A Time Projection Chamber
for a Future Linear Collider

High spatial resolution pad and pixelated TPC technology R&D for e^+e^- collider

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on behalf of LCTPC international collaboration

1st ECFA Workshop on e+e- Higgs/EW/Top Factories
October 5-7, 2022, Hamburg

Content

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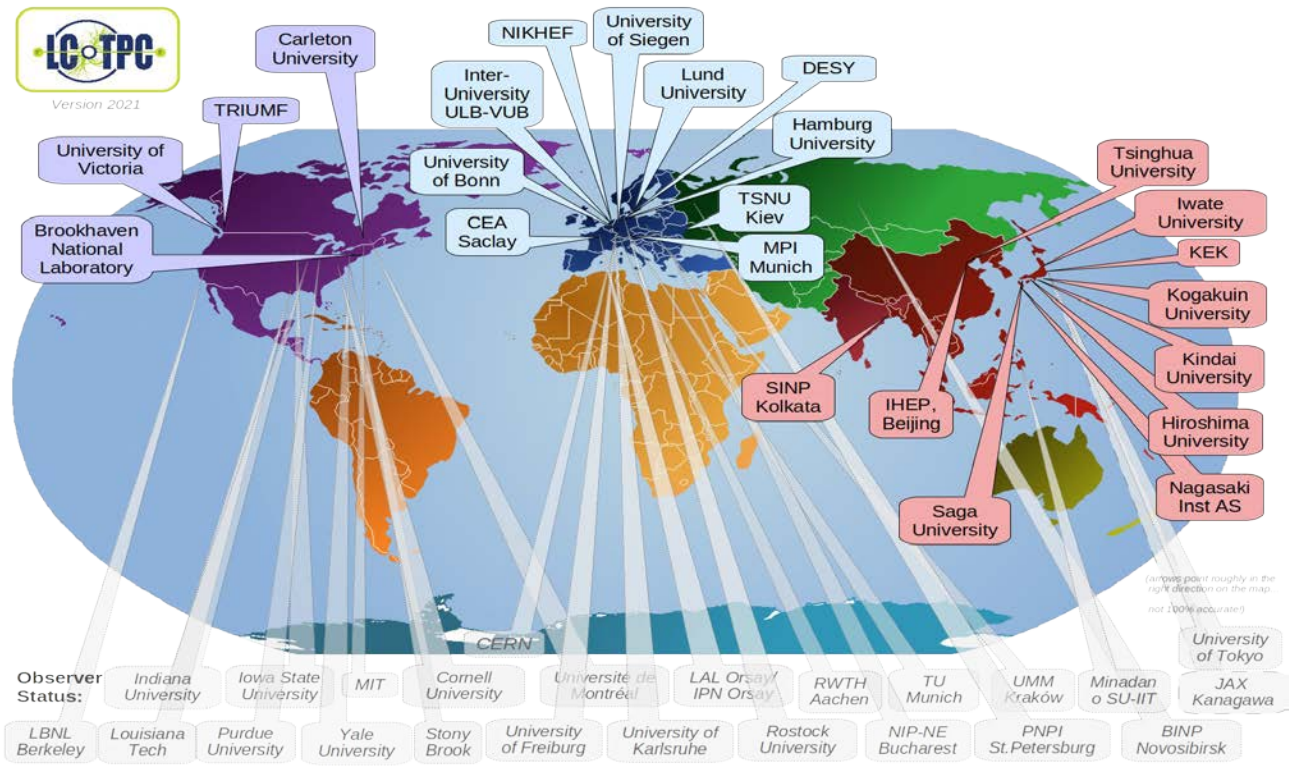
- **High spatial resolution pad readout TPC**
- **Pixelated readout TPC R&D**
- **Summary**

TPC R&D in LCTPC Collaboration

- MPGDs for TPC readout is a **baseline solution and further R&D** features many benefits:
  - Small pitch of gas amplification regions => strong reduction of E×B-effects
  - No preference in direction => all 2 dim. readout geometries possible
  - **Ion backflow** can be reduced significantly (Gating, Hybrid structure…)
  - Continue electronics, cooling, UV laser track and low power consumption FEE development



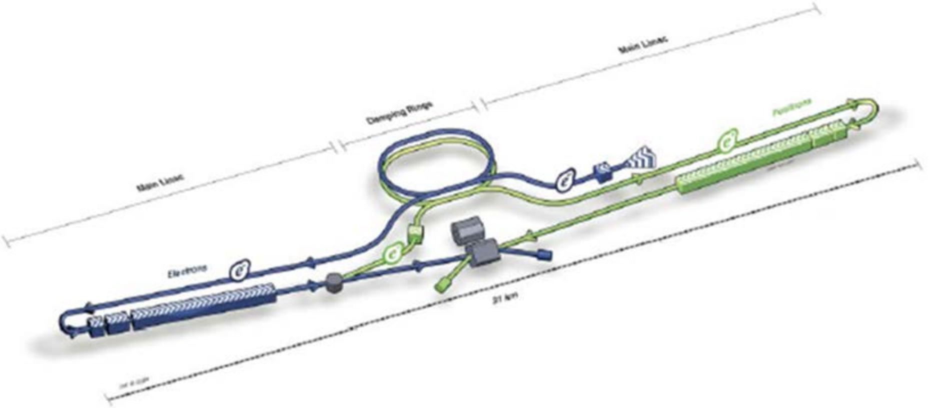
LCTPC-collaboration studies MPGD detectors for the ILD-TPC:
24 Institutes from
11 countries
+ 24 institutes with observer status

Various **gas amplification stages** are studied: GEMs, Micromegas, GEMs with double thickness and GridPixes.

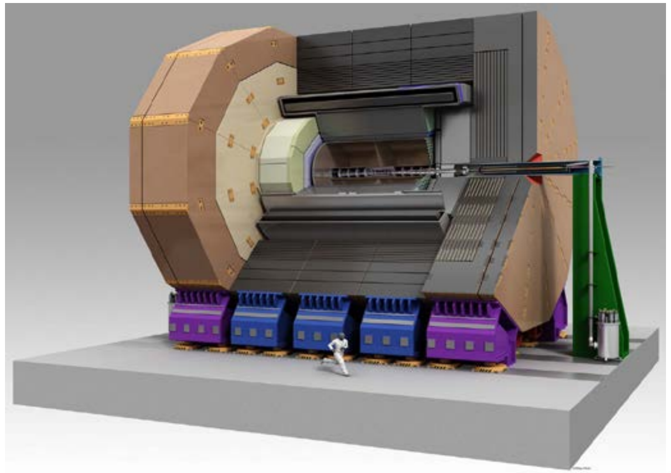
https://www.lctpc.org/

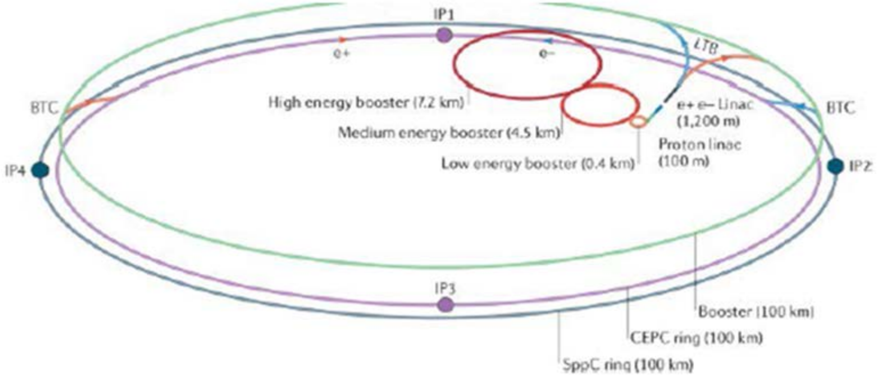
TPC technology for the future e+e- colliders

- A TPC is the main tracking detector for **some candidate experiments at future e+e- colliders**
  - ILD at ILC and the baseline detector concept of CEPC
- TPC technology can be of interest for other future e+e- colliders

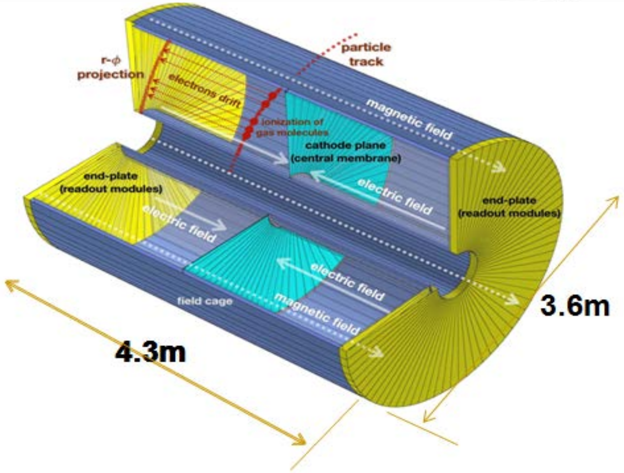


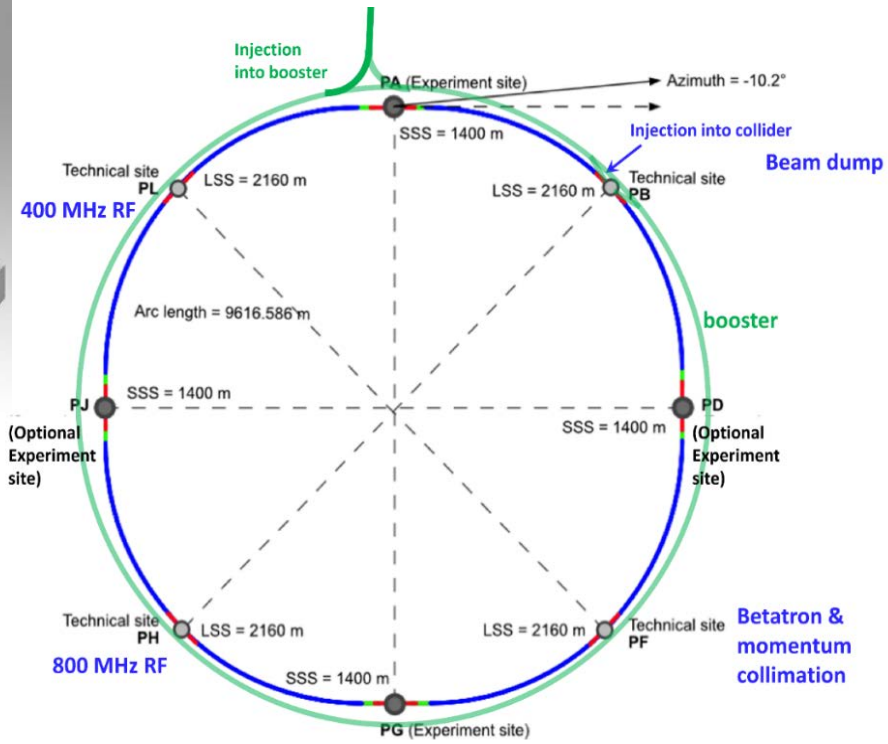
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)



