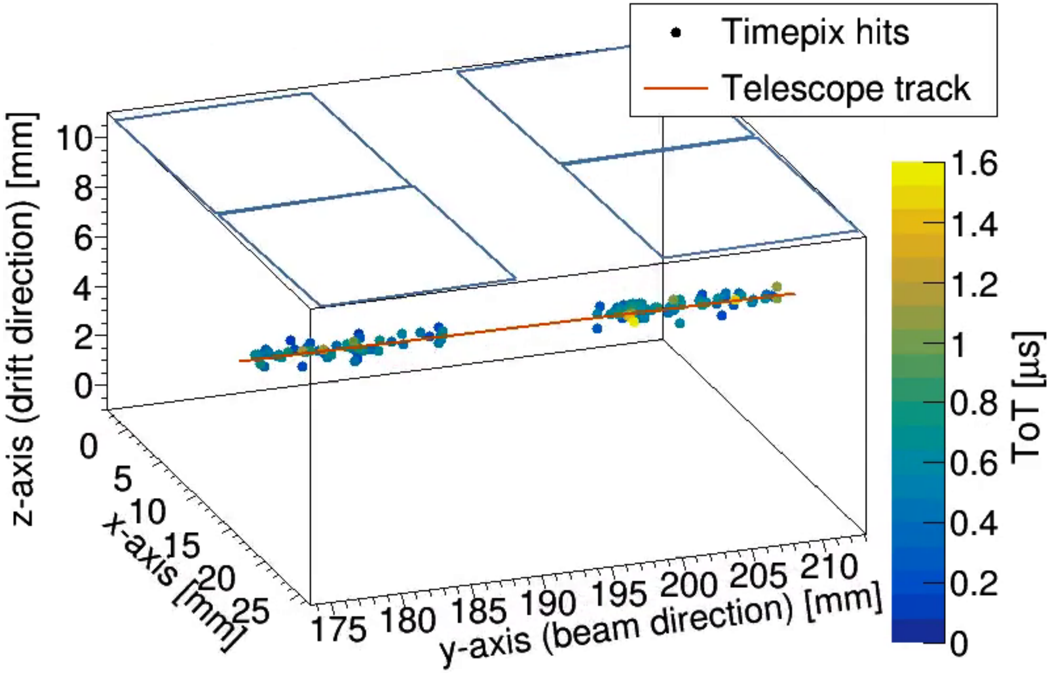


Pixel TPC R&D

*Cornelis Ligtenberg**,** Y. Bilevych, K. Desch, H. van der Graaf, M. Gruber, F. Hartjes, K. Heijhoff,*

*J. Kaminski, **P.M. Kluit**, N. van der Kolk, G. Raven, T. Schiffer, J. Timmermans*

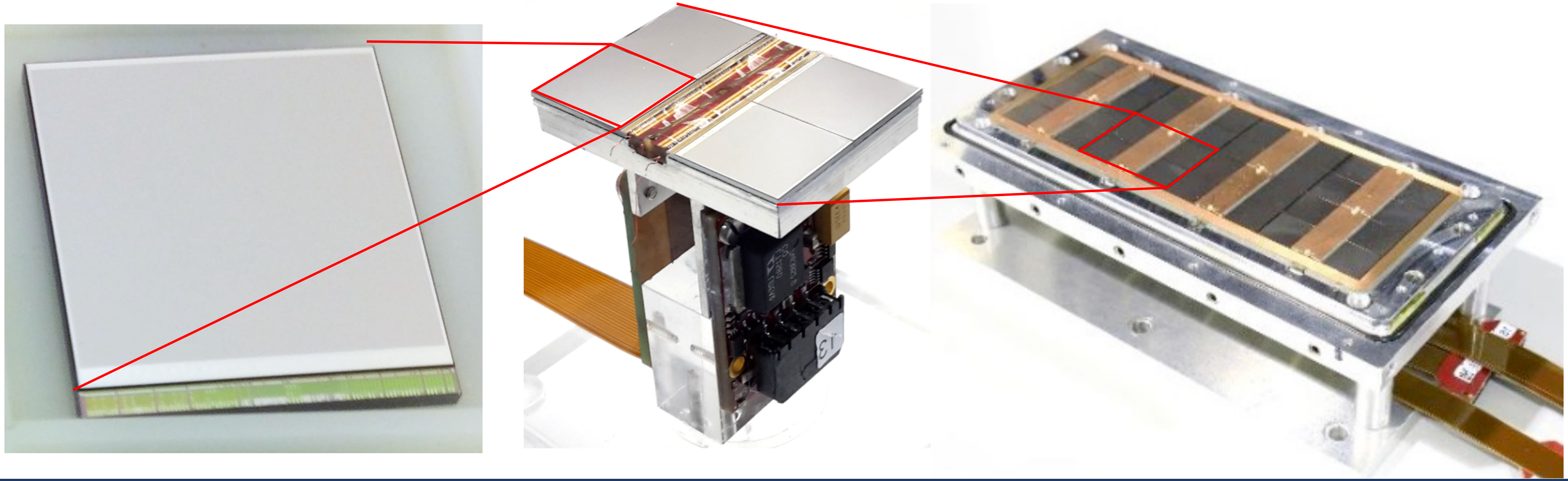
Nikhef UNIVERSITÄT BONN LC TPC

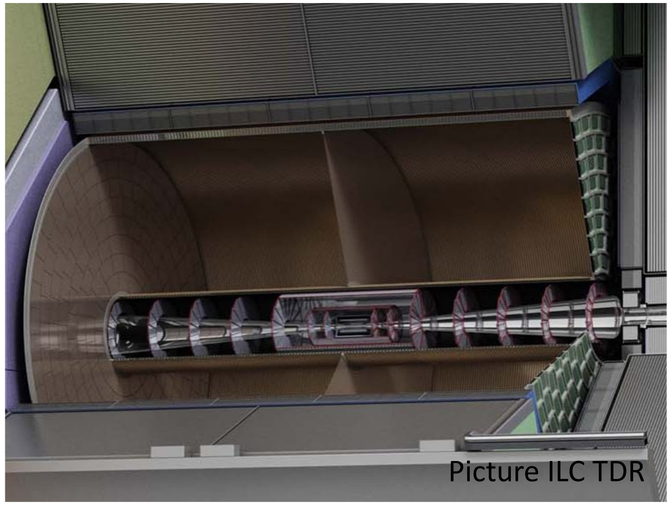
International Workshop on the High Energy Circular Electron Positron Collider Shanghai 2020

Introduction and outline

- <u>GridPix is a 55 µm × 55 µm pixel readout for a gaseous TPC</u>
- First Timepix3 based GridPix test beam (2017)
- Quad module performance from test beam (2018)
- Investigations of the 8 quad detector (2020)
- Future applications in a collider experiment e.g. CEPC

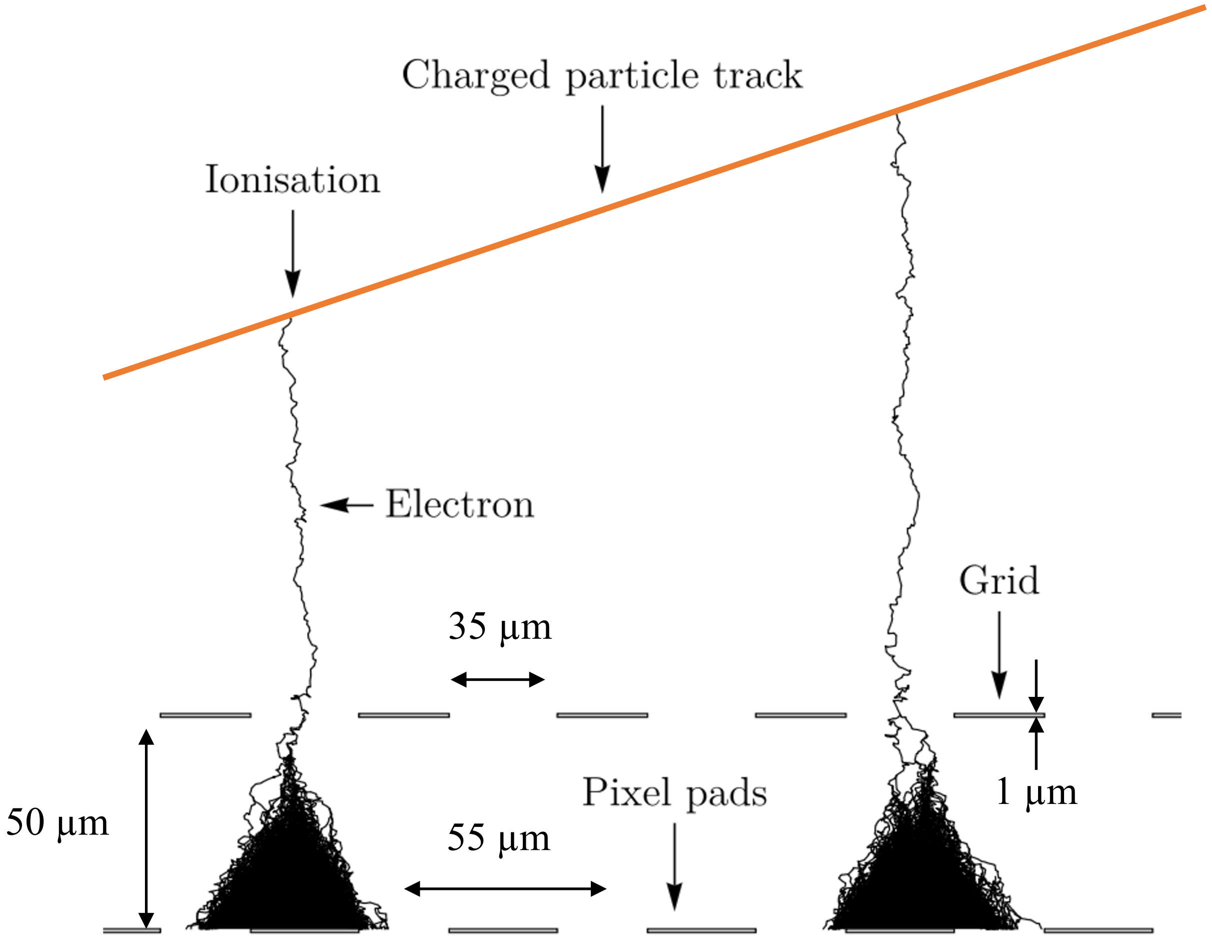
▪ CEPC workshop Beijing 2019; Cornelis Ligtenberg

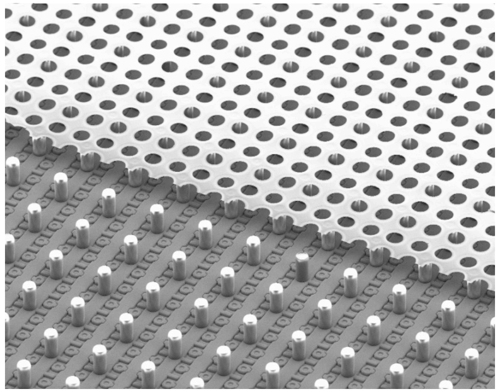


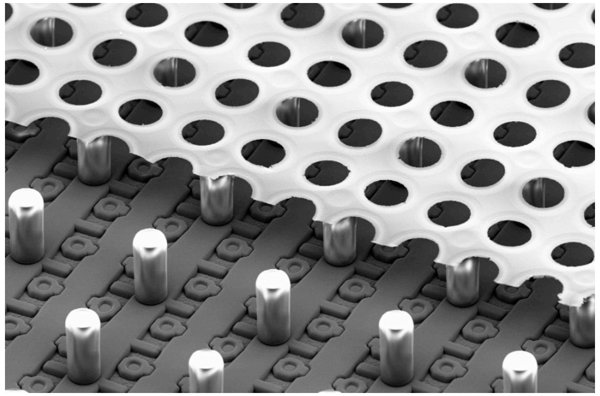


GridPix technology

- GridPix is a type of micro-pattern gaseous TPC readout
- The GridPix based on a Timepix3 chip
  - 55 µm × 55 µm pixels
  - Digital simultaneous registration of Time of Arrival (1.56 ns) and Time over Threshold
  - An aligned Aluminium amplification grid is added by photolithographic postprocessing techniques
- Single ionisation electrons are detected with high efficiency
  - The maximum possible information from a track is acquired
  - dE/dx by cluster counting

