Flavor Physics Driven Particle Identification and Pad Optimization for TPCs at Future e^+e^- Colliders

Jinxian Zhang, Huirong Qi, Jianbo Zheng, Jianchun Wang, Yifang Wang

1. Institute of High Energy Physics, CAS
2. University of Chinese Academy of Sciences

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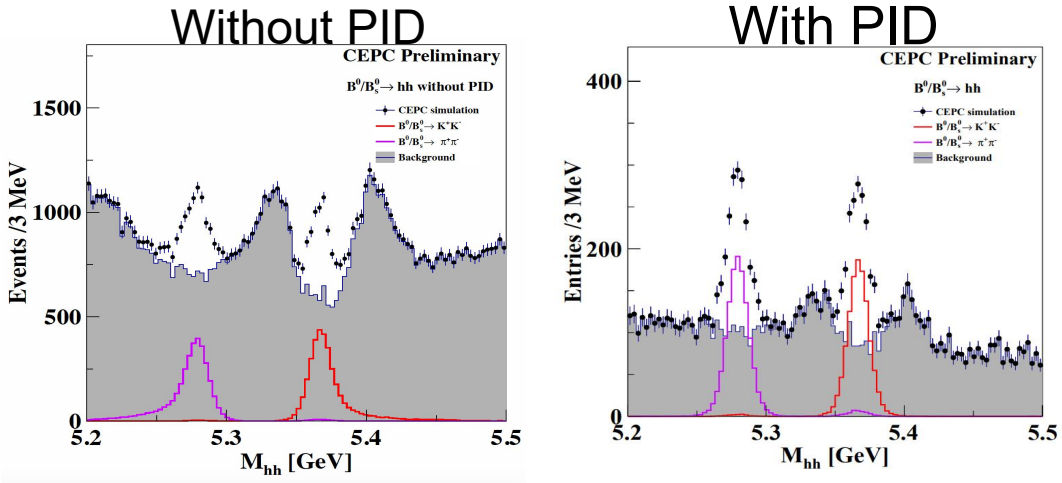
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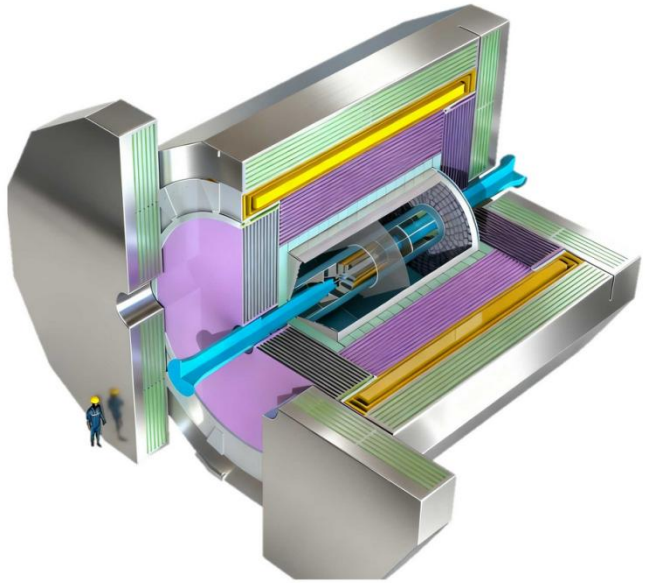
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Physics Requirements at Future e^+e^- Colliders

- **CEPC / FCC-ee / ILC** aim at precision Higgs, electroweak, and flavor physics.
- Broad momentum range up to 20 GeV/c demands π/K separation > 3σ for reliable PID.
- The **Time Projection Chamber (TPC)** is chosen as the main tracker because:
  - Low material budget (~0.1 X_0)
  - Excellent spatial resolution (~100 μm)
  - Promising PID capability via **dE/dx** and **cluster counting (dn/dx)**
- **Reference:** CEPC Ref-TDR (2025) sets baseline performance
  - **Tracking:** $\sigma(1/p_T) \sim 10^{-4}$ (GeV/c)$^{-1}$ for TPC alone; combined with Si → 3×10^{-5}.
  - **PID:** **π/K separation > 3σ** up to 20 GeV





Detector layout in AGORA

The CEPC Reference TPC Design (AGORA)

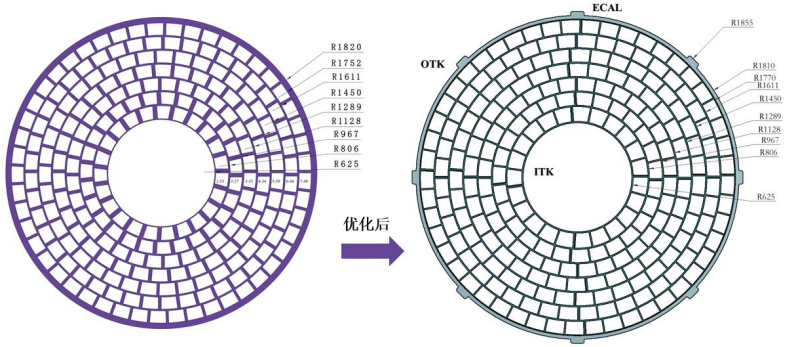
- **Detector geometry:**

  $r_{inner} = 0.6$ m $r_{outer} = 1.8$ m

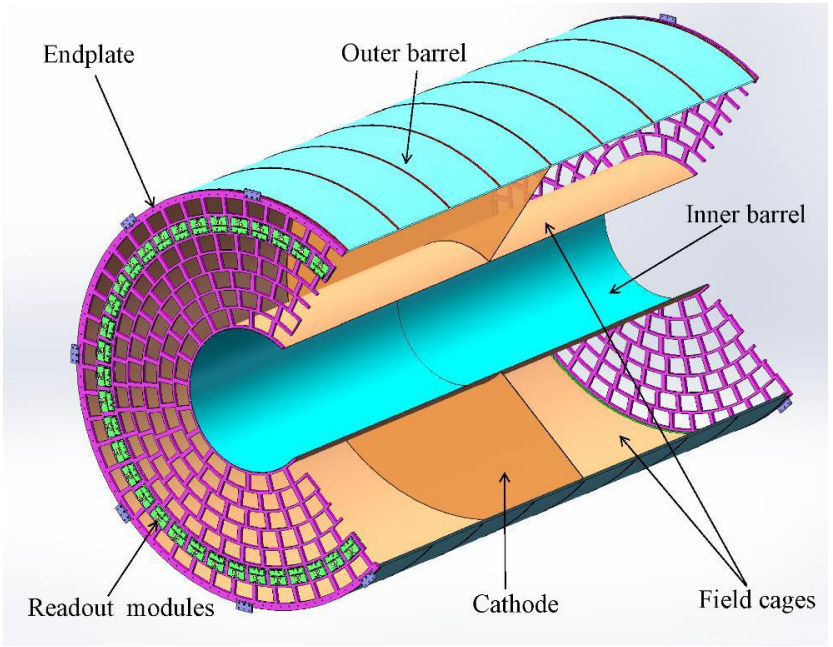
  $L_{drift} = 2.9$ m

  Endcaps: modular design, 248 readout modules, **~96% active area coverage** (~9 m^2 total).

