PID with Cluster Counting for the CEPC Drift Chamber

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CEPC Day
June 29th, 2022

The 4^{th} conceptual detector

Scint Glass PFA HCAL

Advantage: Cost efficient, high density
Challenges: Light yield, transparency, massive production.

Solenoid Magnet (3T / 2T) Between HCAL & ECAL

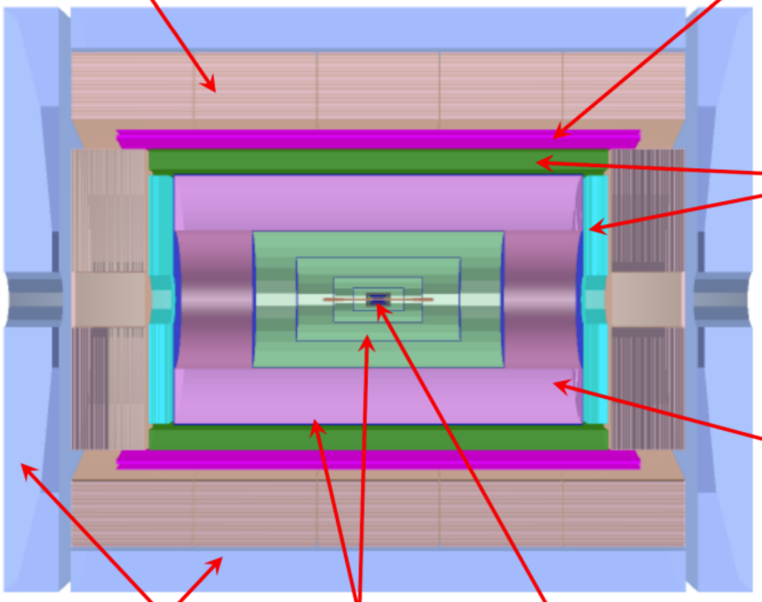
Advantage: the HCAL absorbers act as part of the magnet return yoke.
Challenges: thin enough not to affect the jet resolution (e.g. BMR); stability.

Transverse Crystal bar ECAL

Advantage: better π^0/γ reconstruction.
Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

A Drift chamber that is optimized for PID

Advantage: Work at high luminosity Z runs
Challenges: sufficient PID power; thin enough not to affect the moment resolution.

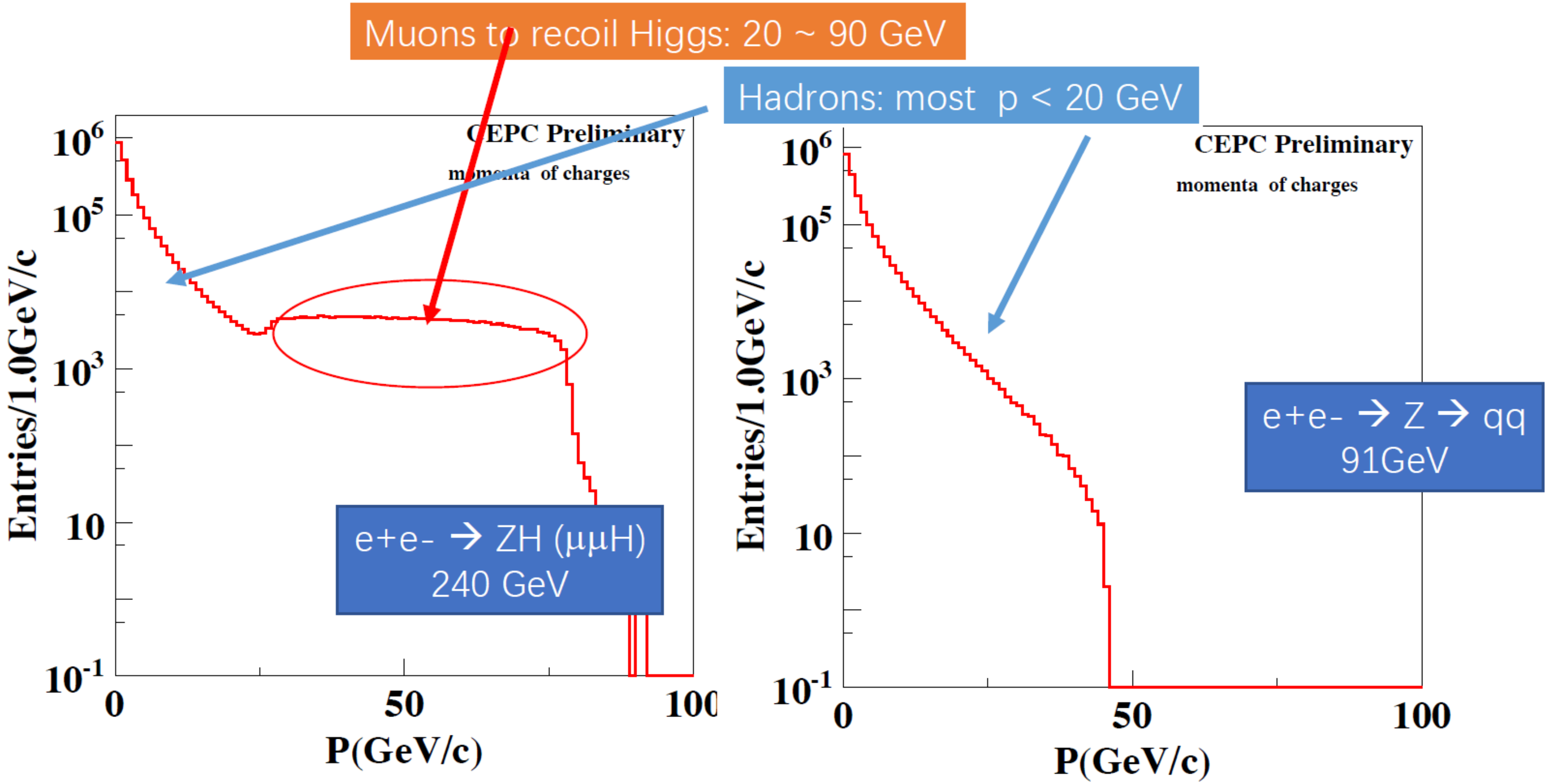


Muon+Yoke **Si Tracker** **Si Vertex**

Det	Technology
Pixel Vertex	JadePix
	TaichuPix
	Arcadia
	CPV(SOI)
	Stiching
Tracker & PID	TPC
	CEPCPix
	Drift chamber
	PID DC
	LGAD
	Silicon Strip

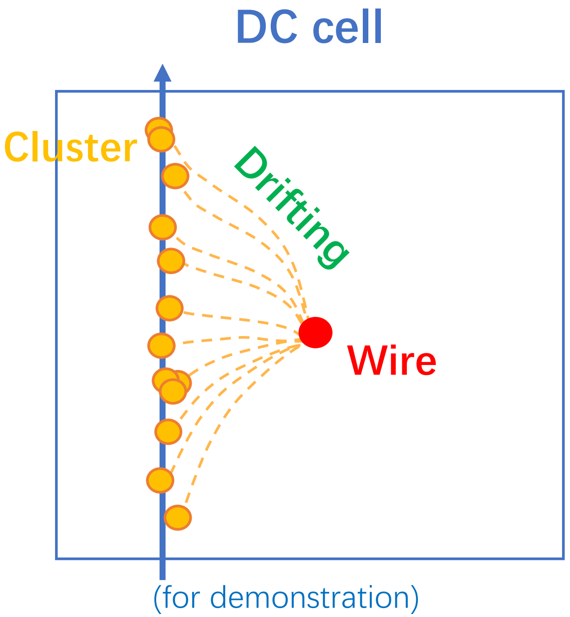
Det	Technology
Calorimeter	Crystal ECAL
	Si+W ECAL
	Scint+W ECAL
	Scint AHCAL
	ScintGlass AHCAL
	RPC SDHCAL
	MPGD SDHCAL
	DR Calorimeter
Muon	Scintillation Bar
	RPC
	μ-Rwell
Lumi	SiTrk+Crystal ECAL
	SiTrk+SiW ECAL

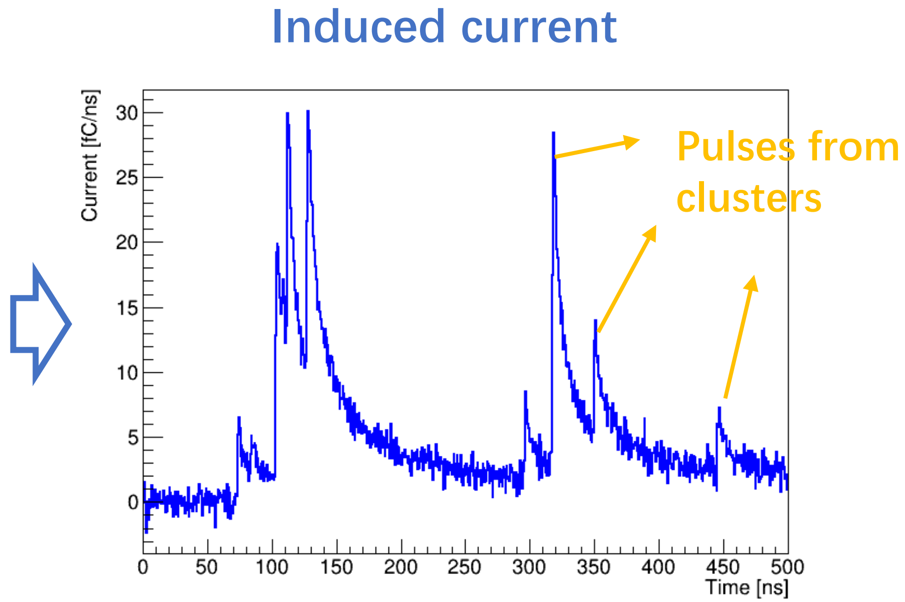
Physics requirements: hadron momenta



- Most hadrons from Higgs/Z pole data are below 20 GeV/c
- The drift chamber should have sufficient PID separation power for hadrons < 20 GeV/c