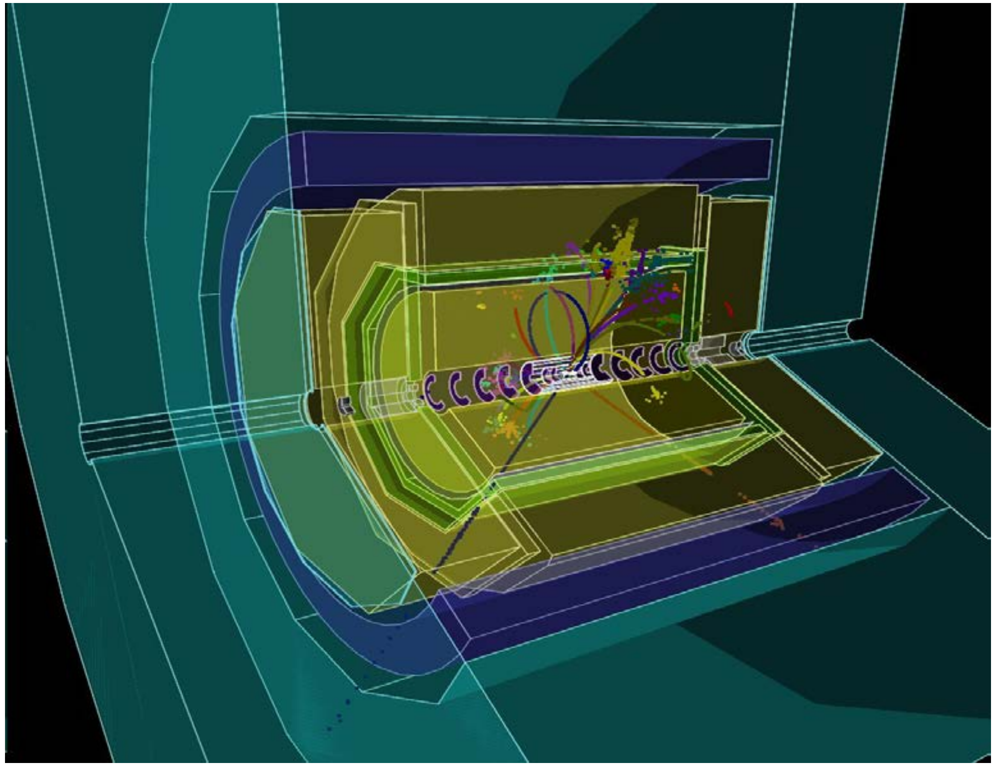


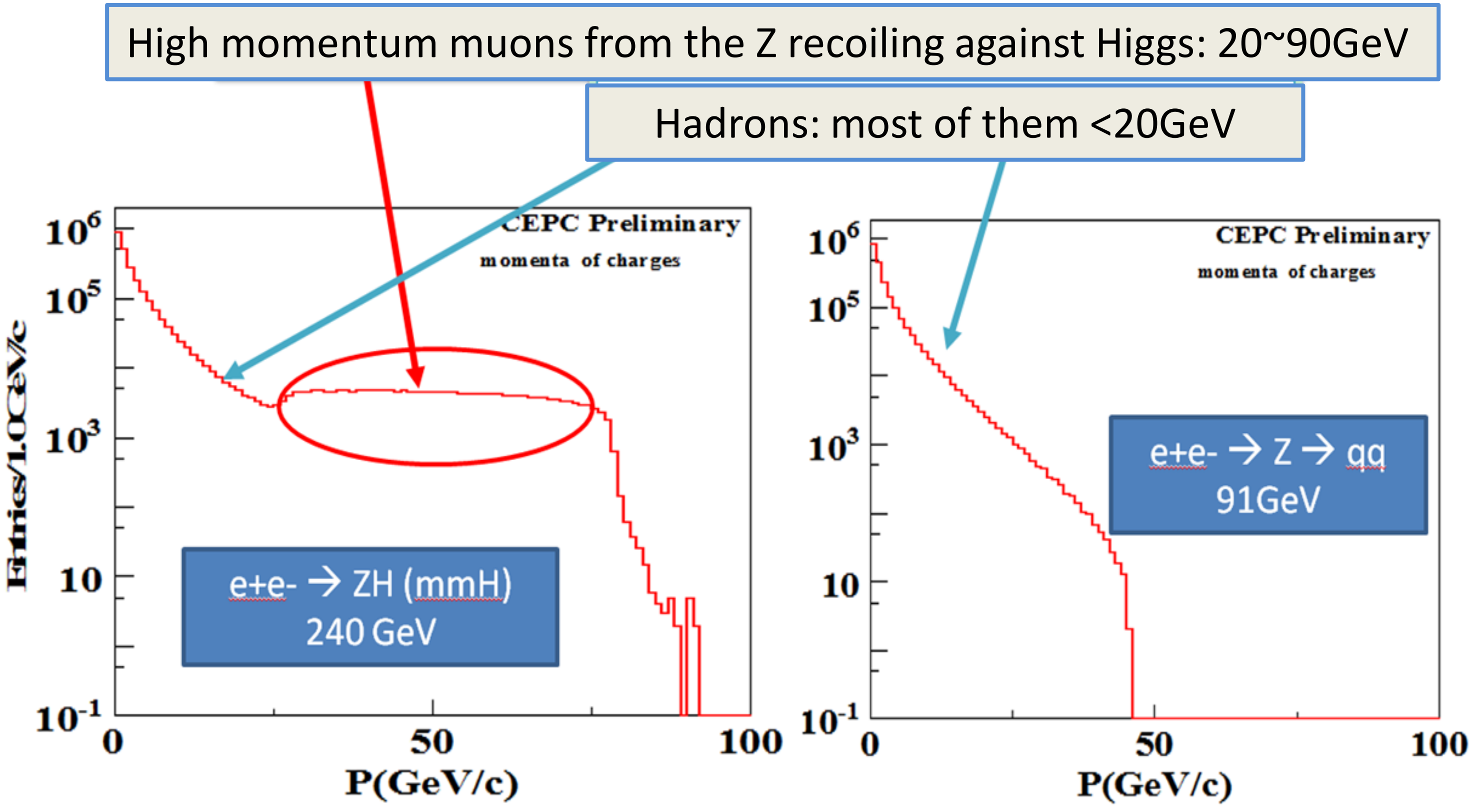
Future Circular Collider (FCC-ee)

https://arxiv.org/abs/2203.06520

TPC requiremetns from e+e- Higgs/EW/Top factories

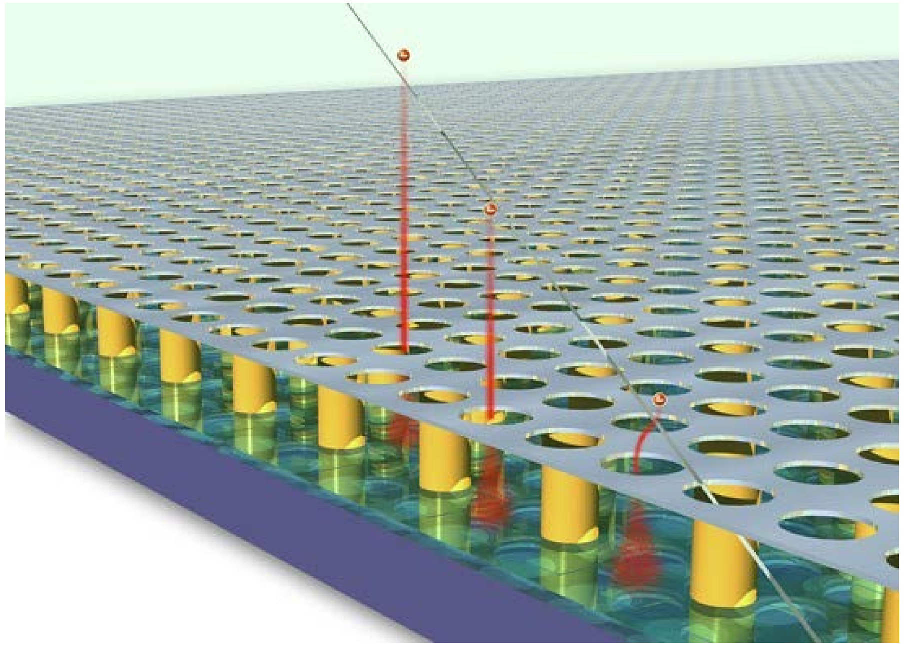
- TPC can provide hundreds of hits (for track finding) with high spatial resolution compatible with PFA design (**very low material** in chamber)
    - $\sigma_{1/pt} \sim 10^{-4}$ $(GeV/c)^{-1}$ with TPC alone and σ_{point}<100μm in rϕ
- **Provide dE/dx and dN/dx with a resolution** <4%
    - Essential for Flavor physics @ Z run
    - Beneficial for jet at higher energy





Pad and pixelated readout TPC technology

- TPC as the main tracker detector to satisfy the physics requirements :
  - For Higgs, W and top running, **no problem** for all TPC readout technologies.
- For high luminosity **(2×10^{36})** Z running
  - Pixelated readout TPC is a good option at **high luminosity** on the circular e+e- collider
  - Pixelated readout TPC is a realistic option to provide
    - High spatial resolution **under 2T or 3T magnetic field**
    - Better momentum resolution
    - High-rate operation (MHz/cm^2)
    - dE/dx and Cluster counting (**in space**)
    - Excellent two tracks separation



Standard charge collection:

Pads (1 mm × 6 mm)/ long strips

Pixelated readout:

Bump bond pads are used as charge collection pads.

