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Pixelated readout gaseous detector for PID

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and some inputs from LCTPC collaboration

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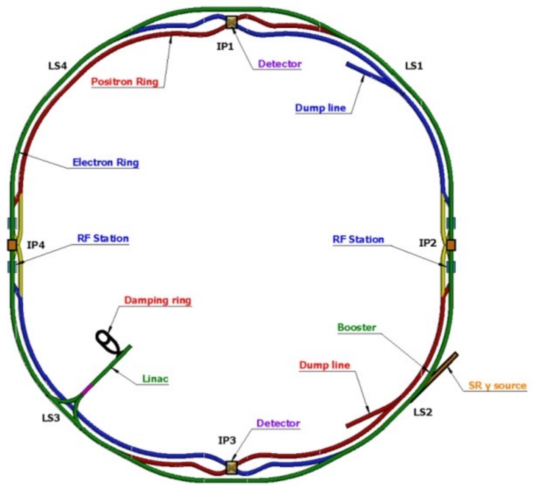
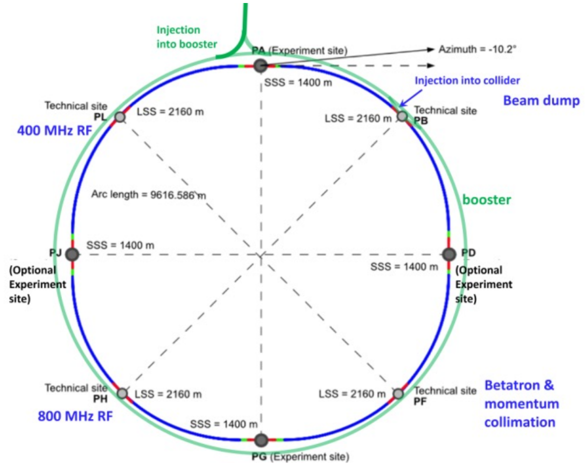
TPC technology for future e+e- Colliders

- Some advantages of TPC detector
  - Operation under **3&2 T magnetic field**
  - Capturing a large number of 3D space points
  - Possessing excellent pattern recognition capabilities
  - Ideal for 3D tracking and PID

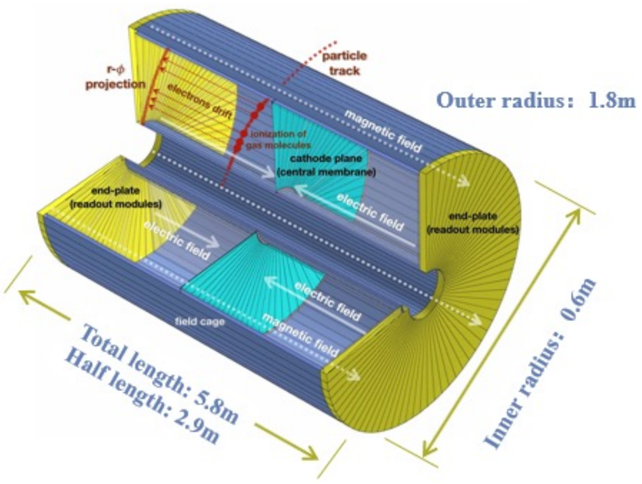
- TPC detector plays a crucial role in the future e+e- Colliders
- Significant R&D already underway (LCTPC, CEPC TPC)



Circular Electron Positron Collider CEPC



Future Circular Collider (FCC-ee)



CEPC TPC

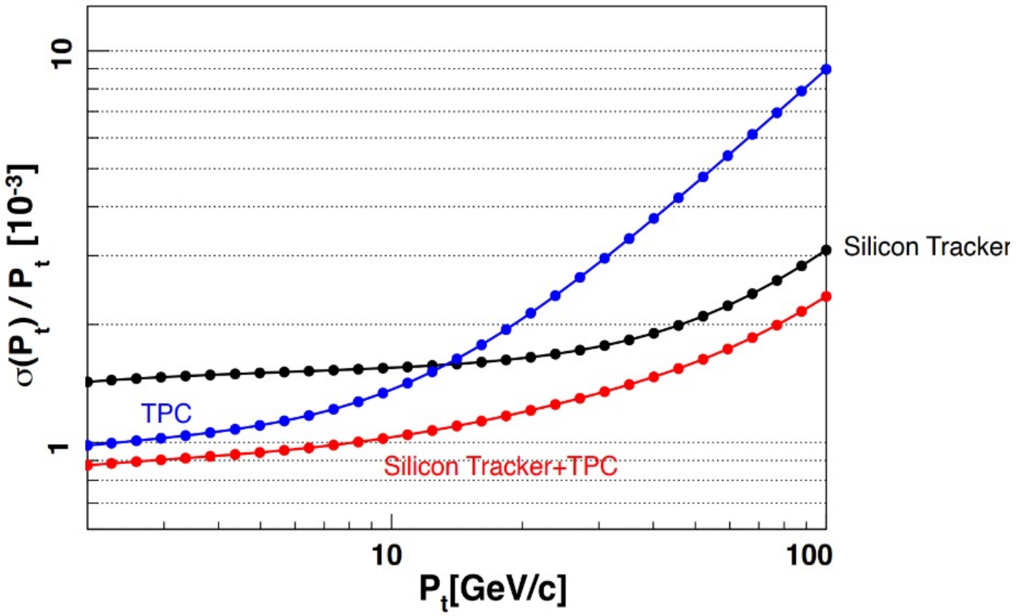
CEPC Physics Requirement

- CEPC Operation stages in TDR: **10-years Higgs → 2-years Z pole → 1-year W**
- Phys. Requirements of the track detector
  - Handle thousands of hits with high spatial resolution, compatible with the PFA algorithm
  - $\sigma_{1/pt} \sim 10^{-4} GeV/c^{-1}$ (TPC alone) and $\sigma_{point} < 100\ \mu m$
  - Provide dE/dx and dN/dx with a resolution < 3%

→ Effectively improve the Particle ID

Sub-detector	Key technology	Key Specifications
Silicon vertex detector	Spatial resolution and materials	$\sigma_{r\phi} \sim 3\ \mu m$, $X/X_0 < 0.15\%$ (per layer)
Silicon tracker	Large-area silicon detector	$\sigma(\frac{1}{p_T}) \sim 2 \times 10^{-5} \oplus \frac{1 \times 10^{-3}}{p \times \sin^{3/2}\theta} (GeV^{-1})$
TPC/Drift Chamber	Precise dE/dx (dN/dx) measurement	Relative uncertainty 3%
Time of Flight detector	Large-area silicon timing detector	$\sigma(t) \sim 30$ ps
Electromagnetic Calorimeter	High granularity 4D crystal calorimeter	EM energy resolution $\sim 3\%/\sqrt{E(GeV)}$ Granularity $\sim 2 \times 2 \times 2\ cm^3$
Magnet system	Ultra-thin High temperature Superconducting magnet	Magnet field 2 − 3 T Material budget $< 1.5 X_0$ Thickness < 150 mm
Hadron calorimeter	Scintillating glass Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(GeV)}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(GeV)}$

Physics Requirement on CEPC Detectors



Particle Identification Requirements

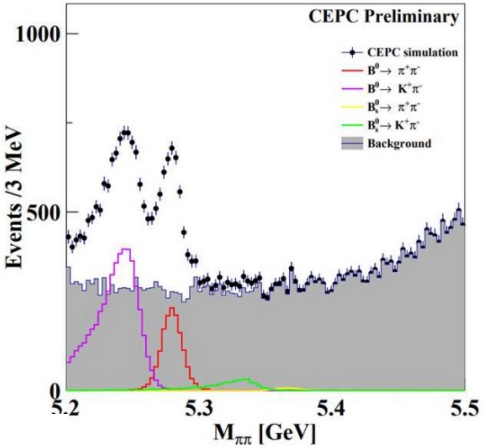
- Physical Target
  - The goal is to achieve a K/π separation power above 3σ at a momentum of 20 GeV/c
    - Improving jet Energy Resolution
    - Beneficial for Flavor @ Z pole

      → better b-tagging and c-tagging capabilities

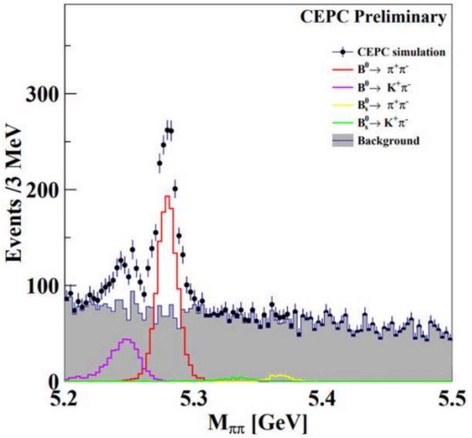
      → D meson spectroscopy (kaon/pion separation)

