Investigation of the primary clusters for the high precision particle identification (PID) at CEPC

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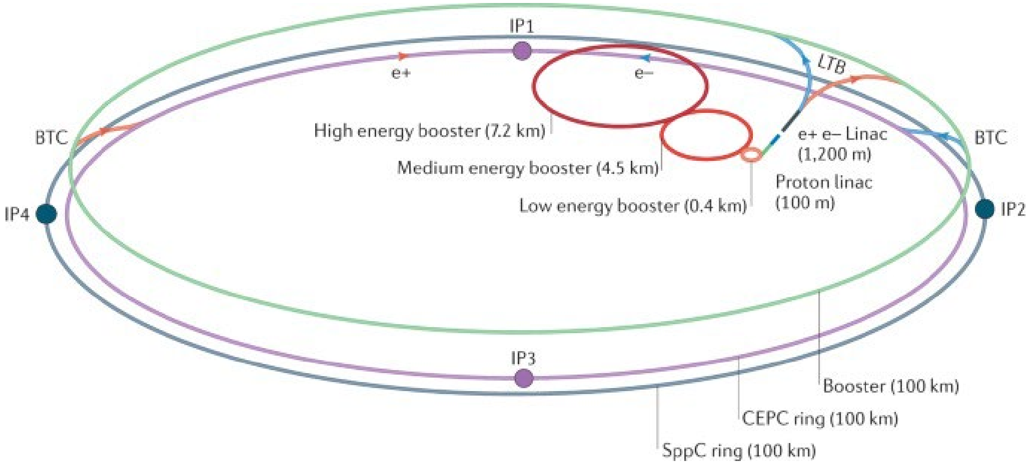
CONTENTS

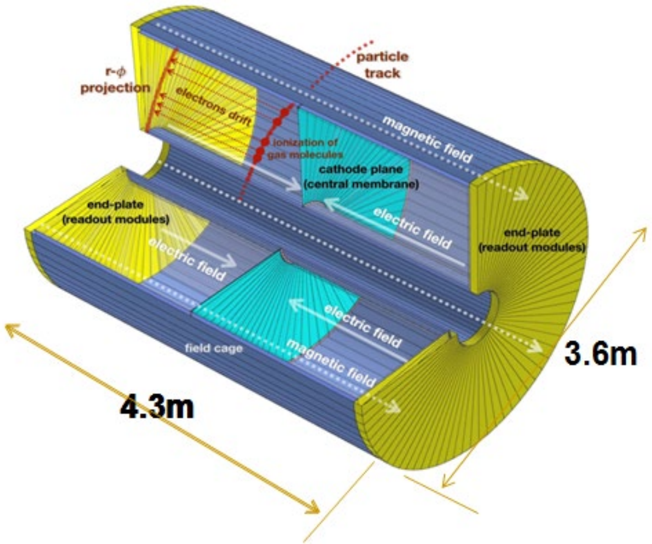
TPC technology for future e+e- Colliders

- Some advantages of TPC detector
  - Operation under 3&2 T magnetic field
  - Full 3D tracker
  - Excellent pattern recognition capability
  - good dE/dx resolution due to a large number of sampling points

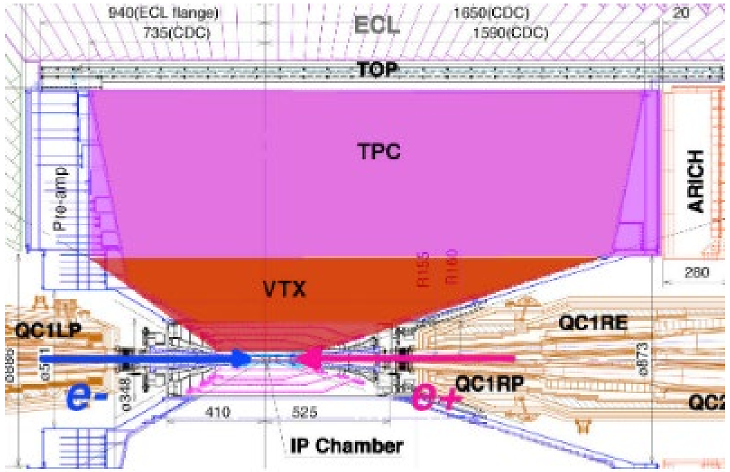
- TPC detector plays a crucial role in the future e+e- Colliders
- A lot of R&D already present (LCTPC, CEPC)



CEPC



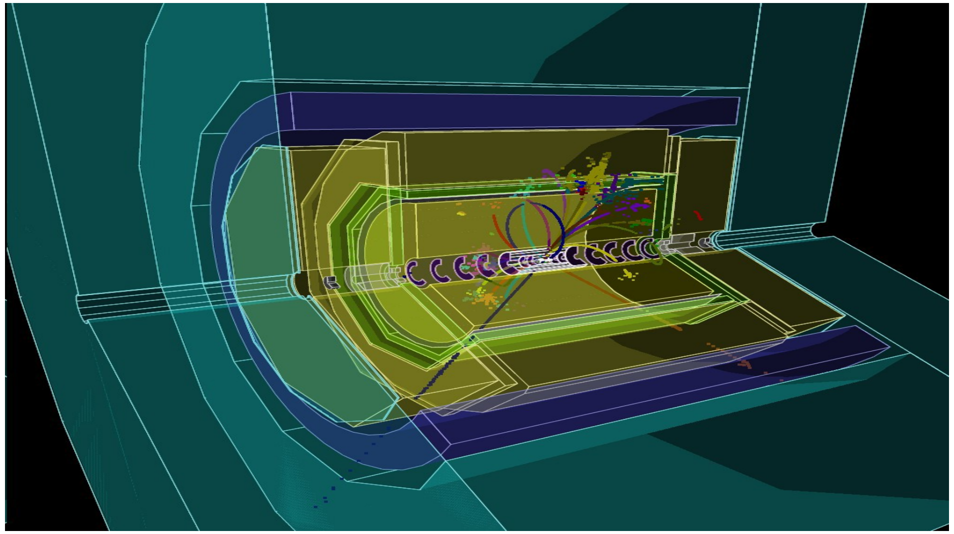
CEPC TPC

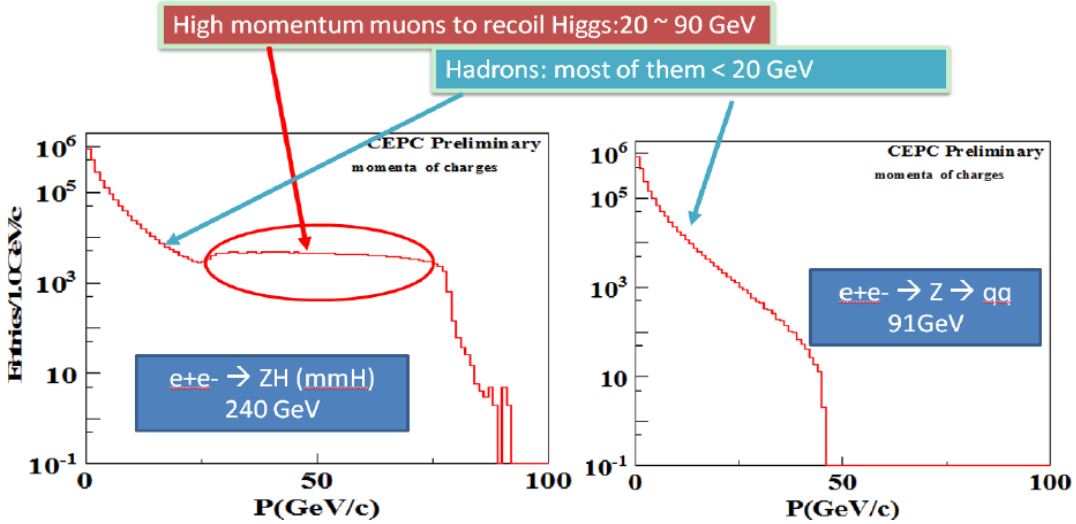


Belle II TPC upgrade plan

TPC requirements for e+e- Higgs/EW/Top factories

- Provide decent #Hits (for track finding) with high spatial resolution compatible with PFA design
- $\sigma_{1/pt}$~10^{-4}GeV/c^{-1}(TPC alone) and σ_{point} <100 μm
- Provide dE/dx and dN/dx with a resolution < 3%
  - Essential for Particle ID
  - Beneficial for Flavor @ Z pole & jet
    - b-tagging (electrons from semi-leptonic b-decays)
    - c-tagging, D meson spectroscopy (kaon/pion separation)





dE/dx Resolution of TPC

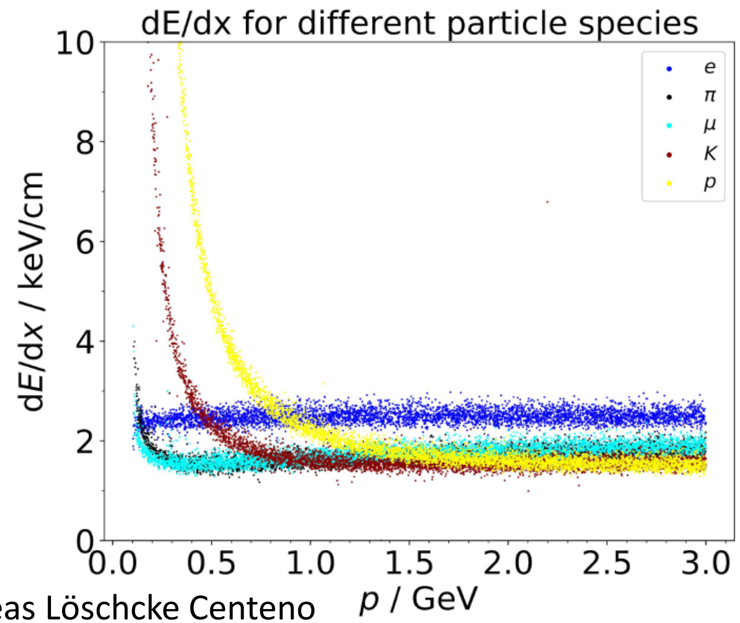
5.4% typical dE/dx resolution for 1m track (fit in 2021)

