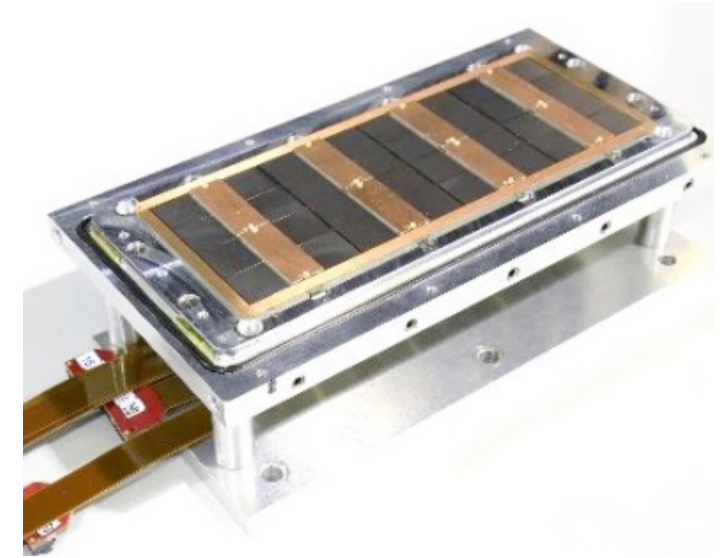
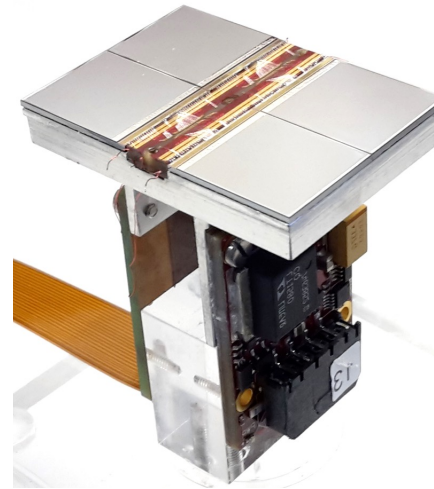


Yevgen Bilevych, Klaus Desch,  
Sander van Doesburg, Harry van  
der Graaf, Fred Hartjes, Jochen  
Kaminski, Peter Kluit, Naomi van  
der Kolk,  
Cornelis Ligtenberg,  
Gerhard Raven, and  
Jan Timmermans



LCTPC 28 March 2024

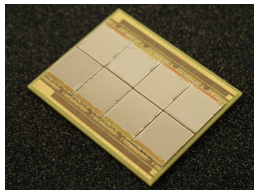


LCTPC WP 28 March 2024

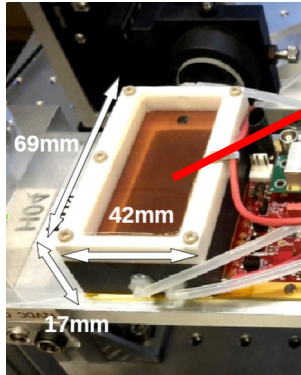
Peter Kluit (Nikhef)



# Pixel TPC

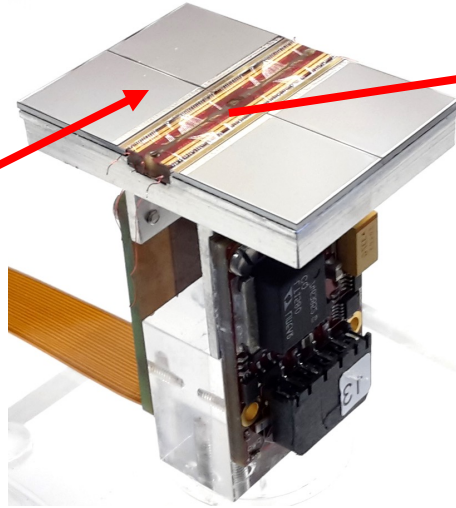


(Octopuce)



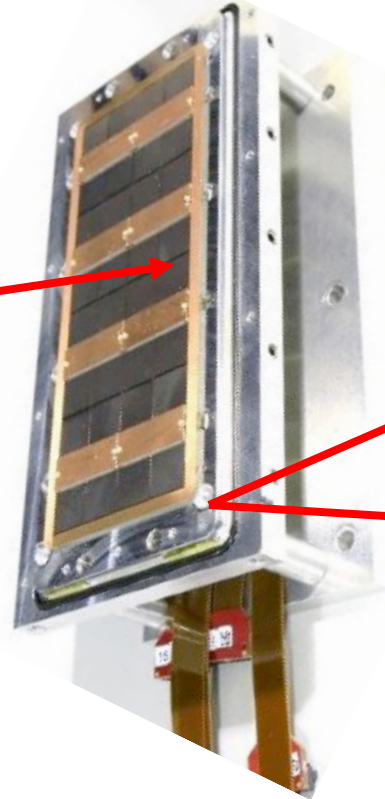
TPX3 chip

2017



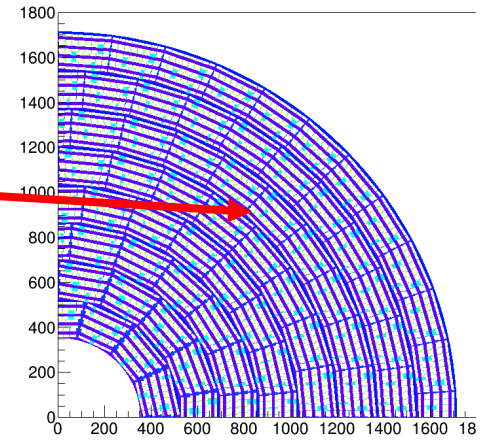
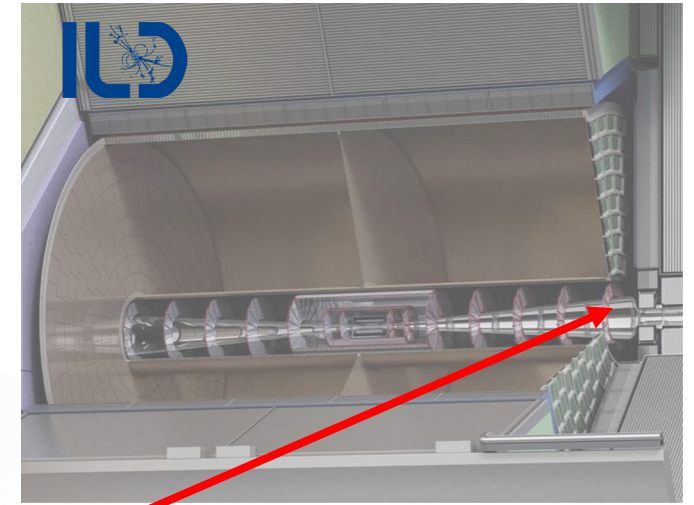
Quad

