

Performance of a GridPix TPC readout based on the Timepix3 chip

Cornelis Ligtenberg, Y. Bilevych, K. Desch, H. van der Graaf, M. Gruber, F. Hartjes, K. Heijhoff, J. Kaminski, N. van der Kolk, P.M. Kluit, G. Raven, L. Scharenberg, T. Schiffer, S. Schmidt, J. Timmermans



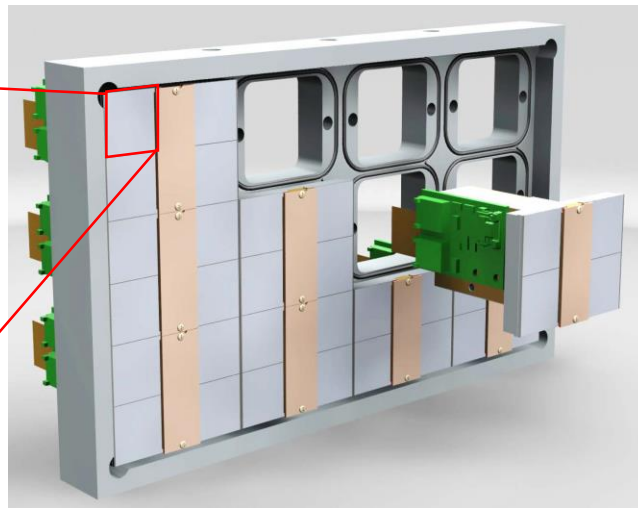
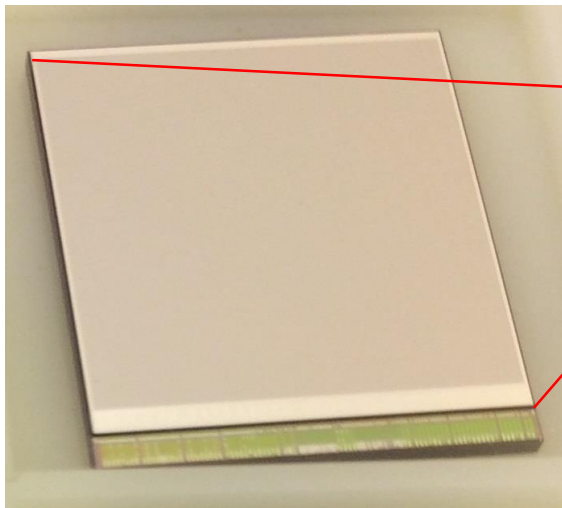
24 October 2018, International Workshop on Future Linear Colliders, LCWS2018

Introduction and outline

The goal is to develop a pixel-based readout for the ILD TPC at ILC

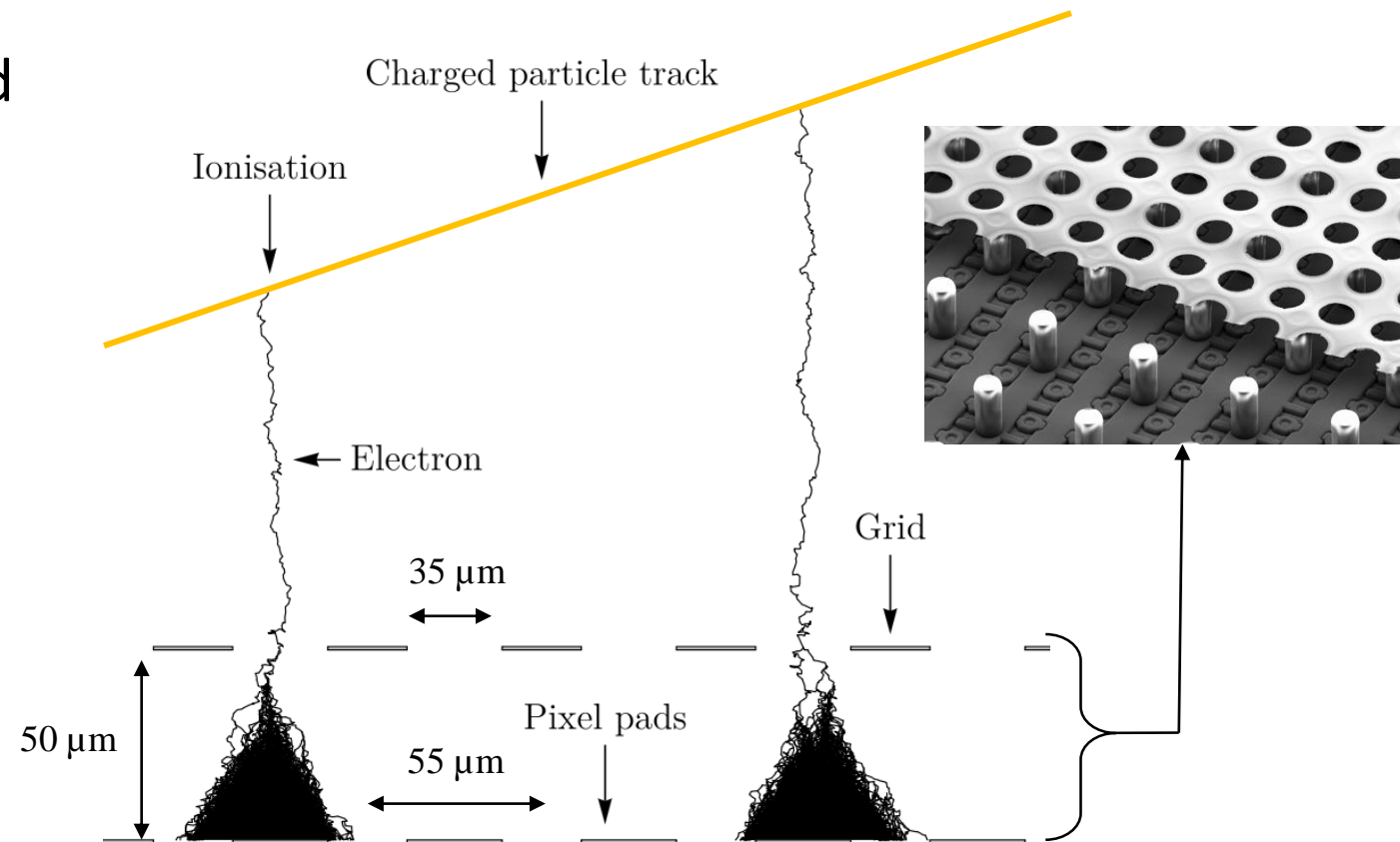
Outline:

1. Test beam results from a single chip detector
2. Development of quad module to cover large areas
3. Expected performance of the ILD TPC from simulations



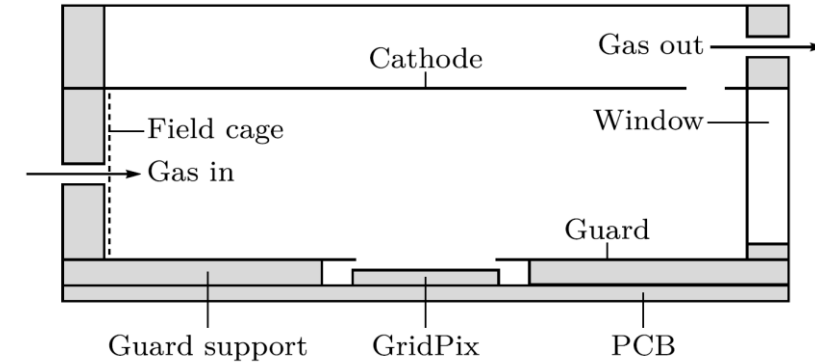
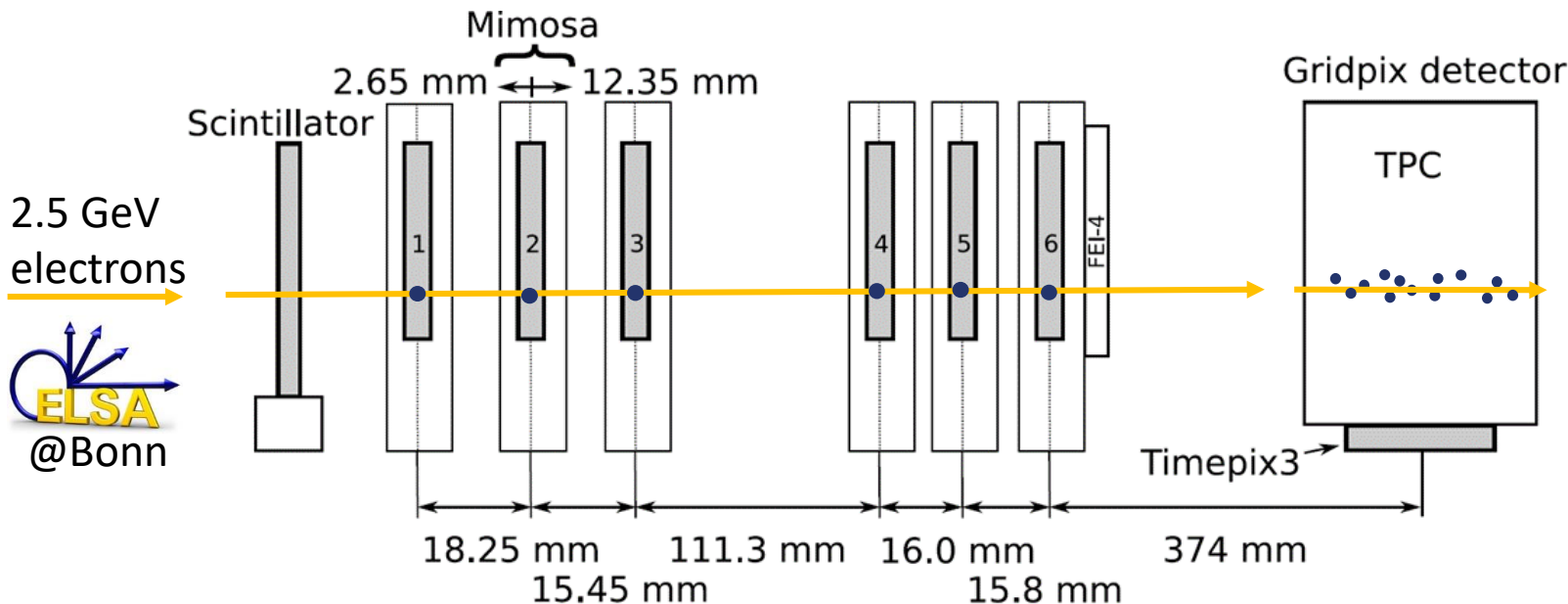
GridPix technology

- GridPix is a type of micro-pattern gaseous detector
- The GridPix consists of a Timepix3 with an aligned Aluminium amplification grid added by photolithographic postprocessing techniques
- Single ionization electrons are detected with high efficiency:
 - The maximum possible information from a track is acquired
- The chip has been made spark proof using a 4 μm thick Silicon rich Nitride protection layer

