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Simulation of the high granularity readout TPC at CEPC Phy.&Det.TDR

Yue Chang

Huirong Qi,Guang Zhao, Linghui Wu, Xin She, Chunxu Yu ,Jian Zhang, Hongliang Dai, Zhi Deng, Yulan Li Manqi Ruan, Gang Li, Jianchun Wang, Yuanbo Chen, and some inputs from LCTPC collaboration

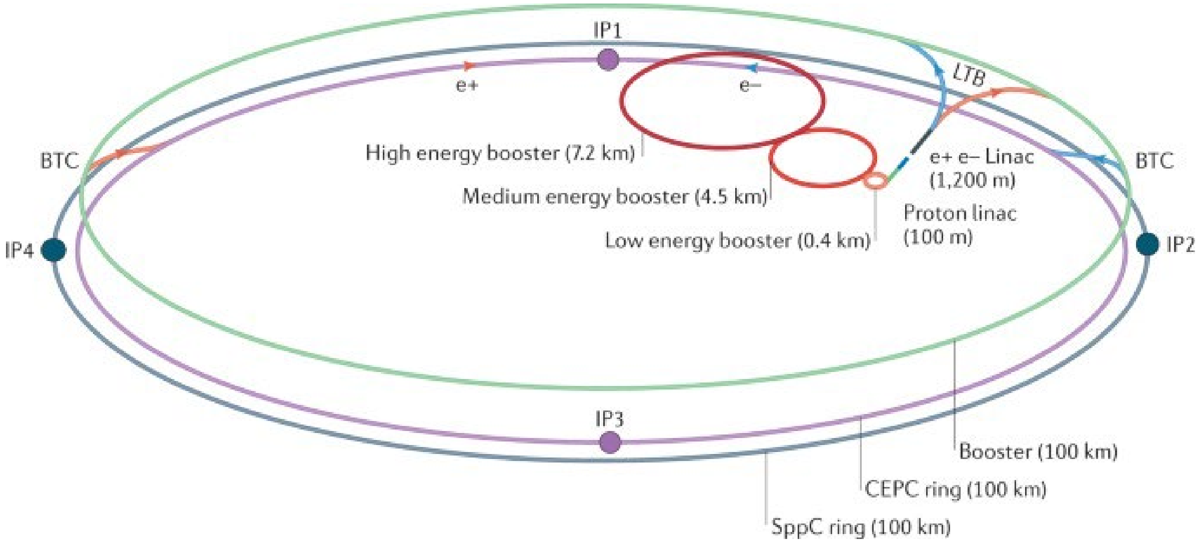
2024 LCTPC Collaboration Meeting , DESY, Mar 12-14, 2024

CONTENTS

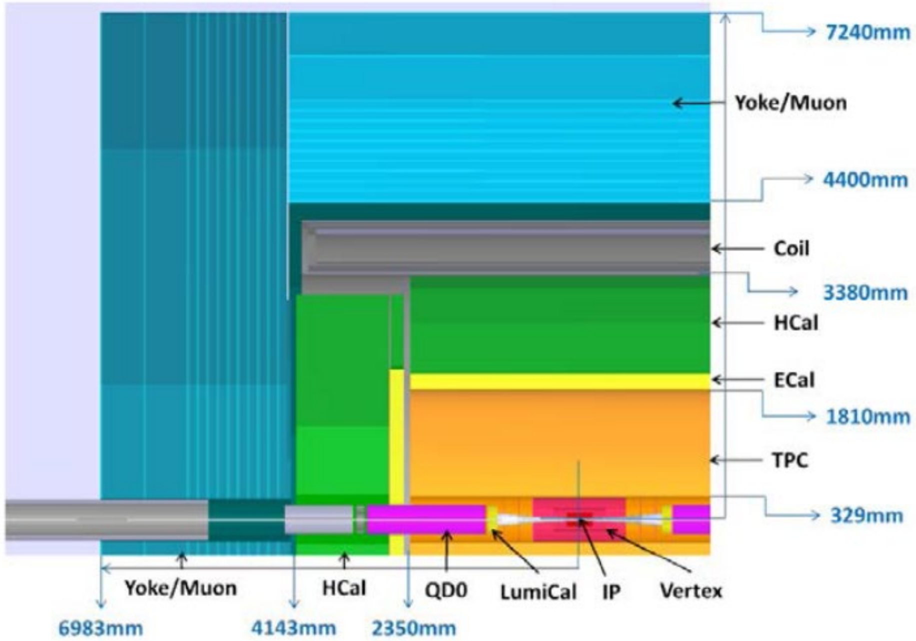
TPC technology for future e+e- Colliders

- 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, CEPC TPC)



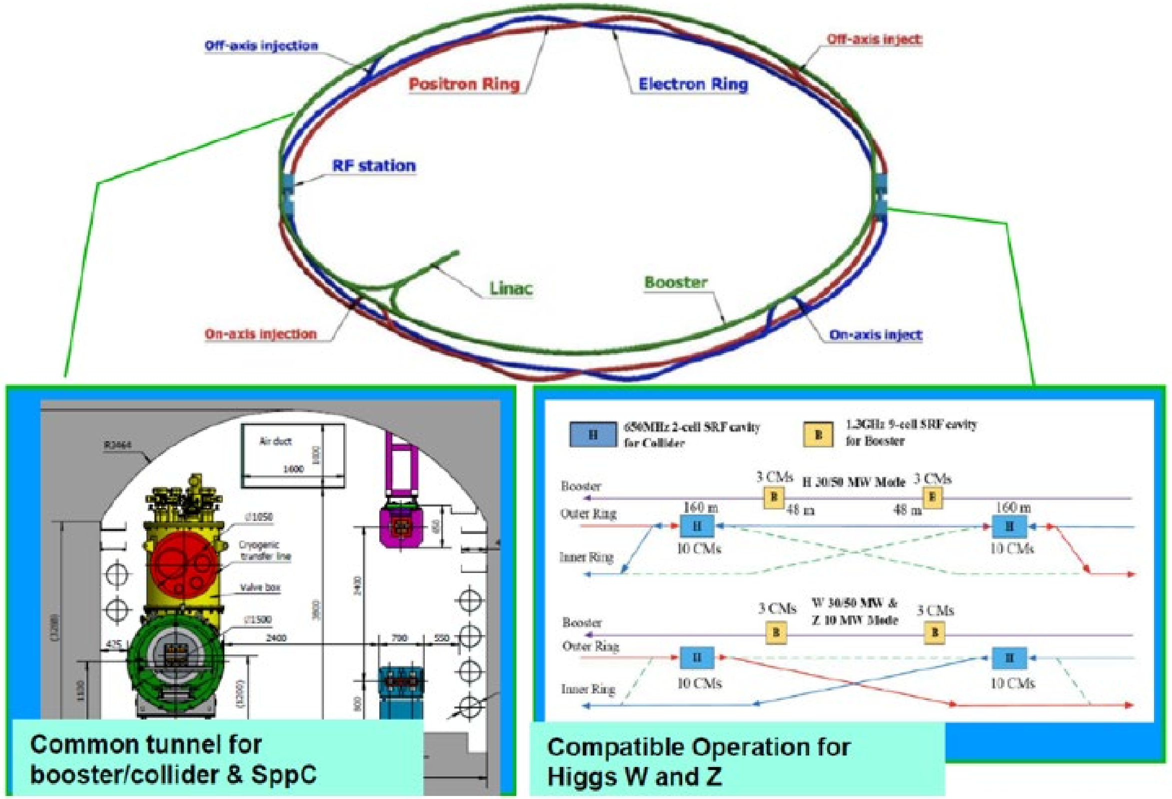
CEPC

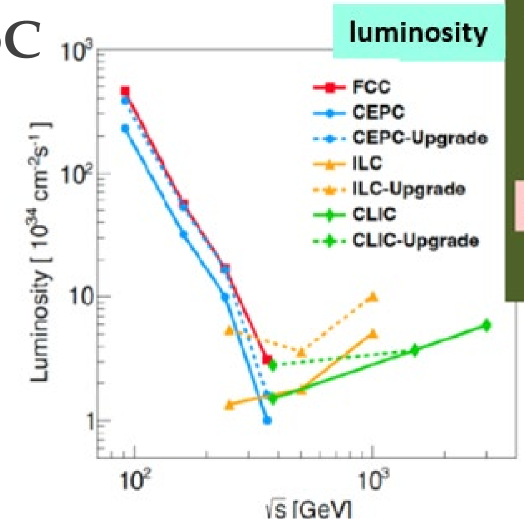


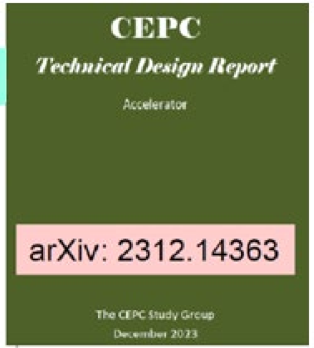
The structure of the baseline CEPC detector design

