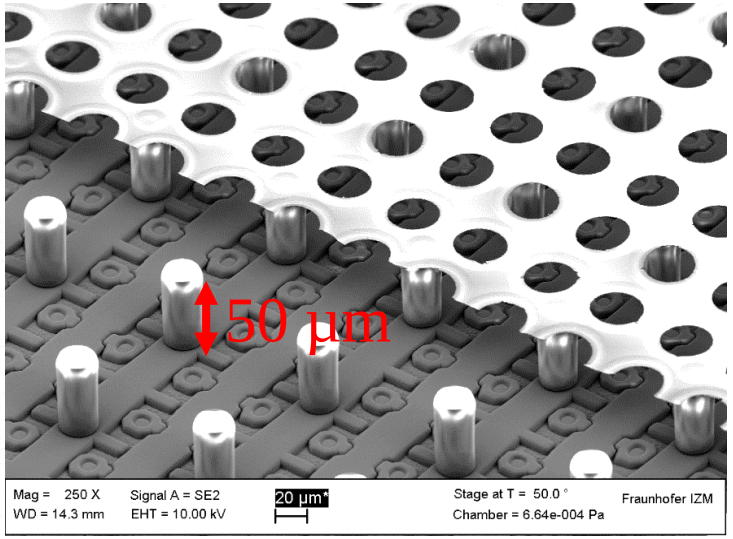
- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 μm)
- detecting individual electrons





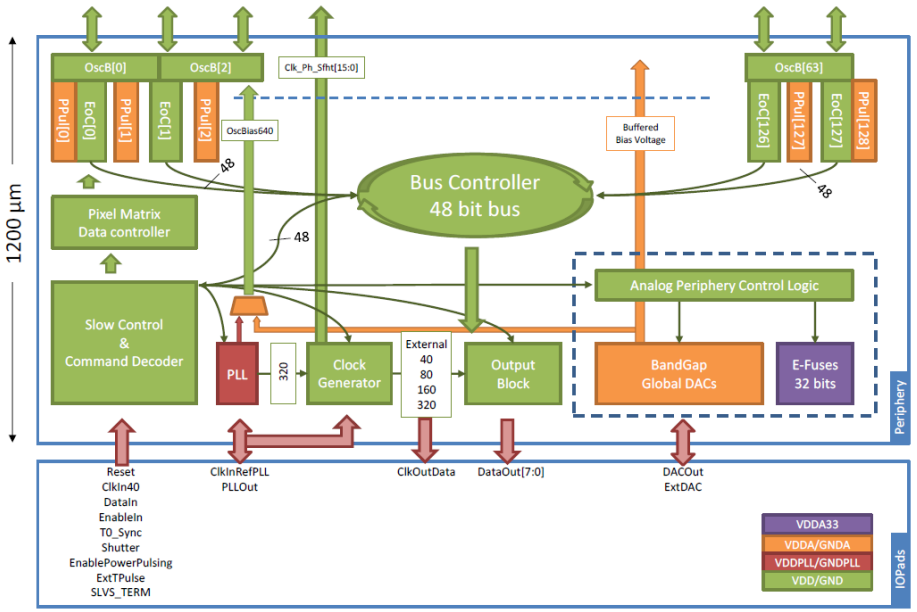
- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability

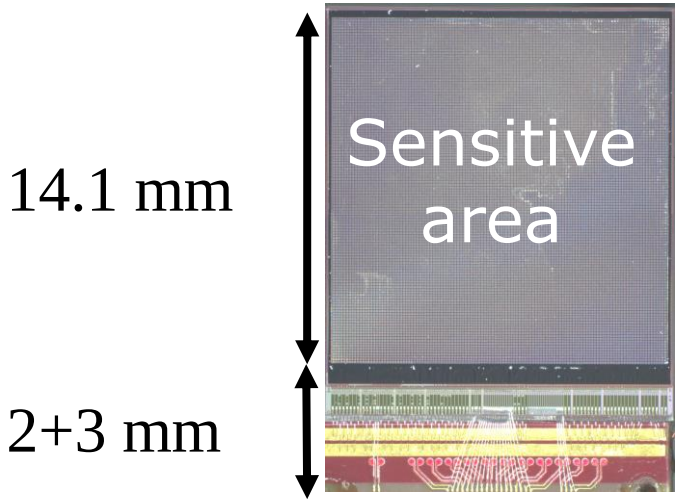




Pixel chip: TimePix3

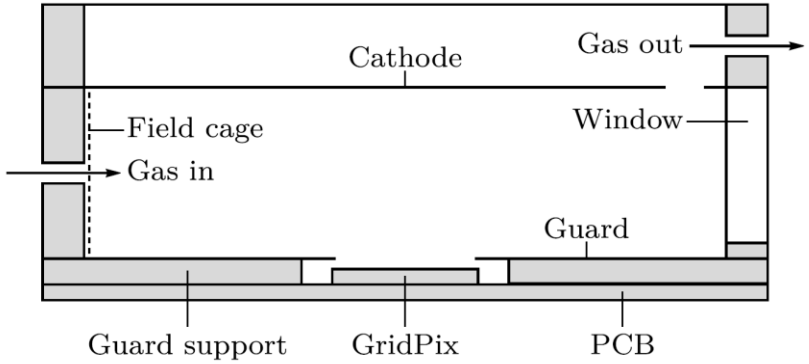
- 256 x 256 pixels
- 55 x 55 μm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **610 MHz clock** (1.64 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
  - compensation for time walk
  - **Trigger** (for t_0) added to the data stream as an additional time stamp
- Power consumption
  - ~1 A @ 2 V (2W) depending on hit rate
  - good cooling is important

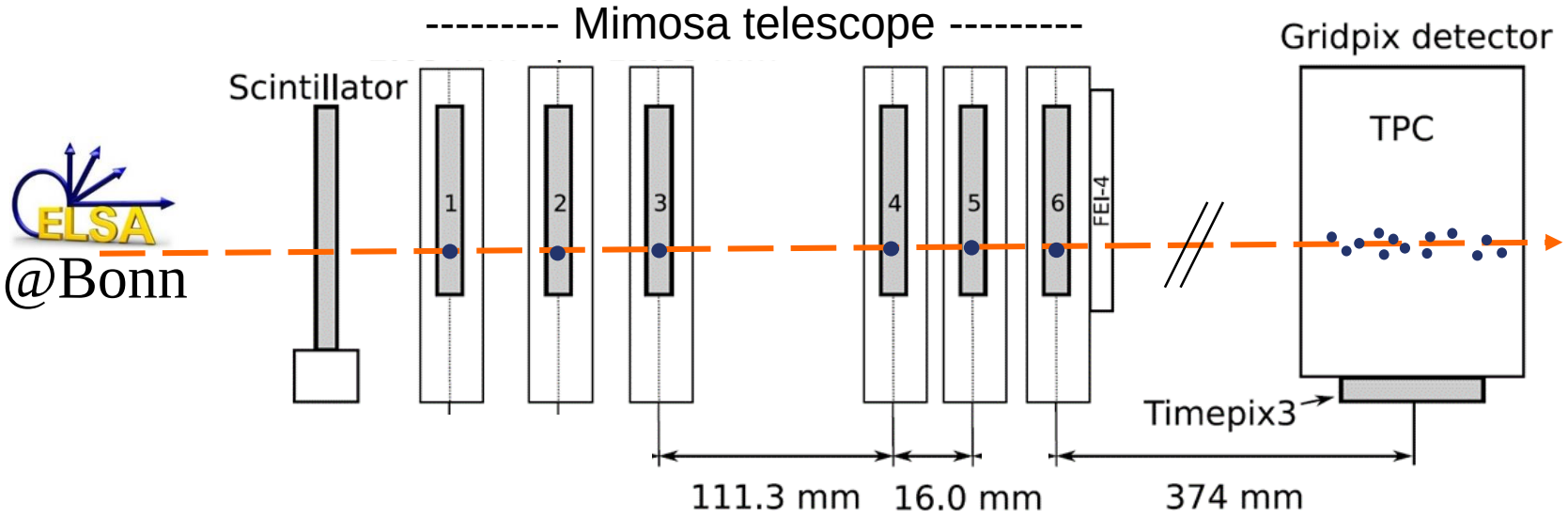




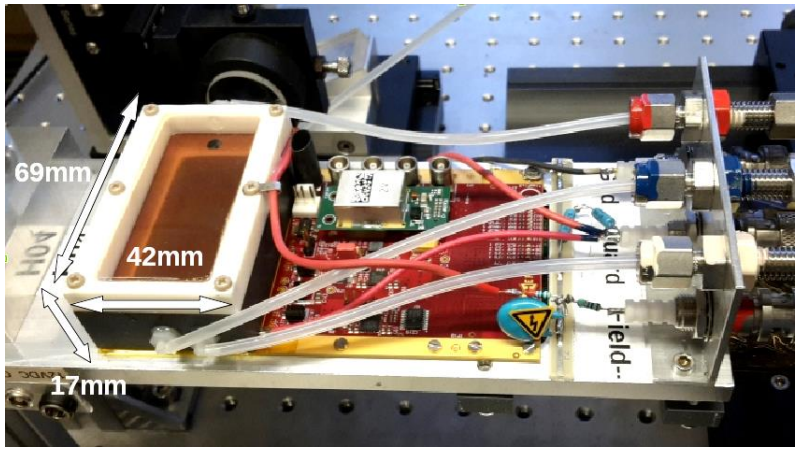
Single chip test in test beam Bonn (June 2017)

- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- Electrons: ~100 e/cm
- E_d = 280 V/cm, V_{grid} = -350 V