Simulation B^0/B_s^0 using Delphes

Without PID



With PID



From Xu Gao

Differential Material Budget.
Requirement: < 10%/50% X0 in Barrel/endcap
Ref: CDR baseline design + BMR & Material Dependence

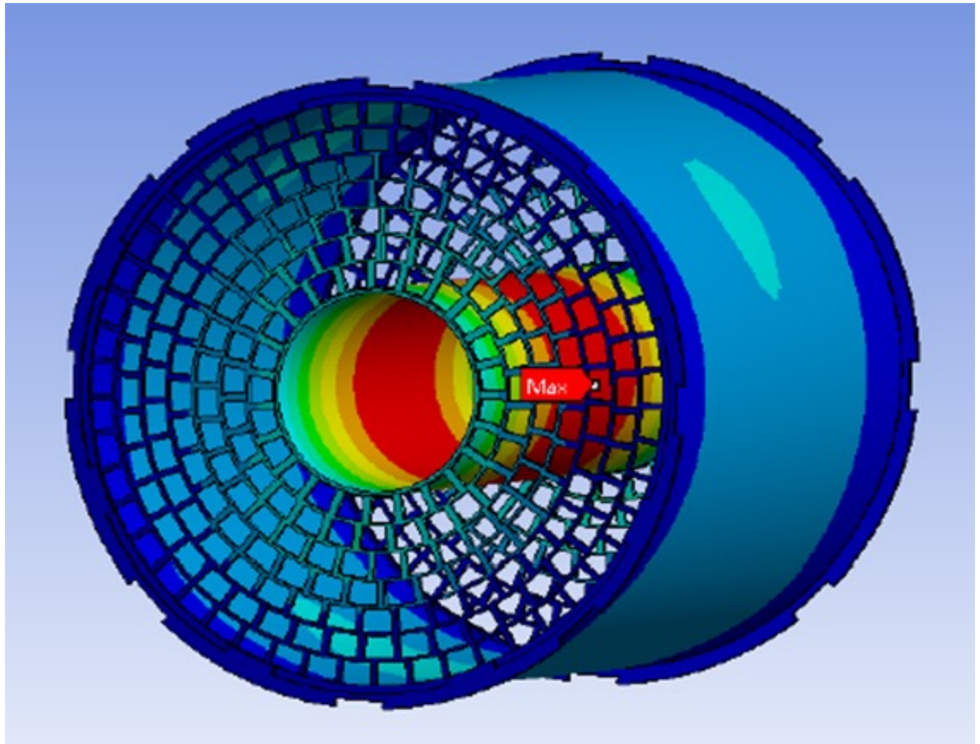
Differential Resolution of 5 track parameters.
Requirement: In the barrel
δ(D0/Z0) ~ < 3 micro meter at 20 GeV
δ(Pt)/Pt ~ o(0.1%)
Ref: CDR baseline performance

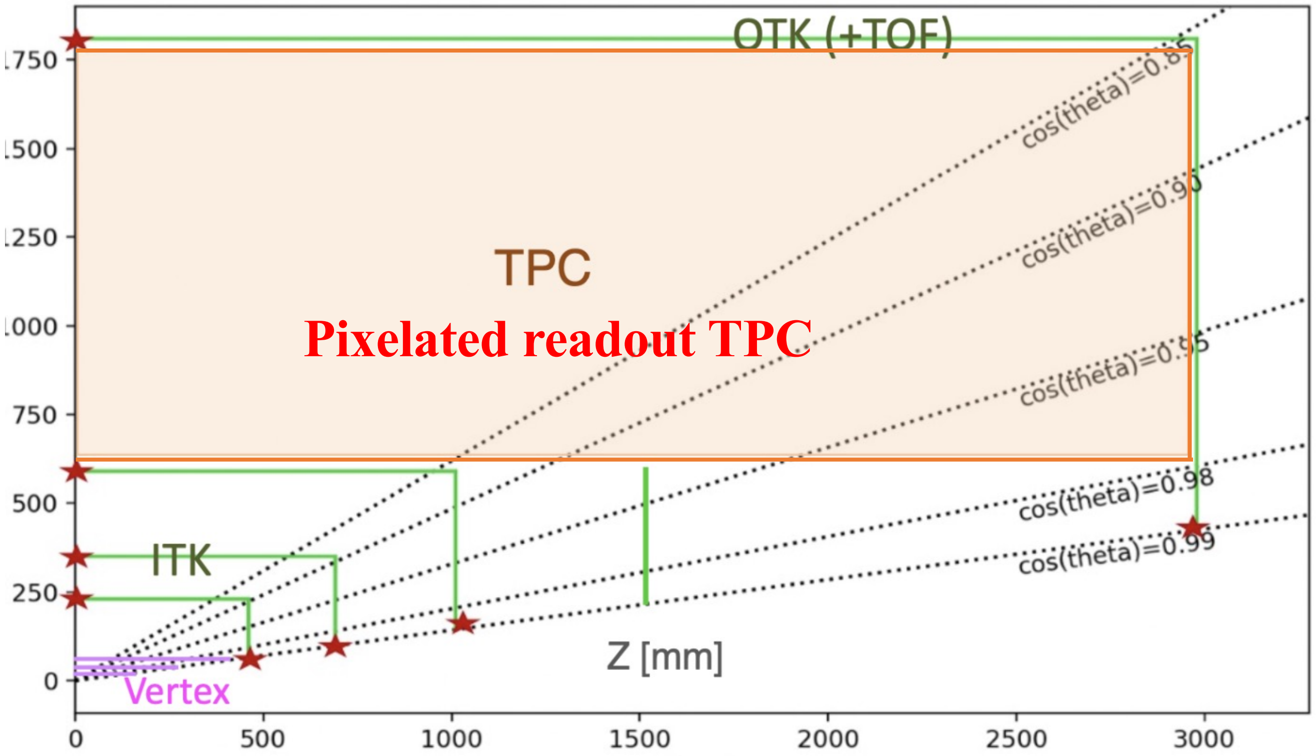
Differential Pid Capability: eff*purity of Kaon id @ Z pole.
Requirement: eff*purity > 90% for all charged Kaon (@ Z pole)
~ relative resolution of dE/dx (or dN/dx) be better than 3%
ToF of 50 ps
Ref: Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835

Sep. power: On 3 prong tau decay @ Z pole.
Requirement: efficiency > 99% at 3-prong tau
Ref: CDR baseline performance

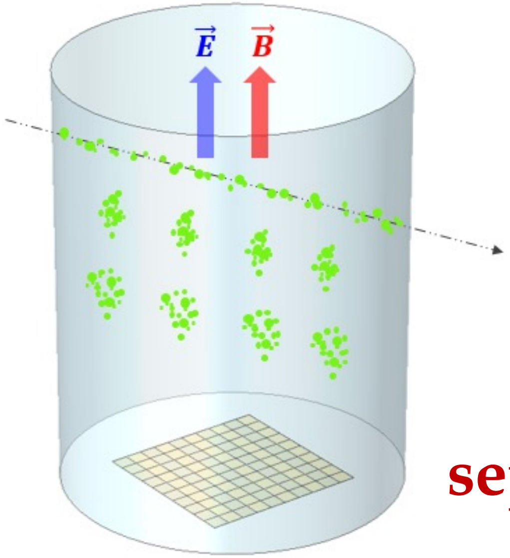
Baseline track detector: Pixelated TPC

- The track detector system combines silicon detectors with a gaseous chamber for tracking and PID
- TPC is as the **baseline track detector** in CEPC ref-TDR
  - Pixelated readout TPC as the **main track (MTK)** from a radius of 0.6m to 1.8m





Classical dE/dx Measurement

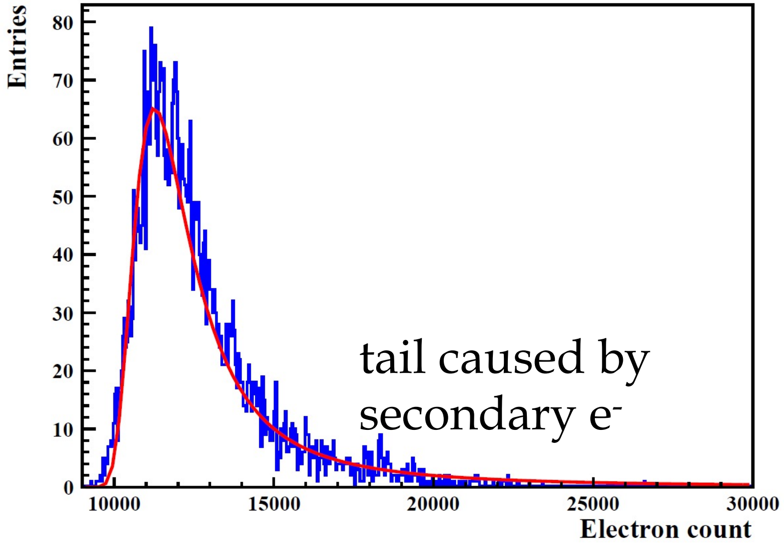


$$p_T = 0.3\ Br$$

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

p + dE/dx → PID

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



distribution of electrons on the track

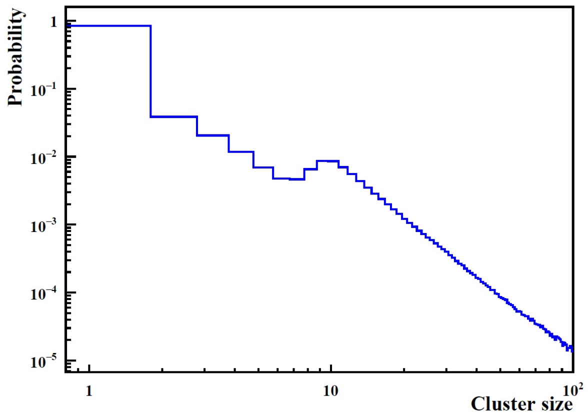
- **Classical dE/dx measurement by charge (charge ≈ number of primary + secondary electrons)**