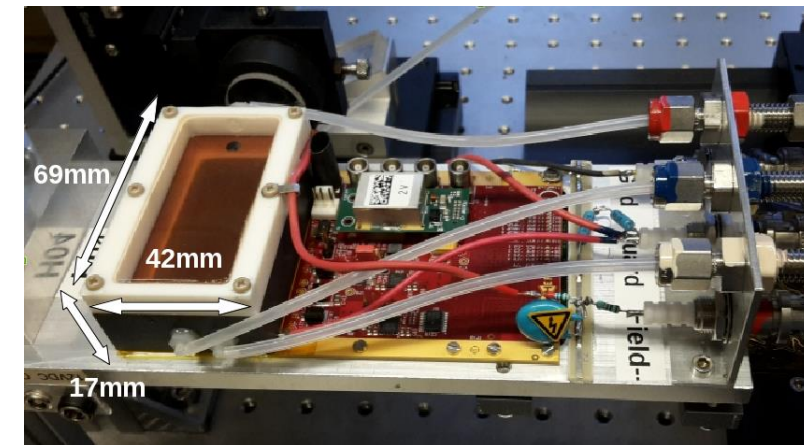


Detector setup at Bonn test beam (2017)

- A Timepix3 based Gridpix with SPIDR readout
 - Simultaneous data-driven detection of time and time over threshold (charge) allows for timewalk corrections
 - Higher rates and more precise (1.56 ns time resolution) compared to its predecessor Timepix1



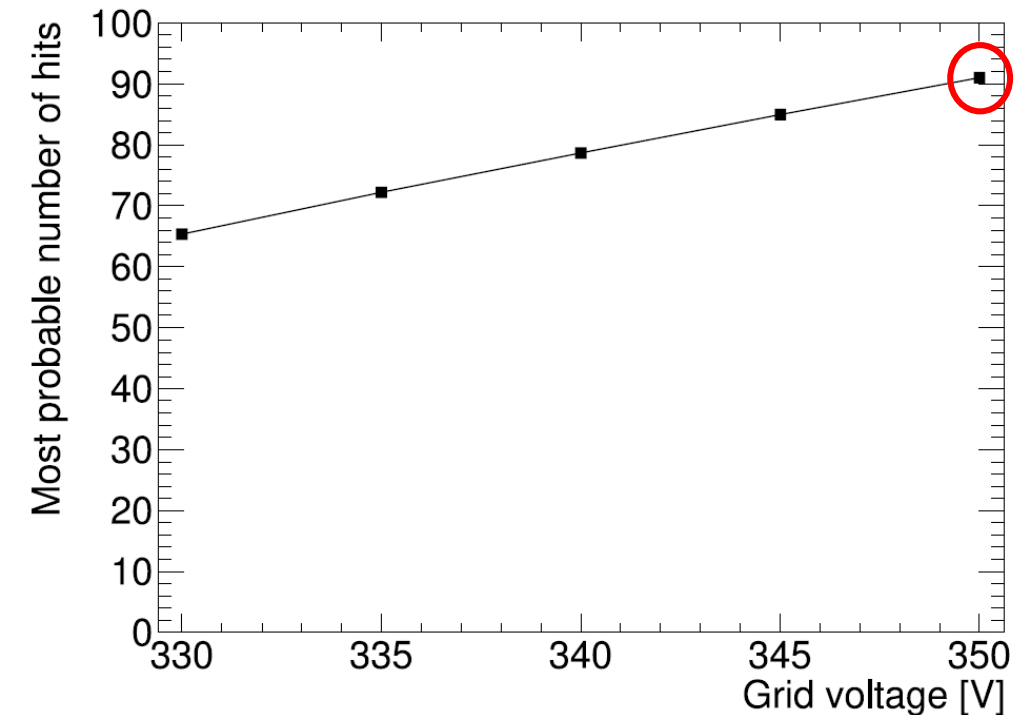
Detector with guard and field shaper



See also paper on this testbeam: <https://doi.org/10.1016/j.nima.2018.08.012>

Run parameters and selection

- Use run with the highest single electron efficiency (close to 1)
- Use basic selection cuts to find clean tracks (69% efficiency)
- Drift velocity for T2K gas from Magboltz was $78.9 \mu\text{m}/\text{ns}$ (consistent with data)



Run 347	
Duration	60 min.
Triggers	4 733 381
V_{grid}	350 V
E_{drift}	280 V/cm
Rotation	17 degr. 0 degr.
Threshold	800 e

Telescope

At least 4 planes hit
Reject outliers ($>700 \mu\text{m}$)
Telescope track goes through TPC

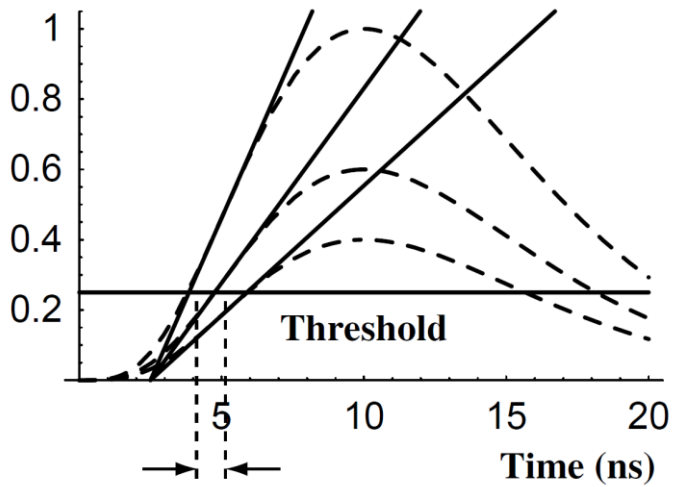
GridPix detector

Hit ToT $> 0.15 \mu\text{s}$
At least 30 hits
Reject outliers ($> 3\sigma_{\text{drift}}, > 2\sigma_{\text{plane}}$)
At least 75% of total number of GridPix hits in fit
Track projection crosses first and last pixel column

Matching of telescope and GridPix detector

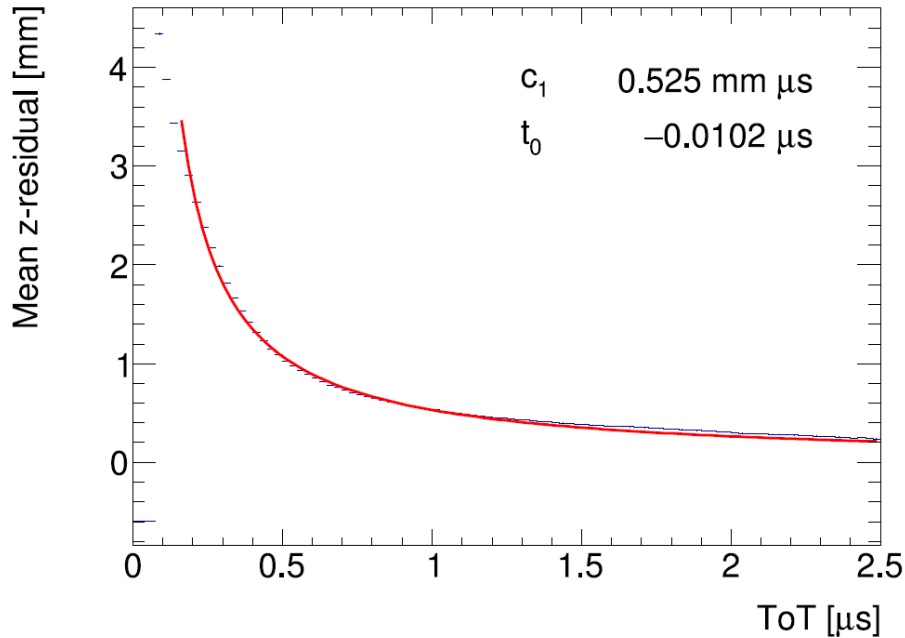
Tracks closer than 1 mm at center of TPC
A unique track pair match

Time walk correction



Blum, Particle detection 2008

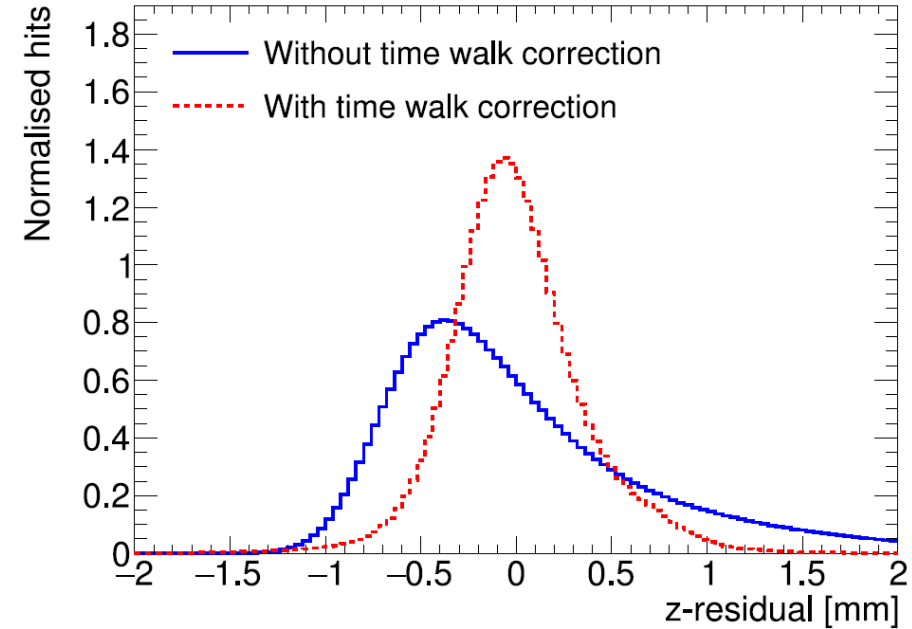
Time walk error: time of arrival depends on signal amplitude



Time walk can be corrected using Time over Threshold (ToT) as a measure for signal strength

First order correction fitted and applied:

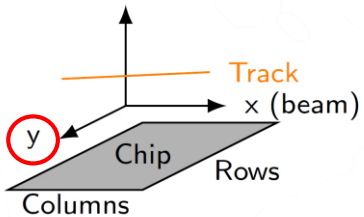
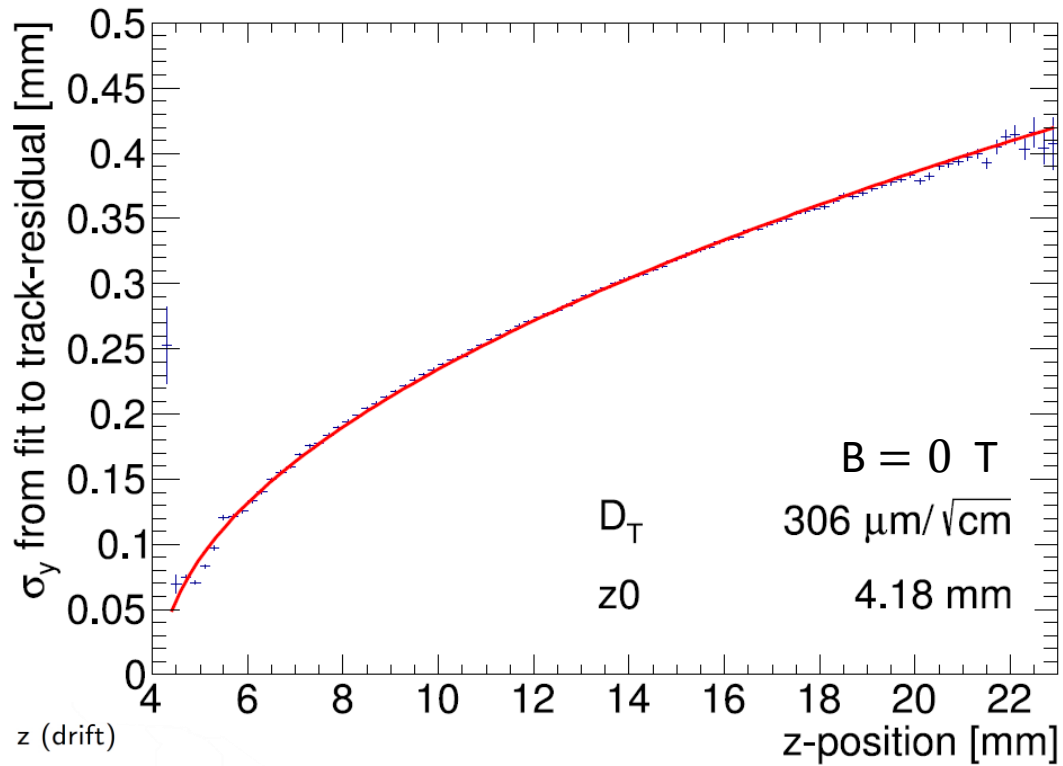
$$\delta z_{\text{timewalk}} = \frac{c_1}{t_{\text{ToT}} + t_0} + z_0$$



Residual distribution improved

Higher order corrections were also tried but did not yield further improvements

Single hit resolution in pixel plane



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

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

Single hit resolution in pixel plane:

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

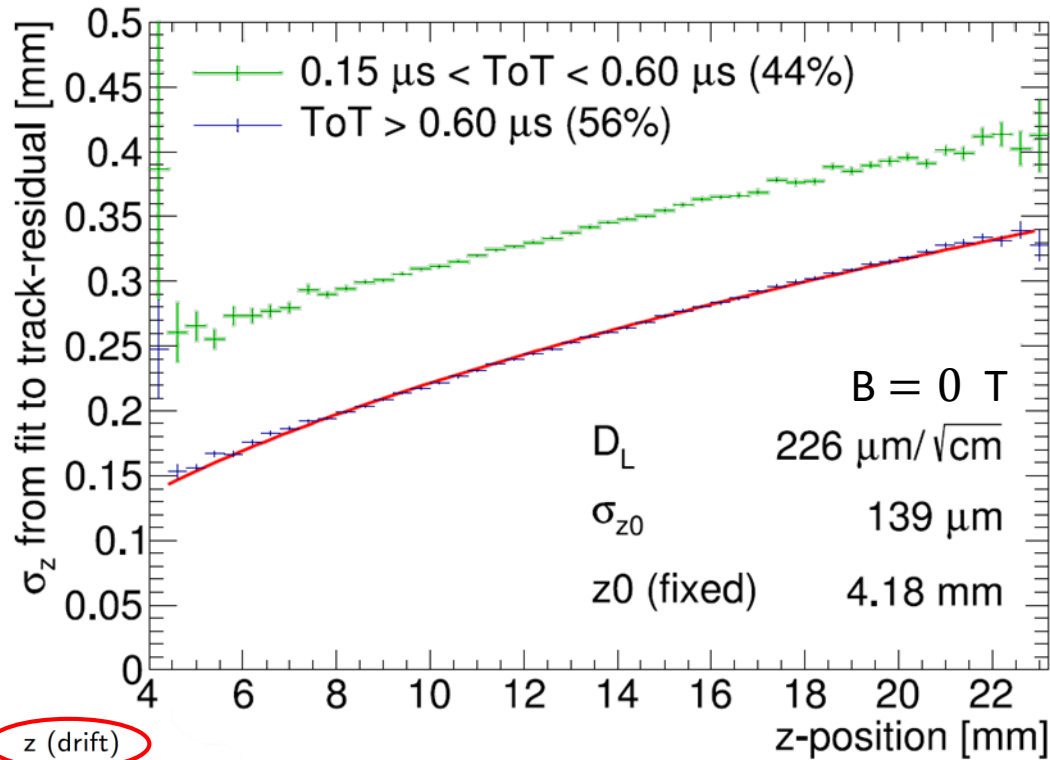
Depends on:

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

Note that:

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

Single hit resolution in drift direction



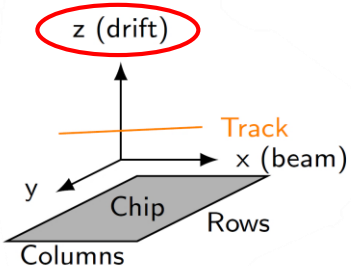
Single hit resolution in drift direction

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

Depends on

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

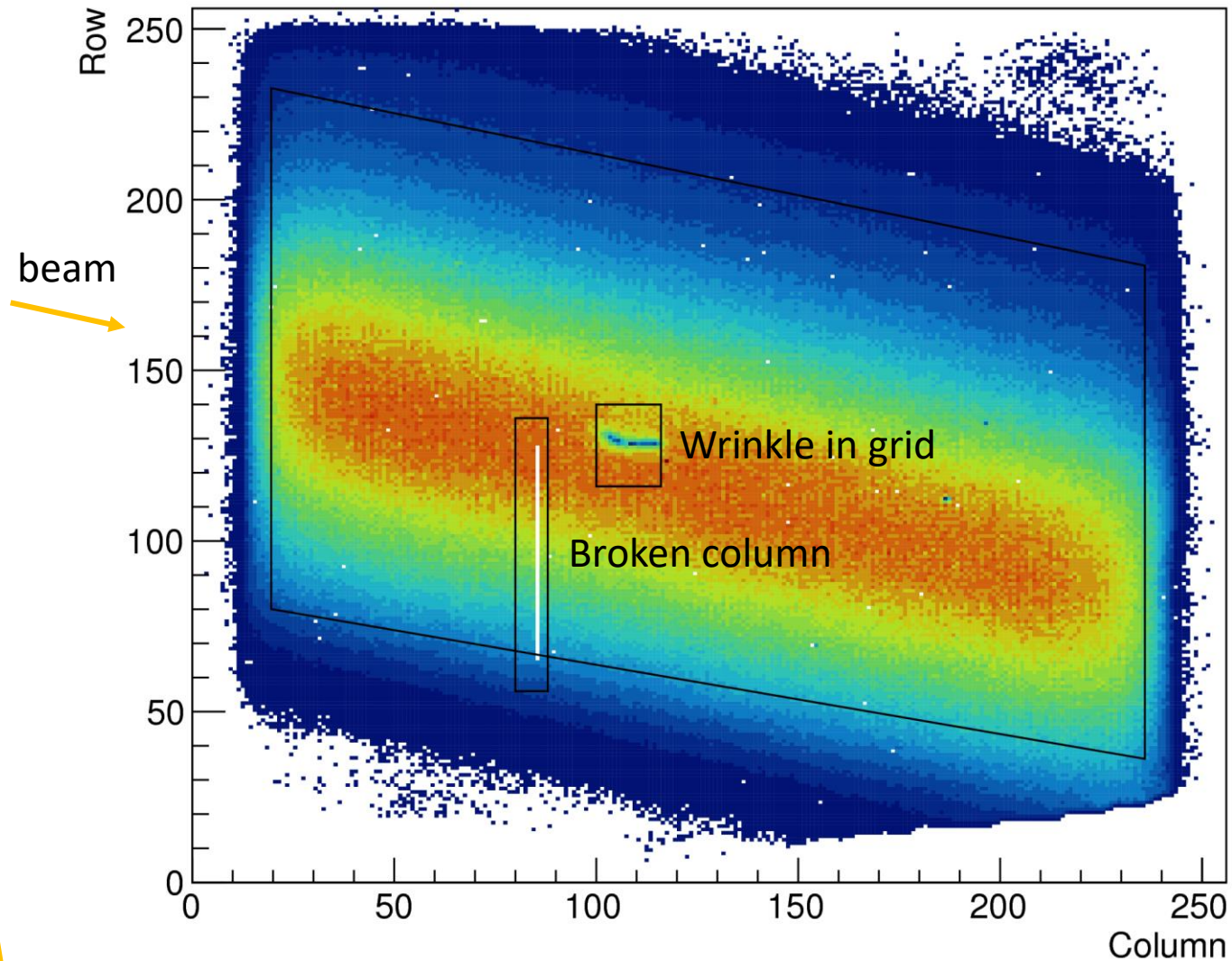
Because of a large time walk error in hits with a low signal strength, an additional ToT cut ($>0.60 \mu\text{s}$) was imposed



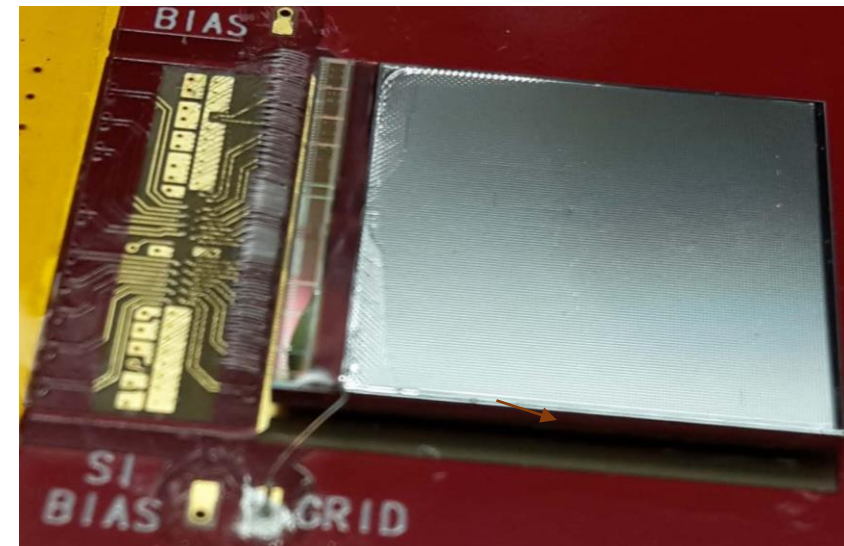
$$D_L = 226 \mu\text{m}/\sqrt{\text{cm}}$$

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

Map of Timepix3 hits



- Successfully measured a large number of hits
- The chip and grid have some small defects