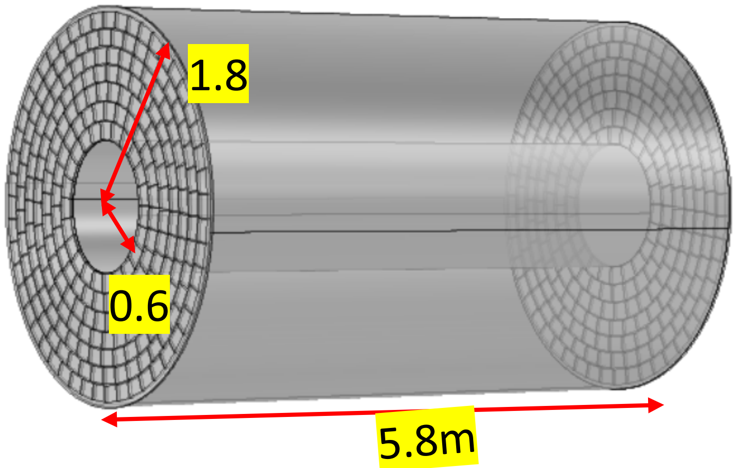
TPC at CEPC TDR Design

- Circular Collider: High luminosity than collider
- 100km circumference: Optium total cost, good also for Sppc
- Shared tunnel: Accommodate CEPC booster & collider and SppC
- Swichable operation： Higgs, W/Z, top









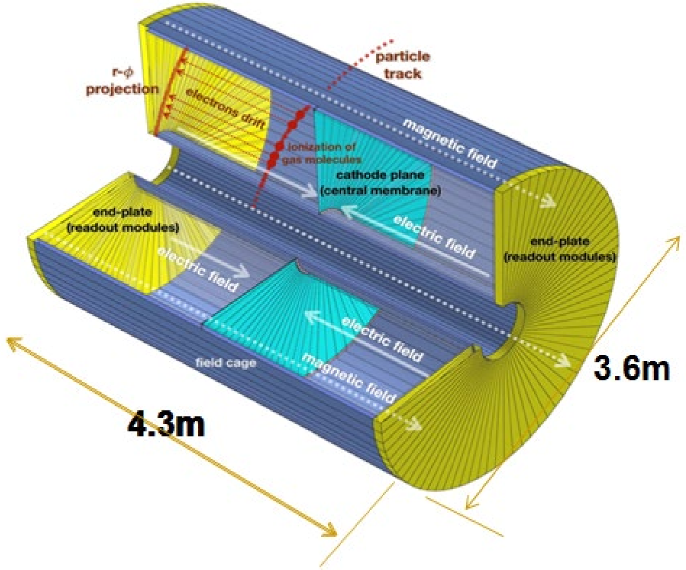
TPC requirements for e+e- Higgs/EW/Top factories

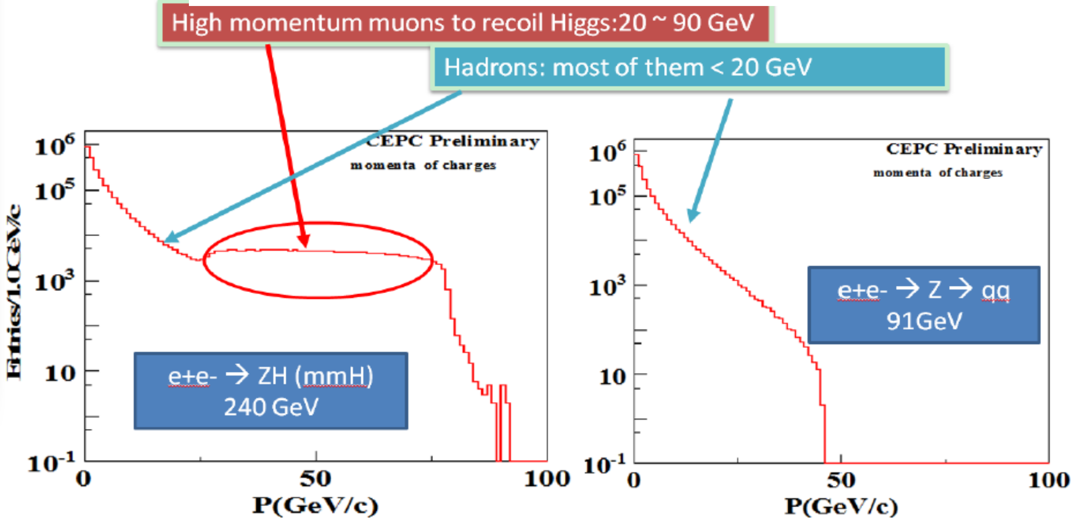
- Provide decent #Hits (for track finding) with high spatial resolution compatible with PFA design
- $\sigma_{1/pt}$~10^{-4}GeV/c^{-1}(TPC alone) and σ_{point} <100 μm
- Provide dE/dx and dN/dx with a resolution < 3%

→ 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

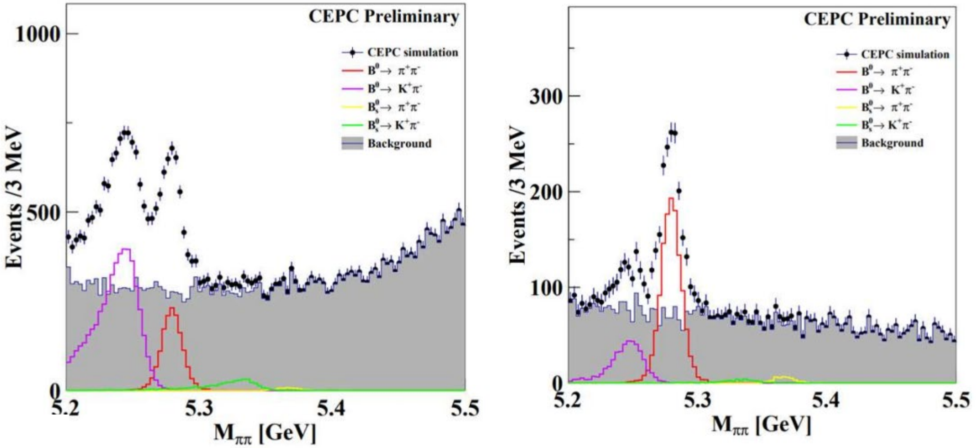
- Physical Target
  - K/π separation power to be above 3σ at a Momentum of 20 GeV/c
    - Improving jet Energy Resolution
    - Beneficial for Flavor @ Z pole

      → 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



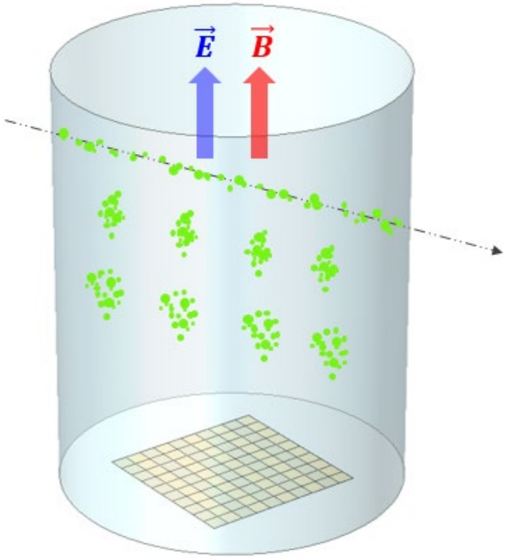
From Xu Gao

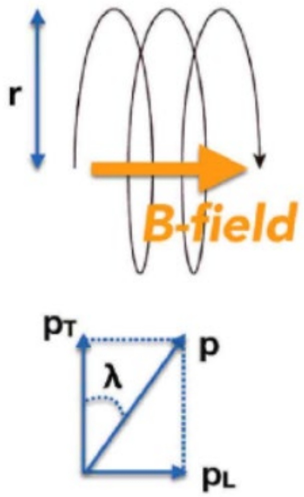
Requirements of TPC

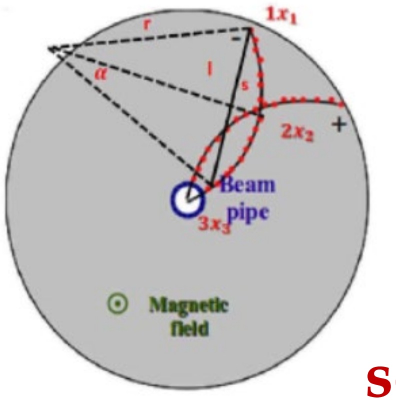
Parameter	
Geometrical parameters	r_{in} 329 mm, r_{out} 1808 mm, z ± 2350 mm
Solid angle coverage	up to $\cos\theta \simeq 0.98$ (10 pad rows)
TPC material budget	$\simeq 0.05\ X_0$ including outer fieldcage in r
	$< 0.25\ X_0$ for readout endcaps in z
Number of pads/timebuckets	$\simeq$ 1-2 $\times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

dE/dx & dN/dx

Classical dE/dx Measurement







$$p_T = 0.3\,Br$$

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

p + dE/dx → 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)

