Progress on cluster counting

Guang Zhao, Shuiting Xin, Mingyi Dong, Siman Liu, Linghui Wu, Shengsen Sun

zhaog@ihep.ac.cn

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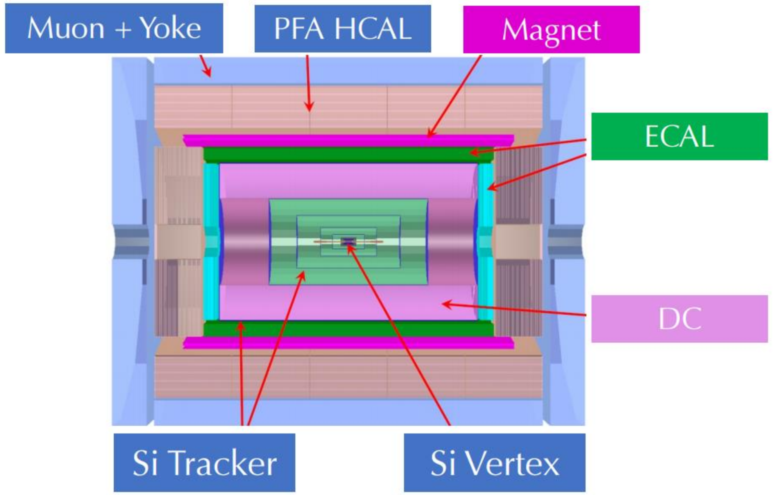
Outline

- **Introduction**
- **Updates in simulation**
  - Peak finding algorithm
  - Gas mixture study
- **Status of experiment**
  - Prototype experiment at IHEP
  - Beam test data analysis
- **Summary**

Introduction

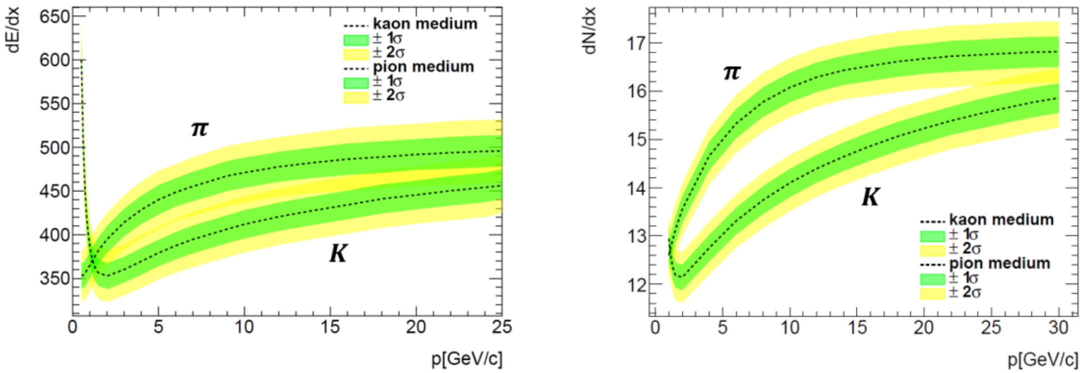
- **Particle ID with a drift chamber is a key feature for the 4th conceptual detector**
- **Ionization measurement using the cluster counting technique (dN/dx) can benefit from small fluctuations**
- **Need detailed simulation for the feasibility and performance study**
- **Input from experiment is essential**

