A Time Projection Chamber
for a Future Linear Collider

Status of TPC R&D in LCTPC

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on behalf of LCTPC international collaboration

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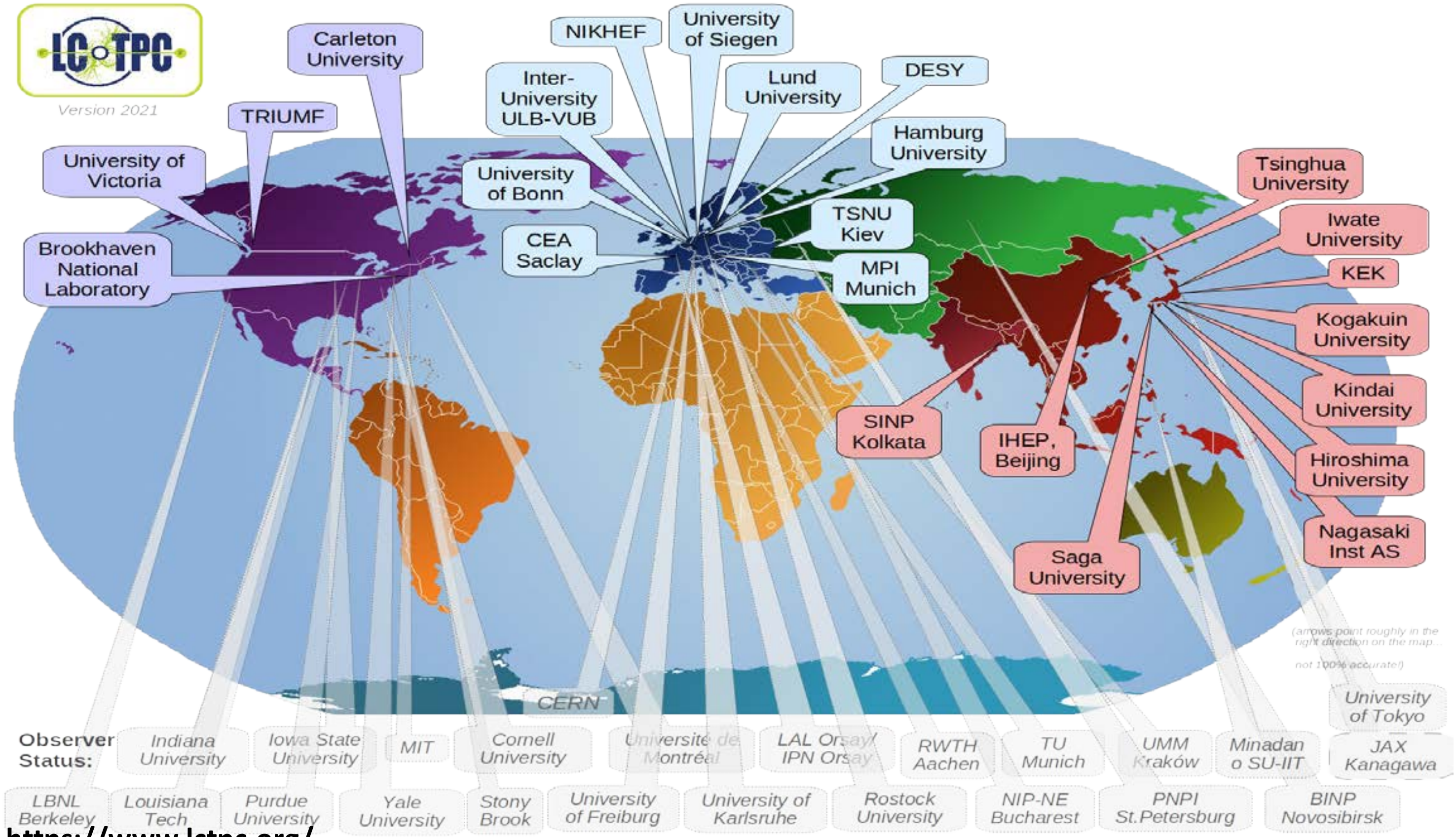
Content

- **TPC detector for e+e- colliders**
- **High spatial resolution pad readout TPC**
- **Pixelated readout TPC for Tera-Z**
- **Beam and cooling for TPC**
- **Summary**

Status of LCTPC Collaboration

- MPGDs for TPC readout is a **baseline solution and further R&D** features many benefits:
  - Small pitch of gas amplification regions in all 2 dim. => strong reduction of E×B-effects
  - **Ion backflow** can be reduced significantly (Gating, Hybrid structure…)
  - Continue electronics, cooling, UV laser track and low power consumption FEE development
- **From 2023, a new DRD1 Collaboration included the TPCs technologies**



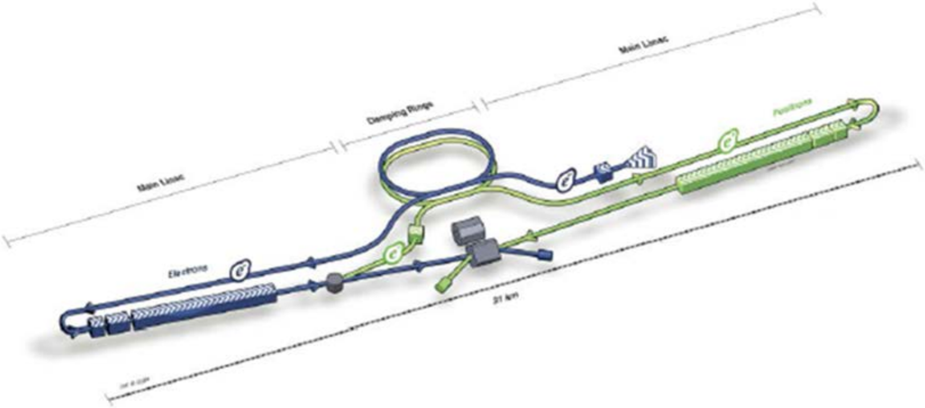
https://www.lctpc.org/

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

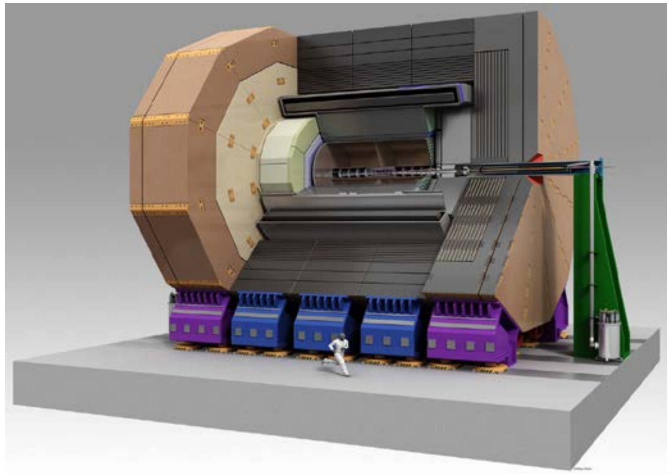
Various **gas amplification stages** are studied: GEMs, Micromegas, GEMs with double thickness and GridPixes.

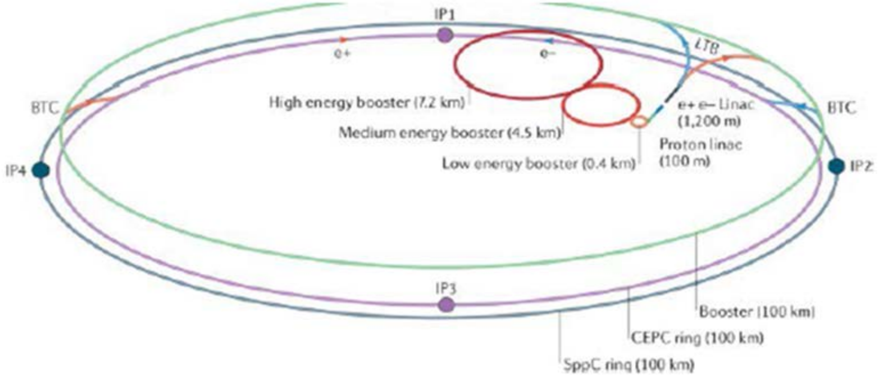
TPC technology for the future e+e- colliders

- 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 colliders (FCC-ee, EIC, KEKb…)

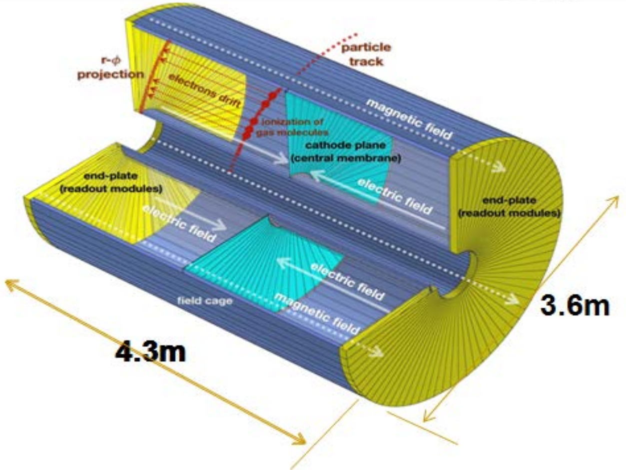


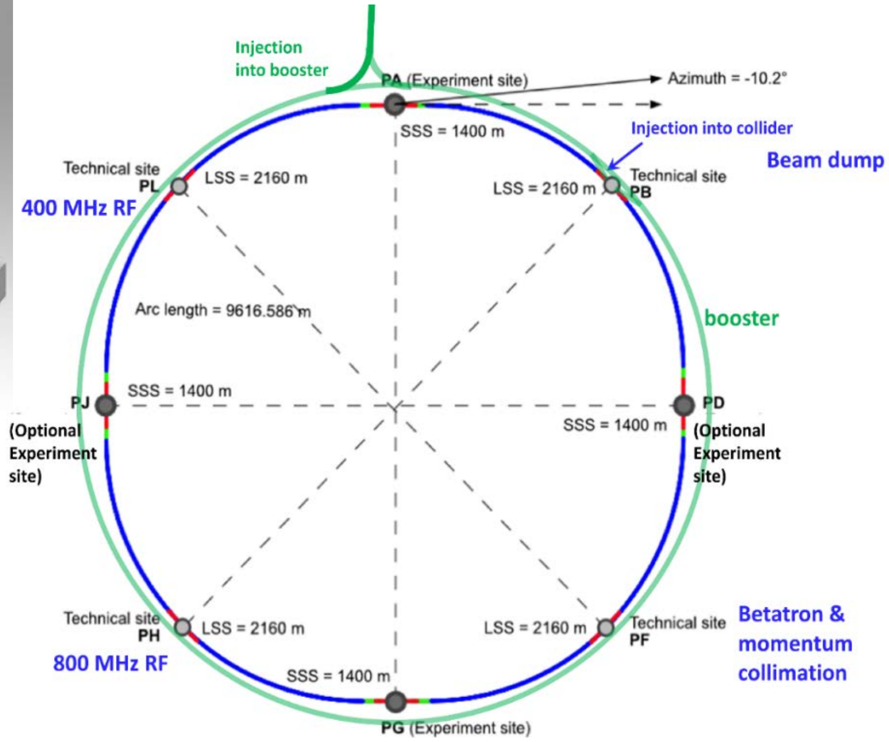
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)



