# Simulation of the high granularity readout TPC at e+e- collider

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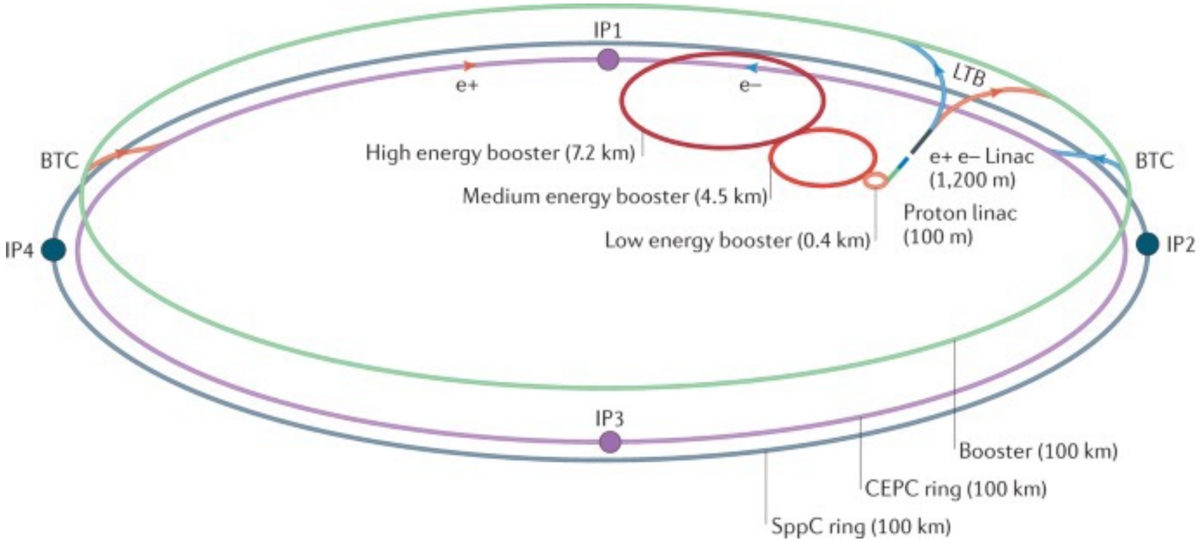
# CONTENTS

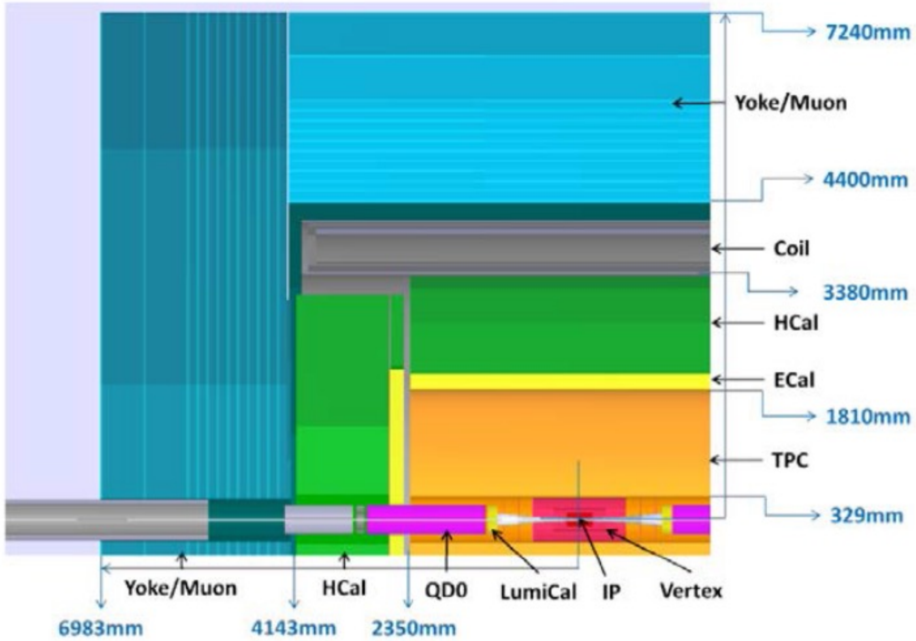
# TPC technology for future e+e- Colliders

- Some advantages of TPC detector
  - Operation under **3&2 T magnetic field**
  - A large number of 3D space points
  - Excellent pattern recognition capability
  - Ideal for 3D tracking and PID

- TPC detector plays a crucial role in the future e+e- Colliders
- A lot of R&D already present (LCTPC, CEPCTPC)




CEPC

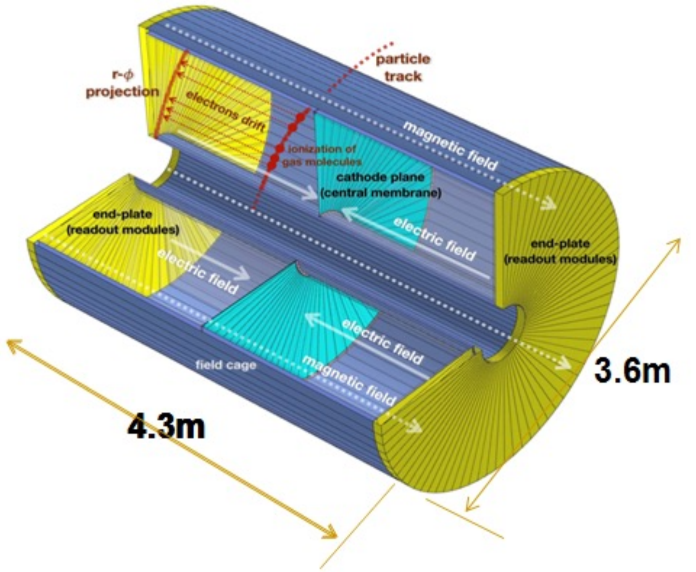



The structure of the baseline CEPC detector design

# TPC requirements for e+e- Higgs/EW/Top factories

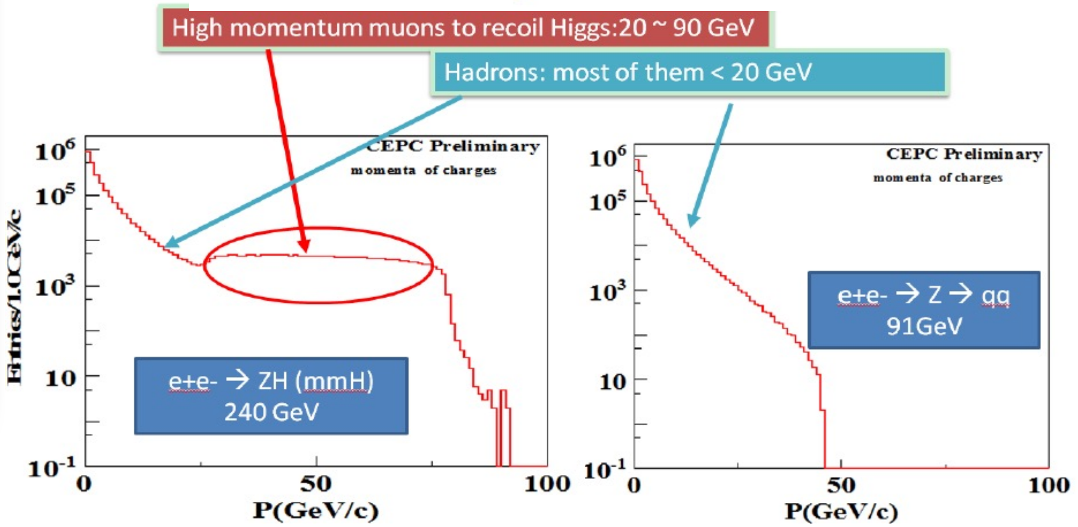
- Provide decent #Hits (for track finding) with high spatial resolution compatible with PFA design
- $\sigma_{1/pt}$~$10^{-4}$GeV/c$^{-1}$(TPC alone) and $\sigma_{point}$ <100 µm
- Provide dE/dx and dN/dx with a resolution < 3%

→ **Effectively improve the Particle ID**




| Particle | $E_{c.m.}$ (GeV) | Run Years | SR Power (MW) | Lumi./ IP ($10^{34}cm^{-2}s^{-1}$) | Integrated Lumi./ yr ($ab^{-1}$,2 IPs) | Total Integrated L ($ab^{-1}$,2 IPs) |
|---|---|---|---|---|---|---|
| H | 240 | 10 | 50 | 8.3 | 2.2 | 21.6 |
| | | | 30 | 5 | 13 | 13 |
| Z | 91 | 2 | 50 | 192 | 100 | 100 |
| | | | 30 | 115 | 60 | 60 |
| W | 160 | 1 | 50 | 26.7 | 6.9 | 6.9 |
| | | | 30 | 16 | 4.2 | 4.2 |
| $t\bar{t}$ | 360 | 5 | 50 | 0.8 | 1.0 | 1.0 |
| | | | 30 | 0.5 | 0.65 | 0.65 |

