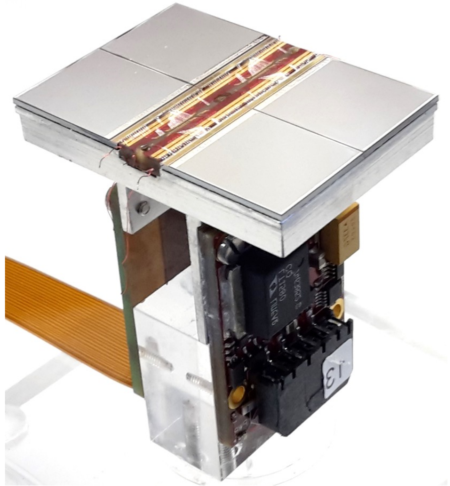
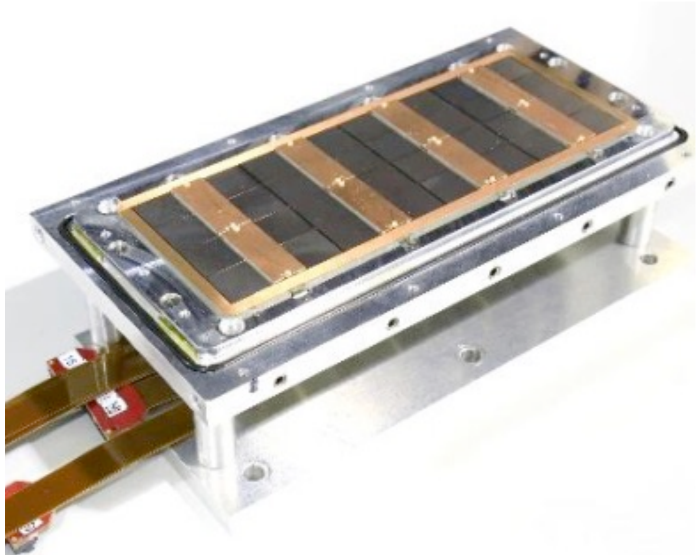
Pixel TPC dEdx performance in ILD

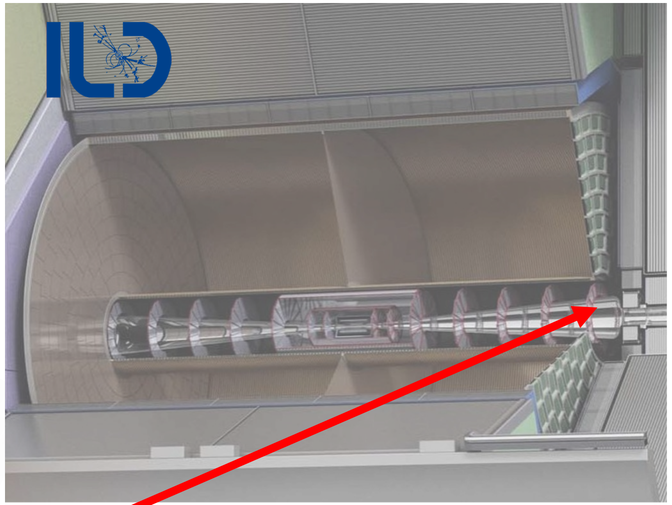
Yevgen Bilevych, Klaus Desch,
Sander van Doesburg, Harry van der Graaf, Fred Hartjes, Jochen Kaminski, Peter Kluit, Naomi van der Kolk,
Cornelis Ligtenberg,
Gerhard Raven, and
Jan Timmermans

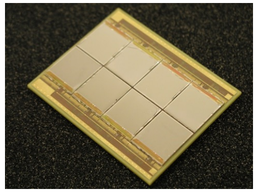




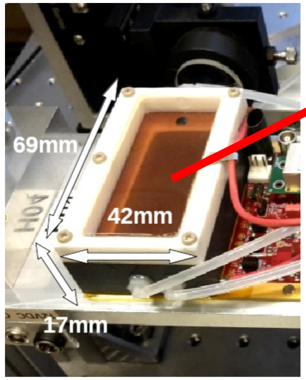
ILD analysis meeting 27 March 2024

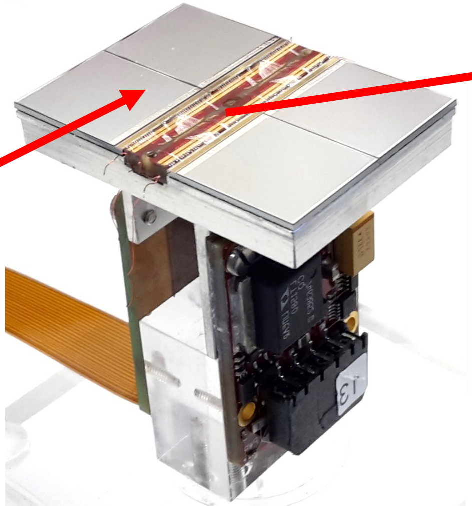
Pixel TPC

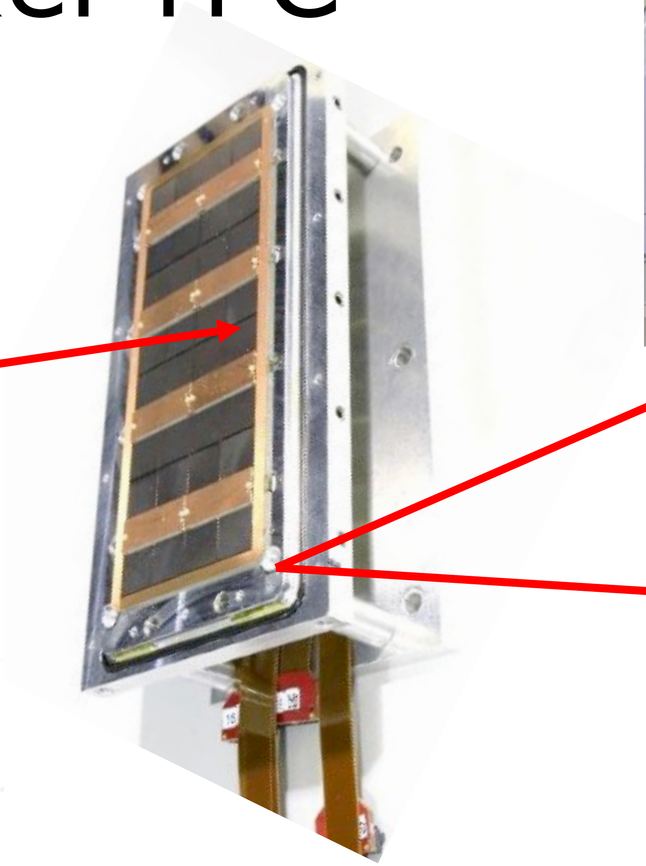


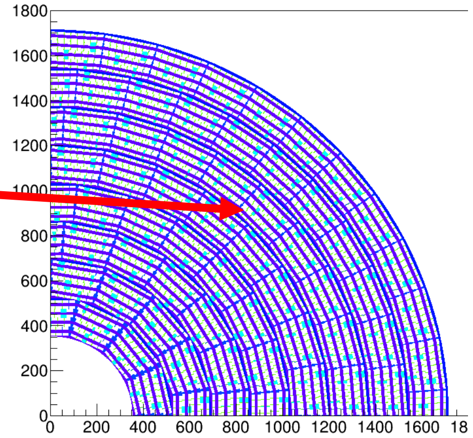


(Octopuce)





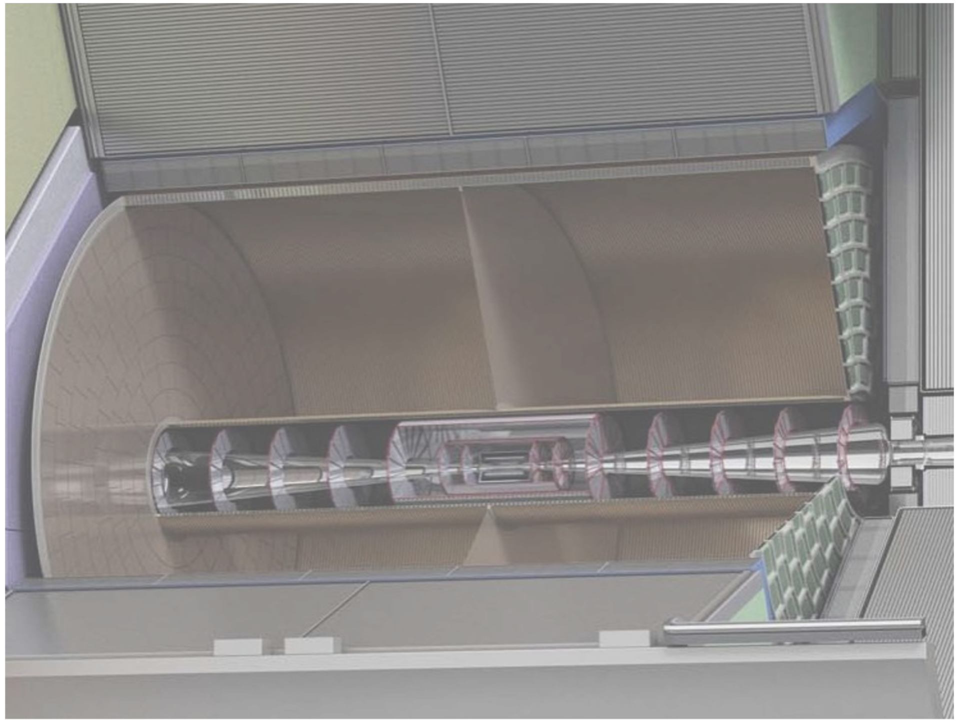




(TimePix1) TPX3 chip Quad Module TPC plane

(2007-14) 2017 2018 2019

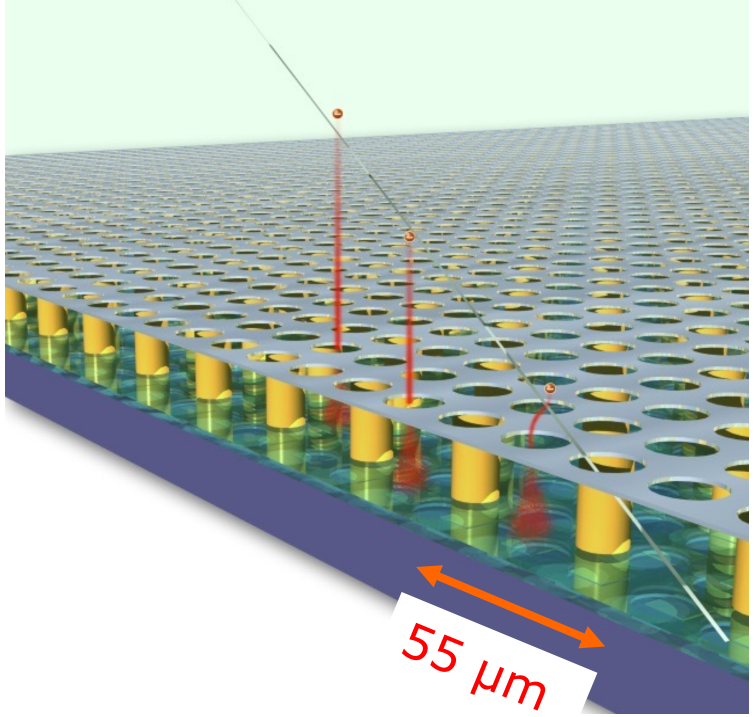
Pixel TPC

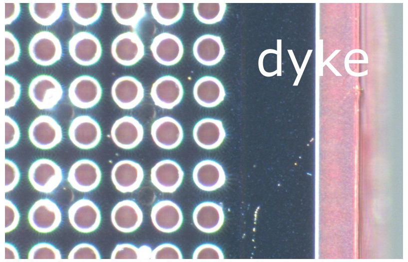


- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between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

