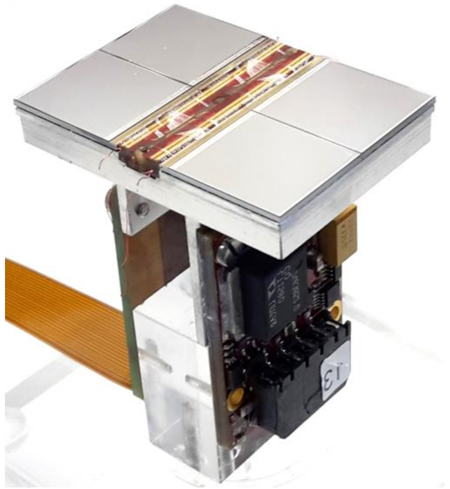
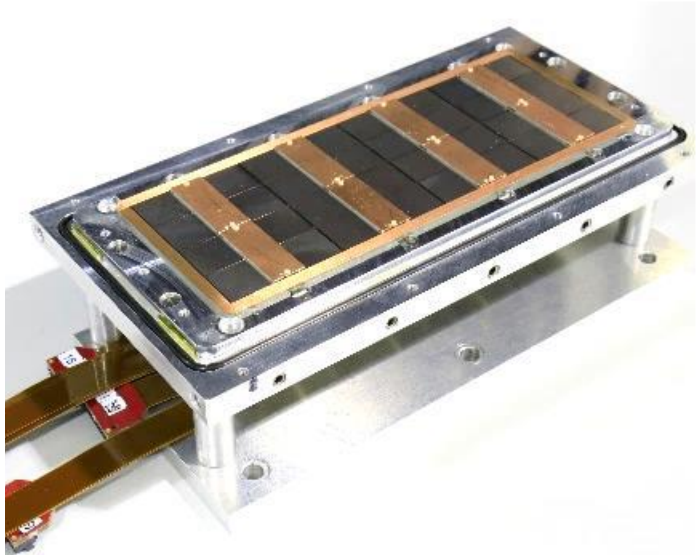
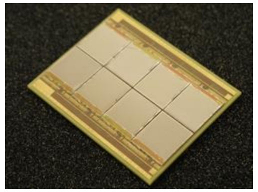
Pixel TPC tracking and dE/dx performance

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

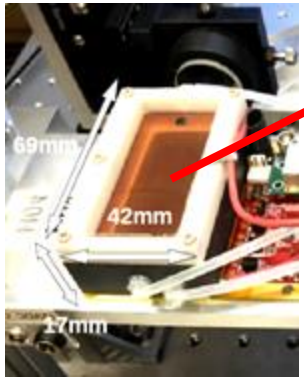


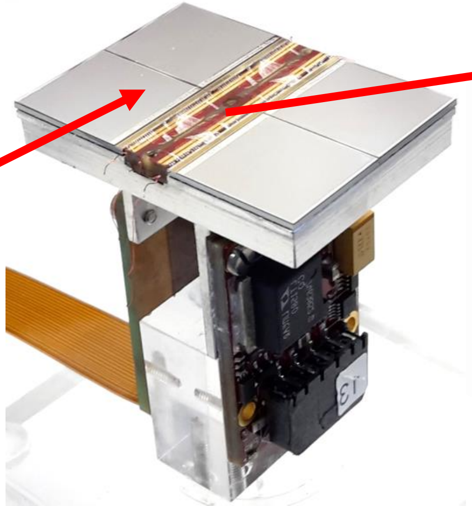


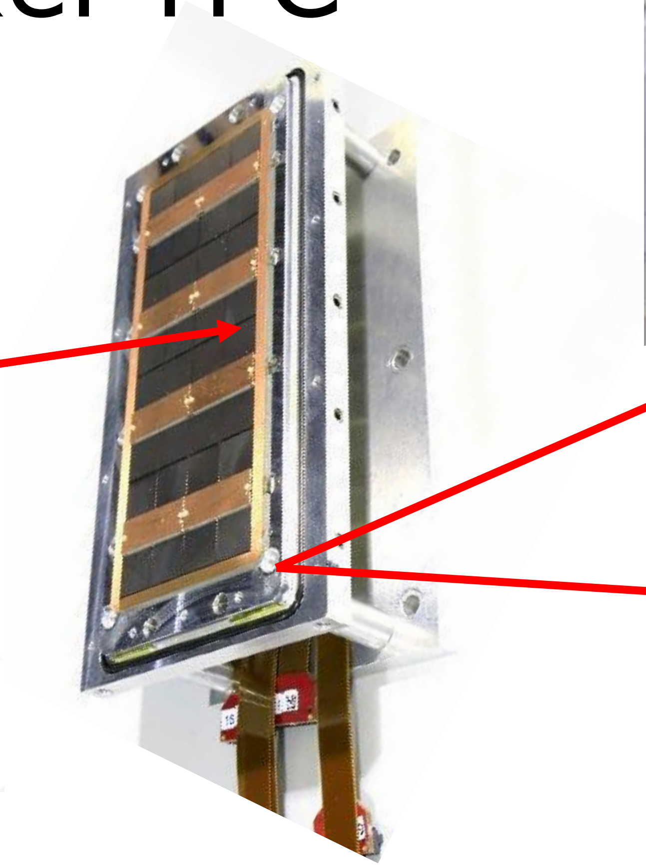
Pixel TPC

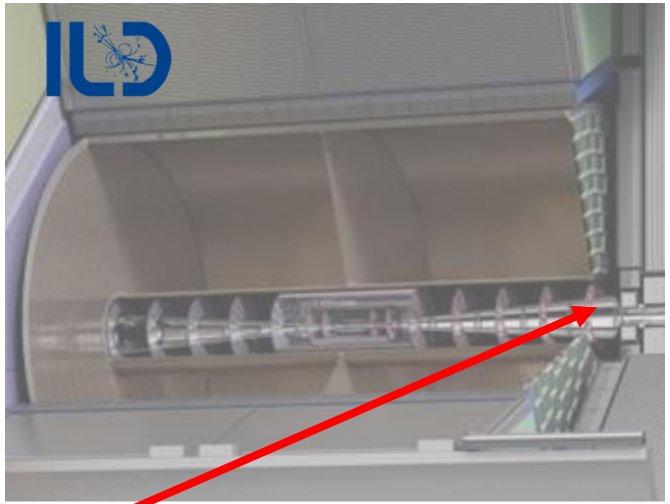


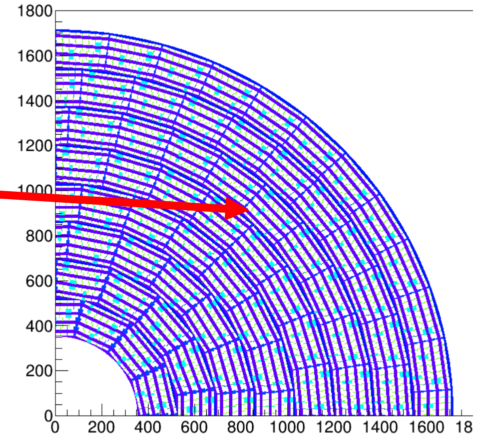
(Octopuce)







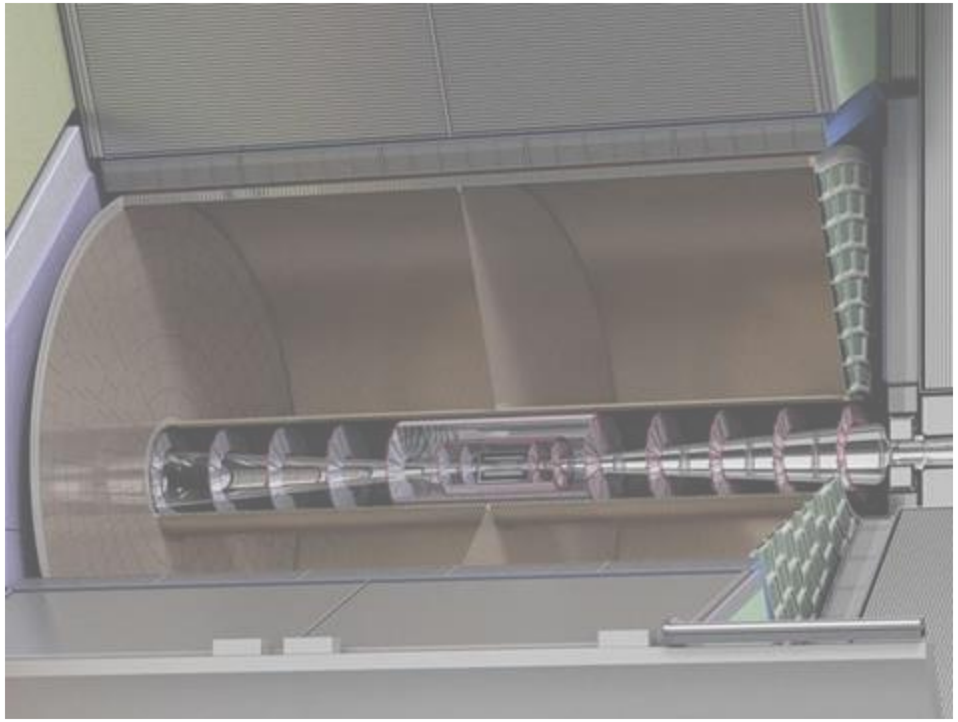




(TimePix1) TPX3 chip Quad Module TPC plane

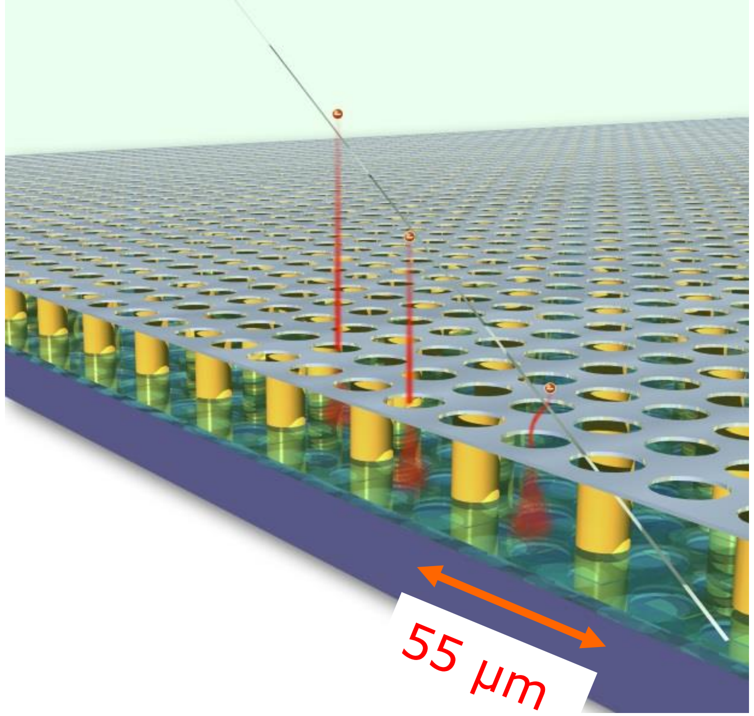
(2007-14) 2017 2018 2019

Pixel TPC

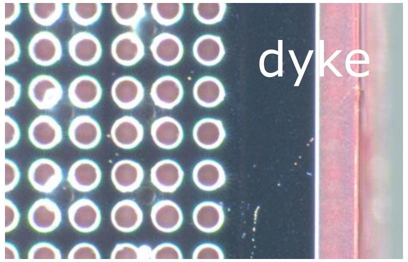


- Material budget is
  - 0.01 X_0 TPC gas
  - 0.01 X_0 inner cylinder
  - 0.03 X_0 outer cylinder
  - < 0.25 X_0 endplates (incl readout)
- Note the very low budget in the barrel region. Material budget can be respected by different technologies like GEM, MicroMegas and Pixels
- TPC is sliced between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

