A Time Projection Chamber
for a Future Linear Collider

TIPP2023
TECHNOLOGY IN INSTRUMENTATION & PARTICLE PHYSICS CONFERENCE
4 - 8 SEPTEMBER 2023

TPC technology development for the ILD Detector at future e+e- collider

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on behalf of LCTPC international collaboration

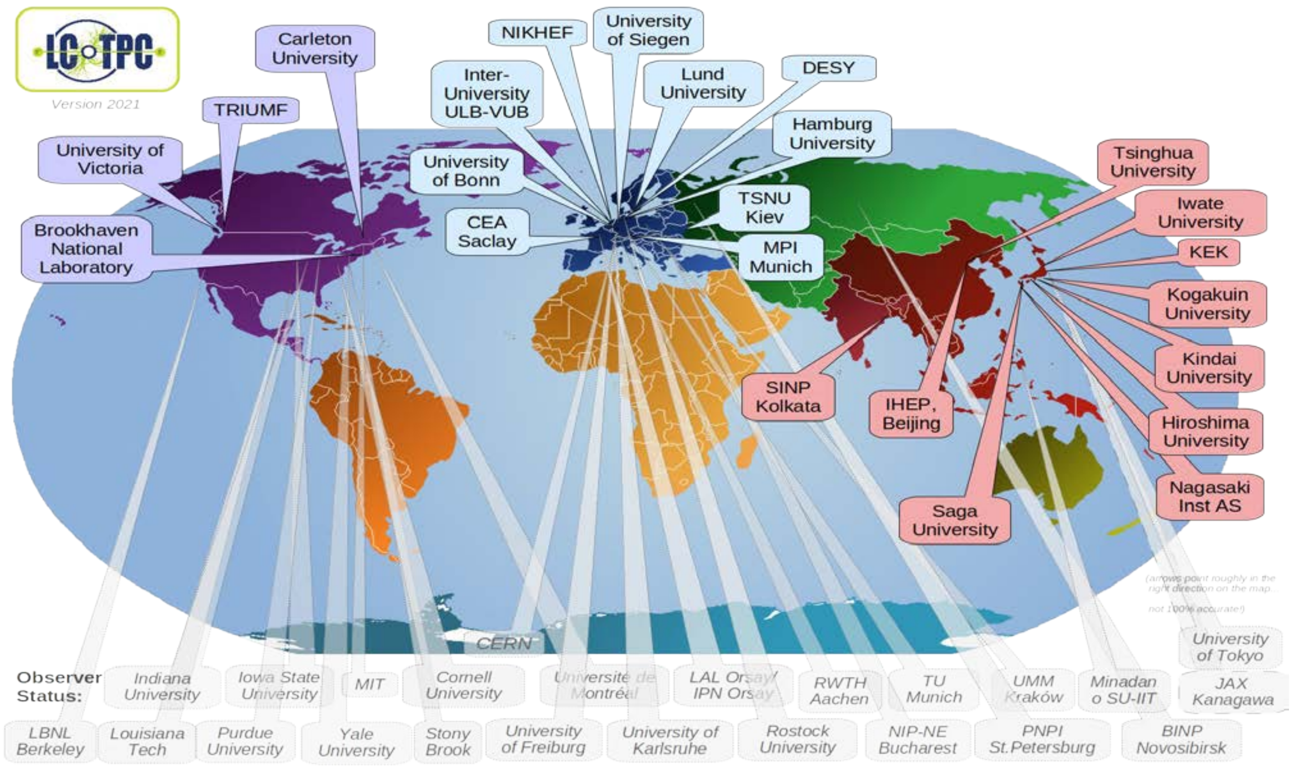
TIPP Conference, 4 - 8 September, 2023, Cape Town

Content

- **TPC detector for e+e- colliders**
- **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
- **All research will be integrated with DRD1 of CERN from 2023**

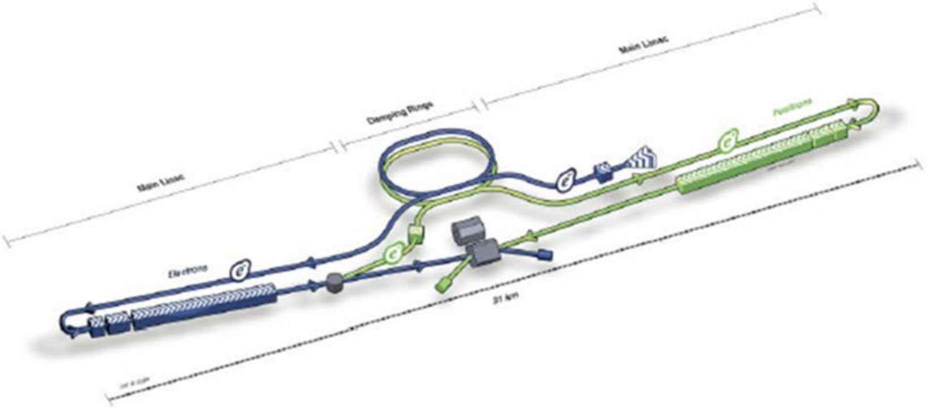


https://www.lctpc.org/

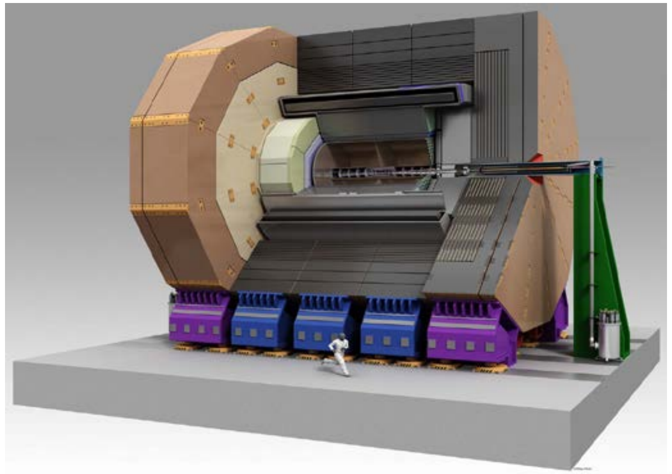
LCTPC-collaboration studies MPGD detectors for the ILD-TPC:
24 Institutes from
11 countries
+ 24 institutes with observer status

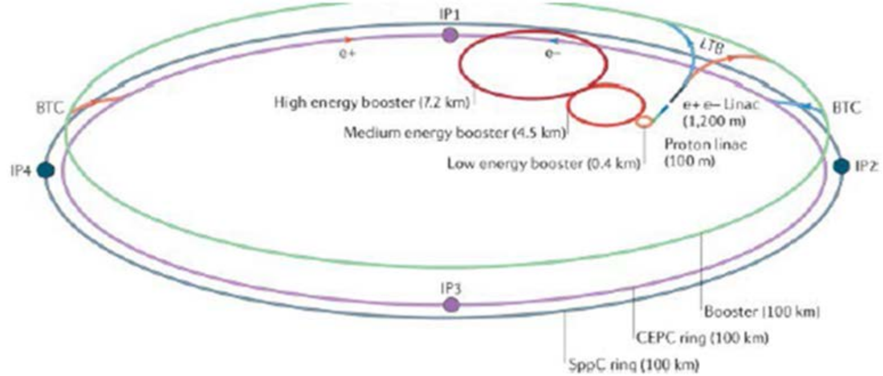
Various **gas amplification stages** are studied: GEMs, Micromegas, GEMs with double thickness and GridPixes.

- 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

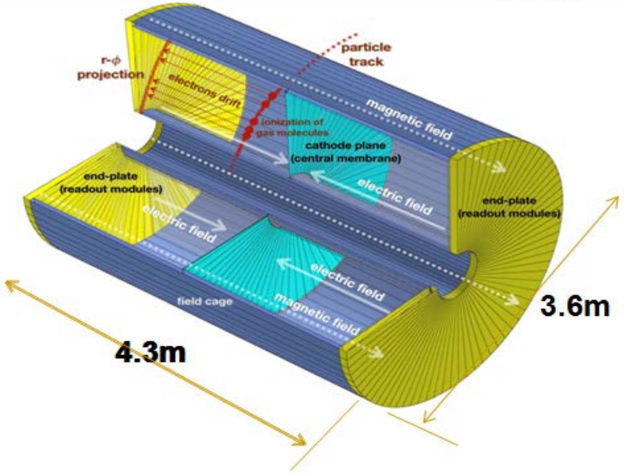


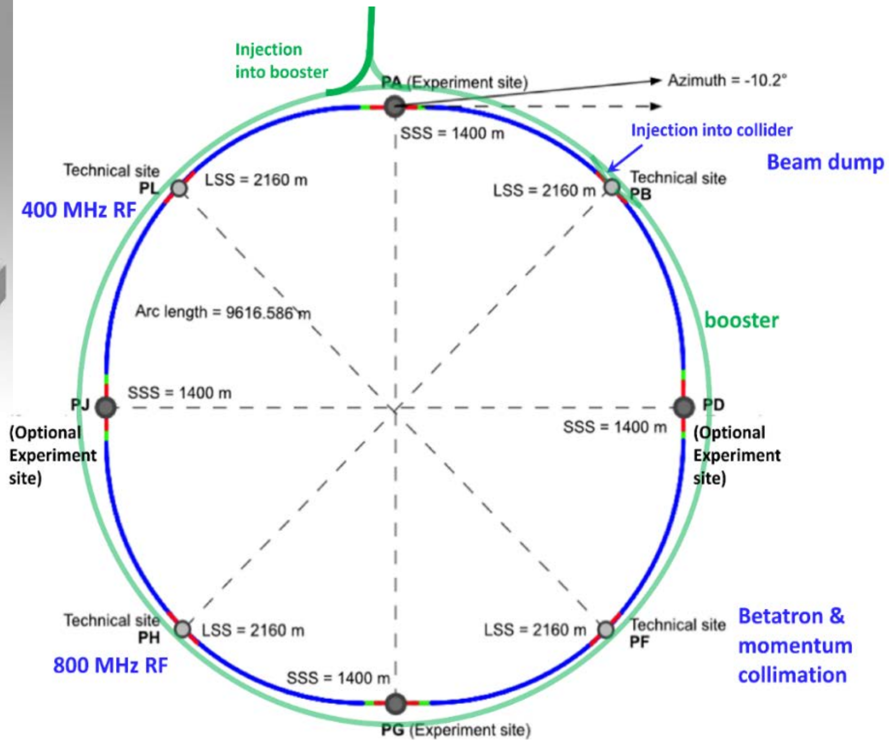
International Linear Collider (ILC)





Circular Electron Positron Collider (CEPC)