2018



Module

2019



TPC plane

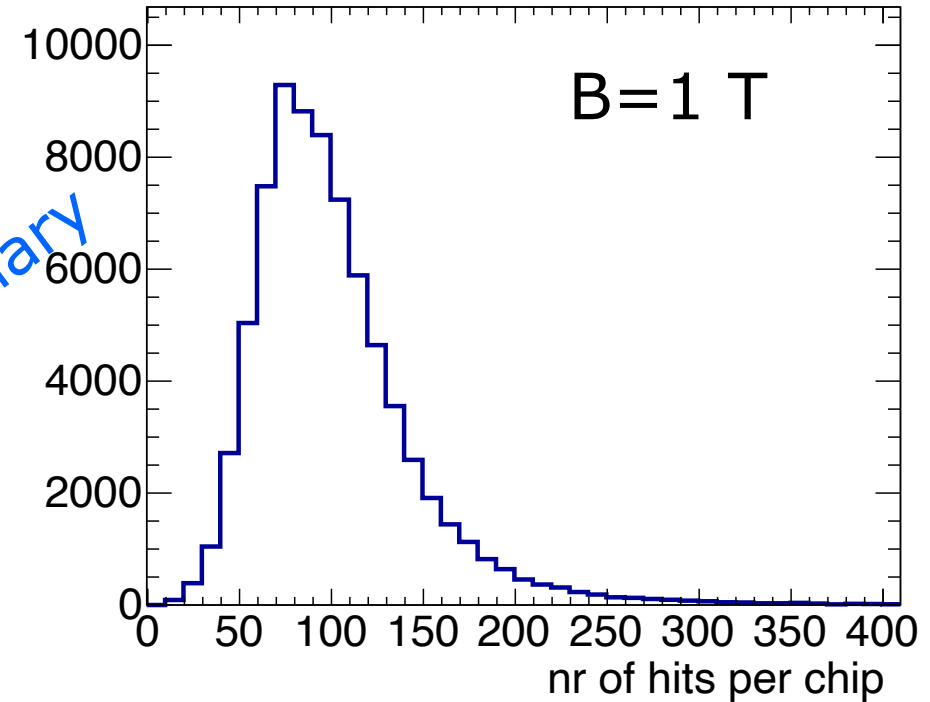
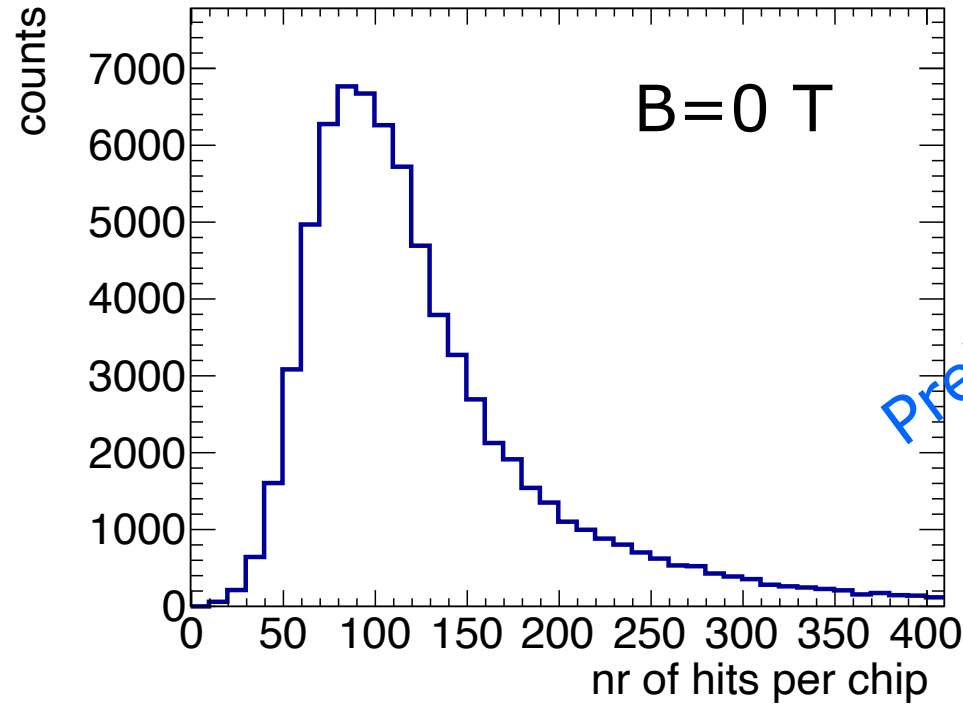
(TimePix1)

(2007-14)

## Performance of dEdx

- It is possible to study in data the energy loss of electrons
- The Pixel TPC has measurements with 55  $\mu\text{m}$  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 (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

### Testbeam performance of dEdx



Preliminary

- 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

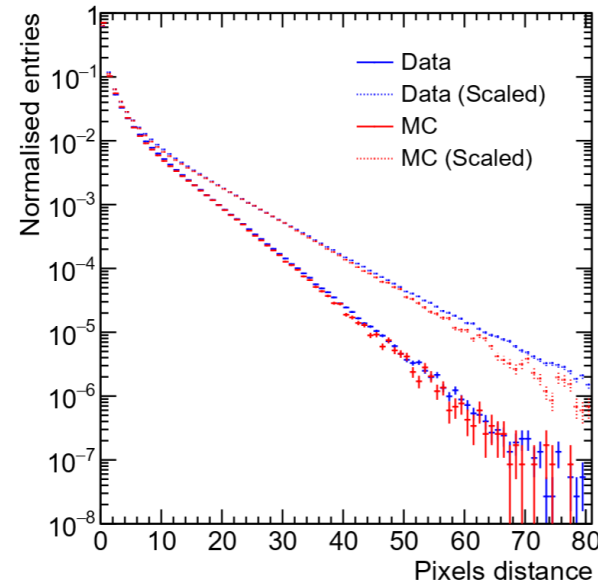
- Combine chips to form a 1 m long track with 60 % coverage for electrons
- Method 1) reject large clusters and then run dEdx @ 90% using slices of 20 pixels along track (xy) (gives nr of selected hits). A large cluster has more than 6 hits in 5 consecutive pixels.
- Method 2) fit the slope of the  $N_{\text{scaled}}$  minimum distance (d) distribution with an exponential function ( $N_{\text{scale}}(d)$ =defines the inverse weights):  
$$N(d)_{\text{scaled}} = N_{\text{scale}}(d) N_{\text{observed}}(d)$$
$$N(d)_{\text{scaled}}$$
 is then fitted for each track with  $N_0 \exp(-\text{slope } d)$
- Calculate the “dEdx” variable for electrons and MIP (==70% of hits)
  - method 1 = nr of selected hits
  - method 2 = slope
  - Resolution is  $\sigma = \sigma(\text{dEdx})/\text{dEdx}$  (for  $\sigma$  we use the rms)

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

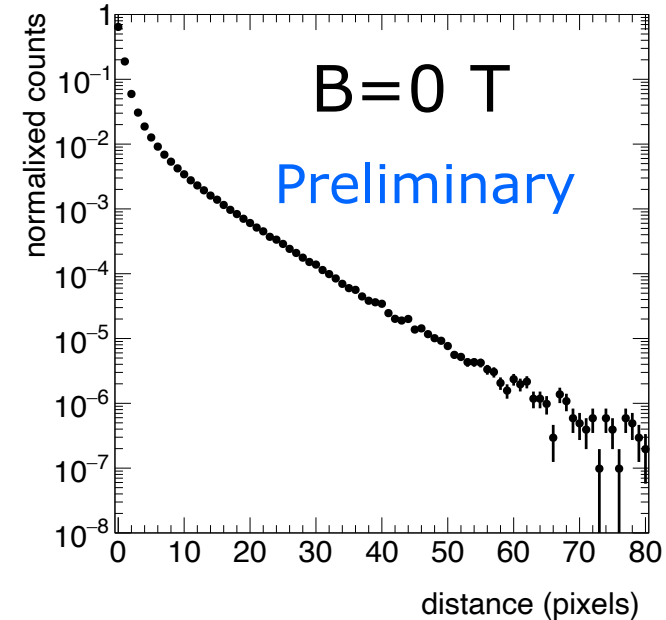
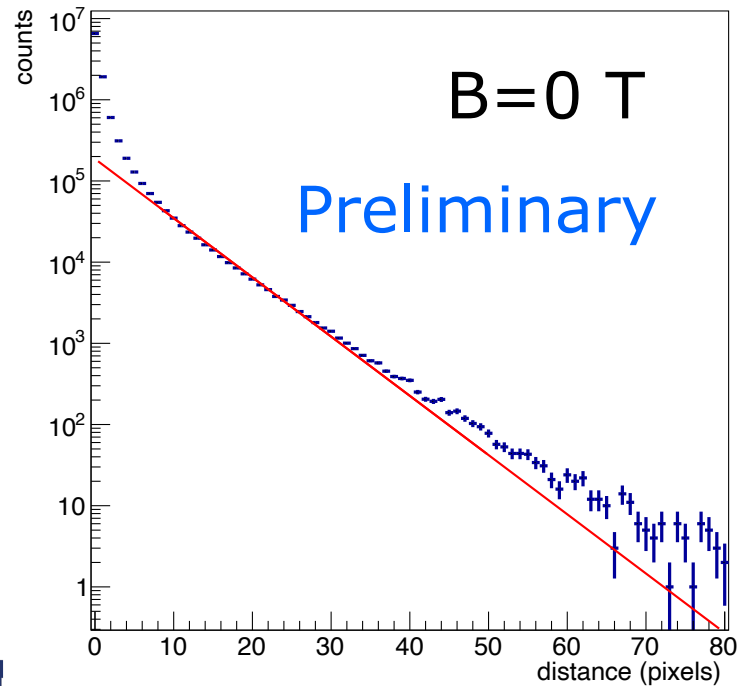


Figure 5.19: Distribution of distance between hits for a 2.5 GeV electron in pixels from test beam data (blue) and from a Monte Carlo simulation (red).