- **Working gas:** T2K mixture ($Ar:CF_4:iC_4H_{10} = 95:3:2$)
- **Field:** $E = 230$ V/cm, $B = 3$ T
- **Electronics:** TEPIX front-end ASIC, low power consumption (<10 kW per endcap).
- **Readout:** High-granularity pixelated pads (variable size, ~500 μm).



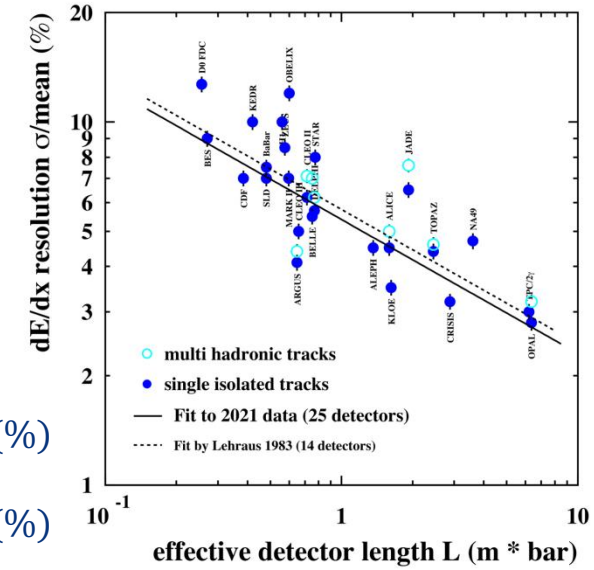
Readout module layout (optimized)



TPC layout

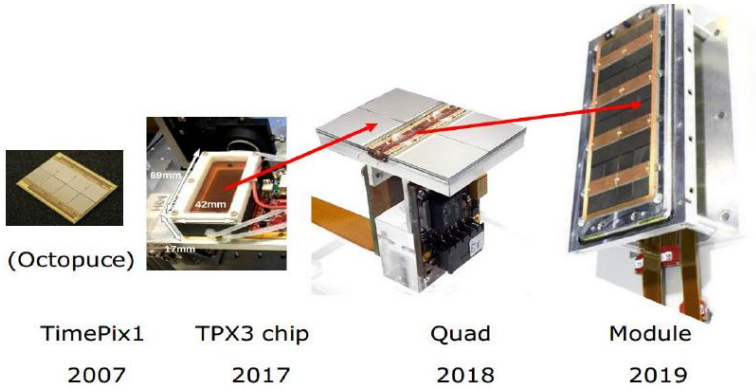
From dE/dx to Cluster Counting

- **Conventional approach:** Large pads (~1 mm × 6 mm) + dE/dx
  - Limitations: Long Landau tails, limited PID performance
- **Cluster counting with pixelated readout:**
  - Based on GridPix, LCTPC has demonstrated a preliminary dn/dx resolution of ~2.9% at 1 T (55 μm pixel pitch)



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

Detector	Acceterator	Size(φ×L)	B (T)	N_Samples	Control sample	Effective detector length (bar*m)	dE/dx
ALEPH	LEP	3.6 m × 4.4 m	1.5	388	e	45.6	4.5%
ALICE	LHC	5 m × 5 m	0.5	159	π	6.0	4.5%
STAR	RHIC	4 m × 4.2 m	0.5	45	π	0.4 – 0.6	8.0%
TOPAZ	TRISTAN	2.4 m × 2.2 m	1	175	π	0.4 - 0.6	4.4%
DELPHI	LEP	2.4 m × 2.7 m	1.2	192	π	0.4 – 0.6	5.7%



Cluster counting with High-Granularity Readout

- **Approach proposed by AGORA:** Pixelated readout (**~500 μm**)

  + **cluster counting**

  - Counts the number of ionization clusters per unit length
  - More robust against fluctuations, superior PID potential

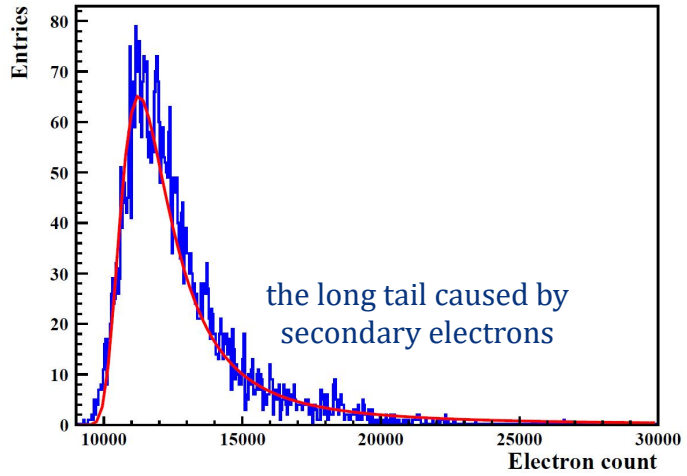
  Ionization clusters in T2K: ***~37cluster/cm***

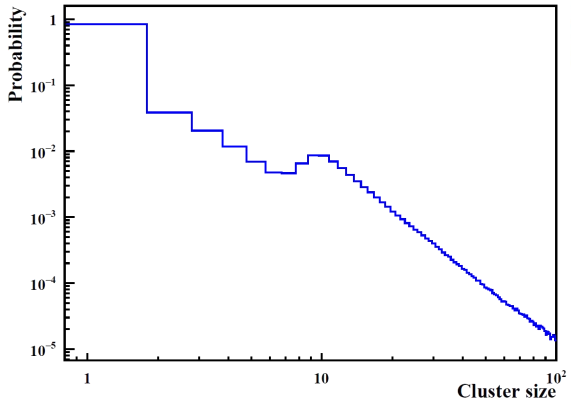
  = ~1.8 clusters/ 500 μm , ~1.2 clusters/ 300 μm

  Therefore: ***A pixel size of 300 ~ 500 μm*** *enables counting of individual ionization clusters.*

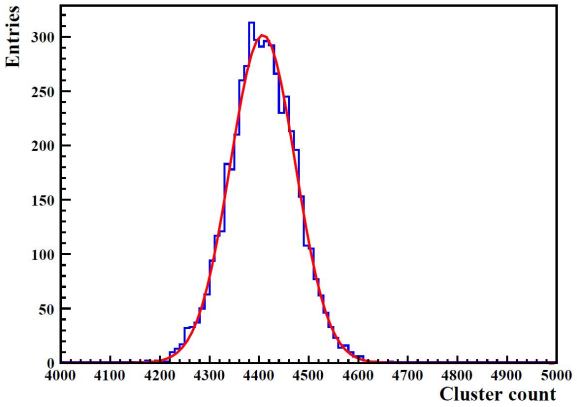
- **Key challenge:** Accurately count clusters – achieved via **fired-pad counting**

