PID-Driven High-Granularity Readout TPC Technology for e^+e^- Colliders

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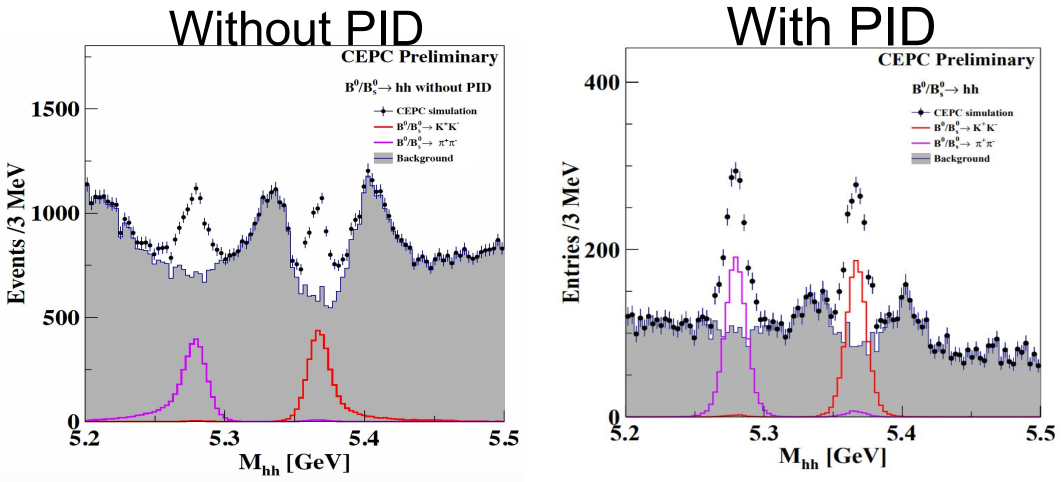
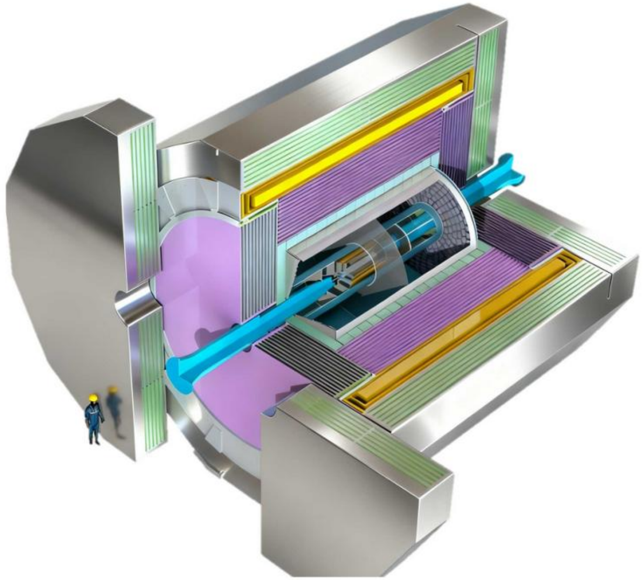
Physics Requirements at Future e^+e^- Colliders

- **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)

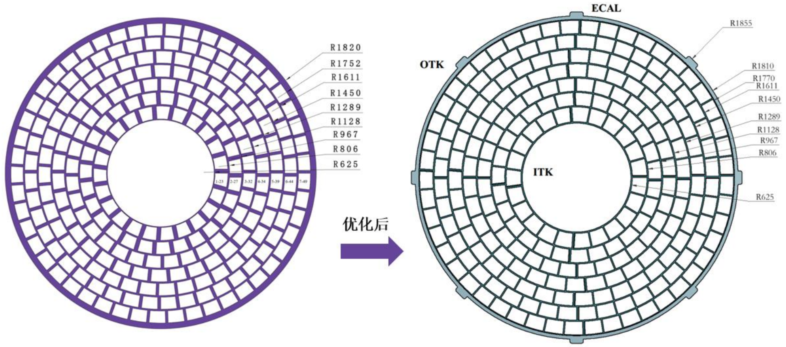
- **Detector geometry:**

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

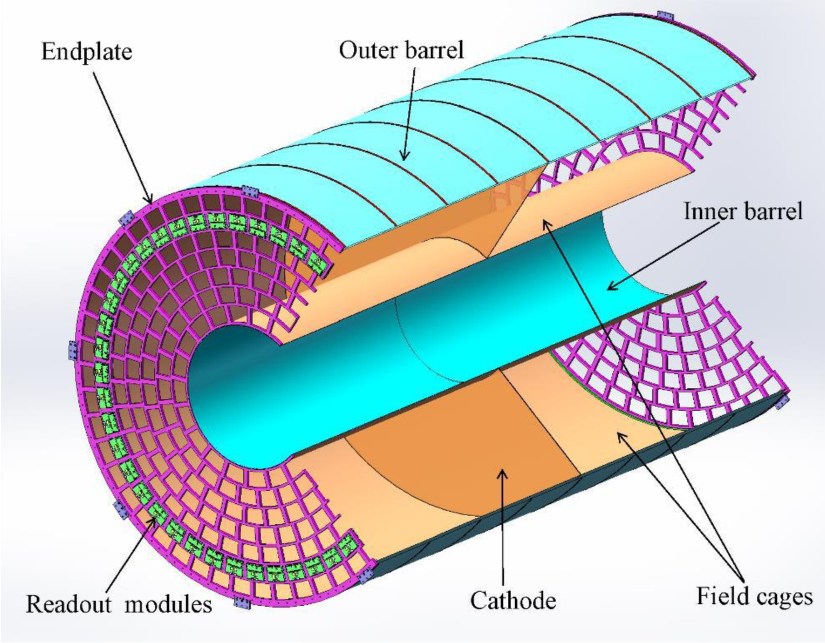
  $L_{drift} = 2.9$ m

  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)