Thesis Kees Ligtenberg

## 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 ( $N_{\text{scale}}(d) = 1/\text{weight}$ ). 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 };

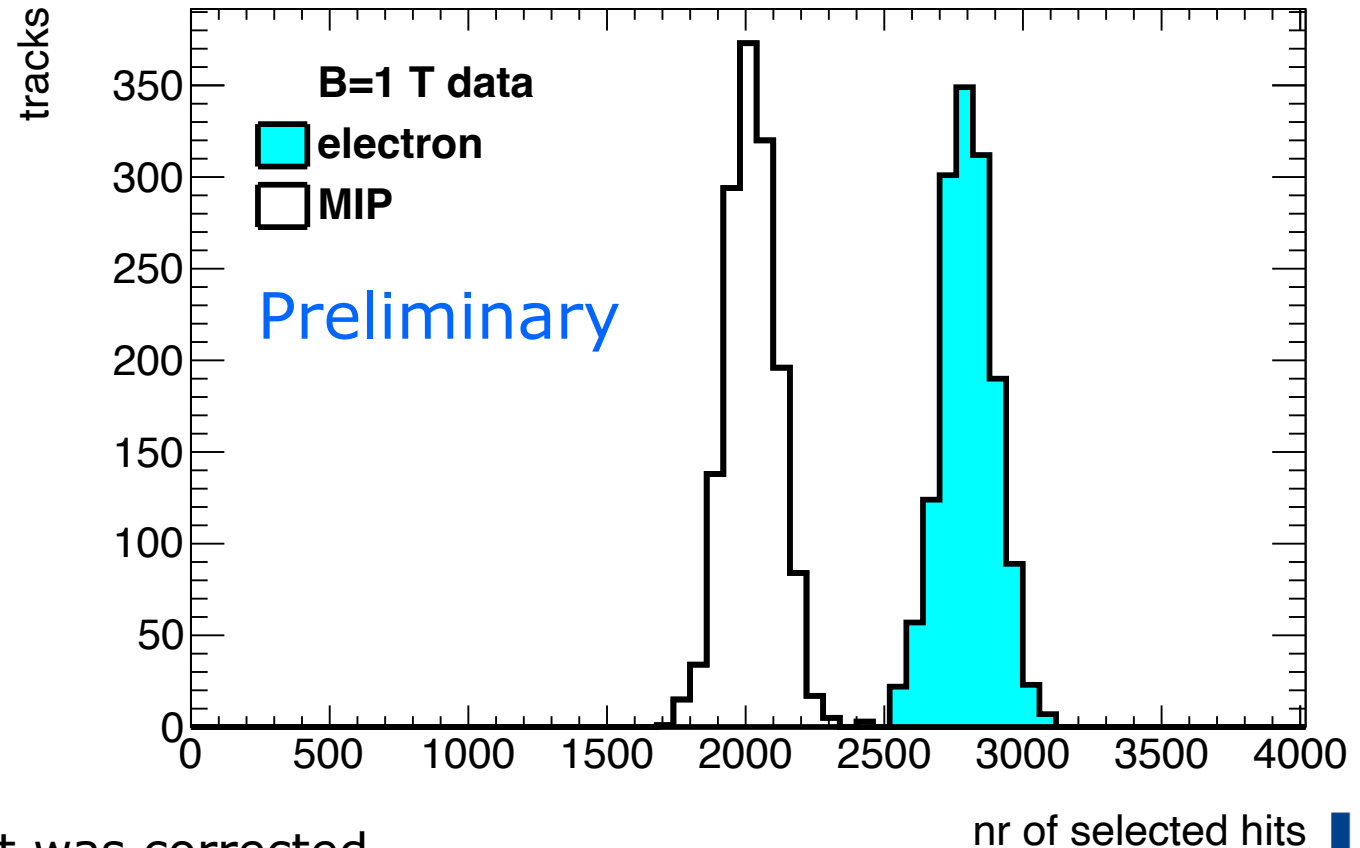
Note the difference in weights in the B=0 and 1 T data sets. This is related to the fluctuations

## 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



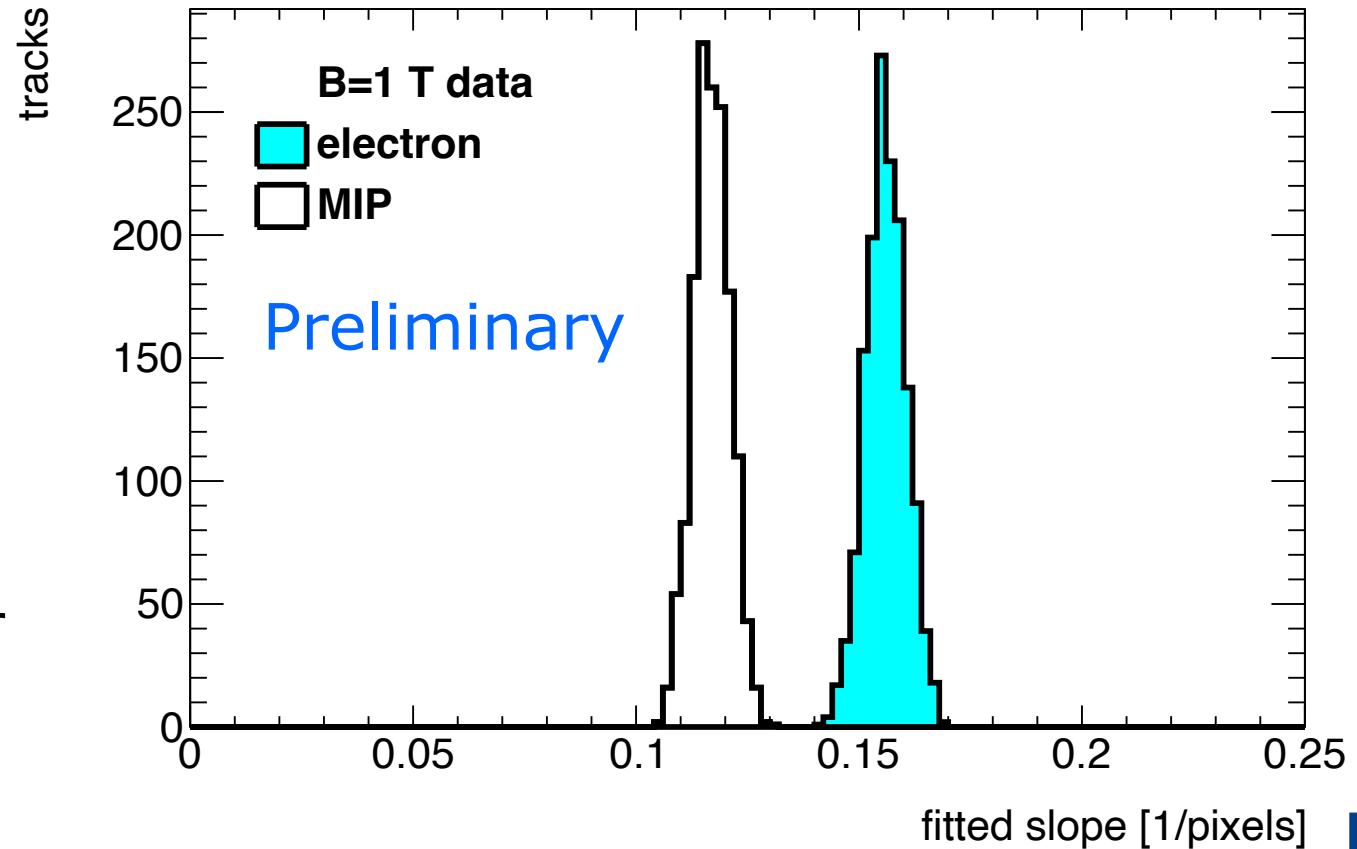
## dEdx performance method 2

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



## 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  $\sim 60\%$  coverage.

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)

