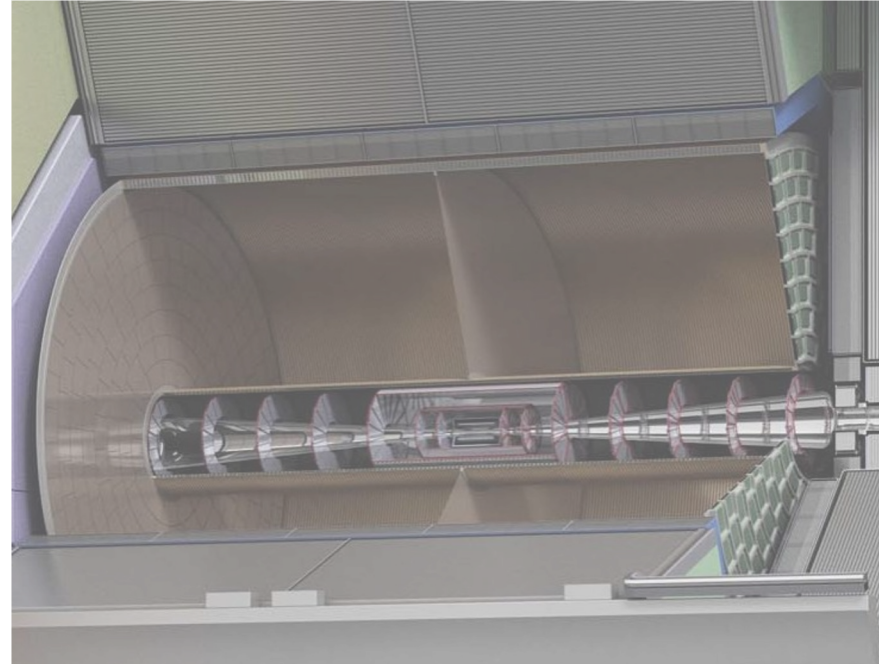


A (Pixel) TPC for ILD @ FCC

Based on the ILD-TPC
Workshop

On behalf of ILD TPC group

Peter Kluit



CERN ILD workshop September 2026



Peter Kluit (Nikhef)





TPC requirements

The R&D on a TPC for a e.g. Linear Collider is done in the LCTPC collaboration

Requirements for a TPC from the ILC TDR

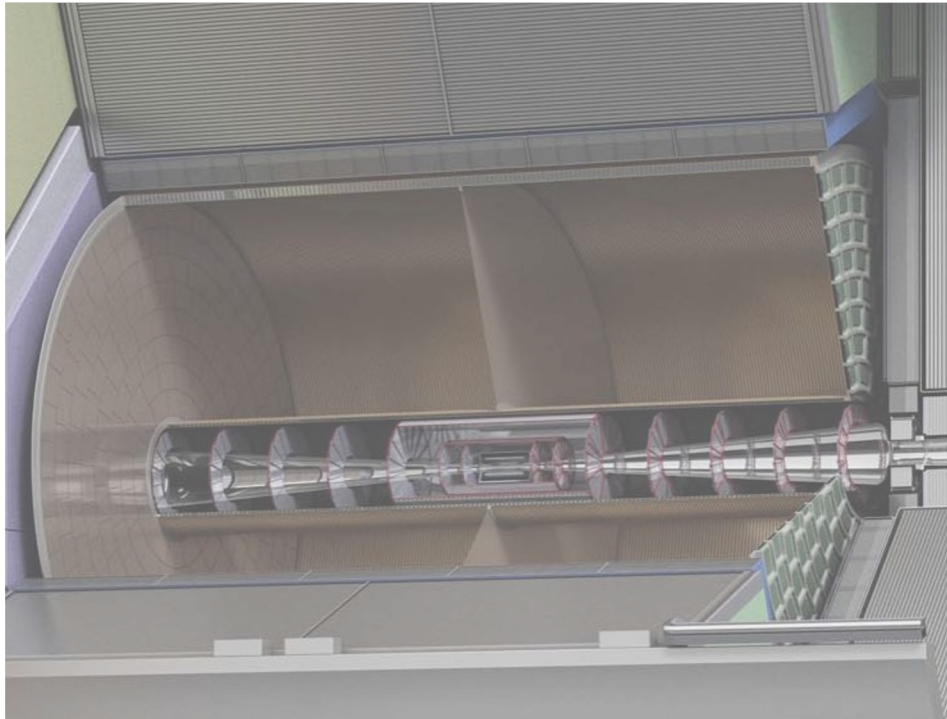
Table, large TPC, for pad/pixel electronics

Parameter	
B-field	3.5T
Geometrical parameters	r_{in} r_{out} z 329 mm 1808 mm ± 2350 mm
Solid angle coverage	Up to $\cos \theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05 X_0$ including outer fieldcage in r $< 0.25 X_0$ for readout endcaps in z
Number of pads/timebuckets	$\simeq 10^6/1000$ per endcap
<i>Number of pixels/timebuckets</i>	<i>$\simeq 10^9/1000$ per endcap</i>
Pad pitch/ no.padrows	$\simeq 1 \times 6 \text{ mm}^2 / 213$
σ_{point} in $r\phi$	$\simeq 60 \mu\text{m}$ for zero drift, $< 100 \mu\text{m}$ overall
σ_{point} in $r\phi$	$\simeq 0.055\text{mm}/\sqrt{12}$ for zero drift, 0.4mm for max drift
σ_{point} in rz	$\simeq 0.4 - 1.4 \text{ mm}$ (for zero – full drift)
2-hit separation in $r\phi$	$\simeq 2 \text{ mm}$
2-hit separation in rz	$\simeq 6 \text{ mm}$
dE/dx resolution	$\simeq 5 \%$
<i>dE/dx resolution</i>	<i>$\simeq 4 \%$</i>
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}/\text{GeV}/c$ (TPC only)
<i>Momentum resolution at B=3.5 T</i>	<i>$\delta(1/p_t) \simeq 0.8 \times 10^{-4}/\text{GeV}/c$ (60% cov, TPC only)</i>



- ILD like detector concept with a TPC central tracker can be used for FCC
- Challenging tracking precision
 - driven by Higgs running
- For Z running the requirement on $\delta(1/p_t)$ can IMO be loosened by e.g. a factor 10 (LEP like)

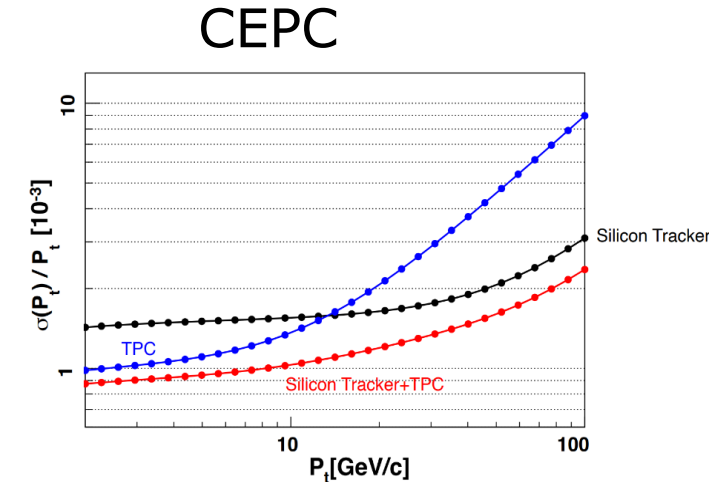
ILD TPC layout



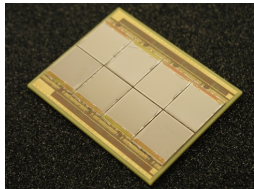
- Material budget is
 - 0.01 X_0 TPC gas
 - 0.01 X_0 inner cylinder
 - 0.03 X_0 outer cylinder
 - $< 0.25 X_0$ endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between silicon detectors VTX, SIT and SET
- pixel readout is a serious option for the TPC readout plane @ ILC/FFC-ee/CLIC/CEPC colliders

Why a (pixel) TPC as a central tracker

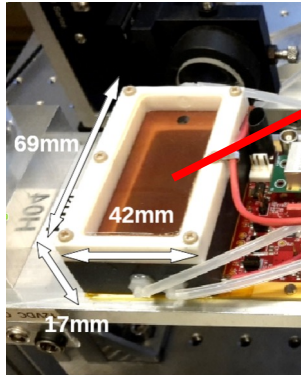
- Low material budget that allows high precision tracking
- Continuous 3D tracking (x,y, t) and track following
 - Excellent v0 reconstruction
 - Ideal for particle flow and combined calorimetry
- TPC is sliced between silicon detectors
 - provides required momentum resolution and constraints
- Very powerful particle identification based on dEdx
 - for electrons (suppress pions)
 - for kaons ($H \rightarrow ss$) and protons
- TPC excellent option for FCCee WW, ZH, tt etc running
- Running at the Z is challenging due to synchrotron backgrounds
- A pixel TPC combines a large drift volume with a silicon read out plane
 - tracking with high granularity and low systematic uncertainties due to "silicon" precision (1-10 μm) in the production process
 - the best (see slides) PID performance dEdx and cluster counting



Pixel TPC

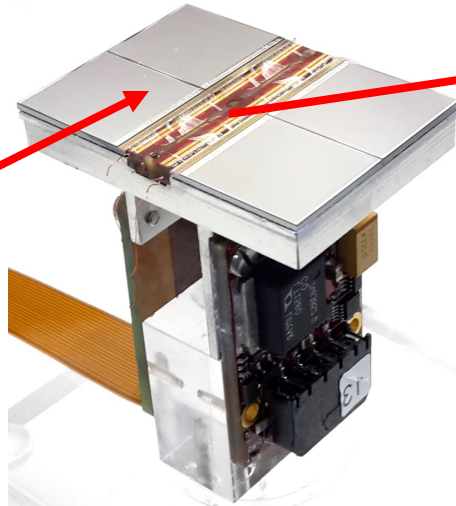


(Octopuce)



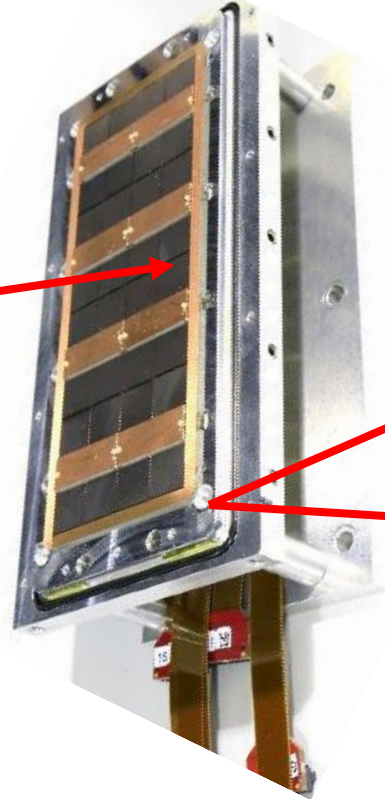
TPX3 chip

2017



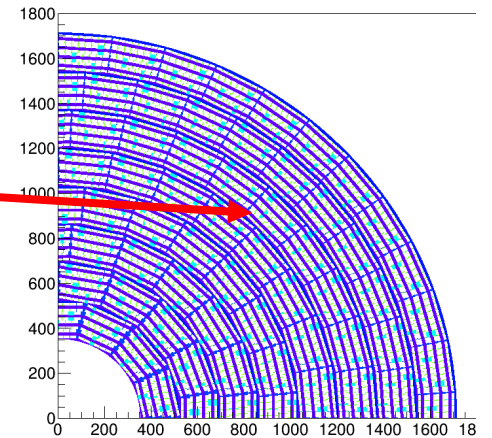
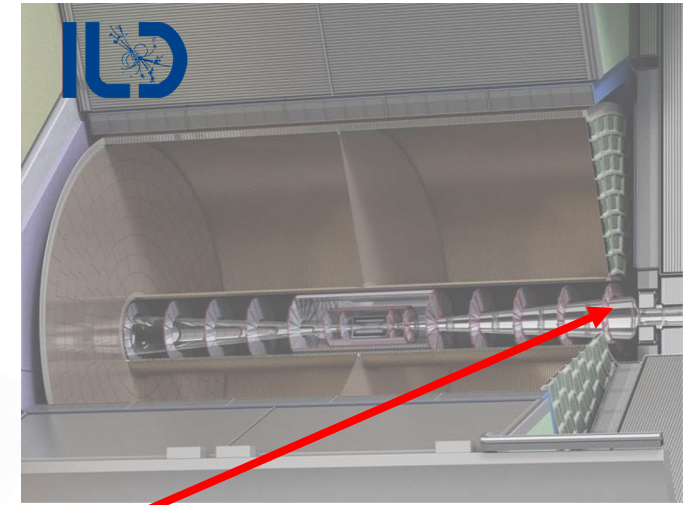
Quad

2018



Module

2019



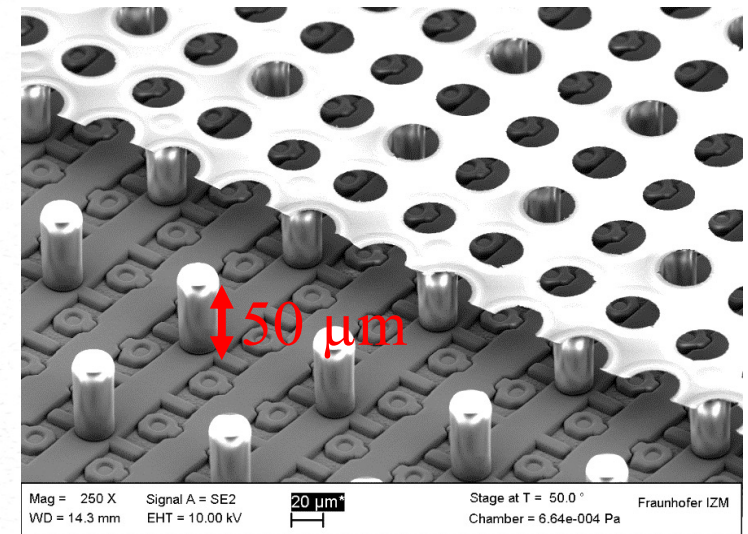
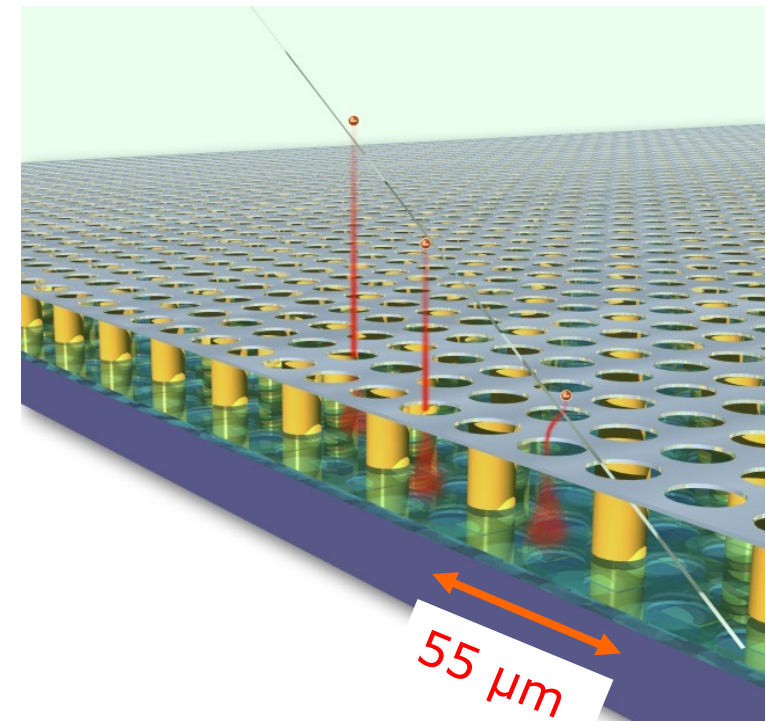
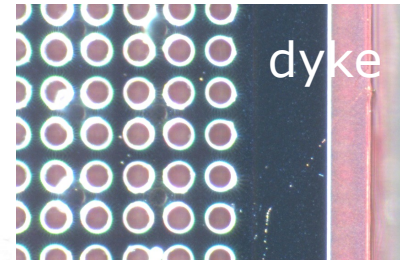
TPC plane

