# Simulation of Cluster Counting with TPC

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# Outline

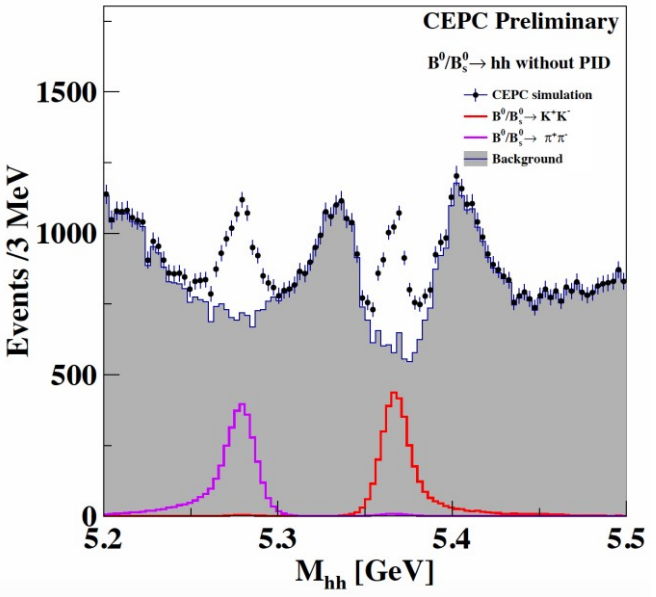
- **Introduction: Cluster counting basics**
- **Simulation study of pixelated TPC**
  - Primary cluster simulation
  - Full simulation
- **Summary**

# Motivation: Particle identification

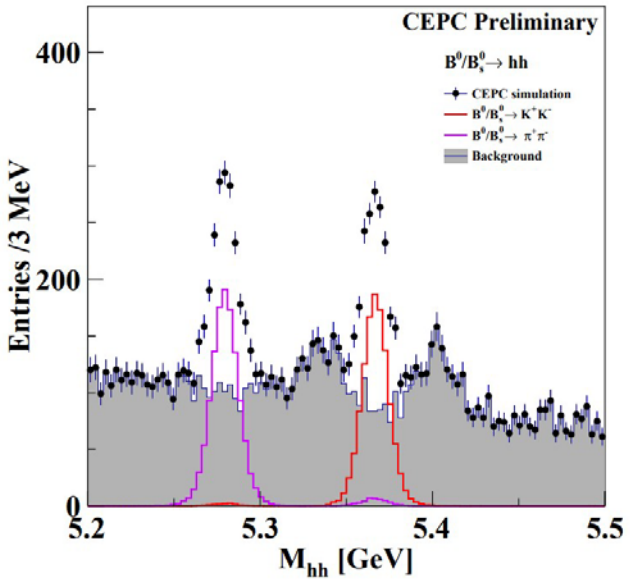
- **Particle identification is essential for flavor physics and jet study**
  - Reduce combination background
  - Improve mass resolution
  - Improve jet energy resolution
  - Benefit flavor tagging

**Simulation of $B^0/B_s^0$ with Delphes**

Without PID



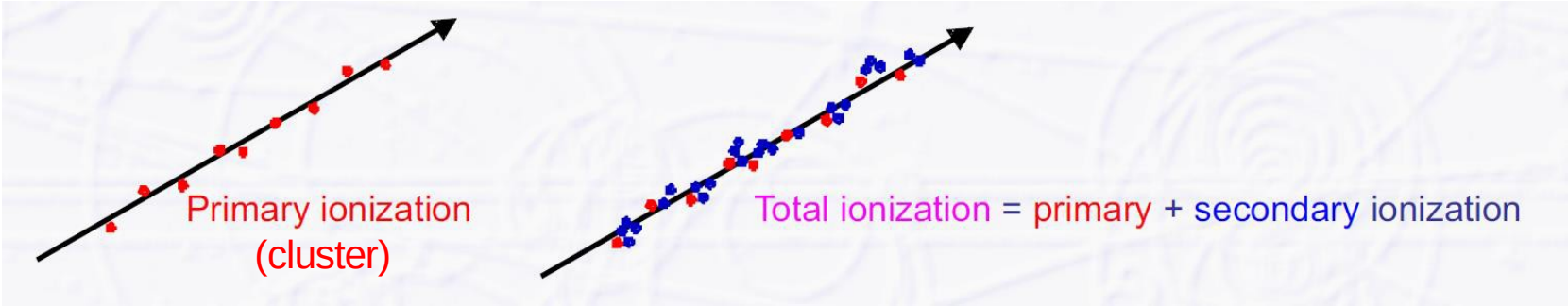

With PID




From Xu Gao

# PID by ionization

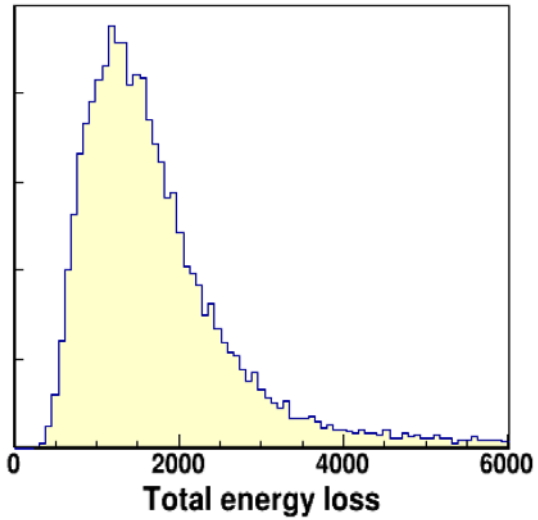
- **Main mechanism: Ionization of matter by charged particles**