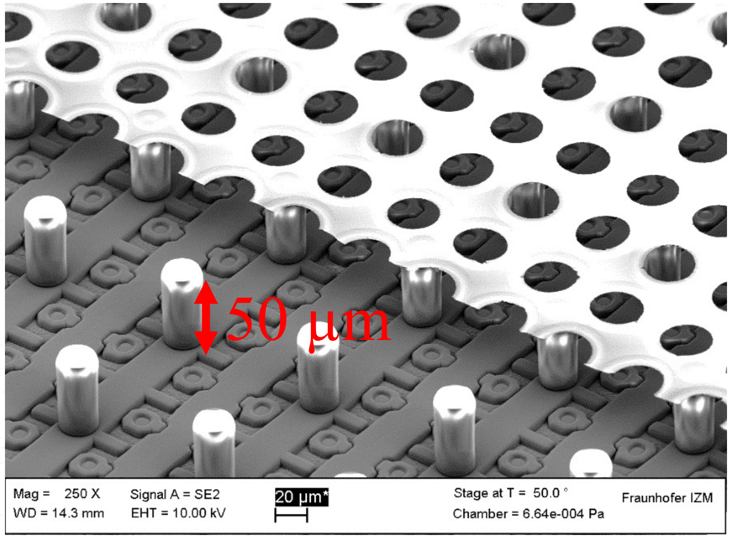
GridPix technology

- 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



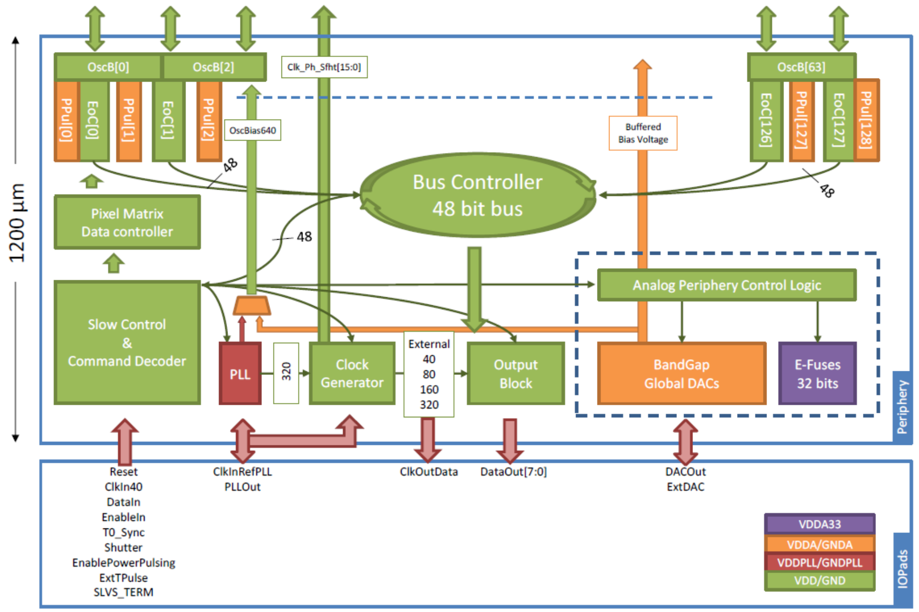


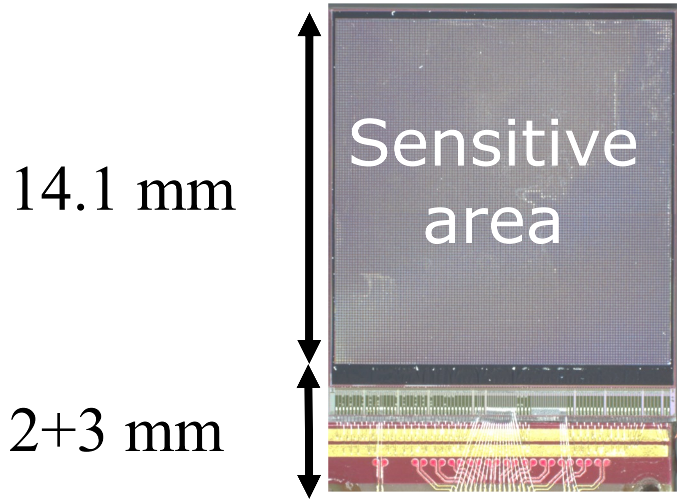
- Aluminium grid (1 μm thick)
- 35 μm wide holes, 55 μm pitch
- Supported by SU8 pillars 50 μm high
- Grid surrounded by SU8 dyke (150 μm wide solid strip) for mechanical and HV stability



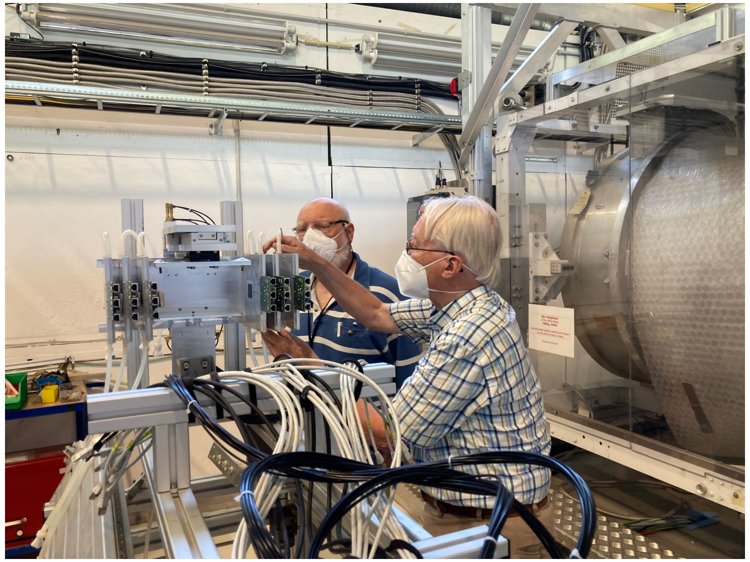
Pixel chip: TimePix3

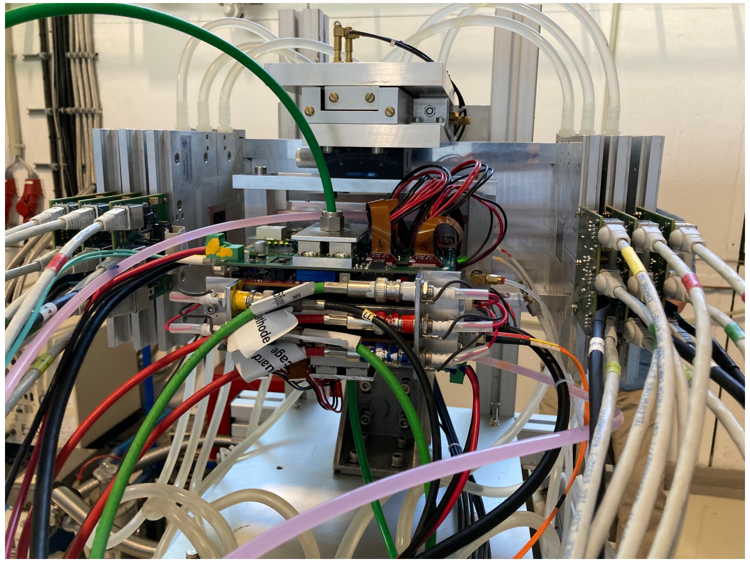
- 256 x 256 pixels
- 55 x 55 µm pitch
- 14.1 x 14.1 mm sensitive area
- TDC with **640 MHz clock** (1.56 ns)
- Used in the data driven mode
  - Each hit consists of the **pixel address** and **time stamp** of arrival time (ToA)
  - Time over threshold (ToT) is added to register the signal amplitude
  - compensation for time walk
  - **Trigger** (for t_0) added to the data stream as an additional time stamp
- Power consumption
  - ~1 A @ 2 V (2W) depending on hit rate
  - good cooling is important

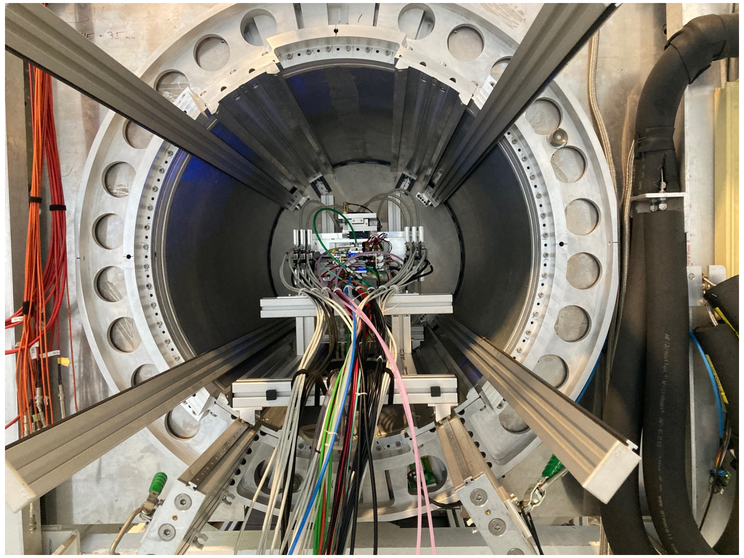




DESY testbeam June 2021







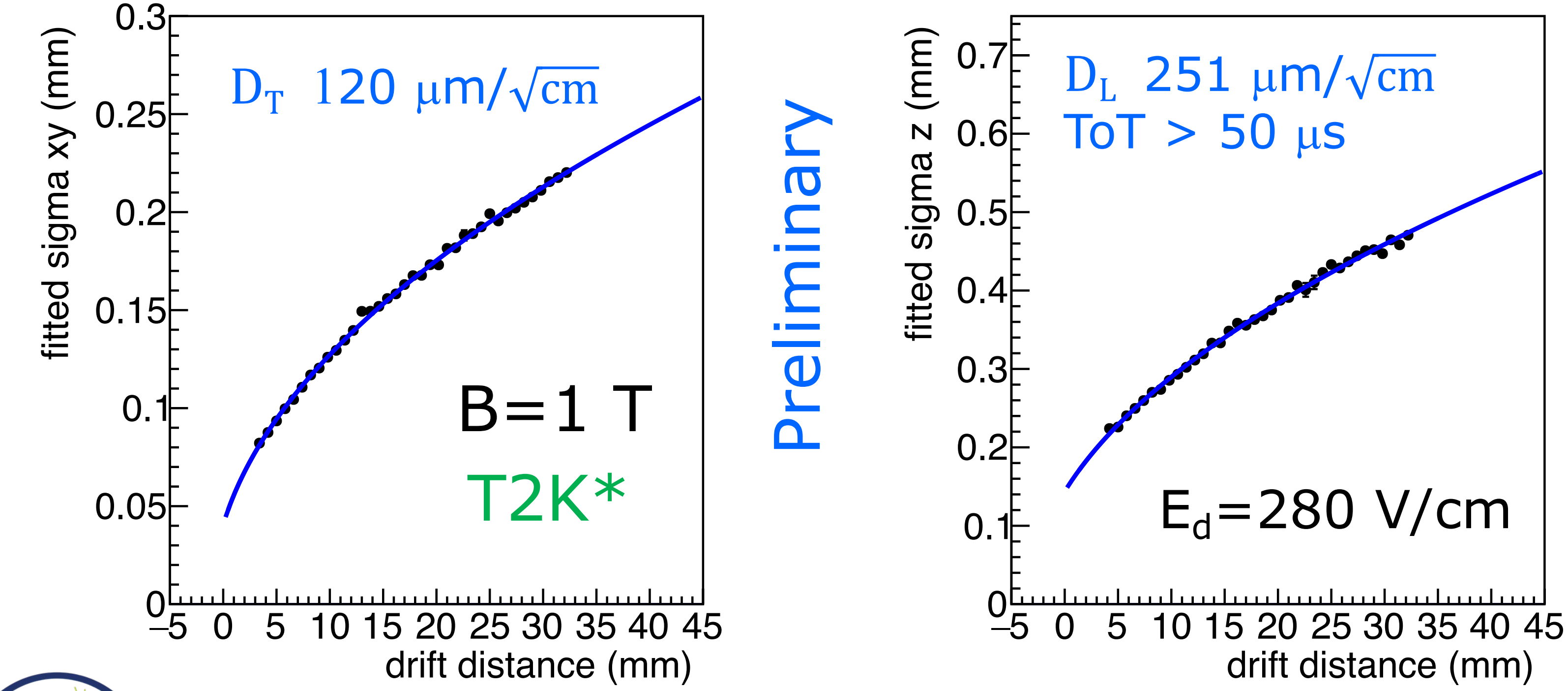
Mounting the 8 quad module between the silicon planes
sliding it into the 1 T PCMAG solenoid

DESY testbeam Module Analysis

Run 6983-6990 B=1 T p=5 and 6 GeV

Fitted resolution

$$\sigma_{xy,z}{}^2 = \sigma^2_{xy_{0},z_0} + D^2_{xy,z}\,(z - z_0)$$



$\sigma^2{}_{xy0} = \sigma^2{}_{pixel} + \sigma^2{}_{xy\ tele}$

$\sigma^2{}_{pixel} = 55^2/12\ \mu m^2$

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

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

T2K* = T2K gas
with O_2 and H_2O

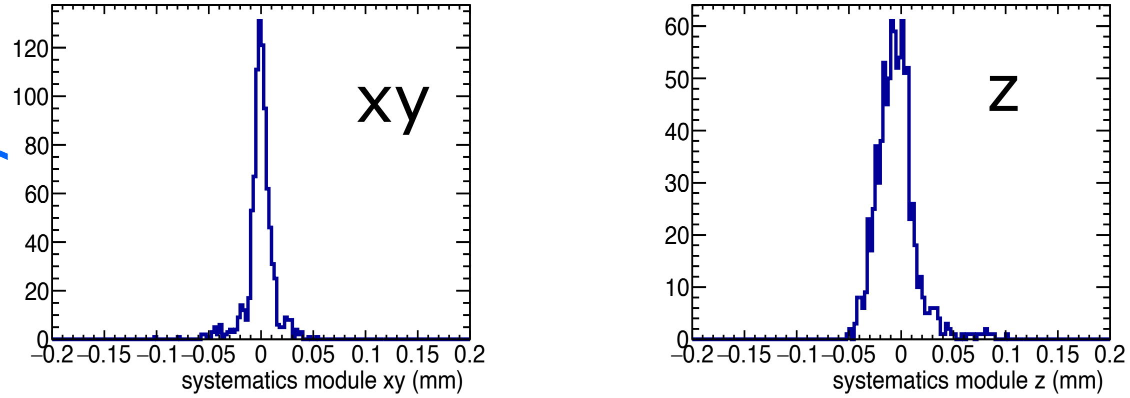
DESY testbeam Module Analysis

Runs 6983-6988 B=1T p=5 GeV

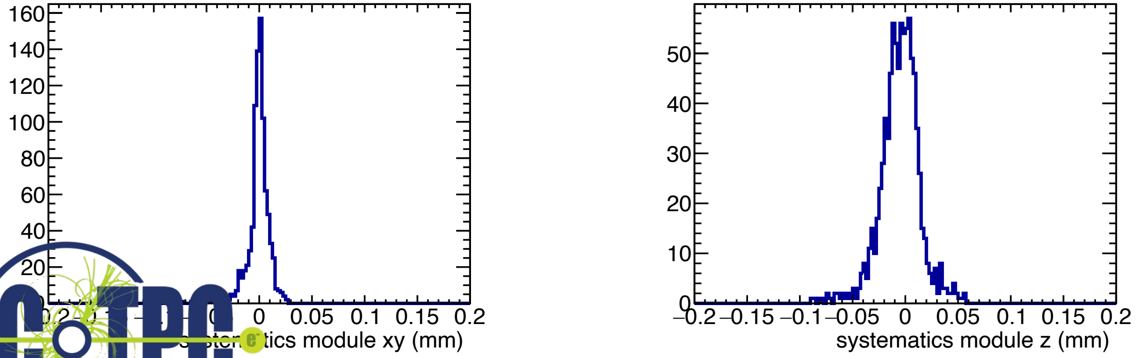
Distribution of mean residuals in the plane

Preliminary

Method row



Method column



B=1 T situation

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.