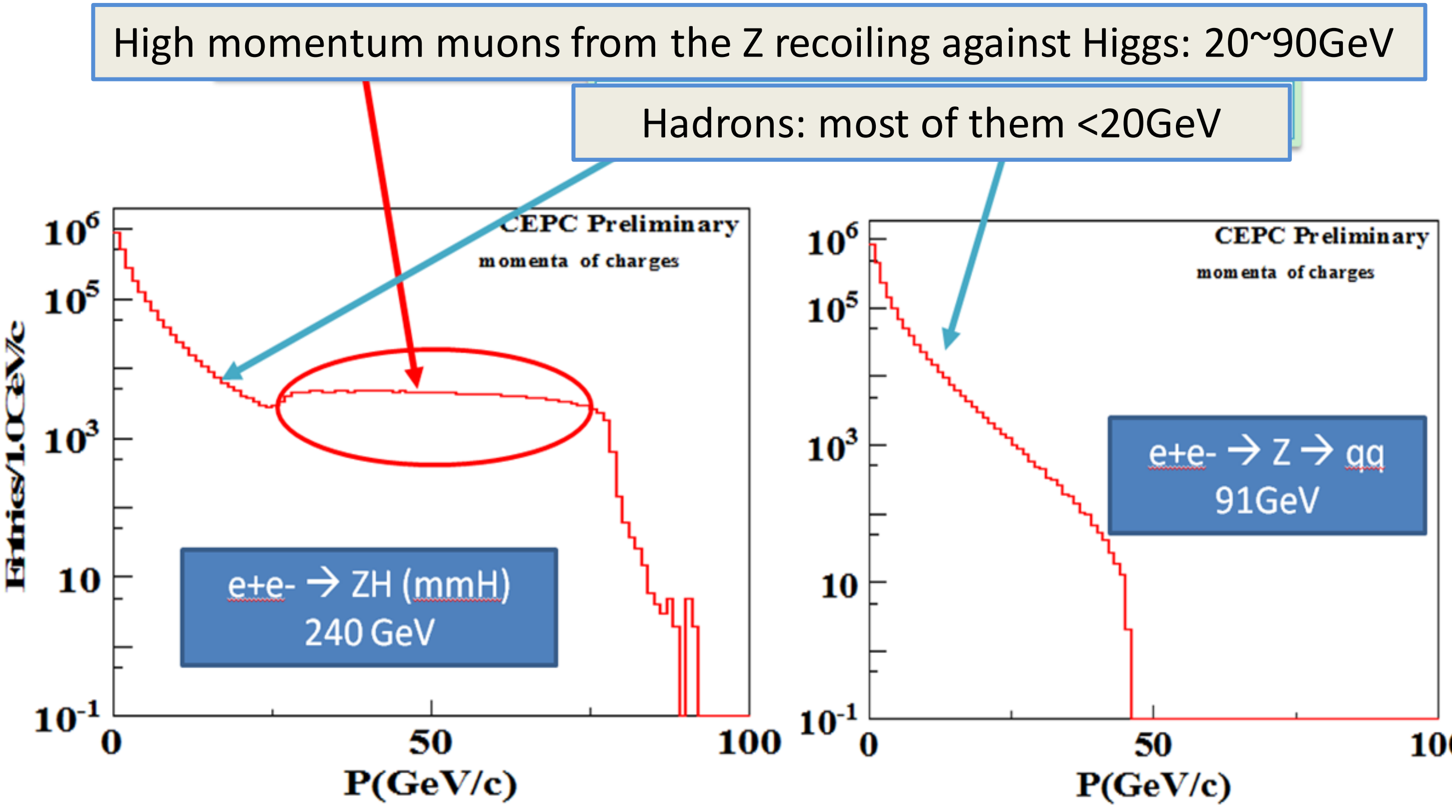


Future Circular Collider (FCC-ee)

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)
  - $\sigma_{1/pt}$ ~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

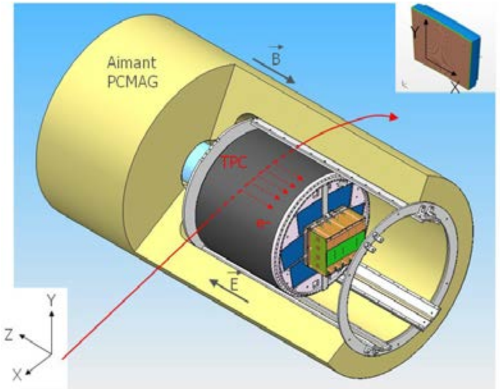


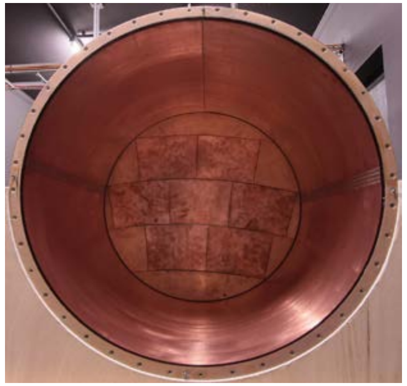
https://indico.desy.de/event/33640

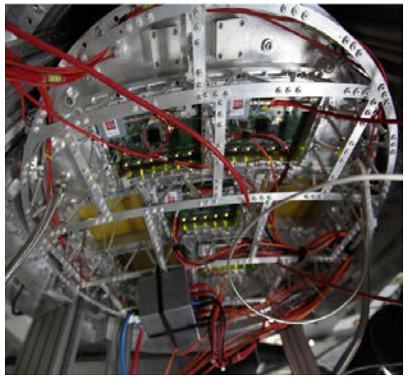
- High spatial resolution pad TPC technology

Pad TPC technology – Test setup at DESY

- **Large Prototype setup has been built to compare different detector readouts** under identical conditions and to address integration issues.
  - PCMAG: B < 1.2T, bore Ø: 85cm
  - Electron test beam: E = 1- 6GeV
  - LP support structure (3D movable) Beam and cosmic trigger
    - Silicon tracker inside PCMAG LYCORIS (single point res.: 7μm)
- **LP Field Cage Parameter:**
  - Length = 61cm, inner Ø = 72cm drift field up to E ≈ 350V/cm
  - Made of composite materials: 1.24 % X_0
- **Modular End Plate**
  - Two end plates for the LP made from Al with 7 module windows (one end plate has space frame)
  - ALTRO based readout electronics (7212 channels)







https://doi.org/10.48550/arXiv.2006.08562

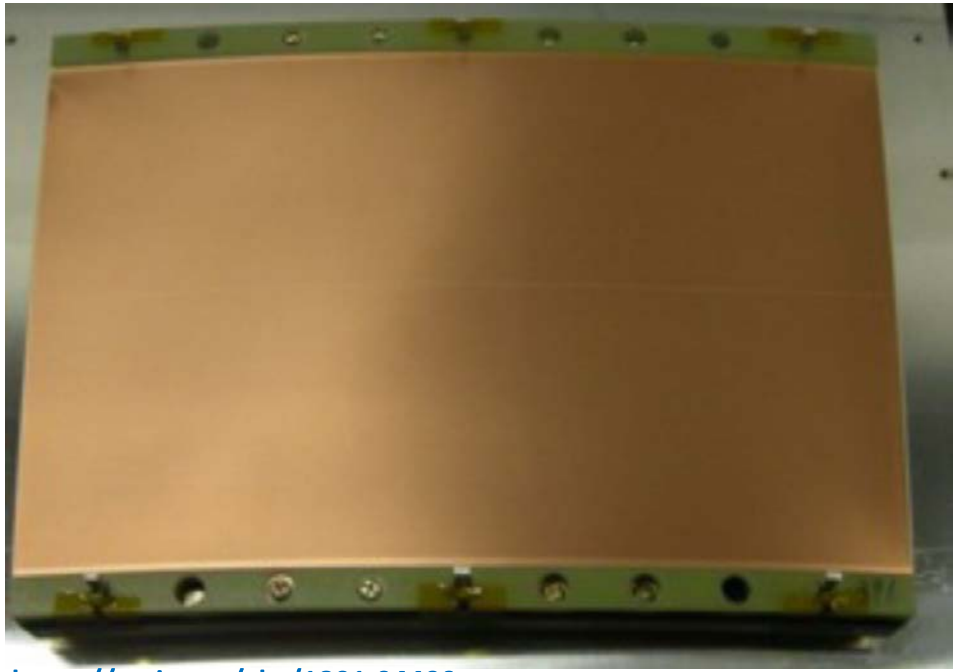
JINST 5: P10011, 2010
JINST 16: P10023, 2021

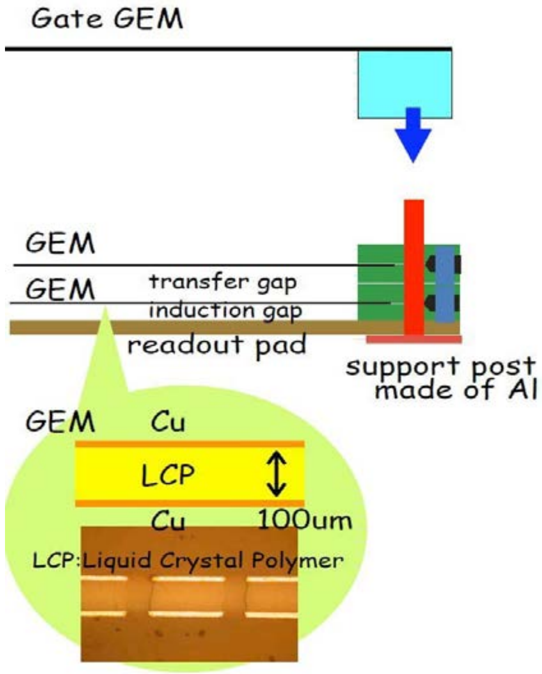
Pad TPC technology - double GEMs

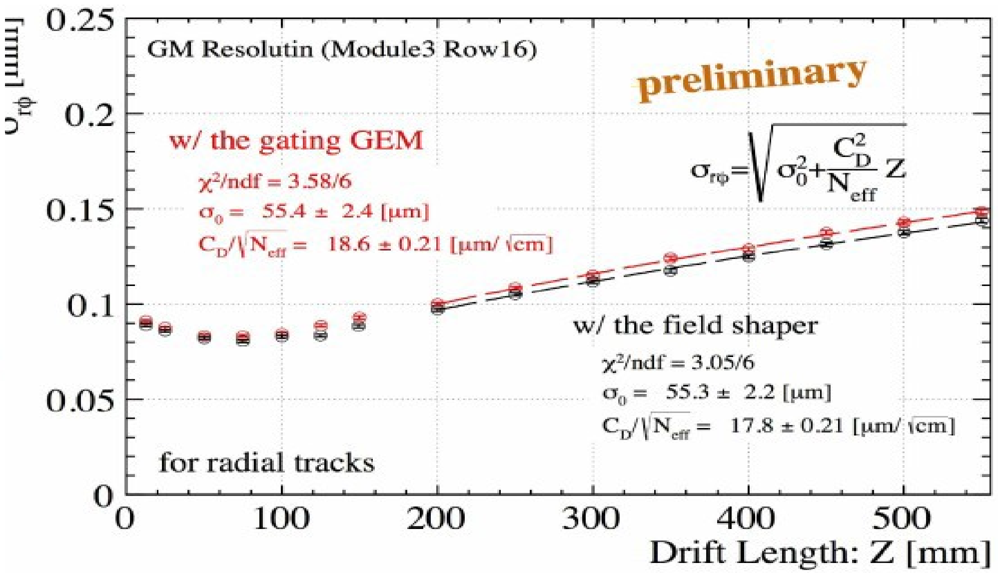
- GEMs: copper-insulator- copper sandwich with holes
- Double GEMs module are being tested:
  - GEMs with 100μm LCP insulator
  - Standard GEM from CERN
- Design idea of the GEM Module:
  - **No frame** at modules both sides
  - Spatial resolution of $\sigma_{r\phi} \leq 100$ μm, more stability by the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