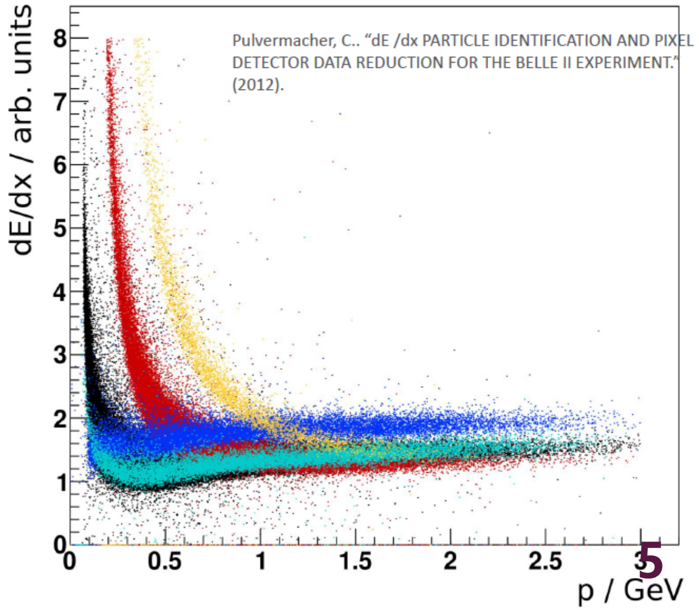
Detector	Acceterator	Size(φ×L)	B (T)	N_Samples	Control sample	Effective detector length (bar*m)	dE/dx
ALEPH	LEP	3.6 m × 4.4 m	1.5	388	e	45.6	4.5%
ALICE	LHC	5 m × 5 m	0.5	159	π	6.0	4.5%
STAR	RHIC	4 m × 4.2 m	0.5	45	π	0.4 – 0.6	8.0%
TOPAZ	TRISTAN	2.4 m × 2.2 m	1	175	π	0.4 - 0.6	4.4%
DELPHI	LEP	2.4 m × 2.7 m	1.2	192	π	0.4 – 0.6	5.7%

An F, et al. Monte Carlo study of particle identification at the CEPC using TPC dE/dx information[J]. The European Physical Journal C, 2018, 78(6): 1-8.
Ligtenberg C, et al. Performance of a GridPix detector based on the Timepix3 chip[J]. NIMA, 2018, 908: 18-23.

dE/dx Performance

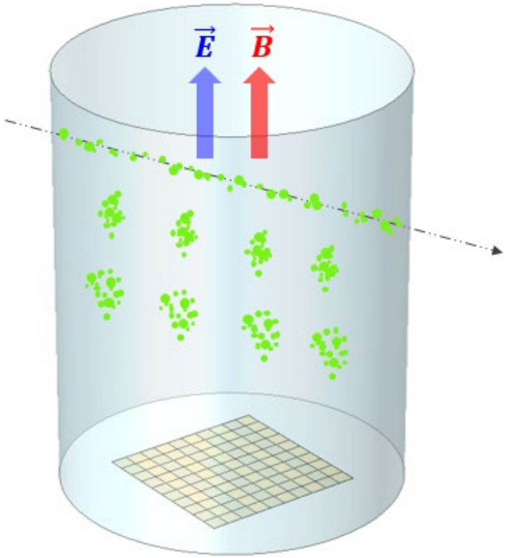
- Separation looks clearer in TPC (first study)→ shows a promising result
- Momentum increases →PID decreases
- For track-finding purposes the number of hits per cm → **d*N*/dx, is of interest**

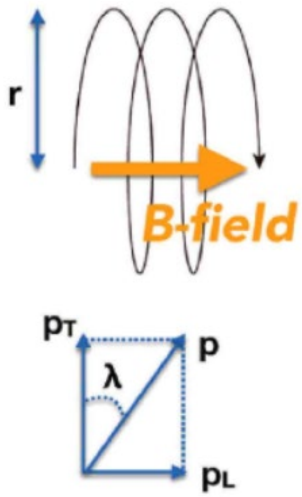


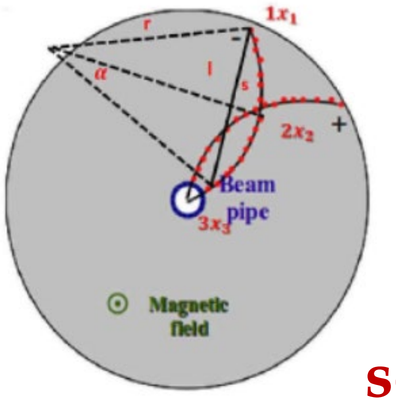


dE/dx & dN/dx

Classical dE/dx Measurement







$$p_T = 0.3\,Br$$

$$p = \sqrt{1 + tan^2\gamma}$$

p + dE/dx → PID

separation power = $\frac{dE/dx(A) - dE/dx(B)}{\sigma(dE/dx)}$

- Classical dE/dx measurement by charge (charge ≈ number of primary + secondary electrons)

  - measure charge per sample along a track
  - get "a mean" charge over the sample = dE/dx
  - the fundamental, central problem of all dE/dx measurements by charge summation

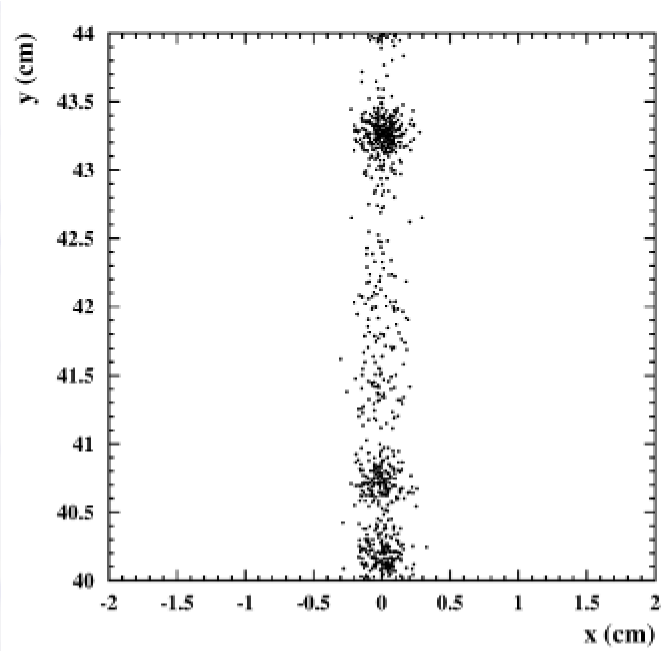
Problem → sensitive to large fluctuations

dN/dx Measurement by Cluster Counting

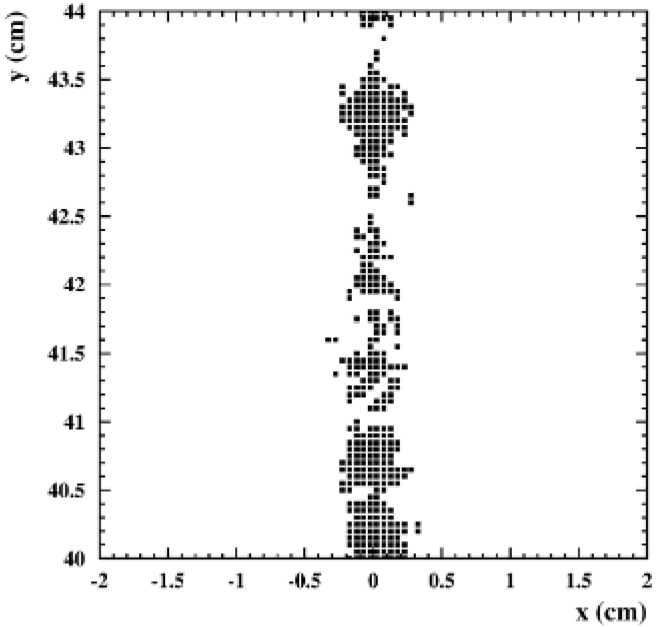
- Direct cluster counting → ultimate way to measure dE/dx
  - avoid any problems with cluster fluctuations
  - no charge measurement need, just counting
  - < 3% dE/dx resolution by cluster counting (statistical error only)
  - 5.4% dE/dx resolution by charge measurement
- Obvious problem
  - How to resolve individual clusters and count them?
    - high cluster density(~30 cl./cm in Ar mixture for m.i.p → typical drift velocities of 50 μm/ns → 6 ~10 ns in between clusters → fast-shaping electronics (~ns needed) In time)
  - Need devices with high time resolution or high granularity to resolve them
    - difficult to achieve
    - need more R&D