55µm × 55 µm or larger

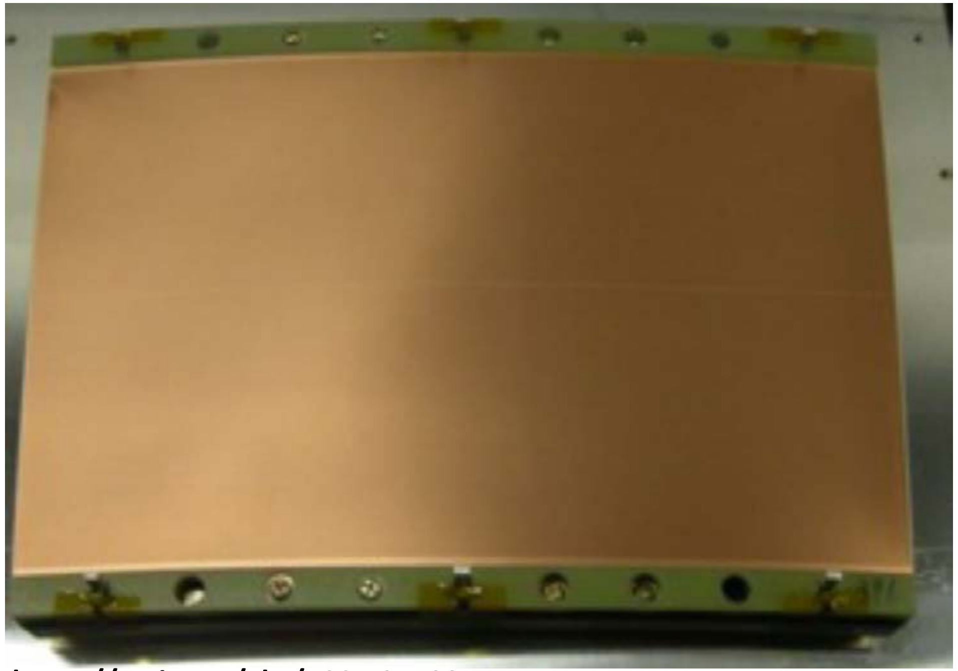
- High spatial resolution pad TPC technology

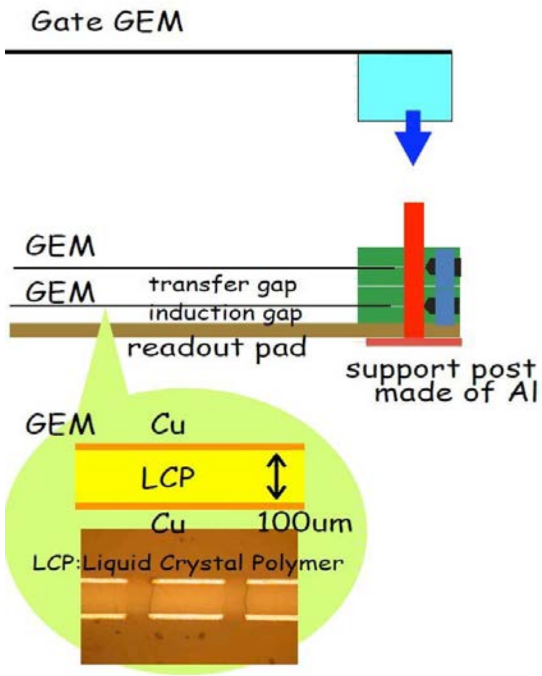
Pad TPC technology - double GEMs

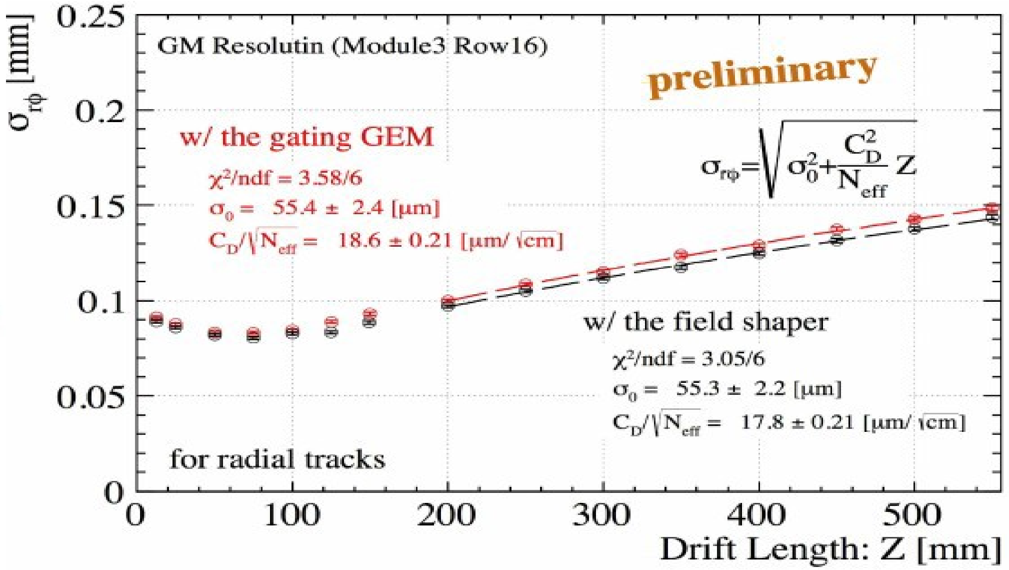
- GEMs: copper-insulator- copper sandwich with holes
- Double GEMs module are being tested:
  - GEMs with 100μm LCP insulator
  - Standard GEM from CERN
- Design idea of the GEM Module:
  - **No frame** at modules both sides
  - Spatial resolution of $\sigma_{r\phi} \leq 100$ μm, more stability by the broader arcs at top and bottom

GEM Module 1:

- 2 GEMs made of 100 μm thick LCP
- $1.2 \times 5.4 mm^2$ pads







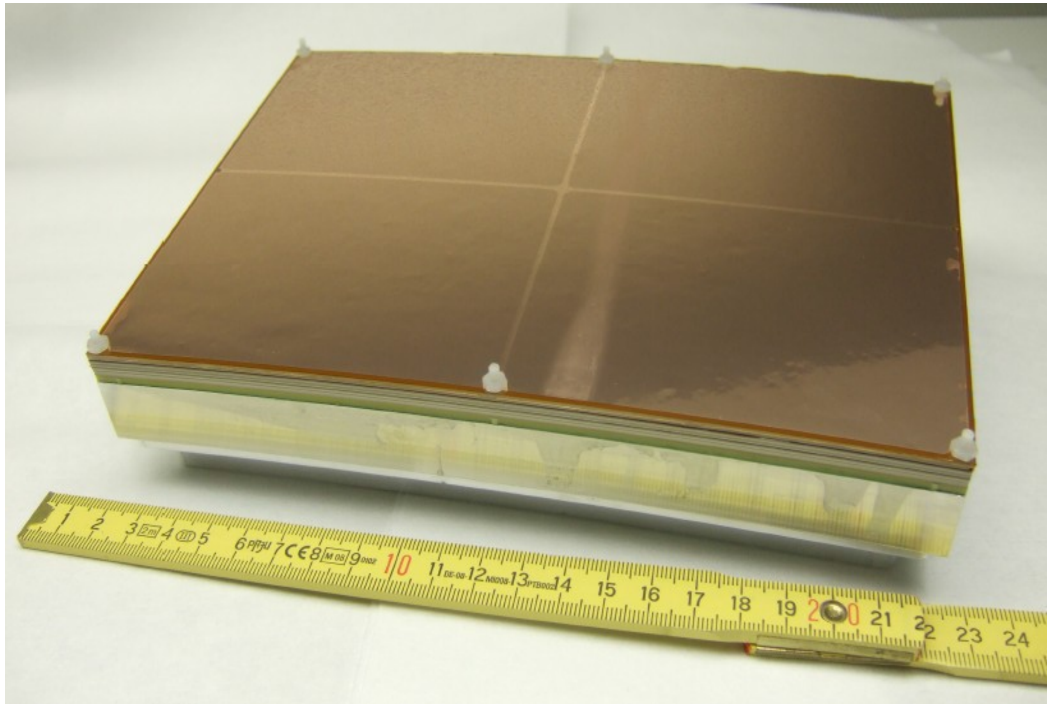
https://arxiv.org/abs/1801.04499

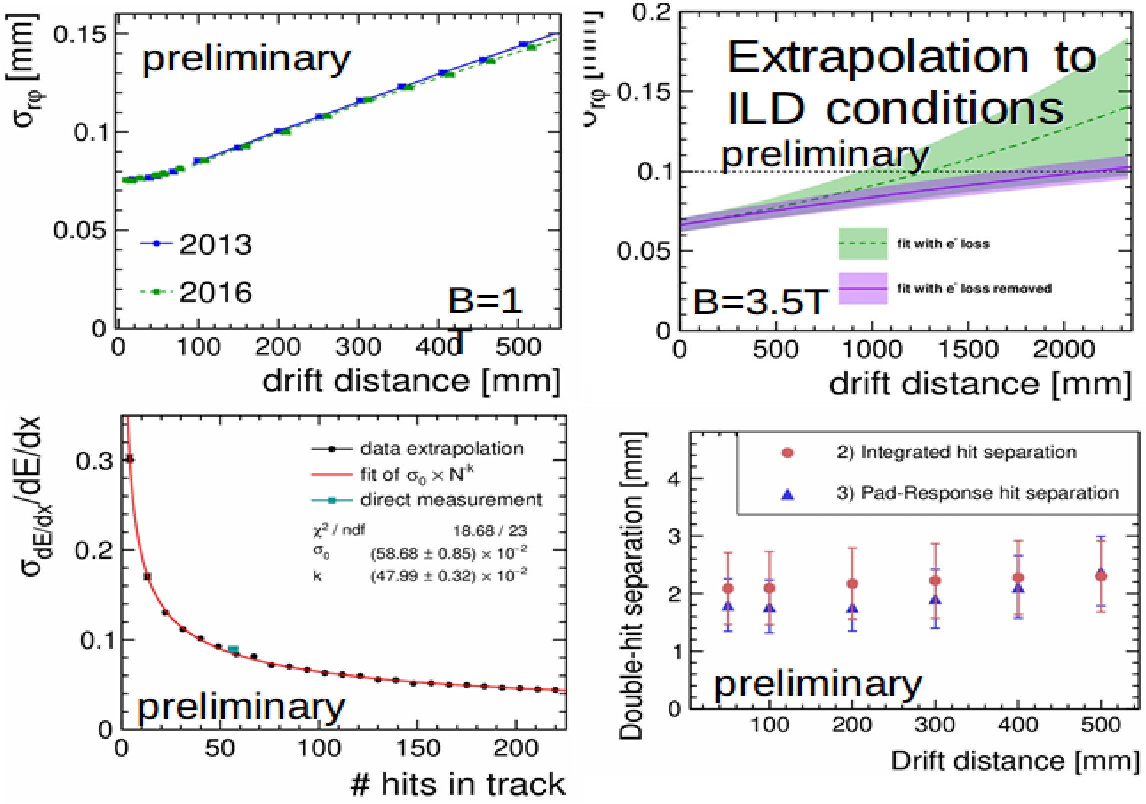
Pad TPC technology - triple GEMs

- Design idea of GEM Module 2:
  - Minimize dead area
  - **Without frame** to stretch GEMs, but a 1 mm grid to hold GEM
- Spatial resolution of $\sigma_{r\phi} \leq 100\ \mu m$, **and double track resolution and dE/dx calculated** in dependence on the pad sizes

GEM Module 2:

- 1.26 × 5.85mm2 pads – staggered
- Field shaping wire on side of module to compensate the field distortions