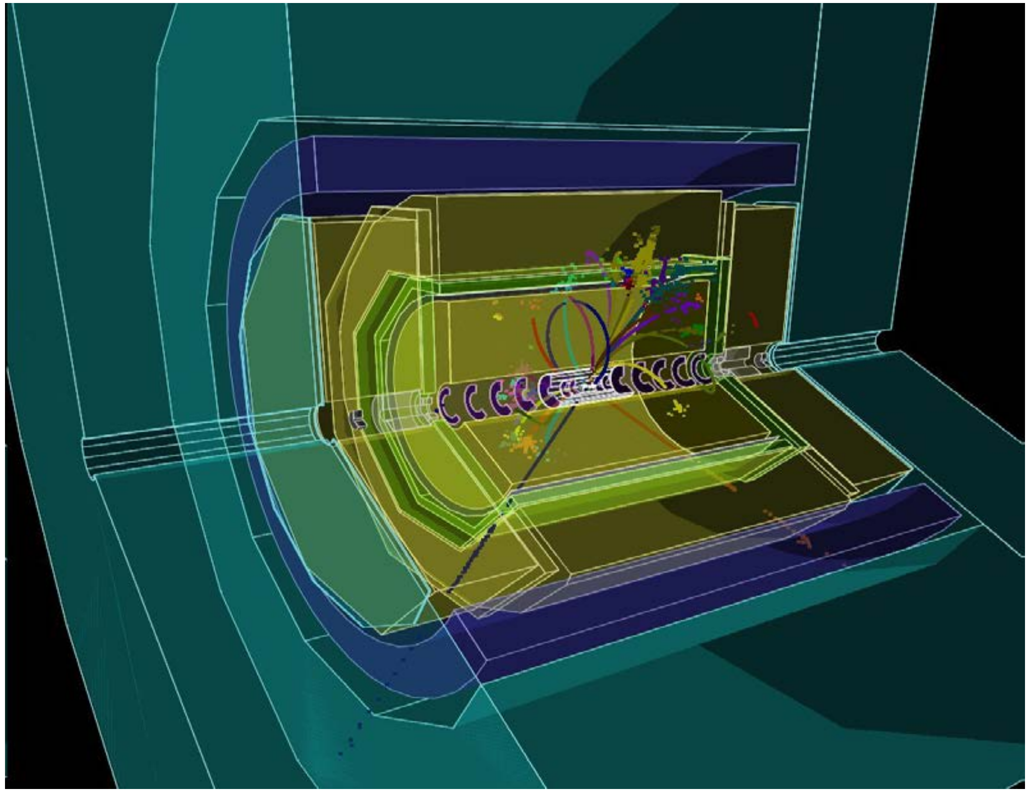


Future Circular Collider (FCC-ee)

https://arxiv.org/abs/2203.06520

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

- TPC can provide hundreds of hits with high spatial resolution compatible, with PFA design (**very low material** in detector chamber)
  - $\sigma_{1/pt}$ ~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



Physics requirements of TPC

Parameter			
Geometrical parameters	r_{in}	r_{out}	z
	329 mm	1808 mm	± 2350 mm
Solid angle coverage	up to $\cos\theta \simeq 0.98$ (10 pad rows)		
TPC material budget	$\simeq 0.05\ X_0$ including outer fieldcage in r		
	$< 0.25\ X_0$ for readout endcaps in z		
Number of pads/timebuckets	$\simeq$ 1-2 $\times$ 10^6/1000 per endcap		
Pad pitch/ no.padrows	$\simeq$ 1× 6 mm^2 for 220 padrows		
σ_{point} in $r\phi$	$\simeq$ 60 μm for zero drift, $<$ 100 μm overall		
σ_{point} in rz	$\simeq 0.4 - 1.4$ mm (for zero – full drift)		
2-hit resolution in $r\phi$	$\simeq$ 2 mm		
2-hit resolution in rz	$\simeq$ 6 mm		
dE/dx resolution	$\simeq$ 5 %		
Momentum resolution at B=3.5 T	$\delta(1/p_t) \simeq 10^{-4}$/GeV/c (TPC only)		

What about Experiments at other Colliders (CEPC, FCCee)?

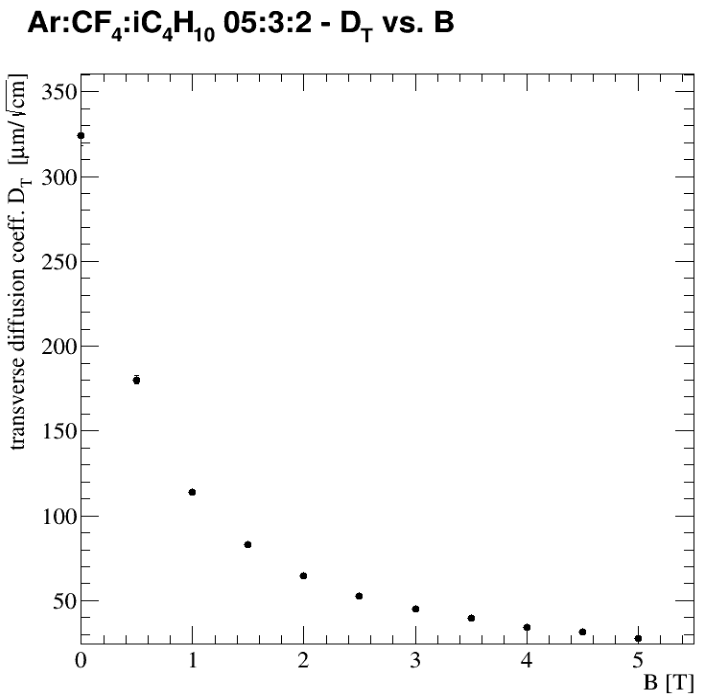
See Paul 's talk and Peter's talk on 12-13th, Feb. mini-workshop

- **Crucial considerations are listed here**:
  - Ions from the gas amplification and primary ionization
    - At linear collider, Higgs studies that machine background contributes most ions. Density would be 1-5 ions/cm^3 resulting in **distortions of <5μm**.
    - At circular collider, the conditions are **similar for Higgs studies** (probably even less background)
    - At Tera-Z, IBF can be reduced to **0.6 but ongoing R&D at the gain of 2000** (Bonn)
    - Recent 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 straphung: Detector optimization and shielding is important for TPC and Silicon detectors to reduce pair background (MDI session in this conference)
    - **Distortions can be mapped out using the VTX-SIT/SET detectors**
  - Power consumption (no power pulsing possible)
    - Pad readout promised and validated using TPC prototype R&D with the cooling.
    - Current power consumption **TPX3 chip: ~2W/cm^2**
    - TPX4 chips can be run in **Low Power Mode: ~1W/cm^2**
    - Final goal of the power: **100mW/cm^2**

What about Experiments at other Colliders (CEPC, FCCee)?

- **Crucial considerations are listed here**:
  - Operation at **2T during the Z pole running**
    - Transverse diffusion degrading the spatial resolution.

$$\sigma = \sqrt{\sigma_0^2 + D_T^2 x}$$

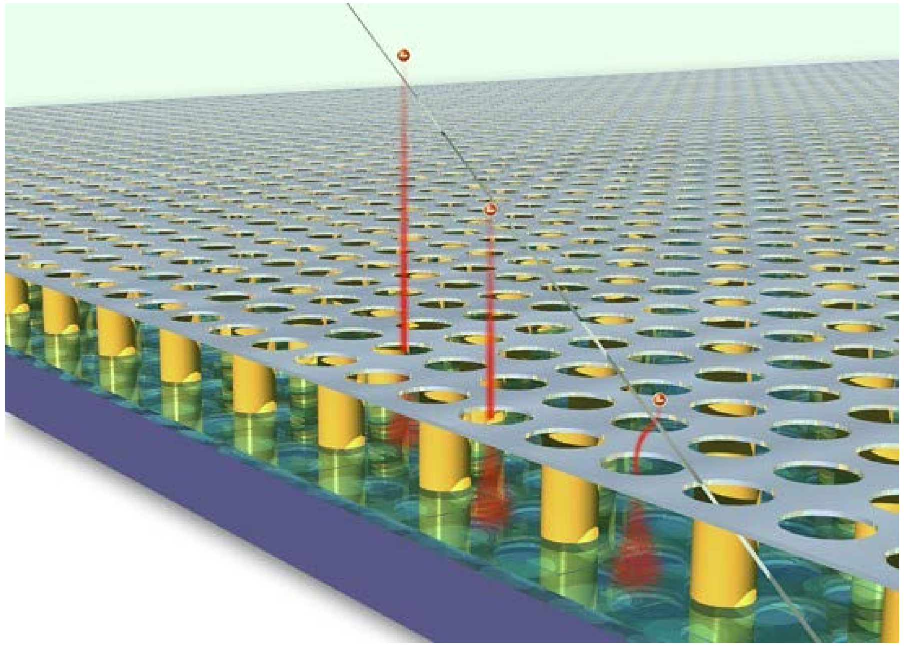


  - Pixelated TPC technology
    - The **Z physics program at FCC-ee or CEPC** with an ILD-like detector with a Pixel TPC (with double grid structures) sliced between two silicon trackers (VTX-SIT and SET) can be fully exploited.
    - A pixel TPC can perfectly run at WW, ZH or tt energies where track distortions are several orders of magnitude smaller
    - The excellent time resolution: time stamping of tracks <1.2 ns allows to resolve and reconstruct the events.
    - **PID performance** can be improved, dE/dx can be measured by cluster counting and performance separation enhanced.