Cluster Counting in Space

- **TPC with cluster counting**
  - Cluster Counting so far based on time measurement in small drift cells
  - Pixelated TPC makes space measurement possible
    - GEMs/Micromegas + small pixels have high granularity → resolve clusters in space
    - Time information added → 3D position in space



projection of single electrons on endplate



pad response (0.5 x 0.5 mm^2) above threshold (1500 e^-)

More detail - Michael Hauschild RD51 Workshop on Gaseous Detector Contributions to PID

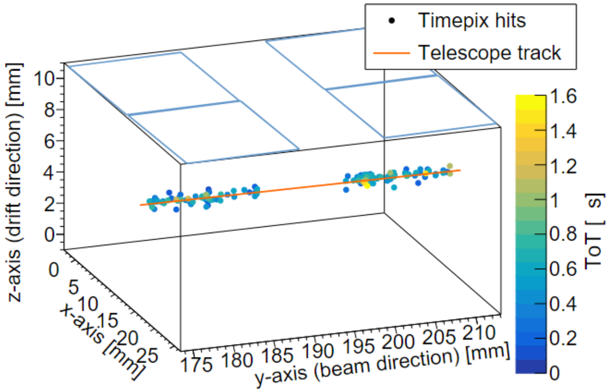
Pixelated readout technology

Why Pixelated readout?

- High granularity readout allows measuring every ionization cluster
- High spatial resolution under 2T or 3T magnetic field
- Better momentum resolution
- High-rate operation (MHz/cm^2)
- Excellent two tracks separation

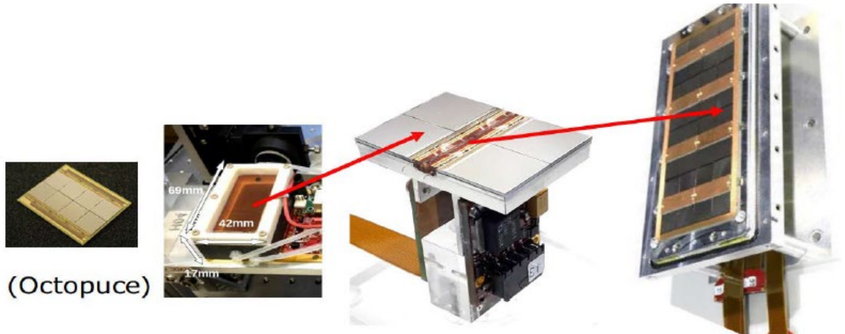
Challenge

- Optimize Pixel Size



Pixelated TPC with GridPixes

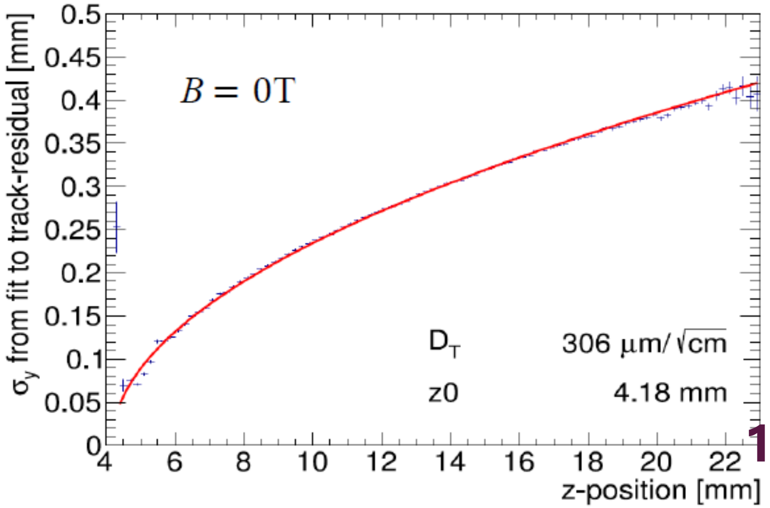
- Tests with single and quad devices have been successfully done.
- ~4.1% dE/dx resolution at B = 1.0T at DESY



(Octopuce)

TimePix1	TPX3 chip	Quad	Module
2007	2017	2018	2019

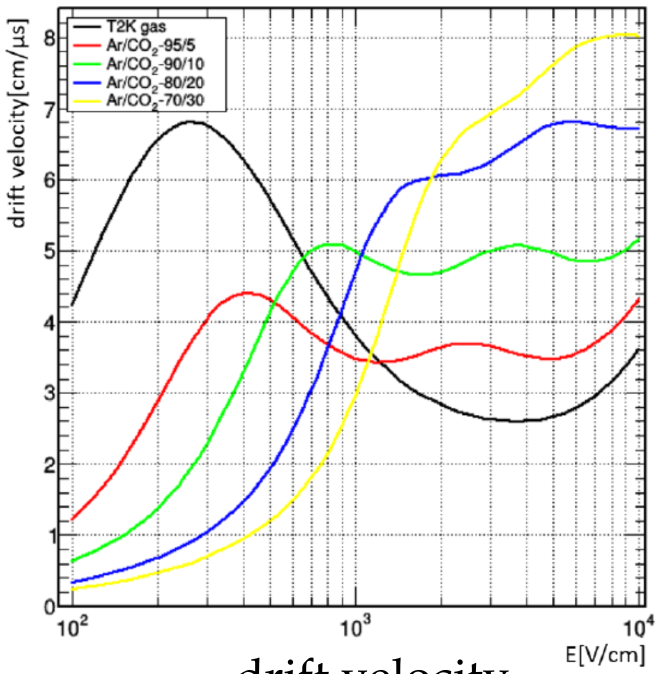
https://arxiv.org/abs/1902.01987



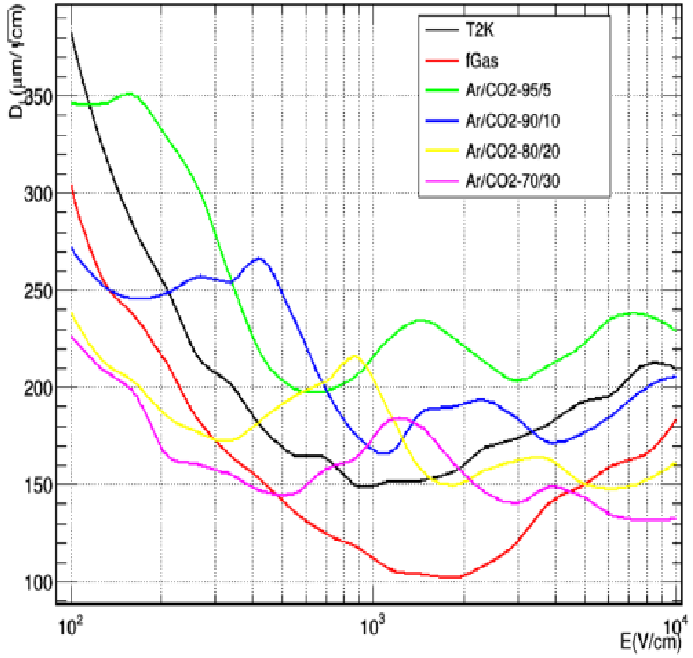
Simulation of pixelated readout

Magboltz Simulation – Working Gas

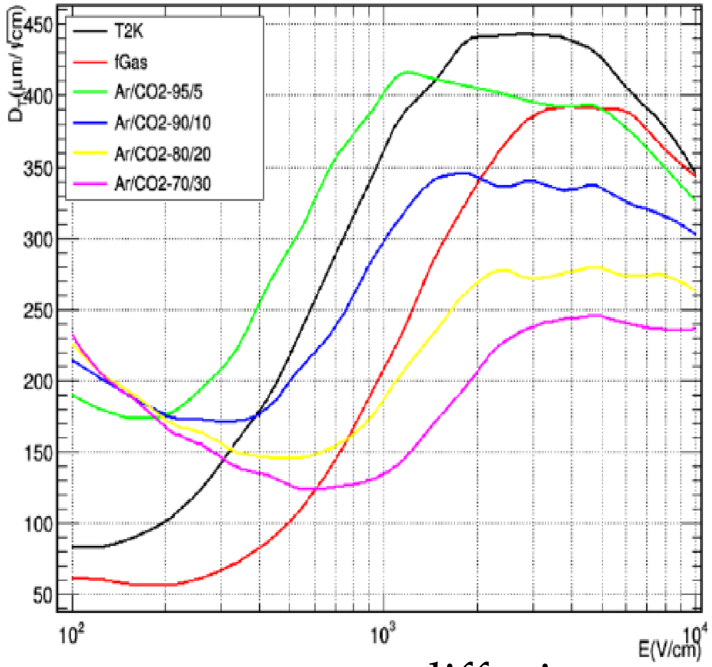
- Magboltz simulation for optimal working point of electrical field for various parameters
  - Gas mixture parameters (drift velocity, attachment, diffusion) → Provide key parameters for pixel size optimization
  - **T2K has a faster drift velocity & smaller longitudinal &transverse diffusion**
  - **T2K gas has stable properties in TPC** (LCTPC, T2K experiment)