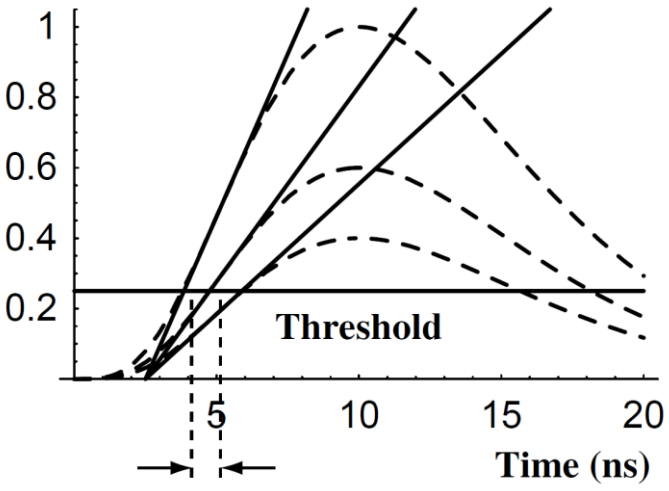


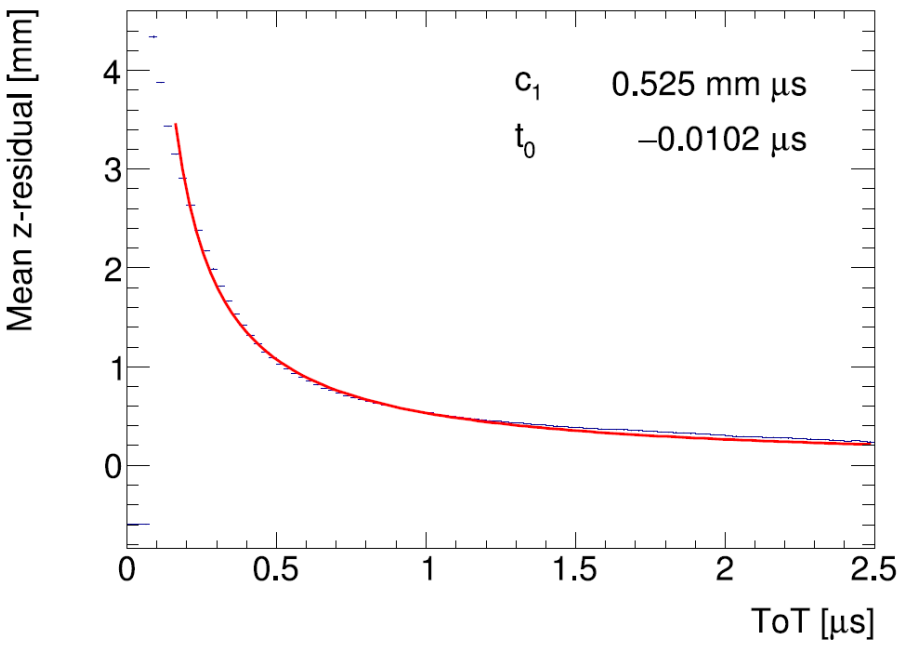
Detector with guard and field shaper

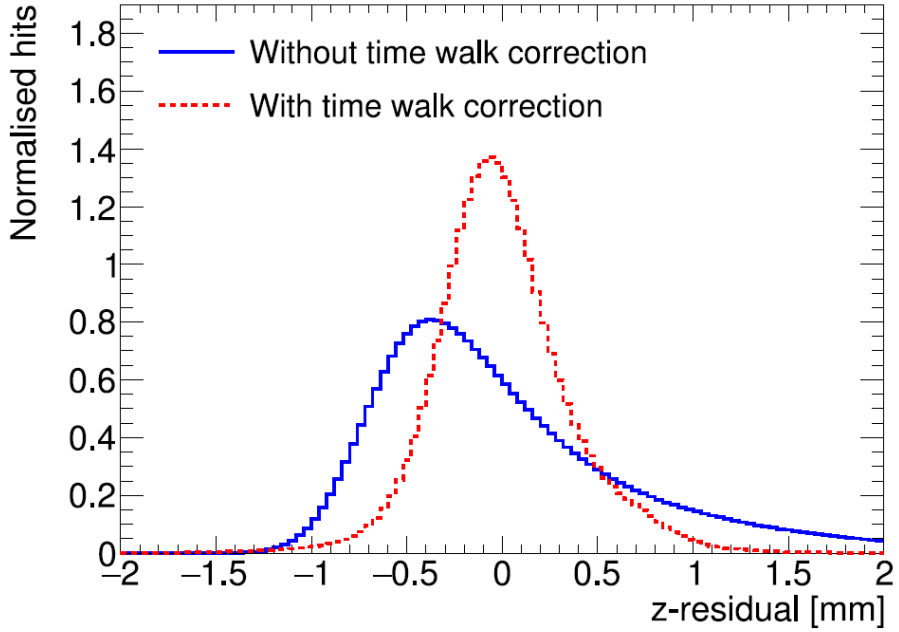


Published paper on 2017 testbeam: https://doi.org/10.1016/j.nima.2018.08.012

TimePix3 time walk correction







Time walk error: time of arrival depends on signal amplitude

(Blum, Particle detection 2008)

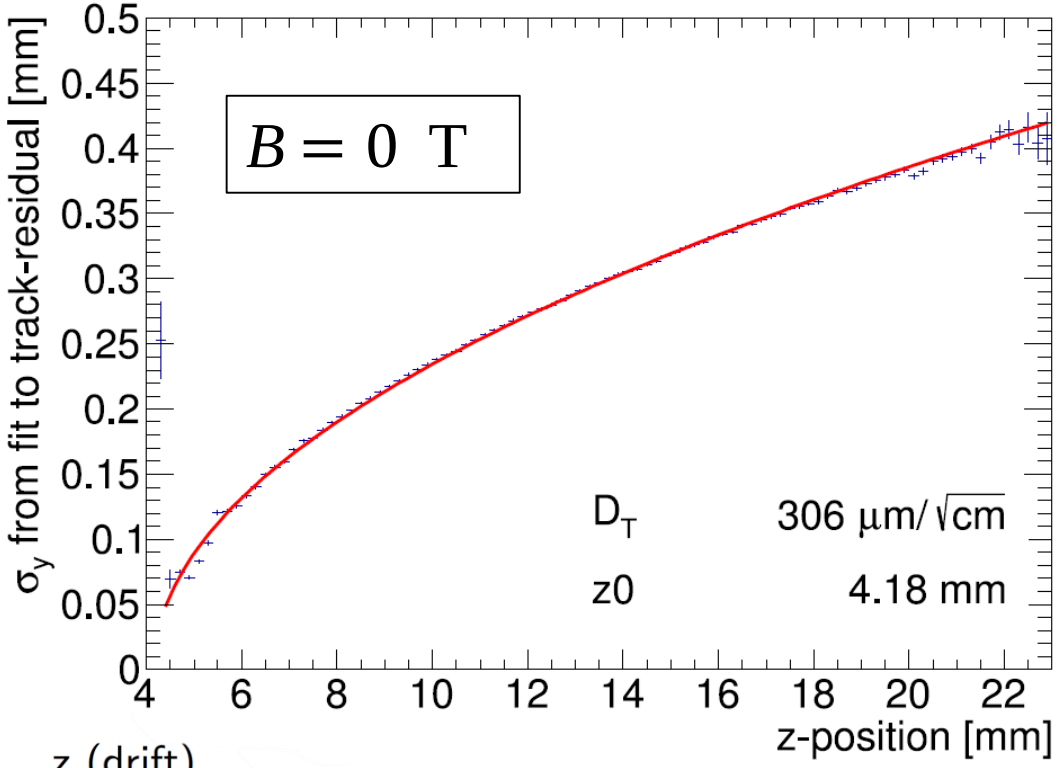
Correction using Time over Threshold (ToT) as a measure of signal strength

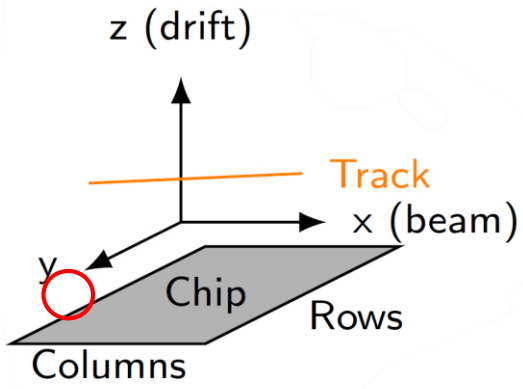
$$\delta z_{\text{timewalk}} = \frac{c_1}{t_{\text{ToT}} + t_0} + z_0$$

Residual distribution improved

Higher order corrections did not yield further improvements

Single hit resolution in transverse direction





$D_T = 306\ \mu\text{m}/\sqrt{\text{cm}}$

($318 \pm 7\ \mu\text{m}/\sqrt{\text{cm}}$ expected)

Single hit resolution in pixel plane:

$$\sigma_y^2 = \sigma_{y0}^2 + D_T^2(z - z_0)$$

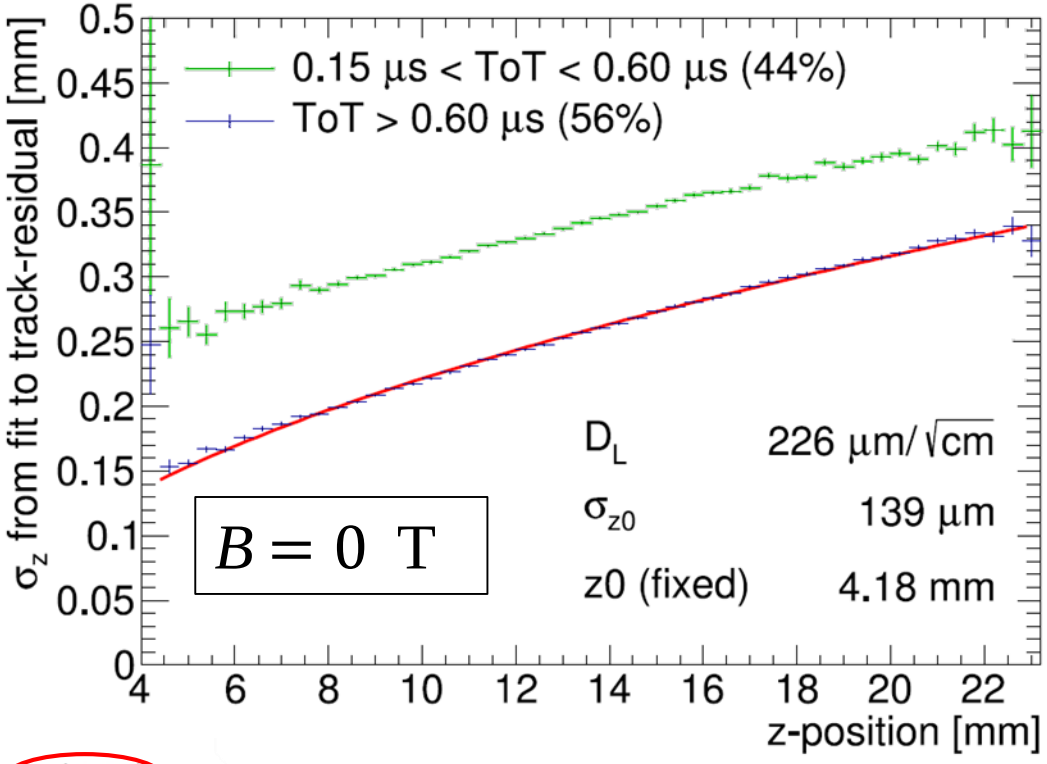
Depends on:

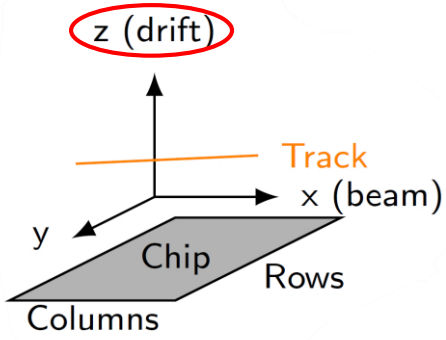
- σ_{y0} = pixel size $/\sqrt{12}$
- Diffusion D_T from fit

Note that:

- A hit resolution of ~250 μm is ~25 μm for a 100-hit track (~ 1 cm track length)
- At $B = 4$ T , $D_T = 25\ \mu\text{m}/\sqrt{\text{cm}}$

Single hit resolution in longitudinal direction





$$D_L = 226\ \mu\text{m}/\sqrt{\text{cm}}$$

$(201 \pm 5\ \mu\text{m}/\sqrt{\text{cm}}$ expected)

Single hit resolution in drift direction

$$\sigma_z^2 = \sigma_{z0}^2 + D_L^2(z - z_0)$$

Depends on

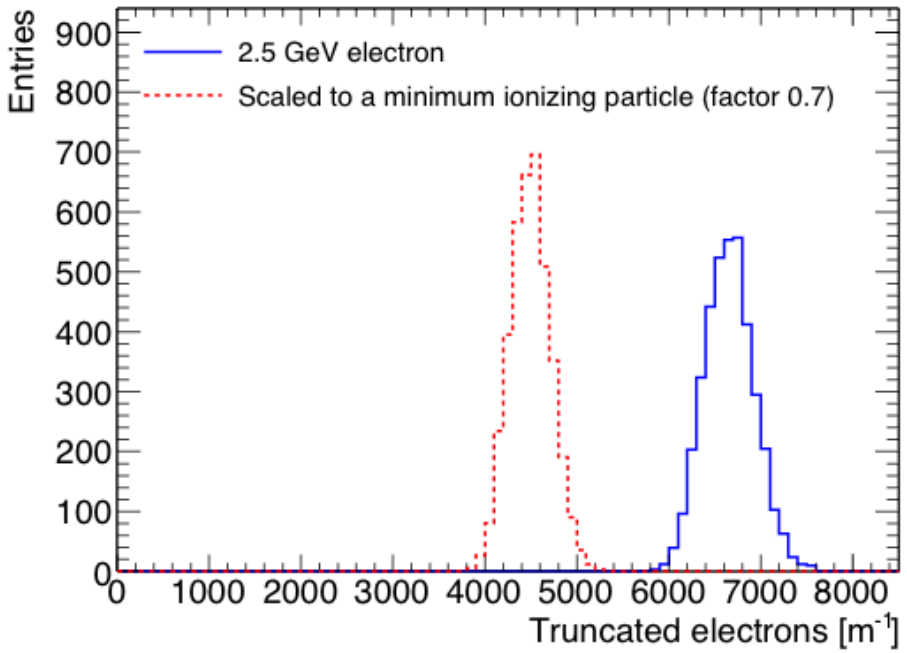
- σ_{z0} from fit
- Diffusion D_L from fit

The additional ToT cut (>0.60 μs) was applied to avoid large time walk errors

Pixel dE/dx performance

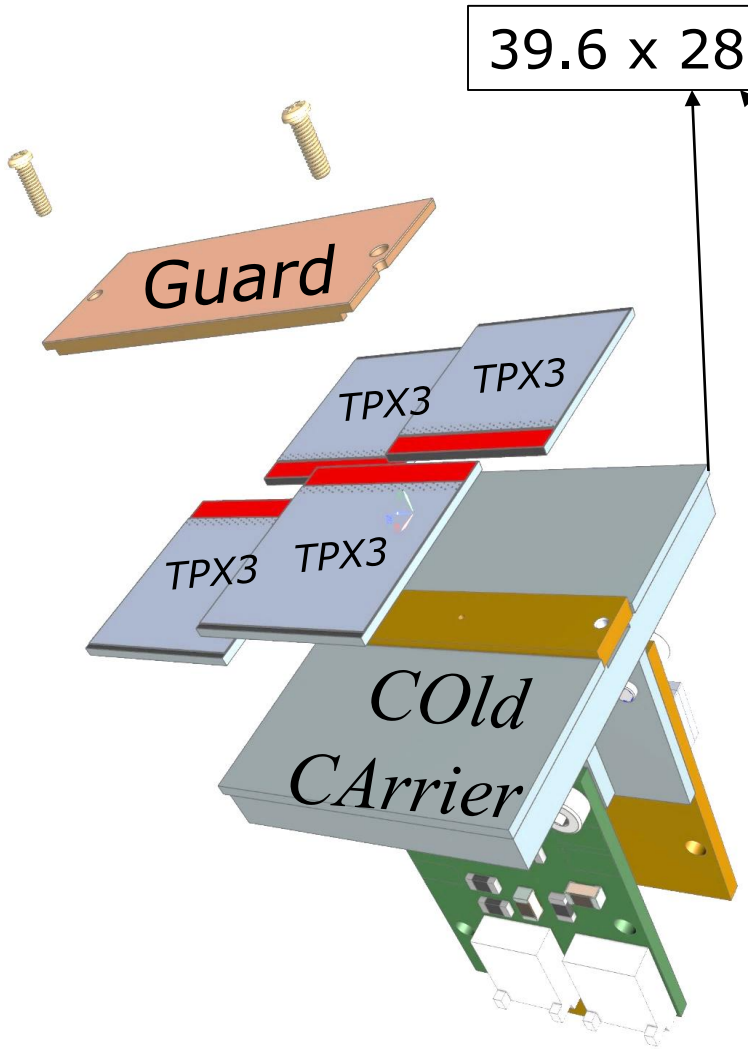
- dE/dx resolution with truncated mean
  - From the single chip tracks; 1 m long tracks are made;
  - nr of electrons counted in slices of 20 pixel and reject 10% highest slices
  - Distances along track are scaled by 1/0.7 to get an estimation for the dE/dx of a MIP
  - Resolution is 4.1% for a 2.5 GeV electron and 4.9% for a MIP
- Separation $S = (N_e - N_{MIP})/\sigma_e$
- 8σ MIP-e separation for a 1 meter track

- A pixel readout can in principle within the resolution (diffusion) separate primary from secondary clusters. dE/dx can be measured by cluster counting and performance separation enhanced.

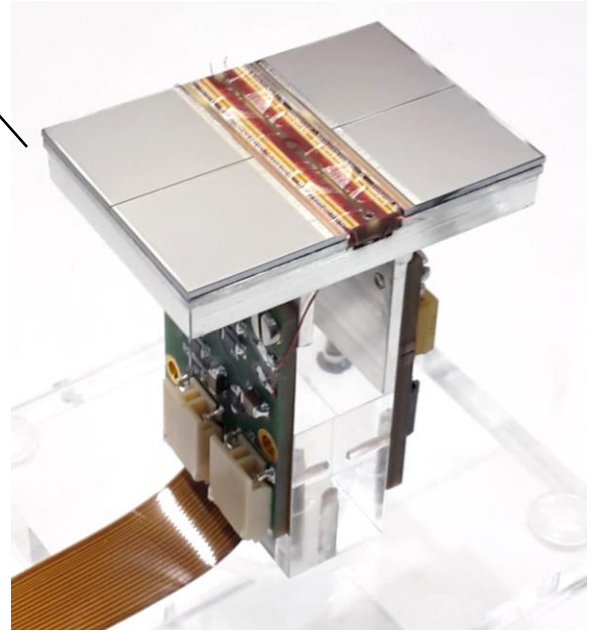


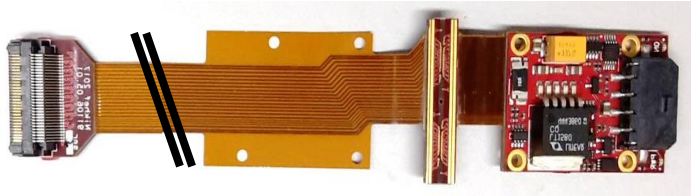
QUAD design and realization

- Four-TimePix3 chips
- All services (signal IO, LV power) are located under the detection surface
- The area for connections was squeezed to the minimum
- Very high precision 10 μm mounting of the chips and guard
- QUAD has an sensitive area of 68.9%
- DAQ by SPIDR