R&D ongoing in LCTPC group

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

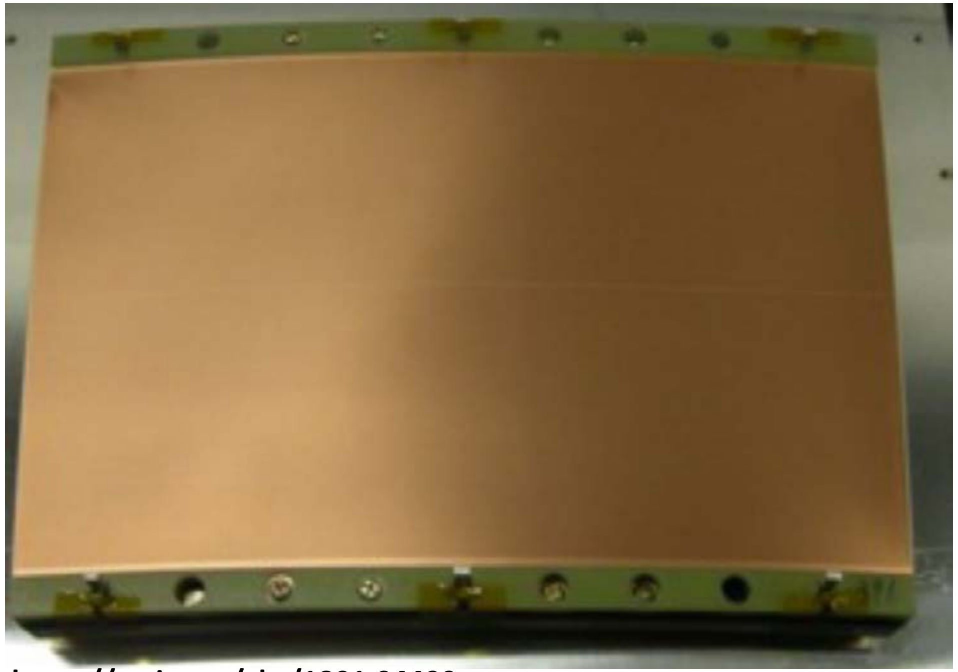
- High spatial resolution pad TPC technology

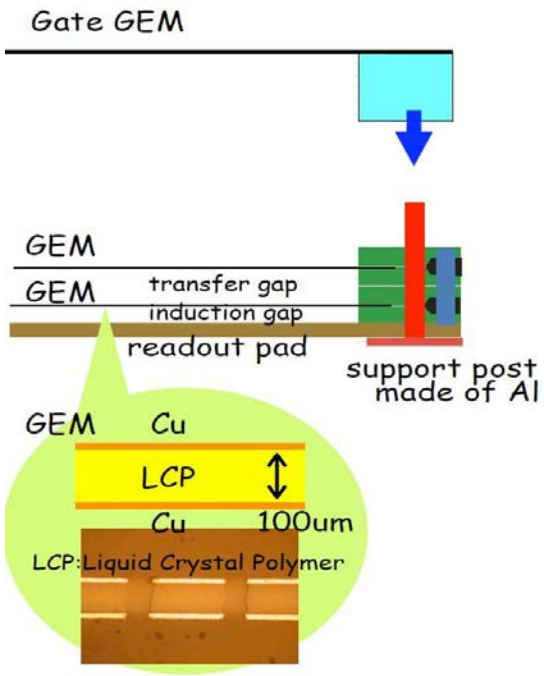
Pad TPC technology - double GEMs

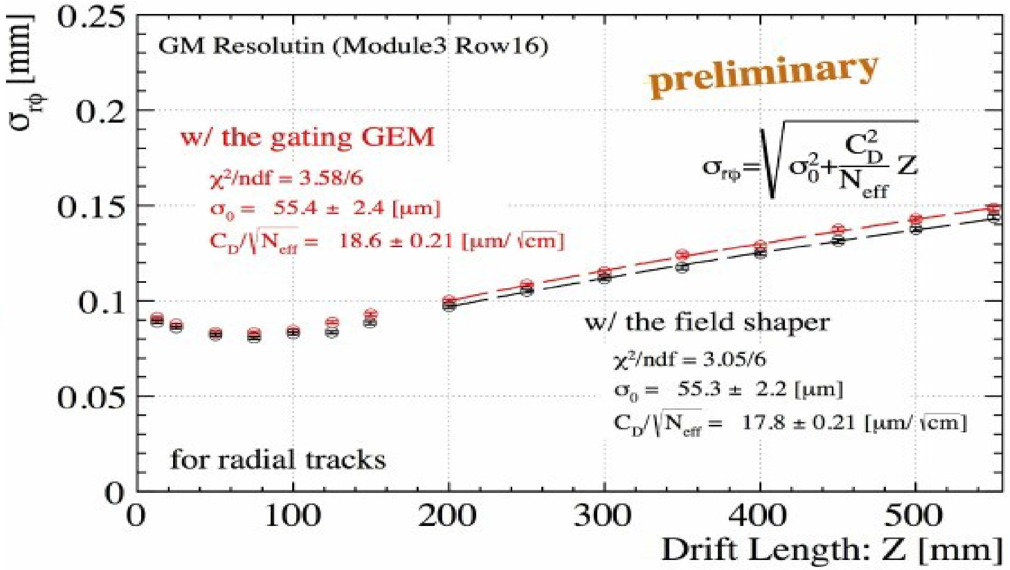
- GEMs: copper-insulator- copper sandwich with holes
- Double GEMs module are being tested:
  - GEMs with 100μm LCP insulator
  - Standard GEM from CERN
- Design idea of the GEM Module:
  - **No frame** at modules both sides
  - Spatial resolution of $\sigma_{r\phi} \leq 100$ μm, more stability by the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







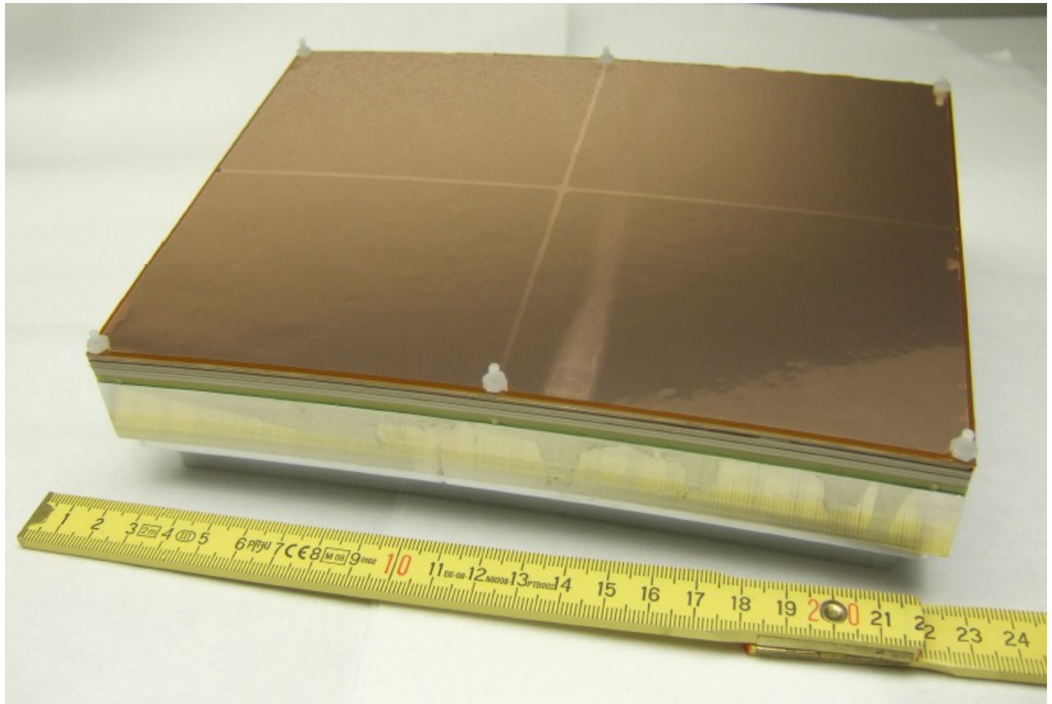
https://arxiv.org/abs/1801.04499

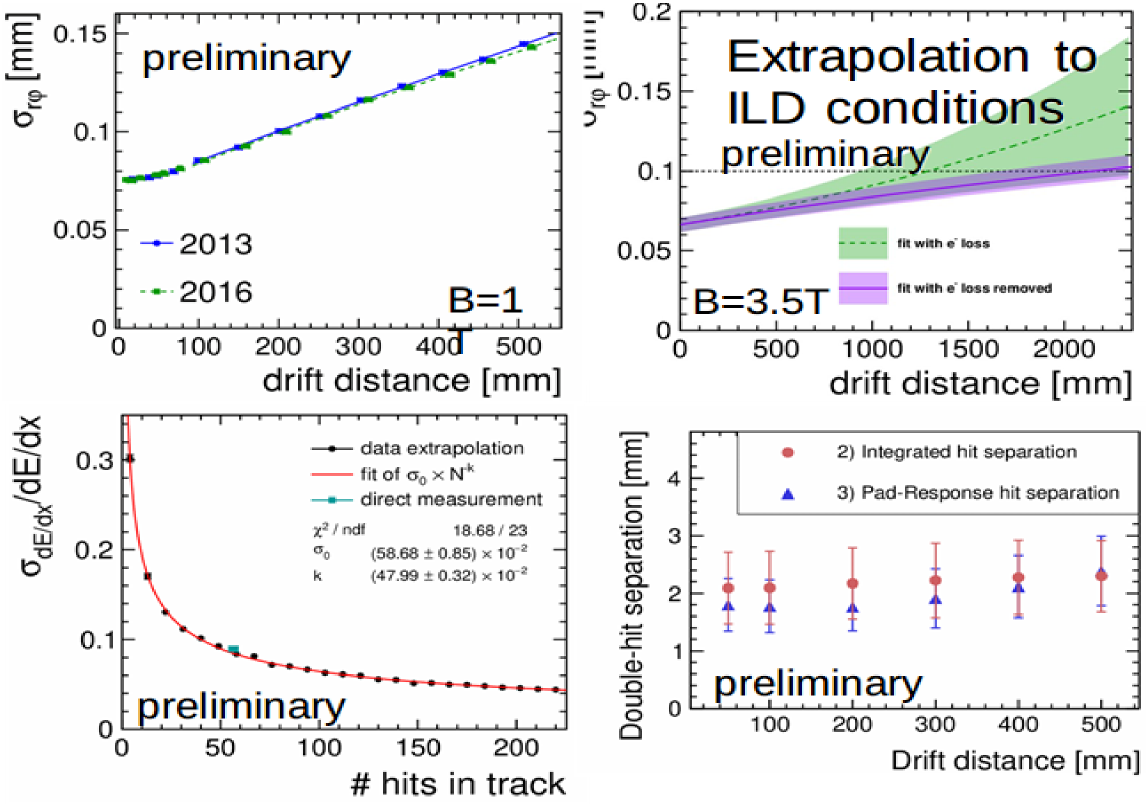
Pad TPC technology - triple GEMs

- 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 $\sigma_{r\phi} \leq 100$ μm, **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