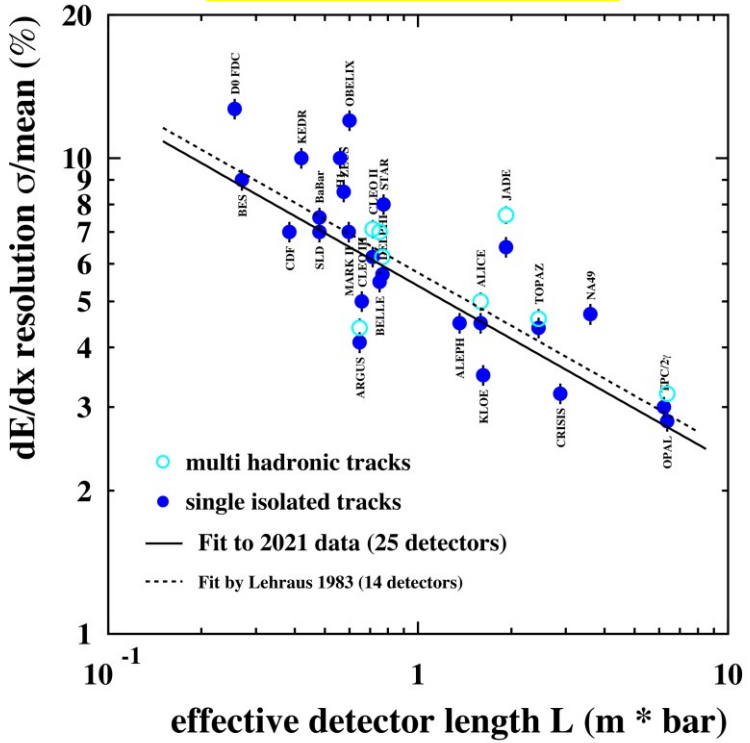

- Number of clusters per unit length is Poisson- distributed
- Primary electrons sometimes get large energies
  - Can make secondary ionization
  - Can even create visible secondary track (“delta- electron”)

# Energy loss measurement: dE/dx

- **dE/dx: Total energy loss per unit length**
  - Landau distribution due to secondary ionizations
  - Large fluctuation due to energy loss, amplification …




"Lehraus" Plot 2021*



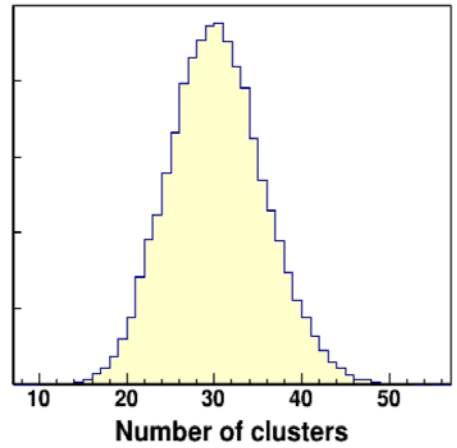

- **Fit by Lehraus 1983:**
  - dE/dx res. = **5.7** * $L^{-0.37}$ (%)
- **Fit in 2021:**
  - dE/dx res. = **5.4** * $L^{-0.37}$ (%)

- **No significant improvement in the past 40 years**

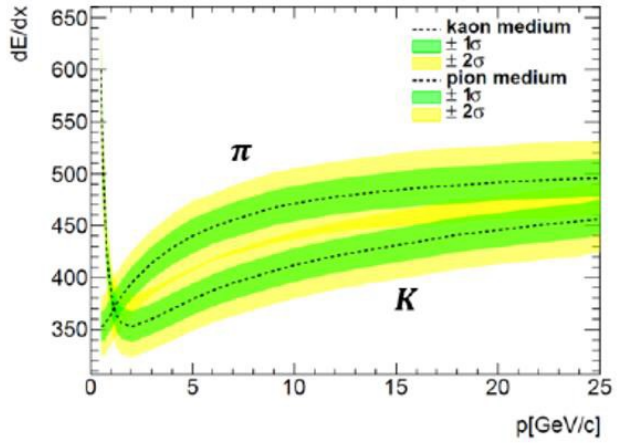
* From Michael Hauschild's talk @ RD51 workshop

# Cluster counting measurement: dN/dx

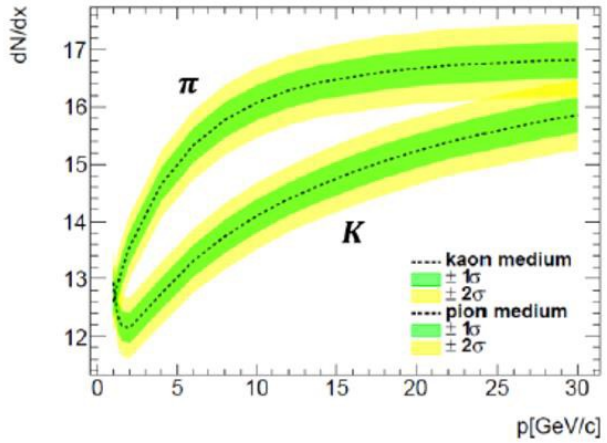
- **dN/dx: Number of primary ionization clusters per unit length**
  - Ideal measurement of ionization, clean in statistics
  - Poisson distribution ➔ Get rid of the secondary ionizations
  - Small fluctuation ➔ Potentially, a factor of 2 better resolution than dE/dx