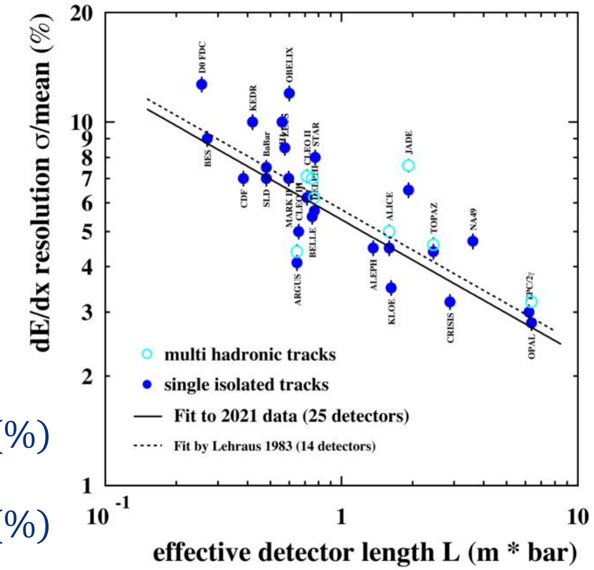


TPC layout

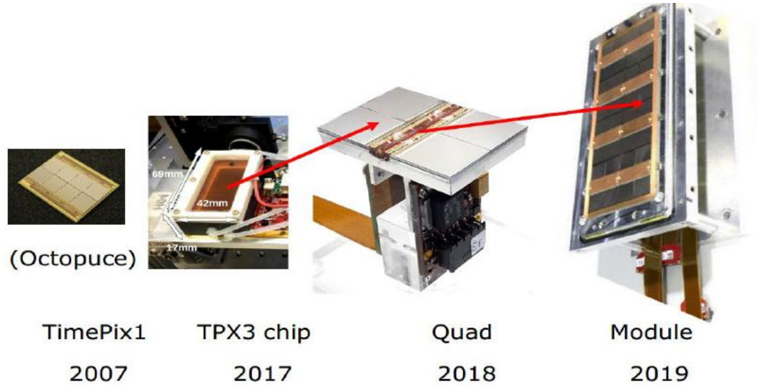
From dE/dx to Cluster Counting

- **Conventional approach:** Large pads (~1 mm × 6 mm) + dE/dx
  - Limitations: Long Landau tails, limited PID performance
- **Cluster counting with pixlated 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

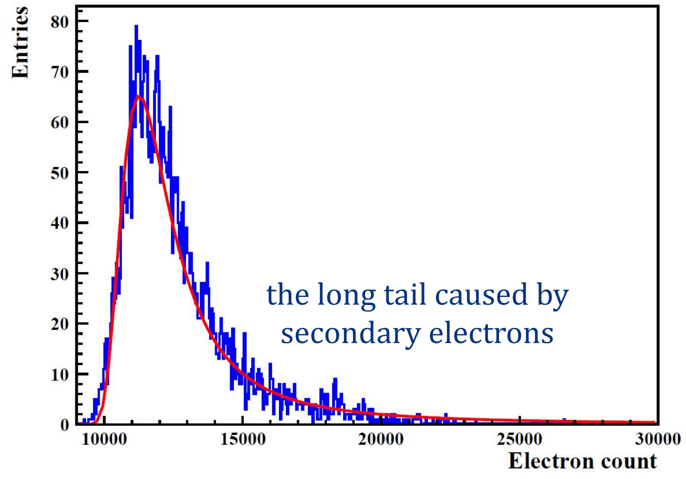
Ionization clusters in T2K: ~37cluster/cm

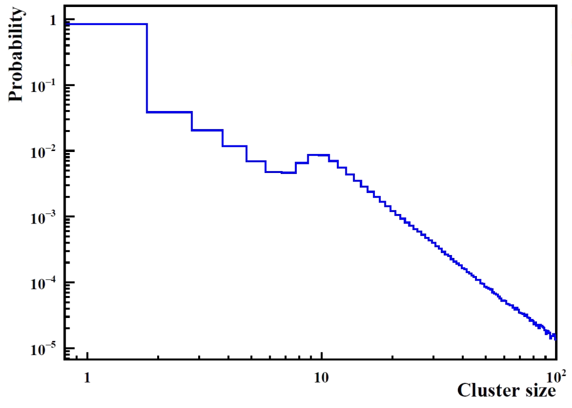
= ~1.8 clusters/ 500 µm , ~1.2 clusters/ 300 µm

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

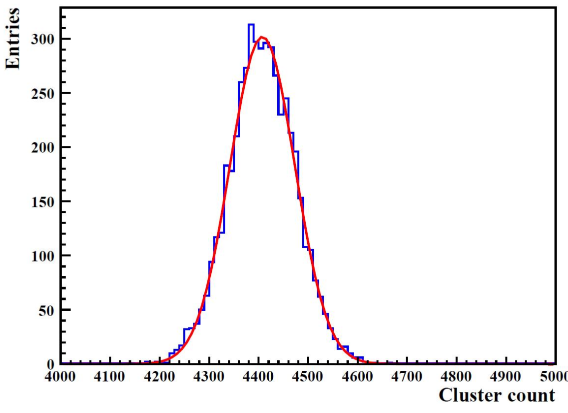
- **Key challenge:** Accurately count clusters – achieved via **fired-pad counting**

