Ionization Simulation of the Drift Chamber

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Outline

- **Introduction**
- **Detailed simulation with electronics**
  - Full waveform + electronics + cluster counting → dN/dx
- **Simplified simulation in CEPCSW**
  - Hit-level sampling of dN/dx + TOF calculation → PID
- **Summary**

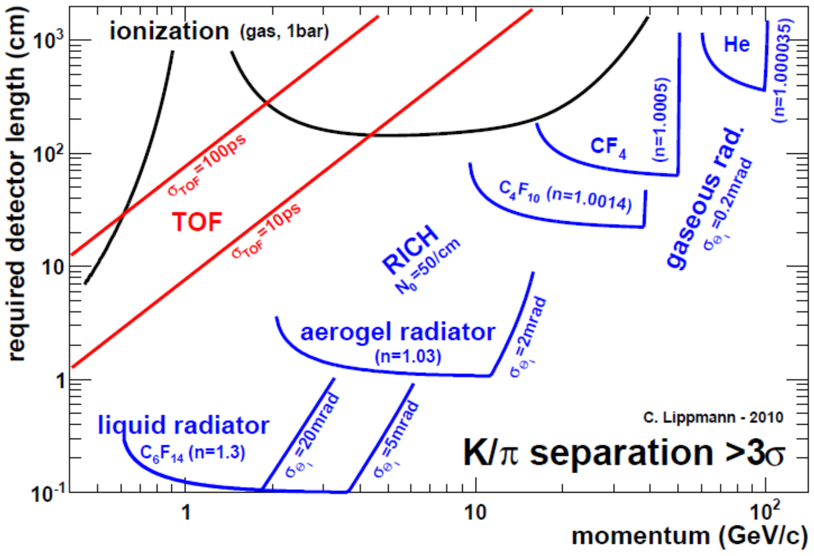
Motivation

- **Particle identification (PID) is essential for flavor physics and jet study**

- **Ionization measurement with a gaseous detector can provide 3σ of K/pi separation power up to dozens of GeV within an acceptable detector size ➔ Drift chamber for PID is proposed**

- **CEPC Requirements*:**
  - Kaons up to 20 GeV should be identified
  - 3-sigma separation of K/pi, corresponding to 2% of dE/dx resolution, is appreciated

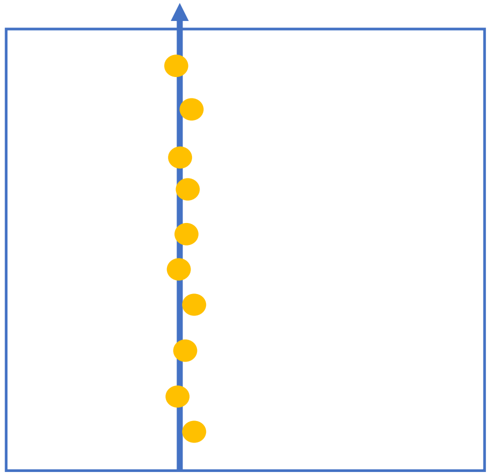
arXiv:1101.3276v4



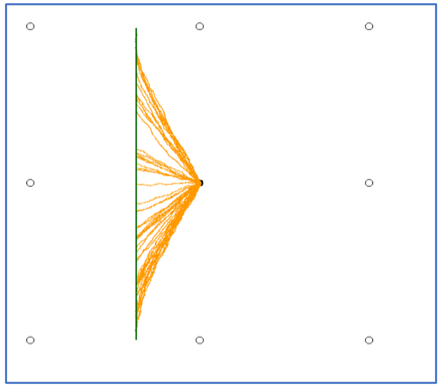
* https://indico.ihep.ac.cn/event/12787/session/2/contribution/7/material/slides/0.pdf

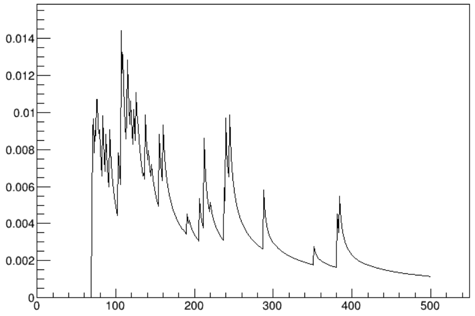
Introduction to the ionization measurement (I)

1. Primary Ionizations are produced



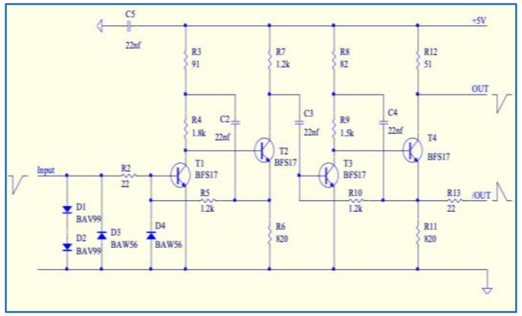
2. Electrons are drifted to the signal wire





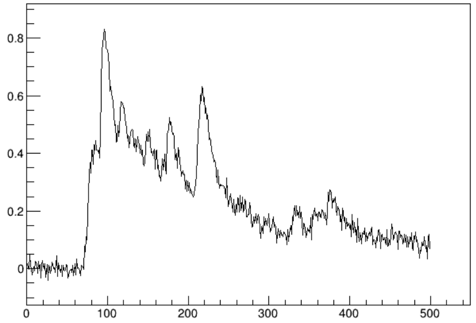
3. After the avalanche process, currents are induced on the wire

4. The current signals are feed to the electronics system for amplification and shaping

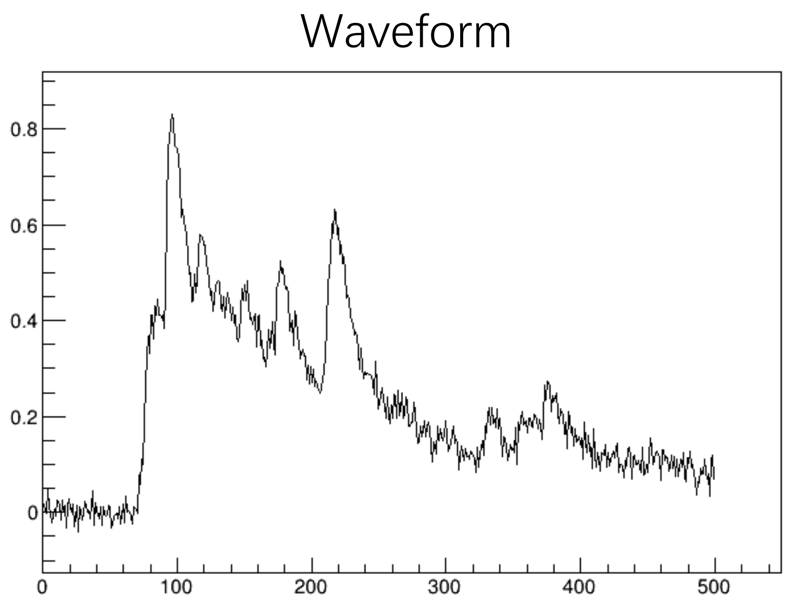


5. Measurement:

- dE/dx: integration
- dN/dx: cluster counting



Introduction to the ionization measurement (II)