- 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**

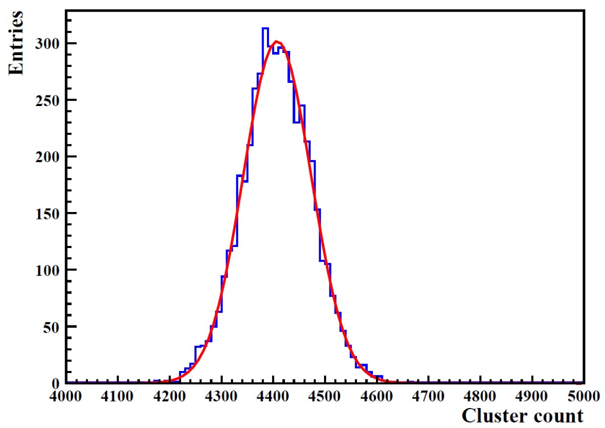
Problem → **sensitive to large fluctuations**

dN/dx Measurement by Cluster Counting

- **Direct cluster counting → ultimate way to measure dN/dx**
  - Measure the number of ionization cluster of the incident particle
  - avoid any problems with cluster fluctuations
  - < 3% dN/dx resolution by cluster counting (statistical error only)
  - 5.4% dE/dx resolution by charge measurement



Cluster size

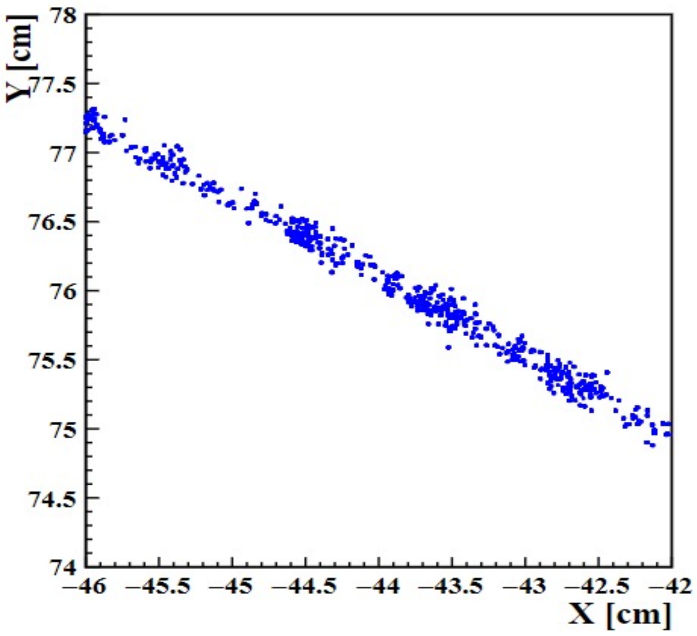


distribution of cluster on the track

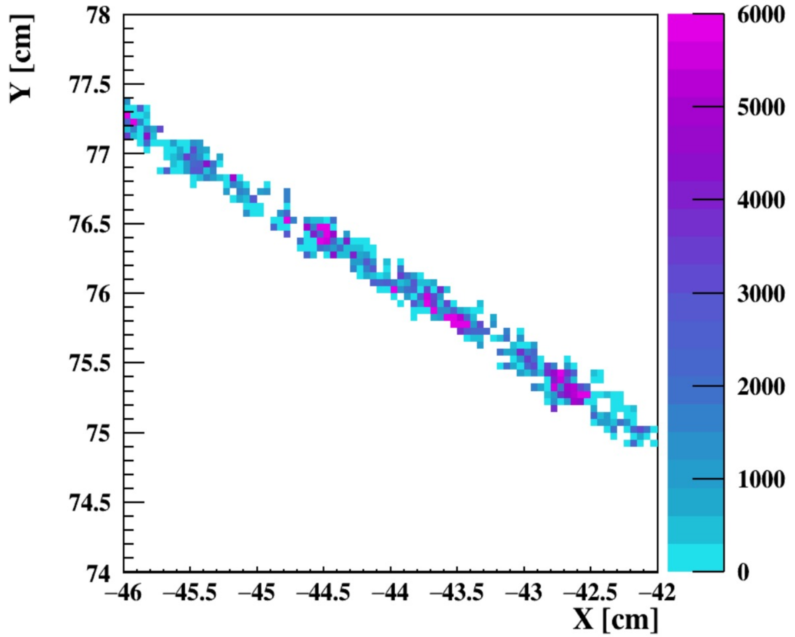
- **Obvious problem**
  - How to resolve individual clusters and count them?
    - **high cluster density**(~30 cl./cm in Ar mixture for m.i.p → typical drift velocities 50 μm/ns → 6 ~10 ns in between clusters → **fast-shaping electronics (~ns needed) In time**)
  - Need devices with **high time resolution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

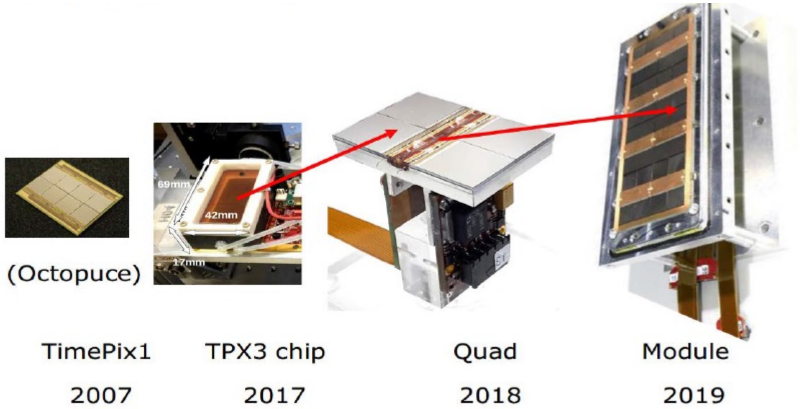


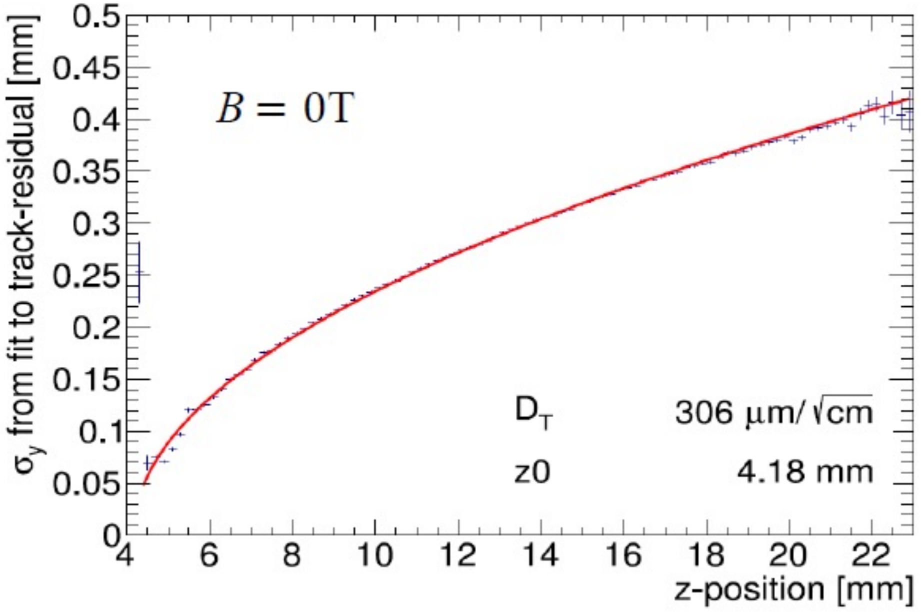
pixel response (500 μm× 500 μm)