(TimePix1)

(2007-14)

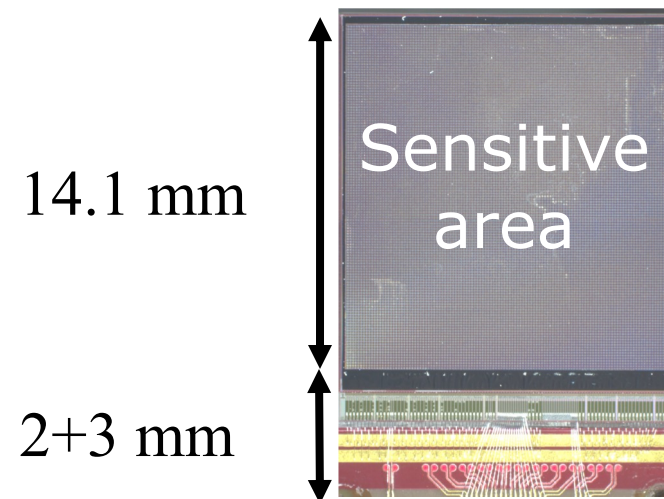
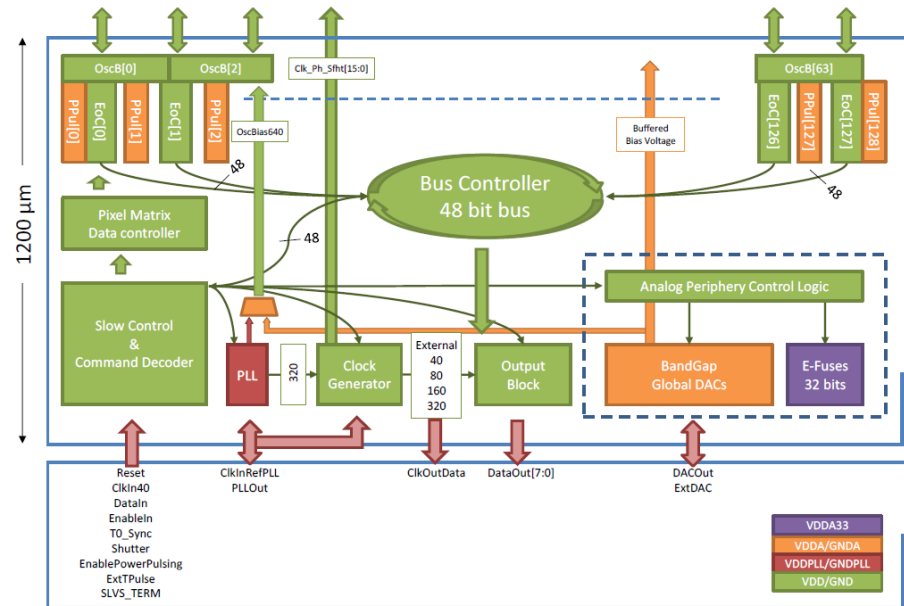
GridPix technology

- Pixel chip with integrated Grid (Micromegas-like)
 - InGrid post-processed @ IZM (in 2025 @ Bonn)
 - 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



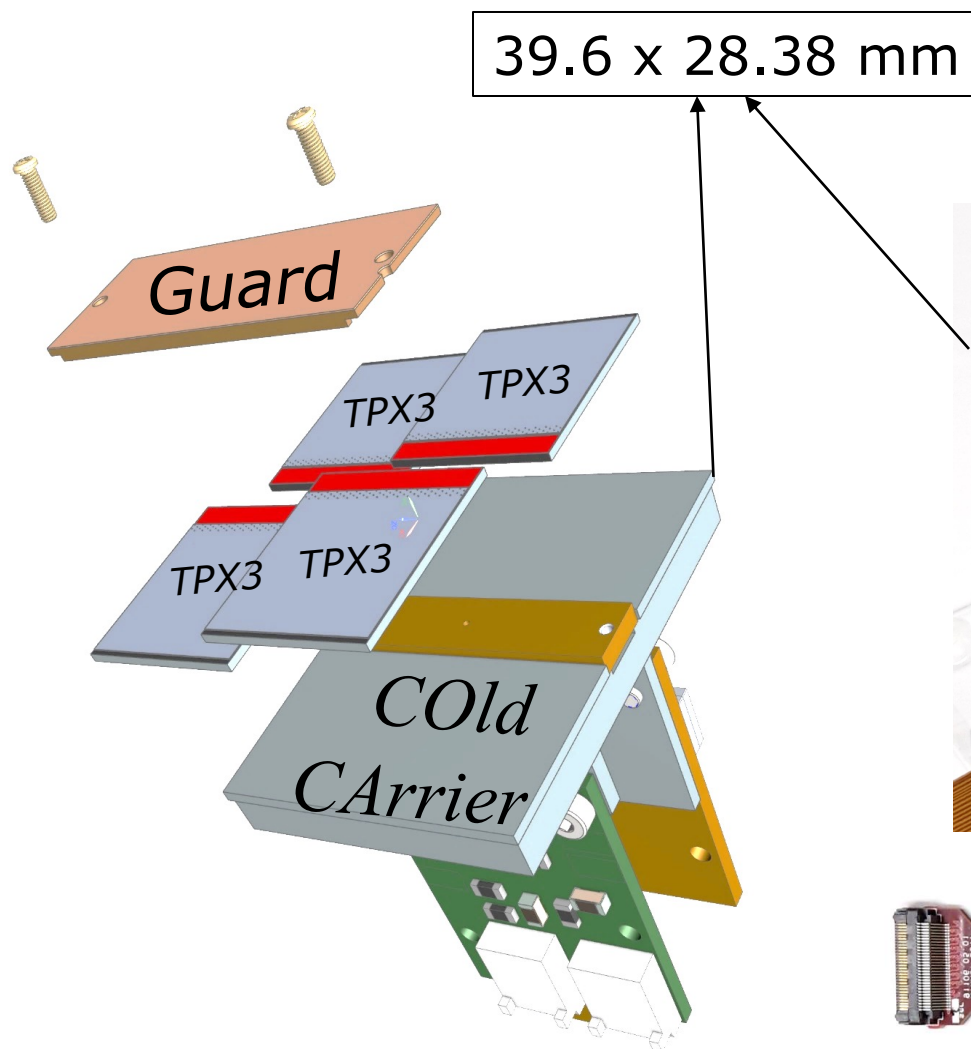
Pixel chip: TimePix3

- 256 x 256 pixels
- 55 x 55 μm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.56 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
 - $\sim 1\text{ A}$ @ 2 V (2W) depending on hit rate
 - good cooling is important

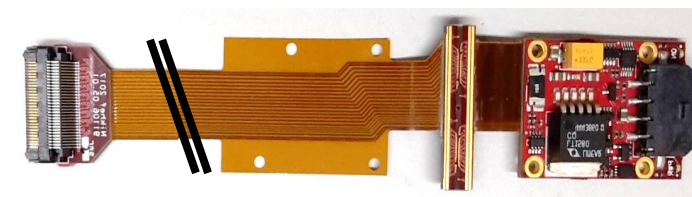
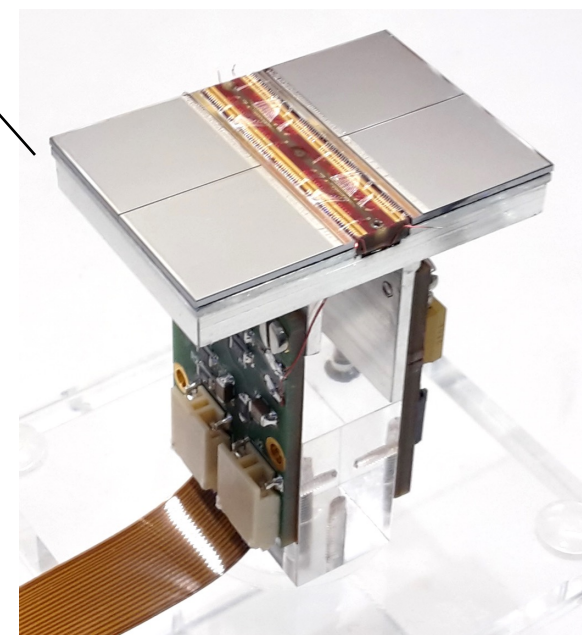


QUAD design and realization

- 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 a sensitive area of 68.9%
- DAQ by SPIDR board

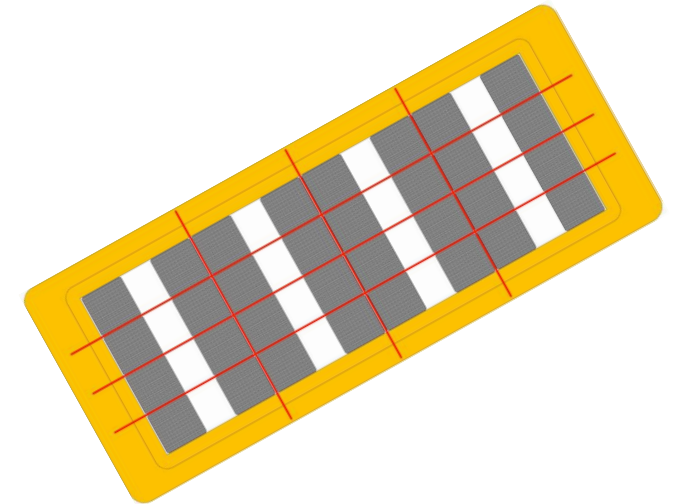
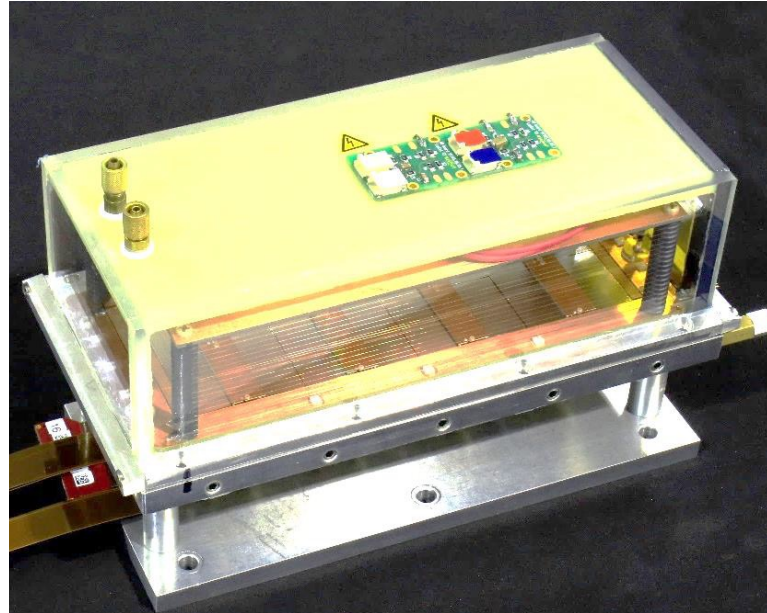
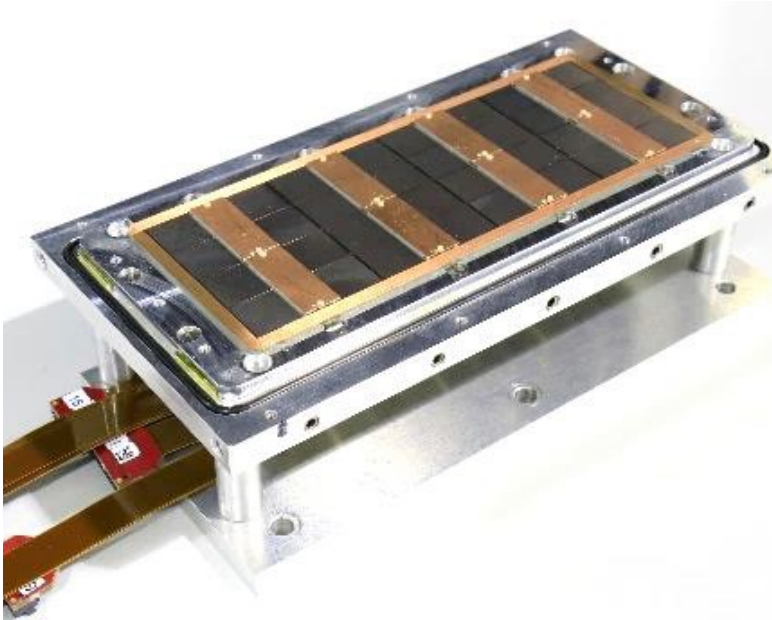