series of QUADs

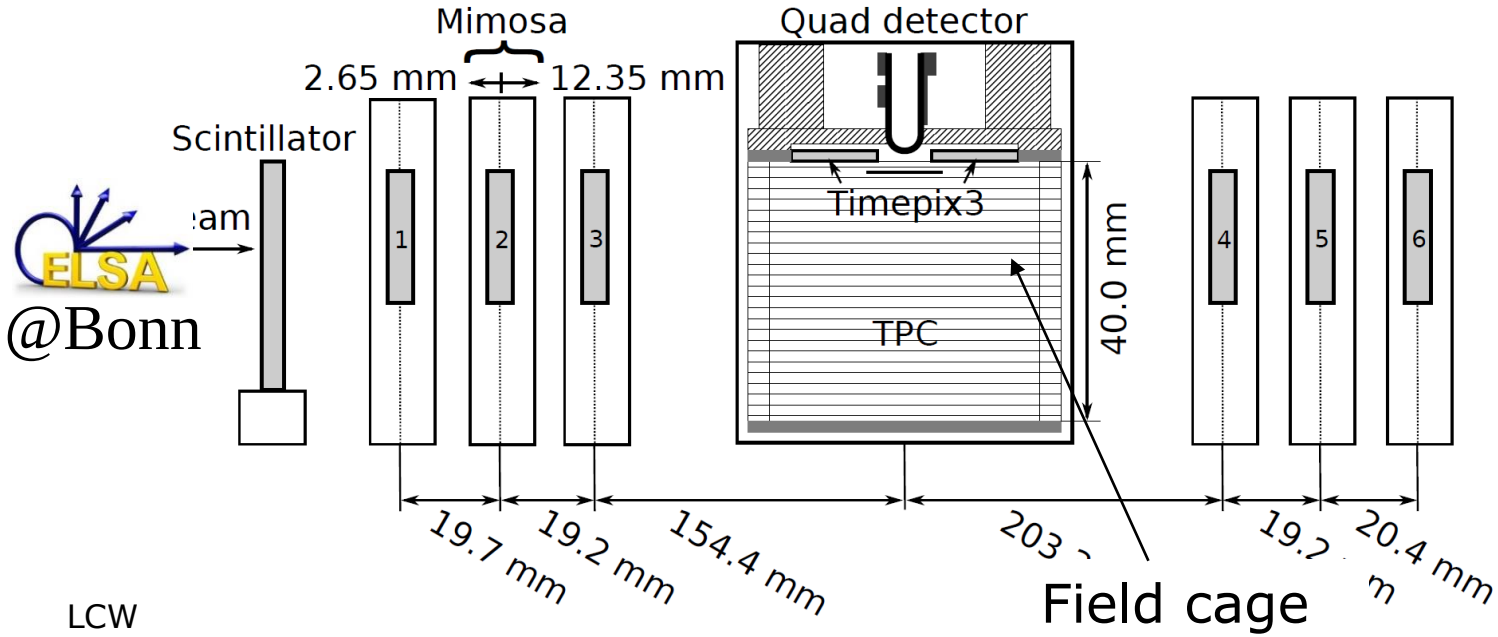


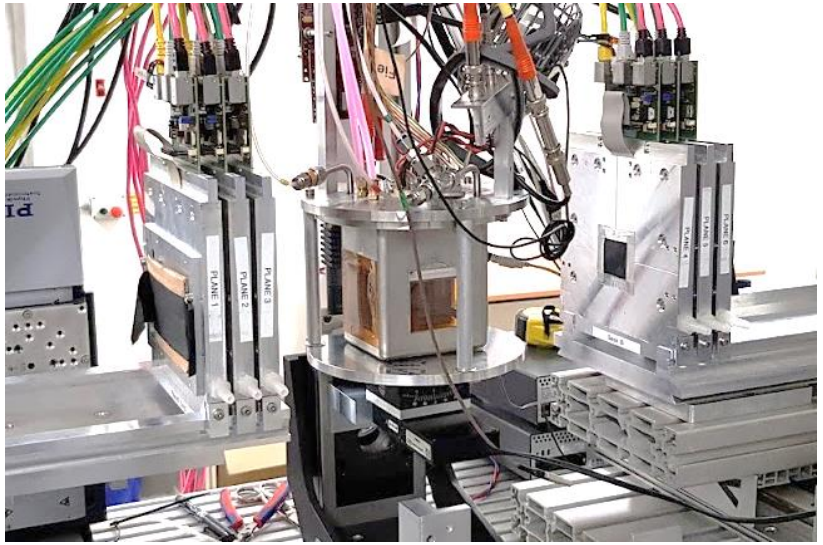


QUAD test beam in Bonn (October 2018)

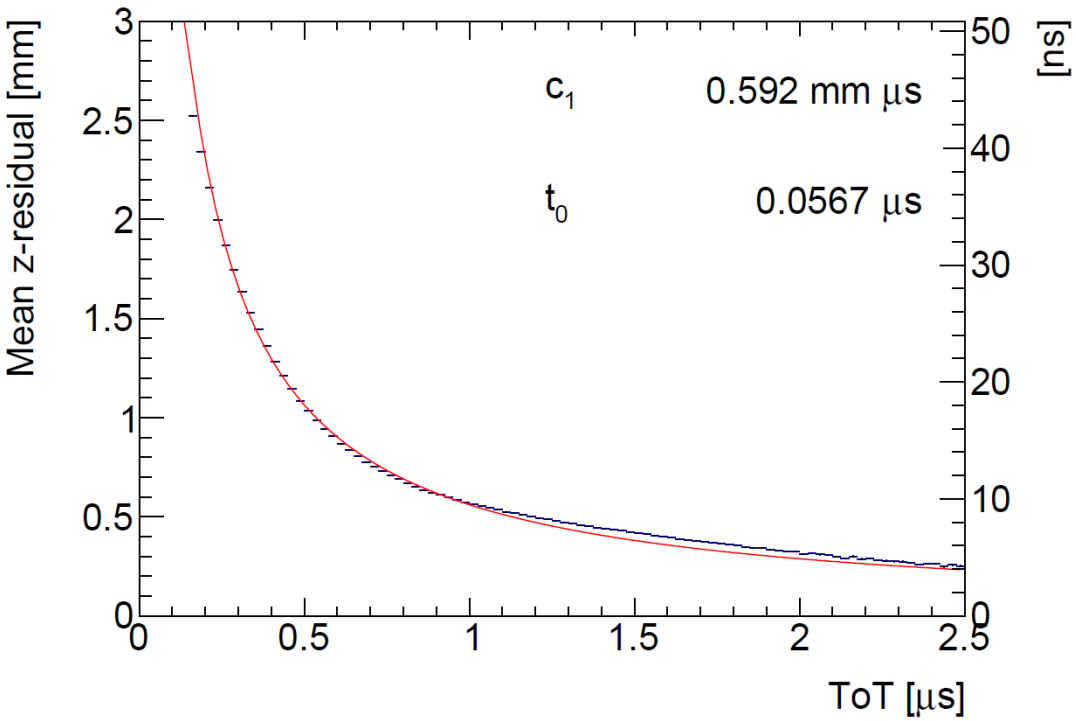
- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
  - Largely improved track definition
  - 6 planes with 18.4 μm × 18.4 μm sized pixels
- Gas: $Ar/CF_4/iC_4H_{10}$ 95/3/2 (T2K)
- E_d = 400 V/cm, V_{grid} = -330 V
- Typical beam height above the chip: ~1 cm

