PID with Cluster Counting for the CEPC Drift Chamber

Guang Zhao (on behalf of the DC-PID working group)
zhaog@ihep.ac.cn

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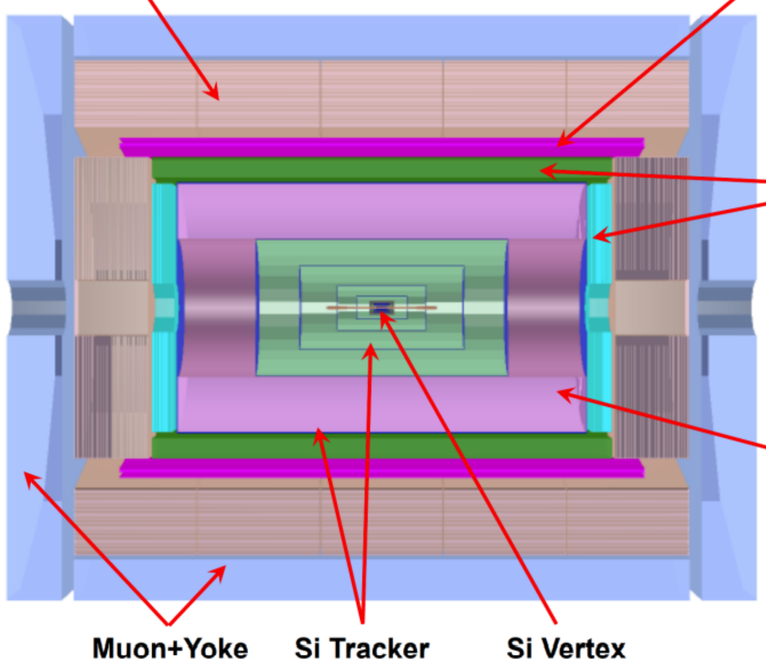
The 4th conceptual detector



Advantage: Cost efficient, high density

Challenges: Light yield, transparency, massive production.

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.

Advantage: better π^0/γ reconstruction.

Challenges: minimum number of readout channels; compatible with PFA calorimeter; maintain good jet resolution.

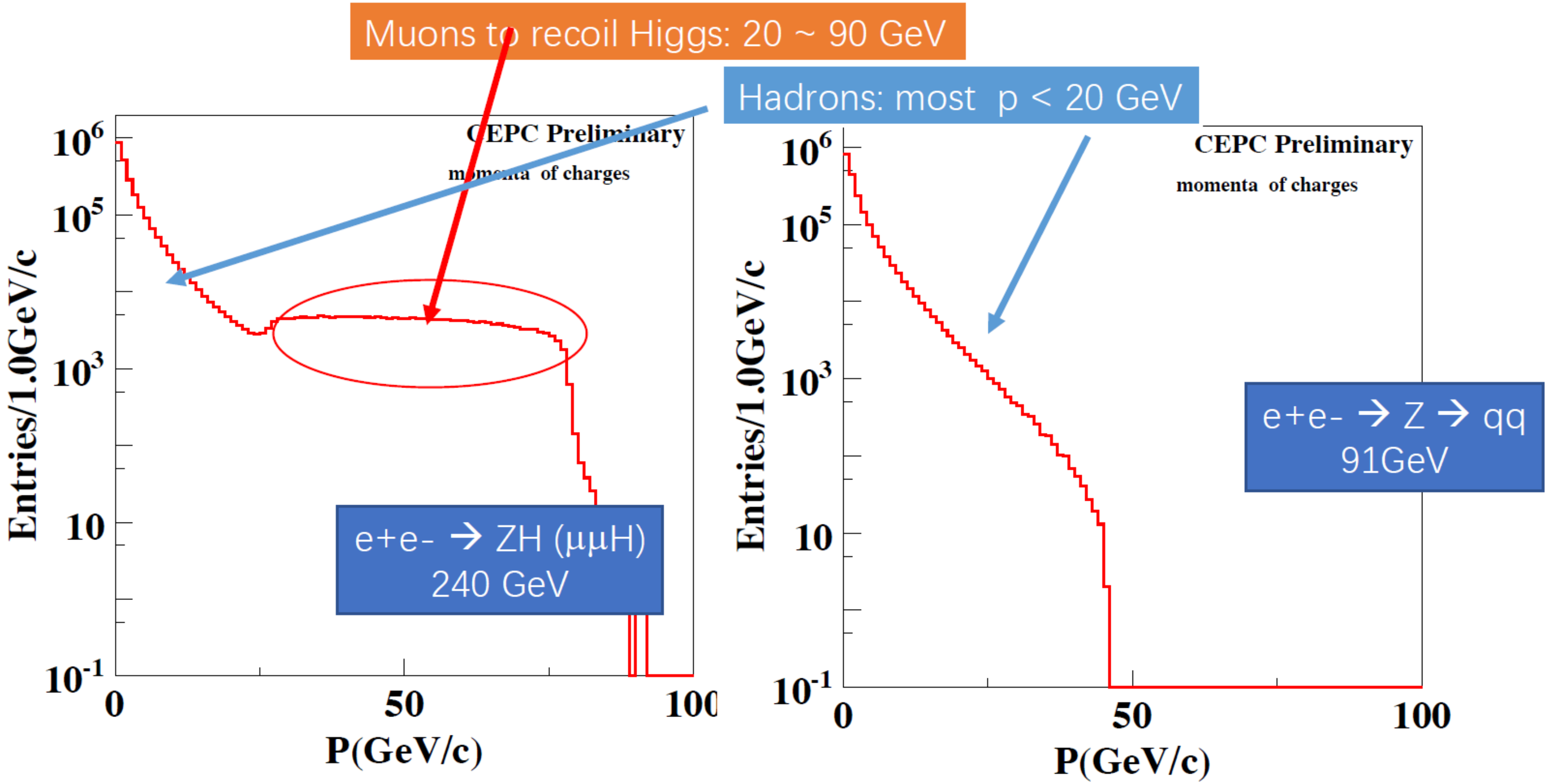
Advantage: Work at high luminosity Z runs

Challenges: sufficient PID power; thin enough not to affect the moment resolution.