Latest CEPC Operation Plan from Yuhui Li on Monday



# Particle Identification Requirements in TPC

## Physical Target

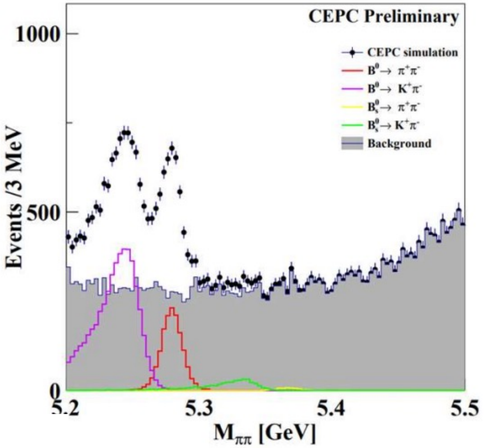
- *K/π* separation power to be above 2σ at a Momentum of 20 GeV/c
  - Improving jet Energy Resolution
  - Beneficial for Flavor @ Z pole

    → b-tagging (electrons from semi-leptonic b-decays)

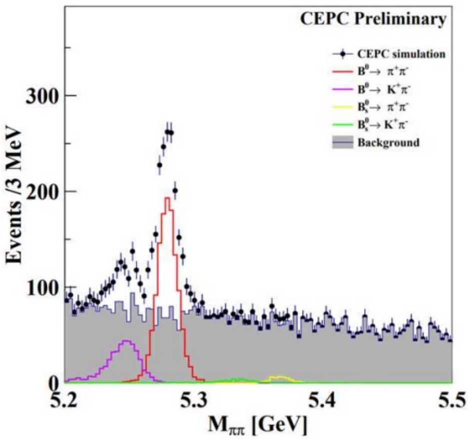
    → c-tagging, D meson spectroscopy (kaon/pion separation)

### Simulation $B^0/B_s^0$ using Delphes

Without PID




With PID



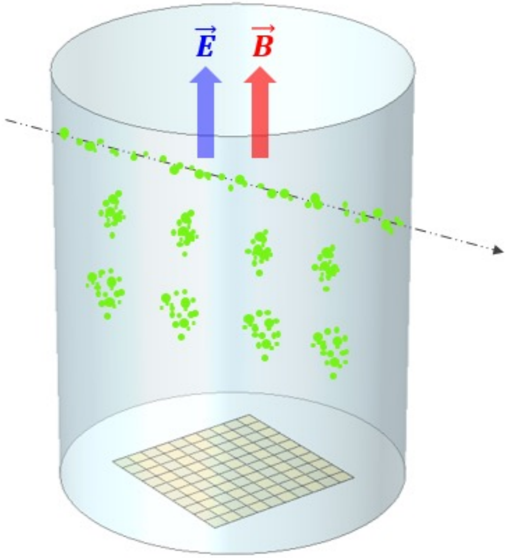

From Xu Gao

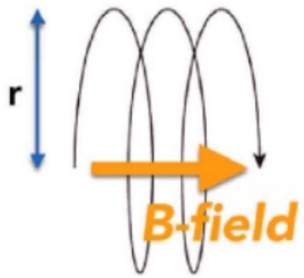
### Requirements of TPC

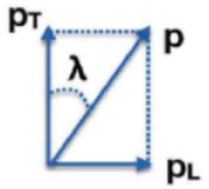
| Parameter | |
|---|---|
| Geometrical parameters | $r_{in}$ 329 mm, $r_{out}$ 1808 mm, z ± 2350 mm |
| Solid angle coverage | up to $\cos\theta \simeq 0.98$ (10 pad rows) |
| TPC material budget | $\simeq$ 0.05 $X_0$ including outer fieldcage in $r$ |
| | $<$ 0.25 $X_0$ for readout endcaps in $z$ |
| Number of pads/timebuckets | $\simeq$ 1-2 $\times$ $10^6$/1000 per endcap |
| Pad pitch/ no.padrows | $\simeq$ 1$\times$ 6 mm$^2$ for 220 padrows |
| $\sigma_{\text{point}}$ in $r\phi$ | $\simeq$ 60 $\mu$m for zero drift, $<$ 100 $\mu$m overall |
| $\sigma_{\text{point}}$ 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) |

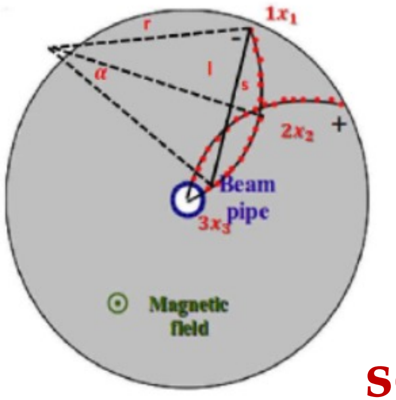
# dE/dx & dN/dx

# Classical dE/dx Measurement




$$p_T = 0.3\,Br$$

$$p = \sqrt{1 + tan^2\gamma}$$

$$p \;+\; \text{dE/dx} \;\rightarrow\; \text{PID}$$

$$\text{separation power} = \frac{dE/dx(A) - dE/dx(B)}{\sigma(dE/dx)}$$

- Classical dE/dx measurement by charge (charge ≈ number of primary + secondary electrons)

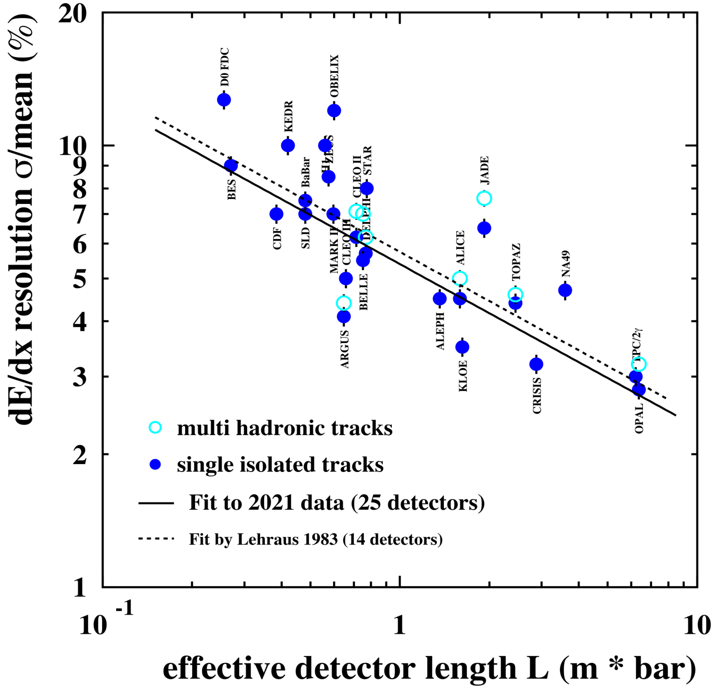
- measure charge per sample along a track
- Long tail worsens the correlation of the measured average energy loss and the particle species
- the fundamental, central problem of all dE/dx measurements by charge summation

Problem → sensitive to large fluctuations

# dN/dx Measurement by Cluster Counting

- **Direct cluster counting → ultimate way to measure dN/dx**
  - avoid any problems with cluster fluctuations
  - no charge measurement need, just counting
  - < 3% dN/dx resolution by cluster counting (statistical error only)
  - 5.4% dE/dx resolution by charge measurement

“Lehraus” Plot 2021*



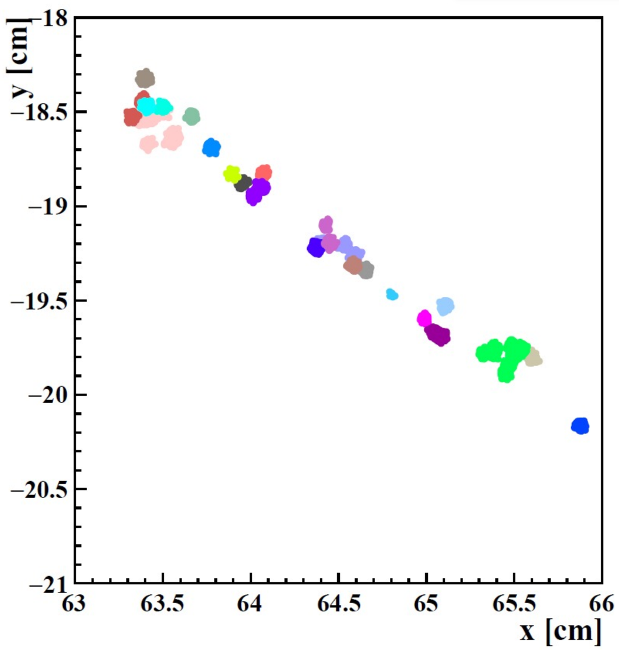

* From Michael Hauschild’s talk @ RD51 workshop

- Fit by Lehraus 1983:
  dE/dx res. = 5.7 * $L^{-0.37}$ (%)
- Fit in 2021:
  dE/dx res. = 5.4 * $L^{-0.37}$ (%)