drift velocity



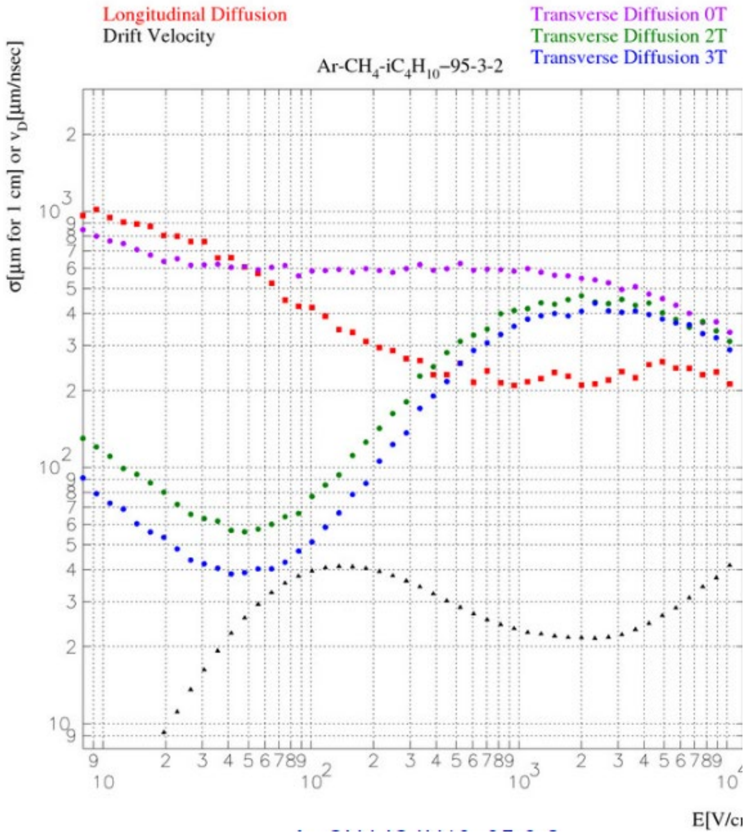
longitudinal diffusion

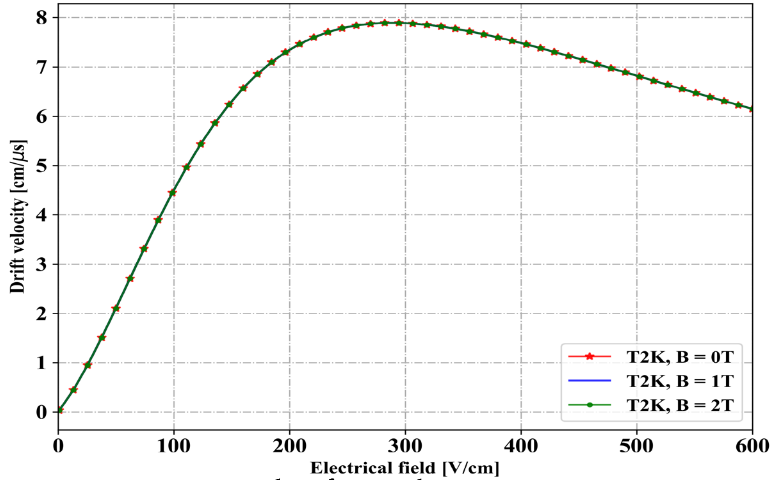


transverse diffusion

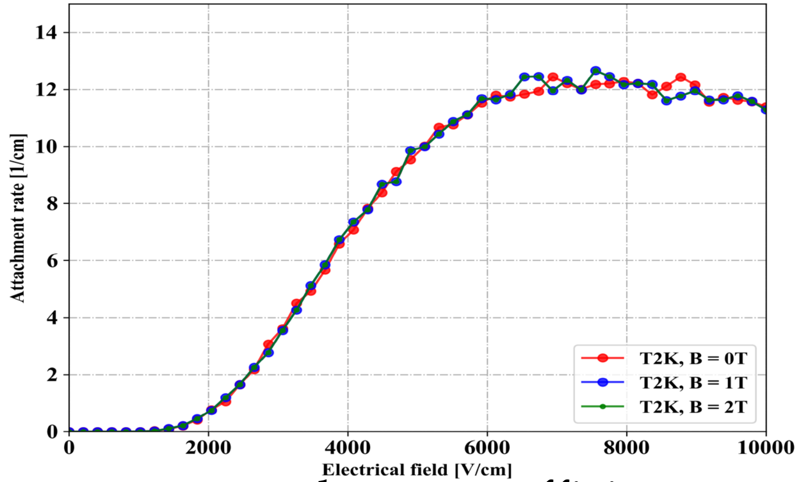
Magboltz Simulation – Magnetic Field

- The transverse diffusion decreases under a higher magnetic field

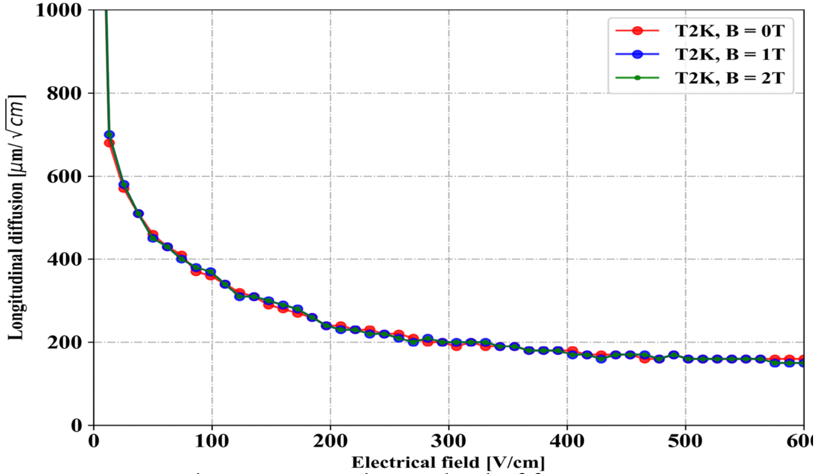




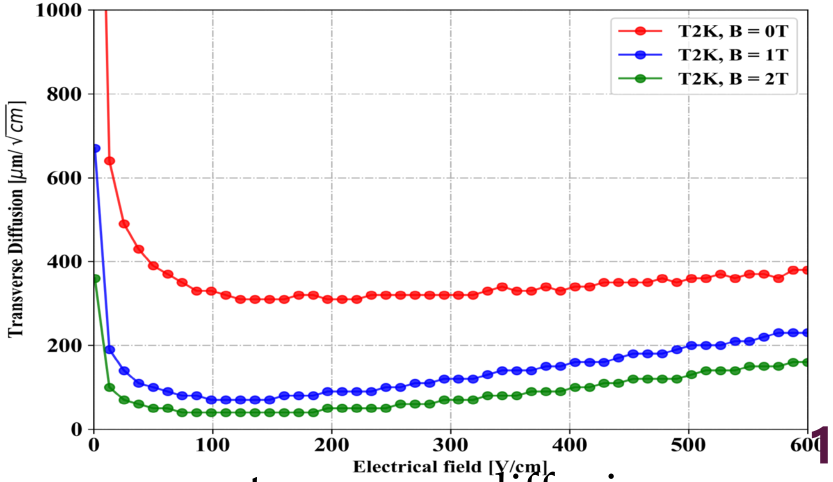
drift velocity



attachment coefficient



longitudinal diffusion



transverse diffusion

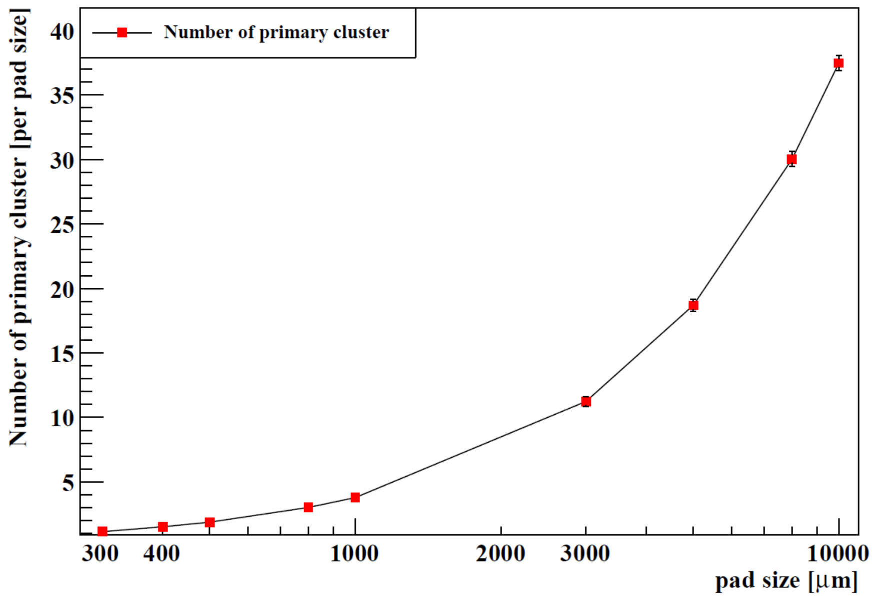
Simulation of the primary cluster

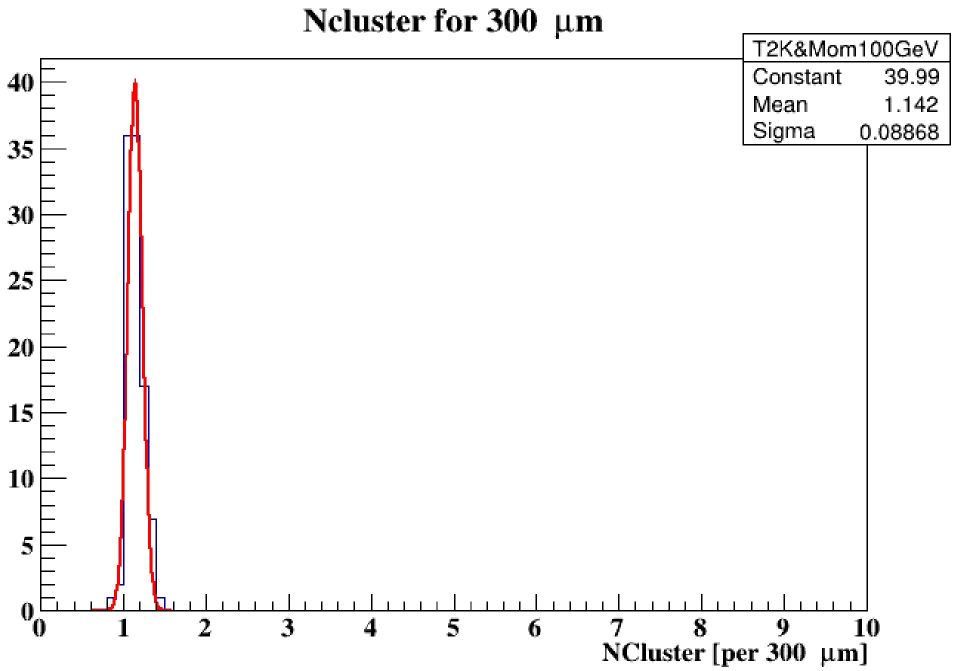
Heed Simulation