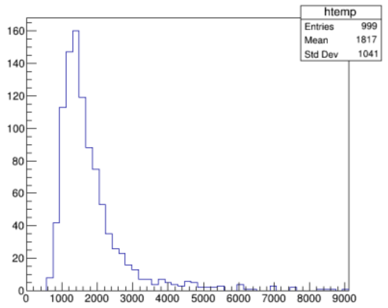


Integration

Cluster counting

Energy measurement (dE/dx):

- $\langle E \rangle = \langle N_I \rangle \times \overline{W}$
- Resolution:
  - $\frac{\sigma_{\langle E \rangle}}{\langle E \rangle} = \sqrt{\left(\frac{\sigma_{\langle N_I \rangle}}{\langle N_I \rangle}\right)^2 + \left(\frac{\sigma_{\overline{W}}}{\overline{W}}\right)^2}$
  - Typical value*: 3~5% (truth)



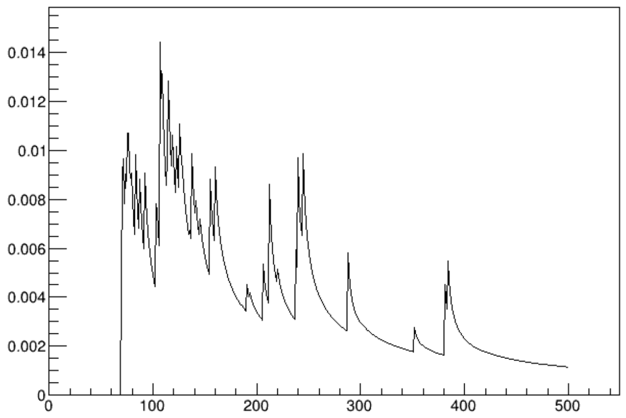
Yields measurement (dN/dx):

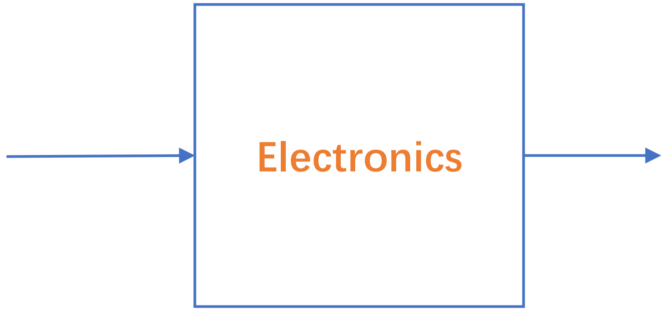
- $\langle N_I \rangle$
- Resolution:
  - $\frac{\sigma_{\langle N_I \rangle}}{\langle N_I \rangle}$
  - Typical value*: <2% (truth / **NO** electronics)
  - Better resolutions as no uncertainties from $\overline{W}$, but can still be worsened by the electronics

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

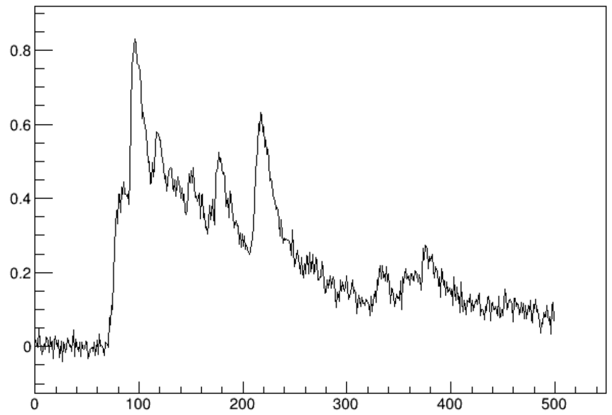
The detailed simulation flow

Induced current





Realistic waveform



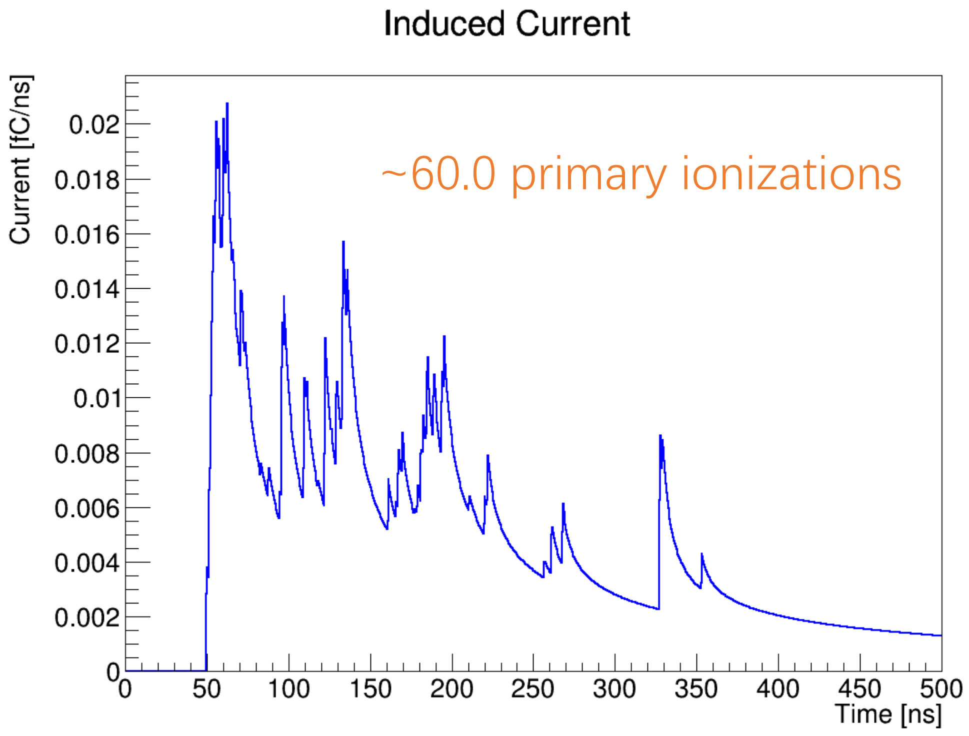
- **Garfield++**
- **OR: Fast Simulation (ongoing)**
  - Simplified electron drift model
  - Simplified avalanche process