series of QUADs

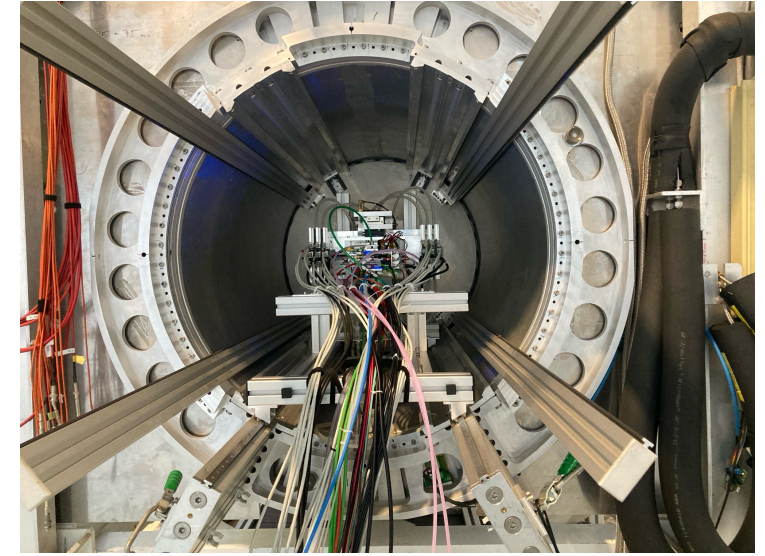
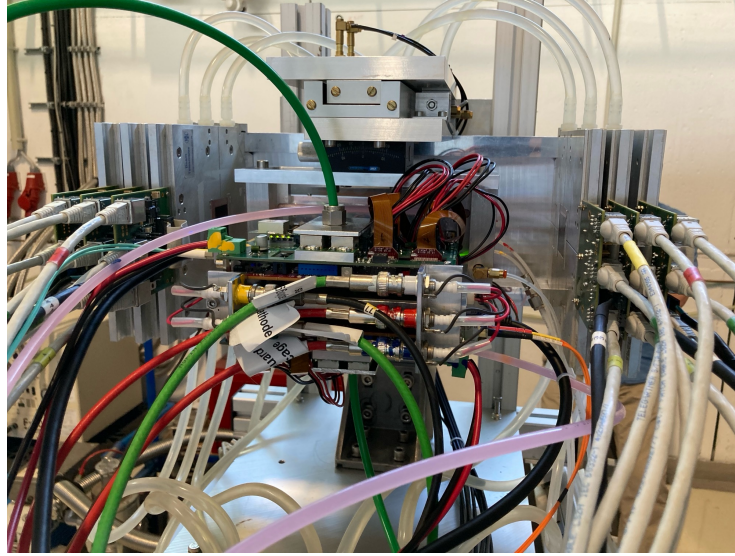
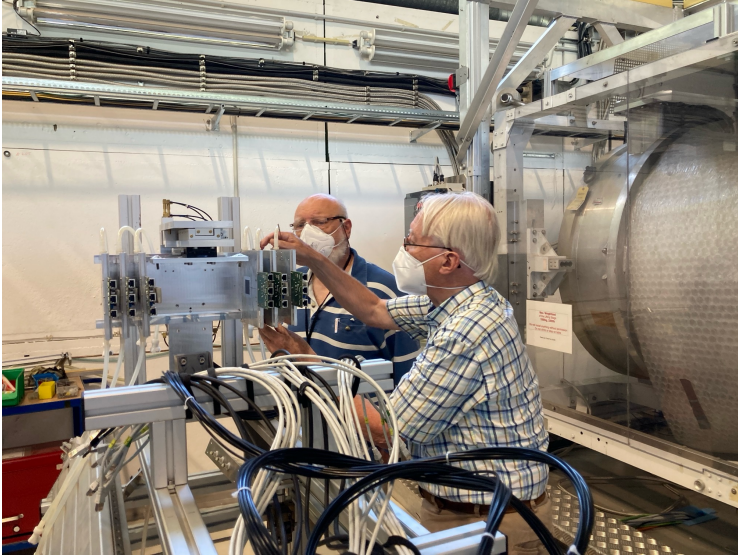


QUAD as a building block

8-QUAD module (2x4 quads) with field cage



in red guard wires



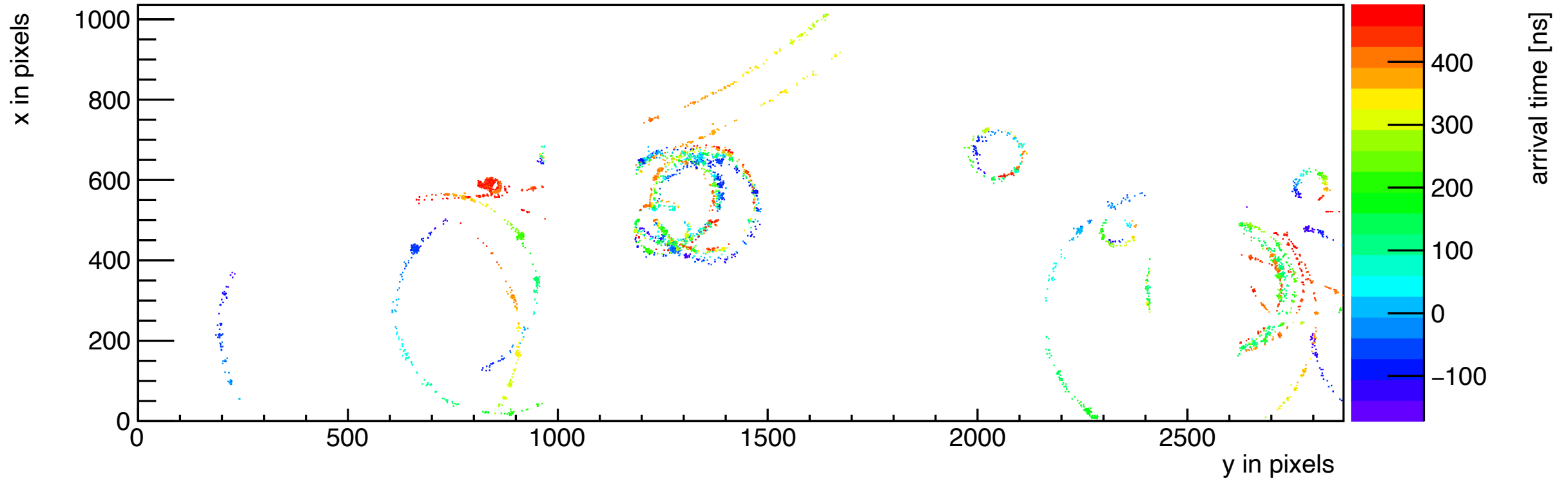
Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

Towards a Pixel TPC part I: construction and test of a 32-chip
GridPix detector, Nucl. Instrum. Meth. A 1075 (2025) 345

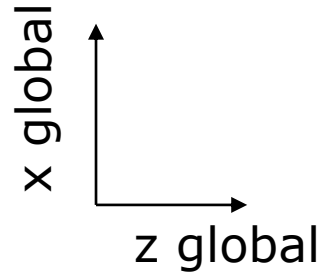
DESY LCTPC-Pixel Testbeam

Run 6969 Event 2

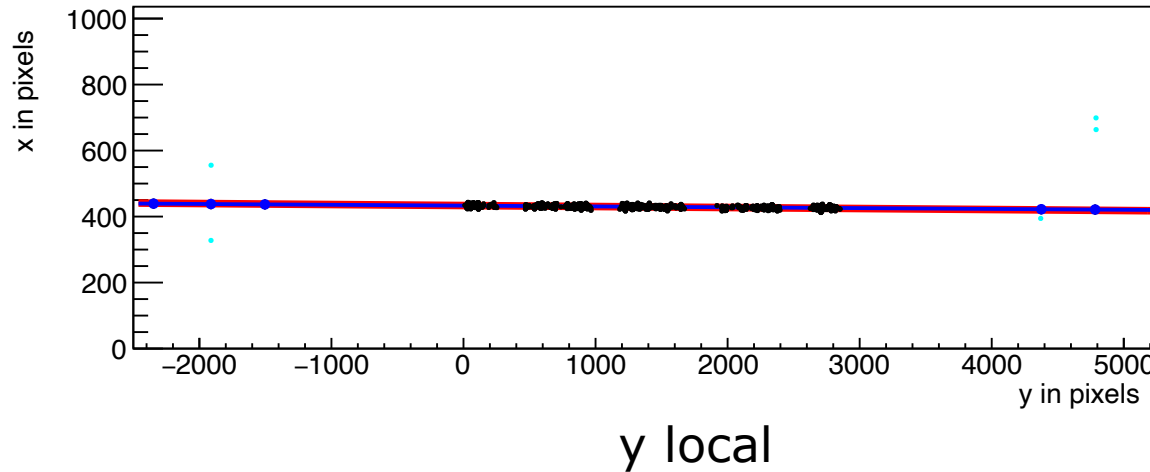
Bfield 1.0 T beam momentum 6 GeV/c



DESY LCTPC-Pixel Testbeam Run 6916 Event 12 Bfield 0 T beam momentum 6 GeV/c



x local



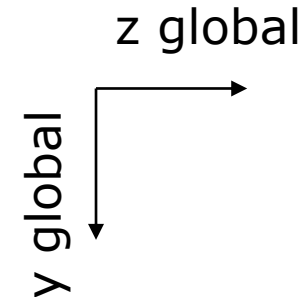
Event display with
module and telescope

TPX3 track 1130 hits

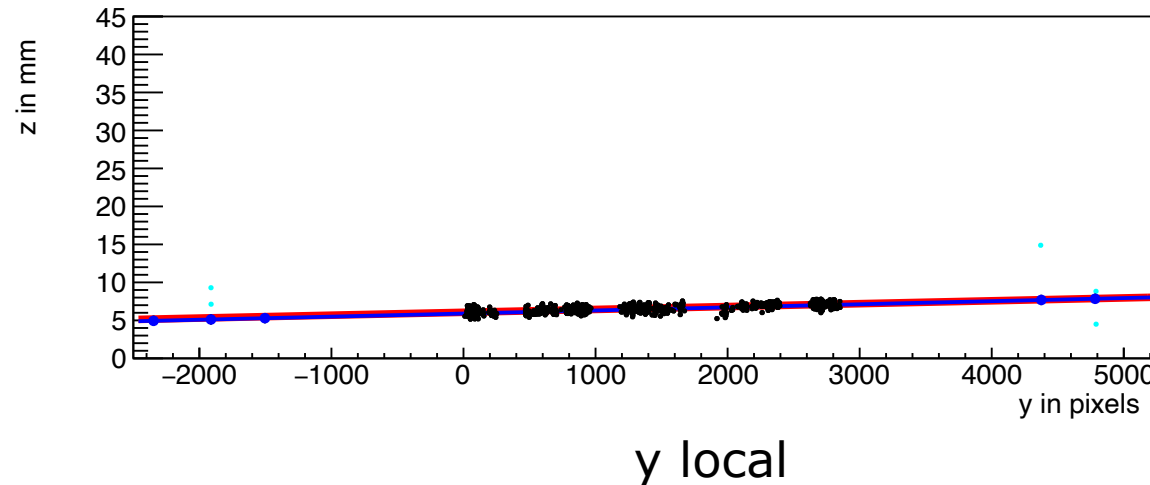
$$\chi^2_{xy} = 677.5/1128$$

$$\chi^2_z = 775.9/1069$$

Asymmetric tail outlier
removal applied 1071
hits in z kept.



z local drift



TPX3 track hits

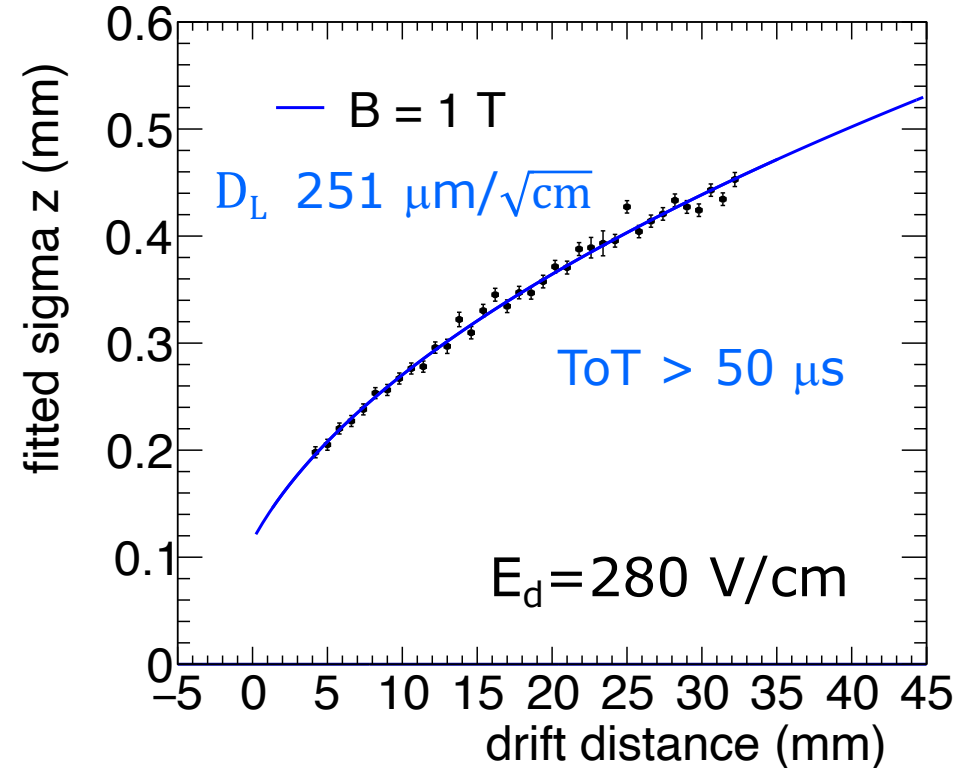
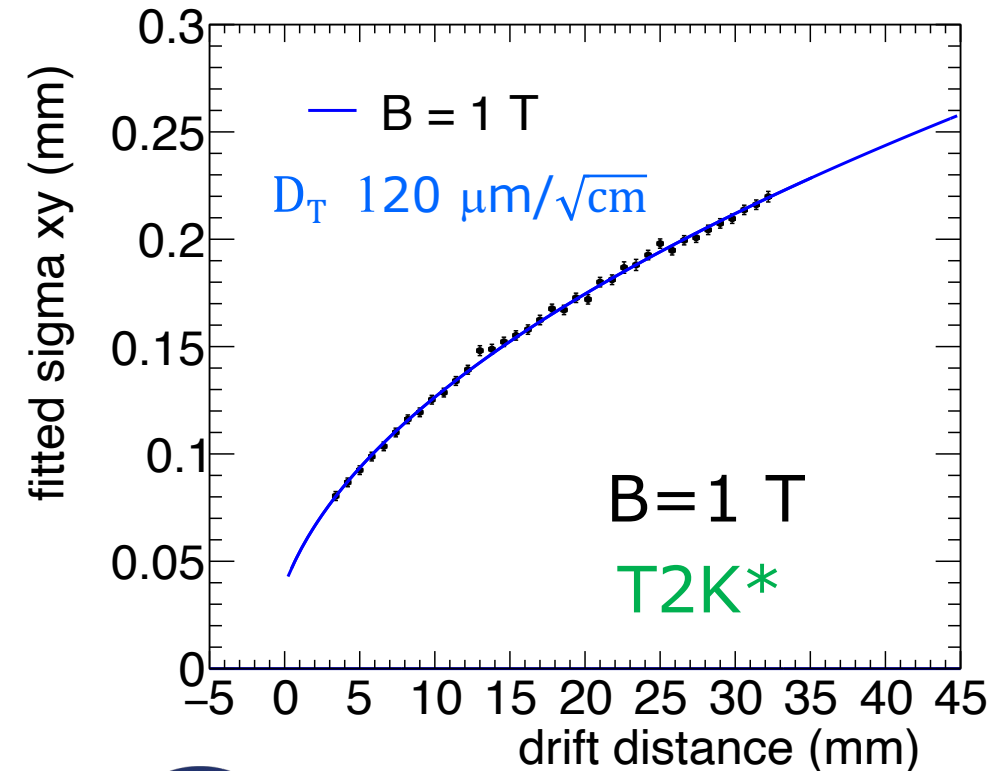
Telescope track hits (off
track green)