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

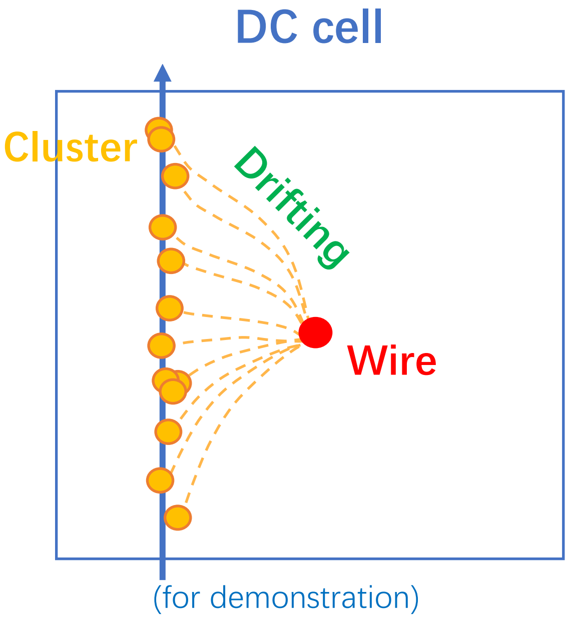
Det	Technology
Calorimeter	Crystal ECAL
	Si+W ECAL
	Scint+W ECAL
	Scint AHCAL
	ScintGlass AHCAL
	RPC SDHCAL
	MPGD SDHCAL
	DR Calorimeter
Muon	Scintillation Bar
	RPC
	μ-Rwell
Lumi	SiTrk+Crystal ECAL
	SiTrk+SiW ECAL

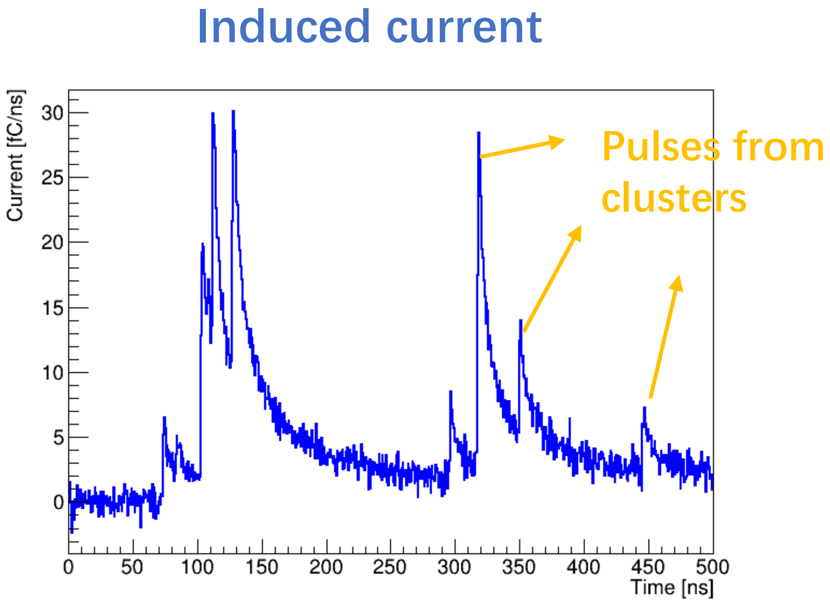
Physics requirements: hadron momenta



- 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

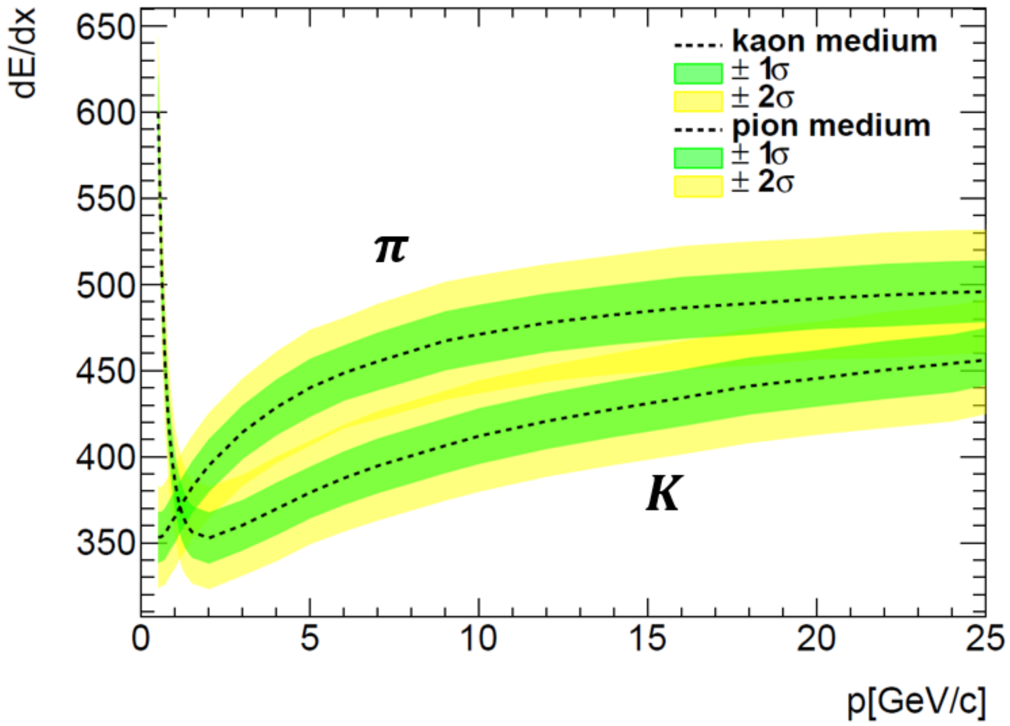




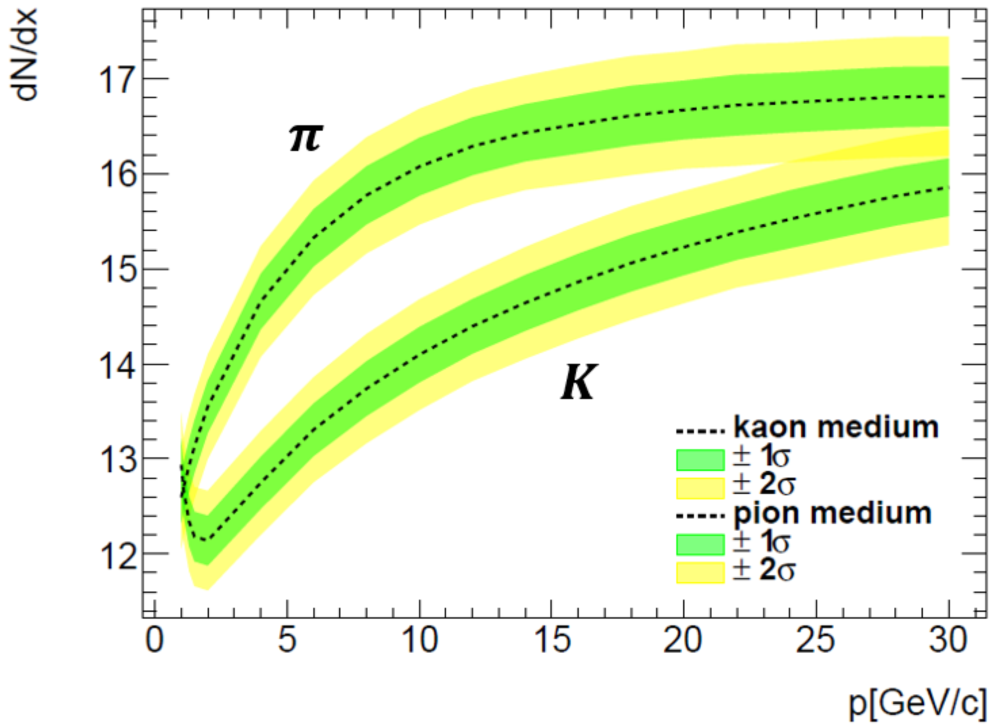
- ✓ **Cluster counting:** Measure # of clusters per length (**dN/dx**)
- ✓ **Clean in statistics:** $P(\bar{N}_p, k) = \frac{\bar{N}_p^k}{k!} e^{-\bar{N}_p}$
- ✓ **Theoretical resolution:** $\frac{1}{\sqrt{N_p}} = \frac{1}{\sqrt{\rho_{cl} \times L}}$ (potentially a factor > 2 better than **dE/dx**)