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

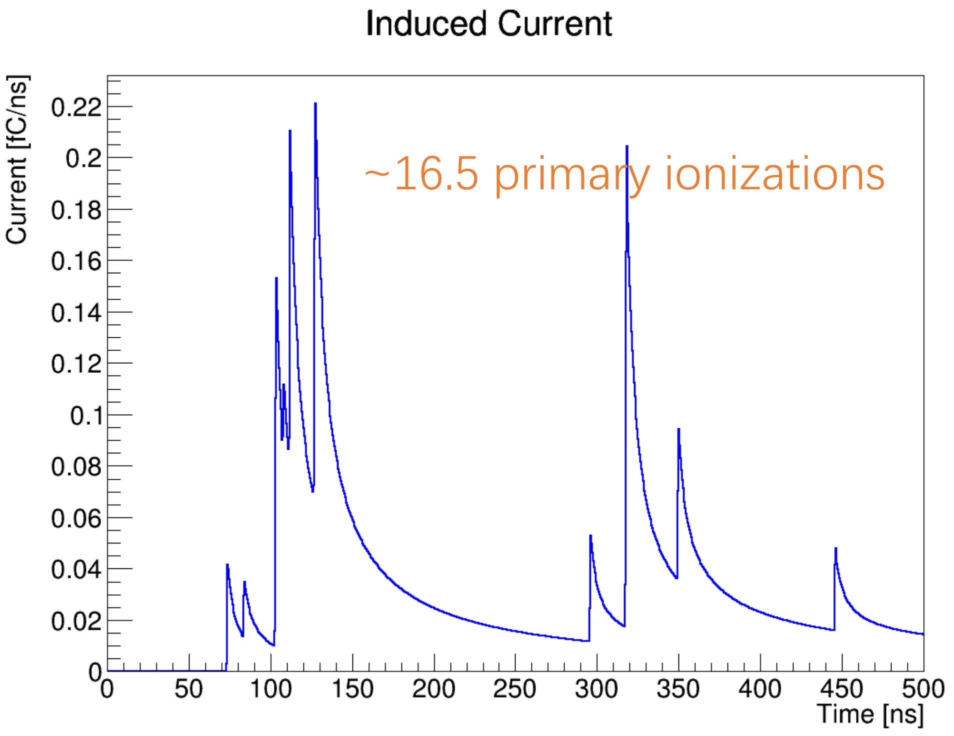
Essential to simulate the distortion and interference of the signals

Induced current from Garfield++

He 50% + iC_4H_{10} 50% (He50)



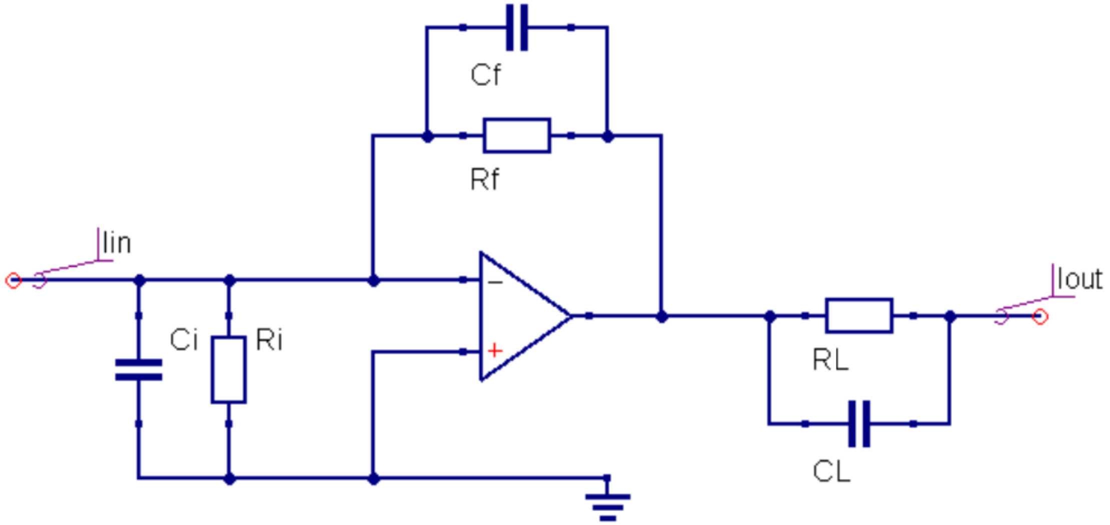
He 90% + iC_4H_{10} 10% (He90)



Two gas compositions are considered. He50 has more statistics but also more pile-ups, which means it is more challenging for cluster counting

Electronics (I): preamplifier

A simple current-sensitive preamplifier:



Assuming $R_i \parallel C_i \gg R_f \parallel C_f$ and $C_L = 0$
We can calculate the transfer function in Laplace domain is:

$$H(s) = \frac{1}{R_L C_f} \times \frac{1}{s + \frac{1}{R_f C_f}}.$$

The impulse response in time domain is:

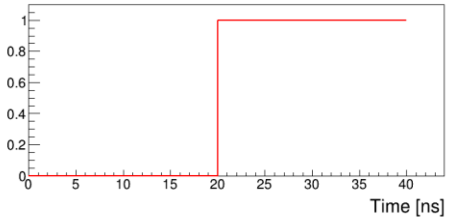
$$h(t) = \frac{1}{R_L C_f} \times e^{-\frac{t}{R_f C_f}},$$

where $\tau \equiv R_f C_f$ is the time constant that can broaden the raw signal.

