Simulation studies of PID for the CEPC TPC

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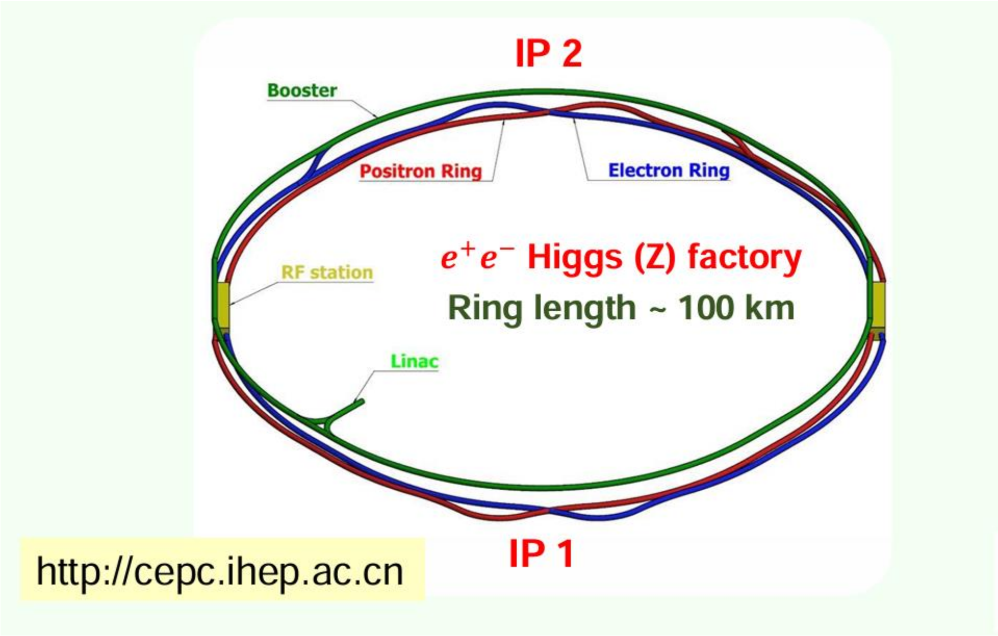
Outline

- Introduction
- Simulation of Pixelated TPC
- PID Performances
- Summary

Circular Electron Position Collider (CEPC)

- The CEPC was proposed in 2012 right after the Higgs discovery. It aims to start operation in 2030s, as an e^+e^- Higgs / Z factory
- To produce Higgs / W / Z / top for high precision Higgs, EW measurements, studies of flavor physics & QCD, and probes of physics BSM.

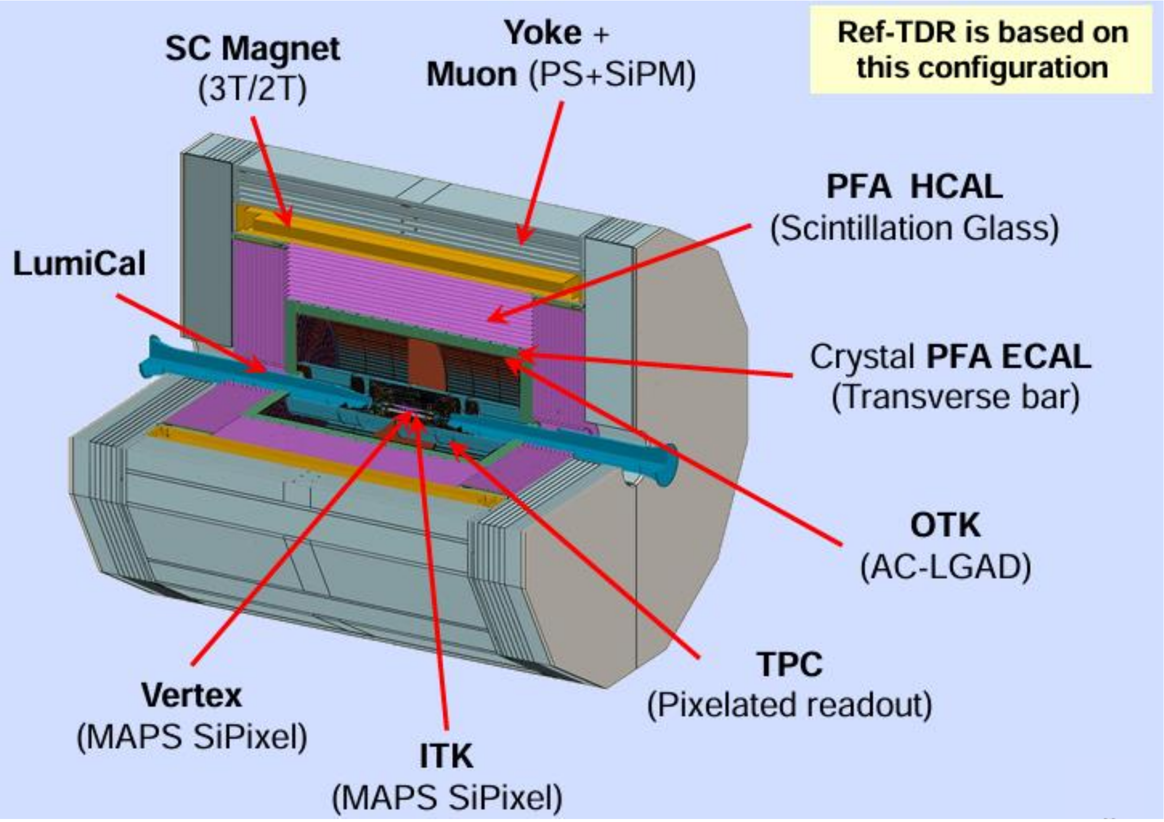


CEPC 4^{th} Concept Detector

Performance requirements

Sub-system	Key Specifications
Vertex	$\sigma_{r\phi}$ ~ 3 μm, X/X_0 < 0.15% per layer
Tracking	$\sigma\left(\frac{1}{P_T}\right) \sim 2\times10^{-5} \oplus \frac{1\times10^{-3}}{P\times sin^{3/2}\theta}(GeV^{-1})$
Particle ID	Relative uncertainty ~ 3% σ(t) ~ 30 ps
EM calorimeter	EM resolution ~ $3\%/\sqrt{E(GeV)}$ Granularity ~ 1×1×2 cm³
Hadron calorimeter	Support PFA jet reconstruction Single hadron $\sigma_E^{had} \sim 40\%/\sqrt{E(GeV)}$ Jet $\sigma_E^{jet} \sim 30\%/\sqrt{E(GeV)}$

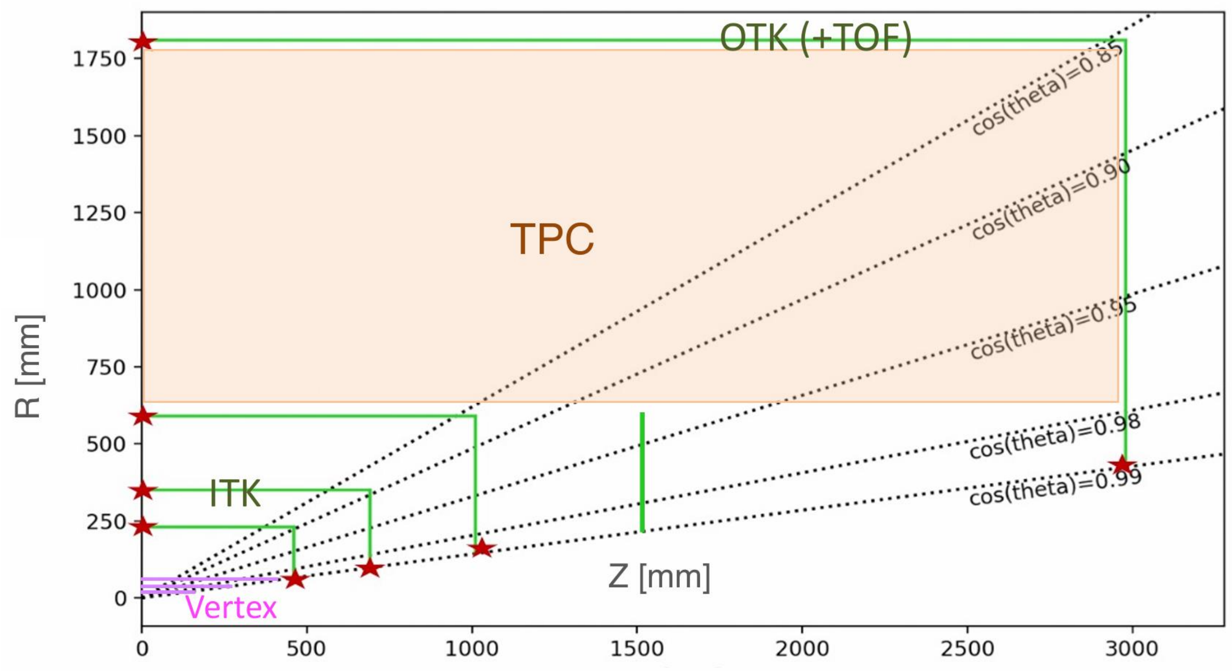
4^{th} concept baseline



CEPC Baseline Gaseous Detector: TPC

Pixelated TPC:

- **High-performance particle identification** and high-precision tracking

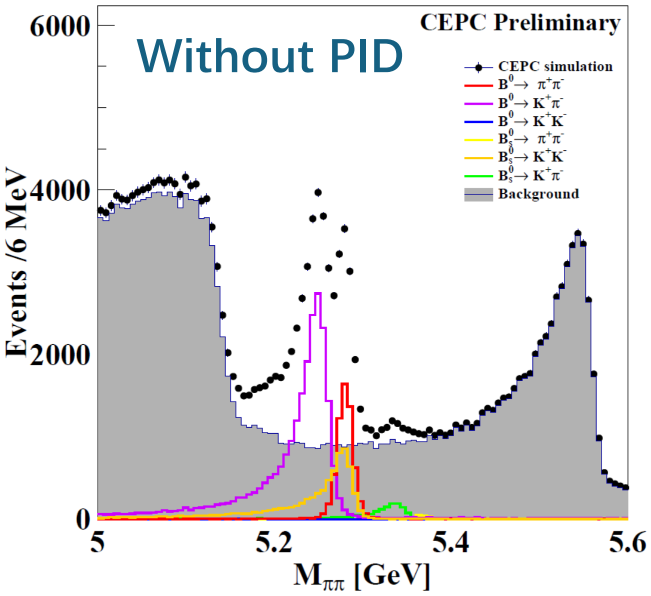


<table>
<tr><th colspan="4">TPC Parameters</th></tr>
<tr><td colspan="2">Radius</td><td colspan="2">0.6 – 1.8 m</td></tr>
<tr><td colspan="2">Half length</td><td colspan="2">2.9 m</td></tr>
<tr><td colspan="2">Readout size</td><td colspan="2">0.5 x 0.5 mm^2</td></tr>
<tr><td colspan="2">Total # of channels</td><td colspan="2">2 x 3 x 10^7</td></tr>
<tr><td colspan="2">Material budget (barrel/endcap)</td><td colspan="2">0.59 % / 15% X_0</td></tr>
<tr><td rowspan="2">PID Performance</td><td>K/π separation @ 20 GeV/c</td><td colspan="2">3.0 σ</td></tr>
<tr><td>Resolution</td><td colspan="2">3 %</td></tr>
<tr><td colspan="2">Tracking Performance: $\sigma_{1/p_T} = \sqrt{a^2 + (b/p_T)^2}$</td><td>$a = 1.9 \times 10^{-5}$
$b = 0.8 \times 10^{-3}$
(3T field)</td><td>$a = 3.3 \times 10^{-5}$
$b = 1.5 \times 10^{-3}$
(2T field)</td></tr>
</table>

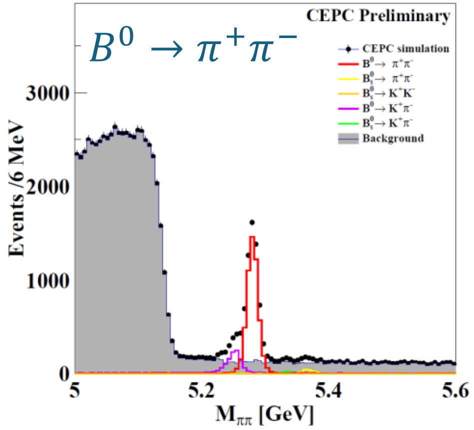
PID is important for CEPC physics

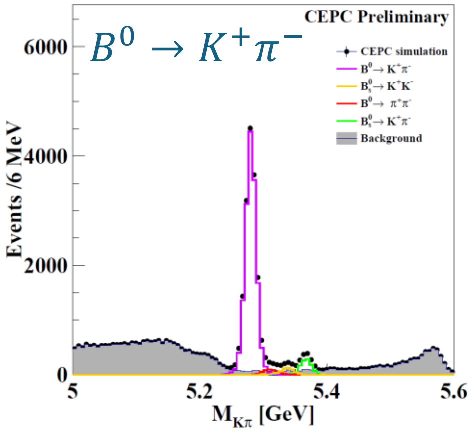
- **Decent PID is required**
  - For flavor physics, PID is essential especially for measurements involving B/D mesons…
  - For identification of jet origin, PID can influence all physics measurements with hadronic final state

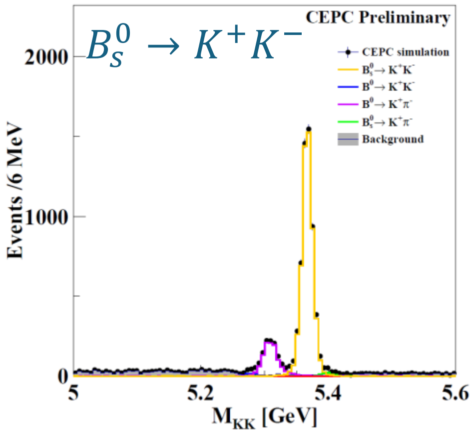
Benchmark channel:
$B^0_{(s)} \rightarrow h^+h'^-$



With PID





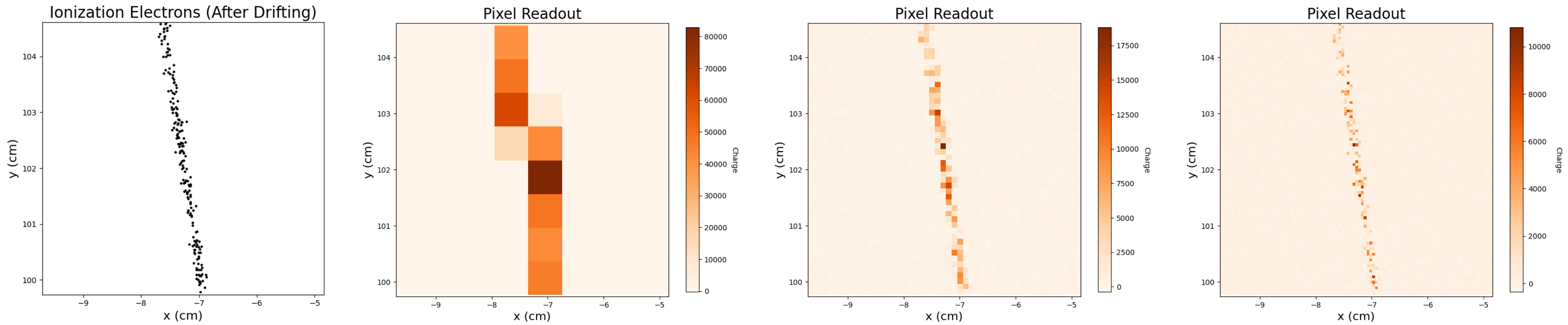


Ionization measurement in TPC

Single electrons on endcap

Pad response: Large pad ➔ Small pixel

6x6 mm^2 **1x1 mm^2** **0.5x0.5 mm^2**



dE/dx (traditional method):

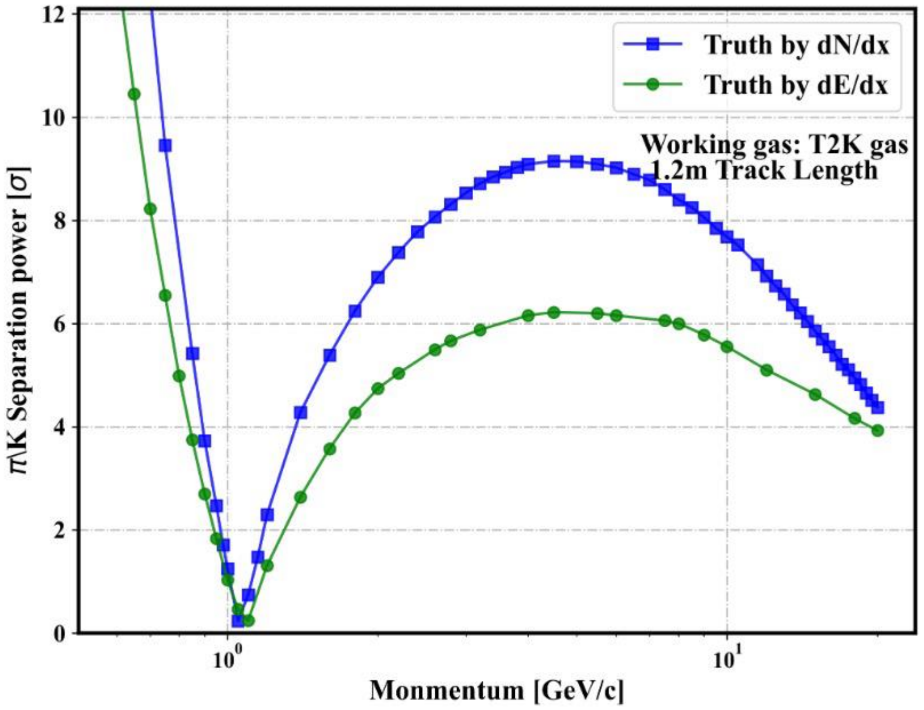
- **Method:** Total energy loss measurement by integrating the energies in large pads
- **Characteristics:**
  - Large fluctuations from energy measurements, amplification, secondary ionizations, etc

dN/dx or cluster counting ("ideal" method):

- **Method:** Number of primary ionization cluster measurement, **requiring high granularity readout**
- **Characteristics:**
  - **Small fluctuation (resolution potentially improved by a factor of 2)**

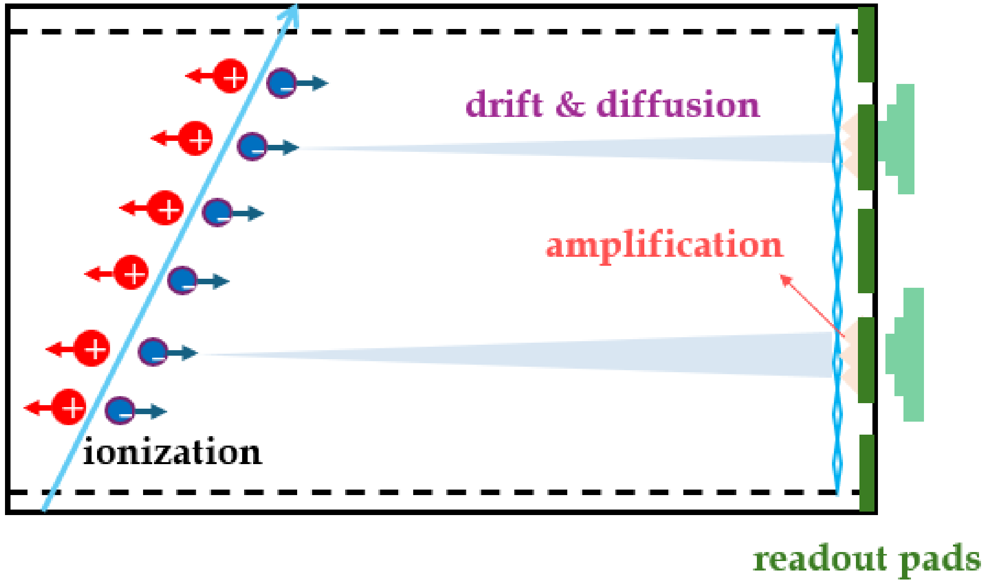
dN/dx vs. dE/dx

- **Particle separation power:**
  - Definition: $\frac{\text{separation}}{\text{resolution}} = \frac{|\mu_A - \mu_B|}{(\sigma_A + \sigma_B)/2}$



dN/dx has much better PID power than dE/dx
dN/dx represents a breakthrough in PID