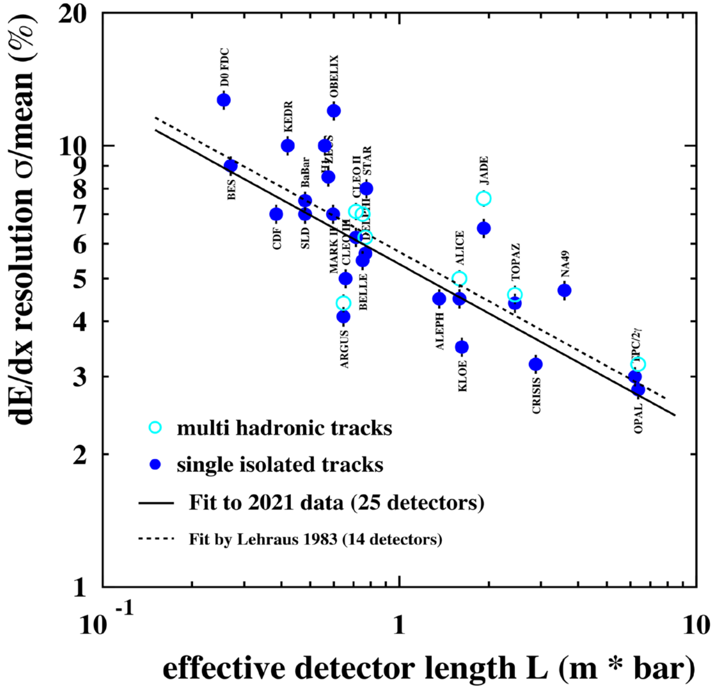
- measure charge per sample along a track
- Long tail worsens the correlation of the measured average energy loss and the particle species
- the fundamental, central problem of all dE/dx measurements by charge summation

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*



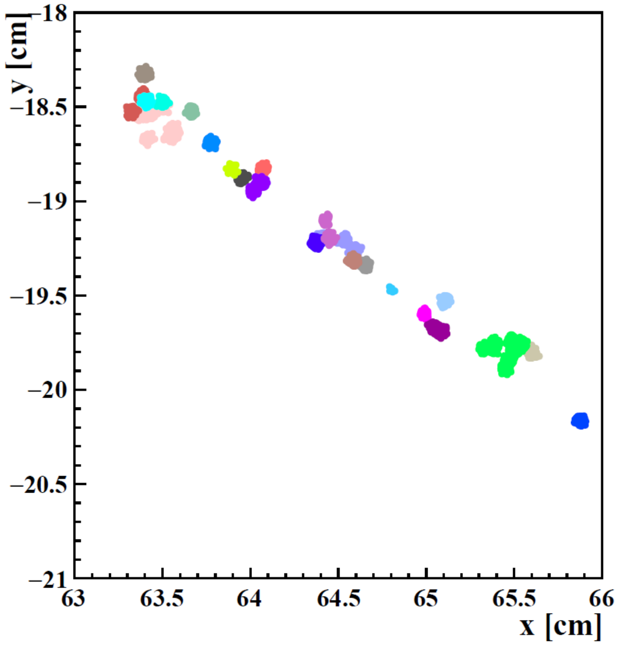
* From Michael Hauschild’s talk @ RD51 workshop

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

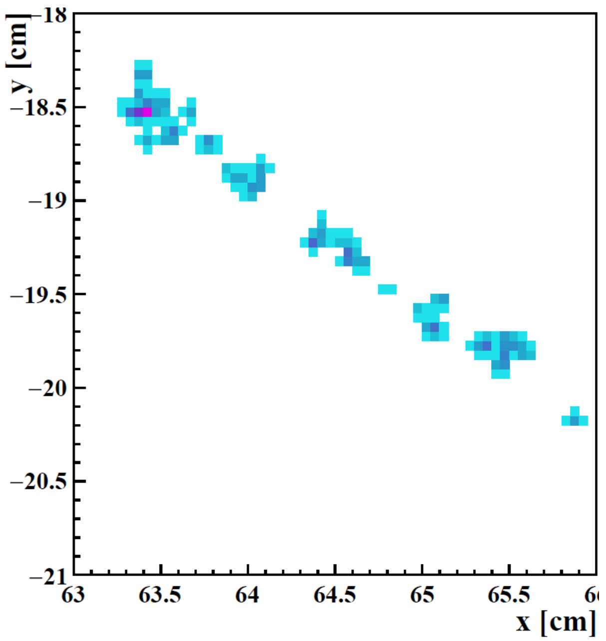
- Obvious problem
  - How to resolve individual clusters and count them?
    - **high cluster density**(~30 cl./cm in Ar mixture for m.i.p → typical drift velocities 50 μm/ns → 6 ~10 ns in between clusters → **fast-shaping electronics (~ns needed) In time**)
  - Need devices with **high time resolution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

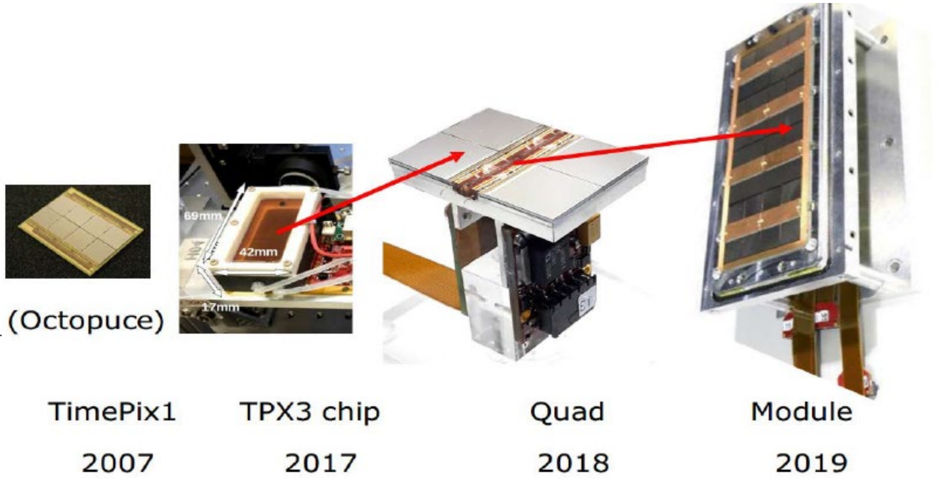


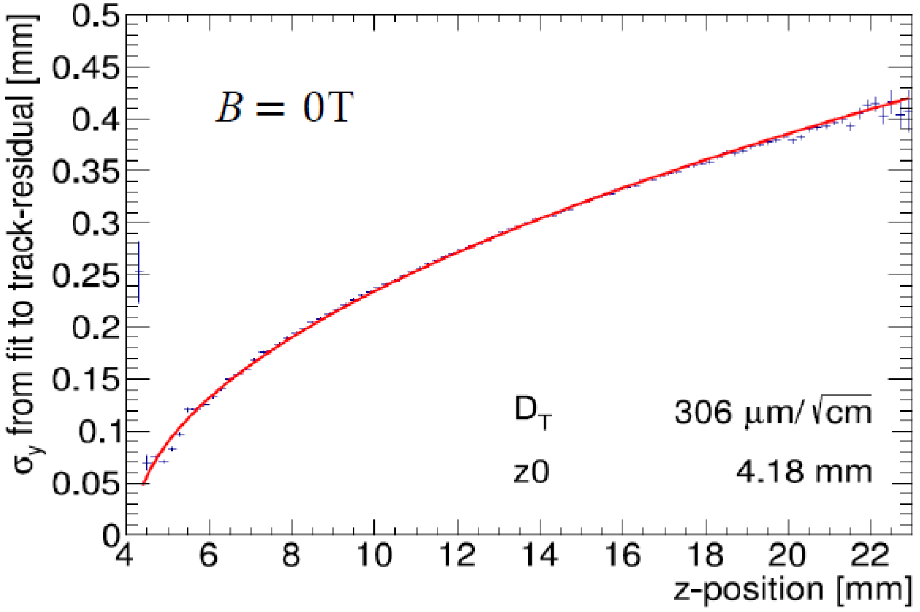
pixel response (500 μm× 500 μm)