Conclusions on module performance
Resolution and precision

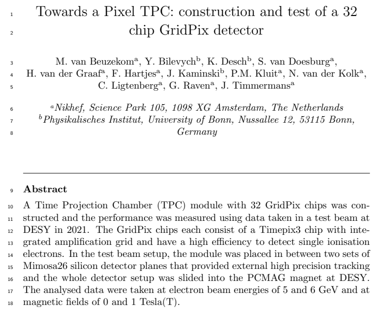
- Preliminary results of the 8 Quad Module in the DESY test beam in June 2021 have been presented
- One chip (nr 11) out of 32 was disconnected due to a short*
- In run 6916 e.g. 964 tracks were selected with 1009 hits on track
- The tracking precision: position 9 (xy) 13 μm (z) in angle 0.19 (dx/dy) 0.25 (dzdy) 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 see backup slide

Conclusions on module performance
Resolution and precision

- 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

- Writing a NIM paper (including more results)
- More details on the results LCTPC annual gathering



Towards a Pixel TPC: construction and test of a 32 chip GridPix detector

M. van Beuzekom[a], Y. Bilevych[b], K. Desch[b], S. van Doesburg[a],
H. van der Graaf[a], F. Hartjes[a], J. Kaminski[b], P.M. Kluit[a], N. van der Kolk[a],
C. Ligtenberg[a], G. Raven[a], J. Timmermans[a]

[a]*Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[b]*Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany*

Abstract

A Time Projection Chamber (TPC) module with 32 GridPix chips was constructed and the performance was measured using data taken in a test beam at DESY in 2021. The GridPix chips each consist of a Timepix3 chip with integrated amplification grid and have a high efficiency to detect single ionisation electrons. In the test beam setup, the module was placed in between two sets of Mimosa26 silicon detector planes that provided external high precision tracking and the whole detector setup was slided into the PCMAG magnet at DESY. The analysed data were taken at electron beam energies of 5 and 6 GeV and at magnetic fields of 0 and 1 Tesla(T).

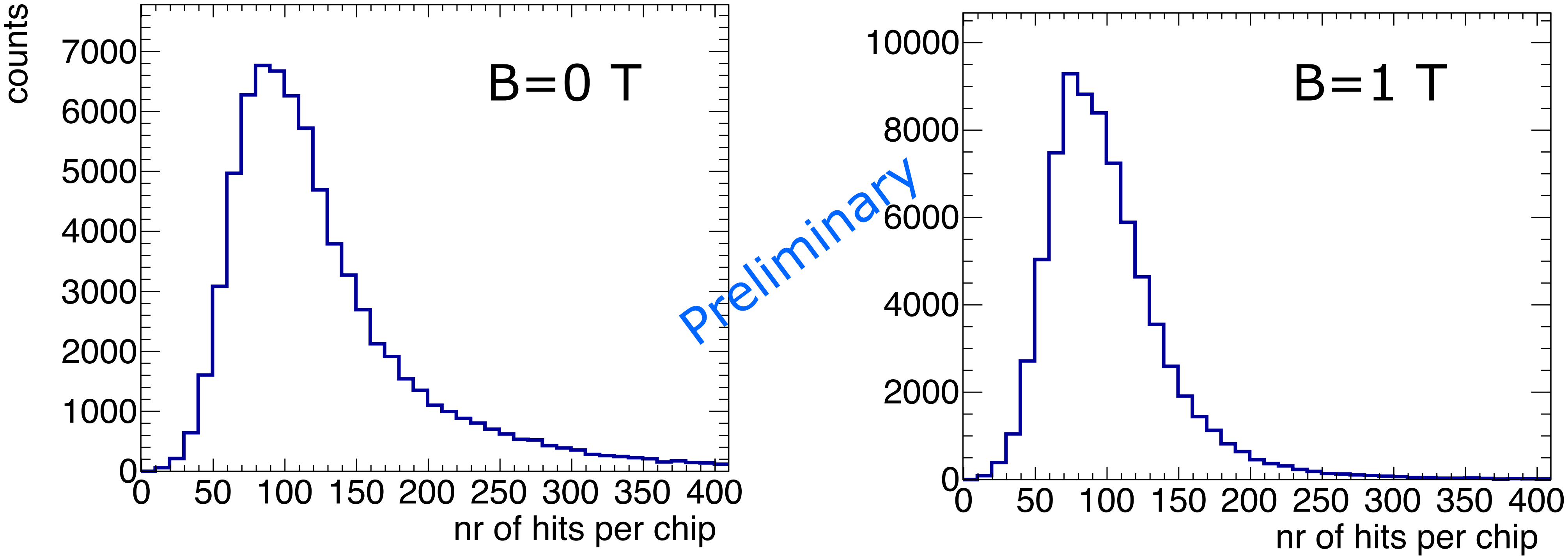
DESY testbeam Module Analysis

Performance of dEdx

- It is possible to study in data the energy loss of electrons
- The Pixel TPC has measurements with 55 μm pixel size
- This allows to measre the number of hits as a function of the distance along the track dN/dx (dE/dx) with high granularity
- It is possible to use also the ToT (a measure of the deposited charge) but this is not explored
- The advantage of hit counting is that one is NOT getting the fluctuations from the multiplication process. The ToT will include these avalanche fluctuations.
- Using e.g. a pad readout the charge is used as a measure of dEdx
  - This has a worse granularity and includes avalanche fluctuations

DESY testbeam Module Analysis

Testbeam performance of dEdx



- 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 TX3 hits

DESY testbeam Module Analysis

Analysis of dEdx performance

- Combine chips to form a 1 m long track with 60 % coverage for electrons
- Method 1) 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) fit the slope of the N_{scaled} minimum distance (d) distribution with an exponential function (N_{scale}(d)=defines the inverse weights):
  $N(d)_{scaled} = N_{scale}(d)\, N_{observed}(d)$
  $N(d)_{scaled}$ is then fitted for each track with N_0 exp(-slope d)
- Calculate the "dEdx" variable for electrons and MIP (==70% of hits)
  - method 1 = nr of selected hits
  - method 2 = slope
  - Resolution is $\sigma = \sigma$(dEdx)/dEdx (for σ we use the rms)

DESY testbeam Module Analysis
Distance distribution

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 comes from clusters with more than 1 hit.

Single chip

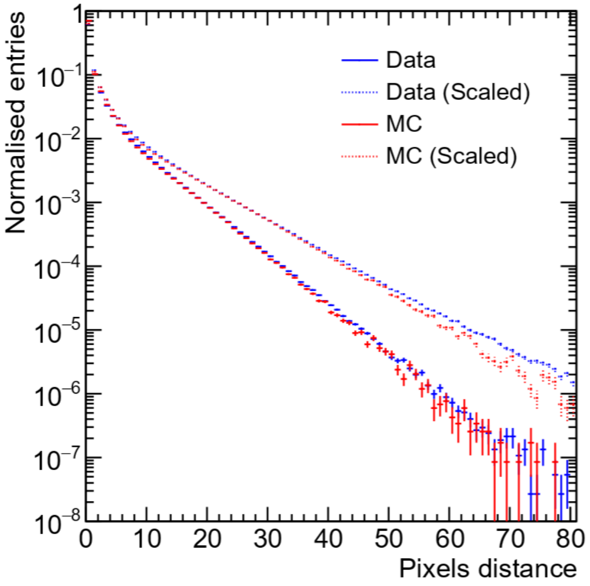
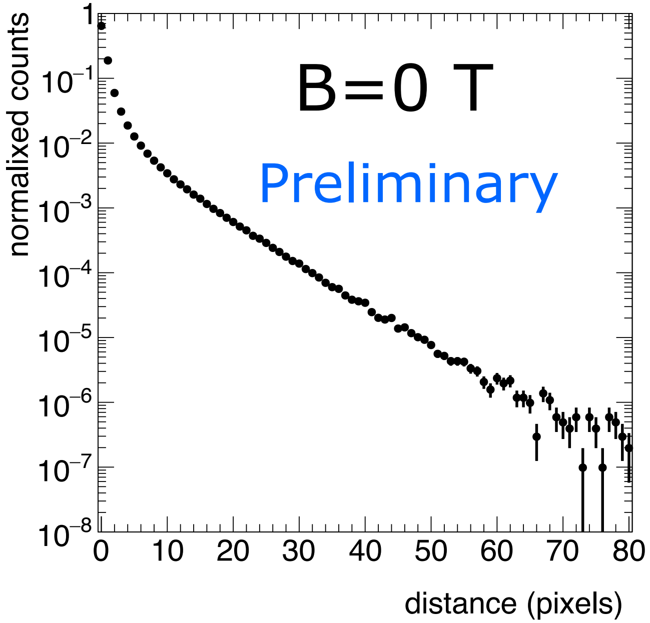


Figure 5.19: Distribution of distance between hits for a 2.5 GeV electron in pixels from test beam data (blue) and from a Monte Carlo simulation (red).

Quad module

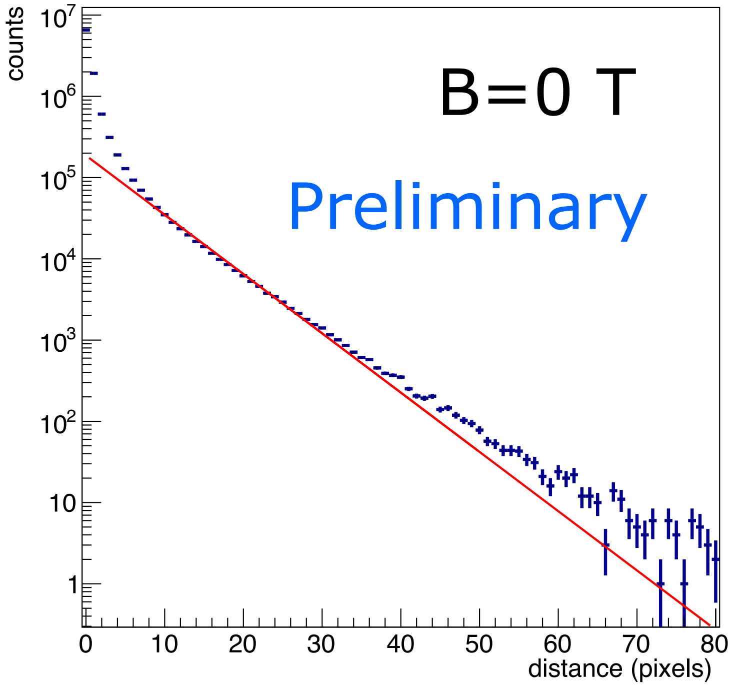


Thesis Kees Ligtenberg

DESY testbeam Module Analysis

Performance of dEdx

Method 2: Fit slope of the distance distribution



From 10 clusters onwards an exponential distribution is followed.
Below 10 the distribution will be down-weighted ($N_{scale}(d)$ = 1/weight). The weights are:

```
Weights B=0 = { 35.0467 , 12.1497 , 4.52914 , 2.76311
, 1.99386 , 1.59795 , 1.3656 , 1.21409 , 1.11898 ,
1.04385 };

Weights B=1 =   { 22.5617 , 7.39573 , 2.43318 ,
1.54528 , 1.23428 , 1.09727 , 1.04368 , 1.01625 ,
1.00182 , 0.998178 };
```