B=1 T p=5 and 6 GeV

Fitted resolution

$$\sigma_{xy,z}^2 = \sigma_{xy0,z0}^2 + D_{xy,z}^2 (z - z_0)$$



$$\sigma_{xy0}^2 = \sigma_{\text{pixel}}^2 + \sigma_{xy \text{ tele}}^2$$

$$\sigma_{\text{pixel}}^2 = 55^2/12 \mu\text{m}^2$$

$$\sigma_{xy \text{ tele}} = 42 \mu\text{m}$$

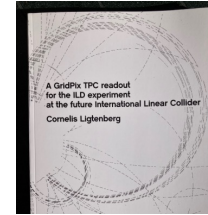
Magboltz gives for
 $D_T = 121 \mu\text{m}/\sqrt{\text{cm}}$

T2K* = T2K gas
 with O₂ and H₂O

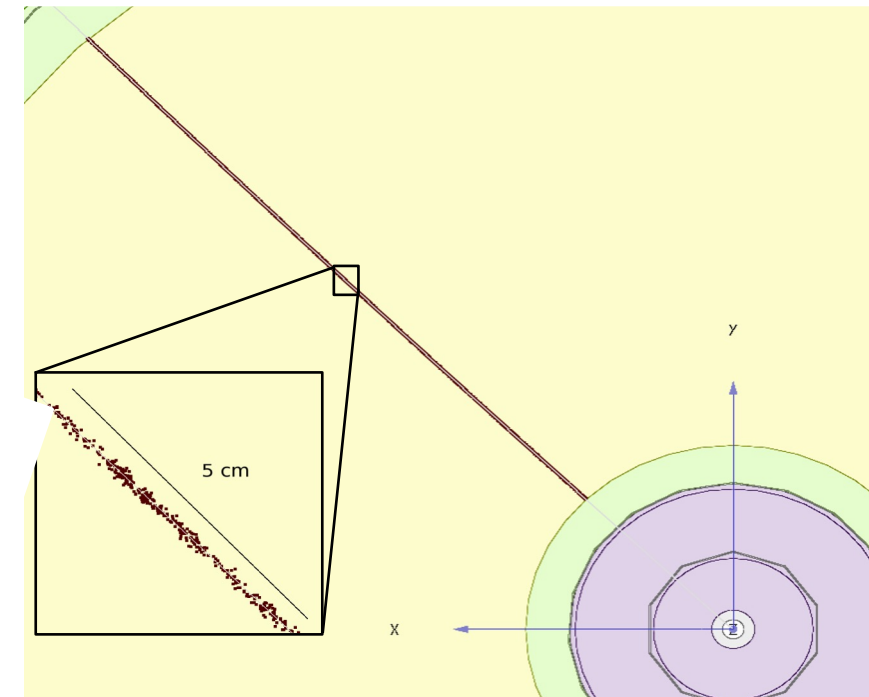
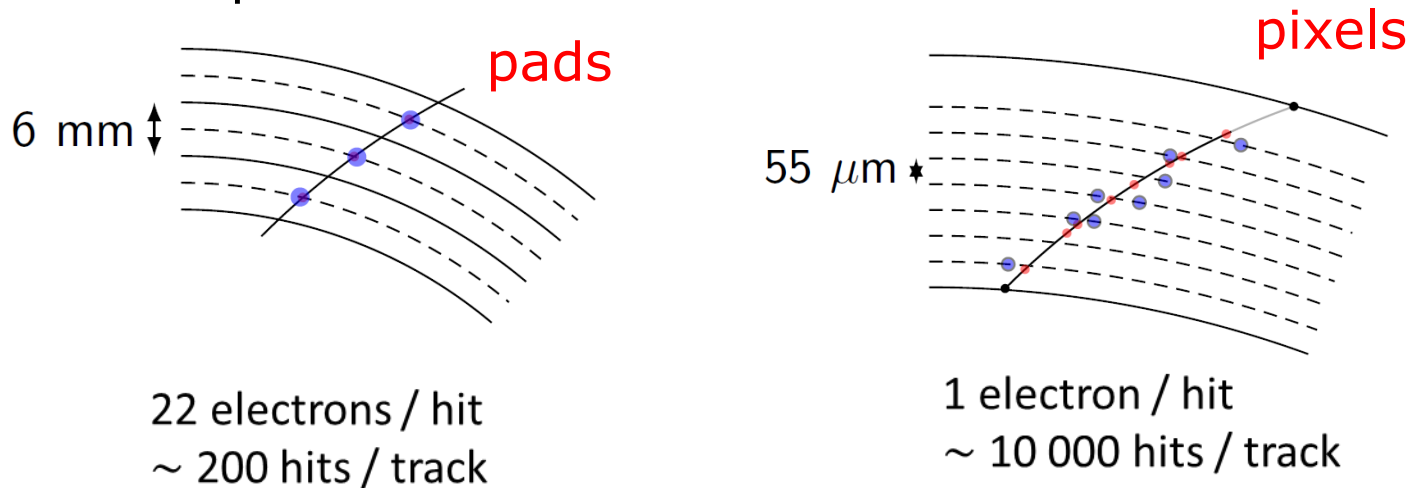
- The test beam results for the module showed that:
 - the HV of the guard wires was well tuned
 - B=0 T rms residuals in the module plane xy 13 μm and z 15 μm
 - The results are compatible with (very) high stats quad measurement
 - B= 1 T rms residuals in the plane xy 13 μm and z 20 μm ;
- High tracking precision is demonstrated with small systematics
 - deformations xy stay below 13 μm
- Published in [Nucl. Instrum. Meth. A 1075 \(2025\) 345](#)
Towards a Pixel TPC part I: construction and test of a 32-chip GridPix detector

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



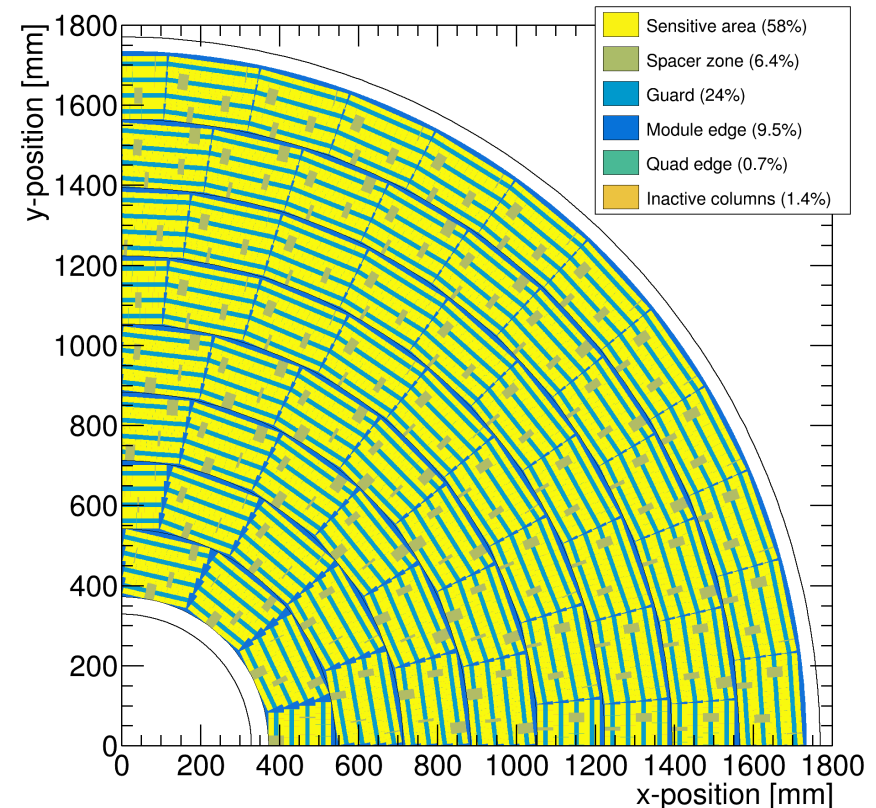
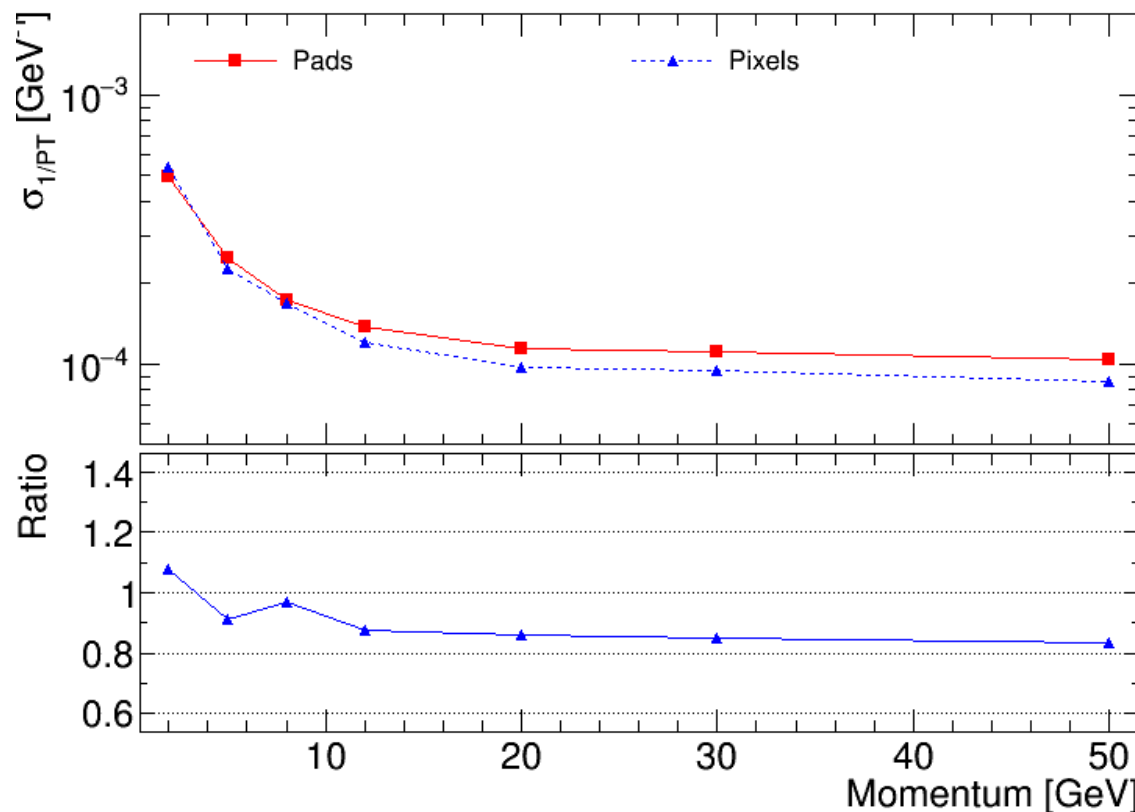
details: PhD [thesis](#)
Kees Ligtenberg 2022



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 coverage 59%) and deltas.

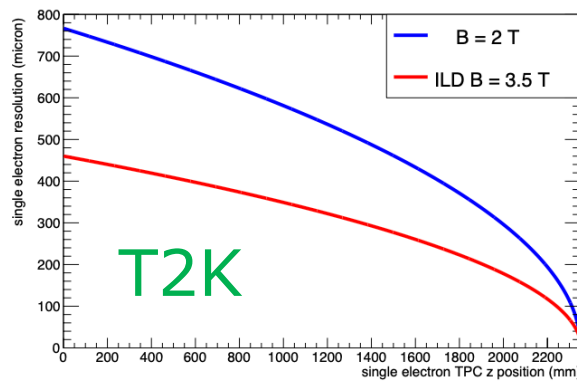


ILD tracking Performance for a Pixel TPC based on test beam

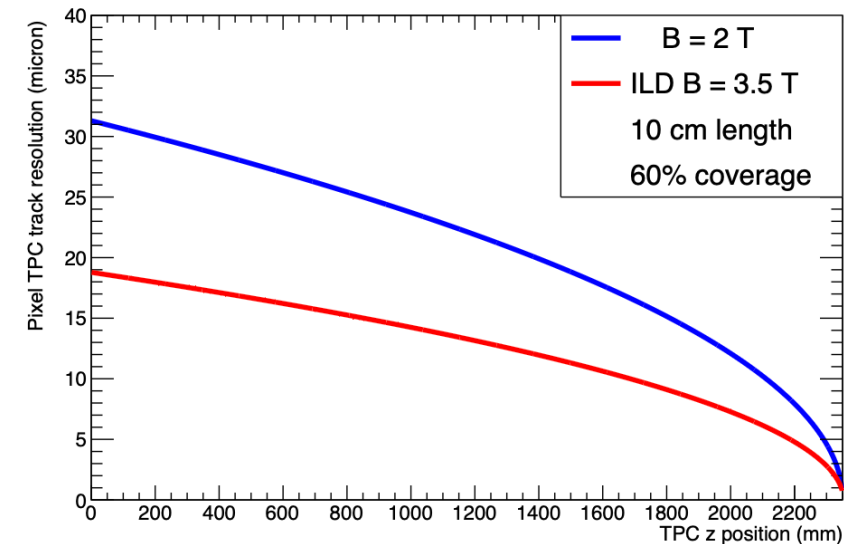
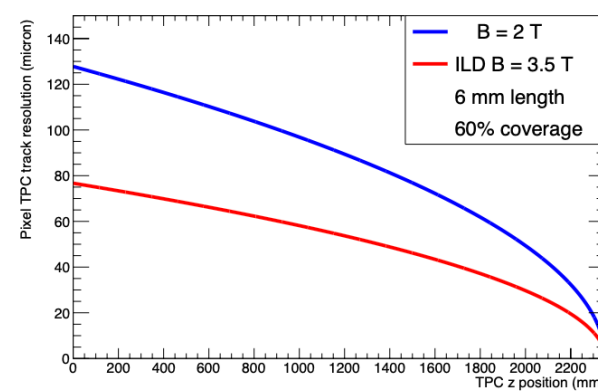
Running at $B=3.5$ T improves the resolution