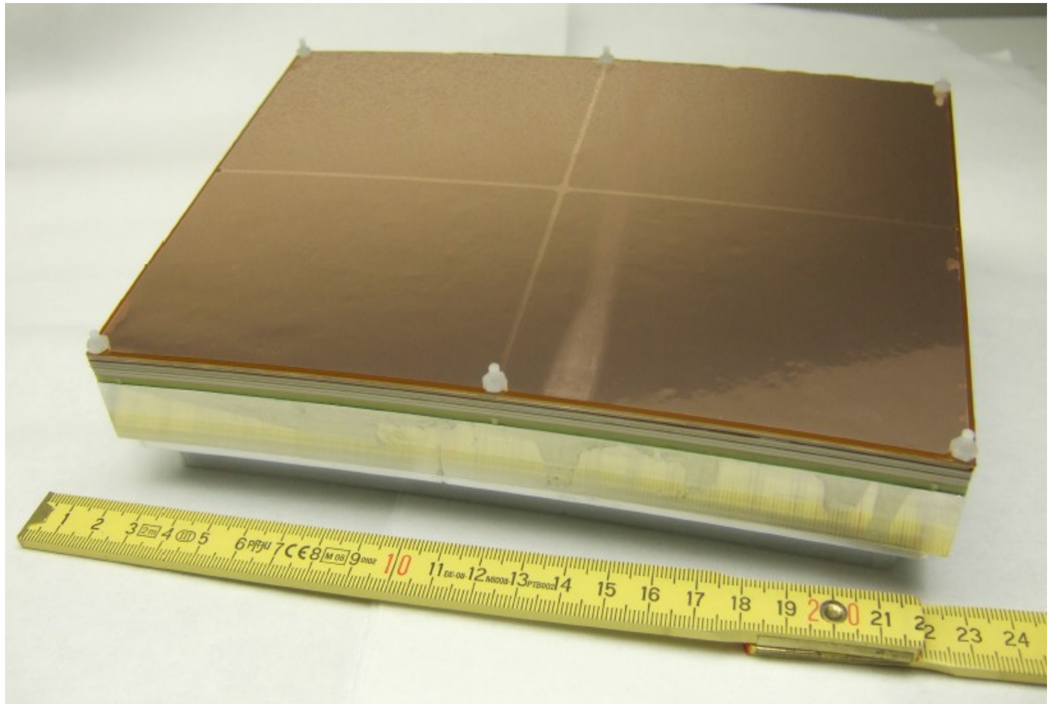
https://arxiv.org/abs/1801.04499

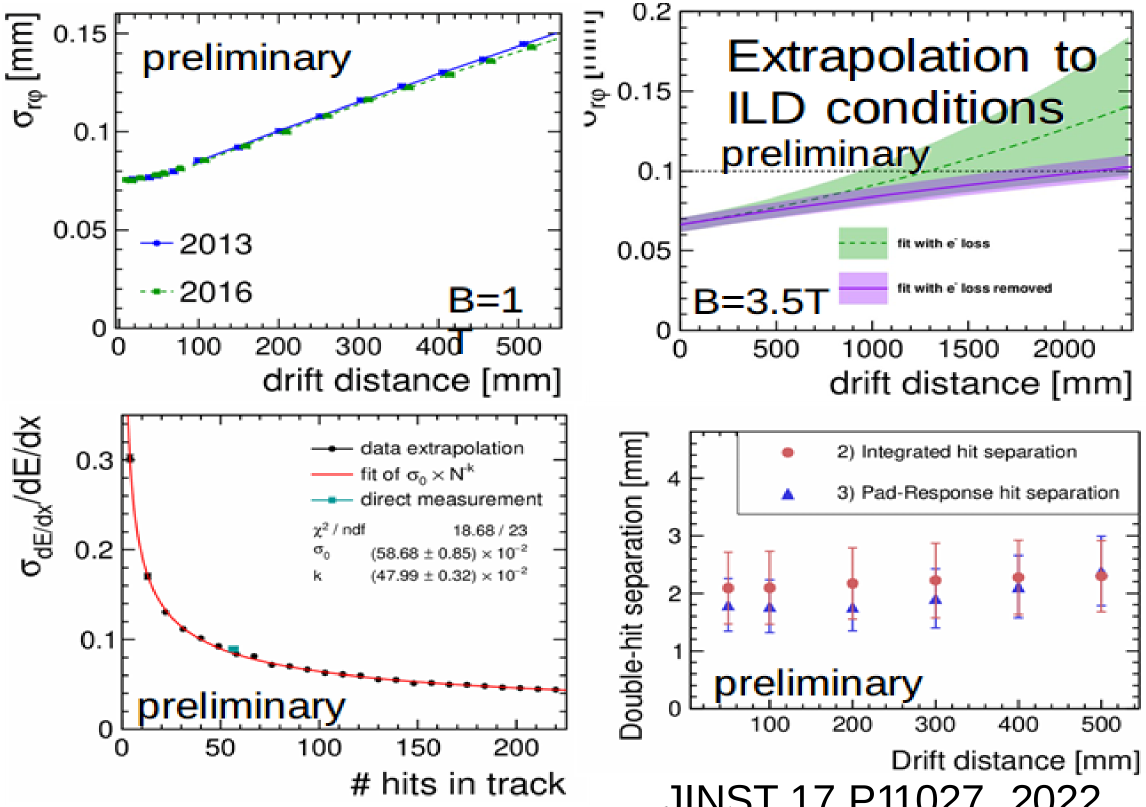
arXiv:2006.085 2020
NIM A608 (2009) 390-396

- 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



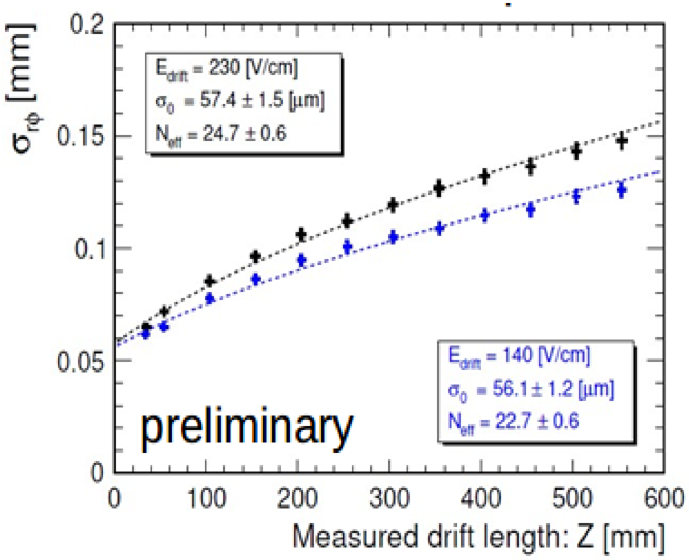


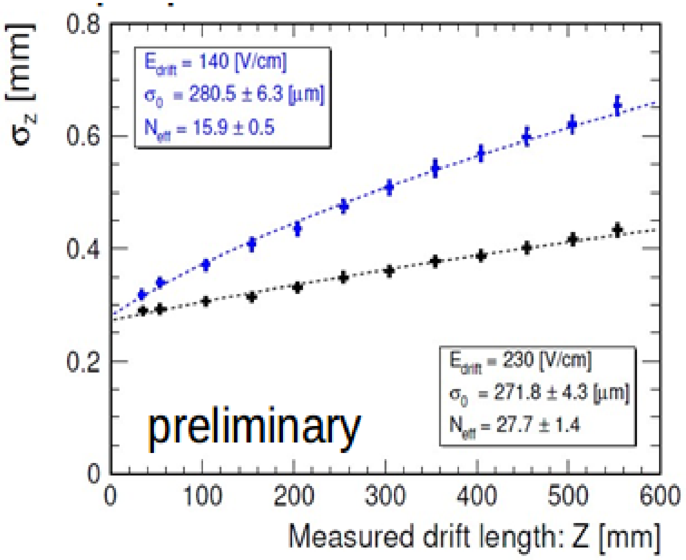
JINST 17 P11027, 2022

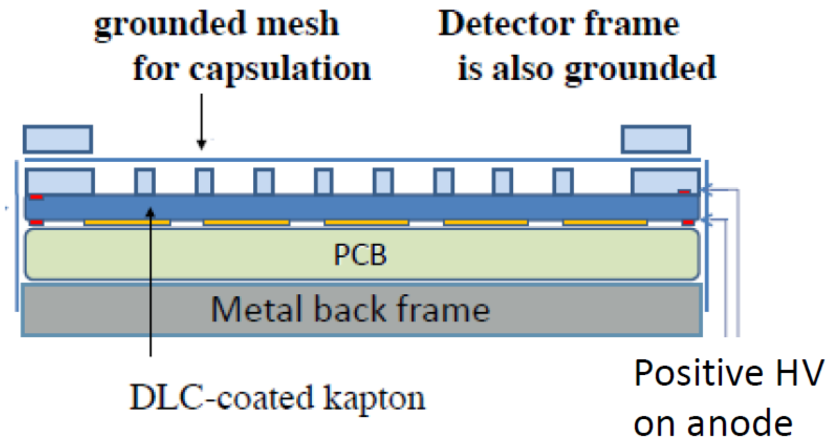
https://arxiv.org/abs/2203.03435

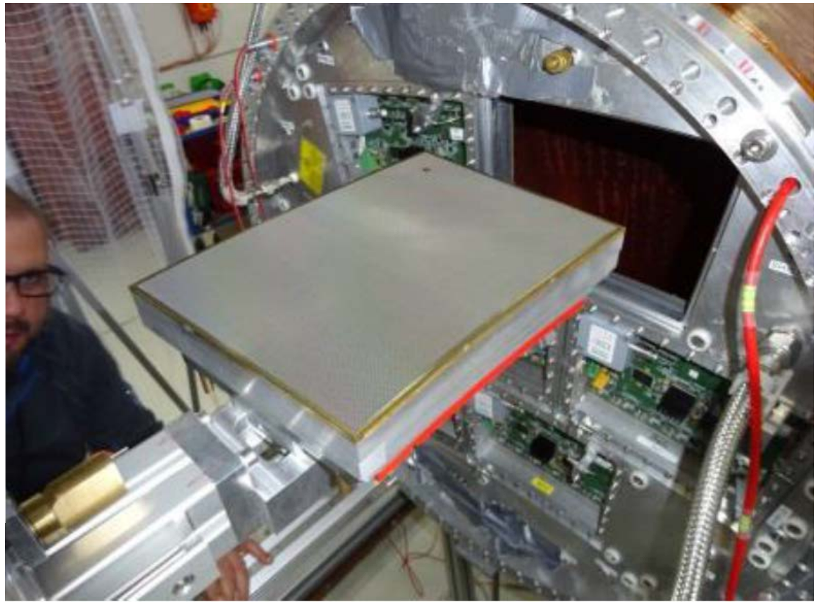
Pad TPC technology - resistive Micromegas