  (dN_p/dx*, or machine learning in the future)*





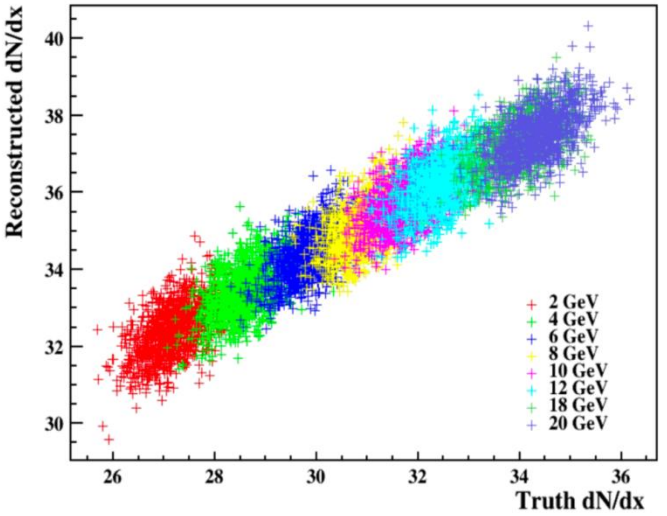
Electron multiplicity per cluster

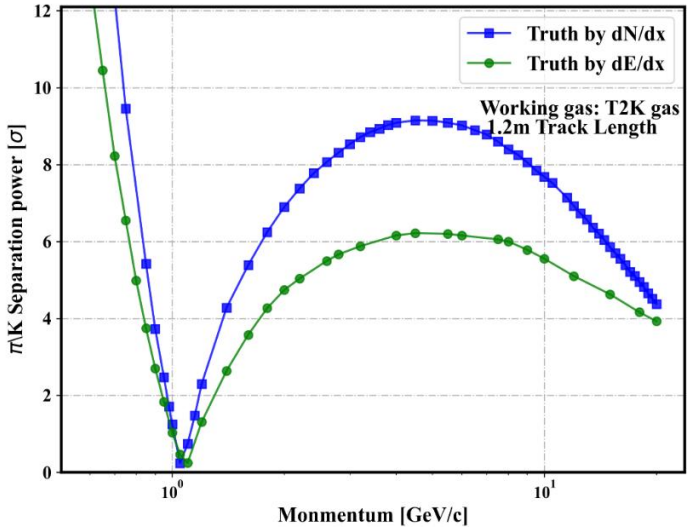


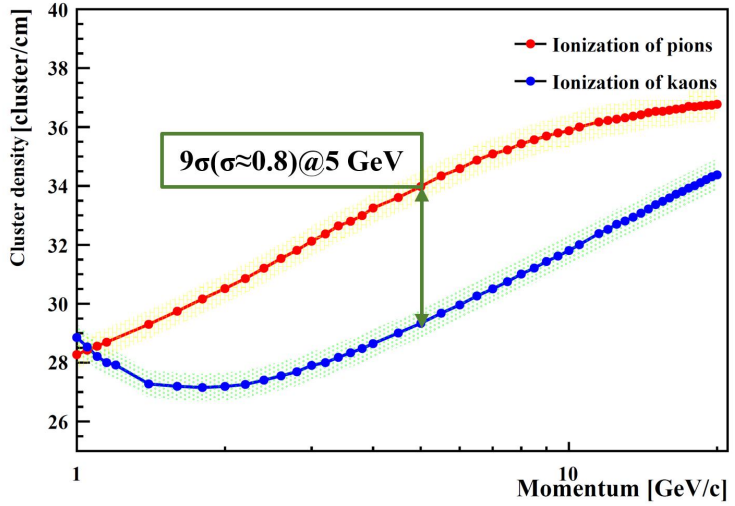
Gaussian distribution of cluster counts along the track

Cluster counting with High-Granularity Readout

- We have validated PID performance using **MC truth** information based on **ionization clusters simulation**:
  - PID performance via **cluster counting (dn/dx)** vs. **dE/dx**
  - dn/dx shows a **significant advantage**: 9 σ separation at 5 GeV, **a 47% improvement** over dE/dx.
- Simulation confirms a linear proportionality between **dN_p/dx (fired-pad count per unit length)** and the **true cluster density (dn/dx)**.
- Therefore, we adopt **dN_p/dx** as a practical, measurable proxy for cluster counting in PID.







Trade-offs of High Granularity Readout

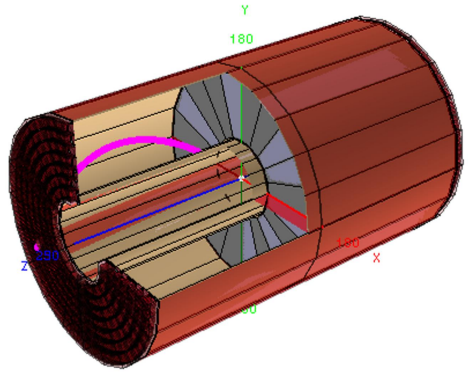
- Preliminary simulation has already shown that, using **Micromegas + pixelated readout**, the **dN_p/dx** approach yields much better PID than traditional dE/dx.
- **Essential trade-offs:**
- Small readout pad (e.g., 55 μm):
  - Excellent single-electron resolution.
  - **Channel count** quadratically increases → **power consumption, cooling problem, and cost**.
  - **Signal-to-noise ratio degrades**.
- Large readout pad (e.g., 500 μm and above):
  - Feasible engineering, lower power.
  - **Cluster differentiation decreases** → potential PID loss.

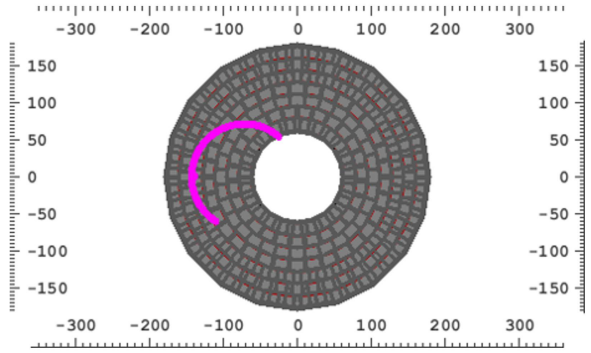
Our study:

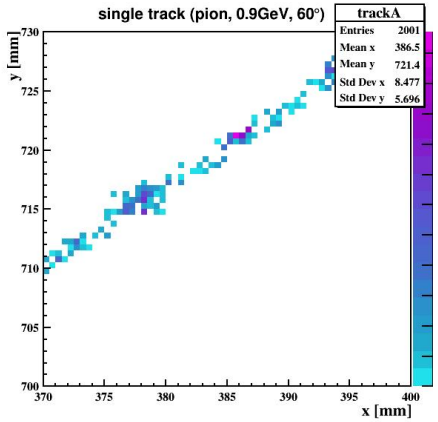
- **Systematic scan** from 55 μm to 1000 μm.
- Evaluate π/K separation power under realistic physics (ionization, diffusion, avalanche).
- **Experimentally validate** the key parameters with a full-drift-length (2.9 m) TPC prototype.