Full Simulation Framework



Garfield++-Based Simulation / Digitization Framework

Ionization → Transport → Amplification → Signal Generation

Simulation:

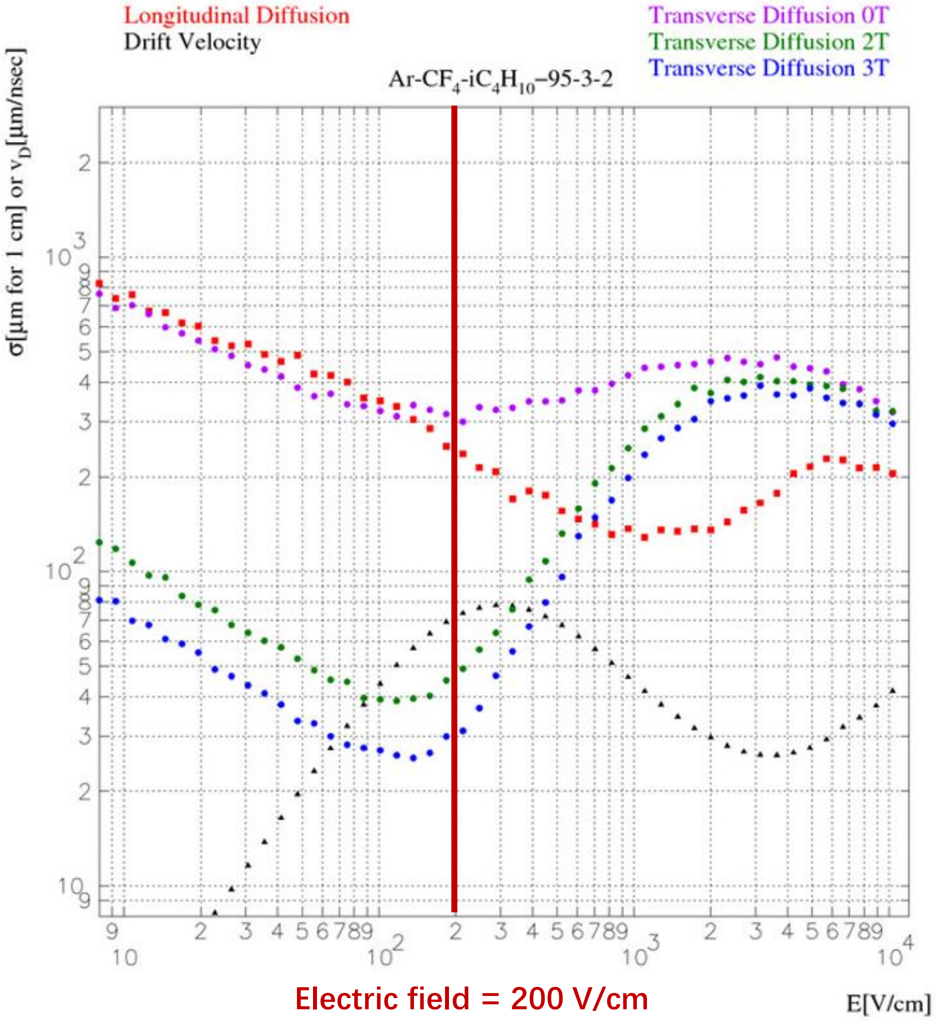
- Full geometry TPC
- Ionization generation by Heed

Digitization:

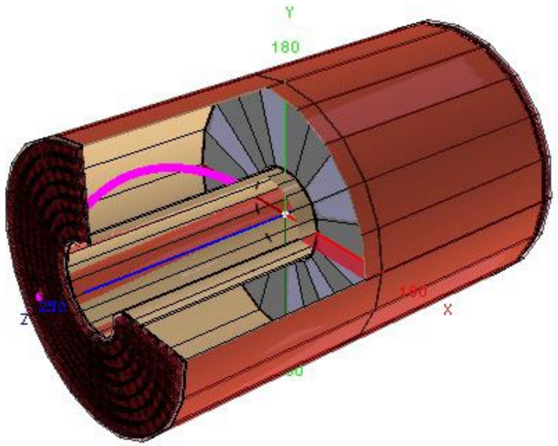
- Amplification:
    - Amplification factor (# of e^-): 2000
    - Signal width in space: RMS = 15 um
- Electronic noise: RMS = 100 e^- / channel

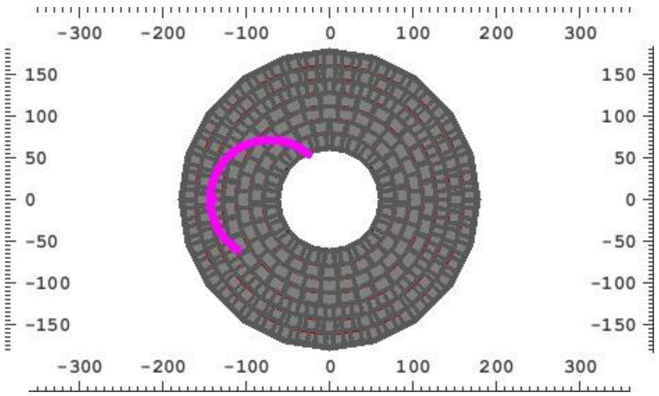
Geometry and gas mixture

- **Full TPC: Radius (0.6-1.8 m), half length (2.9 m)**
- **Magnetic field: 3T/2T**
- **Gas mixture: T2K ($Ar/CF_4/iC_4H_{10}$: 95/3/2)**
  - High drift velocity (70 µm/ns)
  - Low transvers diffusion (30 µm/sqrt(cm))
  - High cluster density (~37 cls/cm)