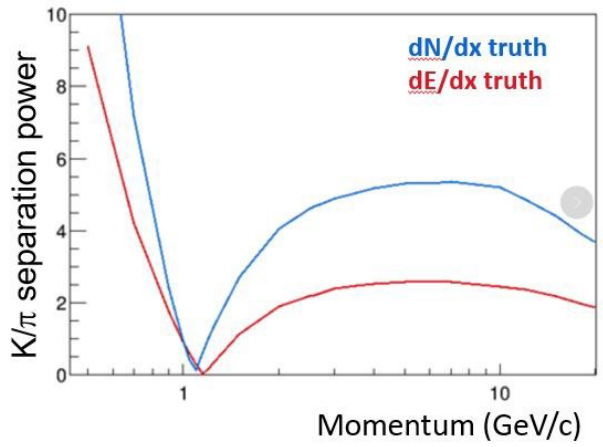

dE/dx




dN/dx

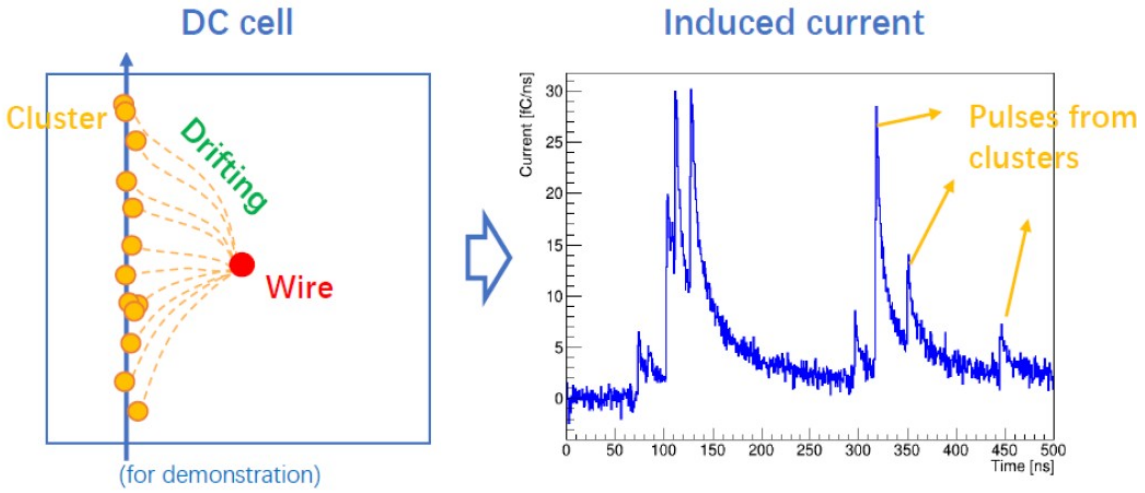


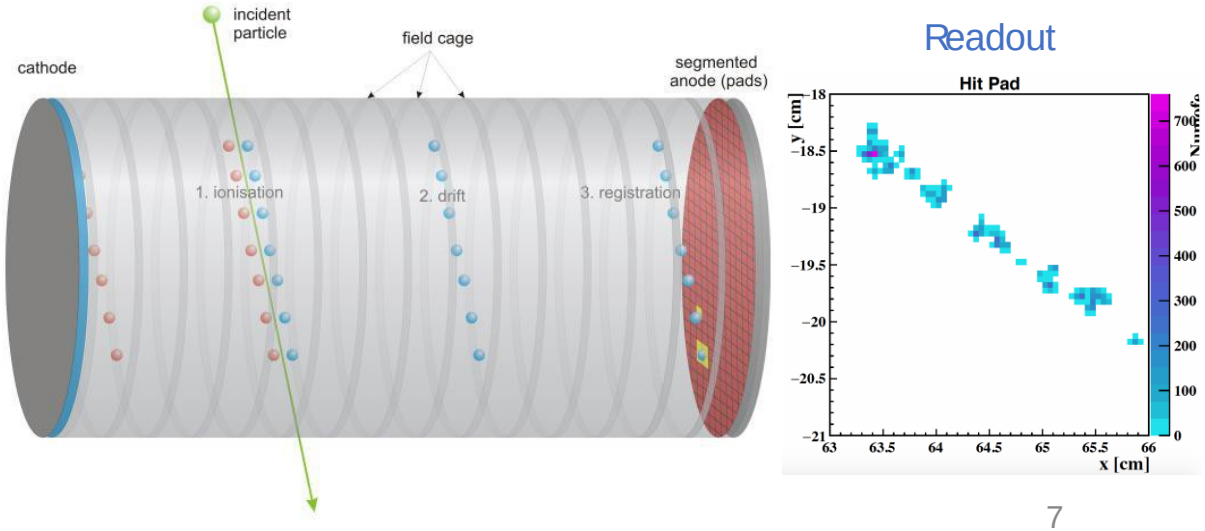

K/π separation power
dN/dx vs dE/dx



# Cluster counting in gaseous detectors

- **In time**
  - **Time measurement in small drift cells of DC**
  - Challenging of fast- shaping electronics (~ns needed)
  - De- couple the charge collection from the cluster counting altogether
  - → optical, with ~(sub) ns continuous readout sensors
- **In space**
  - **Resolve clusters in space by high granularity TPC**
  - Challenging of the low power consumption electronics (>40 mV/fC needed at 2000 of gas gain)
  - Pixelated readout – high granularity
  - → the reasonable pixilation reveals the underlying cluster structure in 3D chamber

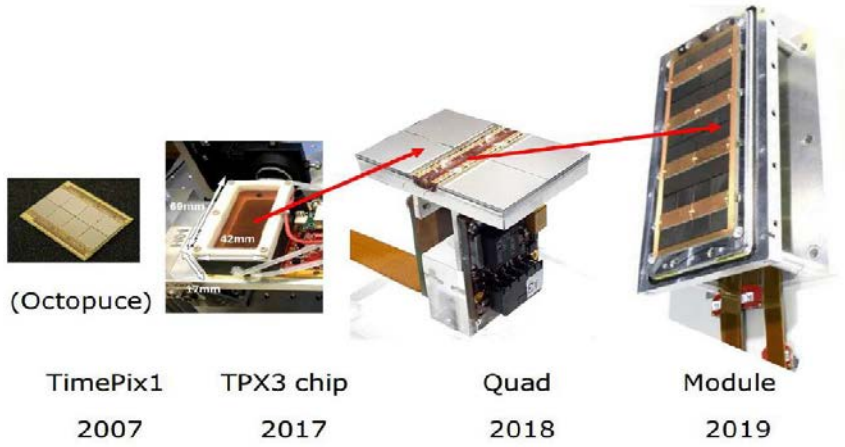


# Pixelated readout TPC for CEPC

- **Pixelated readout TPC is a good option at high luminosity Z running (2x36 $cm^{-2}s^{-1}$)**

- **Pixelated readout TPC is a realistic option to provide**
  - **dE/dx and cluster counting (in space)**
  - High spatial resolution under 2T or 3T magnetic field
  - Better momentum resolution
  - High-rate operation ($MHz/cm^2$)
  - Excellent two tracks separation