10 cm track resolution

Single electron resolution



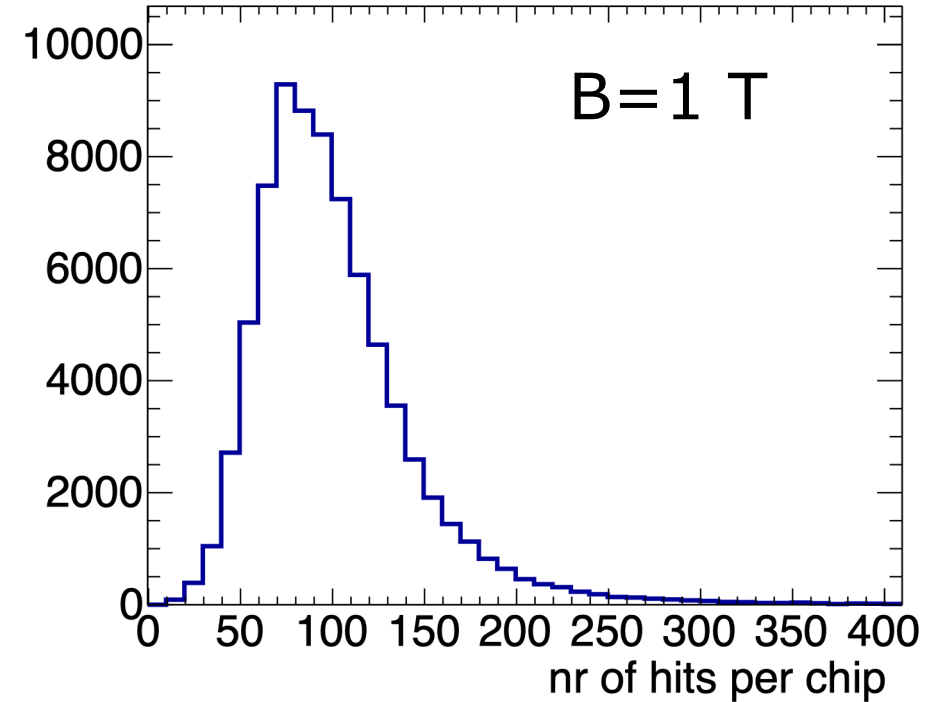
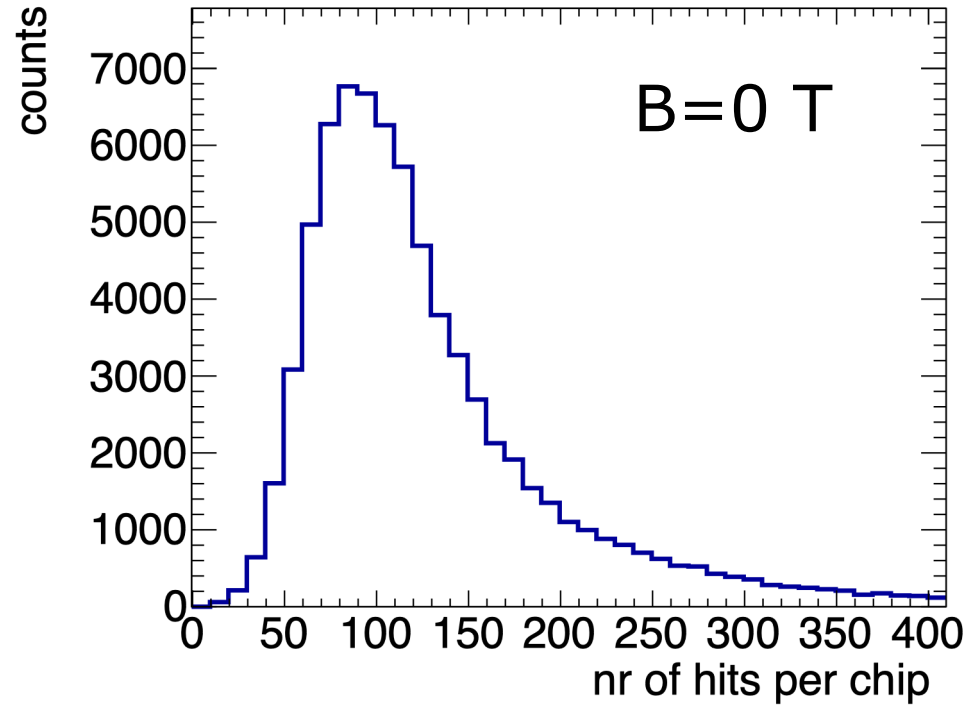
6 mm track("pad") resolution



Each 10 cm we have a point with a resolution of < 18 (31) μm on the track
Comparable to performance of a silicon detector (but TPC gas material).

Testbeam PID performance

NIM A 1075 (2025) 345



- $B=0$ T has a large Landau tail
- $B=1$ T smaller Landau tail and a more gaussian distribution
- An electron crossing 8 chips in the module has about 1000 hits

Combine chips to form a 1 m long track with 60 % coverage for electrons

- ❑ **Method 1 "dEdx truncation"**: reject large clusters and then run dEdx @ 90% using slices of 20 pixels along track (xy) (gives nr of selected hits). A large cluster has more than 6 hits in 5 consecutive pixels.
- ❑ **Method 2 "Template fit"**: fit the slope of the N_{scaled} minimum distance (d) in xy distribution with an exponential function ($N_{\text{scale}}(d)$ =defines the inverse weights):

$$N(d)_{\text{scaled}} = N_{\text{scale}}(d) N_{\text{observed}}(d)$$

$$N(d)_{\text{scaled}} \text{ is then fitted for each track with } N_0 \exp(-\text{slope } d)$$
- ✓ Calculate the PID observable for electrons and MIP (==70% of hits)
 - method 1 = nr of selected hits, method 2 = fitted slope
 - Resolution is $\sigma = \sigma(\text{PID})/\text{PID}$ (for σ we use the rms)

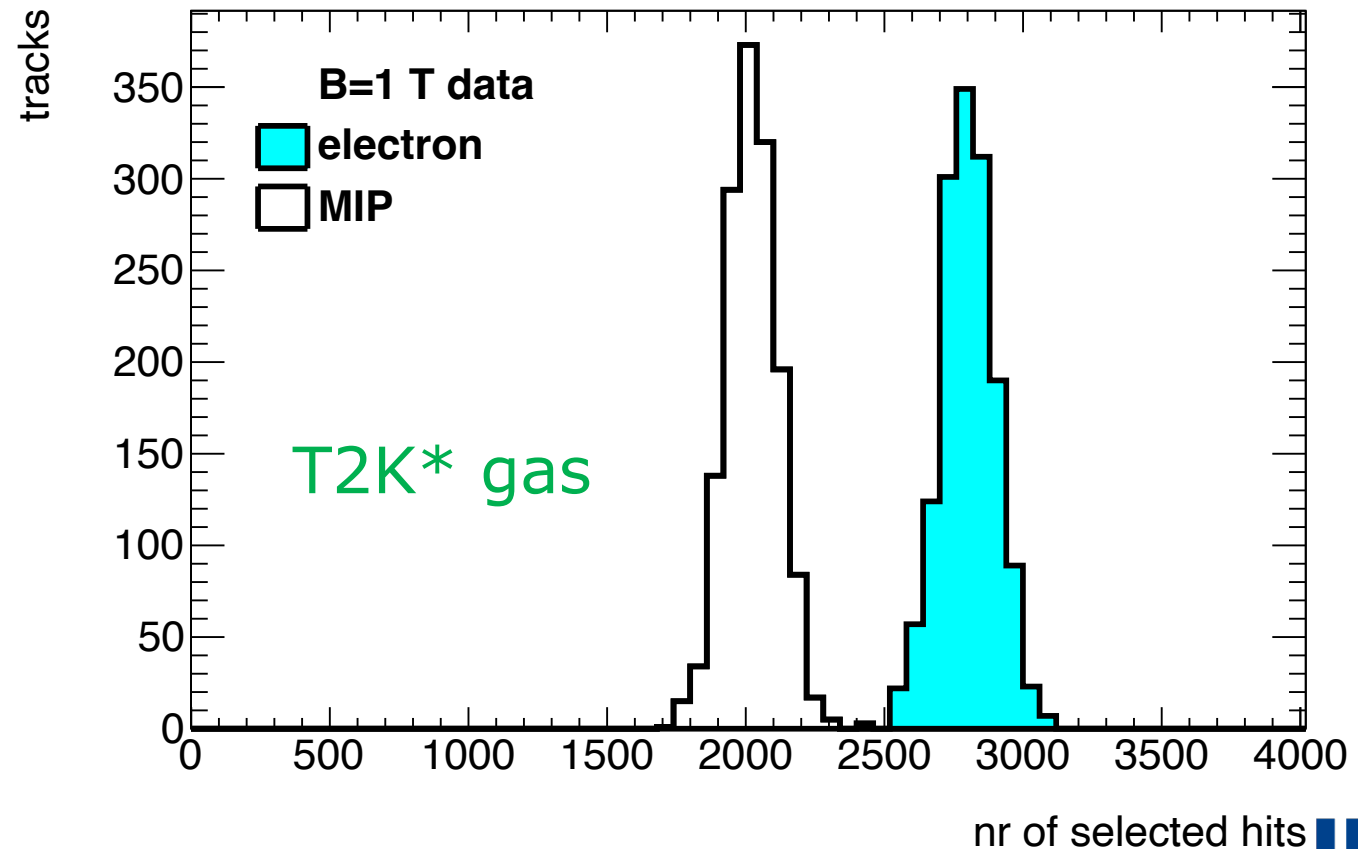
PID performance method "dEdx truncation"

Electron resolution
3.6%

1 m track 60% and
coverage

Linearity MIP-e = 1.03
z drift=5-15 mm (flat)

MIP distribution is obtained
by dropping 30% of the hits

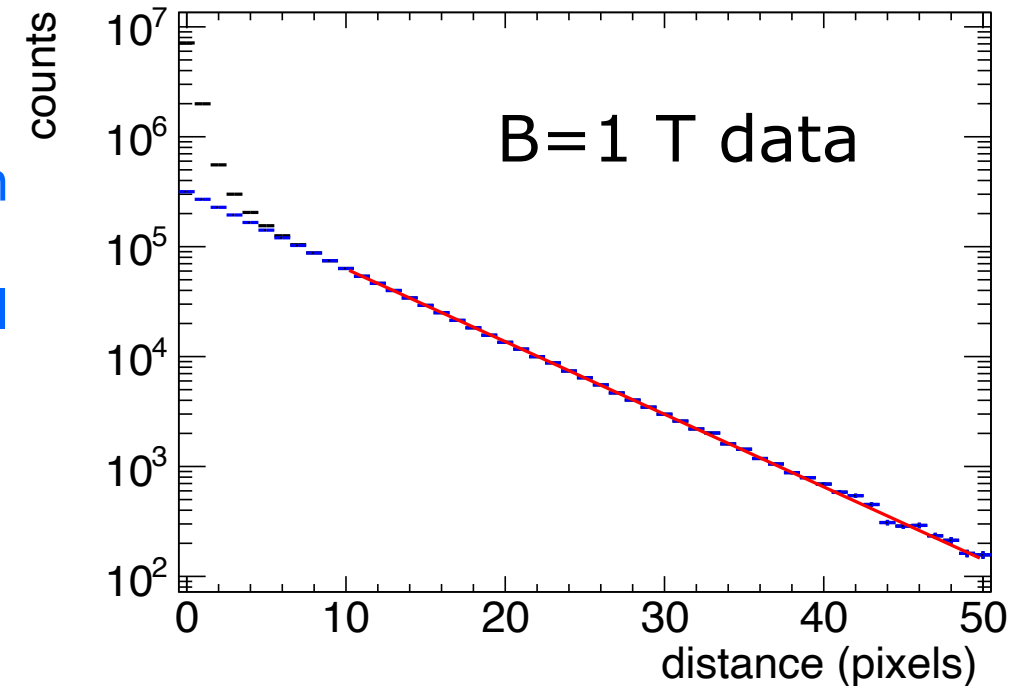


PID performance method "Template fit"

Calculate minimum distance between the hits.
The slope of the distribution is related to the
number of primary clusters /cm

The diffused peak at $d < 10$ (black) comes from
clusters with more than 1 hit. Weights are
applied at $d < 10$ to follow the exponential
cluster distance distribution (blue). In red the
exponential function.

Per 1 m track the slope is fitted to the full
distance distance distribution using a ML fit.