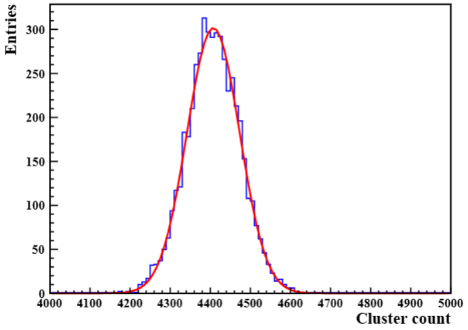
TPC Geometry and event display



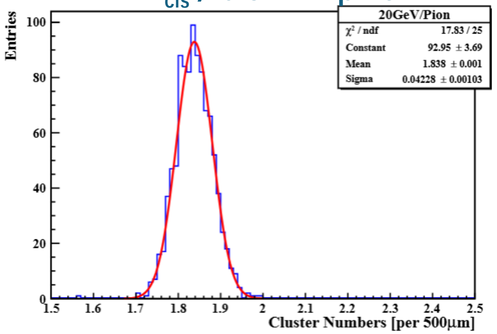


Ionizations

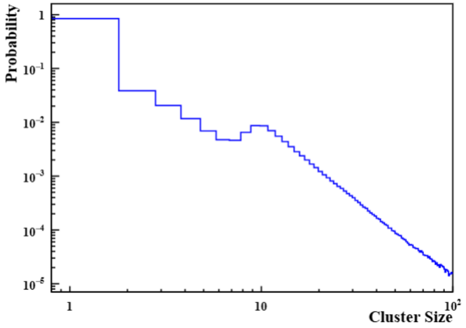
N_{cls} for a 1.2m track

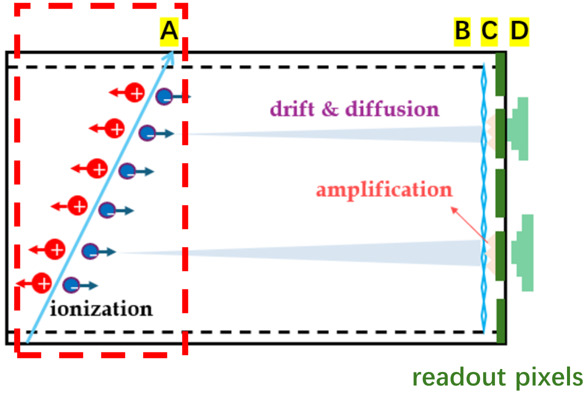


N_{cls} / 0.5 mm pixel

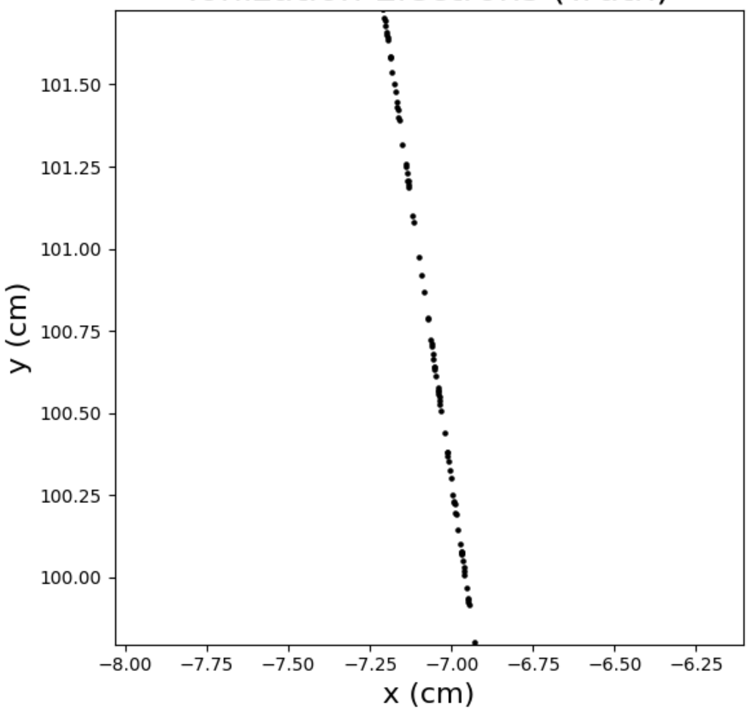


Cluster size



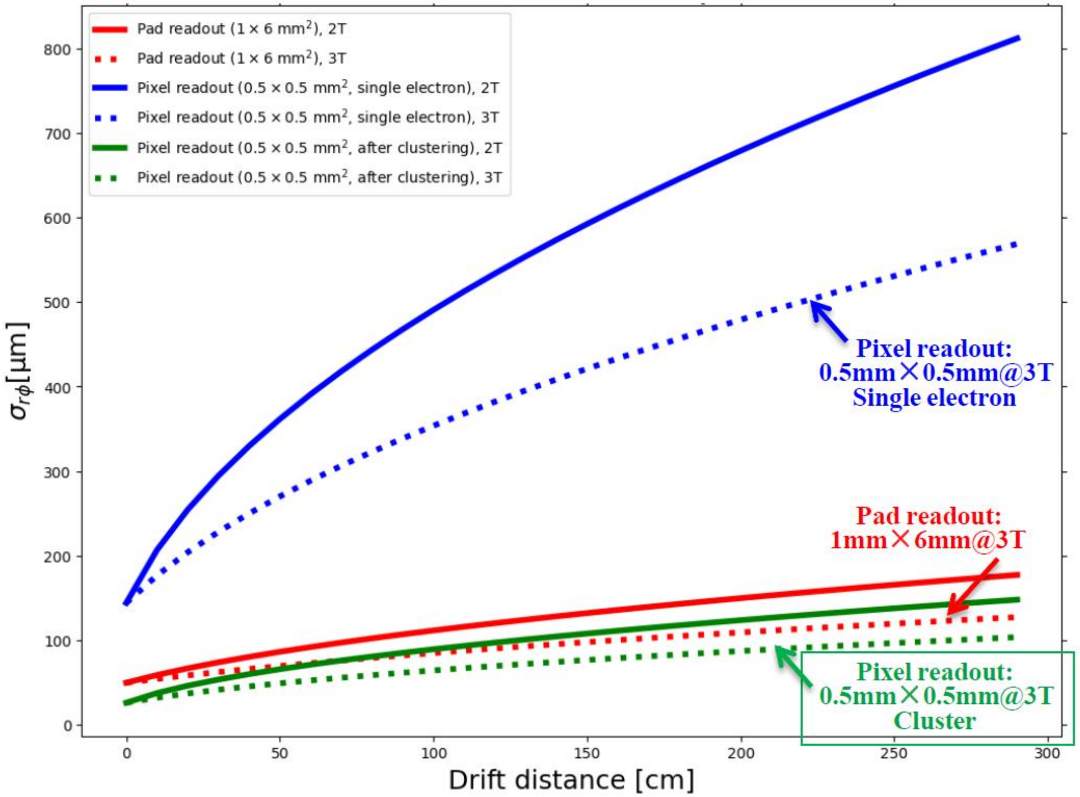


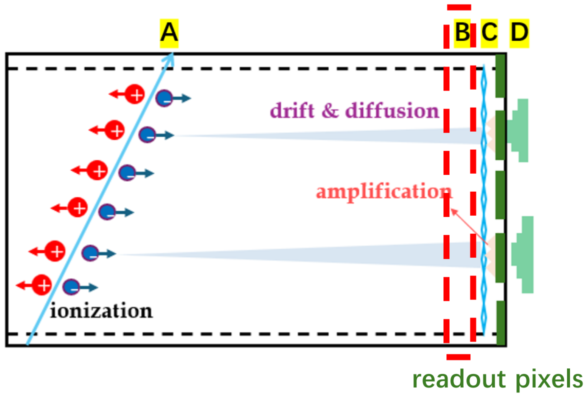
Position A



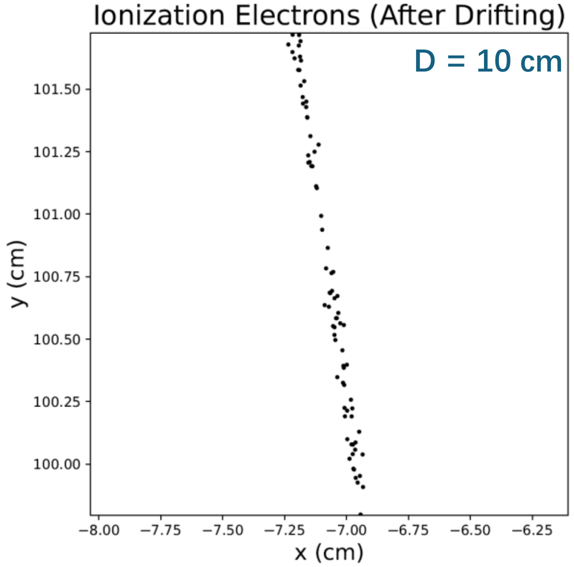
- Ionizations are simulated by Heed
- Gas mixture is T2K: $Ar/CF_4/iC_4H_{10}$ (95/3/2)
- Cluster density: ~37 cls / cm or ~1.8 cls / pixel

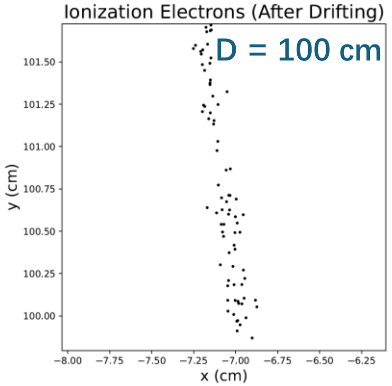
Drift and diffusion

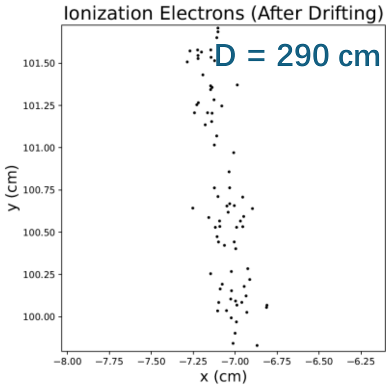




Position B

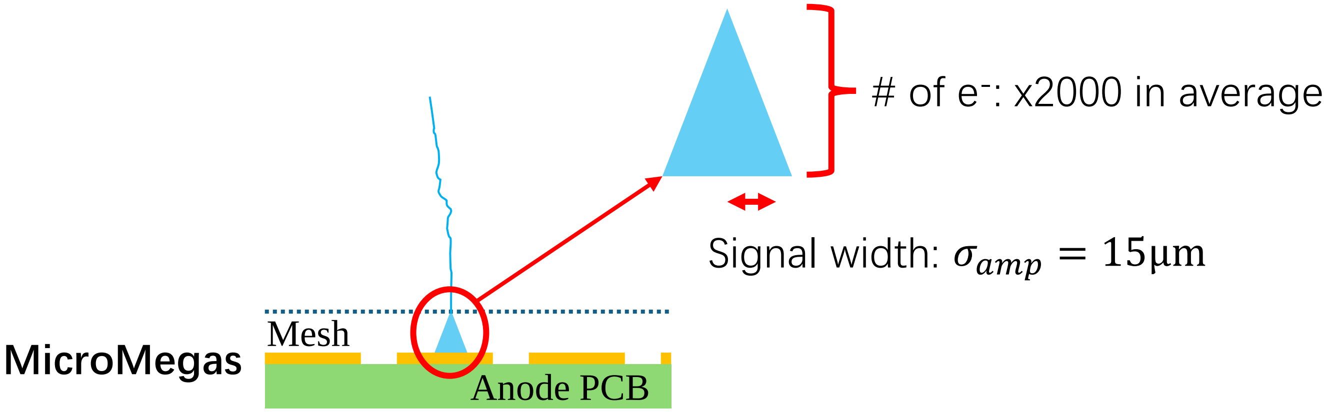


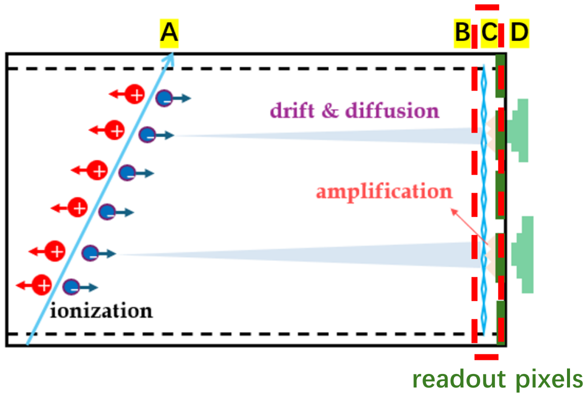


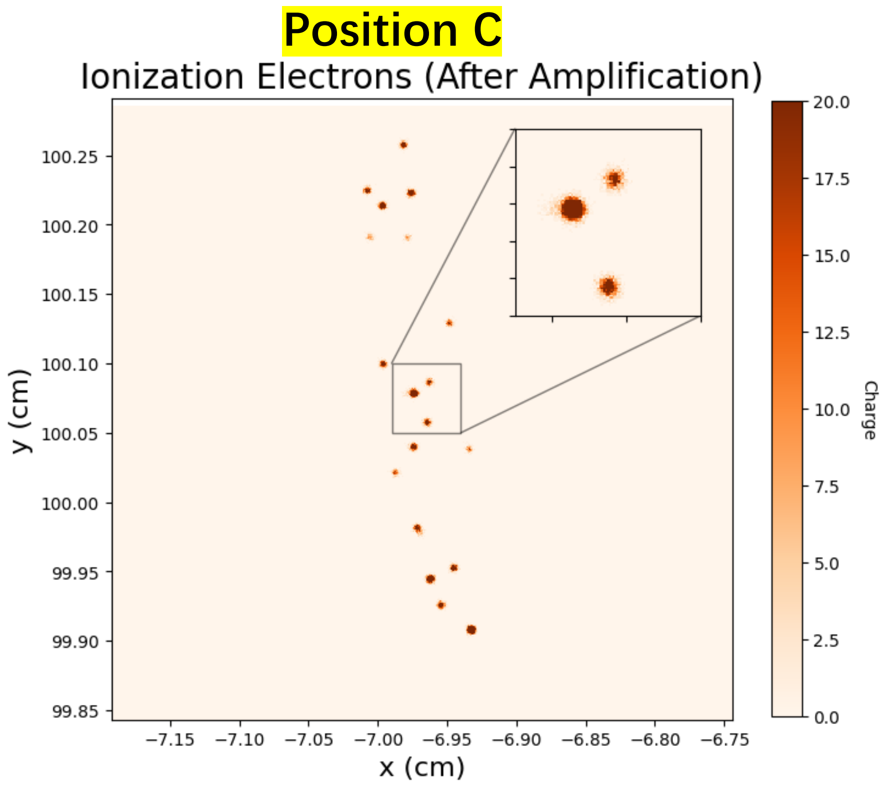


- Electron drift and diffusion is parameterized from Garfield++
- The pixel readout could achieve better hit resolution with reasonable clustering

