Simulation of Cluster Counting with TPC

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CEPC Cay
July 13rd, 2023

Outline

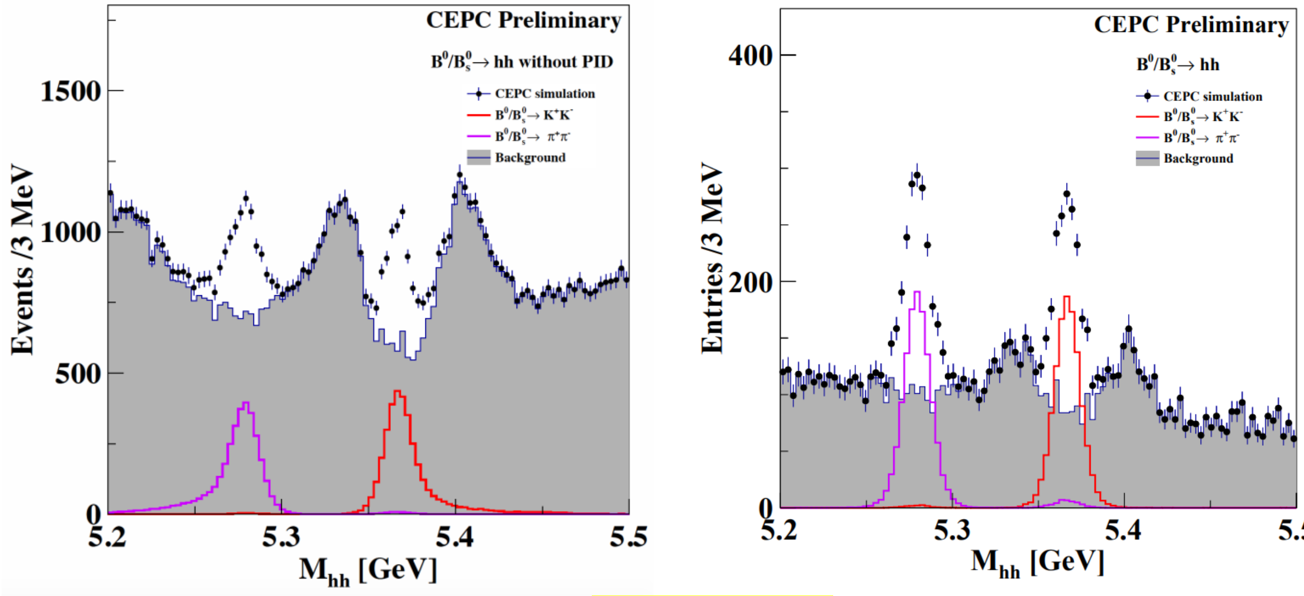
- **Introduction: Cluster counting basics**
- **Simulation study of pixelated TPC**
  - Primary cluster simulation
  - Full simulation
- **Summary**

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

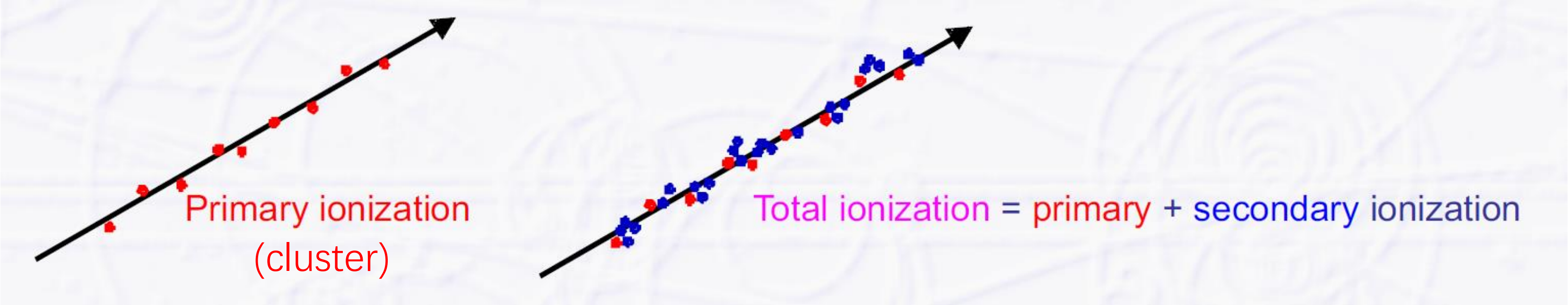
Without PID | With PID



From Xu Gao

PID by ionization

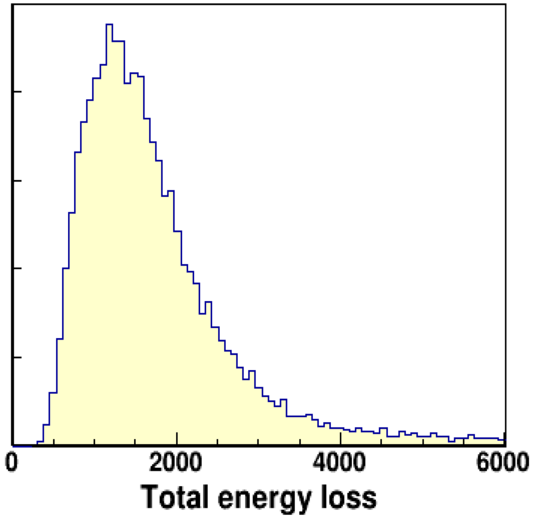
- **Main mechanism: Ionization of matter by charged particles**



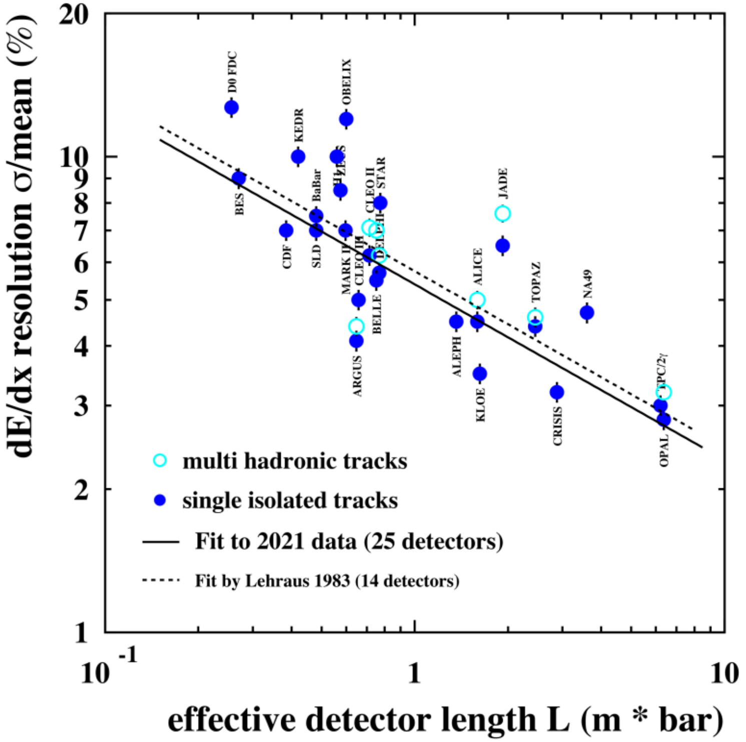
- Number of clusters per unit length is Poisson-distributed
- Primary electrons sometimes get large energies
  - Can make secondary ionization
  - Can even create visible secondary track (“delta-electron”)

