Ionization Measurement using Cluster Counting Method

Guang Zhao, Shuiting Xin, Linghui Wu, Mingyi Dong, Shengsen Sun
zhaog@ihep.ac.cn

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Outline

- **Introduction**
- **Principles**
  - dE/dx vs. dN/dx
- **Simulations**
  - Full waveform + electronics + cluster counting
  - PID preliminary results
- **Summary**

Introduction

- **Particle identification (PID) is essential for flavor physics**
  - Kaon/pion separation up to 20 GeV/c is necessary ➔

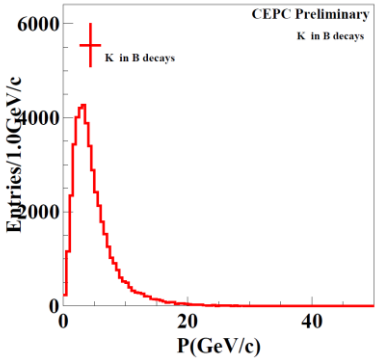
- **Ionization measurement with a gaseous detector can provide powerful K/π separation up to dozens of GeV/c within an acceptable detector size**

➔ Drift chamber (DC) for PID is proposed

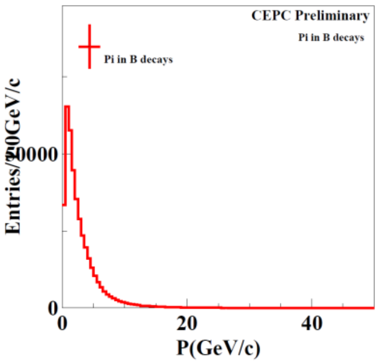
- **Comparing to the energy loss measurement, the cluster counting technique is expected to improve the ionization measurement with small fluctuations**

- **To study the PID capability of DC with cluster counting, a full simulation is performed**

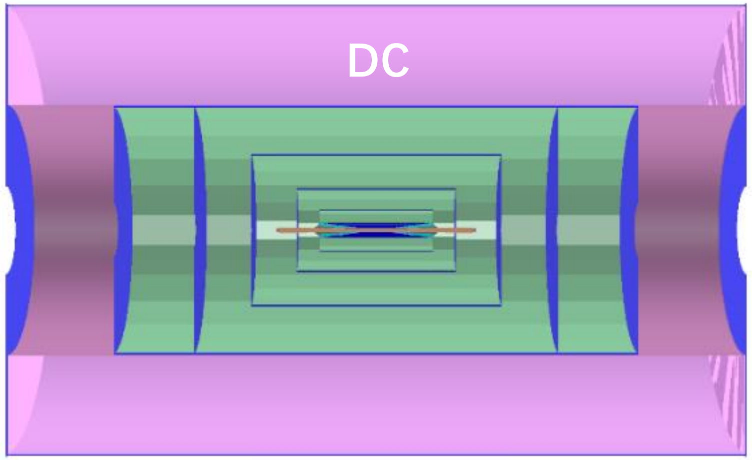
K in B decays



π in B decays

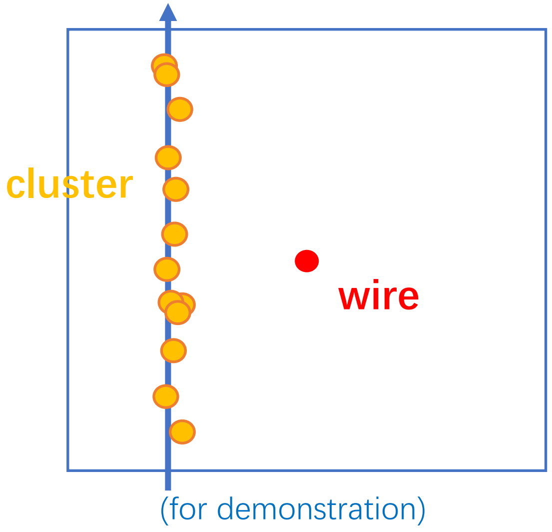


CEPC 4th Conceptual Detector



Principles

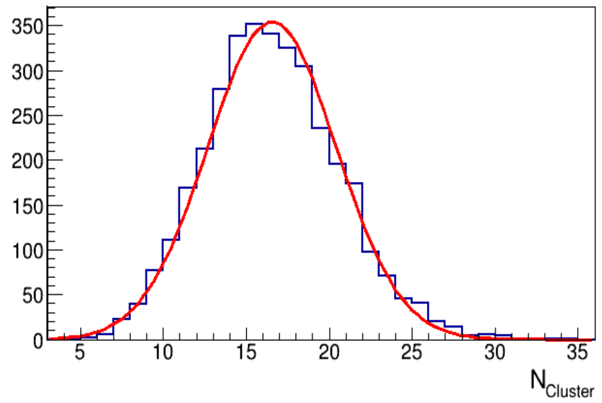
Ionization Process

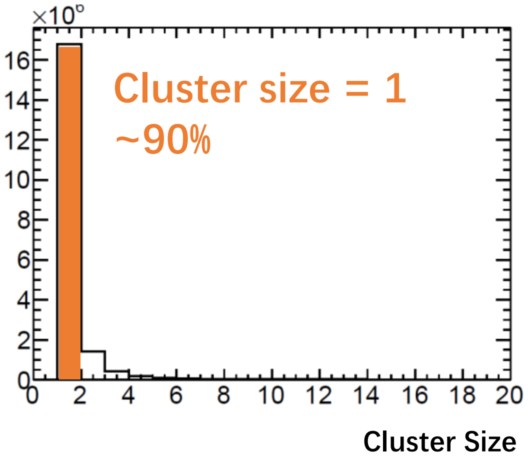


- **A charged particle losses energy when traversing a medium**
- **A sequence of primary interactions (clusters) along the track**
  - The # of clusters can be described by the Poisson distribution

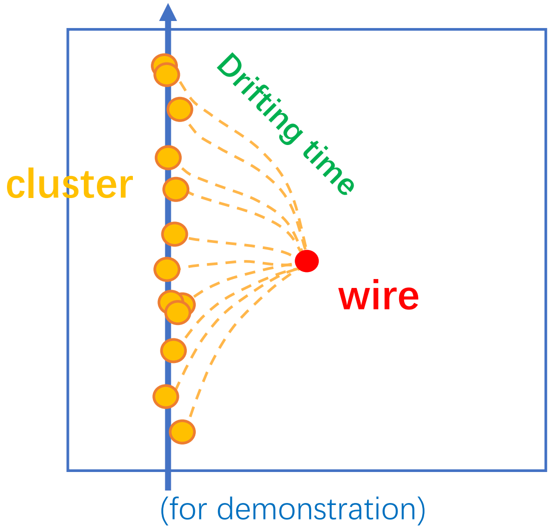
$$P(\bar{N}_p, k) = \frac{\bar{N}_p^k}{k!} e^{-\bar{N}_p}$$

- **For each cluster, one or more electrons are released**
  - Secondaries usually localized to the primaries
  - Cluster size: # of electrons for each cluster

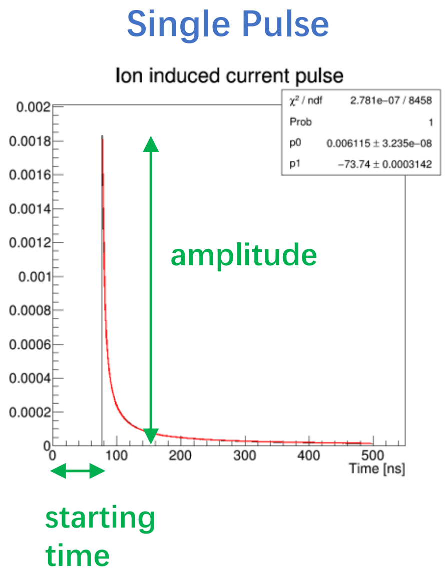


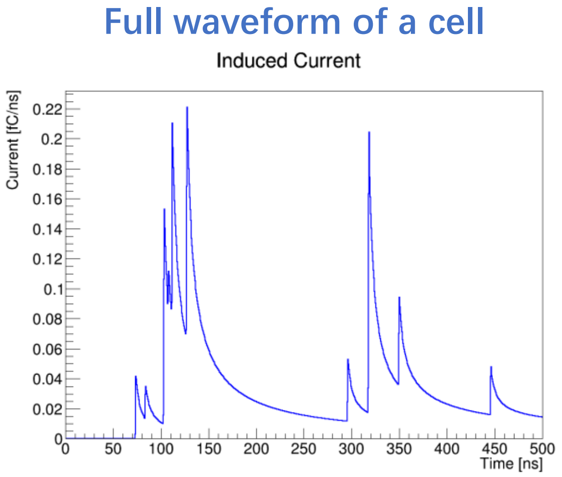


Drifting and current inducing



- **Electrons/ions drift in the fields**
- **Avalanche happens near the wire and signal is induced**
  - Each electron/ion pair produces a current pulse
    - The **amplitude** is proportional to the # of avalanche electrons
    - The **starting time** is almost determined by the **drifting time**
  - Induced current is further fed to the electronics system