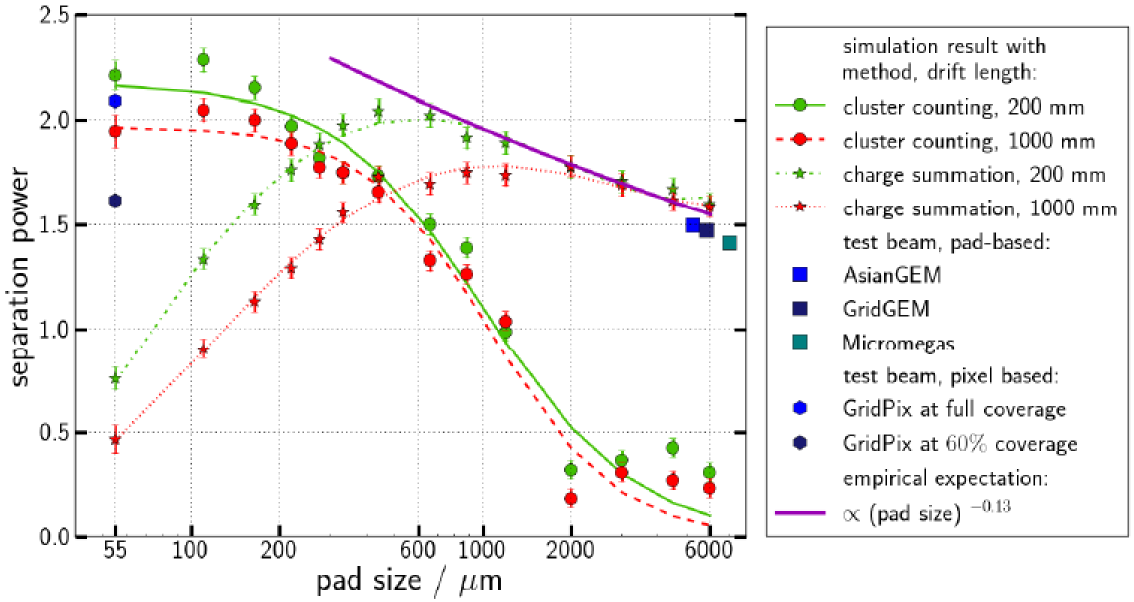
Application of Pixel Readout in LCTPC

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







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

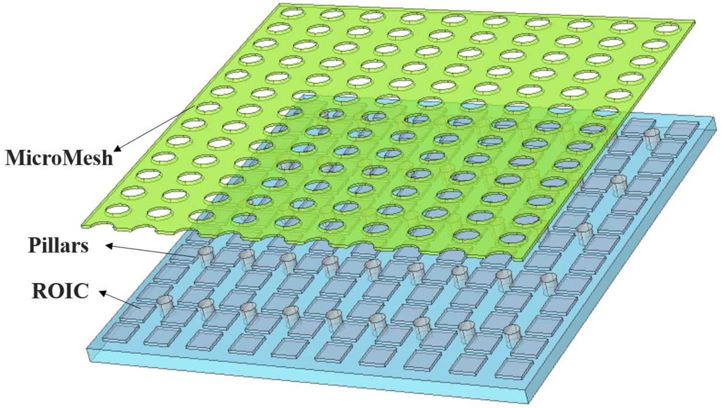
- High granularity readout allows measuring every ionization cluster
- High spatial resolution under 2T or 3T magnetic field
- Better momentum resolution
- High-rate operation (MHz/cm^2)
- Excellent two tracks separation performance

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 : 500 μm × 500 μm
10^6 readout units	10^9 readout units
dE/dx < 5%	dE/dx < 3%
Rate : kHz/cm^2	Rate : MHz/cm^2

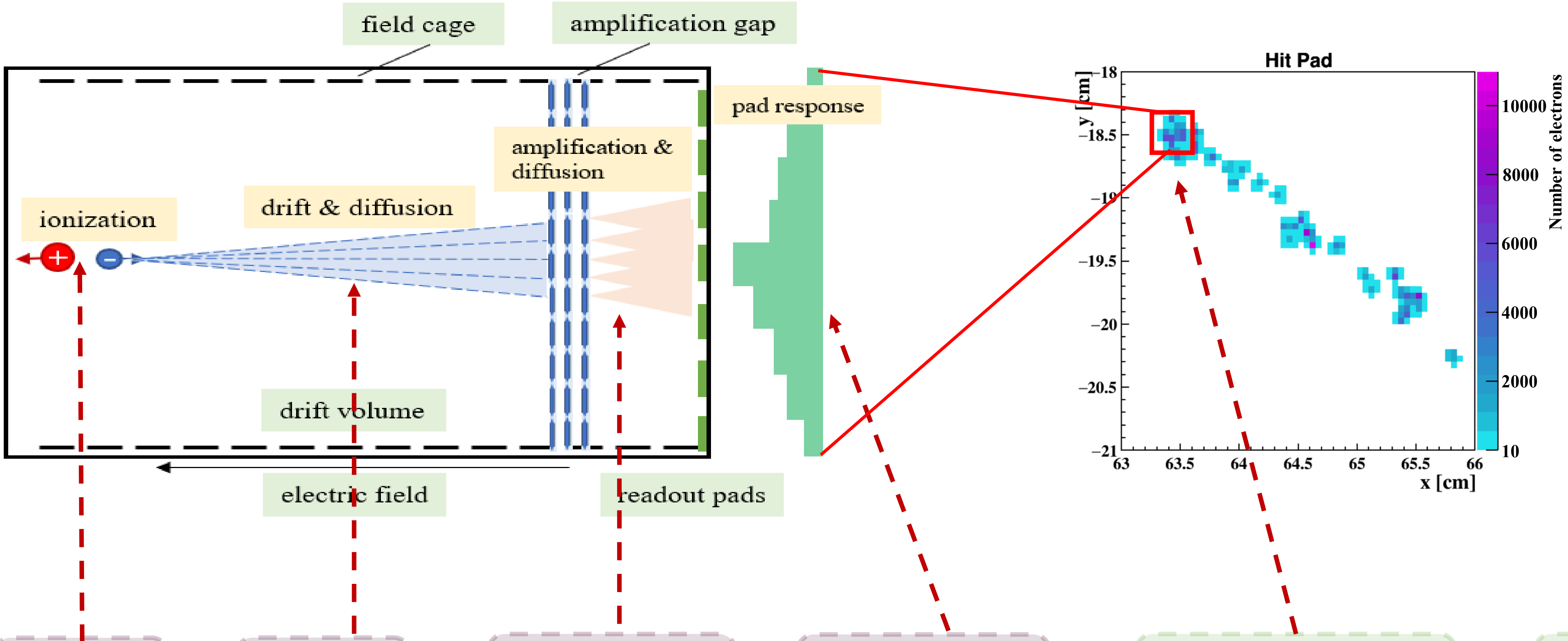
Comparison of Two Readout Methods for CEPC-TPC



schematic diagram of a pixelated readout structure

Simulation of pixel TPC

Full Simulation Framework of Pixel TPC



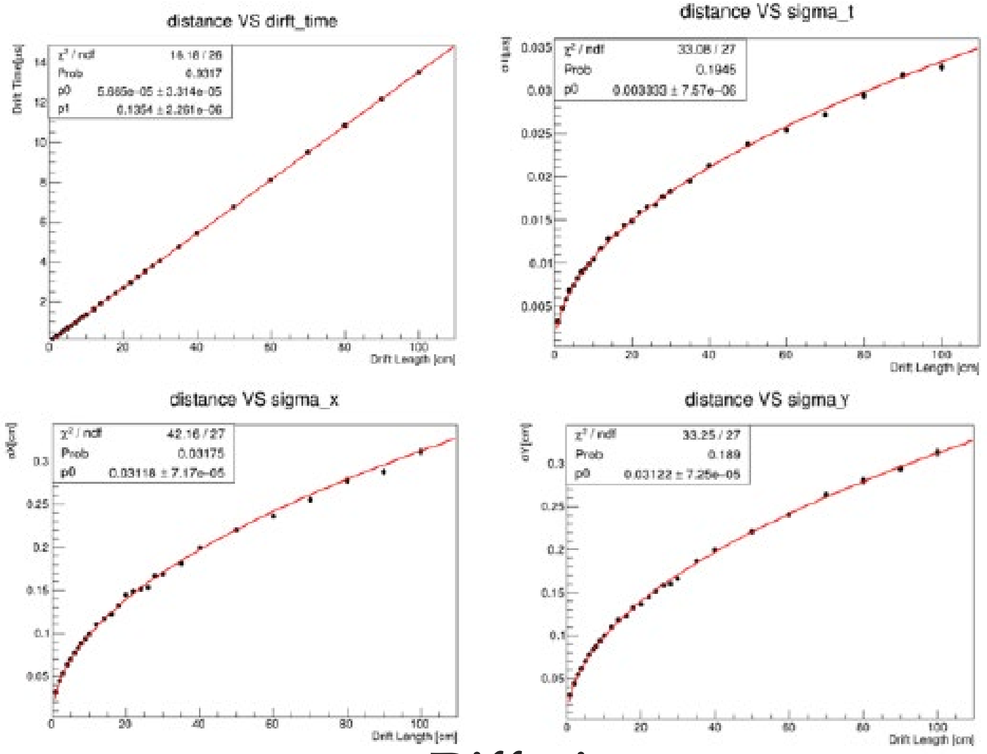
Ionizatin → Drift → Amplification → Signal Generation → Hit Detection & Clustering → dN/dx

Simualtion / Digitization

Reconstruction

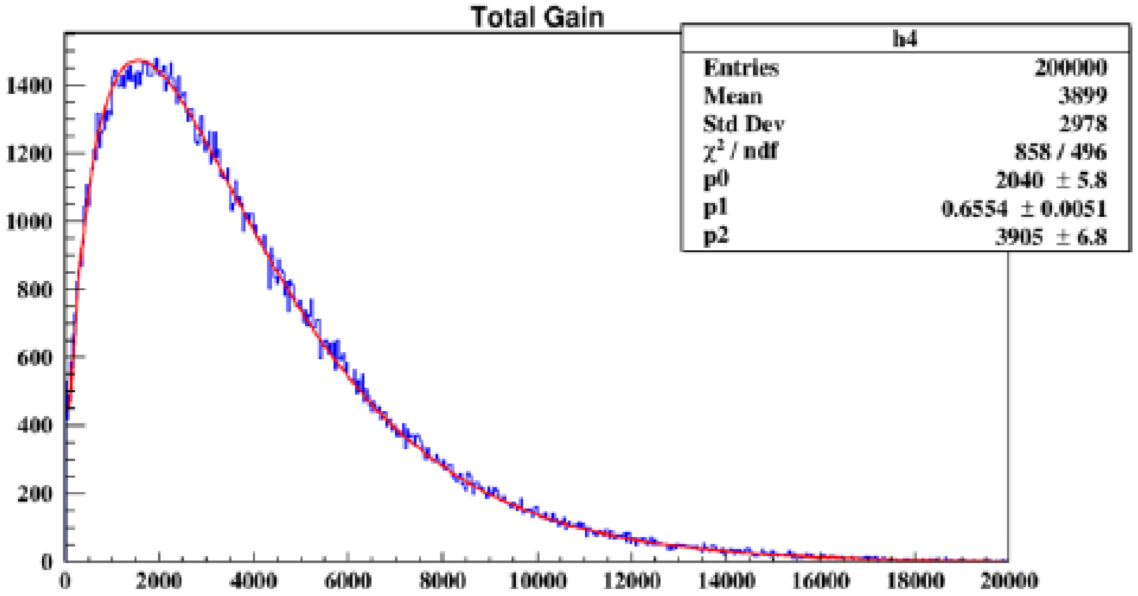
Parametrizations

- To speed up the simulation, make several decompositions and apply parametrized models
- **Electron diffusion:**
  - σ_T vs drift distance
  - σ_X vs drift distance
  - σ_Y vs drift distance