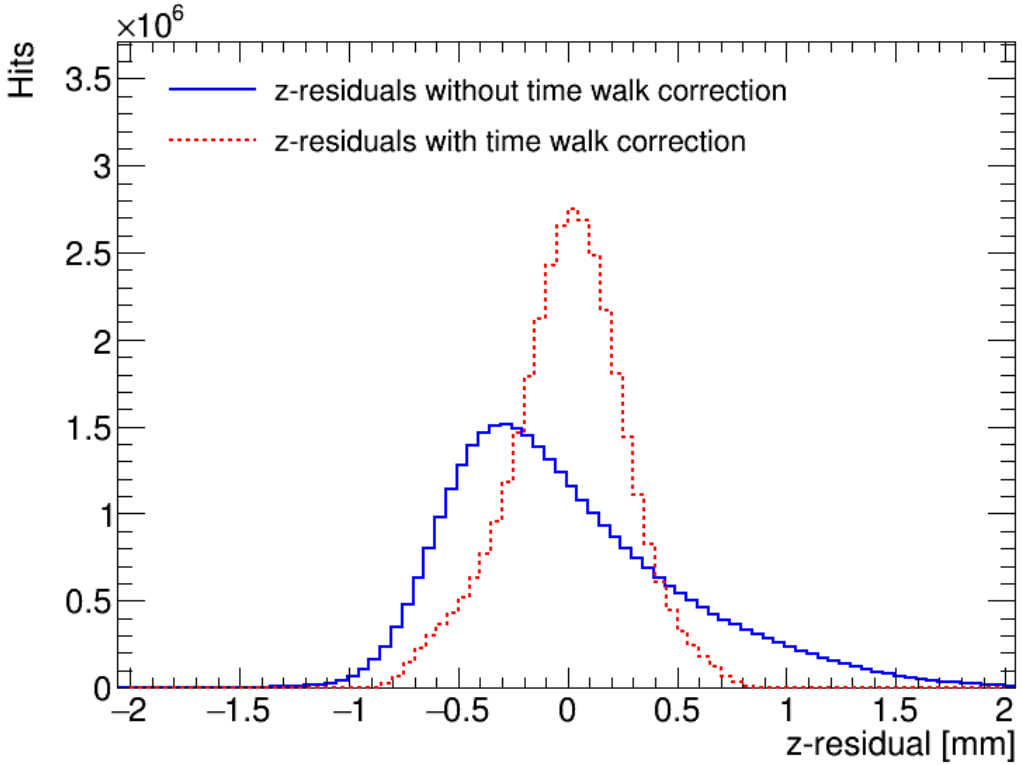
Paper submitted to NIMA





QUAD time walk results



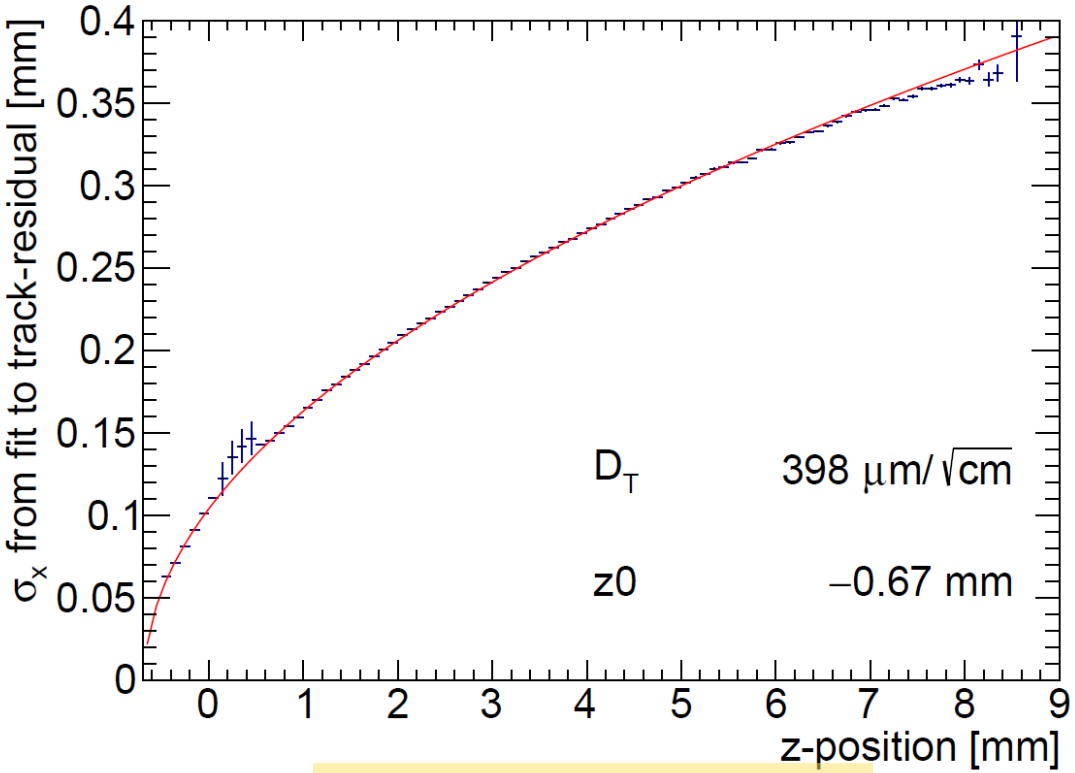


$$\delta z_{\text{timewalk}} = \frac{c_1}{t_{\text{ToT}} + t_0} + z_0$$

- Time walk correction works well
- Applied for all analysis results

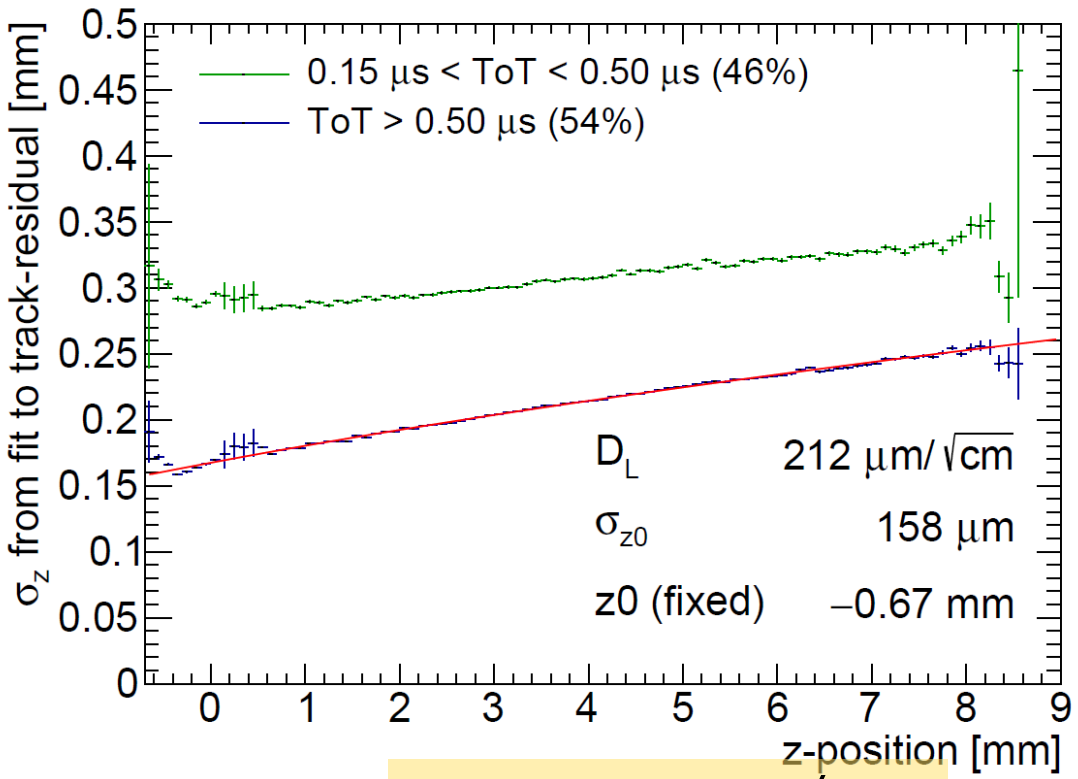
QUAD single hit resolution

Transverse



D_T = 398 μm/√cm

Longitudinal

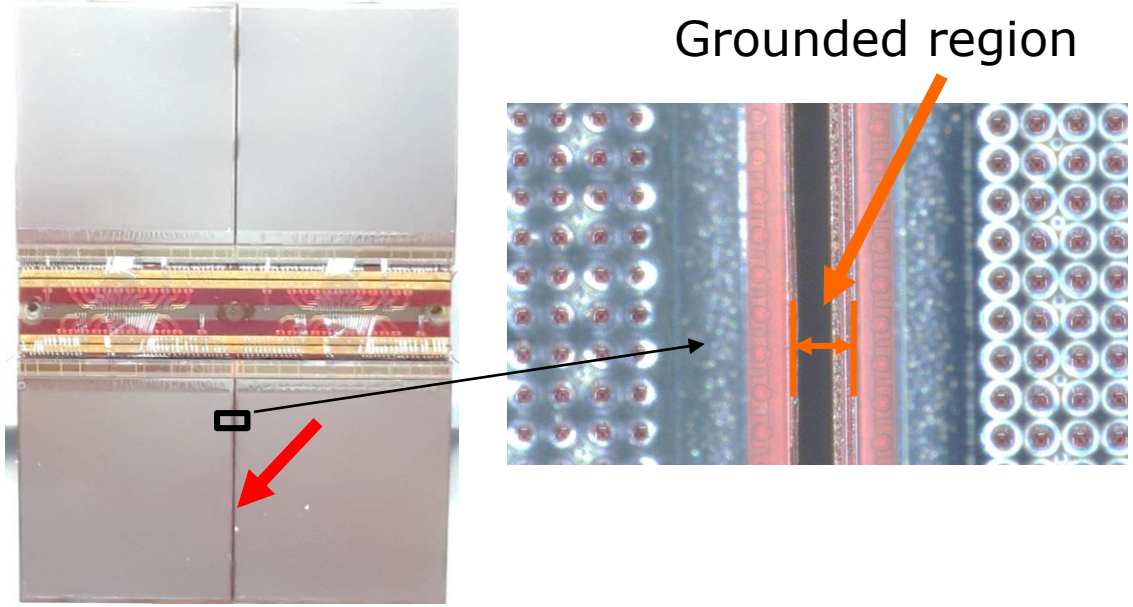


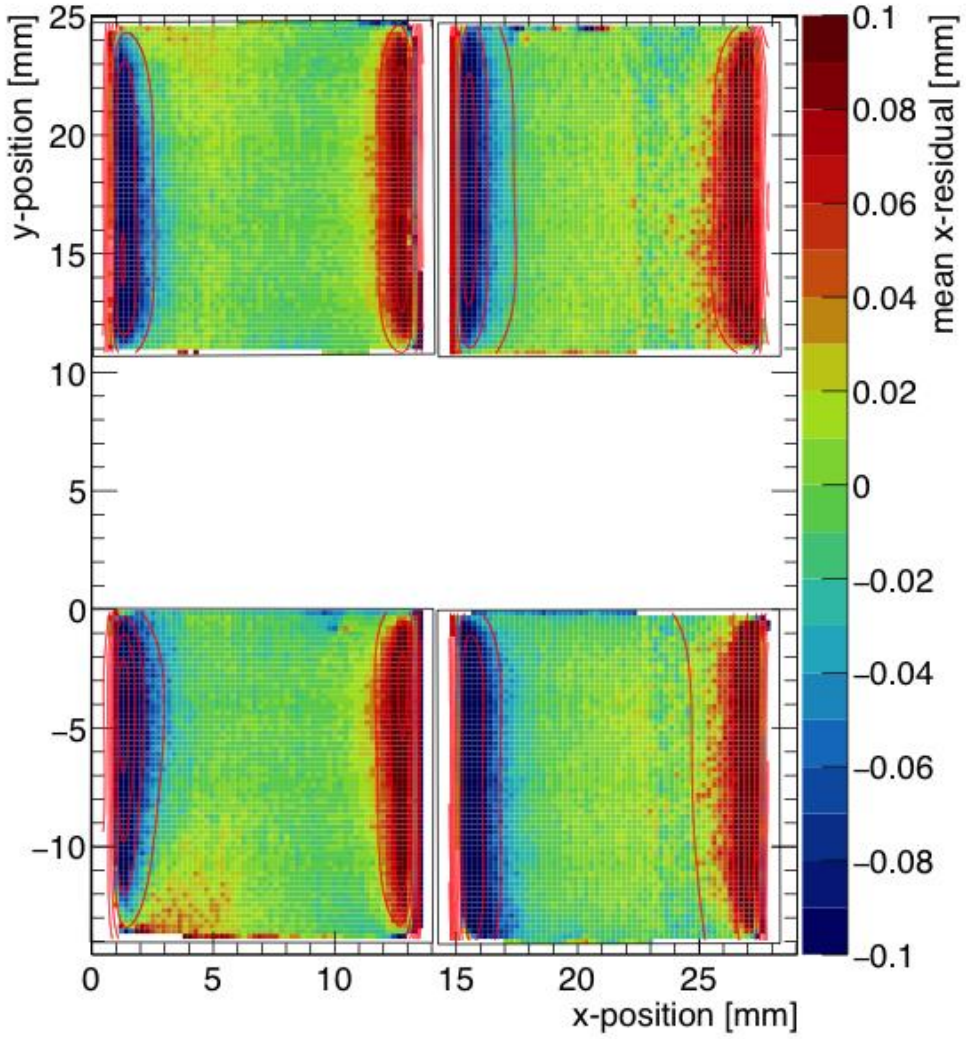
D_L = 212 μm/√cm

The D_T value is rather high due to an error in the gas mixing (too low CF4)

QUAD edge deformations (XY)