- Typically ~30 primary ionization clusters/cm in gas at 1 bar →Verify the validity of the model
- ~1.881 clusters/ 500μm , ~1.142 clusters/ 300μm

More detailed research is needed

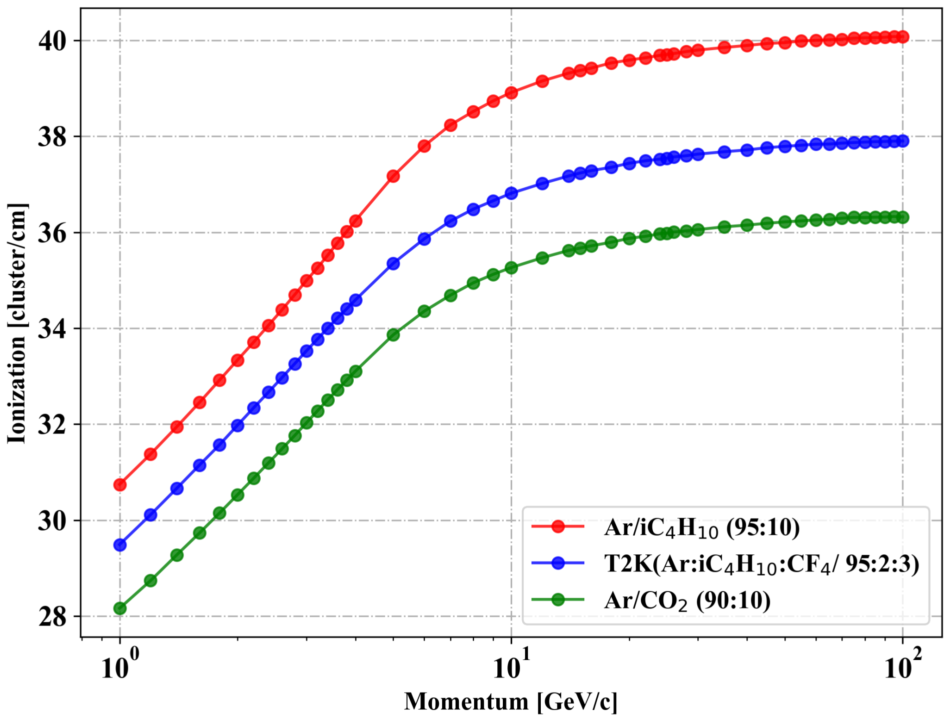
- If pad size is at the level of cluster distances of primary ionization, Cluster counting becomes effective

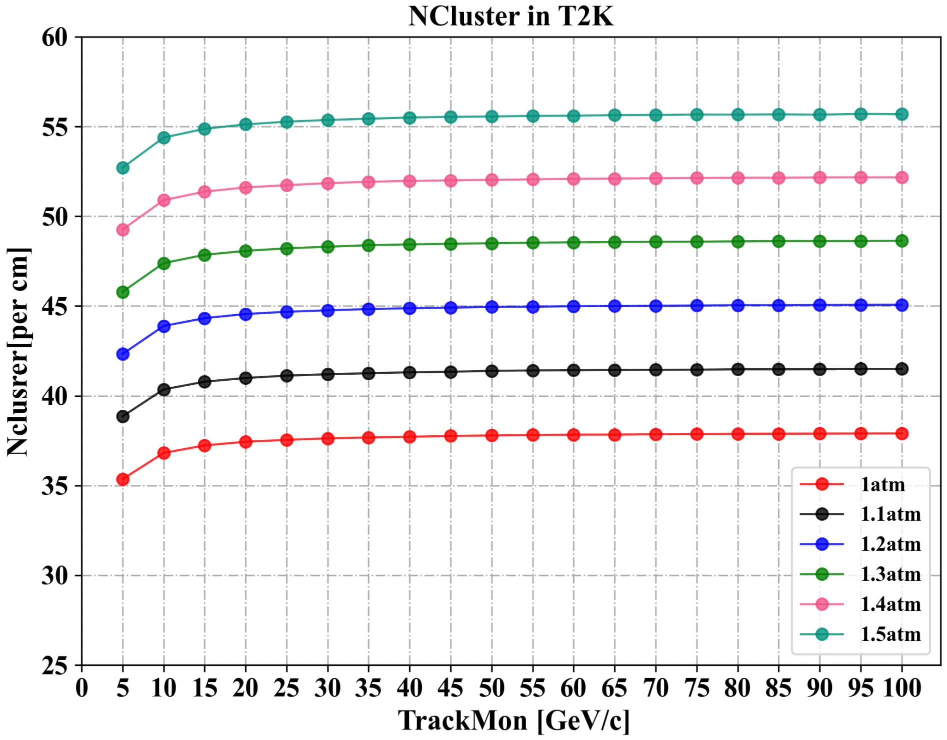




Simulation of the primary cluster

- Simulation Study for 1000 mm tracks in T2K gas with different particles – **different gas & pressure**
  - Need gas with low diffusion & large drift velocity
  - Need gas with good cluster statistic
  - Pixel size → Optimize working gas & pressure