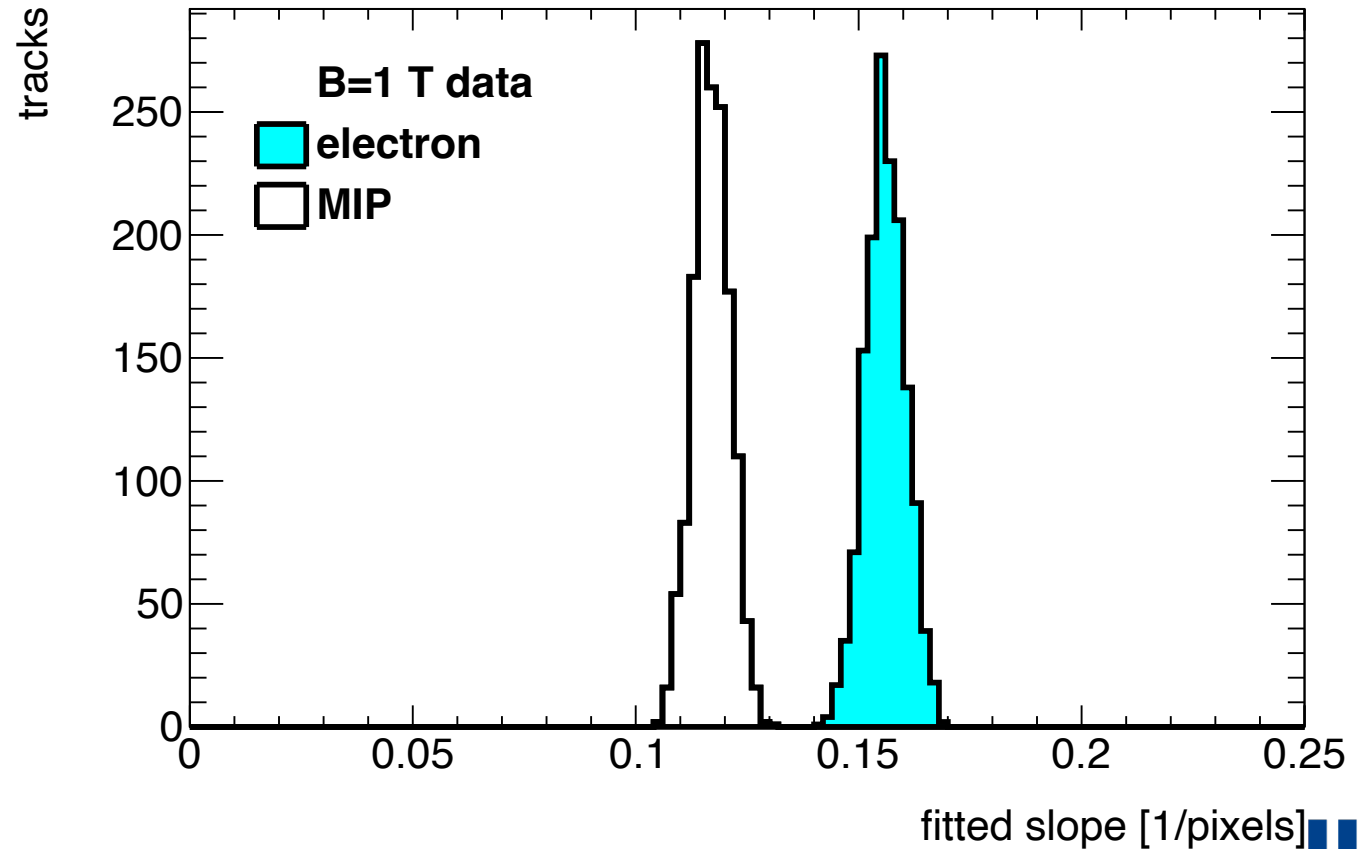
PID performance method "Template fit"

Electron resolution
2.9%

1 m track 60% and
coverage

Linearity MIP-e = 1.07

Ideally this is 1. A number
larger than 1 means that
the resolution is +7% larger



Summary of PID performance

The PID resolution for electrons from data by combining tracks to form a 1 m long track with realistic coverage $\sim 60\%$ coverage.

Method	B=0 Resolution (%)	B= 1 T Resolution (%)
(1) dEdx truncation	6.0	3.6
(2) Template fit	5.4	2.9

The resolution for B=0 is worse than of the B=1 T data because of the larger fluctuations, that were already observed at the chip level.

Published as "Towards a Pixel TPC part II: particle identification with a 32-chip GridPix detector", [Nucl. Instrum. Meth. A 1081 \(2026\) 170849](#)

dEdx Performance extrapolated to the ILD detector

Test beam $B = 1 \text{ T}$
 $p = 5,6 \text{ GeV/c}$

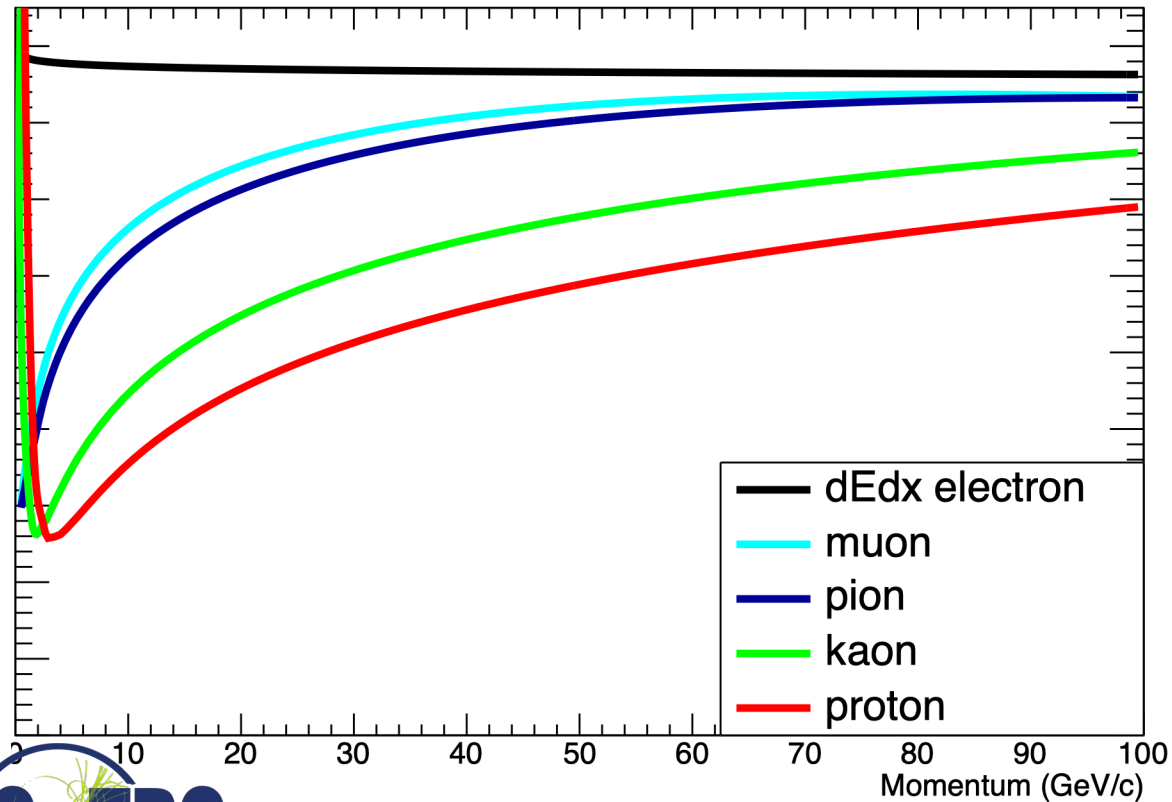
electron resolution $2.9(3.6)\%$
 for method 2 (1)

1 m track 60% and coverage

ILD detector

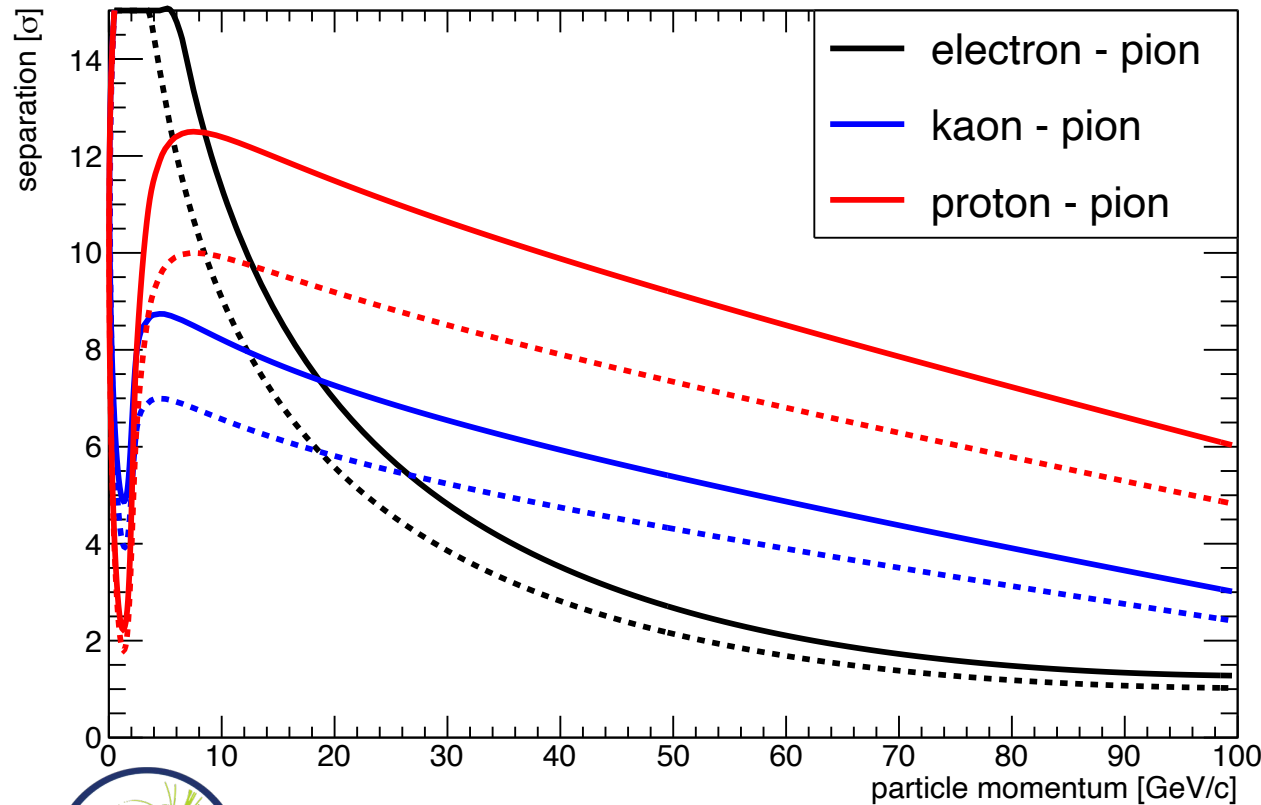
$r_{\text{Inner}} = 329 \text{ mm}$ $r_{\text{Outer}} = 1770 \text{ mm}$
 halflength (z) = 2350 mm
 electron resolution = $2.5(3.0)\%$
 at $\theta = \pi/2$ for method 2 (1)

Assume Pixel TPC performance at
 $B = 1 \text{ T}$ at $p = 5,6 \text{ GeV/c}$



- Ullrich Einhaus performed dEdx studies in ILD and extracted the ILC soft parametrisations for energy loss based on G4 and full simulation of the ILD TPC with T2K gas
- [Link](#) to the software. Samples were generated in 2020 with ILC soft v02-02 and v02-02-01

Pixel TPC PID performance

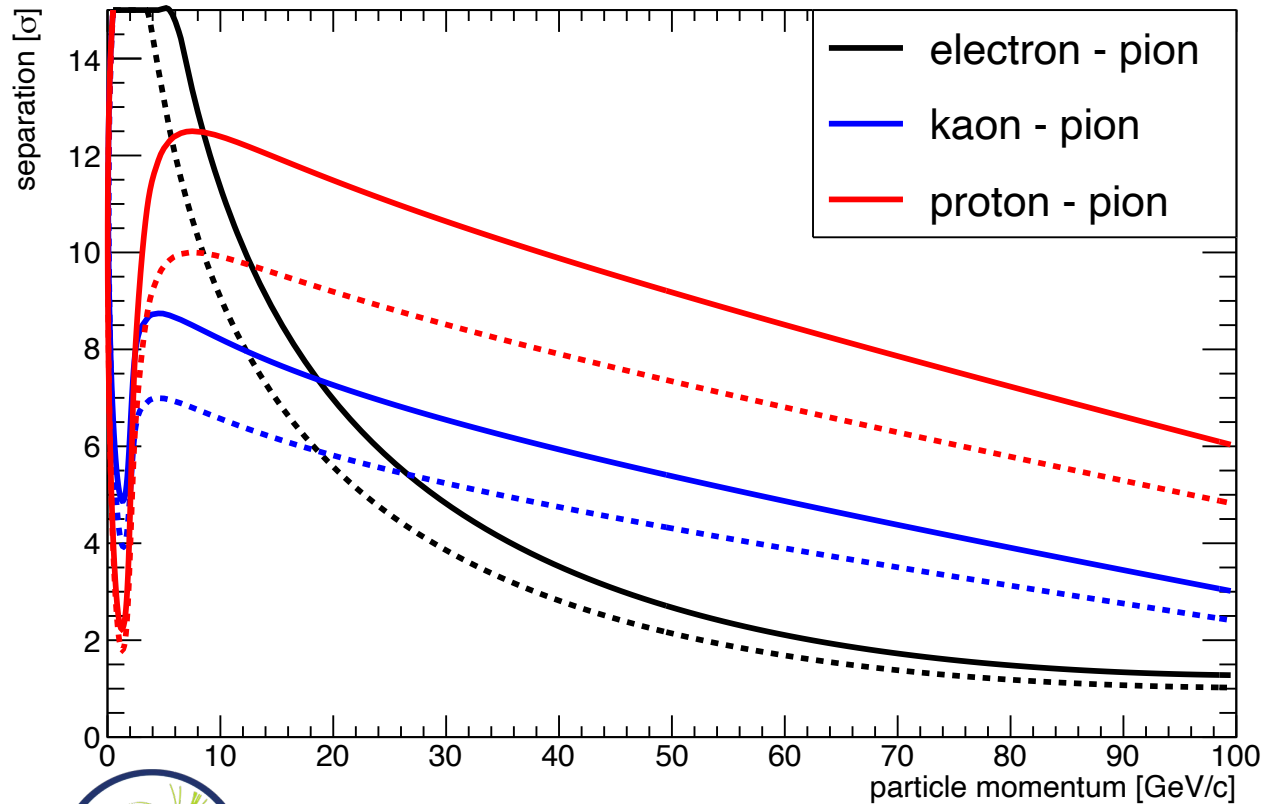


- ILD Performance with specified detector dimensions for particles at $\cos \theta = 0$
- Pixel TPC resolution from electron $p = 5$ (6) GeV test beam (for $B = 1$ T) of 2.5% and 3% (--- = method 1) at $\cos \theta = 0$
- Separation electron pion defined as:

$$|\langle \text{Eloss } e \rangle - \langle \text{Eloss } \pi \rangle| / \sigma_{\pi}$$
- Separation pion kaon as:

$$|\langle \text{Eloss } \pi \rangle - \langle \text{Eloss } K \rangle| / \sigma_{\pi}$$

Pixel TPC PID performance



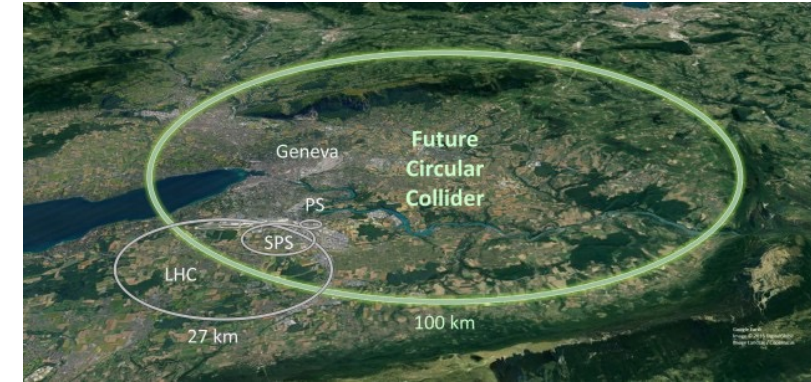
- The expected **pion-kaon** separation for momenta in the range of 2.5-45 GeV/c at $\cos \theta = 0$ is more than **5.5(4.5) σ** for the two resolution scenarios.
- At a momentum of 100 GeV/c the separation is still 3.0(2.0) σ .
- **Protons** can be separated from pions for momenta in the range of 2.5-100 GeV/c with more than **6.0(4.8) σ** .