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





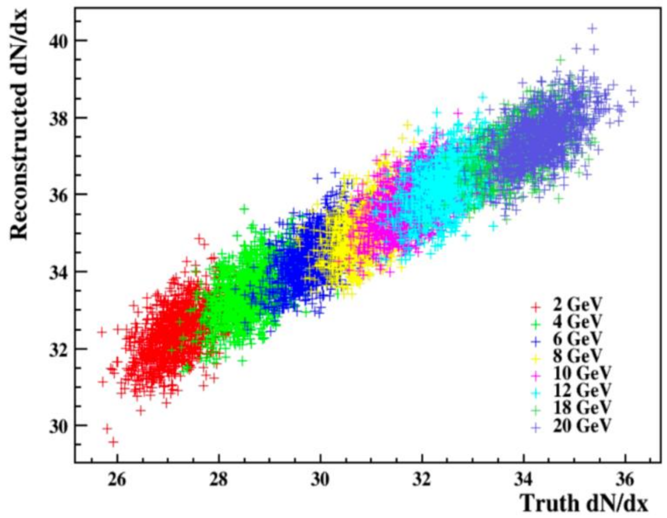
Electron multiplicity per cluster

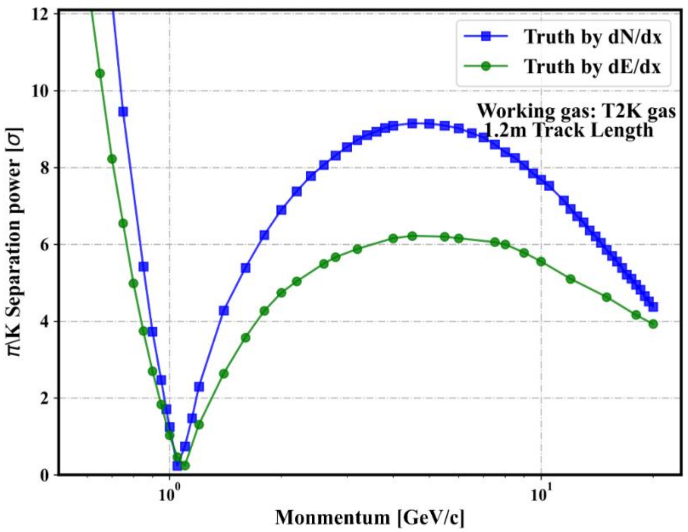


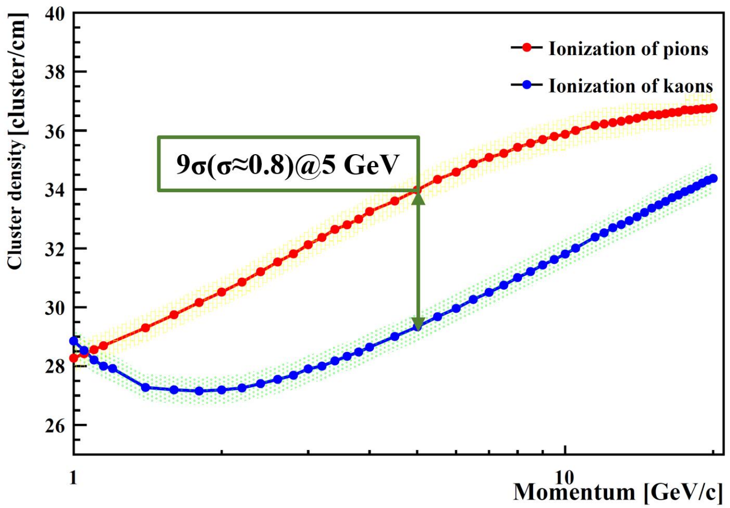
Gaussian distribution of cluster counts along the track

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

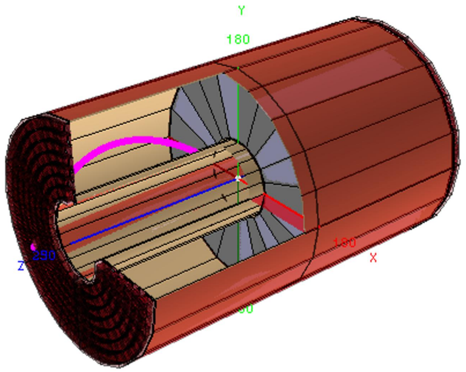
- Preliminary simulation has already shown that, using **Micromegas + pixelated readout**, the **dN_p/dx** approach yields much better PID than traditional dE/dx.
- **Essential trade-offs:**
- Small readout pad (e.g., 55 μm):
  - Excellent single-electron resolution.
  - **Channel count** quadratically 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.

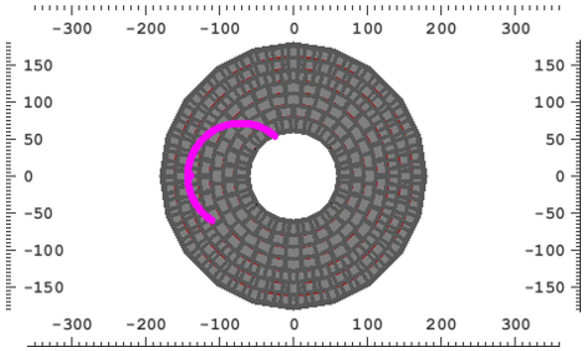
Our study:

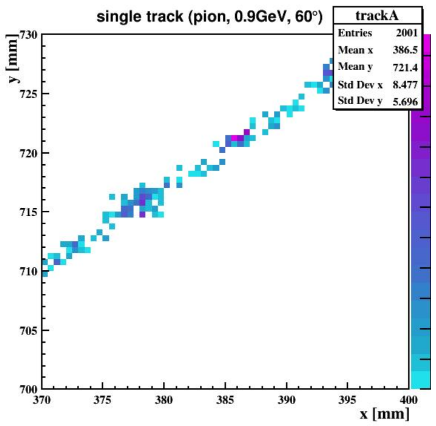
- **Systematic scan** from 55 μm to 1000 μm.
- Evaluate π/K separation power under realistic physics (ionization, diffusion, avalanche).
- **Experimentally validate** the key parameters with a full-drift-length (2.9 m) TPC prototype.

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

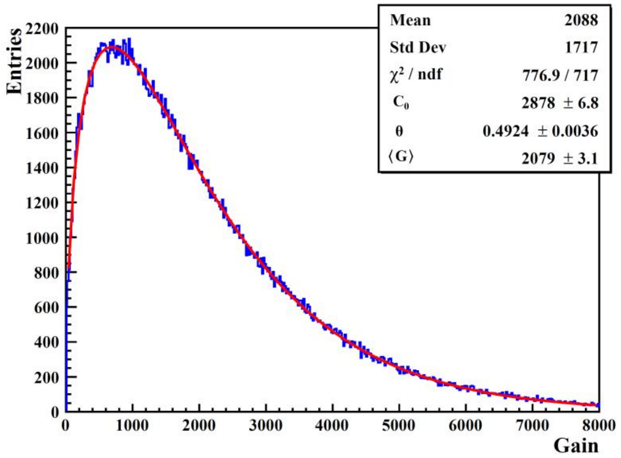
Ionization → Drift diffusion (parameterized) → Avalanche → Signal generate → Hit finding → dE/dx & dN_p/dx

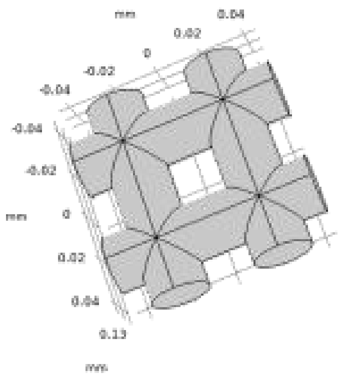
Garfield++ Simulation | Digitization | Reconstruction

Simulation Framework – Drift, Diffudion and Avalanche

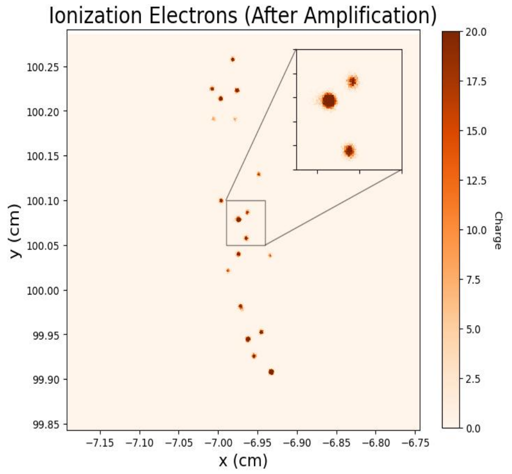
Drift and avalanche:

- 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

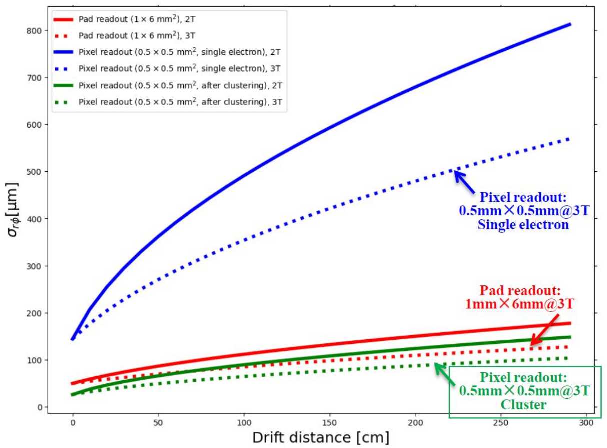




Polya distribution fit to the avalanche gain



Display of electrons after avalanche



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

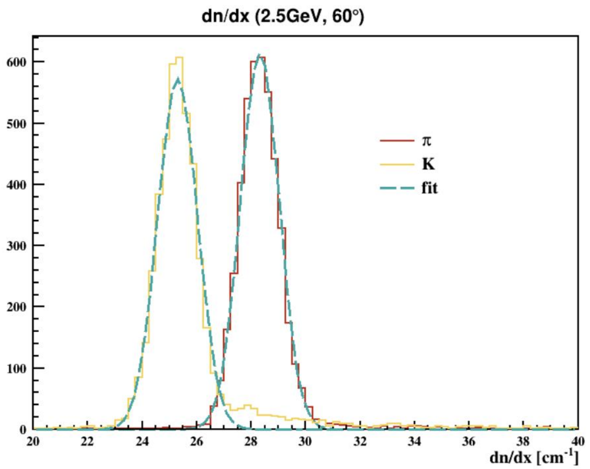
Cluster Counting Principle (dN_p/dx)

- Basically, $dN_\mathrm{p}/dx = \frac{\text{(Num of hits)}}{\text{(Length of track)}}$

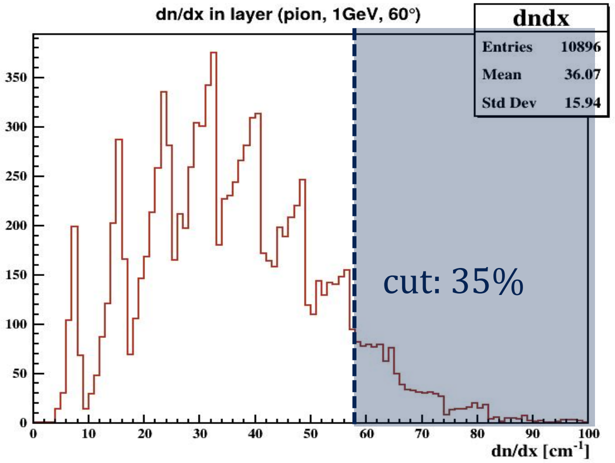
To mitigate the effect of secondary electrons, a layered truncated-mean method is employed for dNp/dx reconstruction:

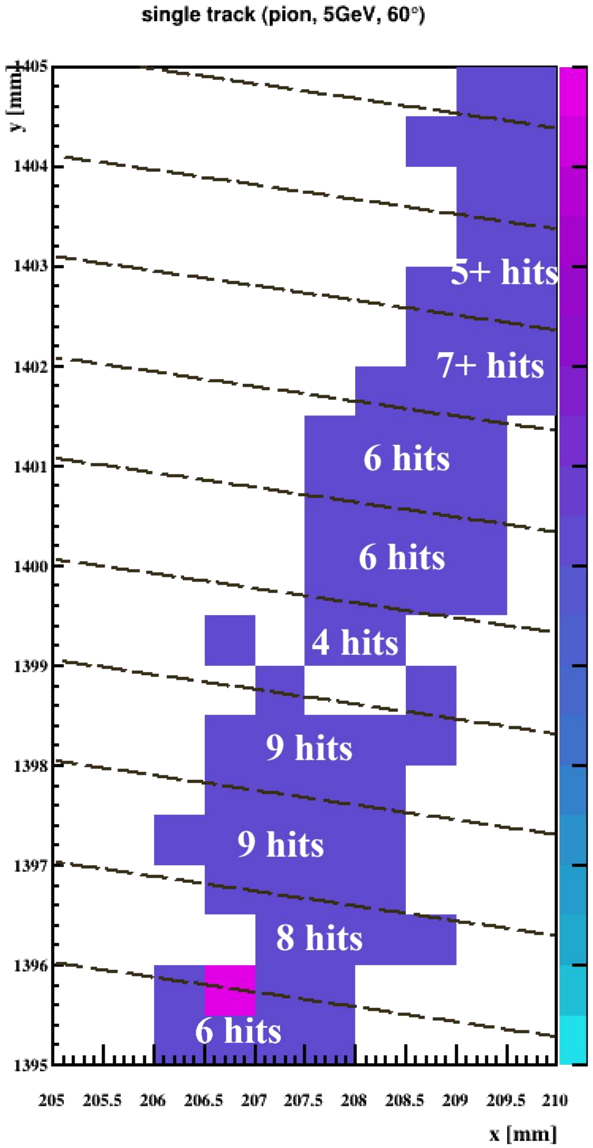
The track is **divided into layers**, and a fixed percentage of layers with the highest values are **discarded** (truncated). Then, calculate **the avarange dN_p/dx** of the remaining layers:

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



A typical dN_p/dx PID example



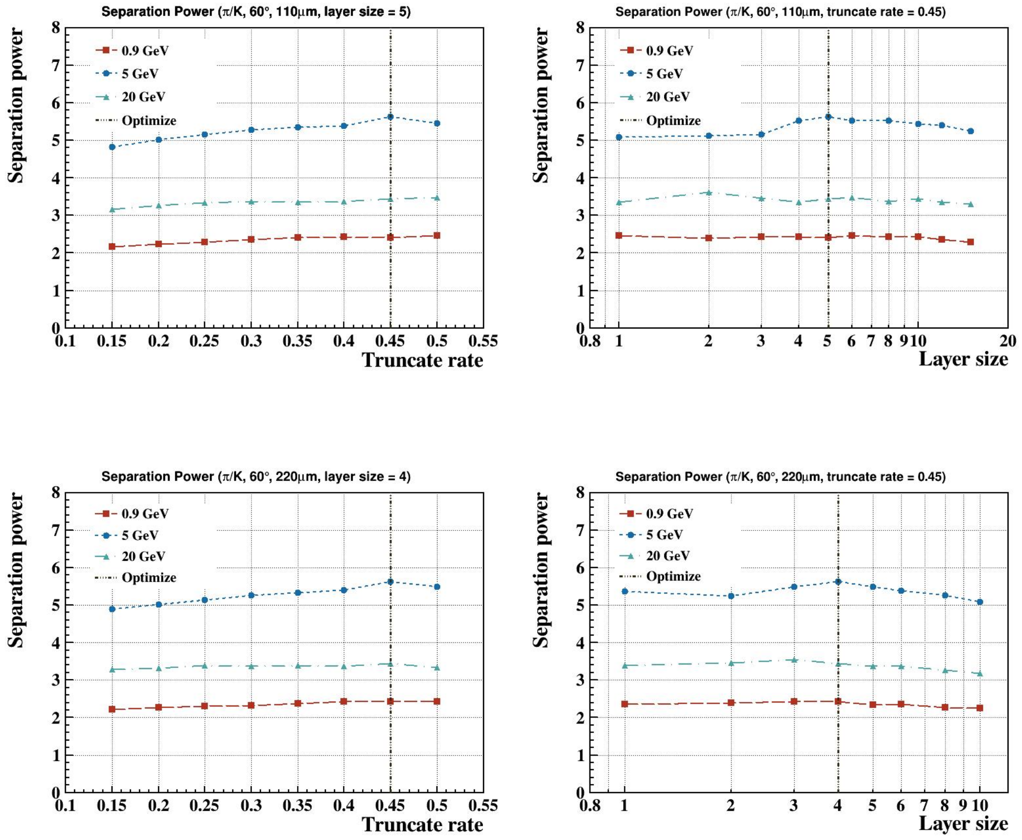


Reconstruction Parameter Optimization

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

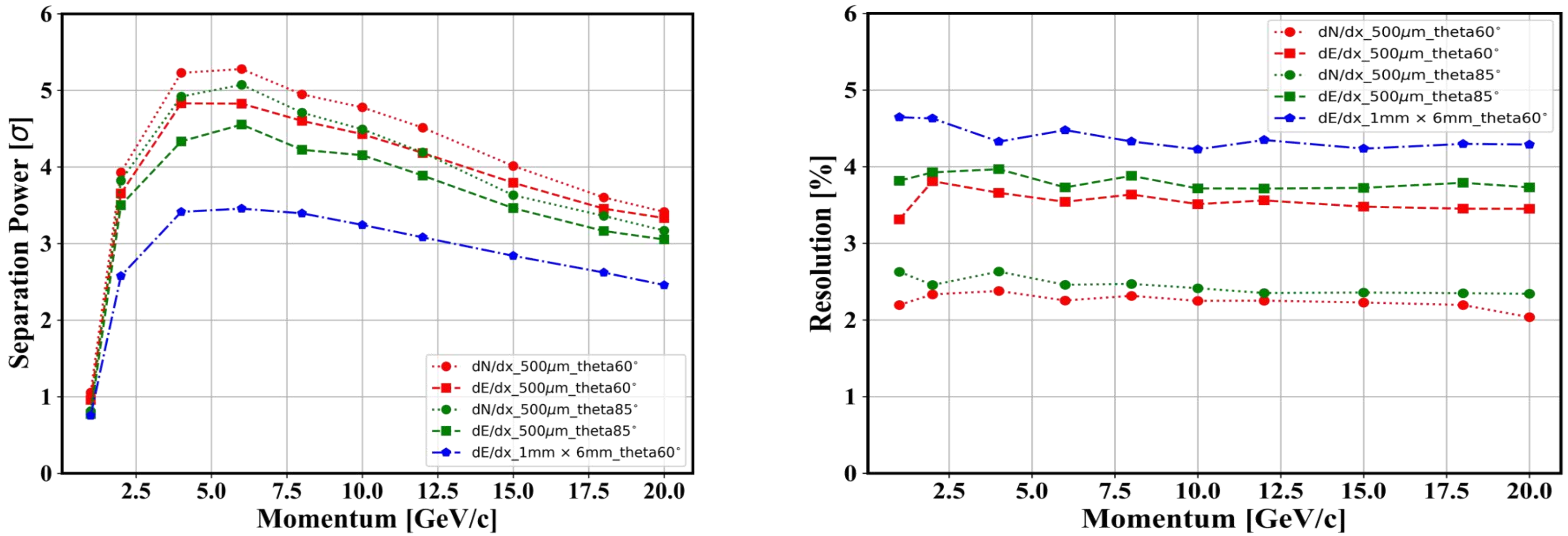


- Using separation power： $Sp_{A,B} = \frac{|\mu_A - \mu_B|}{\sqrt{(\sigma_A^2 + \sigma_B^2)/2}}$

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%**.



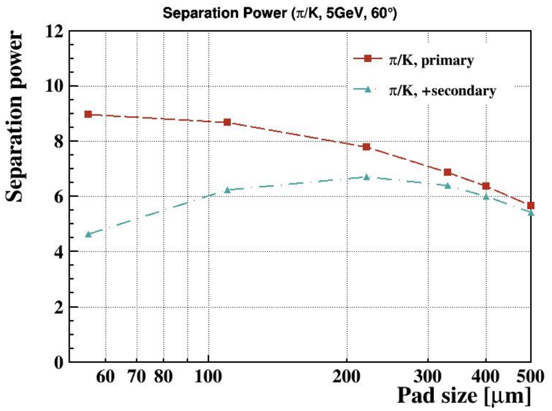
CEPC-TPC separation power (left) and resolution (right) varies with momentum

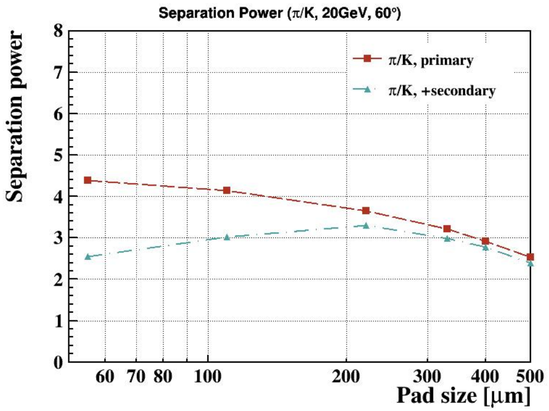
PID Performance without Diffusion (Ideal Case)

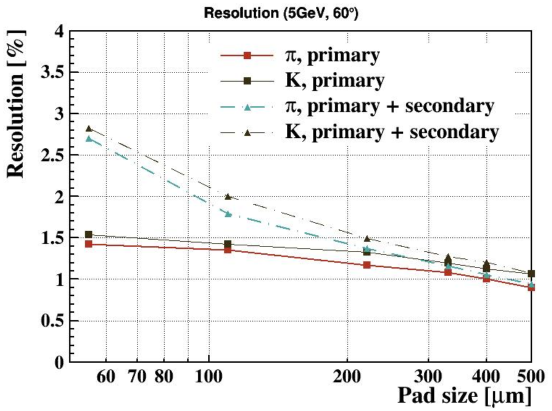
- **Primary electrons only:**
  - Smallest pads (55 μm) give best separation.
- **Including secondary electrons:**
  - **Optimal shifts to ~220 μm** – matches spatial scale of secondary clusters.
  - Truncated-mean not applied here (to isolate ionization effects).