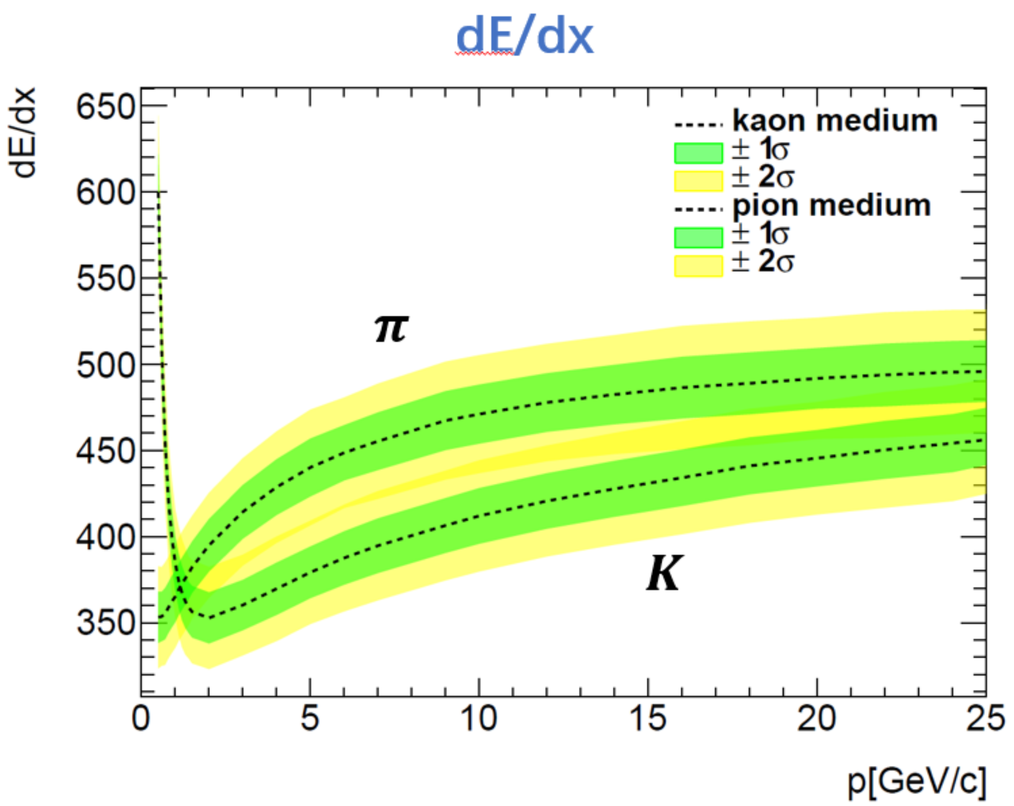
Ionization measurement with cluster counting

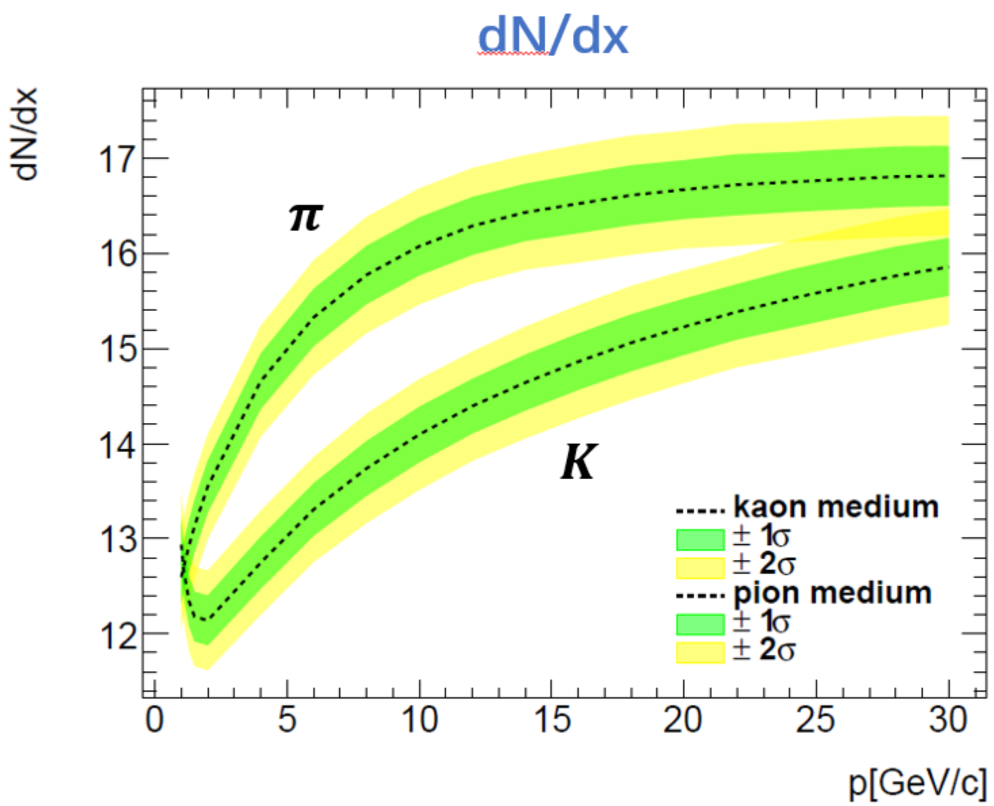




- ✓ **Cluster counting:** Measure # of clusters per length (**dN/dx**)
- ✓ **Clean in statistics:** $P\left(\bar{N}_p, k\right) = \frac{\bar{N}_p^k}{k!} e^{-\bar{N}_p}$
- ✓ **Theoretical resolution:** $\frac{1}{\sqrt{N_p}} = \frac{1}{\sqrt{\rho_{cl} \times L}}$ (potentially a factor > 2 better than **dE/dx**)

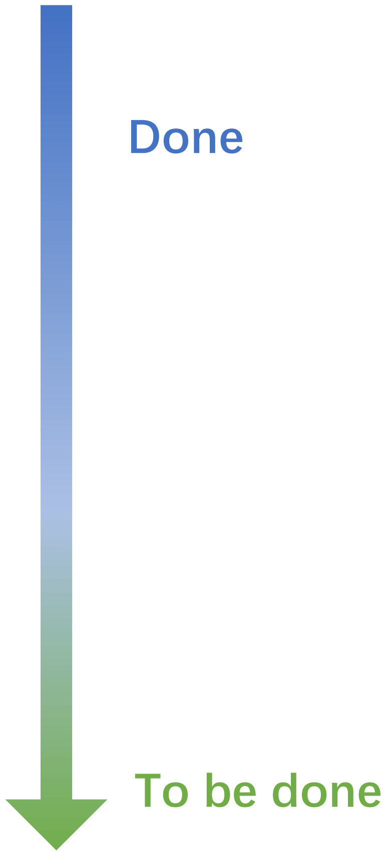
Better K/π separation with dN/dx (MC truth)





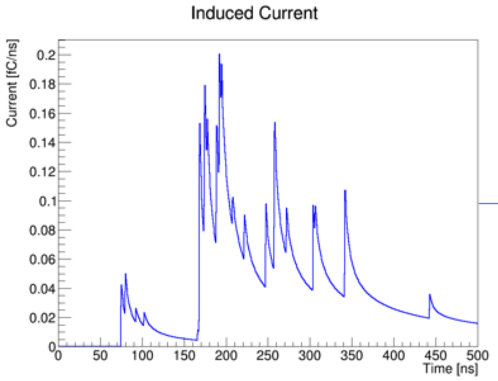
Tasks of DC PID study

- **DC modeling**
  - Simple and proper modeling of DC for configuration study and for general simulation
- **Best algorithm**
  - Efficient cluster finding algorithms to be implemented in front-end electronics
- **Best configuration**
  - **Optimal electronics, gas mixtures, HV for PID alone**
  - **Reduce the radial thickness, cell number, supporting structure for other detectors**
- **Physics performance**
  - Results with selected benchmark channels



DC Modeling: Waveform-based simulation

Induced current



Signal generator (Garfield++):

- Heed: ionization process
- Magboltz: gas properties (drift/diffusion)

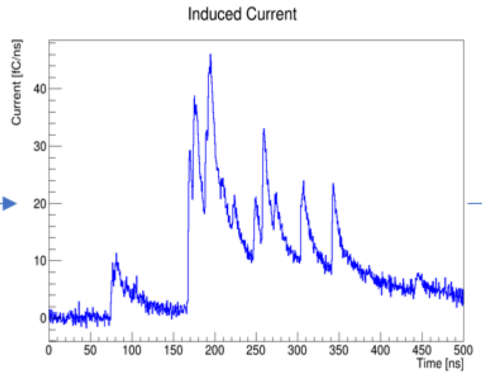
Garfield++ simulation

Electronics

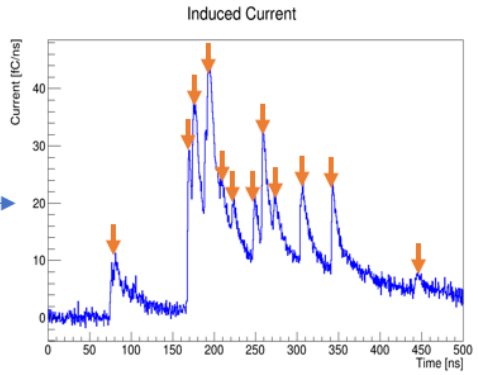
Electronics:

- Preamplifier
- Noises
- ADC

Realistic waveform



Digitization



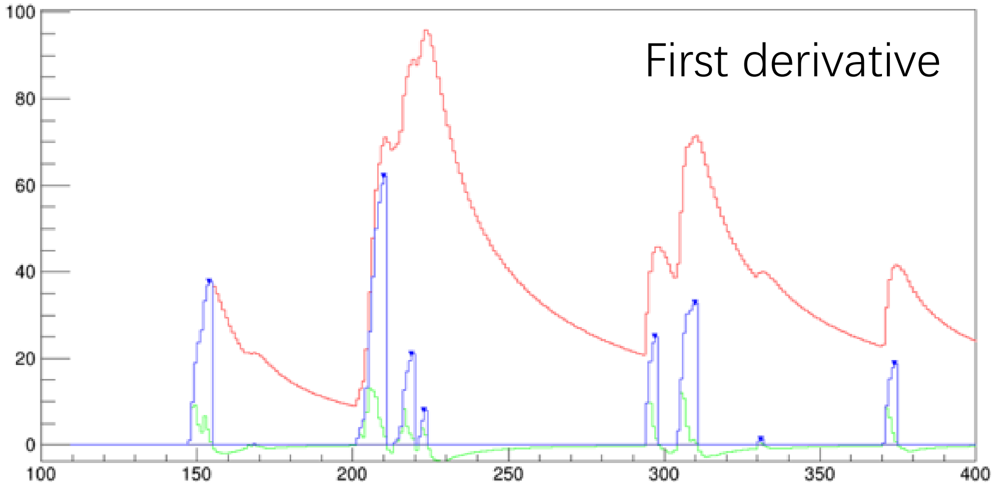
Peak finding algorithm:

- Second derivative

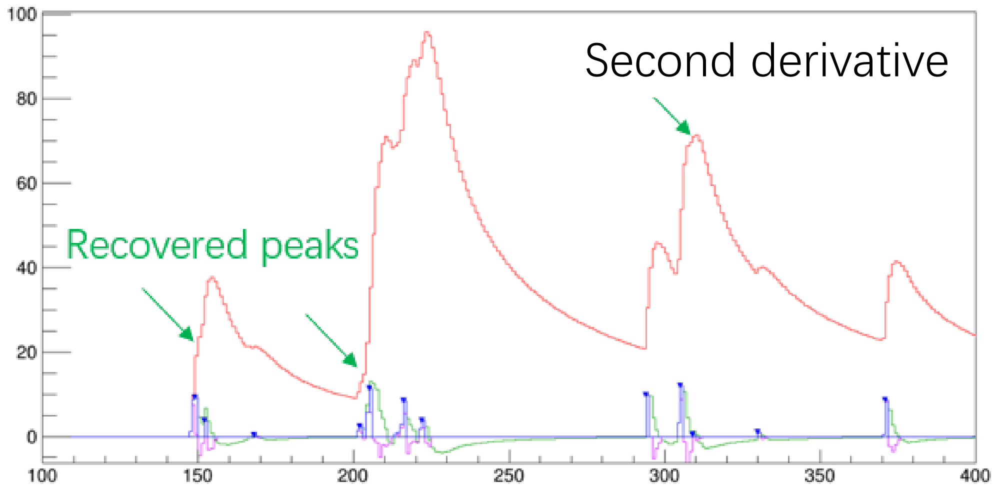
Reconstruction

Algorithm

- **Peak finding algorithm based on 1st and 2nd order derivatives**
  - Fast and efficient
  - Good pile-up recovery ability on the rising edge