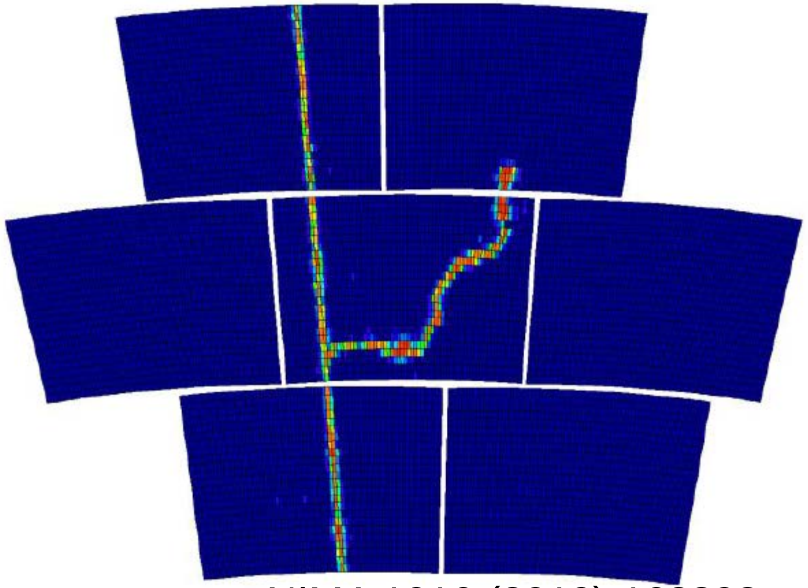
- Resistive Micromegas:
  - Bulk-Micromegas with 128 μm gap size between mesh and resistive layer (**developed in LCTPC**)
- A new HV scheme of the module (ERAM) places grid on ground potential
  - Reduces **field distortions** between modules by a factor of 10









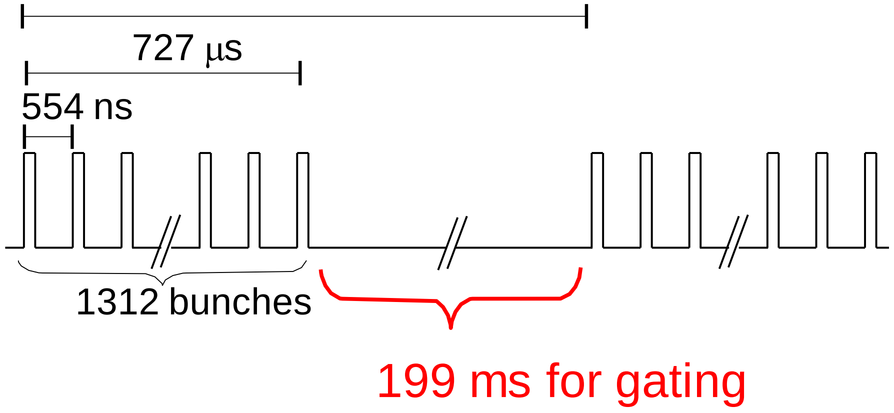


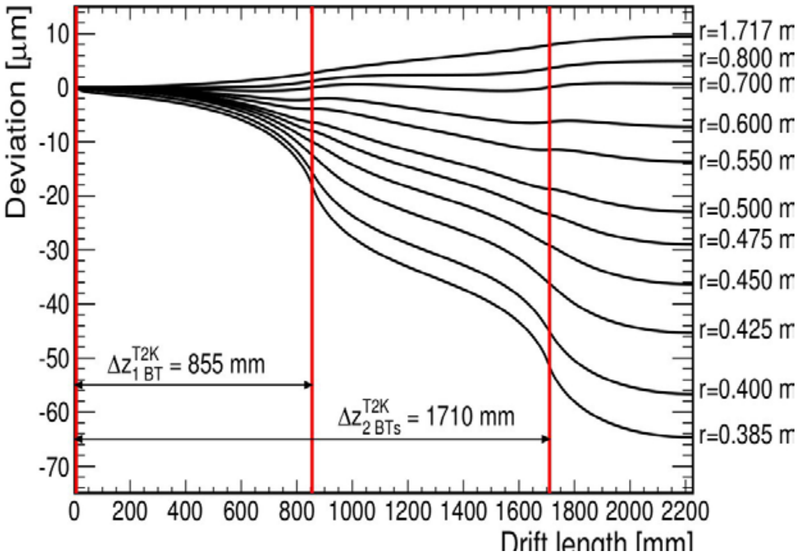
https://doi.org/10.1016/j.nima.2019.162798

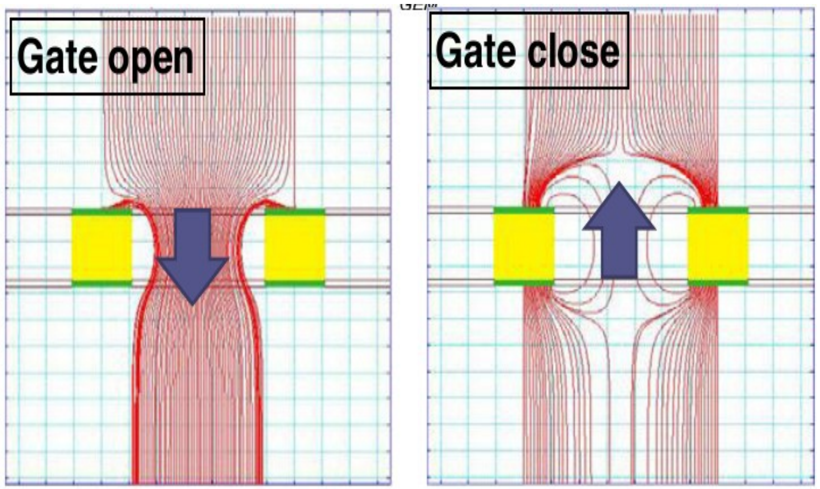
NIMA 1016 (2019) 162898

Ions suppression and TPC module

- **Gating GEM for power pulsing mode**
  - Primary ions create distortions in the electric field which result in O(<1μm) track distortions including a safety margin of estimated BG at Higgs run.
  - Track distortions are 20μm per disc without gating device, **if IBF is 1/gain**.
- Gating GEM is the favorite device. It has large holes (Ø 300 μm) and thin strips in between (30 μm).
  - The **electron transparency** has been determined and corresponds to 82%.
  - The ion blocking power has also been demonstrated and a fast HV switching circuit has to be developed.





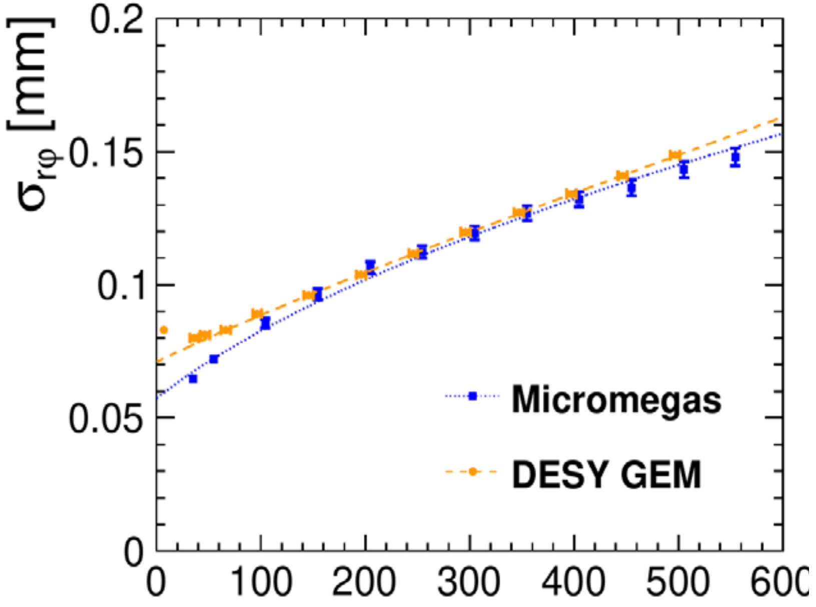


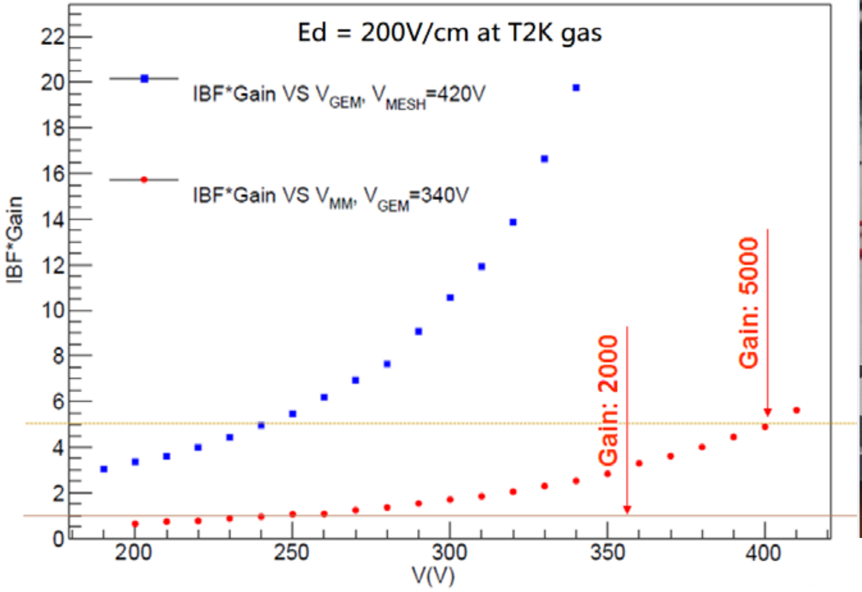
NIM A918 (2019) 41-53

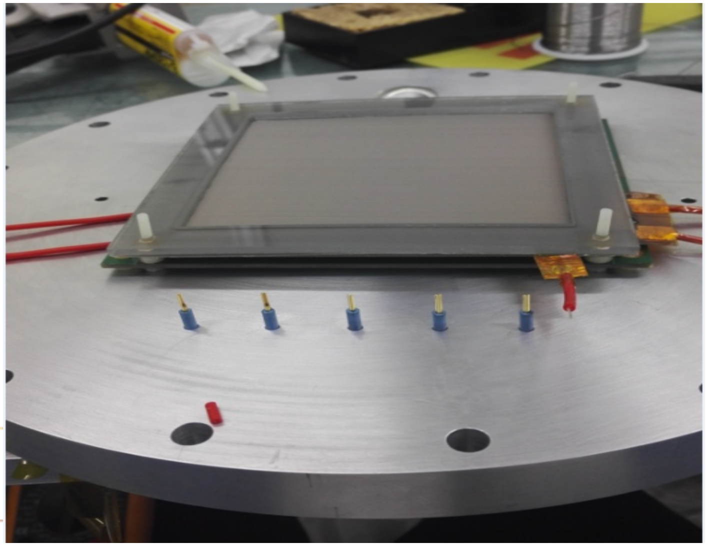
https://doi.org/10.1016/j.nima.2022.167819