Amplification







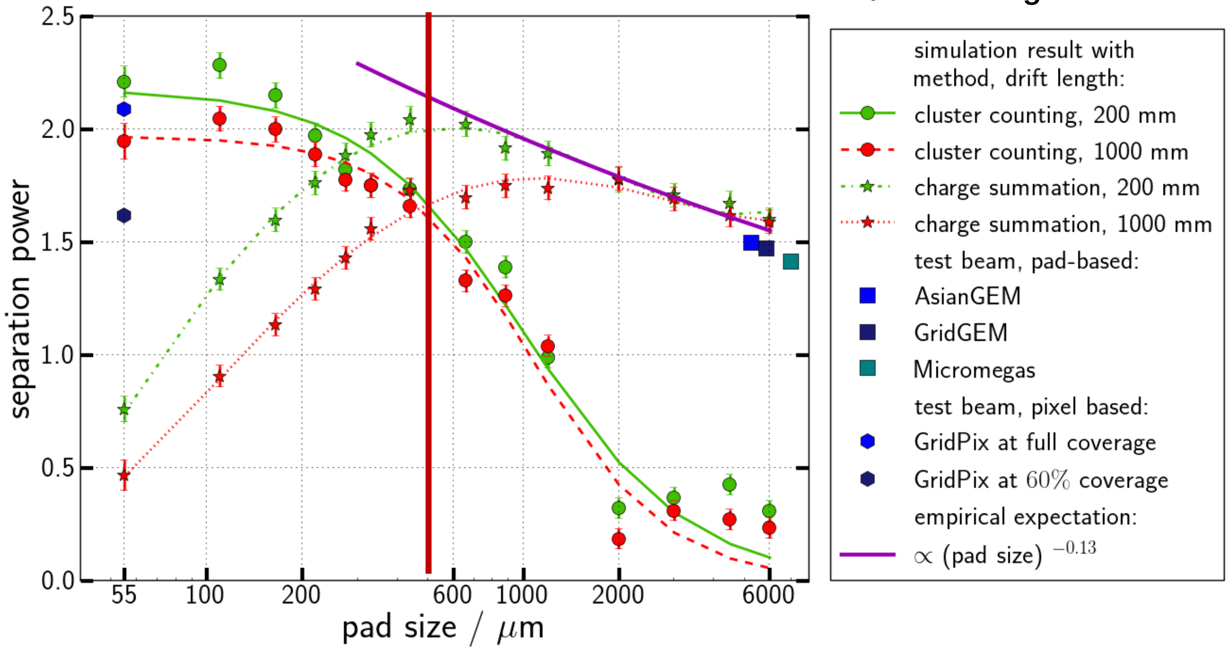
Amplification: Single electron → Avalanche electrons

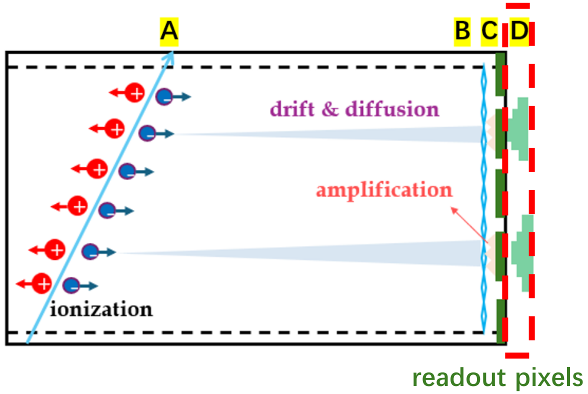
- Amplification factor f_{amp} (# of electrons): x 2000
- Signal width σ_{amp}: 15 μm

Pixel readout

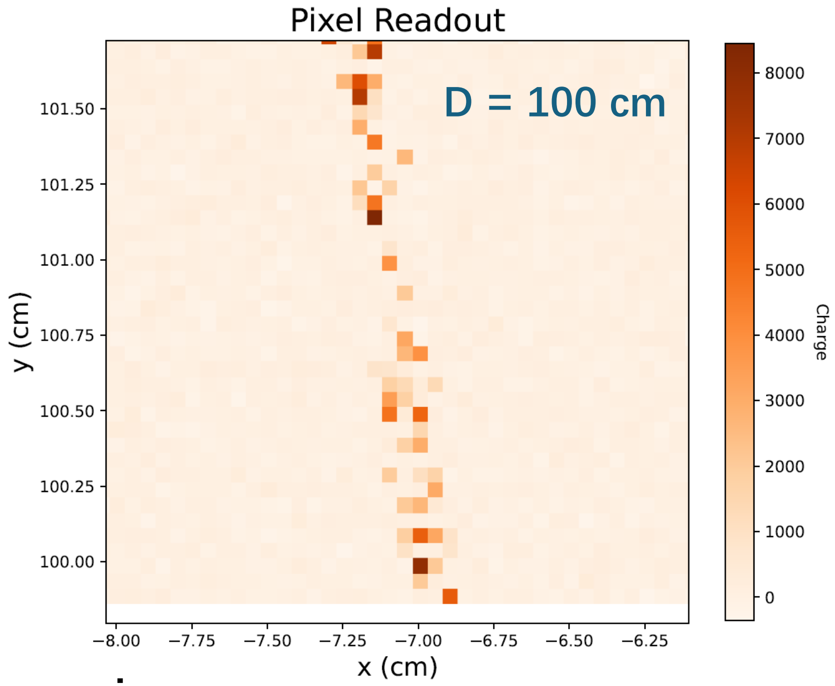
Y. Aoki et al., JINST 17 P11027

dN/dx = cluster counting
dE/dx = charge summation





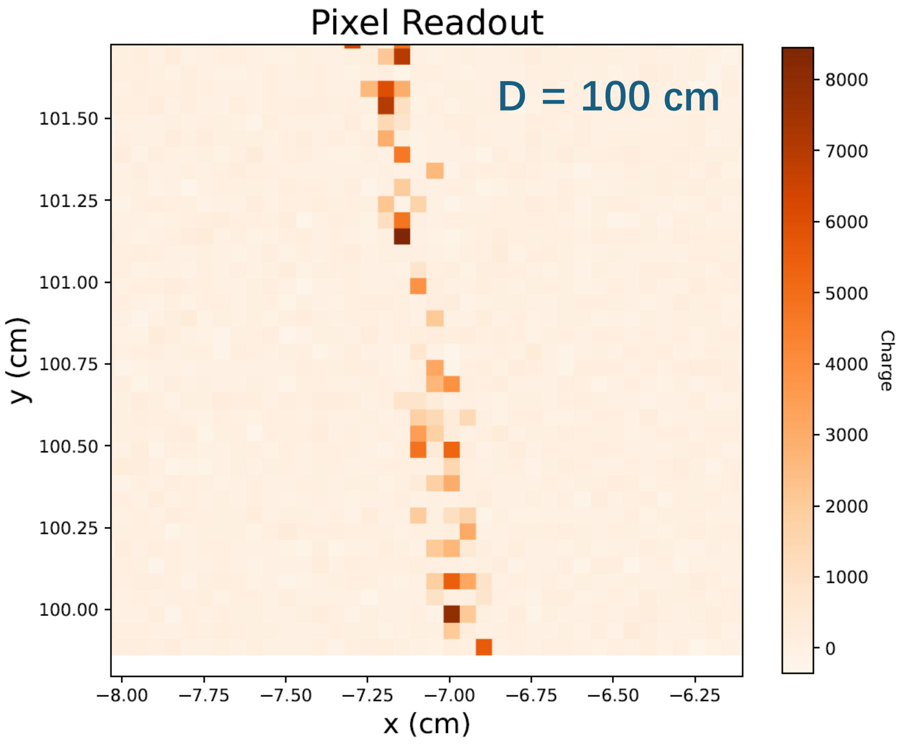
Position D



Pixel size:
- **Current choice: 0.5x0.5 mm^2**
- Need further optimization

Electronics noise:
- Single channel noise: RMS = 100 e^-

Reconstruction



Goal: Pixel responses ➔ Ionizations

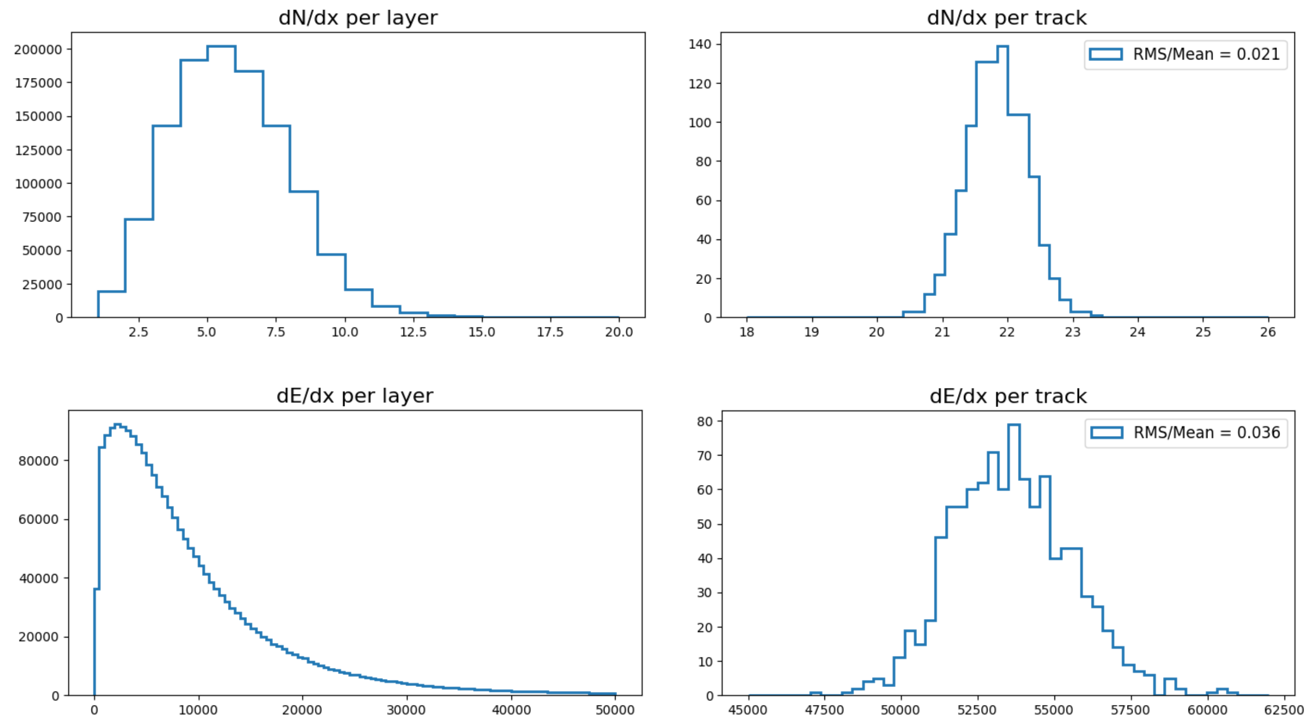
Principle: The ionization is proportional to