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



DC configuration optimization: figure of merit

PID performance is in a higher priority

K/pi separation power n = $\frac{\left|\left(\frac{dN}{dx}\right)_{\pi}-\left(\frac{dN}{dx}\right)_{K}\right|}{(\sigma_{\pi}+\sigma_{K})/2}$

- The n depends on the
  - cluster density ρ_{cl}
  - track length L
  - efficiency ϵ

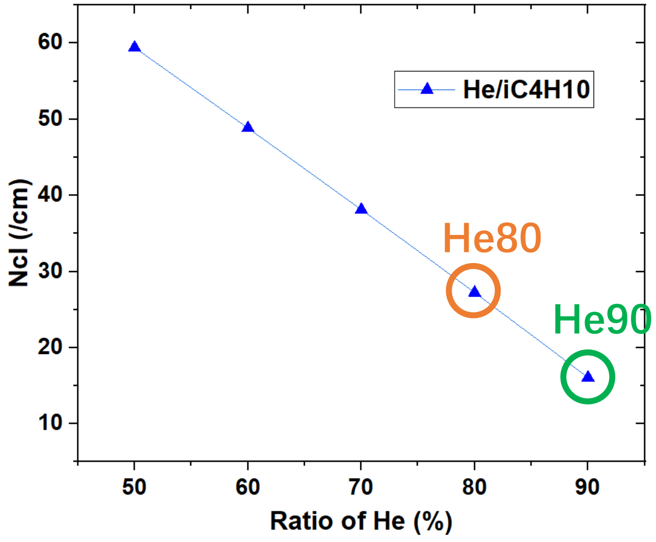
⇔

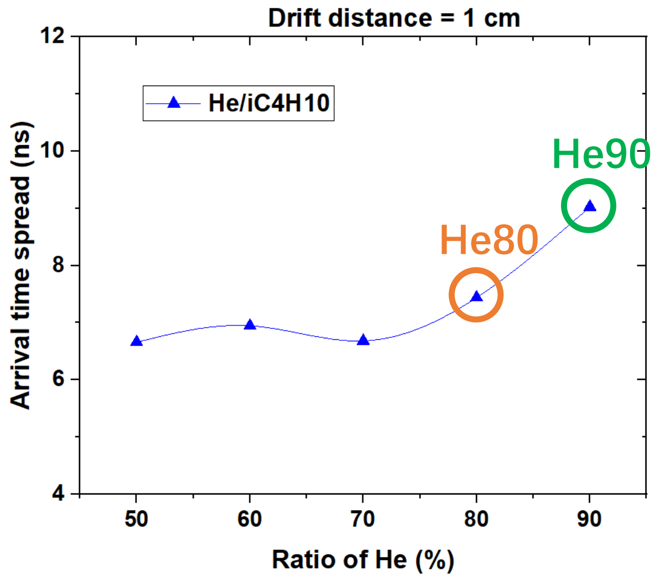
- **gas mixture**
- **cell size**
- **detector thickness**

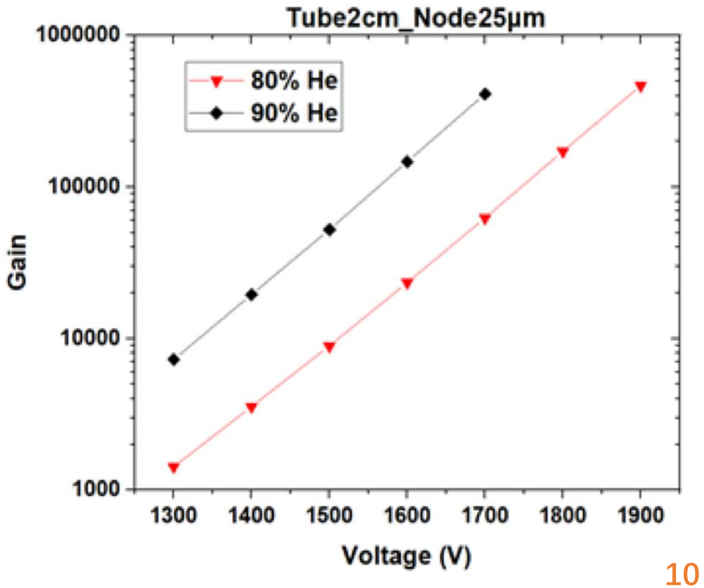
- Parameters in simulation:
  - Track direction: $\cos\theta = 90°$
  - Impact parameter of track w.r.t. sense wire: 0.2 cm

Gas mixture

- **Gas mixtures can affect several properties:**
  - Cluster density (ρ_{cl}): small ρ_{cl} ➔ less statistics, large time separation
  - Drift velocity (v_d): slow v_d ➔ large time separation
  - Longitudinal diffusion (σ_d): small σ_d ➔ less likely double-counting
  - Gas gain
  - …
- **Gas mixture choice: He + C_4H_{10}**

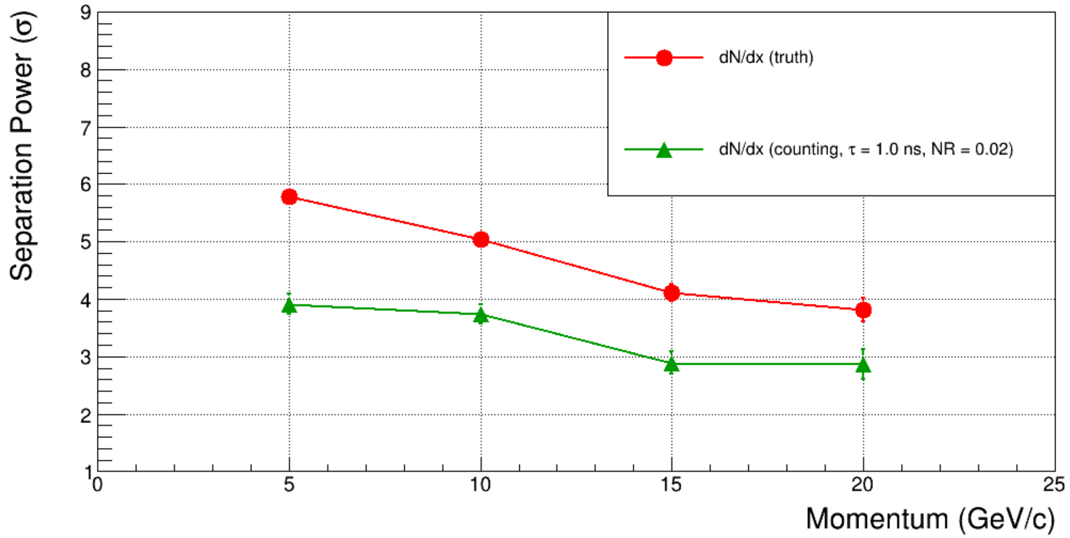




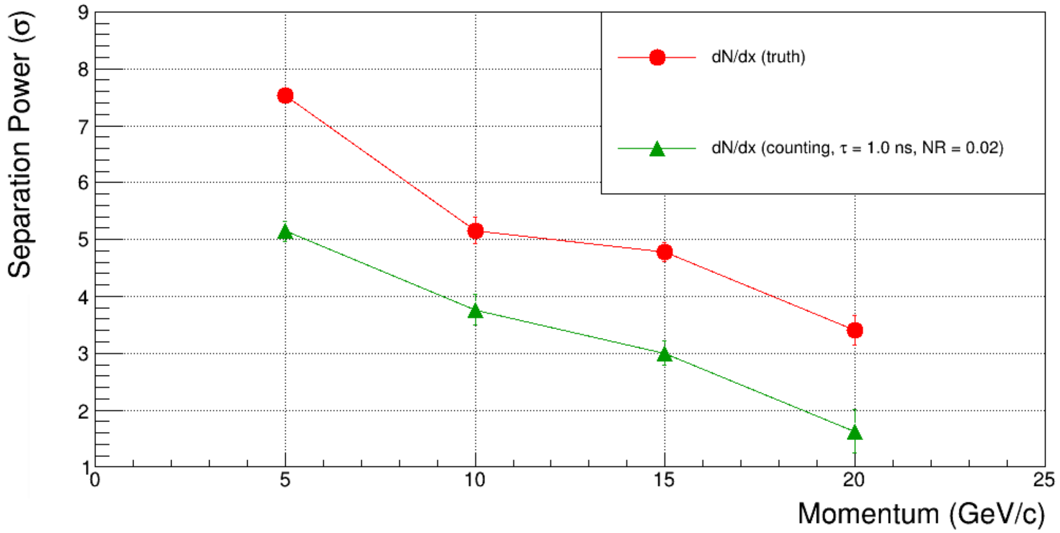


K/π separation for gas mixtures

He 90% + iC_4H_{10} 10%, L = 1m, NR = 0.02， 1x1cm cell



He 80% + iC_4H_{10} 20%, L = 1m, NR = 0.02, 1x1cm cell

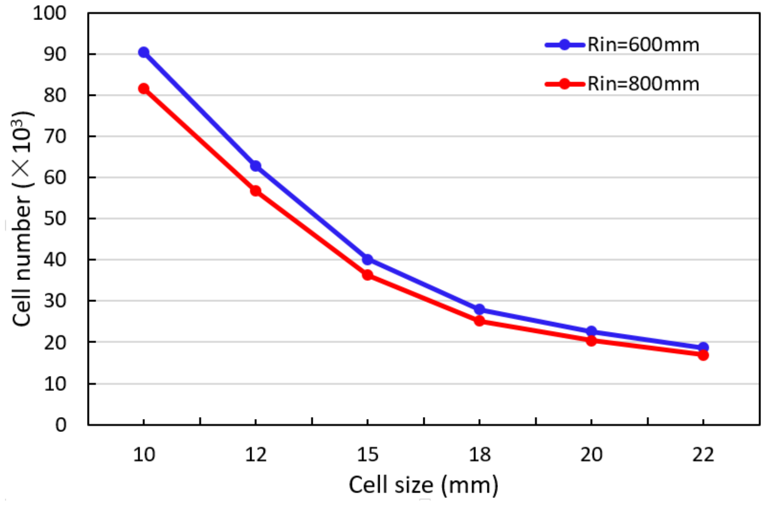


- He 90% + iC_4H_{10} 10% has better K/pi separation for high momentum
- He 80% + iC_4H_{10} 20% has better K/pi separation for low momentum
- PID in low momentum region can be covered by timing detector ➔ **He 90% is favored**