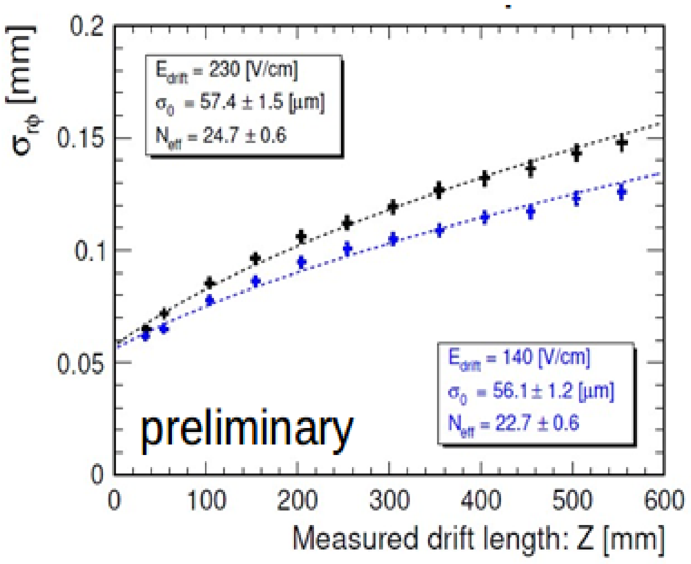


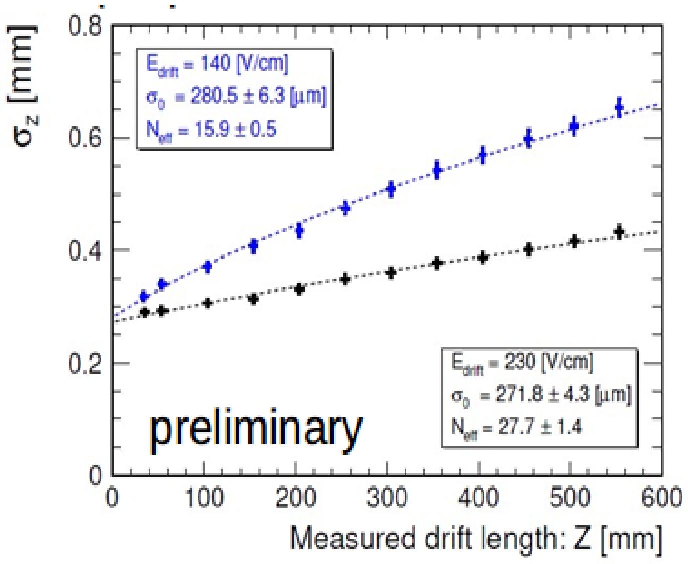


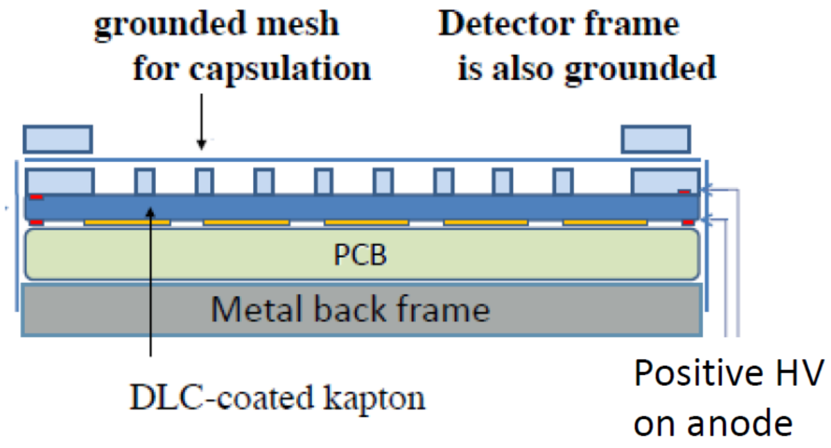
https://arxiv.org/abs/2203.03435

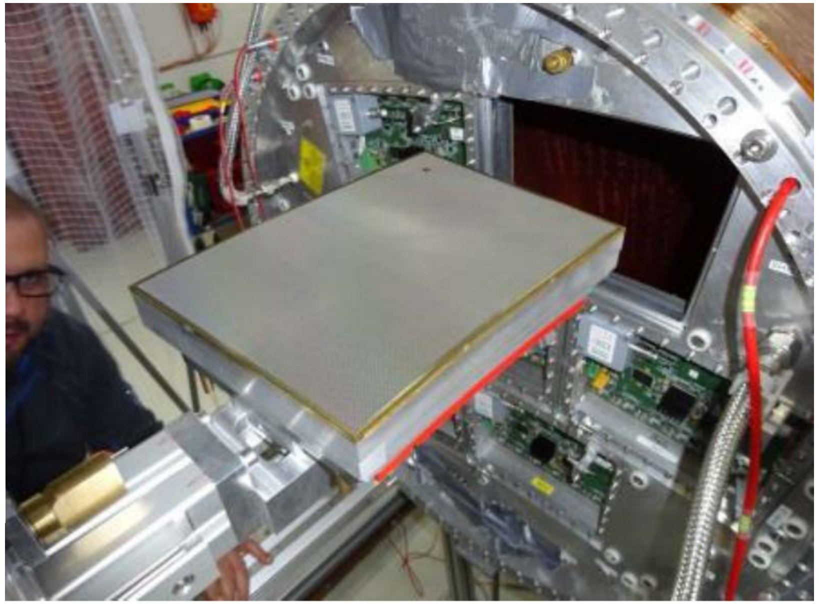
Pad TPC technology - Resistive Micromegas

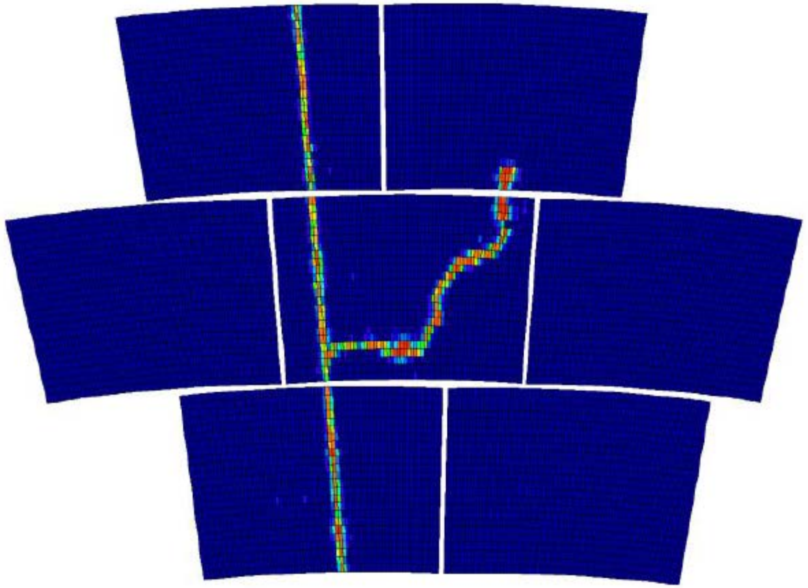
- **Resistive Micromegas:**
  - Bulk-Micromegas with 128 μm gap size between mesh and resistive layer (**developed in LCTPC**)
- A new HV scheme of the module (ERAM) places grid on ground potential
  - Reduces **field distortions** between modules by a factor of 10







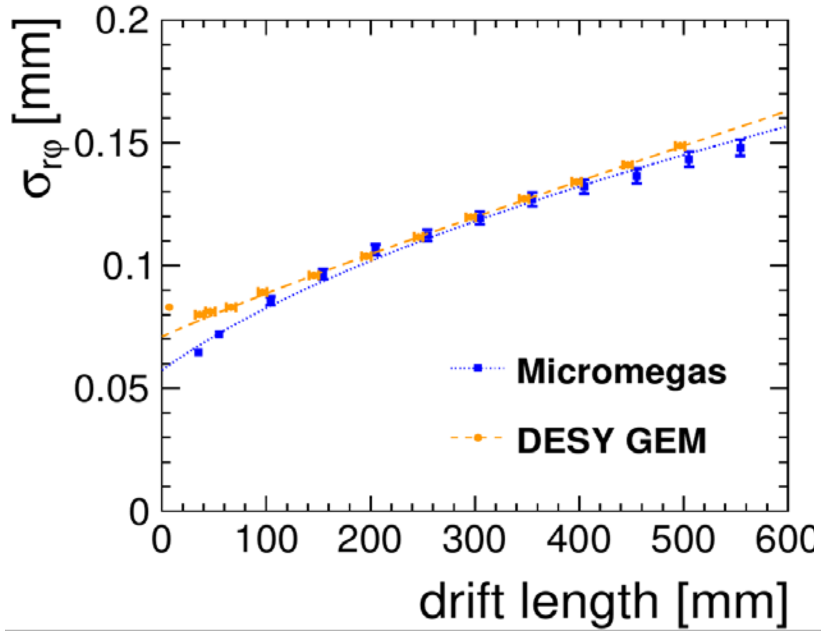


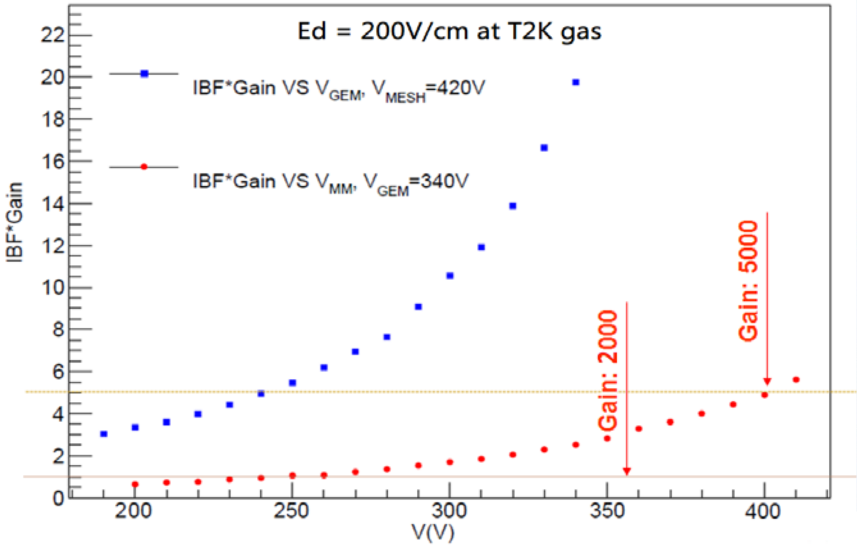


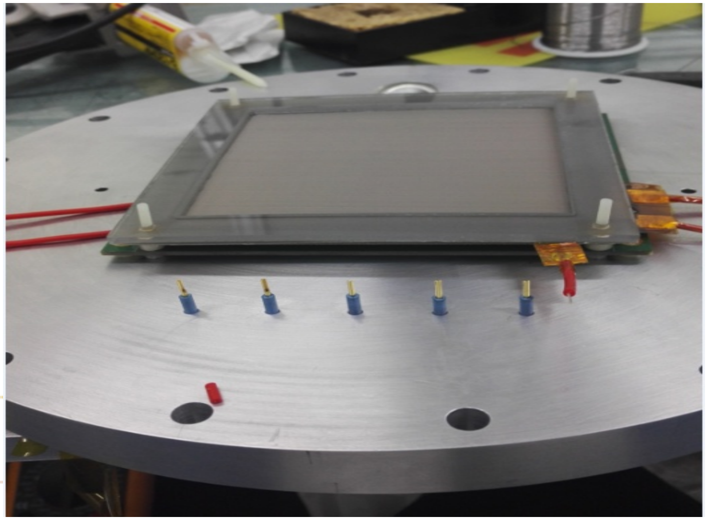
https://doi.org/10.1016/j.nima.2019.162798