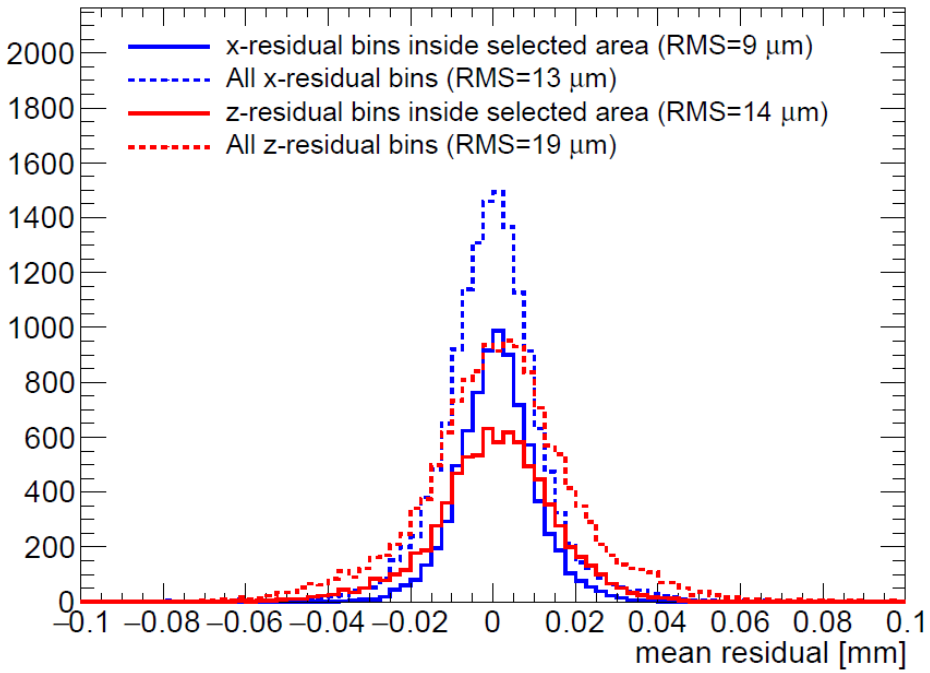
- Small deformations due to
  - Dead zone between chips
  - Grounded region between chips
- Are corrected by:
  - fitted correction function
  - adding proper guard wire electrode

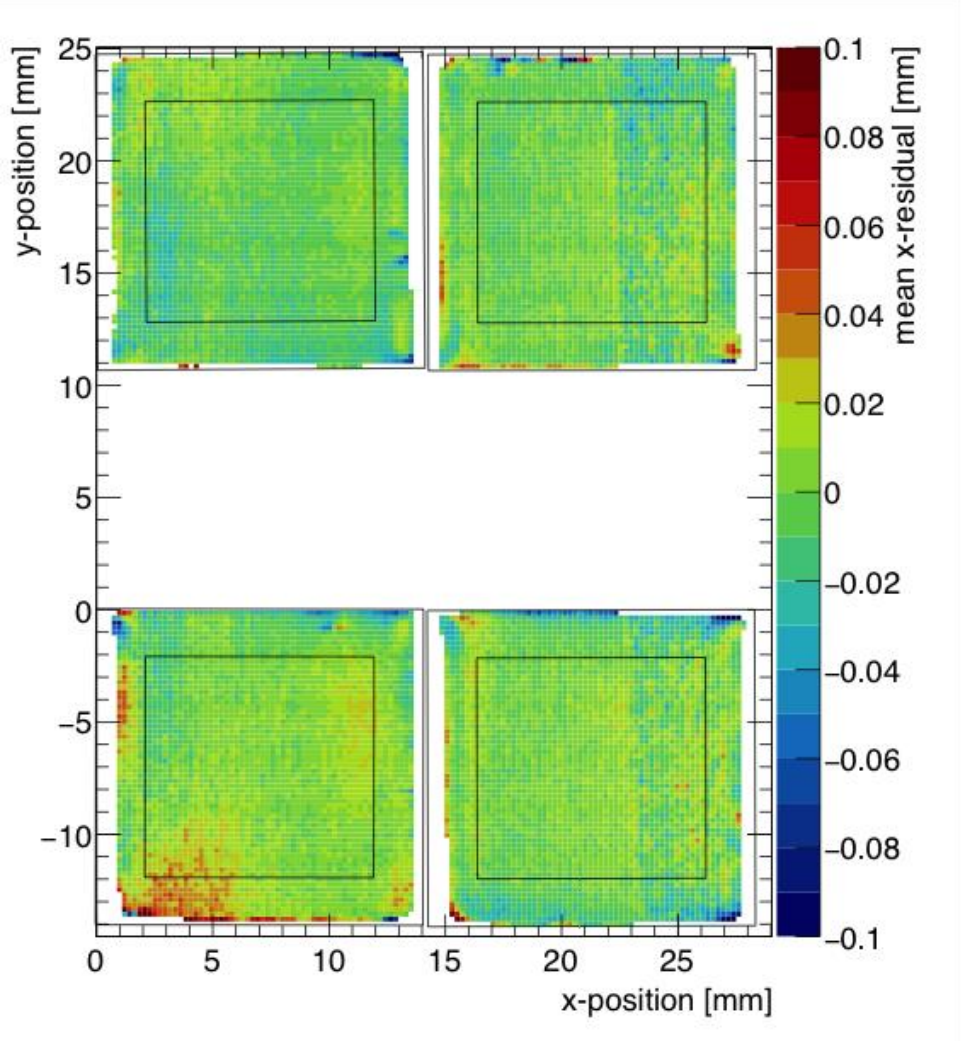




QUAD deformations in transverse plane (XY)

- After applying fitted edge corrections
- RMS of the mean residuals are 13 μm over the whole QUAD

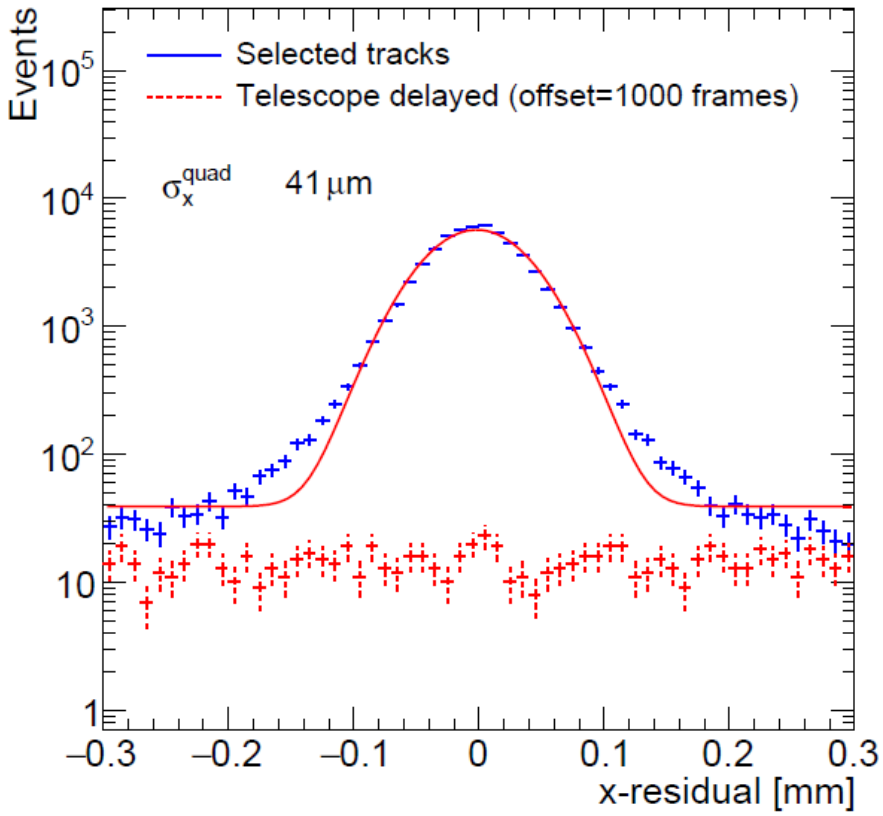




Combined resolution (XY) of a QUAD

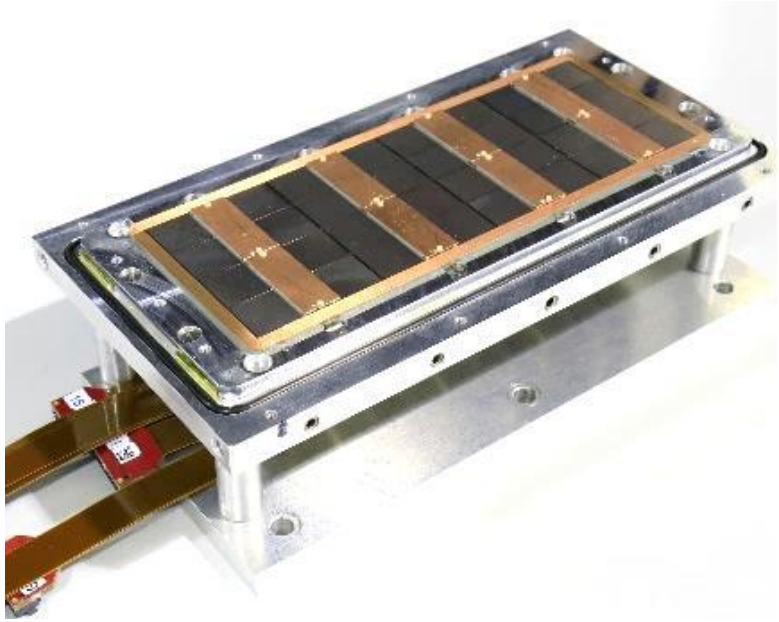
- Below a breakdown of the uncertainties and sources is given
- The observed resolution can be understood up if an additional contribution of 14 μm is added

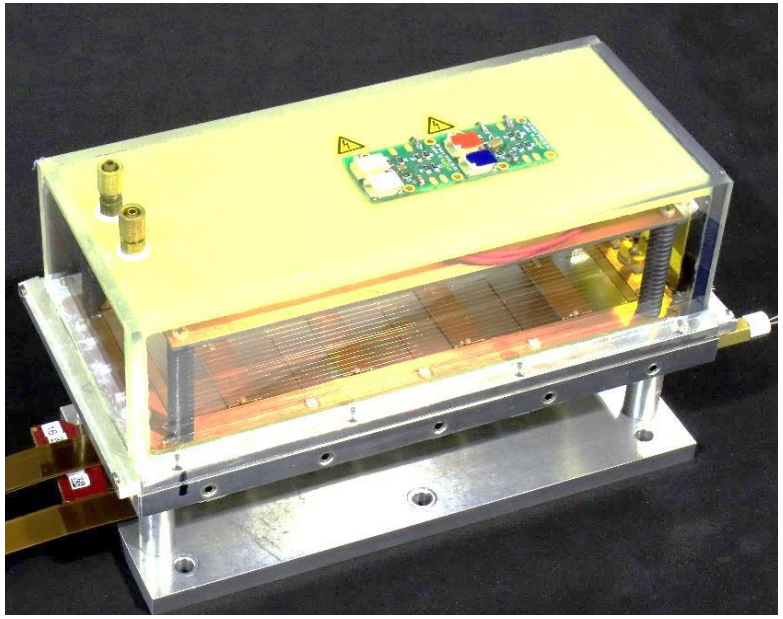
Observed standard deviation	41 μm
Statistical errors	25 μm
Systematic errors in the pixel plane and drift direction	19 μm
Multiple scattering	22 μm
Unidentified systematic error	14 μm