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

dE/dx

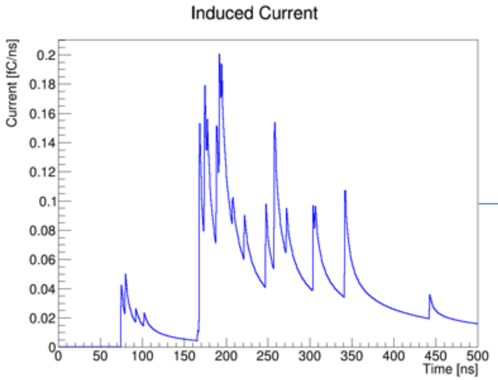


dN/dx



Waveform-based simulation

Induced current



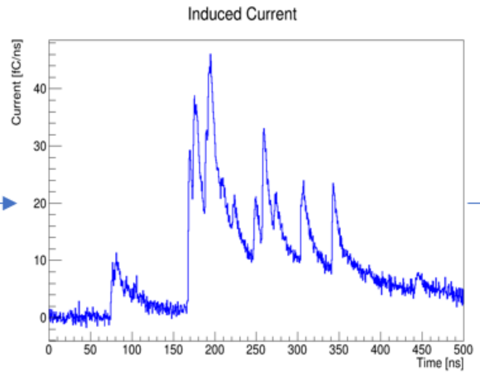
Signal generator (Garfield++):
- Heed: ionization process
- Magboltz: gas properties (drift/diffusion)

Garfield++ simulation

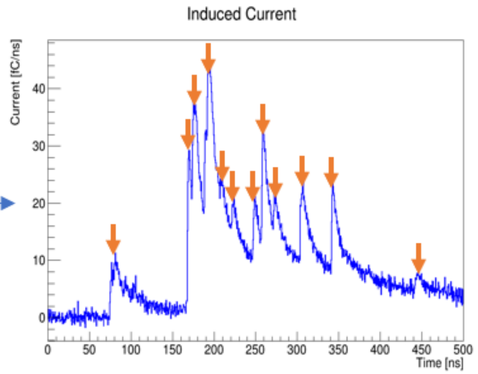
Electronics

Electronics:
- Preamplifier
- Noises
- ADC

Realistic waveform



Digitization

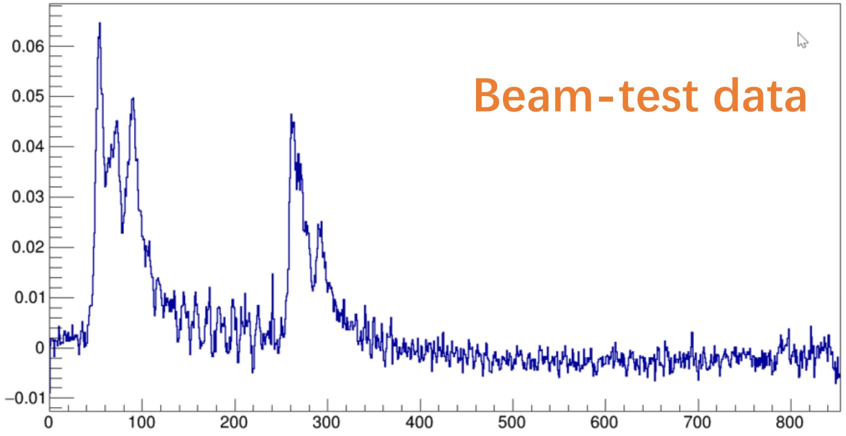


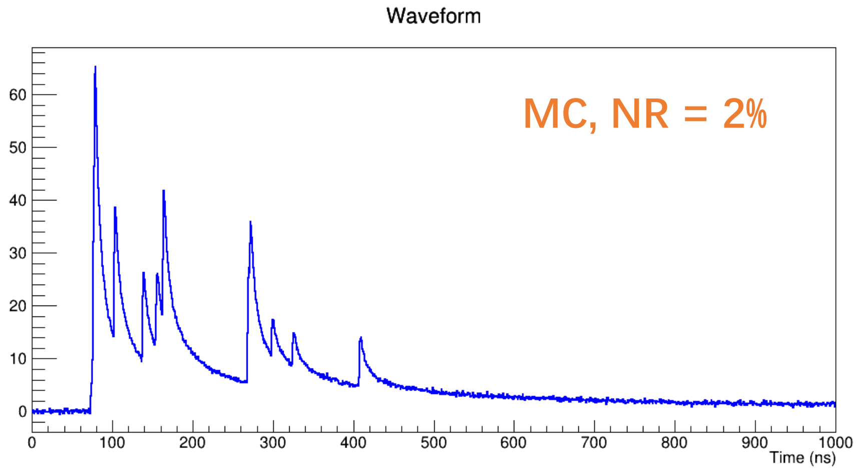
Peak finding algorithm:
- Second derivative