Pad TPC technology – hybrid 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)
- 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**)





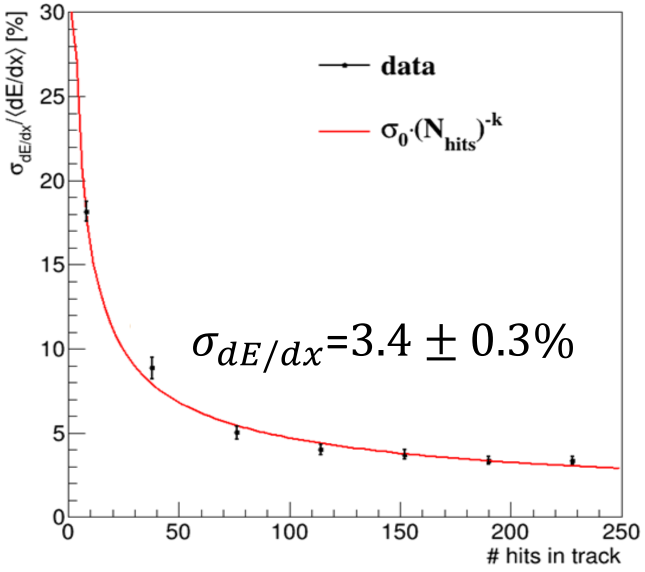


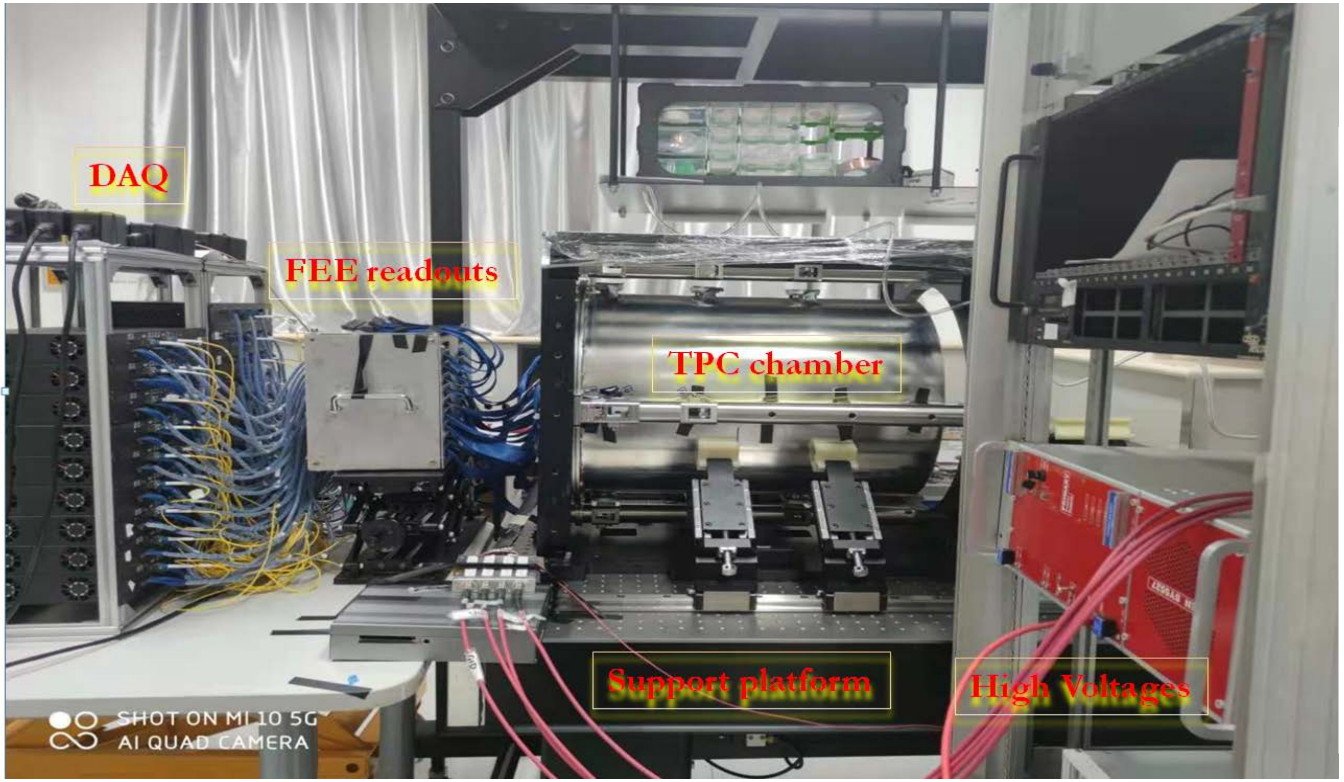
https://iopscience.iop.org/article/10.1088/1674-1137/41/5/056003

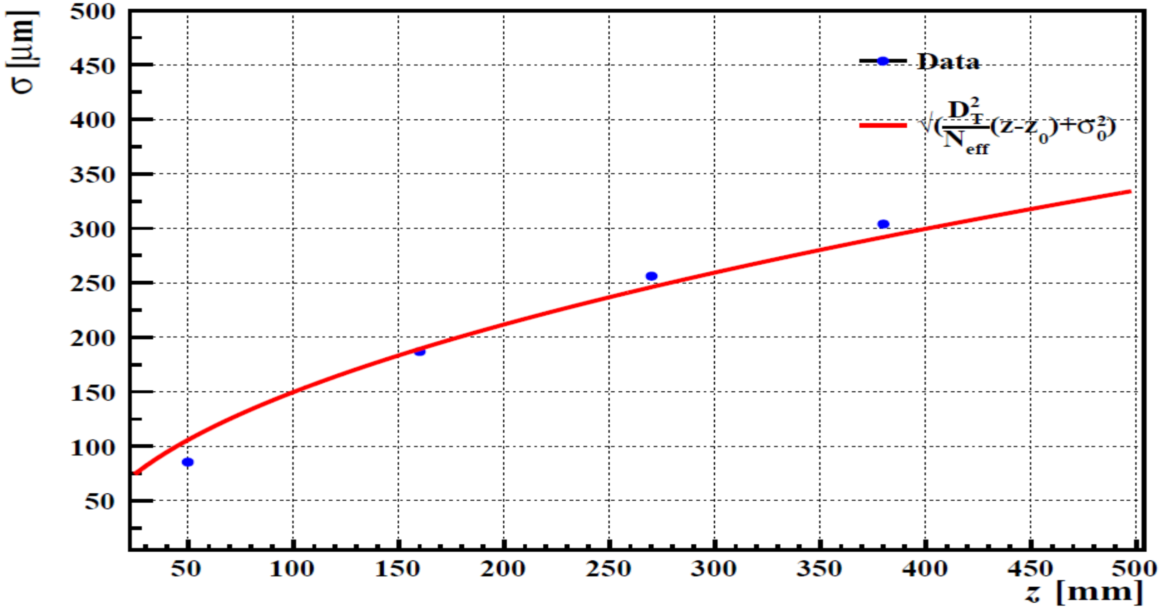
JINST (2022) 012066
JINST (2023) 18 C07015

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 $3.4 \pm 0.3\%$





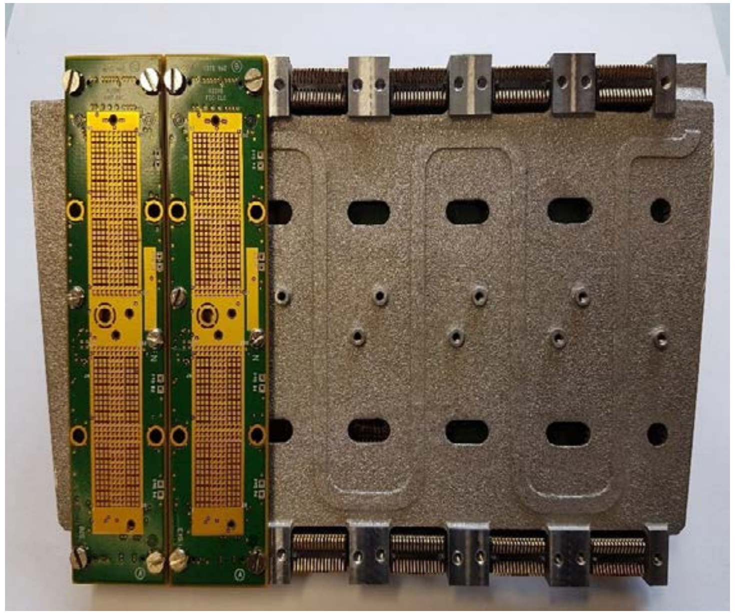


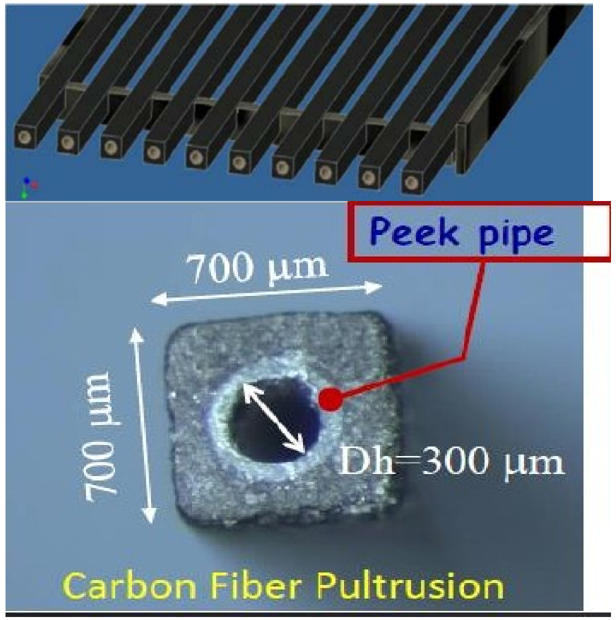
https://doi.org/10.1016/j.nima.2022.167241

NIMA 1040 (2022) 167241

Cooling system for readout electronics

- Readout electronics will require a cooling system. **2-phase CO_2-cooling** is a very interesting candidate.
  - A fully integrated AFTER-based solution tested on 7 Micromegas modules during a test beam.
- To optimize the cooling performance and the material budget **3D-printing of aluminum** is an attractive possibility for producing the complex structures required.
  - A prototype for a full module is available now at CEA, Saclay.
  - It was tested with a full set of electronics in 10/2021 showing excellent cooling performance.
- Alternatively, Lund university is exploring **micro channel cooling** together with Pisa.
  - These consist of pipes with Ø300µm in carbon fiber tubes.