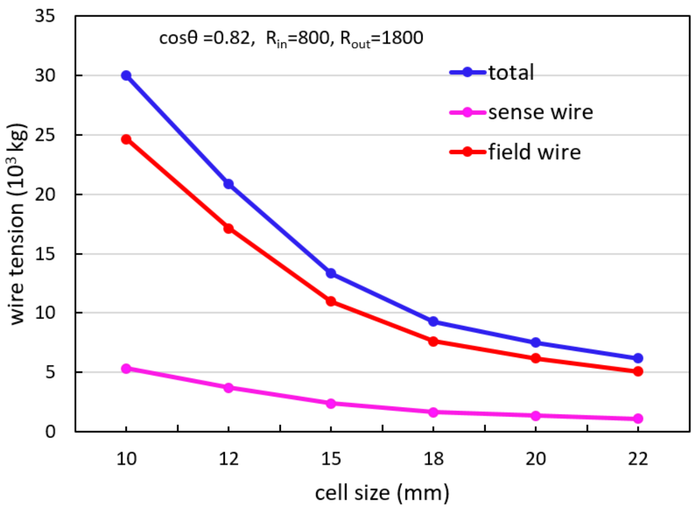
Cell size

- In principle, only the total track length affects the PID, not the granularity
- However, the cell size has impact on the engineering

# of cells vs. cell size

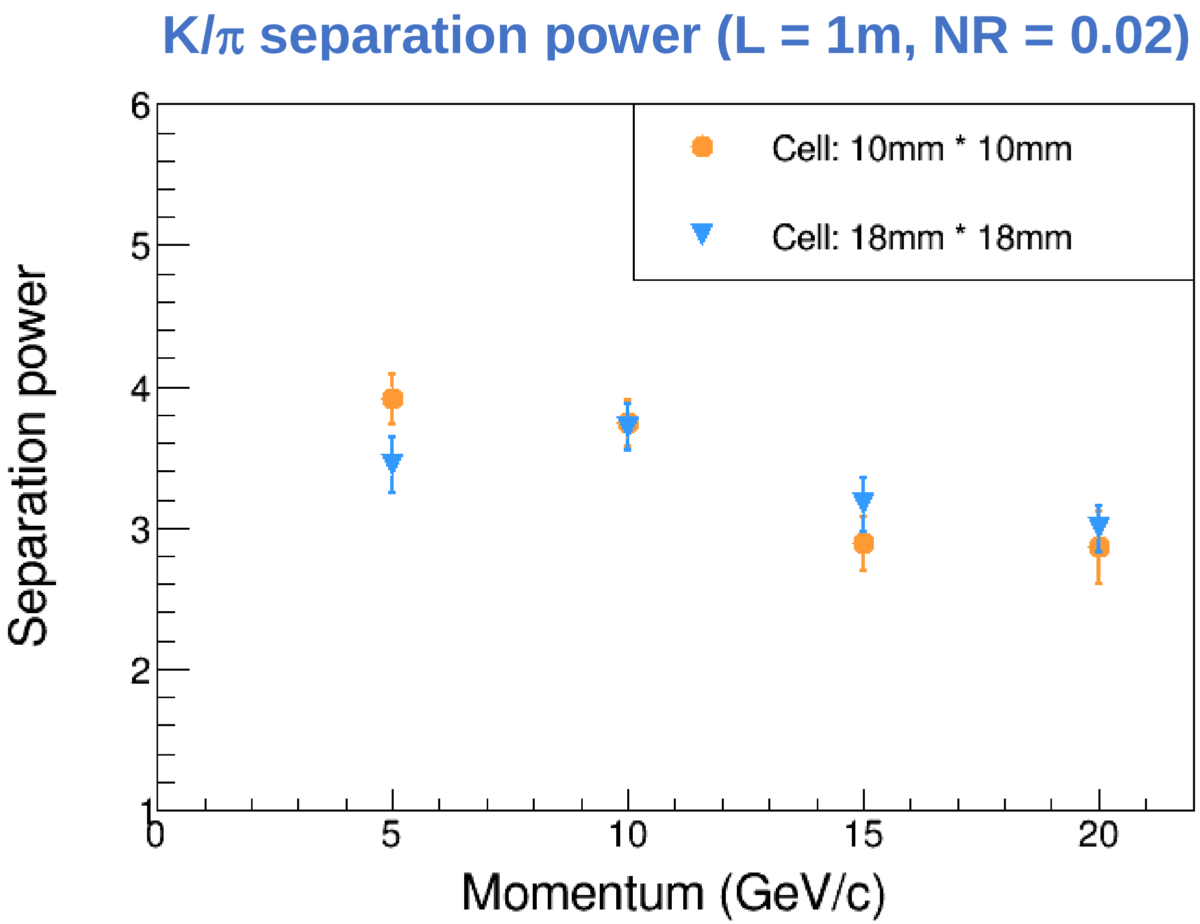


wire tension vs. cell size



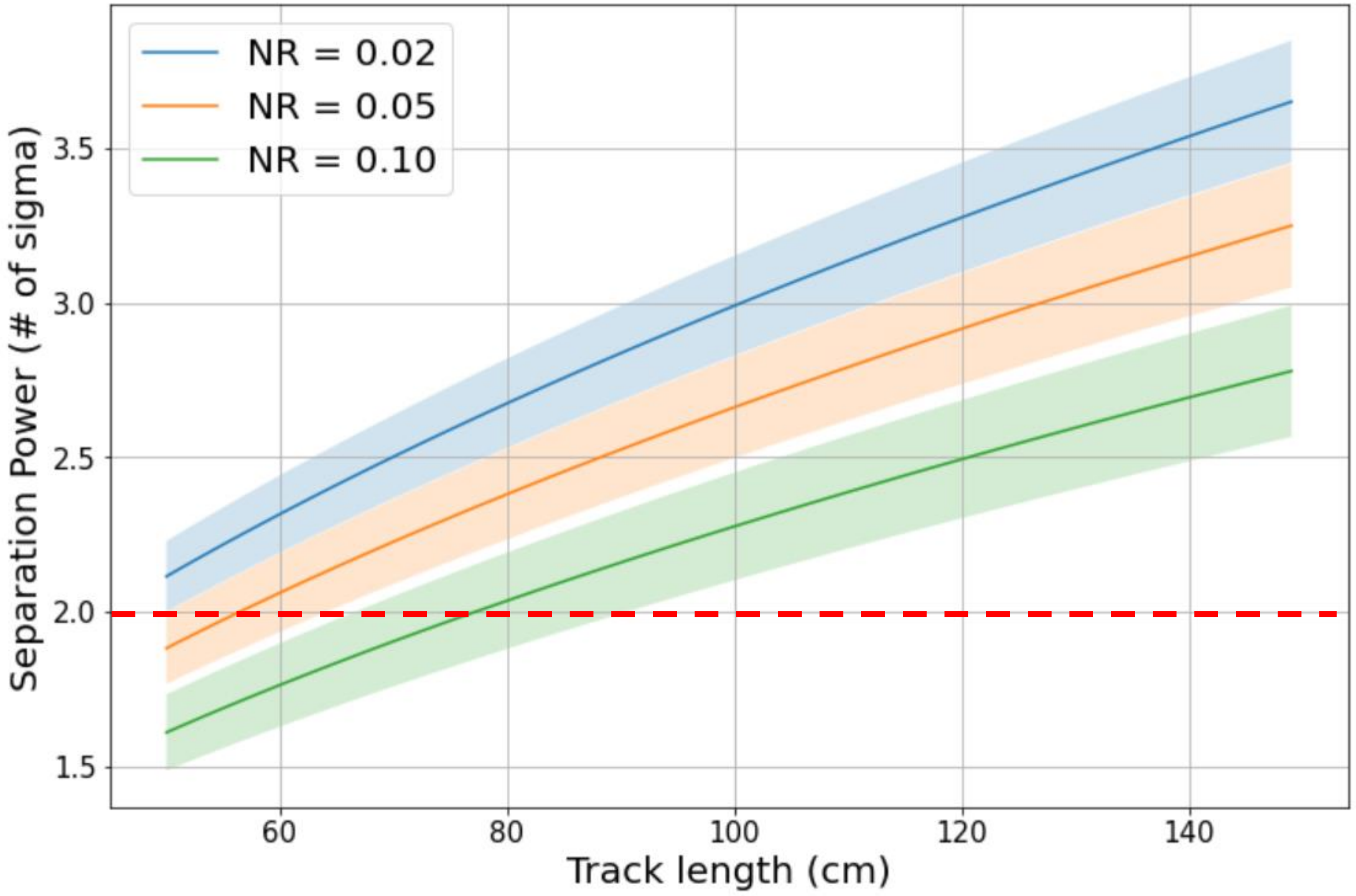
- Larger cell ➔ less wire tension ➔ easy engineering
- **Large cell is favored**

K/π separation for cell sizes



Cell size cannot affect PID significantly.
Cell size = 18 x 18 mm is preferred

K/π separation @ 20 GeV/c for track lengths

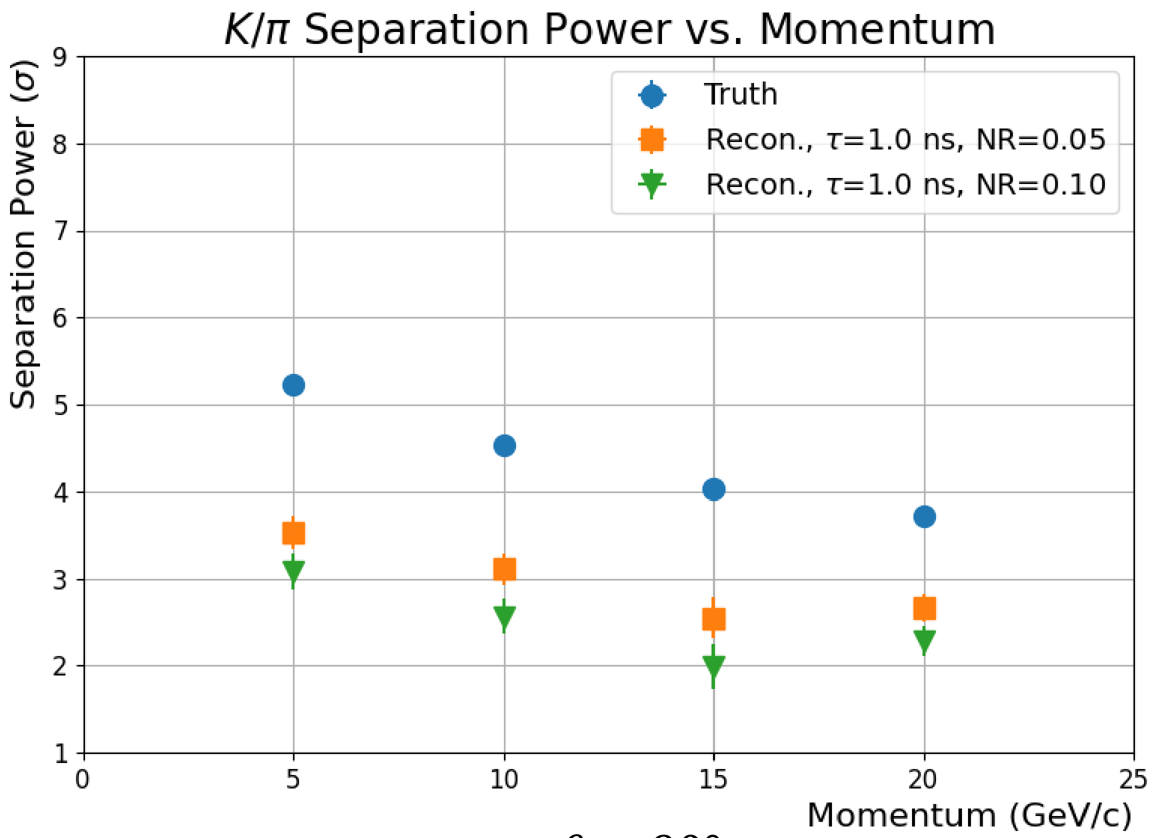


The resolution scales with $L^{-0.5}$
(Noise ratio in beam-test is close to 10%)