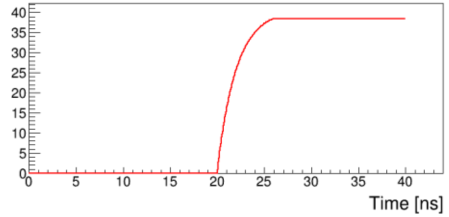
Waveform (I): with preamplifier

Time constants (τ) and risetime:

Step response:



Response after preamplifier:

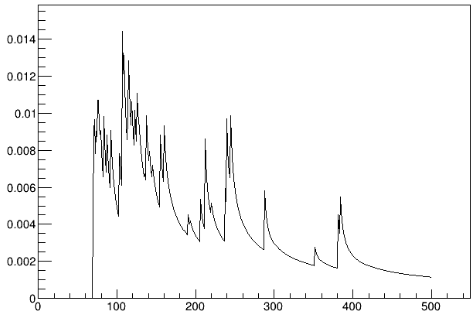


Time Constant (ns)	Risetime (ns)
0.5	0.95
1.0	1.85
2.0	3.70
3.0	5.50
4.0	7.35
5.0	9.20

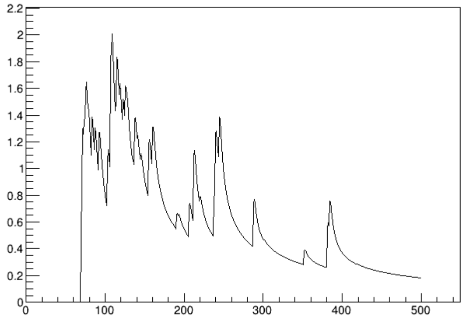
→ BESIII MDC risetime: ~5ns

Broaden of the waveforms with different τ's:

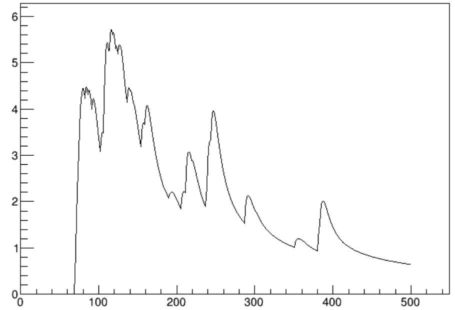
$\tau = 0\ ns$



$\tau = 1\ ns$

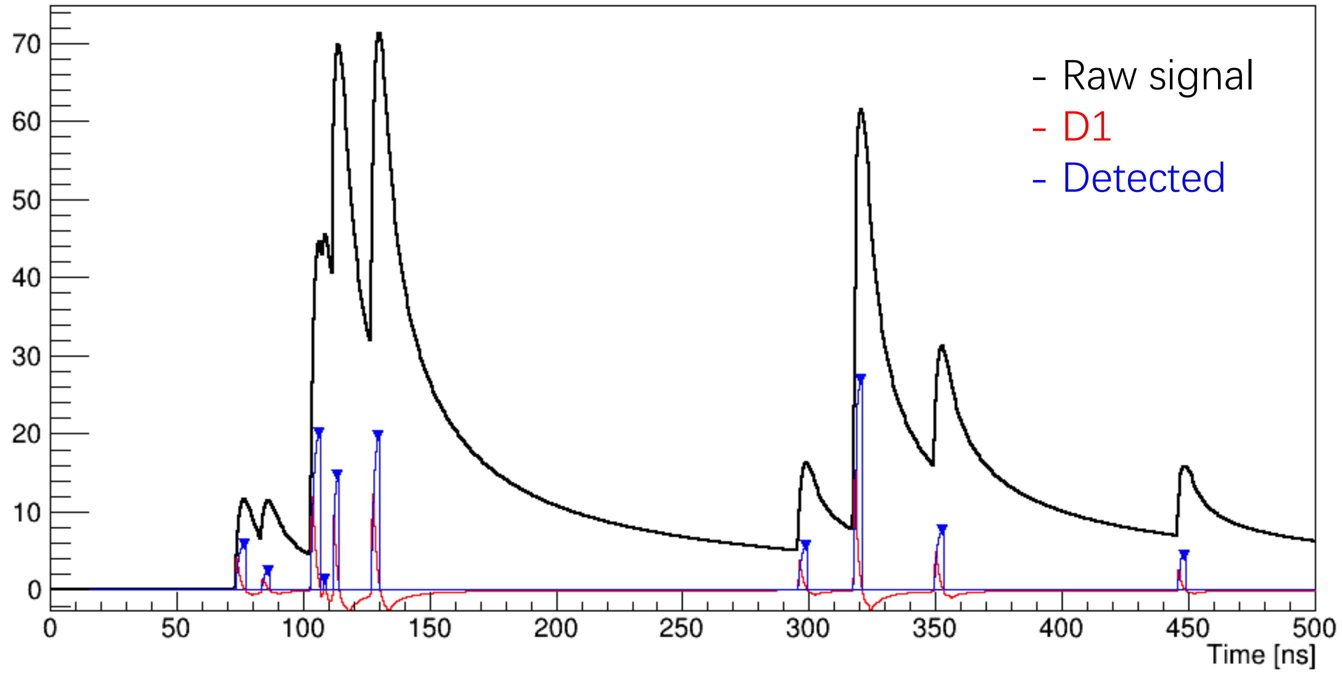


$\tau = 5\ ns$



Cluster counting method (I): D1

- **1st difference filter (D1):** D1[i] = S[i] – S[i – M]

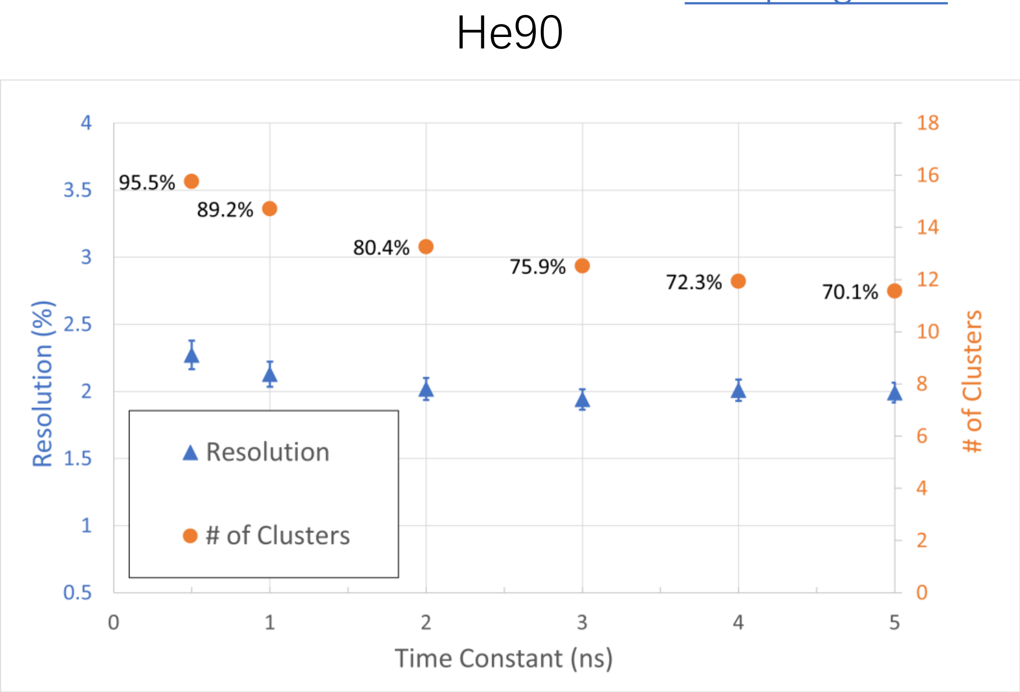


Count the number of pulses by analyzing the waveforms convoluted by the D1 filter

dN/dx resolution and counting efficiency (I)