- # of primary electrons (dN/dx) ➔ Count pixels
- Total energy depositions (dE/dx) ➔ Sum charges

Method:

- Layered measurement
- Truncated mean to reduce the secondary ionizations

Reconstruction (2)

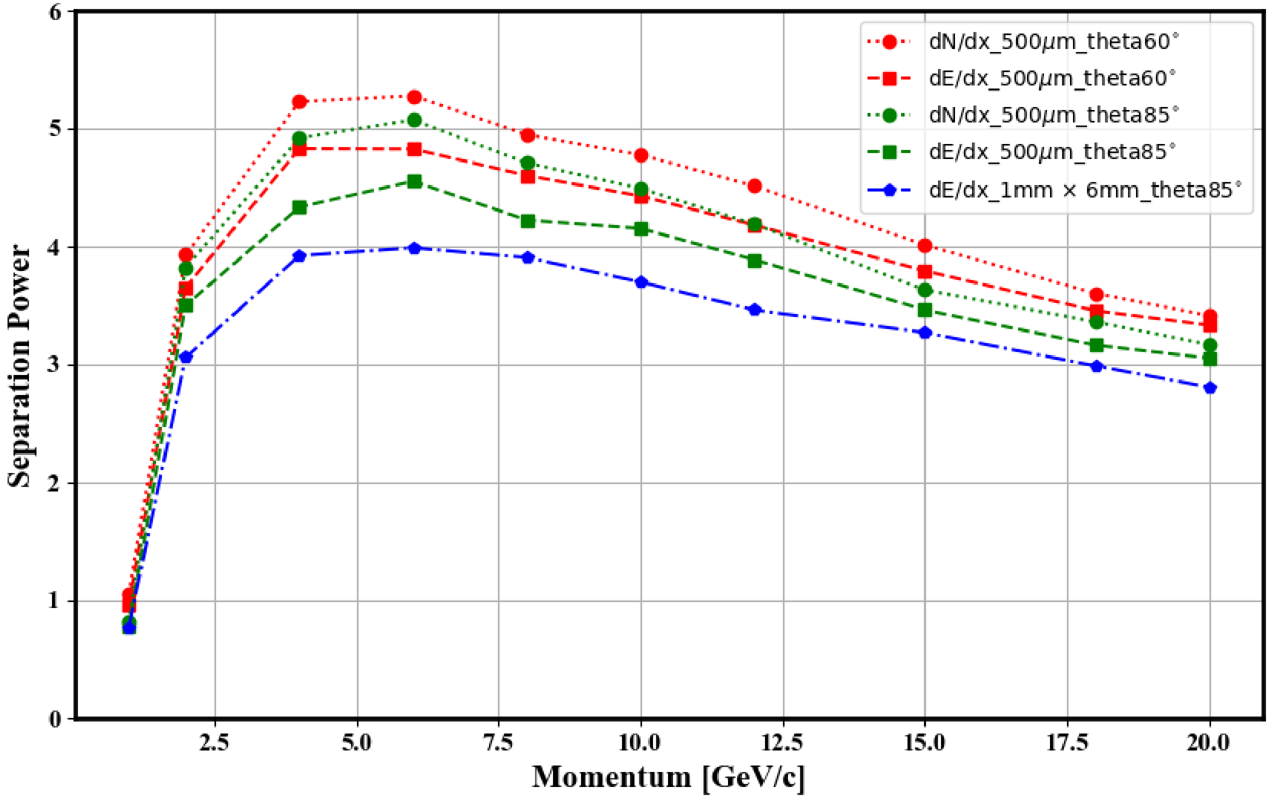


Algorithm:

- Divide the readout into layers
  - Pixels per interval in each layer: N_{layer}
- Measure R_i in each layer:
  - **dN/dx:** Count the # of fired pixels
  - **dE/dx:** Integrate the charge
- Calculate the truncated mean
  - $\langle R \rangle_a = \frac{1}{M} \sum_{i=i}^{M} R_i$
  - Here $R_i \leq R_{i+1}$ for $i = 1, \ldots, n-1$ and M is an integer $M = aN_R$

PID performance

K/π separation power

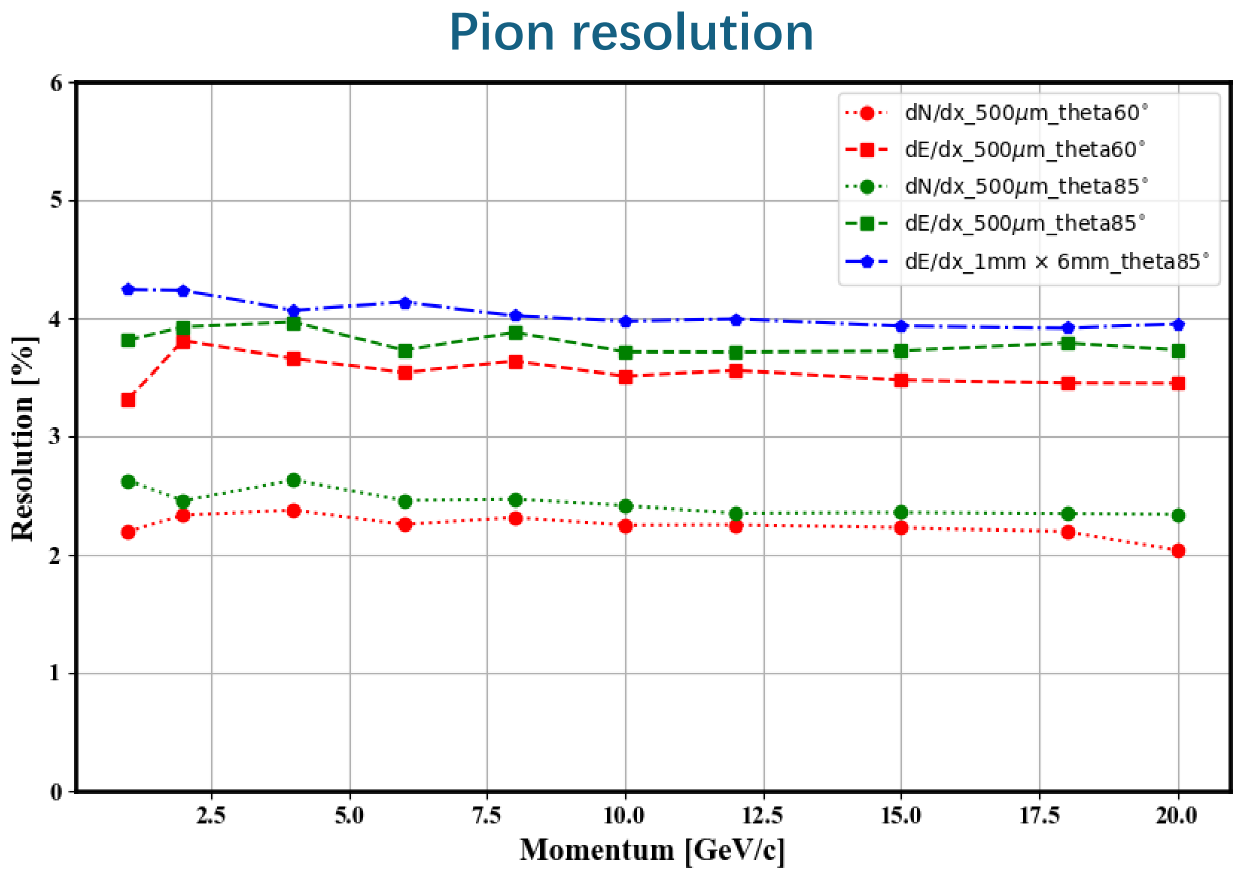


$$\text{Separation Power} = \frac{|\mu_A - \mu_B|}{(\sigma_A + \sigma_B)/2}$$

For 0.5x0.5 mm^2 pixel TPC:

- dN/dx is generally better than dE/dx
- dN/dx or dE/dx is much better than dE/dx in 1x6 mm^2 pad TPC
- 3σ K/π separation can be achieved at 20 GeV/c

PID performance (2)



- dN/dx resolutions are better than 3%

Summary and outlook

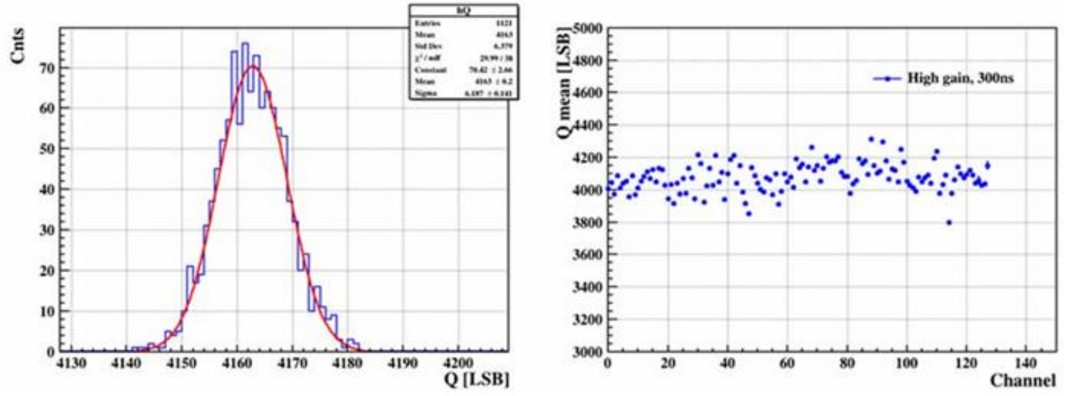
- **A Garfield++-based full simulation framework is developed for the CEPC TPC study**