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** * $L^{-0.37}$ (%)

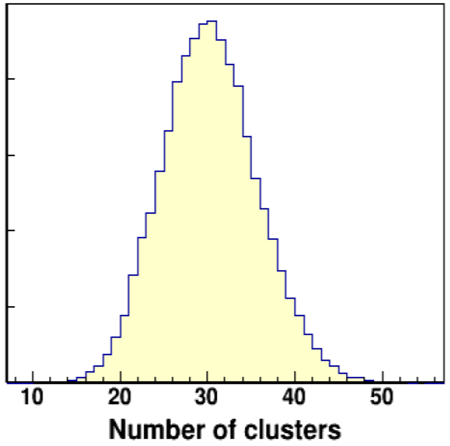
- **Fit in 2021:**
  - dE/dx res. = **5.4** * $L^{-0.37}$ (%)

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

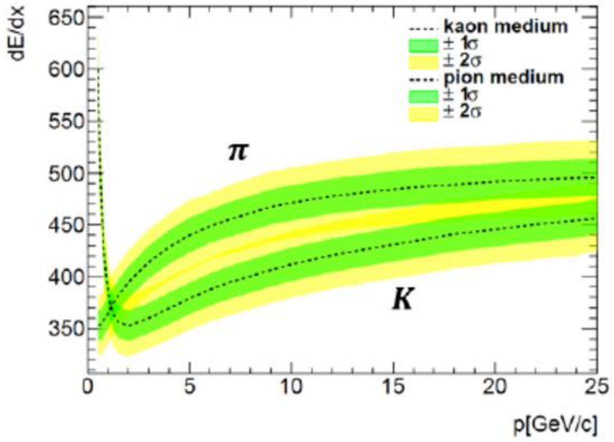
* From Michael Hauschild's talk @ RD51 workshop

Cluster counting measurement: dN/dx

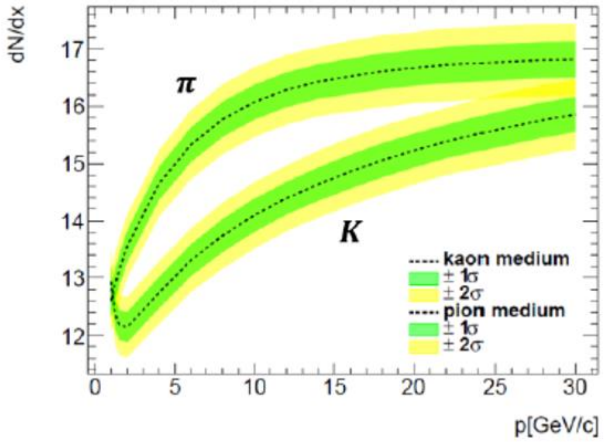
- **dN/dx: Number of primary ionization clusters per unit length**
  - Ideal measurement of ionization, clean in statistics
  - Poisson distribution ➔ Get rid of the secondary ionizations
  - Small fluctuation ➔ Potentially, a factor of 2 better resolution than dE/dx



