PID performance of high-granularity readout TPC for future e^+e^- colliders

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and LCTPC Collaboration

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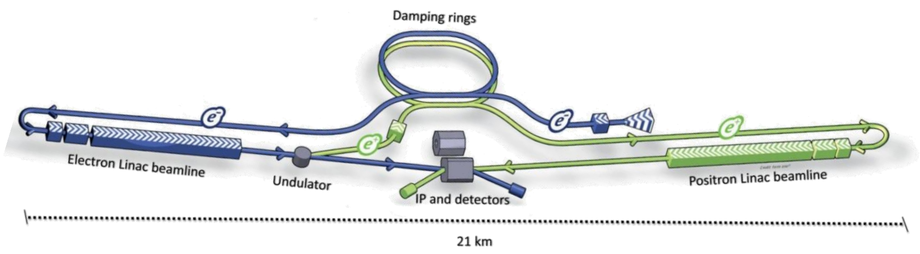
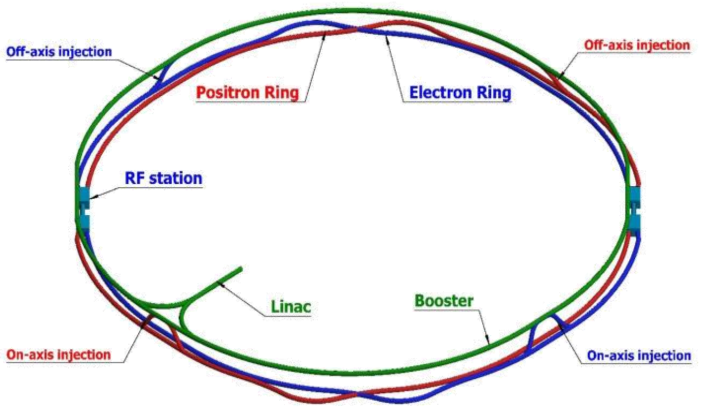
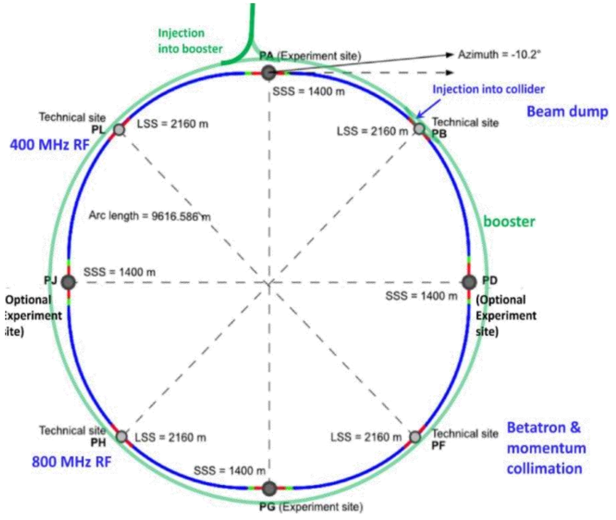
TPC for future e^+e^- colliders

- The TPC is a promising main tracker detector candidate for future e^+e^- collider experiments.
  - A low material budget (ensuring the resolution of low-momentum tracks)
  - Good particle identification (PID) capability
  - Provides data at the hundred-micrometer level (facilitating pattern recognition in track reconstruction)
  - Barrel coverage extends up to $|\cos\theta| > 0.85$
- High-granularity readout TPC is potential to improve PID requirements of flavor physics at e^+e^- collider
- TPC technology can be interest for future colliders (CEPC, FCC-ee, EIC, etc.)



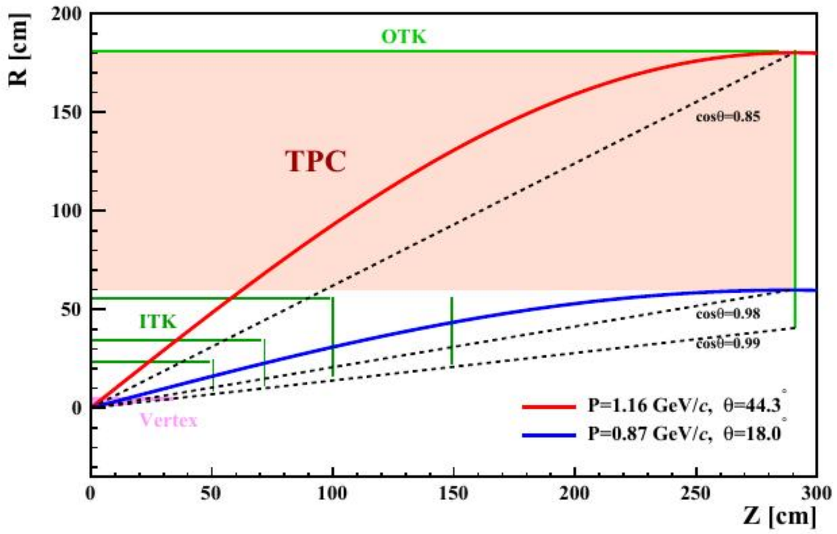




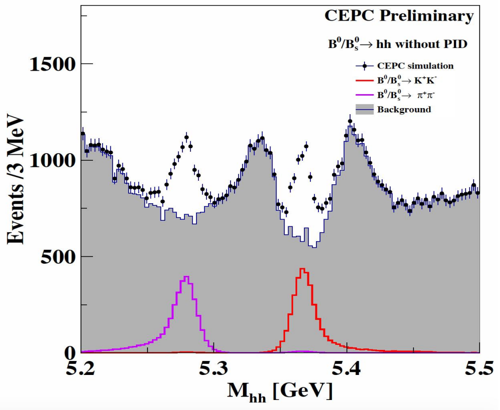
TPC for future e^+e^- colliders

- Physics requirements for TPC:
  - Tracking: $\sigma(1/P_T) \sim 10^{-4}$ (GeV/c)$^{-1}$ (TPC only), $\sigma(1/P_T) \sim 3\times10^{-5}$ (GeV/c)$^{-1}$ (TPC+Si detectors)
  - PID for flavor physics and jet reconstruction: π/K separation power better than 3σ
- Challenges:
  - Beam-induced background
  - Space charge effect and distortions

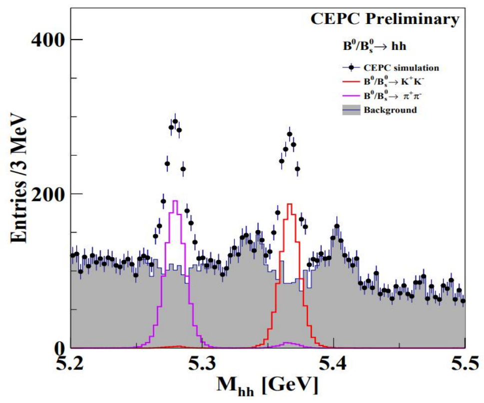
Parameters	Requirements for CEPC
Momentum resolution	$\sigma(1/P_T) \sim 10^{-4}$ (GeV/c)$^{-1}$
Magnetic field	3 T
Space resolution	$\sigma_{r\varphi} < 100$ μm
Reconstruction efficienfy	> 97% (when P_T > 1)
Particle identification	3%