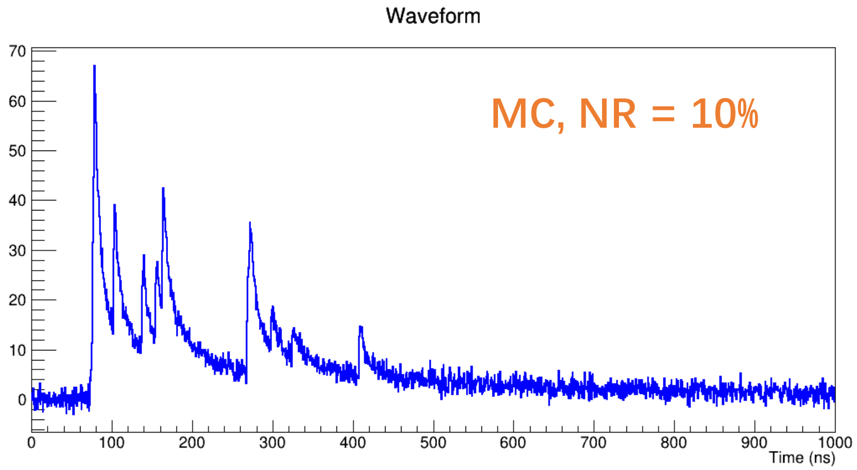
Reconstruction

Noise ratio

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



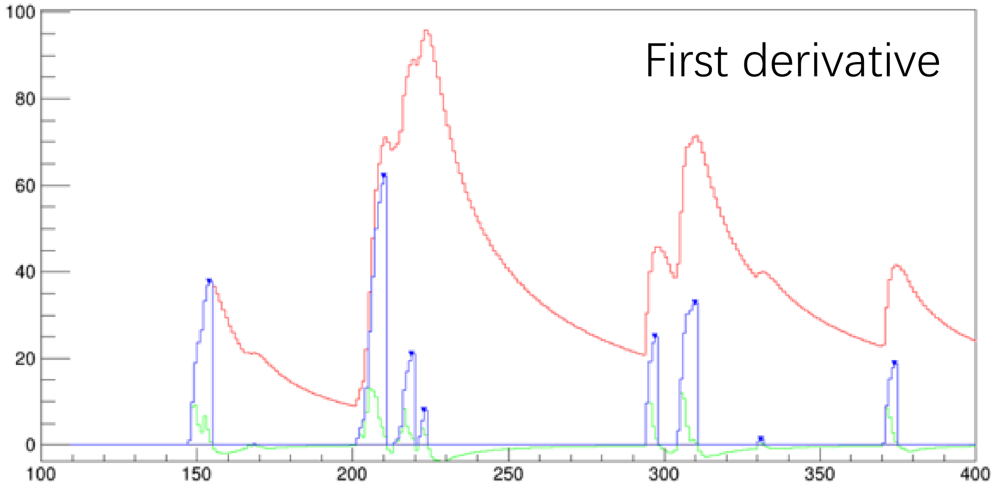


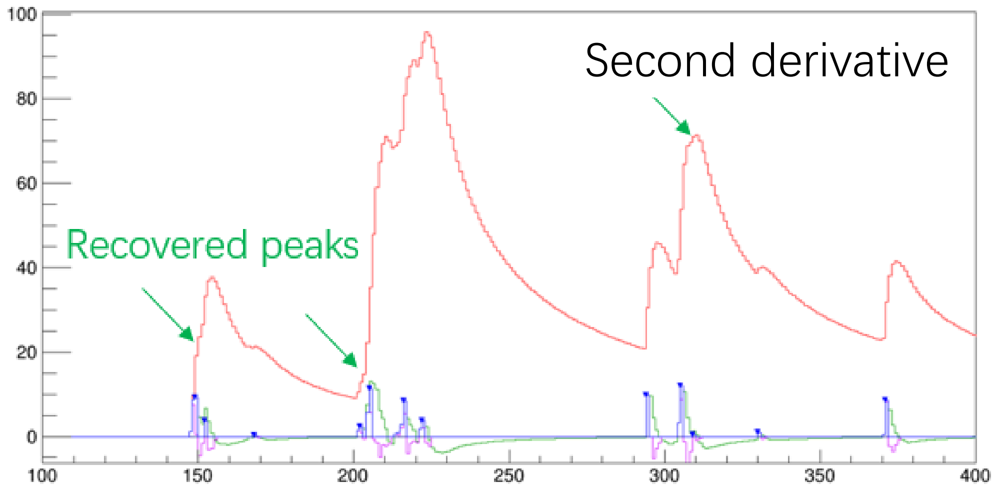


Note: noise ratio in beam-test data is close to ~10%

Peak finding algorithm

- **Base 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.

Detector 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

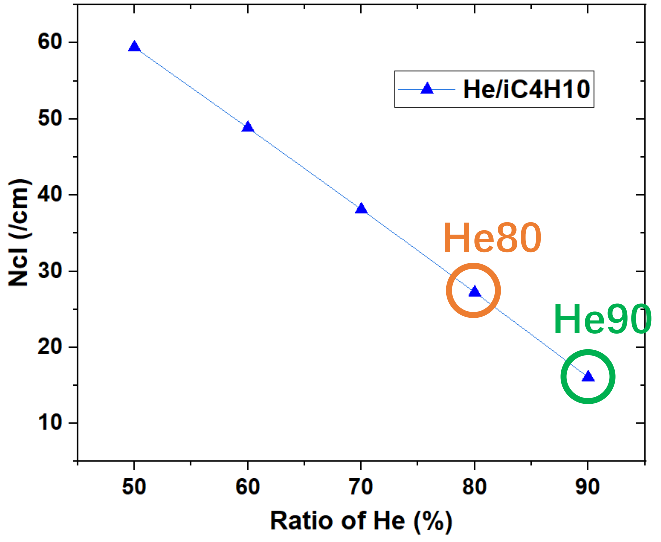
$\Leftrightarrow$

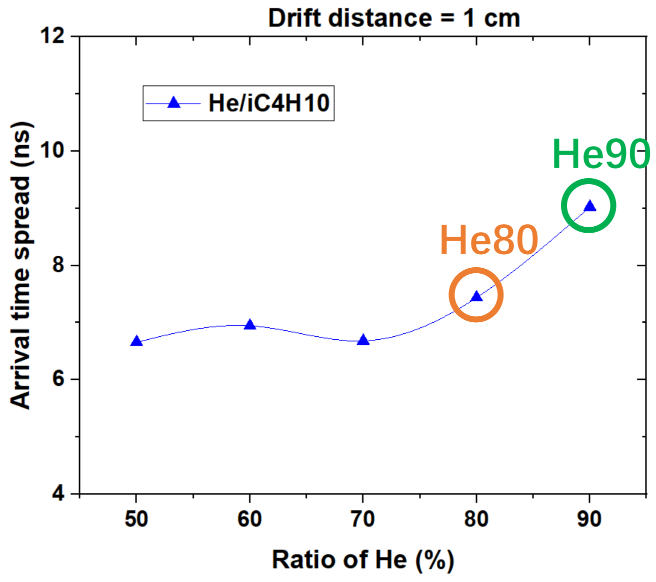
- gas mixture
- cell size
- detector thickness