Note the difference in weights in the B=0 and 1 T data sets. This is related to the fluctutations

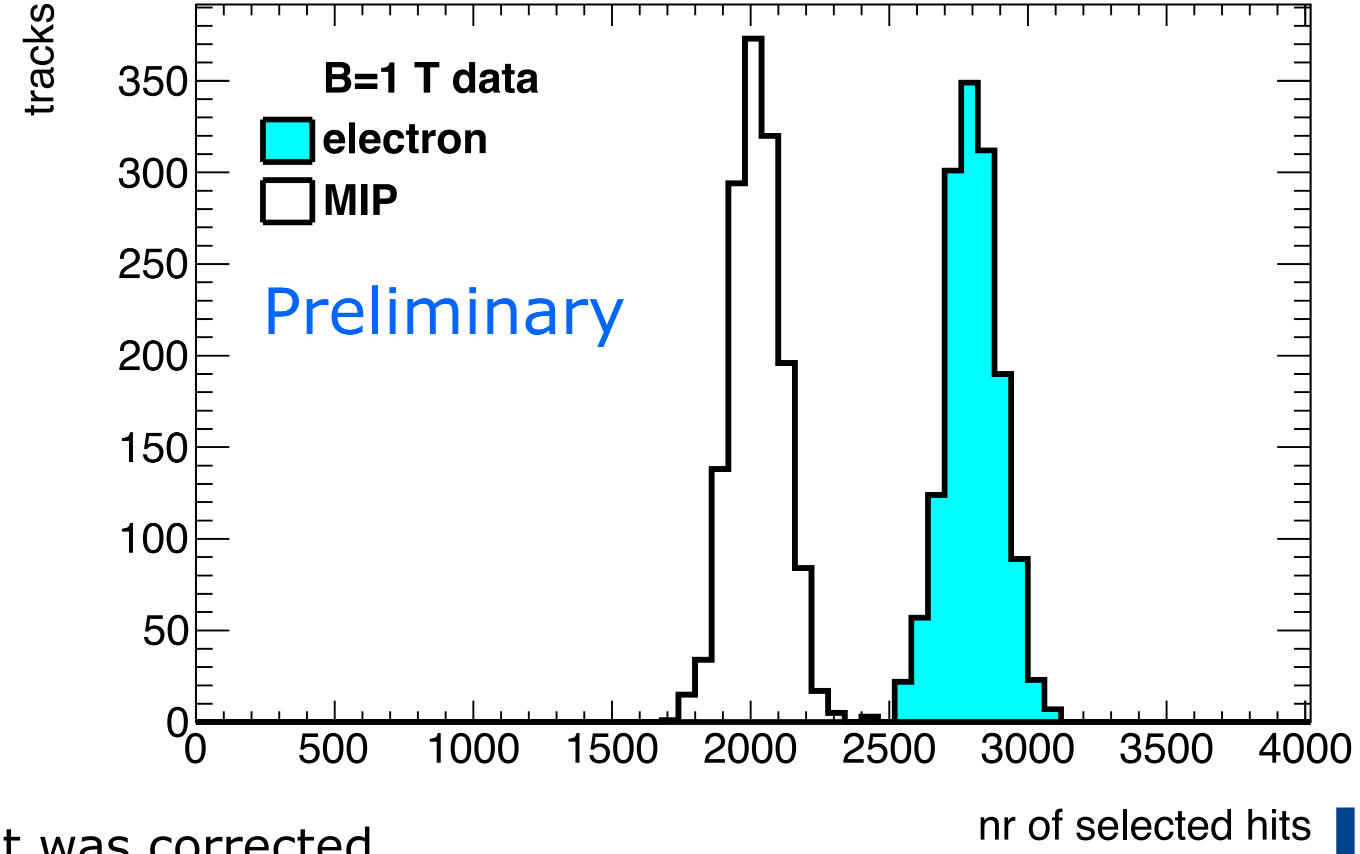
DESY testbeam Module Analysis

dEdx performance method 1

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



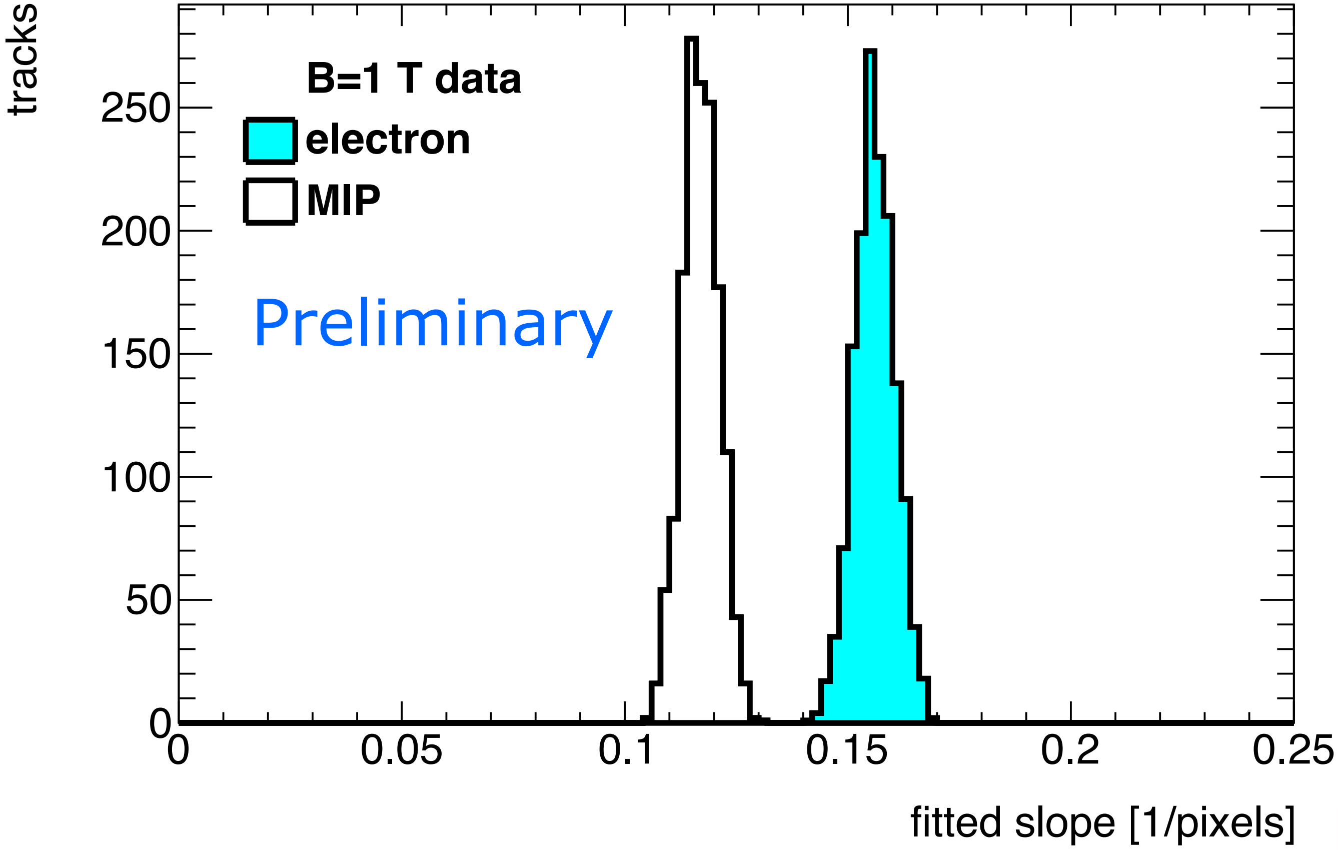
MIP in plot was corrected ...
thanks Ulli

DESY testbeam Module Analysis

dEdx performance method 2

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



DESY testbeam Module Analysis

Summary of performance of dEdx

The dEdx resolution for electrons from data by combining tracks to form a 1 m long track with realistic coverage ~60% coverage.

Preliminary

Method	B=0 Resolution (%)	B= 1 T Resolution (%)
(1) dEdx 90 tail	6.0	3.6
(2) Fit slope	5.4	2.9

The “dEdx 90 tail” method is truncation at 90% where large clusters are identified and removed (tail reduced)
For the “Fit slope” method (2) an exponential distribution (with the slope and amplitude as free parameters) is fitted to the distribution of distance between the hits (as discussed: after applying the weights)

DESY testbeam Module Analysis

dEdx Performance extrapolated to ILD detector

Test beam B = 1 T
p=5,6 GeV/c

Method 2 fit slope of the distance distribution

electron resolution 2.9%

1 m track 60% and coverage

ILD detector

rInner = 329 rOuter = 1770 mm

electron resolution = 2.5%
at $\theta=\pi/2$ (cost=0)

Assume Pixel TPC performance at B = 1 T at p = 5,6 GeV/c

DESY testbeam Module Analysis

dEdx performance and the impact of diffusion

Question by Ulli in LCTPC

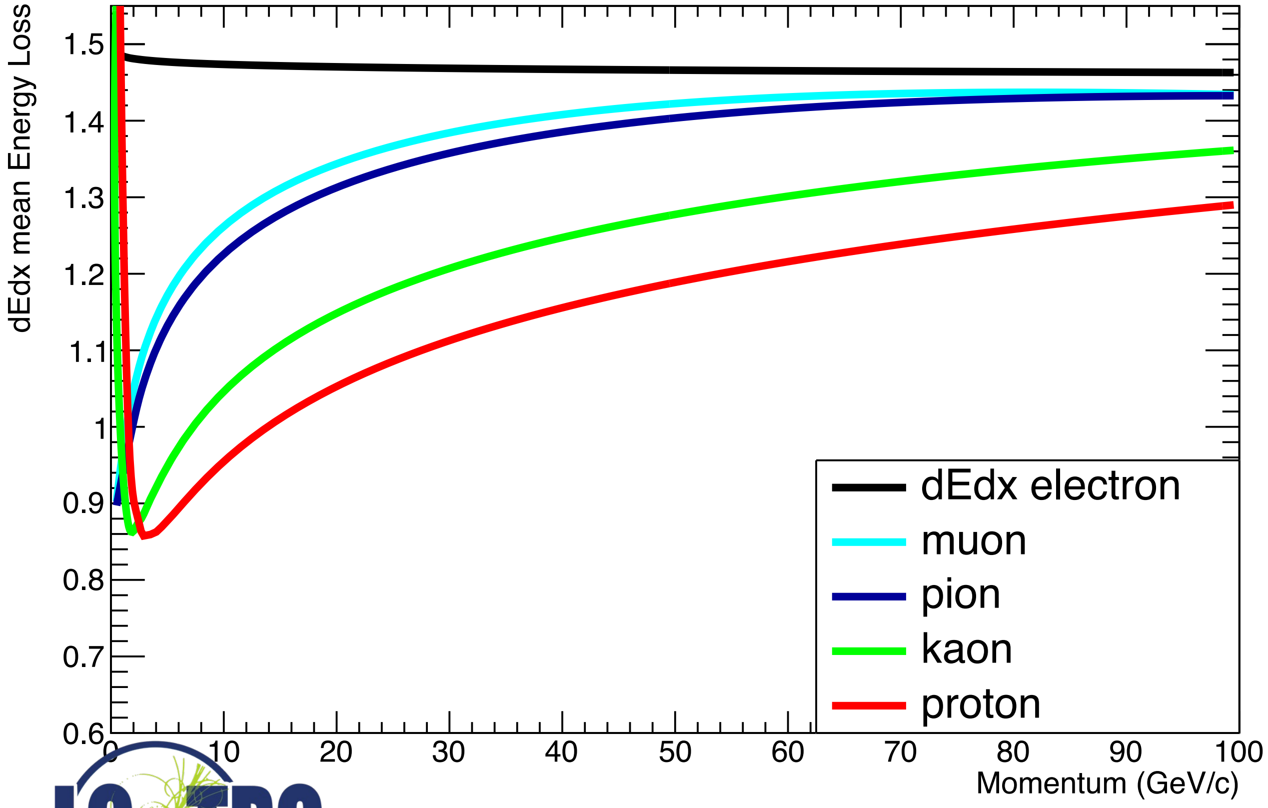
Testbeam electron dEdx resolution 2.9%. The diffusion in the test beam is 130 μm. What is the performance if the diffusion is larger?

In ILD running at a B field of 4 T(2T) the diffusion is $D_T = 25(50)\mu m/\sqrt{cm}$. The ILD-TPC halflength is 235 cm. The total diffusion ranges between say 25 and 380(760) μm. So drift distances in ILD up to only 25(18) cm correspond to the test beam situation.

To study the impact, the testbeam data was used and smeared with an additional 330 (500) μm and the dEdx methods reran. The dEdx resolution is 3.6(3.8)%. It is clear that this is the worst case scenario: by doing a track-by-track fit one will end up closer to 2.9%.