Simulation Framework – Workflow and Geometry

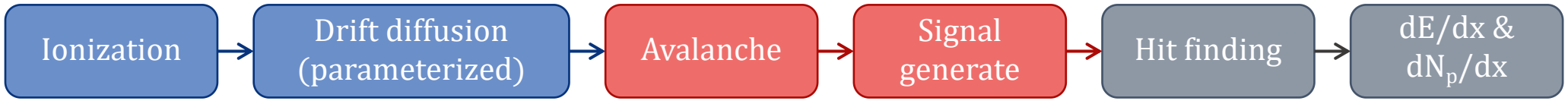
- **Physics processes modeled:**
  - **Primary ionization** (Garfield++), together with secondary (delta) electrons.
  - **Electron drift with diffusion** (longitudinal & transverse).
  - **Avalanche multiplication** at Micromegas (Polya gain).
  - **Signal induction** on readout pads (with noise).
- **Reconstruction algorithms:**
  - Traditional dE/dx (truncated mean).
  - Cluster counting dN_p/dx (truncated mean on pad-row layers).
- **Visualization:** 3D track display and endcap projection.







Visualized track and pad hits

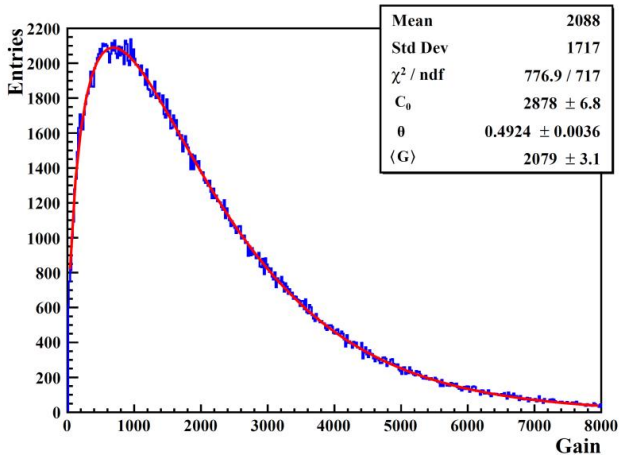


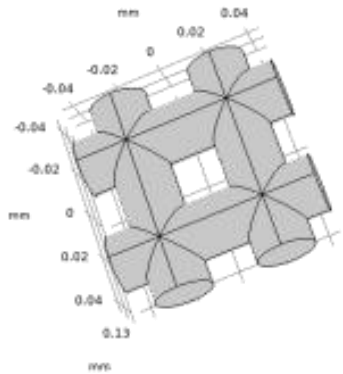
Garfield++ Simulation | Digitization | Reconstruction

Simulation Framework – Drift, Diffusion and Avalanche

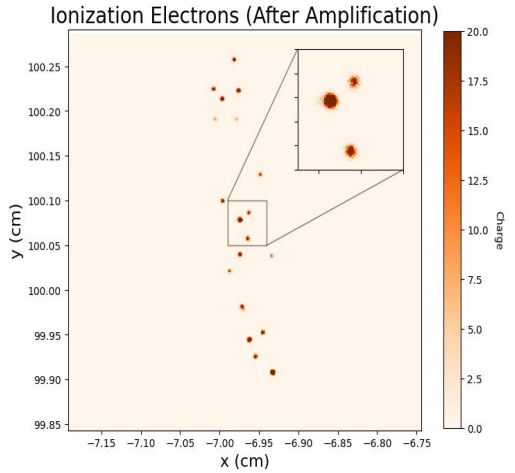
Drift and avalanche:

- Pre-simulated with Garfield++, and implemented as parametrized models in the software framework.
- **Drift Process:**
  - Longitudinal and transverse diffusion of drifting electrons included
- **Avalanche Process:**
  - Use Polya distribution to parameterize the gain fluctuation

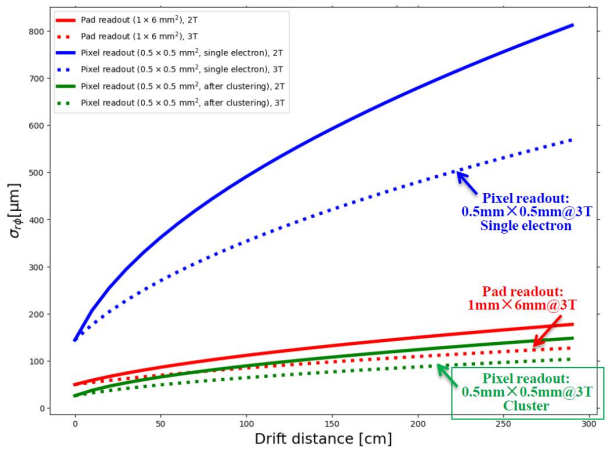




Polya distribution fit to the avalanche gain



Display of electrons after avalanche



Spatial resolution versus drift distance for Pad-type and pixelated readout

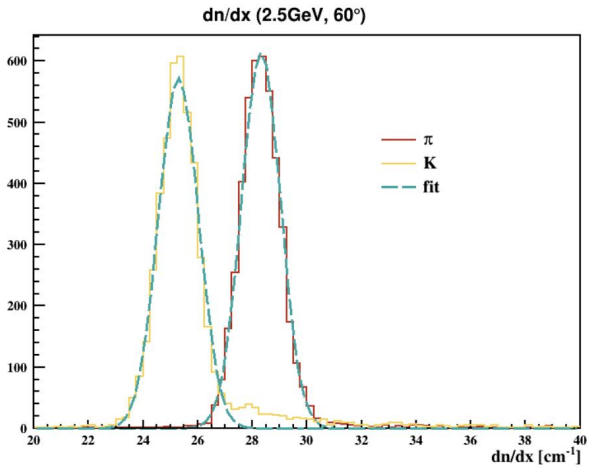
Cluster Counting Principle (dN_p/dx)