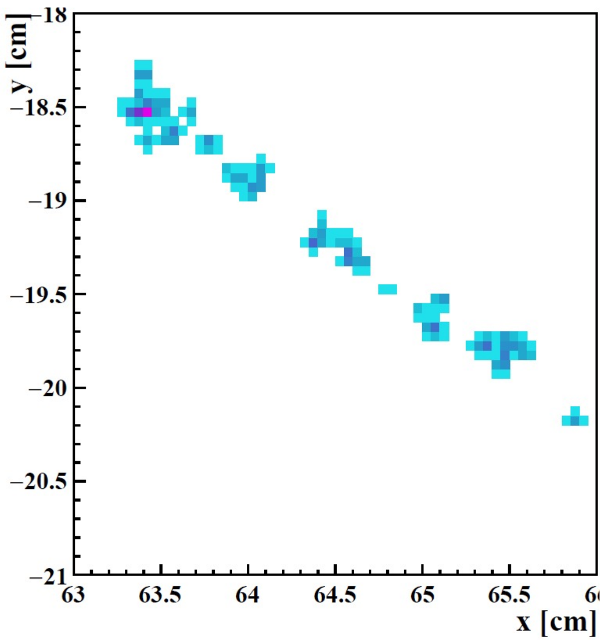
- **Obvious problem**
  - How to resolve individual clusters and count them?
    - high cluster density(~30 cl./cm in Ar mixture for m.i.p → typical drift velocities 50 μm/ns → 6 ~10 ns in between clusters → fast-shaping electronics (~ns needed ) In time)
  - Need devices with high time resolution or high granularity to resolve them

# Cluster Counting in Space

- TPC with cluster counting
  - Cluster Counting so far based on time measurement in small drift cells
  - Pixel TPC makes space measurement possible
    - GEMs/Micromegas + small pixels have high granularity → resolve clusters in space
    - Time information added → 3D position in space




projection of clusters on endplate



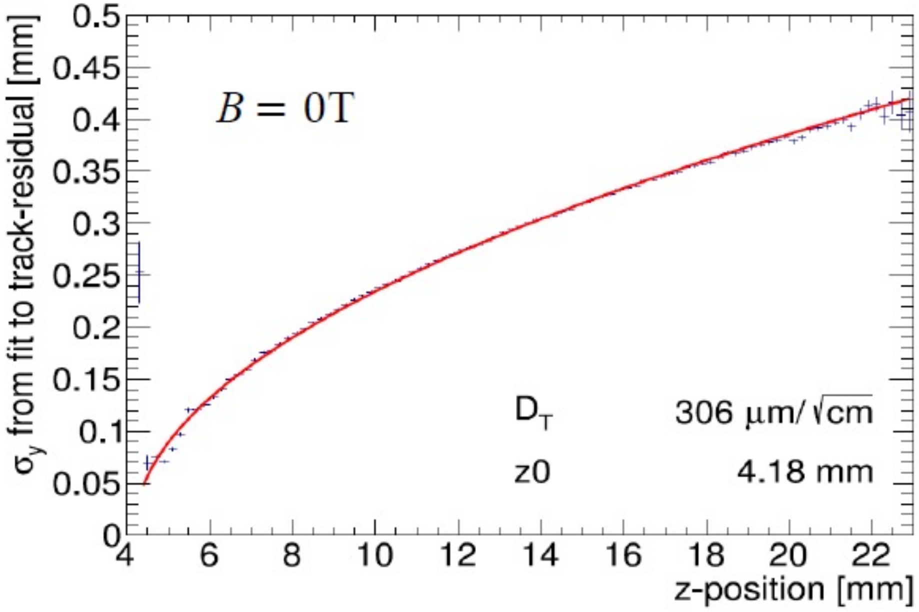

pixel response (500 μm× 500 μm)

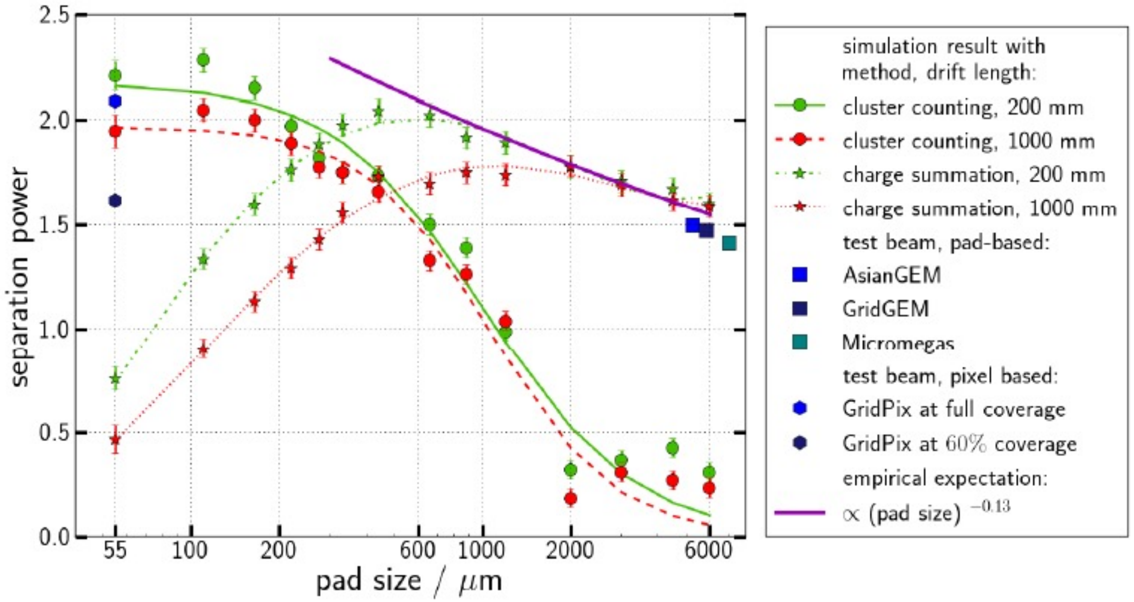
# Application of Pixel Readout in LCTPC

## GridPixes Pixel TPC Readout

- Tests with single and quad devices have been successfully done.
- ~4.1% dE/dx resolution at B = 1.0T at DESY
- For very small readout pads the cluster counting method yields a very good separation power


TimePix1 2007 | TPX3 chip 2017 | Quad 2018 | Module 2019




https://doi.org/10.48550/arXiv.1902.01987

https://doi.org/10.1088/1748-0221/17/11/P11027

# Application of Pixel Readout in CEPC-TPC

## Advantages of Pixel Readout for High Luminosity CEPC-TPC

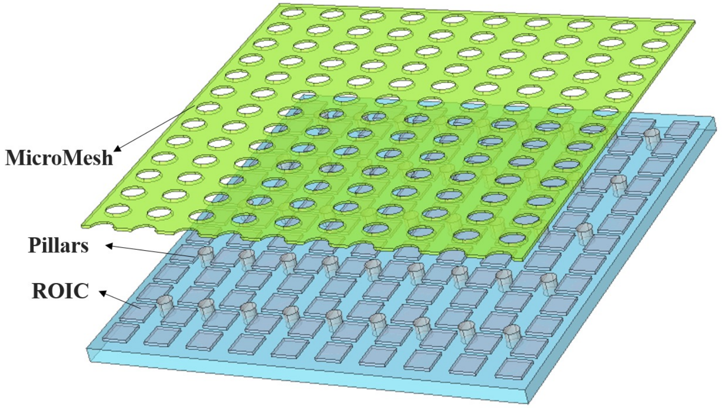
- High granularity readout allows measuring every ionization cluster
- High spatial resolution under 2T or 3T magnetic field
- Better momentum resolution
- High-rate operation (MHz/cm$^2$)
- Excellent two tracks separation performance

**Performance Optimization**

- Pixel size
- Detector geometry
- Occupancy
- Readout power consumption

| Pad readout | Pixel readout |
|---|---|
| Readout size : 2×10 m$^2$ | Readout size : 2×10 m$^2$ |
| MPGD Readout | Micromegas Readout |
| Single Pad size : ≥ 1mm × 6 mm | Single pixel size : ≥ 55 μm × 55 μm |
| $10^6$ readout units | $10^9$ readout units |
| dE/dx < 5% | dE/dx < 3% |
| Rate : kHz/cm$^2$ | Rate : MHz/cm$^2$ |