4th Conceptual Detector

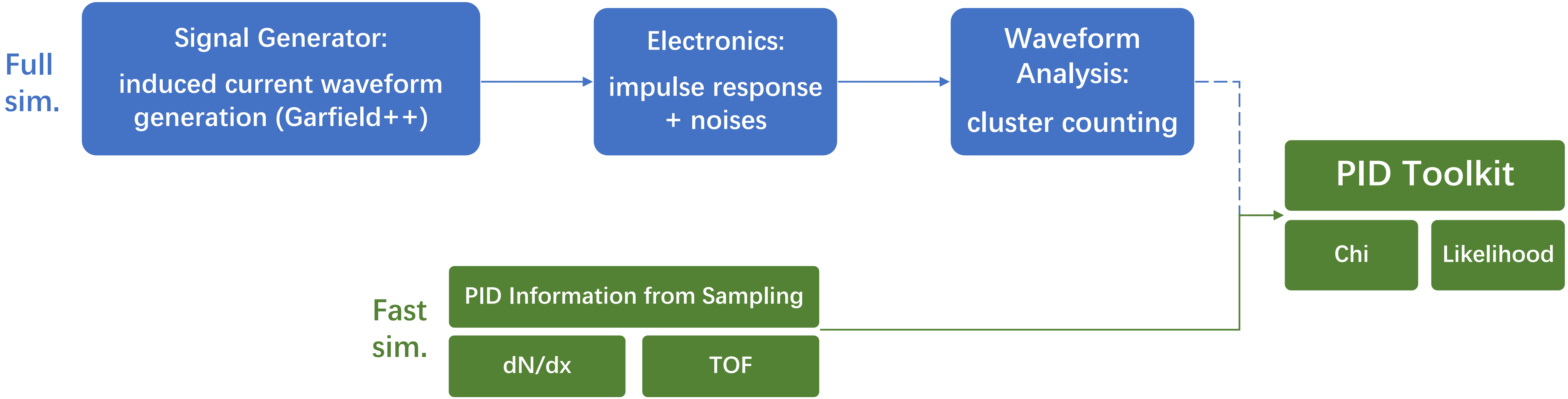


MC truth

dE/dx　　dN/dx



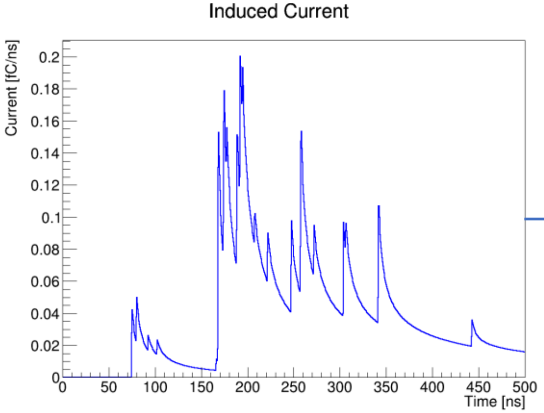
The simulation workflow



A framework of dN/dx simulation is ready

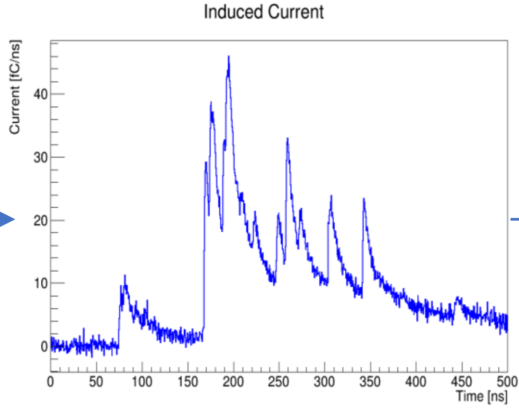
Full simulation

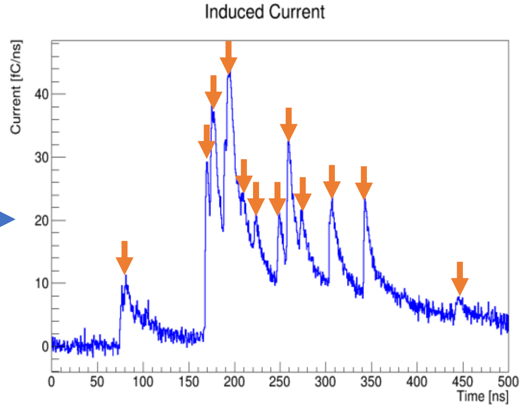
Induced current



Electronics

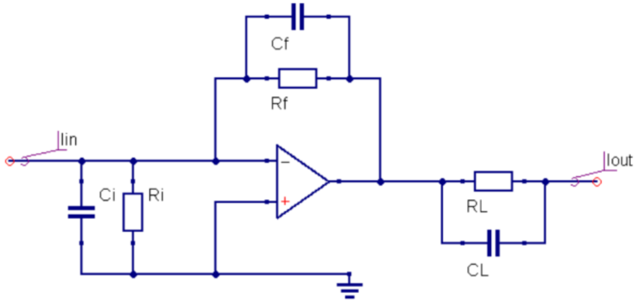
Realistic waveform





Signal generator (Garfield++):
- Heed: ionization process
- Magboltz: gas properties (drift/diffusion)

Electronics:
- Preamplifier
- Noises
- ADC



Peak finding algorithm:
- Low pass filter (smoothing)
- Second derivative (peak detection)

Peak finding algorithm

- **Requirement: fast and efficient**
  - Fast: Data size of waveform is huge. Fast online algorithm at the front-end is recommended
  - Efficient: Good ability to recover pile-up. High pulse detection efficiency

- **Peak finding using derivatives**
  - Insensitive to the baseline
  - Good ability for pile-up recovery
  - Fast
  - Easy to implement in hardware

Peak finding algorithm (II)

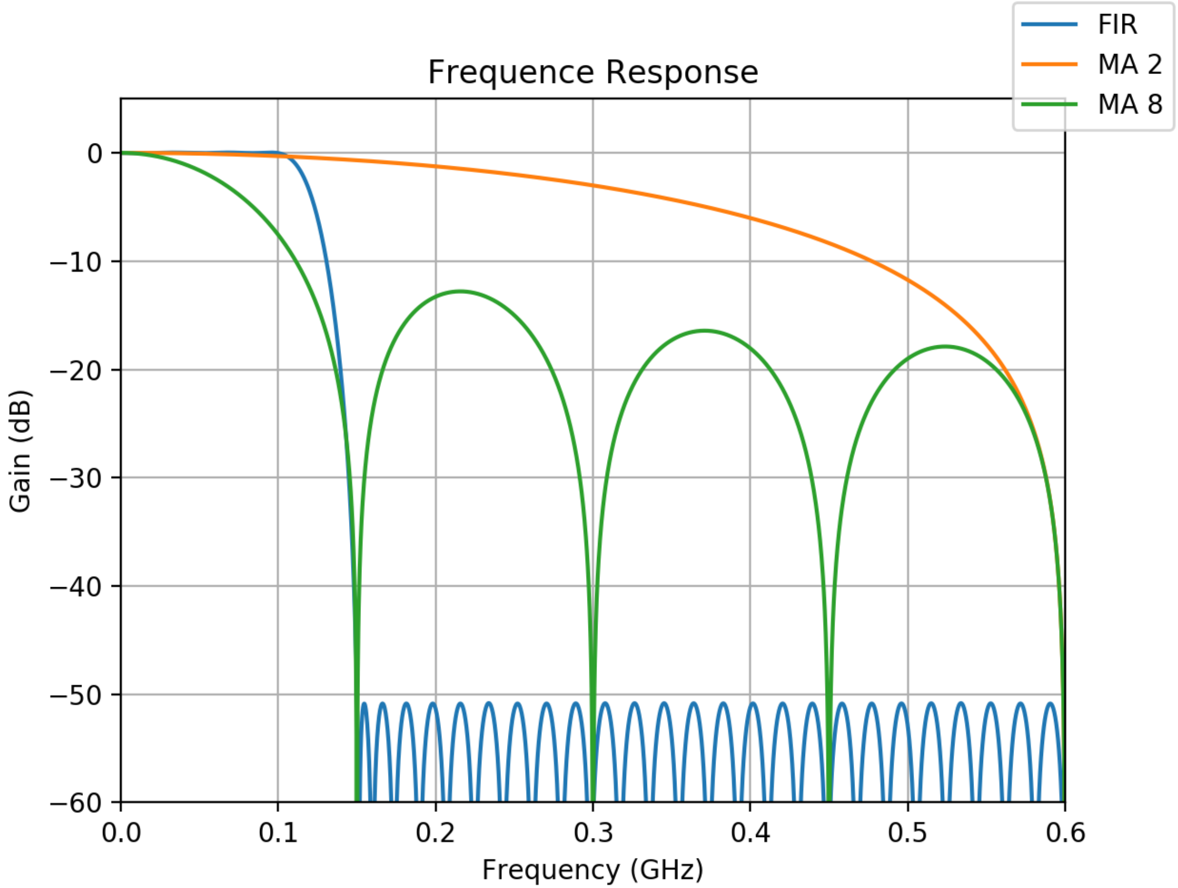
- **Low pass filter (smoothing)**
  - Filter out high frequency noises in the waveforms in order to improve the S/N ratio
  - Finite impulse response (FIR) filter: FIR[i] = a0*x[n] + a1*x[n-1] + ⋯