Without PID

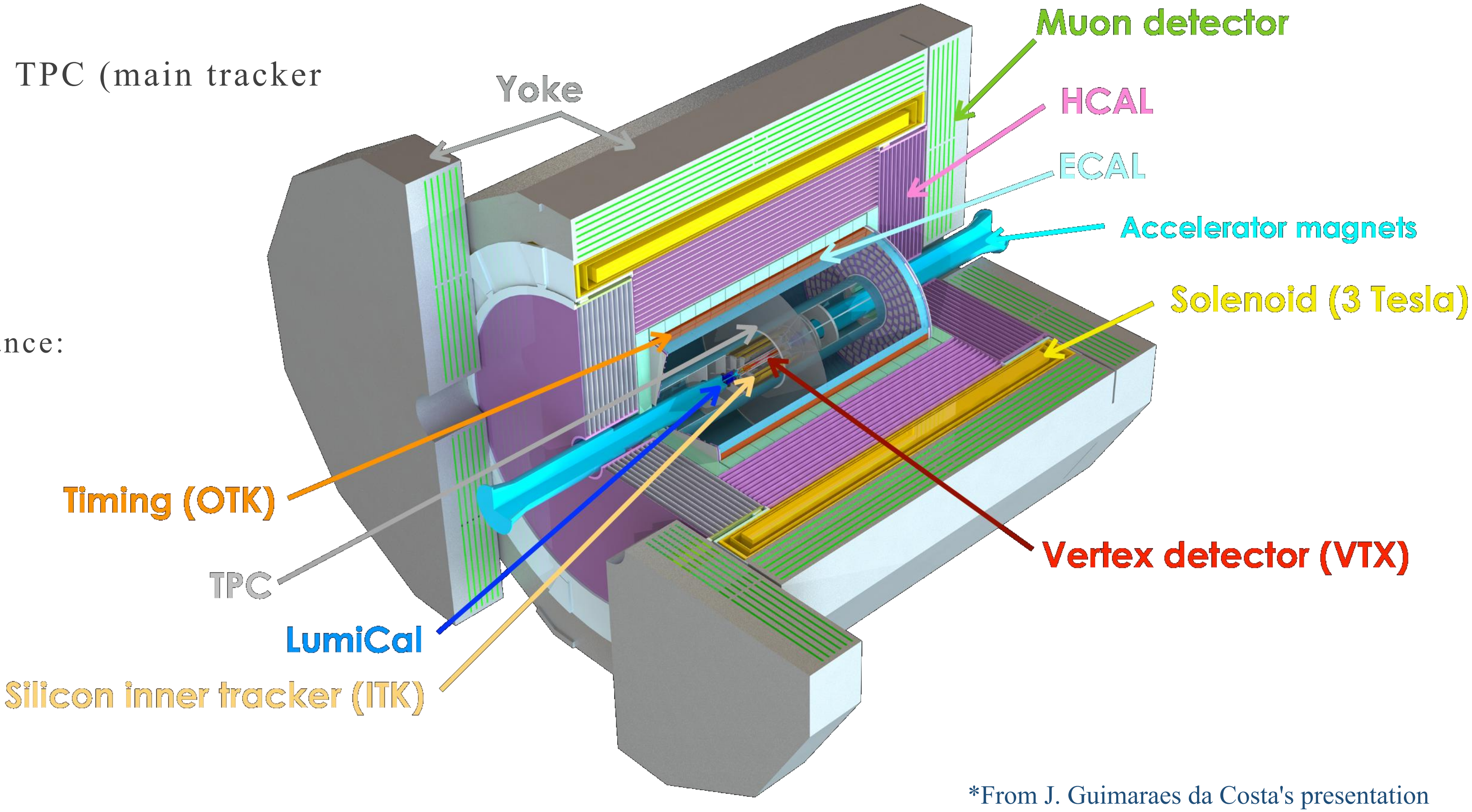


With PID



CEPC detector design

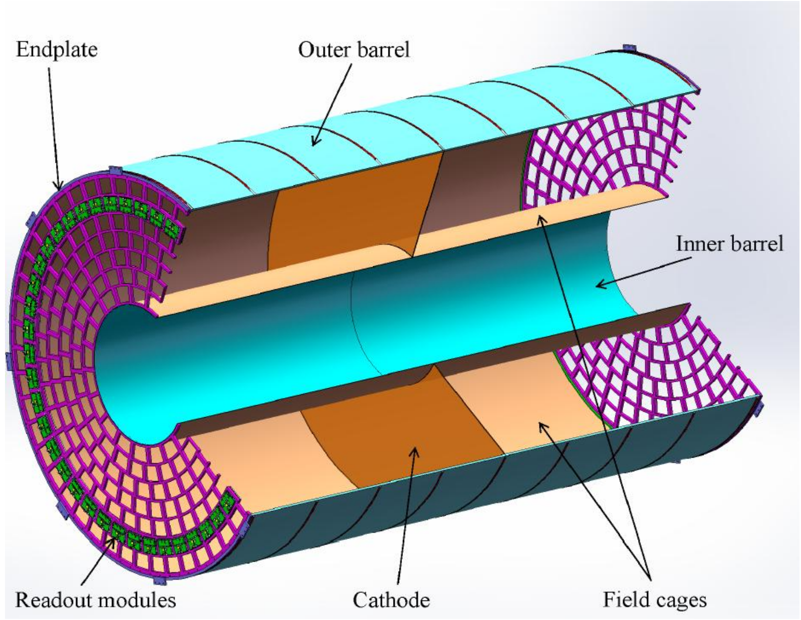
- In CEPC detector design, TPC (main tracker detector) coverage:
  - R = 0.6 ~ 1.8 m
  - Half-L = 2.9 m
  - With optimal performance:
    $|\cos\theta| < 0.85$
  - Maximum coverage:
    $|\cos\theta| < 0.98$