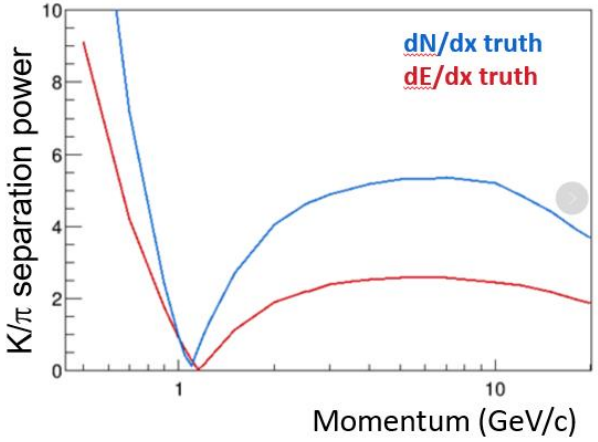
dE/dx



dN/dx

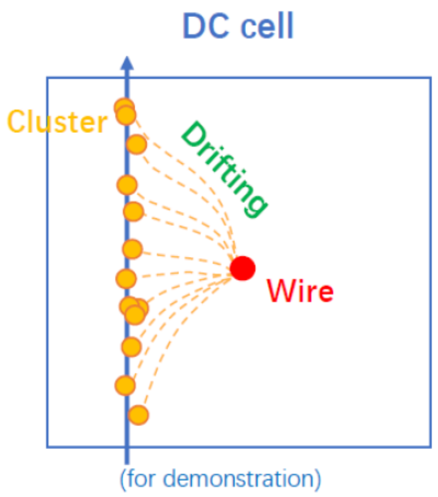


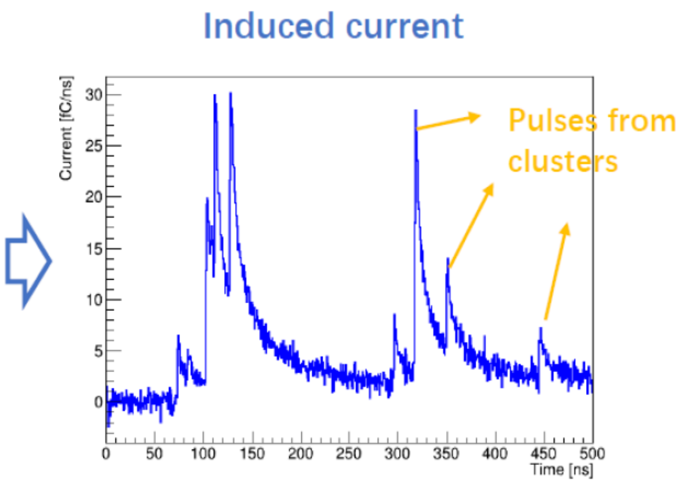
K/π separation power
dN/dx vs dE/dx

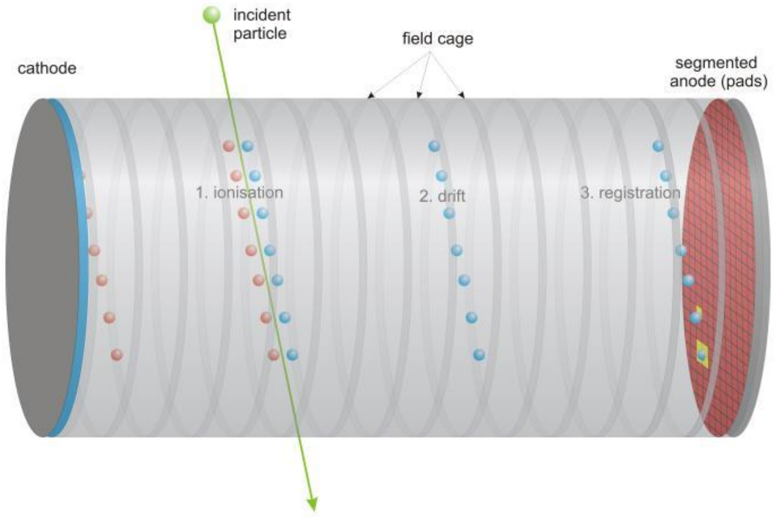


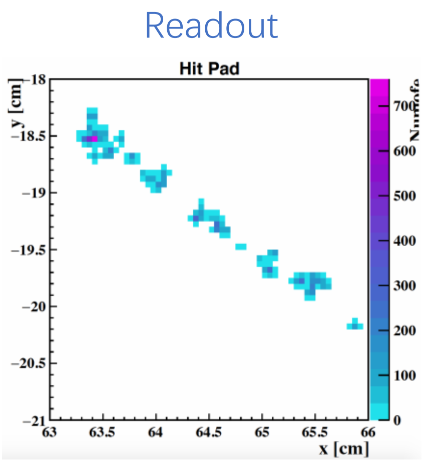
Cluster counting in gaseous detectors

- **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 $cm^{-2}s^{-1}$)**

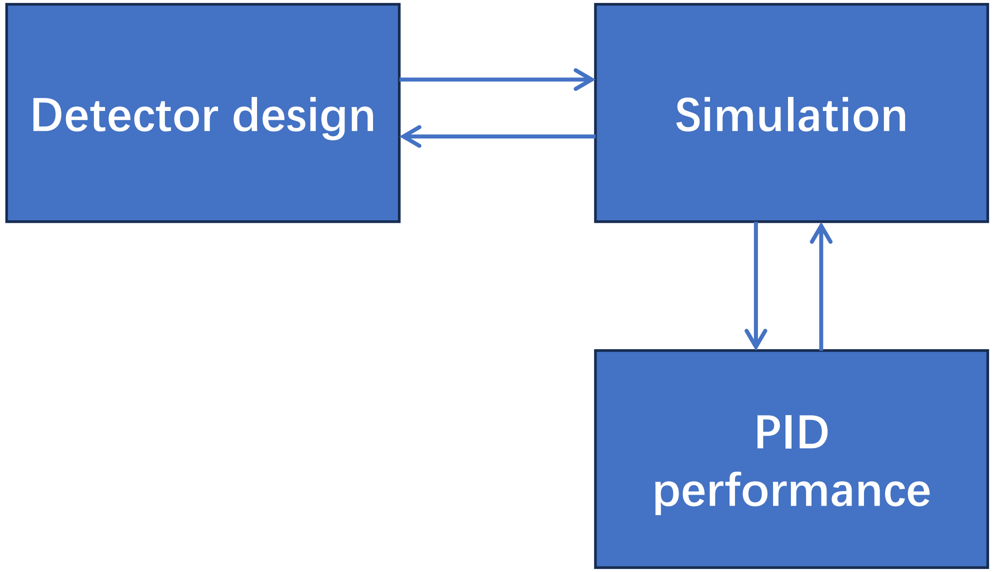
- **Pixelated readout TPC is a realistic option to provide**
  - **dE/dx and cluster counting (in space)**
  - High spatial resolution under 2T or 3T magnetic field
  - Better momentum resolution
  - High-rate operation (MHz/cm^2)
  - Excellent two tracks separation

TimePix1 2007 | TPX3 chip 2017 | Quad 2018 | Module 2019

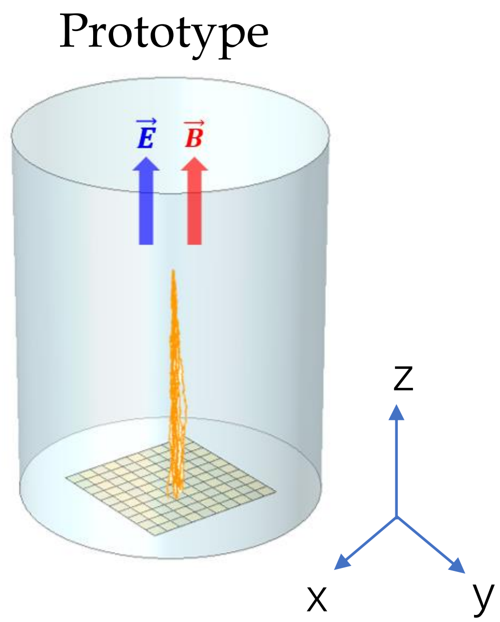
GridPixes

Simulation of cluster counting in TPC

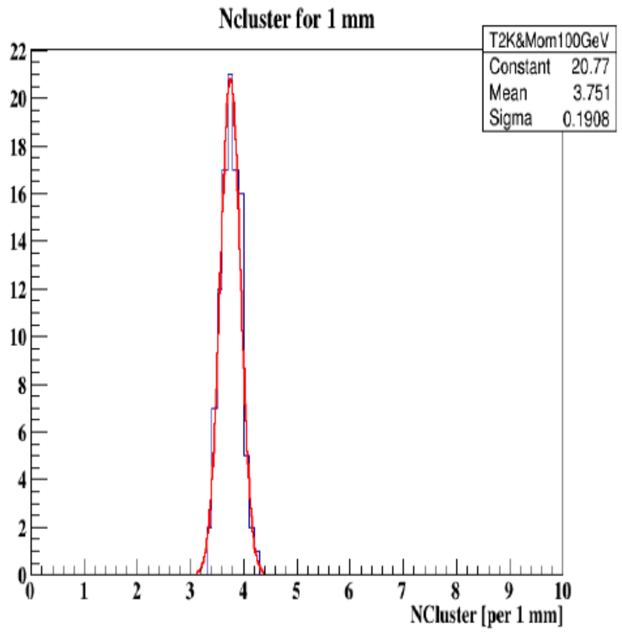
- **Simulation plays an important role in the design stage of an experiment**
- **TPC design optimization**
  - Gas mixture
  - Pressure
  - Readout granularity
  - Occupancy
  - Geometry
  - …