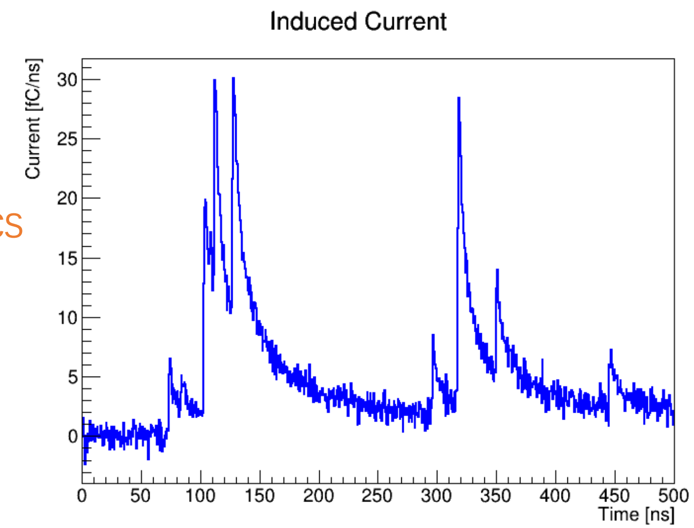


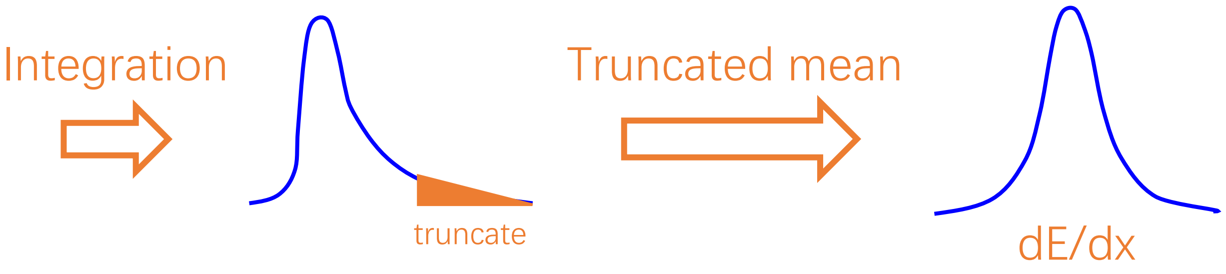
Electronics

Total energy loss measurement: dE/dx

Electronics

Waveform





<u>**dE/dx measurement**</u>: integration of the waveform

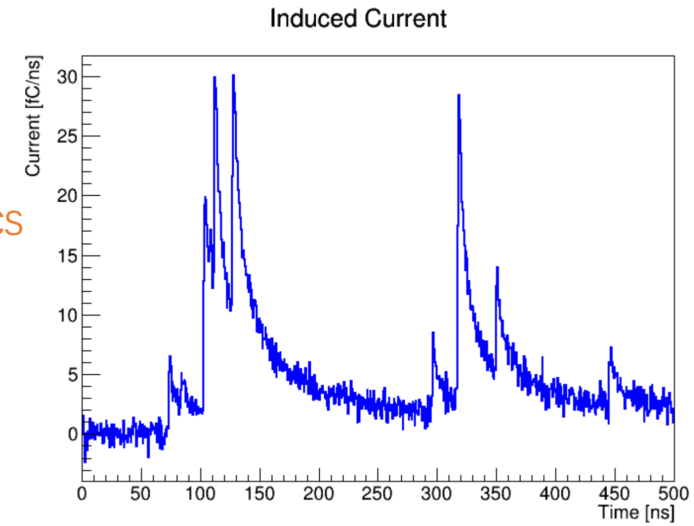
- **Large fluctuation** from
  - Energy loss from all the processes (primary, secondary)
  - Amplification (avalanche)
- **Long tail** due to secondary electrons, usually use truncated mean for a better resolution
- A reference resolution (truth)*: **~3%** (20 GeV/c, pions, det. size=120 cm)

* https://indico.ihep.ac.cn/event/13181/session/0/contribution/7/material/slides/0.pdf

Cluster counting measurement: dN/dx

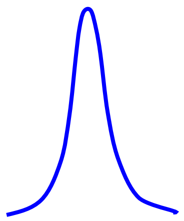
Electronics

Waveform



Cluster counting

dN/dx



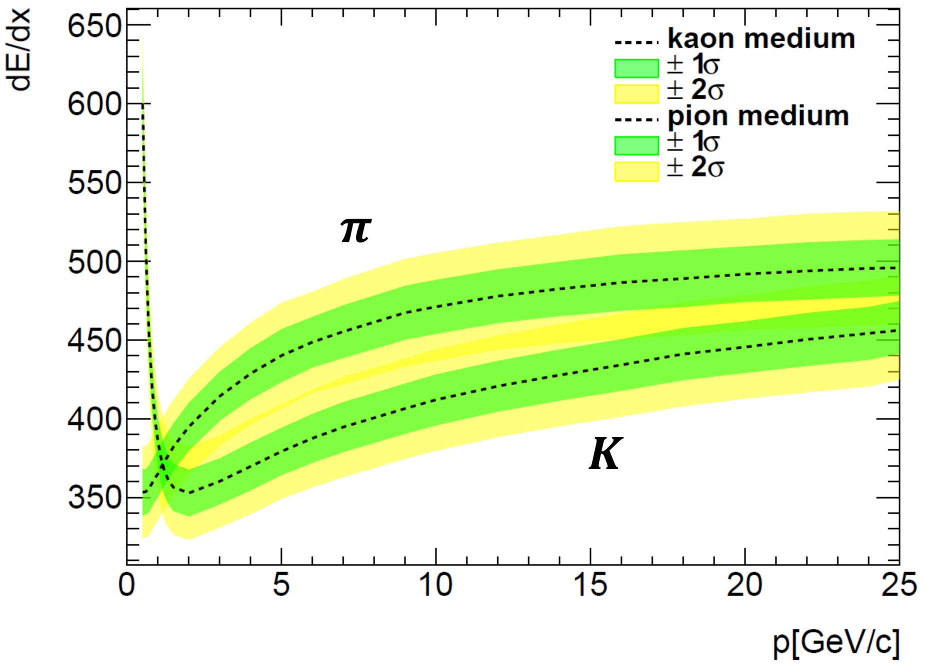
dN/dx measurement: counting the # of primaries

- **Small fluctuation** (only from the Poisson behavior of the primary ionizations)
- Easy to reach the **Gaussian** limit
- A reference resolution (truth)*: **<2%** (20 GeV/c, pions, det. size=120 cm)

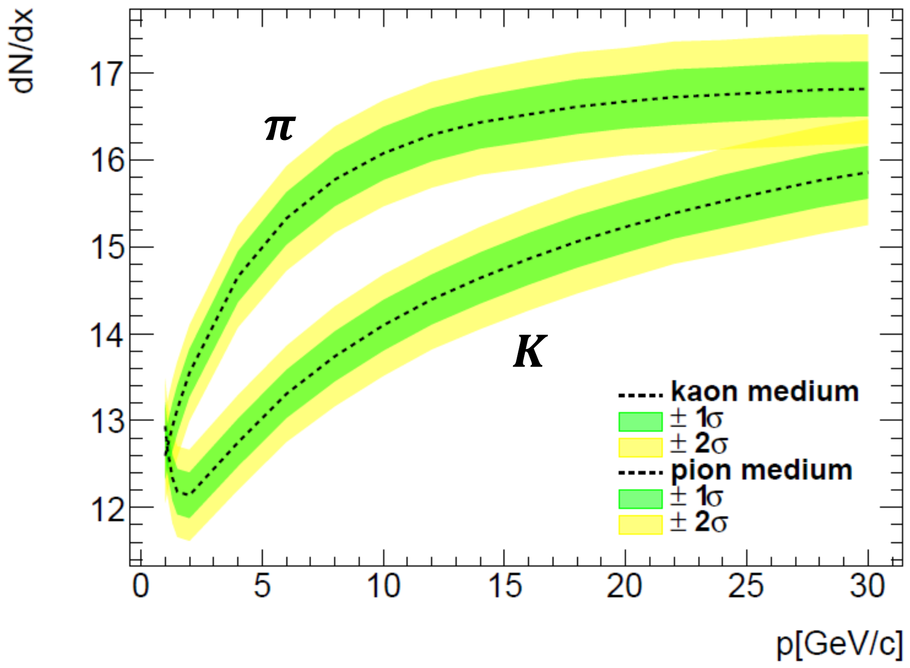
* https://indico.ihep.ac.cn/event/13181/session/0/contribution/7/material/slides/0.pdf