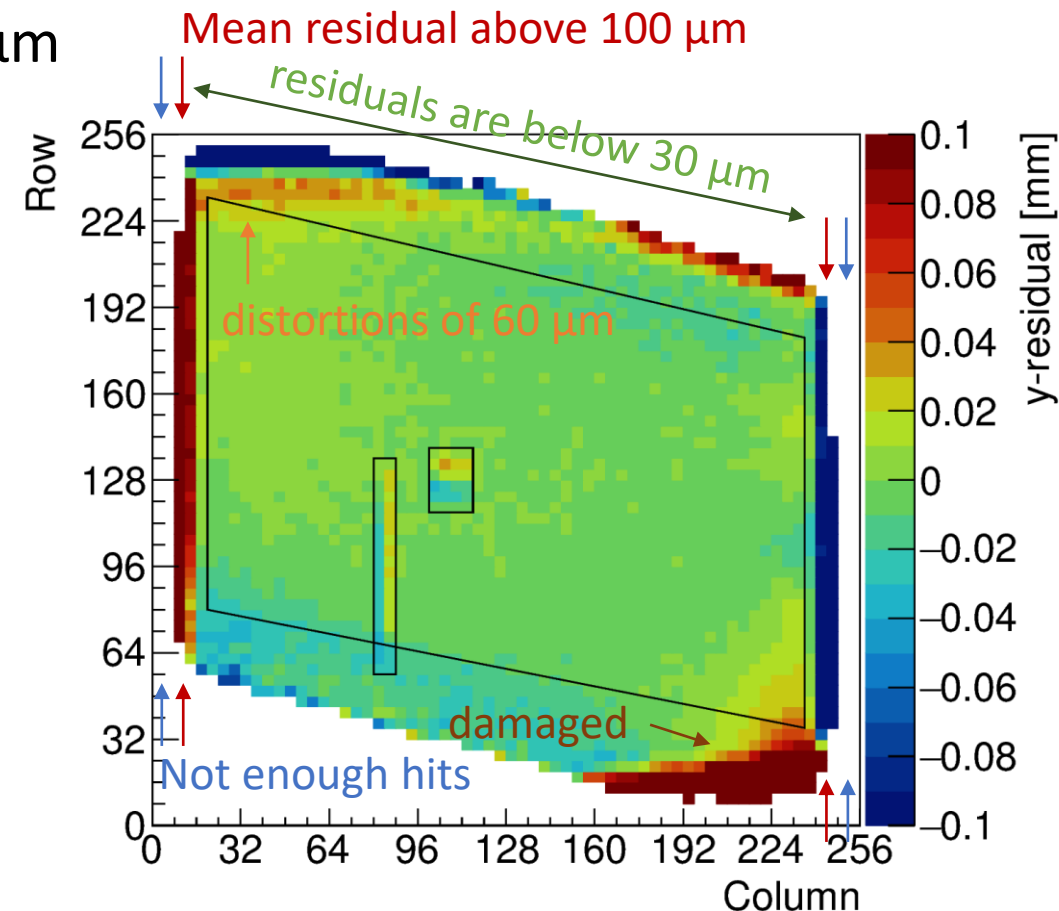


Mean residuals from test beam

- For applications in a large TPC, systematic deviations must be well under control
- Each bin displays mean of residuals from 4×4 pixels
- 1 mm from the edges distortions are below $30 \mu\text{m}$

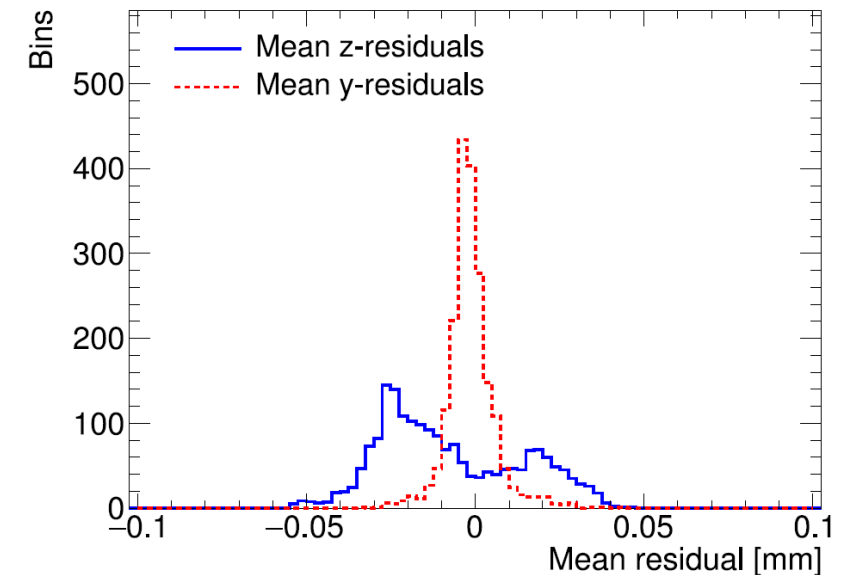
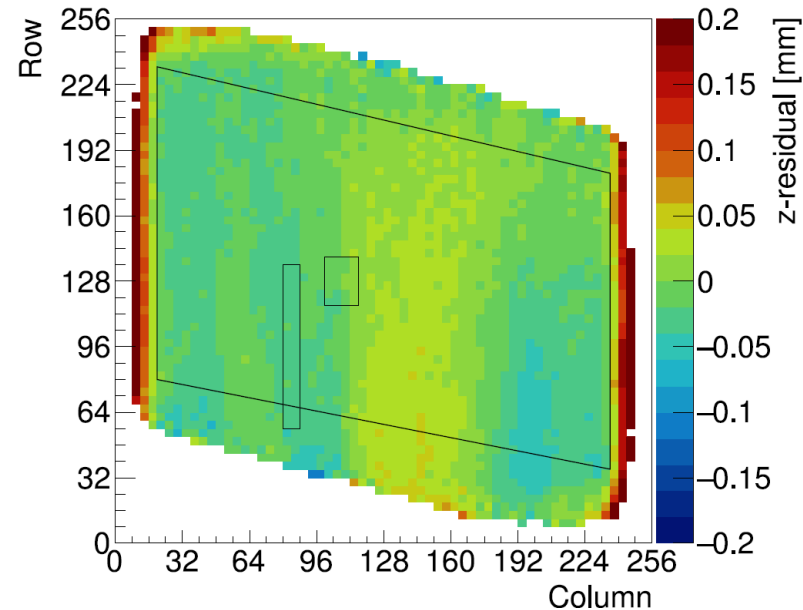
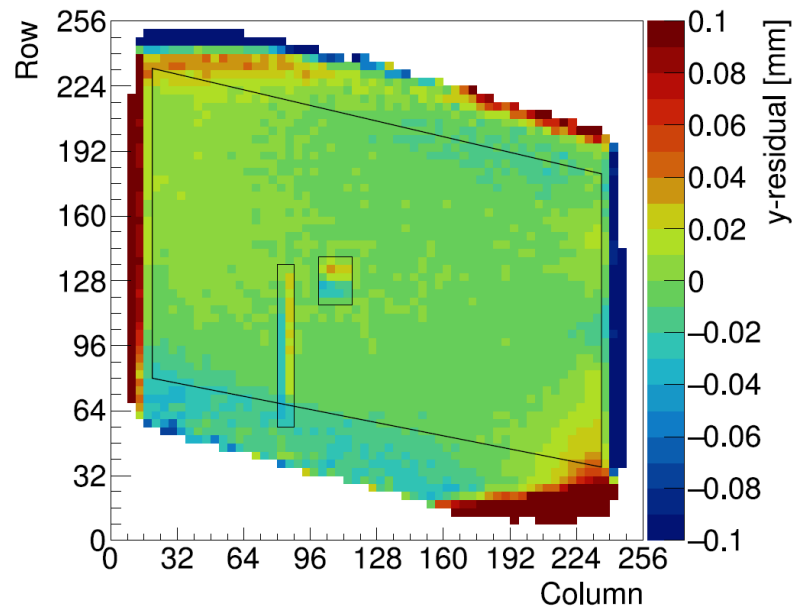


Too small number of hits in first and last 8 columns (at edge)
Mean residual above $100 \mu\text{m}$ for columns 8-16, 240-248
From column 16-240, residuals are below $30 \mu\text{m}$
Bottom right is damaged
Top left has distortions of $60 \mu\text{m}$



Deformations in pixel plane and drift direction

- Each bin displays mean of residuals from 4×4 pixels at expected position
- The RMS of the mean residuals is 7 μm in the pixel plane, and 21 μm (0.3 ns) in the drift direction \Rightarrow Overall grid quality is very good



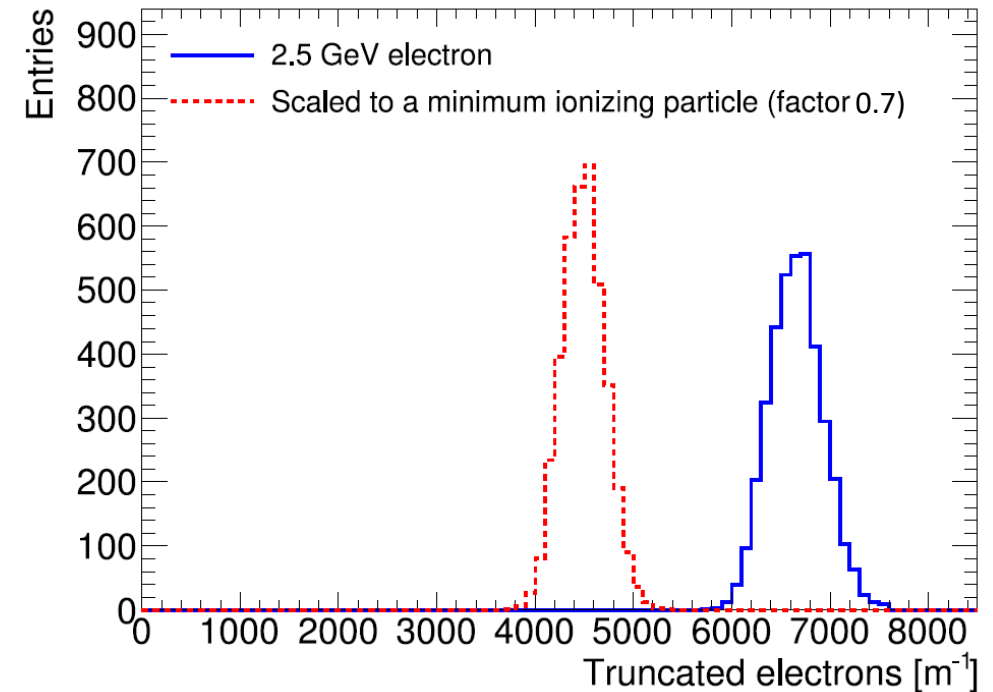
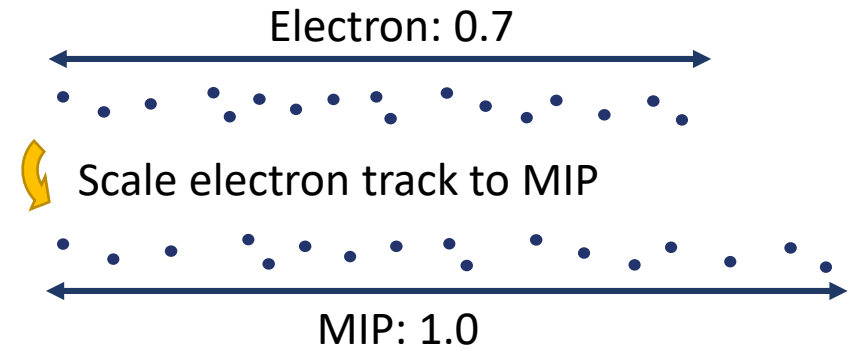
Particle identification by dE/dx