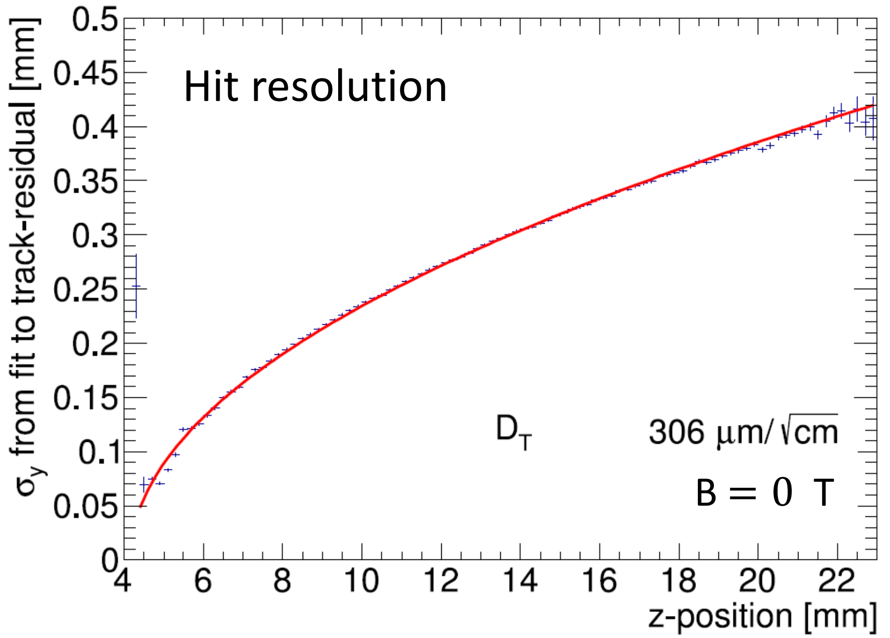


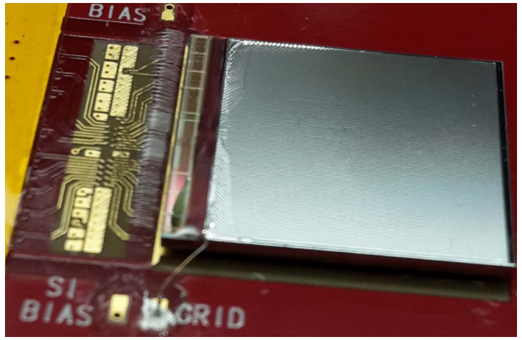


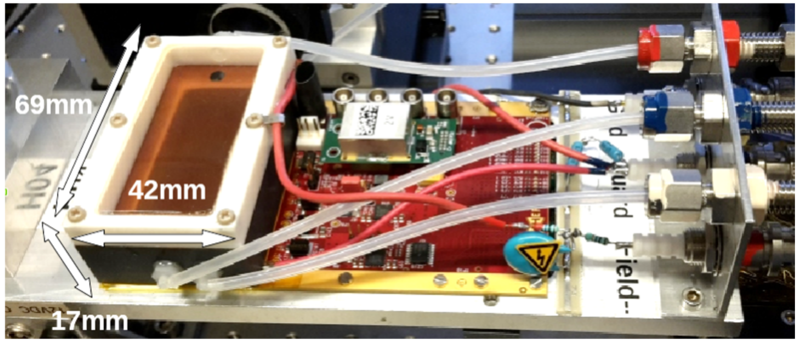


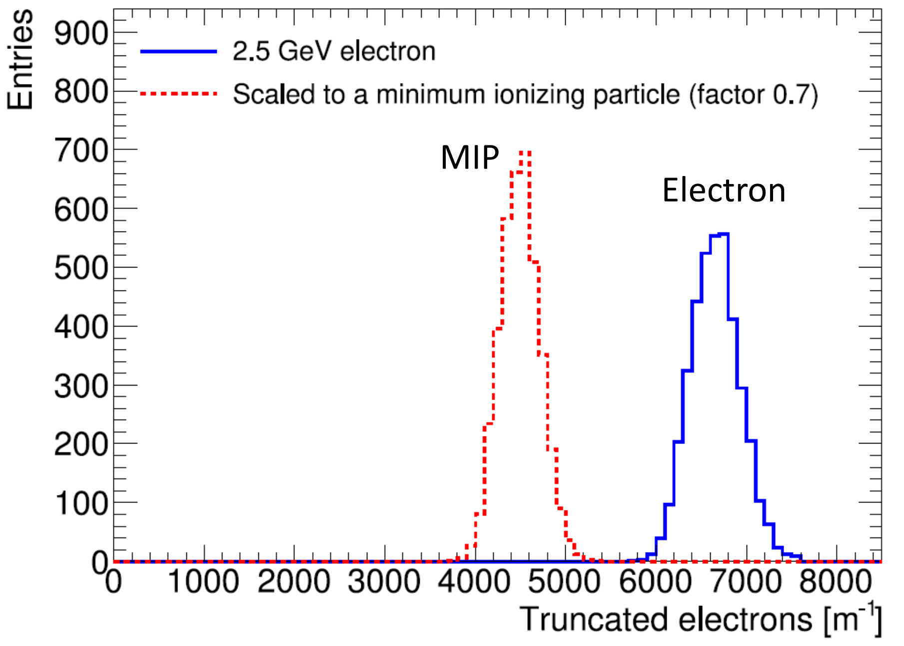
Single chip results (2017)

- A GridPix based on the Timepix3 chip was reliably operated in a test beam setup with 2.5 GeV electrons at ELSA (Bonn)
- Flushed with T2K gas ($Ar/CF_4/iC_4H_{10}$ 95/3/2)
- The resolution is primarily limited by diffusion
- Systematic uncertainties are small: < 10 µm in plane
- Energy loss resolution (dE/dx) by electron counting is 4.1 % per meter





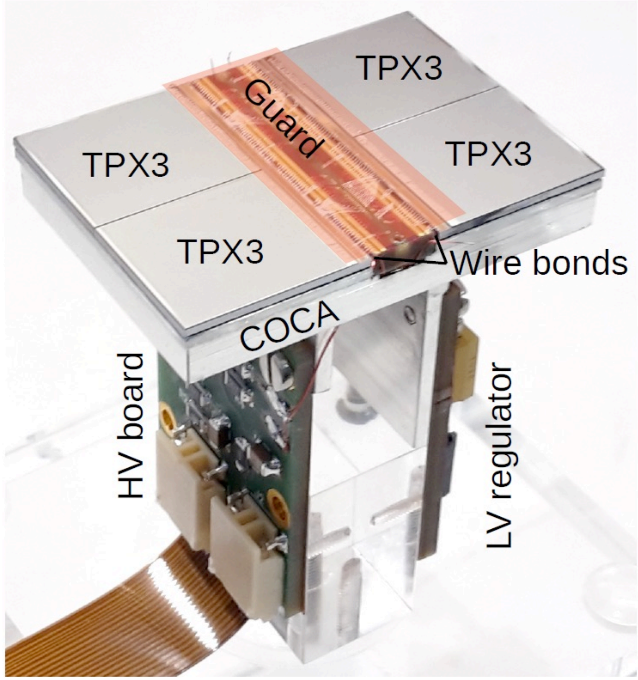


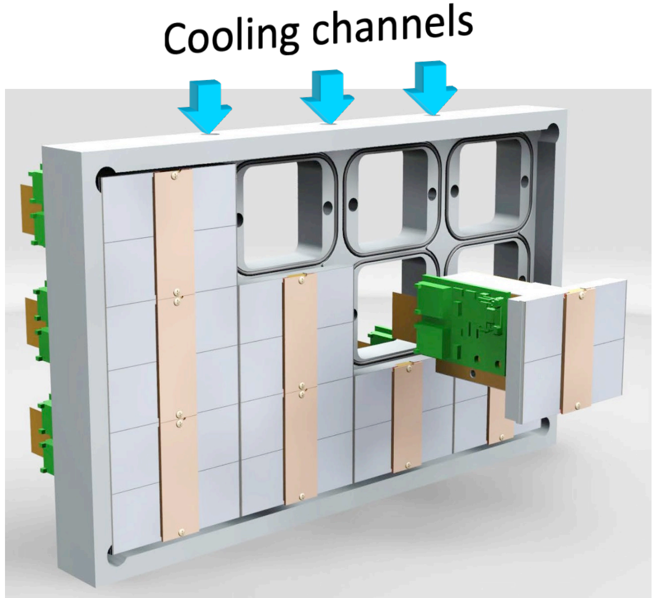


Published paper on this testbeam doi:10.1016/j.nima.2018.08.012

The quad module

- A four chip module sized 39.6 mm × 28.38 mm
- The quad module has all services under the active area
  - Can be tiled to cover arbitrarily large areas.
- Area for IO connections was minimised
  - Maximises active area (68.9%)
- To maintain a homogenous electric field wire bonds are covered by a central guard
- High precision < 20 µm mounting of the chips and guard to limit E (xB) deformations