- **PID performance generally satisfies the CEPC requirements with a pixel size of 0.5x0.5 mm^2**
  - K/π separation $> 3\sigma$ for momentum within [2, 20] GeV/c
  - dN/dx resolution < 3%

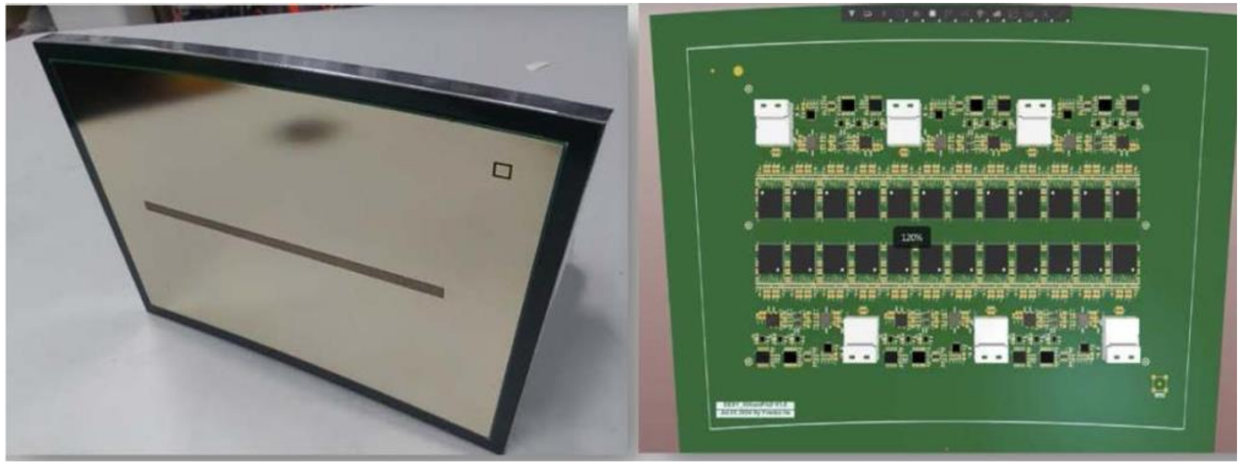
- **There is room to further improve the PID**
  - Pixel size optimization
  - More sophisticated reconstruction/calibration
  - Combine dN/dx and dE/dx

Summary and outlook

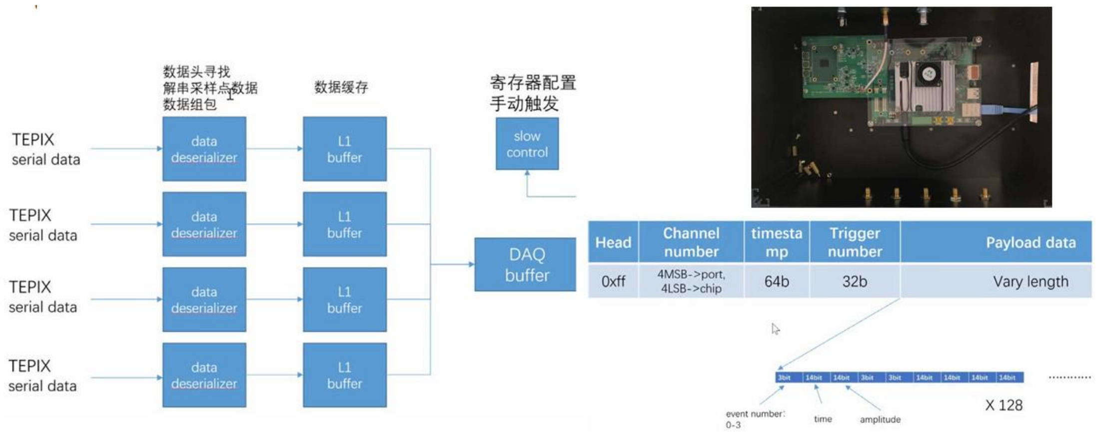
- **Plan of the testbeam validation**
  - R&D on pixelated TPC readout is ongoing
  - Testbeam at DESY is in preparation (early 2025)



Chip testing is done



TPC modules assembled for the testbeam

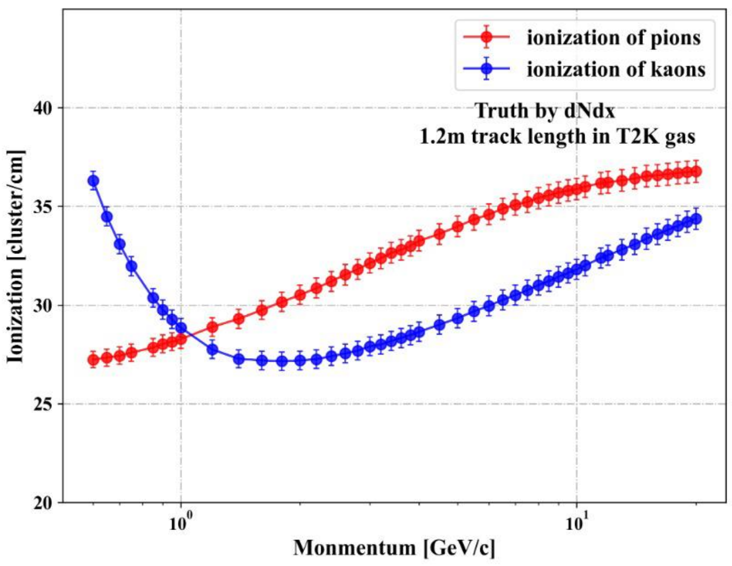


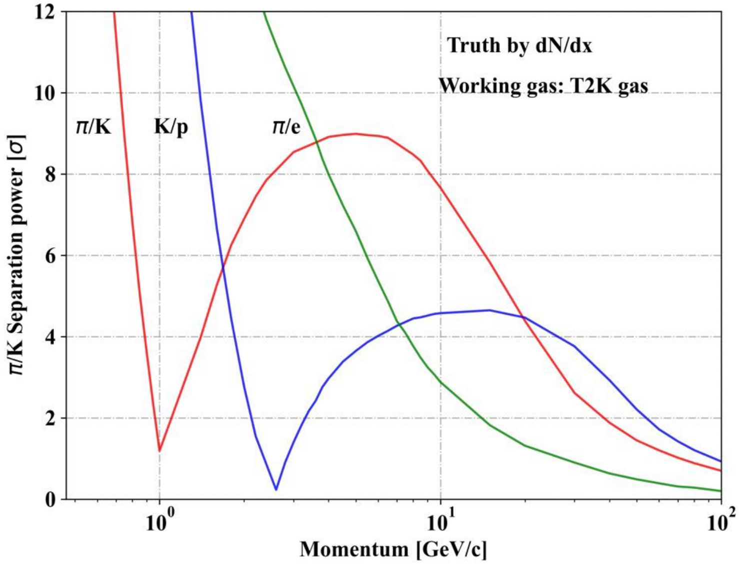
DAQ firmware development is ongoing

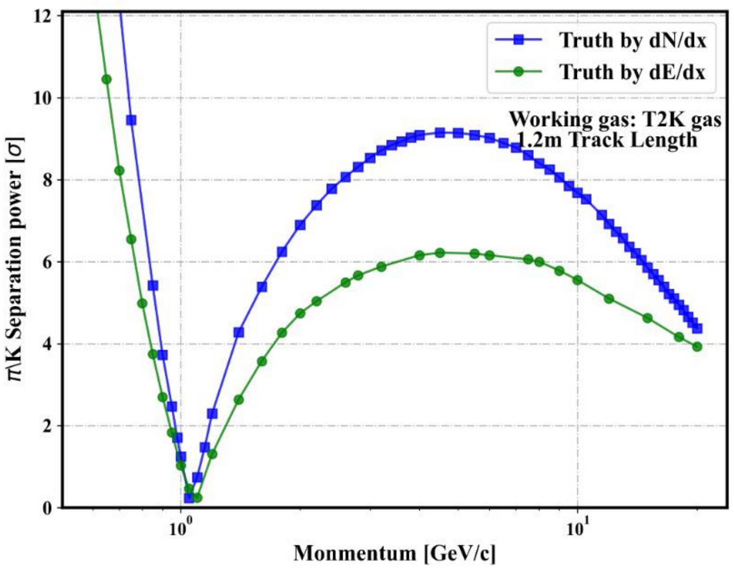
Backup

Particle Separation Power (MC truth)

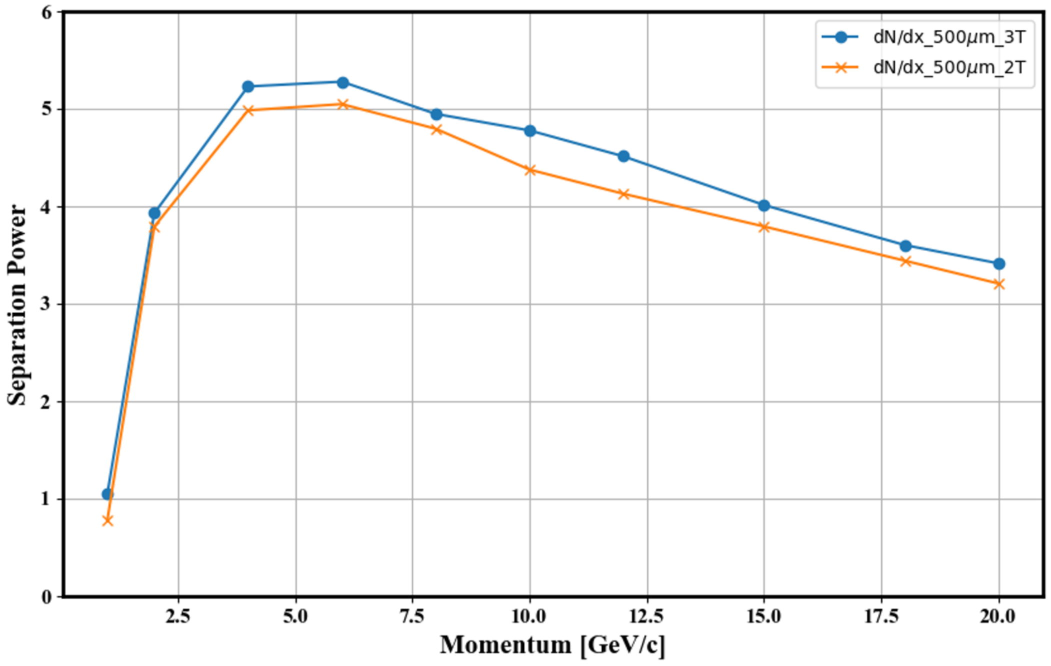
- **Simulating pion/kaon within [0.1 - 20] GeV/c in T2K gas**
  - The performance of particle separation power is proportional to the difference in the average ionization
  - The relative ionization of different particle species depends on the momentum
  - Cluster counting exhibits excellent potential for particle identification