Find the energy loss (dE/dx) by truncated sum:

- Merge 83 single chip events together to make one track of 1 meter
- Count the number of hits per intervals of 20 pixels
- Reject the top 10% of intervals with the most hits and sum the other 90% into a truncated sum

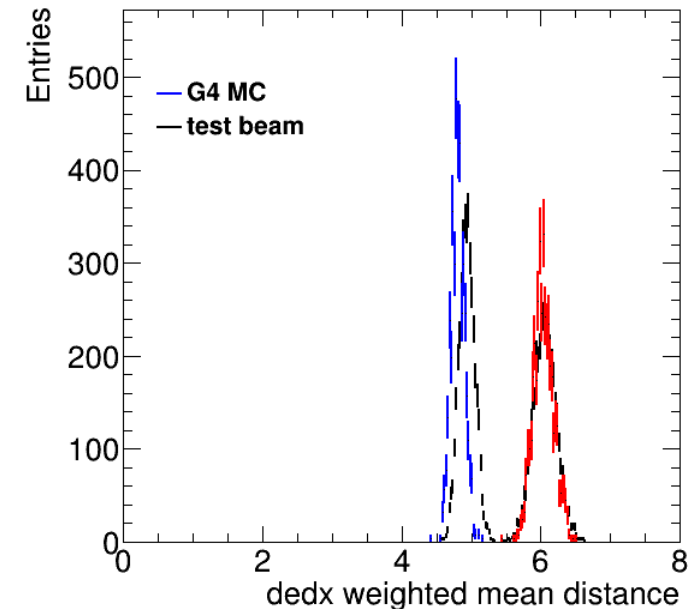
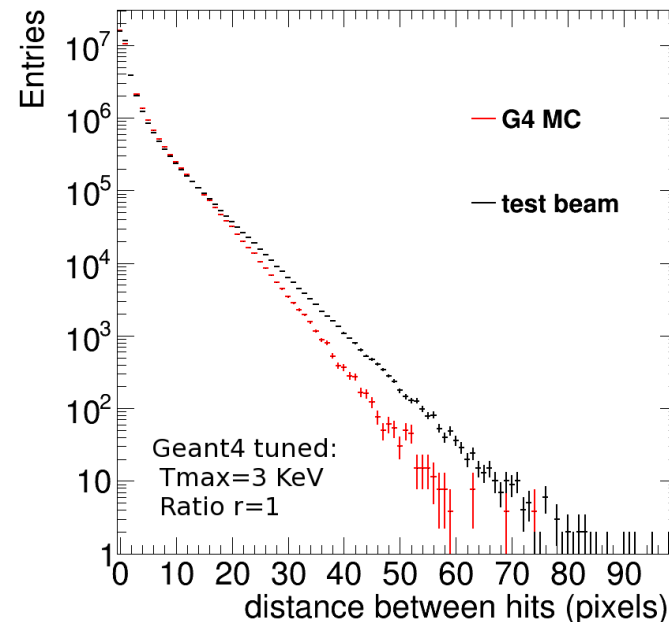
There is a 6.2σ separation between a 2.5 GeV electron and minimum ionizing particle

The resolution (RMS/mean) is 4.1% for an effective track length of 1 m (\approx ILD TPC effective track length)



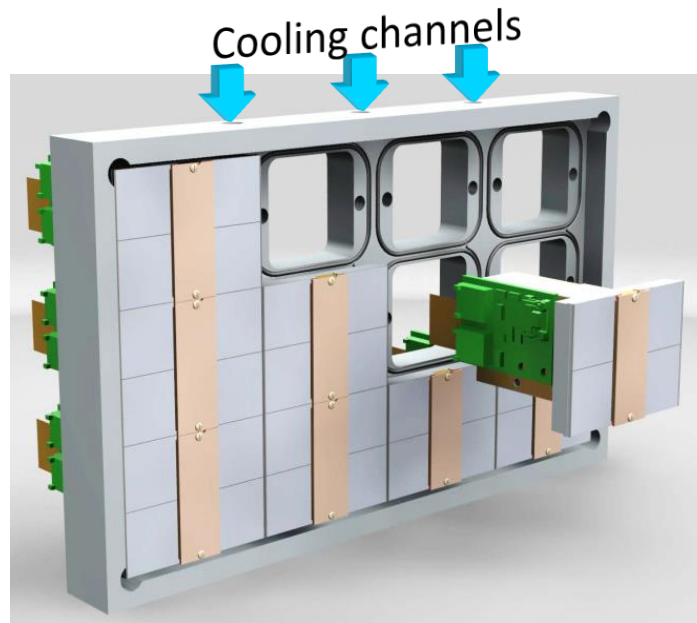
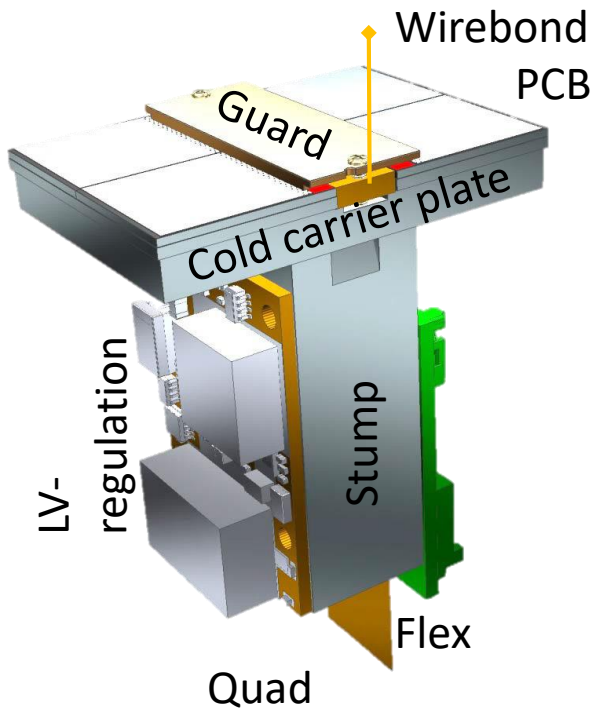
Energy loss resolution by cluster counting

- With the pixel granularity ionization clusters can be partially resolved
- This gives the possibility to improve the dE/dx resolution by cluster counting
- Various algorithms were tried
- Weighted mean distance between hits is a good measure of dE/dx
- Use (actual/Poisson)-fluctuation as weights
- 2.7% resolution or 9.2σ separation between MIP and 2.5 GeV electron

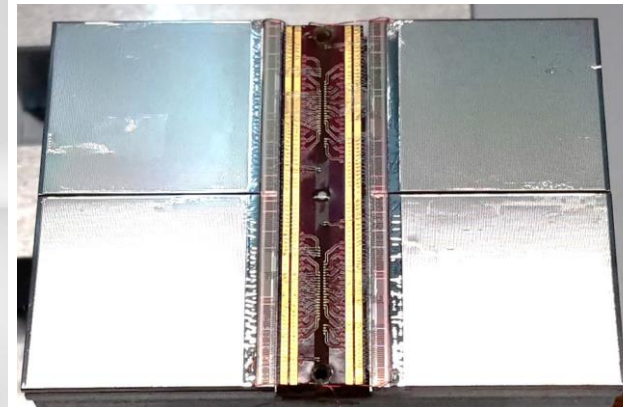


Quad module development

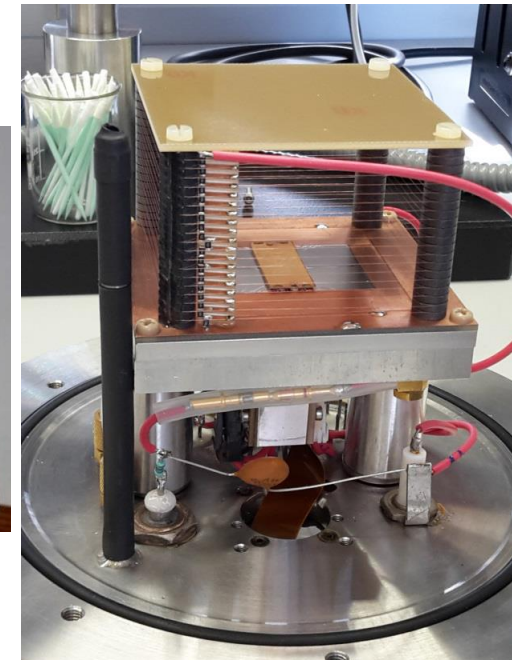
- Developed a 4-chip module with all services under the active area
- Active area overage is 70% (Through-silicon via technology might increase this)
- Can be used as a building block to cover arbitrarily large TPC areas