DESY testbeam Module Analysis

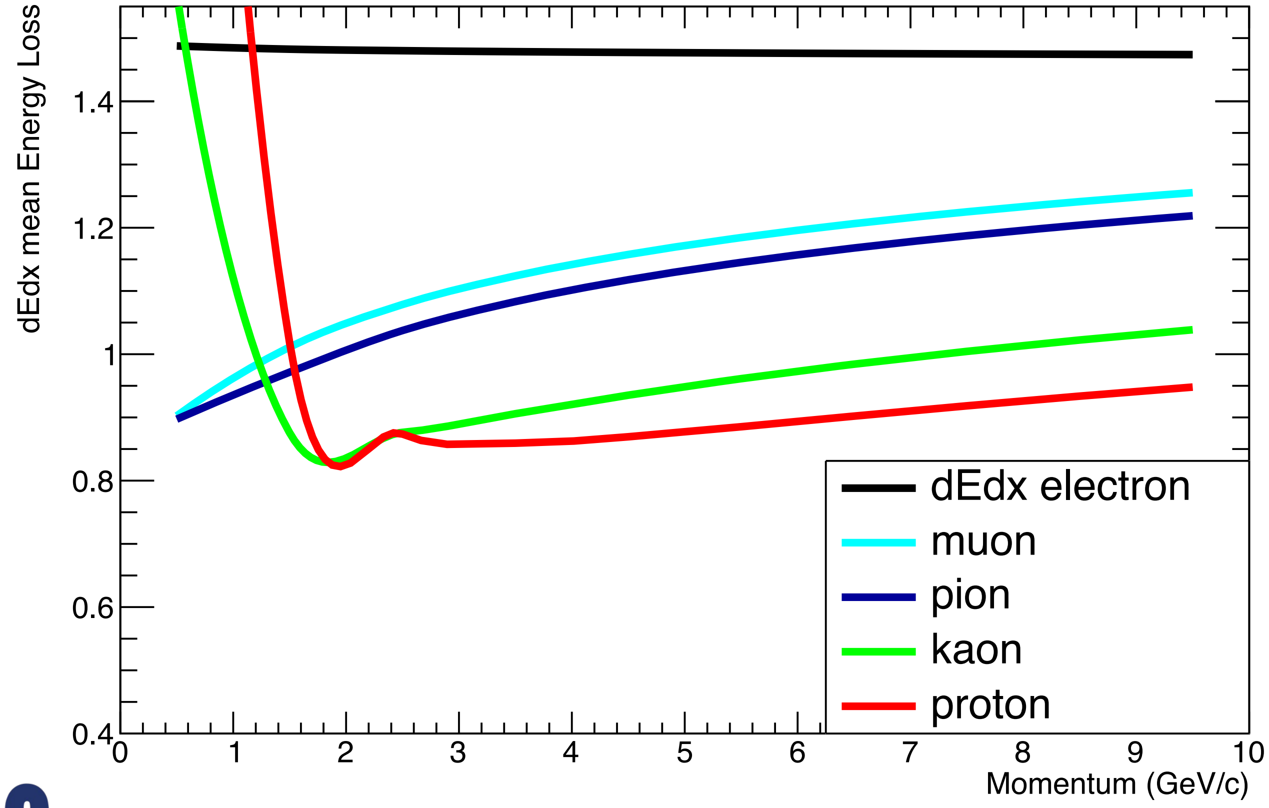
ILD dEdx performance



- Contacted Ullrich Einhaus for dEdx studies in ILD
- Extracted the ILC soft parametrisations for energy loss based on G4 and full simulation of the ILC TPC with T2K gas
- Link generated in 2020 with ILC soft v02-02 and v02-02-01

DESY testbeam Module Analysis

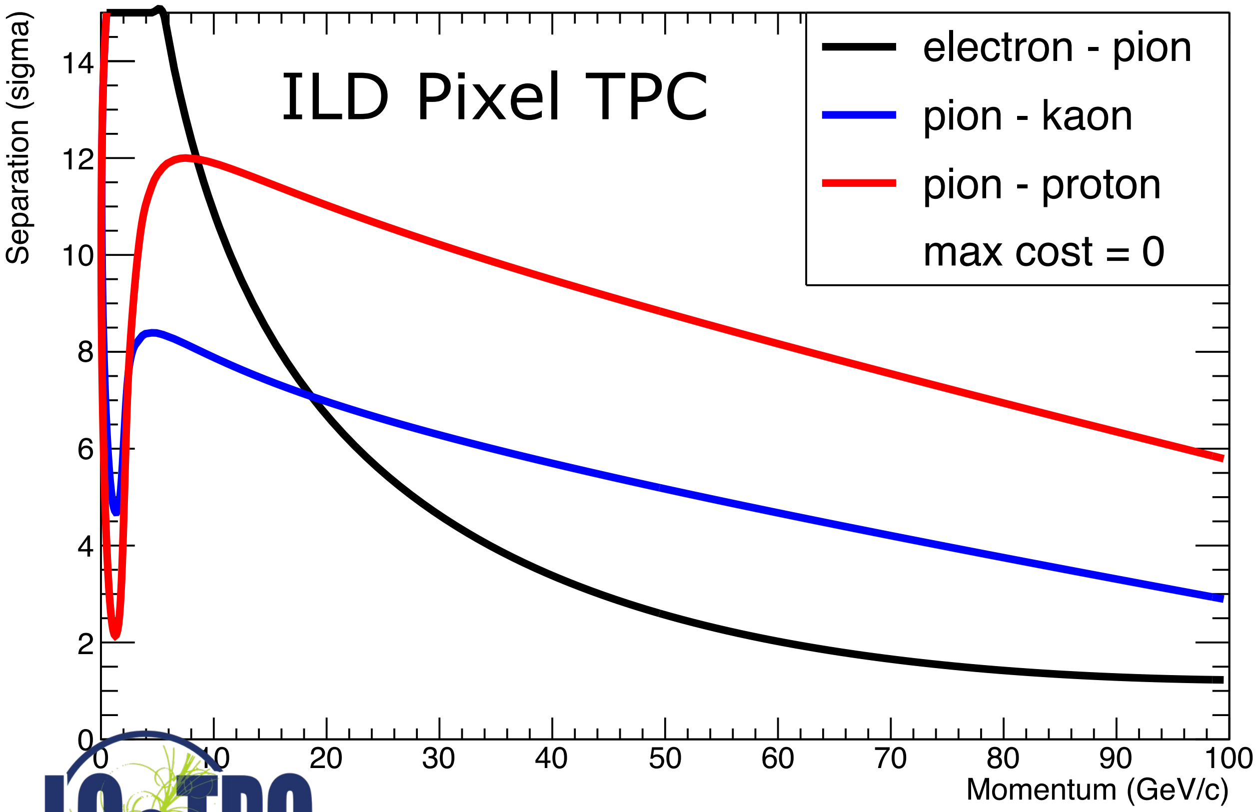
dEdx performance



- zoom on Low momenta

DESY testbeam Module Analysis

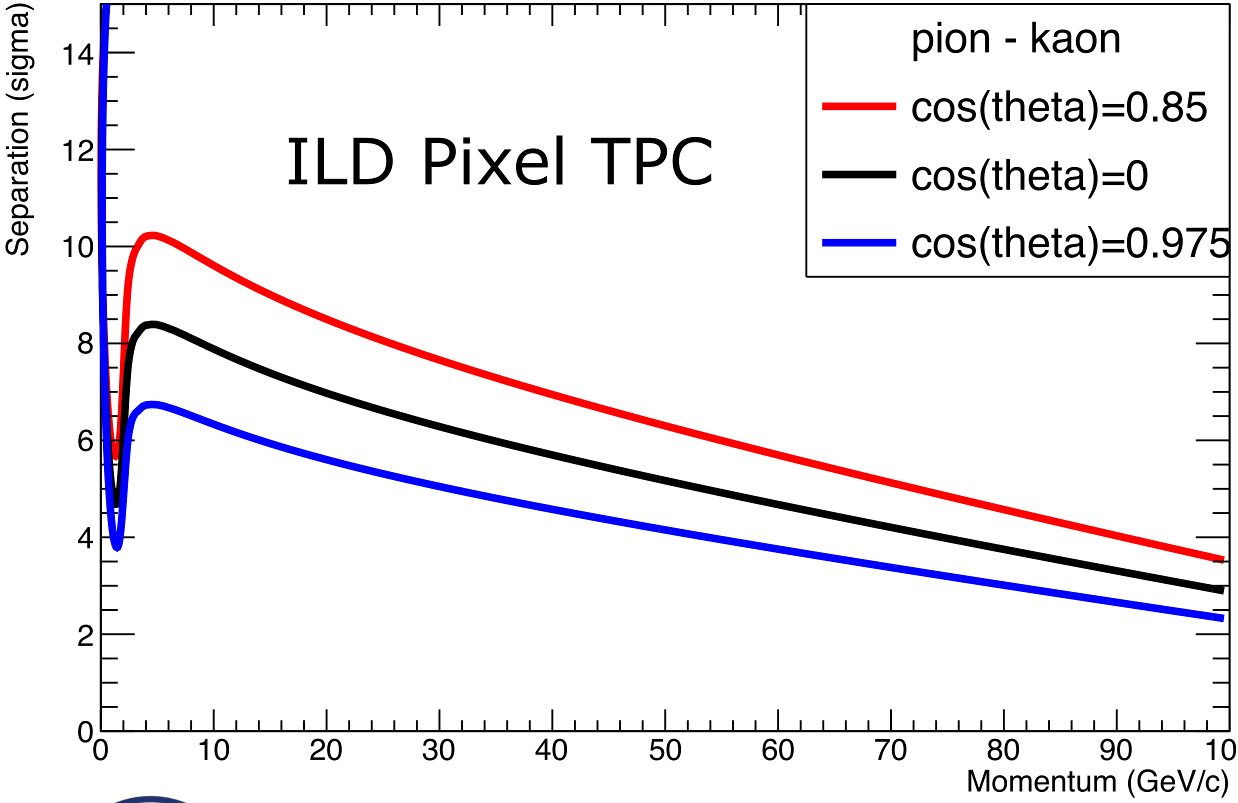
Pixel TPC dEdx performance



- ILD Performance with:
  rInner = 329 rOuter = 1770 mm
  zMax = 2350 mm // half length
- Pixel TPC resolution from electron p = 5 (6) GeV test beam (for B = 1 T) of 2.5% - the 'max' scenario at $\cos\theta = 0$
- Resolution scales as:
  $1/\sqrt{\text{track length} \ < \text{Eloss} >}$
- Separation electron pion
  $|<\text{Eloss e}> - <\text{Eloss } \pi>| \ / \ \sigma_{\pi}$
- Separation pion kaon
  $|<\text{Eloss } \pi> - <\text{Eloss K}>| \ / \ \sigma_{\pi}$