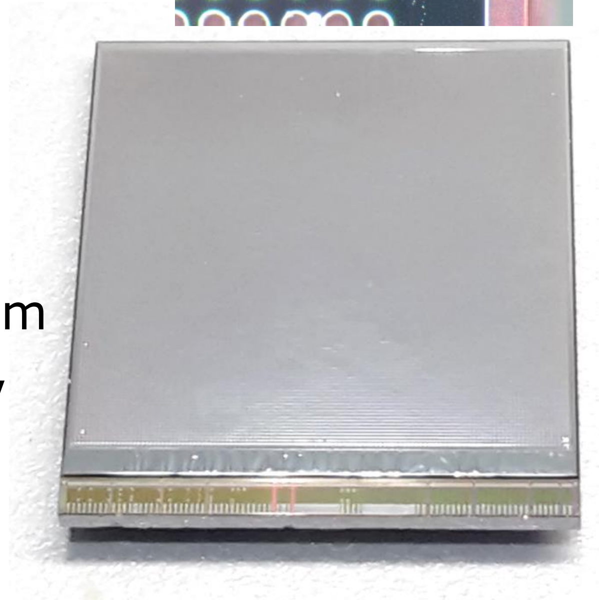
GridPix technology

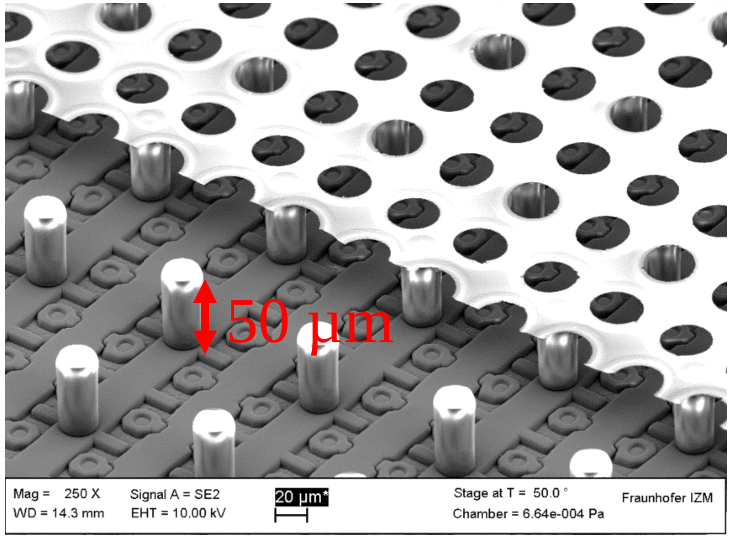


- Pixel chip with integrated Grid (Micromegas-like)
- InGrid post-processed @ IZM
- Grid set at negative voltage (300 – 600 V) to provide gas amplification
- Very small pixel size (55 µm)
- detecting individual electrons



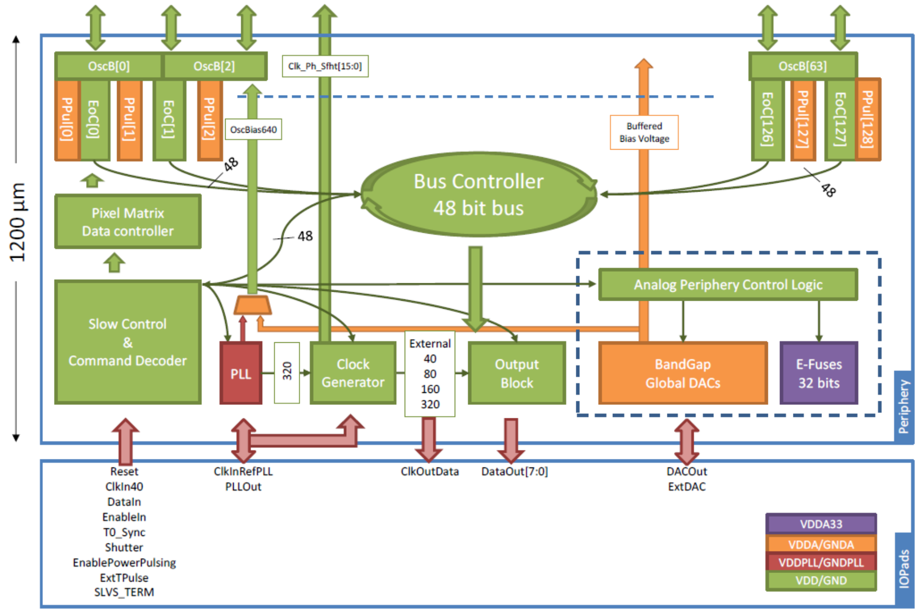
- Aluminium grid (1 µm thick)
- 35 µm wide holes, 55 µm pitch
- Supported by SU8 pillars 50 µm high
- Grid surrounded by SU8 dyke (150 µm wide solid strip) for mechanical and HV stability

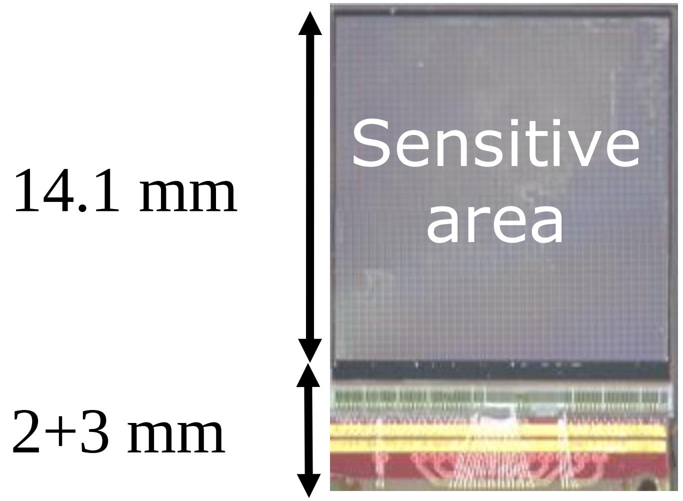




Pixel chip: TimePix3

- 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



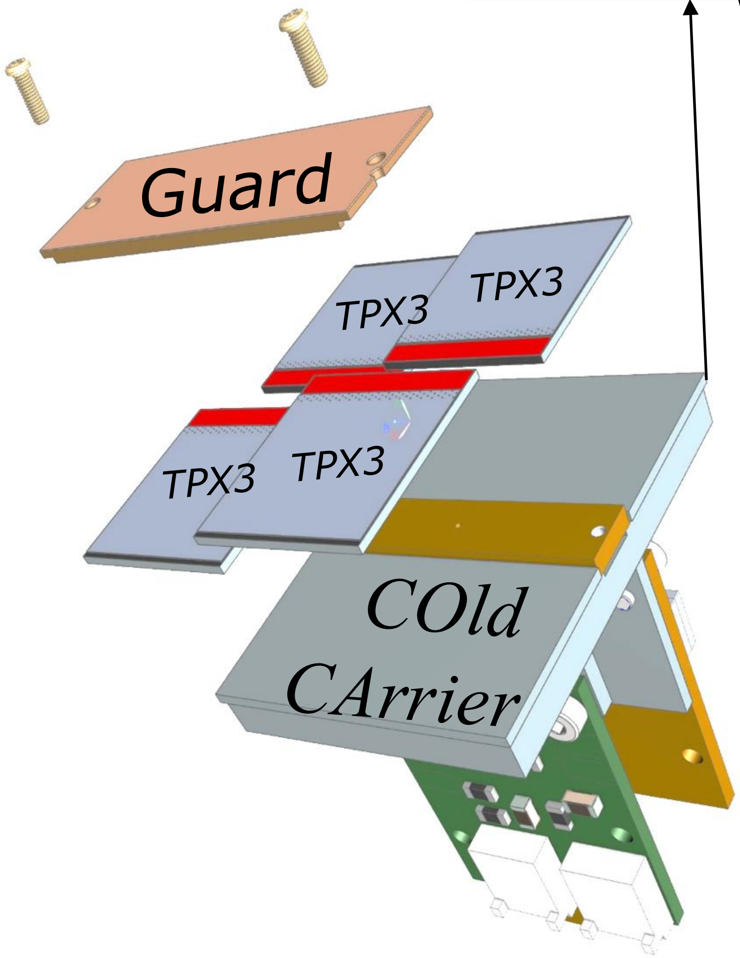


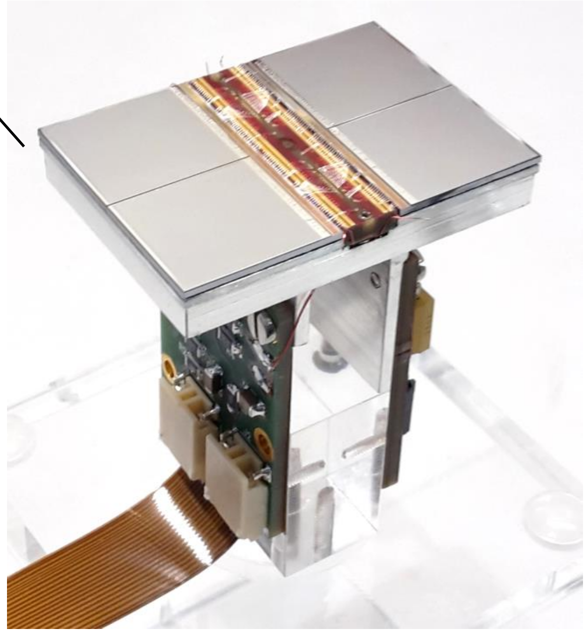
QUAD design and realization

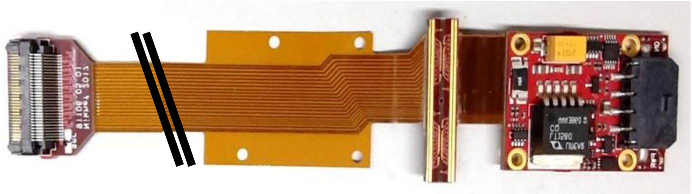
series of QUADs

- 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

39.6 x 28.38 mm



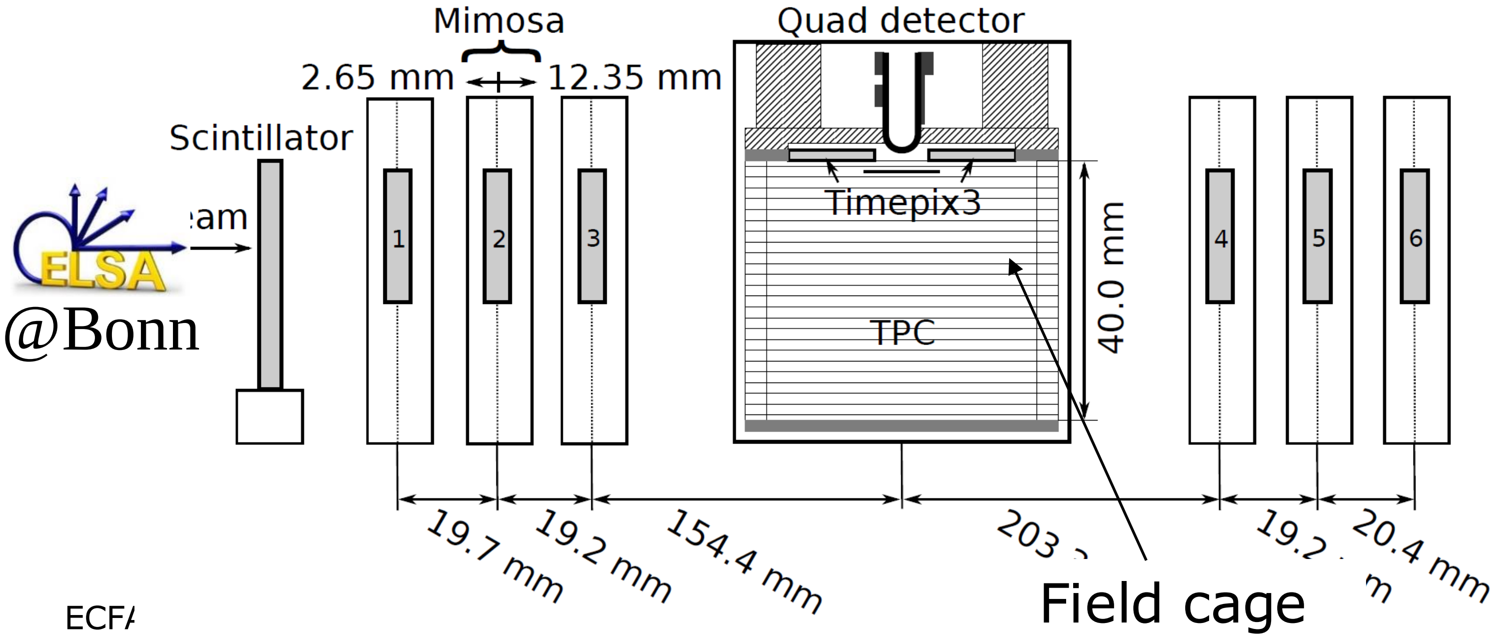


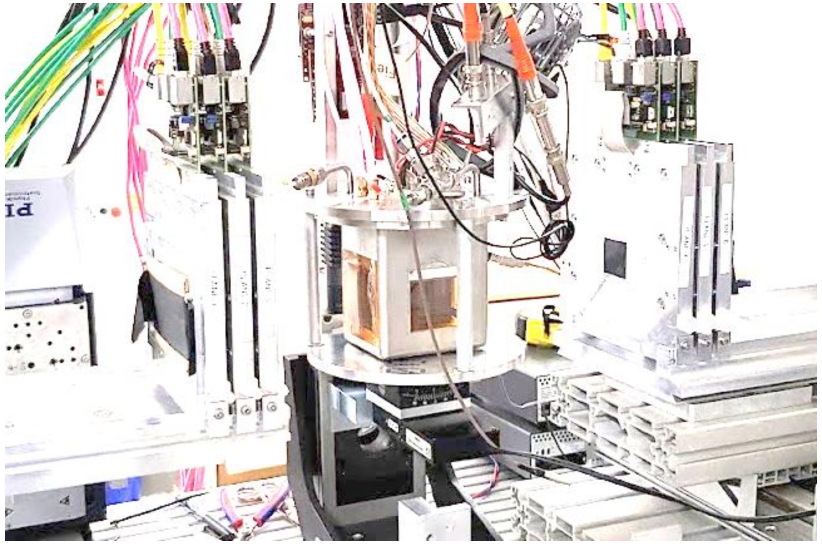


QUAD test beam in Bonn (October 2018)