- Small radial thickness (while keeping sufficient PID performance) to reduce the impact on other detectors (e.g., SiTrk, Calorimeters)
- **The min. radial thickness could be < 100 cm for a 2σ K/π separation @ 20 GeV/c**
- The requirement of separation power needs further studies with physics channels

Optimization results and PID performance

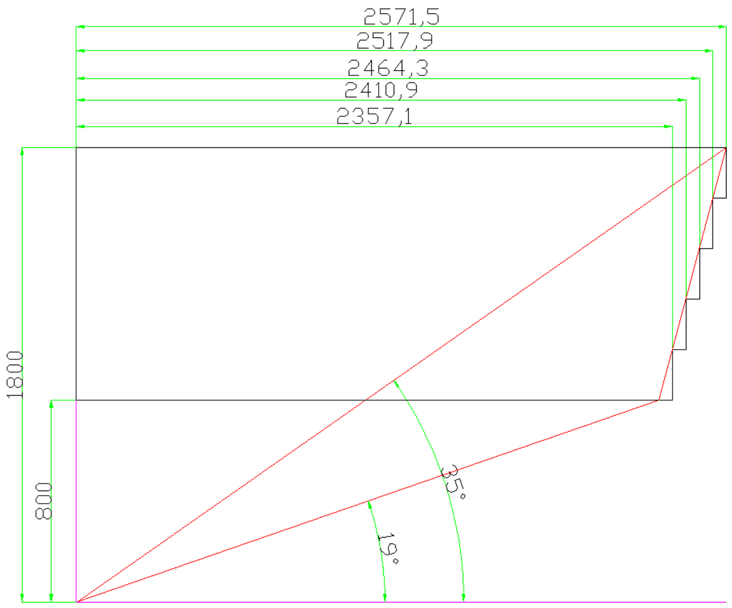
DC Parameters	
Radius extension	800-1800 mm
# of layers	55
Cell size	18 mm × 18 mm
Gas mixture	He/iC_4H_{10}=90:10



$\theta = 90°$

Mechanical study: wire tension

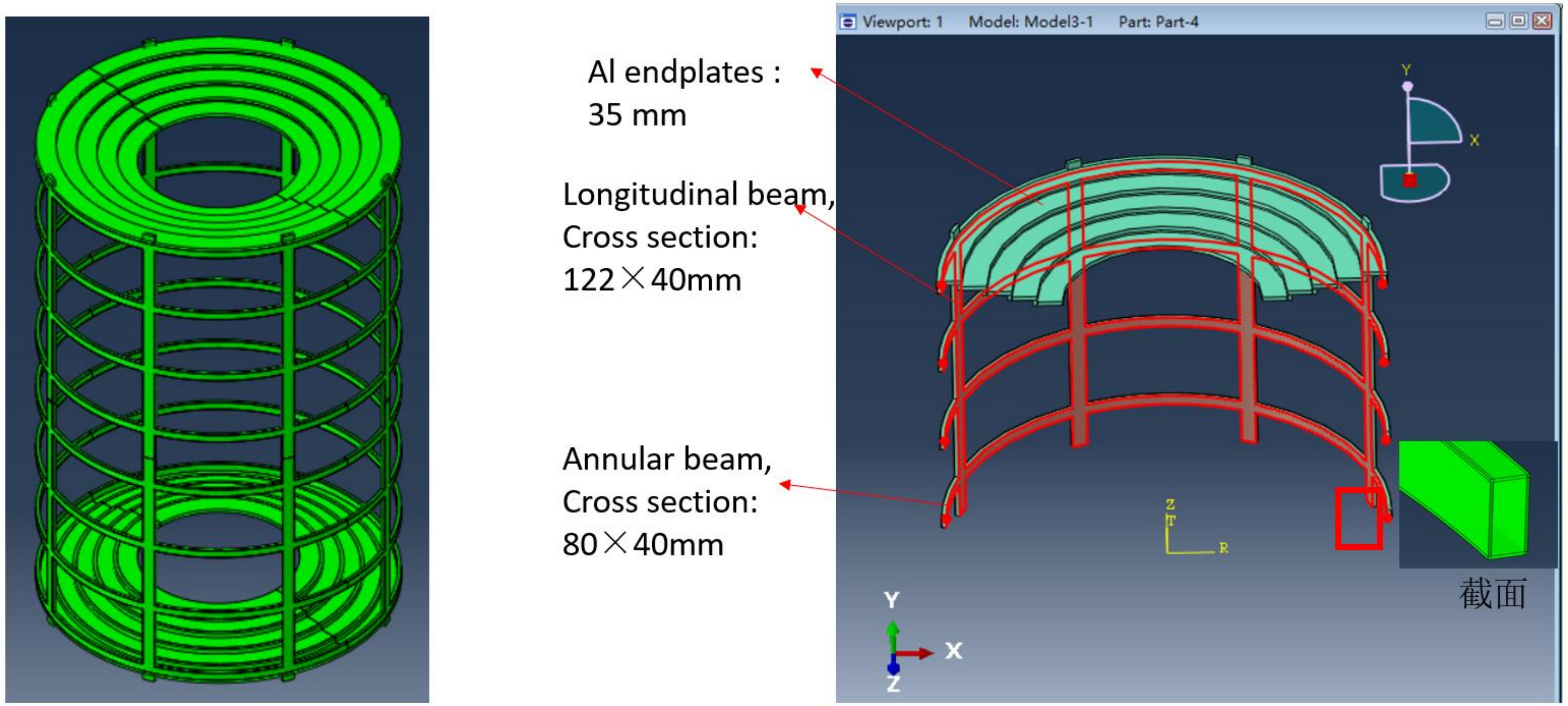
- ✓ Diameter of field wire (Al coated with Au) : 60μm
- ✓ Diameter of sense wire (W coated with Au): 20μm
- ✓ Sag = 280 μm



Step	cell number /step	length	single sense wire tension (g)	Single field wire tension (g)	total tension /step (kg)
1	3417	4715	60.15	92.42	1153.08
2	4185	4822	62.91	96.66	1477.02
3	4953	4929	65.74	101.00	1826.47
4	5721	5036	68.62	105.44	2202.24
5	6489	5143	71.57	109.96	2605.11
total	24766				9263.92

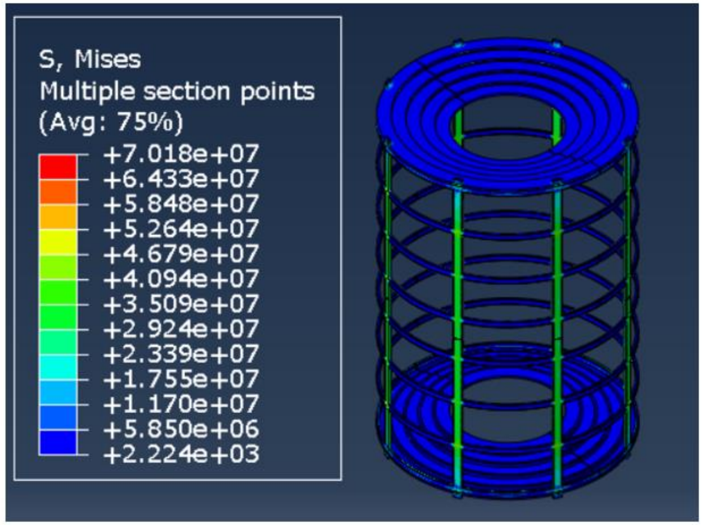
Meet requirements of stability condition: $T > (\frac{VLC}{d})^2/(4\pi\varepsilon_0)$

Mechanical study: support structures

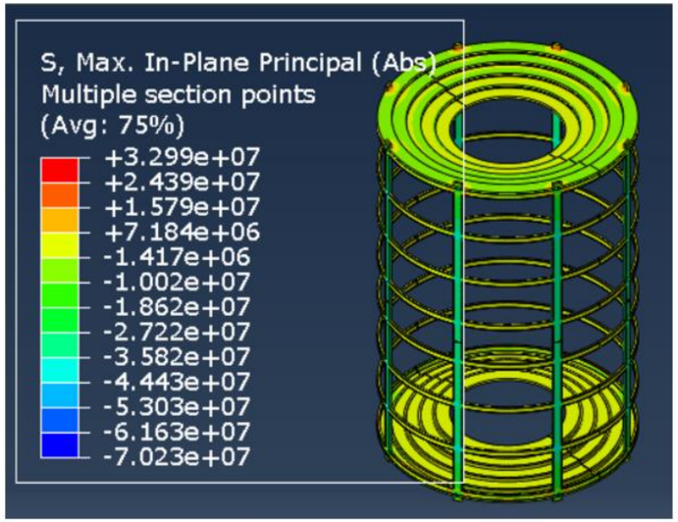


- Carbon fiber frame structure, including 8 longitudinal hollow beams and 8 annular hollow beams
- Thickness of inner CF cylinder: 200 μm/layer
- Effective outer CF frame structure: 1.63 mm
- Thickness of end Al plate: 35 mm

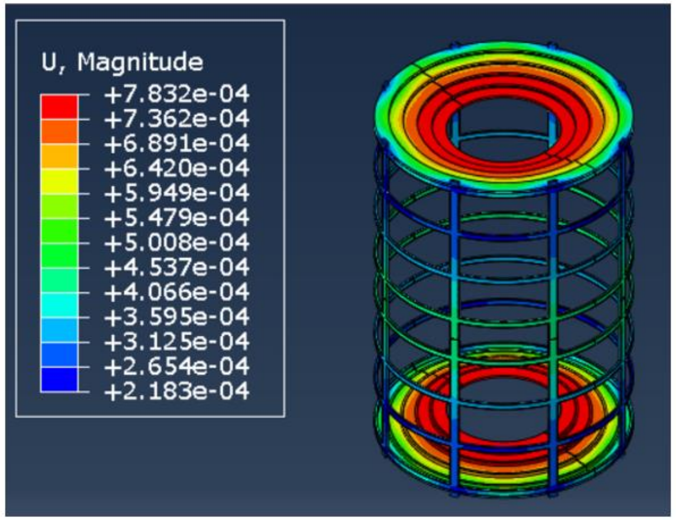
Mechanical study: stability



Mises stress



Principle stress



Deformation

Finite element model——wire tension + weight loads (supported by eight blocks at each endplate)