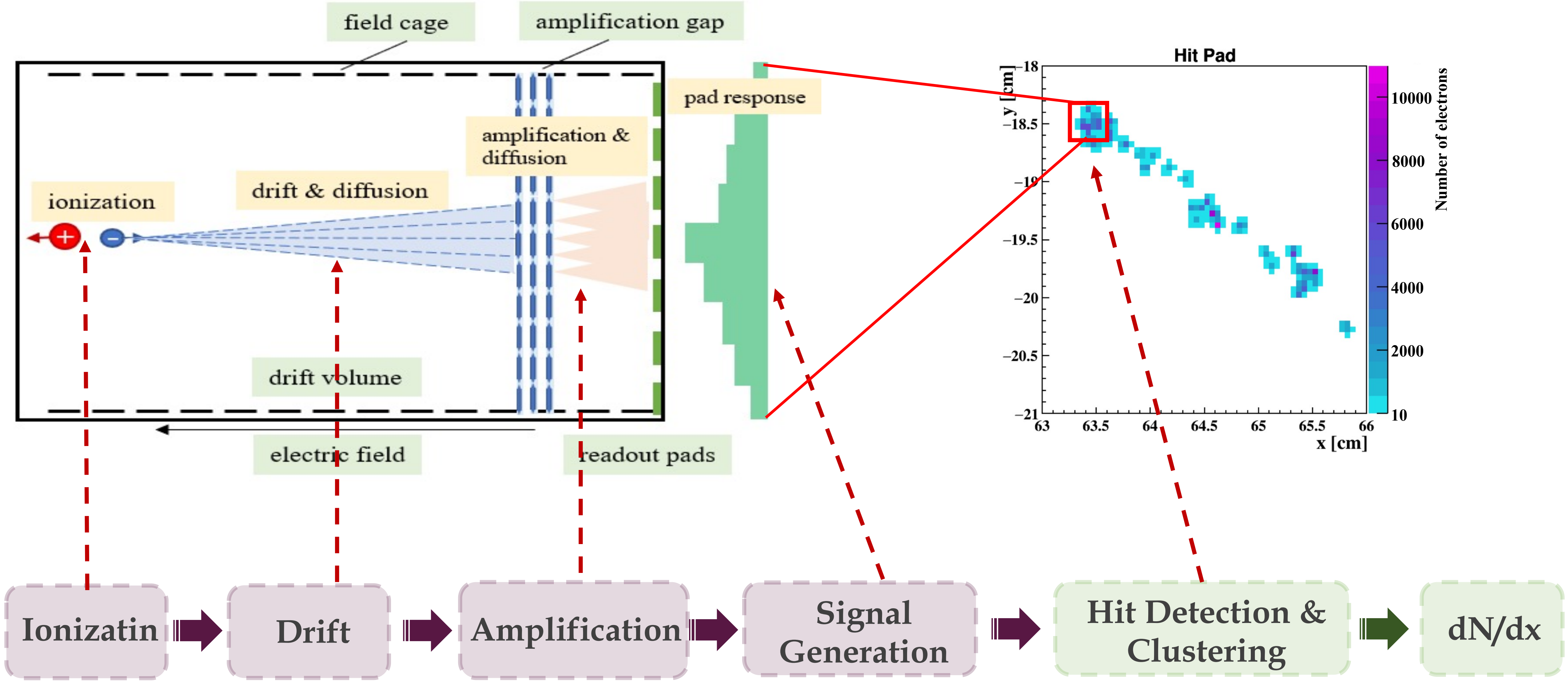
Comparison of Two Readout Methods for CEPC-TPC




schematic diagram of a pixelated readout structure

# Simulation of pixel TPC

# Full Simulation Framework of Pixel TPC

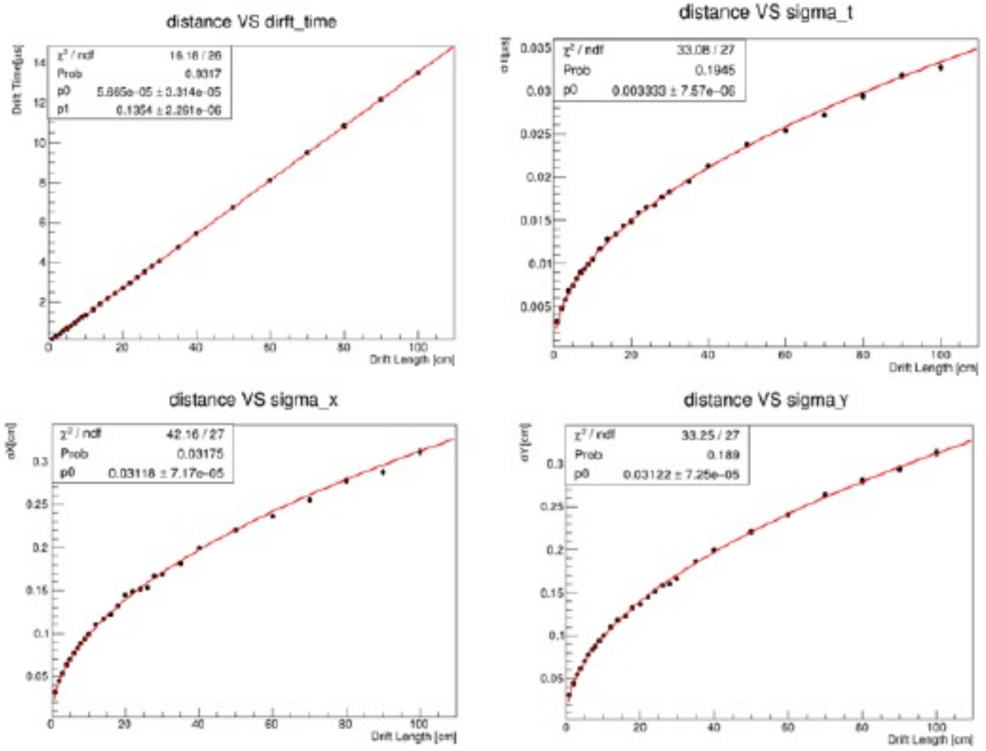



Simualtion / Digitization

Reconstruction

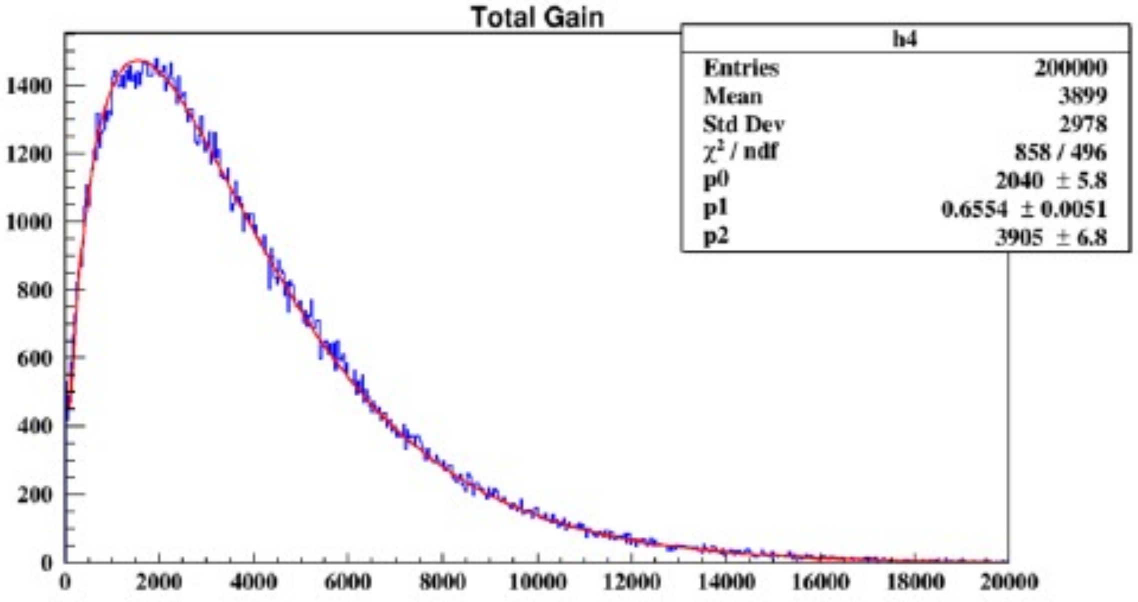
# Parametrizations

- To speed up the simulation, make several decompositions and apply parametrized models
- **Electron diffusion:**
  - $\sigma_T$ vs drift distance
  - $\sigma_X$ vs drift distance
  - $\sigma_Y$ vs drift distance




Diffusion

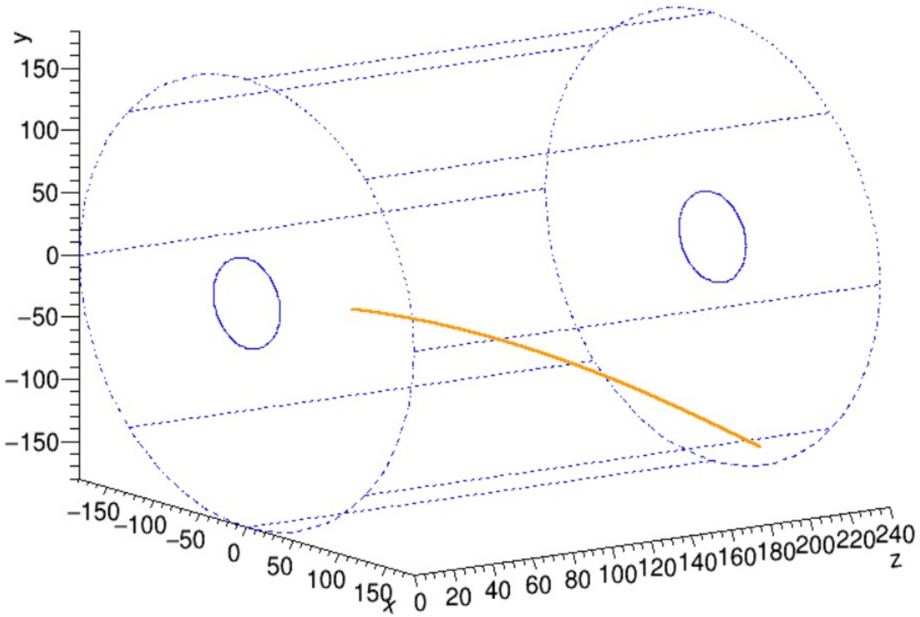
- **Amplification:**
  - Polyafunction sampling
- **Signal generation**
  - Double-Gaussian sampling