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

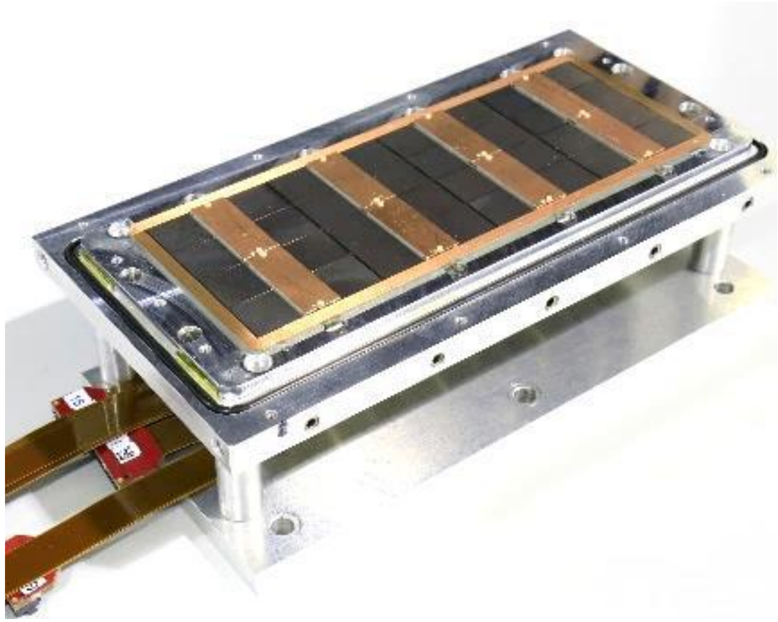
Published NIMA https://doi.org/10.1016/j.nima.2019.163331