dE/dx vs. dN/dx (truth)

dE/dx



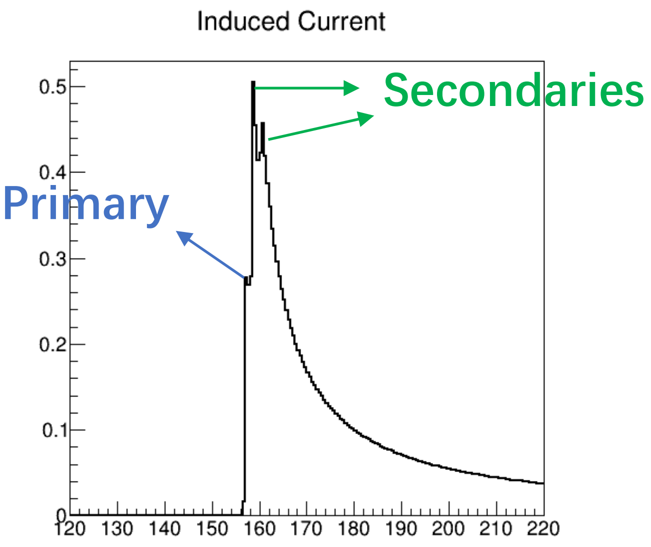
dN/dx

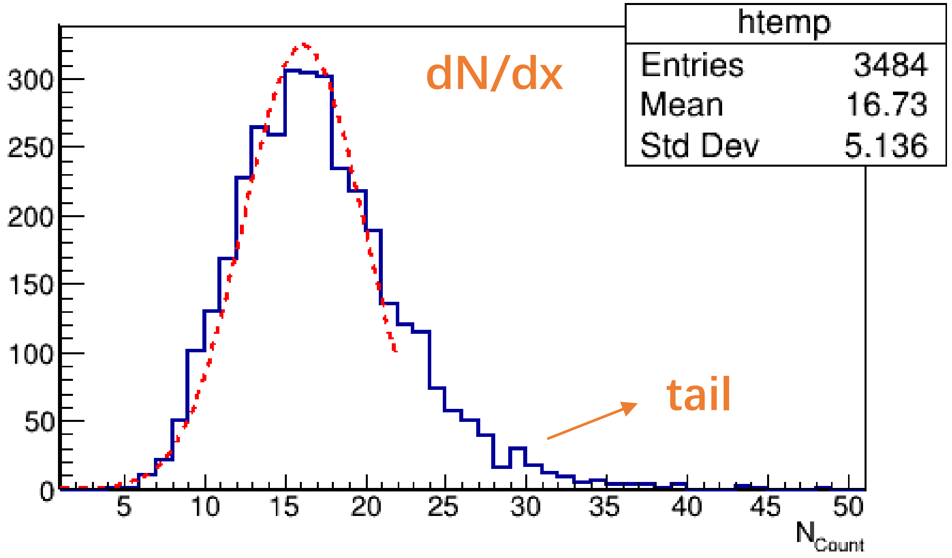


More powerful for K/pi separation with dN/dx

Secondaries suppression

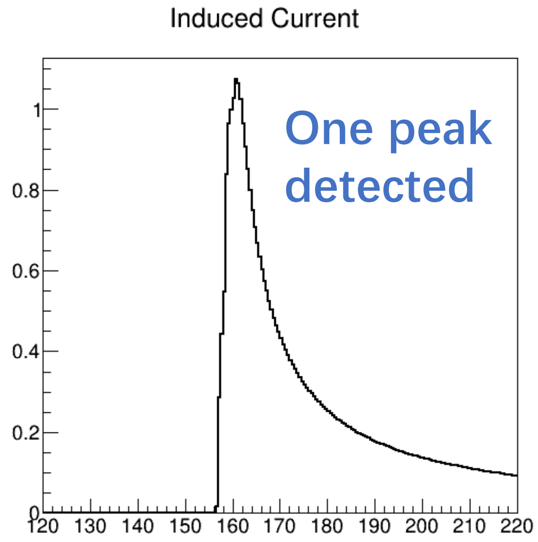
- **~10% of clusters have more than 1 electrons (secondaries) released**
  - Form multiple peaks in the signal due to diffusion
  - The peaks are close to the primary one due to the localization of the secondary electrons
- **Detected secondaries can lead to a tail in dN/dx, which can worsen the resolution**



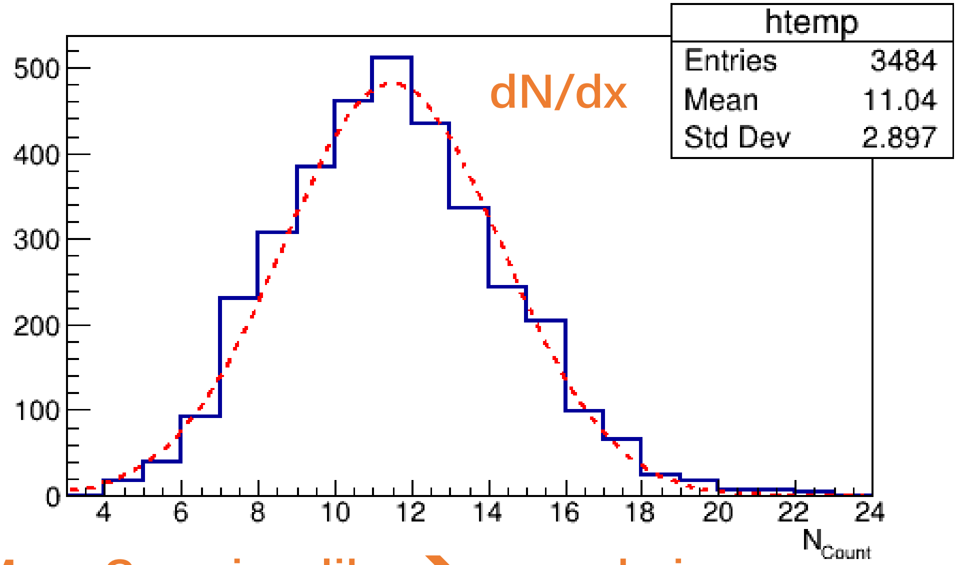


Secondaries suppression (II)

- **A practical detection ability can group the primary/secondary peaks, which can also reduce the tail in dN/dx**
  - Electronics/noises: make the secondaries less distinguishable
  - Counting algorithm: merge the count