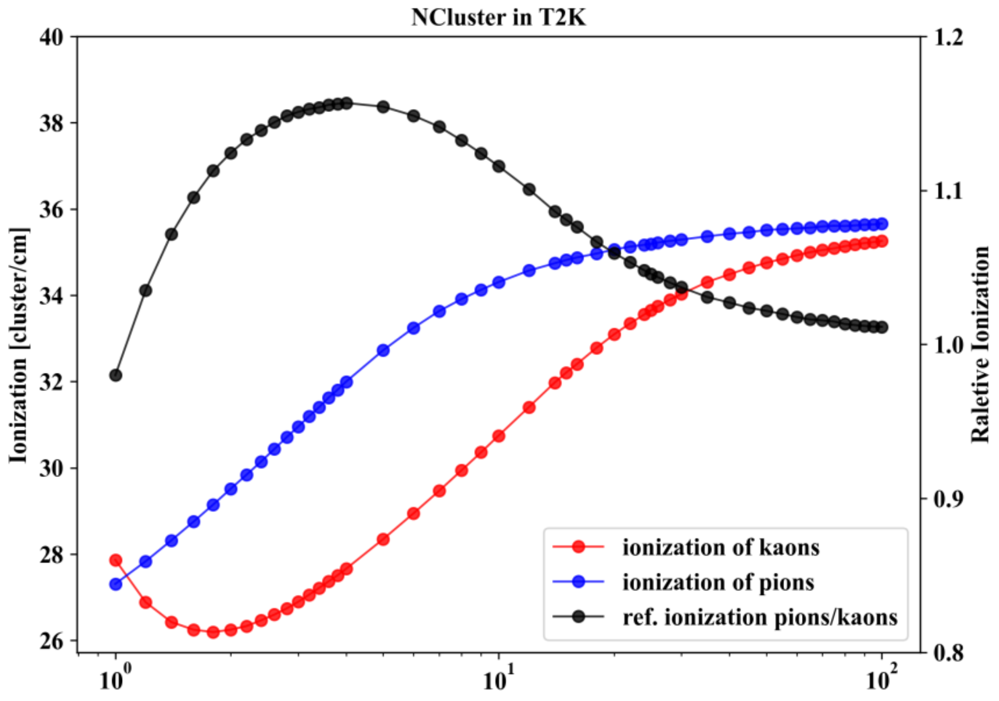


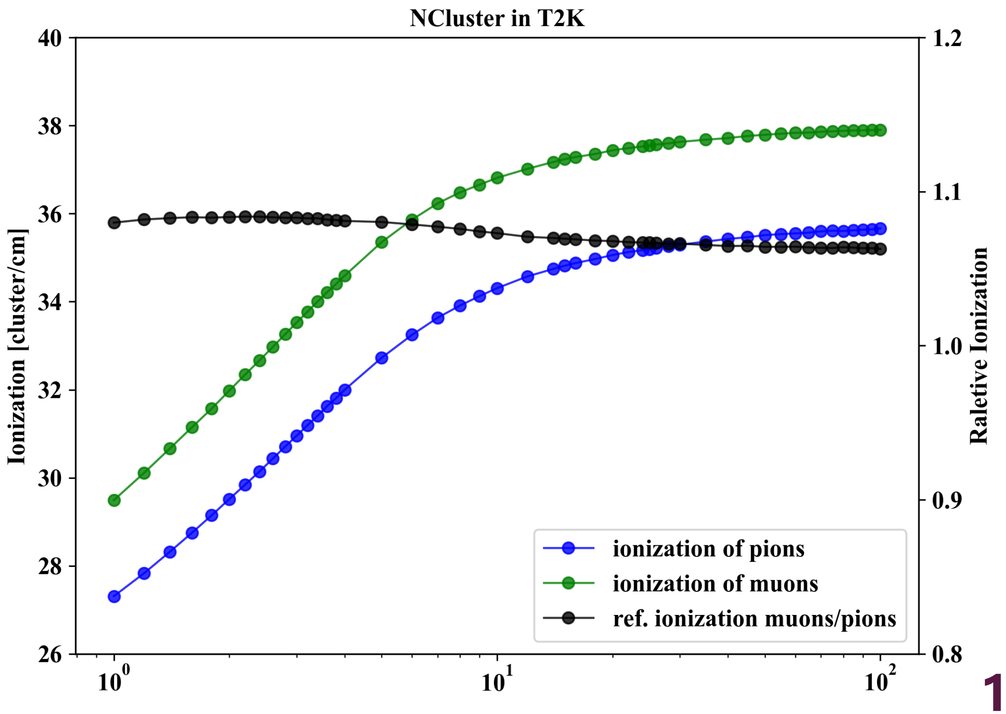
Particle Separation by Cluster Couting

- Simulation Study for 1000 mm tracks in T2K gas with different particles - π/κ/μ
  - The performance of particle separation is proportional to the difference in the average ionization
  - The relative ionization of different particle species depends on the momentum
  - Use always 1000 mm tracks of pions and kaons at maximum ionization difference at about 3 GeV

estimators for the energy loss

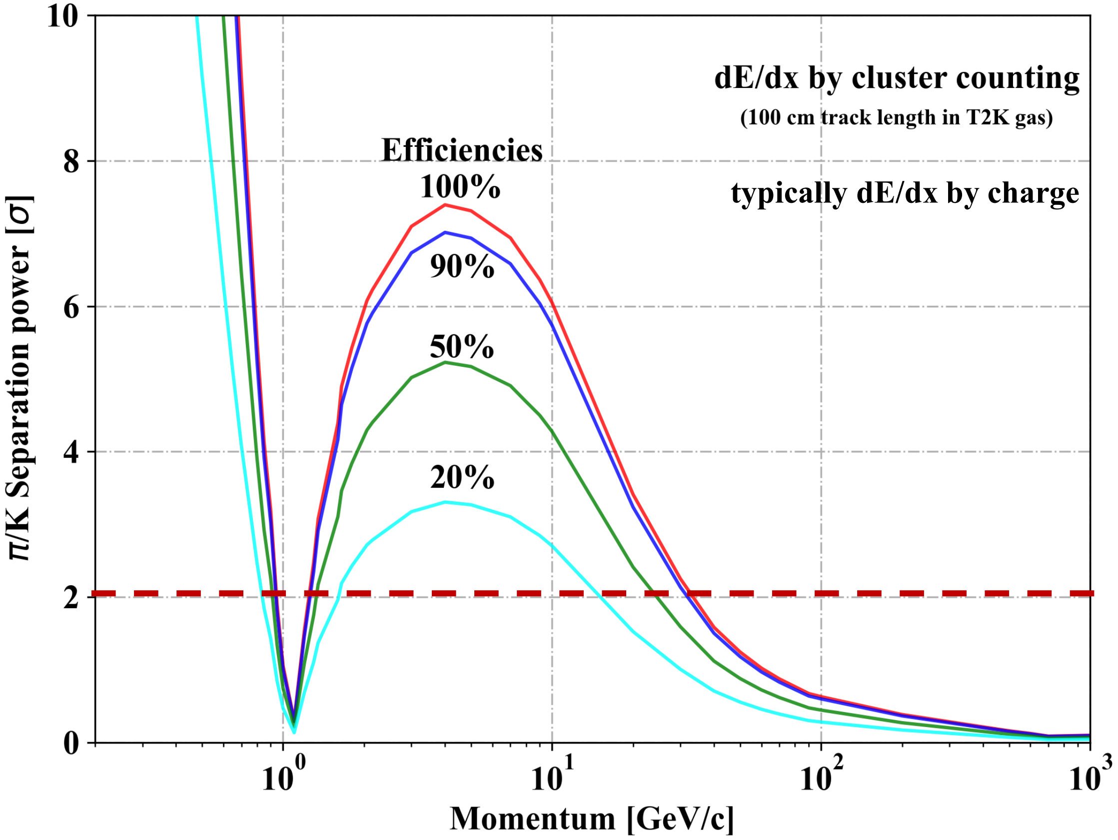
$$S = \frac{|\mu_A - \mu_B|}{\sqrt{\frac{\sigma_A^2 + \sigma_B^2}{2}}}$$