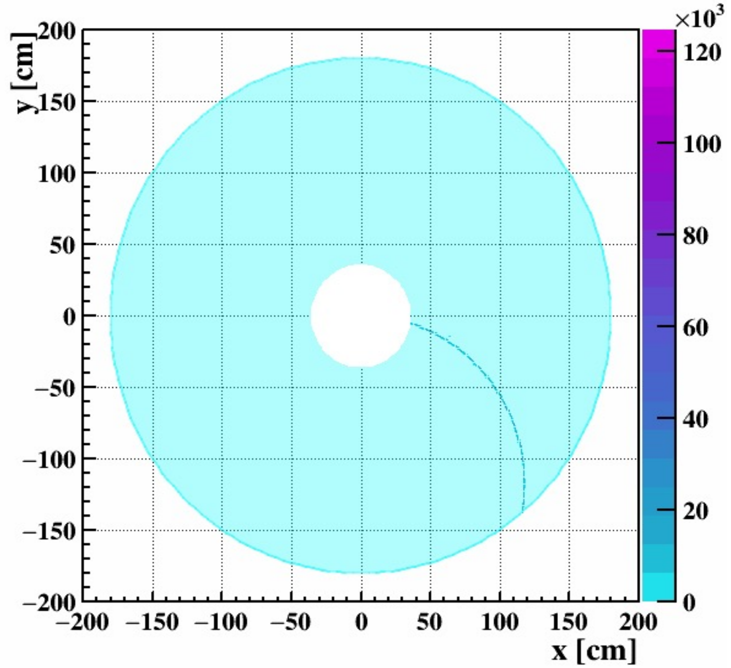

Amplification

# Simulation setup

- Magnetic field: 2T (Z-pole run)
- Gas mixture: T2K ($Ar/CF_4/iC_4H_{10}$ : 95/3/2)
- Detector Layout : R (0.3 m 1.8 m); L (2.34 m)




A track of 1 GeV/c pion in TPC




Projection of the same track on endplate

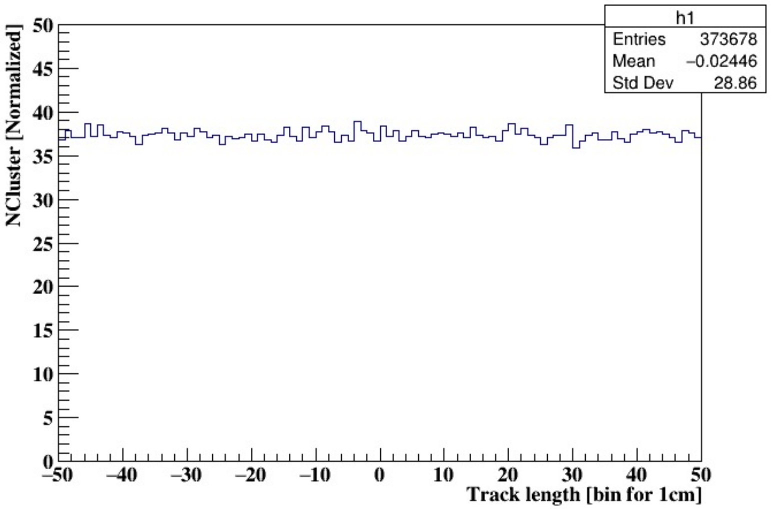
# Simulation of the primary cluster

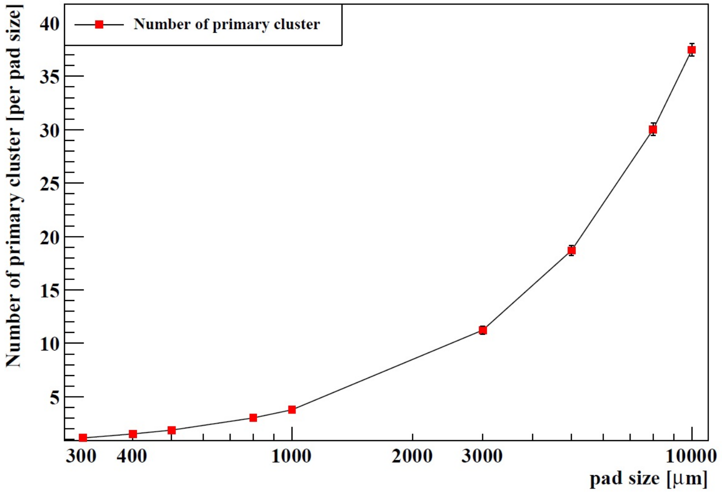
## Heed Simulation

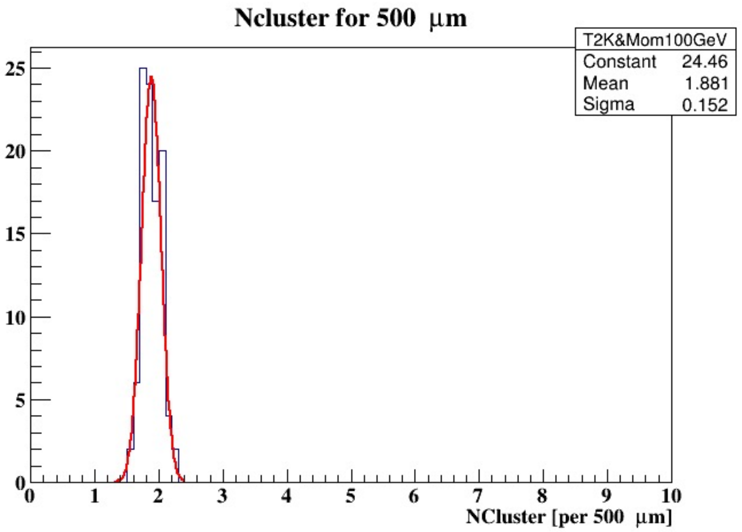
- The distribution of clusters is uniform along the track
- Typically ~30 primary ionization clusters/cm in gas at 1 bar → T2K :37.4cluster/cm
- ~1.9 clusters/ 500 μm , ~1.2 clusters/ 300 μm

More detailed research is needed

- If pixel size is at the level of cluster distances of primary ionization, Cluster counting becomes effective



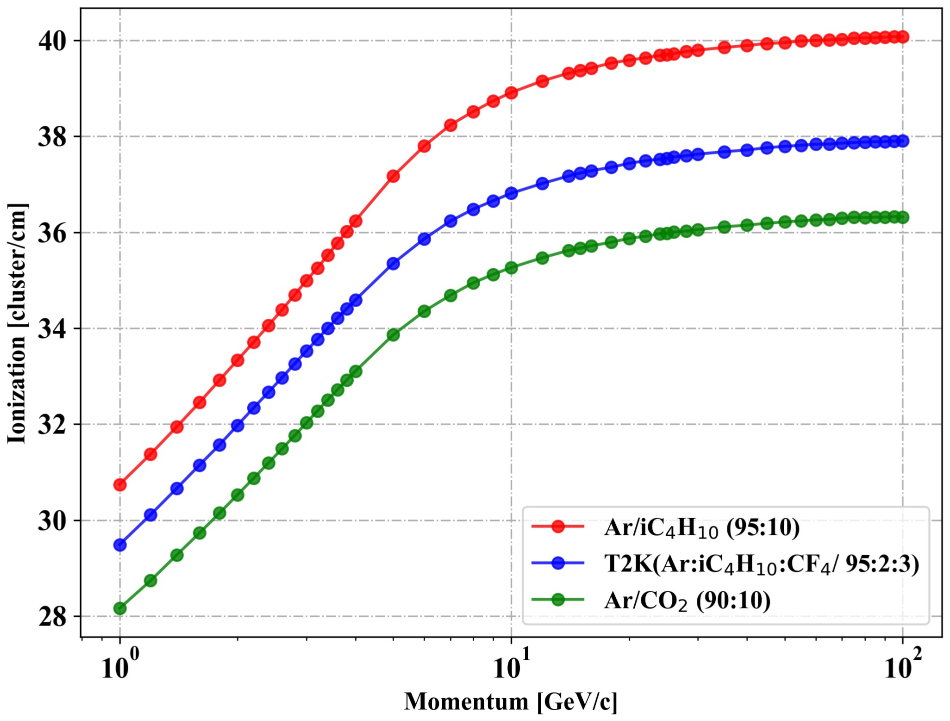



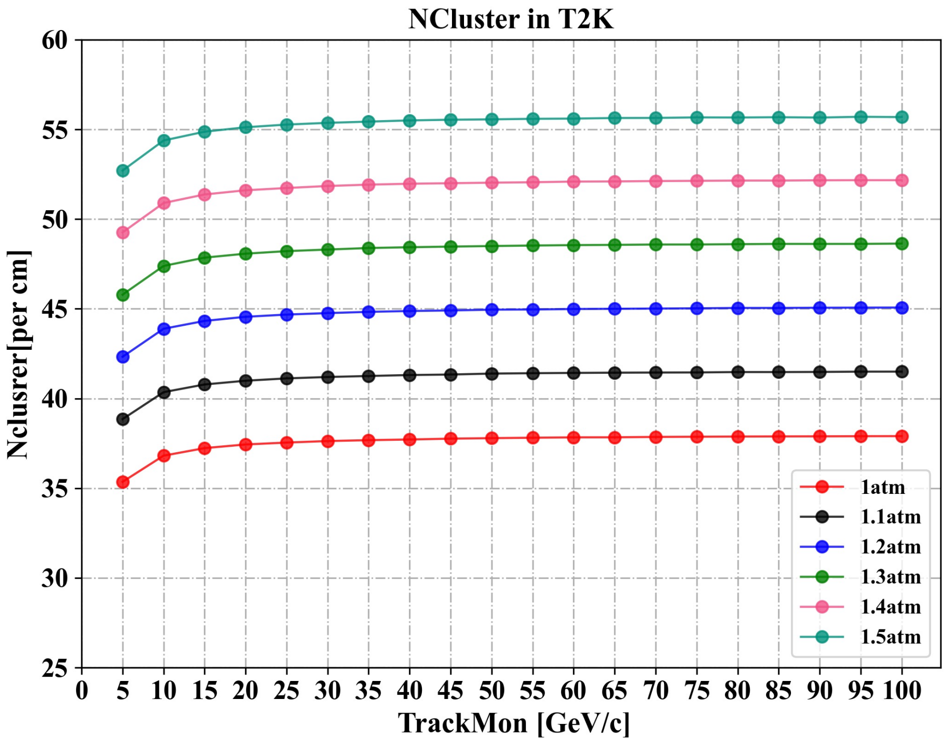




Pad size = 500 um Ncluster/cm

# Simulation of the primary cluster

- Simulation Study for 1 m tracks in T2K gas with different particles – different gas &  pressure
  - Need gas with low diffusion & large drift velocity
  - Need gas with good cluster statistic
  - Pixel size → Optimize working gas & pressure