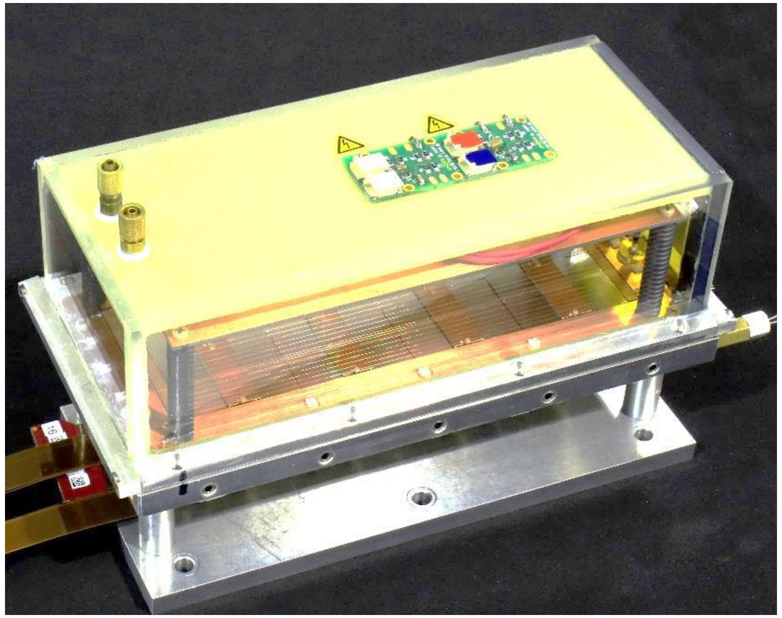


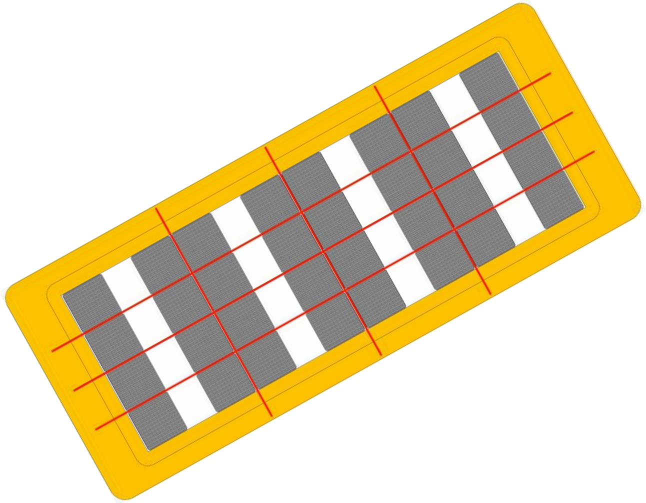


QUAD as a building block

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

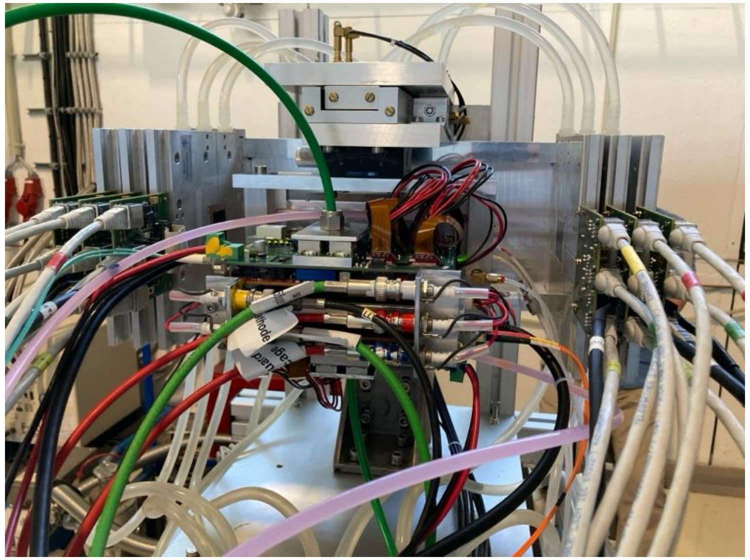


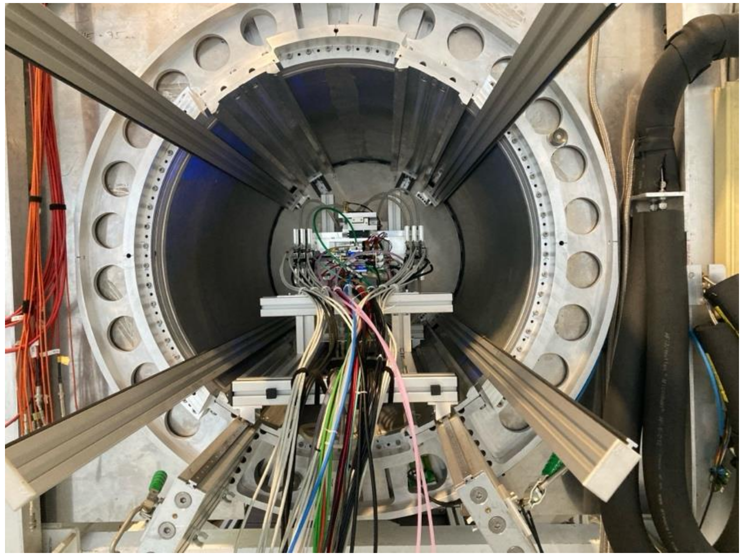




in red guard wires

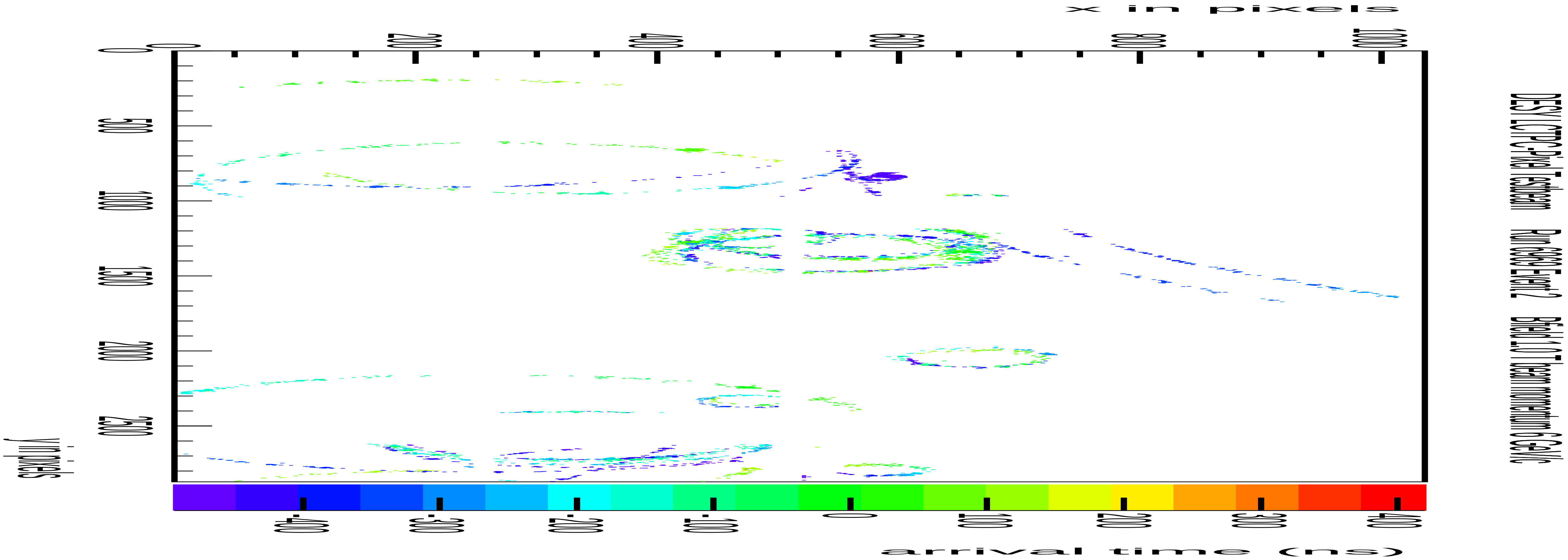
DESY testbeam June 2021





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

DESY testbeam June 2021



DESY testbeam Module Analysis

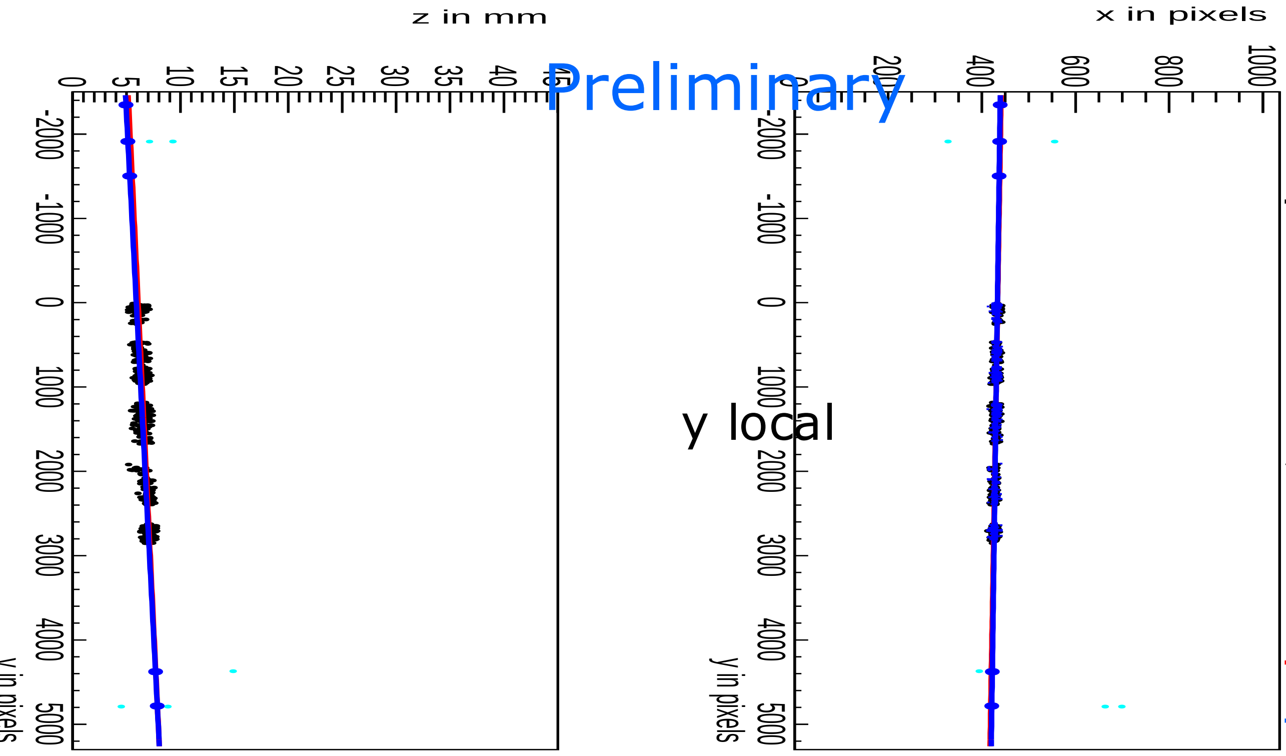
x global

z global

z global

y global

x local



z local drift

y local

y local

Event display with module and telescope

TPX3 track 1130 hits

χ^2_{xy} = 677.5/1128

χ^2_{z} = 775.9/1069

Asymmetric tail outlier removal applied 1071 hits in z kept.

TPX3 track hits

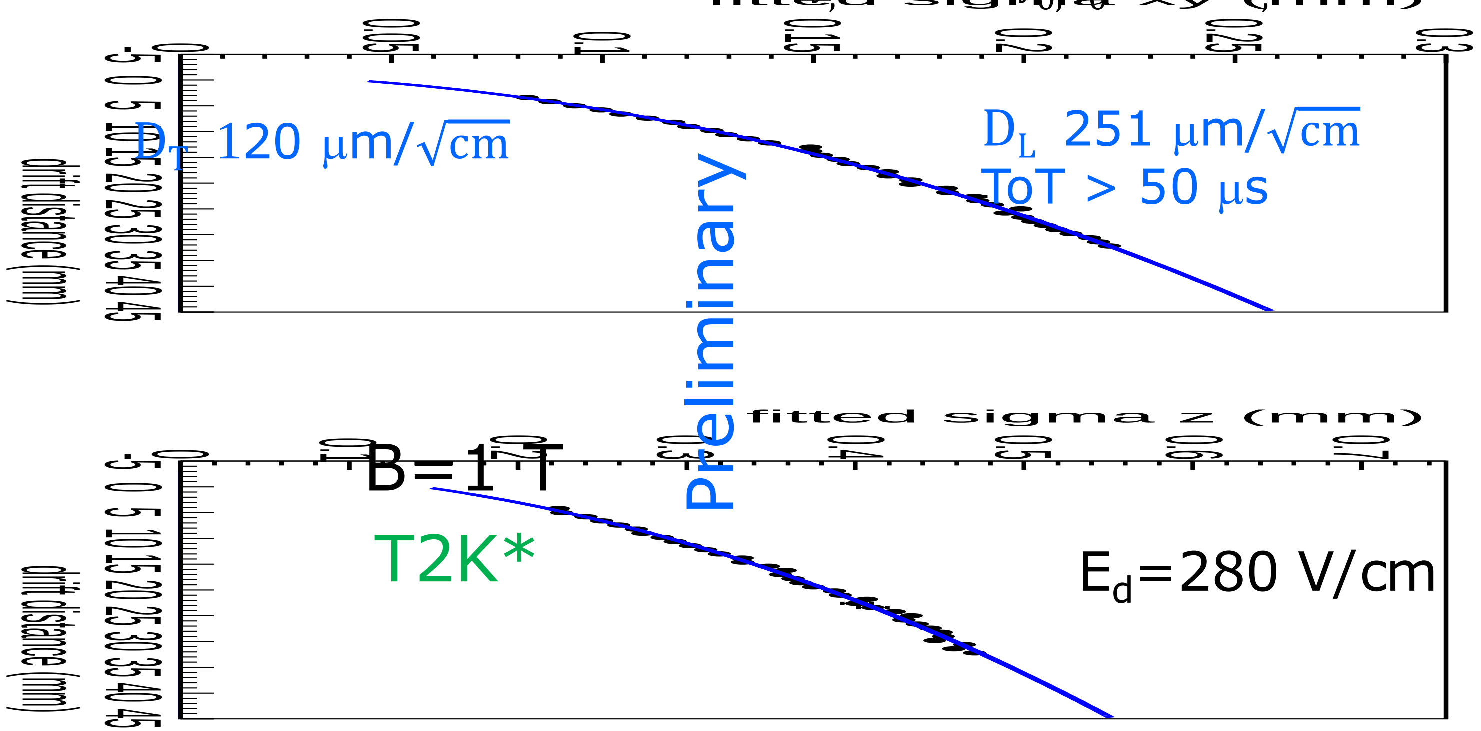
Telescope track hits (off track green)

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

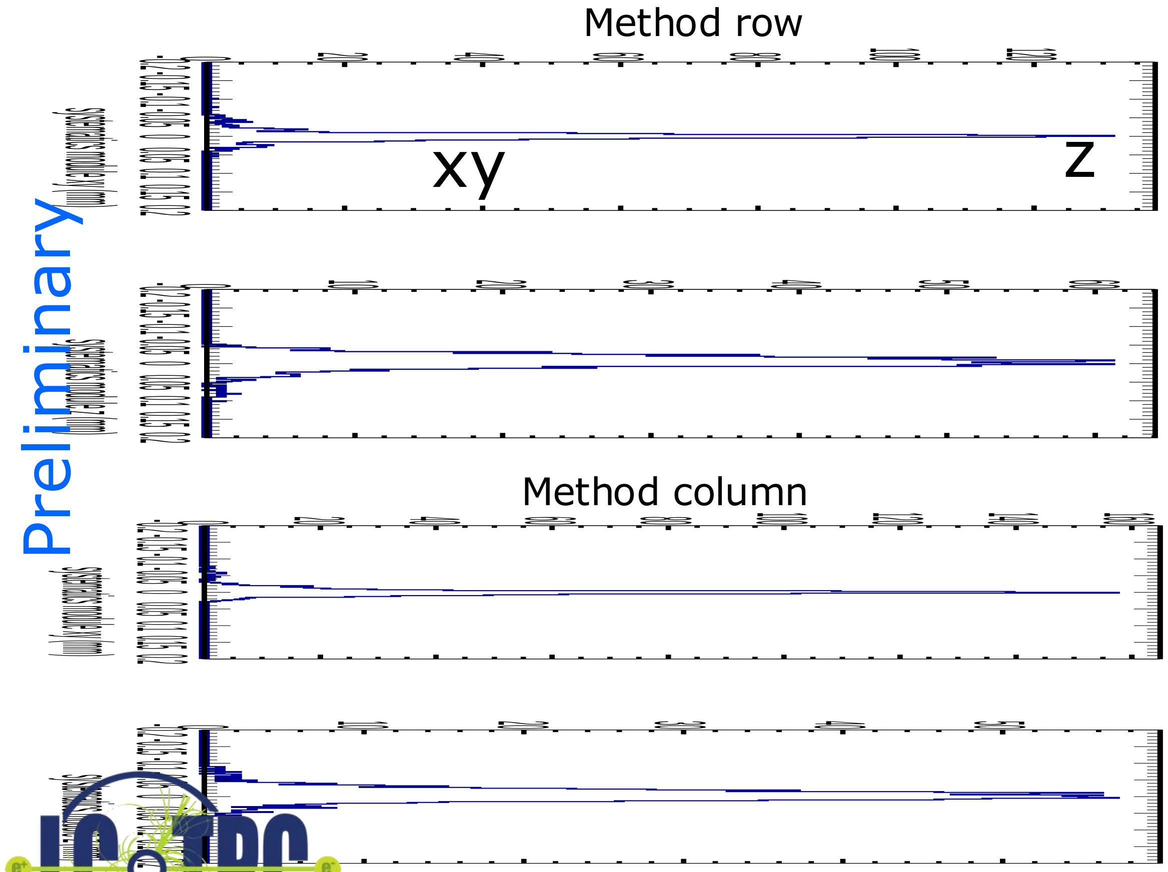
D_T =121 $\mu m/\sqrt{cm}$

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 module plane



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.

Tracking 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 $D_{xy} = 287\ \mu m/\sqrt{cm}$ $D_z = 273\ \mu m/\sqrt{cm}$
- The diffusion coefficients at B=1 T is $D_{xy} = 120\ \mu m/\sqrt{cm}$ $D_z = 251\ \mu m/\sqrt{cm}$
  - In agreement with Magboltz $D_{xy} = 121\ \mu m/\sqrt{cm}$

*the chip was successfully repaired in 2023 Bonn

Tracking 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
- A NIM paper has been submitted and is reviewed

Towards a Pixel TPC part I: 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]

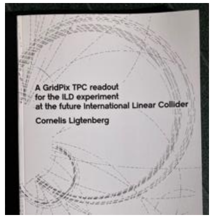
[a] *Nikhef, Science Park 105, 1098 XG Amsterdam, The Netherlands*
[b] *Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany*

Abstract

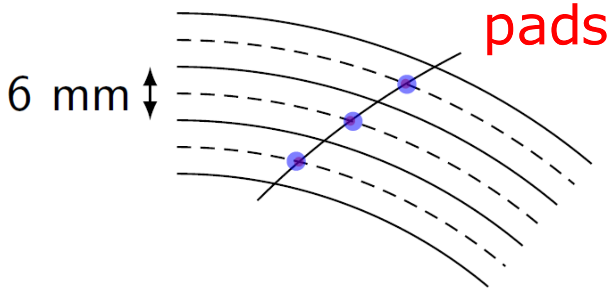
A Time Projection Chamber (TPC) module with 32 GridPix chips was constructed and the performance was measured using data taken in a testbeam at DESY in 2021. The GridPix chips each consist of a Timepix3 ASIC (TPX3) with an integrated amplification grid and have a high efficiency to detect single ionisation electrons. In the testbeam 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 momenta of 5 and 6 GeV/c and at magnetic fields of 0 and 1 Tesla(T).