Pad TPC technology – Detector Module

- **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 (primary ions level)**

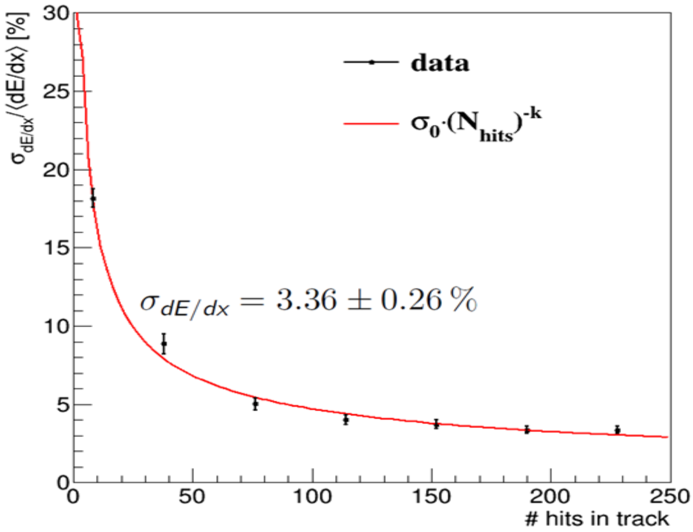


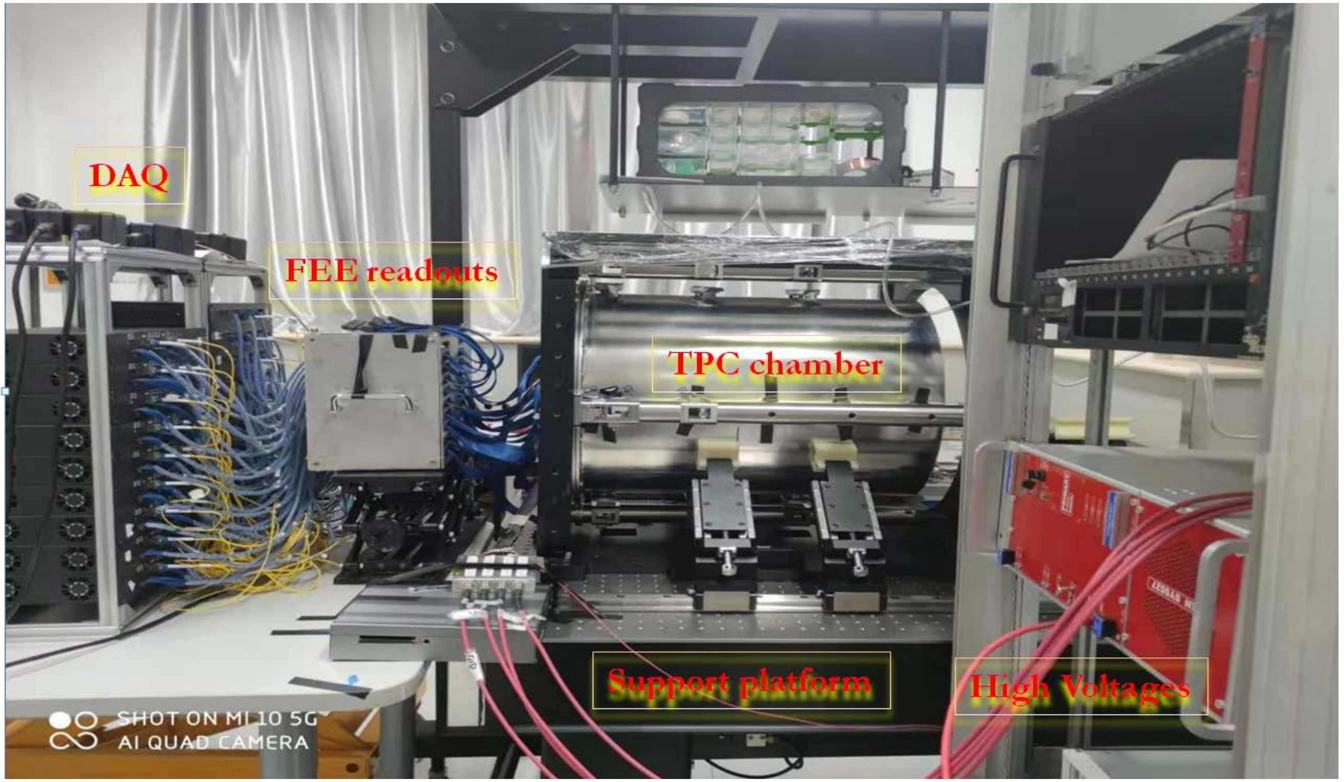


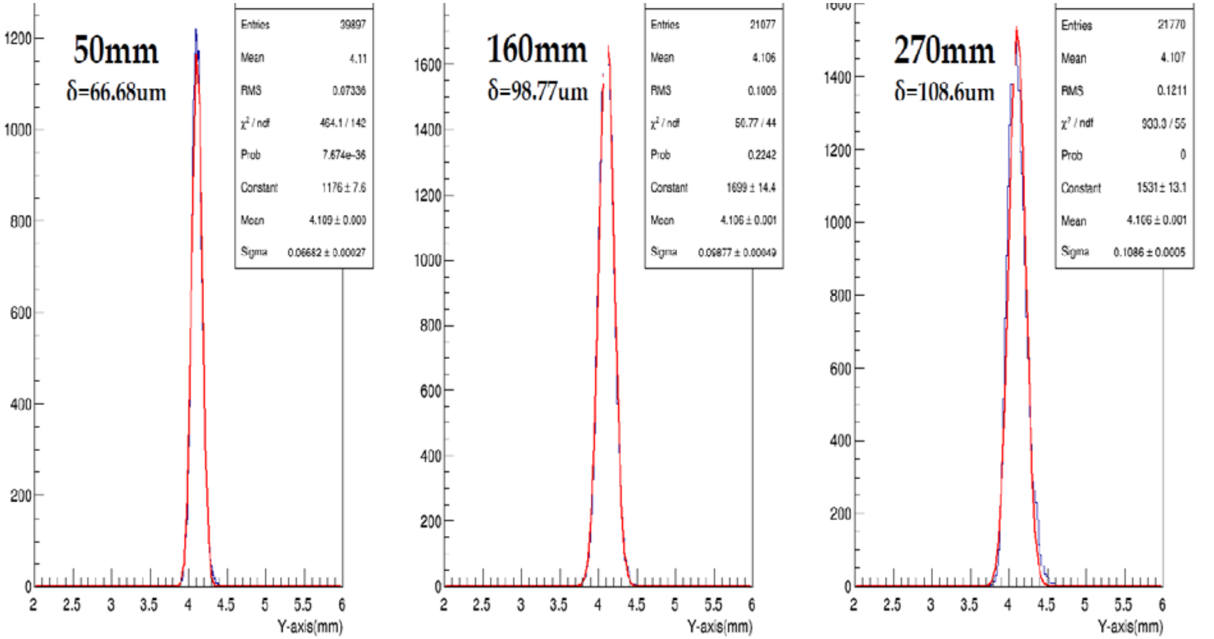


TPC prototype with 266nm UV laser tracks at IHEP

- 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 for Tera-Z

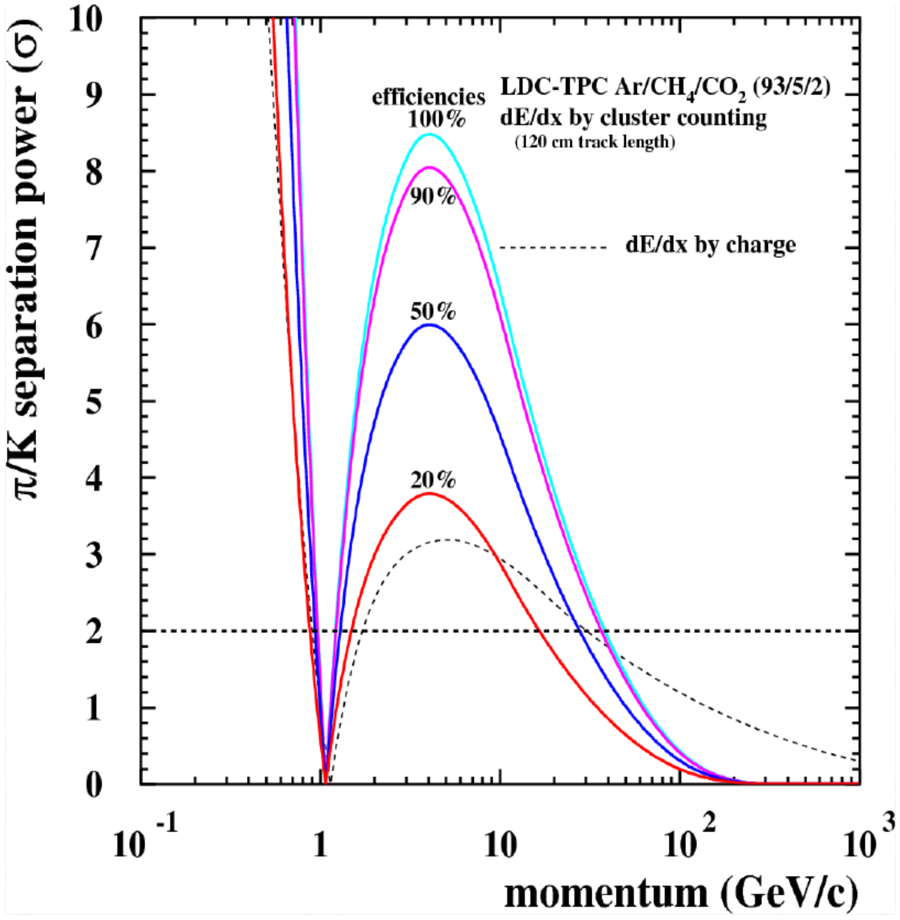
High granularity for improved PID in TPC