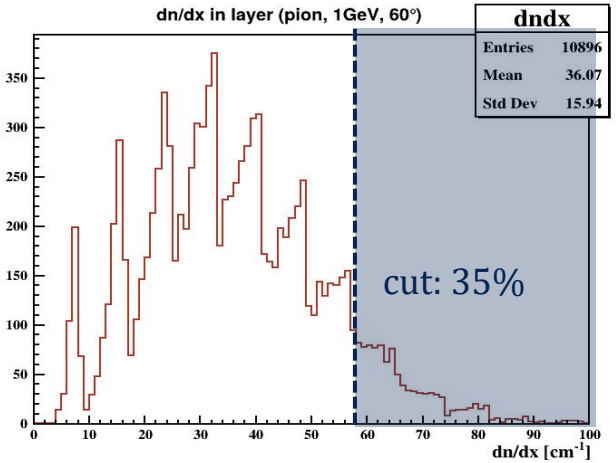
- Basically, $dN_p/dx = \dfrac{(\text{Num of hits})}{(\text{Length of track})}$

To mitigate the effect of secondary electrons, a layered truncated-mean method is employed for dNp/dx reconstruction:

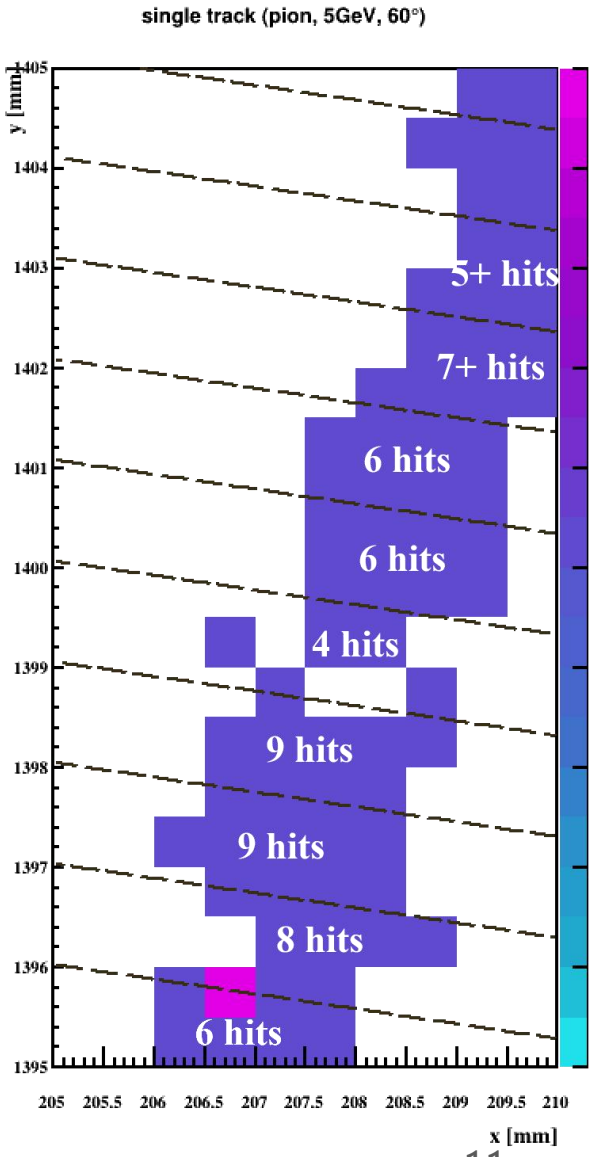
The track is **divided into layers**, and a fixed percentage of layers with the highest values are **discarded** (truncated). Then, calculate **the avarange dN_p/dx** of the remaining layers:

$$dN_p/dx = \left(\sum_{\text{layer}} (\text{Num of hits})_{\text{in layer}}\right) \Big/ \left(\sum_{\text{layer}} (\text{Length of track})_{\text{in layer}}\right)$$





A typical dN_p/dx PID example



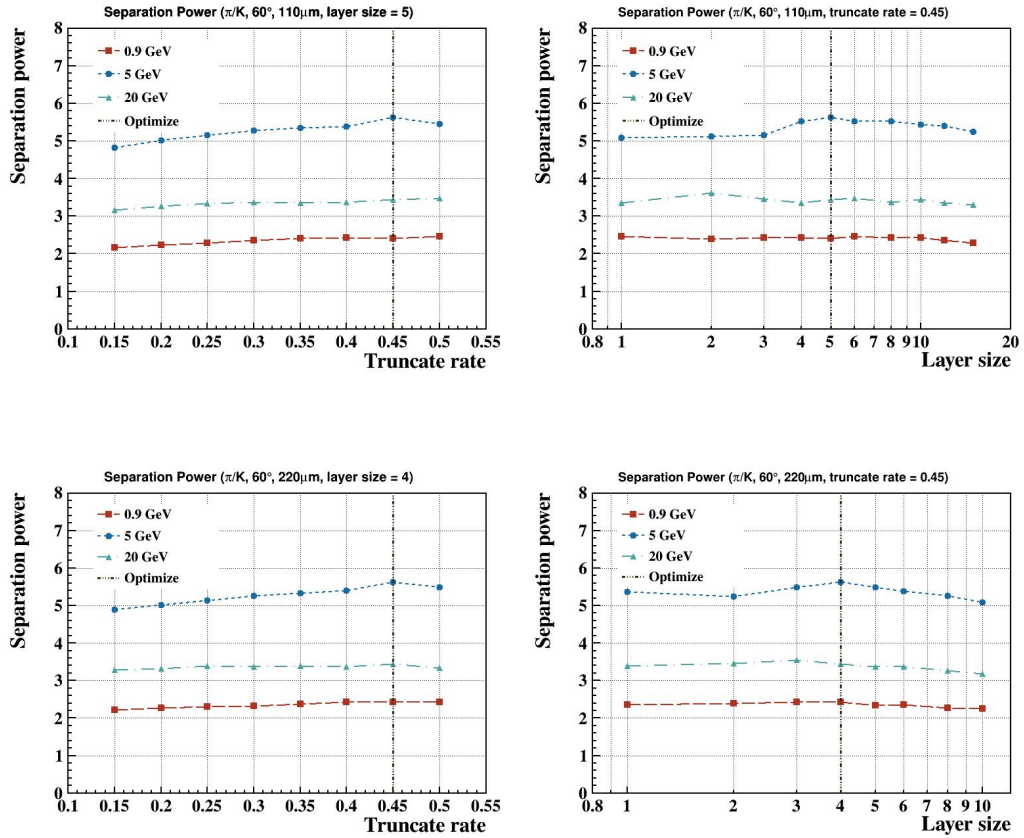
Reconstruction Parameter Optimization

Optimizing the Truncated-Mean Method for Each Pad Size

- We group **several adjacent pad rows (How many?)** into one layer.
- **A fixed percentage** of layers with the highest dN_p/dx (or dE/dx) is discarded.
- **These two parameters are optimized** from scan at θ=60°, p = 0.9, 5, 20 GeV/c (**top priority given to the performance at 20 GeV/c**):