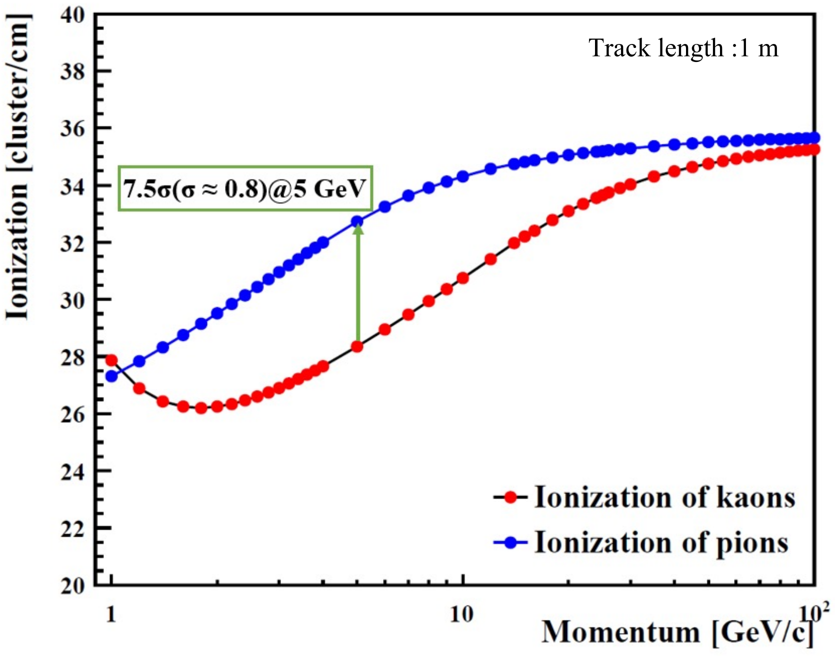



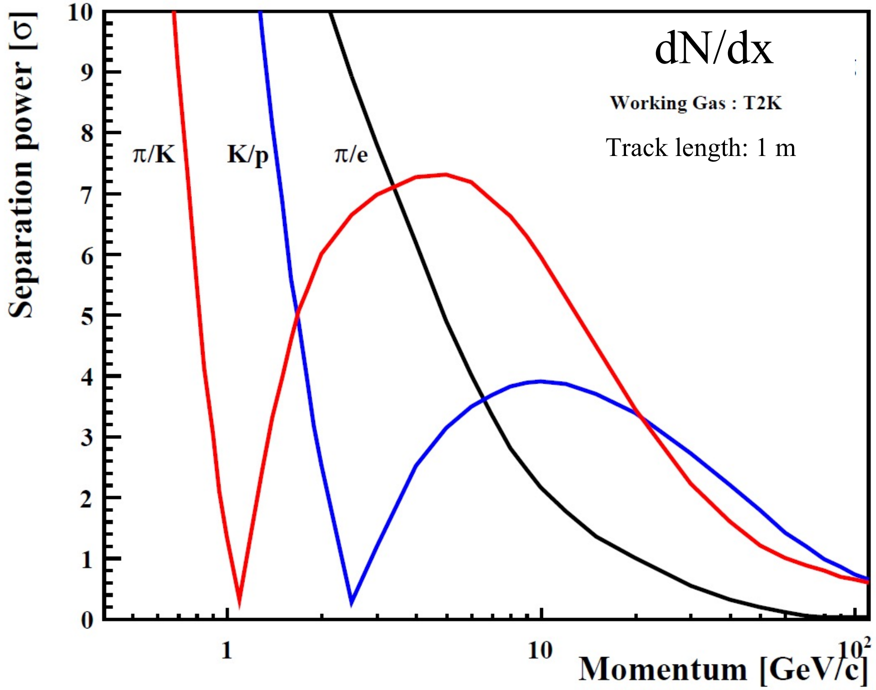
# Particle Separation from MC Truth

- Simulating pion/muon/kaon within [0.1-100] GeV/c in T2K gas
  - The performance of particle separation is **proportional to the difference in the average ionization**
  - The relative ionization of different particle species depends on the momentum
  - At 5 GeV, the particle separation power for pion/kaon particles can achieve 7.5 σ
  - **Cluster counting exhibits excellent potential for particle identification**

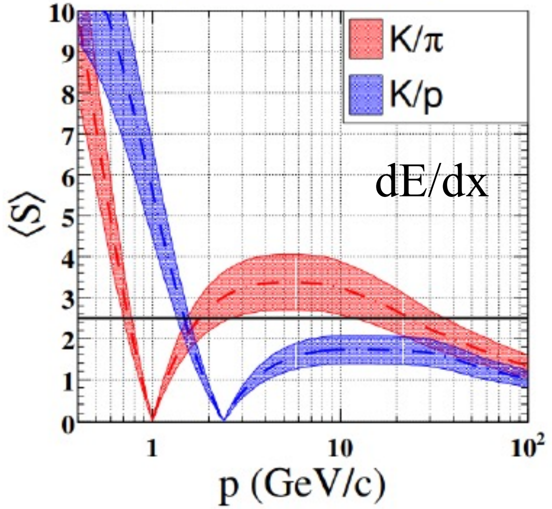
Number of Primary Ionization Clusters per Unit Distance

$$Sp = \frac{|\mu_A - \mu_B|}{\sqrt{\frac{\sigma_A^2 + \sigma_B^2}{2}}}$$



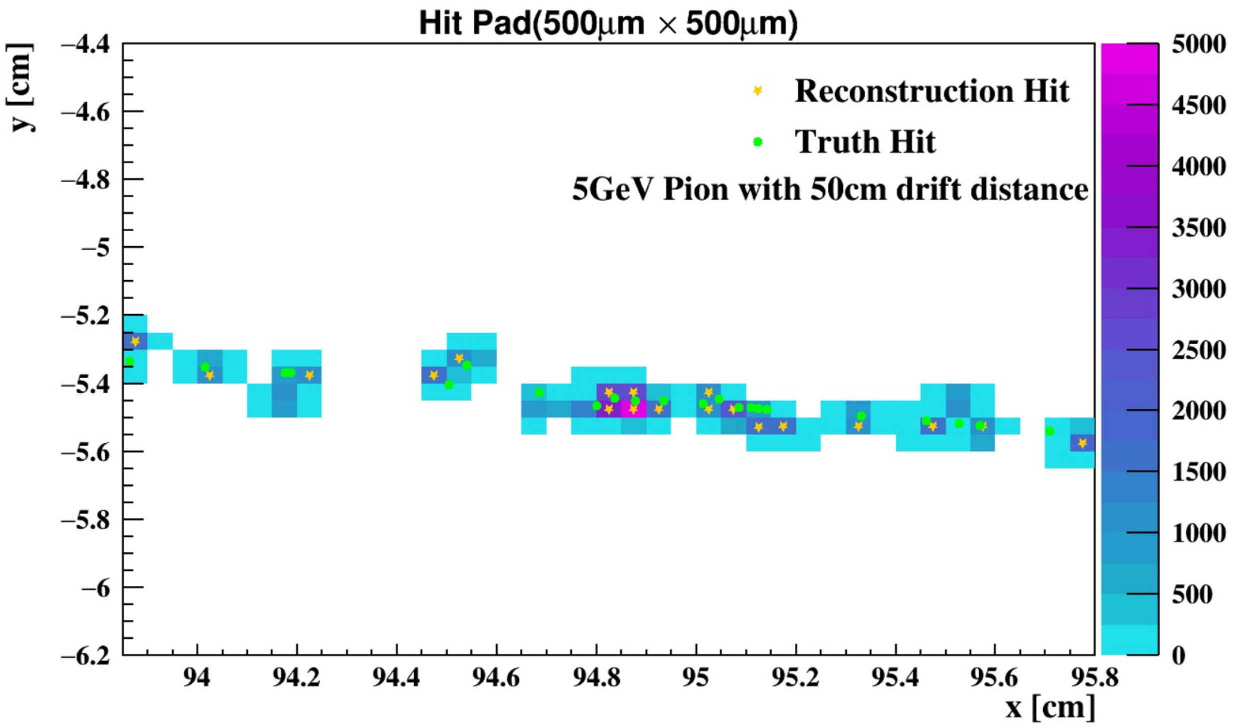

EPJ C 78, 464 (2018)