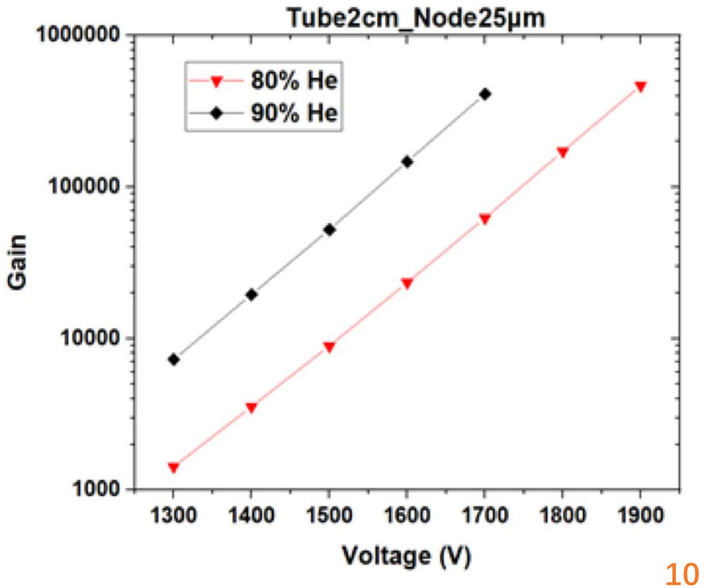
- <u>Parameters in simulation:</u>
  - Track direction: $\cos\theta = 90°$
  - Impact parameter of track w.r.t. sense wire: 0.2 cm

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}**

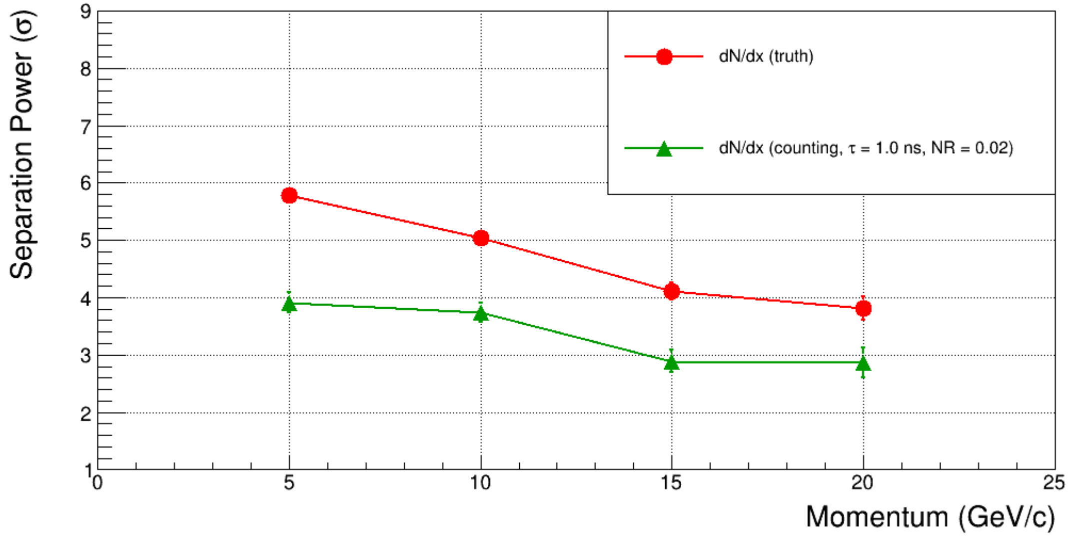




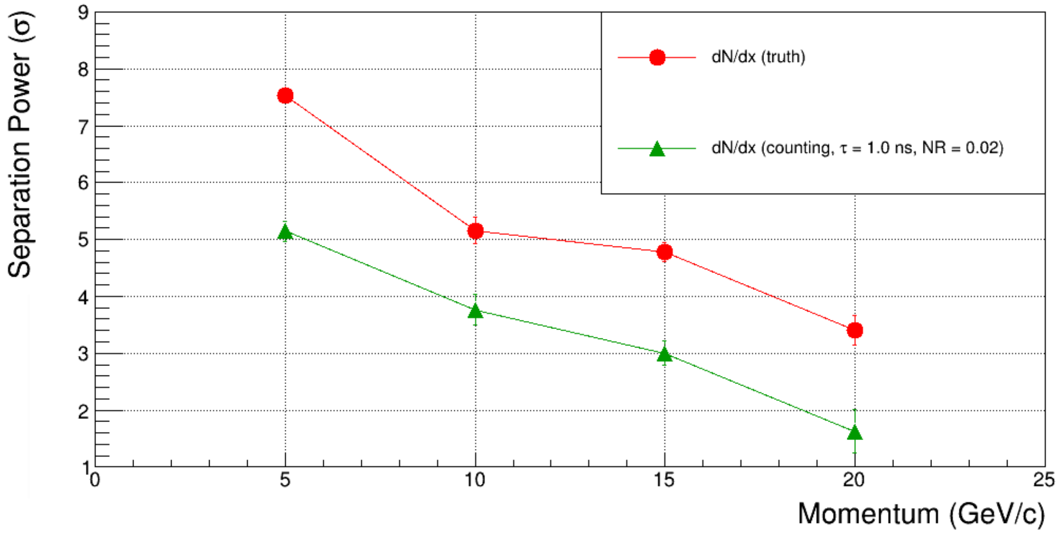


K/π separation for gas mixtures

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



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

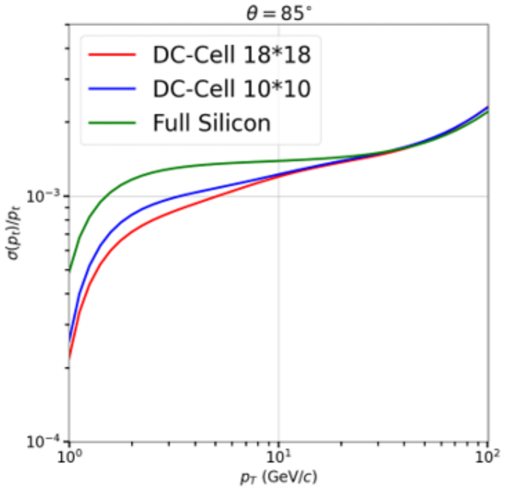


- He 90% + iC_4H_{10} 10% has better K/pi separation for high momentum
- He 80% + iC_4H_{10} 20% has better K/pi separation for low momentum
- PID in low momentum region can be covered by timing detector ➔ **He 90% is favored**