Pad size [μm]	Rows per layer	Truncate rate
55	8	0.45
110	5	0.45
220	4	0.45
330	3	0.4
400	3	0.4
500	2	0.35

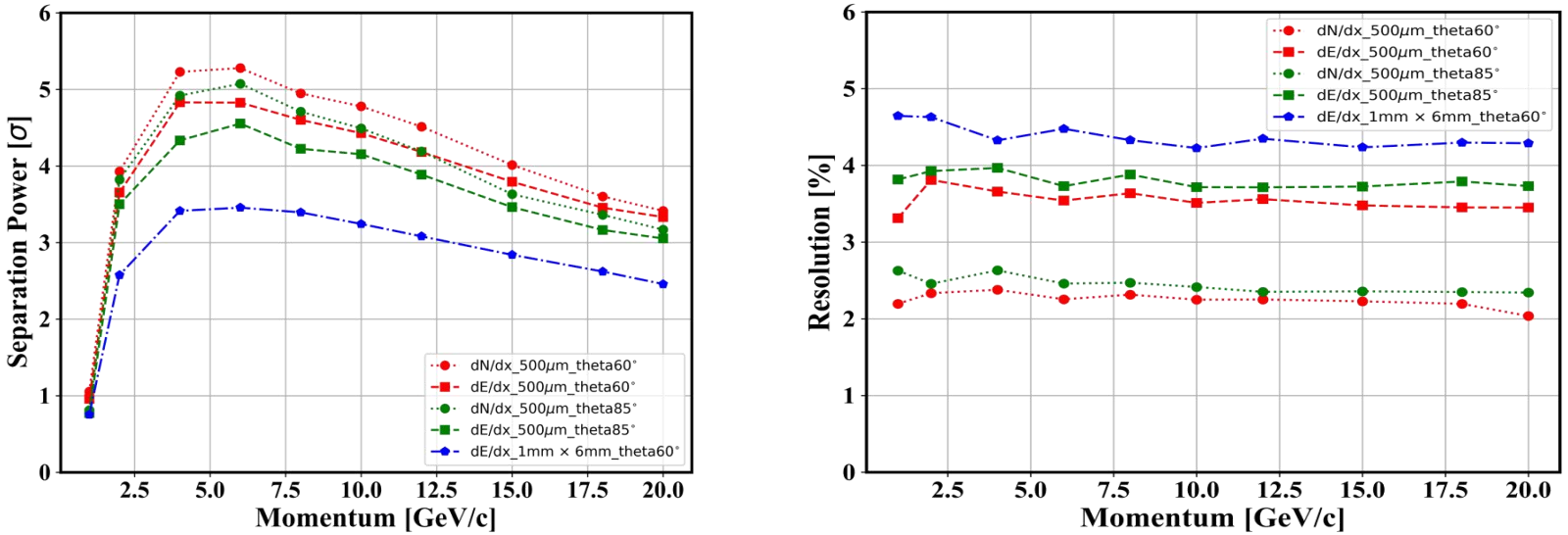
- Using separation power: $Sp_{A,B} = \frac{|\mu_A - \mu_B|}{\sqrt{(\sigma_A^2 + \sigma_B^2)/2}}$



Preliminary Results of Pixelated-Readout TPC

Preliminary simulation results (before optimizing the pad size):

- **Both dn/dx and dE/dx** with pixelated readout significantly outperform conventional pad-type readout.
- dn/dx achieves better PID performance: **π/K separation = 3.5 σ**, compared to **3.3 σ for dE/dx**
- Pixelated readout meets the CEPC TDR requirement of **3 σ**
- dn/dx resolution reaches **~2.2–2.5%**, far better than the CEPC requirement of **<4%**.



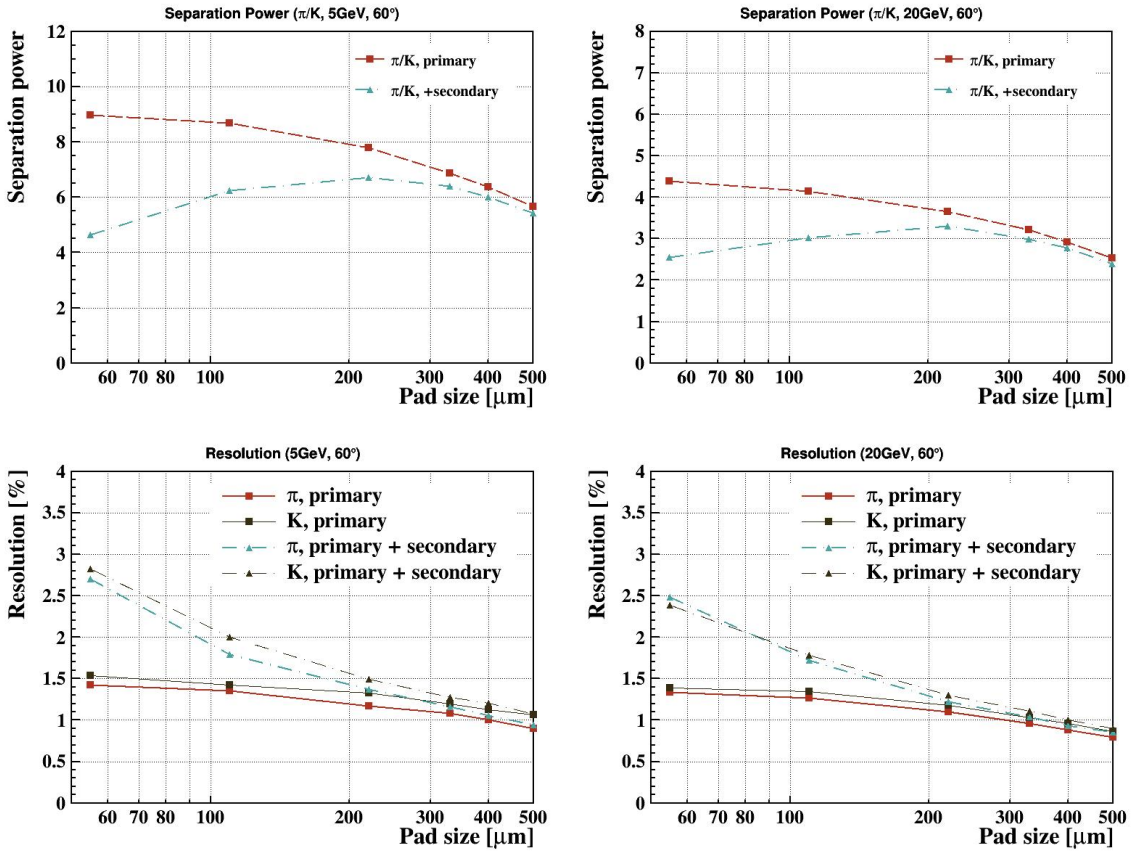
CEPC-TPC separation power (left) and resolution (right) varies with momentum

PID Performance without Diffusion (Ideal Case)

- **Primary electrons only:**
  - Smallest pads (55 μm) give best separation.
- **Including secondary electrons:**
  - **Optimal shifts to ~220 μm** – matches spatial scale of secondary clusters.
  - Truncated-mean not applied here (to isolate ionization effects).