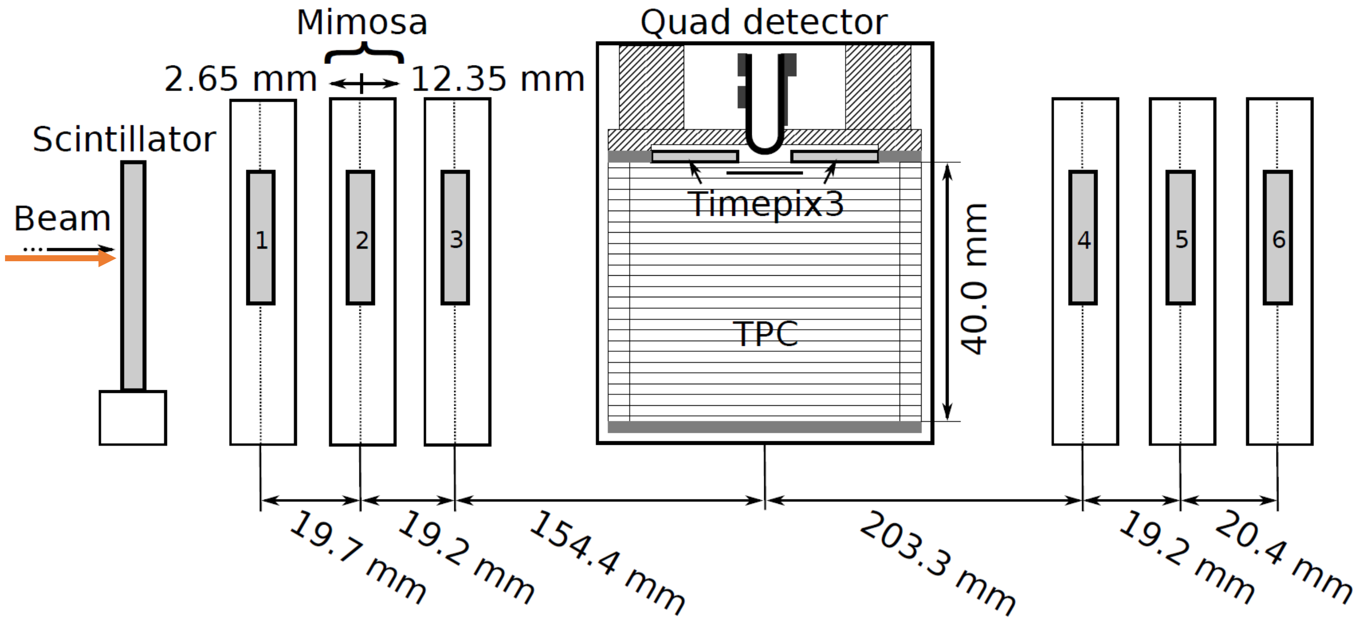


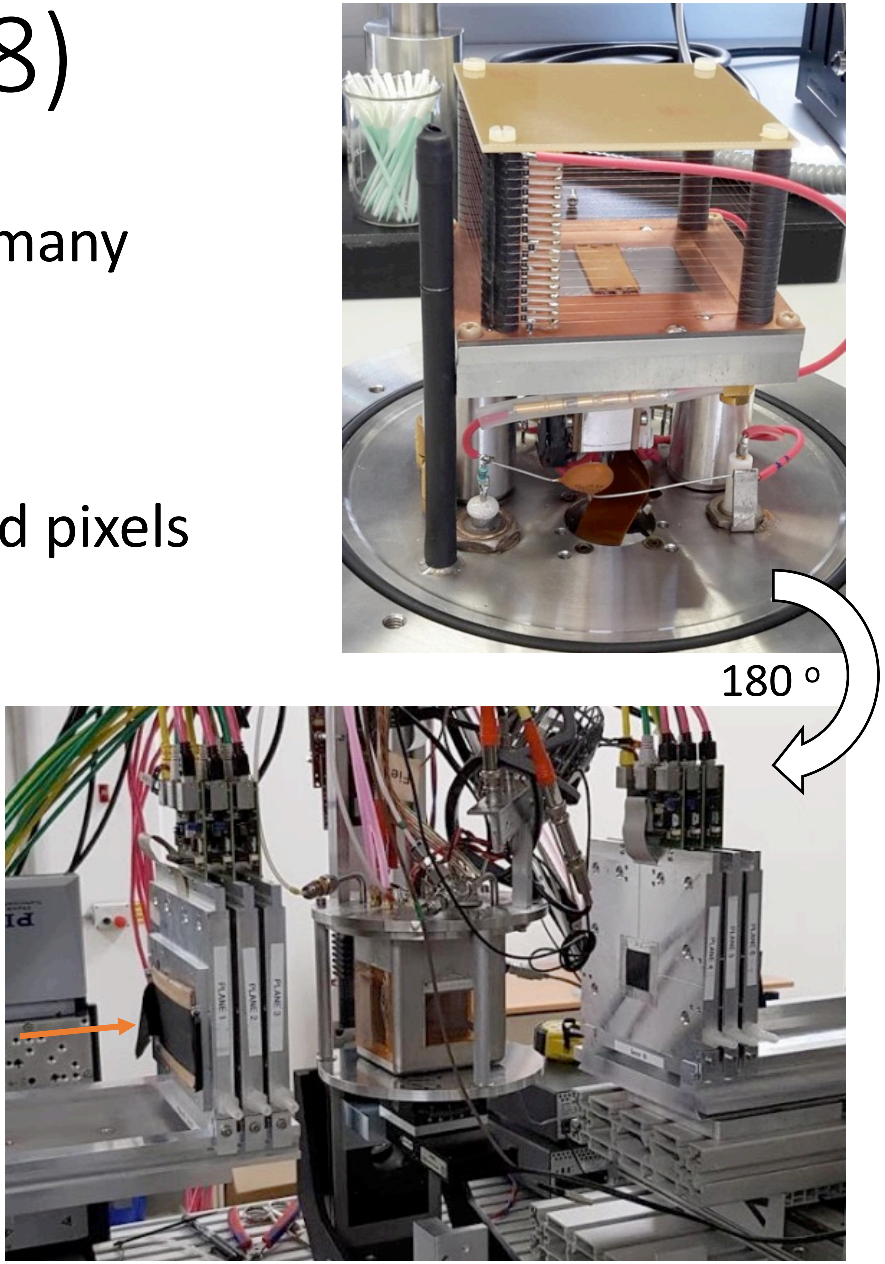


Published paper on quad testbeam: doi:10.1016/j.nima.2019.163331

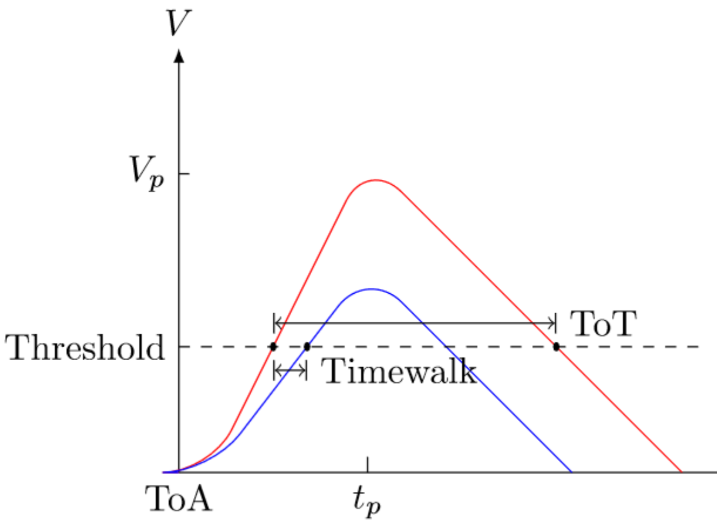
Test beam measurements (2018)

- 2.5 GeV electrons at the ELSA accelerator in Bonn, Germany
- T2K gas with E_{drift} = 400 V/cm, V_{grid} = -330 V
- Events are triggered by a scintillating plane
- 6 plane mimosa telescope with 18.4 µm × 18.4 µm sized pixels



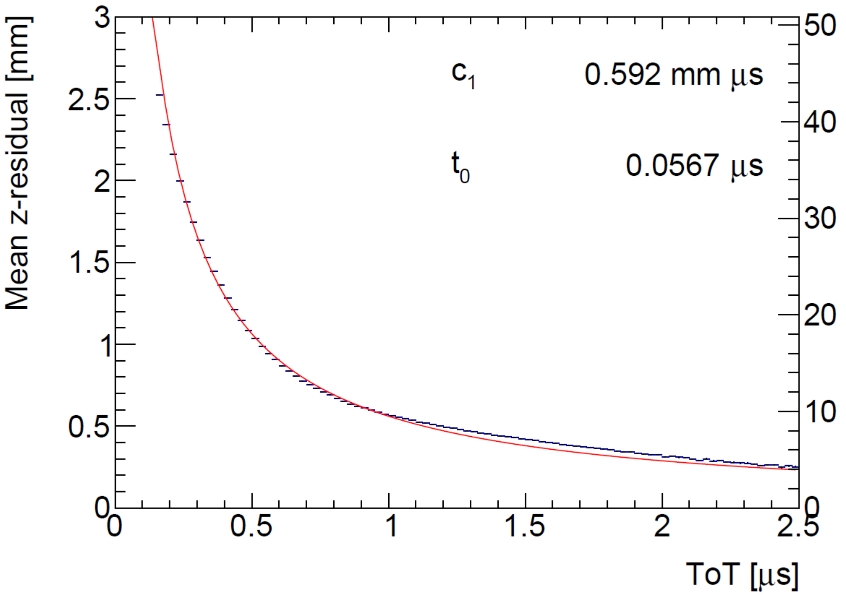


Time walk correction with the Timepix3



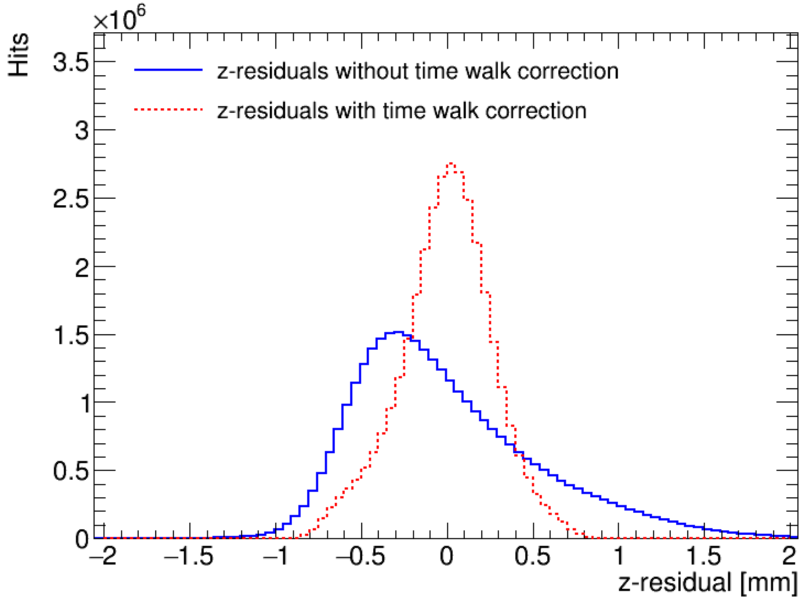
Time walk error: time of arrival depends on signal amplitude

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



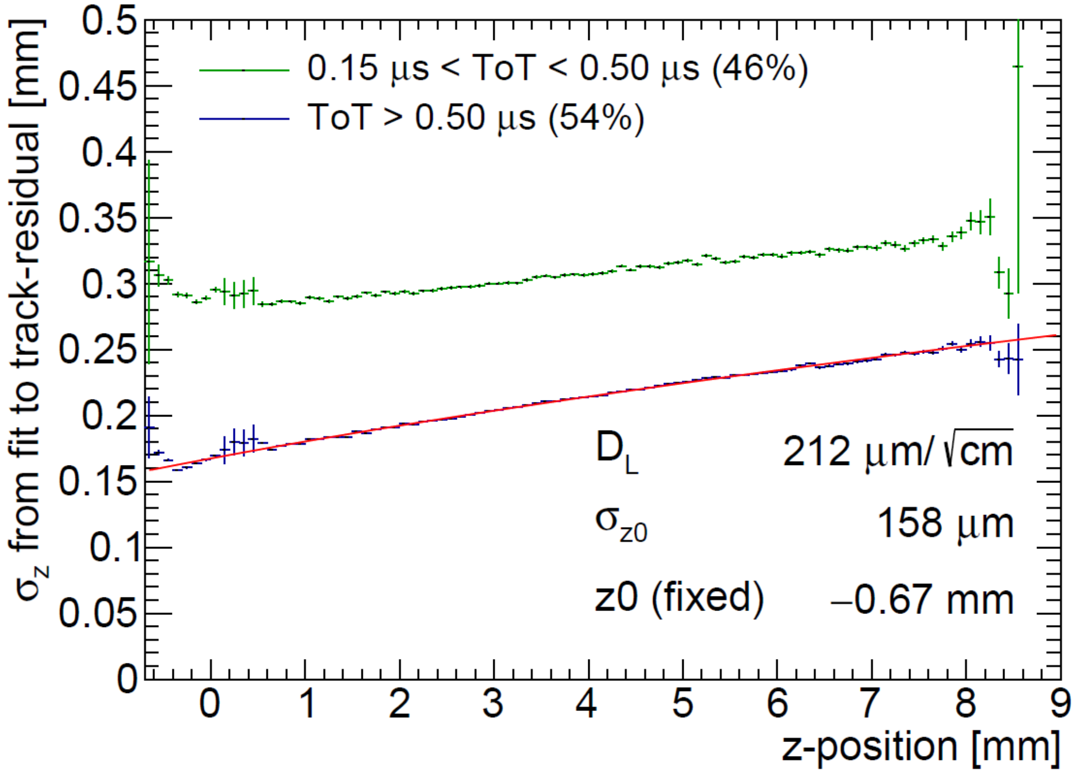
First order correction fitted and applied:

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



Distribution of residuals becomese more Gaussian after the time walk correction

Hit resolution in the drift direction



Single hit resolution in drift direction

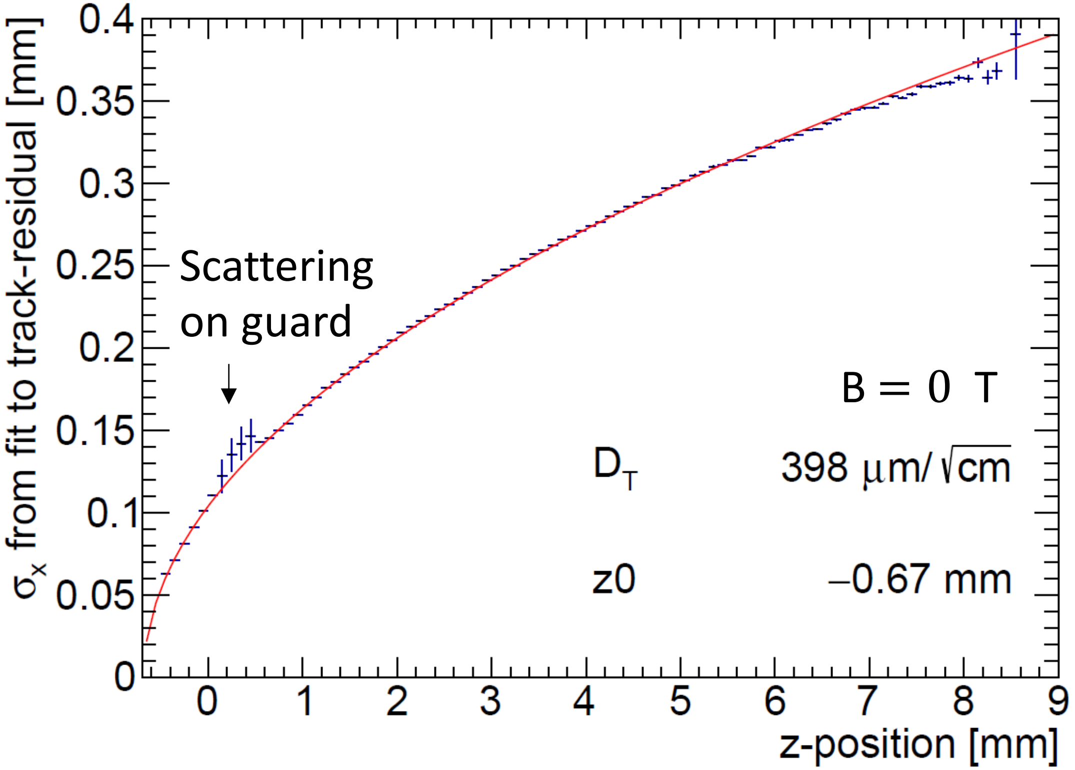
$$\sigma_z^2 = \sigma_{z0}^2 + D_L^2(z - z_0)$$

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 (> 0.50 µs) was imposed

Hit resolution in the pixel (precision) plane



Single hit resolution in pixel (precision) plane:

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

Depends on:

- σ_{y0} = pixel size 55 µm/$\sqrt{12}$
- Diffusion D_T from fit

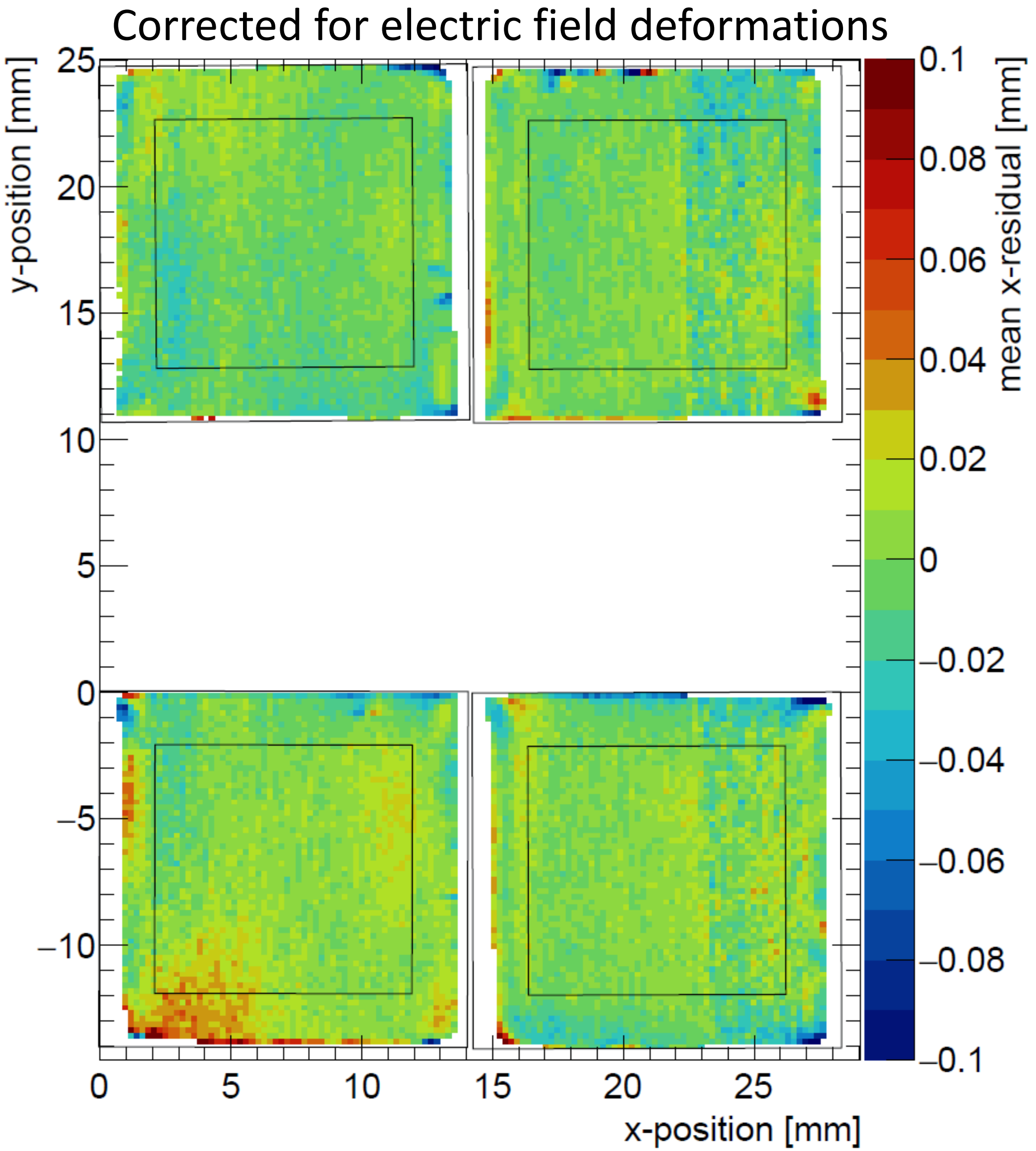
Note that:

- A hit resolution of ~250 µm is ~25 µm for a 100-hit track (~ 1 cm track length)
- At $B = 4$ T , expected $D_T = 25\ \mu\text{m}/\sqrt{\text{cm}}$
- At $B = 2$ T , expected $D_T = \sim 60\ \mu\text{m}/\sqrt{\text{cm}}$

Deformations in the pixel (precision) plane

- Investigation of systematic deviations over the pixel plane
- Each bin displays mean of residuals from 4 × 4 pixels
- After correction of the residuals for the distortions from the electric field

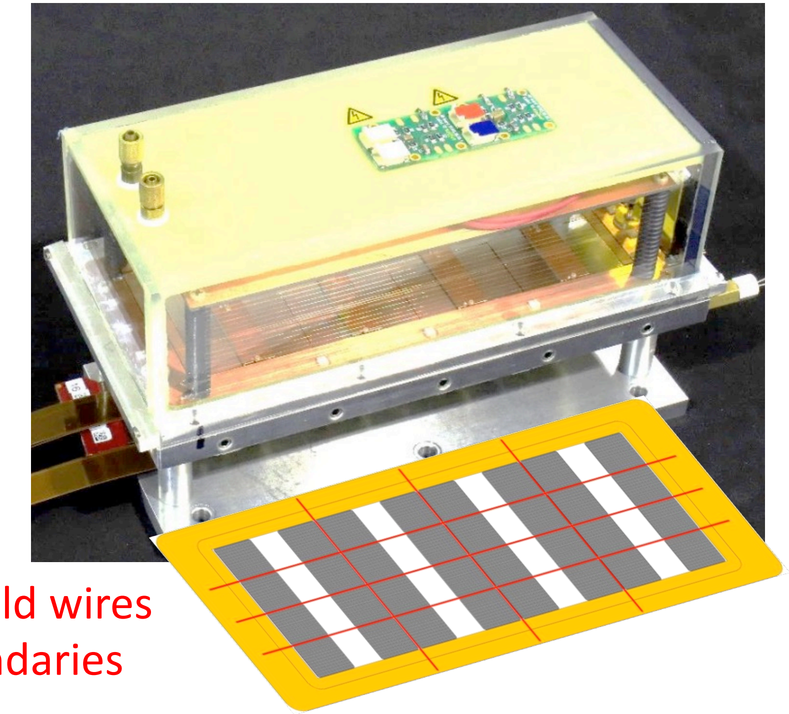
- The RMS is 13 µm over the whole chip, and 9 µm in the centre (black outline)



8 quad module development

- The 8 quad test box has 32 chips in total
- Simultaneous read out through one SPIDR board using data concentrators
- Field wires added to improve electric field, and reduce deformations

Will be tested in a test beam with magnetic field at DESY in 2021



with field wires at boundaries

A TPC at a future collider experiment

A collider experiment benefits from a TPC, because of the minimal material budget, continuous 3D tracking, dE/dx measurements, and cost-effectiveness.

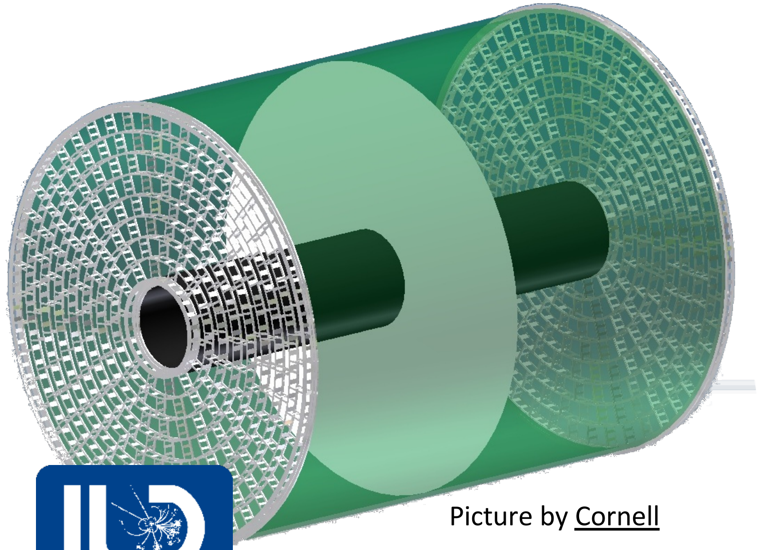
Currently there are three read-out technologies: Pads, MicroMegas and Pixels.

All technologies have the challenge to measure the track position in the bending plane with a distortions of less than $\mathcal{O}$(10-20 μm). With the modular quad detector we are close to realize this. R&D is done in the LCTPC collaboration.

In the context of ILC and the ILD experiment detailed simulations are performed and the tracking performance specifications – needed for the precision physics - can be reached. Also the performance of different technologies can be compared.

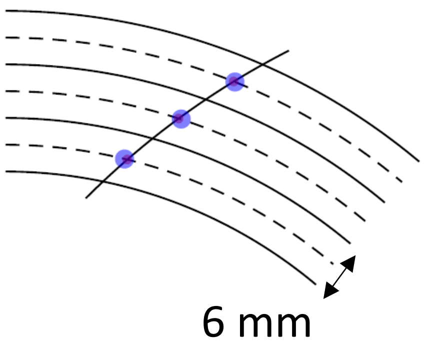
Simulation of ILD (ILC) TPC with pixel readout