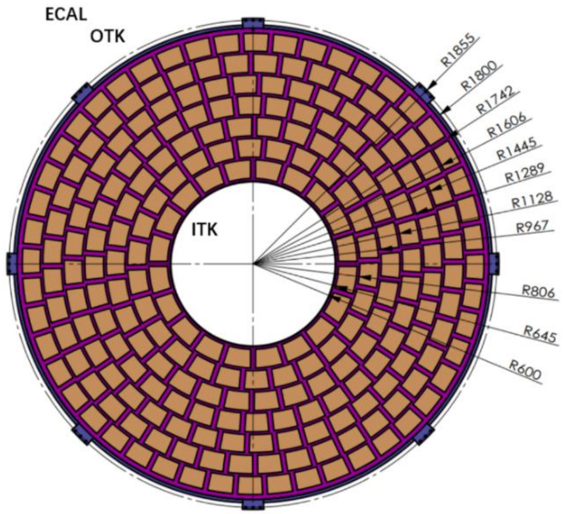


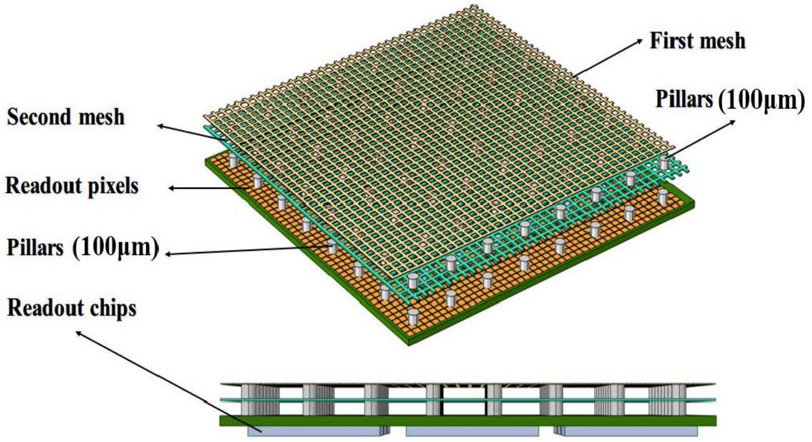
*From J. Guimaraes da Costa's presentation

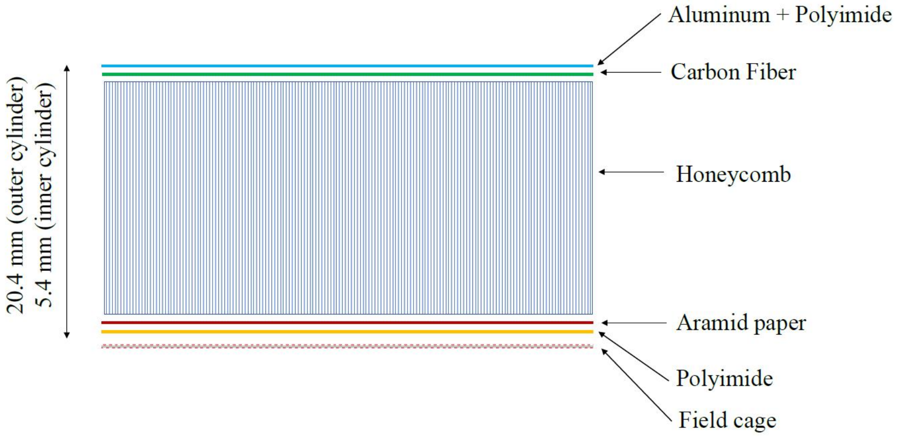
Baseline design of the TPC

- Overall design of the TPC in CEPC Ref-TDR
  - Inner radius = 0.6m / Outer radius = 1.8m / Max. drift length ~ 2.75m (volume = 52.48m^3)
  - **End-plate**: 248×2 modules, Double-Micromegas + 500μm×500μm readout pad
  - **Light barrel**: 0.69% X_0 for the outer cylinder and 0.45% X_0 for the inner cylinder wall



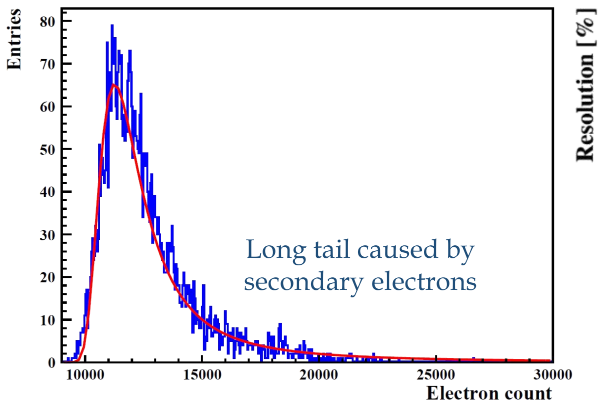


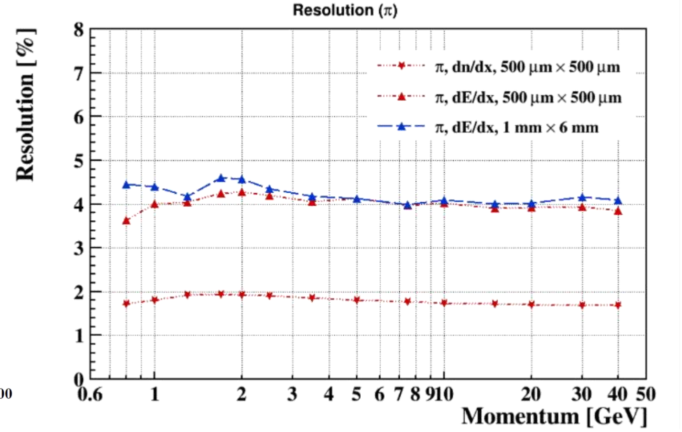


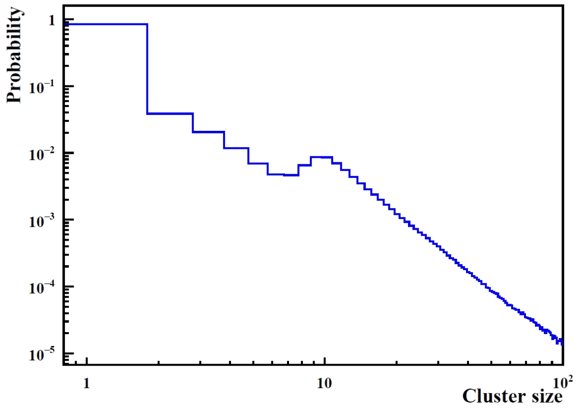


High-granularity readout

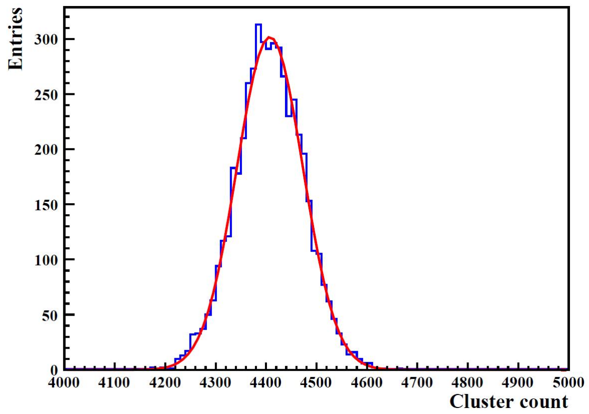
- Traditional TPC readout: ~1mm×6mm pad size, dE/dx PID
  - A well-established and mature technology
  - Limited number of sampling points
  - A long tail in the distribution of dE/dx, making it sensitive to fluctuations
- For future large colliders, we proposed a high-granularity readout design for TPC:
  - Readout pad size: ~500 μm
  - With the cluster counting (dN_p/dx) algorithm, it can achieve better PID performance
  - Challenge: the smaller readout units lead to higher overall power consumption and greater cooling requirements