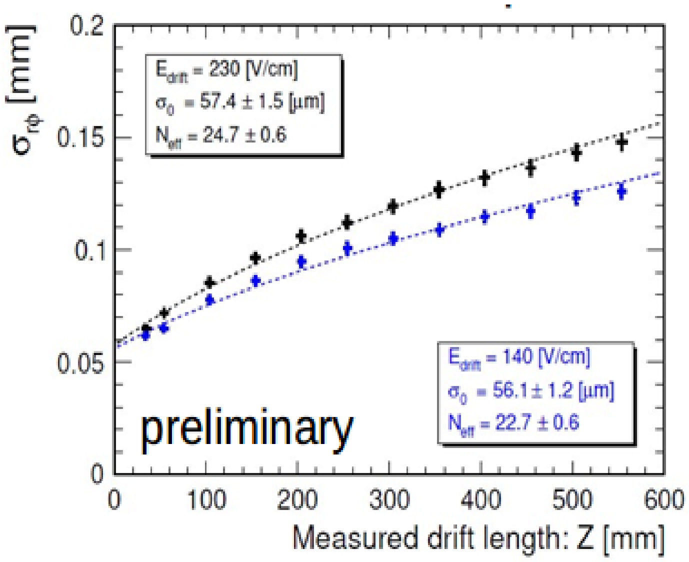


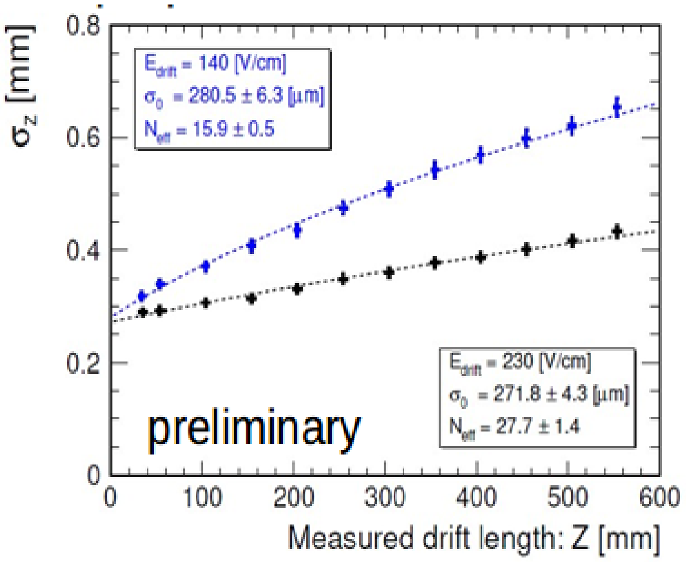


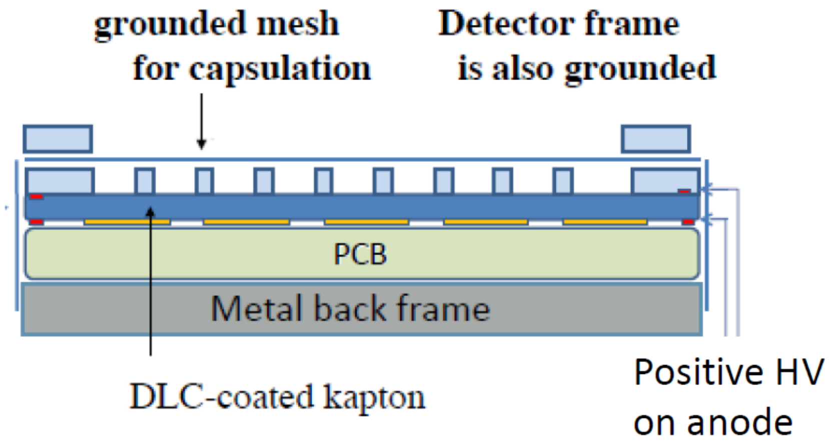
https://arxiv.org/abs/2203.03435

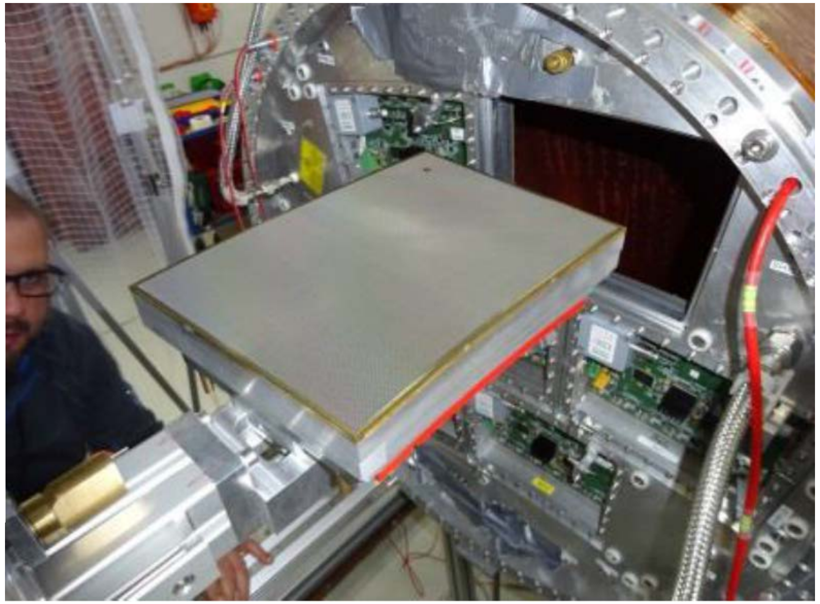
Pad TPC technology - Resistive Micromegas

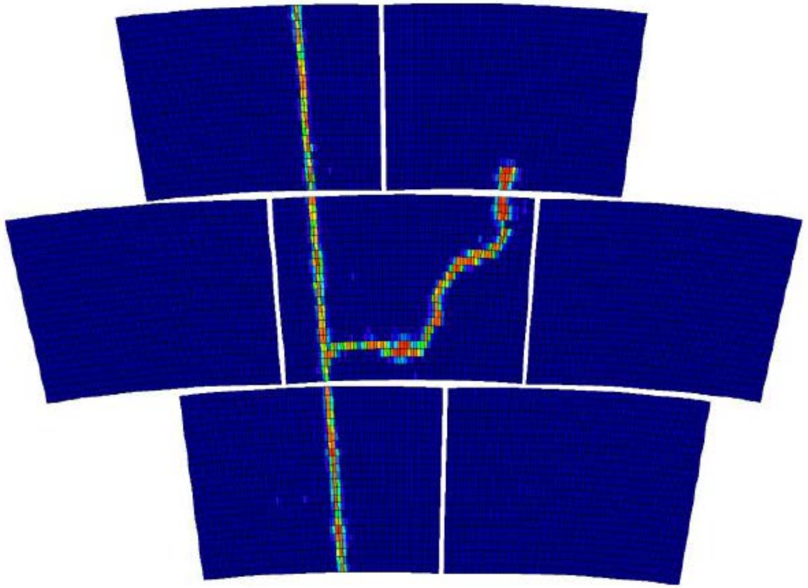
- Resistive Micromegas:
  - Bulk-Micromegas with 128 μm gap size between mesh and resistive layer (**developed in LCTPC**)
- A new HV scheme of the module (ERAM) places grid on ground potential
  - Reduces **field distortions** between modules by a factor of 10





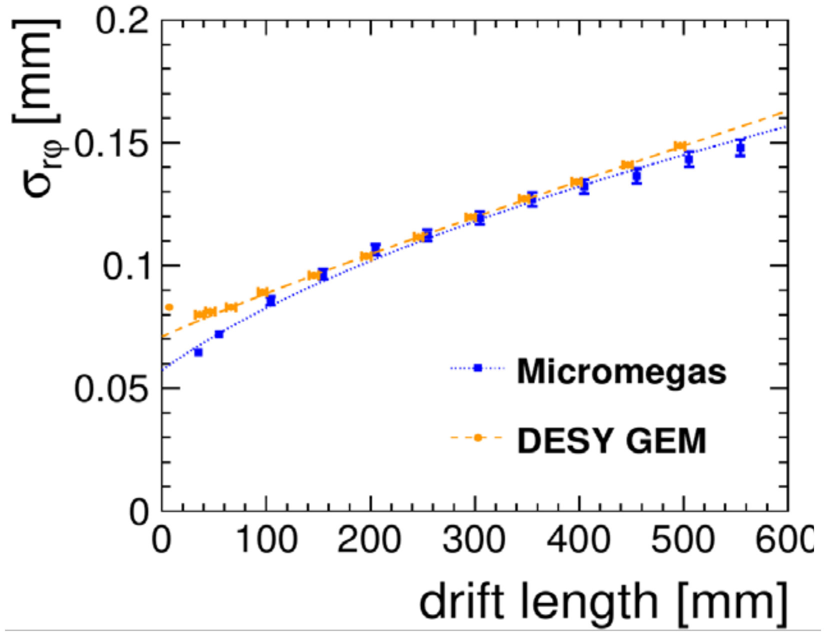


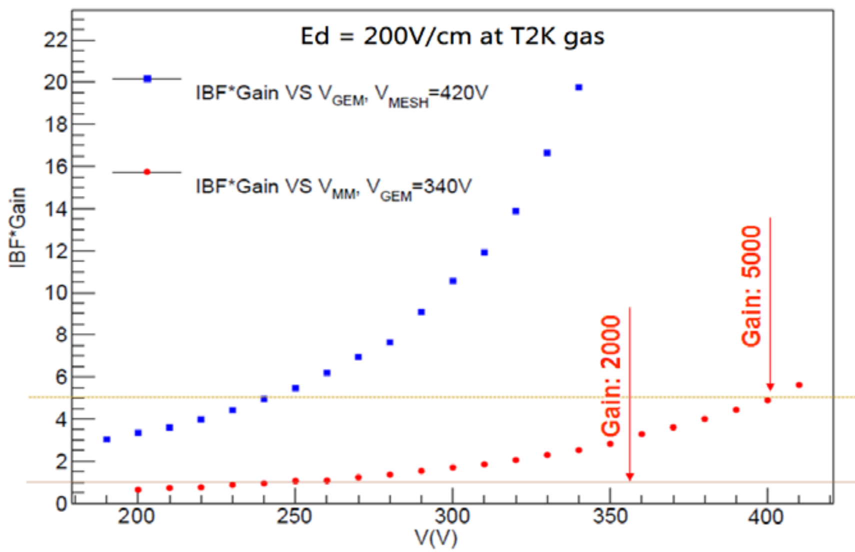


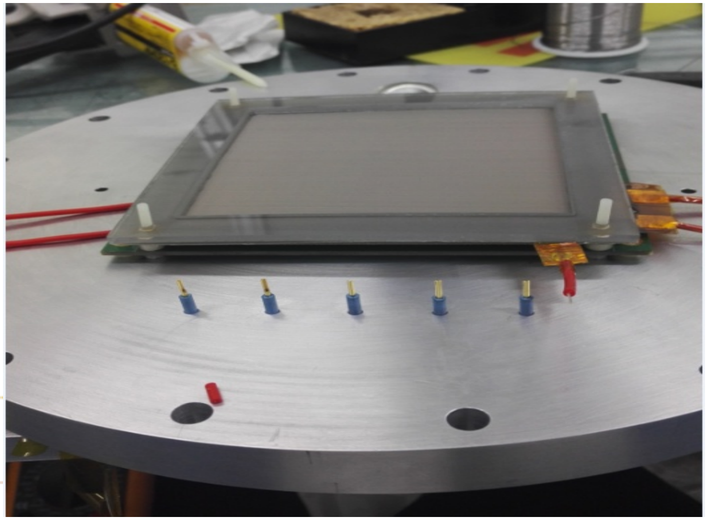


https://doi.org/10.1016/j.nima.2019.162798

- **GEM and Micromegas** groups have finished analysis of test beam data with previous set of detector modules. Both technologies show **very similar performance**.
- LCTPC want to implement improvements in a **new generation of modules** => **common modules**
    - Common readout electronics (sALTRO)
    - Only the gas amplification stage differs
- Combined Micromegas + GEM readout has been developed, which promises a **lower ion backflow** (IBF) at CEPC TPC group without gating.
    - IBF×Gain ~ 1 at total gain of 2000