- 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



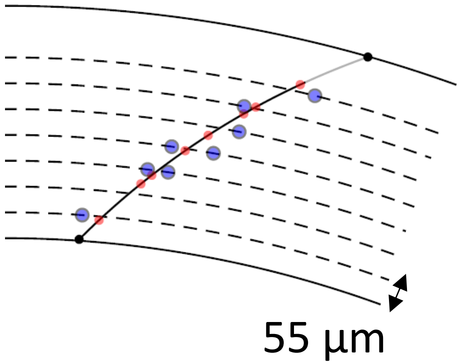
Picture by Cornell

Pads



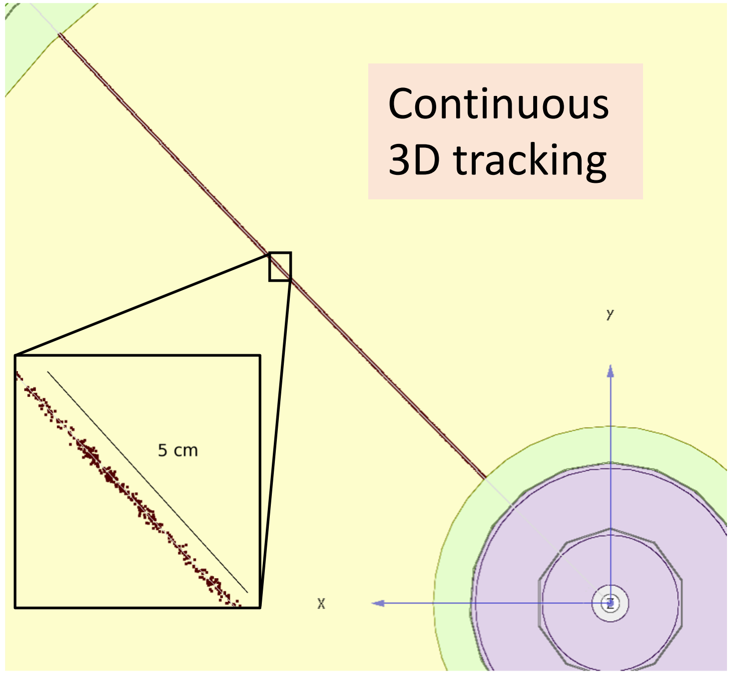
22 electrons / hit
~200 hits / track

Pixels



1 electron / hit
~10 000 hits / track

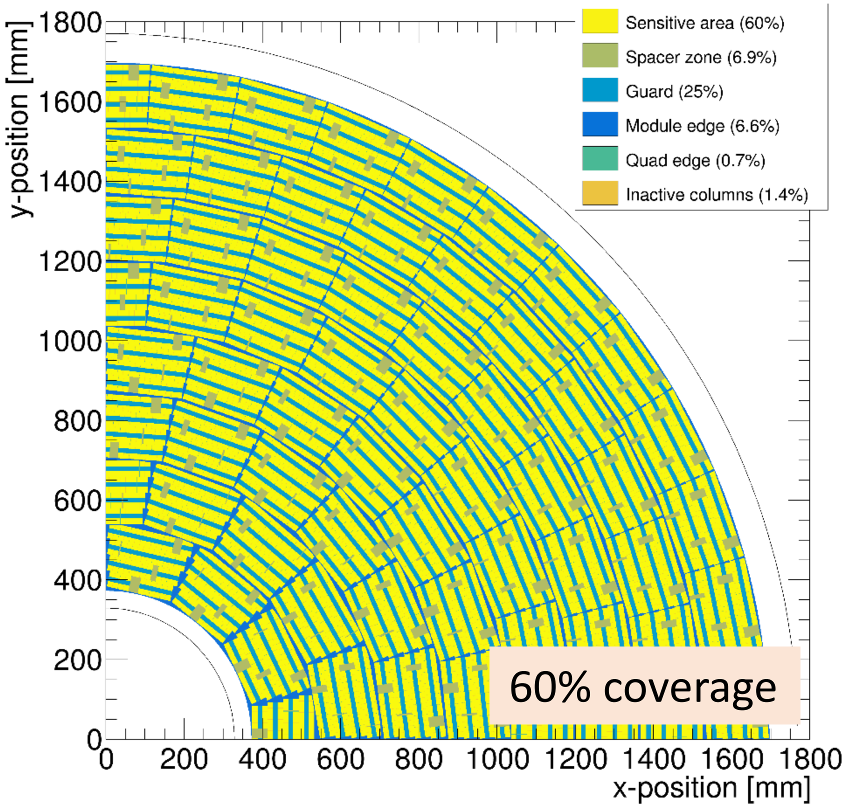
50 GeV muon track with pixel readout



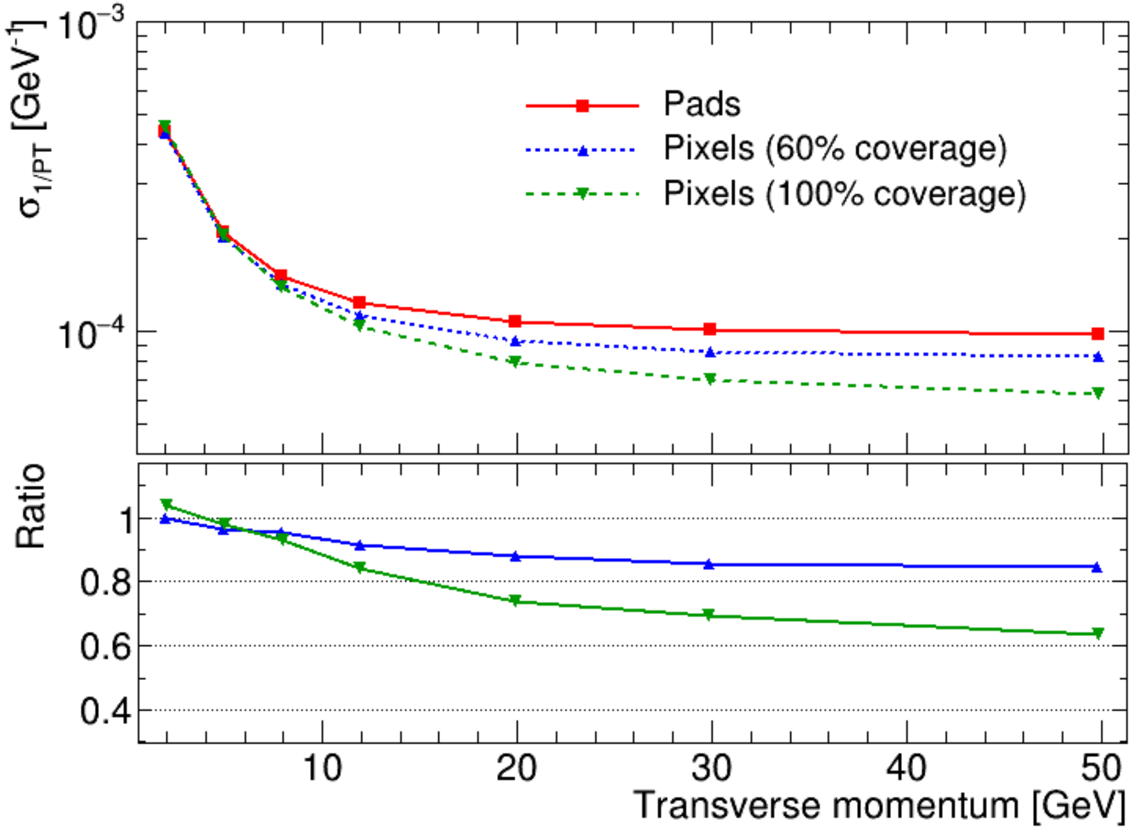
Performance of a GridPix TPC at ILC

- From full simulation, momentum resolution can be determined
- Momentum resolution is ~15% better (with realistic 60% coverage)

Realistic tiling with quad module



Momentum resolution of the TPC for a simulated muon



A TPC at a future collider experiment

Potential issues at future colliders for all read-out technologies:

- Ions in the drift chamber from either primary ionisation or ion backflow cause distortions, which should be limited to about $\mathcal{O}$(10-20 μm)
  → Backflow ions can be captured by an active gate in front of the readout
- The readout occupancy should be sufficiently low for track finding (typically < 10% voxel occupancy)
  → A pixel readout has a greatly reduced occupancy compared to a pad readout

- Other - not critical – R&D items are already (partially) addressed:
  - The material (X0) has to (re)optimized
  - The power consumption has to be reduced as much as possible
  - Adequate cooling has to be realised
  - The quad detector was already tested in a high rate beam environment

Prospects for a TPC at a future collider

Non-exhaustive list of potential issues with indicative expectations:

Potential issues → / Future colliders ↓	Ions in drift chamber		Readout Occupancy
	Primary ions	Backflow ions	
ILC 1 TeV	Acceptable	GEM ion gate	Low (< 1% voxel)
CLIC 3 TeV	Requires investigation	Gating is possible	100% pads (30% voxel) 40% pixel (lower voxel)
FCC-ee 91 GeV ($L = 230 \cdot 10^{34}\ cm^{-2}\ s^{-1}$)	Too high (distortions > 100 µm)	Too high (gating is not possible)	Most likely low
CEPC 91 GeV ($L = 34 \cdot 10^{34}\ cm^{-2}\ s^{-1}$)	Acceptable	~25% event loss if gated Other solutions	Low (<< 1% voxel)

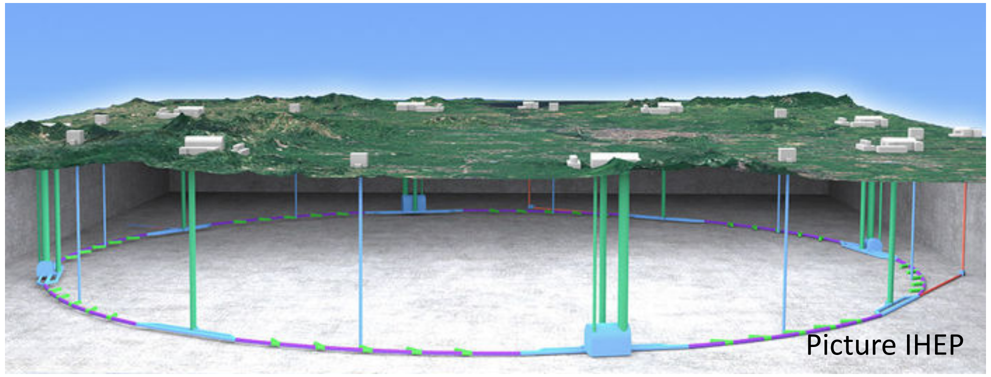
See backup slide for sources

A Pixel TPC at the CEPC?

CEPC running above the Z (WW, Higgs) there are no critical issues

A Pixel TPC can deal with the high beam rates at the CEPC

- At the Z pole the CEPC with L = 34 10^{34} cm^{-2} s^{-1} will produce Z bosons at ~10 kHz
- Link speed of Timepix3 (in Quad) is 80 Mbps: 2.6 MHits/s per 1.41 × 1.41 cm^2
- Excellent time resolution: time stamping of tracks < 1.2 ns
- Power consumption ~2W/chip depends on hit rate
  - No power pulsing possible at the CEPC
  - Good cooling is important



- Ion backflow of the quad is measured to be 1.3%

  at a gain of ~2000. So IBF*Gain is ~25.

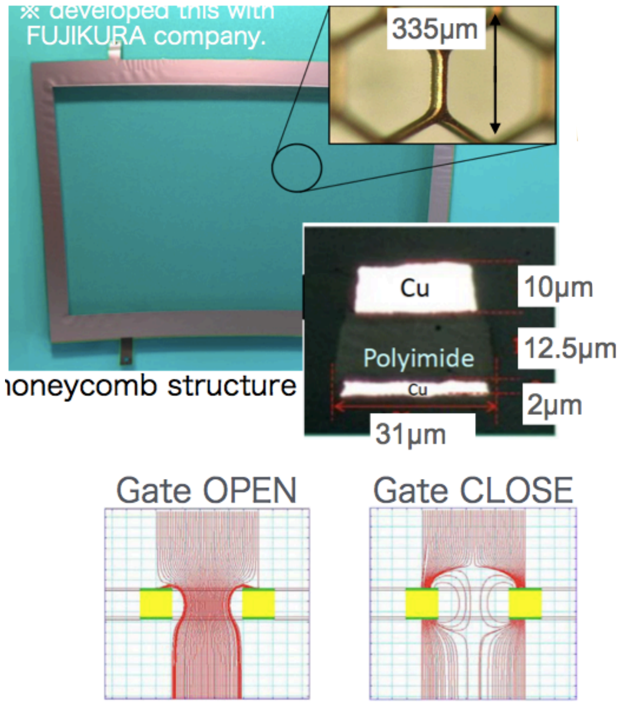
  NB: to limit the distortions in de drift volume one needs to achieve < 4 ■ LCWS 2019 Sendai Huirong Qi

Reducing the Ion back flow in a (Pixel) TPC

The Ion back flow can be reduced – while running at the Z:

- By installing a gating device and closing the gate after a trigger.

  E.g.the Gating GEM as developed in the contect of the ILD experiment



- LCWS19 presentation ILD gating GEM by Yumi Aoki (KEK)

Can we apply gating in Z collisions?
High luminosity CEPC L = 32-50 10^{34} $cm^{-2}s^{-1}$. Time between Z interactions 120-60 μs TPC drift takes 30 μs. So events are separated in the TPC; gating is possible.
Gate length of 20-60 μs would stop the ions in triggered mode.