- The PID resolution for an electron with $p=5,6$ GeV/c of 1 m track length with 60% coverage is measured to be 2.9(3.6)% at $B = 1$ Tesla.
- The extrapolated PID resolution for an ILD detector is 2.4% (3%)
- This allows for particle identification and separation of kaons from pions up to momenta of 45 GeV with more than 5.5σ (4.5σ) for $\cos \theta = 0$. The separation increases up to $\cos \theta = 0.85$ (see back up slide).
- As demonstrated, the digital read out of a pixel TPC with a small pixel size allows to perform hit and cluster counting
- Currently a coverage of $\sim 60\%$ is realized with the TPX3 chip. Using the next generation TPX4 chip with Through Silicon Via's will allow to enlarge the coverage and increase the PID and tracking performance. The R&D is part of the DRD1 program.

A Pixel TPC at FCC



At the FCCee a pixel TPC as a central tracker – sliced between silicon detectors as in the ILD concept detector - is well suited to carry out the WW, ZH and tt physics program.



At the CEPC a pixel TPC is selected as one of the baseline CDR/TDR detectors

A more challenging situation for a TPC is running at the Z and in particular the FCCee Tera Z program with $L = 140 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and Z bosons produced at a rate of $\sim 40 \text{ kHz}$ and huge beam backgrounds. The largest background is from SR.

For the WW and Higgs runs the backgrounds are much smaller.



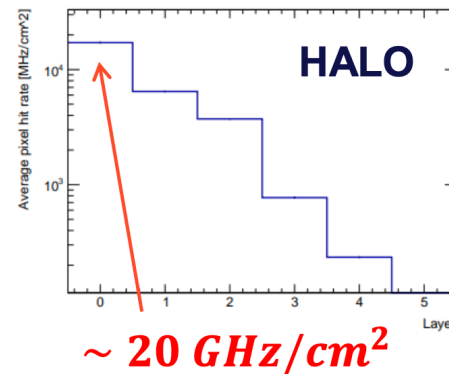
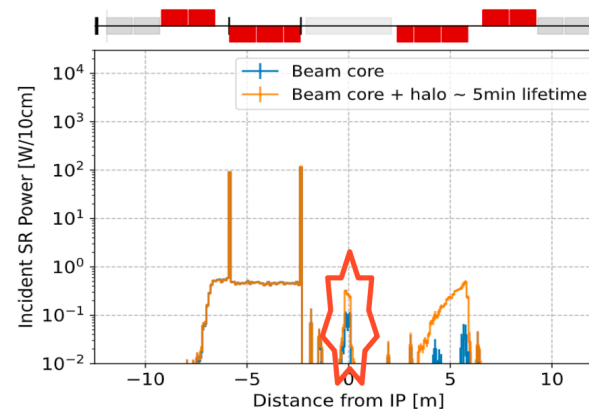
FCC Tera Z background



Synchrotron Radiation (SR)

- SR sources are upstream dipoles and beam tails at FFQs.
- **Dedicated collimation system reduces residual SR at IP.**
- **SR at IP mainly from beam tails at FFQs – difficult to shield.**
- **Photons are energetic enough to scatter off the beam pipe and enter the detector.**
- **Occupancies are currently very challenging for both the vertex detector and the main tracking systems.**
- **Multiple solutions are under investigation** to reduce the impact of SR:
 - increasing SR collimation and beam-pipe shielding
 - using a corrugated beam pipe (as at SuperKEKB) to reduce scattering
 - enlarging the central beam pipe radius (currently 10 mm)
 - optimizing IR optics to minimize direct SR hits

More info on SR sources ([here](#)) and occupancies in vertex ([here](#)) and main tracker ([here](#)).



Basically **no detector can be operated** under these conditions.

The MDI of the FCC should be optimized in order to bring down this background three orders of magnitude.

For the Linear Colliders this was done and it took several years.

Only then we have a clean dream e^+e^- machine.



Backgrounds and distortions



- A large background has an impact on the **TPC design**. Firstly, one has to deal with the large hit rates. And probably one wants to reject at an early stage background hits. For a pixel TPC with a fine granularity that is feasible. But the prize is cooling: the higher the hit rate, the more heat is produced.
- Secondly, the charge in the volume (created by the background) will distort the drift process and lead to track distortions (for beam-beam background of the order of mm). By optimization of the FCC MDI this can be reduced.
- Detailed simulations e.g. by Daniel Jeans were performed to study this aspect.
- The ILD detector concept – with the TPC sliced between Si detector - allows to fit these distortions out (on a track by track basis). For the CEPC detector a larger inner radius of the TPC was chosen (reduces bkg by a factor ~ 10)
- The ions created in the avalanche that flow back (IBF) in the drift volume and distort the drift process. There is active R&D going on in DRD1 to make a double grid structure to suppress the IBF or to use a mesh that is captures the ions.
- One could consider to use Ne as a TPC gas for the Tera-Z running, that would reduce the background hits significantly (factor 40? see backup slides).



Conclusions: Pixel TPC for ILD @



- The performance of a pixel TPC based on GridPixes has been studied based on prototypes and test beam measurements. It provides
 - high precision continuous tracking with a low material budget
 - very powerful particle identification
- At the FCCee a pixel TPC as a central tracker – sliced between silicon detectors as in the ILD detector - is well suited to carry out the WW, ZH and tt physics program.
- For the Tera Z program the MDI should be optimized and backgrounds should be reduced by several orders of magnitude. No detector can be operated under these harsh conditions.
- R&D on a Pixel TPC with GridPix devices with larger coverage (we now have ~60%) an improved protection layer and reduced ion back flow based on the TPX3 or TPX4 ASICs are part of the DRD1 program
- One could consider to use Ne as a TPC gas for the Tera-Z running

* For detailed studies/questions/answers see backup slides

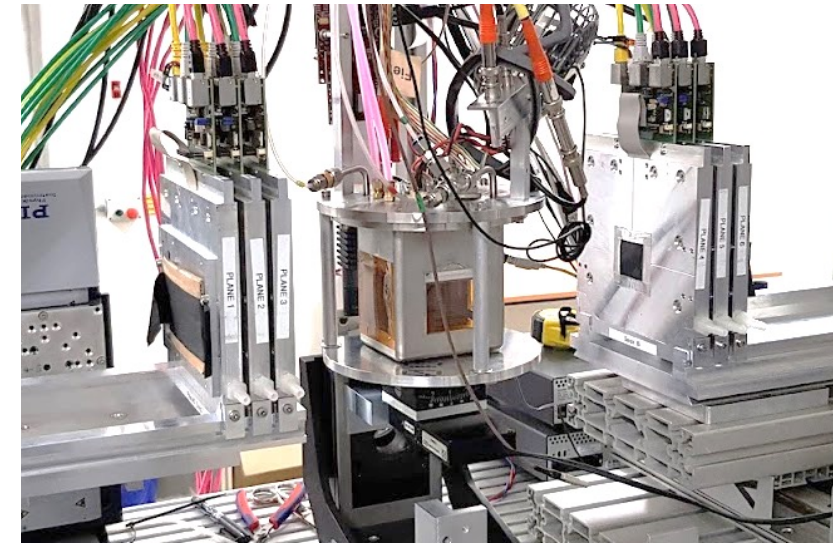
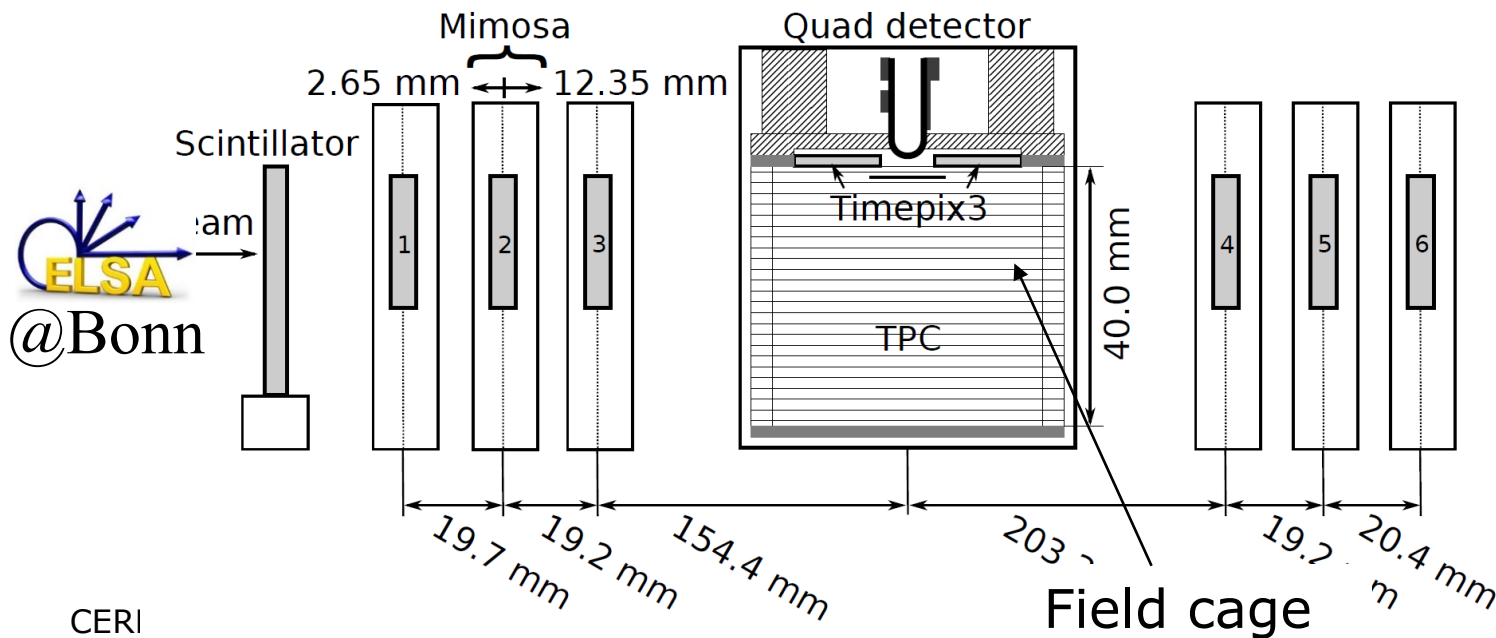


Backup material

QUAD test beam in Bonn (October 2018)

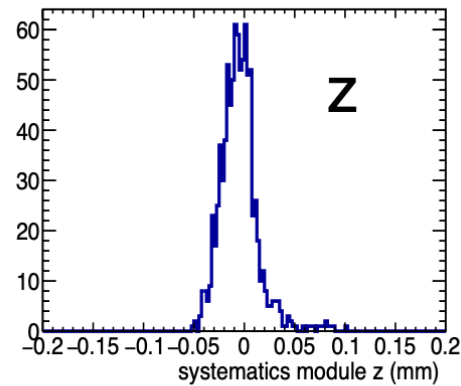
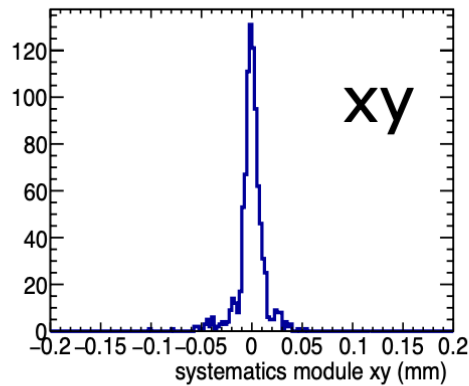
- ELSA: 2.5 GeV electrons
- Tracks referenced by Mimosa telescope
- QUAD sandwiched between Mimosa planes
 - Largely improved track definition
 - 6 planes with $18.4 \mu\text{m} \times 18.4 \mu\text{m}$ sized pixels
- Gas: Ar/CF₄/iC₄H₁₀ 95/3/2 (T2K)
- $E_d = 400 \text{ V/cm}$, $V_{\text{grid}} = -330 \text{ V}$
- Typical beam height above the chip: $\sim 1 \text{ cm}$

Published NIMA
<https://doi.org/10.1016/j.nima.2019.163331>

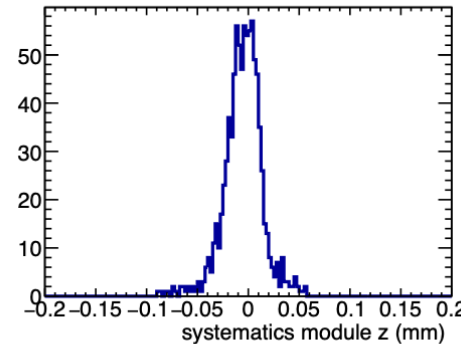
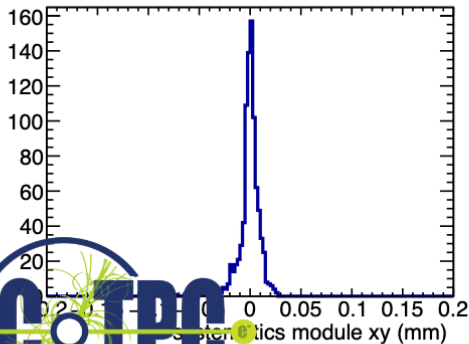


Distribution of mean residuals in the module plane

Method row



Method column



B=1 T data set

method	rms (stat) xy	bins xy	rms (stat) z	bins z
row	13 (2) μm	896	19 (5) μm	896
column	11 (2) μm	880	20 (5) μm	880

* We did not include the 4 corner chips and (11), 14, 8, 13 and 19. These are affected by the field cage and the short in chip 11.