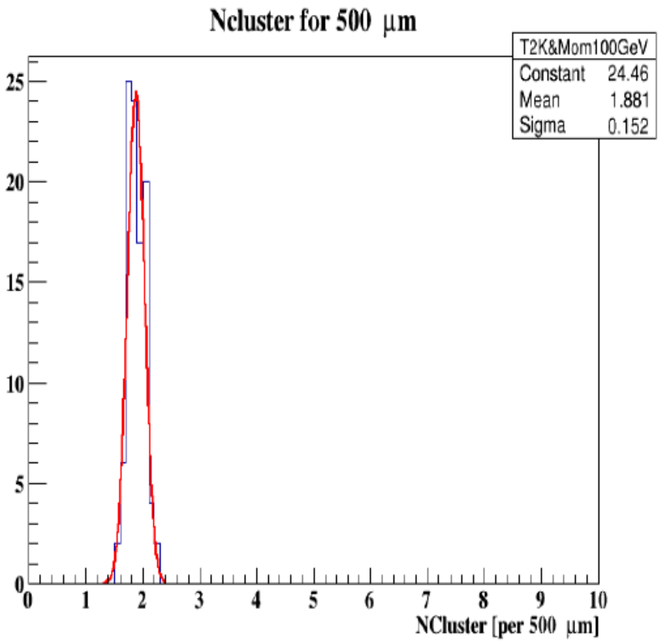
Primary cluster simulation



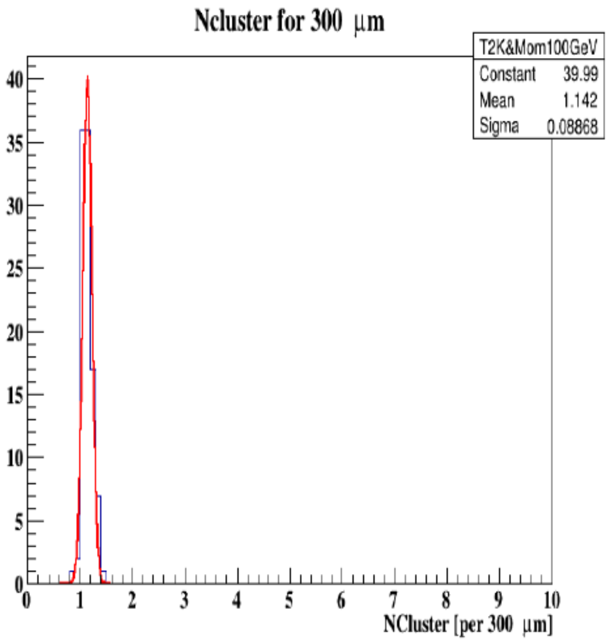
- **Primary cluster profile**
  - Running 10000 events using Garfield++
  - Operation gas: T2K @ 1 atm
  - Particle: muons @ 100 GeV/c



Bin: per 1mm



Bin: per 500um

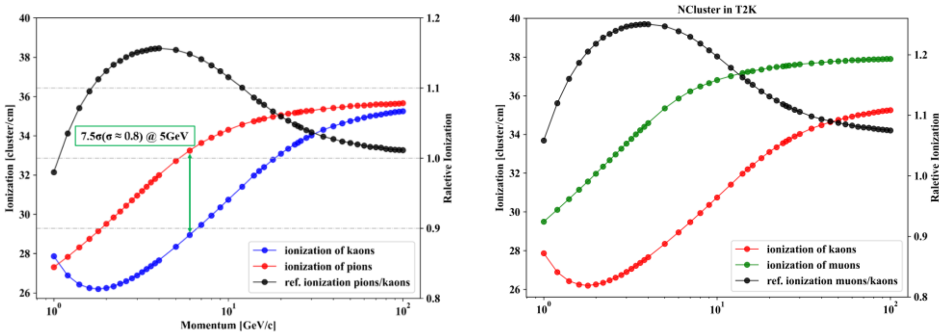


Bin: per 300um

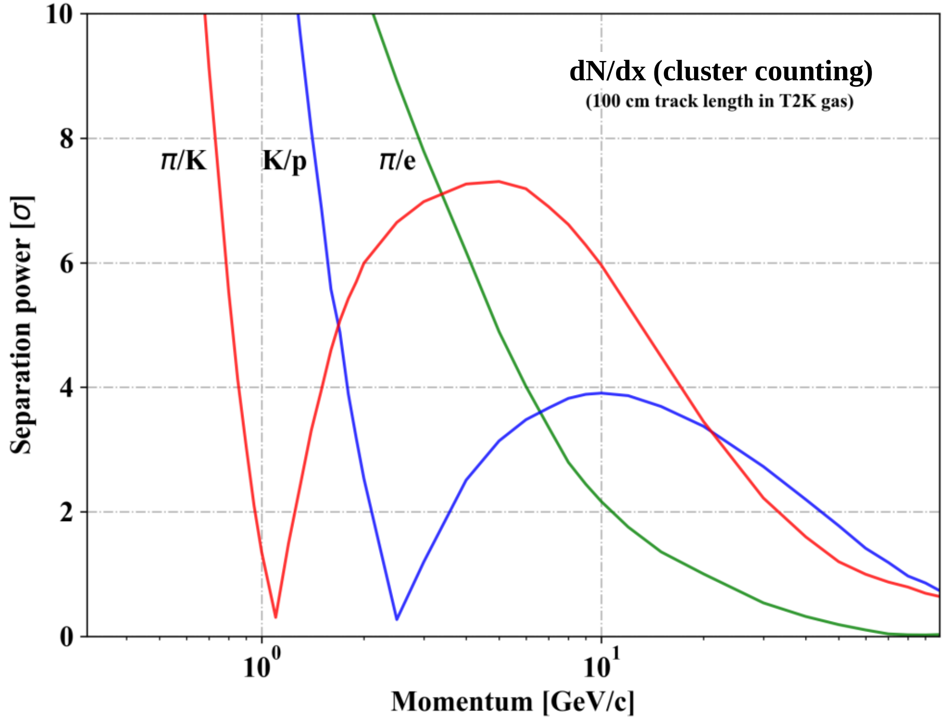
Pad size of 300-500 µm may meet the pixelated readout TPC