w/ electronics

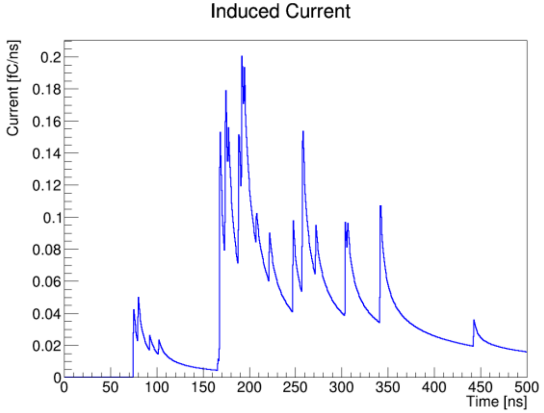


More Gaussian-like ➔ secondaries suppressed

Simulations

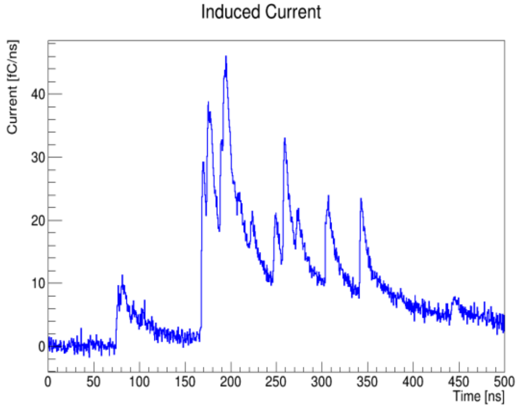
The simulation flow

Induced current



Electronics

Realistic waveform



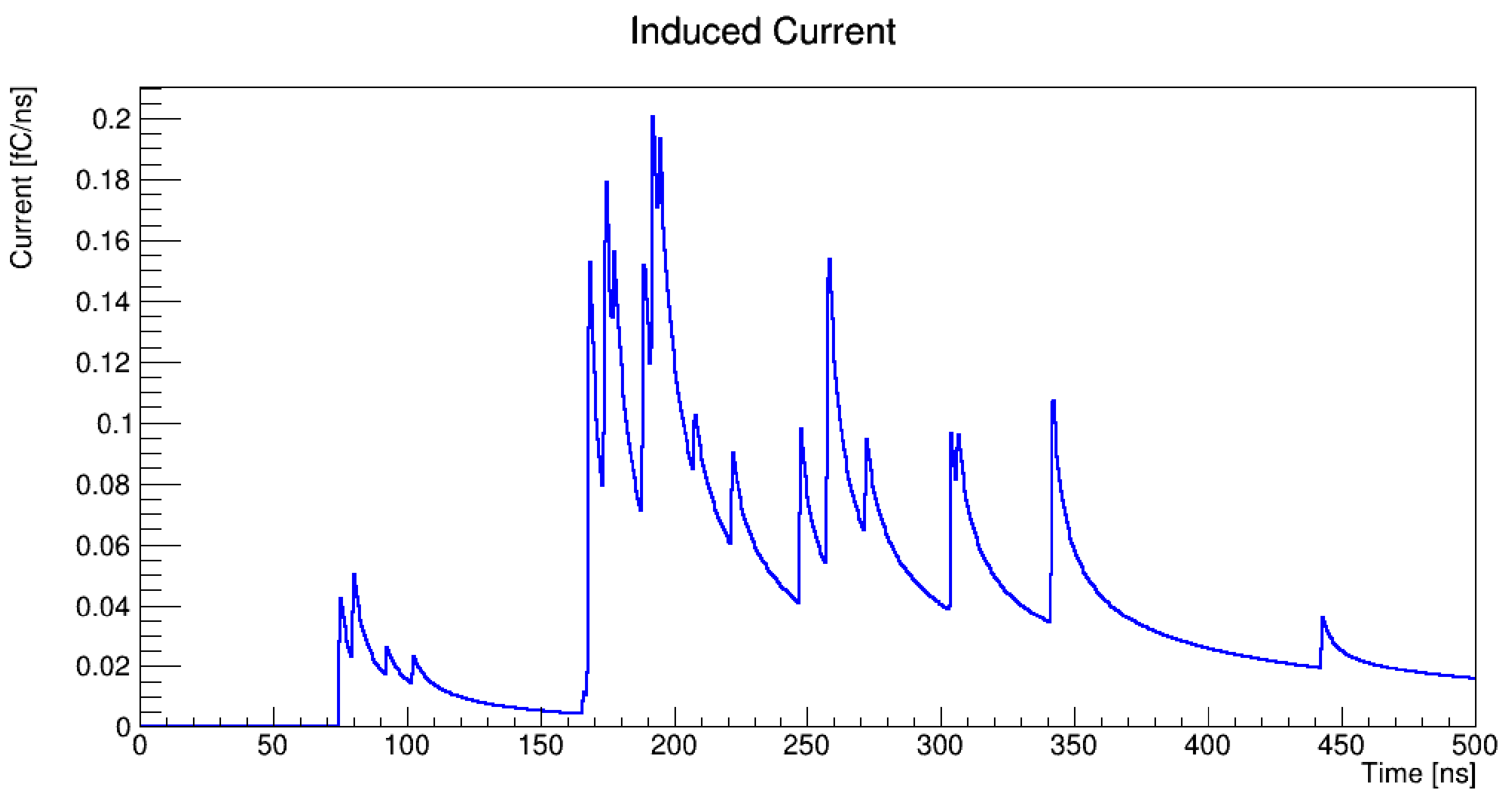
Counting

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

- **Preamplifier**
  - Impulse response
- **Noises**
  - Amplitude
- **ADC**
  - Sampling rate

Essential to simulate the distortion and interference of the signals

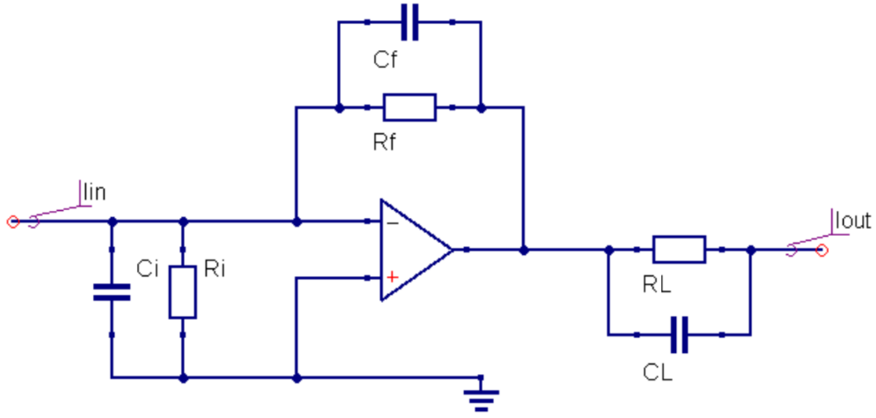
Induced current from Garfield++



Gas composition: He 90% + iC_4H_{10} 10%
Cell size: 1x1 cm
Particle: 10 GeV/c pions, θ = 90 deg
Average N_{cl}: ~16.5

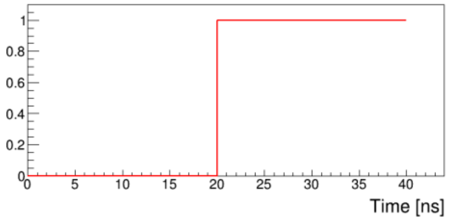
Electronics (I): preamplifier

A simple current-sensitive preamplifier

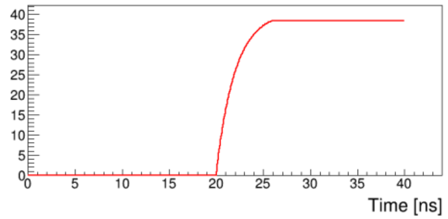


Time constants (τ) and risetime:

Step response:



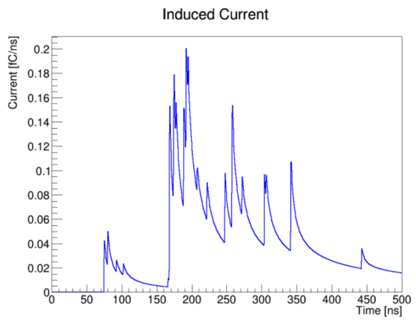
Response after preamplifier:



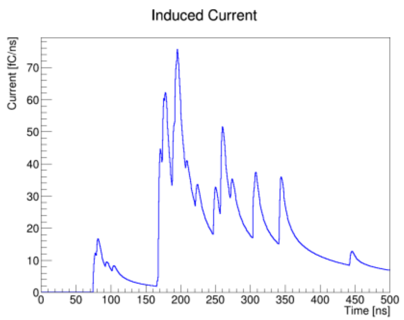
Time Constant (ns)	Risetime (ns)
0.5	0.95
1.0	1.85
2.0	3.70
3.0	5.50
4.0	7.35
5.0	9.20

Broaden of the waveforms with different time constants:

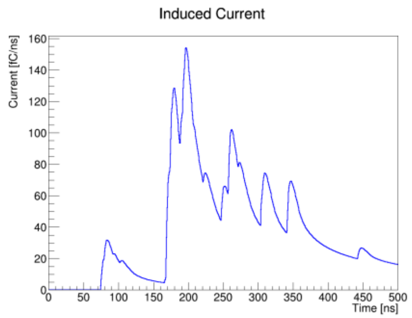
$\tau = 0\ ns$



$\tau = 2\ ns$

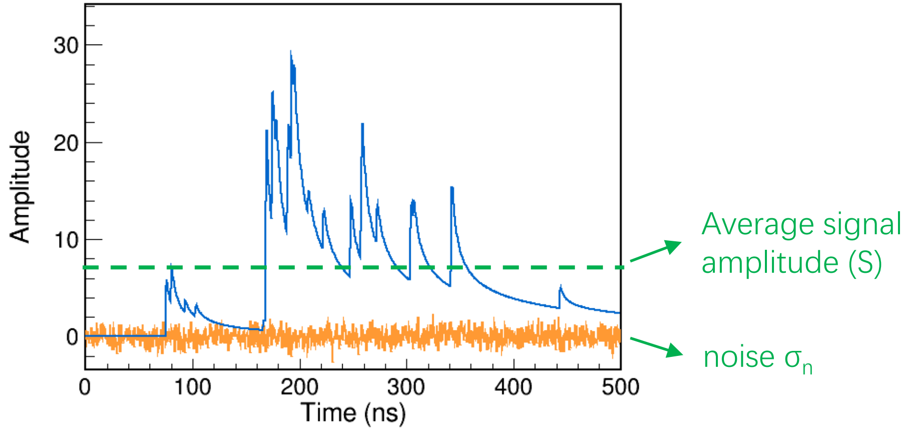


$\tau = 5\ ns$

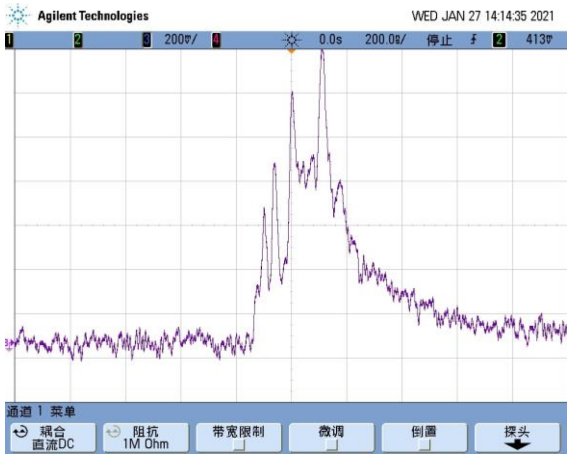


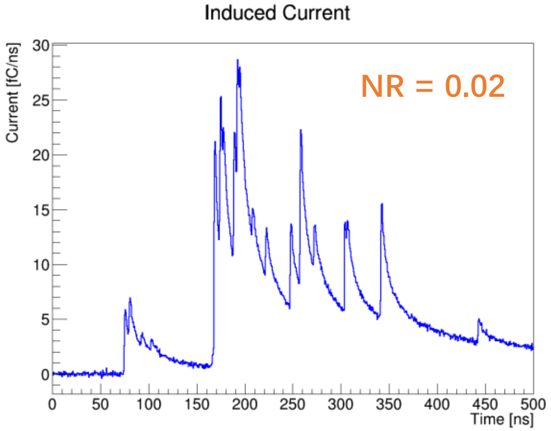
Electronics (II): noises

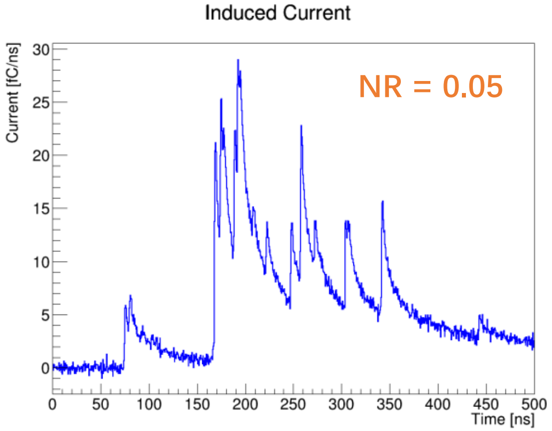
- **Add white noises to the raw current signal**
- **Relative noise ratio (NR): $\frac{\sigma_n}{S}$**
  - σ_n: Standard deviation of noises
  - S: Average signal amplitude per bin (for pions @ 10 GeV/c)