Diffusion

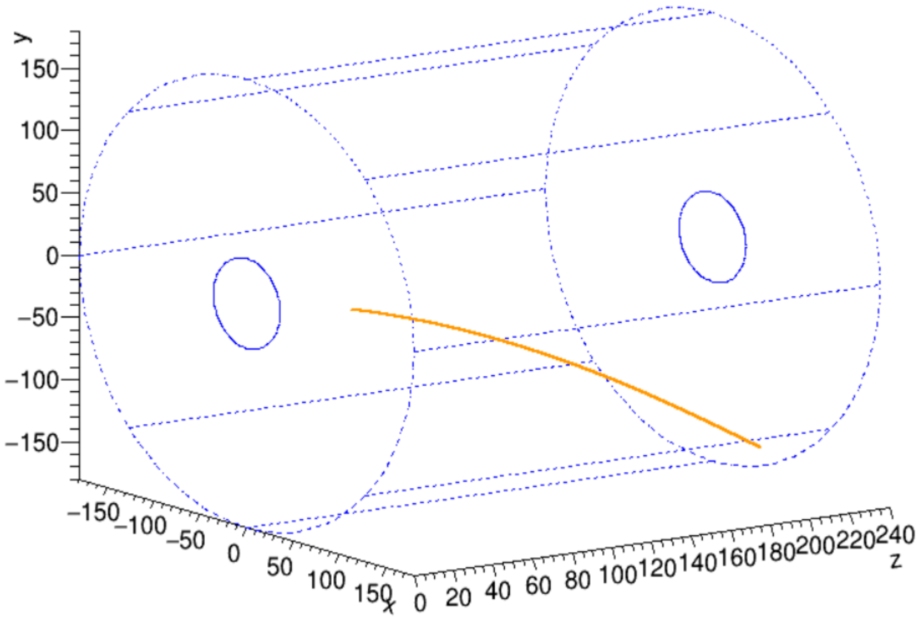
- **Amplification:**
  - Polyafunction sampling
- **Signal generation**
  - Double-Gaussian sampling



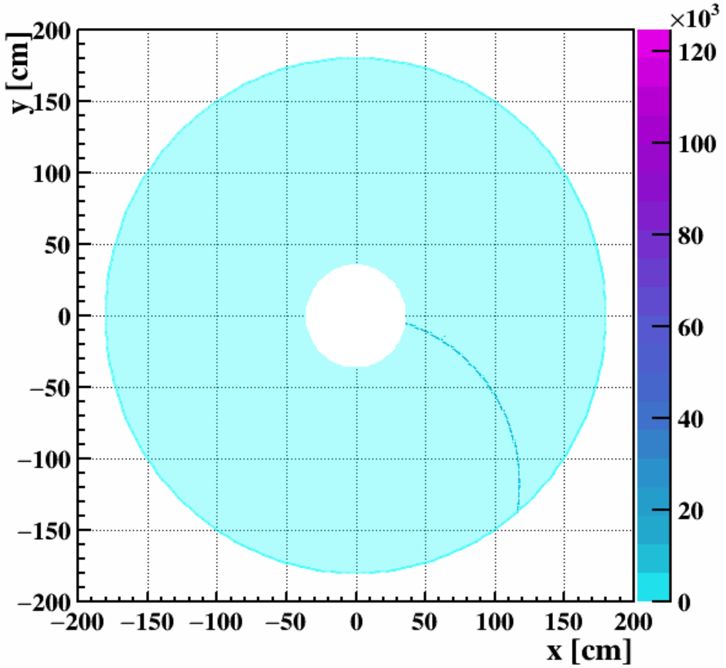
Amplification

Simulation setup

- Magnetic field: 2T (Z-pole run)
- Gas mixture: T2K ($Ar/CF_4/iC_4H_{10}$: 95/3/2)
- Detector Layout : R (0.6 m 1.8 m); L (2.9 m)



A track of 1 GeV/c pion in TPC



Projection of the same track on endplate

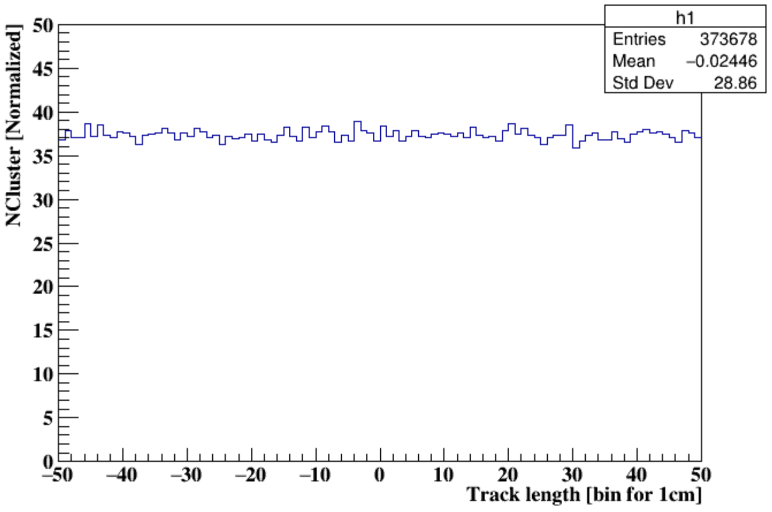
Simulation of the primary cluster

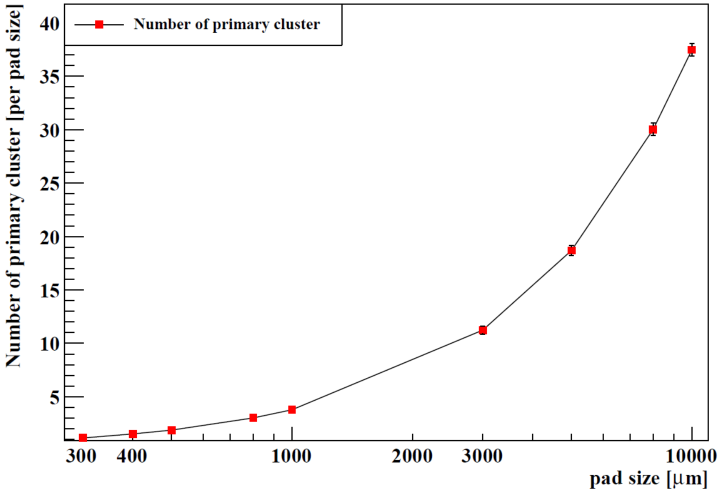
Heed Simulation

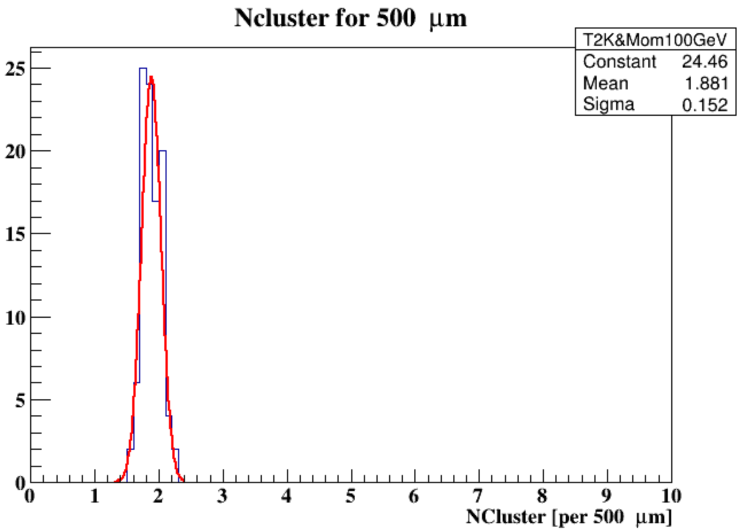
- The distribution of clusters is uniform along the track
- Typically ~30 primary ionization clusters/cm in gas at 1 bar → T2K :37.4cluster/cm
- ~1.9 clusters/ 500 μm , ~1.2 clusters/ 300 μm