Quad base plate



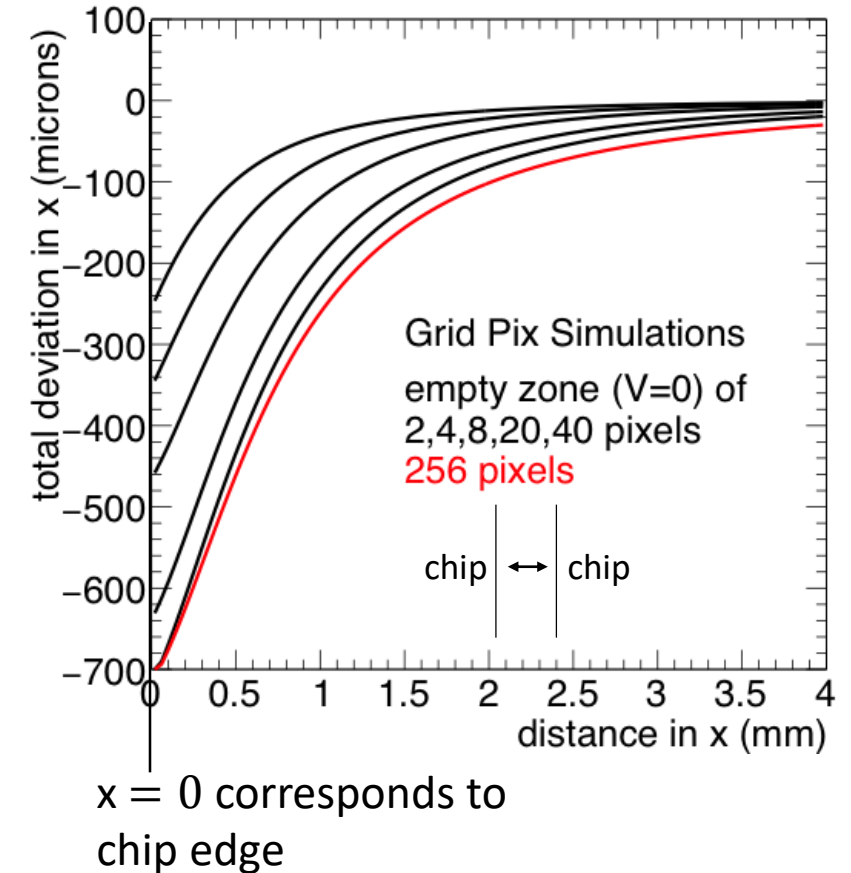
Quad without guard



Test Box

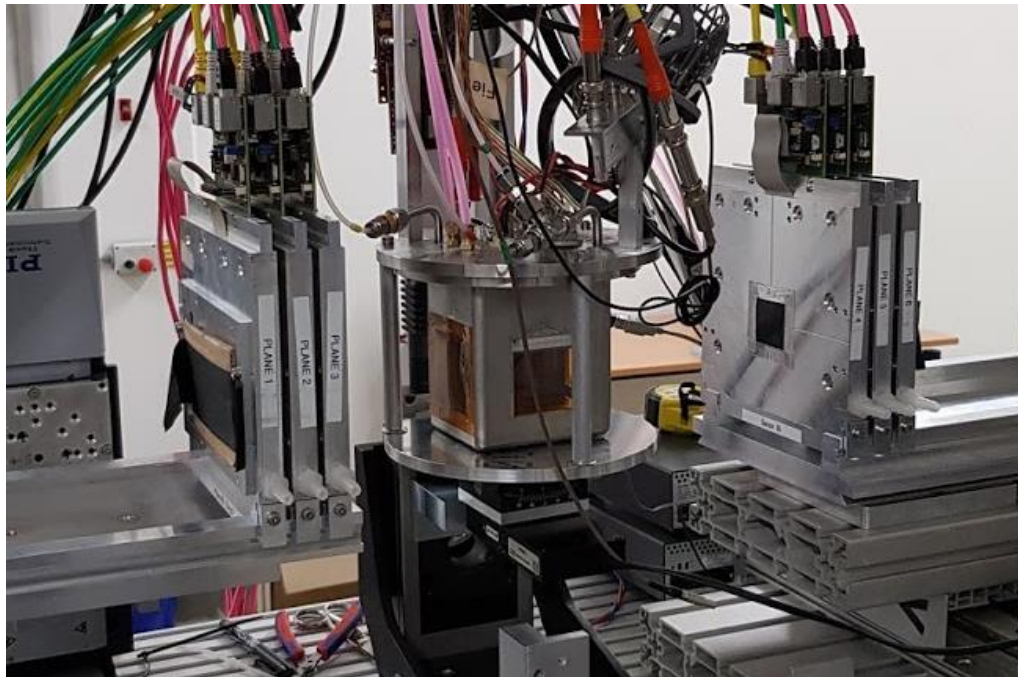
Chip placement requirements in Quad design

- To design a precise module with multiple chips, the electric field behavior at edges is studied with simulations
- Hit deviations are calculated for different distances between chip edges
- For the top curve with 2 pixels (110 μm) distance, deviations $< 20 \mu\text{m}$ are found $> 1 \text{ mm}$ from the edge
- Larger distances must be bridged with a guard structure
- The Quad module is designed for these stringent requirements on chip placement:
 - chip-chip distance $< 100 \mu\text{m}$
 - guard height precise at $20 \mu\text{m}$ level

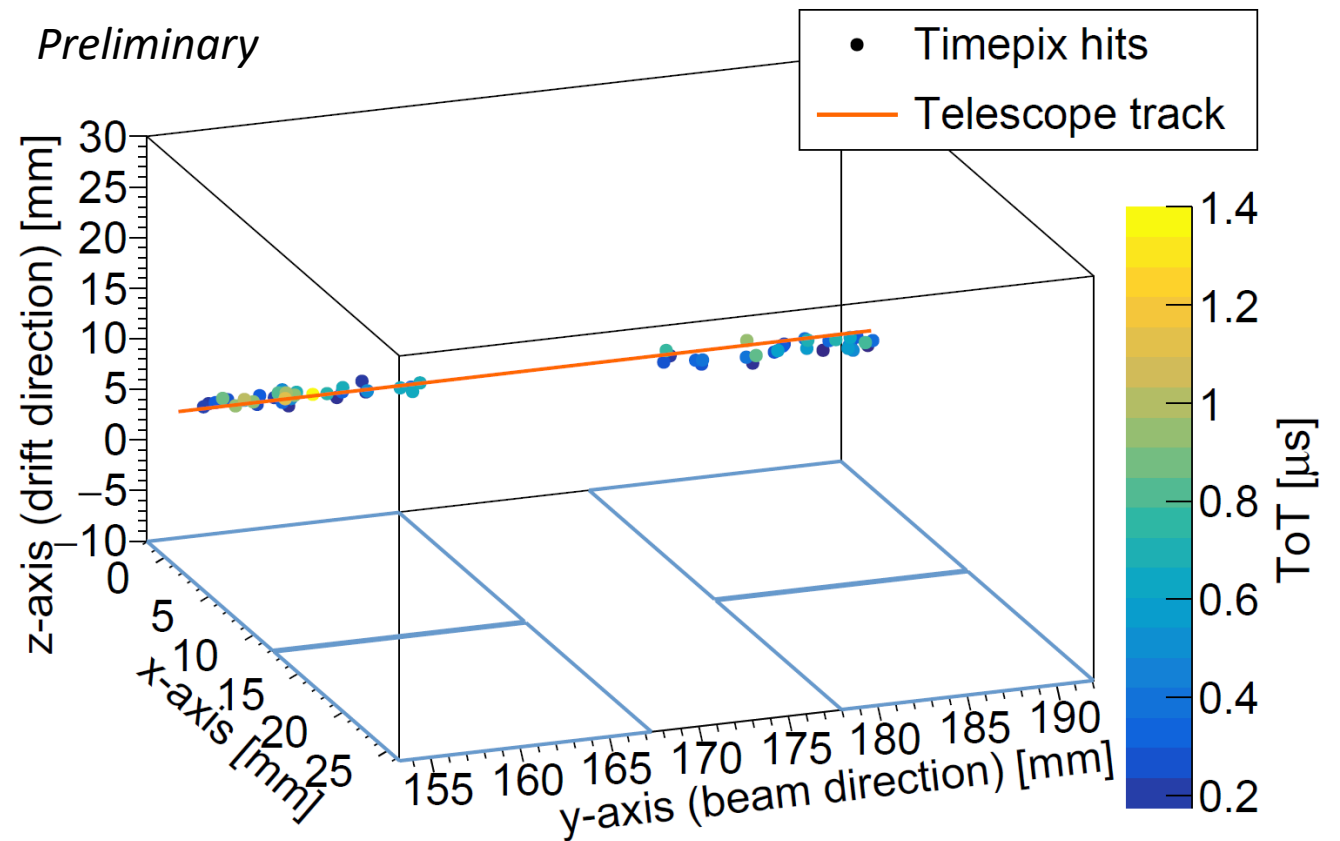


Quad tested with electron beam at Bonn (2018)

- Also tested in another testbeam with 2.5 GeV electrons at the ELSA Facility in Bonn on 4-5 October 2018
- Analysis just started...

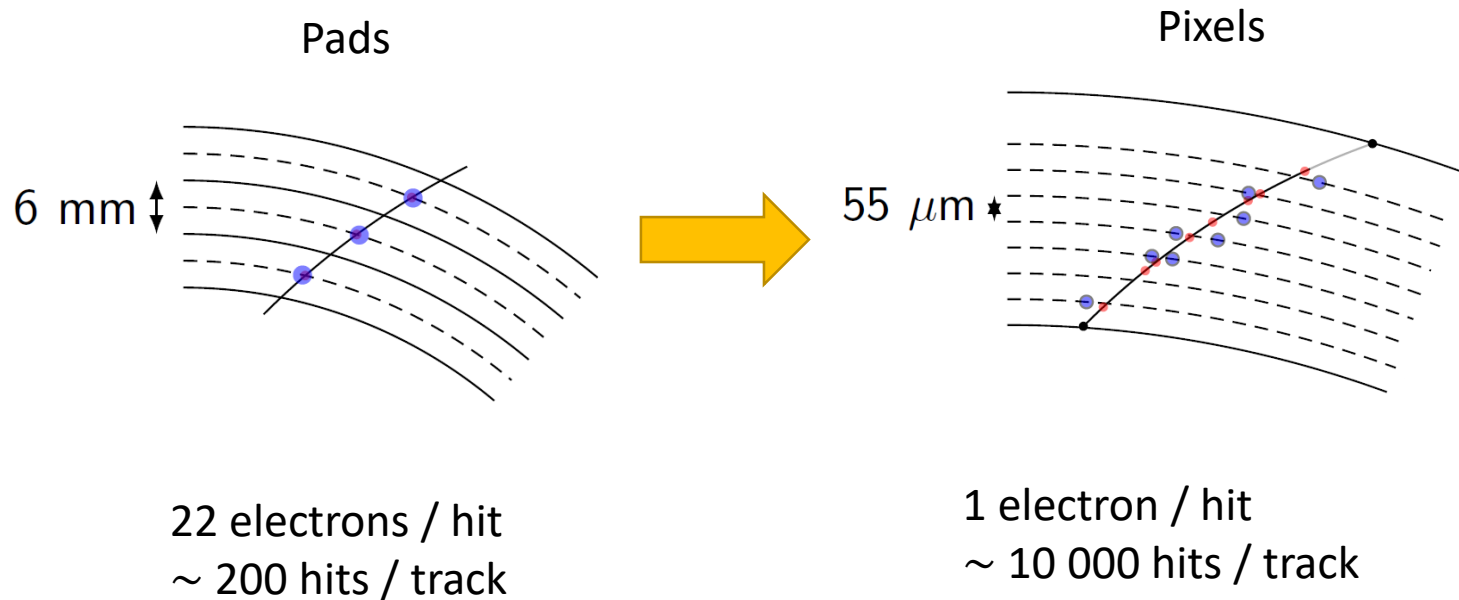


Improved Quad setup in test beam at Bonn

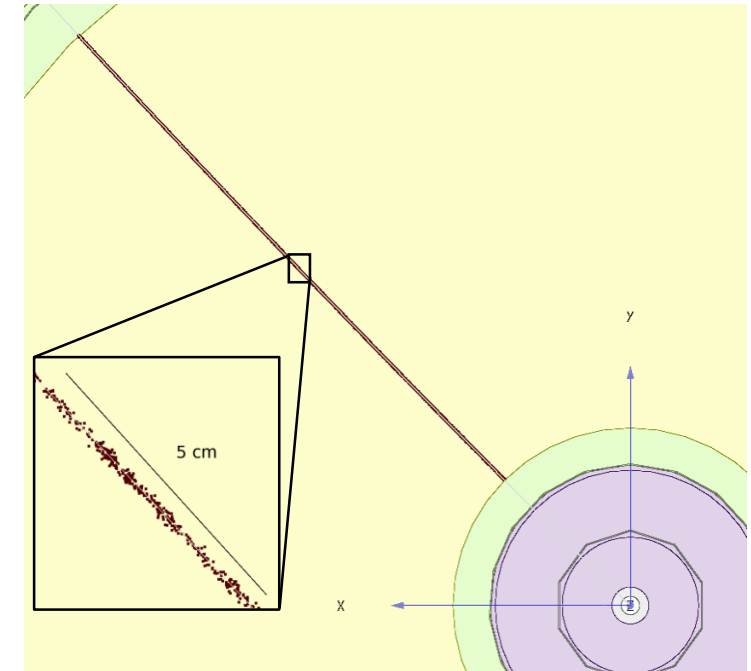


Simulation of ILD TPC with pixel readout

- To study the performance of a large pixelised 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