Most clusters produce only 1~2 electrons

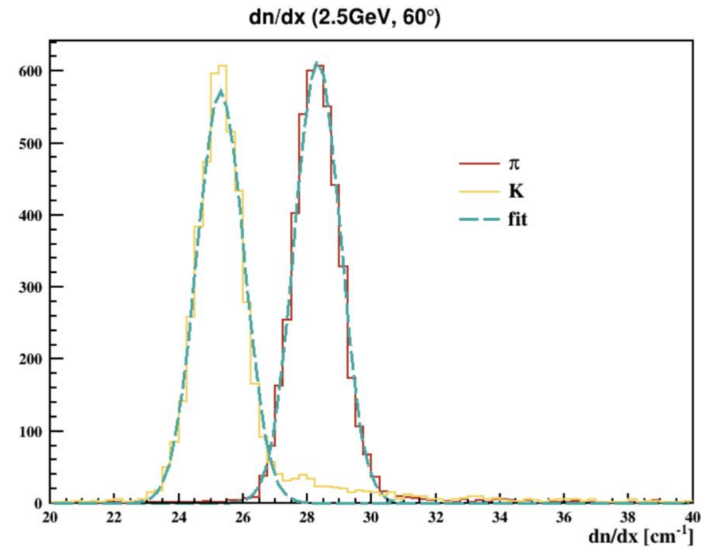


Number of clusters in one track

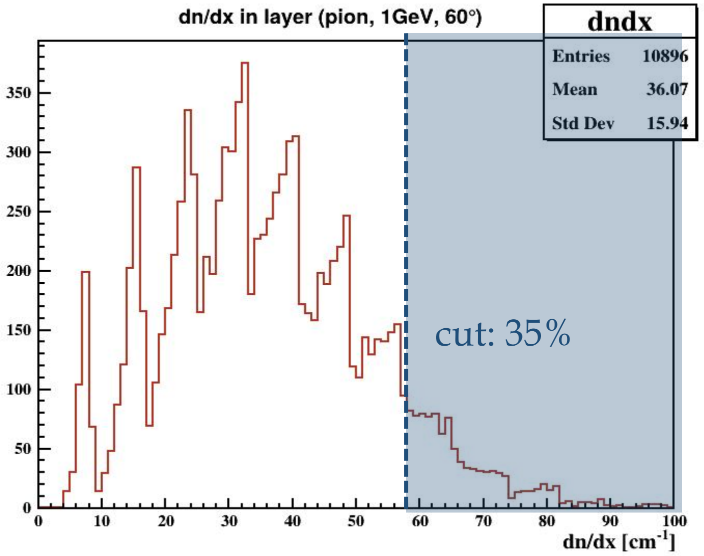
dN_p/dx PID algorithm

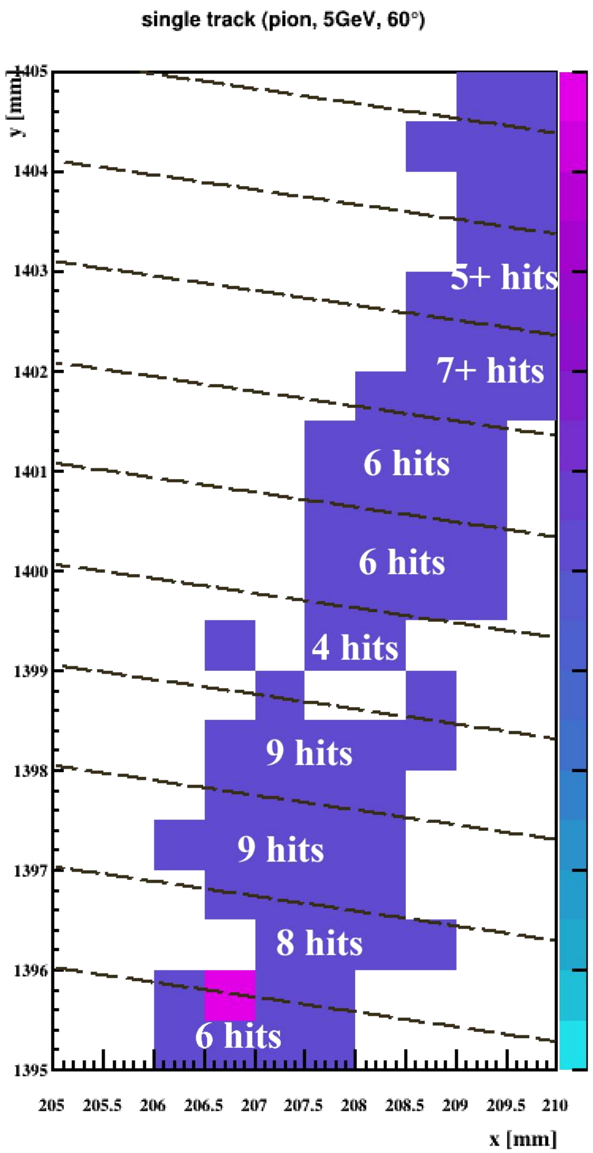
- Basically, $dN_p/dx = \frac{\text{(Num of hits)}}{\text{(Length of track)}}$
- In order to cut down the effect of the secondary ionization, we divide the hits into layers, and truncate the tail:

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



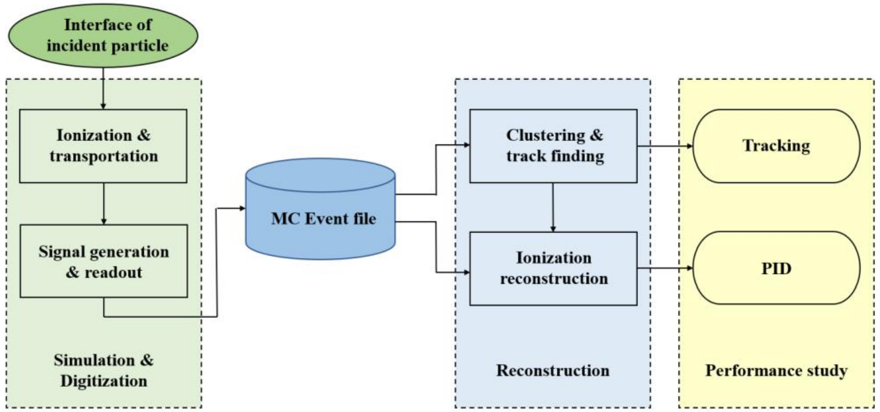
A typical dN_p/dx PID example

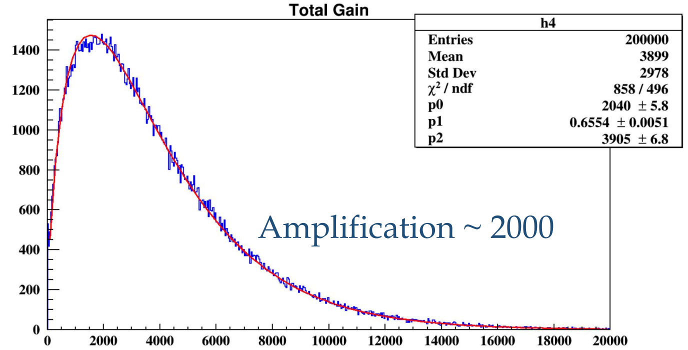




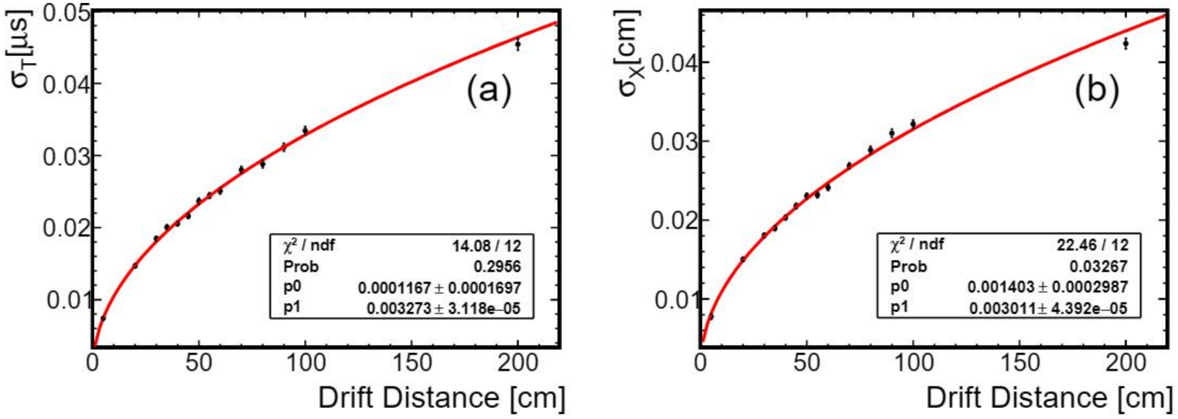
TPC Simulation Framework

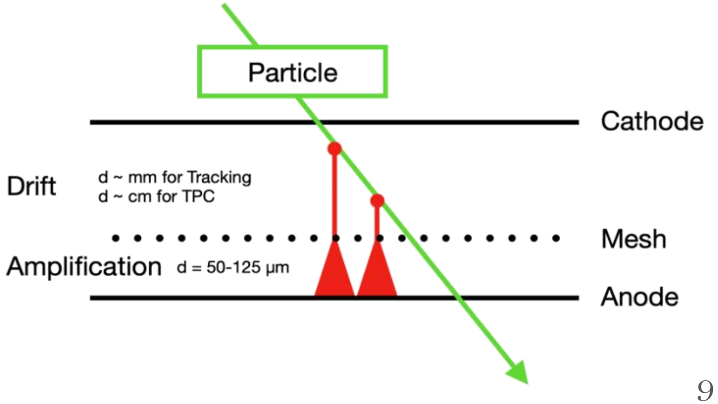
- A sophisticated software was developed to investigate the TPC's performance.
  - Geometry implementation based on CEPC Ref-TDR
    - Cathode, Micromegas readout and endplate, barrel, gas volume
  - Garfield++ based ionization, parameterized drifting and amplification
  - PID with dN_p/dx
  - Tracking: reconstruction with parameterized hit resolution





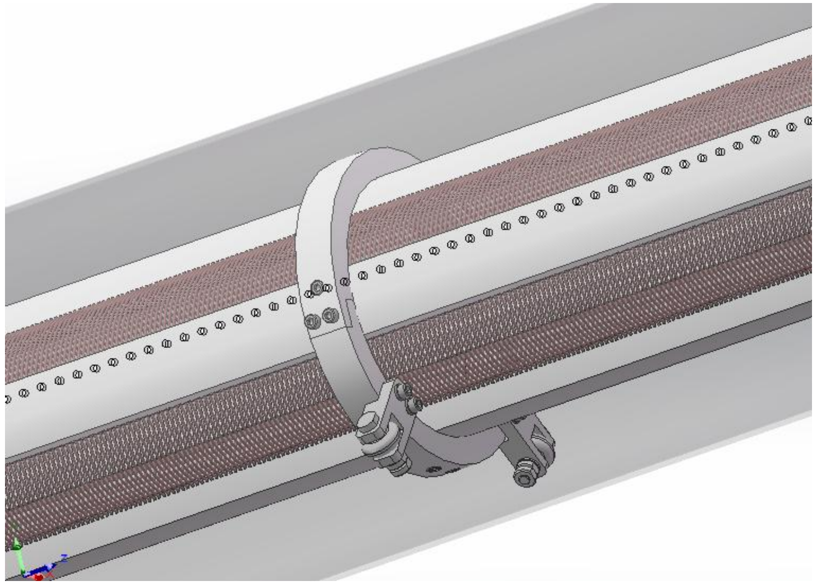
$$\sigma_{x,\,y,\,t}(\text{cm}) = p_0 + p_1\sqrt{L_{\text{drift}}\ (\text{cm})}$$