A signal of cosmic ray in T channel for the BESIII MDC



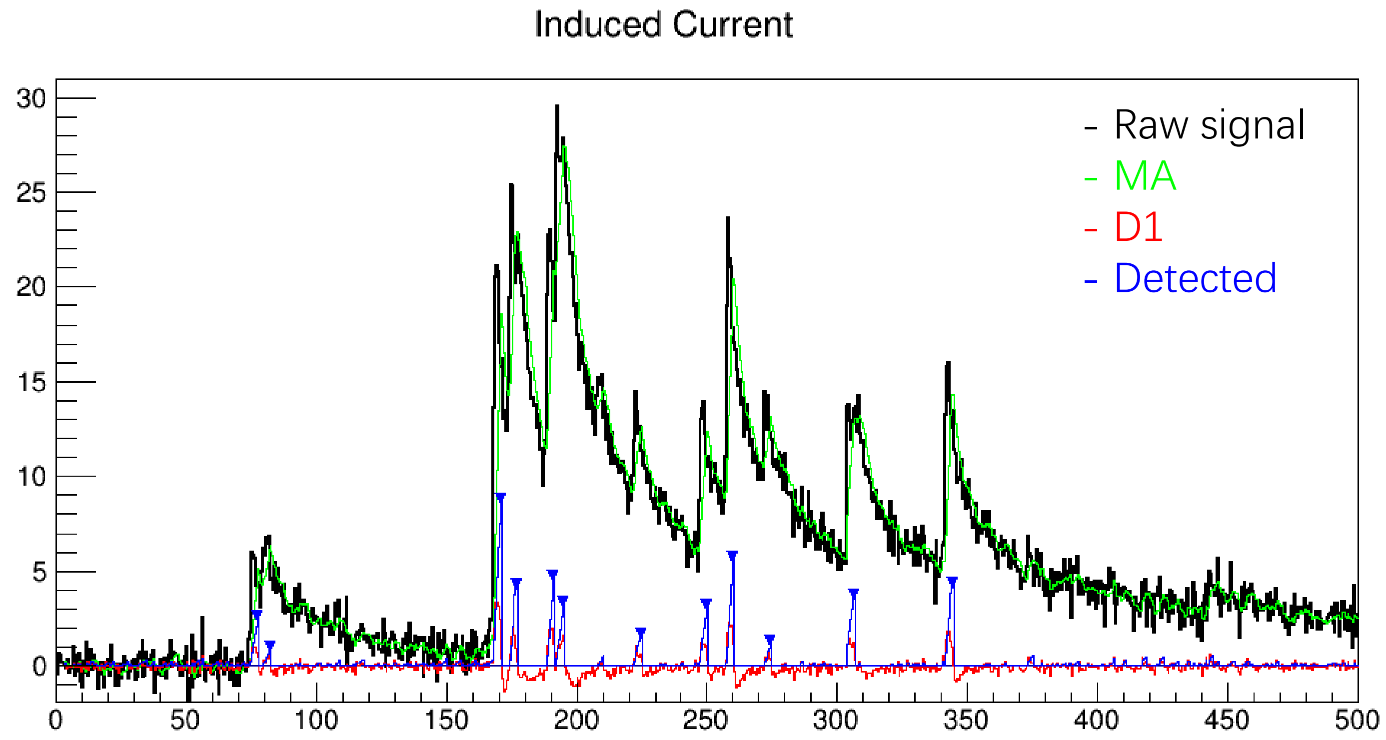




pre-amp: $\tau = 0.5\ ns$

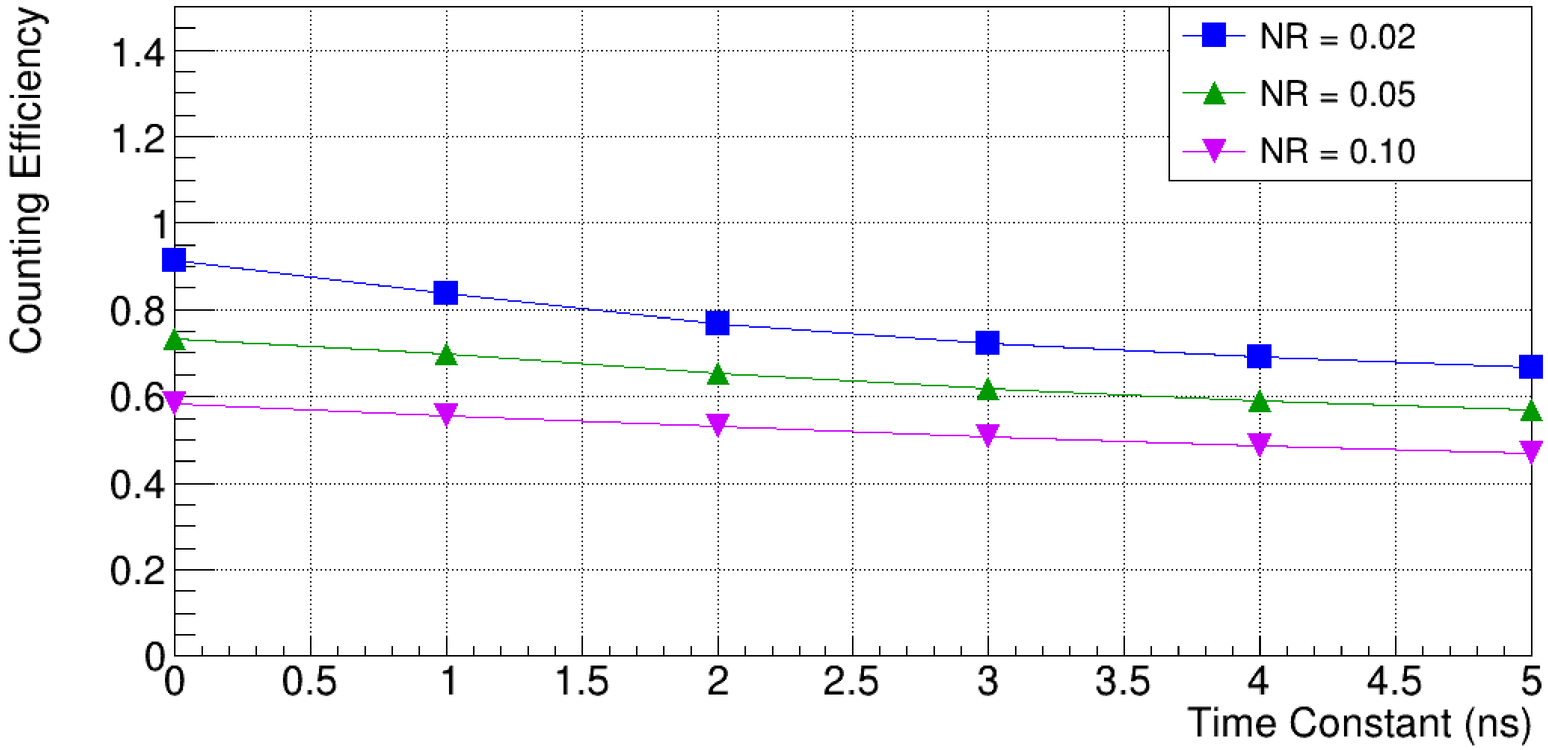
Cluster counting method: MA + D1

- Moving average (MA) filter: $\mathbf{MA[i]} = \frac{1}{M} \times \sum_{k=0}^{K<M} S[i-k]$ (smoothing)
- First difference (D1) filter: D1[i] = MA[i] – MA[i – 1]

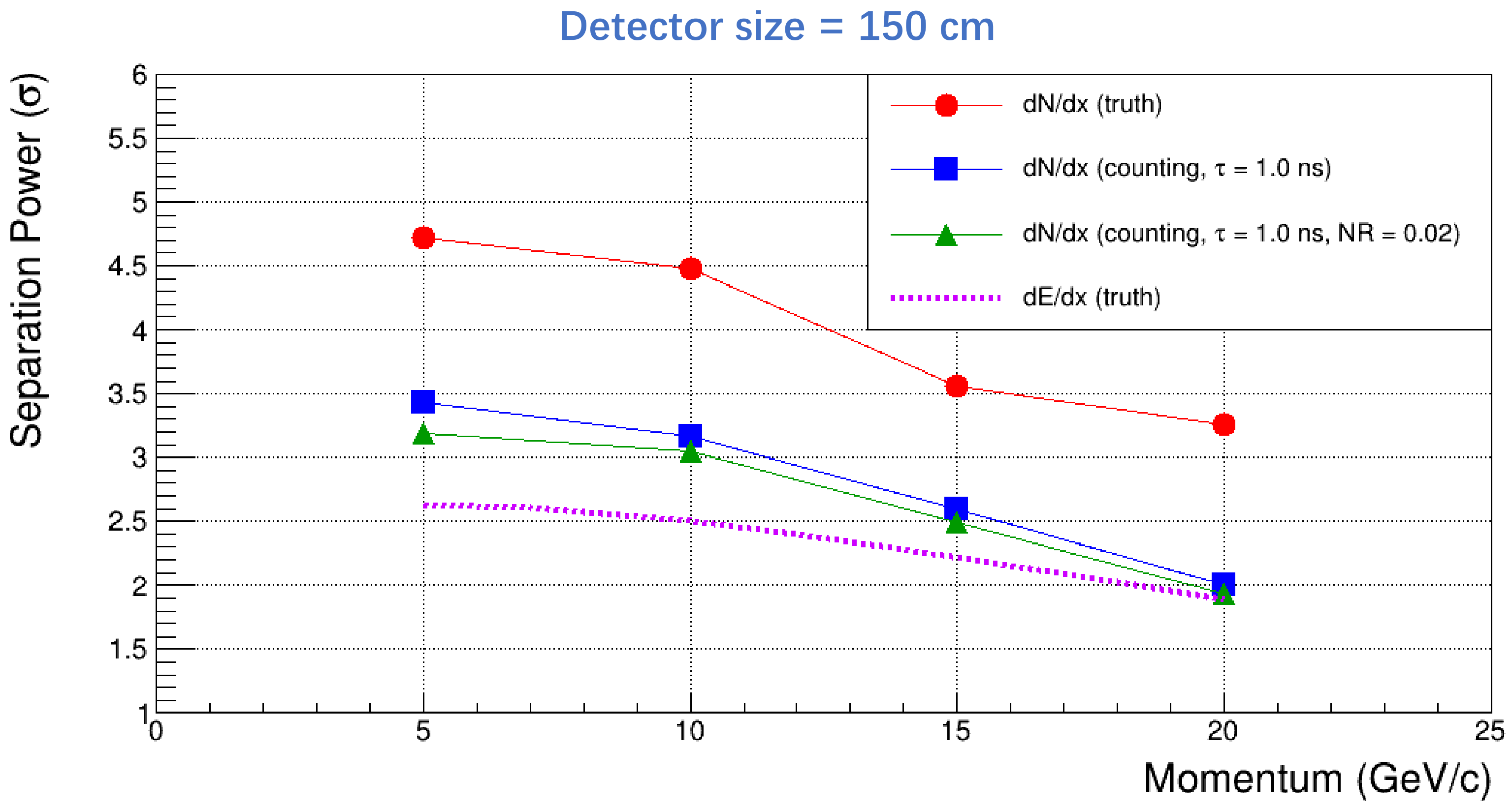


Counting efficiency

Particle: 10 GeV/c pions, $\theta = 90°$
Sampling rate: 2 GHz



K/pi separation power (det. size = 150 cm)