DESY testbeam Module Analysis

Pixel TPC dEdx performance

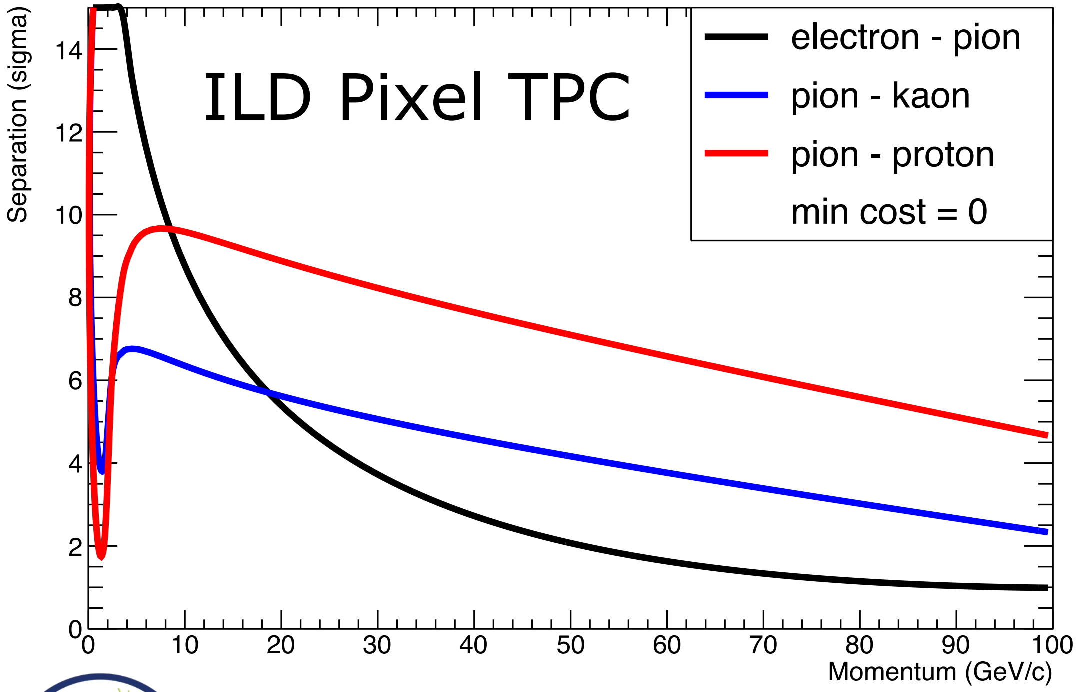


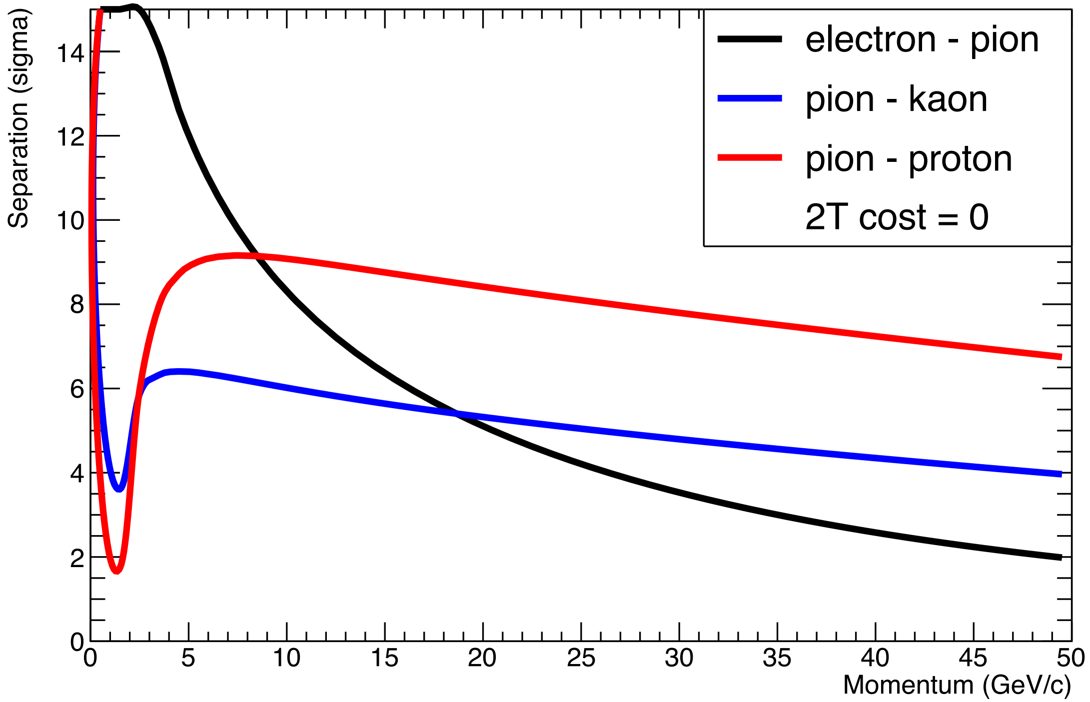
- Separation pion kaon
  |<Eloss π > - <Eloss K>| / σ_π
- Separation pion kaon for different cos(theta) values due to the track length dependence
- For cos(theta)=0 till 0.95 the separation lies between the black and red curves. Only above 0.95-0.975 the separation drops till the blue curve.
- Excellent performance over very large polar angle range

DESY testbeam Module Analysis

Pixel TPC dEdx performance

Worst case ILD Performance with: 3.1% and 3.3 % (2T) at cos θ = 0

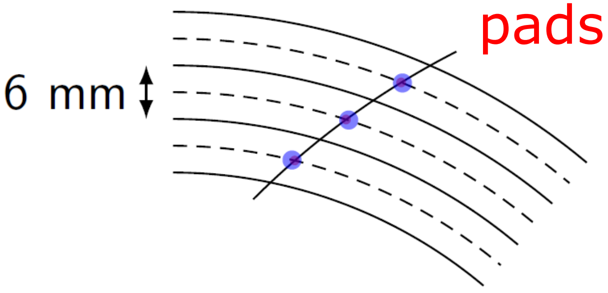




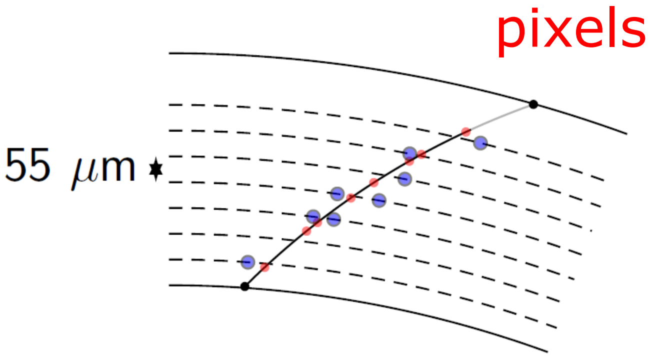
Note the momentum range (50 GeV) B= 2T for Z running

Simulation of ILD TPC with pixel readout

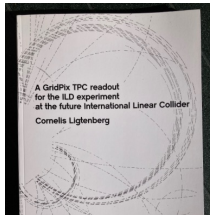
- To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Adapted Kalman filter track reconstruction to pixels



22 electrons / hit
~ 200 hits / track



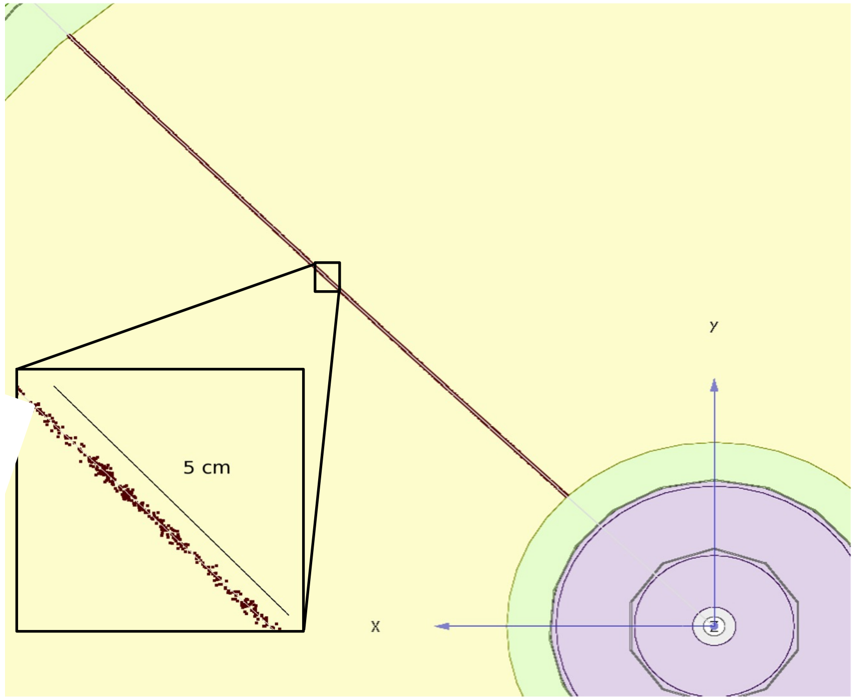
1 electron / hit
~ 10 000 hits / track



A GridPix TPC readout
for the ILD experiment
at the future International Linear Collider

Cornelis Ligtenberg

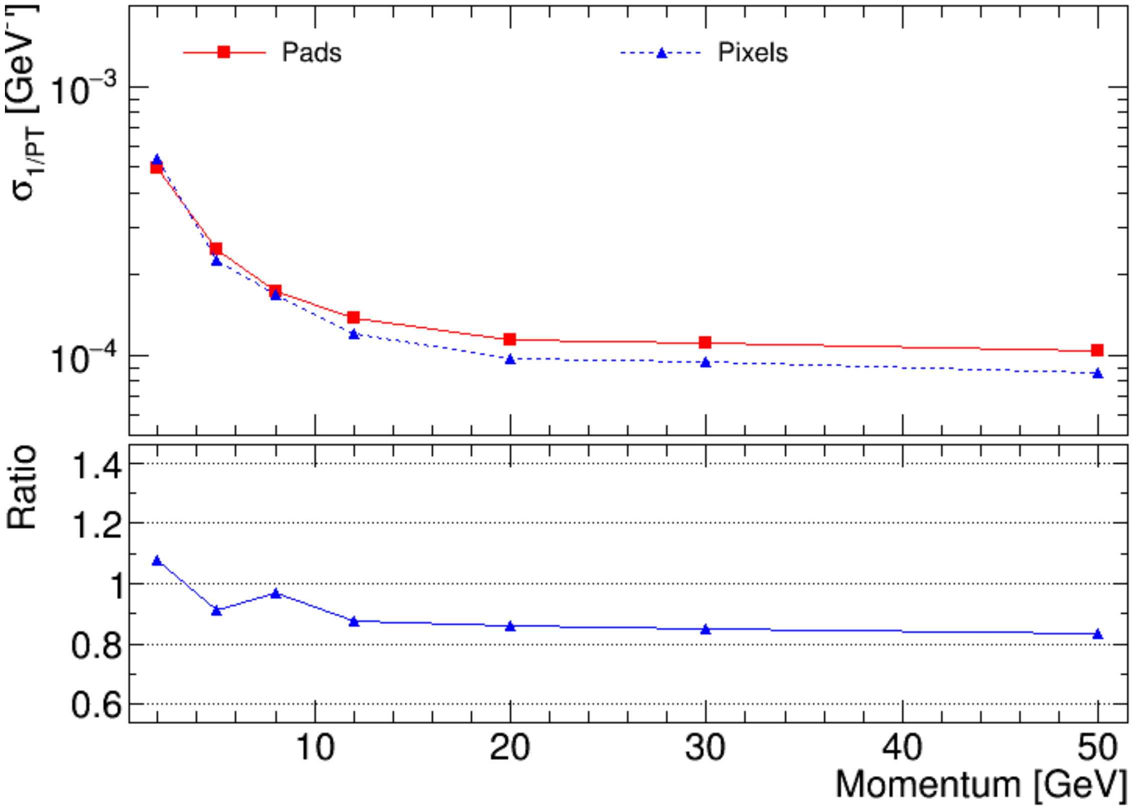
details: PhD thesis
Kees Ligtenberg

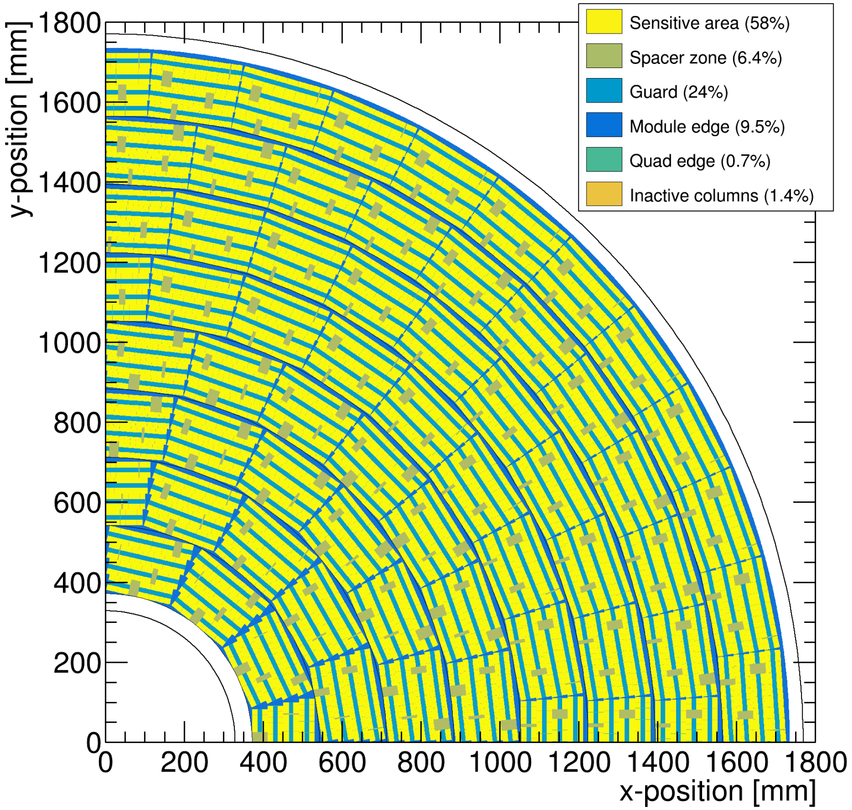


50 GeV muon track with pixel readout

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.





Performance of a GridPix TPC

Further integration of the Pixel TPC in the ILD software

A thought by Frank Gaede about combining pixels into pads:

- one could easily project the pixels into pads - of similar/same size as in the current ILD simulation
- but rather than simply adding up the charge, you can compute the true center-of-gravity based position and charge of the virtual pad
- in a second step you combine neighbouring pads to a cluster and compute the position (in r-phi, z) of the cluster and create a SimHit from this
- both operations should be linear in time (i.e. one loop over pixels/pads)

This procedure should preserve all the point resolution information of the pixels but allow you to run standard Clupatra as for the pad based TPC reconstruction.