- 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

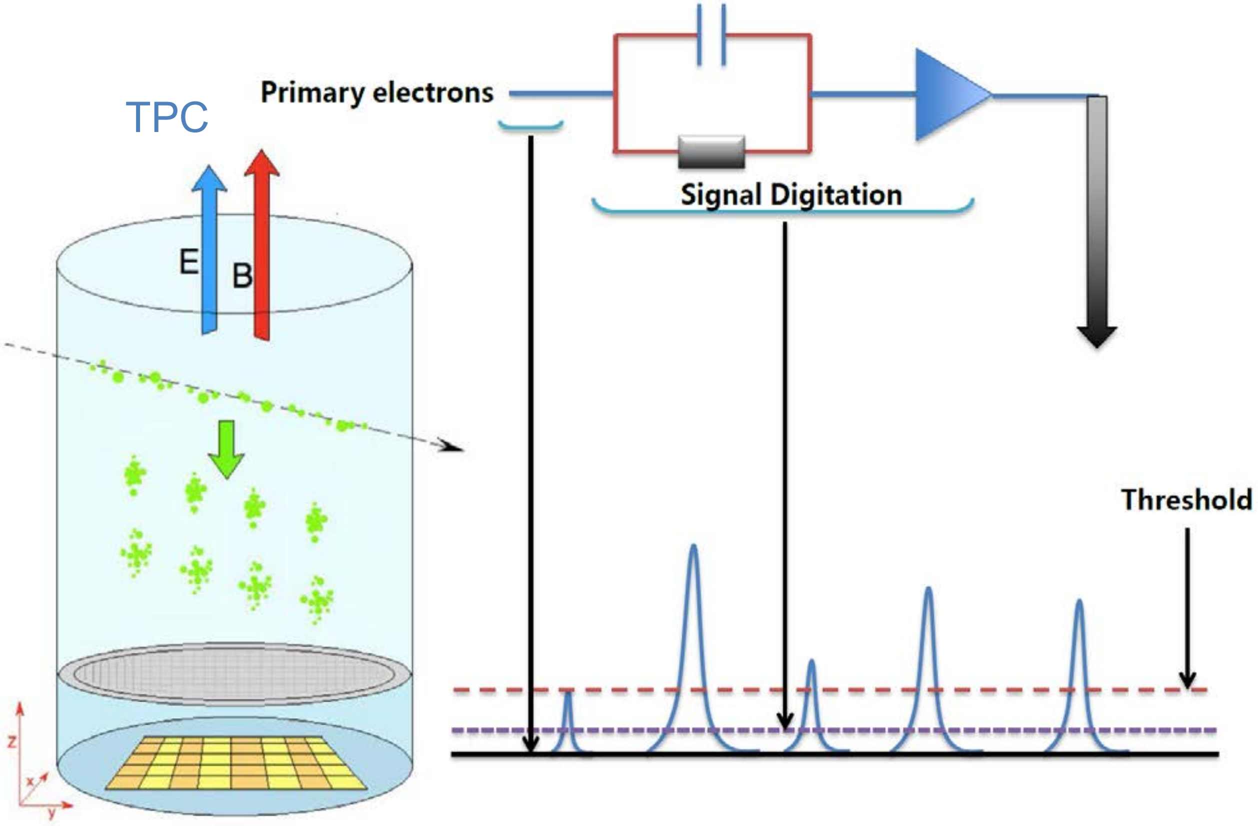
- PID performance improvement
  - The potential of **better resolution by at least a factor 2**
  - Novel method studied by several R&D groups for the TPC for the e+e- collider



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

dN/dx cluster counting

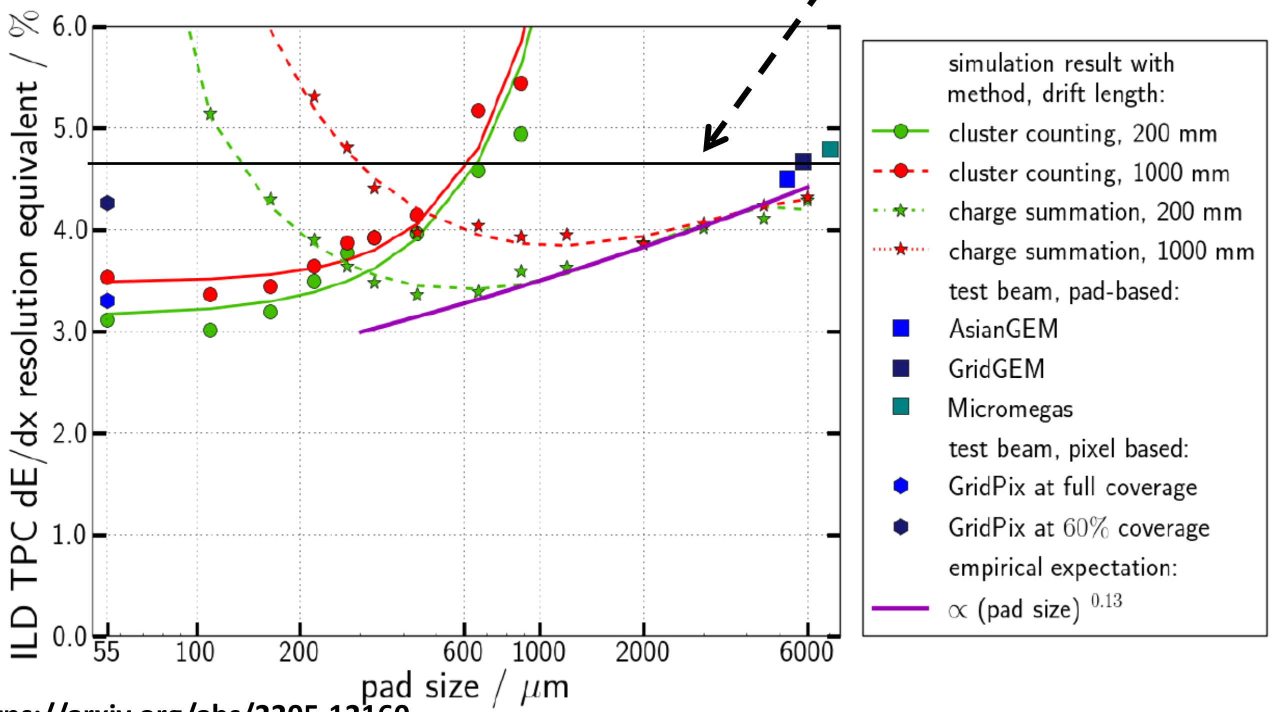
- Challenging for the **low power consumption** electronics (>40mV/fC needed at 2000 of gas gain)
- Pixelated readout
    - → **high granularity readout in endplate**
    - → the reasonable pixilation reveals the underlying cluster structure in 3D chamber
- Occupancy of the pixelated TPC
    - Occupancy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



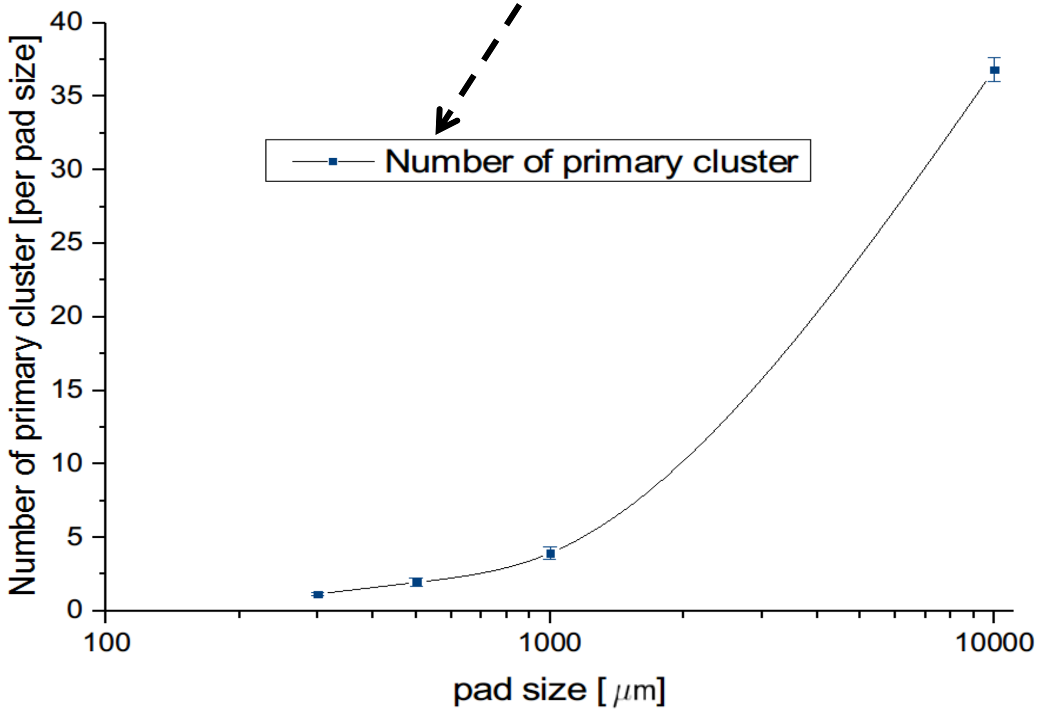
High granularity for improved PID in TPC

- 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

current resolution in the full ILD reco
assuming 6 mm pads



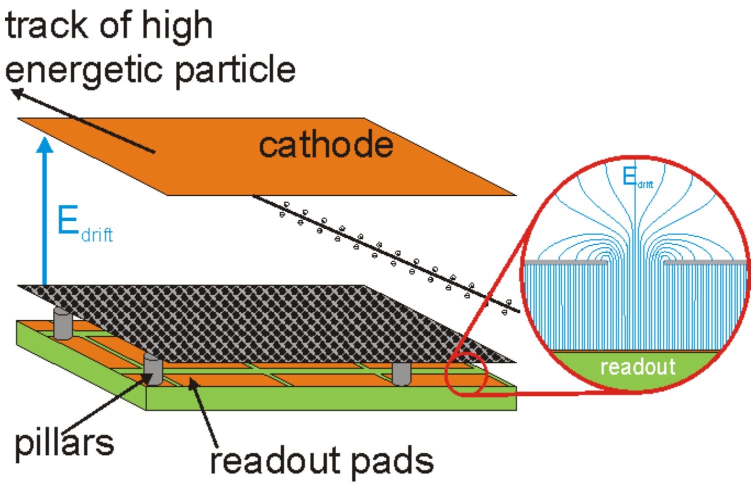
Simulation of the primary cluster
along the drift length