Simulation of ILD TPC with pixel readout

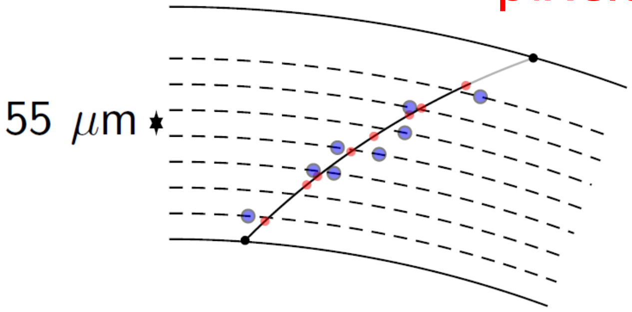
- To study the performance of a large pixelized TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Adapted Kalman filter track reconstruction to pixels



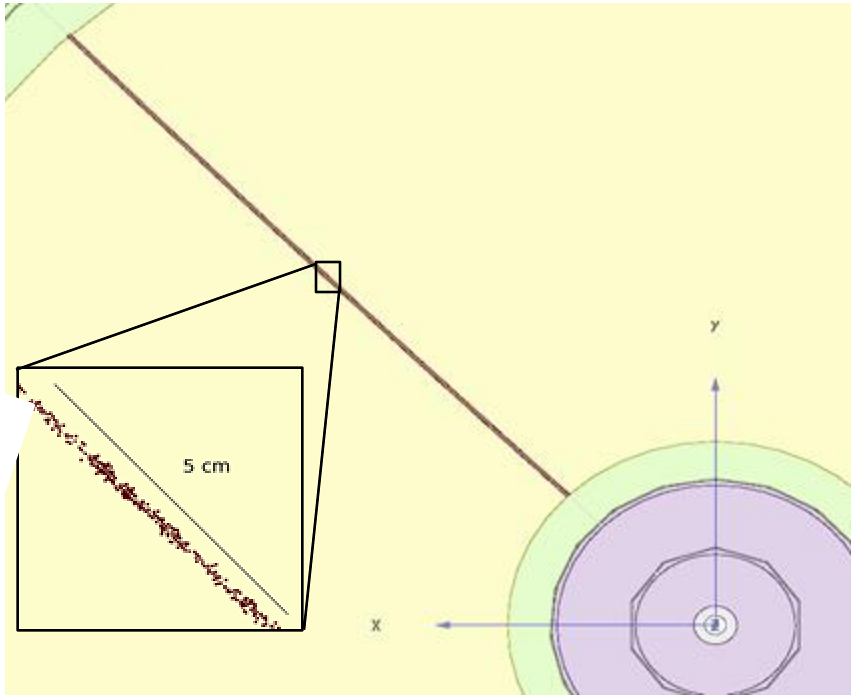
details: PhD thesis
Kees Ligtenberg 2022



22 electrons / hit
~ 200 hits / track



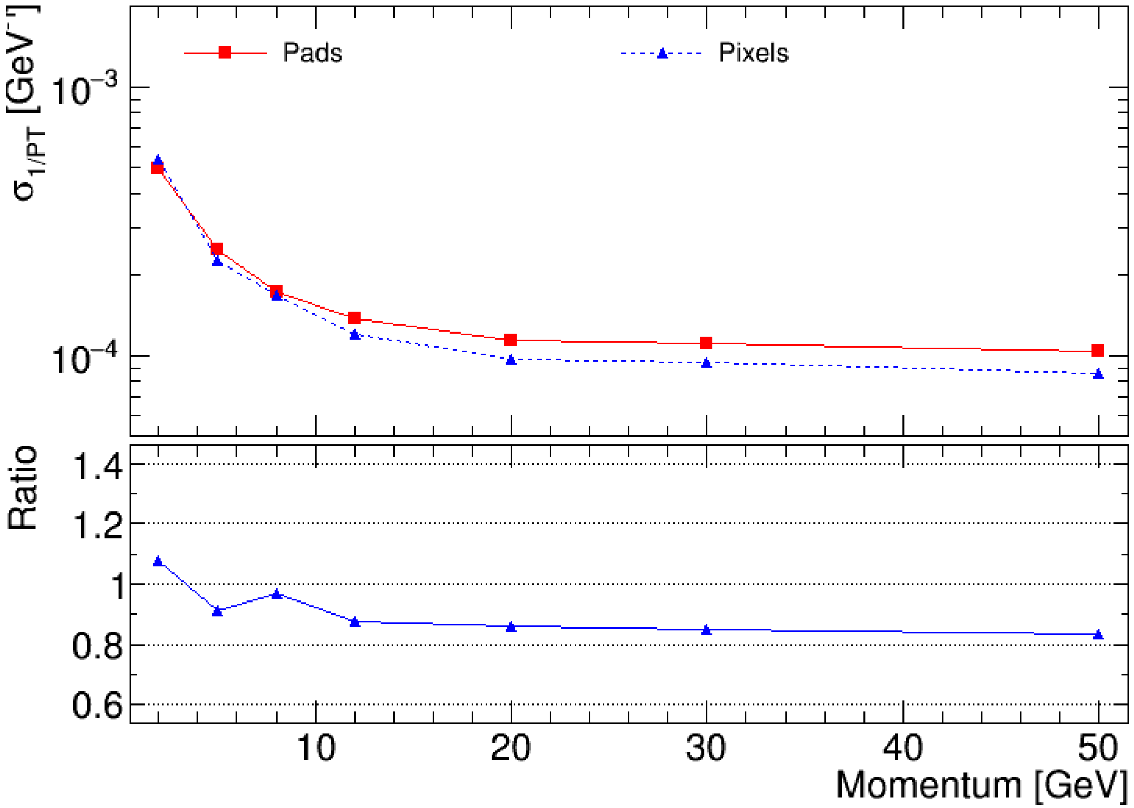
1 electron / hit
~ 10 000 hits / track

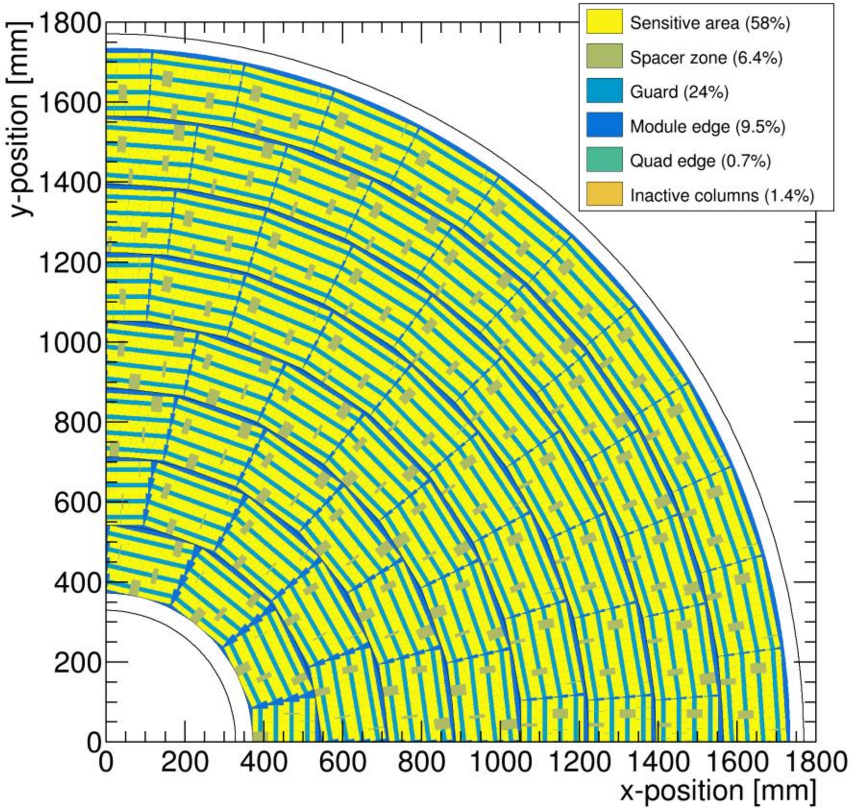


50 GeV muon track with pixel readout

Performance of a GridPix TPC at ILC

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

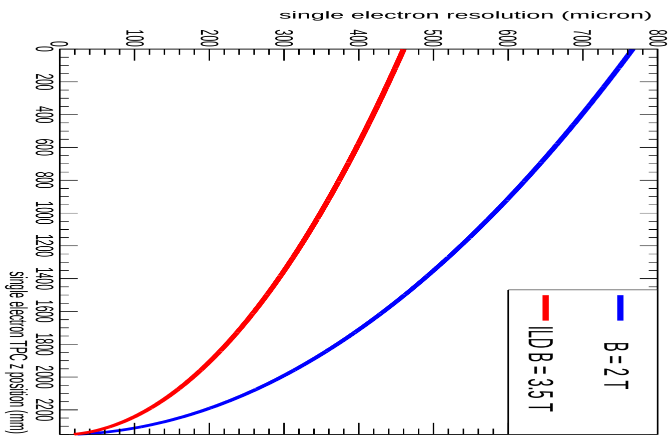




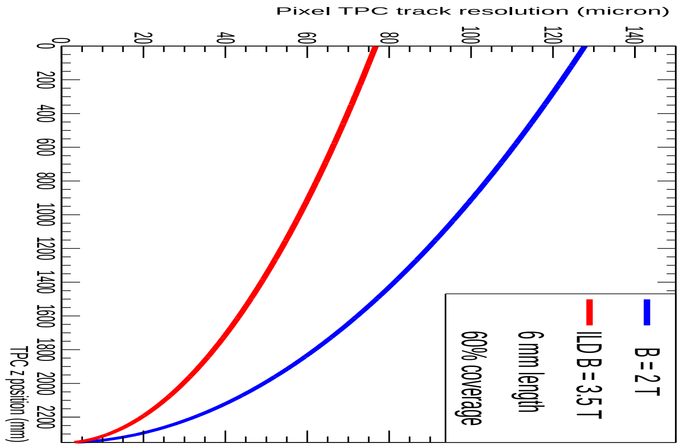
Pixel TPC tracking studies

ILD tracking Performance for a Pixel TPC based on test beam

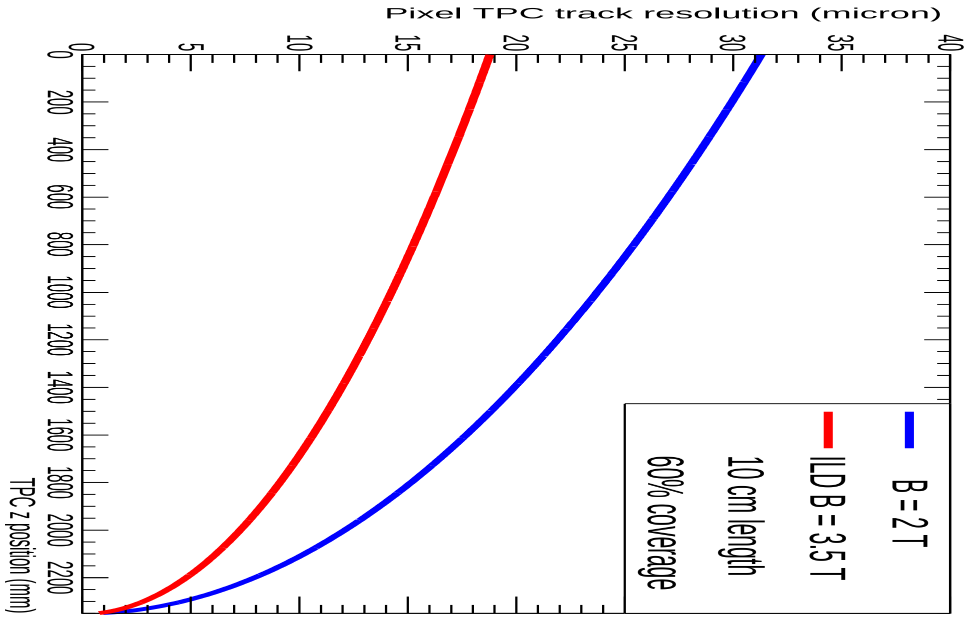
Single electron resolution



6 mm track("pad") resolution



10 cm track 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).