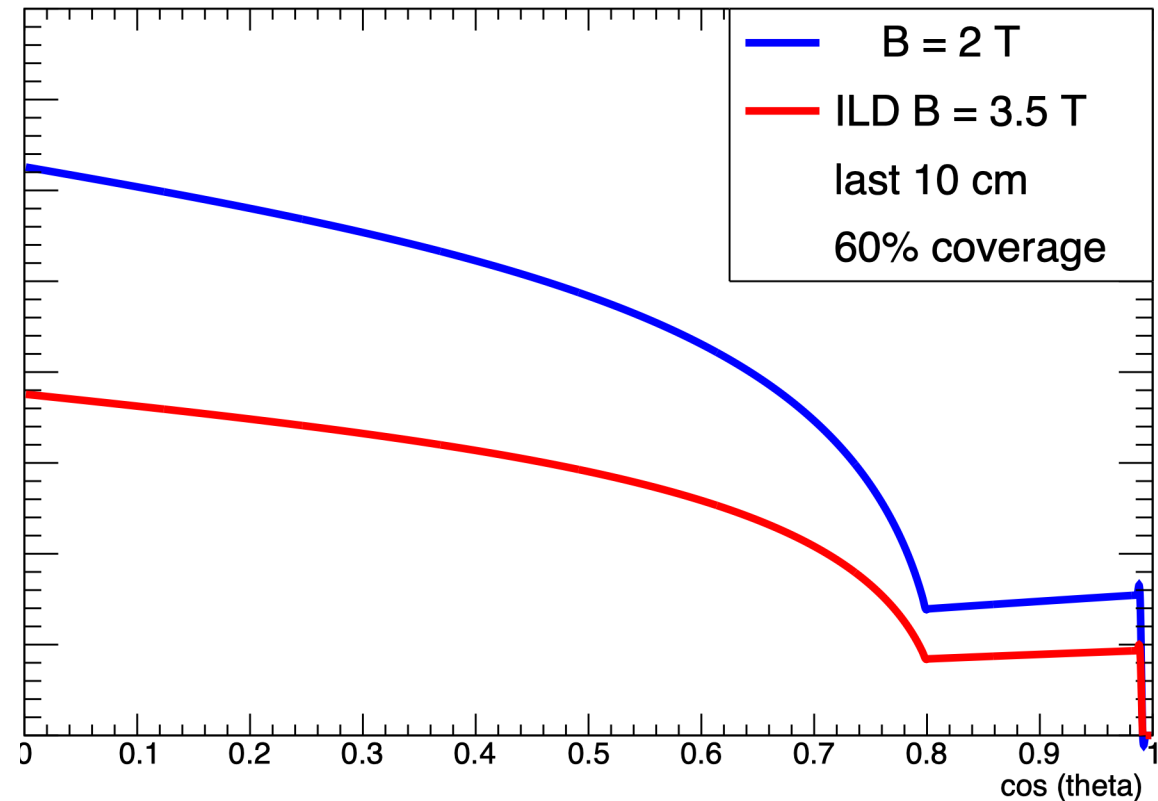
- The results of the 8 Quad Module in the DESY test beam in June 2021 have been presented
- One chip (nr 11) out of 32 was disconnected due to a short*
- In run 6916 e.g. 964 tracks were selected with 1009 hits on track
- The tracking precision: position 9 (xy) 13 μm (z) in angle 0.19 (dx/dy) 0.25 (dz/dy) mrad for a module or tracklength is 157.96 mm
- The diffusion coefficients at B=0 T $D_{xy} = 287 \mu\text{m}/\sqrt{\text{cm}}$ $D_z = 273 \mu\text{m}/\sqrt{\text{cm}}$
- The diffusion coefficients at B=1 T is $D_{xy} = 120 \mu\text{m}/\sqrt{\text{cm}}$ $D_z = 251 \mu\text{m}/\sqrt{\text{cm}}$
 - In agreement with Magboltz $D_{xy} = 121 \mu\text{m}/\sqrt{\text{cm}}$

*the chip was successfully repaired in 2023 Bonn

ILD tracking Performance for a Pixel TPC based on test beam

The last 10 cm track provides very high resolution 'point' in the endcap ($\cos \theta > 0.8$). This is due to the short drift distance and the high resolution pixel readout.

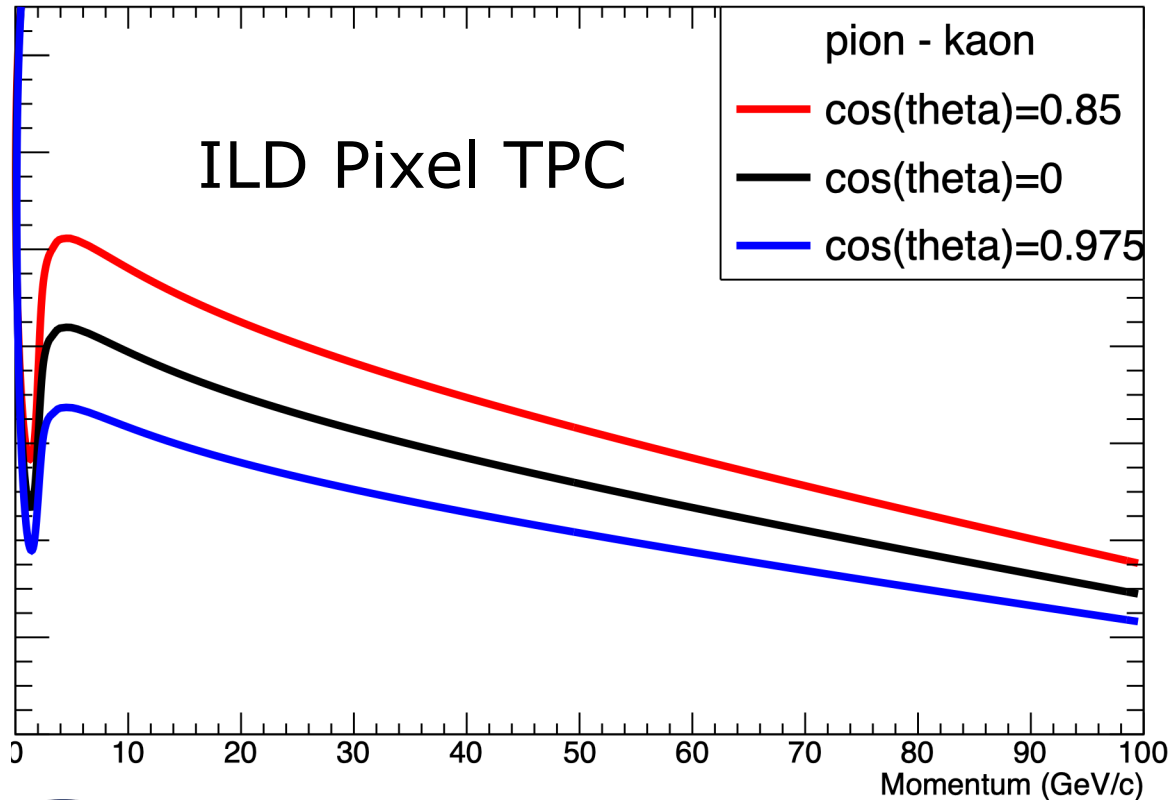
One use the endcap 'point' to calibrate out (part of) the TPC distortions.



Particle identification (PID) performance

- It is possible to study in test beam data the dE/dx or dN/dx of electrons
- The Pixel TPC has measurements with $55\text{ }\mu\text{m}$ pixel size
- It detects single electrons with an efficiency $> 85\%$
- This allows to measure the number of clusters (hits) as a function of the distance along the track dN/dx (dE/dx) with high granularity
- The advantage of hit counting in a Pixel TPC is – due to the digital read out – that one is not including the fluctuations from the multiplication process in the charge measurement
- Using e.g. a pad readout, the charge is used as a measure of $dEdx$
 - This readout has a larger granularity and includes avalanche fluctuations
 - One has to go to very small pads ('pixels') to measure the clusters

Pixel TPC dEdx performance acceptance



- Separation pion kaon
 $|\langle E_{\text{loss}} \pi \rangle - \langle E_{\text{loss}} K \rangle| / \sigma_{\pi}$
- Separation pion kaon for different $\cos(\theta)$ values due to the track length dependence
- For $\cos(\theta)=0$ till 0.95 the separation lies between the black and red curves. Only above 0.95-0.975 the separation drops till the blue curve.
- Excellent performance over very large polar angle range

A Pixel TPC at a circular collider

■ Can a pixel TPC reconstruct the Z events?

- The TPC total drift time is about 30 μs
- This means that there is on average 1.2 event / TPC readout cycle
- YES: The excellent time resolution: time stamping of tracks < 1.2 ns allows to resolve and reconstruct the events

■ Can the current readout deal with the Z rate?

- Link speed of Timepix3 (in Quad): 2.6 M hits/s per $1.41 \times 1.41 \text{ cm}^2$ **In the module testbeam we tested up to rates of 5.7 kHz**
- YES: This is sufficient to deal with hits from Z's in high luminosity Z running
 - Expect about 90 kHz/cm² from hadronic Z decays@inner radius

■ What is the current power consumption?

- No power pulsing is possible at a circular collider (at e.g. ILC power pulsing is possible)
- Current power consumption TPX3 chip $\sim 2\text{W}/\text{chip}$ per $1.41 \times 1.41 \text{ cm}^2$
- So: good cooling is important but no show-stopper.
- In LCTPC, CO₂ cooling has been developed and tested for the MM read-out technology
- To save power the TPX3/4 chips can be run in LowPowerMode: **reduction factor 10.**

A Pixel TPC at a circular collider

- The importance of the beam background and the optimization of the FCCee machine detector interface MDI
 - Hit rates from beam background are significant (wrt hits of Z decays)
 - In ICHEP26 it was shown that the FCC MDI is not optimal. The synchrotron radiation background is 3 orders of magnitude high than the beam background. It is very hard to operate any detector in that environment.
 - The Pixel TPC – due to the high granularity – has an occupancy of $< 1\%$ for 300 MHz/cm² (@inner radius). The read-out speed of the current TPX3 has to be upgraded to cope with the large background SR rates. R&D for a fast read-out based on TPX3/4, like the VeloPix (LHCb) is needed.

A Pixel TPC at a circular collider

■ What about track distortions?

- Not an issue for running at cms energies of WW, ZH, tt
- There are two important sources of track distortions of the TPC drift field:
 - the slowly drifting primary ions (from Zs and background)
 - the ions produced in the amplification process flowing back (IBF)
- The track distortions from backgrounds should be mitigated by optimizing the MDI
- The distortions from IBF can be reduced by e.g. using a double grid (see below).

■ Is it possible to reduce the IBF for a pixel TPC?

- IDEA: by making chip with a double grid structure (see back up slide further on)
- This idea was already realized as a 'TWINGRID' NIMA 610 (2009) 644-648
- For GEMs for the ALICE TPC this was also the way – use several GEMs to reduce IBF
- The IBF* can be easily modelled and with a hole size of 25 μm an IBF of $3 \cdot 10^{-4}$ can be achieved and the value for IBF*Gain (2000) would be 0.6.
- YES: the IBF can be reduced. It needs R&D that can be done in the detector lab in Bonn.

* Measured IBF of single grid GrixPix is 1.3% and IBF*Gain (2000) is 26.

A Pixel TPC at a circular collider

- What would be the size of the TPC distortions at a TeraZ factory?
 - Tera-Z studies by Daniel Jeans and Keisuke Fuji show that for FCC-ee this means: distortions from Z decays up to $< O(100) \mu\text{m}$.
 - The problem is that the beam and synchrotron backgrounds are by far the dominant source for the ions in the TPC volume. The beam distortions by beam backgrounds are less than 1 cm. The synchrotron backgrounds are largest and the reduction of that background –by optimizing the MDI – is important for all detectors.
 - There is also an idea to operate the TPC with a Neon based gas that could bring the backgrounds down by a factor of 40. This needs study.
 - It can be argued that in an ILD like detector the distortions can be mapped out using the silicon VTX-SIT/SET detectors. See e.g. the backup slide on fitting out TPC distortions.

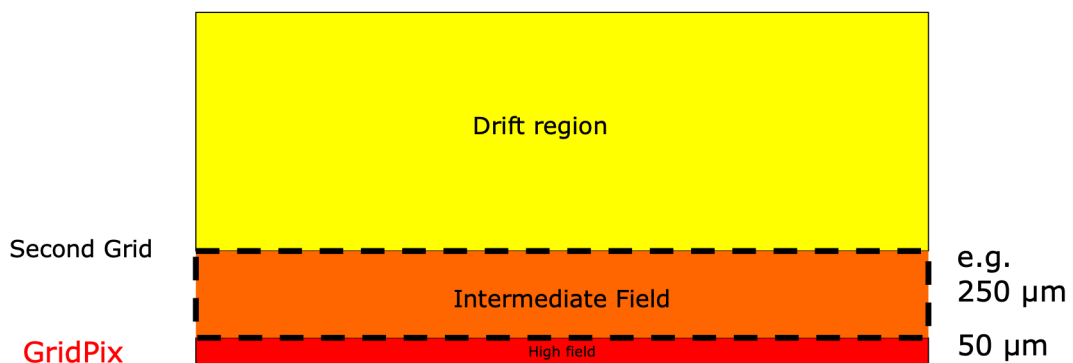
Fitting out and reducing TPC distortions

- It is possible to **map out distortions** using e.g. muons from Z decays
 - E.g. by fitting the 3D spatial distribution as a function of time as was done by ALEPH and more recently by ALICE. Using this distribution the hits positions are corrected and the TPC track refitted.
- However, with **silicon trackers around the TPC**, more elaborate methods can be used. One can use the track predictions based of the silicon trackers SIT and SET to correct on a track-by-track level the TPC track.
 - One can use as a constraint that the extrapolated positions and angles agree with the measured in the SIT and SET.
 - Practically, one can e.g. correct the TPC track parameters
- The ultimate way is a **fitting technique** similar to ATLAS. In the ATLAS track fit the common systematics is fitted out for sets of Muon hits. For ILD @ FCC the fit would fit free parameters in the distortion model, while using as a constraint the SIT and SET position and direction measurements.
 - The simplest case is a model where the strength (amplitude) and radial dependence would be scaled and a model is used for the 3D extrapolations.

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 $25\text{ }\mu\text{m}$ an IBF of $3\text{ }10^{-4}$ can be achieved and the value for $\text{IBF} \cdot \text{Gain} (2000)$ would be 0.6.



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	$12\text{ }10^{-4}$	$3\text{ }10^{-4}$	$1\text{ }10^{-4}$
transparency	100%	99.4%	91.7%