- Secondary clusters have **spatial extent matching 220 μm**, and pads of this size allow **efficient signal collection** without **splitting clusters** and introducing extra fluctuations.

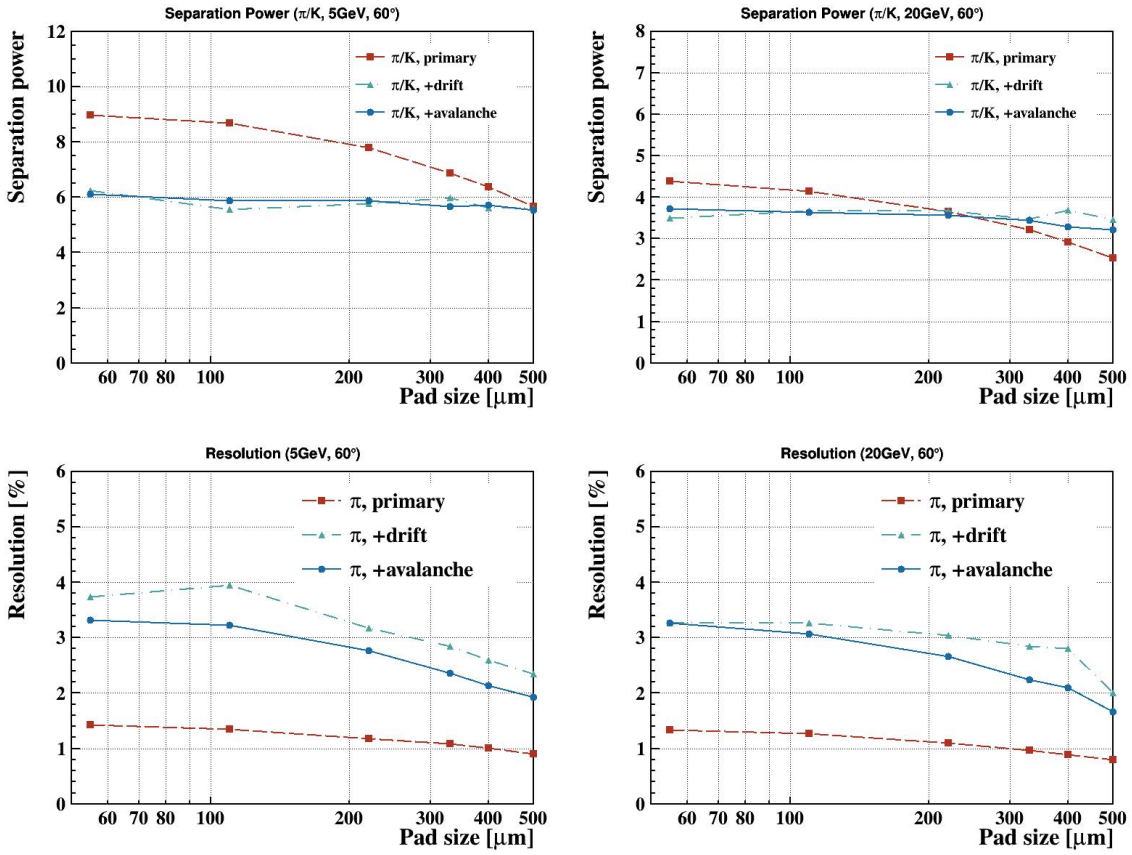
  (Further investigation shows that introducing truncated-mean in this step increase separation power for small pads and decrease it for large pads.)



PID Performance with Realistic Diffusion & Avalanche

Full Physics: drift + avalanche diffusion included, applying truncation-mean method (optimized for each pad size)

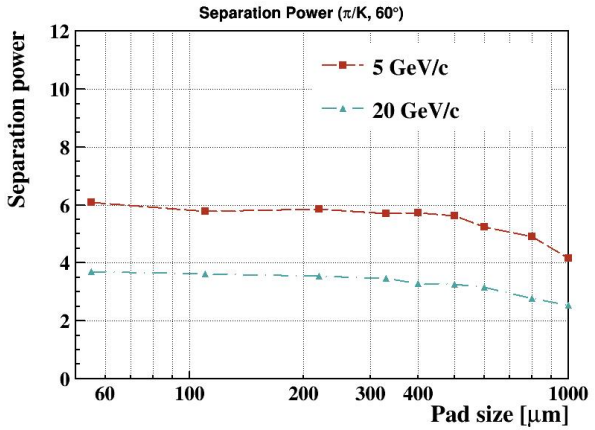
- PID performance becomes **almost constant** across 55–500 μm (plateau).
- Notably, for larger pads (>330 μm) at 20 GeV, separation power with diffusion is **higher than pure primary case**.
  - This is because **diffusion spreads electrons** that would otherwise pile on same pad, recovering resolution.
- All sizes meet **3σ** requirement up to 20 GeV.



Noise Tolerance & Extended Size Scan

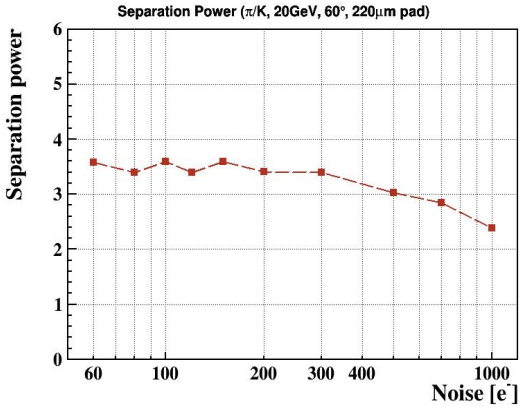
- **Extended to 1000 μm:**
  - Clear degradation when pad size >500 μm (separation drops below 3σ at 20 GeV).
- **Noise tolerance:**
  - 220 μm pad can tolerate **~300 e⁻ ENC**.
  - 500 μm pad tolerates **>400 e⁻ ENC**.
  - Larger pads allow lower power (<0.1 mW/ch) and simpler cooling.
- Thus **500 μm is a robust choice** balancing performance and engineering.
- If engineering allows, **220–330 μm can further secure PID performance**.