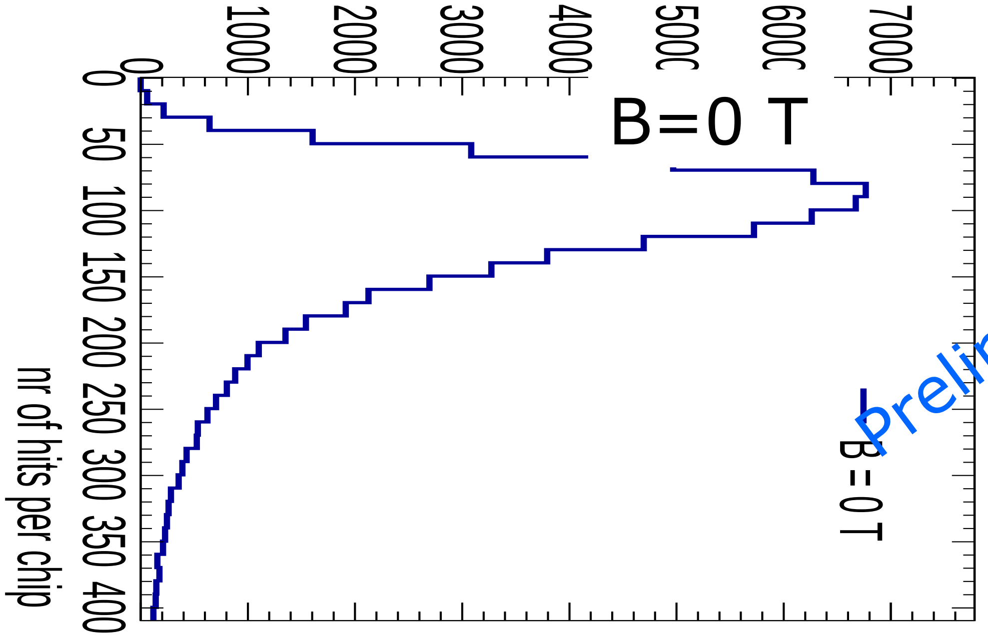
DESY testbeam Module Analysis

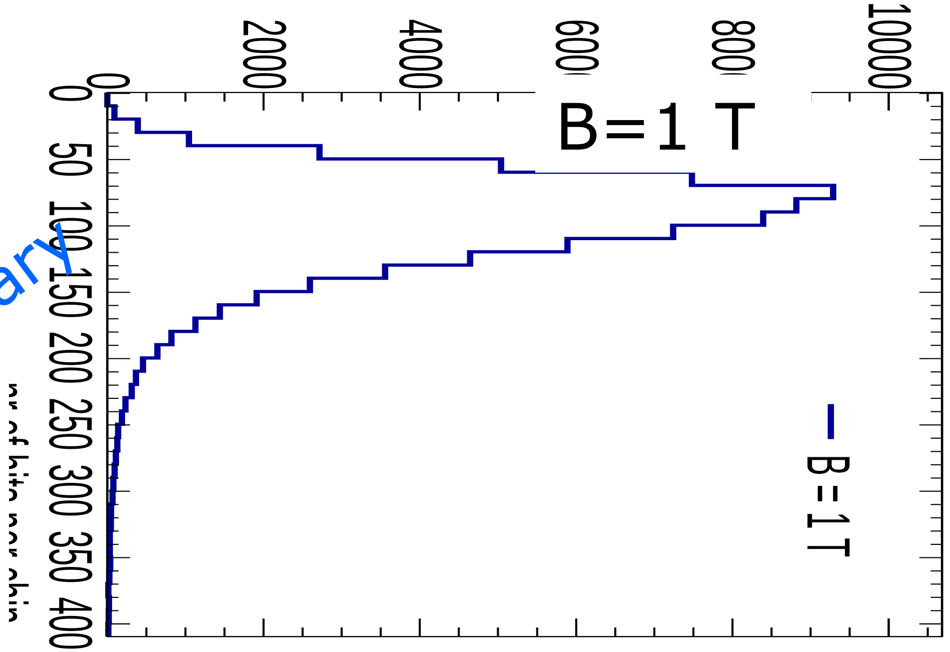
Performance of dEdx

- 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 measure 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 (time over threshold as a measure of the deposited charge) but this is not explored
- The advantage of hit counting in a Pixel TPC 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 readout 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 ”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_{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” observable for electrons and MIP (==70% of hits)
  - method 1 = nr of selected hits, method 2 = fitted slope
  - Resolution is $\sigma = \sigma$(dEdx)/dEdx (for σ we use the rms)

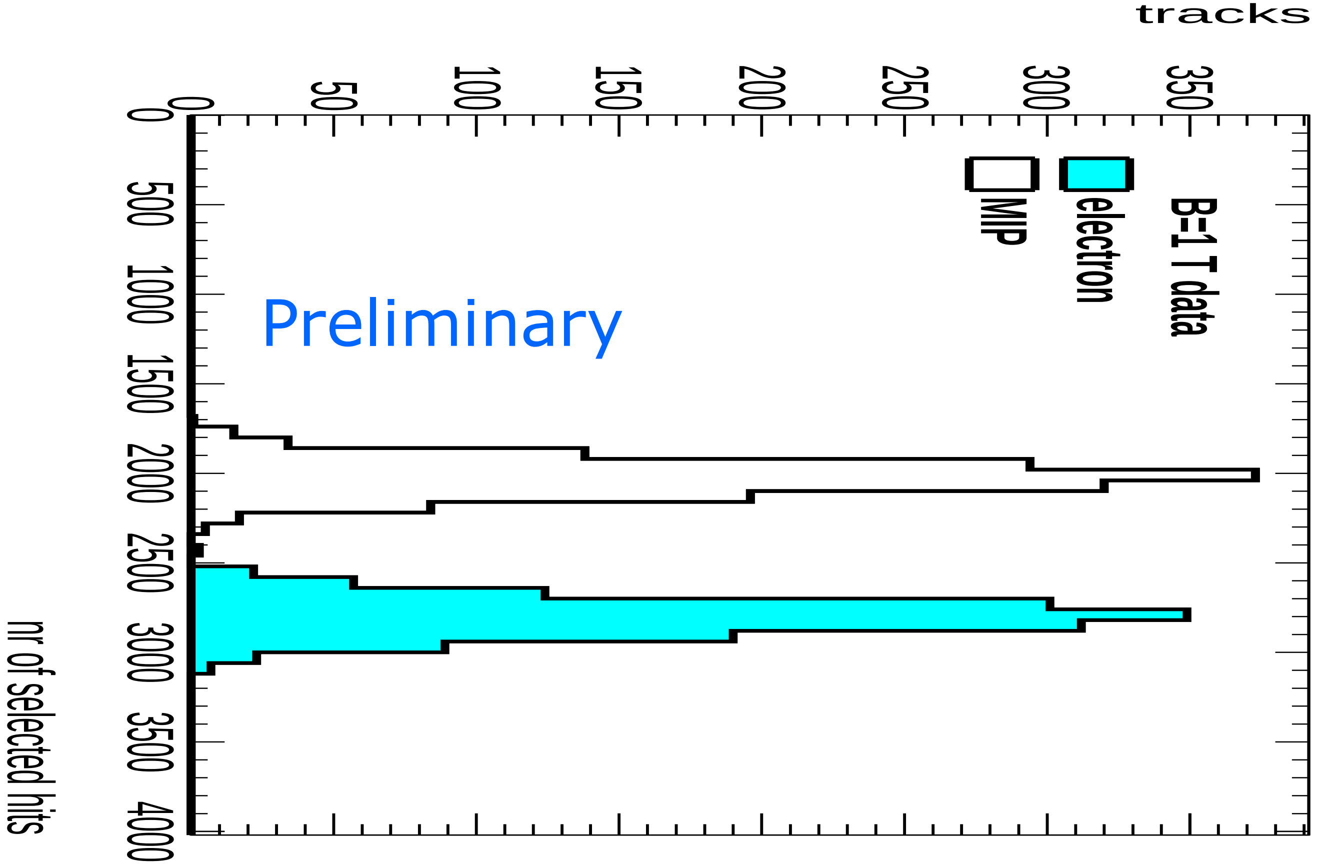
DESY testbeam Module Analysis

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

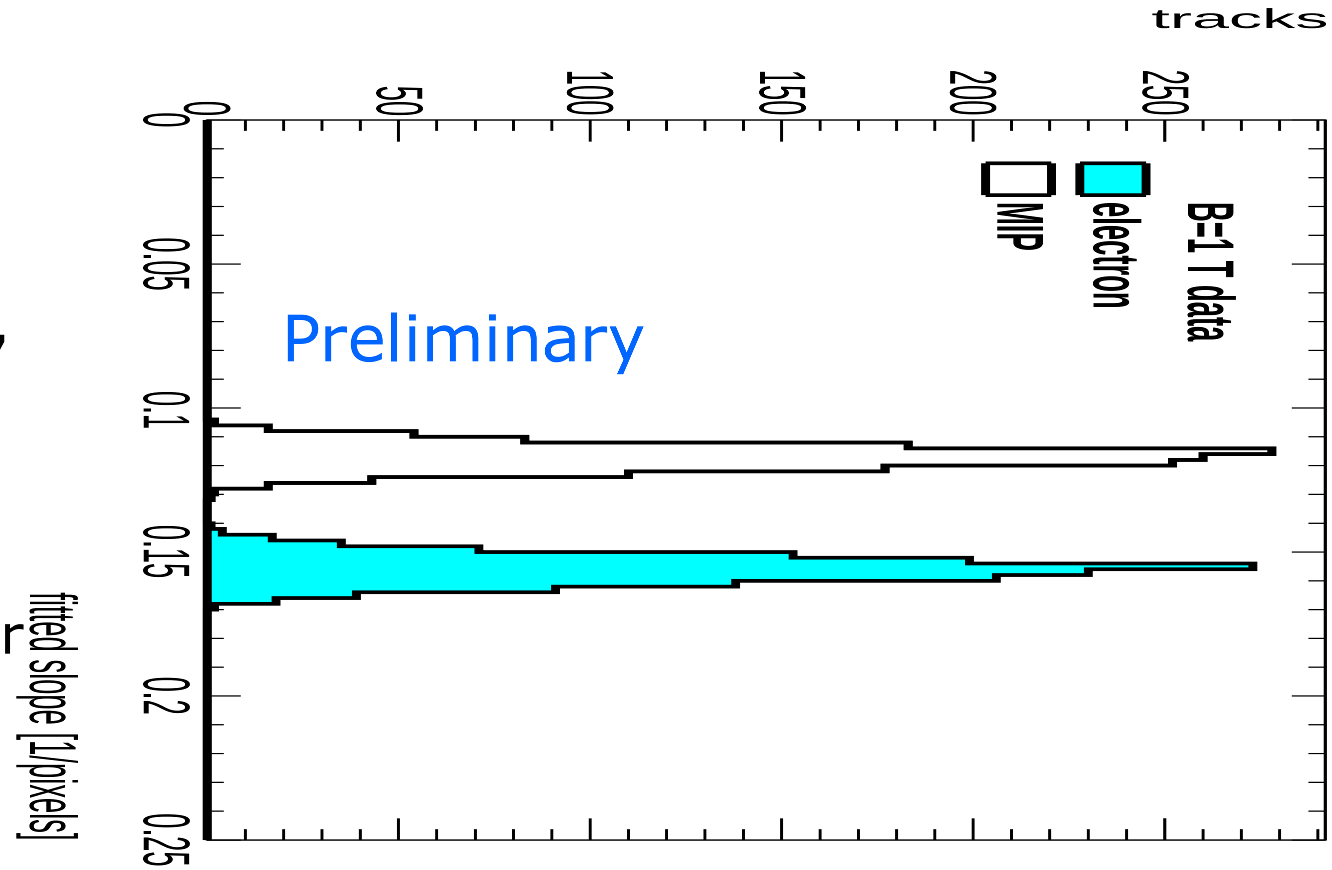


DESY testbeam Module Analysis

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 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.

DESY testbeam Module Analysis

dEdx Performance extrapolated to the ILD detector

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

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

1 m track 60% and coverage

ILD detector

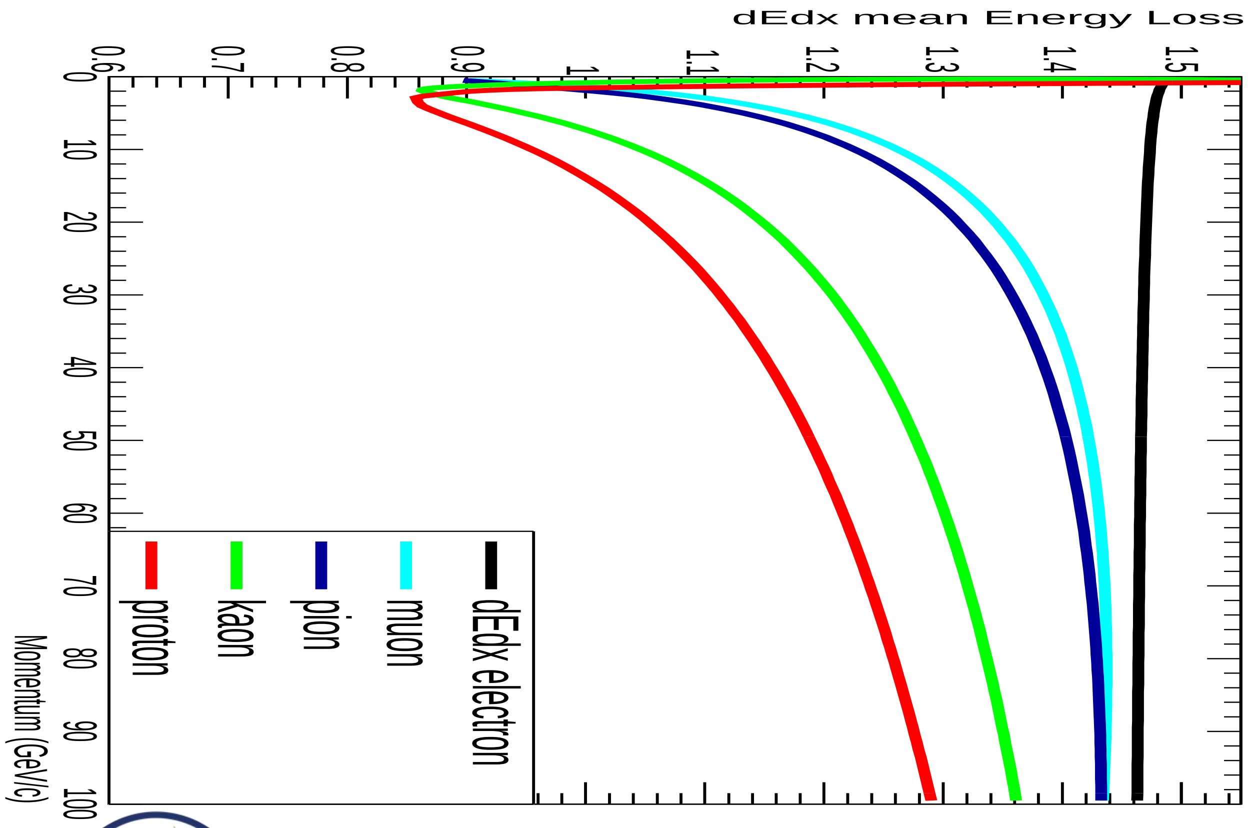
rInner = 329 rOuter = 1770 mm

electron resolution = 2.5(3.0)%
at $\theta=\pi/2$ for method 2 (1)