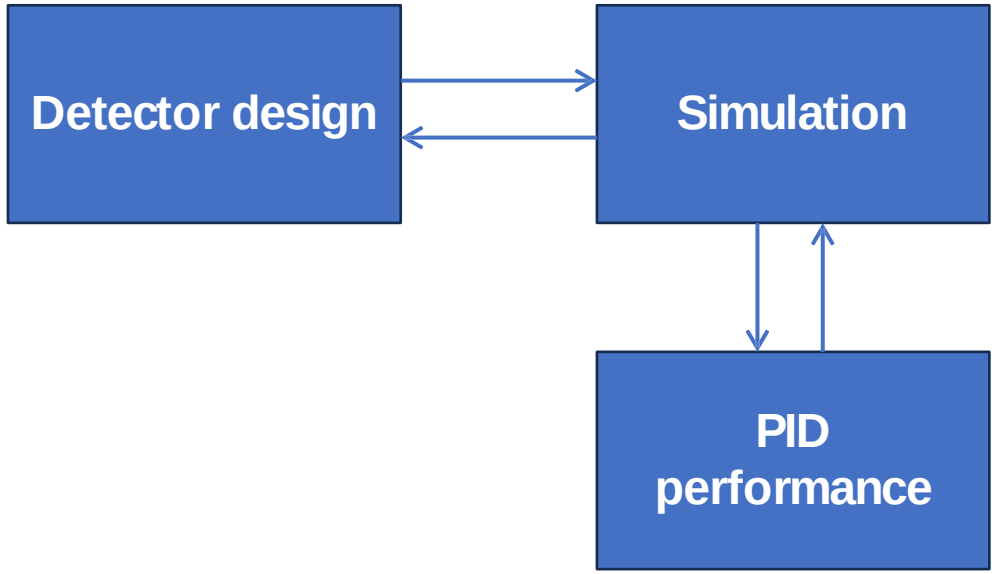



GridPixes

# Simulation of cluster counting in TPC

- **Simulation plays an important role in the design stage of an experiment**

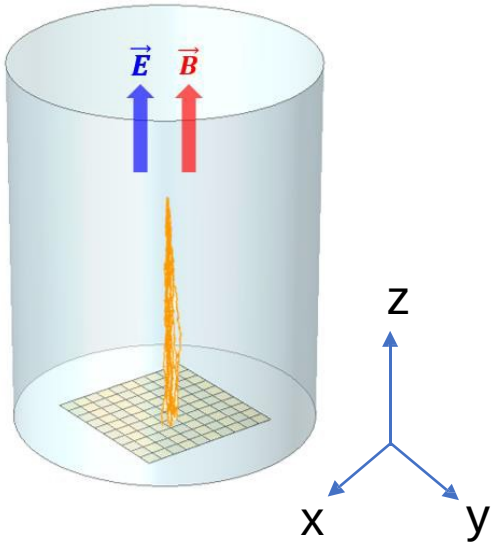
- **TPC design optimization**
  - Gas mixture
  - Pressure
  - Readout granularity
  - Occupancy
  - Geometry
  - …

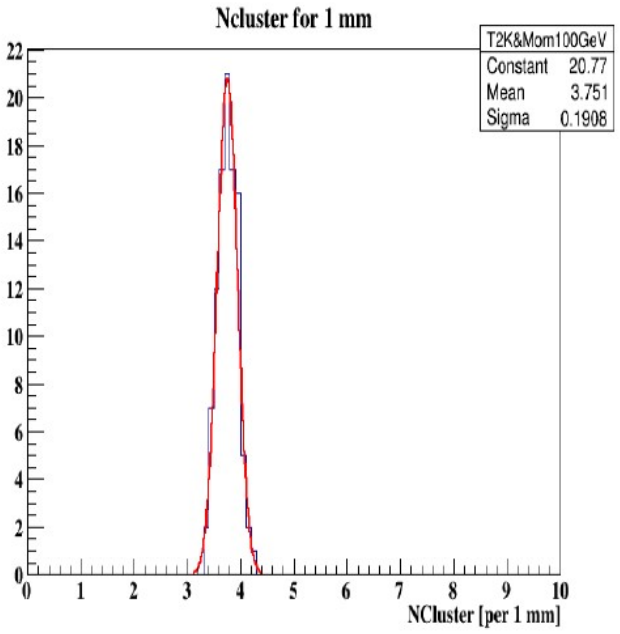


# Primary cluster simulation

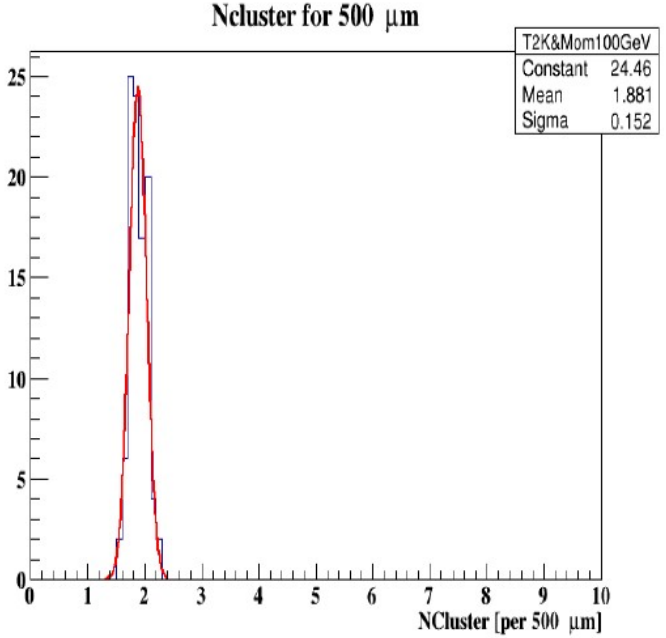
- **Primary cluster profile**
  - Running 10000 events using Garfield++
  - Operation gas: T2K @ 1 atm
  - Particle: muons @ 100 GeV/c