Particle: 10 GeV/c pions
Detector size: 1 cm * 150
Sampling rate: 2 GHz

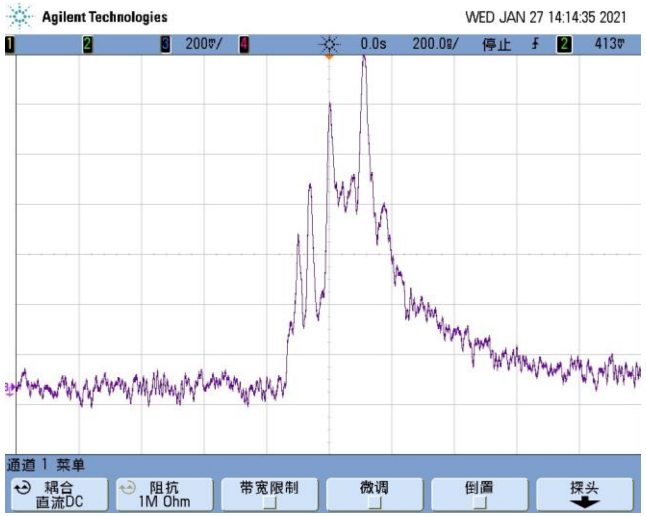
Counting efficiency



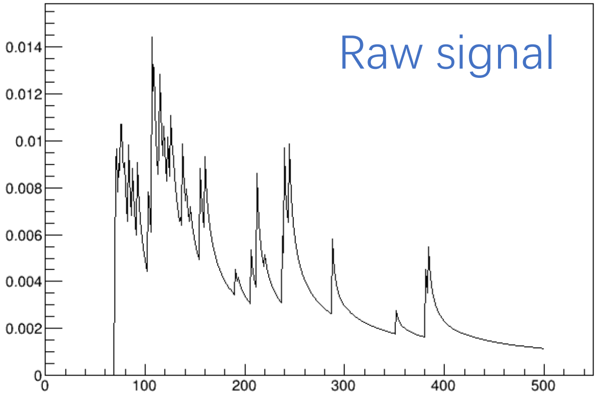
2% resolution is achievable for both cases.
Better resolution for He50, as there are more pulses
Better counting efficiency for He90, as there are less pile-ups

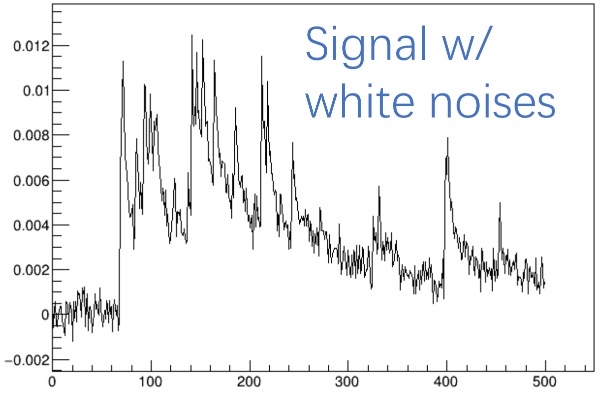
Electronics (II): Noises

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



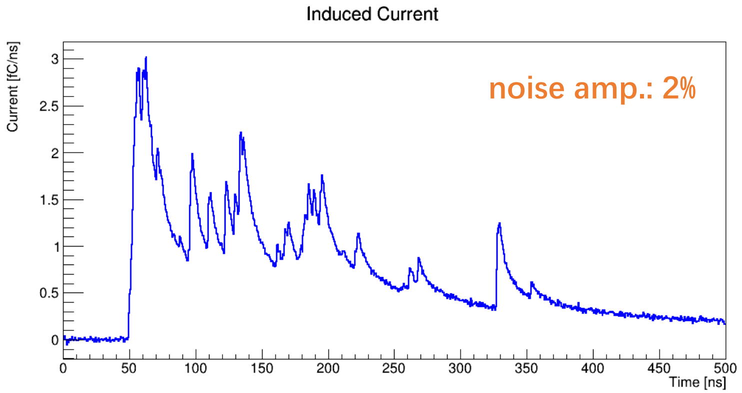
Add white noises on the raw current signal