- **Published in EPJ:** https://doi.org/10.1140/epjs/s11734-026-02533-2

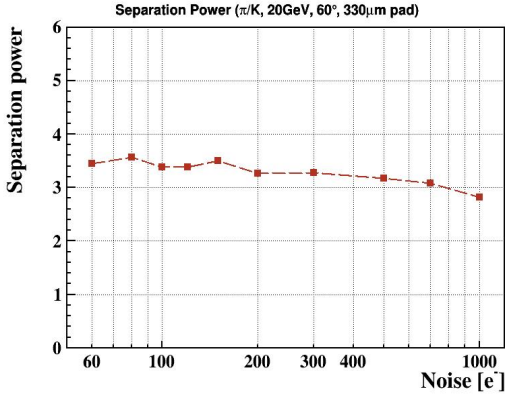


PID performance trend as pad size extends to 1 mm

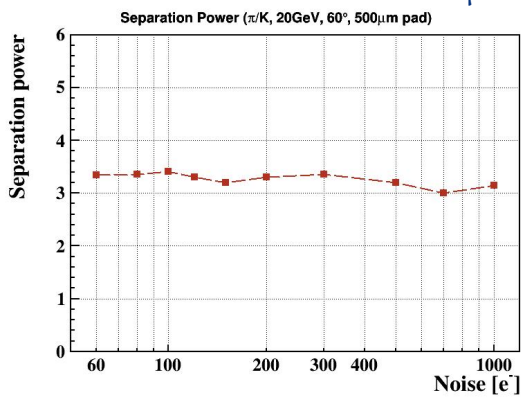
220 μm



330 μm



500 μm

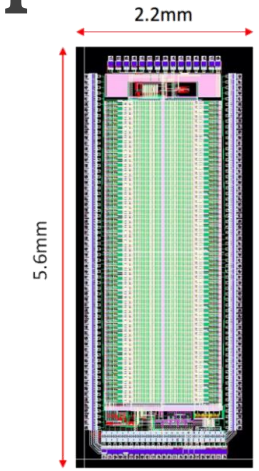


Noise impact on readout pads of different sizes

Detector module towards prototype

High granularity readout Electronics: TEPIX v1

- Charge-sensitive preamplifier
- Correlated double sampling shaper
- 4-channel sample/hold circuits and 10 bit ADC
- 128 channels using 180 nm process
- Chip size: 2.2 mm × 5.6 mm



Total number of channels	30 Million per endplate
Pixel size	500 μm × 500 μm
Equivalent Noise Charge (ENC)	100 e^-
Dynamic range	20 fC
Charge buffer dynamic range	8-10 bit
Event rate	12 kHz/cm^2 max. in low-lumi. Z mode
Event size	64 bit
Readout bandwidth	<10 Gbps per module with compression
Power consumption	<100 mW/cm^2

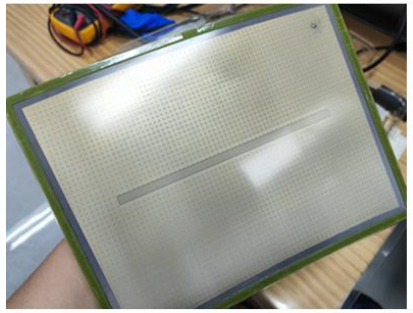
- **A total of 40 chip-in-package devices were commissioned.**

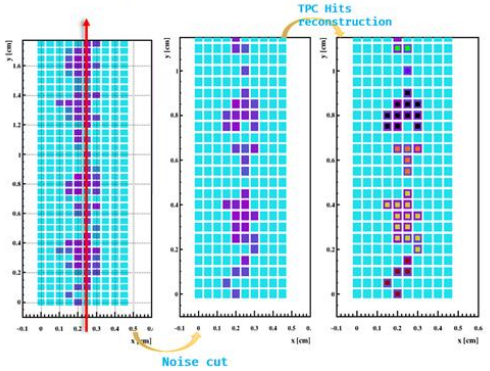
Micromegas:

- **The Micromegas detector integrated with the readout chip has been successfully developed.**
- Based on Garfield++, KalTest and a pixel-type TPC simulation framework:
  - Offline data-processing code developed
  - Time-stamp misalignment across multiple channels



Detector integrated with the high granularity readout

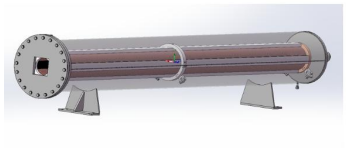




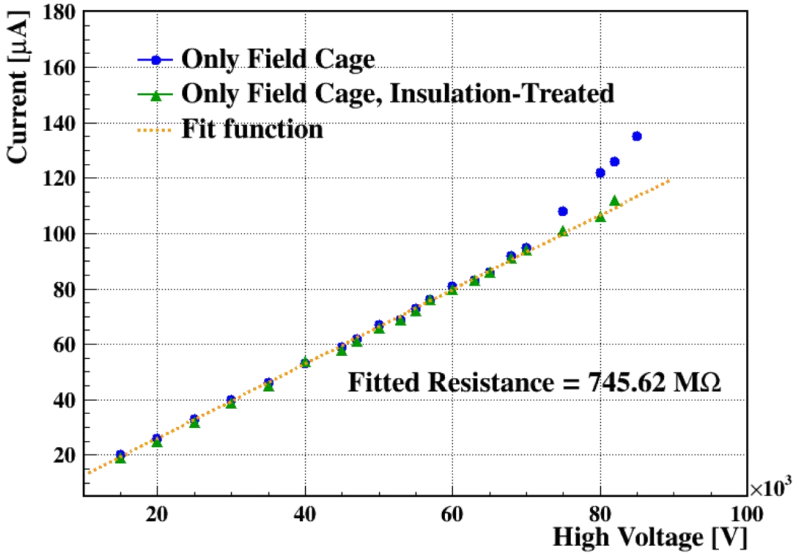
Prototype development & commissioning

- **Goal:**
  - **Validate key drift parameters** (velocity, diffusion, attachment) used in simulations.
  - **Directly measure pad-size dependence** of cluster counting.
- **Design parameters:**
  - **Drift length:** 2.9 m (same as CEPC TDR).
  - **Field cage:** 706 copper rings, 1 MΩ resistors in series for uniformity.
- **High-voltage commissioning:**
  - After insulation, **stable up to 80 kV, meeting operational requirements.**









Summary

- A full-physics TPC simulation framework has been built and validated against CEPC Ref-TDR.

- Under realistic conditions (including drift diffusion, avalanche broadening, and optimized truncation), the π/K separation power is **nearly constant** for pad sizes from **55 μm to 500 μm**.
- **500 μm** is the optimal baseline choice, and if additional PID margin is desired, **220–330 μm** is a viable alternative.
- To validate the key drift parameters and cross-check with the simulation results, a **full-drift-length TPC prototype** is built and under high-voltage commissioning.
- The detector module combining **Micromegas and High granularity readout TEPIX** is **successfully developed.**

THANKS

Thank you for your attention!