More detailed research is needed

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



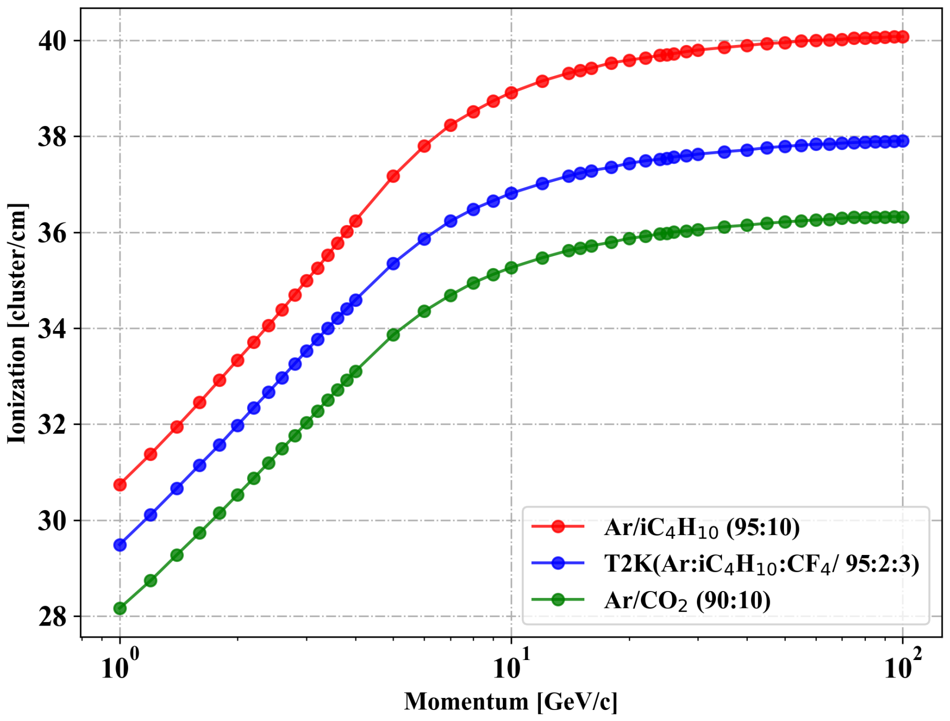


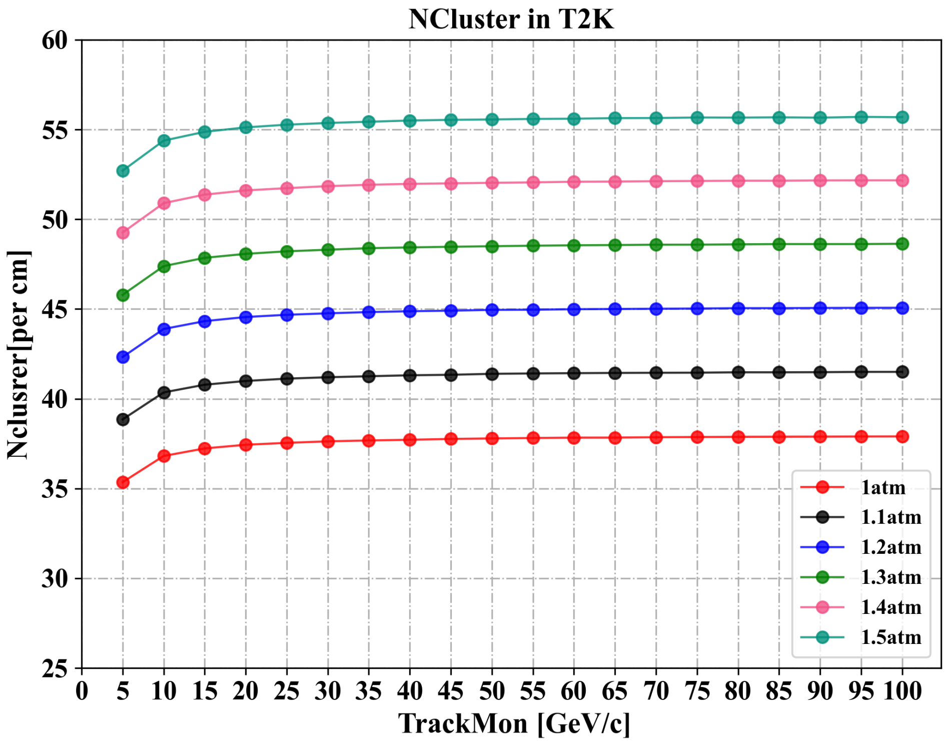


Pad size = 500 um Ncluster/cm

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



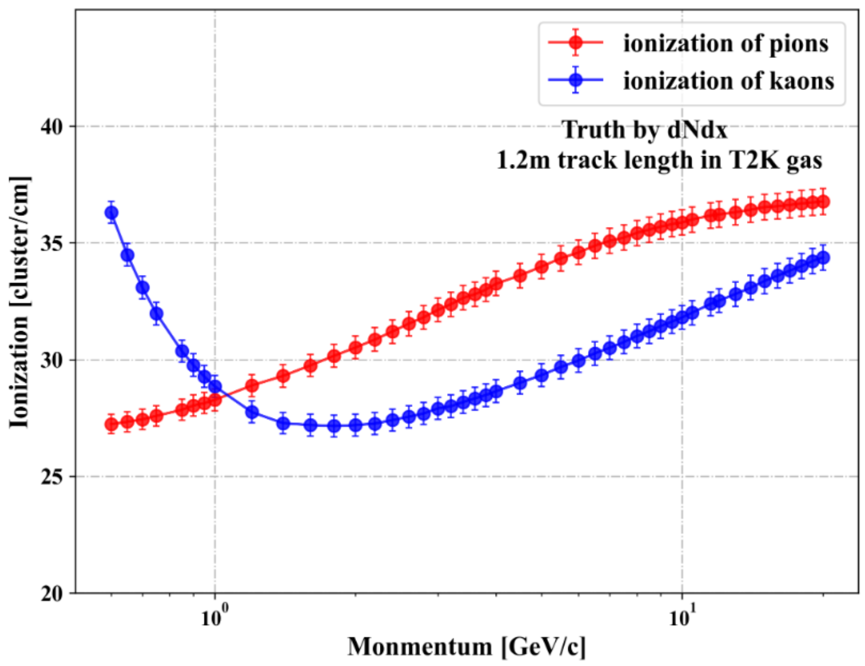


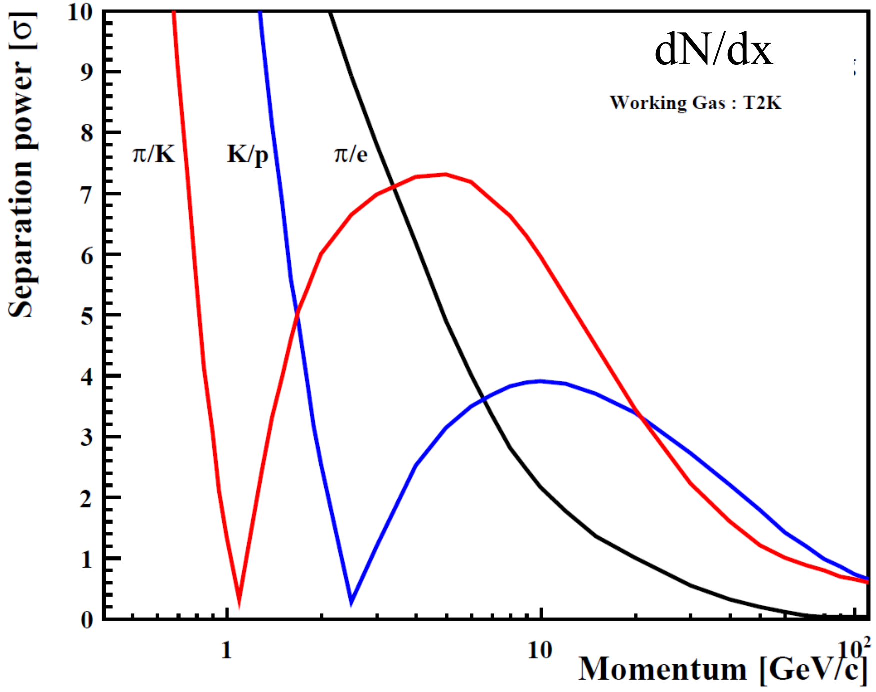
Particle Separation from MC Truth

- 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
  - **Cluster counting exhibits excellent potential for particle identification**

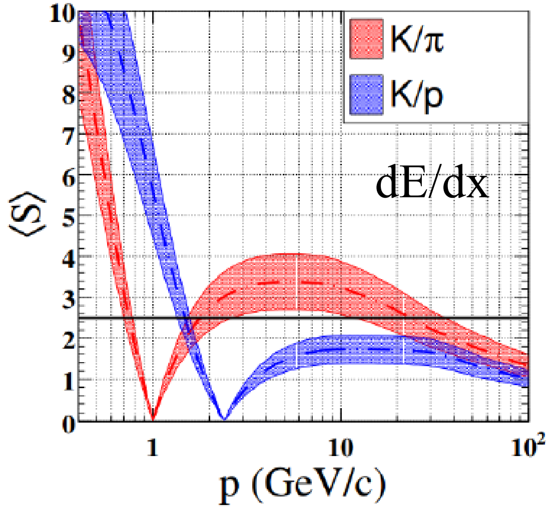
Number of Primary Ionization Clusters per Unit Distance