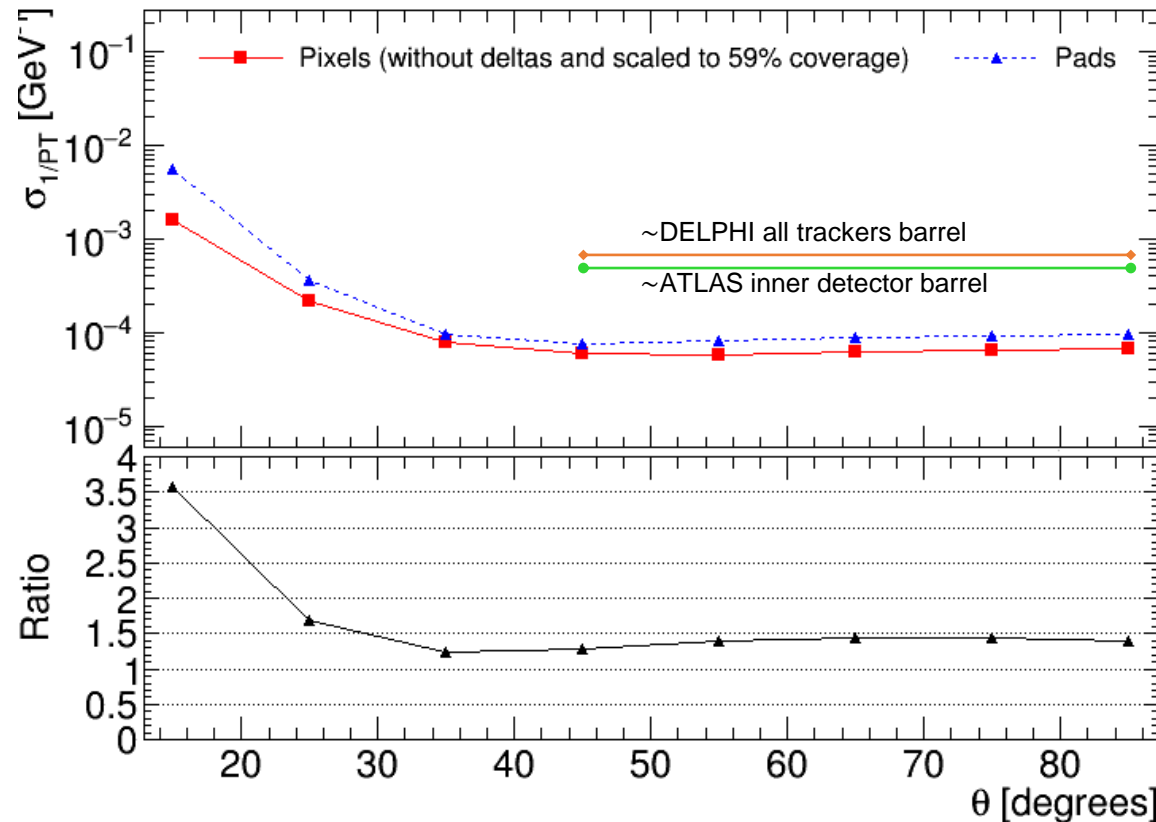
50 GeV muon track with pixel readout



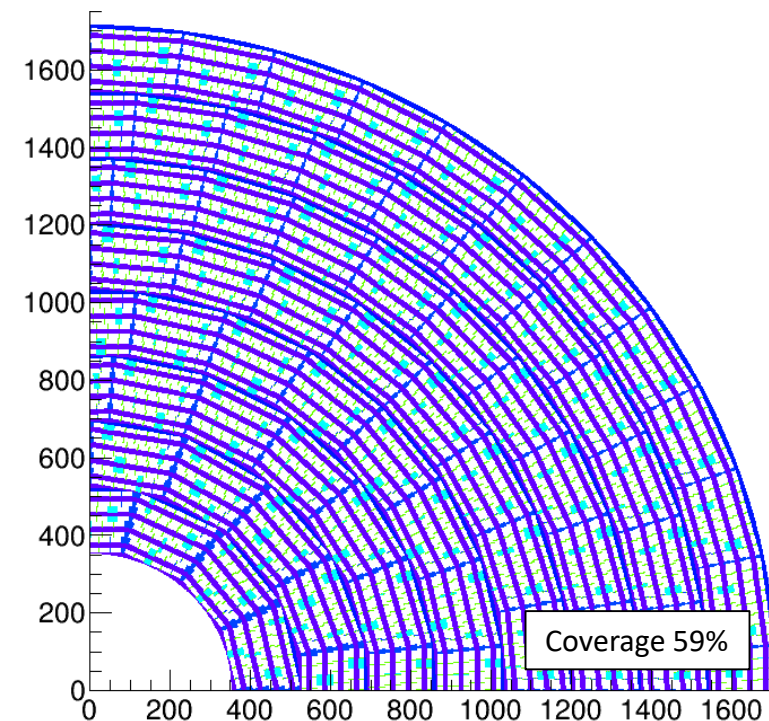
Performance of a GridPix TPC at ILC

- From full simulation, momentum resolution can be determined
- Momentum resolution is $\gtrsim 20\%$ better (scaled from 100% coverage)

Momentum resolution of the TPC for a 50 GeV muon



Realistic tiling with quad module



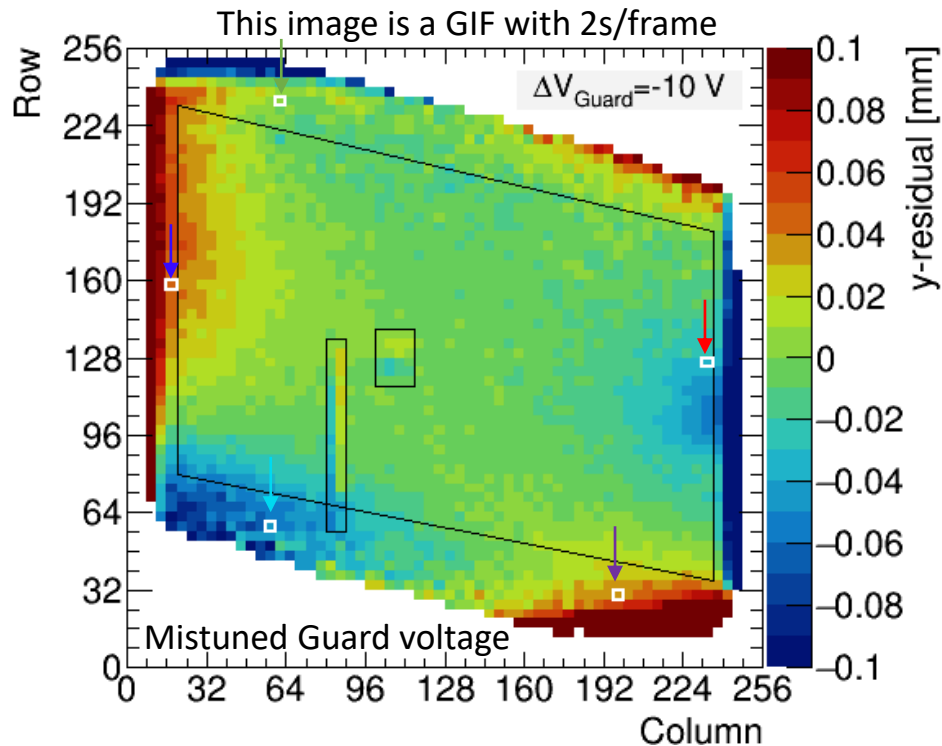
Conclusions

- A GridPix based on the Timepix3 chip was reliably operated in a test beam setup
 - The resolution is primarily limited by diffusion
 - Systematic uncertainties are low: $< 10 \mu\text{m}$ in the pixel plane
 - Energy loss resolution (dE/dx) by truncated sum is 4.1 % per meter
-
- A Quad module is built and data from a test beam is now under investigation
 - Simulations show an improvement in momentum resolution of a pixel TPC readout over a pad readout