DOI 10.1088/1742-6596/2374/1/012149

JINST 1018 (2022) 012149

- Pixelated TPC technology R&D

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

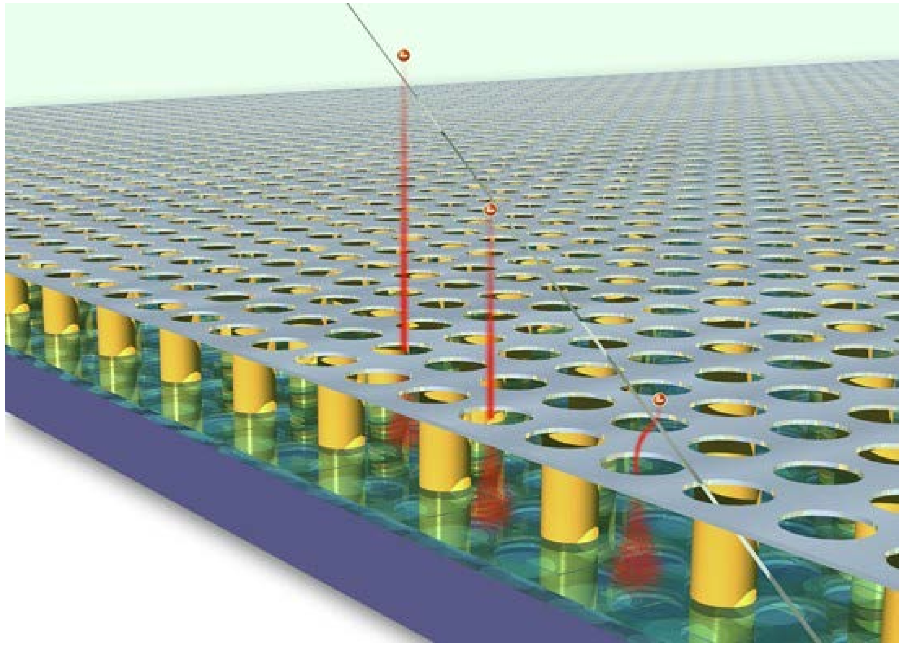
Standard charge collection:

Pads (1 mm×6 mm)/ long strips

Pixelated readout:

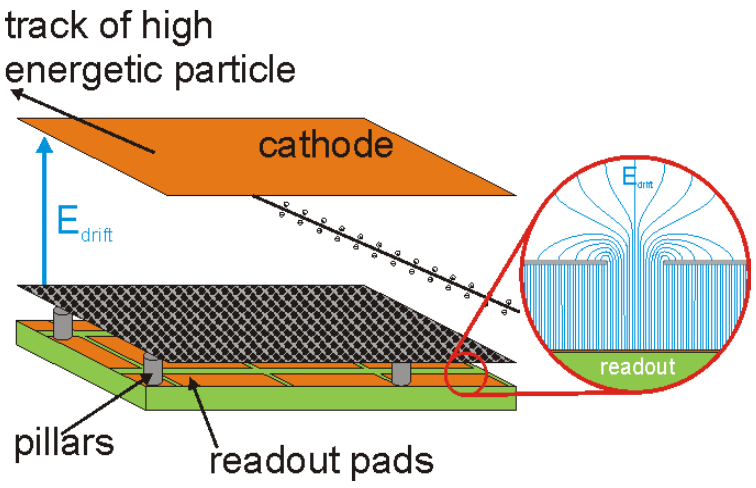
Bump bond pads are used as charge collection pads.

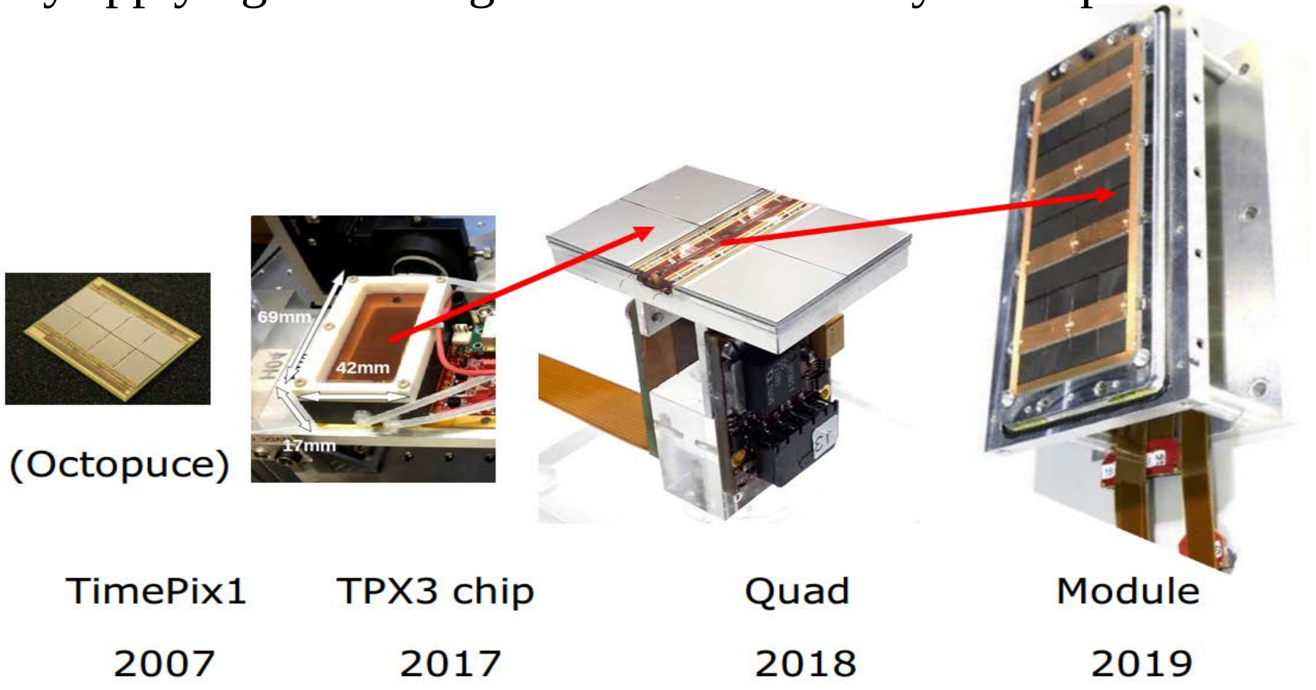
55µm× 55 µm or larger

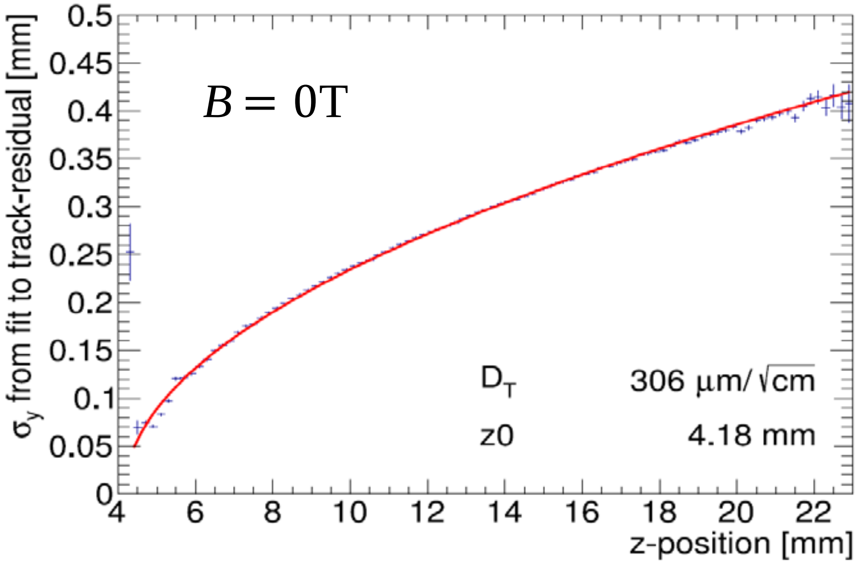


Pixelated TPC technology - Timepix3-based GridPix

- 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.





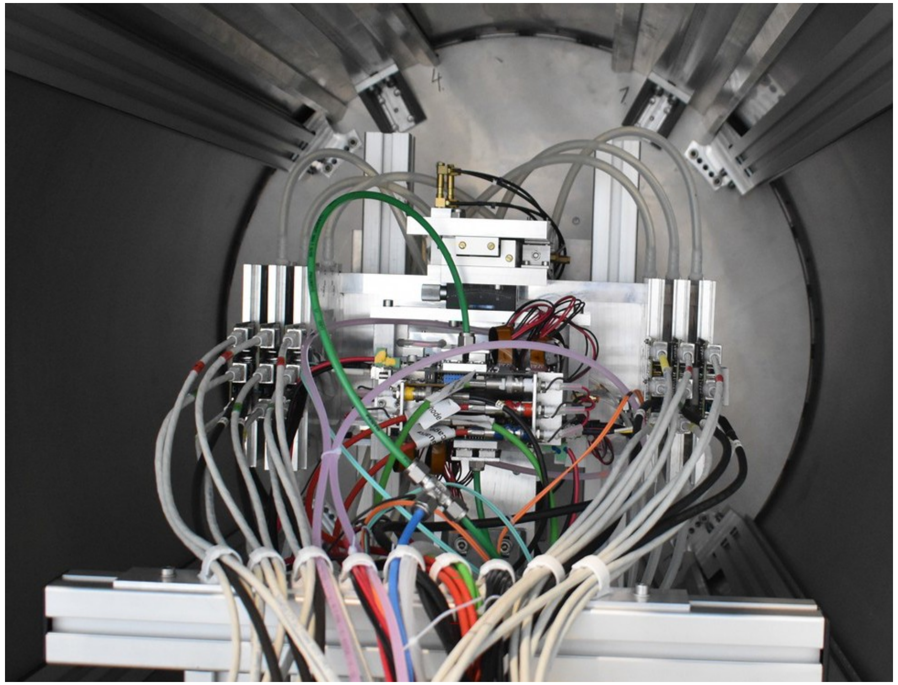


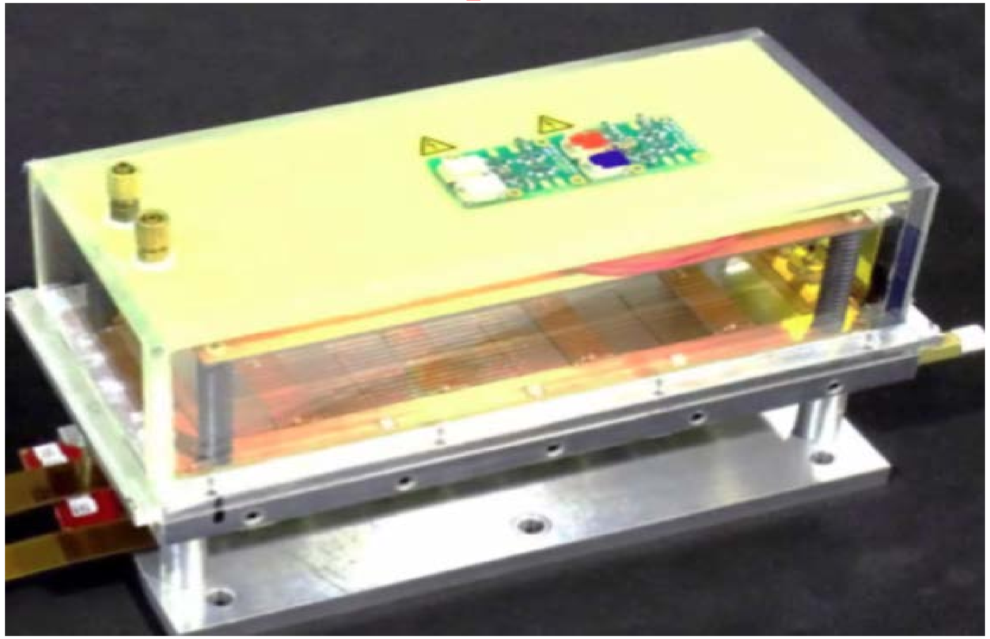
NIM A535 (2004) 506-510
NIM A845 (2017) 233-235