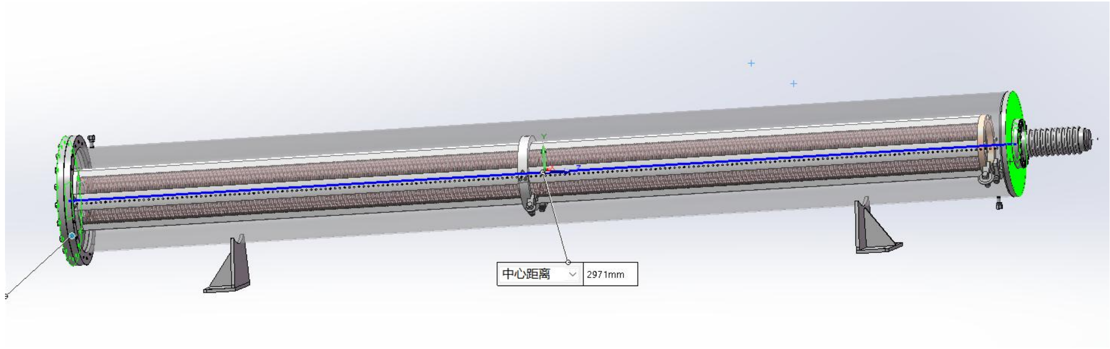


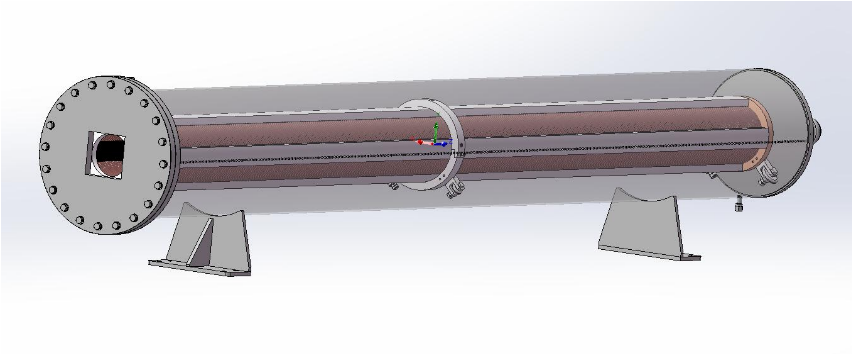


Full-length prototype experiment

- A full-length TPC prototype has been designed for experimental studies on electron drift velocity, attachment coefficient, and transverse/longitudinal diffusion.
    - The prototype's length matches the TPC specification in the CEPC Ref-TDR.
    - Double-Micromegas readout pad
    - 0 ~ 2.9 m adjustable drift length

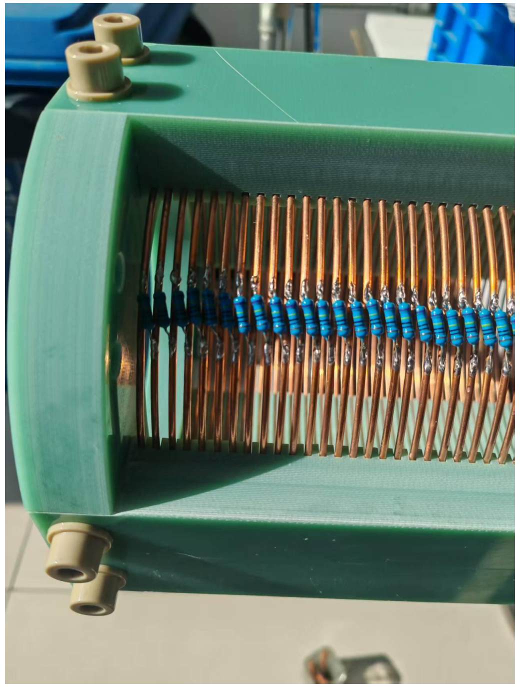






Prototype commissioning

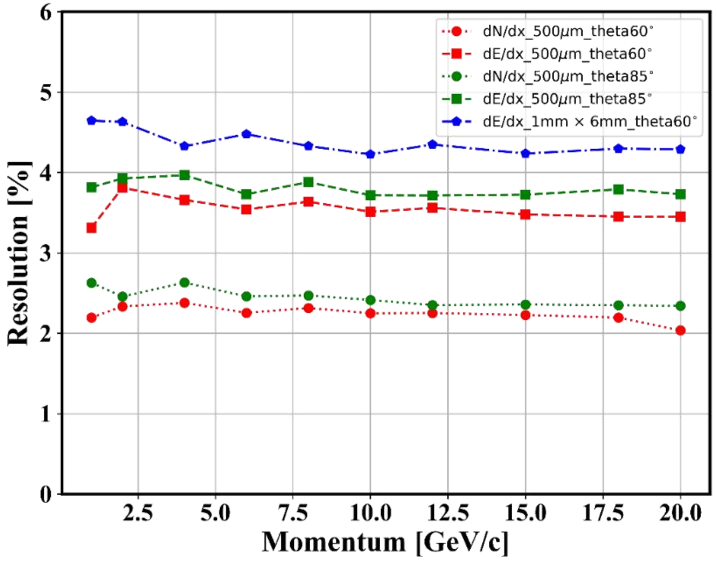
- The mechanical construction has been completed.
- Current status: focusing on the commissioning of the HV electric field.
    - HV system design: 706 copper rings, each with a 1 MΩ resistor (0.1% tolerance)
    - Up to 100 kV HV, meeting all experimental requirements.
    - Reliability: < 0.5W per resistor, ensuring stable and safe long-term operation.

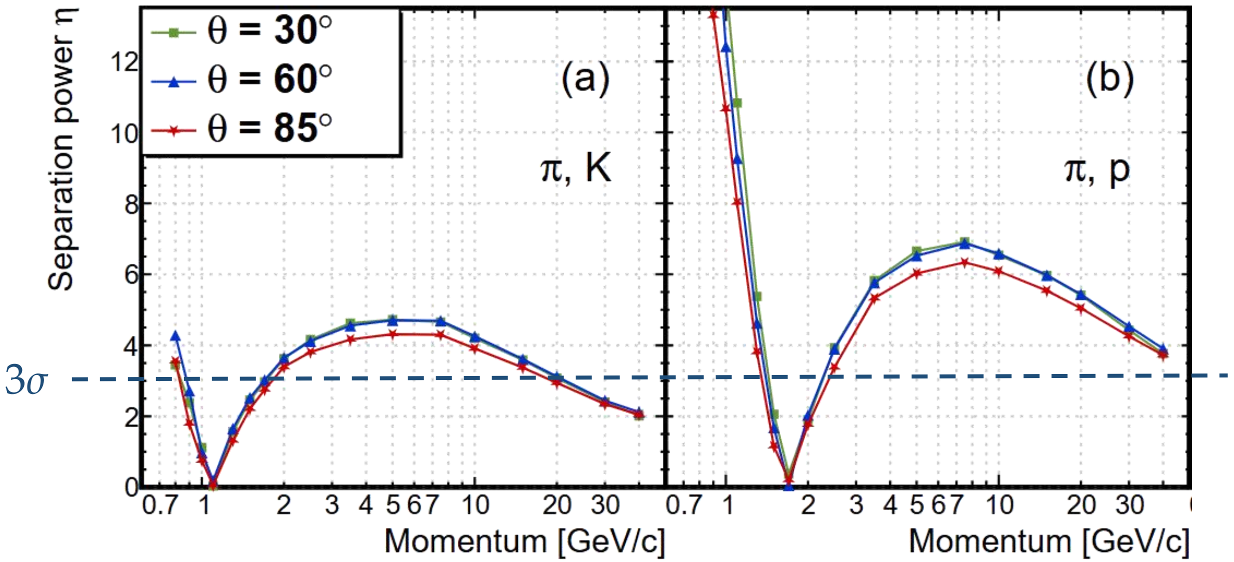


Overall PID performance

- Updated dN_p/dx reconstruction (+20% improvement than traditional dE/dx results):
  - Pad size: 500μm × 500μm
  - Pad counting: counting pads with charges above a threshold and normalizing by the track length in each layer (dN_p/dx in layer)
  - Separation power $\eta \geq 3\sigma$ between K/π and π/p with momentum up to 20 GeV/c