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





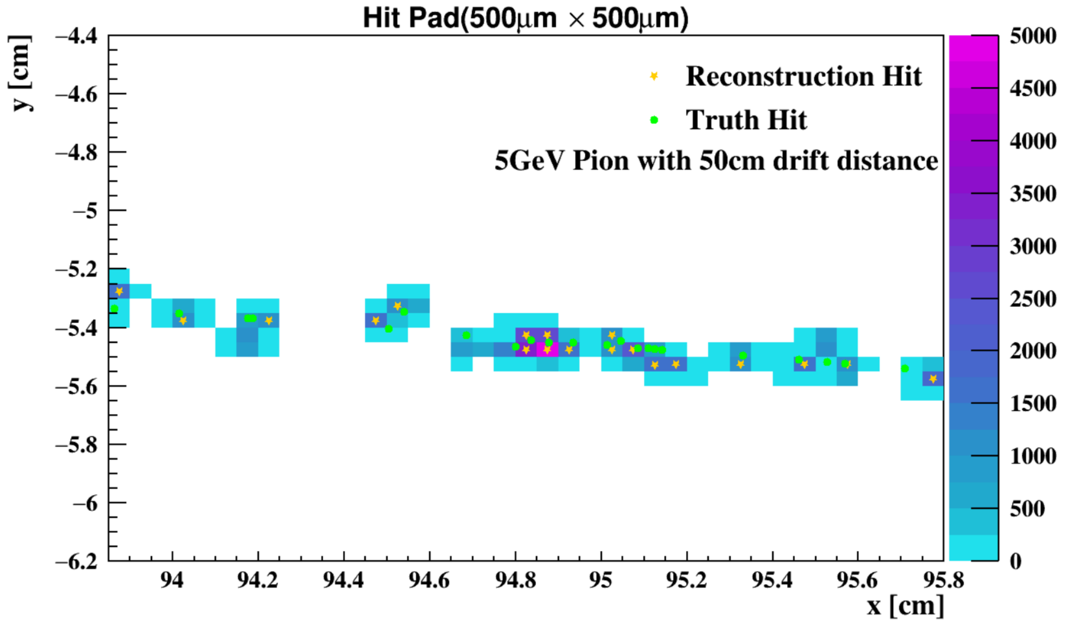
EPJ C 78, 464 (2018)

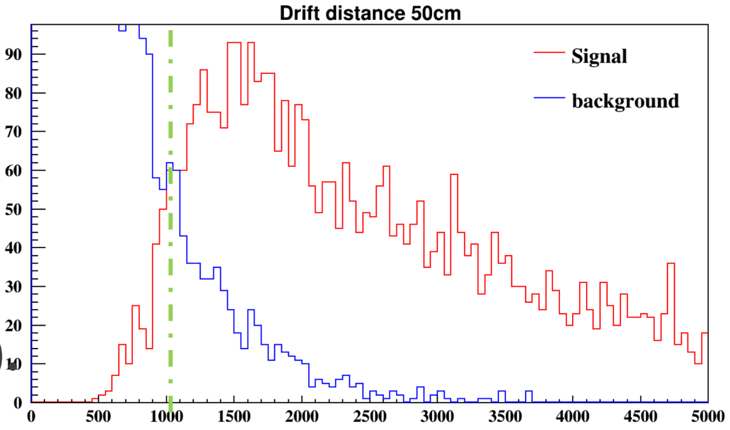


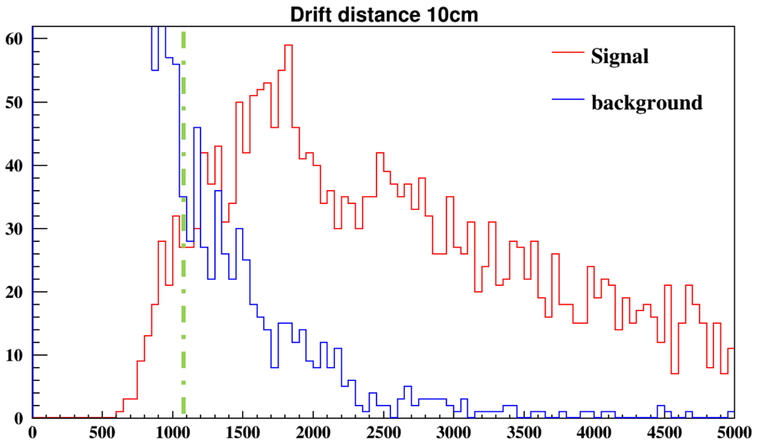
Averaged separation power of dE/dx in hadronic decays at the Z-pole

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
- The reconstruction efficiency is related to the particle drift distance and requires calibration. (The reconstruction efficiency is 90% when the drift distance is 100 cm, and 60% when the drift distance is 50 cm).