Preliminary

## dEdx Performance extrapolated to ILD detector

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

Method 2 fit slope of the  
distance distribution

electron resolution 2.9%

1 m track 60% and  
coverage

## ILD detector

$r_{\text{Inner}} = 329 \text{ mm}$   $r_{\text{Outer}} = 1770 \text{ mm}$

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

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

## dEdx performance and the impact of diffusion

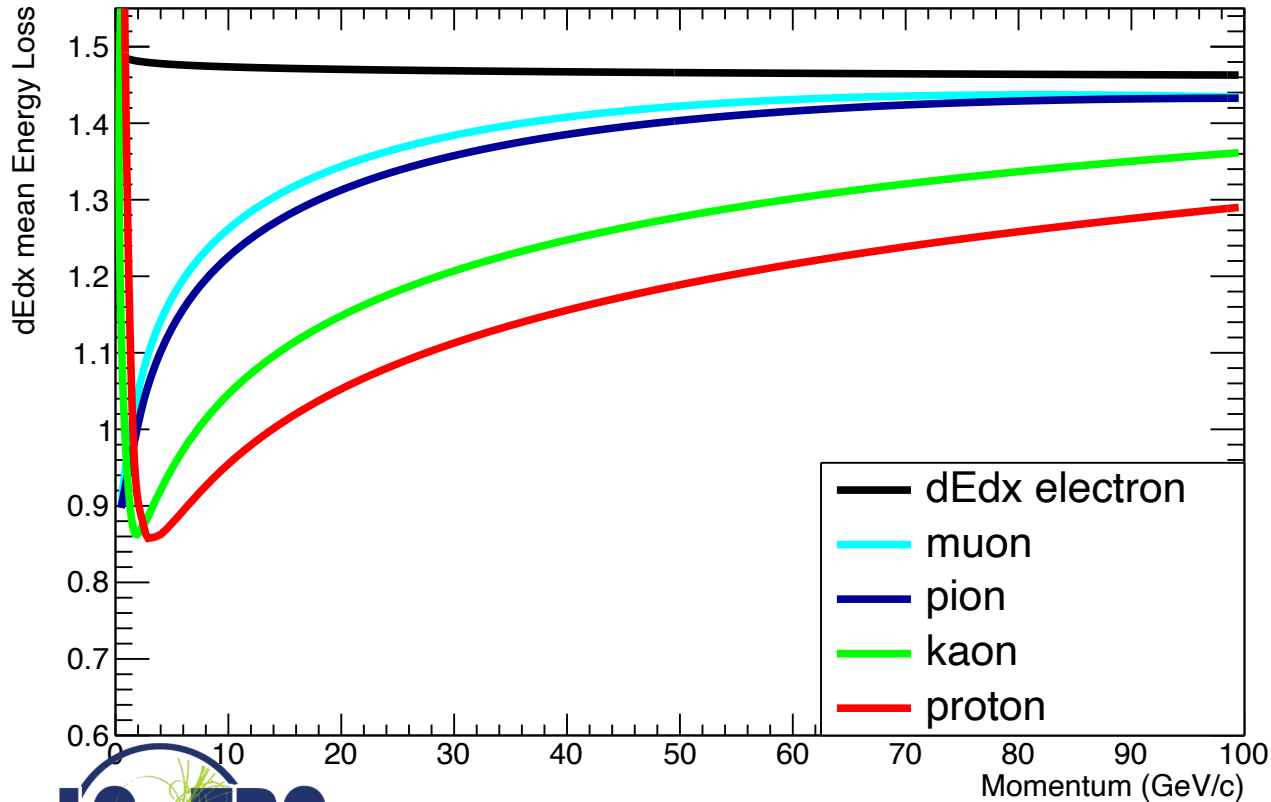
Question by Ulli in LCTPC

Testbeam electron dEdx resolution 2.9%. The diffusion in the test beam is 130  $\mu\text{m}$ . What is the performance if the diffusion is larger?

In ILD running at a B field of 3.5 T(2T) the diffusion is  $D_T=30(50)\mu\text{m}/\sqrt{\text{cm}}$ . The ILD-TPC halflength is 235 cm. The total diffusion ranges between say 30 and 460(760)  $\mu\text{m}$ . So drift distances in ILD up to only 25(18) cm correspond to the test beam situation.

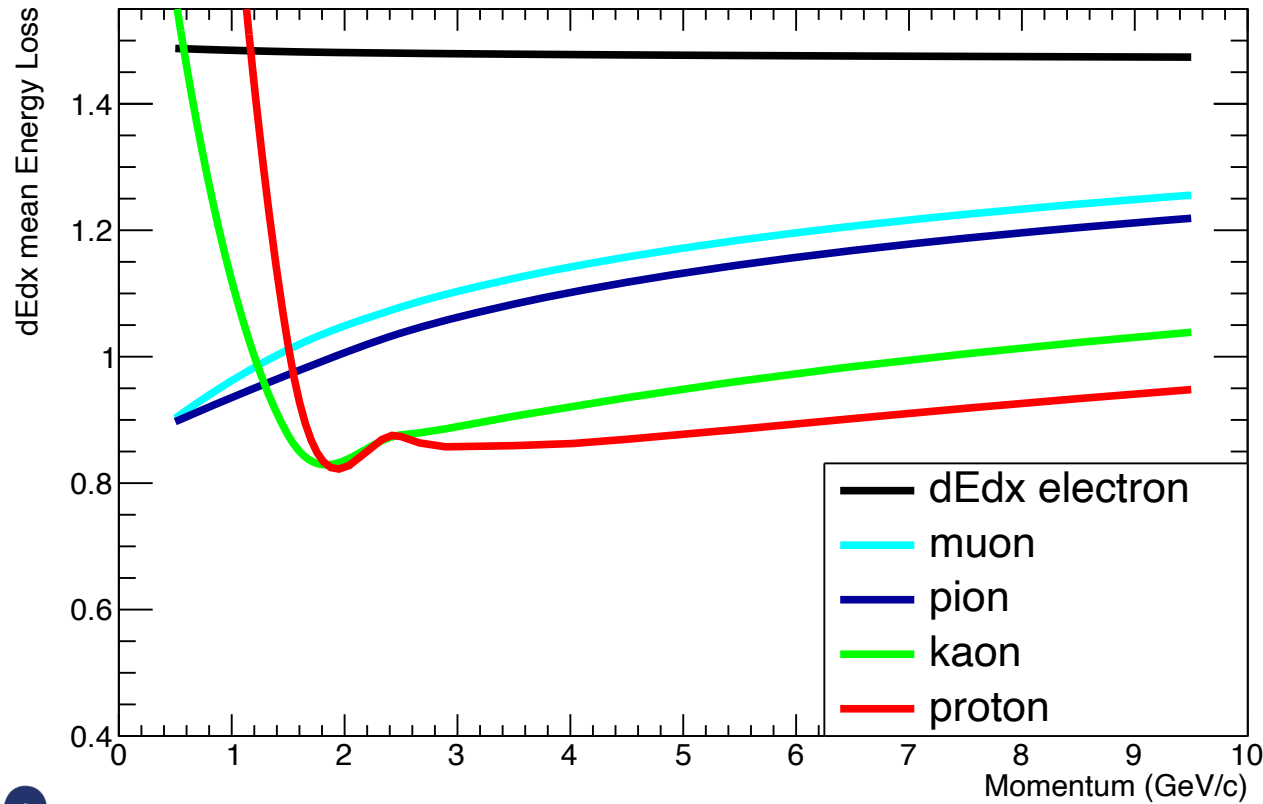
To study the impact, the testbeam data was used and smeared with an additional 330 (500)  $\mu\text{m}$  and the dEdx methods reran. The dEdx resolution is 3.6(3.8)%. It is clear that this is the worst case scenario: by doing a track-by-track fit one will end up closer to 2.9%.