Mises stress: 70MPa
Principal stress : 33MPa
Deformation: 0.8mm
Buckling coefficient: 17.2 , it is safe

The support structure is stable, and the deformation is acceptable

Summary

- **A simulation model and an effective algorithm have been developed for DC PID study**
- **An optimized DC configuration is provided**
  - Gas mixtures: 90% He + 10% C_4H_{10}
  - Min. radial thickness of DC: < 100 cm (2σ K/π separation @ 20 GeV/c)
  - Cell size: 1.8 cm x 1.8 cm
  - Stable mechanical structures

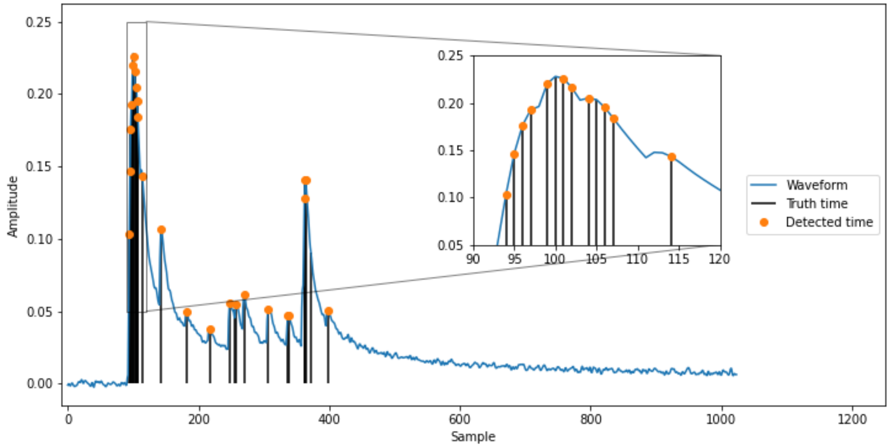
DC Parameters	
Radius extension	800-1800 mm
Length of outermost wires（cosθ=0.82）	5143 mm
Thickness of inner CF cylinder	200 μm
Outer CF frame structure	Equivalent CF thickness: 1.63 mm
Thickness of end Al plate	35 mm
Cell size	18 mm × 18 mm
# of cells	24766
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC_4H_{10}=90:10

Outlook

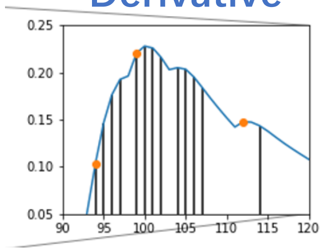
- **Study the PID requirement from physics channels**
  - Physics input to constrain the detector parameters
  - Delphes fast simulation is ongoing

- **More effective peak finding algorithm**
  - An algorithm using deep learning is being developed. Preliminary study shows promising results

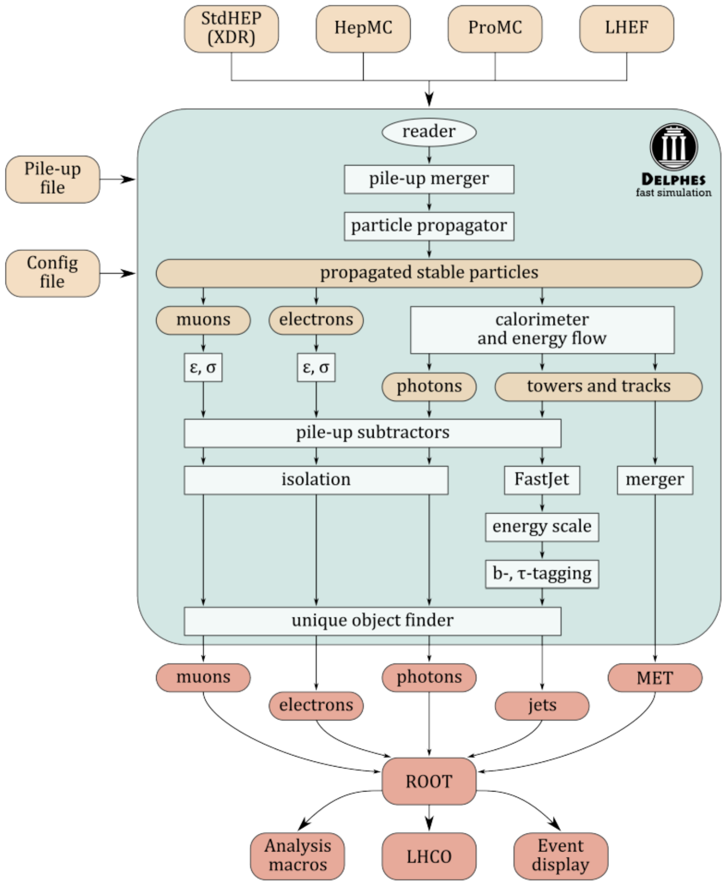
Deep Learning



Derivative



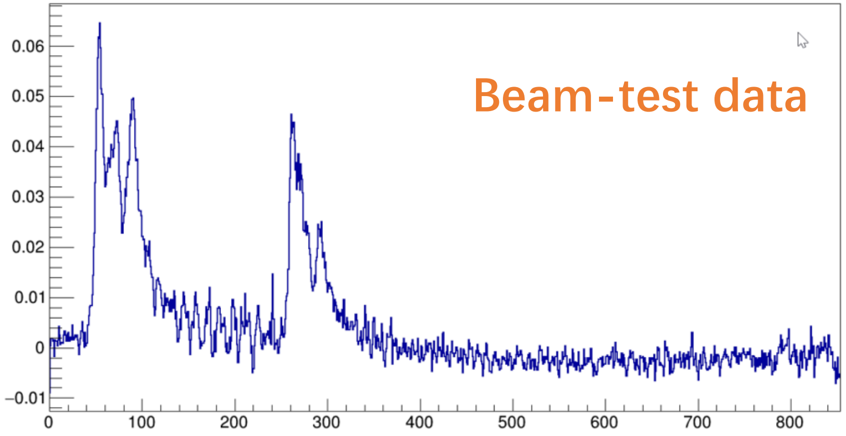
Delphes

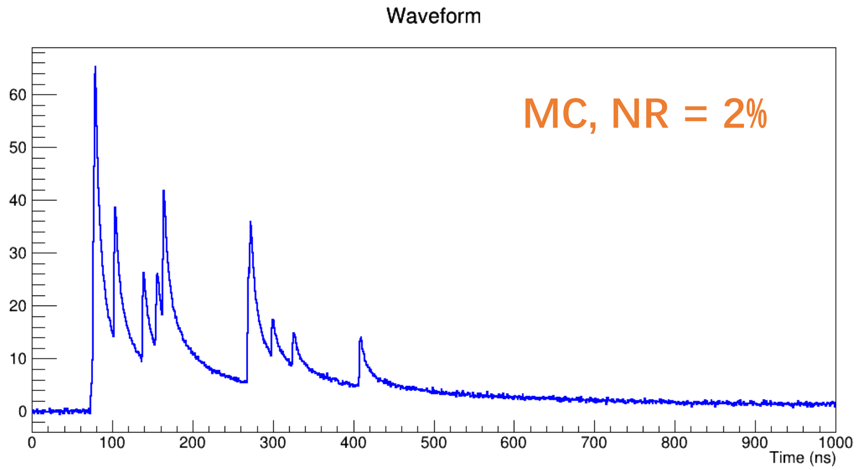


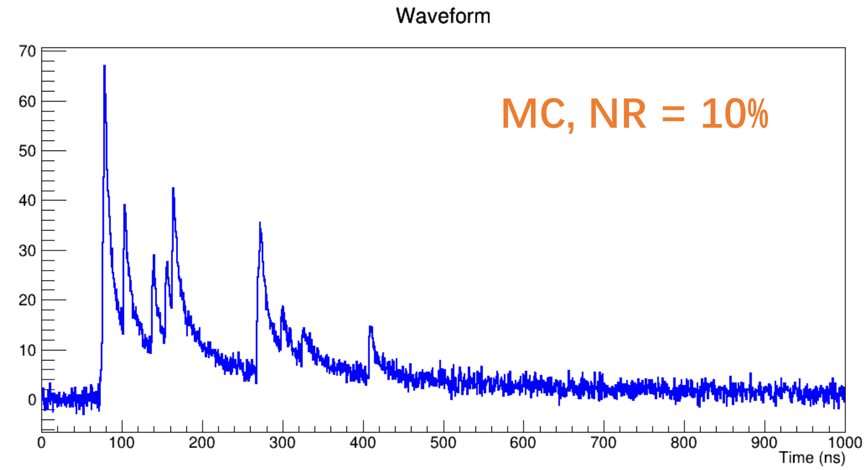
Backup

Noise ratio

- **Noise ratio definition:** $\frac{\sigma_{Noise}}{\bar{A}_{signal}}$
  - $\bar{A}_{signal}$: Averaged single-pulse amplitude
  - σ_{Noise}: Noise RMS