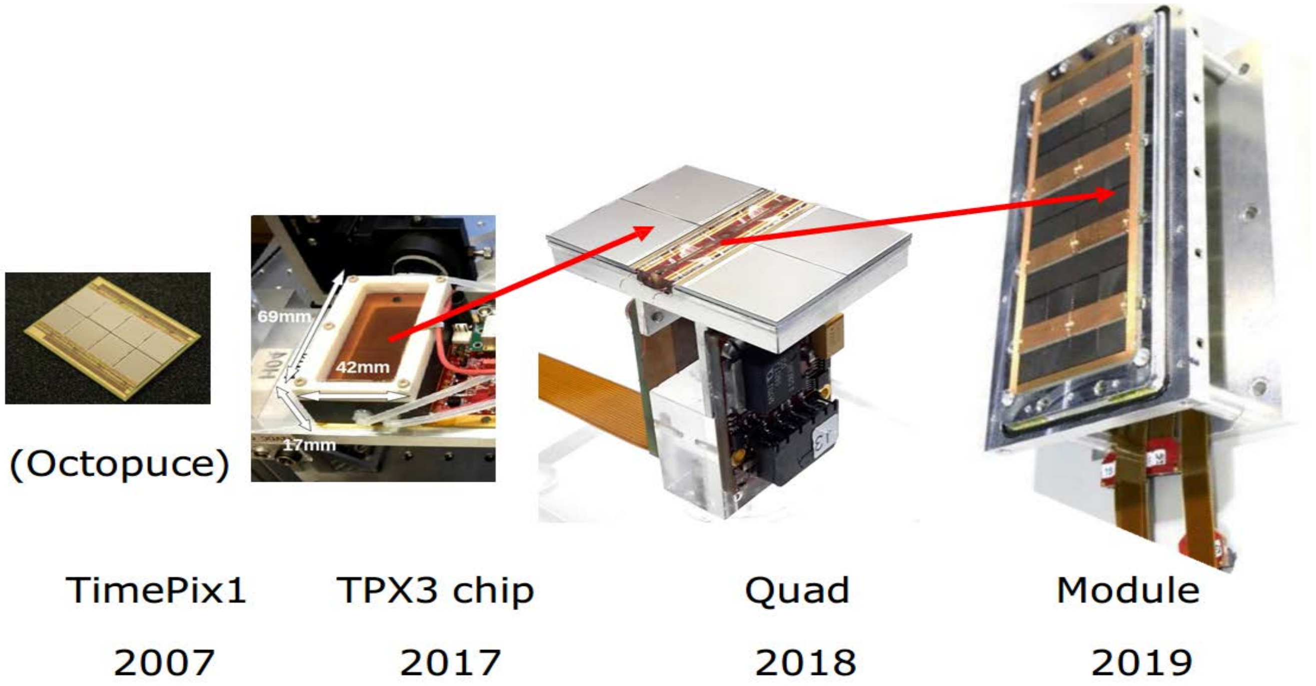


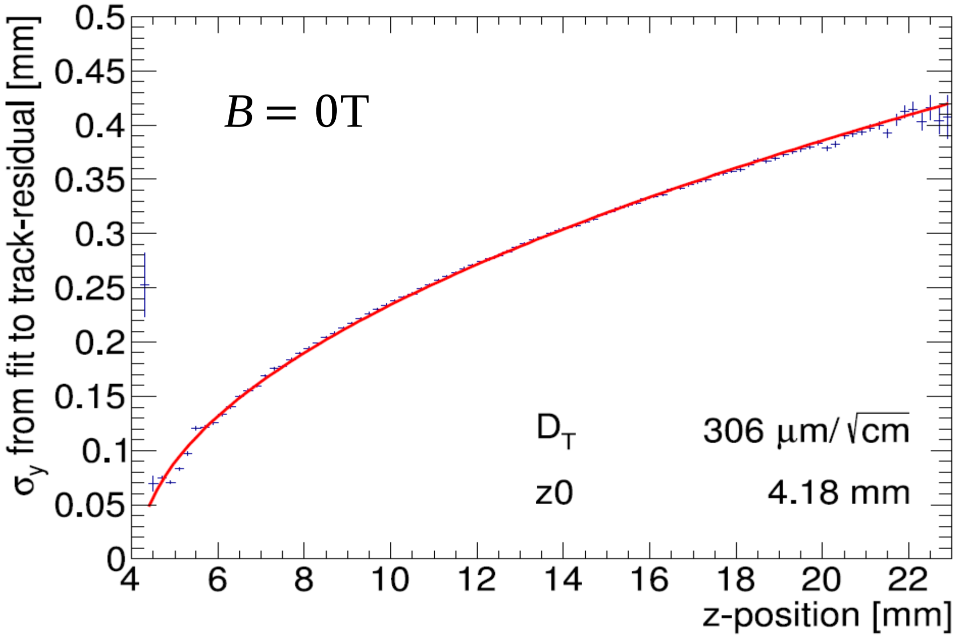
https://arxiv.org/abs/2205.12160

Pixelated TPC technology - Timepix3-based GridPix

- A module **with 32 GridPixes (Timepix3) 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.

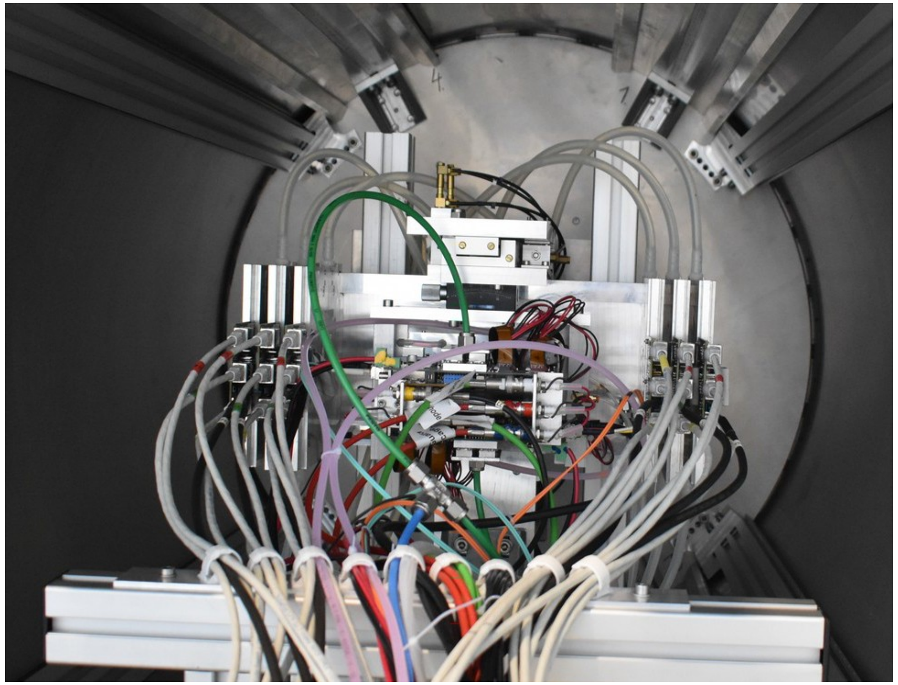


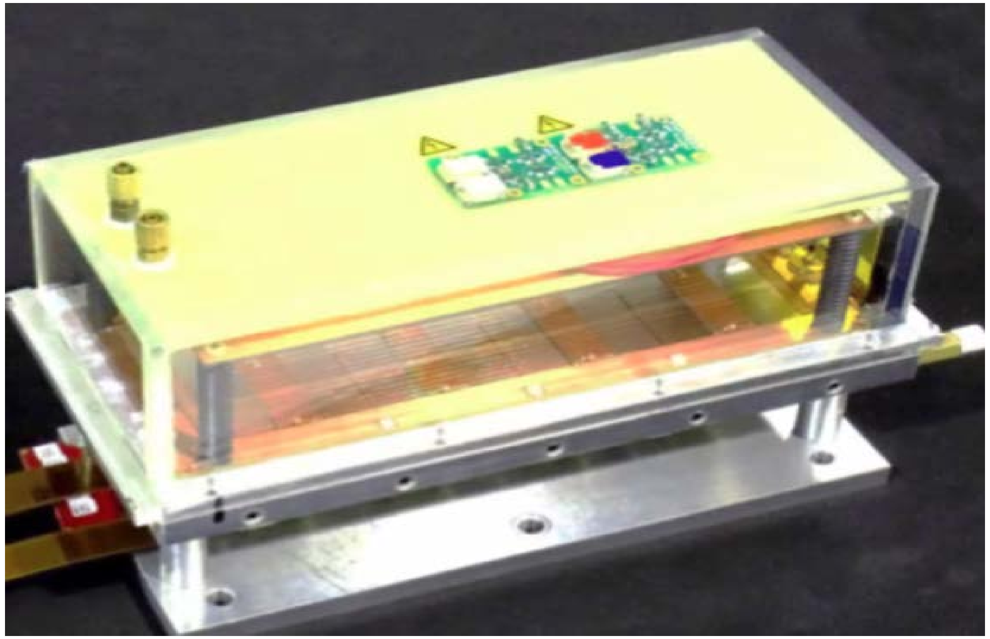


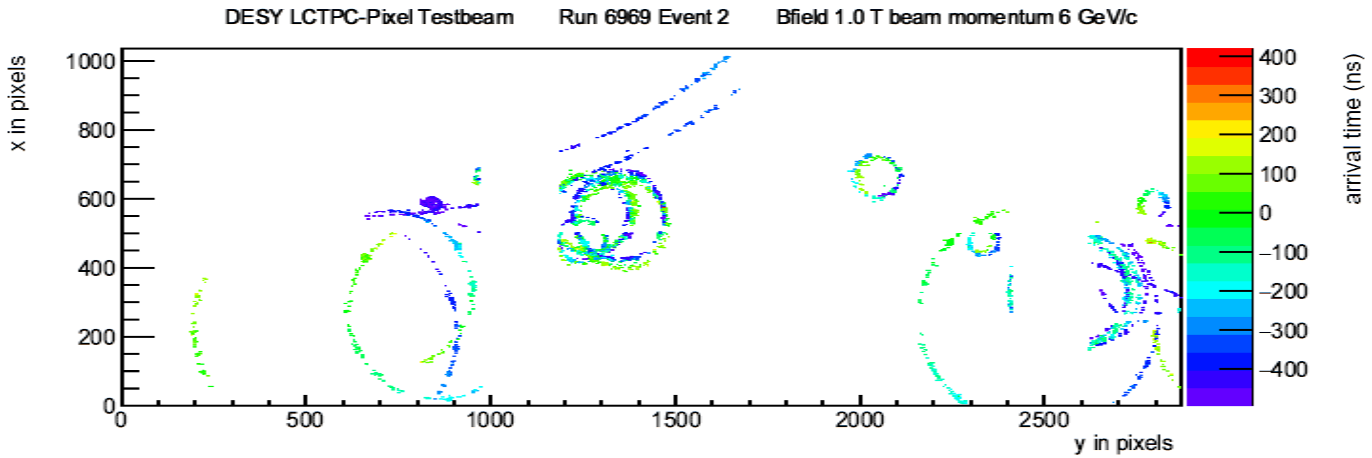


Pixelated TPC technology – Large scale readout

- Pixelated TPC prototype with GridPixes:
  - 8-QUAD module (2x4 quads) with field cage
    → 8-Quad GridPixes covered **an active area of 39.6×28.4 cm²**
  - ~**100-120 chips/module** 240 module/endcap (full size 10m²)
    → 50000-60000 GridPixes
- During the test beam ~10^6 events were successfully collected, all results showed that **a pixel TPC is realistic.**