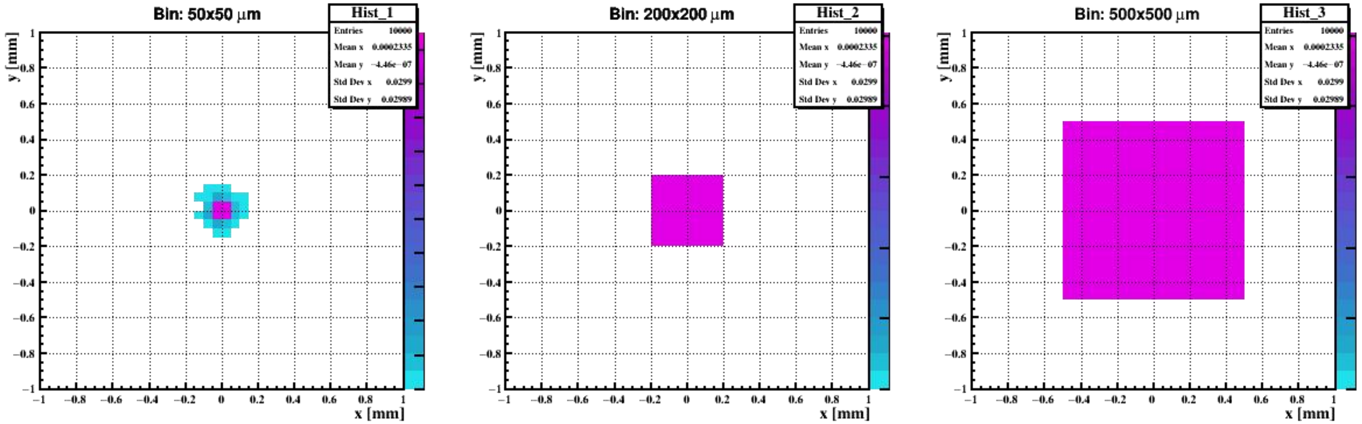
$$\eta_{A,\,B} = \frac{|\mu_A - \mu_B|}{\sqrt{(\sigma_A^2 + \sigma_B^2)/2}}$$



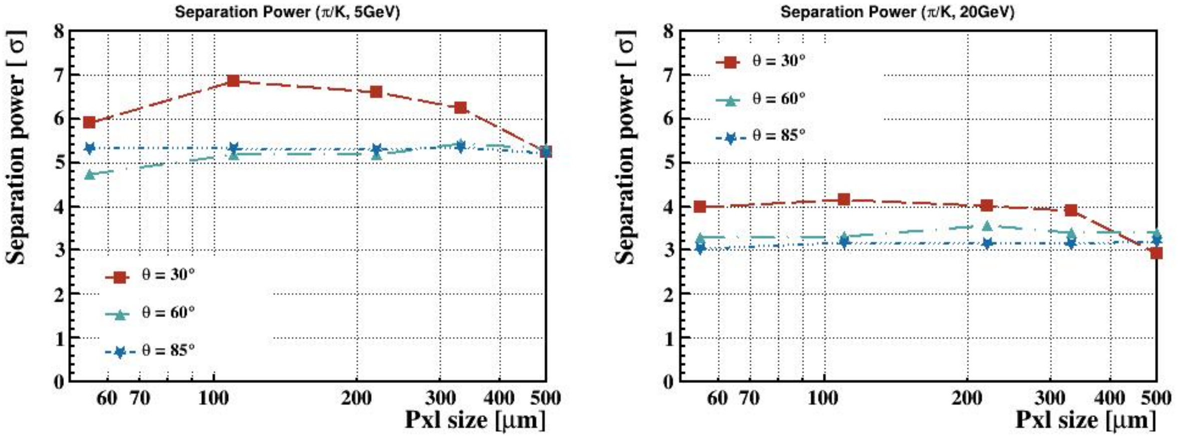


Optimization in pad size

- Possible pad size:
  - 55, 110, 220, 330, 400, 500 μm
- Preliminary optimization: 110 μm pad offers slightly superior PID performance.
- The optimal pad size can be affected by:
  - electron diffusion in drifting and amplification
  - Pad noise and threshold
- Subsequent simulations and experimental studies in these aspects are required to obtain more accurate results.

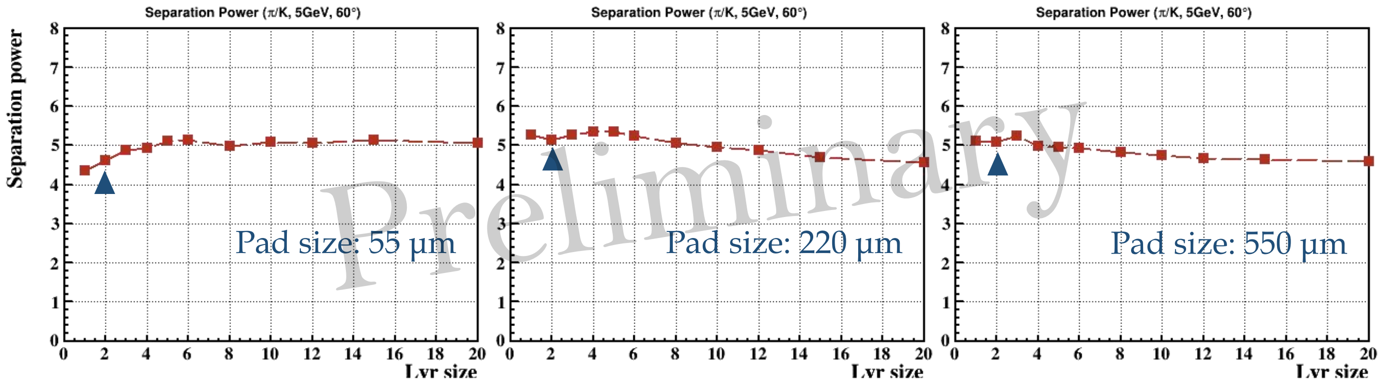


The same primary electron gets different response from pads with different sizes (amplification diffusion: 30 μm)