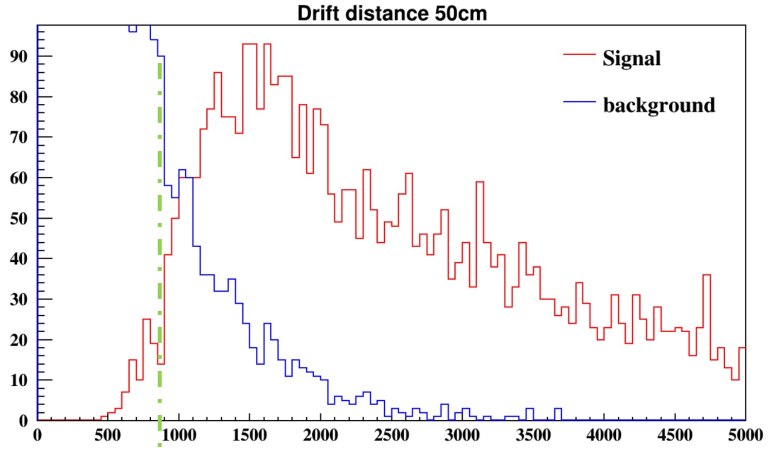


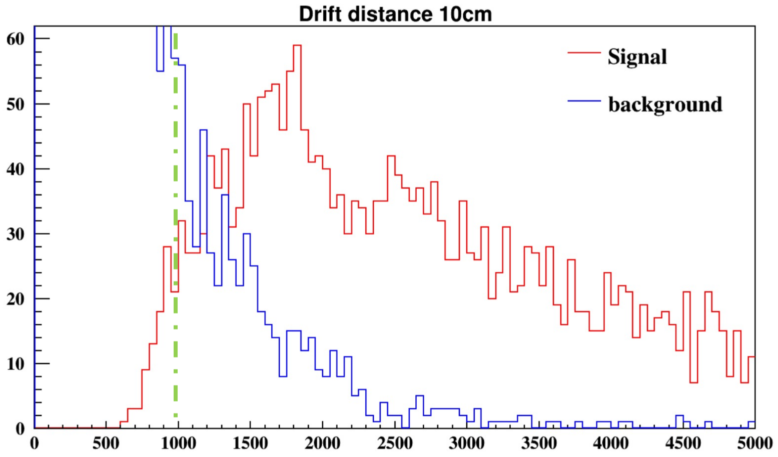

Averaged separation power of dE/dx in hadronic decays at the Z-pole

# Preliminary Cluster Reconstruction

- By using a threshold-based method, preliminary reconstruction of clusters can be achieved
- The drift distance does not affect the threshold setting
- For a 5 GeV pion with 50 cm drift distance ,the reconstruction efficiency can reach 60%.



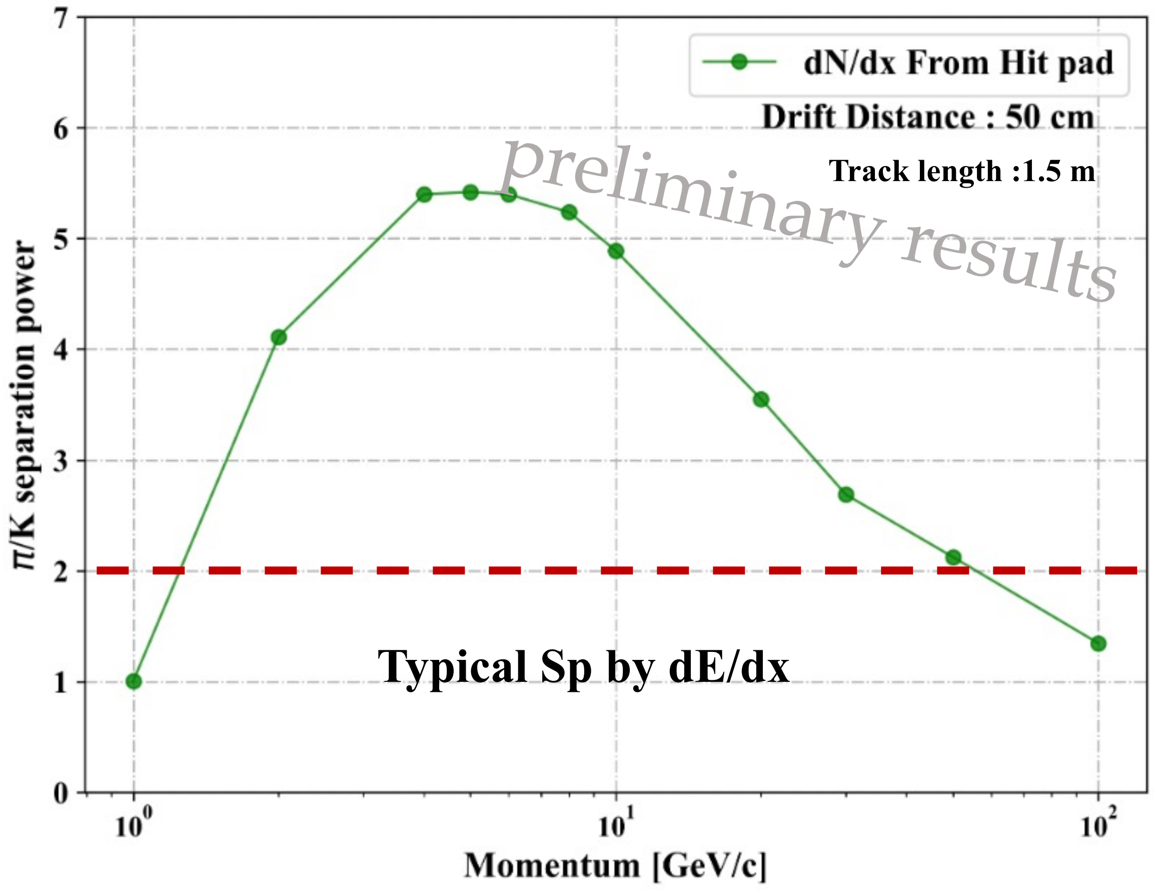



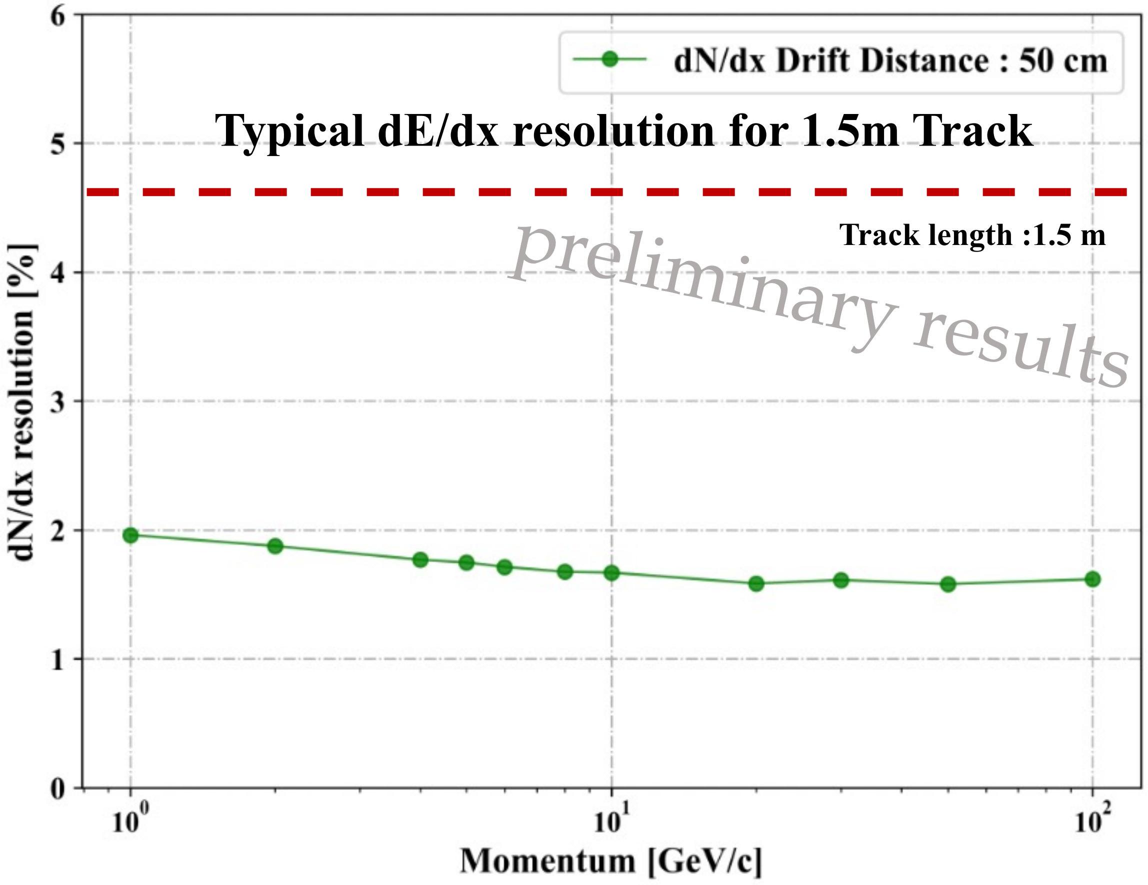



# Preliminary PID Performance

- Investigating the π/K discrimination capability using reconstructed clusters, a 3σ separation at 20GeV with a 50cm drift distance can be achieved
- dN/dx has significant potential for improving resolution