Pixel TPC: Track fitting at the edge

- In case of the a realistic geometry with detector edges, Kees Ligtenberg observed a worsened momentum resolution and momentum biases. This was traced down to be caused by biases in the residuals at the edge of the detector
- The conclusion was that the track fit should be updated to take into account the (small) biases in the residuals at the detector edge(s)
- Recently, a master student (computational physics) at the UvA, Peter Voerman, has written a track fit that corrects the biases in one pass: “Track fitting at the edge”.
- The technique can also be applied to fit hits from other gaseous or non-gaseous detectors:
  - a centre of gravity technique is used (with measured charges over multiple strips near the edge)
  - in case of silicon detector hits near the boundaries of the sensitive volume

Pixel TPC: Track fitting at the edge

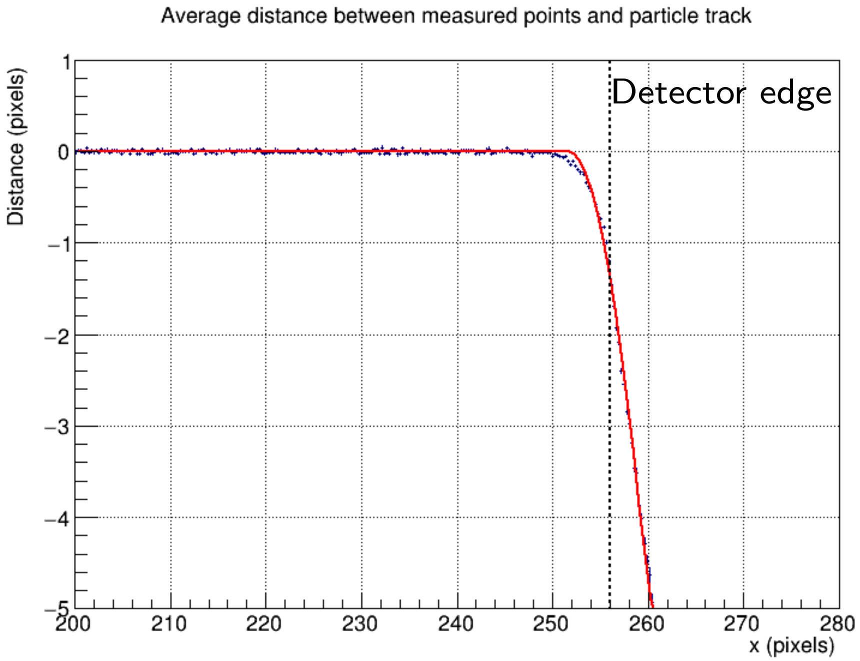
Correcting bias on the detector edge

Peter Voerman

- Close to the edge of a detector, measurements of the particle's position are biased, leading to biased track parameters during track fitting
- The bias in the measurements can be described by this equation:

$$c = \begin{cases} 0 & \text{if } x < p_1 \\ \frac{(x-p_1)^2}{p_0} & \text{if } p_1 < x < p_2 \\ \frac{2(p_2-p_1)(x-p_2)}{p_0} + \frac{(p_2-p_1)^2}{p_0} & \text{if } p_2 < x \end{cases} \qquad (1)$$

- p_0, p_1 and p_2 are dependent on the amount of diffusion in the detector and the detector geometry



1/2

Pixel TPC: Track fitting at the edge

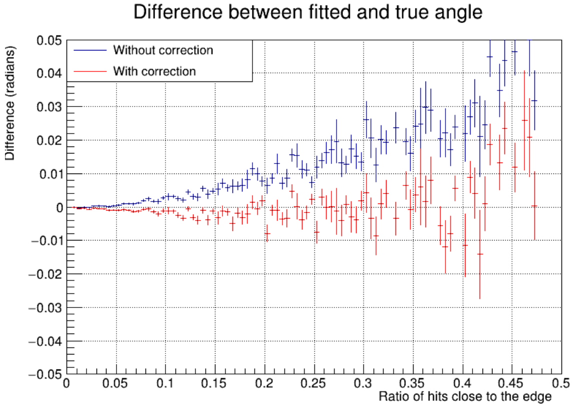
Peter Voerman

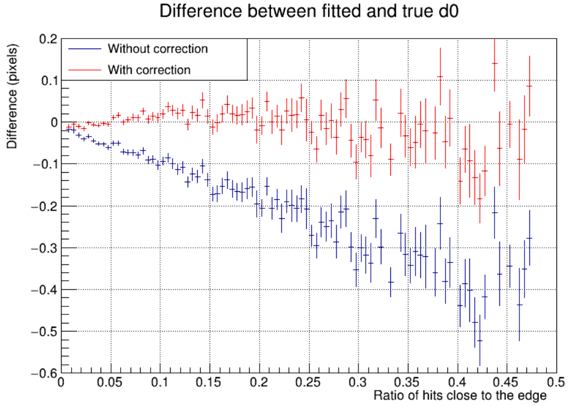
Correcting bias on the detector edge

- The fit is done by minimizing the following χ^2:

$$\chi^2 = \sum_{i=1}^{N} \frac{(\sin(\phi)(x_{m,i} - c_i) - \cos(\phi)y_{m,i} - d_0)^2}{\sigma_i^2} \tag{2}$$

- Without correction, $c_i = 0$
- With correction, c_i is calculated using equation 1
- As seen in the figures, this correction significantly reduces the bias in the fitted parameters as the fraction of measurements close to the edge increases





2/2

Pixel TPC dEdx performance

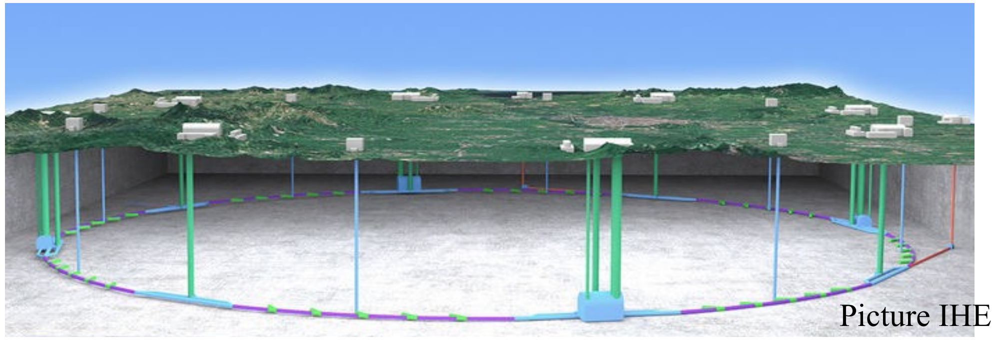
- dE/dx resolution for an electron with p=5,6 GeV/c of 1 m track length with 60% coverage is measured to be 2.9% (at B = 1 Tesla)
- The extrapolated resolution for the ILD detector is 2.5% (w.c. 3.1 and 3.3% 2T)
- This allows for particle identification and separation of Kaons from pions up to momenta of 45 GeV with more than 4-5σ for cos(θ) from 0 to 0.95

- A test beam @ FermiLab with a quad in a TPC is planned (2024, US Grant EIC)
  - an EIC R&D program for CO2 cooling is funded (2023) (Yale, Stony Brook, Purdue, Bonn, Nikhef)
  - Focus is particle identification and tracking at the Electron-Ion-Collider
- A pixel TPC has become a realistic viable option for experiments
  - High precision tracking like ILD@ILC 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

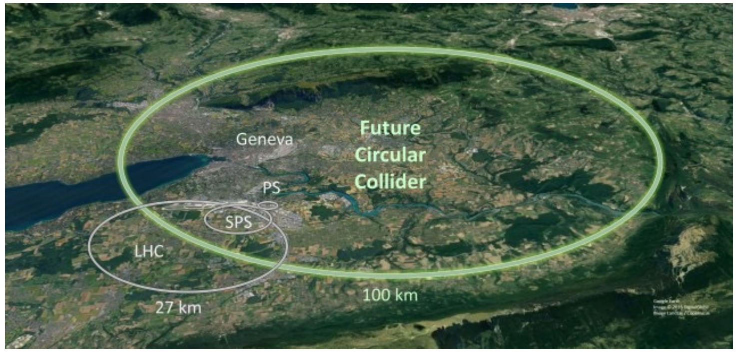
Operation of a Pixel TPC at CEPC or FCC-ee

A Pixel TPC at CEPC or FCC-ee

The most difficult situation for a TPC is running at the Z.
At the Z pole with $L = 200\ 10^{34}\ cm^{-2}\ s^{-1}$ Z bosons will be produced at ~60 kHz



Picture IHEP



- Can a pixel TPC reconstruct the events?
  - The TPC total drift time is about 30 μs
  - This means that there is on average 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 rate?
  - Link speed of Timepix3 (in Quad): 2.6 MHits/s per 1.41 × 1.41 cm^2 Testbeam up to 1.5 kHz
  - YES: This is largely sufficient to deal with high luminosity Z running
  - NB: Data size is not a show stopper as e.g. LHCb experiment shows using the VeloPix chip

A Pixel TPC at CEPC or FCC-ee

- What is the current power consumption?
  - No power pulsing possible at these colliders (at ILC power pulsing was possible)
  - Current power consumption TPX3 chip ~2W/chip per 1.41 × 1.41 cm^2
  - So: good cooling is important but in my opinion no show stopper
  - For Silicon detectors lower consumption for the chips and cooling is an important point that needs R&D (e.g. microchannel cooling).
  - To save power the TPX3/4 chips can be run in LowPowerMode: reduction factor 10.
- Can one limit the track distortions?
  - There are two important sources of track distortions:
    - the distortions of the TPC drift field due to the primary ions
    - the distortions of the TPC drift field due to the ion back flow (IBF)
  - At the ILC gating is possible; for CEPC or FCC-ee this is more involved, for a Pixel TPC a double grid is the best solution (see next slide)

A Pixel TPC at CEPC or FCC-ee

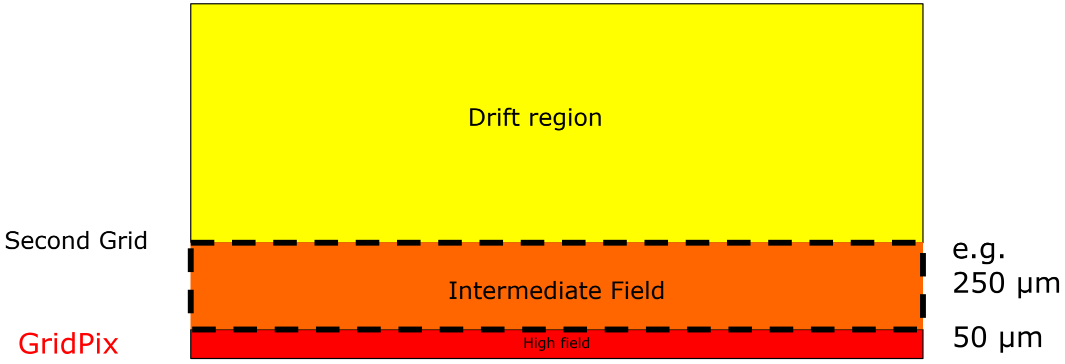
- Is it possible to reduce the IBF for a pixel TPC?
  - IDEA: by making chip with a double grid structure (see next slide)
  - This idea was already realized as a TWINGRID NIMA 610 (2009) 644-648
  - For GEMs for the ALICE TPC this was also the way – several GEMs on top of each other to reduce IBF
  - For the Pixel the IBF can be easily modelled and with a hole size of 25 μm an IBF of $3\ 10^{-4}$ can be achieved and the value for IBF*Gain (2000) would be 0.6.
  - YES: the IBF can be reduced to 0.6 but this needs R&D
  - In the new detector lab in Bonn it is possible to make and study this device
- What would be the size of the TPC distortions?
  - Tera-Z studies by Daniel Jeans and Keisuke Fuji show that for FCC-ee or CEPC this means: distortions from Z decays up to < O(100) μm
  - Beam strahlung gives (now) a factor 200 more background. Detector optimization and shielding is important for TPC and Silicon detectors to reduce pair background.
  - It was argued that in an ILD like detector the distortions can be mapped out using the VTX-SIT/SET detectors.

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 (2000) would be 0.6.