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

DESY testbeam Module Analysis

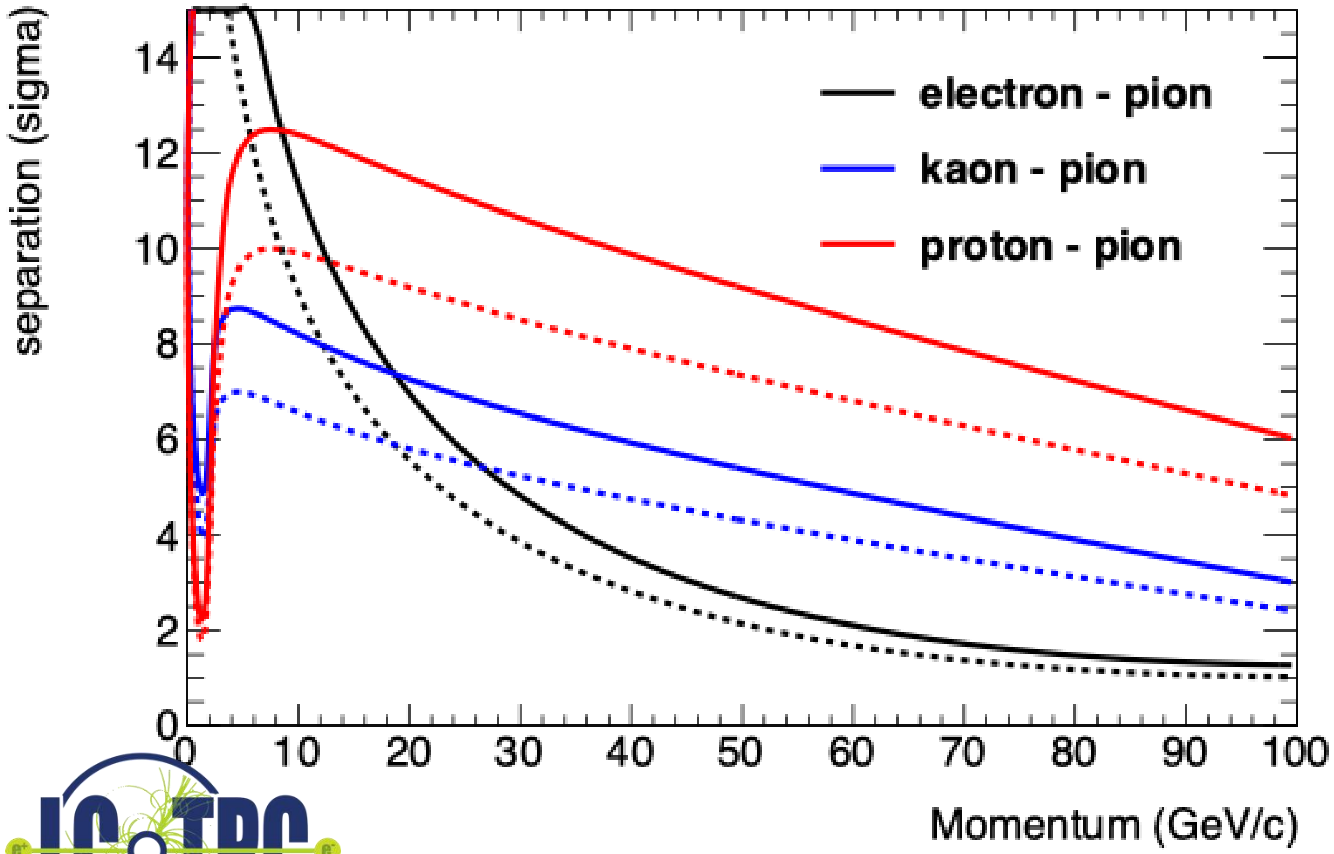
ILD dEdx performance for T2K gas



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

DESY testbeam Module Analysis

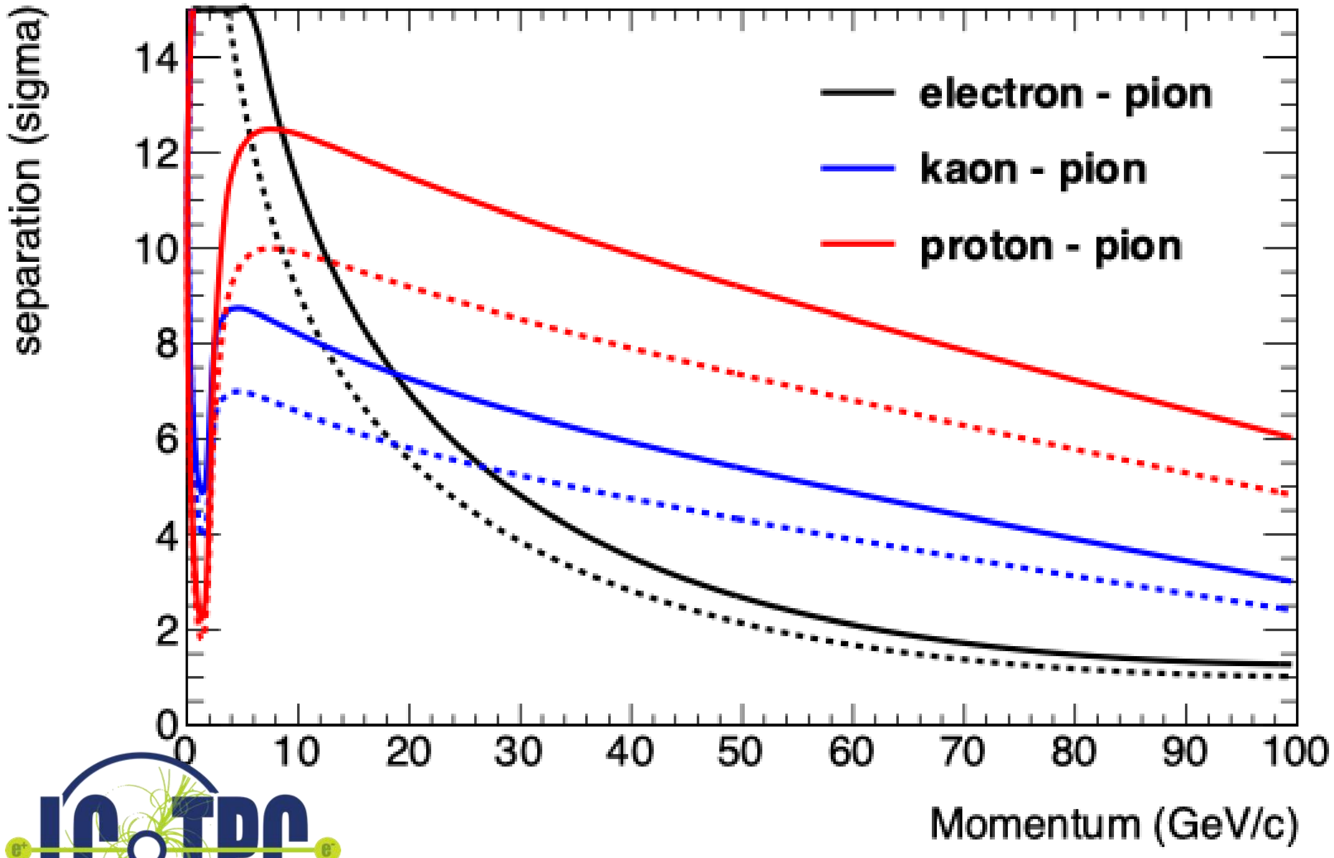
Pixel TPC dEdx performance



- 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% (dashed = method 1) at $\cos\theta = 0$
- Separation electron pion defined as: |<Eloss e> - <Eloss π>| / σ_π
- Separation pion kaon as: |<Eloss π > - <Eloss K>| / σ

DESY testbeam Module Analysis

Pixel TPC dEdx performance



- The expected pion-kaon separation for momenta in the range of 2.5-45 GeV/c at cos θ = 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.

Pixel TPC performance

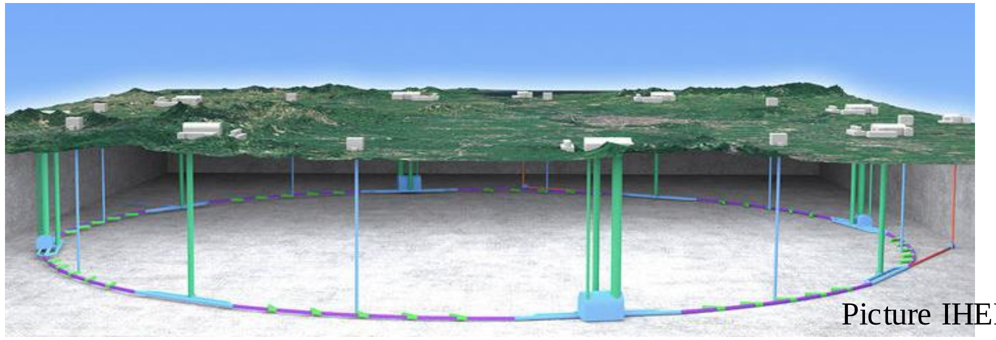
- dE/dx resolution for an electron with p=5,6 GeV/c of 1 m track length with 60% coverage is measured to be 2.9(3.6)% at B = 1 Tesla.
- The dE/dx resolution an ILD detector is 2.4% (3 %)
- This allows for particle identification and separation of kaons from pions up to momenta of 45 GeV with more than 5.5 σ (4.5 σ) for cos θ = 0. The separation increases up to cos θ = 0.85 (see back up slide).
- 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

backup

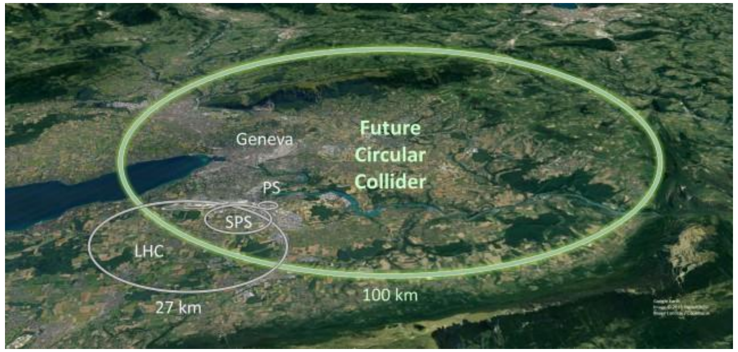
Operation of a Pixel TPC at a circular collider

A Pixel TPC at a circular collider

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 sufficient to deal with hits from Z's in 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 a circular collider

- 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?
  - Not an issue for running at energies higher than the Z (WW, ZH etc).
  - 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; at e.g. 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 back up 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.