- **Derivative (peak detection)**
  - First derivative
    - First derivative (**D1**): D1[i] = FIR[i] – FIR[i – **G**]
    - Positive D1: D1' = H(D1) * D1 (H is heaviside function) (Falling-edge cancelling)

  - Second derivative and detection: recover pile-up peaks on the rising edge
    - Second derivative (**D2**): D2[i] = D1'[i] – D1'[i – **G**]
    - Integration on the positive D2: INT(D2')
    - Hit detection: Passing a threshold **T**

The cutoff frequencies, derivative steps and thresholds are optimized

Smoothing



- Moving average: Poor frequency response
- Optimal filter with Remez exchange algorithm
  - Fast roll-off
  - Good stopband attenuation

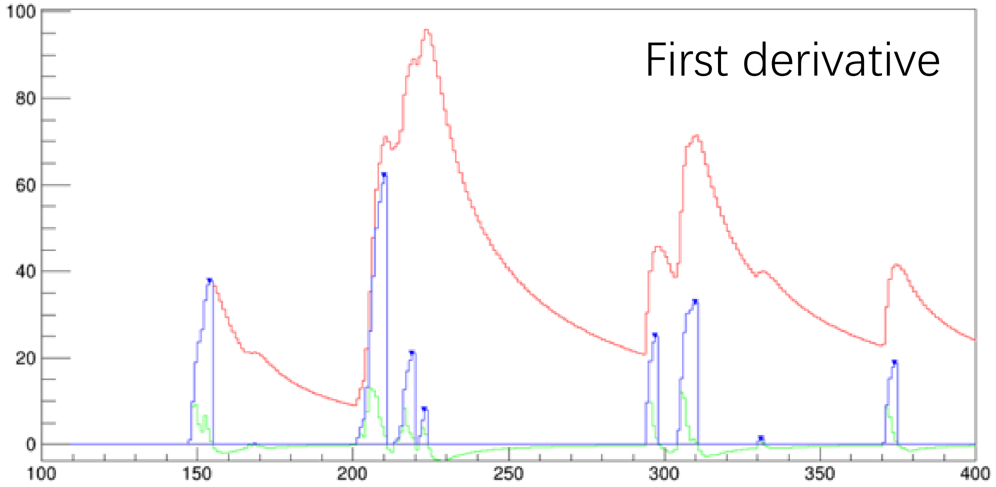
References

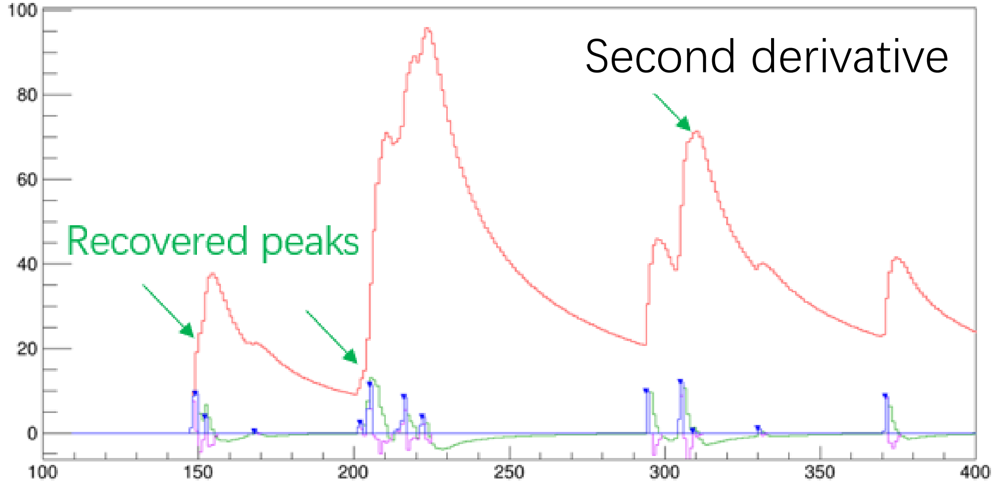
1 J. H. McClellan and T. W. Parks, "A unified approach to the design of optimum FIR linear phase digital filters", IEEE Trans. Circuit Theory, vol. CT-20, pp. 697-701, 1973.

2 J. H. McClellan, T. W. Parks and L. R. Rabiner, "A Computer Program for Designing Optimum FIR Linear Phase Digital Filters", IEEE Trans. Audio Electroacoust., vol. AU-21, pp. 506-525, 1973.

Derivative

- **Use second derivative instead of first derivative (rising-edge pile-ups recovery)**