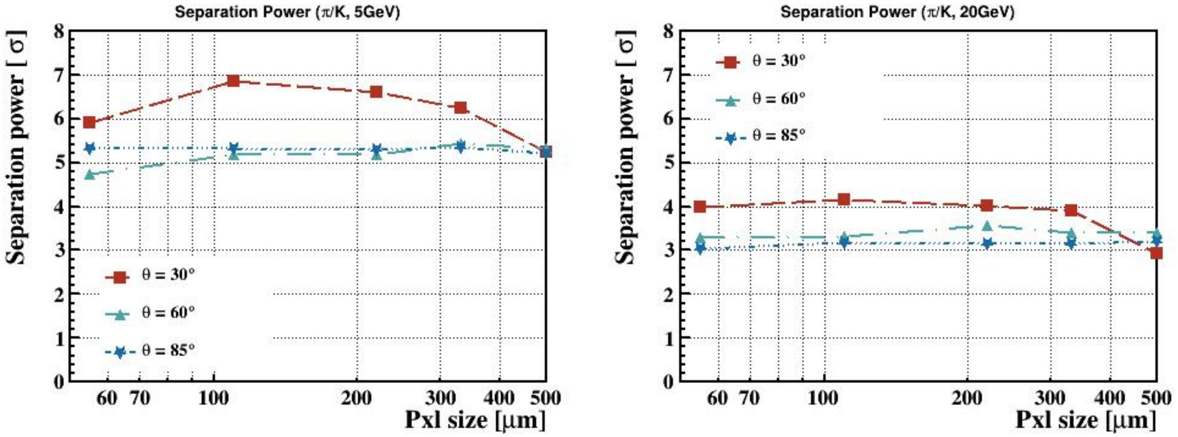
Optimization in dN_p/dx PID parameters

- Further optimization:
- Independent reconstruction parameters optimization for different pad sizes



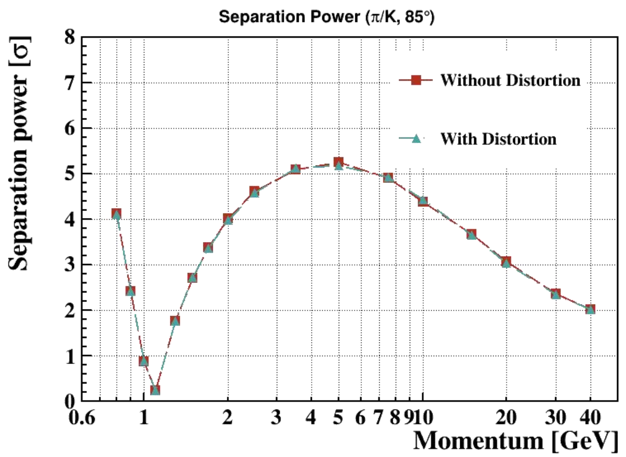
Independent parameters (rows per layer) optimization
Currently in use: 2 rows per layer

- By independently optimizing the reconstruction parameters, the separation power is expected to improve by approximately 6 ~ 10%.

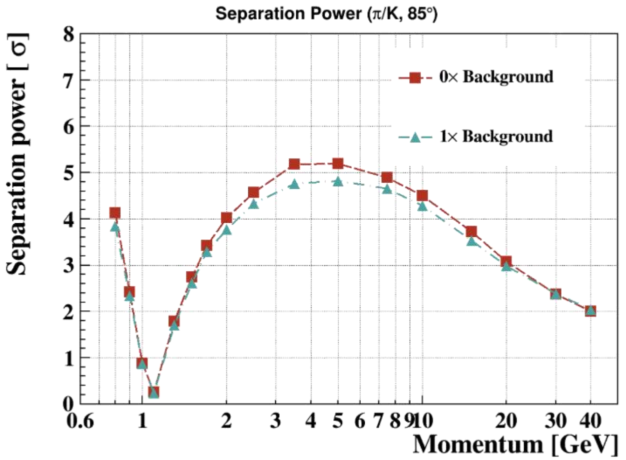


Background effects

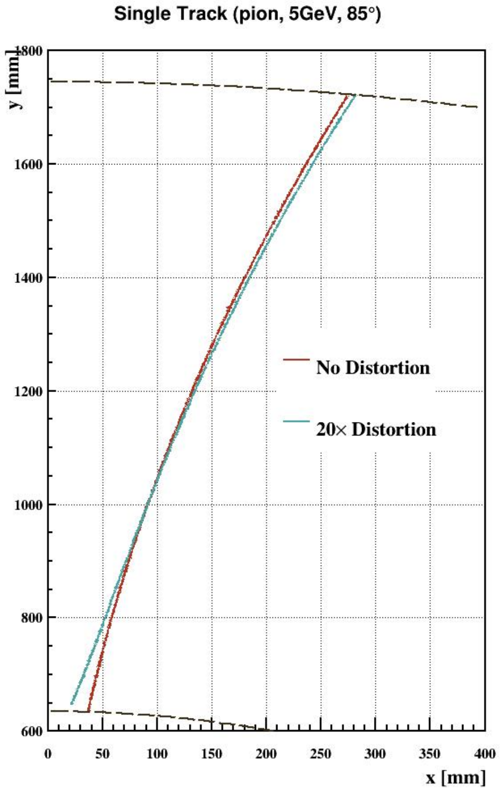
- The two most significant background effects:
  - Track distortion caused by background space charge
  - Extra hits caused by low-momentum background electrons
- Distortion: in Low Lumi Z mode, < 1mm
  - Minimal impact on dN_p/dx calculation and PID itself.
  - However, the distortion can introduce a bias in momentum reconstruction (see Xin She's report)
- Background electrons:
  - In Higgs mode, ~8% reduction in separation power **(a highly conservative upper limit)**
  - Z modes are still under discussion



The affection of distortion, Low Lumi Z mode



The affection of background electrons, Higgs mode



Summary

- The high-granularity TPC with ~500 μm readout pads demonstrates enhanced PID performance using the dN_p/dx method, improving π/K separation beyond 3σ up to 20 GeV/c.
- Optimized pad size and reconstruction parameters can further boost separation power by ~10%.
- Background effects on PID, mainly from space charge and low-energy electrons, are manageable in most operation modes.
- Further studies will focus on the experimental determination of drift, diffusion, and avalanche properties, as well as the optimization of readout pad size and reconstruction parameters.

THANKS

Thank you for listening !