## 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

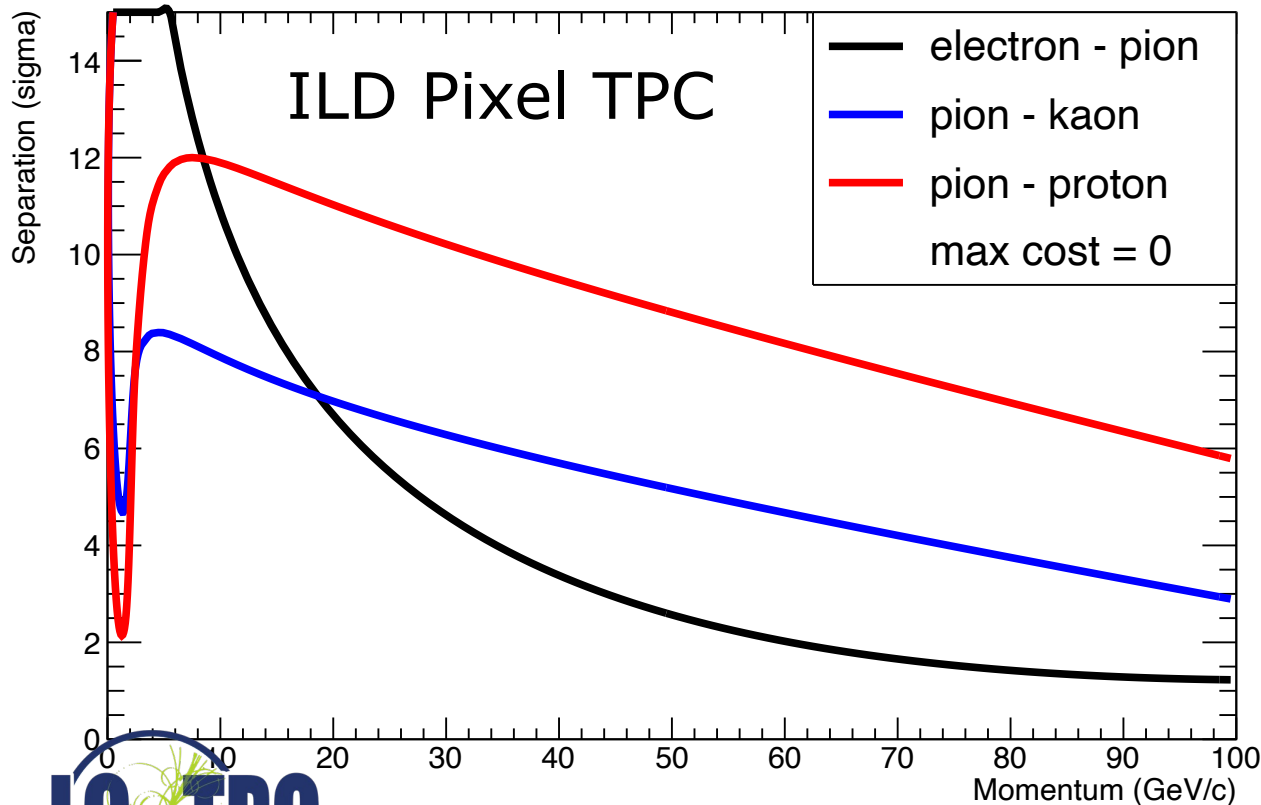
## dEdx performance



- zoom on Low momenta

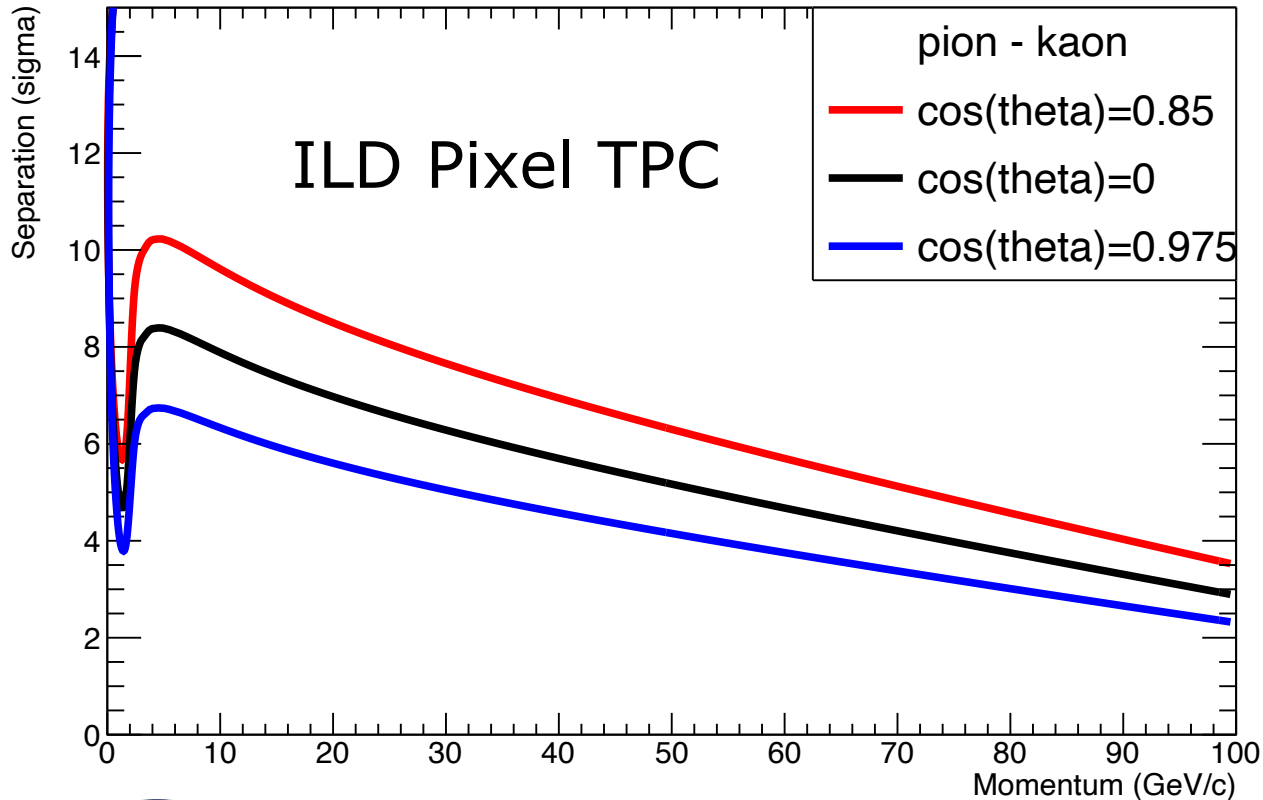
## Pixel TPC dEdx performance

UNIVERSITÄT BONN



- ILD Performance with:
  - rInner = 329 mm 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 θ = 0
- Resolution scales as:
 
$$1/\sqrt{\text{track length} \cdot \langle E_{\text{loss}} \rangle}$$
- Separation electron pion
 
$$|\langle E_{\text{loss}} e \rangle - \langle E_{\text{loss}} \pi \rangle| / \sigma_{\pi}$$
- Separation pion kaon
 
$$|\langle E_{\text{loss}} \pi \rangle - \langle E_{\text{loss}} K \rangle| / \sigma_{\pi}$$