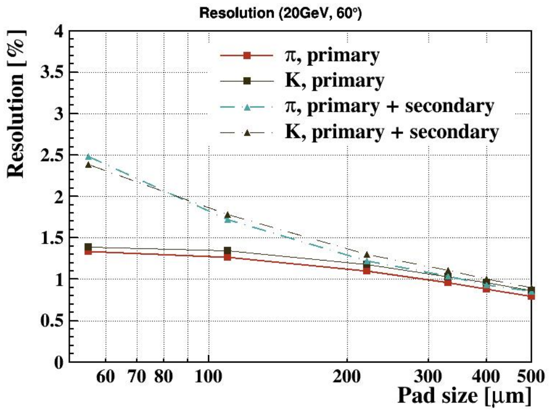
- Secondary clusters have **spatial extent matching 220 μm**, and pads of this size allow **efficient signal collection** without **splitting clusters** and introducing extra fluctuations.

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







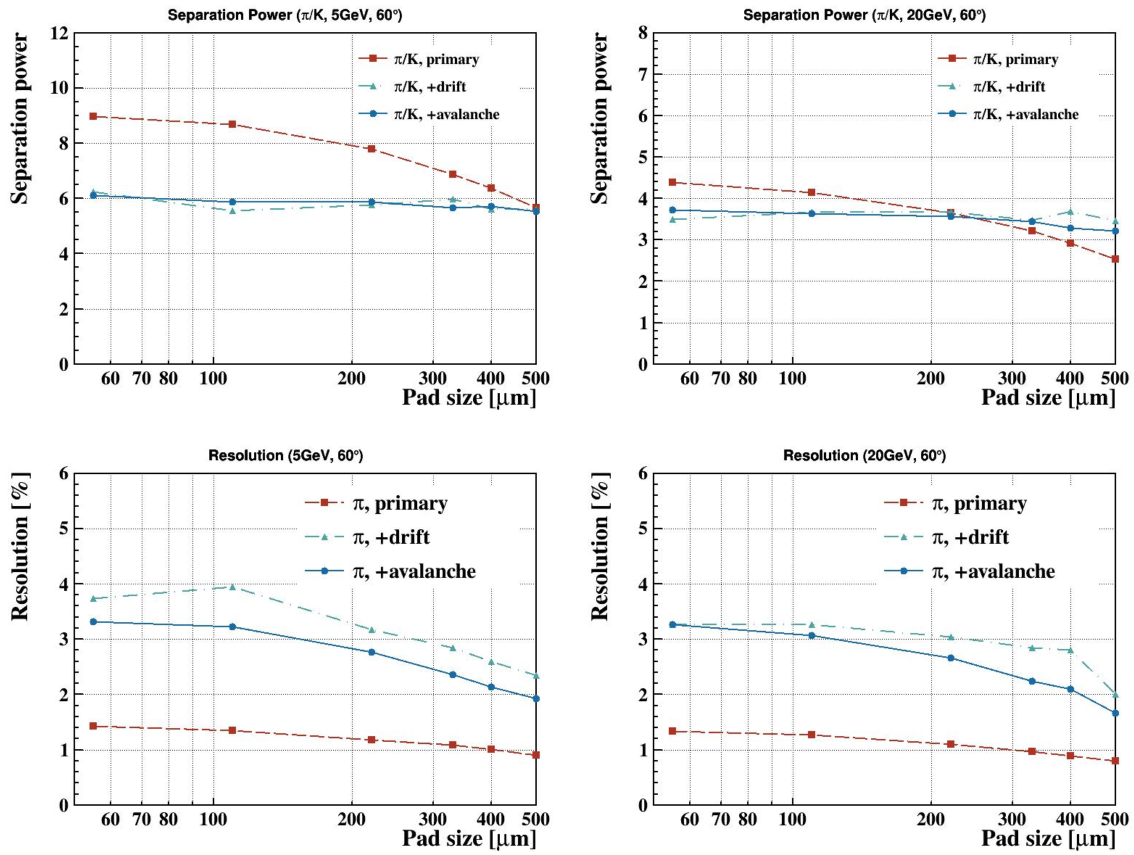


PID Performance with Realistic Diffusion & Avalanche

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).

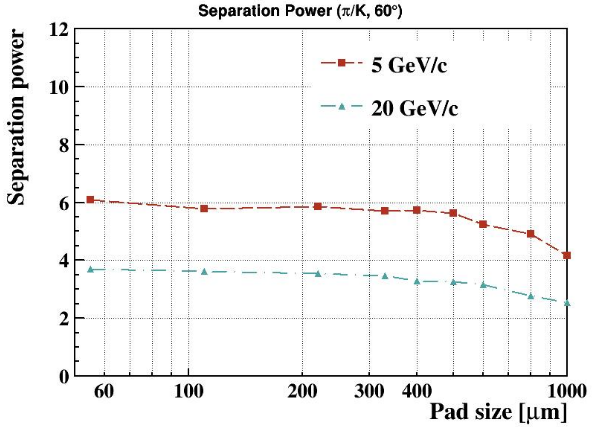
- Notably, for larger pads (>330 μm) at 20 GeV, separation power with diffusion is **higher than pure primary case**.
  - This is because **diffusion spreads electrons** that would otherwise pile on same pad, recovering resolution.
- All sizes meet **3σ** requirement up to 20 GeV.