Primary cluster simulation

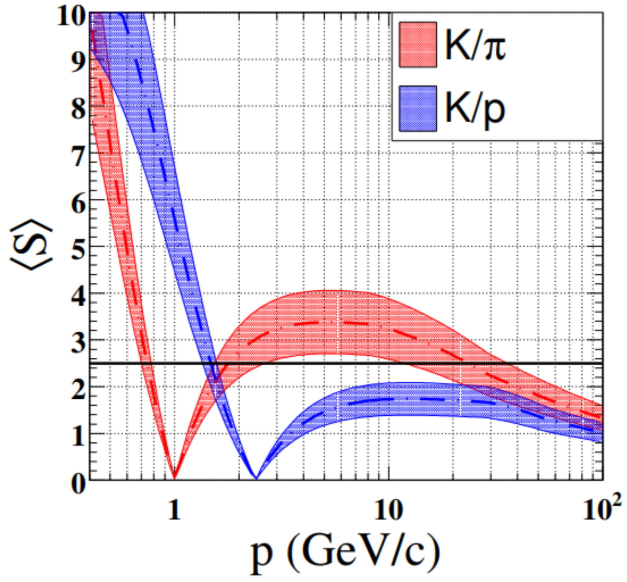
- **Particle separation**
  - Simulating pion/muon/kaon within [0.1-100] GeV/c
  - Operation gas: T2K



$$S = \frac{|\mu_A - \mu_B|}{\sqrt{\frac{\sigma_A^2 + \sigma_B^2}{2}}}$$

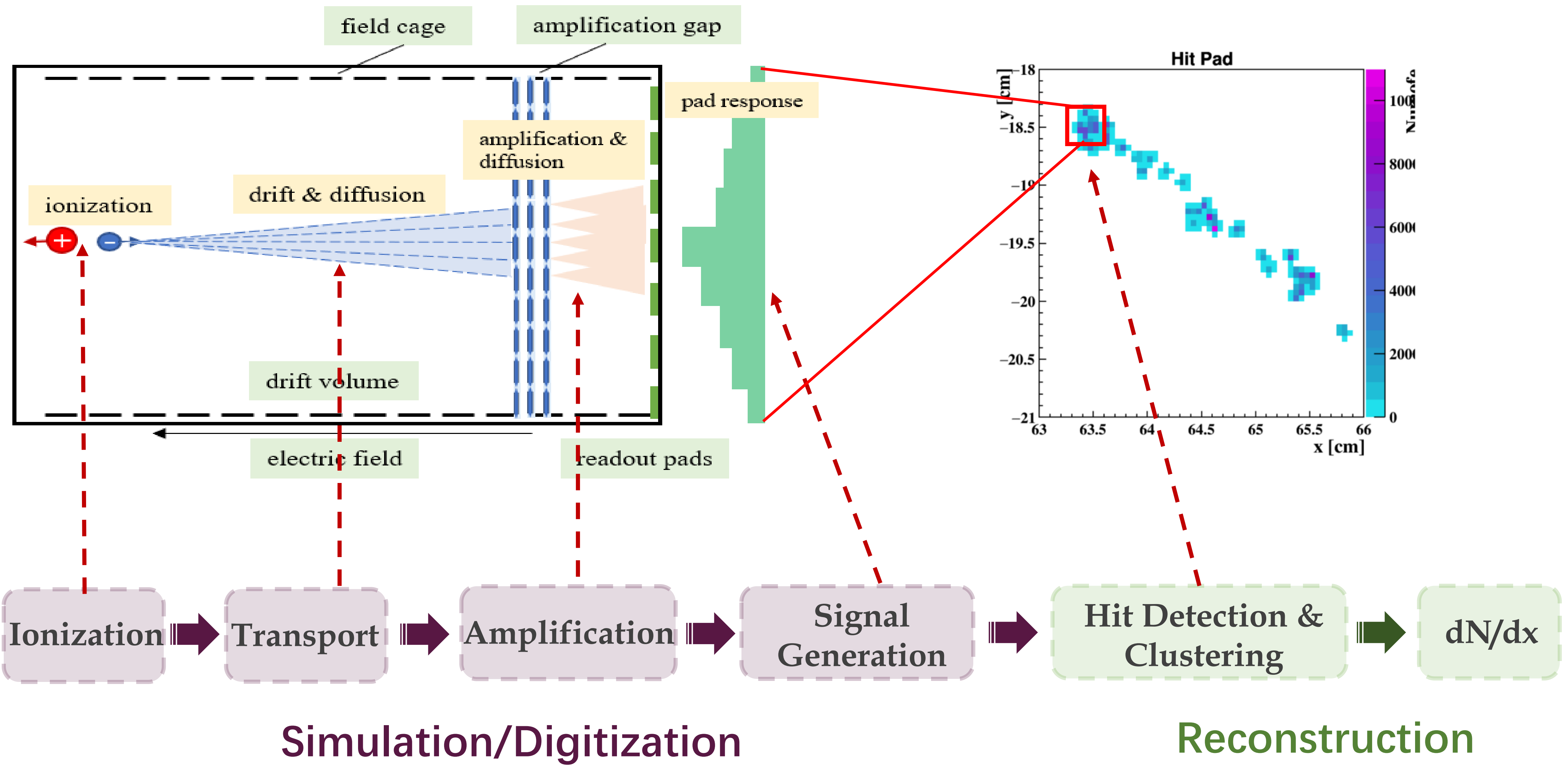


EPJ C 78, 464 (2018)



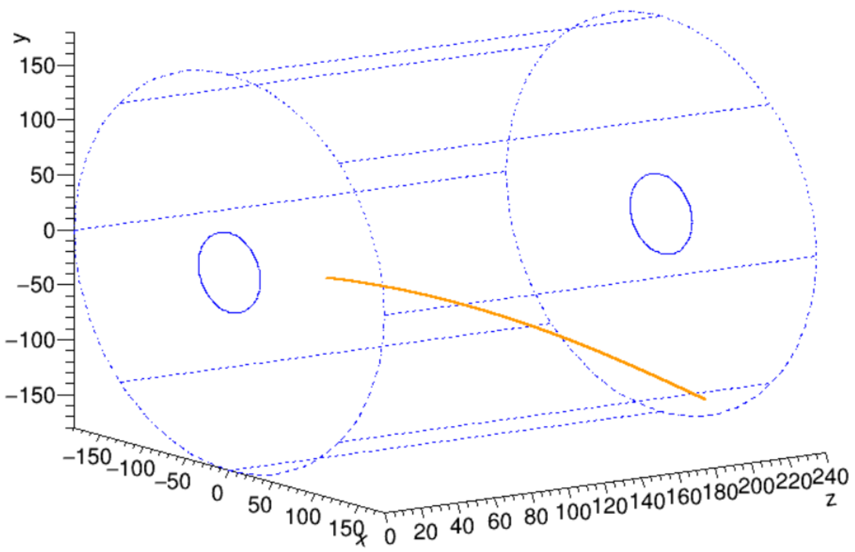
Averaged separation power of dE/dx in hadronic decays at the Z-pole