Prototype

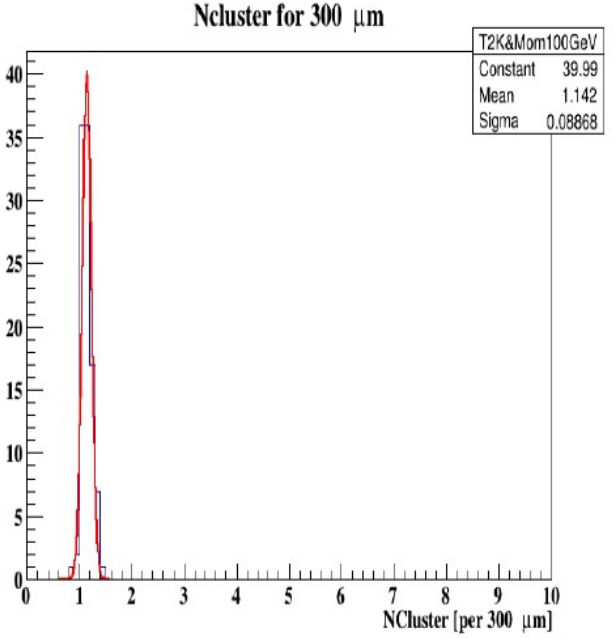



Bin: per 1mm




Bin: per 500um

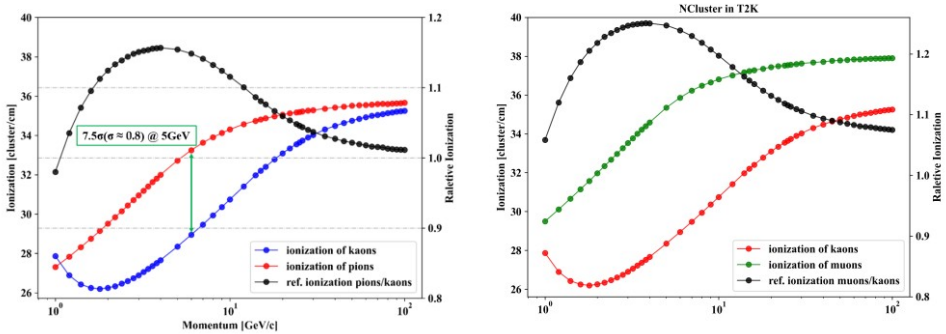



Bin: per 300um

Pad size of 300- 500 µm may meet the pixelated readout TPC

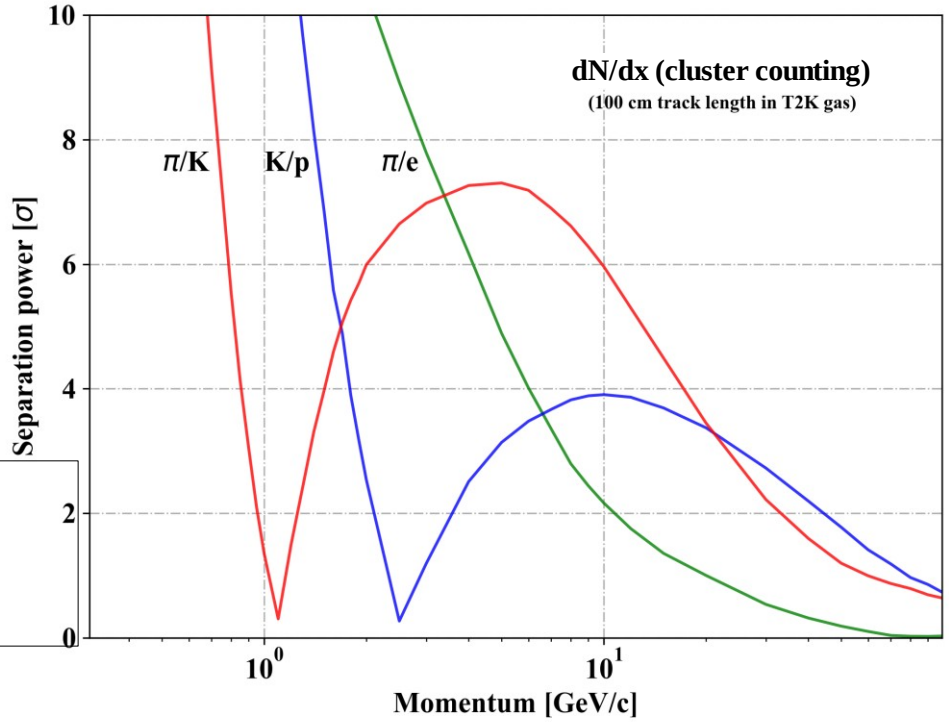
# Primary cluster simulation

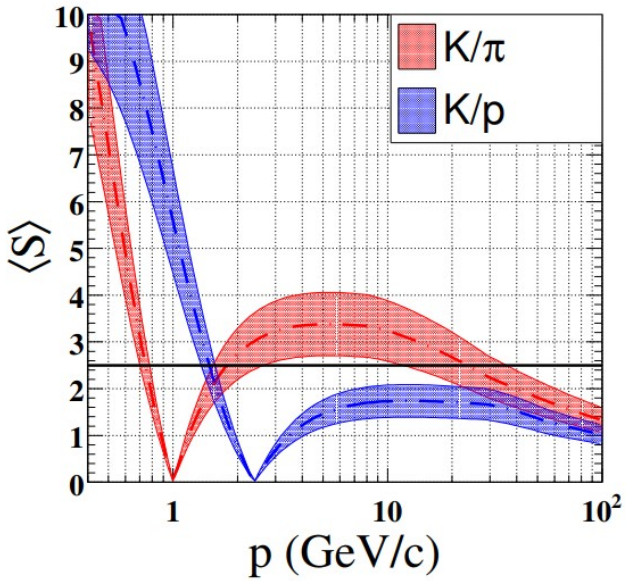
- **Particle separation**
  - Simulating pion/muon/kaon within [0.1- 100] GeV/c
  - Operation gas: T2K




EPJ C 78, 464 (2018)

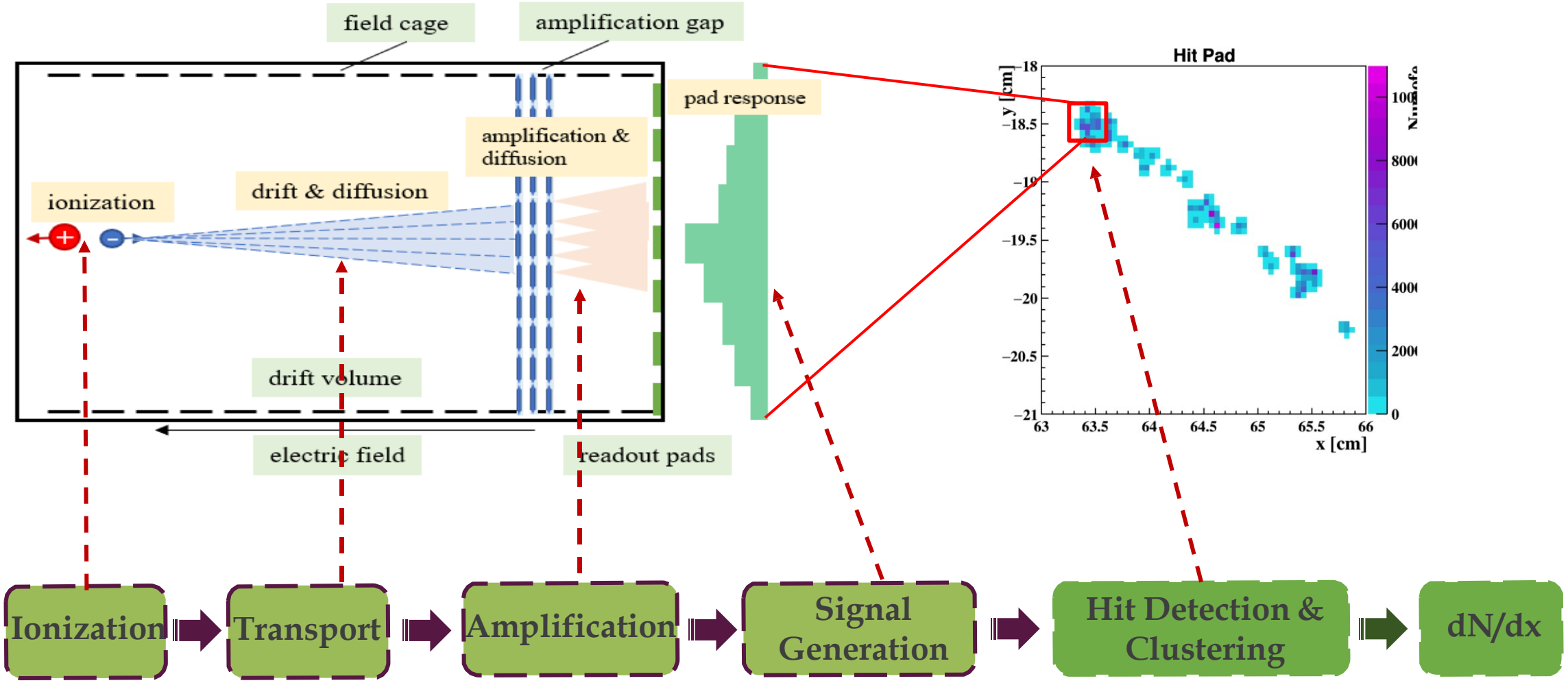
$$S = \frac{|\mu_1 - \mu_2|}{\sqrt{\frac{\sigma_1^2 + \sigma_2^2}{2}}}$$