Application of Pixel Readout in LCTPC

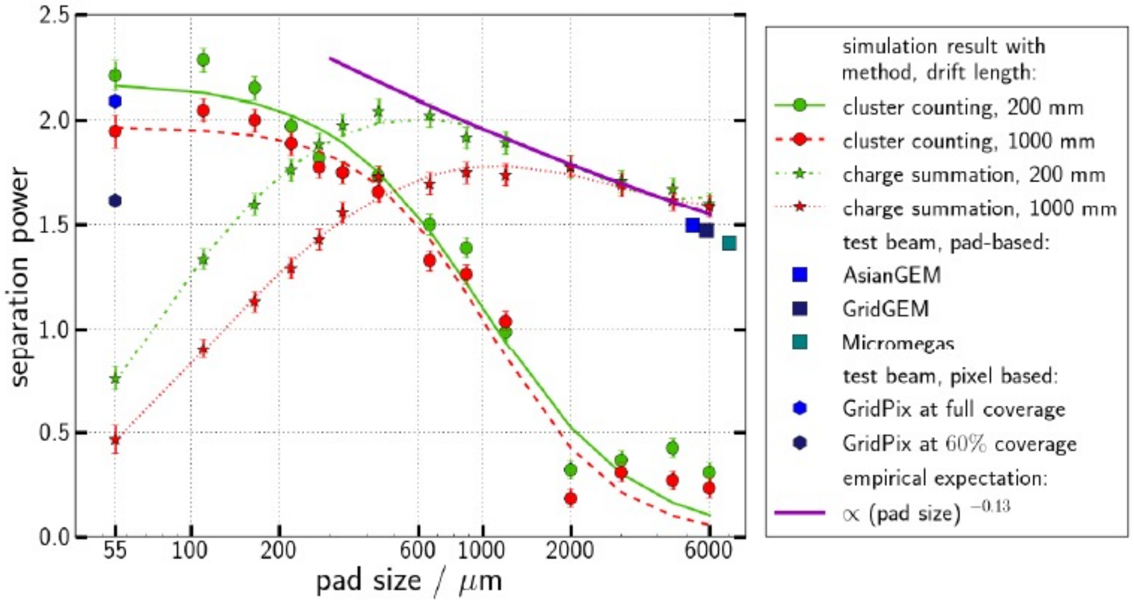
GridPixes Pixel TPC Readout

- Tests with single and quad devices have been successfully done.
- For very small readout pixels the cluster counting method yields a very good separation power
- **dN/dx ~2.9% @1T , power consumption (2W/cm²)**





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



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

Application of Pixelated Readout in CEPC-TPC

Advantages of Pixelated Readout for High Luminosity CEPC-TPC

- High precision resolution (~100 μm) with thousands of hits per track
- High momentum resolution (~10^{-4} GeV/c) and high capabilities for PID (~3%)
- Utilizing the timing of drift in the *z*-direction (nanoseconds)
- A magnetic field parallel to the electric field direction (Higgs: 3T, Tera-Z: 2T)
- Easy installation and replacement with modular design

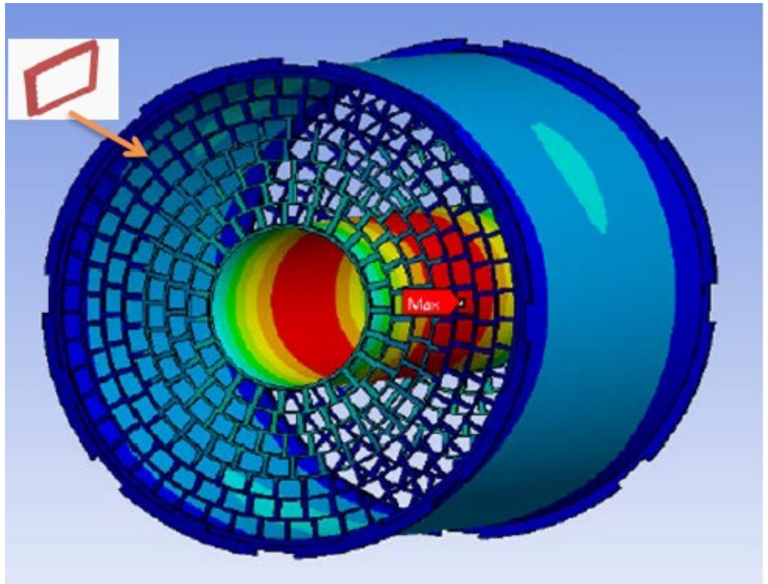
Performance Optimization

- Pixel size
- Detector geometry
- Occupancy
- Power consumption

Parameters	Higgs run	Z pole run
B-field	3.0 T	2.0 T
Readout size (mm)/All channels	0.5mm×0.5mm /2×3×10^7	0.5mm×0.5mm /2×3×10^7
Layers per track in rφ	2300	2300
Material budget barrel (X_0)	0.59 %	0.59 %
Material budget endcap (X_0)	15 %	15 %
$\sigma_{r\varphi}$ (cluster level)	120μm (full drift)	400μm (full drift) w. distortion
σ_z (cluster level)	≃ 0.6 - 1.0 mm (for zero – full drift)	≃ 0.6 - 1.0 mm (for zero – full drift)
2-hit separation in rφ	0.5 mm	0.5 mm
K/π separation power @20GeV	2.6 σ	2.6 σ
dE/dx	< 3.0 %	< 3.0 %
Momentum resolution normalized: $\sigma_{1/pT} = \sqrt{a^2 + (b/pT)^2}$	a = 1.9 e -5	a = 3.3 e -5
	b = 0.8 e -3	b = 1.5 e -3

To update in ref-TDR with Full simulation

Performance of pixelated readout TPC



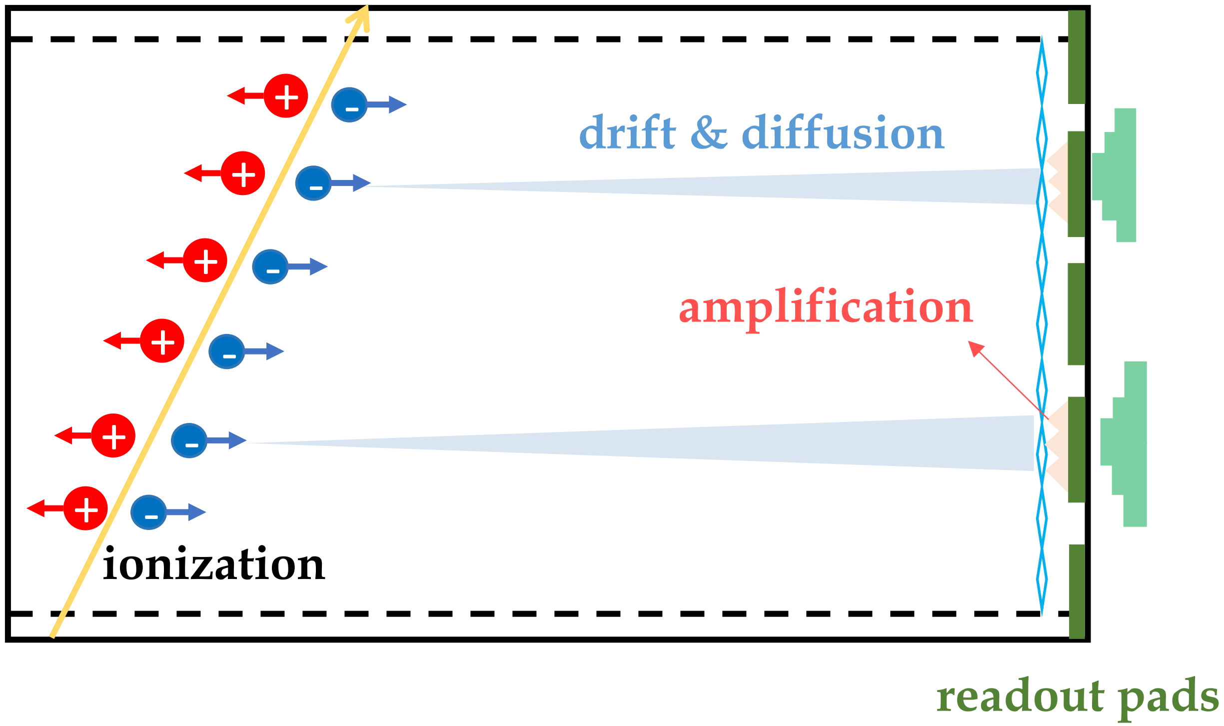
Modular design

Simulation of pixelated TPC

Full Simulation Framework of Pixelated TPC

Simulation / Digitization Framework

Ionization → Transport → Amplification → Signal Generation



Simulation:

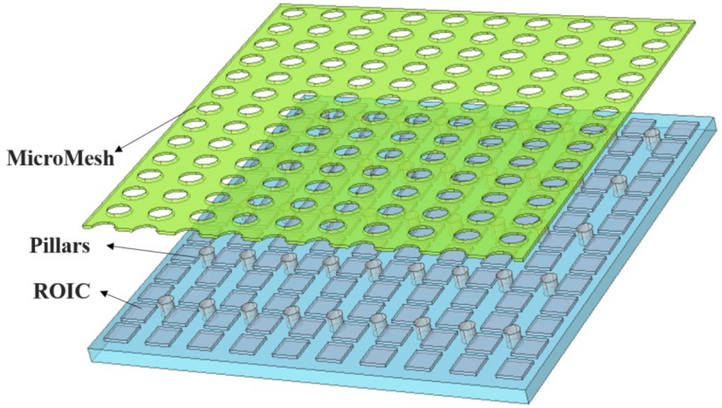
- Full geometry TPC
- Ionization generation by Garfield++

Digitization:

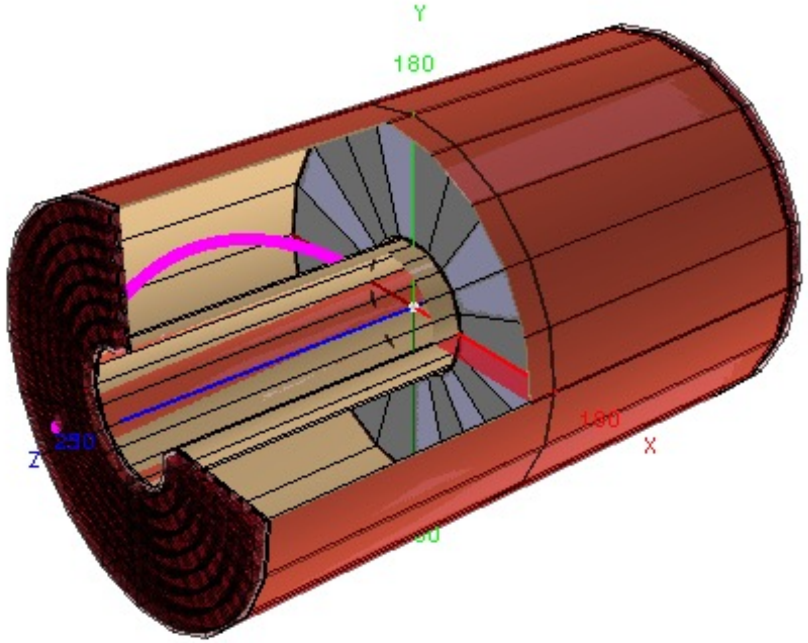
- Electronic noise: 100 e-
- Amplification:
  - Number of electrons: 2000
  - Signal size in space: 100 um

Simulation setup

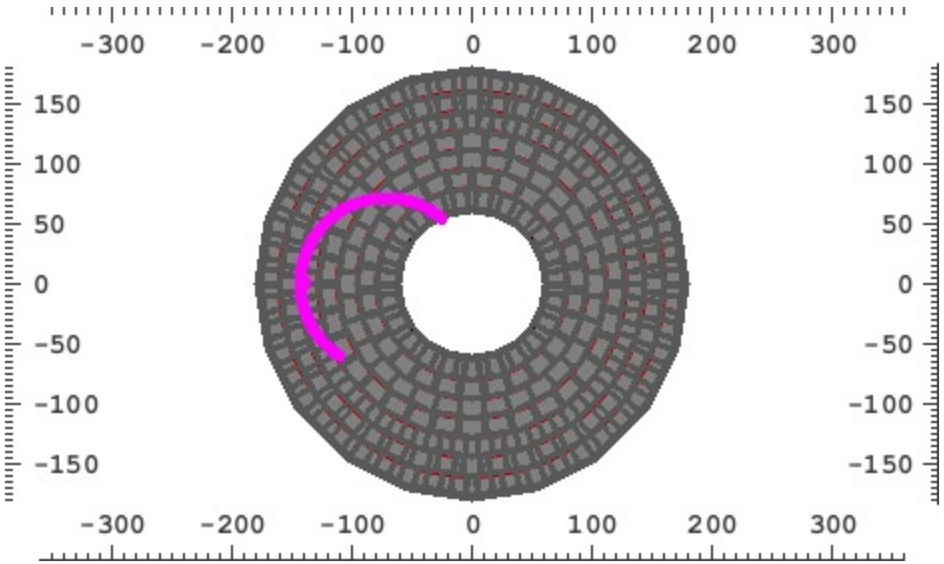
- Magnetic field: 2T/3T (Z-pole run)
- Gas mixture: T2K ($Ar/CF_4/iC_4H_{10}$: 95/3/2)
- Detector Layout : R (0.6 m 1.8 m); Half L (2.9 m)



Pixelated Readout



Track in TPC



Projection of the same track on endplate

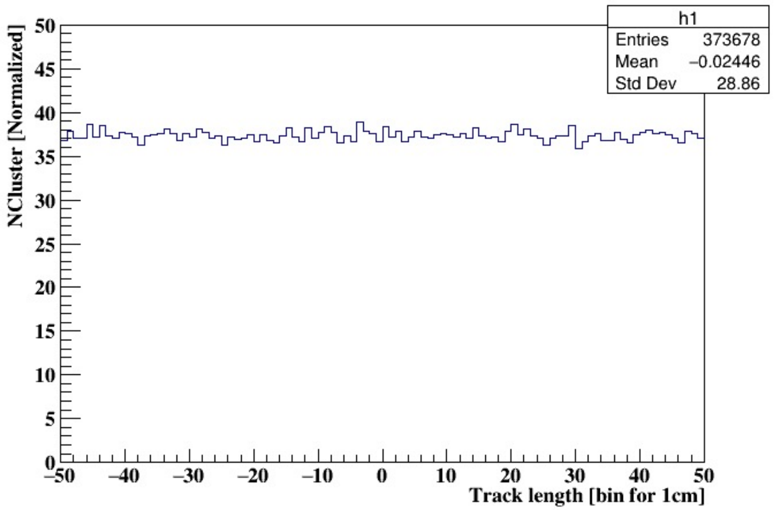
Simulation of the primary cluster

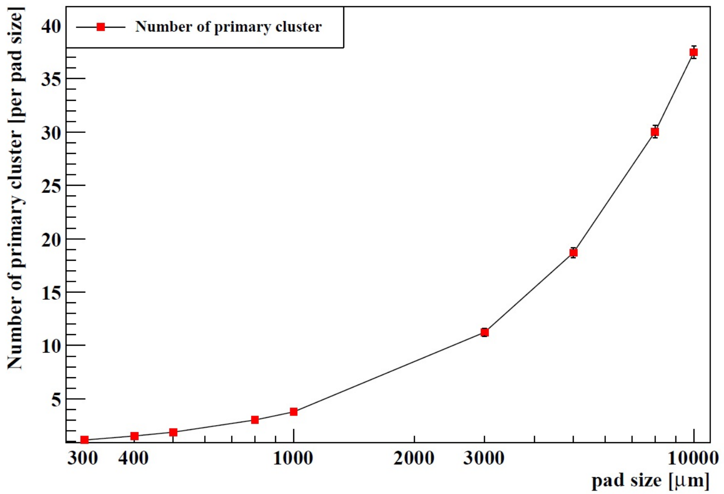
Heed Simulation

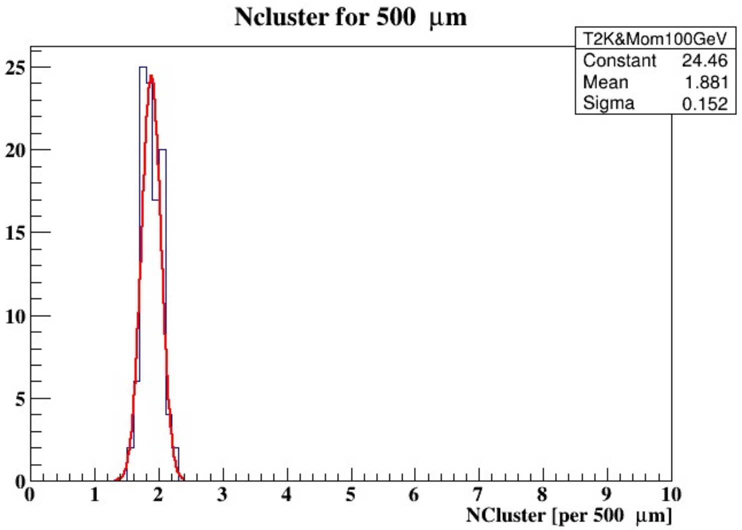
- The distribution of clusters is uniform along the track
- Typically ~30 primary ionization clusters/cm in gas at 1 bar →T2K :37 clusters/cm
- ~1.9 clusters/ 500 μm , ~1.2 clusters/ 300 μm