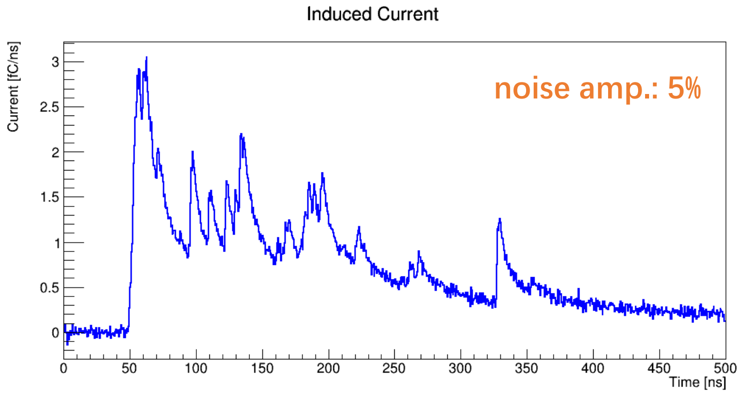


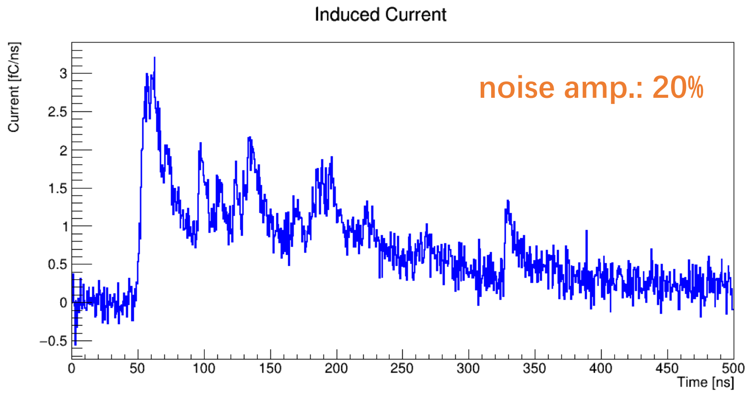


Waveform (II): with preamplifier + noises

- **Noise amplitude:** **fraction of the average signal amplitude**



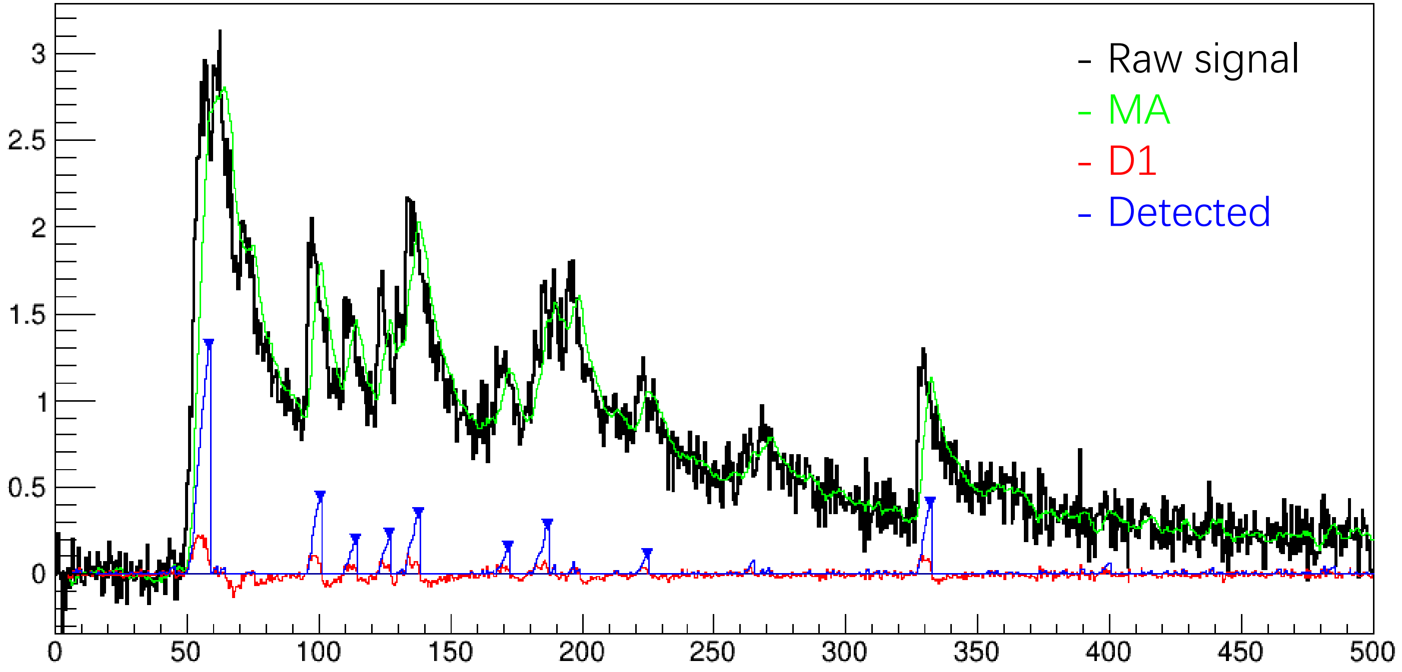




pre-amp: $\tau = 0.5\ ns$

Cluster counting method (II): MA + D1

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

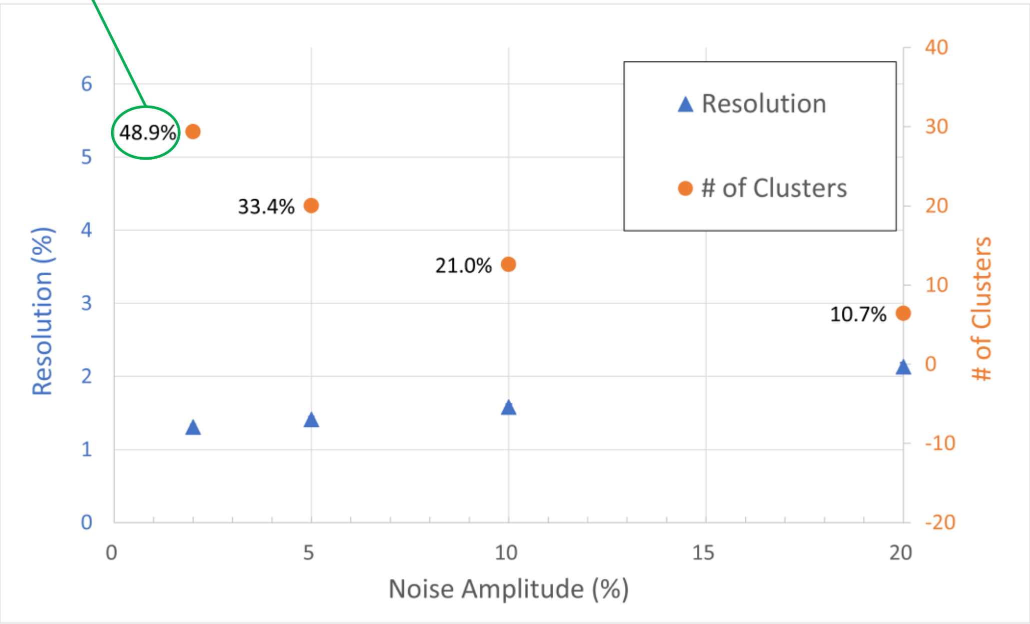


dN/dx resolution and counting efficiency (II)