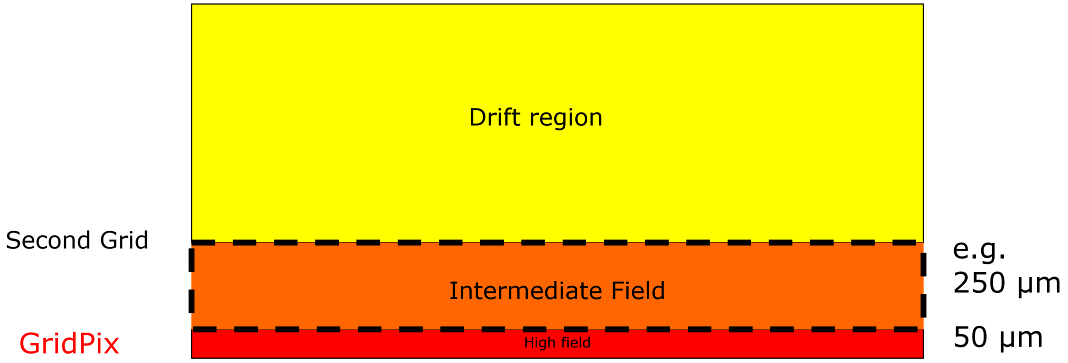
Problem is that the gating will lead to dead time and a data taking efficiency at high luminosities of ∽85%-65% (for a 20 μs gate length).

Reducing the Ion back flow in a Pixel TPC

The Ion back flow can be reduced by adding a second grid to the device.

It is important that the holes of the grids are aligned. The Ion back flow is a function of the geometry and electric fields. Detailed simulations – validated by data - have been presented in LCTPC WP #326.

With a hole size of 25 µm an IBF of $3\ 10^{-4}$ can be achieved and the value for IBF*Gain would be 0.6. Well below the specifications.



We plan to test this idea at Nikhef

Ion backflow	Hole 30 µm	Hole 25 µm	Hole 20 µm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	$12\ 10^{-4}$	$3\ 10^{-4}$	$1\ 10^{-4}$
transparancy	100%	99.4%	91.7%

Conclusions

- A quad module with four Timepix3 based GridPix chips has been designed and built
  - The resolution is limited by diffusion
  - Systematic uncertainties are small: 9 µm in the pixel plane
- A 8 quad detector with 32 chips is operational and will be tested in a beam in 2021
- A Pixel TPC is a good option at the ILC (CLIC) and circular e^+e^- colliders
- Simulations show an improvement in momentum resolution of a pixel TPC readout over a pad readout of 15 – 35 %
- A GridPix readout will allow for dE/dx measurements through cluster counting
- The distortions in the TPC due to the ion back flow while running at the Z pole can be reduced significantly by applying a double grid in a Pixel TPC. There is no need for a gating device.

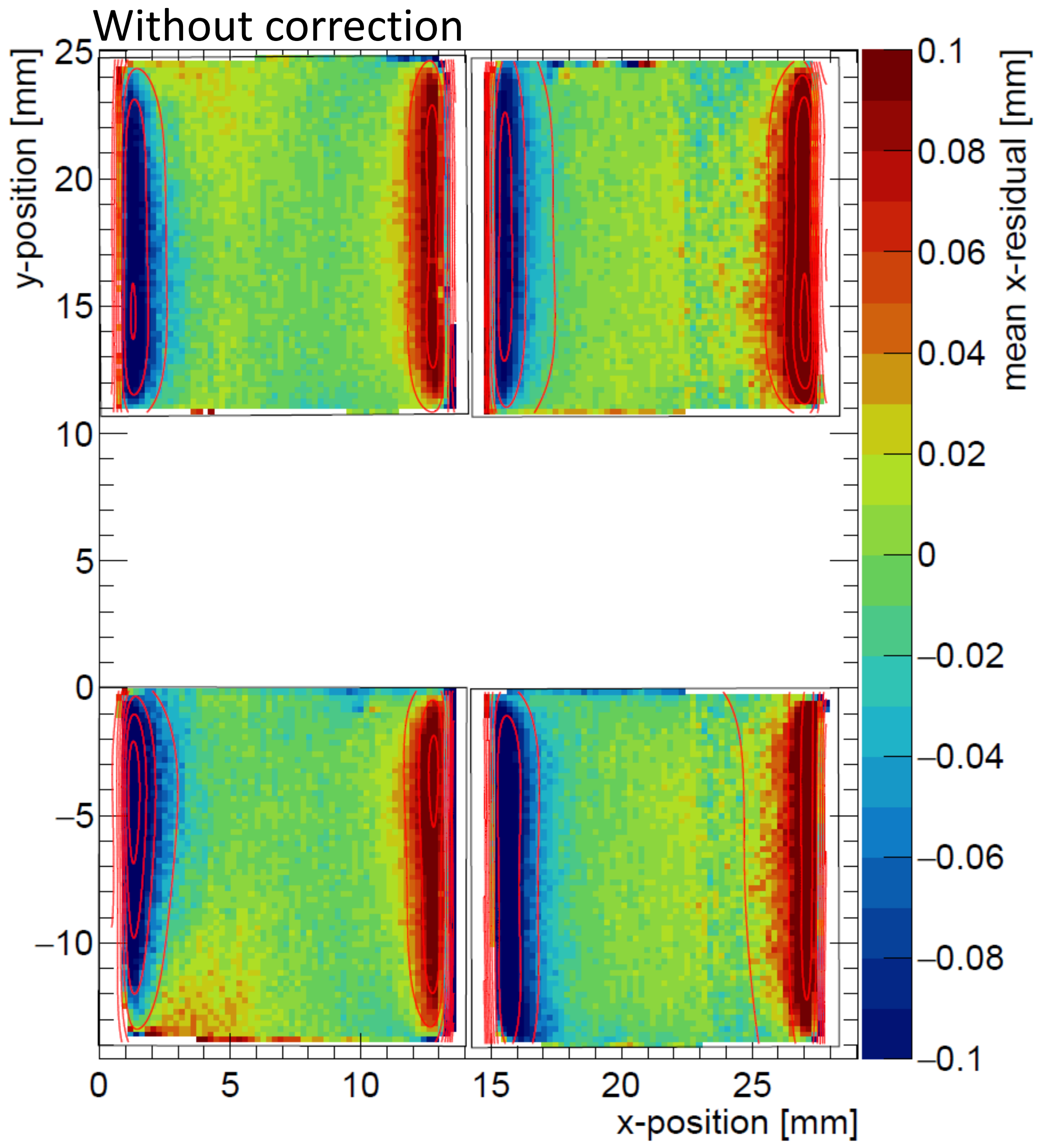
Backup

Deformations in the pixel (precision) plane

- Investigation of systematic deviations over the pixel plane
- Each bin displays mean of residuals from 4 × 4 pixels
- Primarily due to electric field distortions

- Correction of deformations with 4 fitted Cauchy functions per chip:

$$\delta x = \sum_{j=0}^{4}\left(\frac{1}{\pi}\frac{\gamma_j}{(x-d_j)^2+\gamma_j^2}\sum_{i=0}^{4}(c_{ij}y^i)\right)$$



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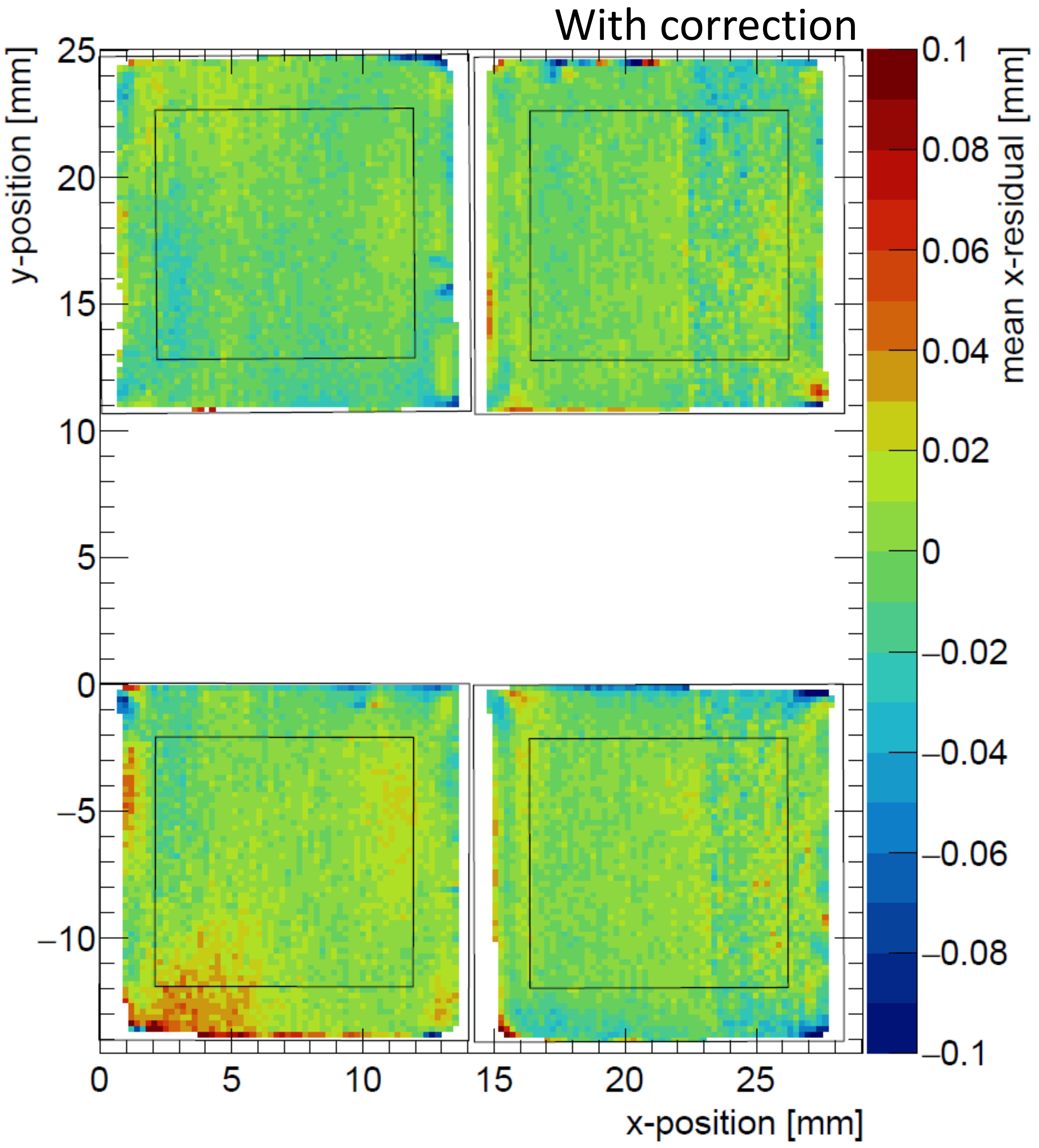
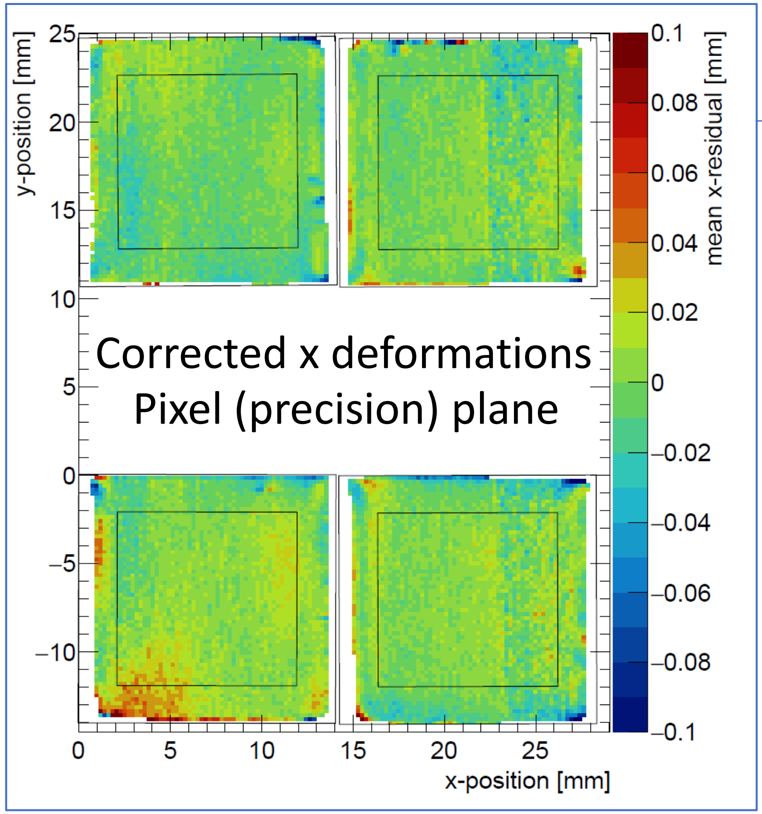
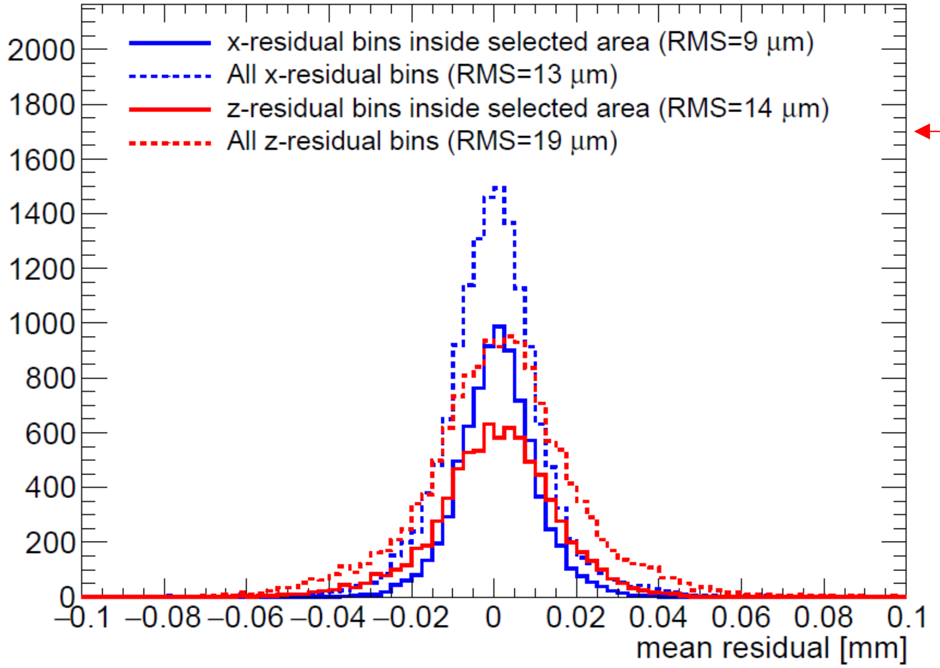
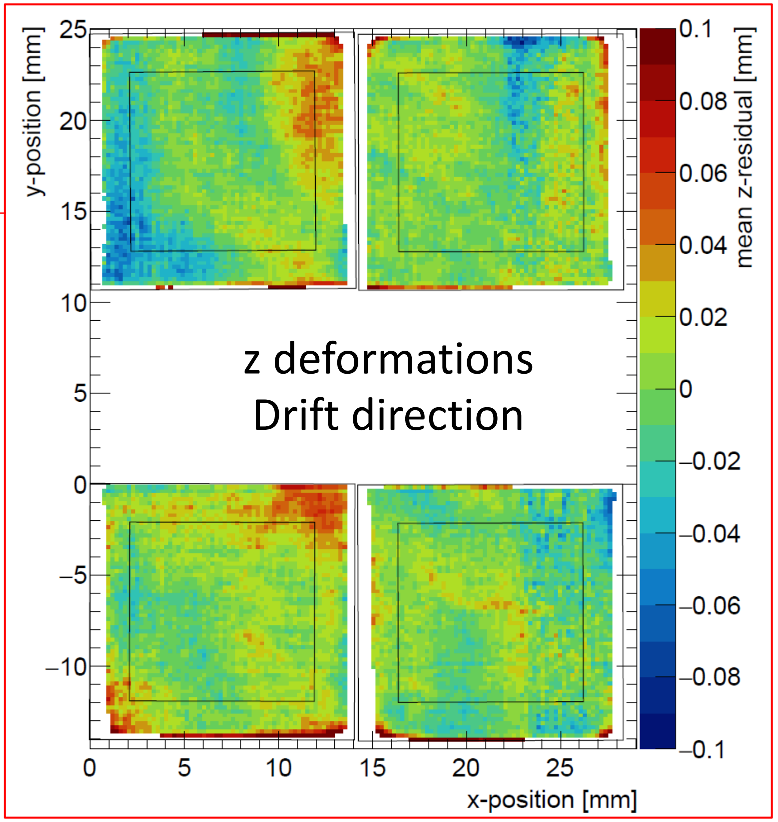