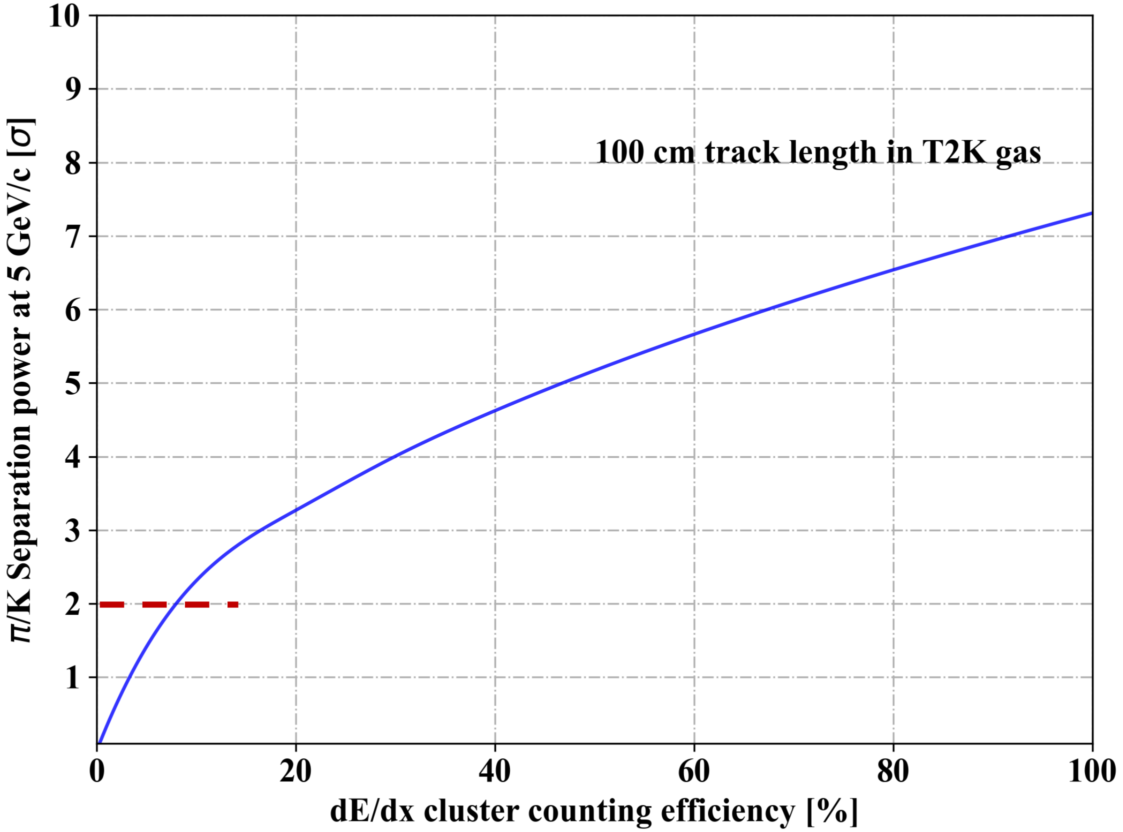




PID Improment by Cluster Counting

- Calculate separation power S to determine PID performance
  - Typical(average) particle separation power: π/k → 2σ up to 8 ~ 20 GeV(max. 2.5 ~ 3.5 σ)
  - Cluster counting efficiency > 25% is sufficient to beat charge measurement
  - The potential of better resolution by at least a factor of 2



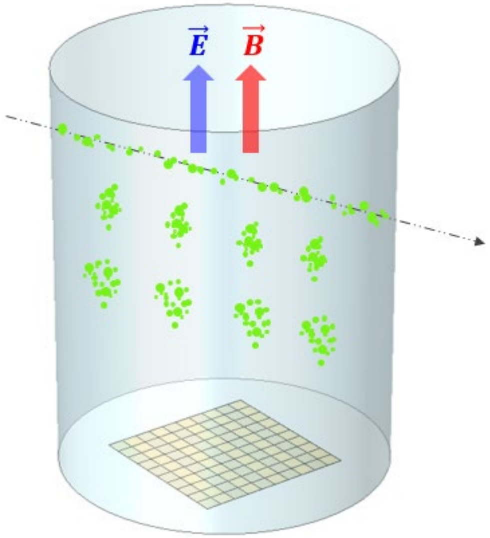


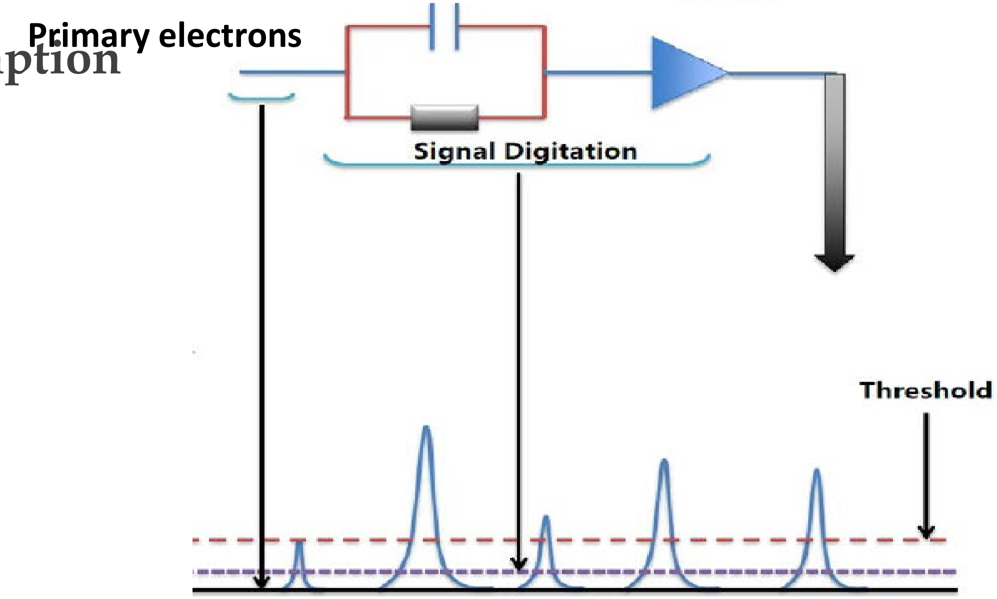
Occupancy

- Occupancy is a very key issue at the high rate or high luminosity
- Smaller pad/pixel size→ smaller occupancy
  - Pad readout (1 mm×6 mm), innermost occupancy 1×10^{-4}
  - Pixelated readout (55 μm ×55 μm), much LOWER innermost occupancy ~ 1×10^{-6}
  - Increase the number of channels & power consumption
- To be addressed by R&D