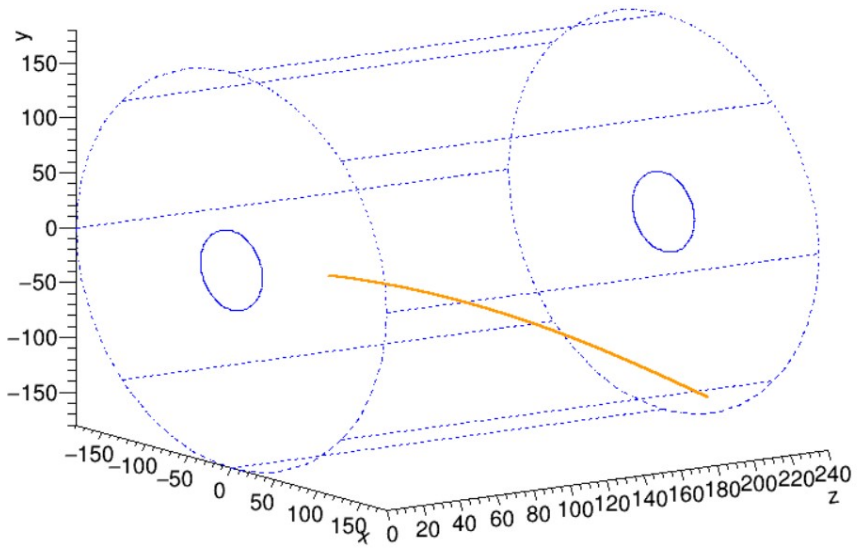

Averaged separation power of dE/dx in hadronic decays at the Z- pole

# Full Simulation framework

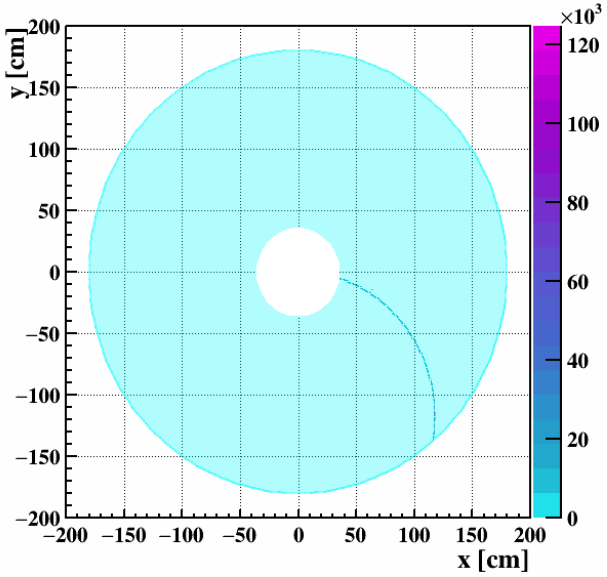


# Simulation setup

- **Magnetic field: 2T (Z- pole run)**
- **Gas mixture: T2K ($Ar/CF_4/iC_4H_{10}$: 95/3/2)**
- **Detector Layout: R (0.3 m - 1.8 m); L(2.34 m)**




A track of 1 GeV/c pion in TPC




Projection of the same track on end- cap

# Parametrizations

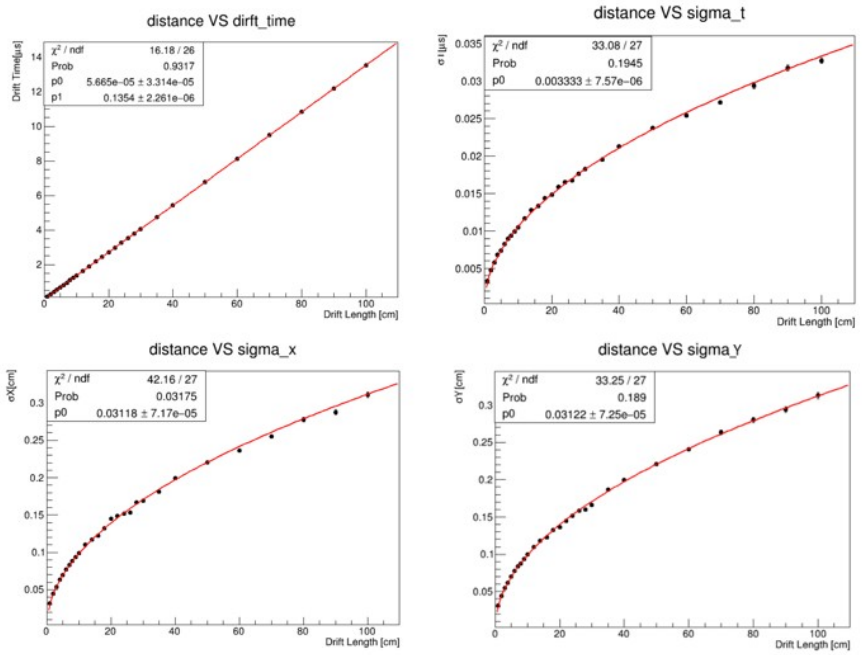
- **To speed up the simulation, make several decompositions and apply parametrized models**

- **Electron diffusion:**
  - $\sigma_T$ vs drift distance
  - $\sigma_X$ vs drift distance
  - $\sigma_Y$ vs drift distance