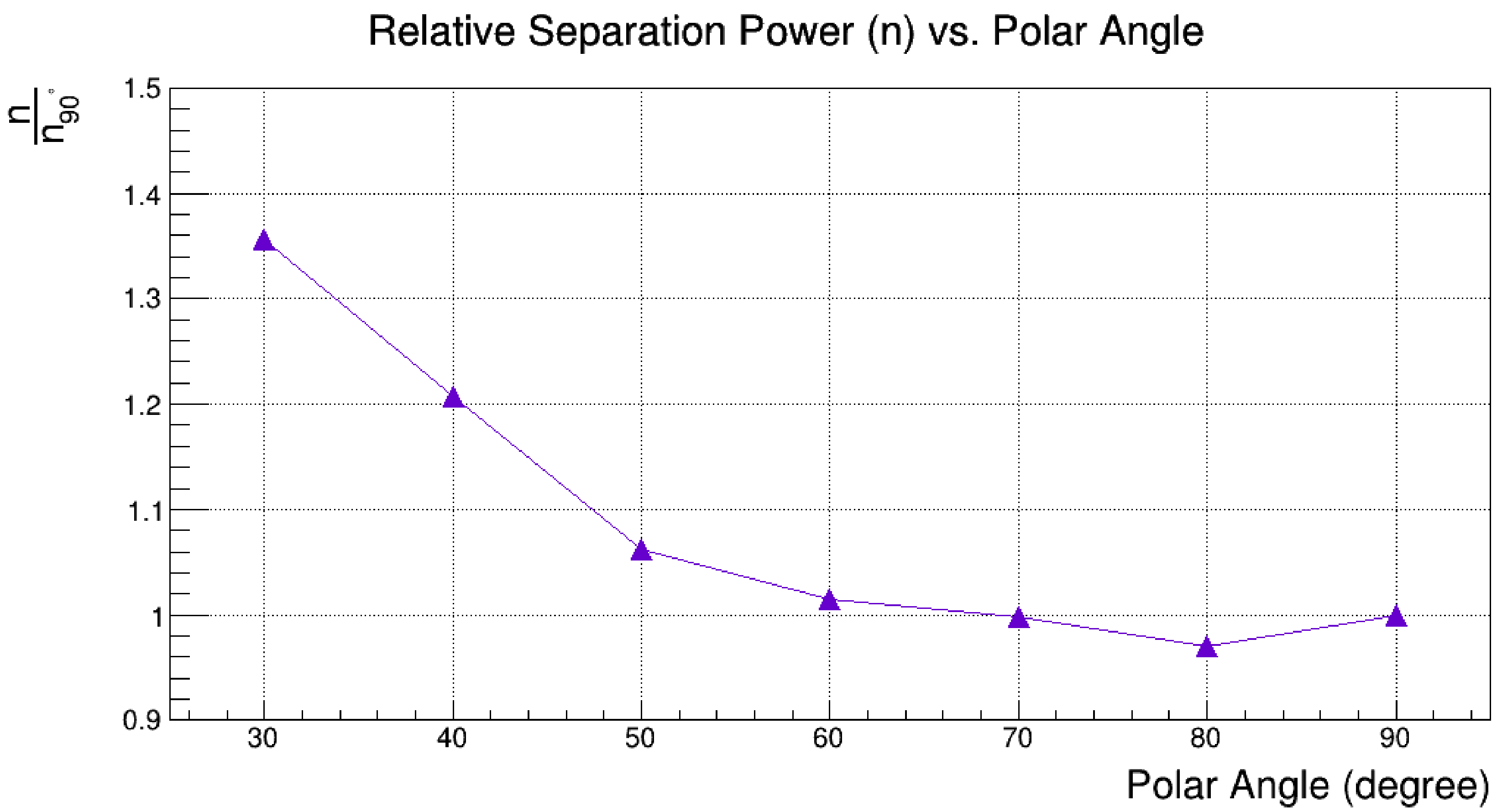






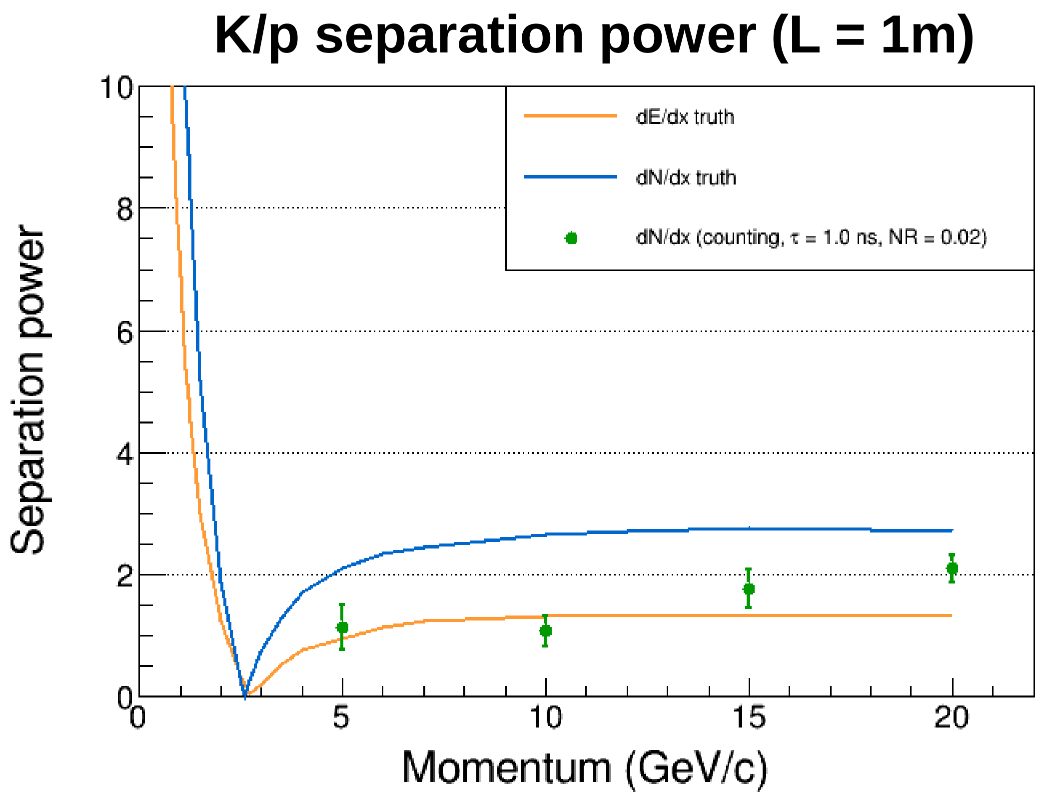
Note: noise ratio in beam-test data is close to ~10%