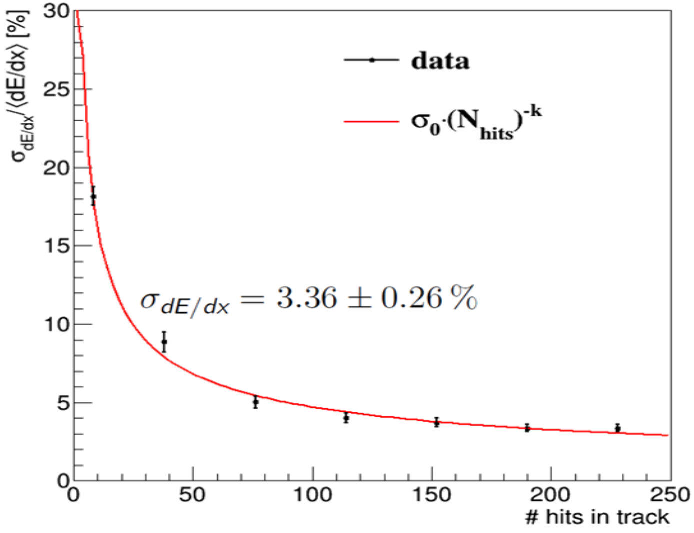


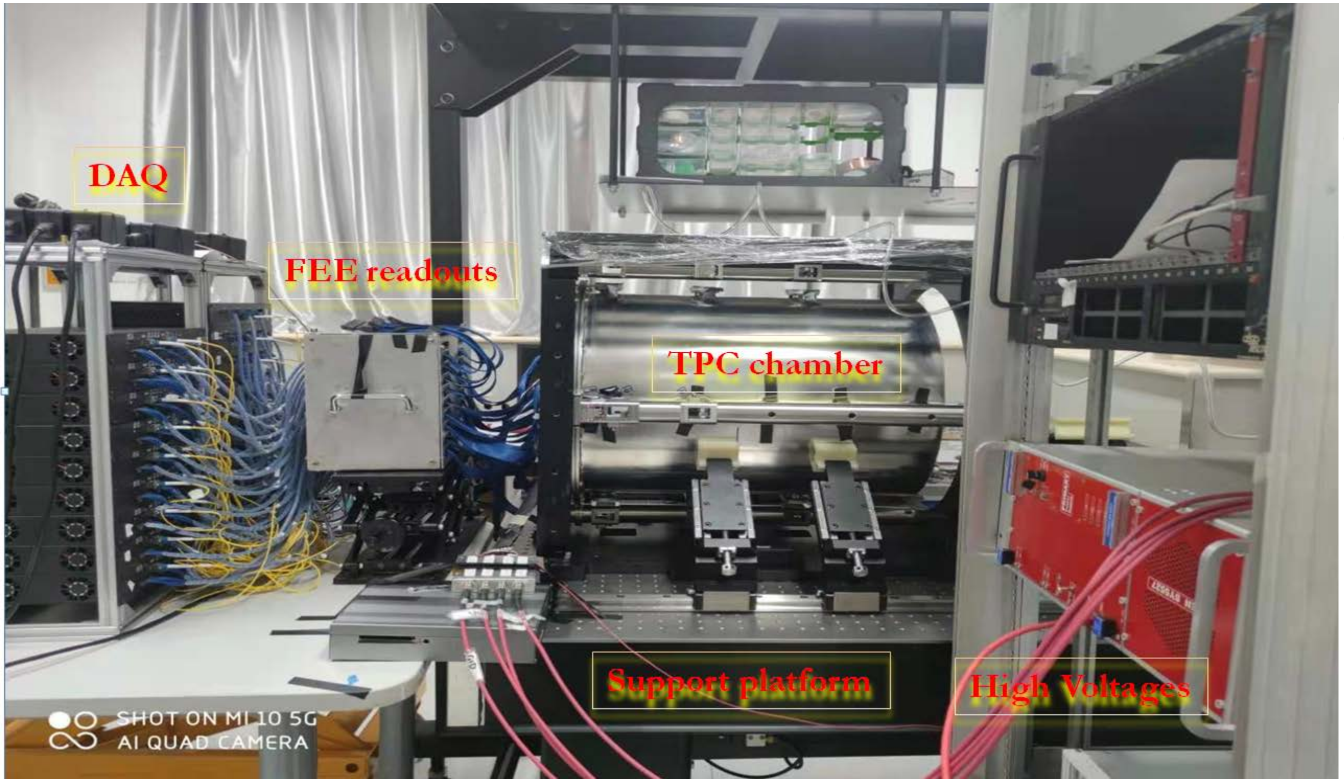


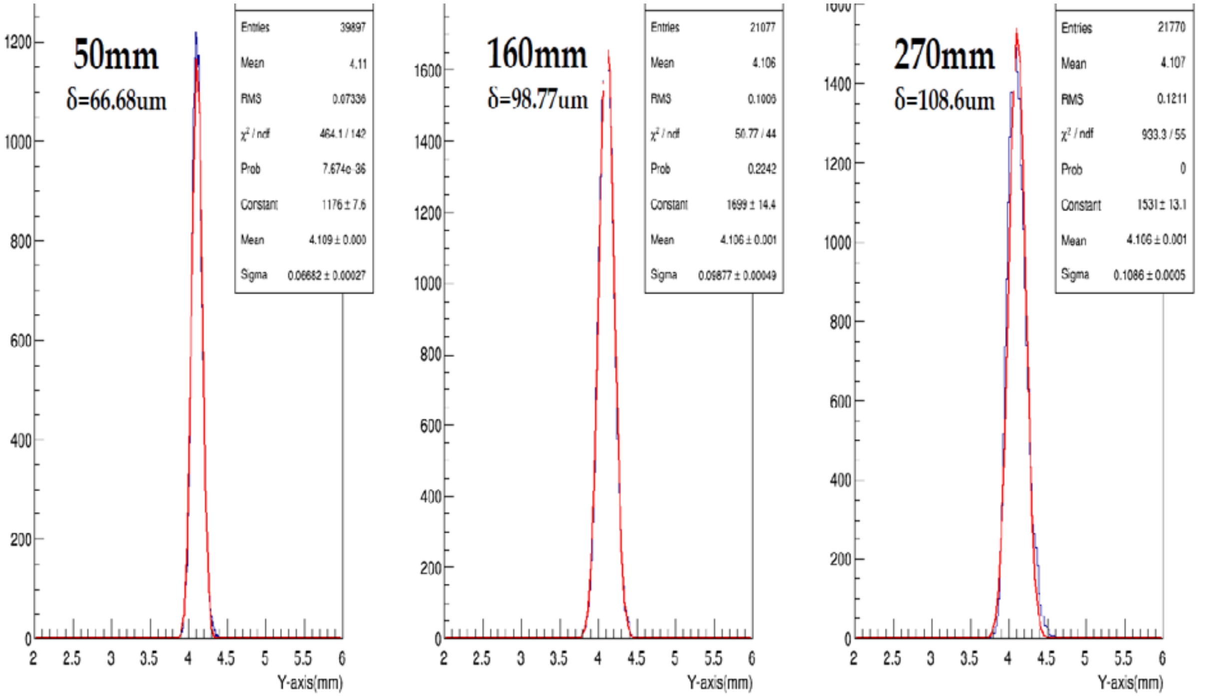


TPC prototype with 266nm UV laser tracks

- The TPC prototype integrated 266nm UV laser tracks has successfully developed.
- Analysis of UV laser signal, the spatial resolution, dE/dx resolution
  - Spatial resolution can be less than **100 μm along the drift length** of TPC prototype
  - Pseudo-tracks with 220 layers (**same as the actual size of CEPC baseline detector concept**) and dE/dx is about 3.4 ± 0.3%