## Pixel TPC dEdx performance

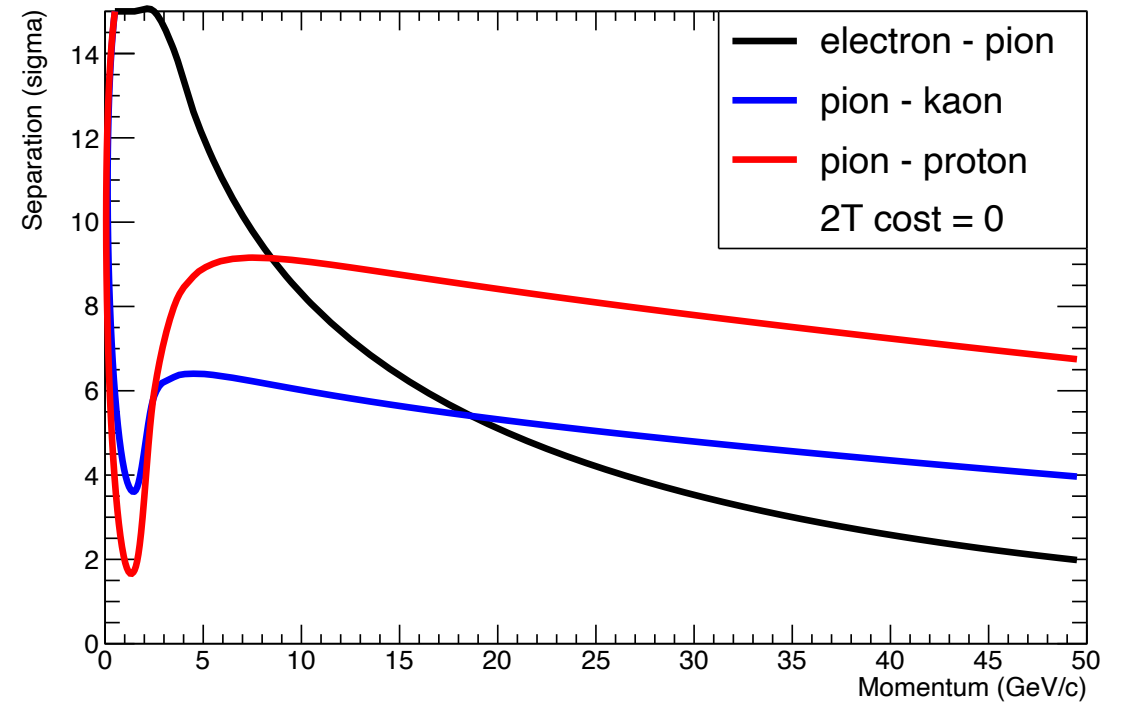
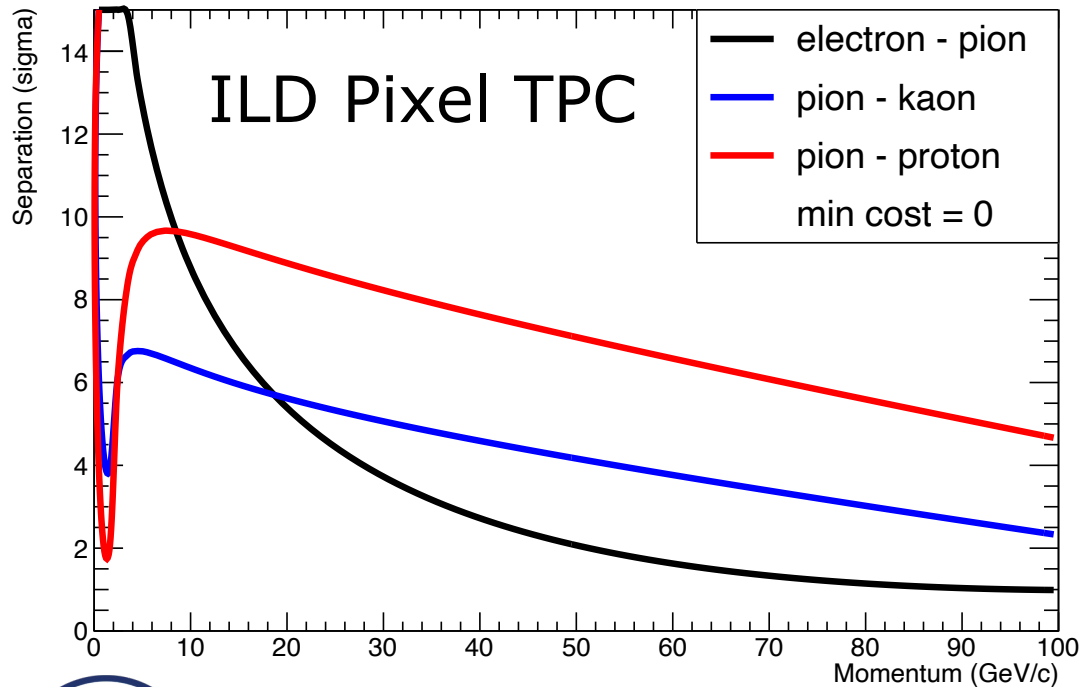


- Separation pion kaon  
 $|\langle E_{loss} \pi \rangle - \langle E_{loss} K \rangle| / \sigma_{\pi}$
- Separation pion kaon for different cos(theta) values due to the track length dependence
- For cos(theta)=0 till 0.95 the separation lies between the black and red curves. Only above 0.95-0.975 the separation drops till the blue curve.
- 'max' scenario with resolution 2.5%
- Excellent performance over very large polar angle range



## Pixel TPC dEdx performance

Worst case **ILD Performance with: 3.1% and 3.3 % (2T) at  $\cos \theta = 0$**



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

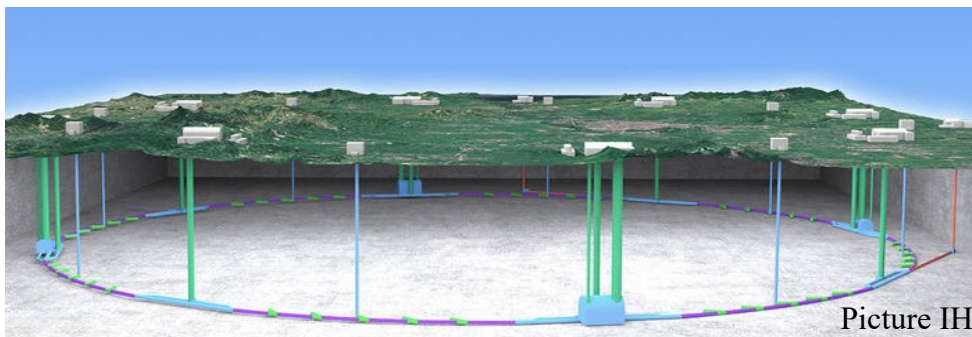
- dE/dx resolution for an electron with  $p=5,6$  GeV/c of 1 m track length with 60% coverage is measured to be 2.9% (at  $B = 1$  Tesla)
- The extrapolated resolution for the ILD detector is 2.5% (w.c. 3.1 and 3.3% 2T)
- This allows for particle identification and separation of Kaons from pions up to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

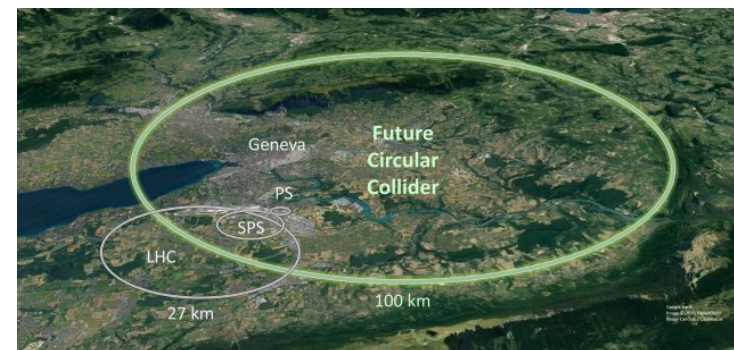
# A Pixel TPC at CEPC or FCC-ee

The most difficult situation for a TPC is running at the Z.