More detailed research is needed

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





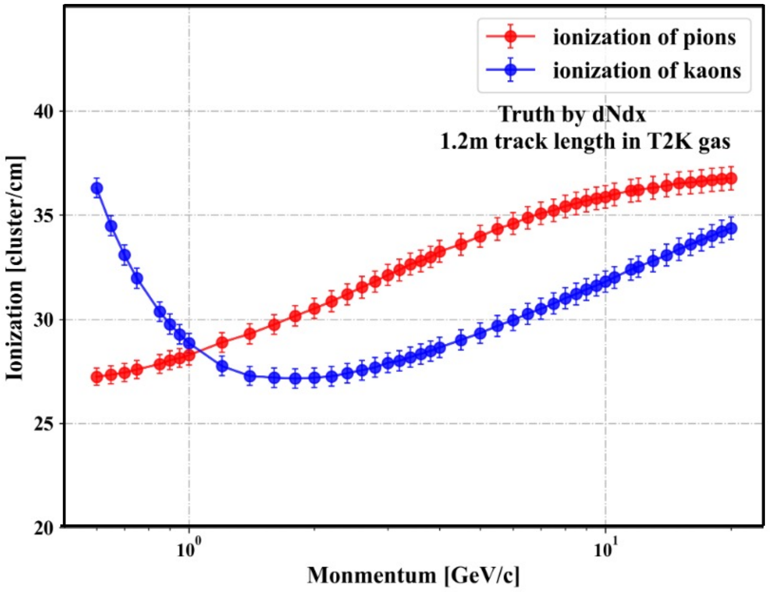


Pad size = 500 um Ncluster/cm

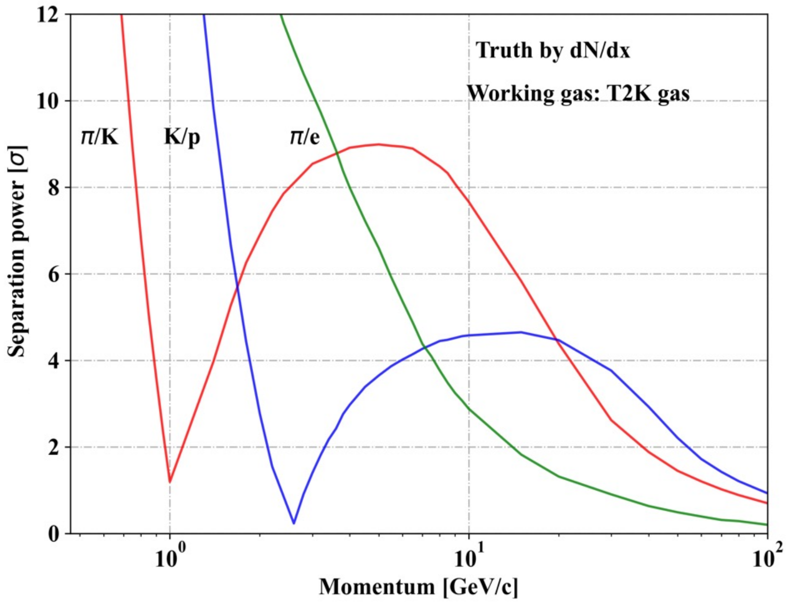
Particle Separation from MC Truth

- Simulating pion/kaon within [0.1-20] GeV/c in T2K gas

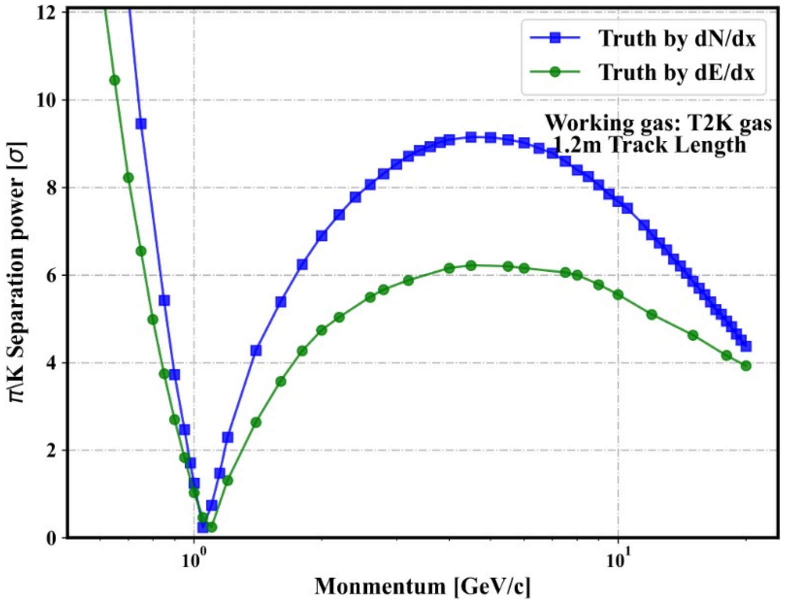
- The performance of particle separation is **proportional to the difference in the average ionization**
- The relative ionization of different particle species depends on the momentum
- **Cluster counting exhibits excellent potential for particle identification**



Primary Ionization cluster of pions & kaons



Sp through dN/dx



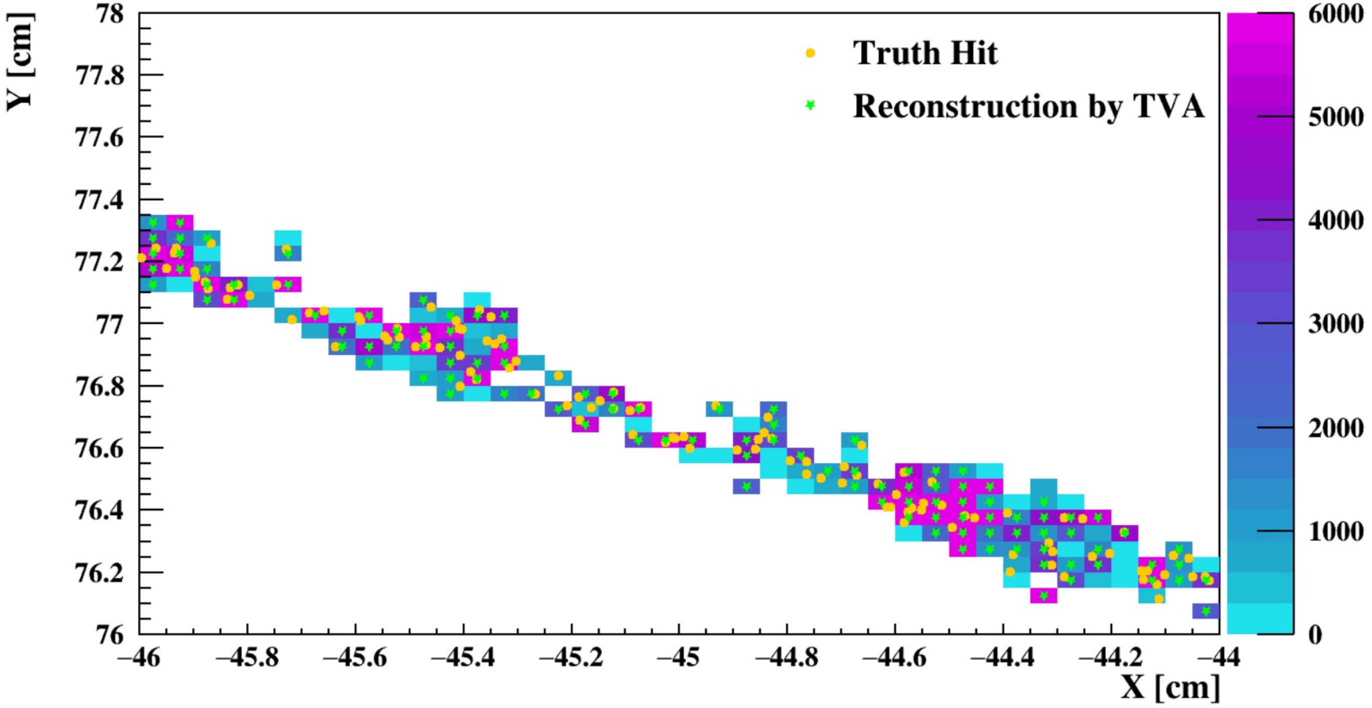
dE/dx & dN/dx based on Truth Information