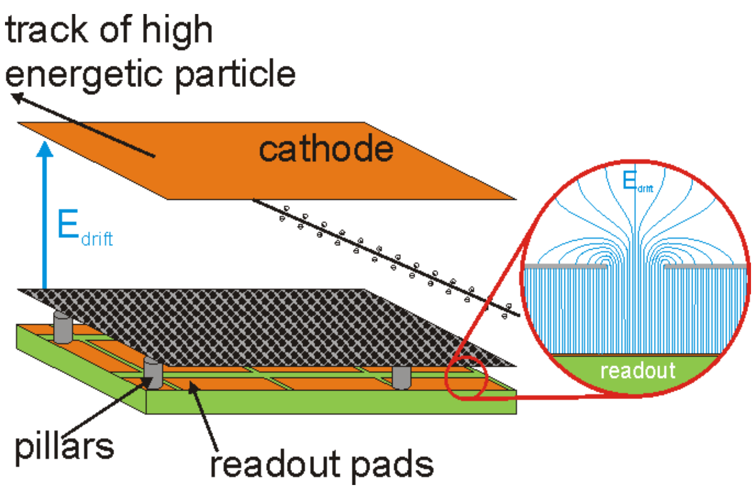


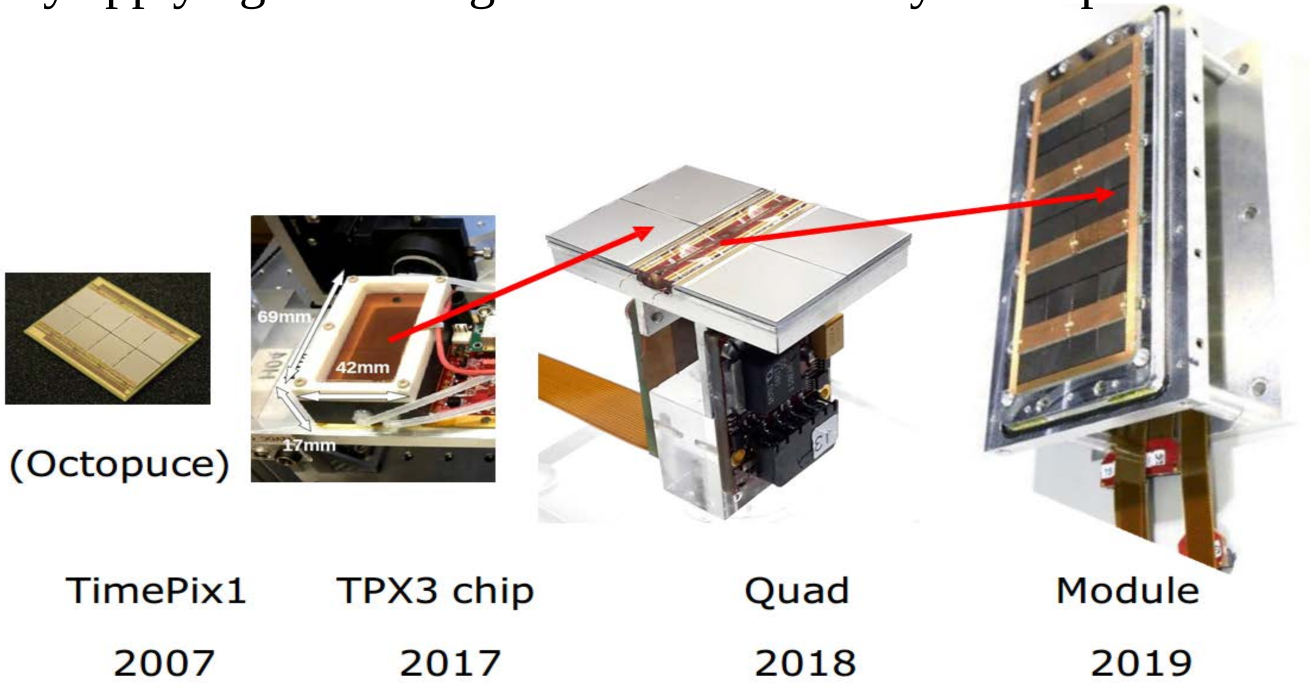
https://doi.org/10.1016/j.nima.2022.167241

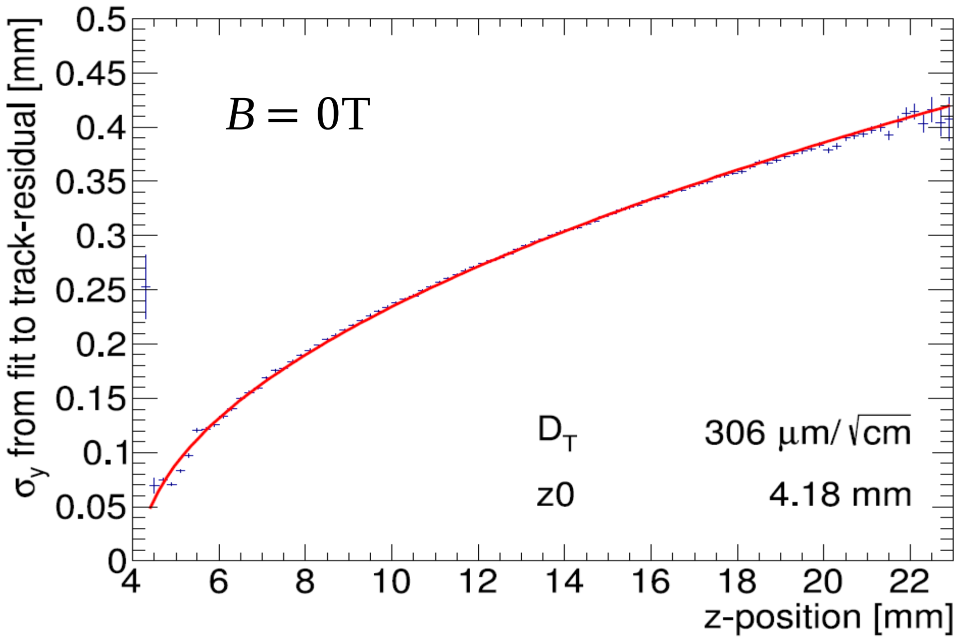
- Pixelated TPC technology

Pixelated TPC technology - Timepix3-based GridPix

- GridPix detector have moved from Timepix to Timepix3 ASICs. Tests with single and quad devices have been successfully done.
- A module **with 32 GridPixes has been constructed** and was in a test beam in B=1.0T at DESY in June 2021.
- Very high detection efficiency results in **excellent tracking and dE/dx performance.** Timepix4 development is ongoing.
- Ion back flow of the module has been measured and can be further reduced by applying a double grid and the resistivity of the protection layer.



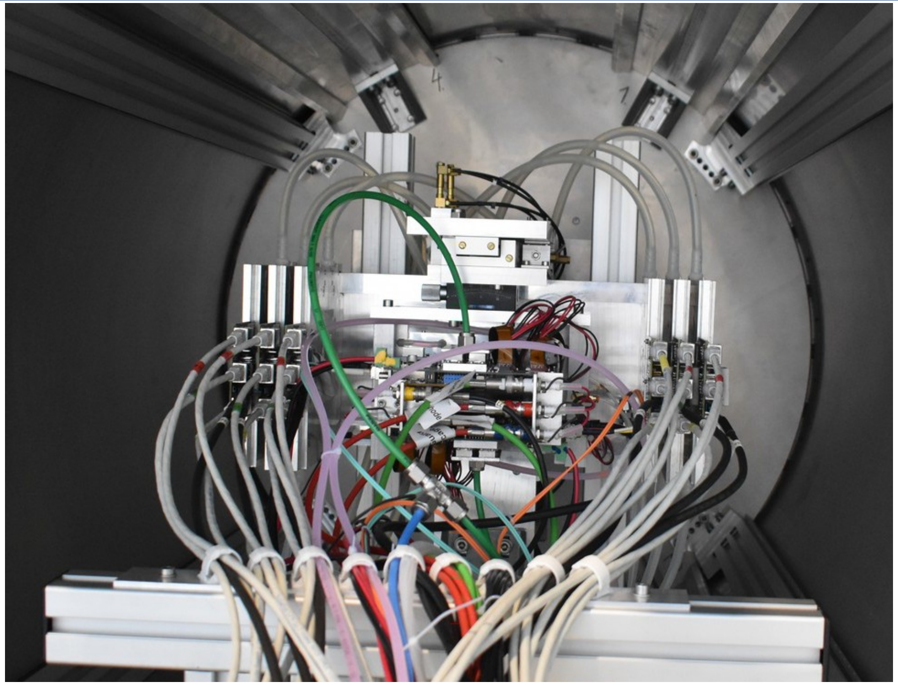


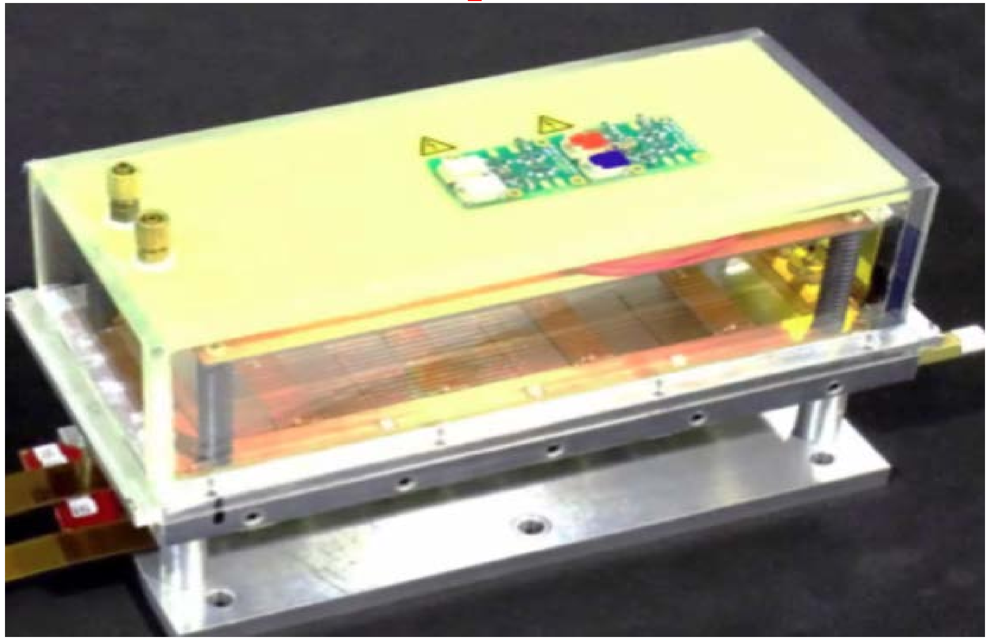


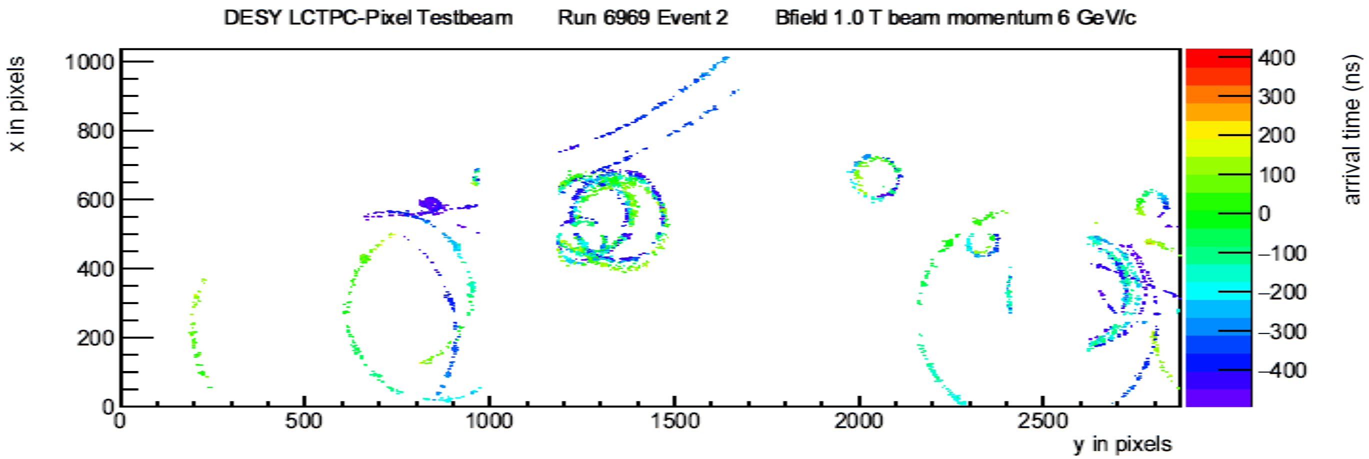
https://arxiv.org/abs/1902.01987

Pixelated TPC technology – Large scale readout

- TPC prototype with GridPixes:
  - ~**100-120 chips/module** 240 module/endcap (10 m²) →50000-60000 GridPixes Demonstration of mass production: One LP-module covered completely with GridPixes (96 → coverage 50%) and two partially covered modules.
  - In total 160 GridPixes covered **an active area of 320 cm²** (10M pixel detector).
- During the test beam ~10^6 events were successfully collected, all results showed that **a pixel TPC is realistic.**