Deformations in pixel plane and drift direction

- Each bin displays mean of residuals from 4 × 4 pixels
- The RMS in the center of the chip is 9 µm (pixel plane after correction) and 14 µm (drift direction), which indicates small systematic errors

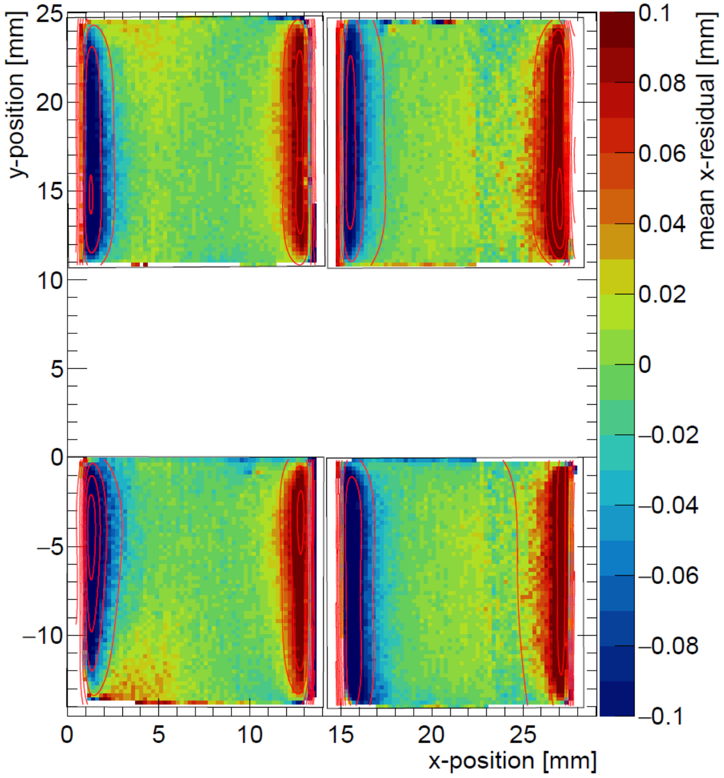




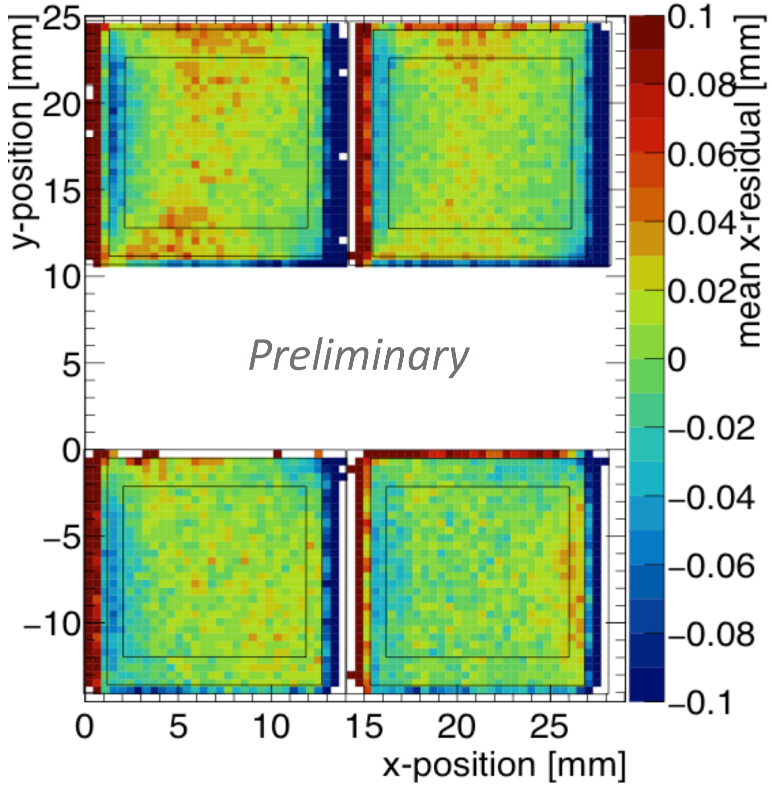


8 quad module development

- Laser test indicate a reduction in electric field deformations with field wires
- Early 2020 test beam planned at DESY with 1 T magnetic field



Uncorrected residuals from quad test beam

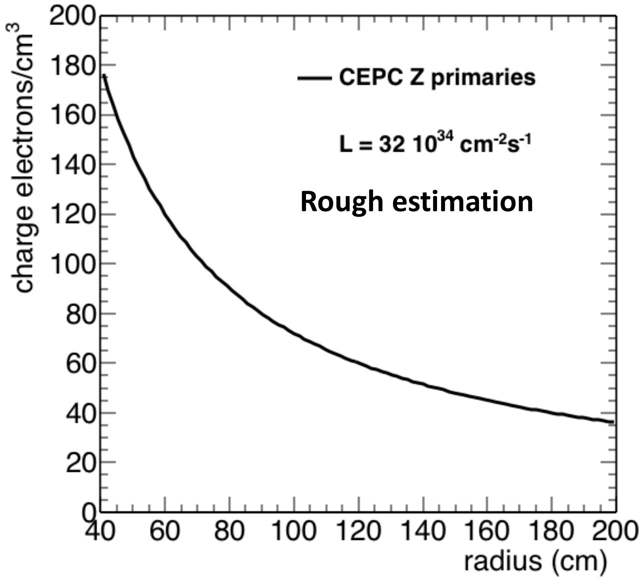


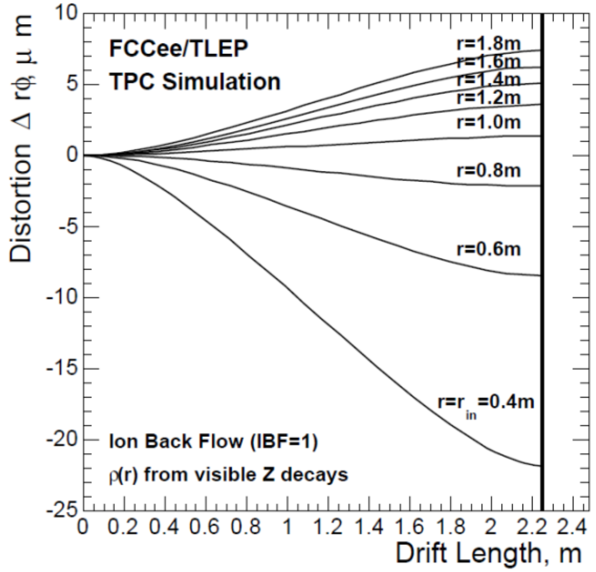
Uncorrected residuals from laser test with field wires

Ions in circular electron positron collider

- Rough estimations at $L = 32 \cdot 10^{34}\ cm^{-2}\ s^{-1}$ indicate primary ionisation at a ILC250 level ⇒ < 5 µm distortions. See Arai Daisuke
- Simulation from CEPC CDR with Gain × IBF = 5 and $L = 17 \cdot 10^{34}\ cm^{-2}\ s^{-1}$ ⇒ < 40 µm distortions (This equals 16 µm at Gain × IBF = 1 and $L = 32 \cdot 10^{34}\ cm^{-2}\ s^{-1}$)
- FCCee/TLEP studies at Gain × IBF = 1 and 16.8 kHz hadronic Zs by Philippe Schwemling ⇒ < 22 µm distortions