Noise Tolerance & Extended Size Scan

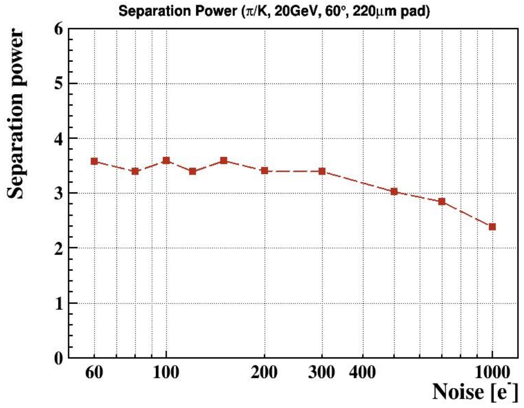
- **Extended to 1000 µm:**
  - Clear degradation when pad size >500 µm (separation drops below 3σ at 20 GeV).
- **Noise tolerance:**
  - 220 µm pad can tolerate **~300 e^- ENC**.
  - 500 µm pad tolerates **>400 e^- ENC**.
  - Larger pads allow lower power (<0.1 mW/ch) and simpler cooling.
- Thus **500 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

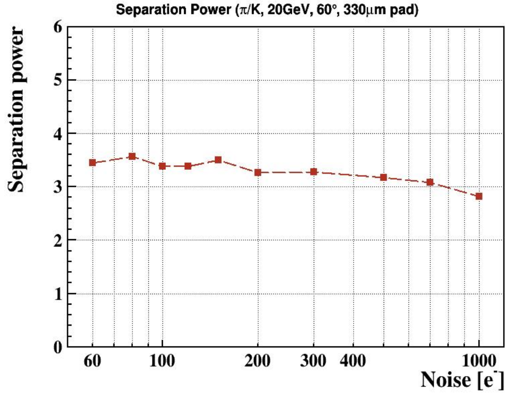


PID performance trend as pad size extends to 1 mm

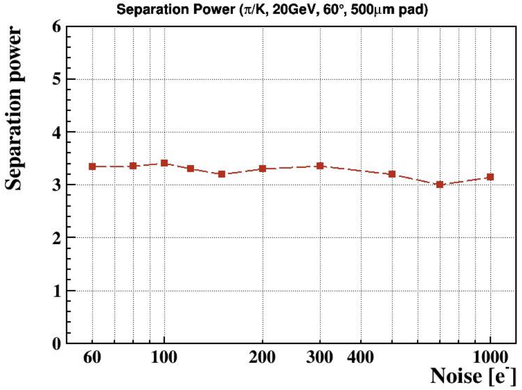
220 µm



330 µm



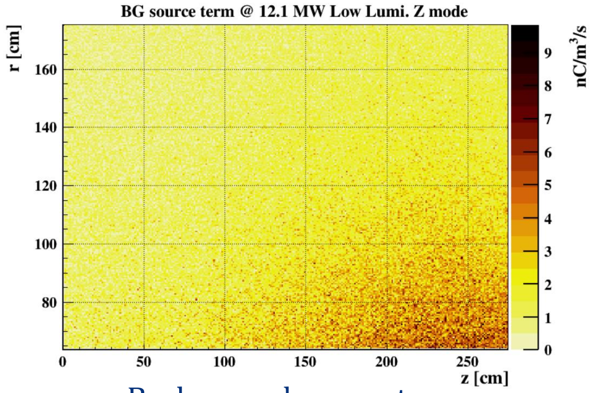
500 µm



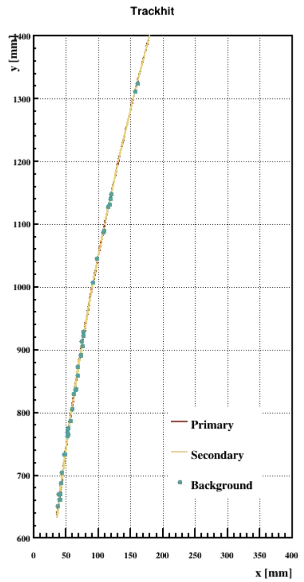
Noise impact on readout pads of different sizes

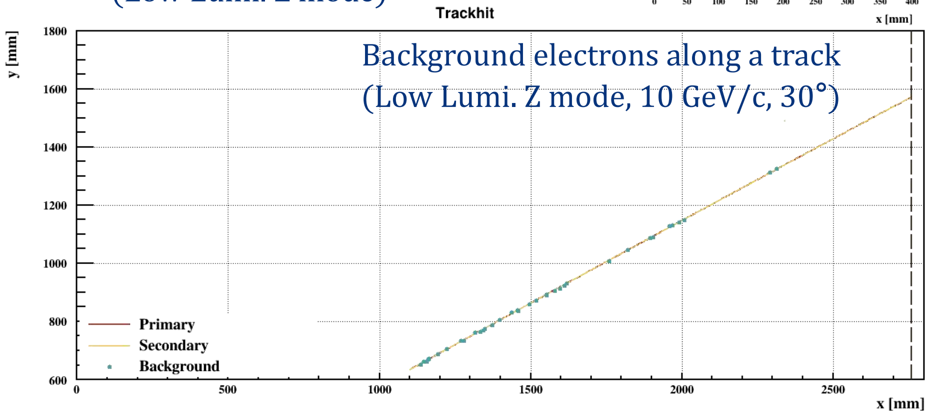
Preliminary Study of Background Effects on PID

- Predictable background effects **on TPC PID**:
  - Track distortion effect on dN_p/dx: **negligible in current stage**
  - Degradation of momentum resolution: **negligible in current stage**
  - Background particles on dN_p/dx: **significant**
- **Method:**
  - In the simulation framework, **inject background hits near the reconstructed track** using background source term files
  - “near the track”: defined as **3σ of the electron diffusion** (drift-distance dependent) – **this is where background electrons mix with track signals**.



Background source term
(Low Lumi. Z mode)



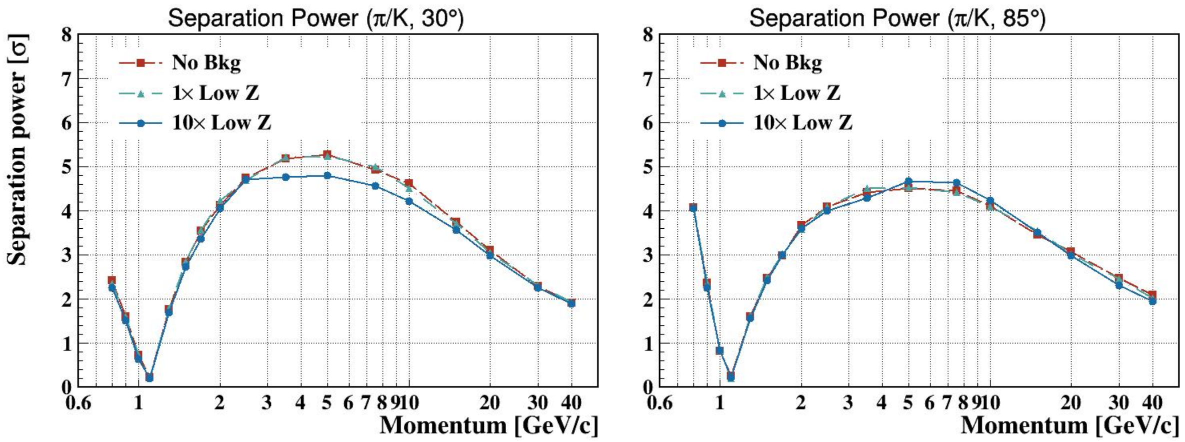


Background electrons along a track
(Low Lumi. Z mode, 10 GeV/c, 30°)

- **Background types implemented:** Beamstrahlung, BGC, BGB, BTH, TSK(from CEPC MDI studies)
- **Synchrotron radiation:** currently difficult to quantify precisely; we apply **scaling factors** to existing backgrounds to set upper-limit constraints.