At the Z pole with  $L = 200 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  Z bosons will be produced at  $\sim 60 \text{ kHz}$



Picture IHEP



## ■ Can a pixel TPC reconstruct the events?

- The TPC total drift time is about  $30 \mu\text{s}$
- This means that there is on average 2 event / TPC readout cycle
- YES: The excellent time resolution: time stamping of tracks  $< 1.2 \text{ ns}$  allows to resolve and reconstruct the events

## ■ Can the current readout deal with the rate?

- Link speed of Timepix3 (in Quad):  $2.6 \text{ MHits/s}$  per  $1.41 \times 1.41 \text{ cm}^2$  [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  $\sim 2\text{W}/\text{chip}$  per  $1.41 \times 1.41 \text{ cm}^2$
  - 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)

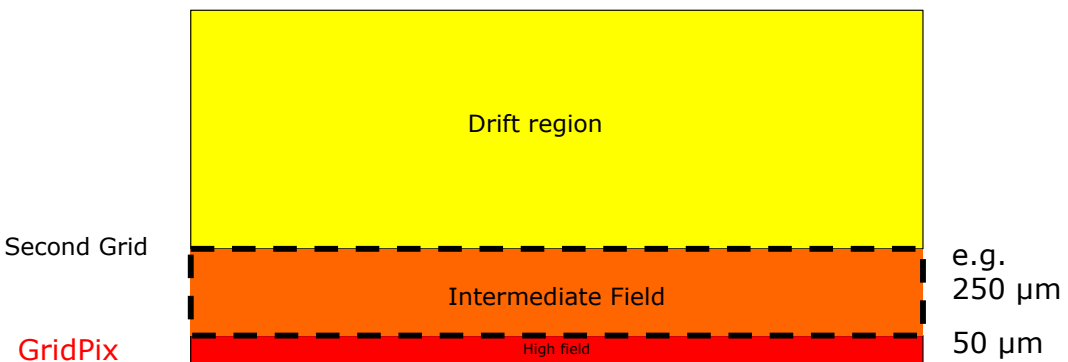
# A Pixel TPC at CEPC or FCC-ee

- **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  $\mu\text{m}$  an IBF of  $3 \cdot 10^{-4}$  can be achieved and the value for  $\text{IBF} \cdot \text{Gain} (2000)$  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  $< O(100) \mu\text{m}$
  - 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  $\mu\text{m}$  an IBF of  $3 \cdot 10^{-4}$  can be achieved and the value for IBF\*Gain (2000) would be 0.6.



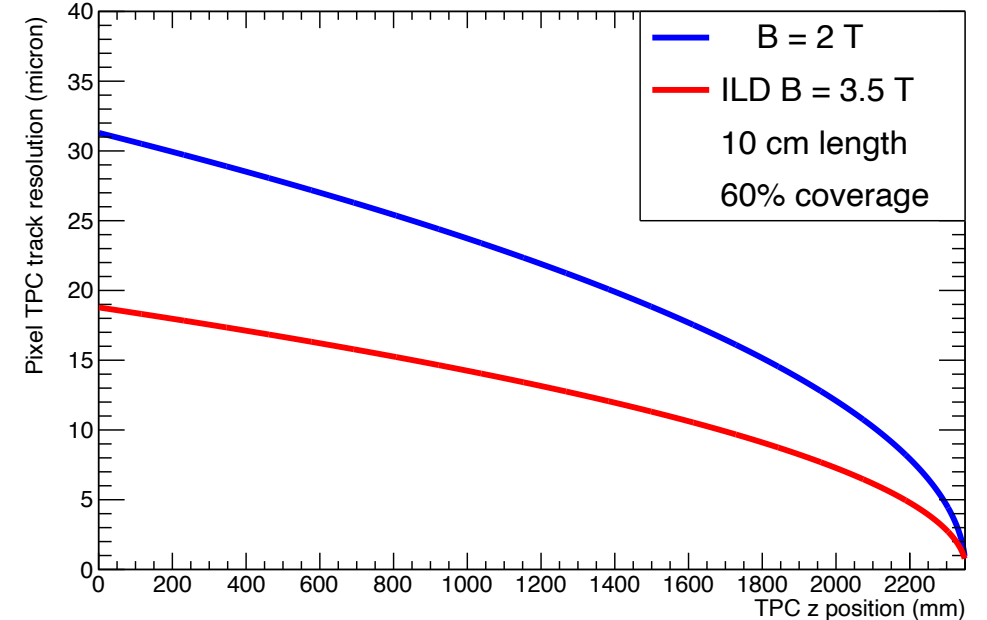
Ion backflow	Hole 30 $\mu\text{m}$	Hole 25 $\mu\text{m}$	Hole 20 $\mu\text{m}$
Top grid	2.2%	1.2%	0.7%
GridPix	5.5%	2.8%	1.7%
Total	$12 \cdot 10^{-4}$	$3 \cdot 10^{-4}$	$1 \cdot 10^{-4}$
transparency	100%	99.4%	91.7%

## ILD tracking Performance for a Pixel TPC based on test beam

### 10 cm track resolution

Single electron resolution

6 mm pad resolution



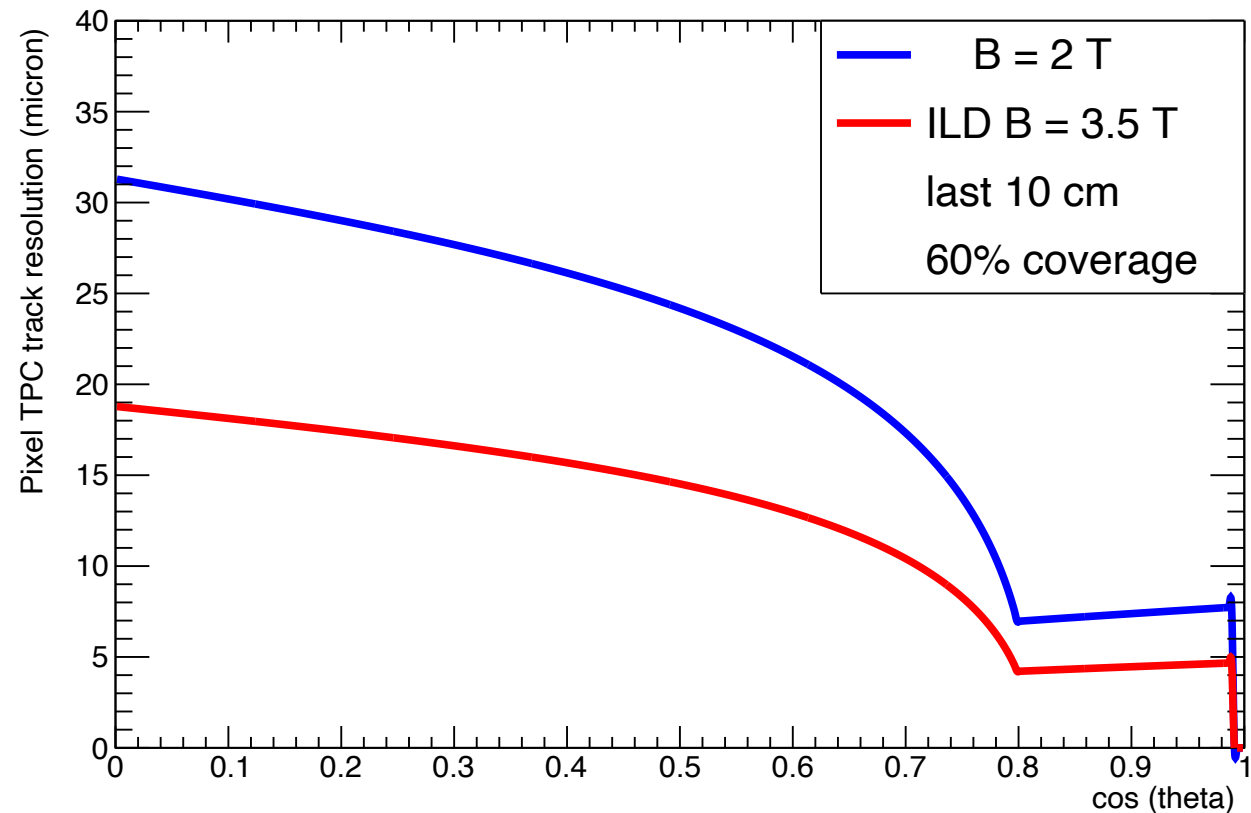
Each 10 cm we have a point with a resolution of  $< 19$  ( $31$ )  $\mu\text{m}$  on the track