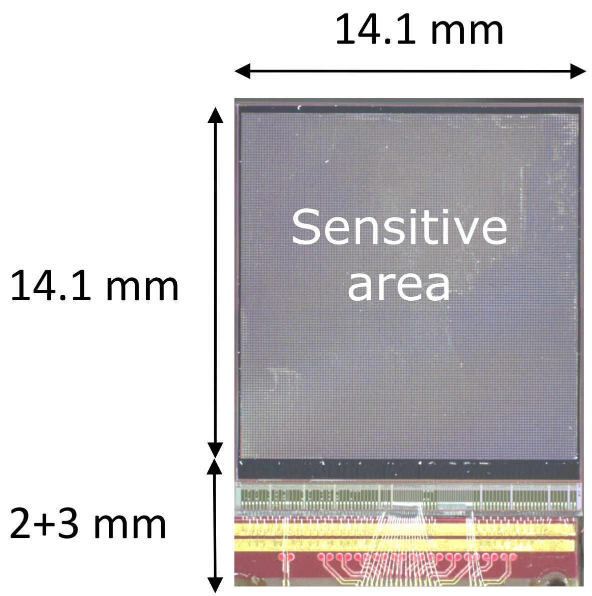
Rough estimation of primary ionisation
- 10 kHz Z event rate; $L = 32 \cdot 10^{34}\ cm^{-2}\ s^{-1}$
- 500 ms will accumulate 5000 Z events
- 20 tracks / Z event and 10 000 e / track will make 10^9 ions in volume
- Volume is ~4 10^7 resulting in 25 e/cm^3
- Similar to ILC250 accumulated charge





Timepix3 pixel chip

- 256 × 256 pixels with 55 µm × 55 µm pitch
- Sensitive area of 14.1 mm × 14.1 mm
- TDC with 640 MHz clock, resulting in a 1.56 ns time resolution
- Per pixel simultaneous measurement of arrival time (ToA) and signal amplitude (ToT)
- Readout using SPIDR
- Power consumption of 2W depending on hit rate
  - good cooling is important
- Wafer post-processed at IZM Berlin



Timepix3

Header	4 bit
Pixel address	16 bit
Course ToA	14 bit
ToT	10 bit
Fine ToA	4 bit

SPIDR

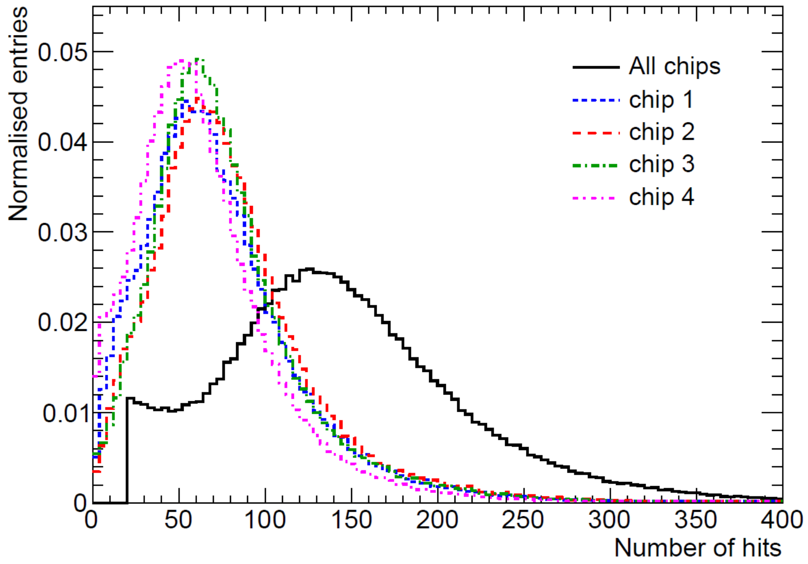
SPIDR timestamp	12 bit

64 bit data packets

Run parameters and selections

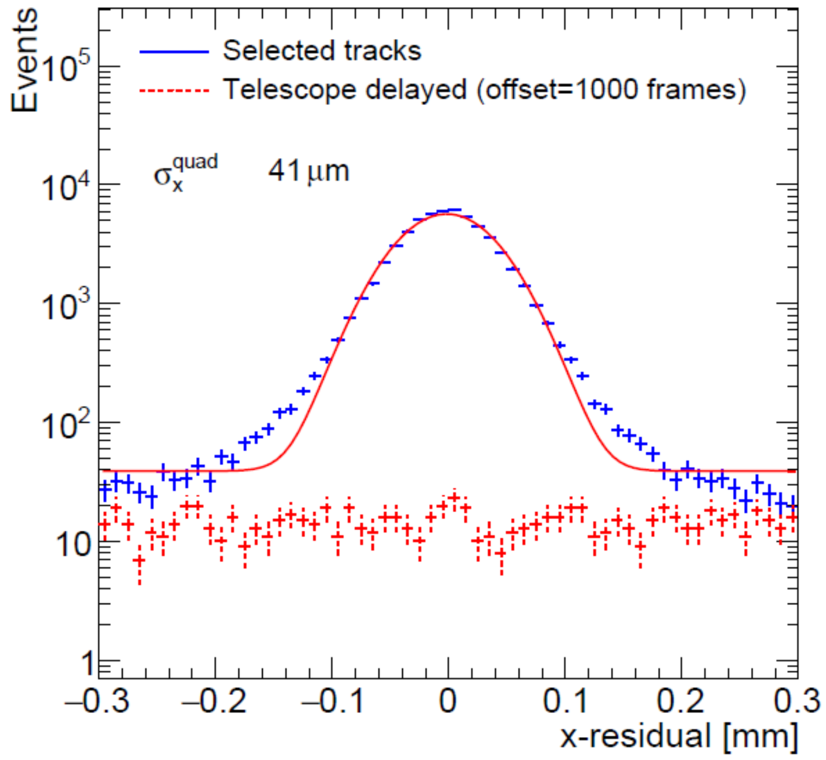
- Used T2K (Ar:CF_4:iC_4H_{10} 95:3:2) gas with a water vapor contamination
  - Drift speed 54.6 µm/ns (59.0 µm/ns expected by Magboltz)
- Most probable number of hits per 27.5 mm was 146 (225 expected)
  - This is due to the low effective grid voltage and possibly read out problems
- Use a stringent selection to get clean tracks

Runs duration	10 minutes
Triggers per run	2.2×10^6 triggers
V_{grid}	330 V
E_{drift}	400 V/cm
Threshold	550 e^-
Temperature	(300.5 ± 0.13) K
Pressure	(1011 ± 0.16) mbar
Oxygen concentration	814 ppm
Water vapor concentration	6000 ppm



Telescope
Number of planes hits ≥ 5
Reject outliers ($r_{x,z} < 50$ µm)
Slope difference between sets of planes < 1 mrad
GridPix hit selection
$-500\,\mathrm{ns} < t_{\mathrm{hit}} - t_{\mathrm{trigger}} < 500\,\mathrm{ns}$
Hit ToT > 0.15 µs
Reject outliers ($r_x < 1.5\,\mathrm{mm}, r_z < 2\,\mathrm{mm}$)
Reject outliers ($r_x < 2\sigma_x, r_z < 3\sigma_z$)
Event Selection
$N_{\mathrm{hits}} \geq 20$
$(N_{r_x<1.5\mathrm{mm}} / N_{r_x<5\mathrm{mm}}) > 0.8$
$\lvert x_{\mathrm{Timepix}} - x_{\mathrm{telescope}} \rvert < 0.3\,\mathrm{mm}$
$\lvert z_{\mathrm{Timepix}} - z_{\mathrm{telescope}} \rvert < 0.3\,\mathrm{mm}$

Resolution of quad module



Determine overall accuracy of a track position measurement by comparing the quad track with the telescope track

- Subtract a background of unrelated tracks

Error contributions:

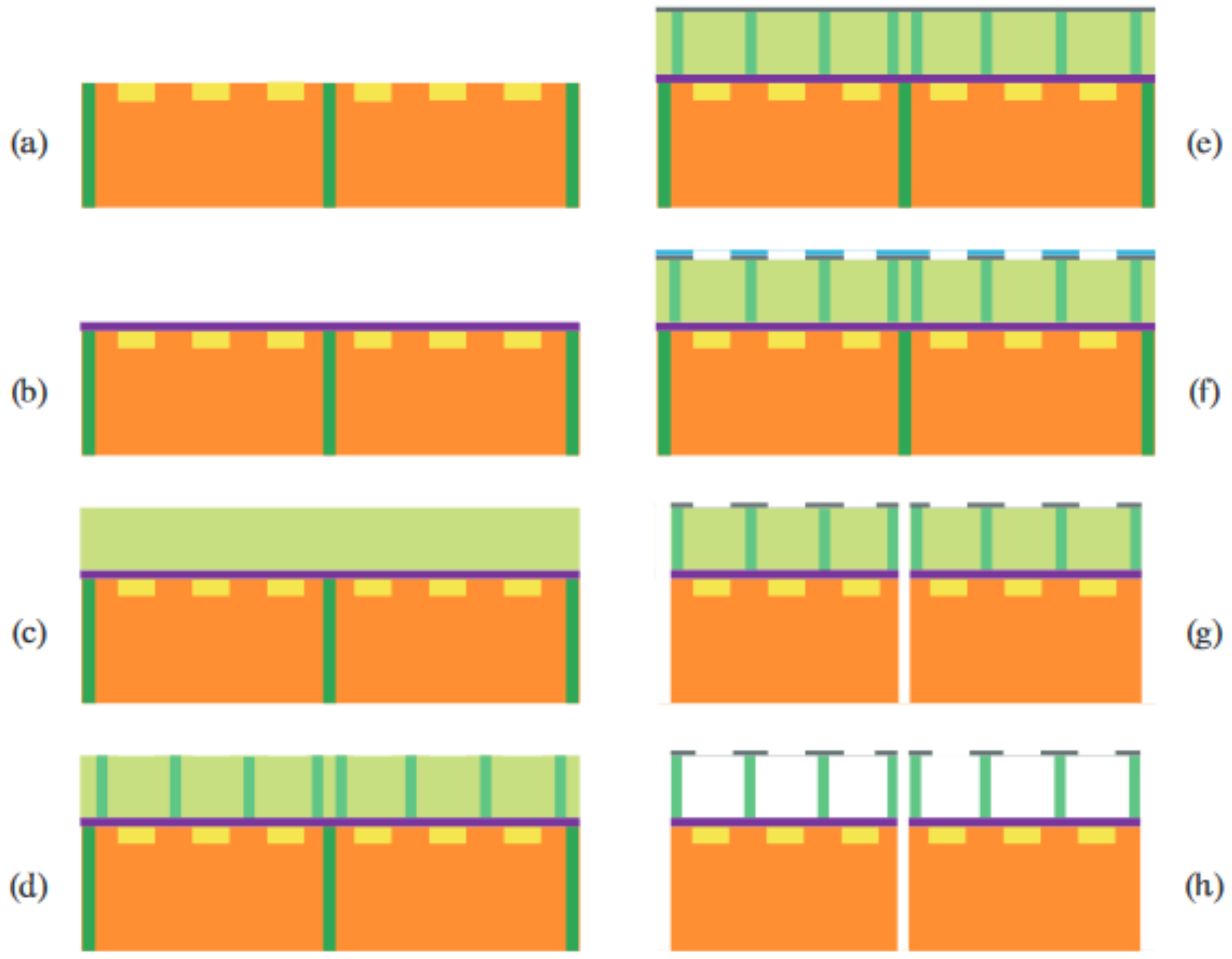
- Statistical error using hit resolution
- Systematic errors from RMS in pixel plane and drift direction
- Multiple scattering contribution from simple Monte Carlo simulation

In the end, an unidentified contribution remains

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

Production of GridPixes

a) Cleaning
b) Deposition of Protection layer
c) SU-8 covering
d) Exposure with mask
e) Aluminium layer is deposited
f) Another layer of photoresist is applied, exposer with a mask creates a hole pattern, and the holes are chemically etched
g) The wafer is diced
h) The unexposed SU-8 is resolved



Thesis Stergios Tsigaridas, *Next Generation GridPix*

Motivation for a pixelised TPC

- Improved dE/dx by cluster counting
- Improved measurement of low angle tracks
- Improved double track separation
- Much reduced hodoscope effect
- Lower occupancy in high rate environments
- Fully digital read out
- Reduced ion backflow by adding a double grid