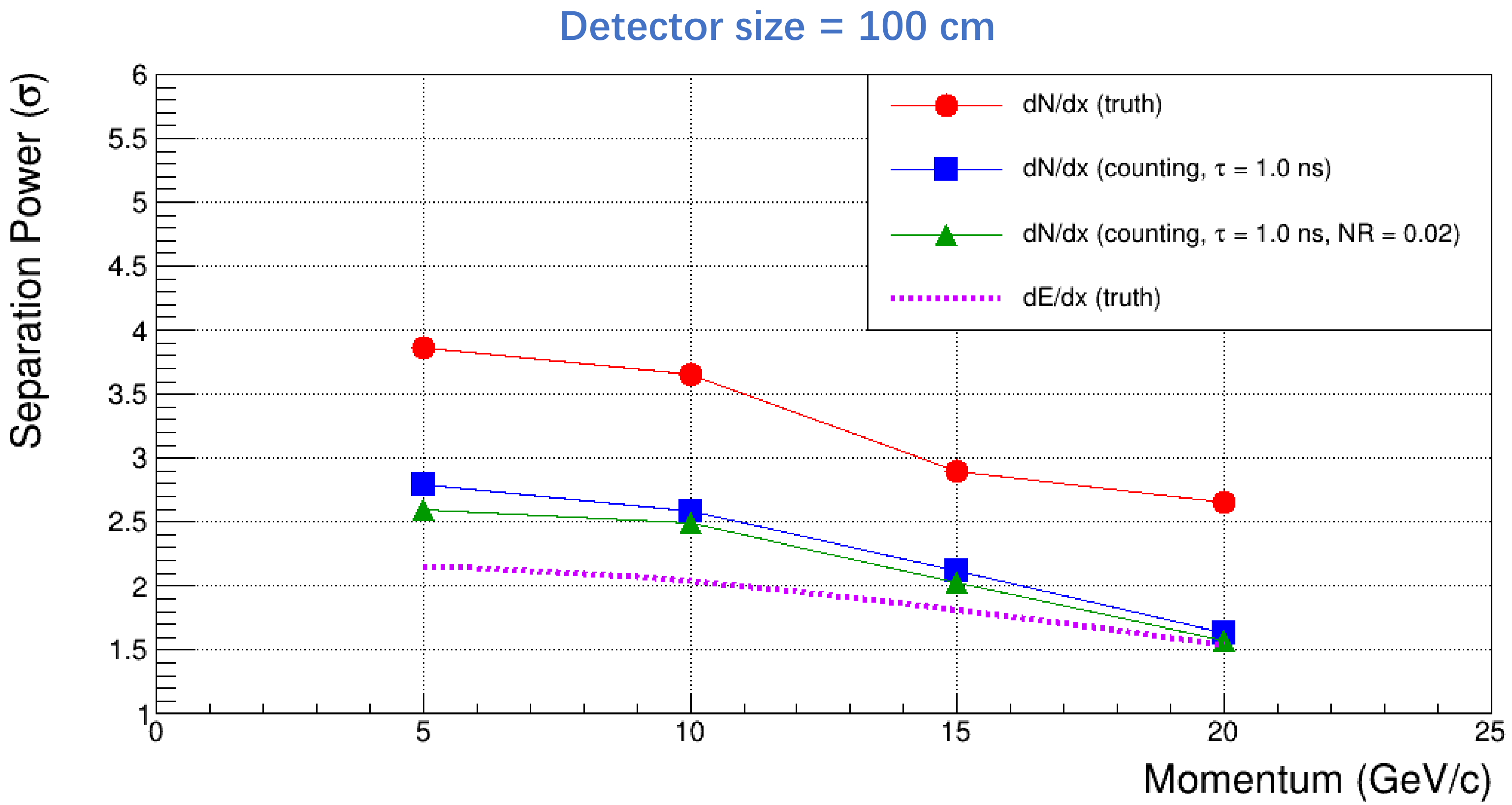


Separation power:

$$\frac{\left|\left(\frac{dN}{dx}\right)_{\pi} - \left(\frac{dN}{dx}\right)_{K}\right|}{\sqrt{\sigma_{\pi}^{2} + \sigma_{K}^{2}}}$$

Can achieve ~3(2)σ K/pi separation power for p < 10(20) GeV/c

K/pi separation power (det. size = 100 cm)

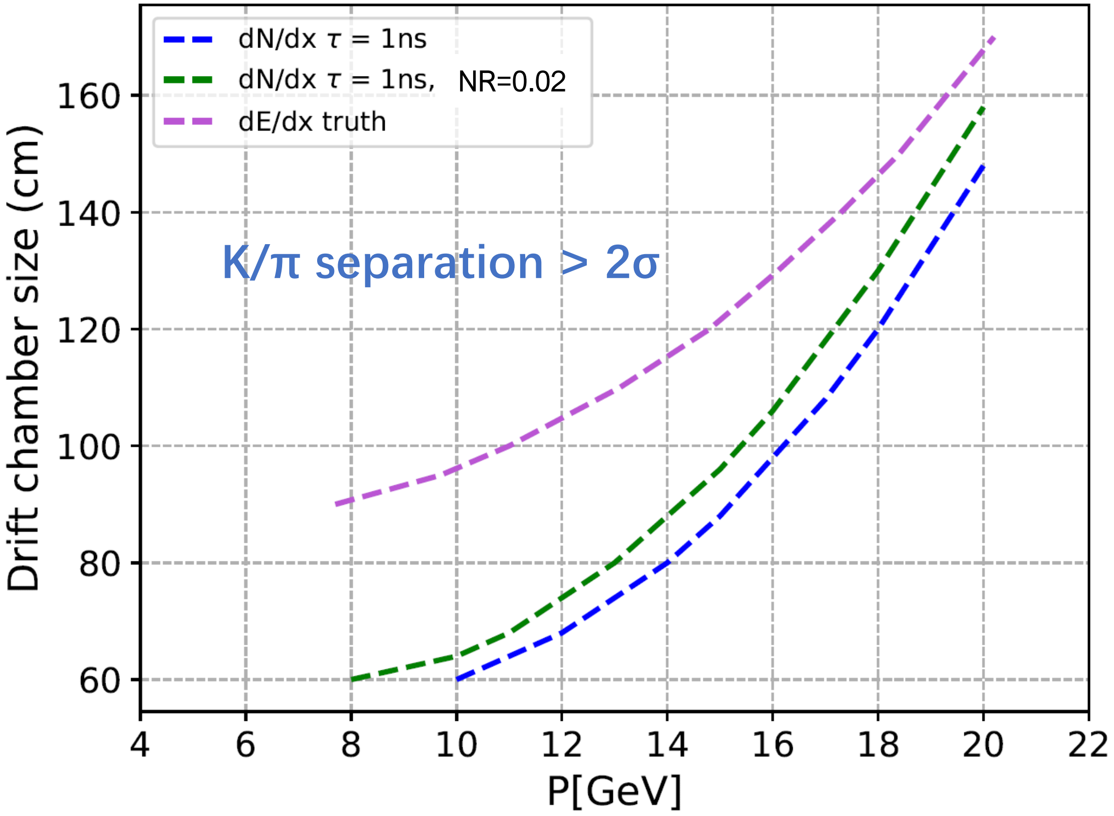


Separation power:

$$\frac{\left|\left(\frac{dN}{dx}\right)_{\pi} - \left(\frac{dN}{dx}\right)_{K}\right|}{\sqrt{\sigma_{\pi}^{2} + \sigma_{K}^{2}}}$$

Can achieve ~2(1.5)σ K/pi separation power for p < 15(20) GeV/c

Detector size requirement for K/π separation > 2σ



A detector size of ~150 (100) cm is needed for 2σ separation up to 20 (15) GeV/c

Summary

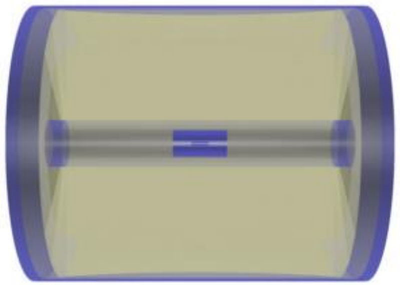
- **A simulation framework for cluster counting is ready**
  - Signal generation using Garfield++
  - Electronics effects
  - Cluster counting algorithm

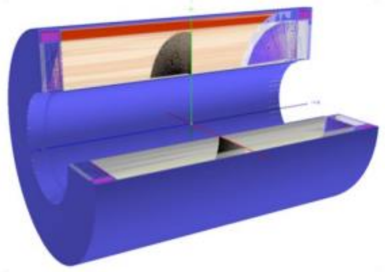
- **Preliminary PID performance with baseline configuration is obtained**
  - det. size = 150 cm: ~3(2)σ K/pi separation is achievable for $p < 10(20)$ GeV/c
  - det. size = 100 cm: ~2(1.5)σ K/pi separation is achievable for $p < 15(20)$ GeV/c

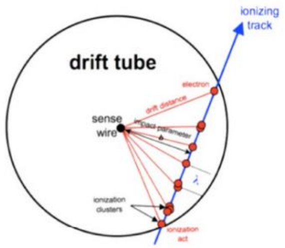
- **Next to do**
  - Optimizations
    - Detector design: layout, cell, gas, …
    - Electronics: tuning parameters based on experiments
    - Reconstruction: counting algorithm, corrections/calibrations
  - Fast simulation development/CEPCSW integration