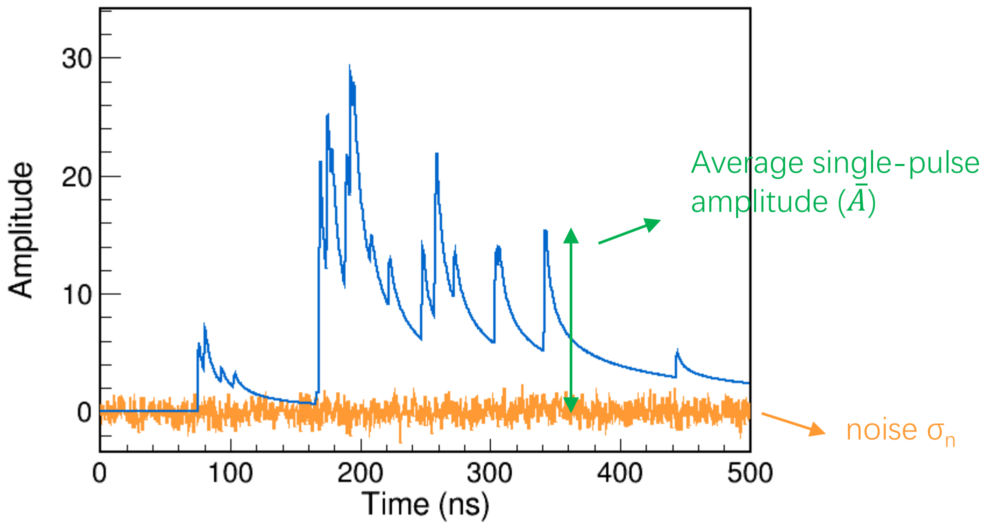




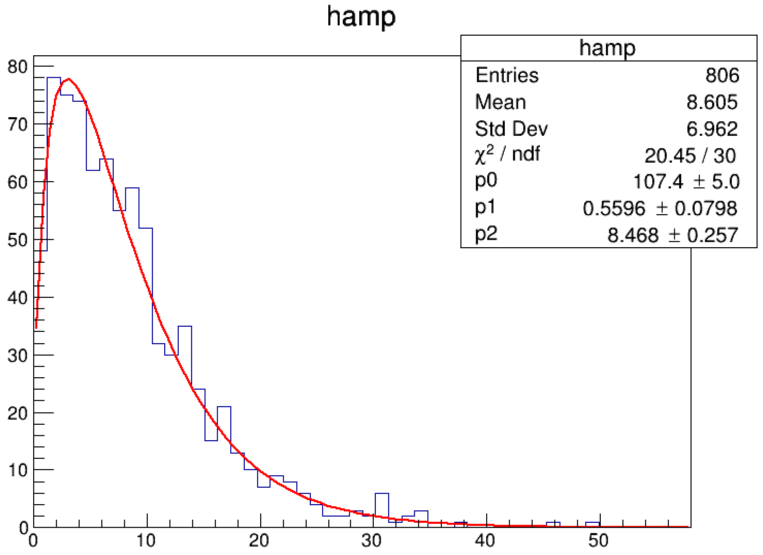
Pile-up on the falling edge is easier to recover. However, it is not the case for pile-up on the rising edge.

Noise definition

- **Noise amplitude related to single-pulse amplitude**
  - Noise level definition: $\frac{\sigma_{Noise}}{\bar{A}_{signal}}$



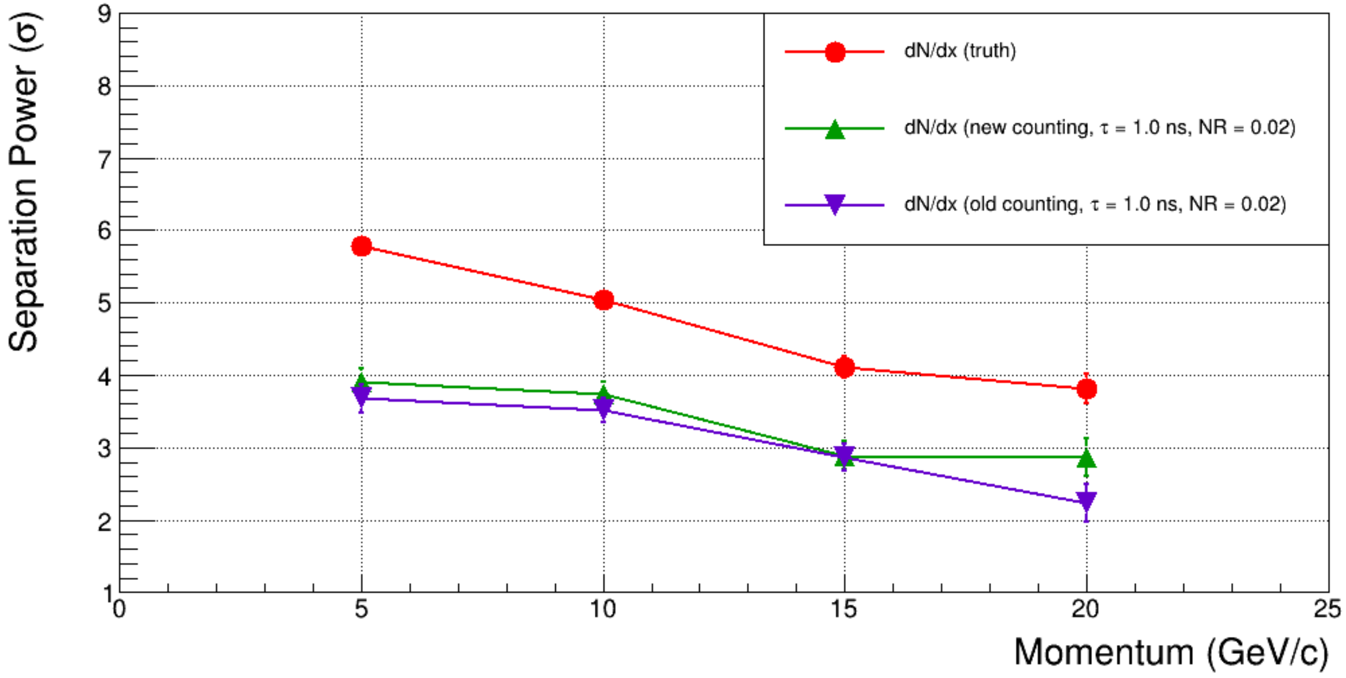
Fit to single-pulse amplitudes with a Polya function



More reasonable noise definition. Noise level is only dependent on the single-pulse amplitudes