### 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.

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



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

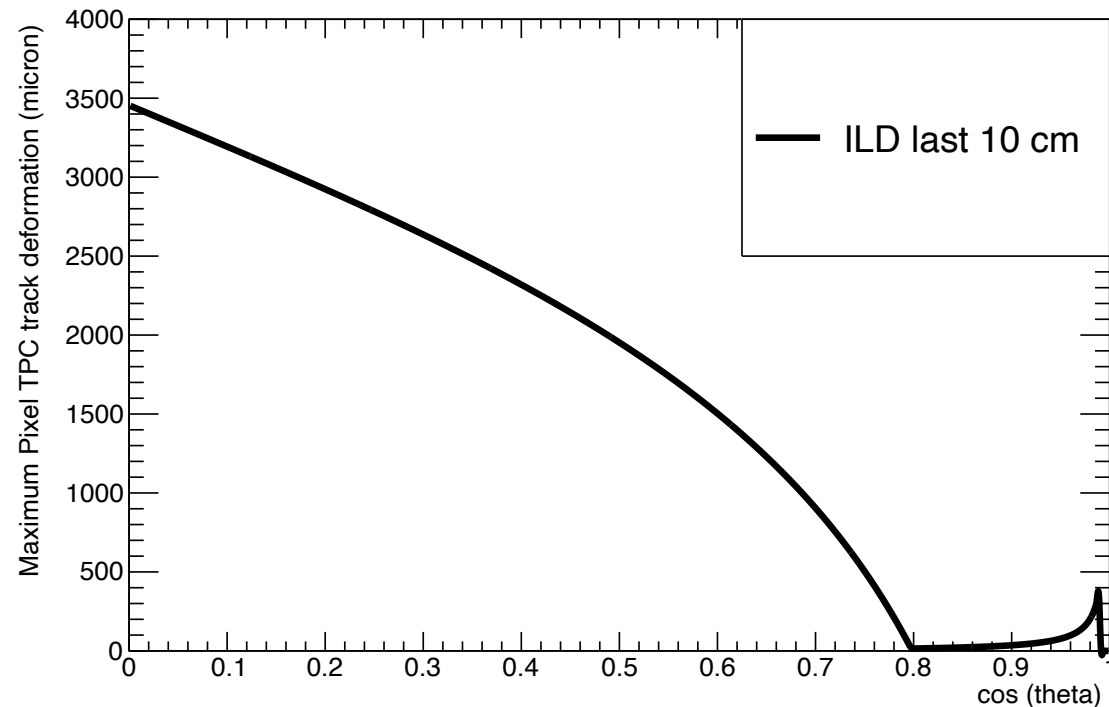
Distortions have an amplitude of **10 cm\*** and are described by the following function:

$$\Delta = 10 \text{ (cm)} \left(\frac{r_{\text{Inner}}}{r}\right)^2 \frac{z}{z_{\text{Max}}}$$

$z$  = drift distance  $r$  = radius

$r_{\text{Inner}}$  and  $z_{\text{Max}}$  from ILD

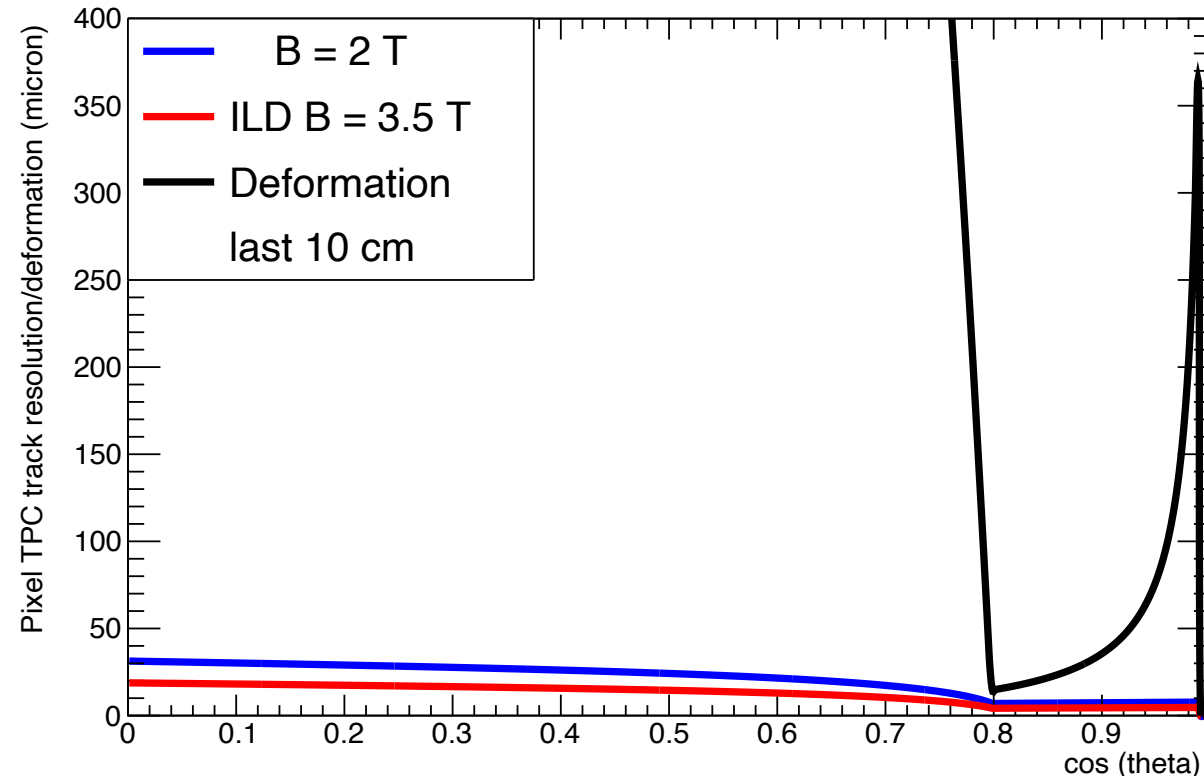
These are **huge\*** distortions. Here we use the last 10 cm of the track. Clearly the Barrel at large radii has 3.5 mm distortions



### 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  $\mu\text{m}$

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 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 on 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  $1\text{W}/\text{cm}^2$ . 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  $O(100)\ \mu\text{m}$
  - 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