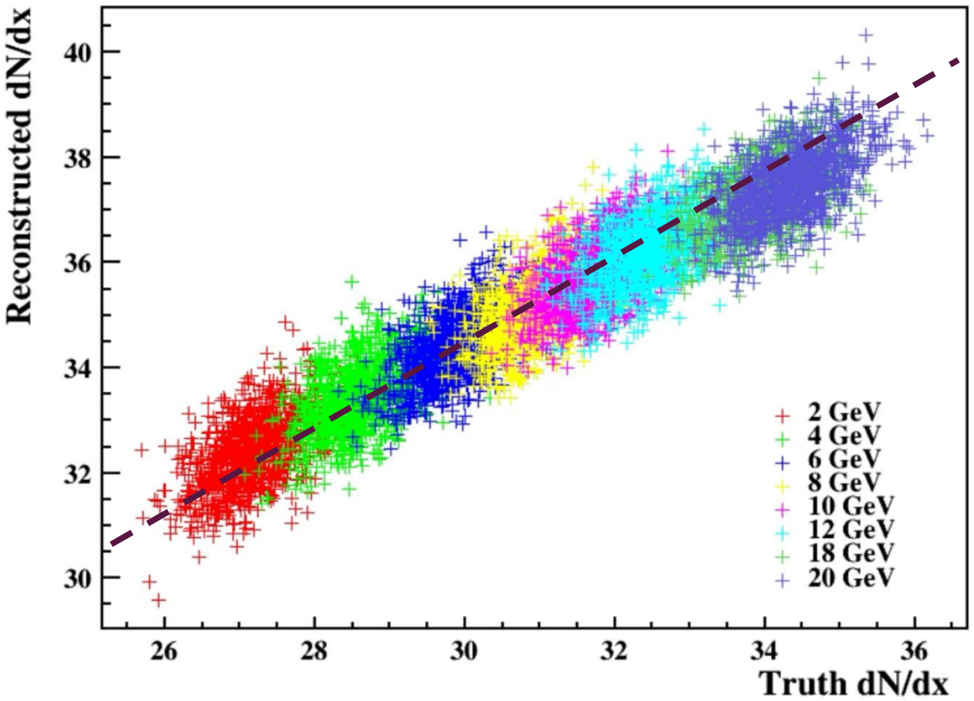
Reconstruction of Pixelated readout TPC

- Reconstruction is achieved by counting the number of fired pixels above a threshold.
- The reconstruction results align closely with the Monte Carlo truth.
- The reconstruction demonstrates good linearity and reliability.

Number of Primary Ionization Clusters per Unit Distance

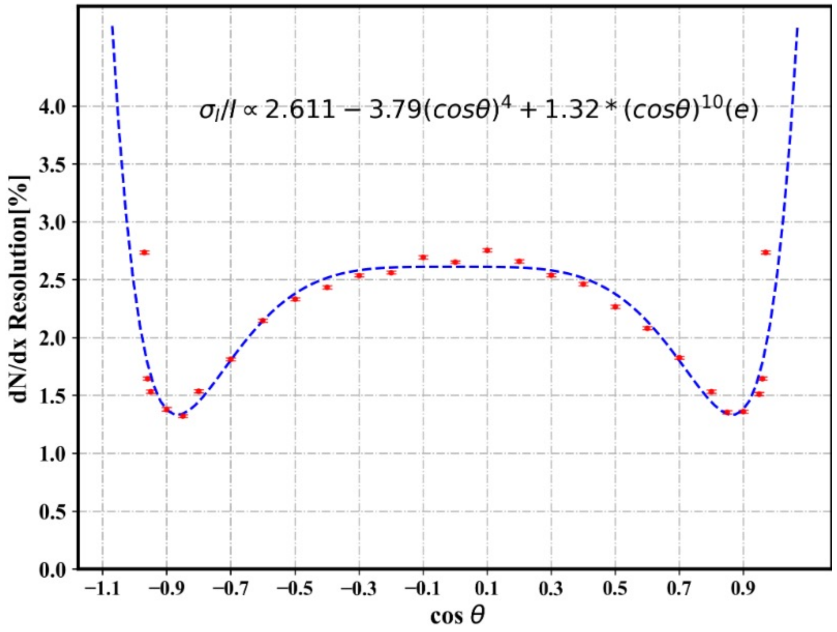
$$Sp = \frac{|\mu_A - \mu_B|}{\frac{\sigma_A + \sigma_B}{2}}$$

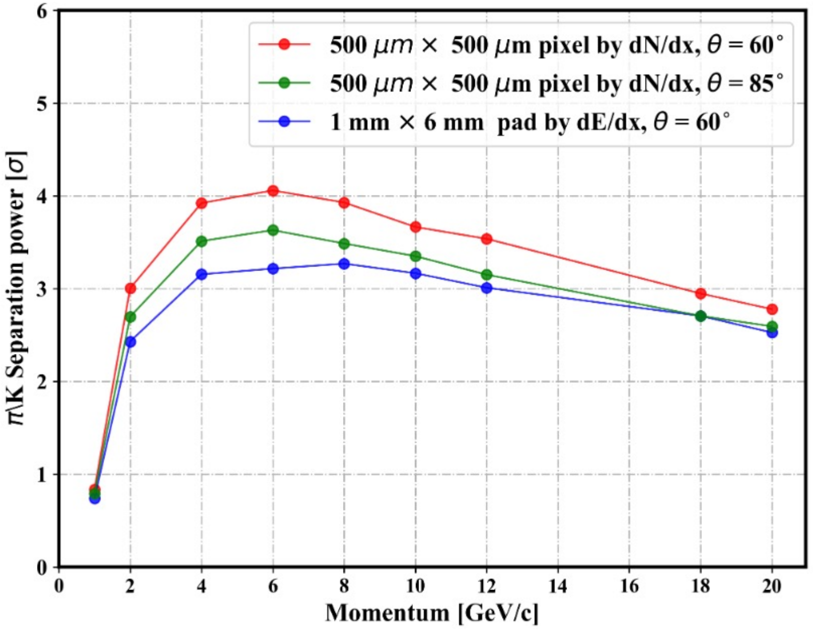


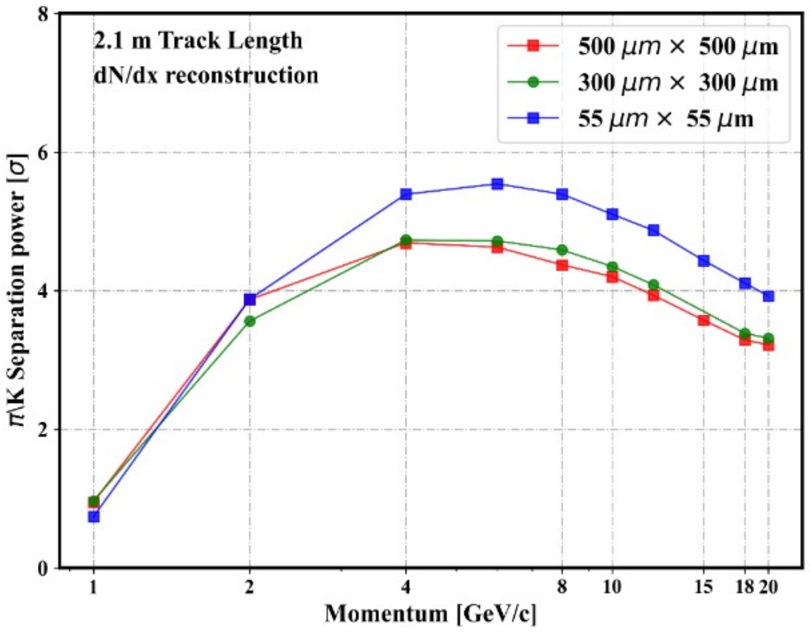


Reconstruction of Pixelated readout TPC

- Using reconstructed clusters, a 2.6σ separation is achieved at 20GeV (θ = 60°).
- Simulation results indicate that the Sp for 300μm is comparable to that for 500μm.
- The focus is on 100mW/cm² and 500μm readout for the CEPC reference TDR.