K/pi separation power with the updated algorithm

He 90% + iC_4H_{10} 10%, DC size = 1m

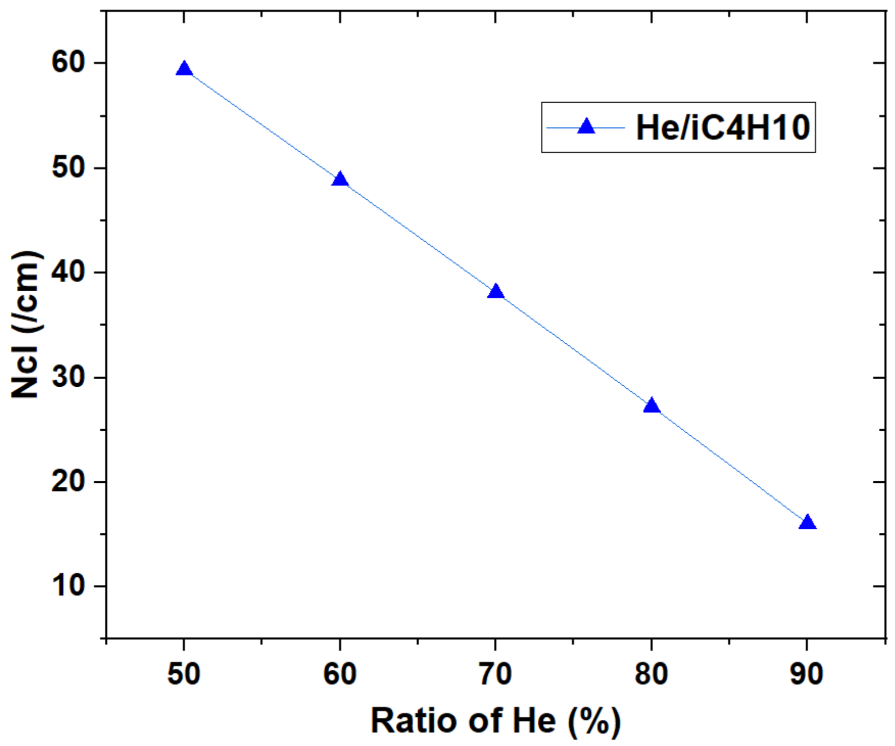


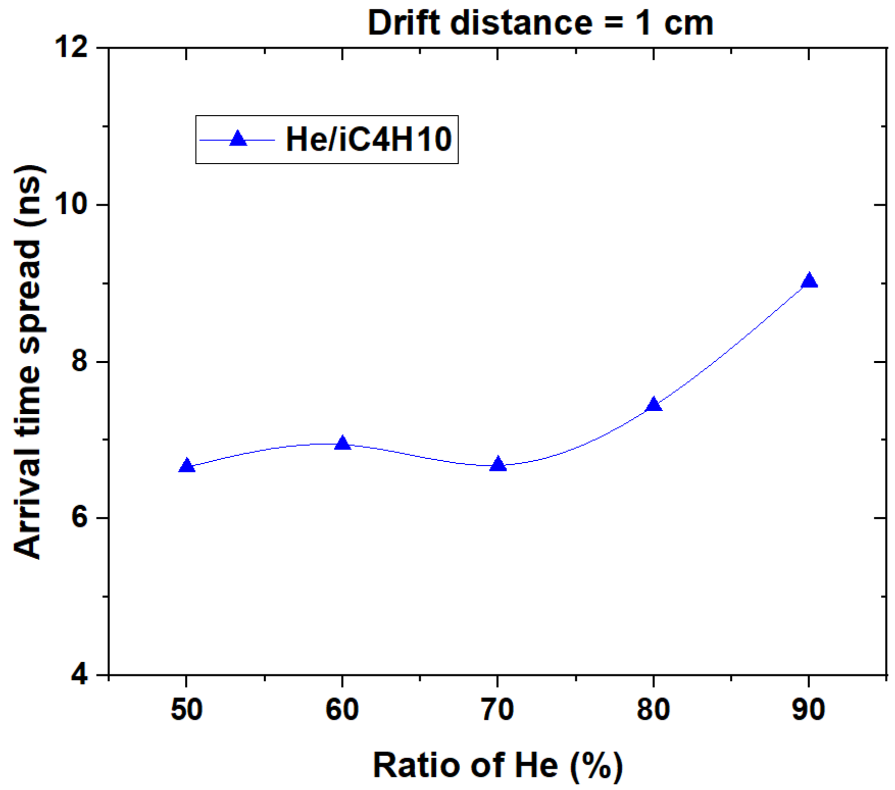
Separation power

$$\frac{\left|\left(\frac{dN}{dx}\right)_\pi - \left(\frac{dN}{dx}\right)_K\right|}{(\sigma_\pi + \sigma_K)/2}$$