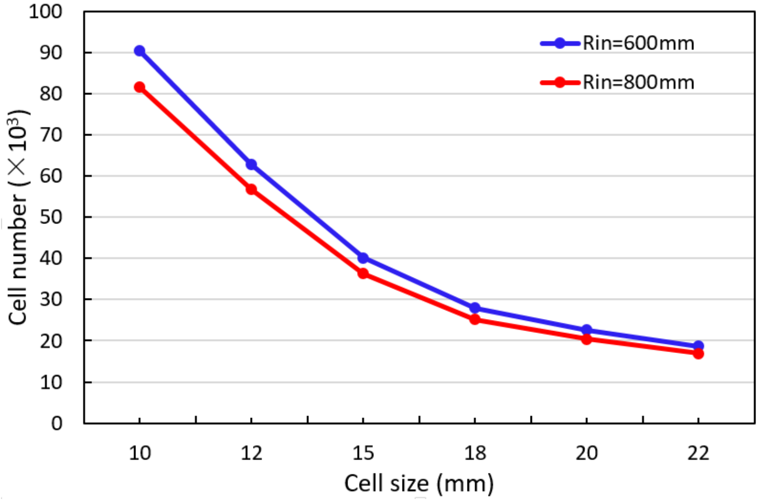
Cell size

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

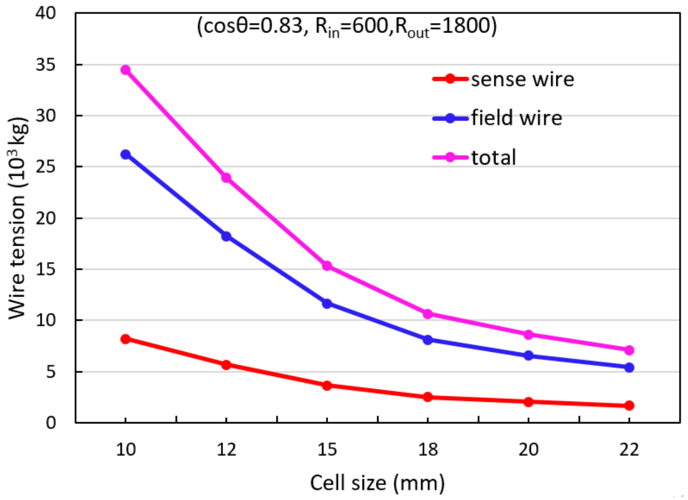
p_T resolution



# of cells vs. cell size

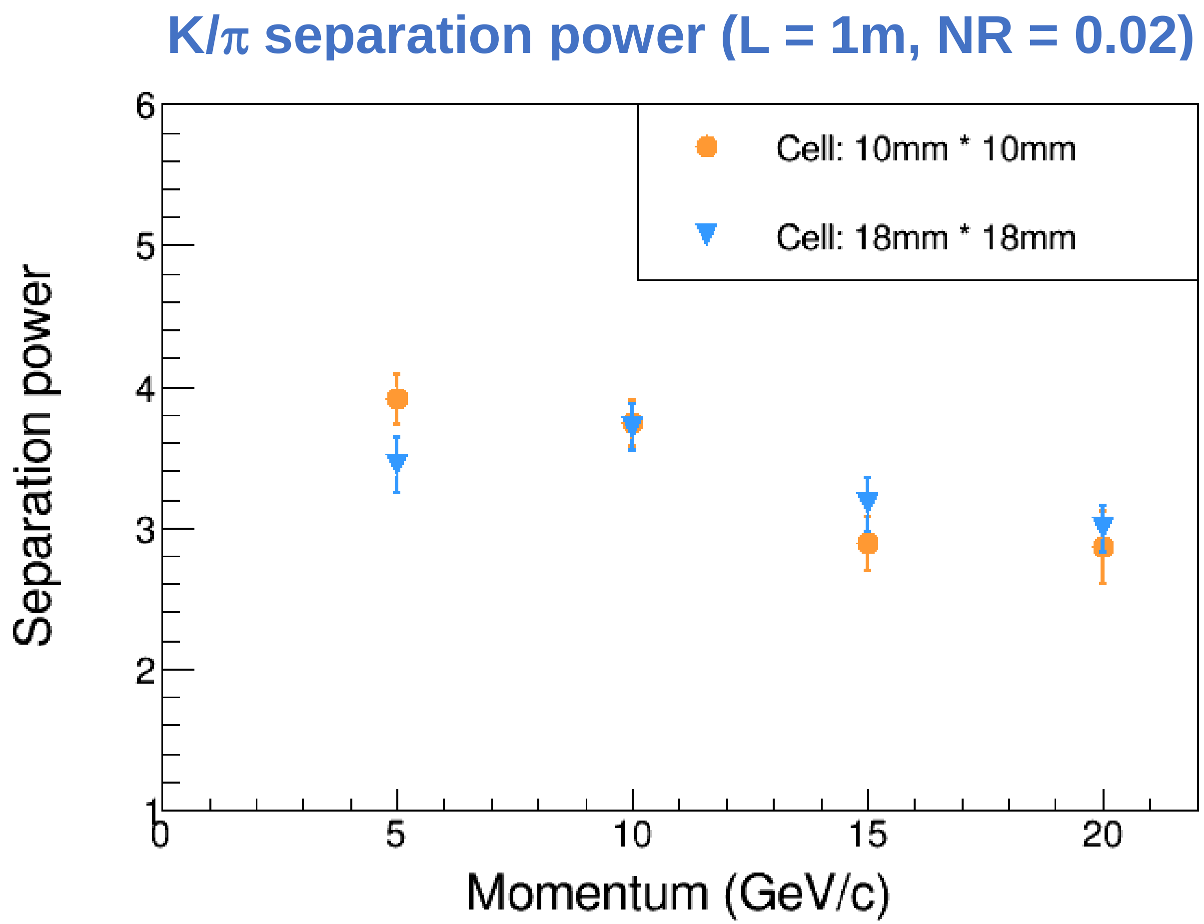


wire tension vs. cell size



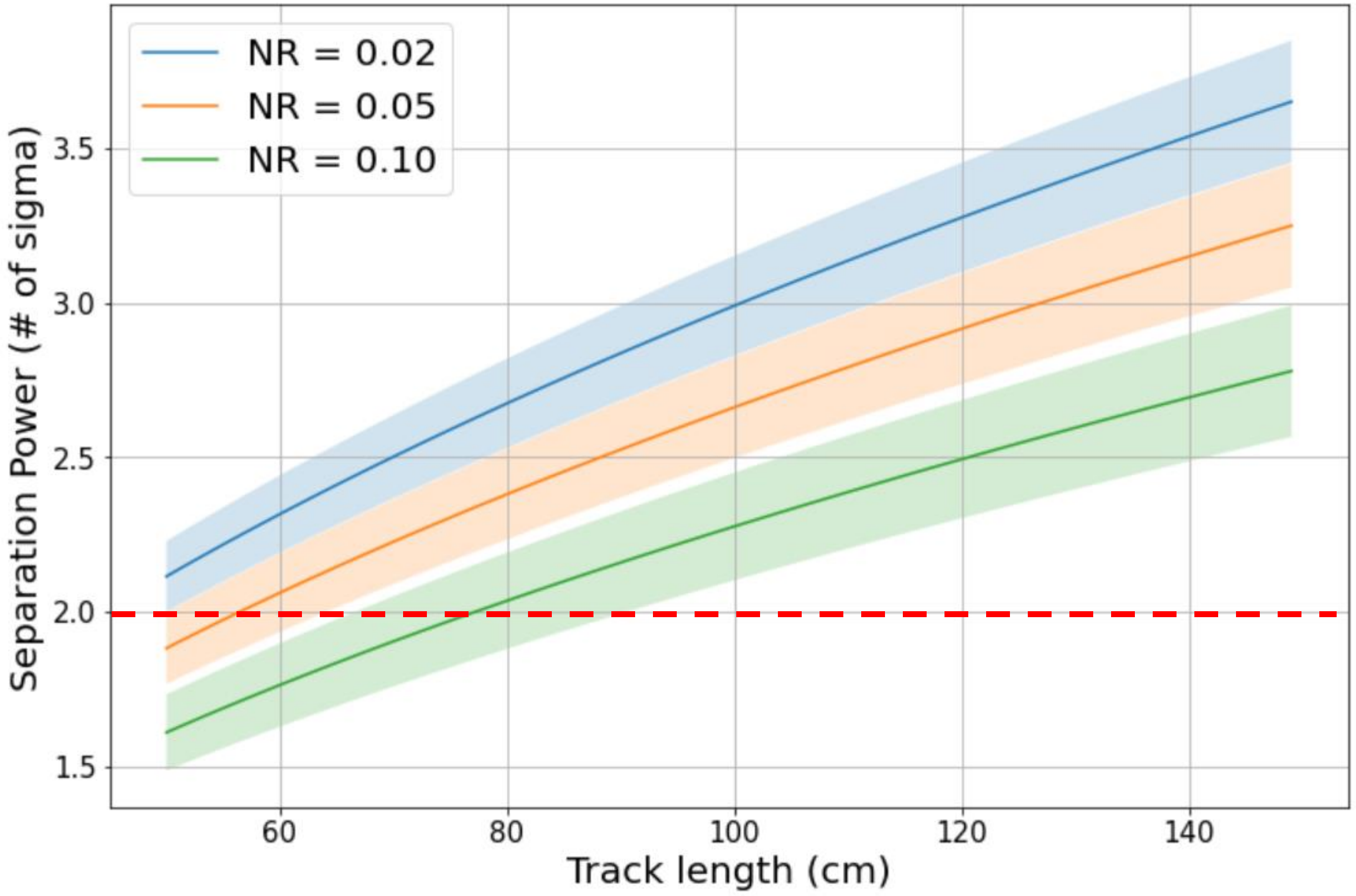
- Larger cell size, less material ➔ less multi-scattering ➔ better $\sigma(p_T)/p_T$ at low p_T