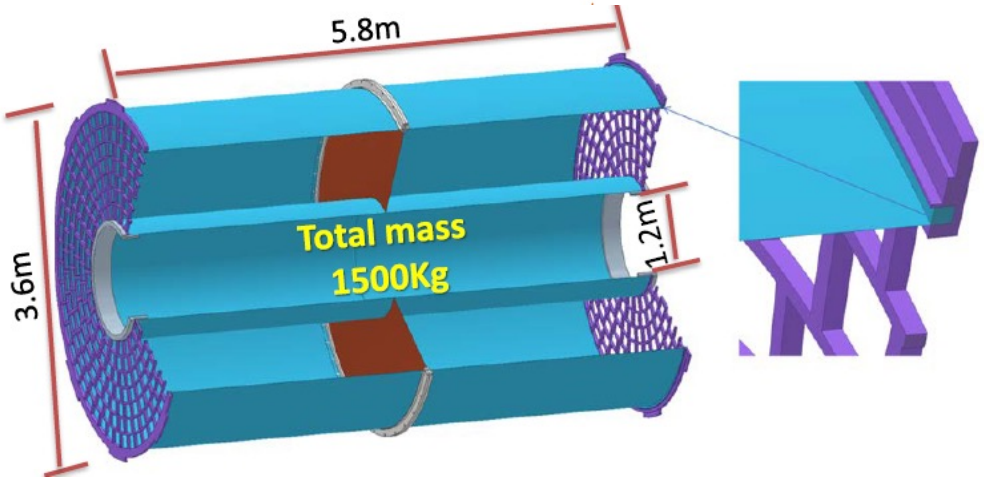


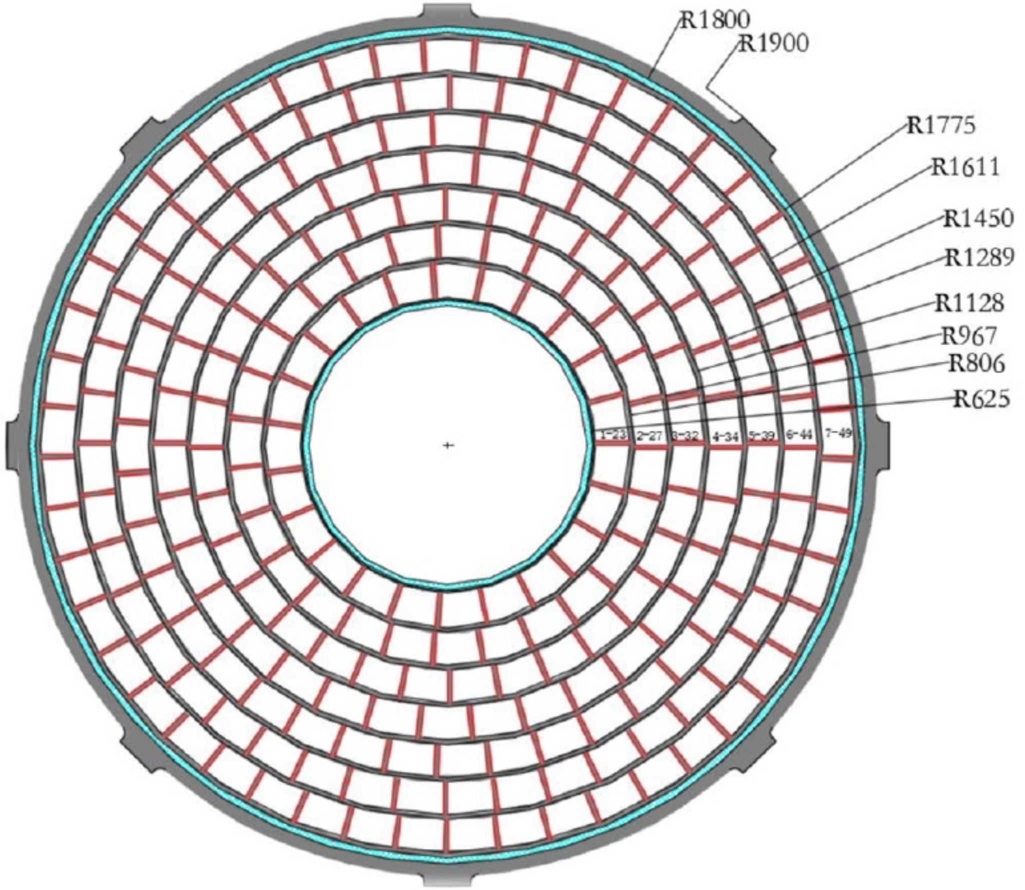
Detailed design & Plan

Detailed design of mechanics

- The optimization work for the modules has been completed, resulting in an increase in the effective area of the sensitive region from 92% to 96%

TPC detector	Key Parameters
Modules per endcap	248 modules /endcap
Module size	206mm×224mm×161mm
Geometry of layout	Inner: 1.2m Outer: 3.6m Length: 5.8m
Voltage of Cathode	- 62,000 V
Operation gases	T2K: Ar/CF4/iC4H10=95/3/2
Total drift time	34μs @ 2.75m
Pixelated detector	Pixelated Micromegas



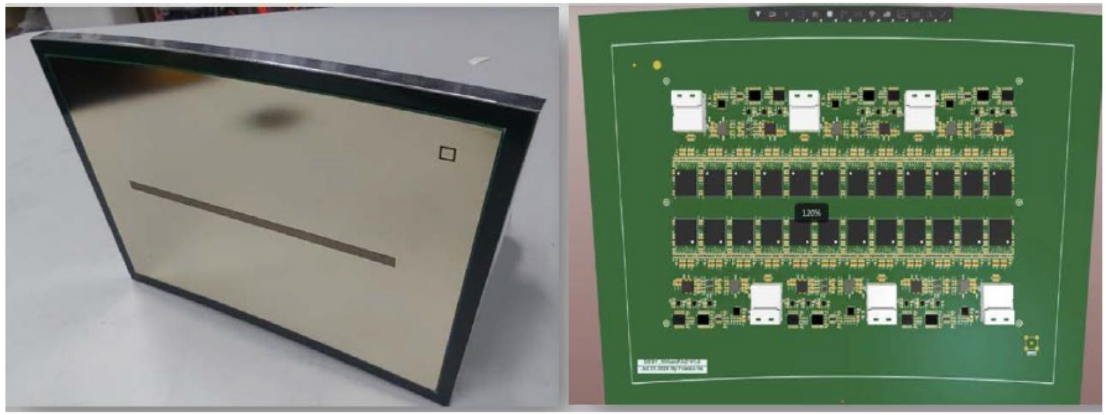


Detailed design of TPC detector in ref-TDR 13

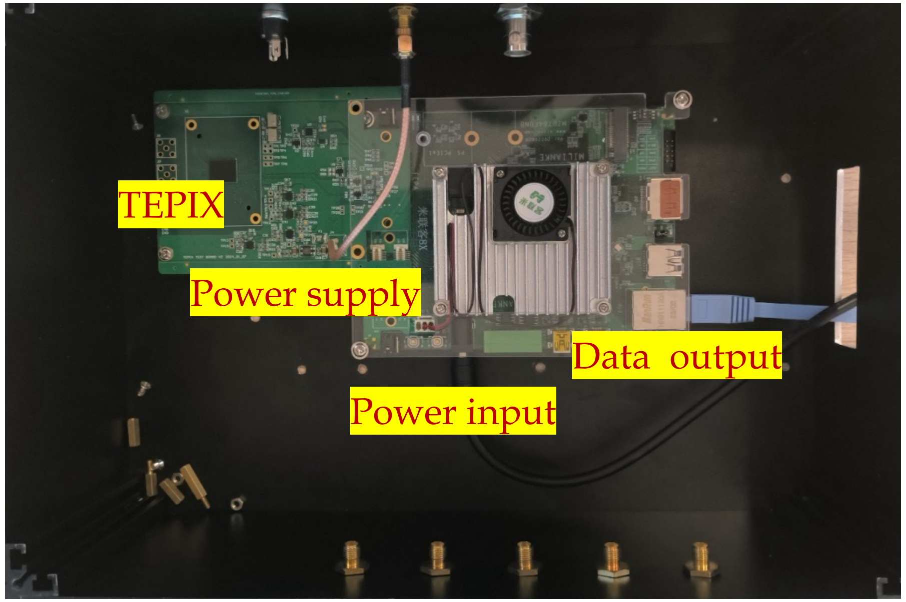
Optimization of Geometry of TPC detector and the Endplate

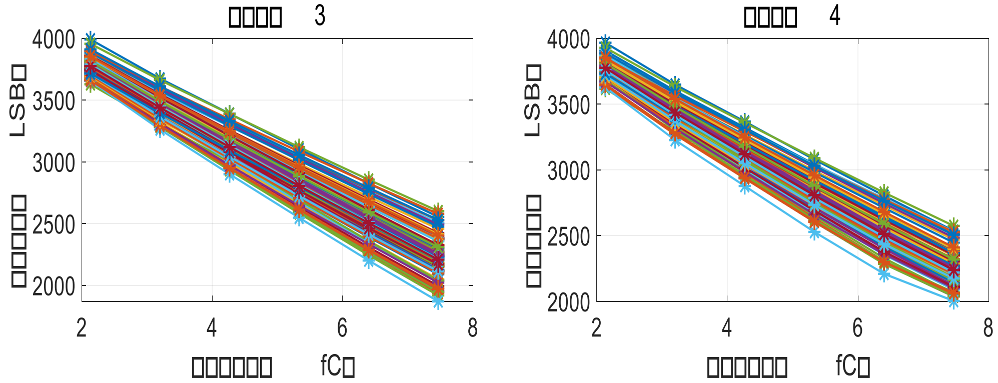
Validation and commission of TPC prototype

- **R&D on Pixelated TPC Readout for CEPC**
  - Development of the pixelated TPC ASIC chip commenced in 2023
  - The design of the second prototype wafer has been completed
  - We are currently prototyping the pixelated readout TPC detector
    - ✓ **<100mW/cm² (Goal)**



Photos TPC modules assembled for the beam test





Inter-channel Inconsistency- Gain Test Results

Summary

- **Pixelated TPC is chosen as the baseline gaseous tracker in CEPC ref-TDR. The simulation results show that both of PID performance and the momentum resolution are good. A 2.6 σ separation at 20GeV can be achieved (θ = 60 °).**

- **Full simulations are still necessary to get the performance of the pixel detector and the studies is ongoing basing on CEPCSW software package.**

- **Validation with TPC prototype in preparation before TDR, This work will contribute to the upcoming release of the CEPC TDR in 2024.**

THANKS !