Better separation power for the updated algorithm with tuned parameters

Properties of gas mixtures

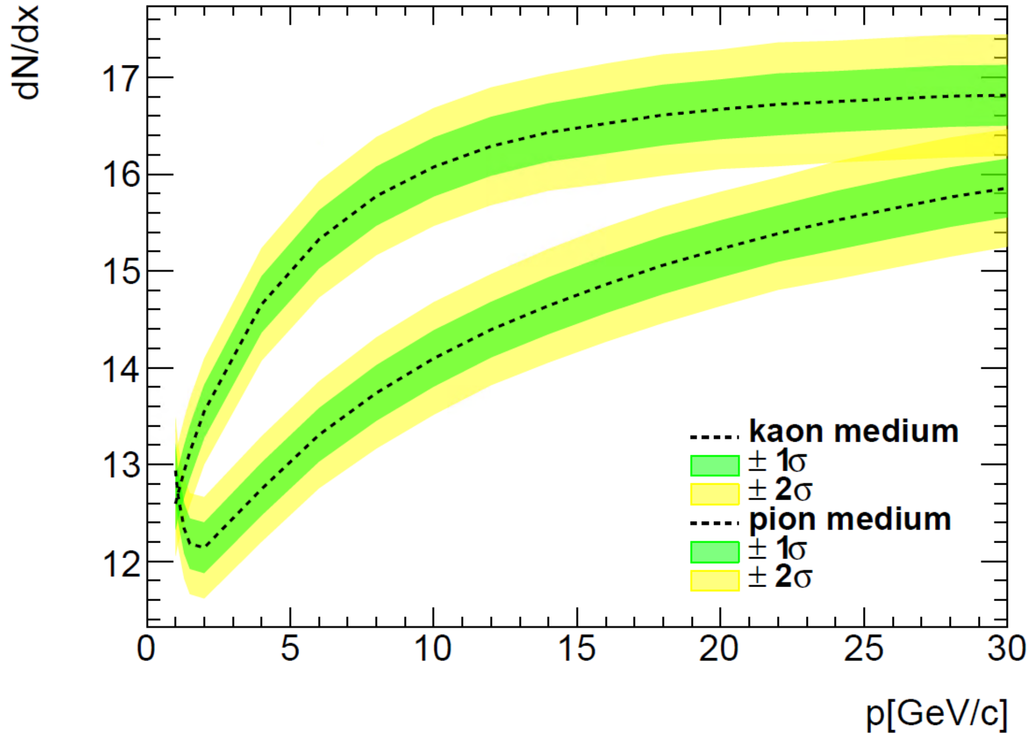




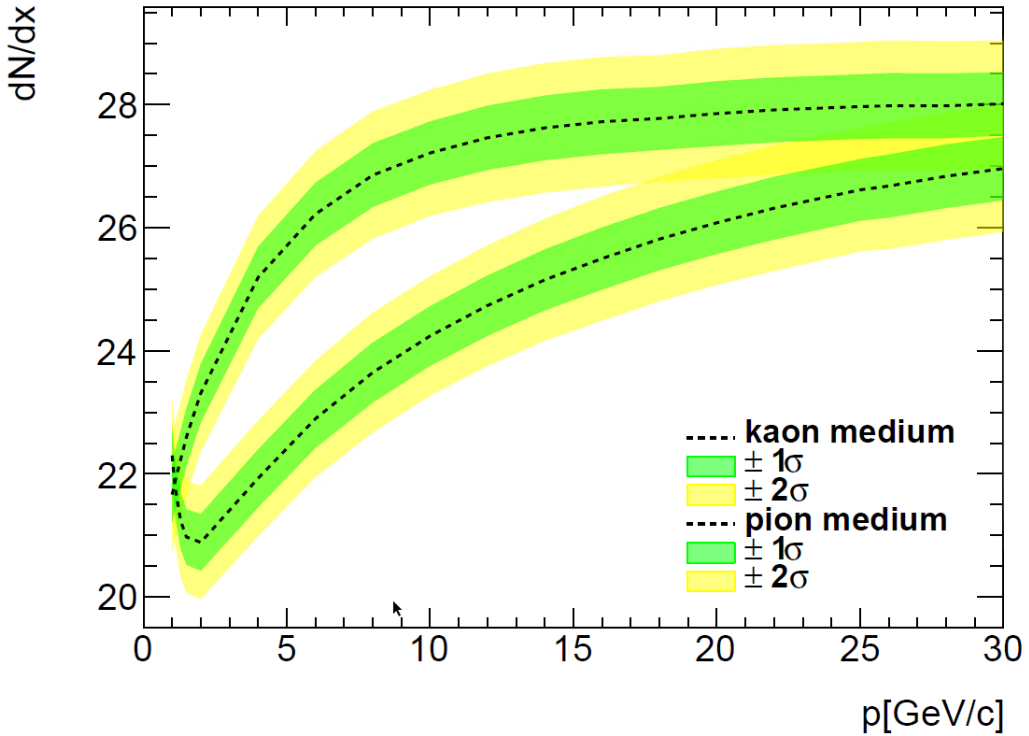
He80: Larger cluster density (more statistics, more pile-ups)
He90: Larger longitudinal diffusion (more pollution from the secondaries)