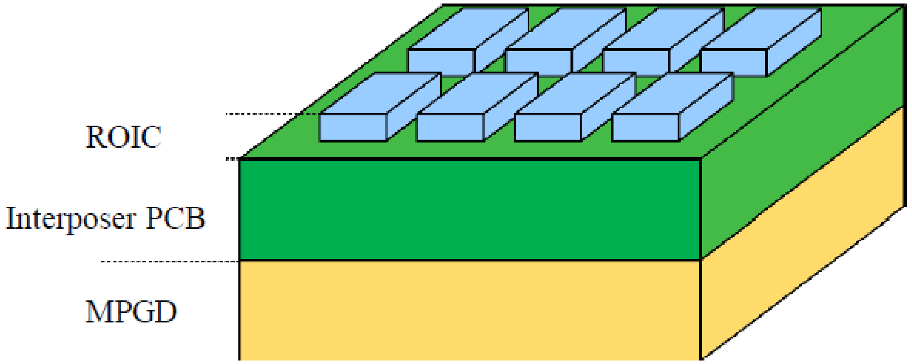




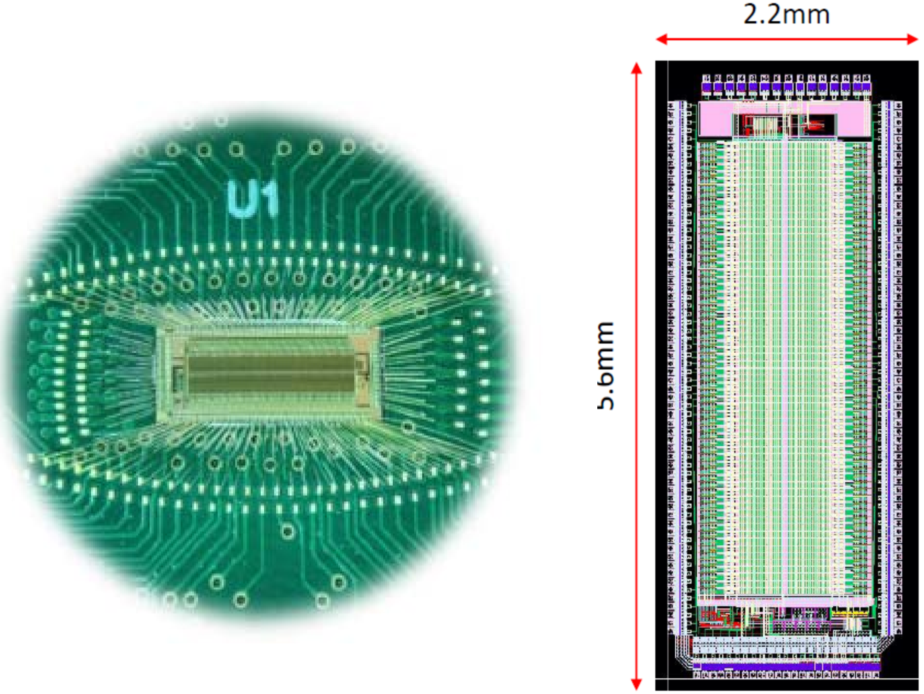
DESY testbeam in June 2021

Current R&D effort: Pixelated TPC R&D for CEPC

- **R&D on Macro-Pixel TPC readout for CEPC**
  - Macro-Pixel TPC ASIC chip was started to developed in this year and **1st prototype wafer has done in last year**.
  - The first version ROIC has been received and under testing.
  - The **TOA and TOT** can be selected as the initiation function in the ASIC chip.
    - 1mm×6mm → 500μm×500μm pixel readout
    - Higher precision and higher rate (MHz/cm^2)
    - Gain of the amplification: >40mV/fC
    - Channels: 128
    - Time resolution: **14bit** (5ns bin)
    - Time discriminator: TOA (Time of Arrival)
    - **Power consumption: <1mW/pixel (1^{st} prototype)**
      - **~400mW/cm^2**
      - **100mW/cm^2 (Goal and final design)**
    - Technology: 180nm CMOS -> 60nm CMOS
    - High metal coverage: 4-side bootable



Principle of Macro-Pixel TPC readout

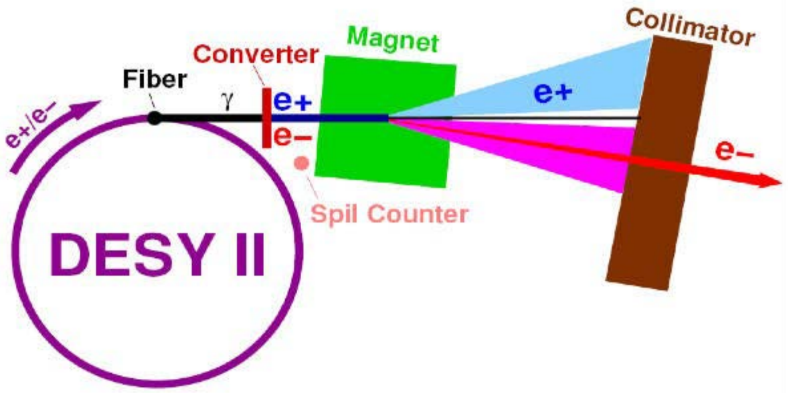


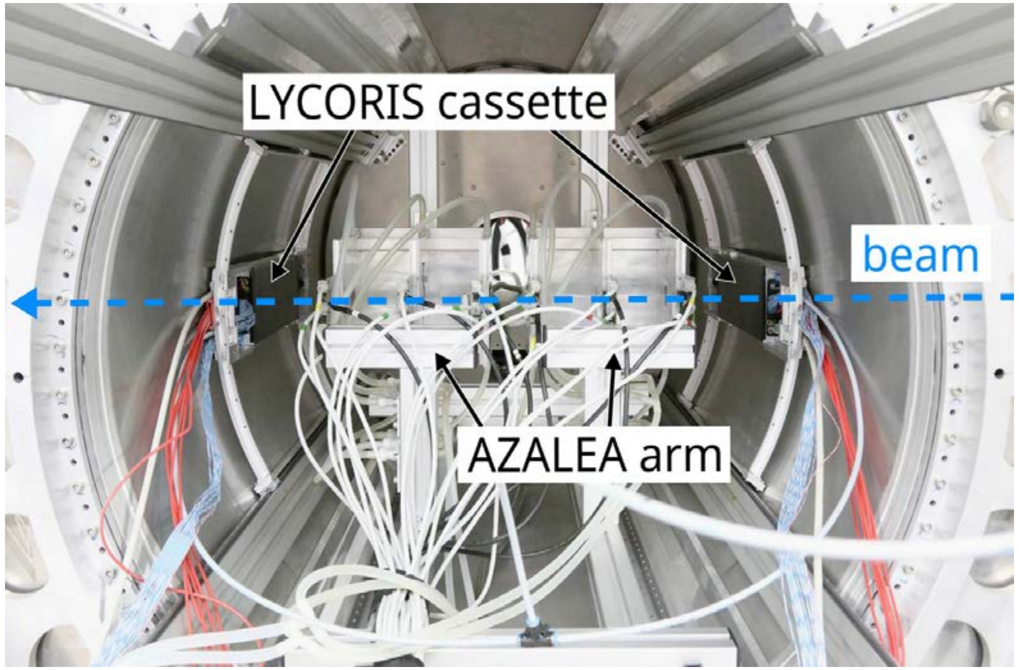
1^{st} readout PCB board and the ASIC layout

- Beam and cooling for TPC

Test beam setup at DESY for TPC

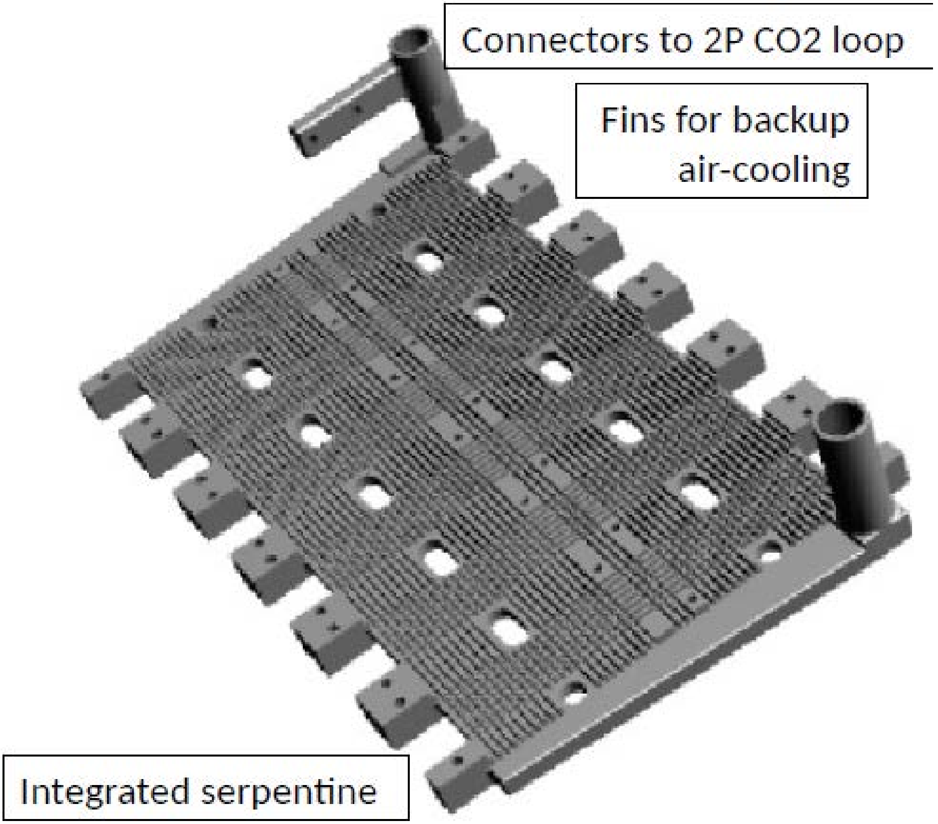
- Electron beam energy: **5-6 GeV**, B-field: **1.0T with 0.8 meter diameter and 1.2 meters length**
- Further improvements of the test beam setup at DESY are in progress or finished:
  - An external silicon tracker is finished and Qualified. Excellent **spatial resolutions down to 7μm** have been demonstrated.
  - Several groups will redo measurements with newest module types to study distortions.
- Construction of an improved field cage for TPC.
- Resistor chain and HV stability studied and good.

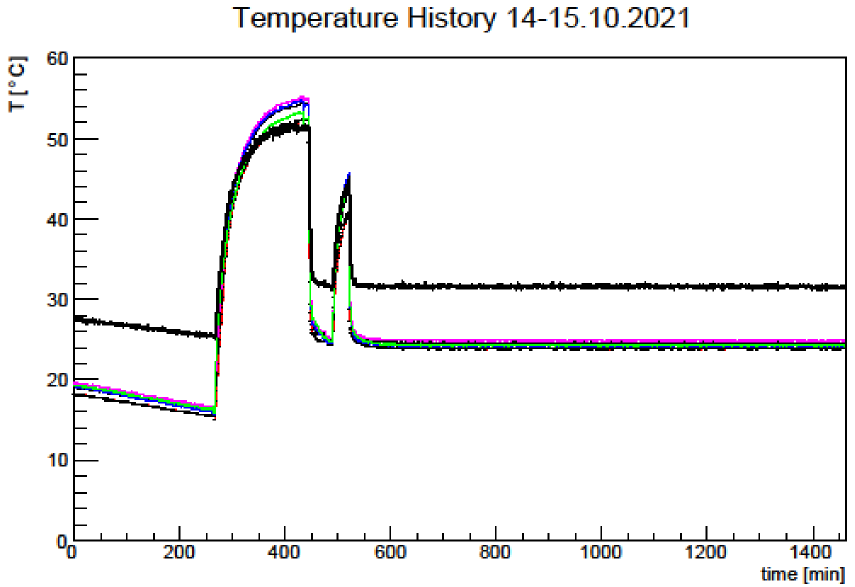




2 phases CO_2 cooling for TPC

- **Same challenges as everyone else:**
  - No time between bunch trains and more cooling needed
  - Material budget of the endplate will be thicker than $0.2X_0$.
  - Number of readout channels could be reduced at the price of worse performance.
- 2 phases CO_2 cooling with **TRACI system** (Transportable Refrigeration Apparatus for CO_2 Investigation)
- The tests with a monolithic 3D printed cooling plate (aluminum) finished for TPC module at DESY.





More than one week tests

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!