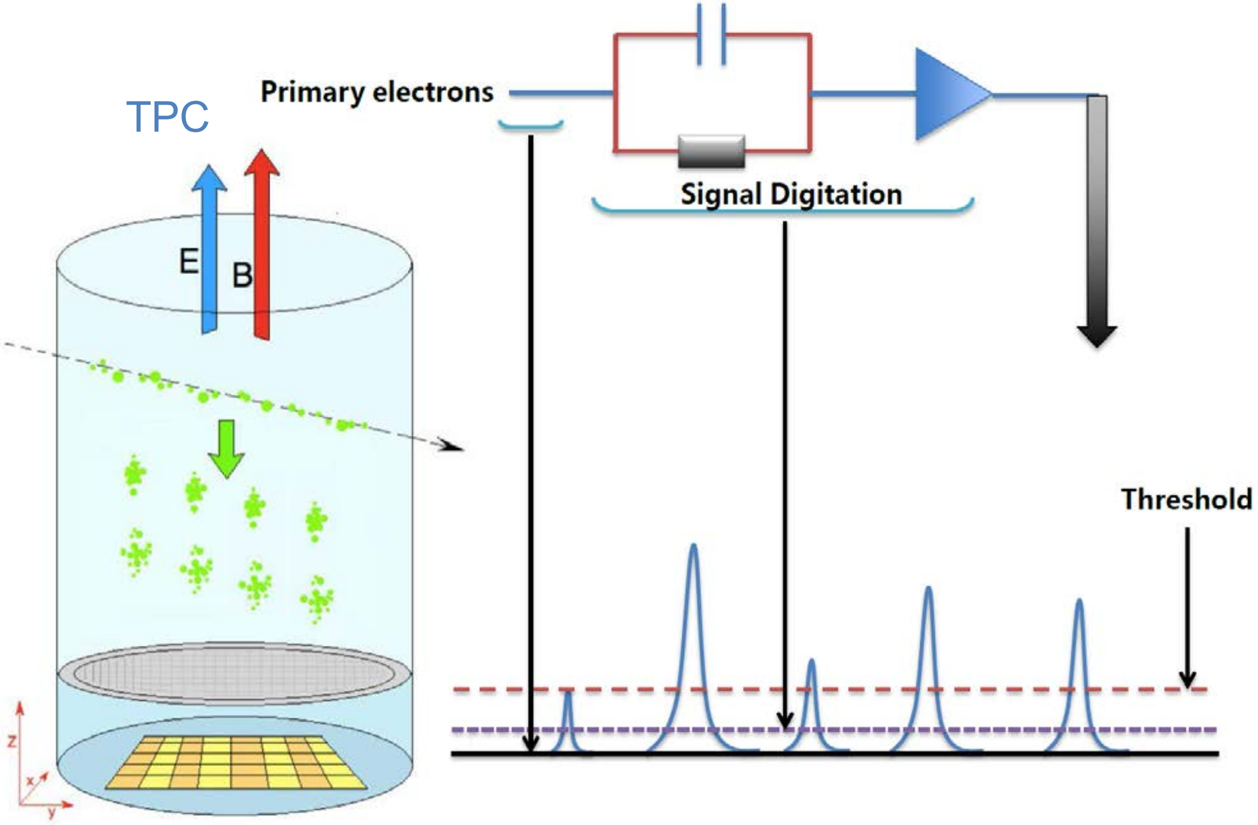
DESY testbeam in June 2021

Identify the clusters to achieve dN/dx and Occupancy

dN/dx cluster counting

- Challenging for the **low power consumption** electronics (>40mV/fC needed at 2000 of gas gain)
- Pixelated readout
    - → **high granularity readout in endplate**
    - → the reasonable pixilation reveals the underlying cluster structure in 3D chamber

- Occupancy of the pixelated TPC
    - Occupancy is very **key issue** at the high rate or high luminosity
    - Smaller pad/pixel size
      → **smaller occupancy**
    - To be addressed by R&D
      → A detailed simulation would be necessary to determine the scaling factor
      → Simulation ongoing at IHEP



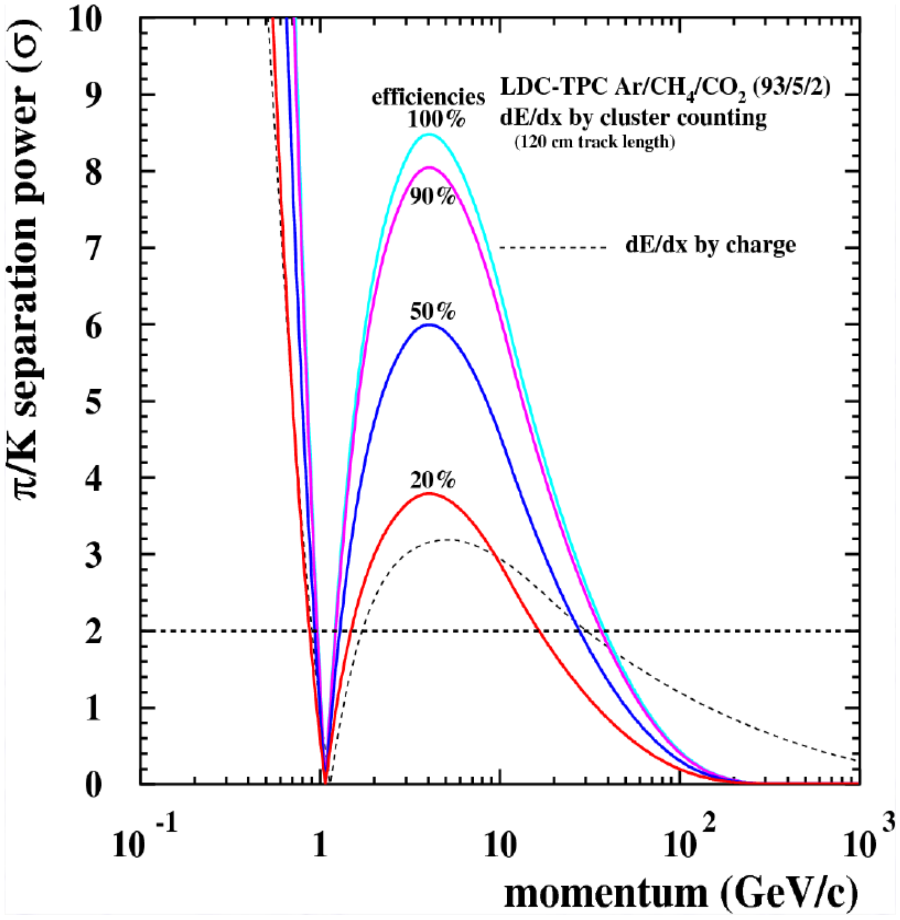
High granularity for improved PID in TPC

- For **traditional dE/dx detection**, the charge summation is performed using the center-of-gravity method.
- In most experimental study from small to large TPC
    - L: track length
    - N: number of readout rows
    - Constant L and changing granularity G = N/L

$$\frac{\sigma_{dE/dx}}{\langle \mu_{dE/dx} \rangle} \propto L^{-0.45} G^{-0.13}$$

- If pad size is at the level of cluster distances of primary ionization
    - i.e. ~ **300-500 μm in Ar-based**
    - Cluster counting becomes effective

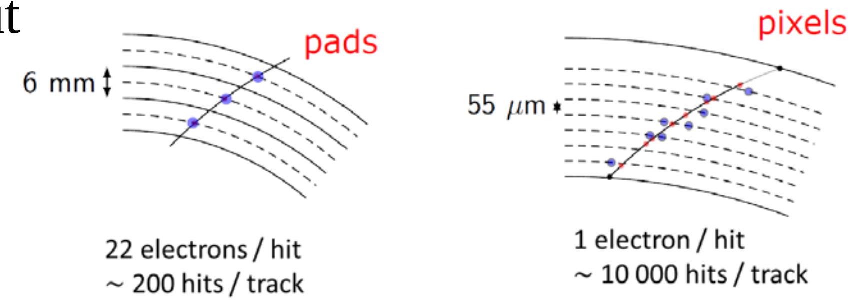
- PID improvement
    - The potential of **better resolution by at least a factor 2**
    - Novel method studied by several R&D groups for the TPC
  for the e+e- collider