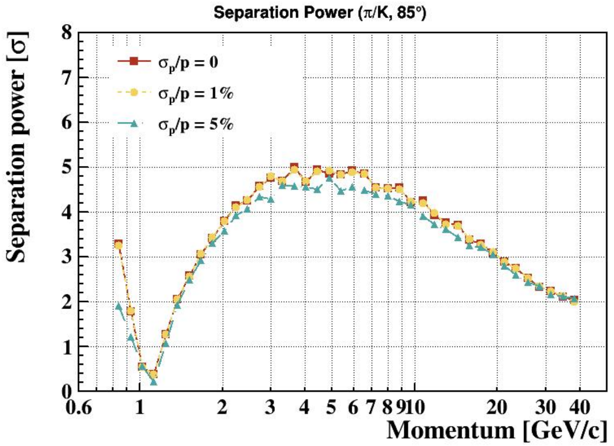
Low Lumi. Z and Scaled Backgrounds

- **Low Lumi. Z mode (×1 intensity):**
  - Background contributes **<0.5% extra electrons** along the track
  - PID performance degradation is **negligible (within statistical uncertainty)**.



PID degradation in Low Lumi. Z mode

- **Low Lumi. Z mode (×10 intensity):**
  - **Performance drop reaches <10%** (10% when θ = 30° and p = 5~10 GeV) in π/K separation power.
  - This scaling study helps constrain the margin for safety.
- **Tera Z mode:**
  - Awaiting updated MDI inputs from the beam-background group.



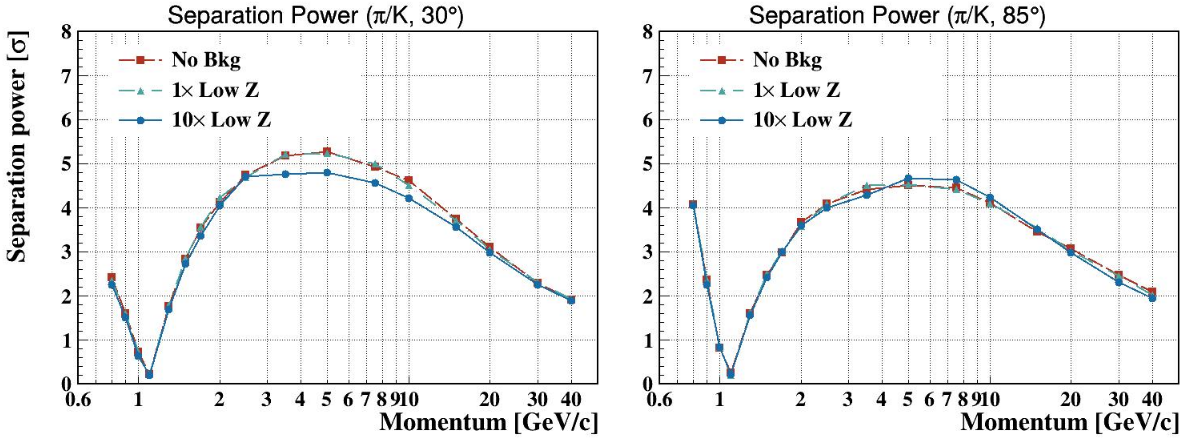
Negligible impact on PID performance when momentum resolution is better than 1%

Interplay Between Backgrounds and Truncation Rates

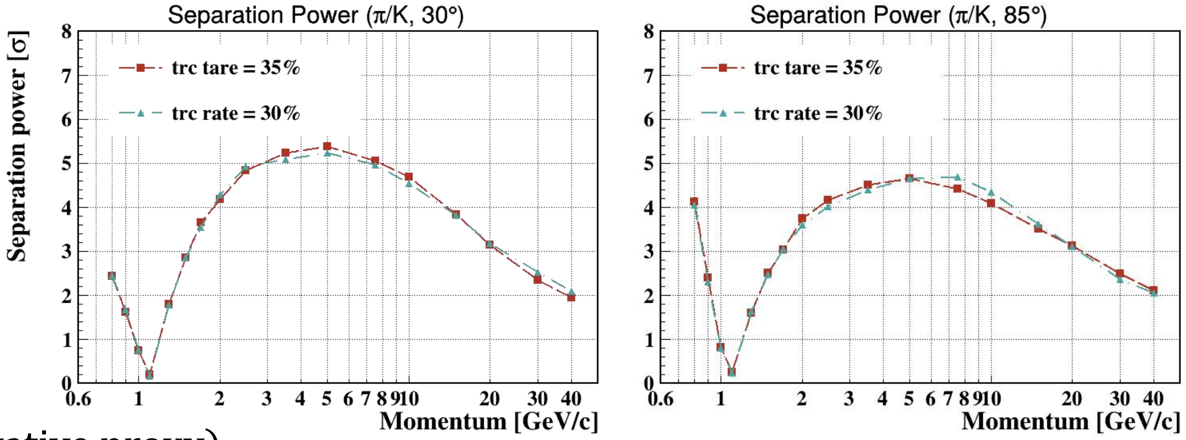
- In some simulated points, adding ×10 Low Lumi. Z background **unexpectedly improved the separation power**:
  - The fixed 35% truncation is **not optimal for those conditions**; the true optimum is lower.
    For any given pad size, however, we must choose a single truncation value.
- **The optimal truncation rate (Page 10) depends on the background occupancy.**
- Currently **no re-optimization performed yet**, because MDI background data (especially synchrotron radiation) is still pending.

Planned comprehensive scan:

- Truncation rate: **0~50 %** Momentum: **15~30 GeV/c**
- **With vs. without background** (using ×10 Low Z as a conservative proxy).



PID degradation in Low Lumi. Z mode



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.

- Low Lumi. Z backgrounds have **negligible effect on PID (<0.5% extra electrons)**.
- ×10 backgrounds cause **~10% degradation**; this provides a safety boundary for future MDI updates.

Future work:

- Complete the scan (truncation 0–50%, momentum 15–30 GeV) with/without background.
- Collaborate with the MDI group to obtain updated particle-flux inputs, and perform dedicated simulations for the high-background running scenario.

THANKS

Thank you for your attention!