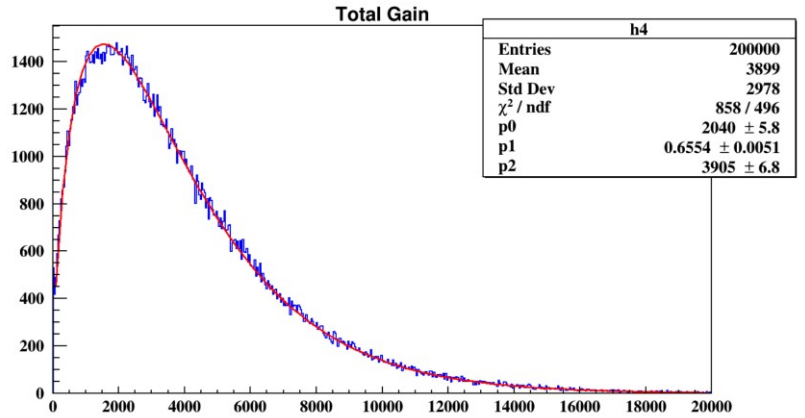
- **Amplification:**
  - Polya function sampling

- **Signal generation:**
  - Double- Gaussian sampling

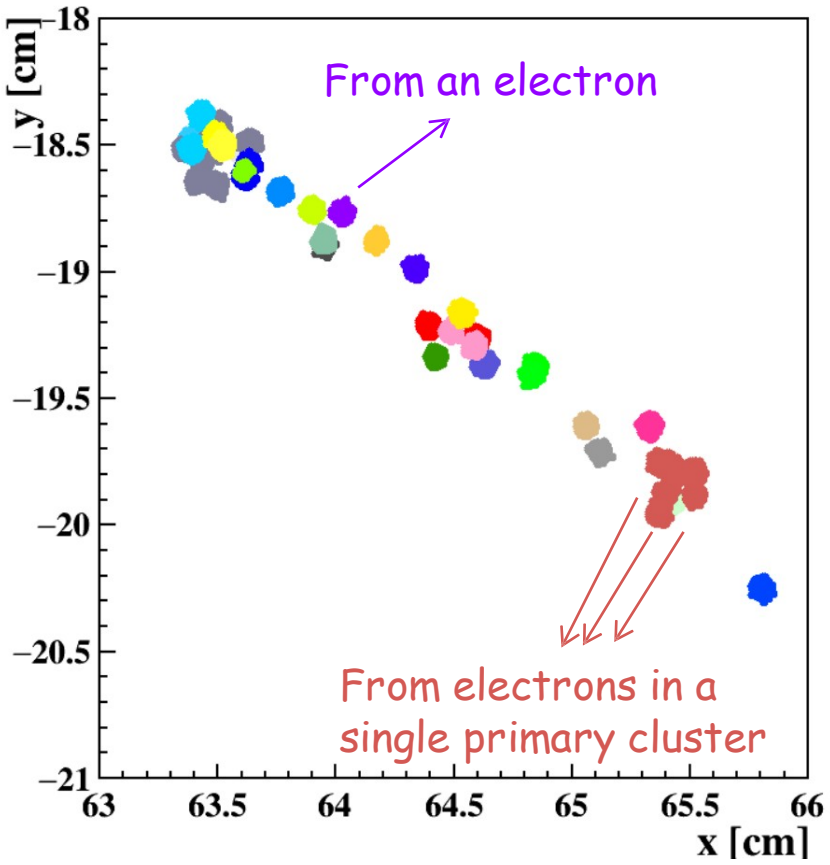
## Diffusion




## Amplification



# MC- truth- level readout

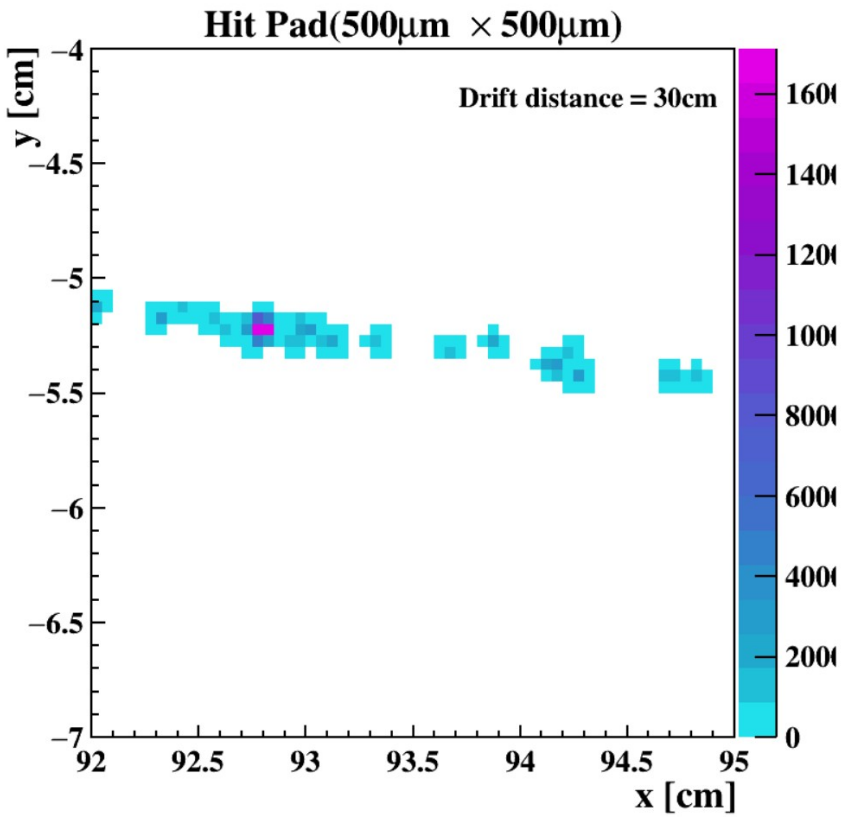


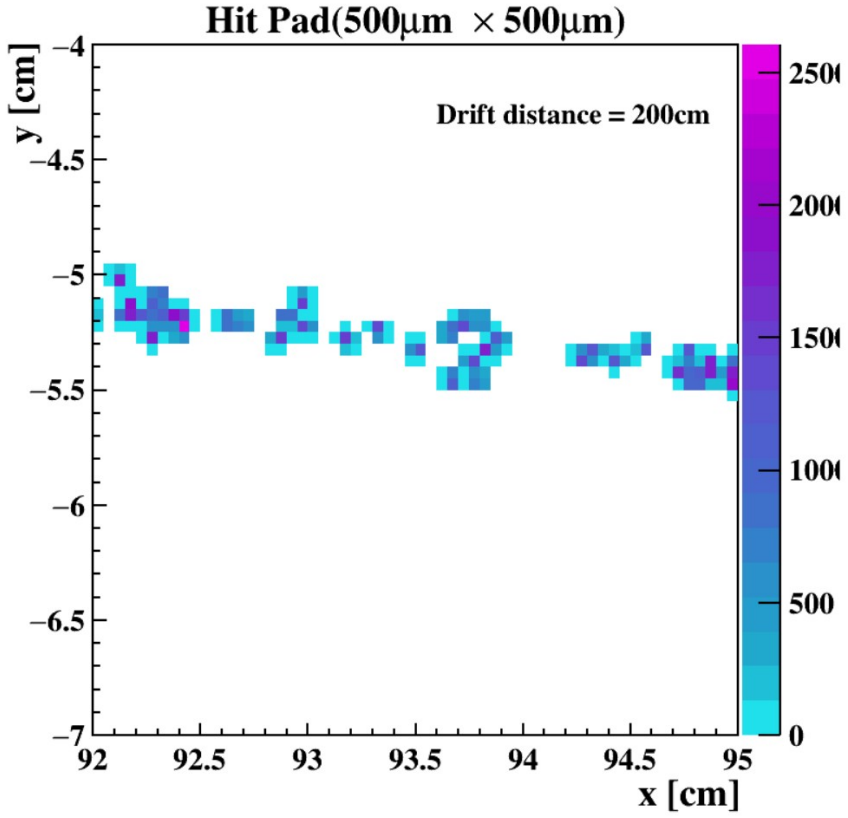

Drift distance: ~160 cm
Magnetic field: 2T

- MC- truth- level readout with simplified amplification and shaping model
- Color code indicates the cluster ID
- **Note:**
  - **Most electrons are separatable**
  - **Electrons from the same cluster are spatially localized**

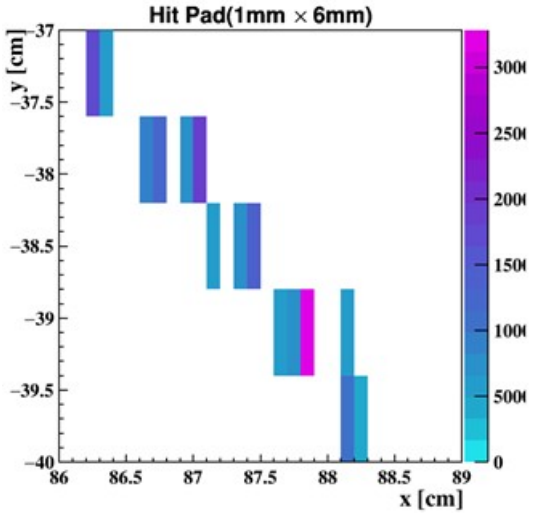