- Larger cell ➔ less wire tension ➔ easy engineering
- **Large cell is favored**

K/π separation for cell sizes



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

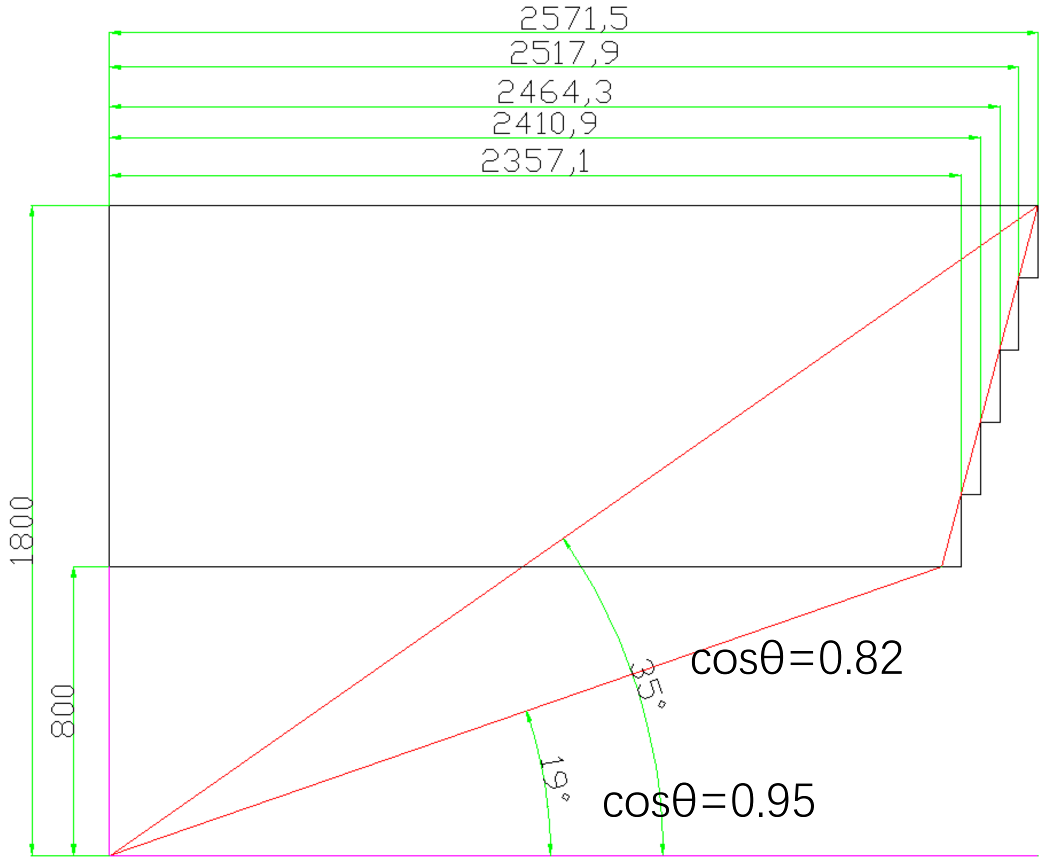
K/π separation @ 20 GeV/c for track lengths



The resolution scales with $L^{-0.5}$

- The track length could be < 100 cm for a 2σ K/π separation @ 20 GeV/c
- The requirement of separation power needs further studies with physics channels