Fitting out TPC distortions in ILD/CEPC

- 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/CEPC 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 Z hit rate running
  - The current MDI design FCCee/CEPC gives a lot of beam-beam background more that a factor 100 more hits from the beam than from the Z. This far from optimal. An improved MDI is needed.
- 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 by an improved MDI – 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

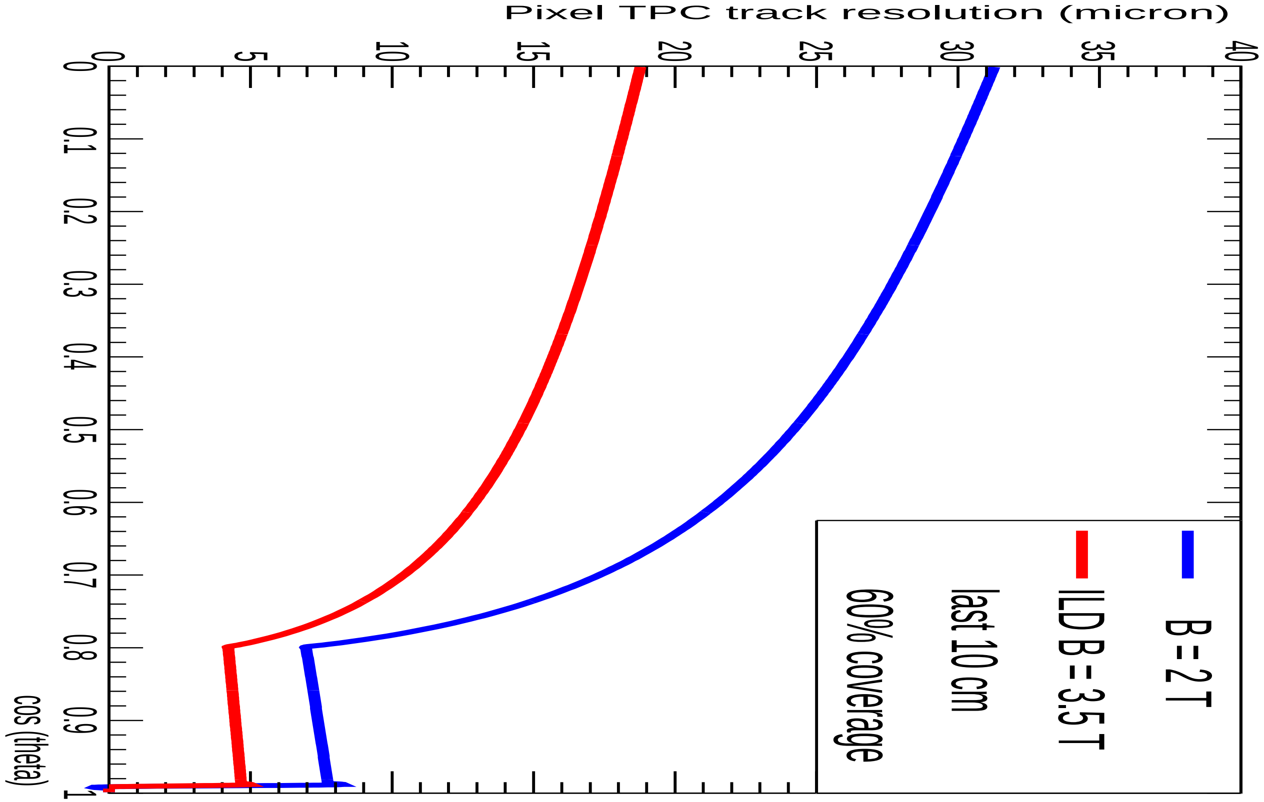
Backup plots

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?



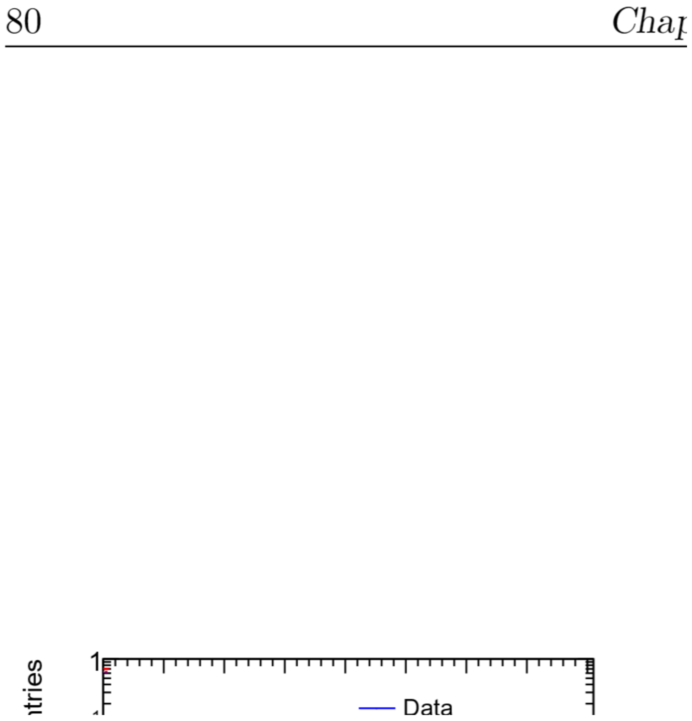
DESY testbeam Module Analysis
Distance distribution

Calculate minimum distance between the hits.

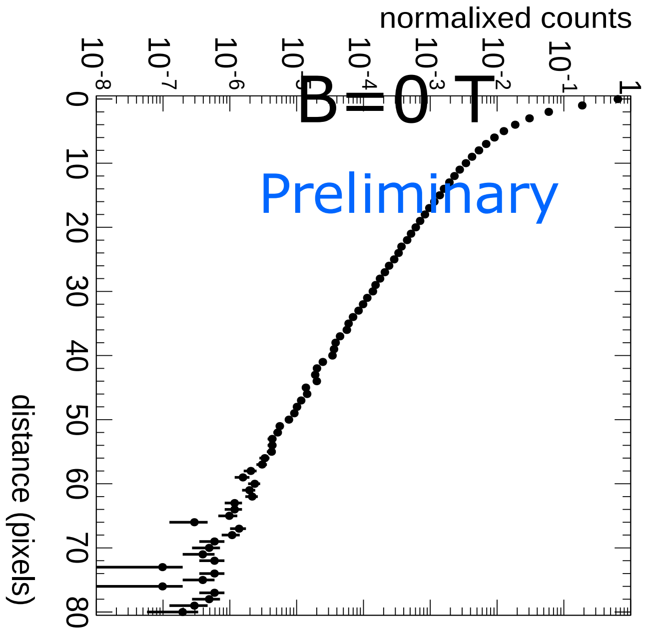
The slope of the distribution is related to the number of primary clusters /cm

The diffused peak at d<10 comes from clusters with more than 1 hit.

Single chip



Quad module

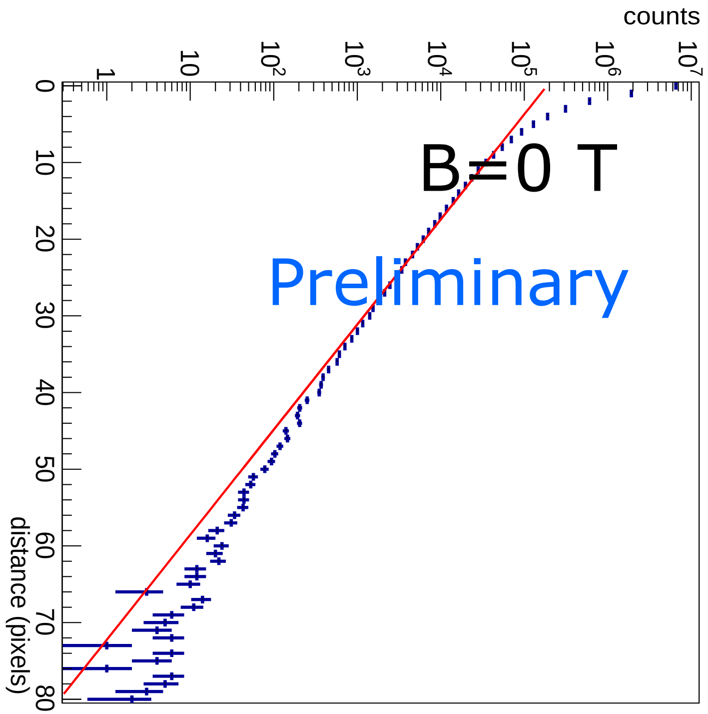


Thesis Kees Ligtenberg

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:

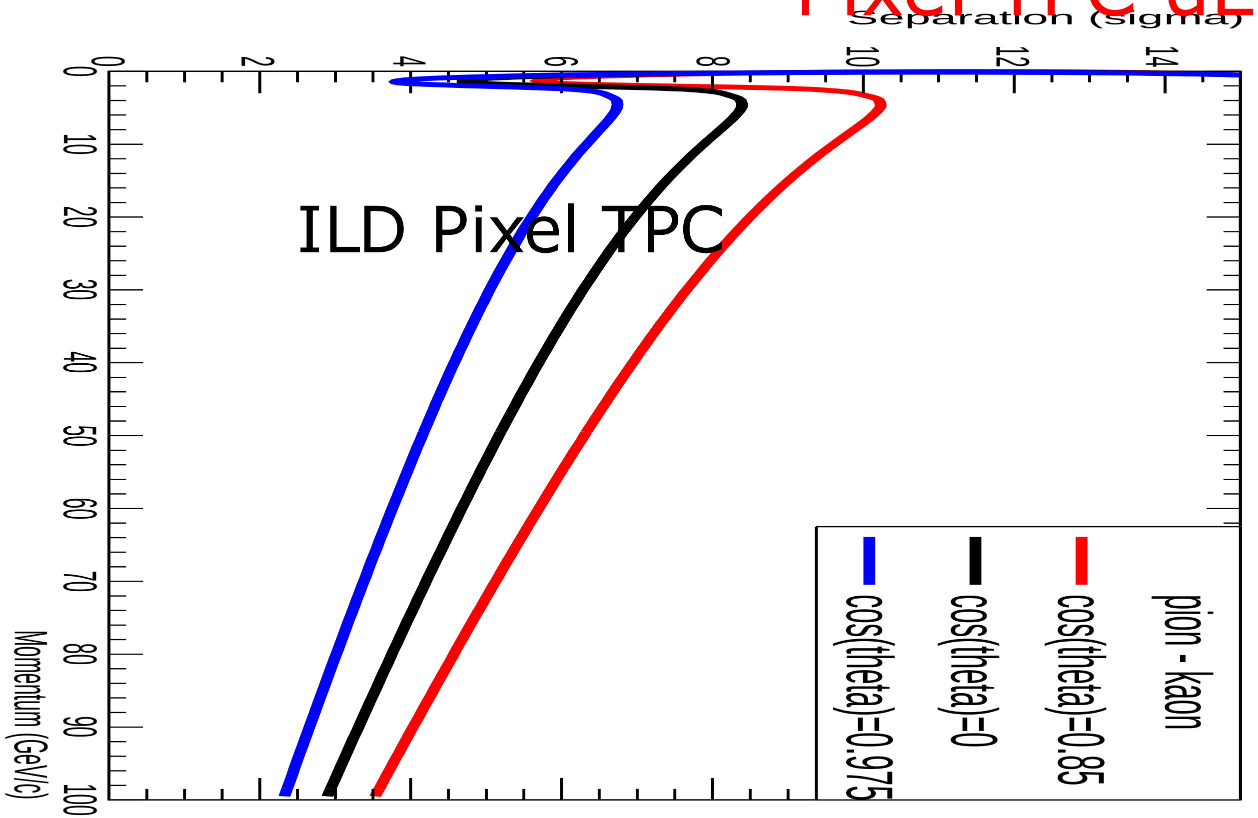
Weights B=0 = { 35.0467 , 12.1497 , 4.52914 , 2.76311 , 1.99386 , 1.59795 , 1.3656 , 1.21409 , 1.11898 , 1.04385 };

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

Pixel TPC dEdx performance



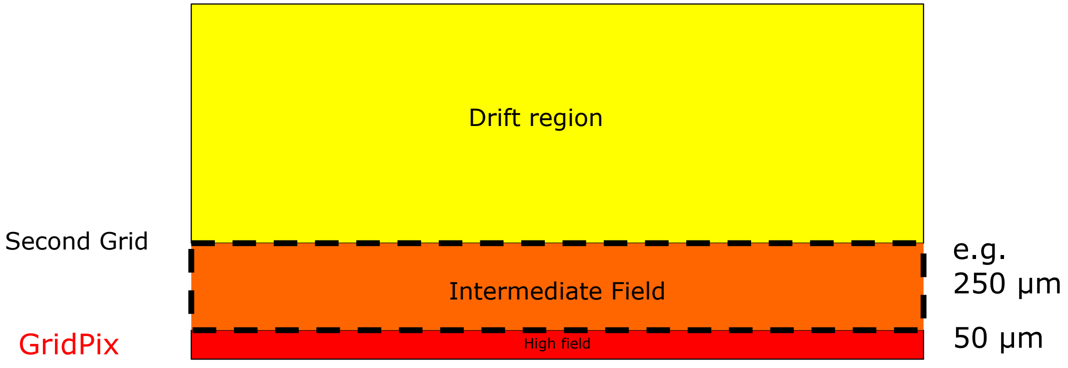
- Separation pion kaon
  $|\langle Eloss\ \pi \rangle - \langle Eloss\ K \rangle| / \sigma_{\pi}$
- Separation pion kaon for different cos(theta) values due to the track length dependence
- For cos(theta)=0 till 0.95 the separation lies between the black and red curves. Only above 0.95-0.975 the separation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

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%