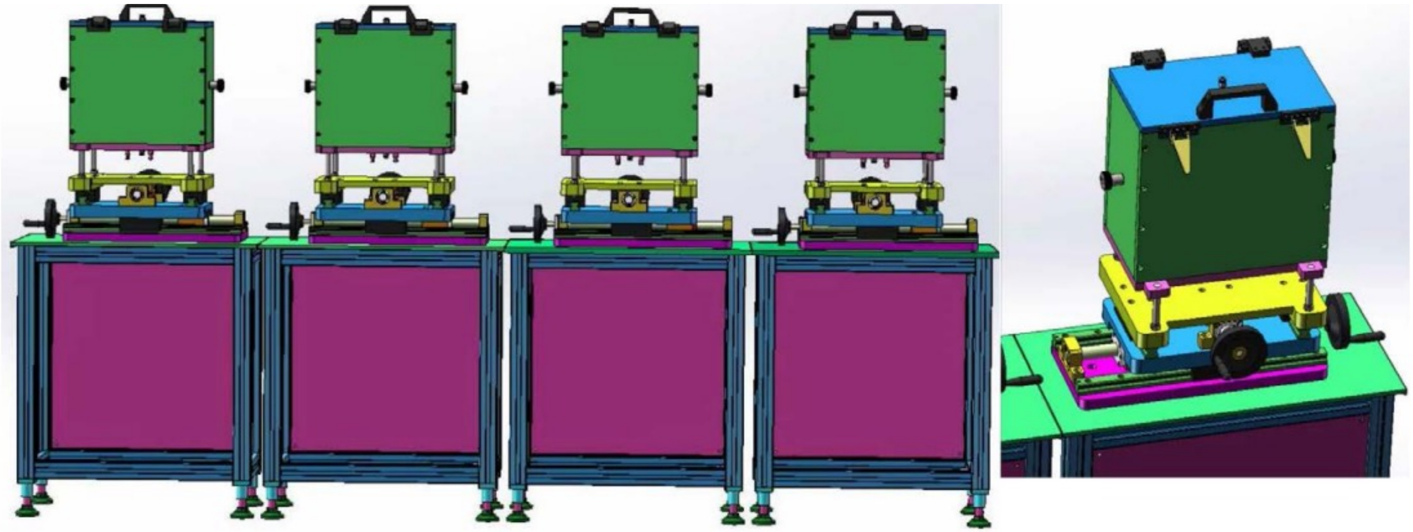
dE/dx res. = **5.4** * $L^{-0.37}$ (%)=5.4*$1.5^{-0.37}$=4.6%

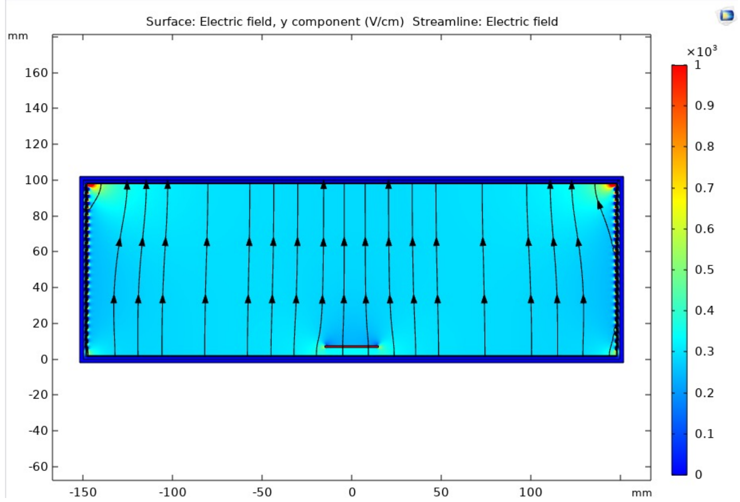


# R&D Plan at IHEP

| Bump bond pixel readout with Micromegas detector | Module size | To be addressed by R&D |
|---|---|---|
| • ≥300 μm×300 μm<br>• Developed the readout chip by Deng Zhi (Tsinghua)<br>• Developed the Micromegas detector sensor at IHEP<br>• Development of the new module and prototype | 1-2 cm$^2$ | • Explore pixel readout technology<br>• Optimization of cluster profile and pixel size<br>• Conduct PID study using $dN_{cl}$+dE/dx |
| | 100 cm$^2$ | • Study the distortion using UV laser tracks and UV lamp to create ions disk<br>• In-situ calibration with UV Laser system<br>• Study of the dE/dx+$dN_{cl}$/dx |





# Current R&D effort

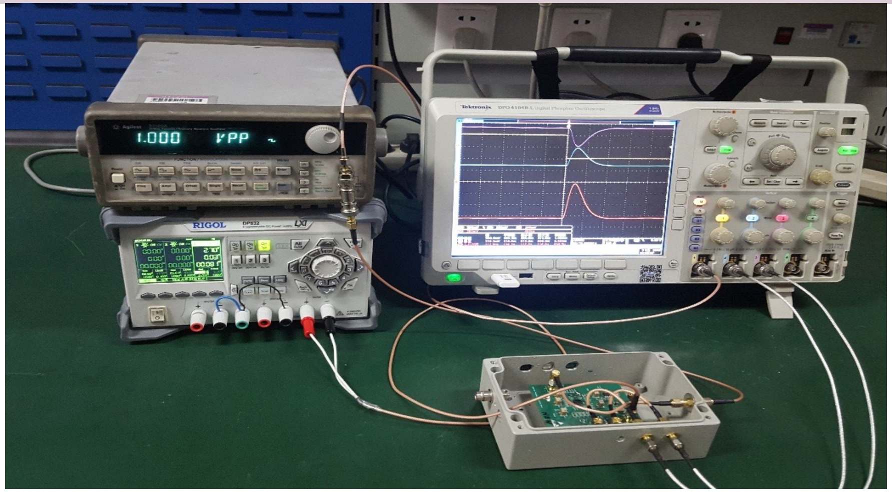
- R&D on pixel TPC readout for CEPC

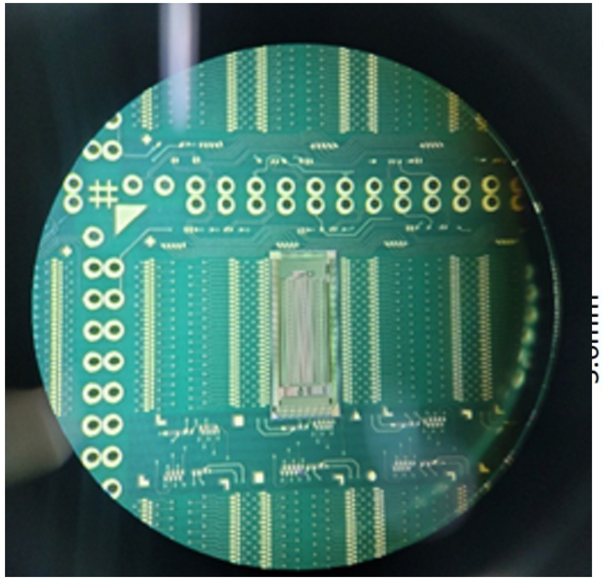
Pixel TPC ASIC chip was started to develop in 2023 and 1st prototype wafer standalone tested in May.

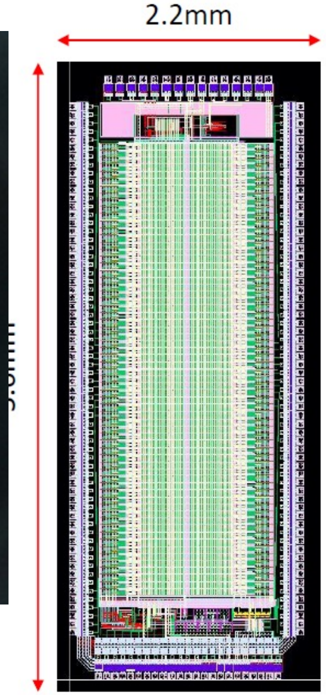
  - ✓ Power consumption: <1.1mW/ch (1st prototype)
  - ✓ <400mW/cm$^2$ (Test)

- 2nd prototype wafer design done
  - ✓ < 100mW/cm$^2$ (Goal and final design)

- The TOA and TOT can be selected as the initiation function in the ASIC chip.






1st readout PCB board and the ASIC layout

# Summary

- Classical PID with dE/dx by TPC charge measurement contributes to many large detectors
  - 5.4% typical dE/dx resolution for 1m track → no miracles to be expected
- Preliminary study show much better PID performance with cluster counting
  - 3σ separation at 20GeV can be achieved
- The pixel readout is an efficient way to count every cluster in space
  - Further simulations are still necessary to understand the detailed requirements of the pixel detector(e.g. More realistic simulation model; More sophisticated reconstruction ; Detector optimization etc.)
  - Pixel R&D is also ongoing currently, with the first prototype wafer undergoing standalone testing in May.
  - new ideas are also welcome

# THANKS !