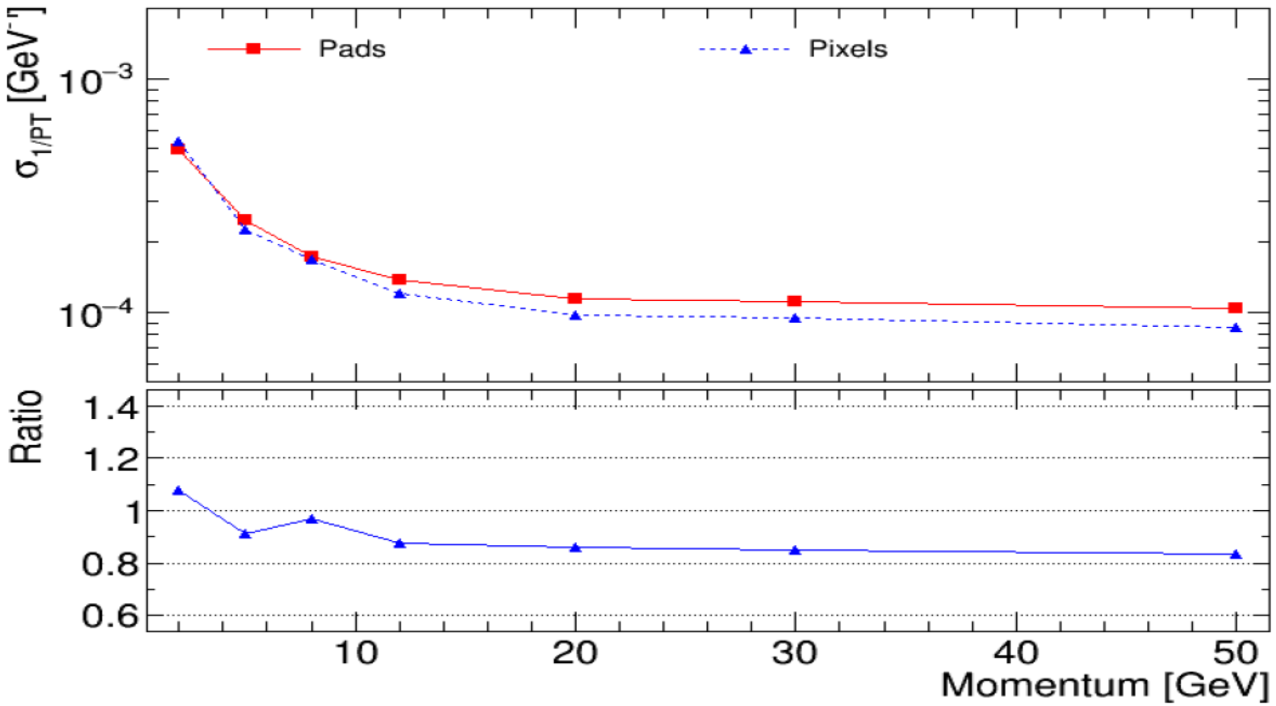


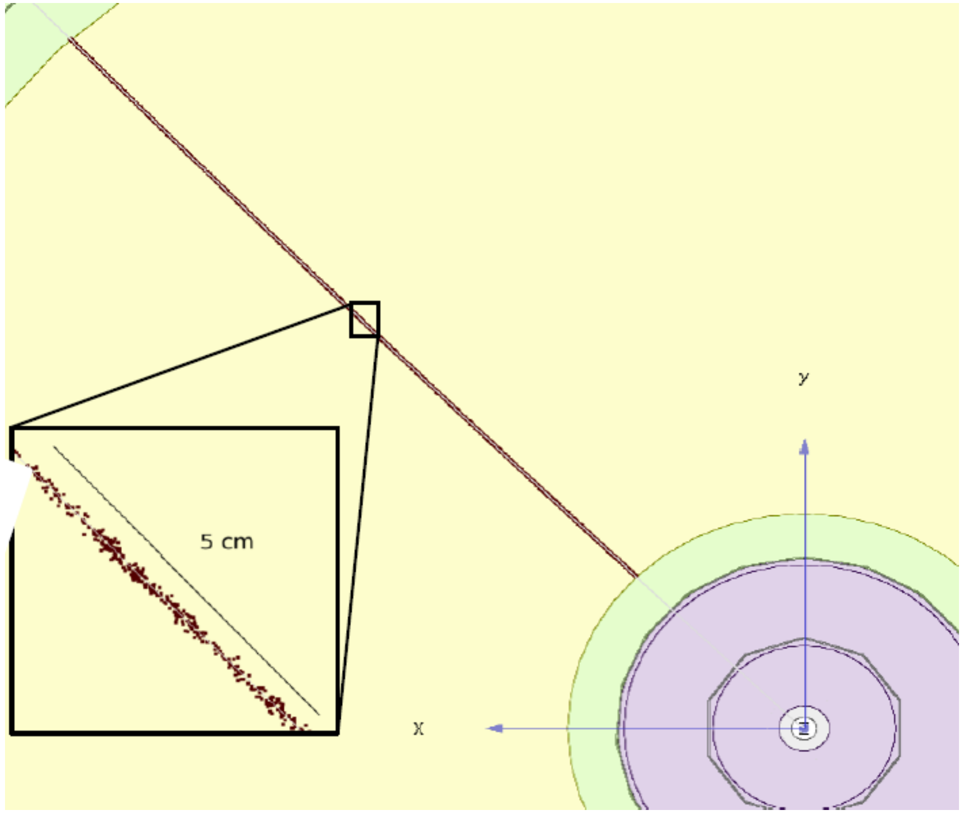
Hauschildt
http://ific.uv.es/~ilc/ECFA-GDE2006/0

Simulation of ILD TPC with the pixel readout

- To study the performance of a large pixelated TPC, the pixel readout was implemented in the full ILD DD4HEP (Geant4) simulation
- Changed the existing TPC pad readout to a pixel readout
- Momentum resolution **preliminarily indicated 15% better** with realistic (59%) coverage of the endplate by the pixel readout.







Simulation of 50 GeV muon track with pixel readout

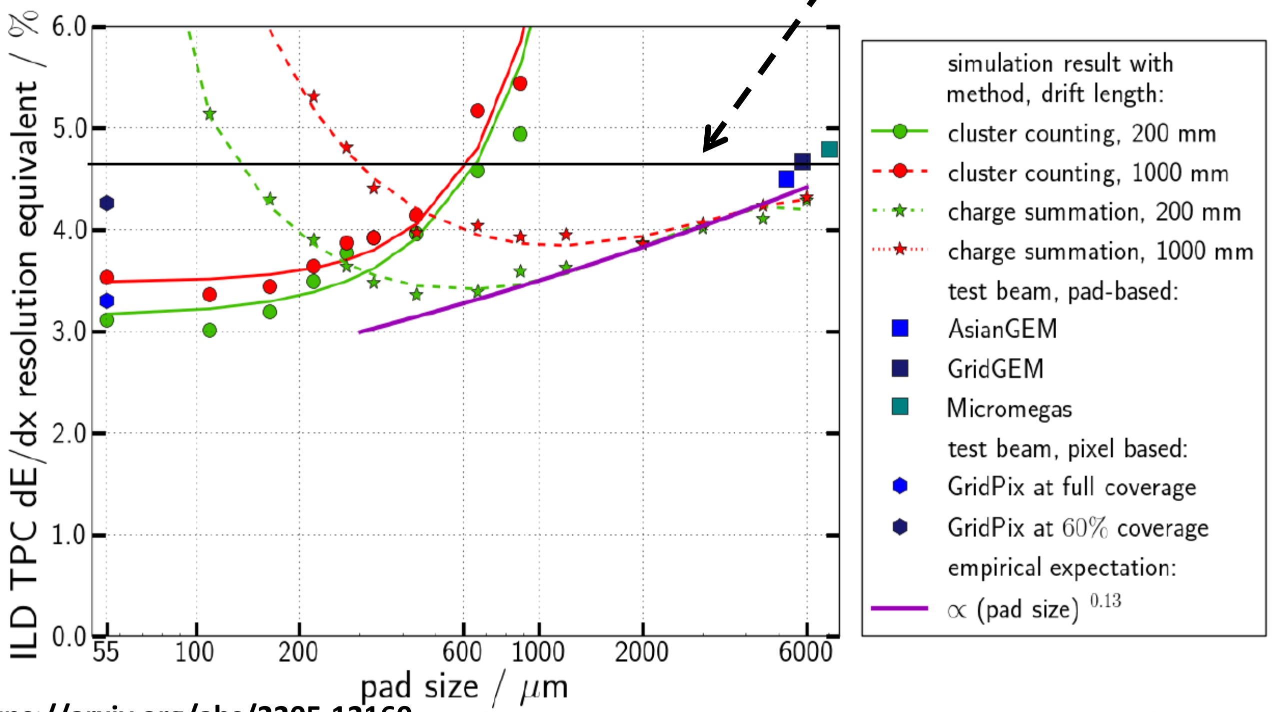
https://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_C_Ligtenberg.pdf

High granularity for improved PID in TPC

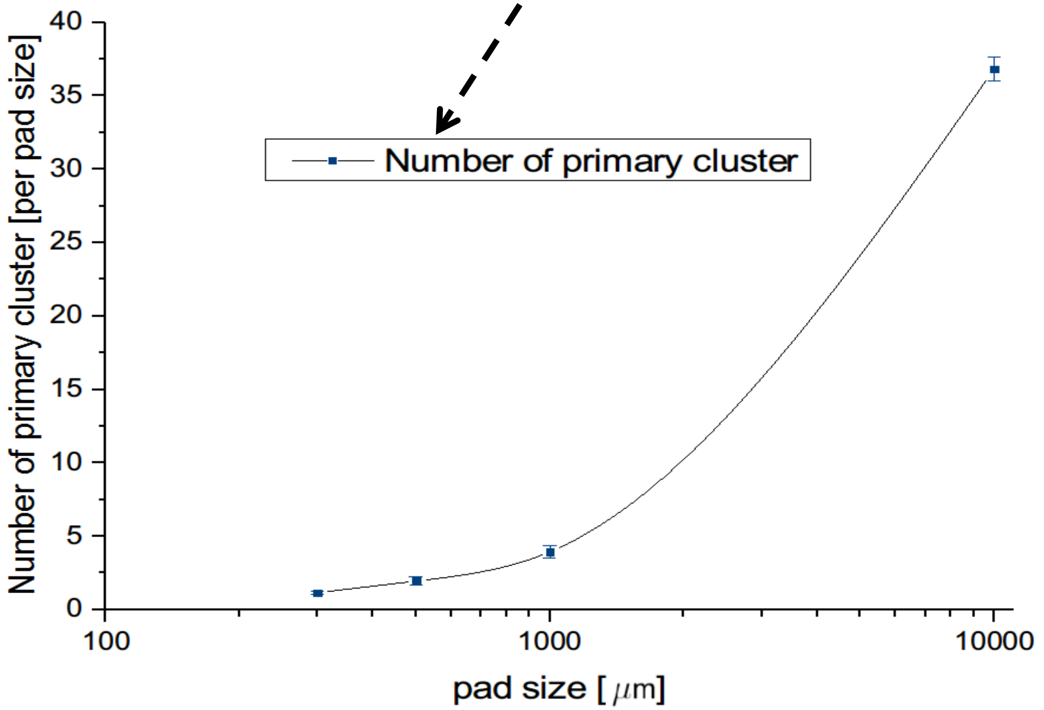
- Current full ILD reconstruction: 6mm pads → **~4.8% dE/dx resolution**
- 6mm → 1mm: 15% improved resolution via the charge summation (dE/dx)
- 6mm → 0.1mm: 30% improved resolution via the cluster counting (dN/dx)
  - Pad size of about 300μm can record **~1 primary cluster along track length** at T2K gas
  - High **readout granularity** VS the primary cluster size optimization

→ All studies ongoing in LCTPC

current resolution in the full ILD reco assuming 6 mm pads



Simulation of the primary cluster along the drift length



https://arxiv.org/abs/2205.12160

Summary

- In LCTPC international collaboration, TPC tracking using GEM, Micromegas and GridPix pad and pixelated readouts have been developed for the future e+e- colliders.
- Analysis of test beam data with similar set of GEM, Micromegas and Gridpix modules demonstrated the proof-of-concept and validated these technologies.
- Many simulations are still necessary to understand the detailed requirements of the pixelated detector (e.g. number of ADC bits, pixel readout sizes, occupancy, ion backflow, etc.), but also new ideas are welcome.
- Synergies with CEPC/FCCee/EIC/T2K/ALICE allow us to continue R&D and ongoing, we learn from their experiences and R&D beyond the scope of ILC.

Many thanks!