Full Simulation framework

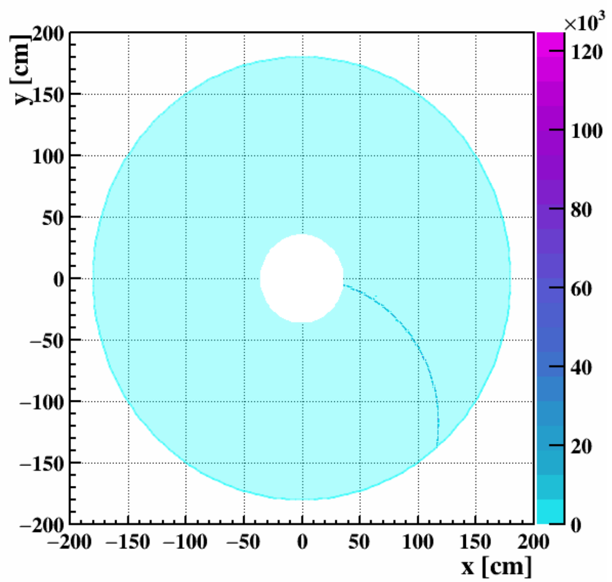


Simulation setup

- 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

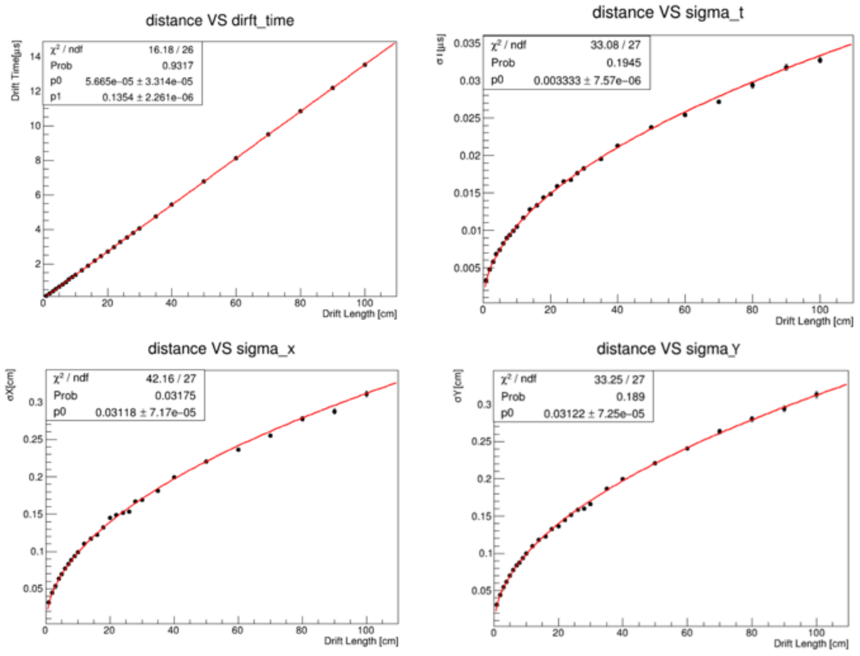


Projection of the same track on end-cap

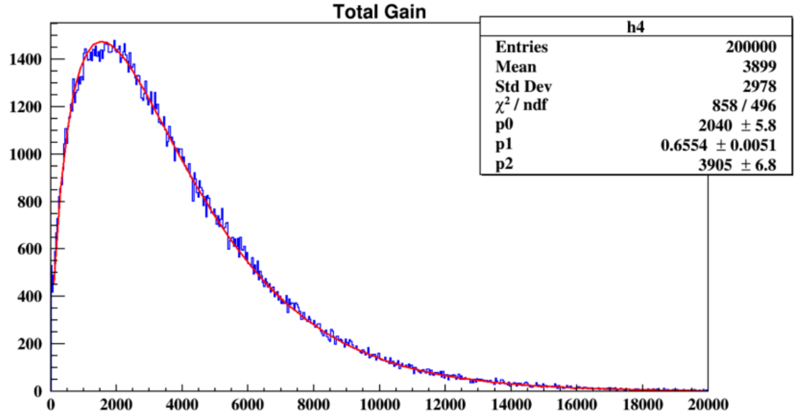
Parametrizations

- **To speed up the simulation, make several decompositions and apply parametrized models**
- **Electron diffusion:**
  - σ_T vs drift distance
  - σ_X vs drift distance
  - σ_Y vs drift distance
- **Amplification:**
  - Polya function sampling
- **Signal generation:**
  - Double-Gaussian sampling