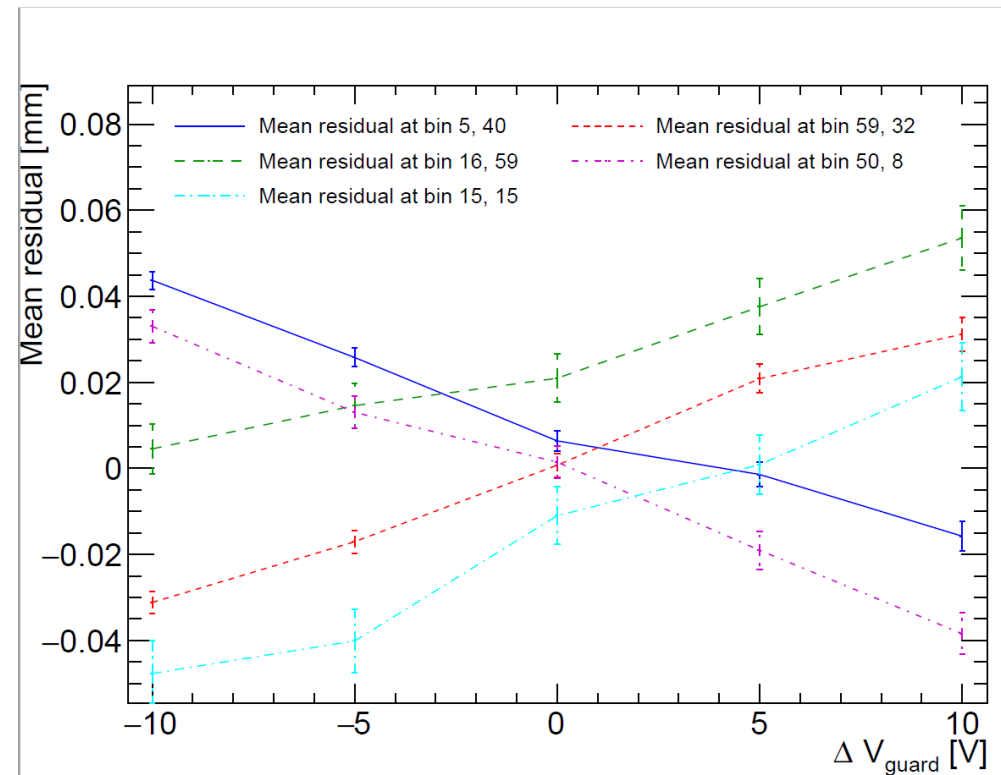
Backup

Distortions at the edges due to variation of guard voltage

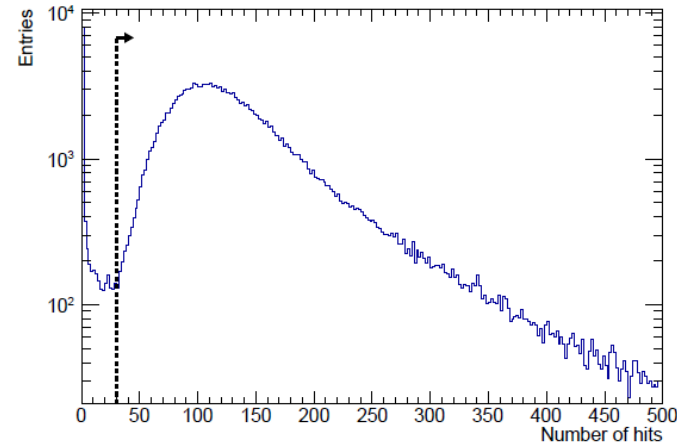
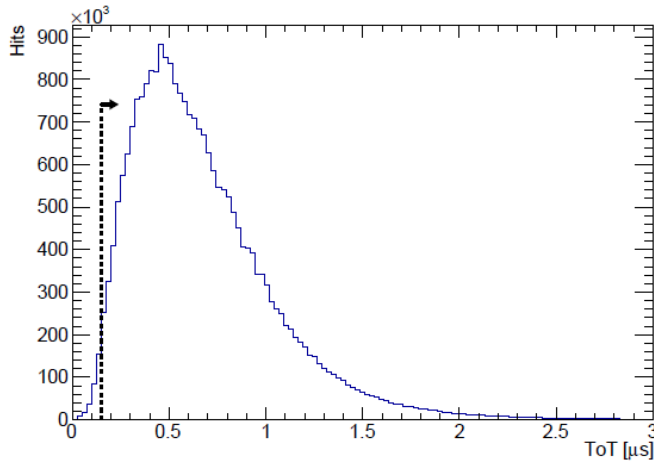
In the deformation plot, the attraction of hits to the guard is visible near the edges



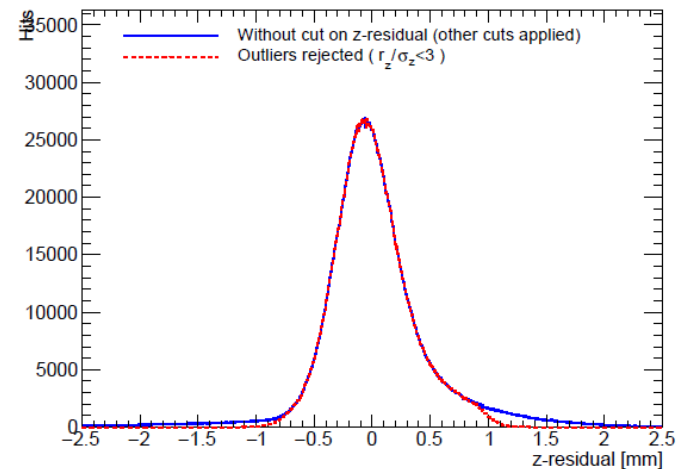
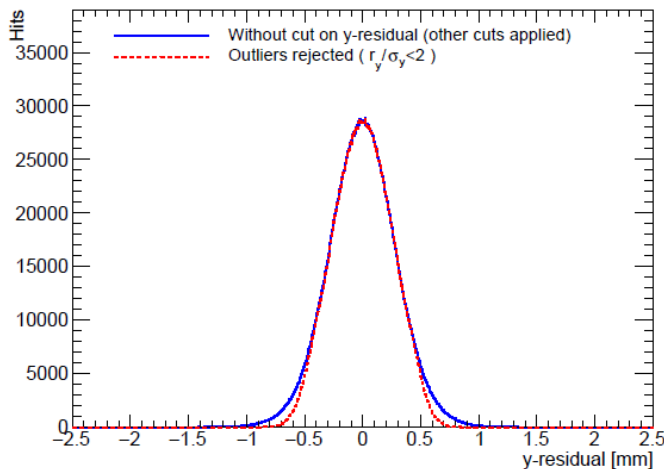
The Projection of selected bins 1-3.5 mm from the edge, shows that deformations are below $\pm 50 \mu\text{m}$ for $\pm 10 \text{ V}$



Outlier rejection



Require Time over Threshold $ToT > 0.15 \mu s$ and more than 30 hits



Require residual $r_y < 2\sigma_y$ and residual $r_z < 3\sigma_z$

Telescope

At least 4 planes hit

Reject outliers ($> 700 \mu m$)

Telescope track goes through TPC

GridPix detector

Hit $ToT > 0.15 \mu s$

At least 30 hits

Reject outliers ($> 3\sigma_{drift}, > 2\sigma_{plane}$)

At least 75% of total number of GridPix hits in fit

Track projection crosses first and last pixel column

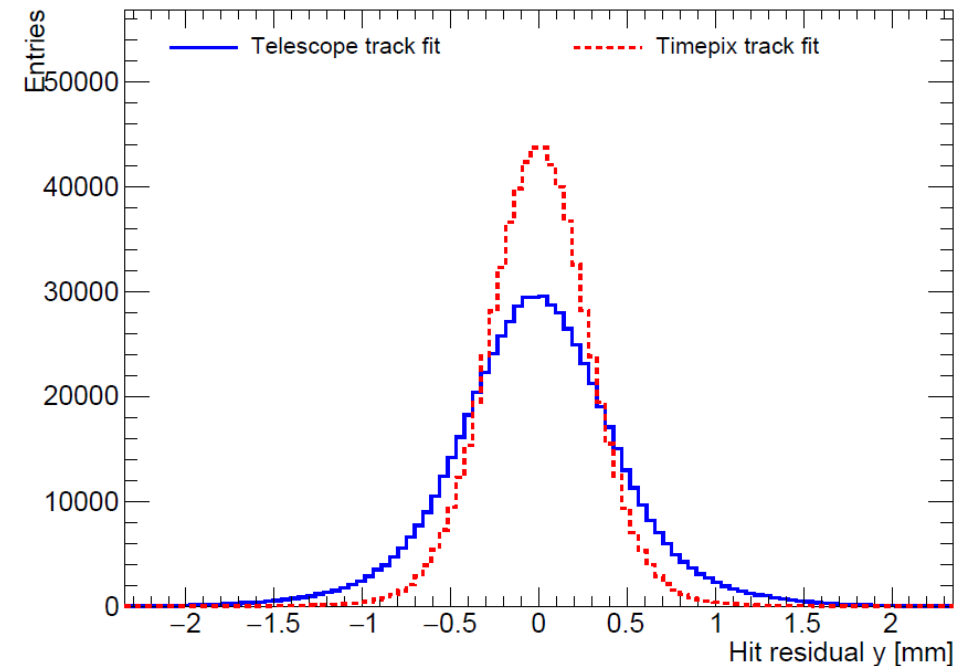
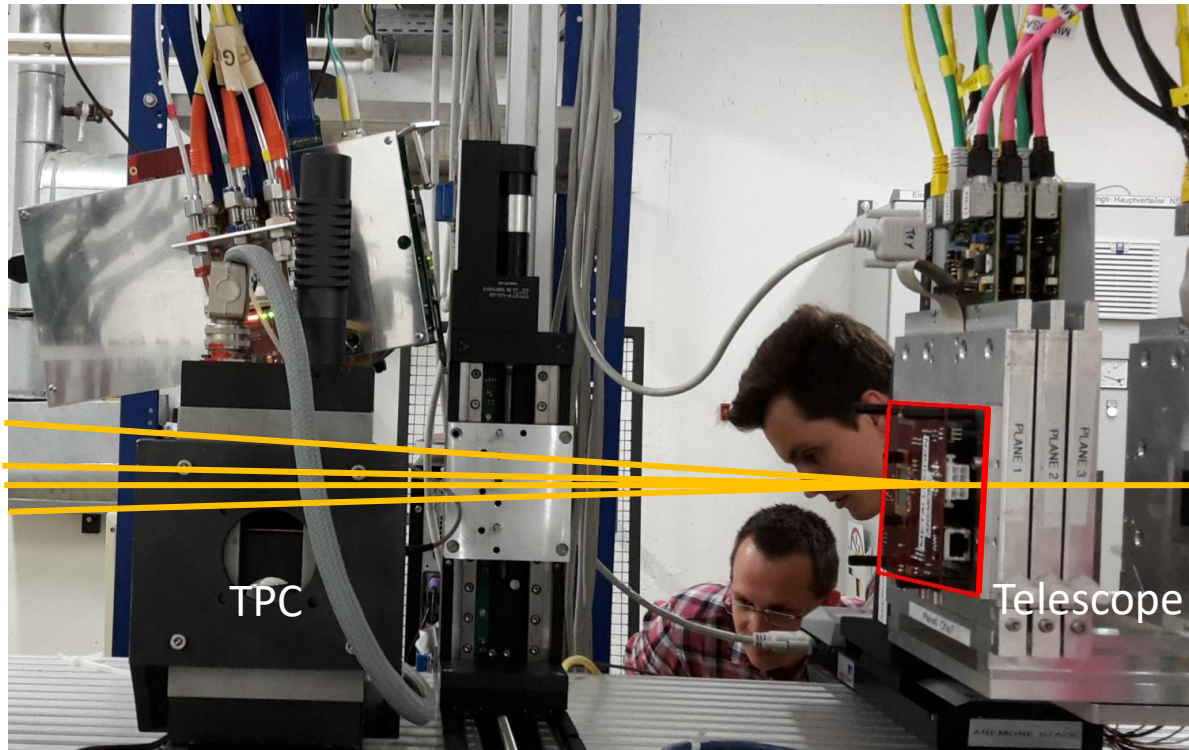
Matching of telescope and GridPix detector

Tracks closer than 1 mm at center of TPC

A unique track pair match

Scatter at last telescope plane (2017)

- Telescope setup was not optimal in 2017: detector was not between planes
- Multiple scattering of ~ 0.7 mrad at last telescope plane
- Only a reliable intercept with $10\ \mu\text{m}$ error from the telescope



Scatter caused broadening of residual distribution