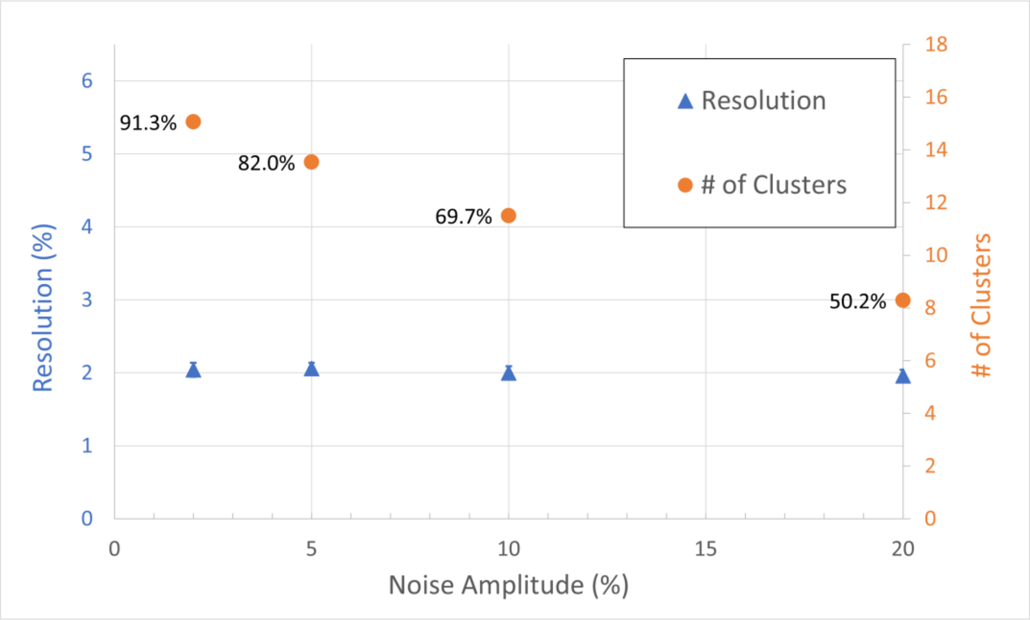
Particle: 10 GeV/c pions
Detector size: 1 cm * 150
Sampling rate: 2 GHz
Time constant: 0.5 ns

Counting efficiency

He50



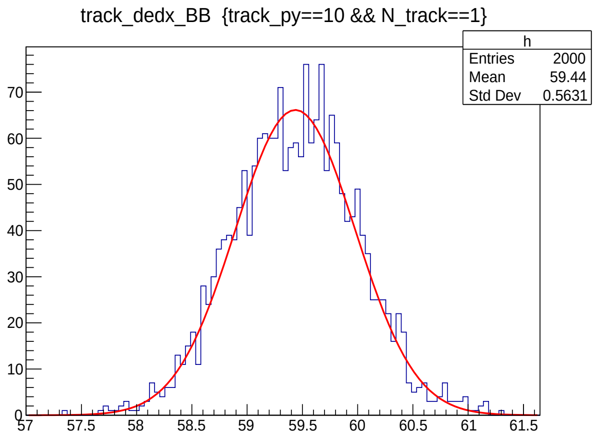
He90



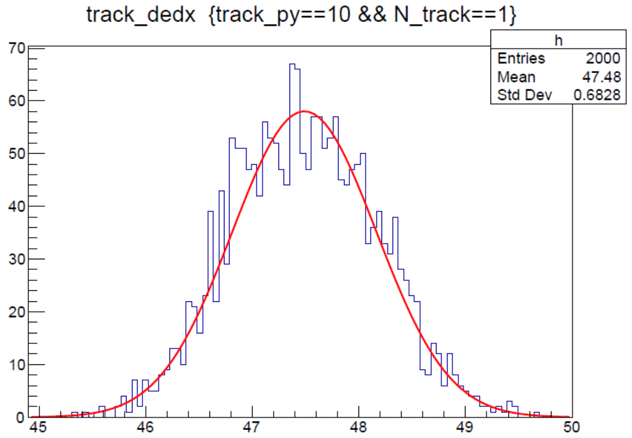
2% resolution is still achievable
He90 is less sensitive to the changing of the noises

Simulation in CEPCSW (I)

- **A simplified dN/dx and TOF simulation is implemented in CEPCSW**
- **dN/dx simulation:**
  - Simulate ionization and obtain the number of clusters N_{truth} at hit level (using Garfield++)
  - To mimic the inefficiency because of electronics/noises, applying a counting efficiency to truth cluster (Poissonian)
  - Expect number of clusters: $N_{expect} = N_{truth} * \mathrm{eff}, \mathrm{eff} \sim \mathrm{Gaus}(\mu, \sigma)$
    - Assuming eff distributions are stable



N_{truth}

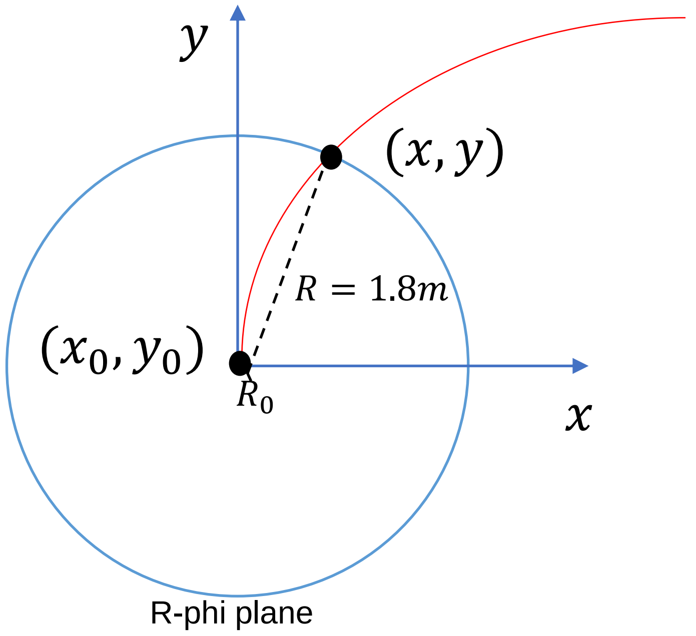


N_{expect} w/ $(80 \pm 10)\%$ efficiency

Thank Wenxing/Tao for the Garfield++ migration

Simulation in CEPCSW (II)

- **TOF simulation:**
  - Assume a cylindrical TOF detector at R = 1.8m
  - Calculate the time-of-flight using the truth momentum and assuming a time resolution of 20 ps



$$L = s\big((x_0, y_0) \rightarrow (x, y)\big)$$

$$t_{truth} = \frac{L}{v}, v = \frac{p_T}{\sqrt{p_T^2 + m^2}} c$$

$$\boldsymbol{tof} = Gaus(t_{truth}, \sigma)$$

Thank Zhijun for the discussion

K/pi separation power (He50)

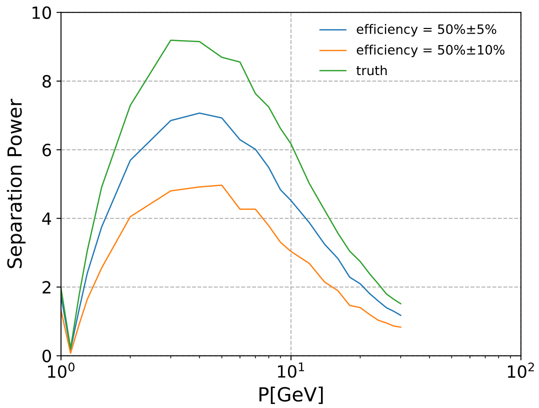
Separation power:

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

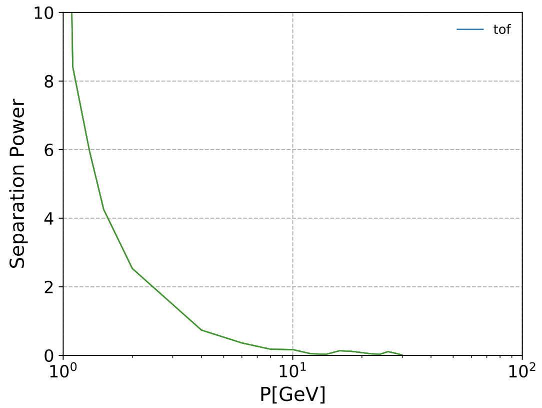
A reference counting efficiency from detailed simulation:

- ✓ Time constant: 0.5 ns
- ✓ Noise amplitude: 2%
- ✓ Counting efficiency: $(48.7 \pm 7.4)\%$

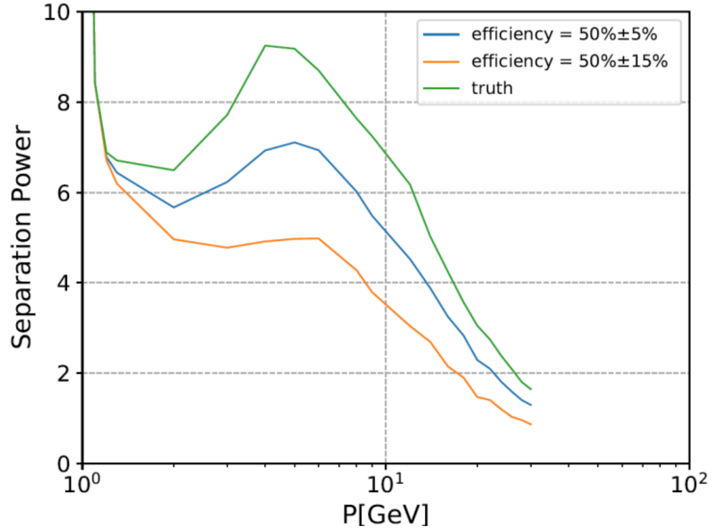
dN/dx



TOF



dN/dx + TOF



Can achieve 3σ K/pi separation power for p < 10 GeV/c

K/pi separation power (He90)

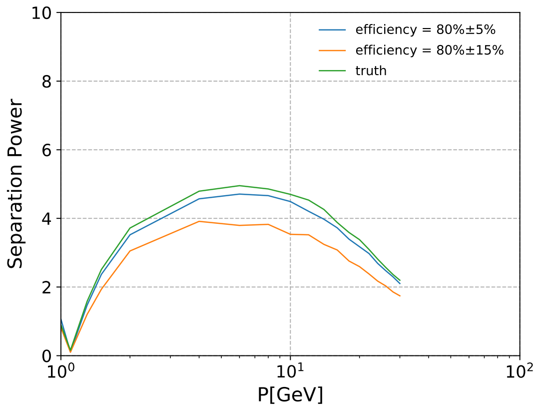
Separation power:

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

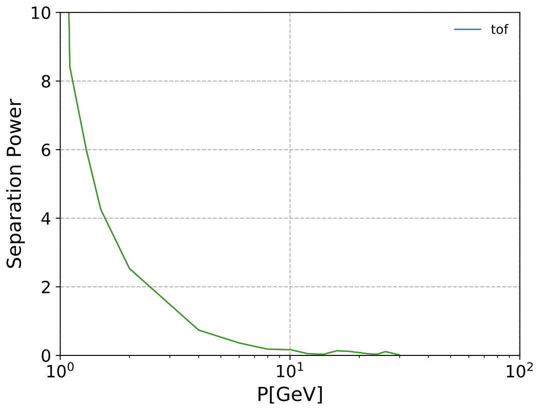
A reference counting efficiency from detailed simulation:

- ✓ Time constant: 0.5 ns
- ✓ Noise amplitude: 5%
- ✓ Counting efficiency: $(82.0 \pm 13.6)\%$

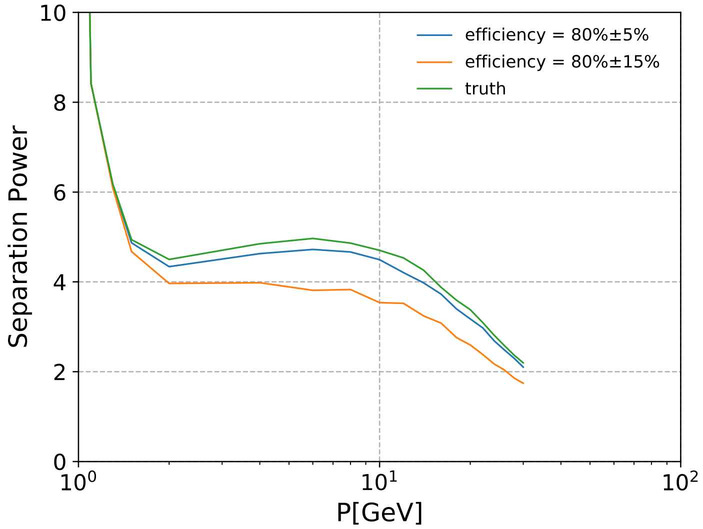
dN/dx



TOF



dN/dx + TOF



Better K/pi separation power for p > 10 GeV

Summary

- **A more realistic simulation is performed with the following electronics effects**
  - Pre-amplifer: broaden the signal pulses
  - Noise: pollute the signal

- **2 gas compositions are considered**
  - He 50% + iC_4H_{10} 50%: better resolution, more sensitive to the electronics
  - He 90% + iC_4H_{10} 10%: better counting efficiency, less sensitive to the electronics

- **The 2% resolution is achievable for the following electronics parameters**
  - Time constant: 0.5-5 ns
  - Noise amplitude: 2% - 20%

Summary (II)

- **A simplified simulation is implemented in CEPCSW, including**
  - dN/dx: hit-level sampling
  - TOF: time-of-flight calculation

- **K/pi separation power is calculated with the simplified simulation**
  - 3σ K/pi separation is achievable for $p < 10$ GeV/c
  - He90 composition has better a separation power for $p > 10$ GeV/c

- **Next to do**
  - Develop the fast simulation tool for the ionization generation
  - Study the effect of the secondary ionizations
  - Measure the PID performance with the detailed simulation

Backup slides

Truth level dN/dx