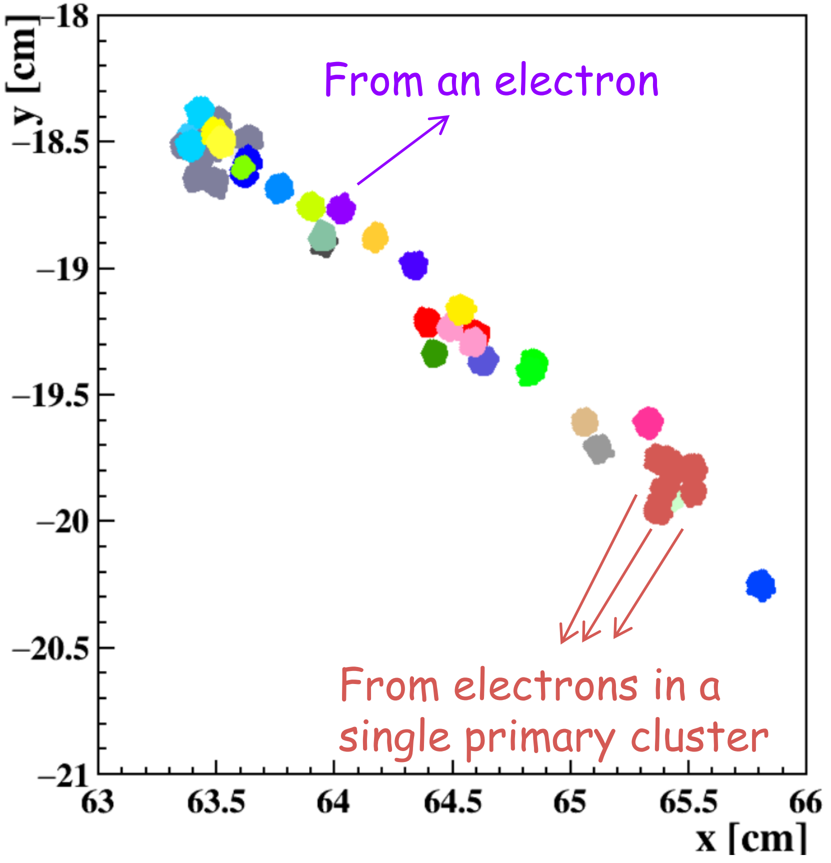
Diffusion



Amplification



MC-truth-level readout



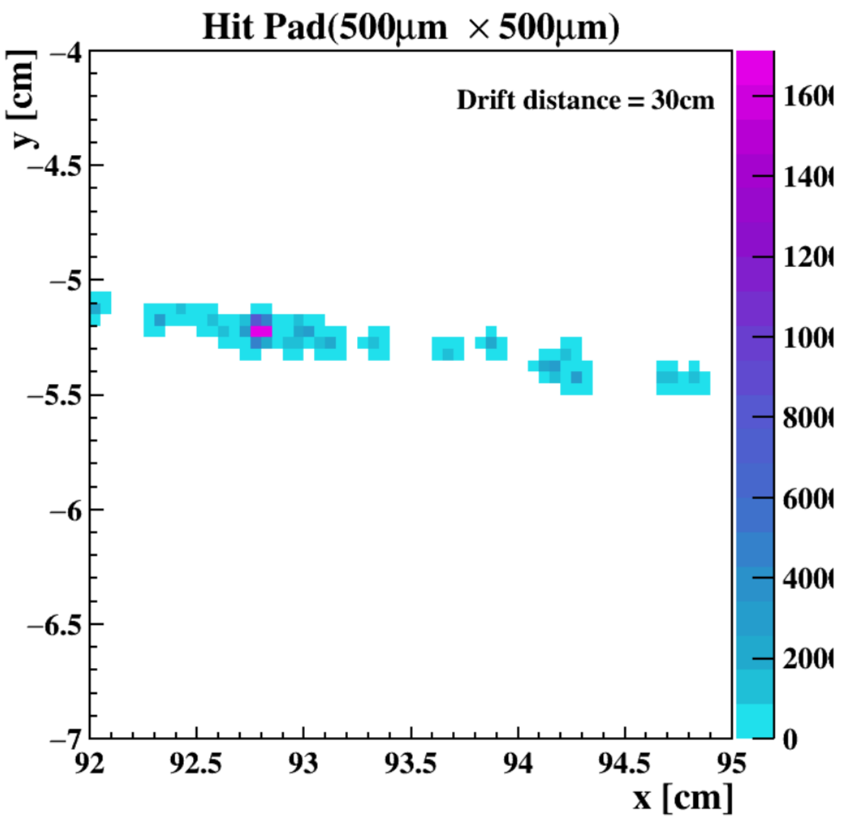
Drift distance: ~160 cm
Magnetic field: 2T

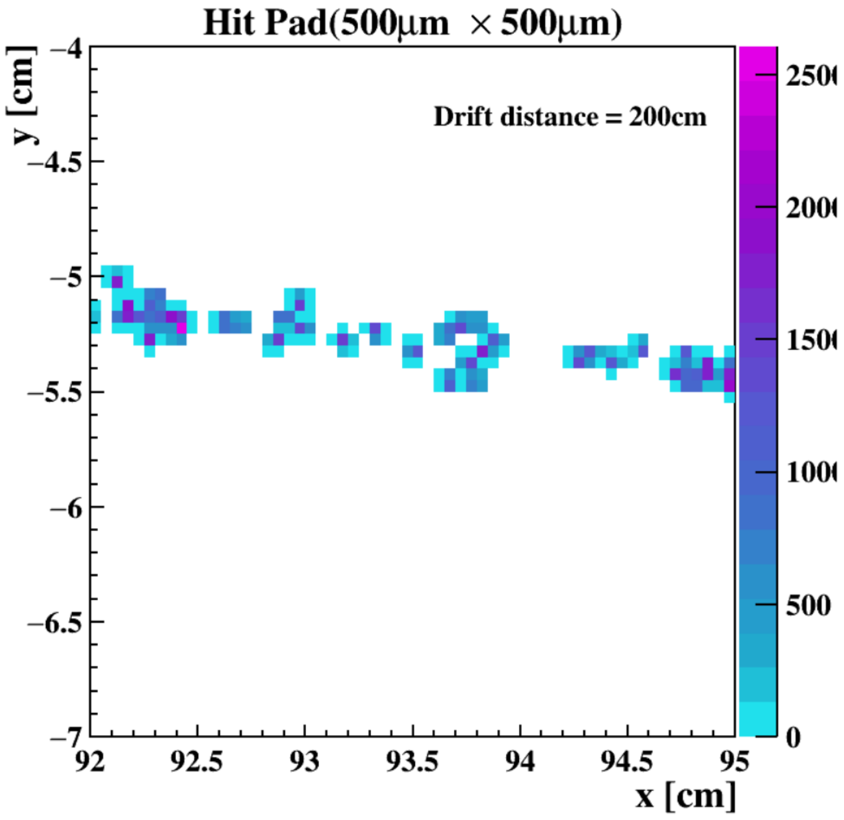
- MC-truth-level readout with simplified amplification and shaping model
- Color code indicates the cluster ID
- **Note:**
  - **Most electrons are separatable**
  - **Electrons from the same cluster are spatially localized**

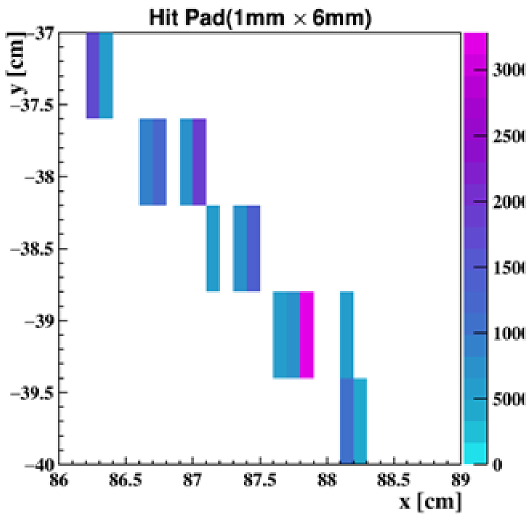
Readout assuming a pixel size of 0.5 x 0.5 mm