# Readout assuming a pixel size of 0.5 x 0.5 mm

## Pixelated Readout (500µm x 500µm )



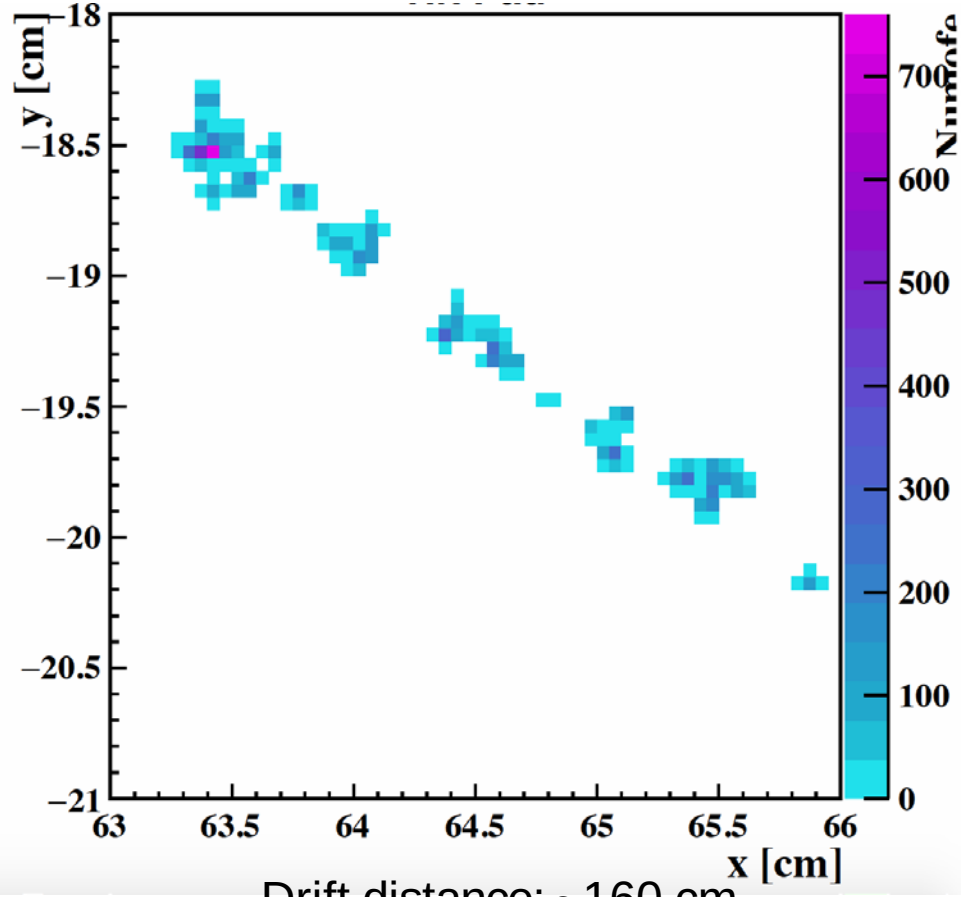




## Pad Readout (1x6 mm)




**Pixelated readout is essential for cluster detection**

# Outlook: Reconstruction




Drift distance: ~160 cm
Magnetic field: 2T

- **The algorithm should be able to**
  - Detect single electron signals
  - Merge single electrons to form a cluster

# Summary

- **Simulation study of cluster counting with TPC is starting**
- **A simulation framework is developed including ionization/transport/signal generation**
- **To complete the software cycle, a reconstruction algorithm is under developing**
- **Optimizations of the detector design will be carried out afterwards**

**Thank you**