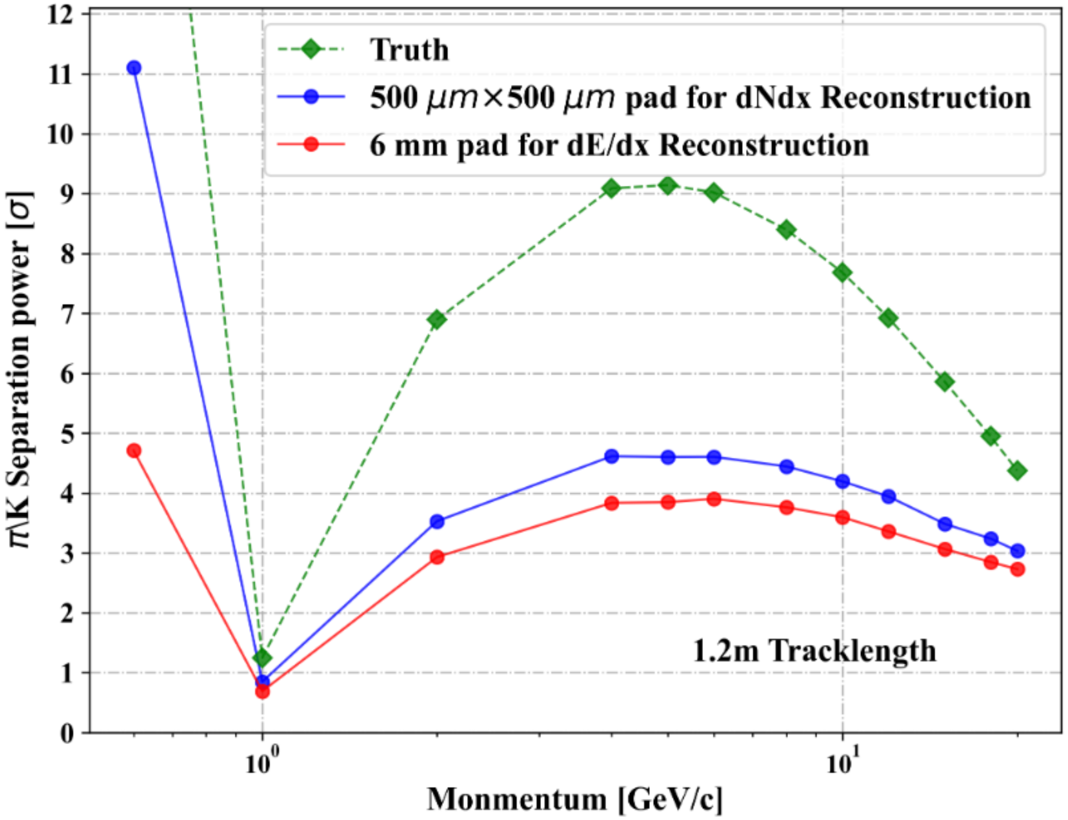


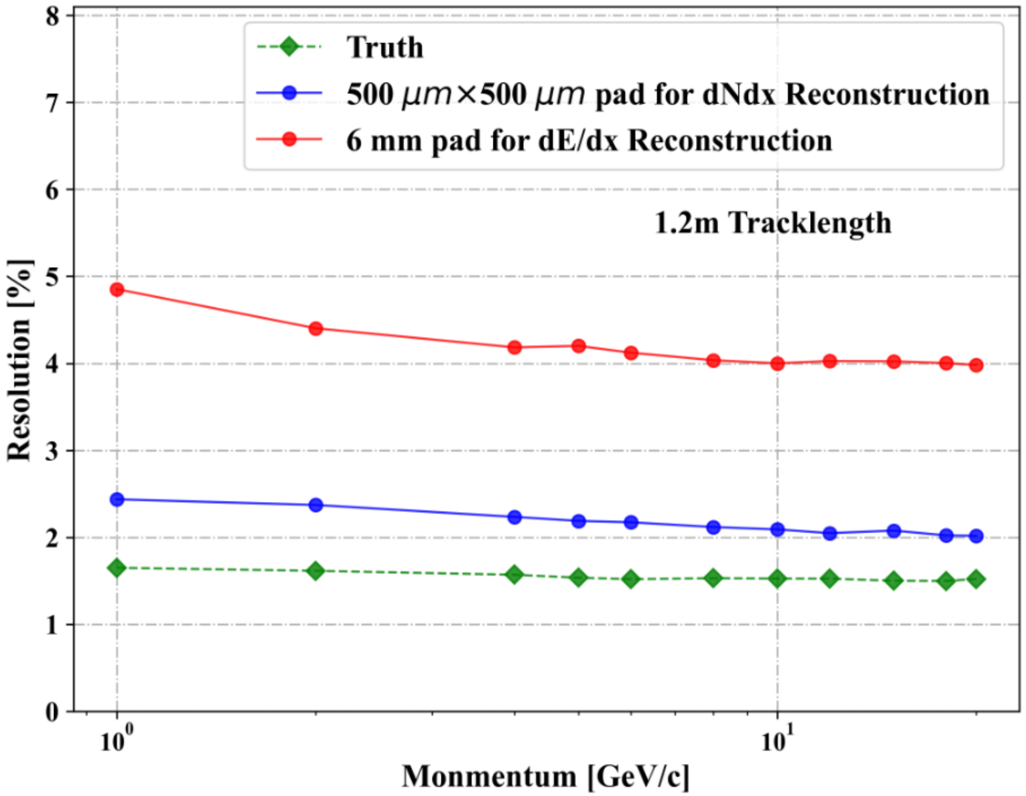




Preliminary PID Performance

- 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

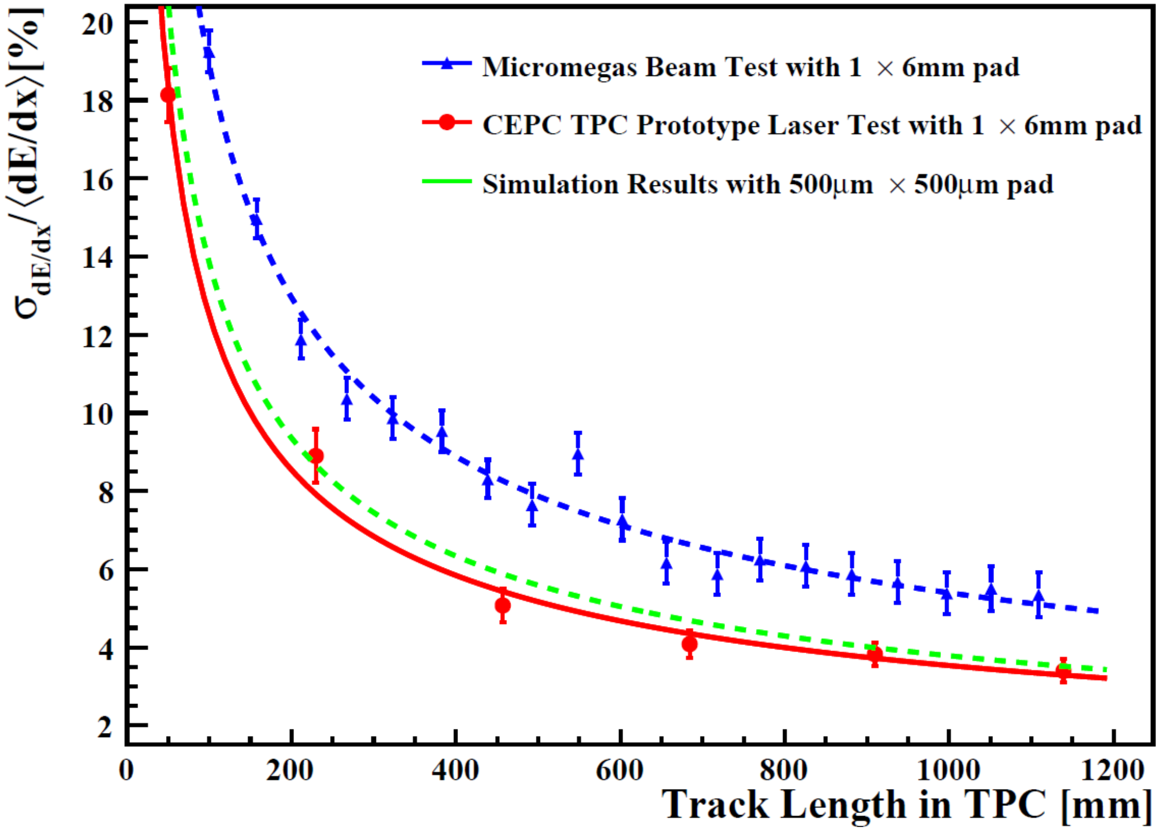


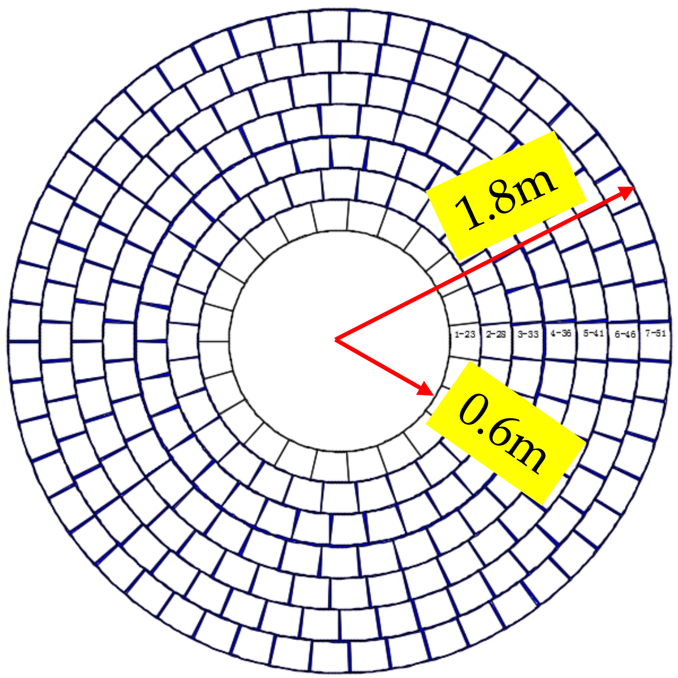


Preliminary dE/dx Performance

- A higher granularity is also very helpful for improving dE/dx.
- According to simulation results, for a pad size of 500um, with the current 1.2-meter track length of CEPC, the dE/dx can reach 3.2%.

$$\sigma_{dE/dx} \sim L^{-0.47} \times G^{-0.13}$$





Current R&D effort

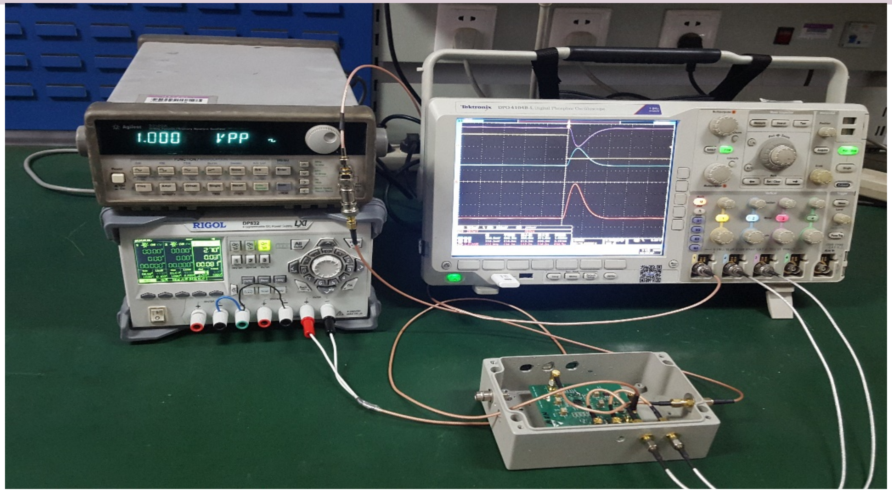
- R&D on pixel TPC readout for CEPC

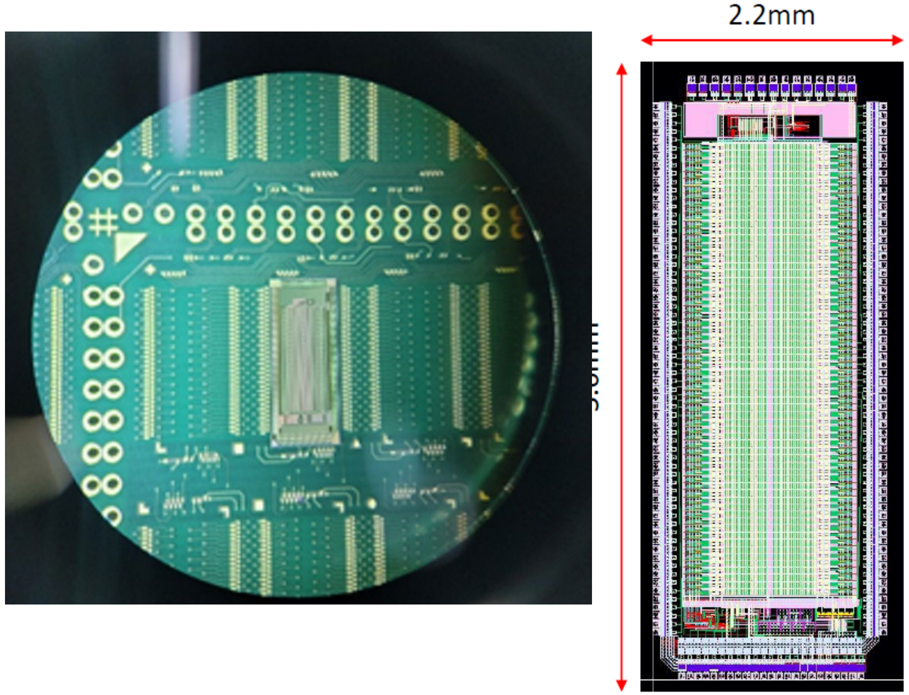
Pixel TPC ASIC chip was started to develop in 2023 and 1st prototype wafer standalone tested in May.

  - ✓ 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.
  - This work will contribute to the upcoming release of the CEPC TDR in 2024.
  - new ideas are also welcome

THANKS!