dN/dx from MC truth

He 90% + iC_4H_{10} 10%



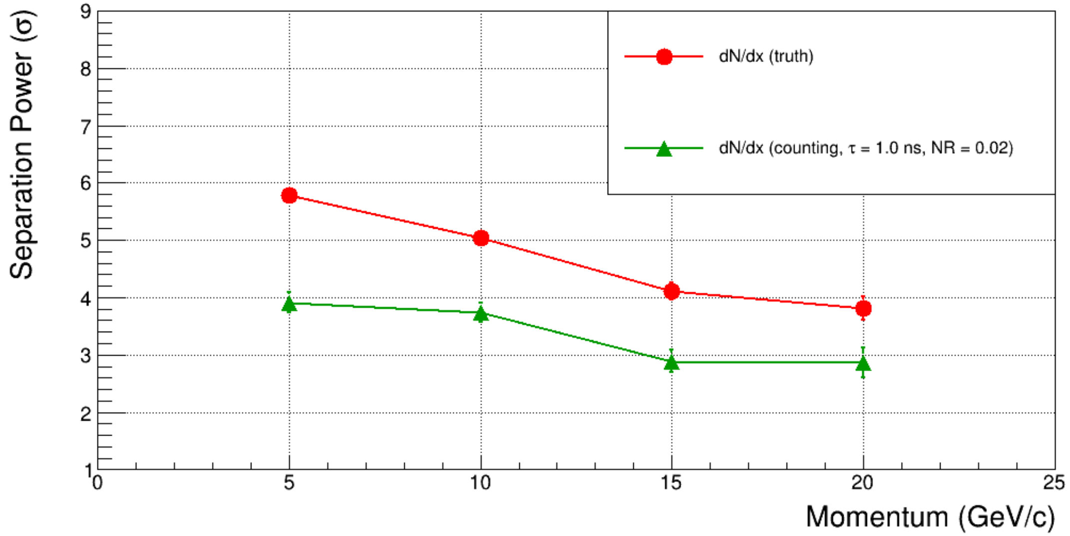
He 80% + iC_4H_{10} 20%



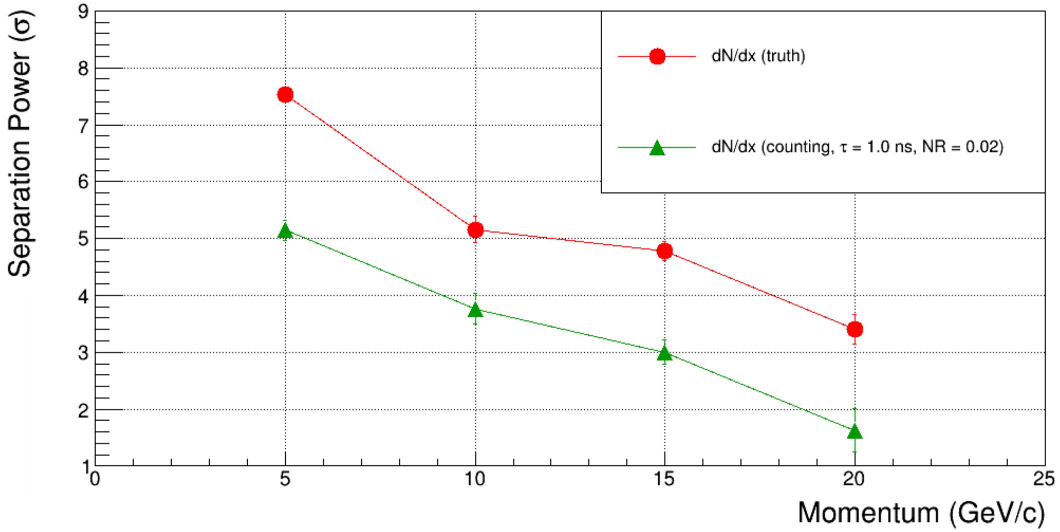
He 90% + iC_4H_{10} 10% mixture has better K/pi separation for high momentum

K/pi separation power for gas mixtures

He 90% + iC_4H_{10} 10%, DC size = 1m



He 80% + iC_4H_{10} 20%, DC size = 1m



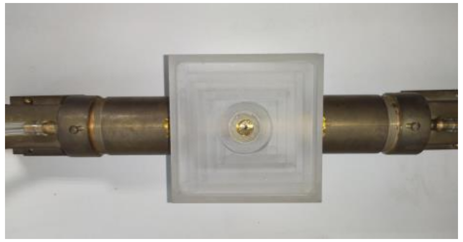
He 80% + iC_4H_{10} 20% has better K/pi separation for low momentum, but worse for high momentum

Prototype test with different gas mixtures

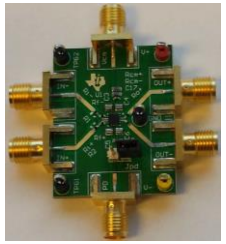
- **Test primary ionization signals with different gas ratios**
  - He/iC_4H_{10} = 90/10
  - He/iC_4H_{10} = 80/20
  - He/iC_4H_{10} = 70/30
- **High He ratio (@ the same HV) means high gas gain and high SNR, which is good for cluster counting**
- **Low He ratio requires preamplifiers with high gain bandwidth product (GBP)**

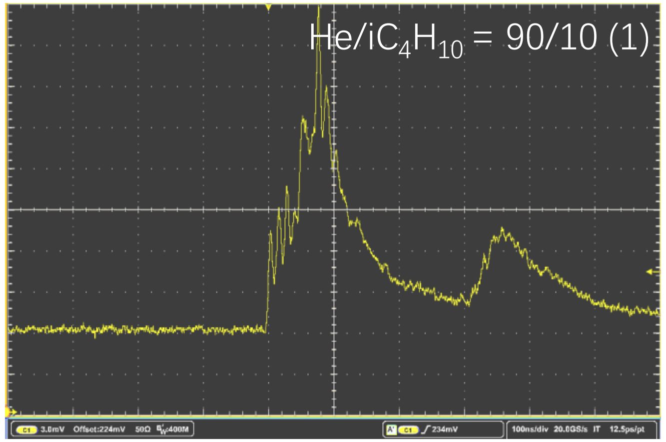
Prototype test @ IHEP

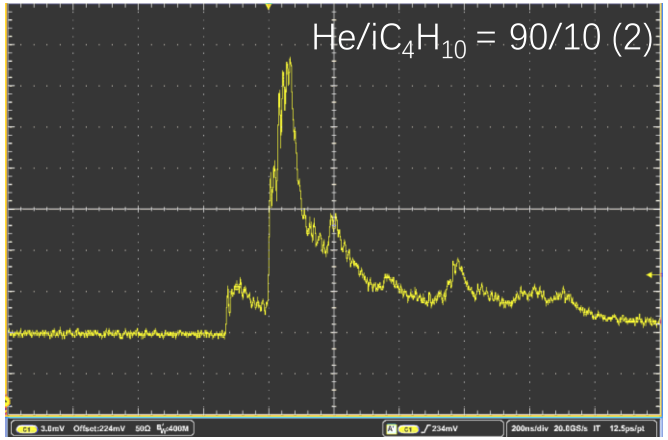
Proportional tube (φ=32mm)