K/π separation vs. polar angles



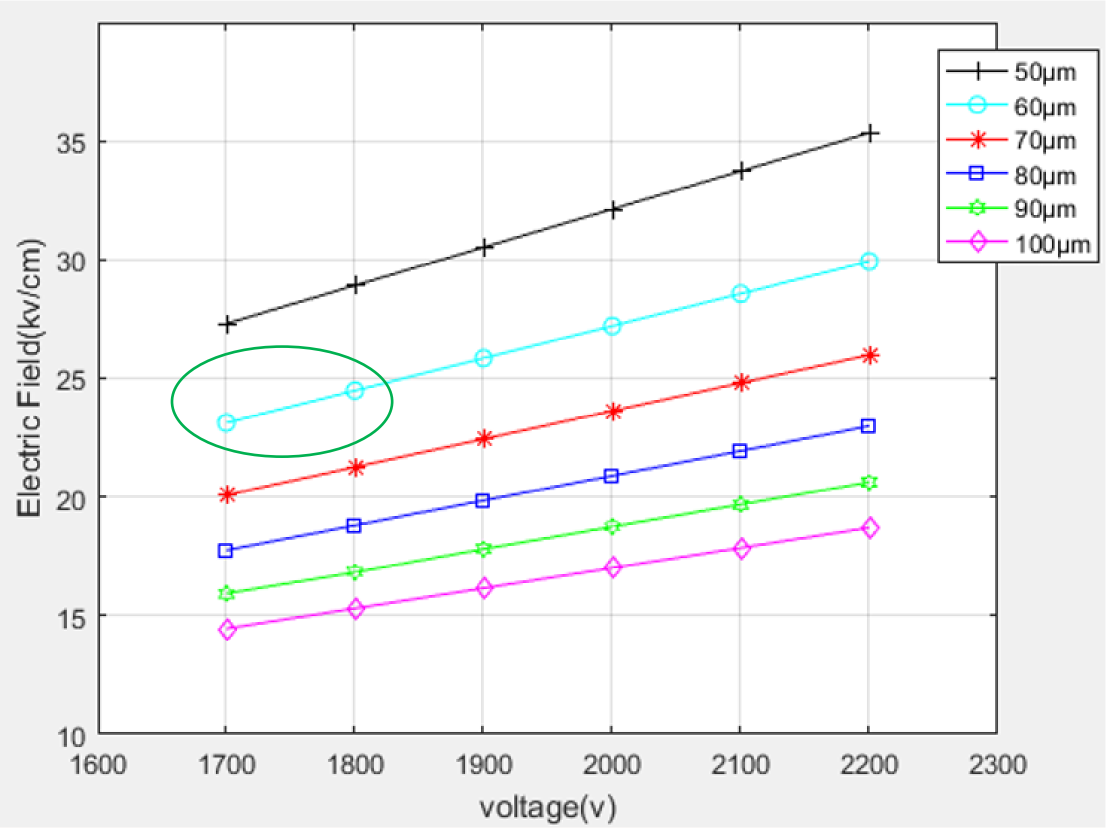
Note: NO space charge in simulation

K/π separation for proton

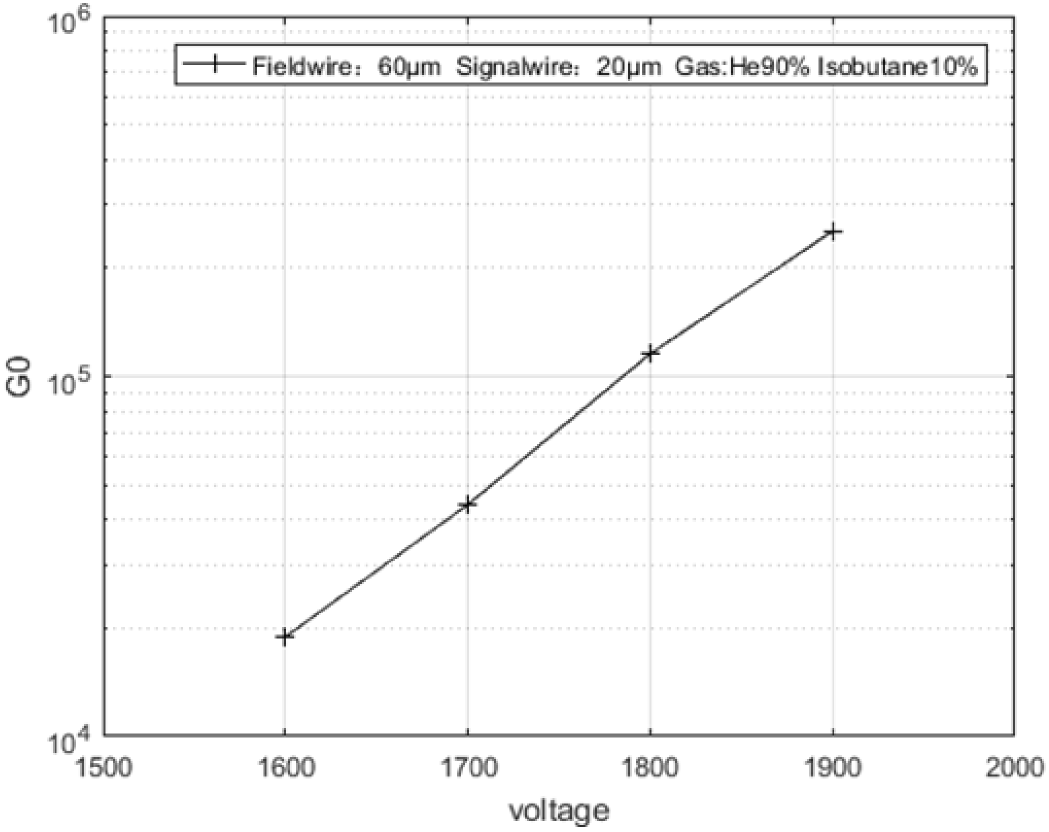


K/p separation power at 20 GeV/c is around 2σ

Field and gain

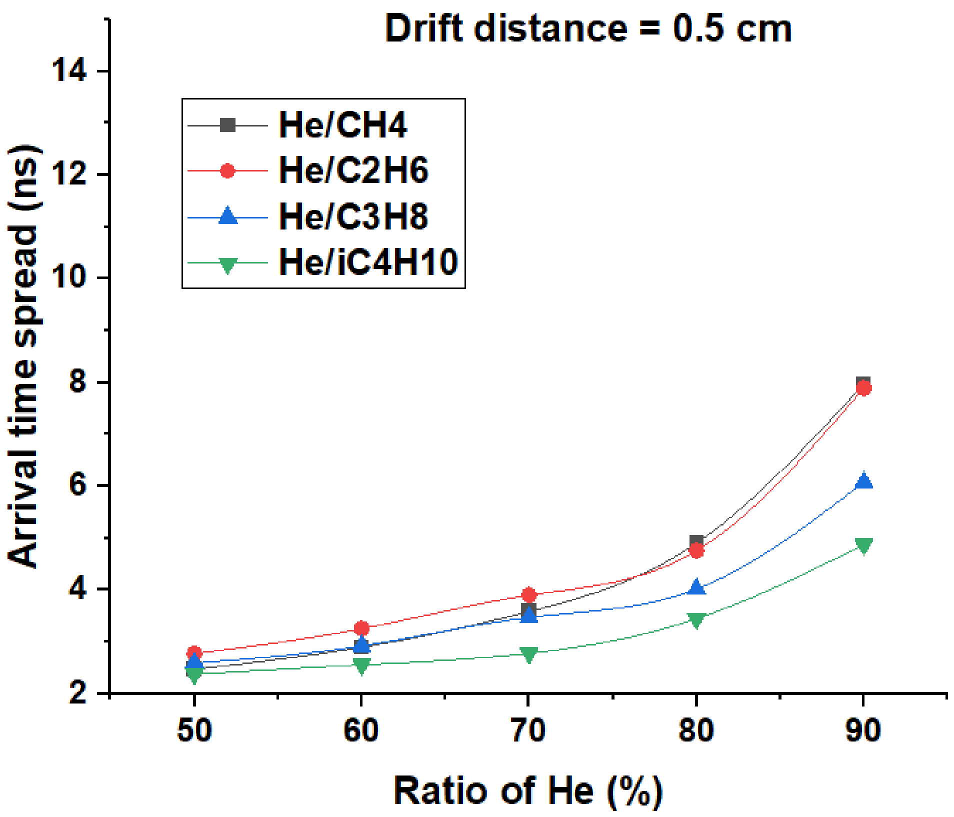


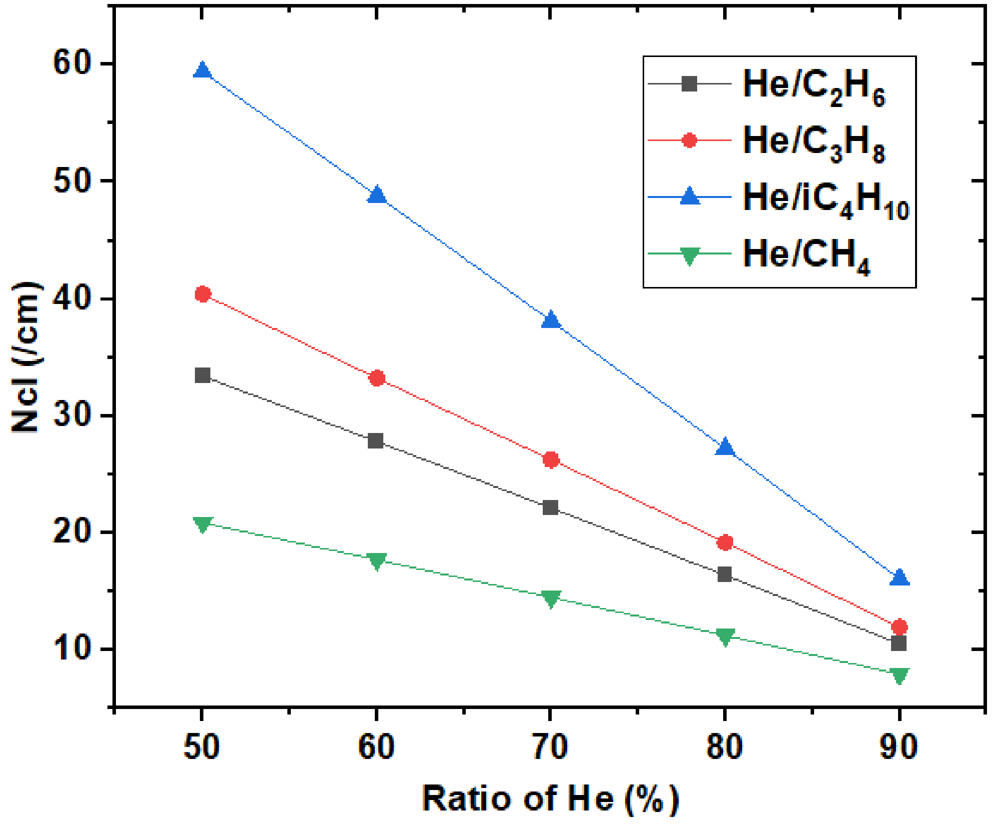
Electric field of field wires



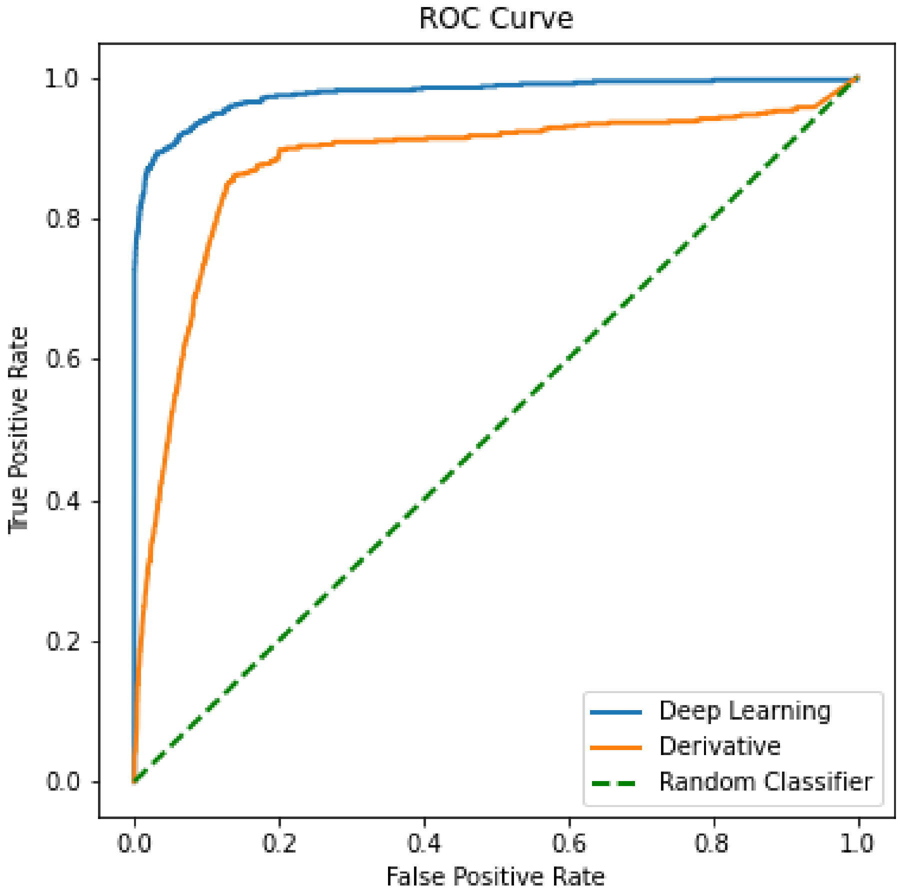
Gain

Properties for more gas mixtures





Receiver Operating Characteristic (ROC)



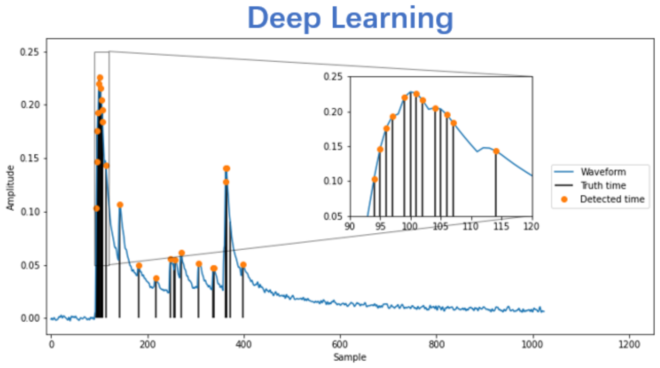
NN is a better binary classifier than the derivative method

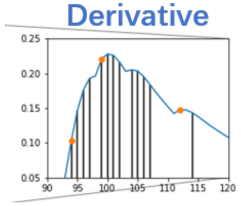
Note: ROC curve is a standard tool for evaluation binary classifiers. ROC curve with larger area-under-curve (AUC) is better

基于机器学习的簇团寻找算法

- **簇团寻找算法是dN/dx关键技术，尝试从算法上寻找突破**
  - 寻峰：寻找所有电子峰（循环神经网络）

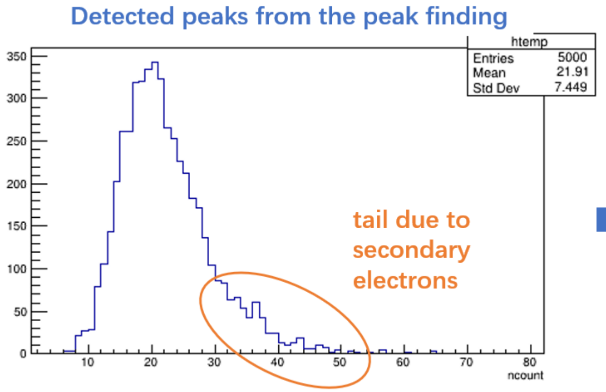
寻峰：



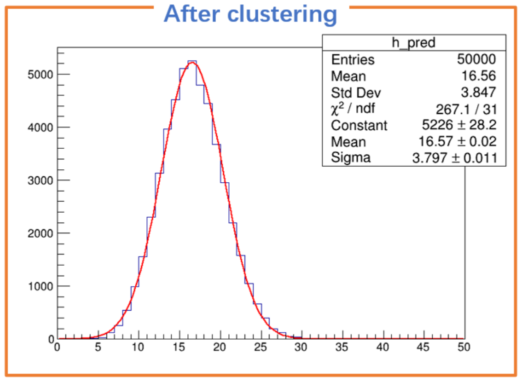


神经网络寻峰算法比传统算法更高效

  - 聚团：确定初级电离的个数（卷积神经网络）



聚团



最终重建dN/dx服从高斯分布。单元分辨~23%，接近MC真实分辨~21%