→ A detailed simulation would be necessary to determine the scaling factor

→ Simulation ongoing at IHEP & LCTPC

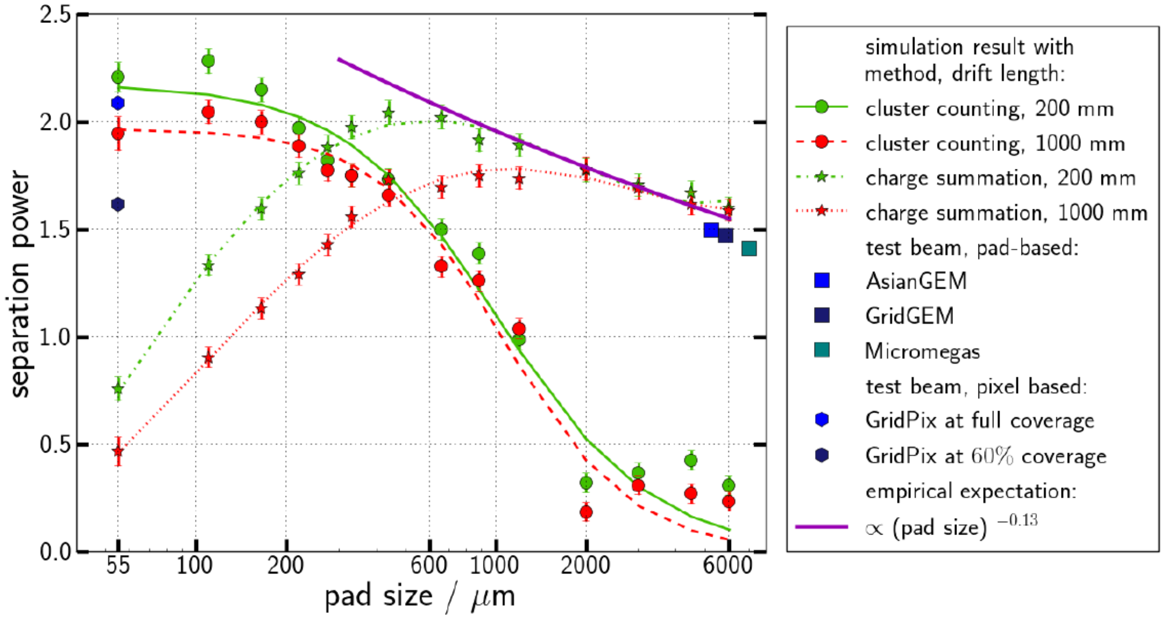




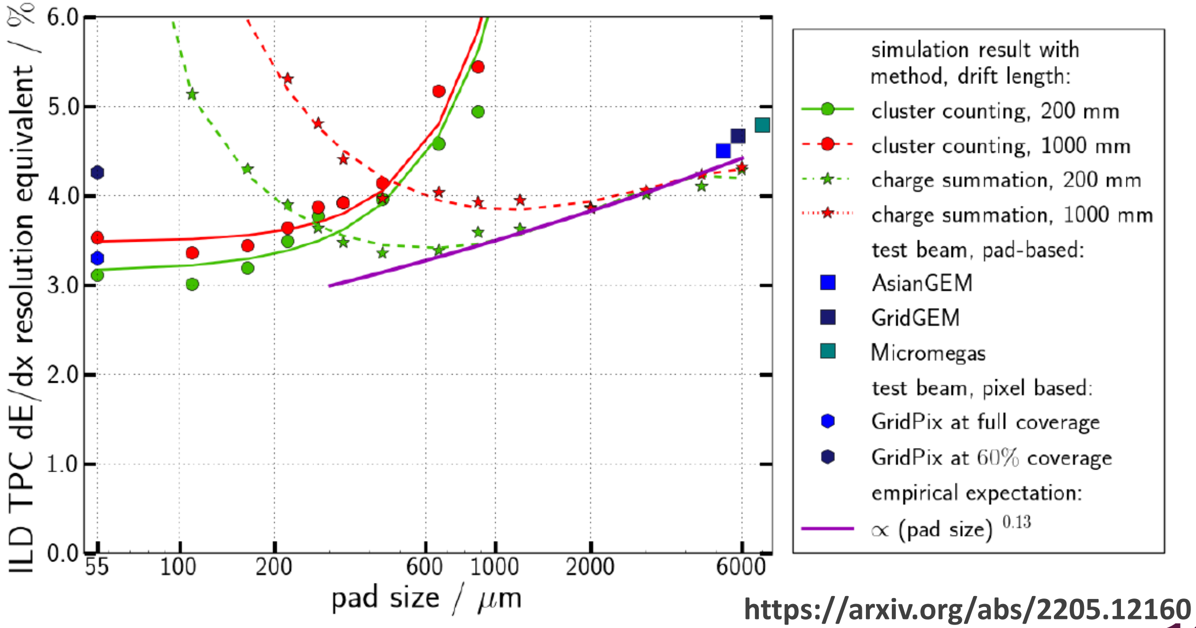
Pixel Size Optimization

dE/dx resolution

- Charge measurement and cluster counting are a function of pad size
- 6mm → 0.1mm : 30% improved resolution via the cluster counting (dN/dx)
- Cluster counting exhibits better pion/kaon separation power
- High readout granularity VS the primary cluster size optimization



pion – kaon separation power



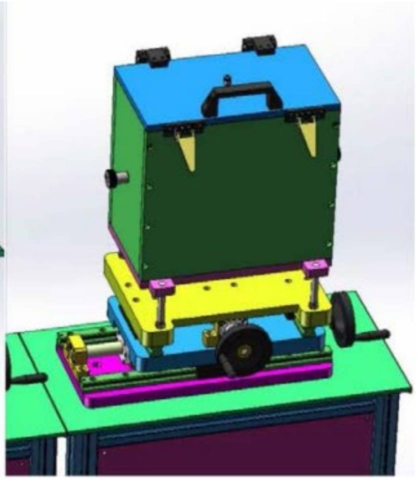
dE/dx resolution

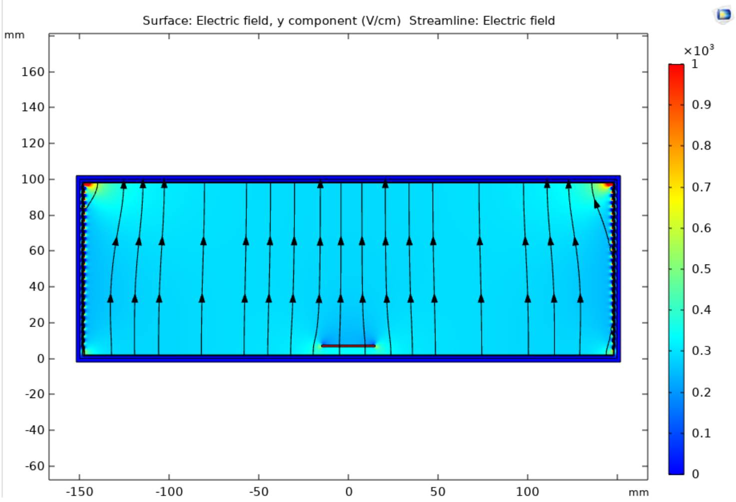
https://arxiv.org/abs/2205.12160

R&D Plan at IHEP

- **Realization of pixelated technology collaborated with Tsinghua**

Bump bond pixelated readout with Micromegas detector	Module size	To be addressed by R&D
• **≥300 μm×300 μm** • Developed the readout chip by Deng Zhi (Tsinghua) • Developed the Micromegas detector sensor at IHEP • Development of the new module and prototype	1-2 cm^2	• Research on pixelated readout technology realization • Optimization of cluster profile and pad size • Study of the ‘dN_{cl}+dx’
	100 cm^2	• Study the distortion using UV laser tracks and UV lamp to create ions disk • In-situ calibration with UV Laser system • Study of the ‘$dE/dx+dN_{cl}/dx$’





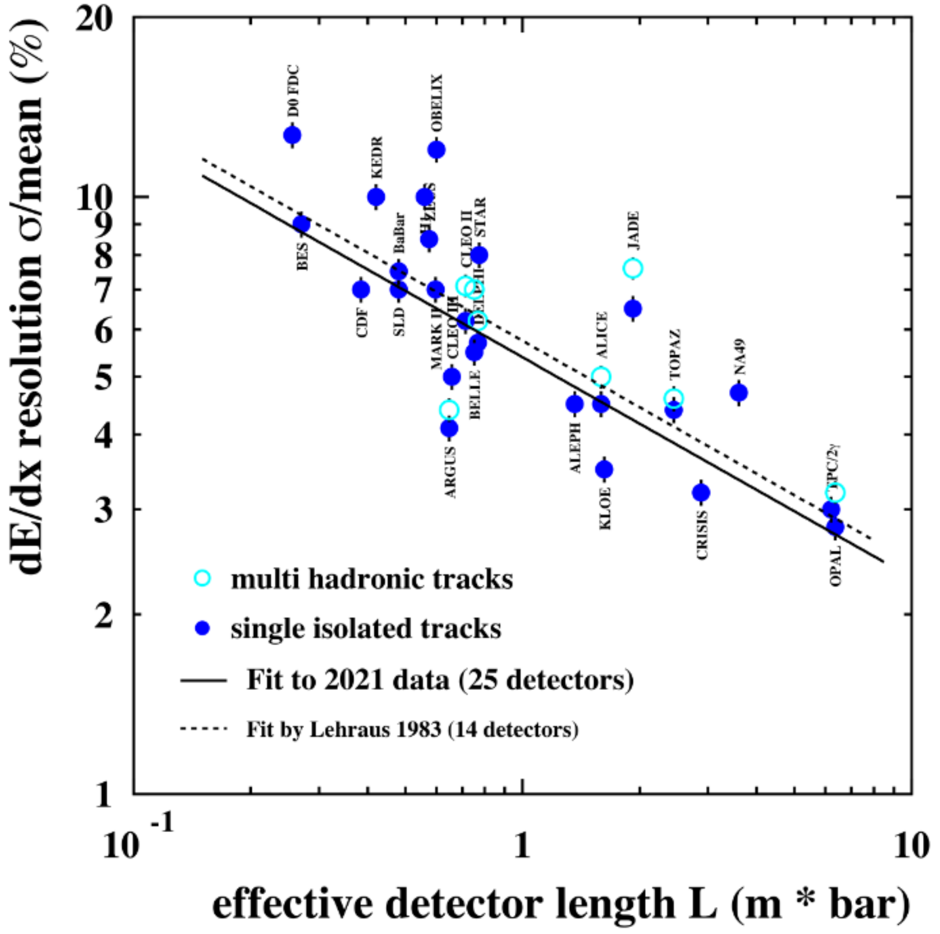
Summary

- Classical PID with dE/dx by TPC charge measurement contributes to many large detectors
  - 5.4% typical dE/dx resolution for 1m track → no miracles to be expected
- Cluster Counting promises better dE/dx resolution (< 3%)
  - The potential of better resolution by at least a factor of 2
  - Cluster counting efficiency > 25% is sufficient to beat charge measurement
- The pixelated readout is an efficient way to count every cluster in space
  - Many simulations are still necessary to understand the detailed requirements of the pixelated detector(e.g. number of ADC bits, pixel readout sizes, occupancy, ion backflow, etc.)
  - new ideas are also welcome

THANKS!

PID from TPC dE/dx information

- TPC provide dE/dx information → significant for PID



effective detector length L = track length * pressure

- Fit by Lehraus 1983 : dE/dx res. = $5.7 * L^{-0.37}$ (%)
- Fit in 2021 (25 large detectors) : dE/dx res. = $5.4 * L^{-0.37}$ (%)
- 5.4% typical dE/dx resolution for 1m track

What's the next?

dE/dx Measurement by Cluster Counting

- **Count number of clusters along track**
  - Cluster density should be proportional to dE/dx
- **Obvious problem**
  - How to resolve individual clusters and count them?
    - high cluster density(~30 cl./cm in Ar mixture for m.i.p → typical drift velocities of 50 μm/ns → 6 ~10 ns in between clusters → fast-shaping electronics (~ns needed) In time)
  - Need device with high time resolution or high granularity to resolve them
    - difficult to achieve
- **Direct cluster counting → ultimate way to measure dE/dx**
  - avoid any problems with cluster fluctuations
  - no charge measurement need, just couting
  - 1.8% dE/dx resolution by cluster counting (statistical error only)
  - 5.4% dE/dx resolution by charge measurement

How to achieve cluster counting?