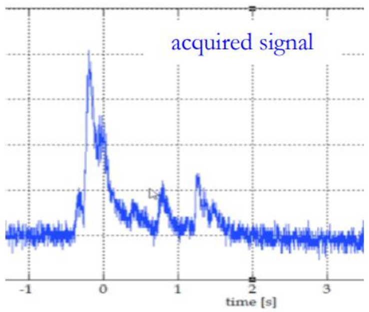
Summary

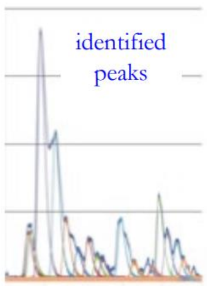
Cluster counting for the IDEA DCH

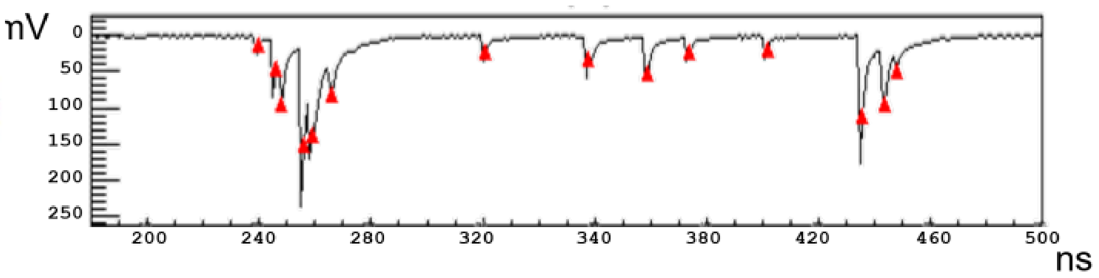












See Federica's talk later today

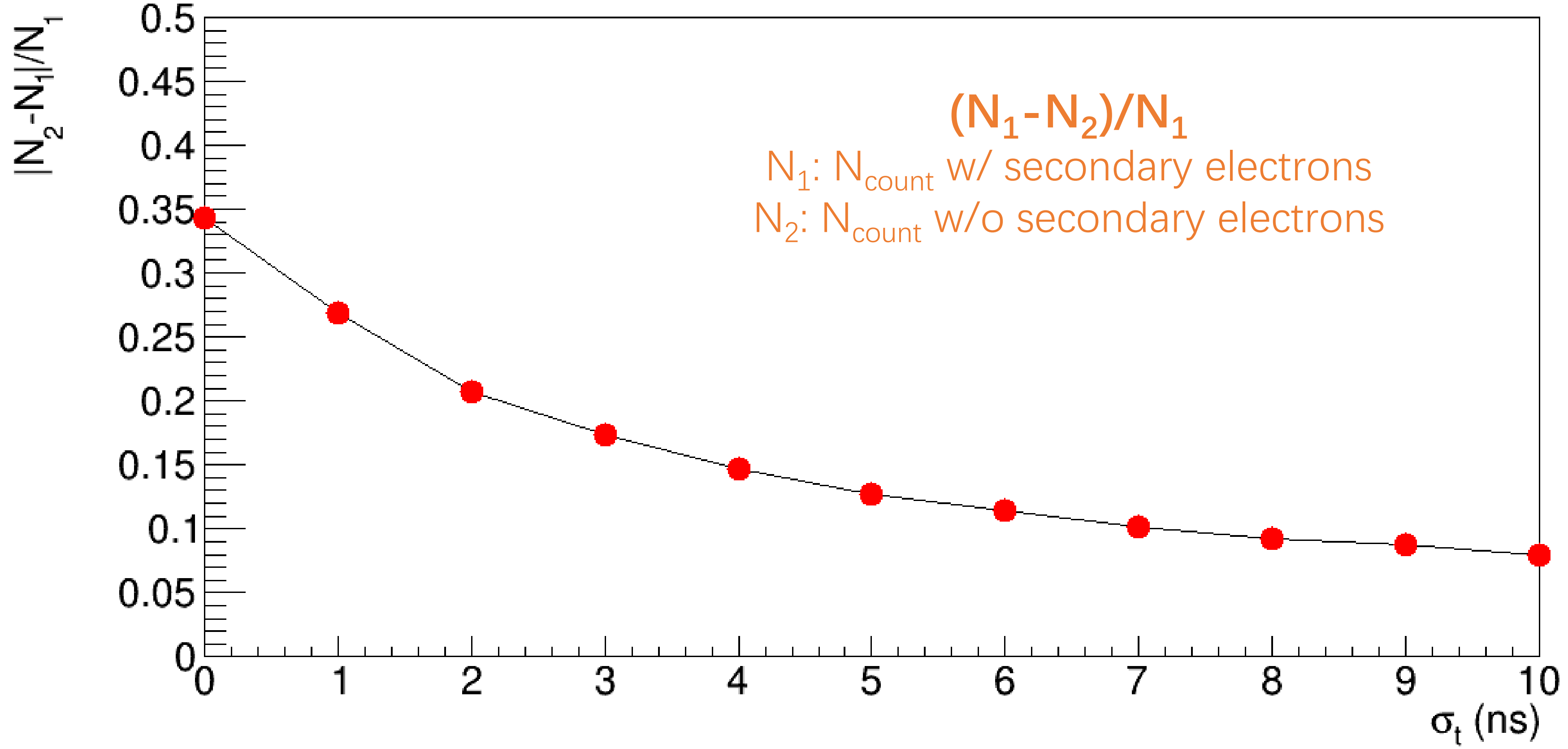
Special thanks to

- ✓ the EPC electronics group,
- ✓ Jianbei Liu,
- ✓ Zhijun Liang,
- ✓ Yuanbo Chen,
- ✓ Huayi Sheng,
- ✓ Franco Grancagnolo,
- ✓ Giovanni Tassielli

for the helpful discussion

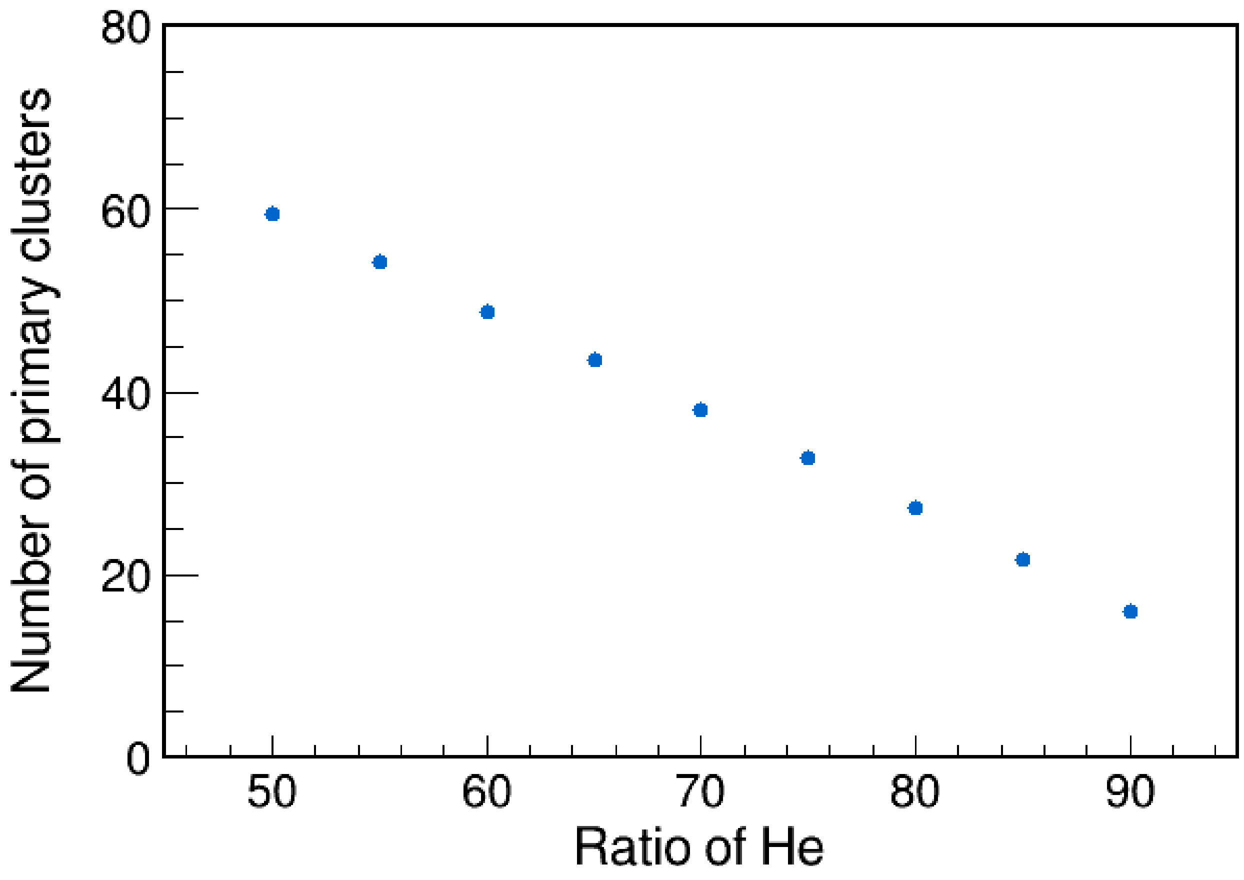
Backup

Extra counting vs. Minimum separatable time difference between 2 peaks (σ_t)



Extra counting due to secondaries is suppressed for larger σ_t

N_{cl} vs. Ratio of Helium



dN/dx resolution for detector size = 150 cm