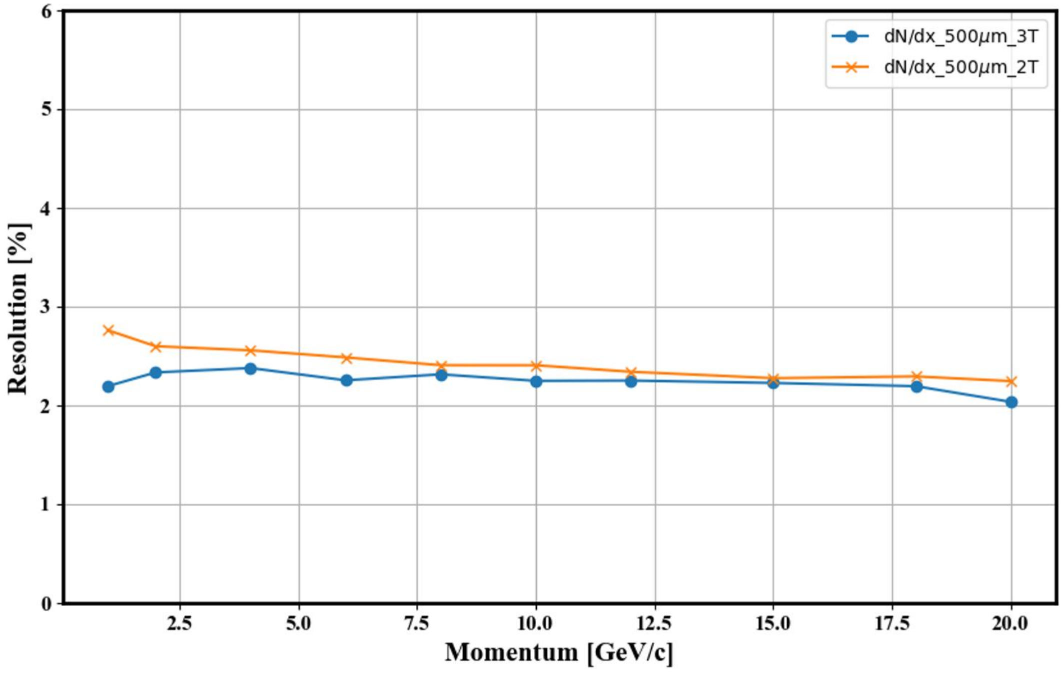






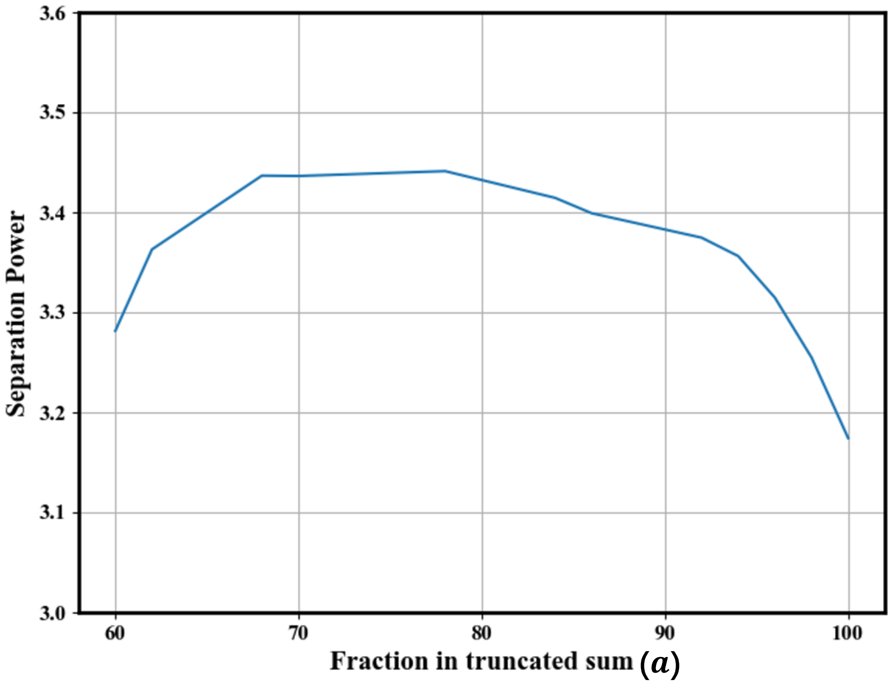
PID Performance (3T and 2T fields)

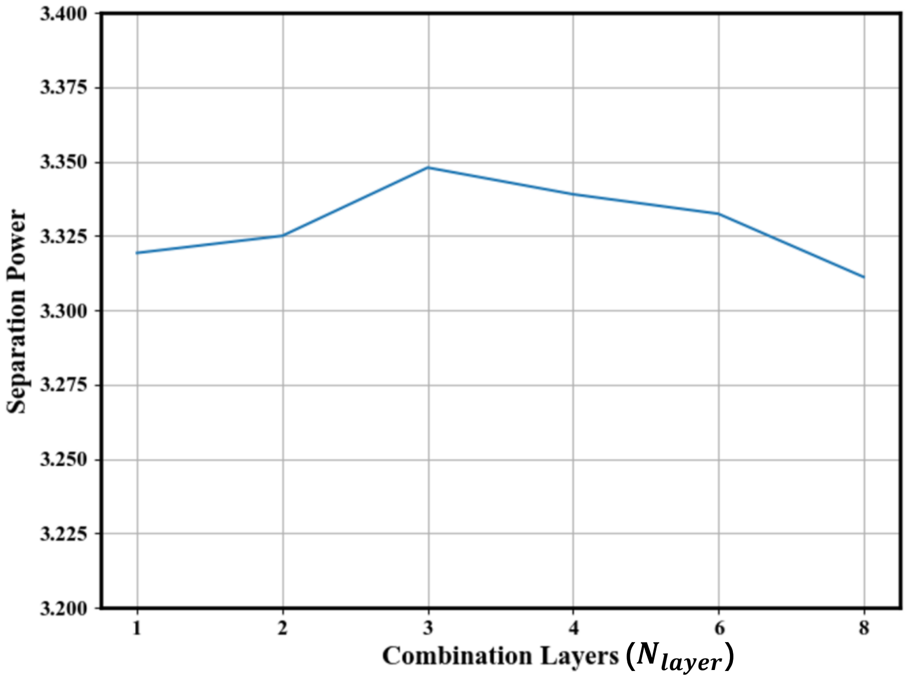




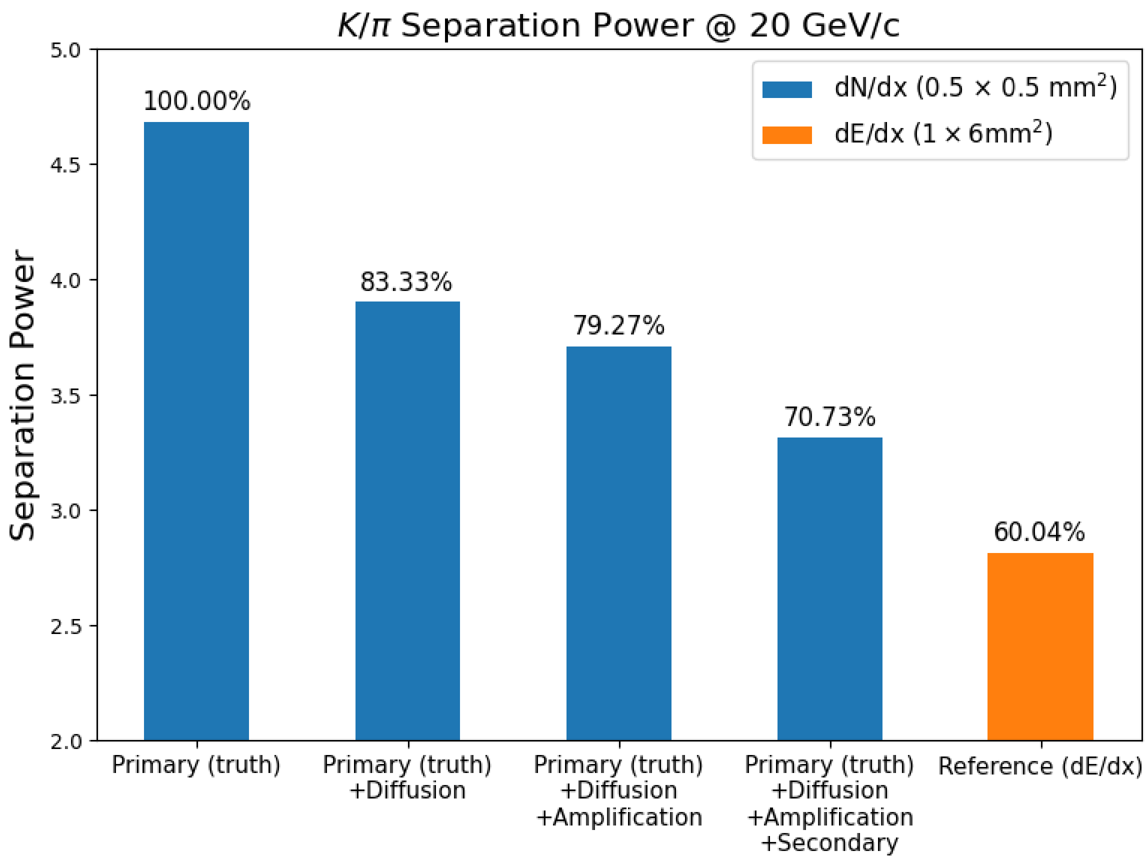
Parameters optimization

Figure of merit: K/π separation power @ 20 GeV





PID performance (3)



Discussions:

- The dN/dx with small pixels are better than the dE/dx with large pads
- The performance degrades when considering detector/electronics responses
- Diffusion and secondary electrons could worsen the performance significantly.
  ➔ More sophisticated algorithm