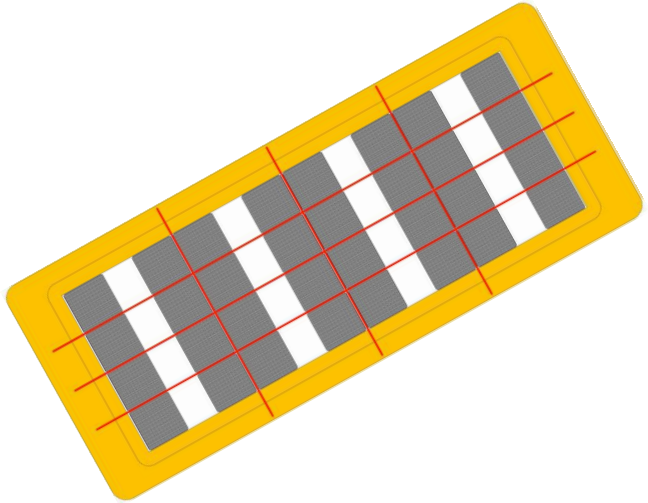


Next: QUAD as a building block

8-QUAD module with field cage





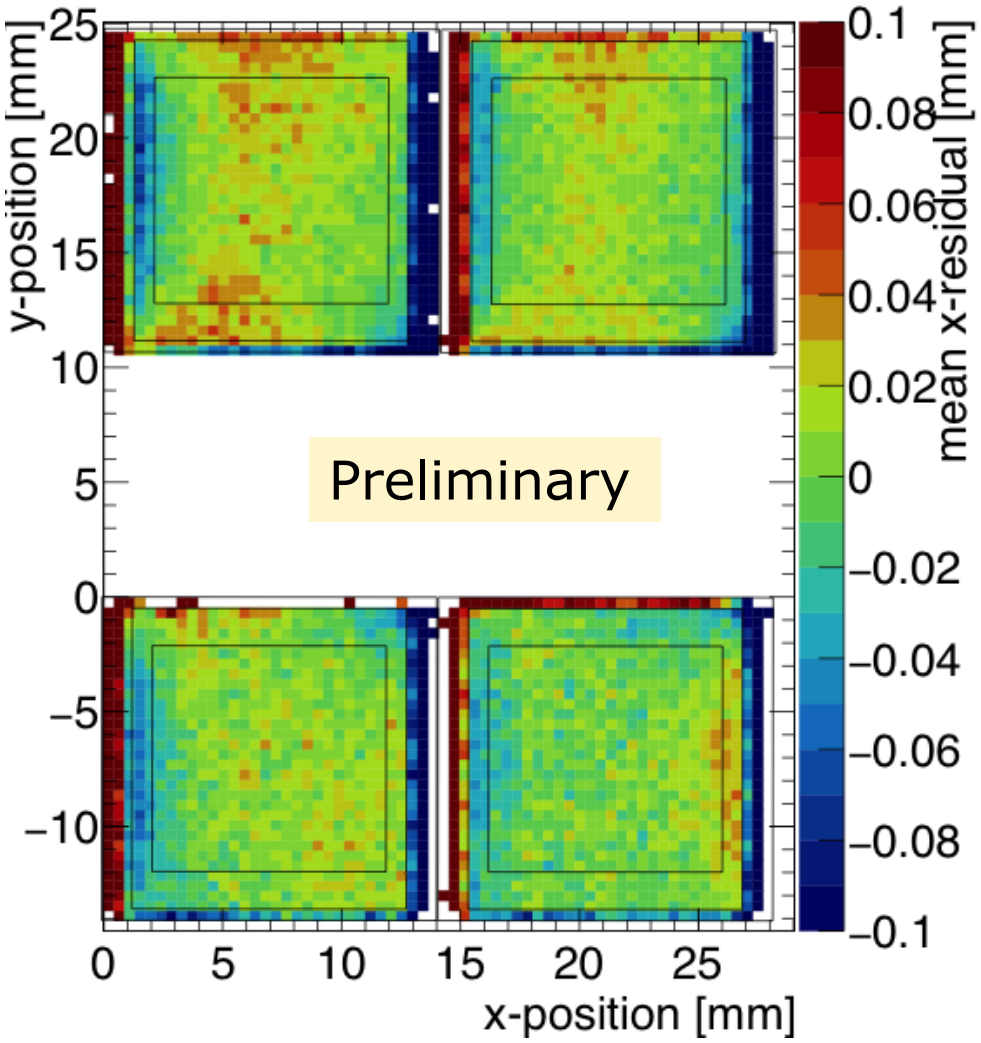


in red guard wires

8-quad module deformations

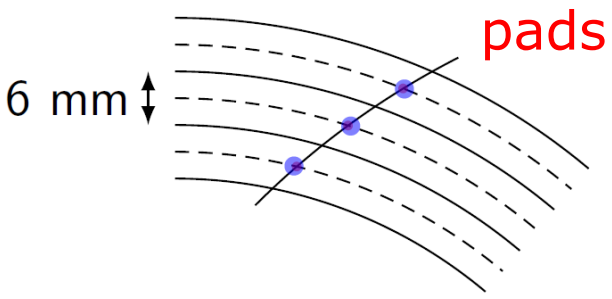
- One of the quads inside the 8-quad modules has been measured using laser tracks
- No edge corrections are applied
- The result is encouraging; the guard wires that run over the quad edges define a homogeneous field
- The RMS in the large rectangular area (near the edges) is only 14 μm

- Current plan is to do a test beam at DESY and Bonn as soon as all 8-quads can be read out simultaneously

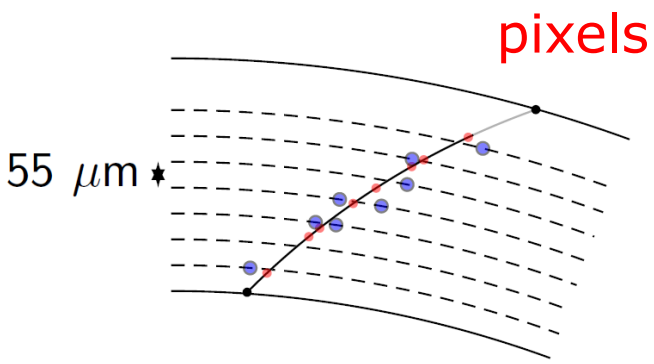


Simulation of ILD TPC with pixel readout

- To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Adapted Kalman filter track reconstruction to pixels