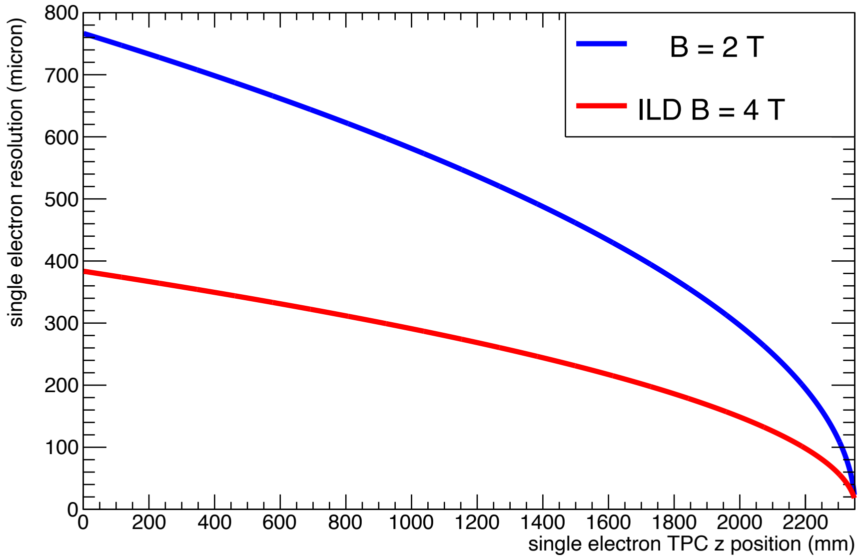


Ion backflow	Hole 30 µm	Hole 25 µm	Hole 20 µm
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	12 10^{-4}	3 10^{-4}	1 10^{-4}
transparancy	100%	99.4%	91.7%

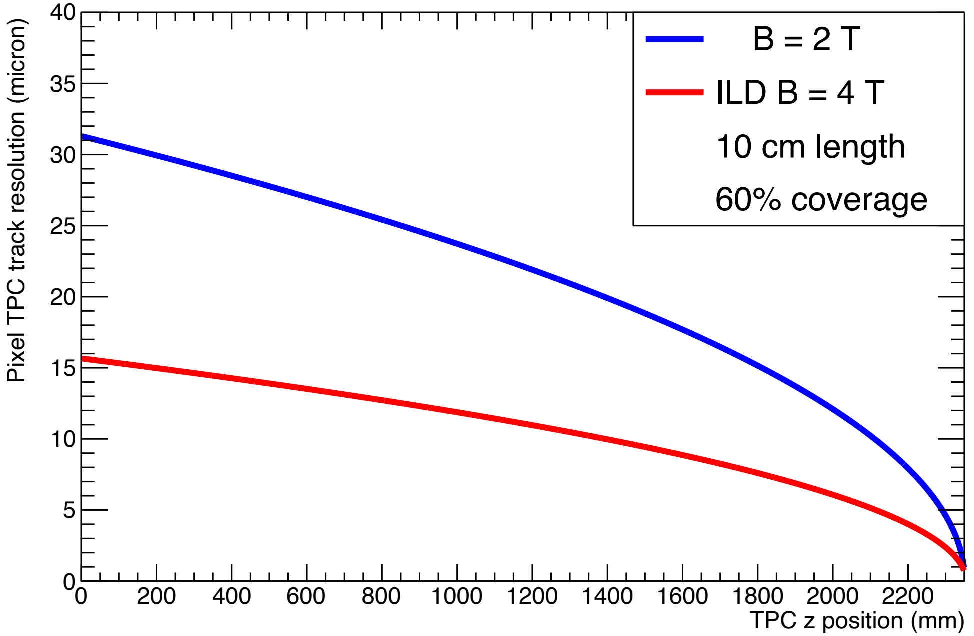
Pixel TPC tracking studies

ILD tracking Performance for a Pixel TPC based on test beam

Single electron resolution



10 cm track resolution



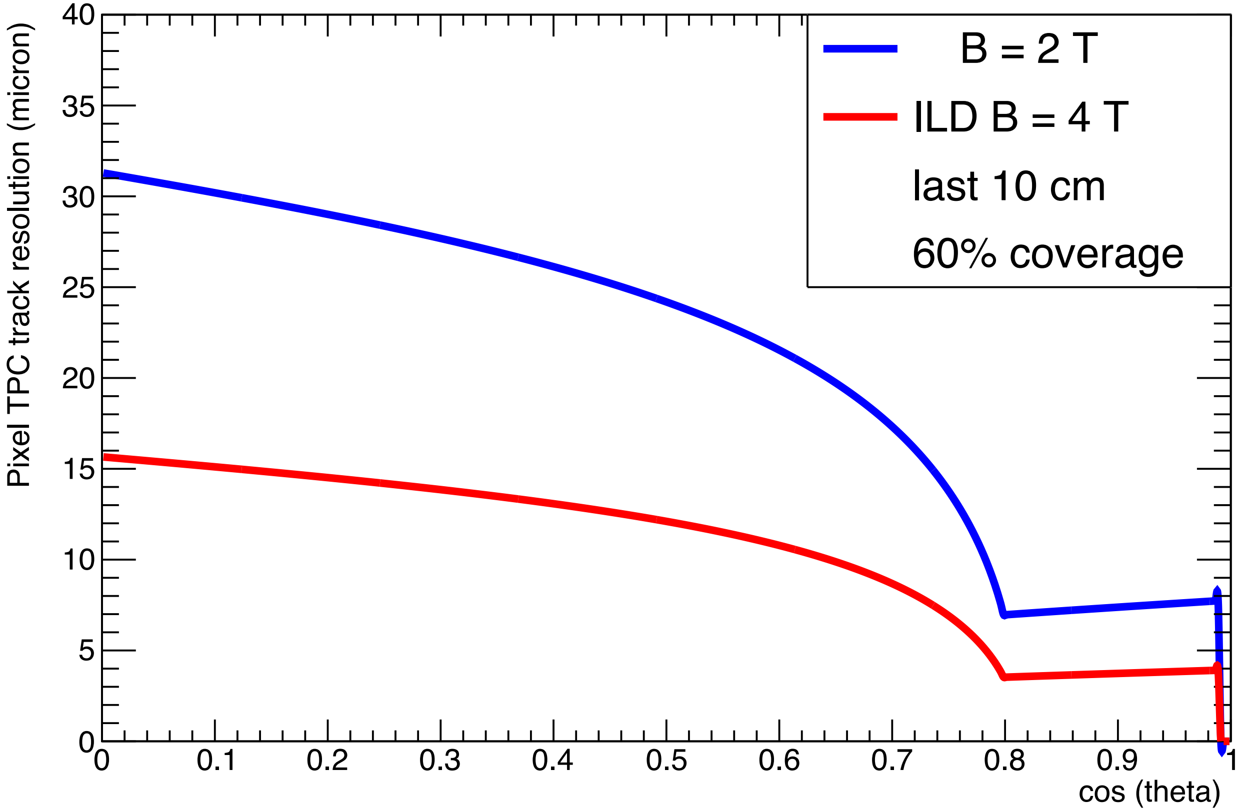
Each 10 cm we have a point with a resolution of < 15 (30) μm on the track

Pixel TPC tracking studies

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 θ>0.8). This is due to the short drift distance and the high resolution pixel readout.

Question can we use the endcap 'point' and calibrate out the TPC distortions?

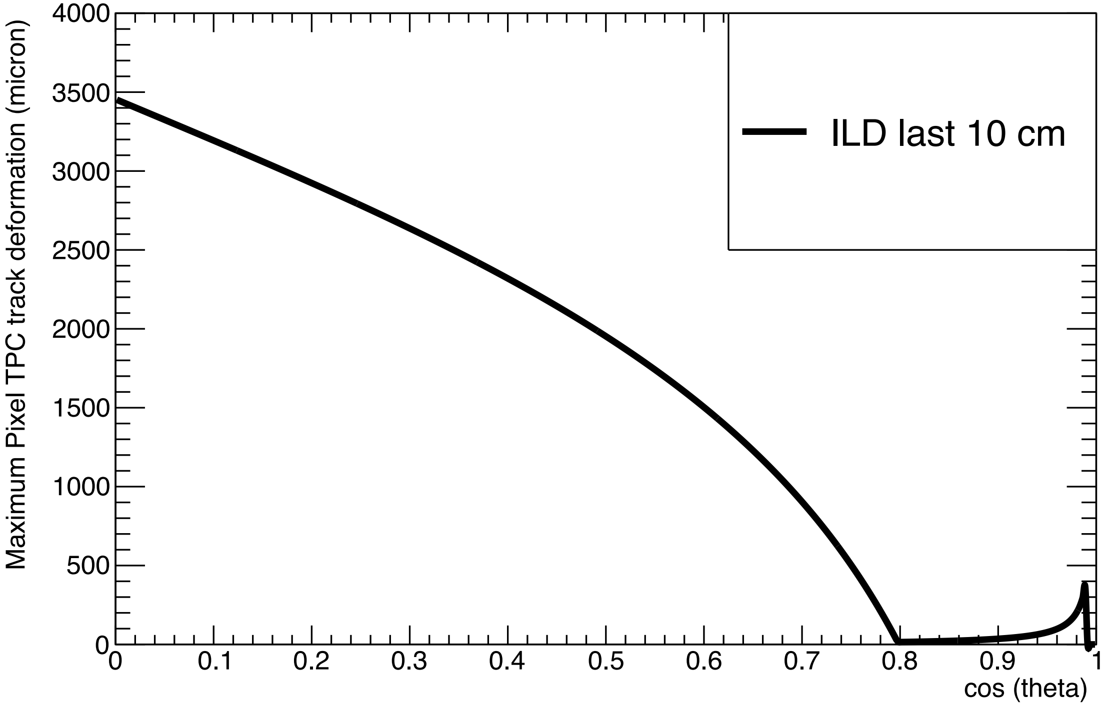


Pixel TPC tracking studies

Crude distortion model for beam-beam background
e.g. for FCCee or CEPC

Distortions have an amplitude of 10 cm* and are described by the following function:
$\Delta = 10\ (\mathrm{cm})\ (\mathrm{rInner}/r)^2\ z/\mathrm{zMax}$
z = drift distance r = radius
rInner and zMax from ILD

These are huge* distortions. Here we use the last 10 cm of the track. Clearly the Barrel at large radii has 3.5 mm distortions

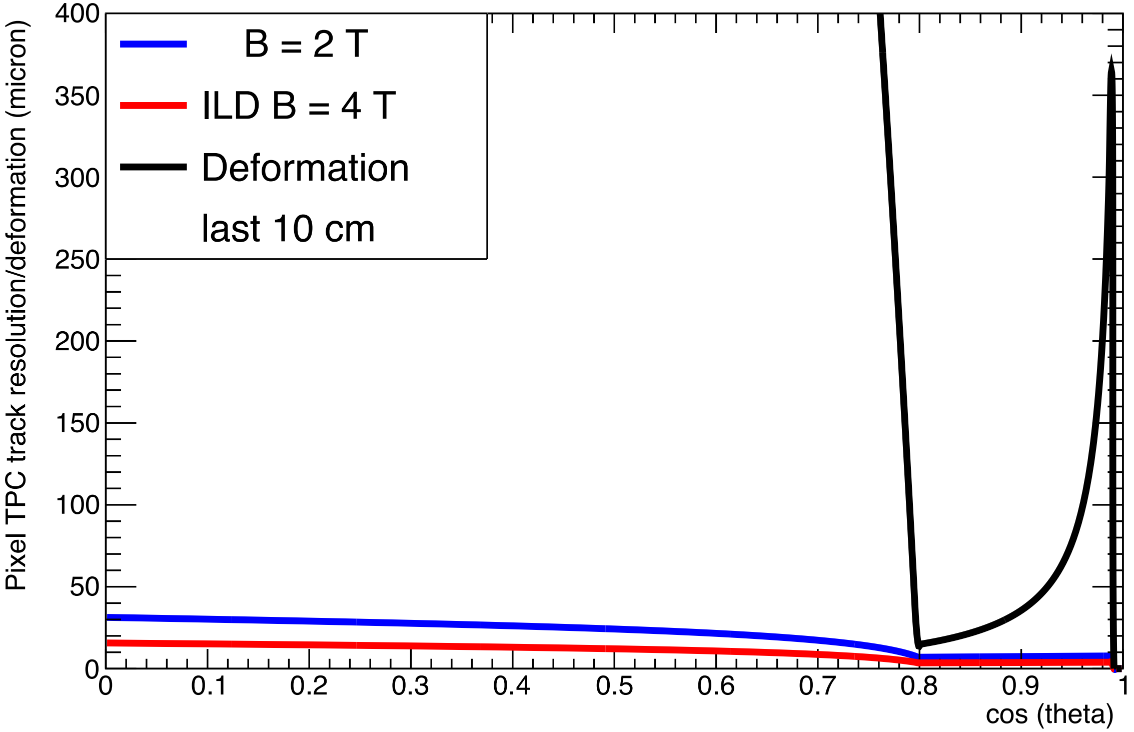


Pixel TPC tracking studies

Crude distortion model for beam-beam background e.g. for FCCee or CEPC

The endcap distortions are much smaller than the barrel and they range from 15-350 μm

So that region is rather quiet and can be used IMO to calibrate pixel TPC distortions.



Fitting out TPC distortions in ILD

- It is possible to map out distortions using e.g. muons from Z decays
  - E.g. by fitting the 3D space charge 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, ILD allows for more elaborate procedures. 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 what is developed in ATLAS. In the ATLAS track fit the common systematics is fitted out for sets of Muon hits. For ILD 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.

Conclusions: Pixel TPC at a circular collider

- YES: a pixel TPC can reconstruct the Z events in one readout cycle
- YES: the current readout of the Timepix3 chip can deal with the rate
- The current power consumption is 1W/cm^2. By running the TPX chips in low power mode this can be reduced by a factor of 10. Still good cooling is important no show stopper; but needs extensive R&D.
- Track distortions in the TPC drift volume are a concern at high lumi Z running:
  - Track distortions from Z decays in TPC are O(100) μm
  - It is possible to reduce the IBF for a pixel TPC by making a device with a double grid
  - A double grid needs dedicated R&D that can be performed in the new lab in Bonn
- The Z physics program at FCC-ee or CEPC with an ILD-like detector with a Pixel TPC (with double grid structures) sliced between two silicon trackers (VTX-SIT and SET) can be fully exploited. The reduction of beamstrahlung – and the fitting out of distortions - needs more study.
- A pixel TPC can perfectly run at WW, ZH or tt energies where track distortions are several orders of magnitude smaller