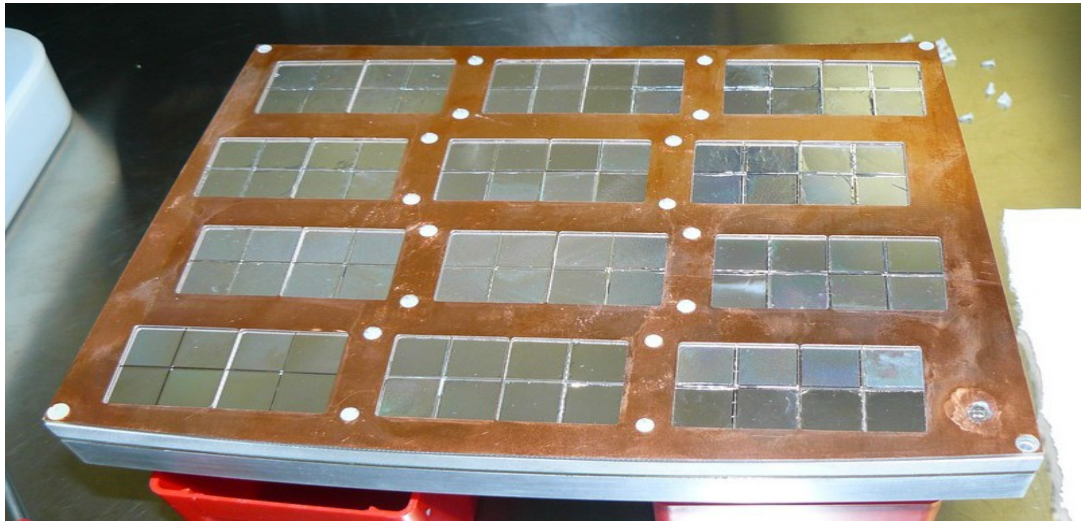
https://arxiv.org/abs/1902.01987

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.**



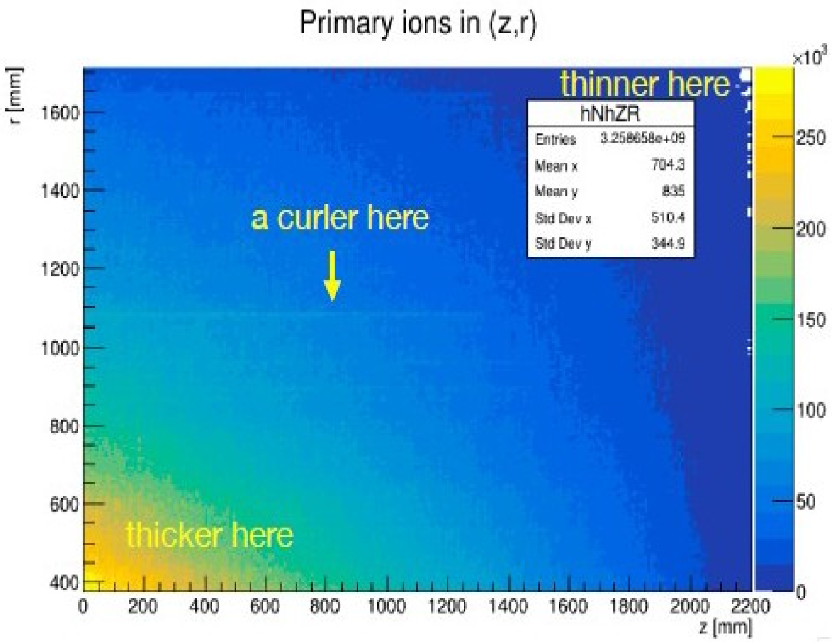


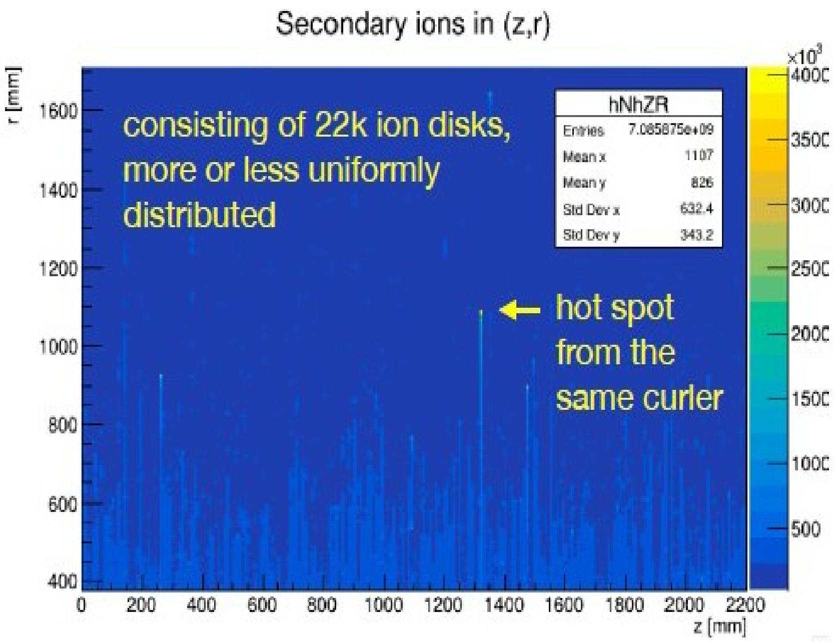


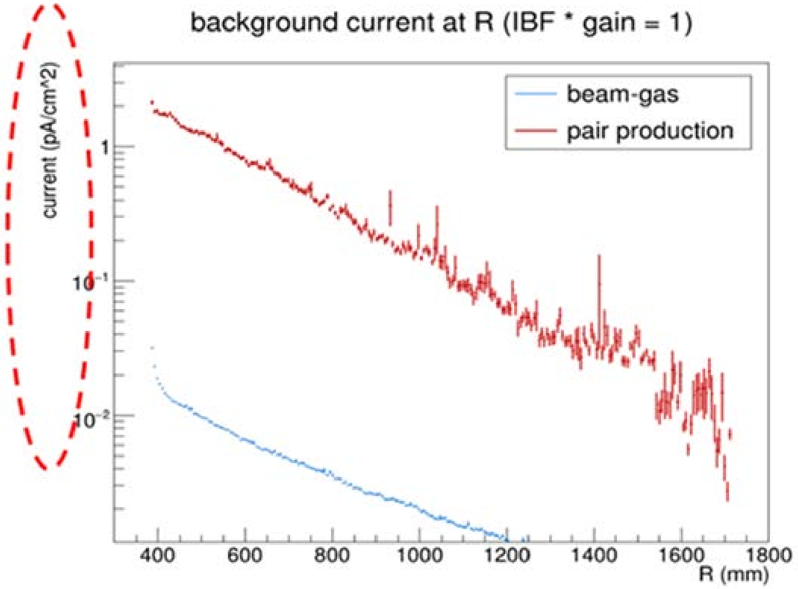
DESY testbeam in June 2021

High granularity TPC R&D for future Circular e+e- Colliders

- Operation of TPC at E > 100 GeV (i.e. for Higgs/t/W-production) **is not a problem.**
  - Cooling and the low power consumption of electronics has been studied.
- At E_{CM} ~ 90 GeV (i.e. Tera-Z) the high luminosities of L ~ 2×10E36 cm-2s-1 are challenging.
  - Z bosons will be **produced at 60 kHz**, creating significant ion background leading to E-field distortions.
  - This could be easily corrected (refer **ALICE TPC**), but many R&D needed.
    - Backgrounds MC simulation, lower gain×IBF and new structures (hybrid or others)







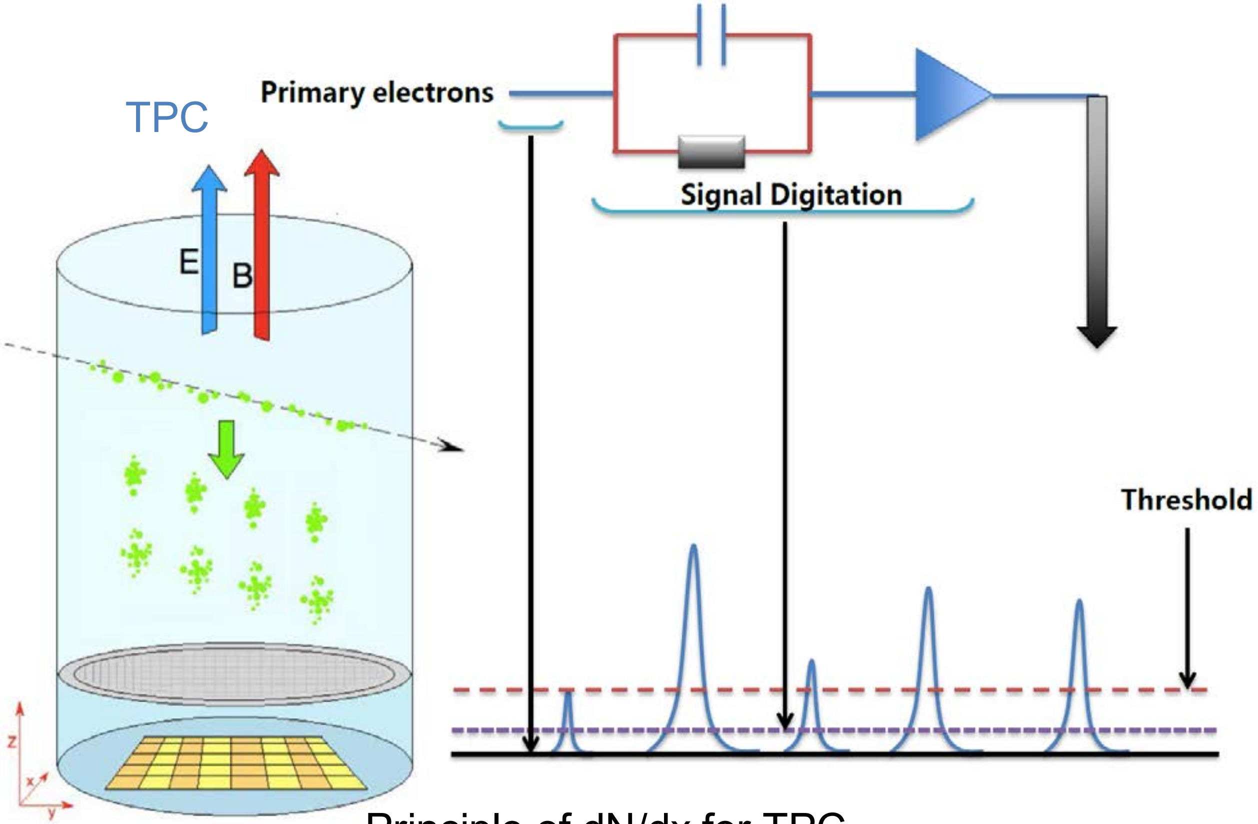
Feasibility study the full simulation of Tera Z (on-going)