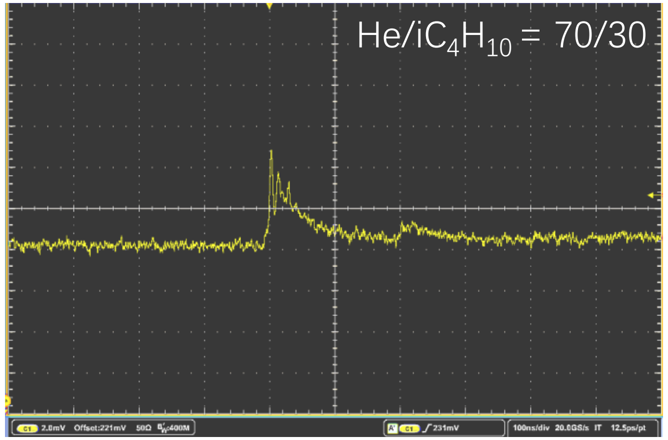


Preamplifier



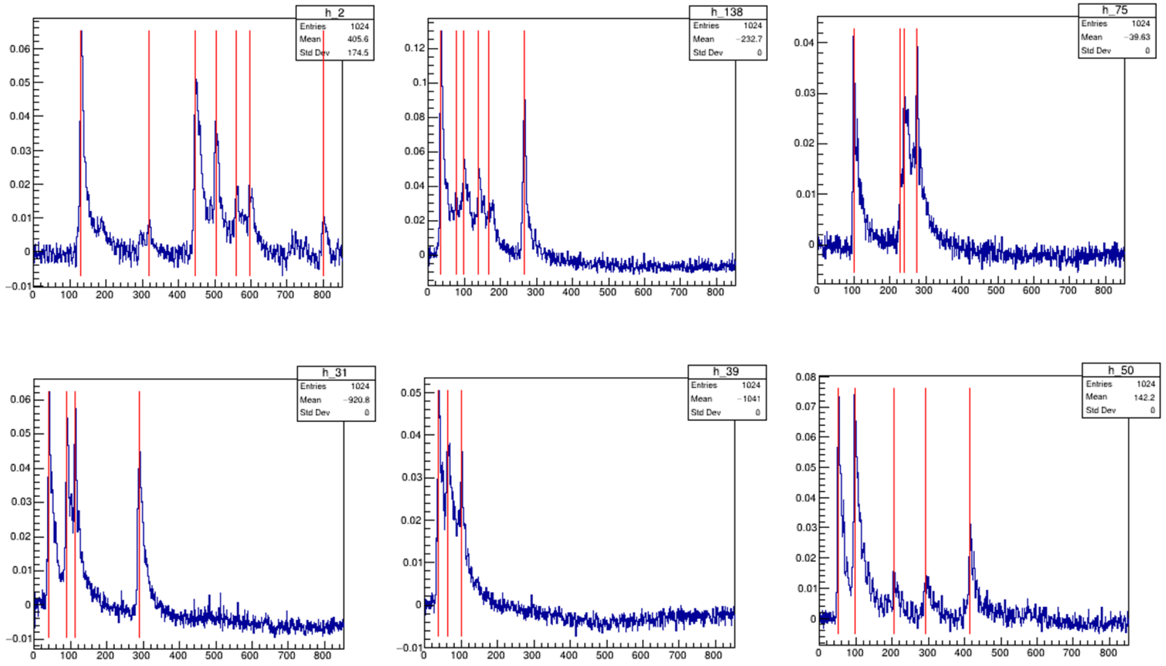






Beam test data analysis

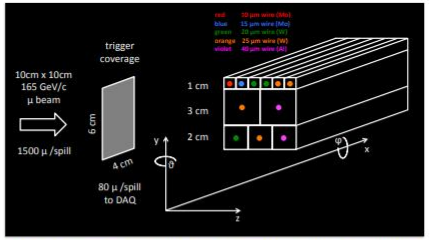
Preliminary peak finding with our algorithm

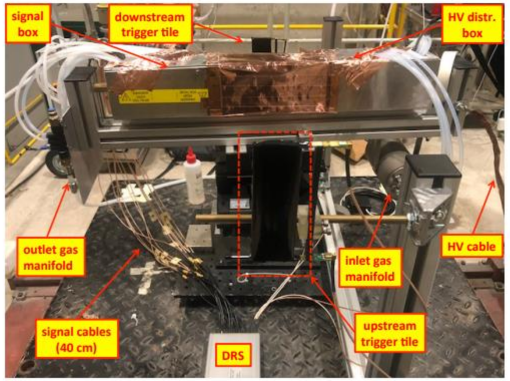


muons_165GeV_angle0_GSPS1p2_delay725ns_7Nov_0321

Beam test @ CERN from F. Grancagnolo's group

schematic





The test was performed during November 2021 at CERN on the H8 beam line in a **parasitic mode**. Main users on the same beam line was a team testing a tile calorimeter and, therefore, requesting for **large part of the time, beams of electrons and hadrons, at various energies,** needed for their calibration, but **useless for our purposes**. Only **sporadically**, a beam of **165 GeV/c muons** was available for us.

Ongoing activities:

- Binary file converter
- Outlier removal
- Event classification
- Tuning peak finding algorithm

Summary

- **Simulation is updated in several aspects**
  - Peak finding algorithm with tuned parameters
  - Noise definition
  - Results with He 80% + iC_4H_{10} 20% gas mixture gives better K/pi separation at low momentum, but worse K/pi separation at high momentum

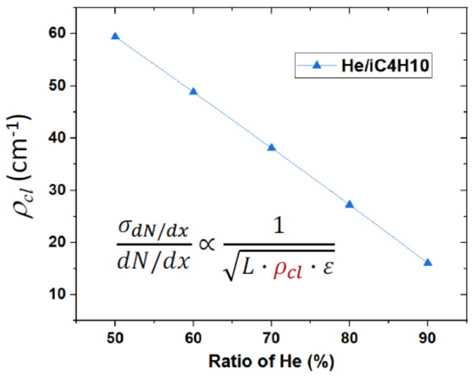
- **Experiment status**
  - Prototype experiment with different gas mixtures
    - High gain and good SNR for high He ratio
    - Need preamplifier with high GBP for low He ratio
  - Data analysis with the beam test data is ongoing

Backup

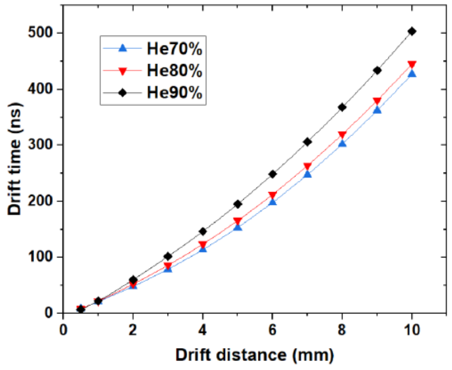
More study of gas mixtures

- choice of the gas mixture is essential
  - High cluster density compatibly with cluster counting efficiency
  - Low drift velocity helps to identify clusters in time
  - Small longitudinal diffusion is beneficial to both spatial resolution and dN/dx measurement
- Simulation of gas mixture performed to understand the gas property and optimize the working point

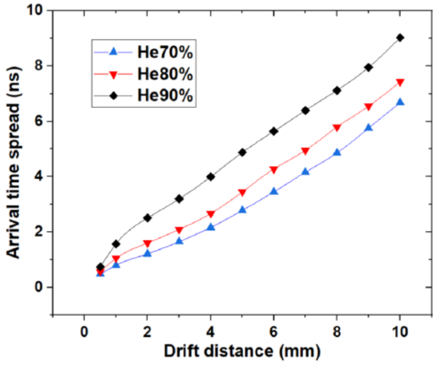
Cluster density vs ratio of He



Drift time vs drift distance



Diffusion effect vs drift distance



Gain vs H.V.