Pixelated Readout (0.5x0.5 mm)

Pad Readout (1x6 mm)

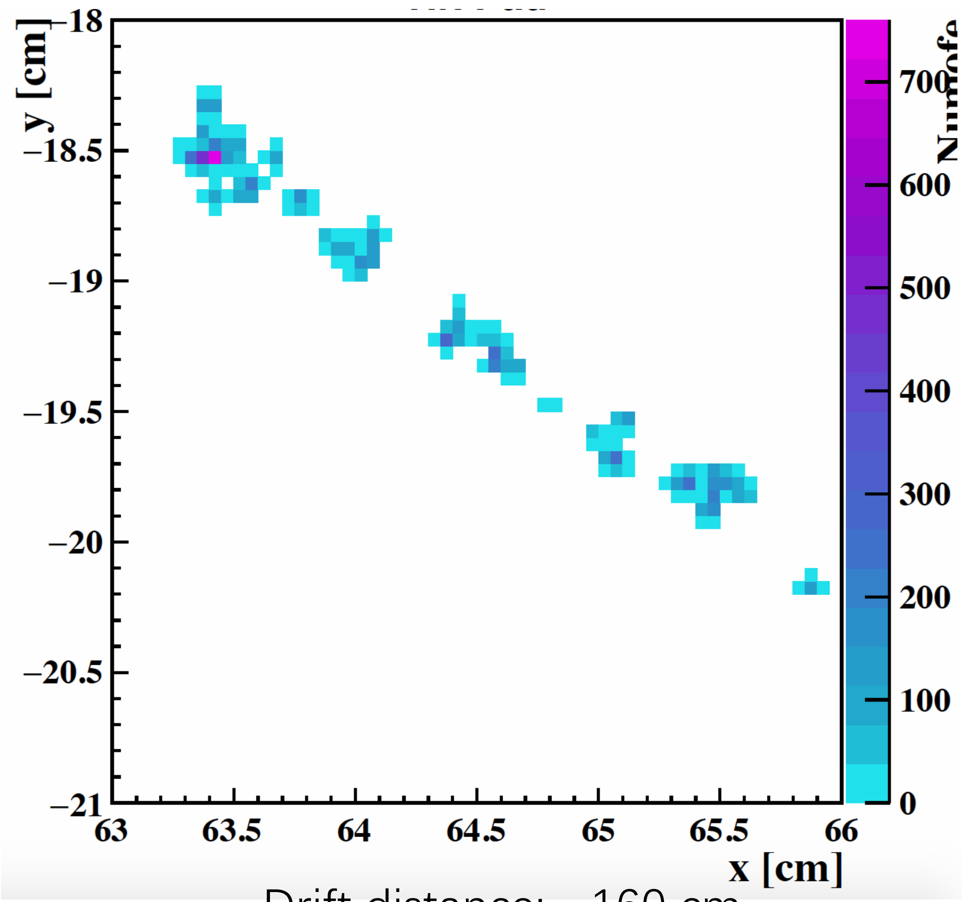






Pixelated readout is essential for cluster detection

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

Backup

Low power consumption pixelated TPC technology IHEP/LCTPC

- R&D @ IHEP based on **0.5×0.5 mm^2 pixels and electronics uses a power of <0.2mW/channel**.
  - For all the active area of 160 000 cm^2 one has 64 M channels and **<1.2 kW** power consumption
  - > 89% coverage in the endplate

- Current TPX3 chip has 256×256 channels and a surface of 1.41×1.41 cm^2
- Power consumption ~2W/chip; this means 30 mW/channel
- A full pixel TPC in the detector will have a total area 160 000 cm^2
  - For full coverage one needs 80 000 chips
  - With the current TPX3 chip one reaches about 60% coverage
  - For the pixel TPC the total power is 160 kW (so 80 kW per endcap)

- Low power consumption **is the first requirement** for the pixelated TPC technology to LCTPC
  - TPX3 Gridpixes in low power mode reduces the power consumption for a pixel TPC to **8 kW per endcap** at the cost of a worse time resolution.

- Ref1 https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01024
- Ref2 https://iopscience.iop.org/article/10.1088/1748-0221/14/01/C01001

Cost estimation

- The total cost of a pad or a pixel readout is **at same level .**
  - The cost goes comparably to pad technology for massive production referred to Gridpix chip of NIKHEF
- All readout options need CO_2 cooling and electronics and that drives the TPC readout cost. (cite#7)

Including the cooling system

TPC COST ESTIMATION(unit: *10K RMB) **Total: 180 Millions RMB**

ITEM	DEVICE ITEM	TYPE	UNIT	Quantity	Prive/	Total
3.1	TPC detector (TPC)					18000.00
3.1.1	Chamber					3600.00
3.1.1.1	Fieldcage		set	1	1200.00	1200.00
3.1.1.2	Connector		set	1	800.00	800.00
3.1.1.3	Barrel		set	1	1000.00	1000.00
3.1.1.4	Support device		set	1	600.00	600.00
3.1.2	Readout					2500.00
3.1.2.1	MPGD detector		set	1	800.00	800.00
3.1.2.2	Support board		set	2	600.00	1200.00
3.1.2.3	Readout board		board	200	2.50	500.00
3.1.3	Electronics					10000.00
3.1.3.1	FEE ASIC readout		channel	1200000	0.002	2400.00
3.1.3.2	Cables		set	50000	0.03	1500.00
3.1.3.3	Optical driver		set	50000	0.03	1500.00
3.1.3.4	Optical link, connectors		set	500	1.00	500.00
3.1.3.5	DAQ		set	5000	0.30	1500.00
3.1.3.6	Crate and controller		set	50	20.00	1000.00
3.1.3.7	Cooling sytem		set	1	1600.00	1600.00
3.1.4	Calibration					500.00
3.1.4.1	Calibration system		set	1	500.00	500.00
3.1.5	HV and Gas system					1400.00
3.1.5.1	HV and low power		set	1	800.00	800.00
3.1.5.2	Gas system		set	1	300.00	300.00
3.1.5.3	Monitor system		set	1	300.00	300.00

cite #7 Cost estimation of ILD concept