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



Principle of dN/dx for TPC

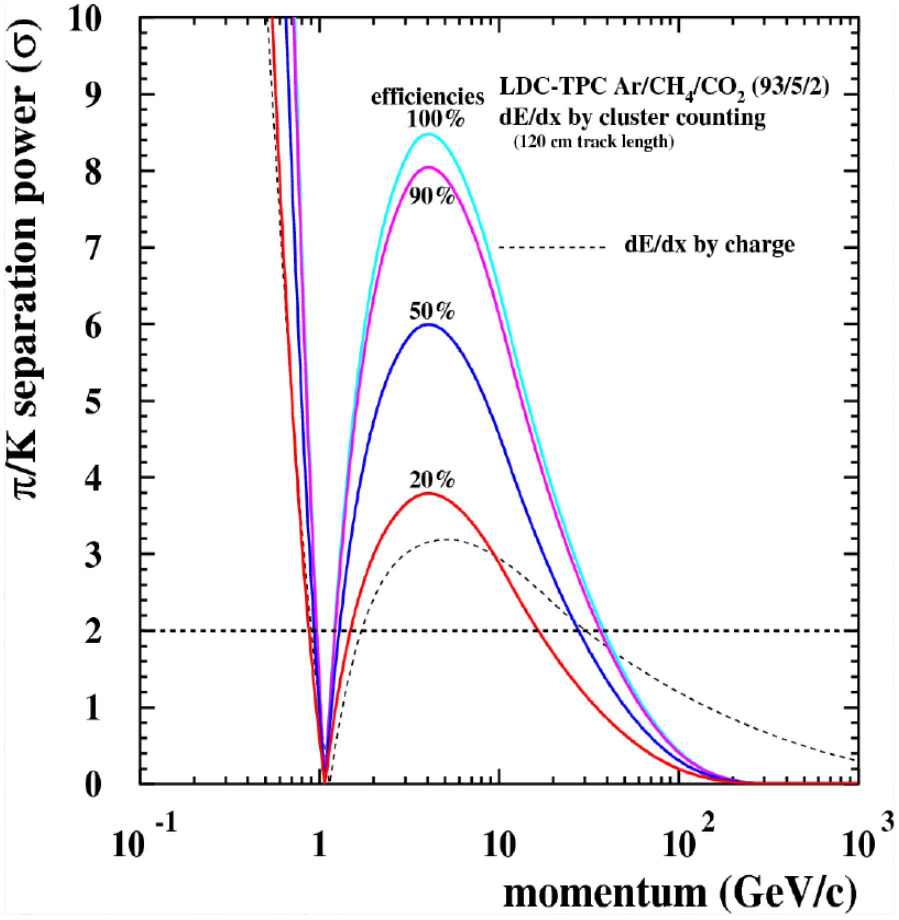
High granularity for improved PID in TPC

- 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



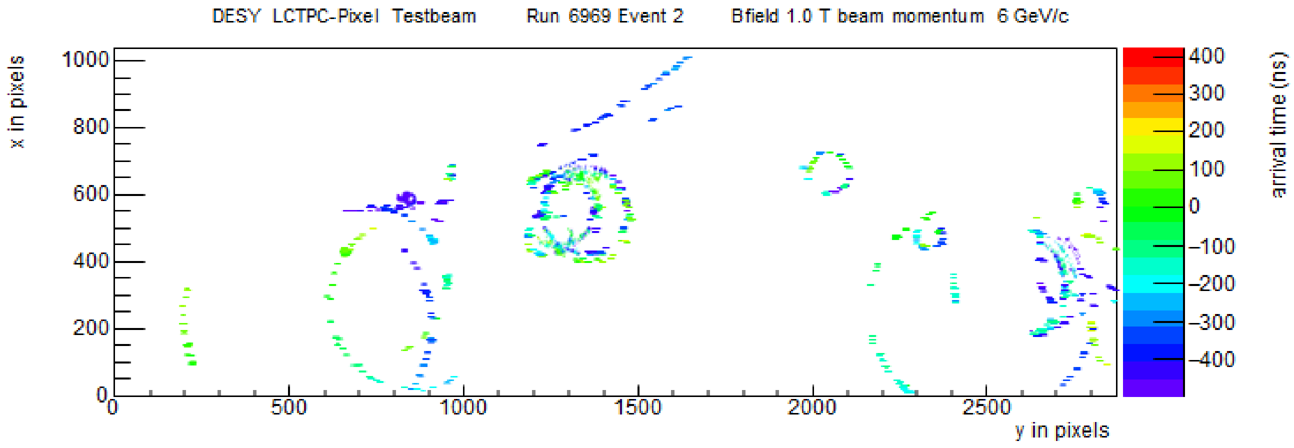
π/k separation power

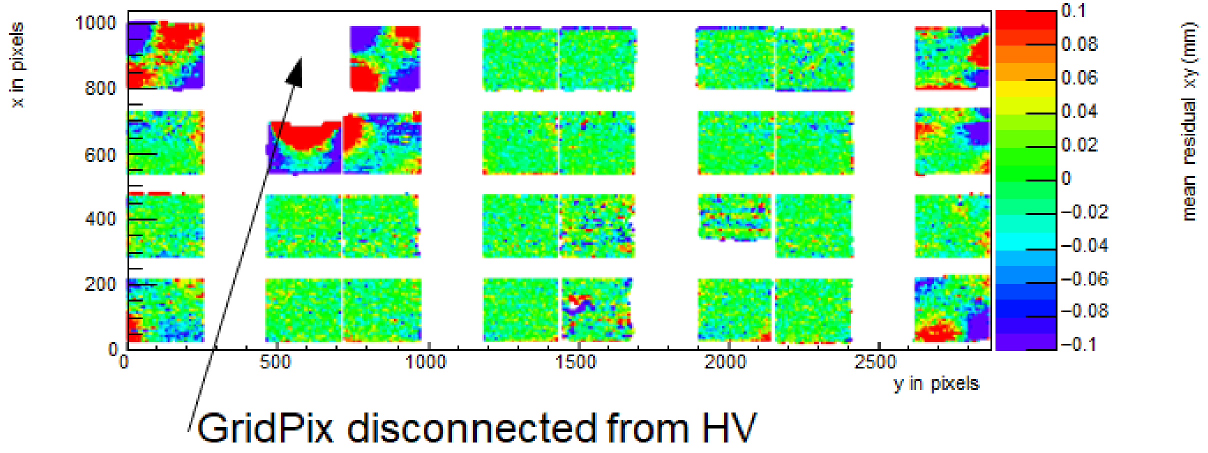
http://ific.uv.es/~ilc/ECFA-GDE2006/0

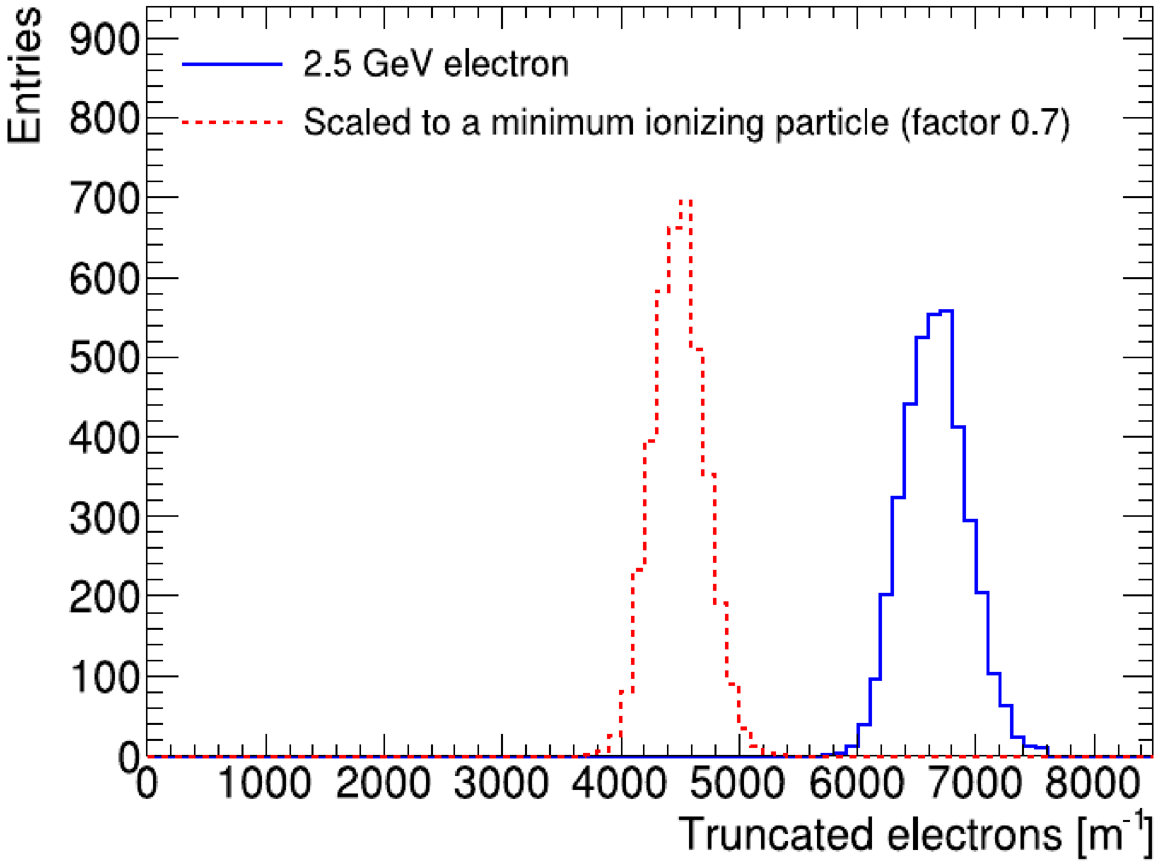
Preliminary Results of 32 GridPix Testbeam

- Mean residuals in the XY-plane with acceptance cuts.
- Events with multiple curlers (not standard) reconstructed in magnetic field B=1.0T at DESY.
- Results of **the tracking precision** (mean rms of residuals)
  - σ_{xy}=9μm, σ_z=13 mm for module length of 157.9mm

R&D of TPC detector for EIC collider from 2023







Summary

- Continue GEM, Micromegas and GridPix detector modules have been tests at the Large Prototype in preparation for the preliminary design of the TPC for ILD.
- A pixelated TPC (with GridPixes) seems **most promising** with many interesting features like electron or cluster counting and some simulation are ongoing.
- 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. In particular studies for circular Higgs factories are needed to understand the **performance of a TPC at Tera-Z**.
- Many simulations are still necessary to understand the detailed requirements of the final detector (e.g. number of ADC bits, pad sizes, etc.), but also **any new ideas for old challenges are welcome**.

Many thanks!