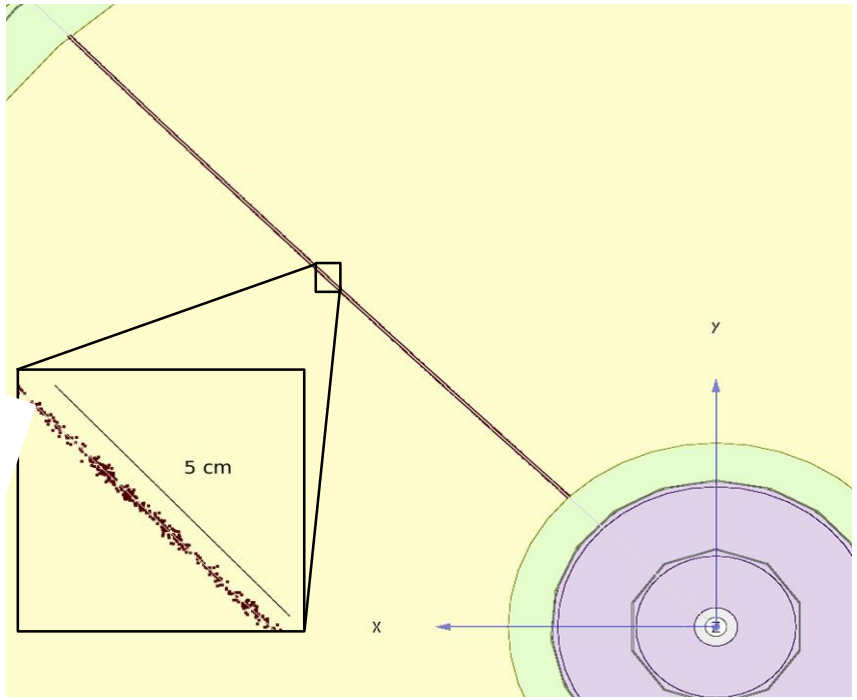


22 electrons / hit
~ 200 hits / track



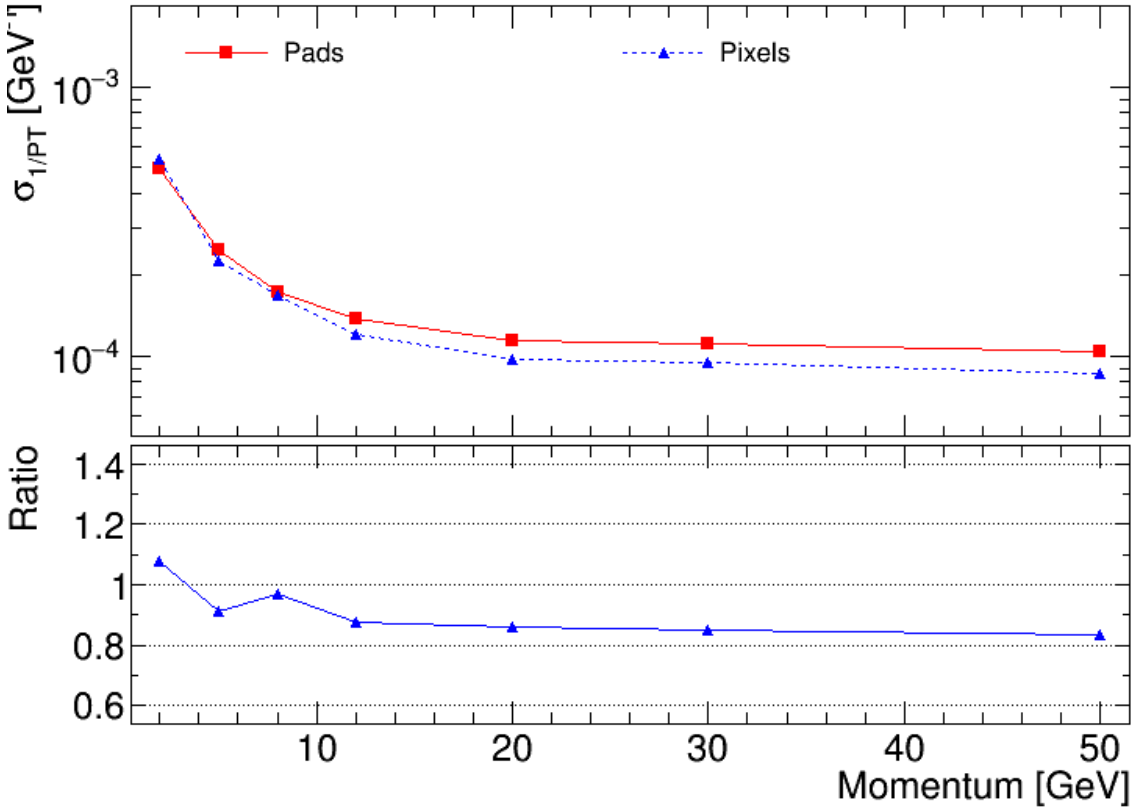
1 electron / hit
~ 10 000 hits / track

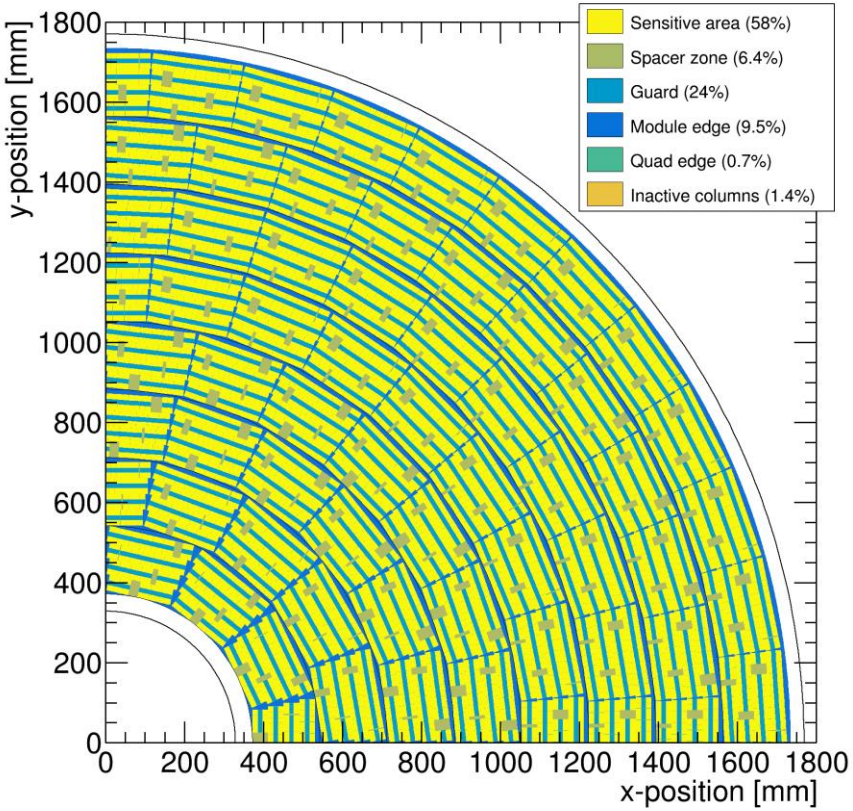
50 GeV muon track with pixel readout



Performance of a GridPix TPC at ILC

- From full simulation the momentum resolution can be determined
- Momentum resolution is about 15% better for the pixels with realistic coverage (with the quads arranged in modules 59%) and deltas.



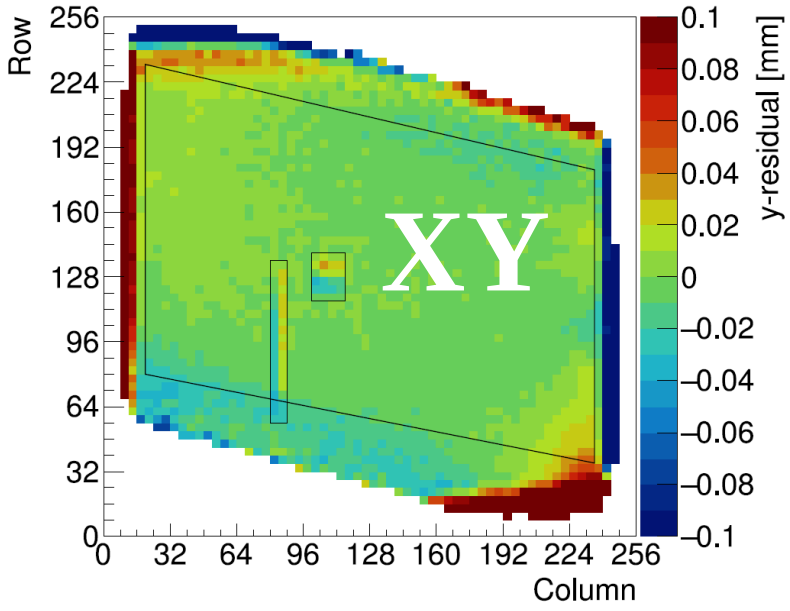


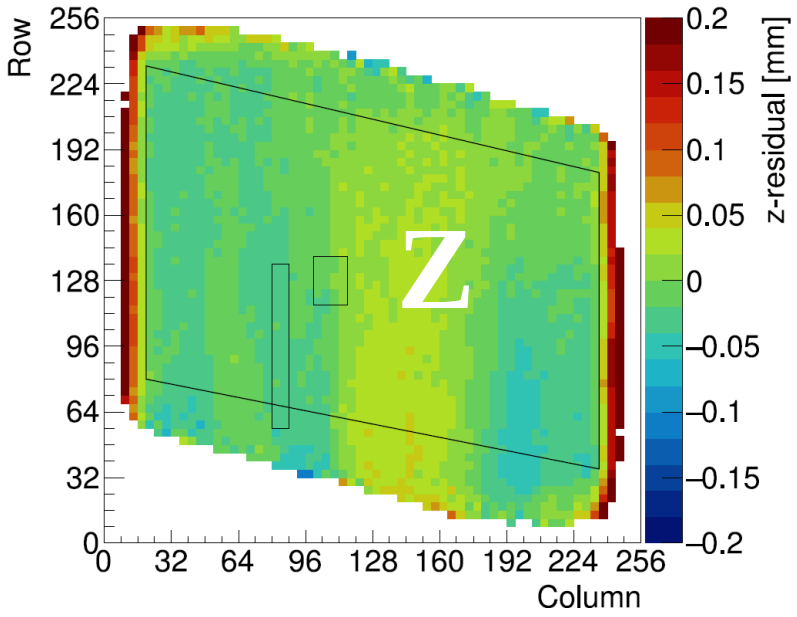
Conclusions

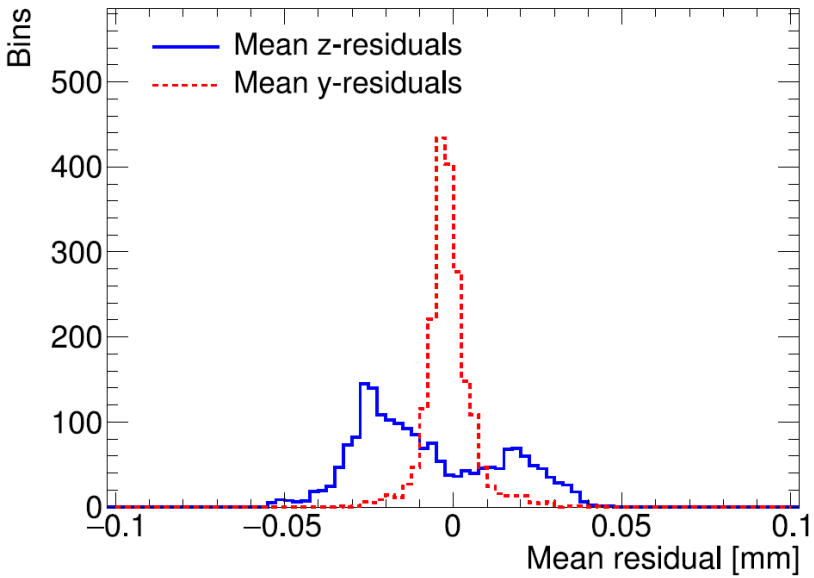
- A single chip GridPix detector was reliably operated in a test beam in 2017
  - Single electron detection => the resolution is primarily limited by diffusion
  - Systematic uncertainties are low: < 10 μm in the pixel xy plane
  - dE/dx resolution for a 1 m track is 4.1%
- A Quad detector was designed and the results from the 2018 test beam presented
  - Small edge deformations at the boundary between two chips are observed
    - added guard wires to the module to obtain a homogeneous field
  - After correcting the edges, deformations in the transverse plane shown to be < 15 μm
- An 8-Quad module has been designed with guard wires
  - Deformations in the transverse plane for one quad are shown to be < 15 μm
  - Test beams are being planned at DESY and Bonn
- A pixel pixel TPC has become a realistic viable option for experiments
  - High precision tracking in the transverse and longitudinal planes, dE/dx by electron and cluster counting, excellent two track resolution, digital readout that can deal with high rates

Single chip deformations

- The RMS of the mean residuals is 7 μm in the pixel plane and 21 μm (0.3 ns) in the drift direction in the selected region







- How can we make an even better detector?
  - Improve the quality (homogenity) of the InGrid; redesign the dike and edges
  - Go to a large areas keeping the field distortions (at edges) minimal -> QUAD

QUAD deformations in drift plane (Z)

- After applying fitted edge corrections
- RMS of the mean residuals are 19 µm over the whole QUAD