Drift chamber design with mechanical structures



Total tension: ~9200 kg

✓ Meet requirements of stability condition:

$$T > \left(\frac{VLC}{d}\right)^2/(4\pi\varepsilon_0)$$

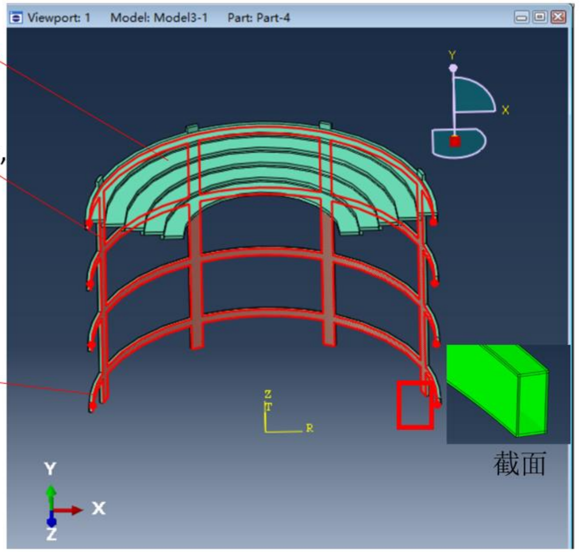
DC Parameters	
R extension	800-1800mm
Length of outermost wires（cosθ=0.82）	5143mm
Thickness of inner CF cylinder	200μm
Outer CF frame structure	Equivalent CF thickness: 1.63mm
Thickness of end Al plate	35mm
Cell size	18 mm × 18 mm
Diameter of field wire (Al coated with Au)	60μm
Diameter of sense wire (W coated with Au)	20μm
Ratio of field wires to sense wires	3:1
Gas mixture	He/iC4H10=90:10

Preliminary stability study

Al endplates : 35 mm

Longitudinal beam, Cross section: 122×40mm

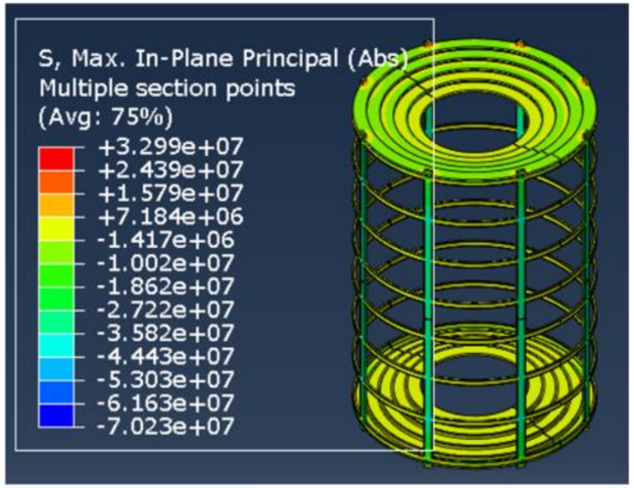
Annular beam, Cross section: 80×40mm



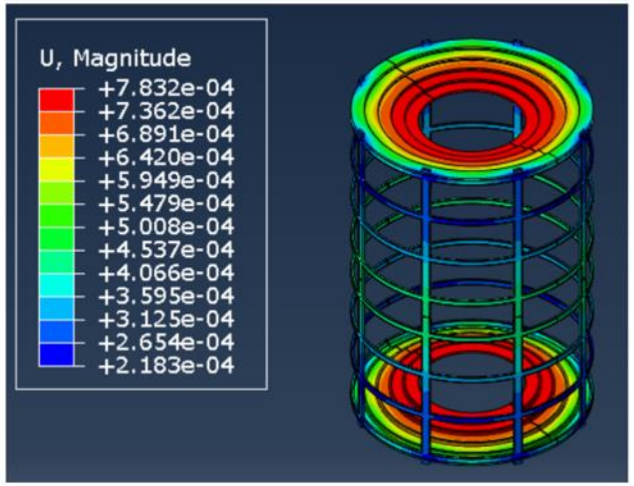
Finite element model——wire tension + weight loads (supported by eight blocks at each endplate)

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



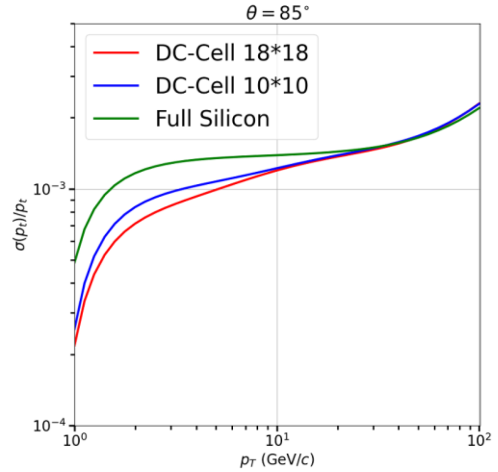
Principle stress



Deformation

Summary

- **Simulation gives us the suggested parameters of DC:**
  - Gas mixtures: 90% He + 10% C_4H_{10}
  - Thickness of DC: < 100 cm (2σ K/π separation @ 20 GeV/c)
  - Cell size: 1.8 cm x 1.8 cm
- **A mechanical design including the support structures is provided**
  - Preliminary infinite element analysis shows good mechanical stability



p_T resolution @ low p_T is even better than full Si design

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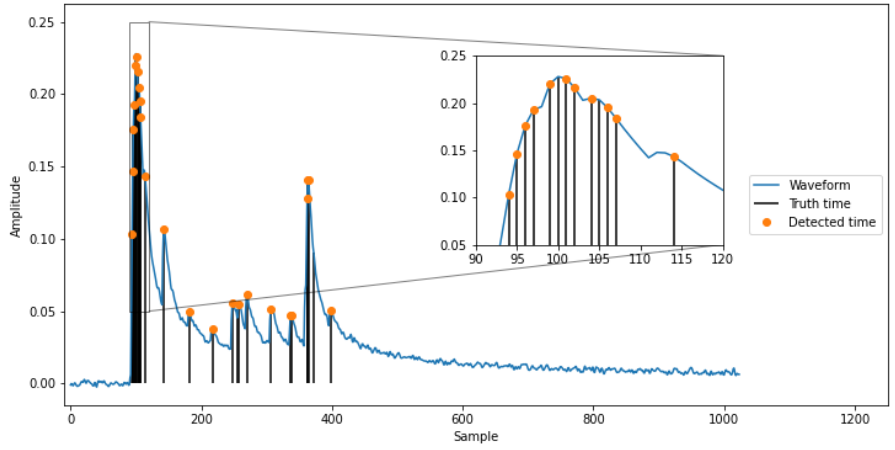
Outlook

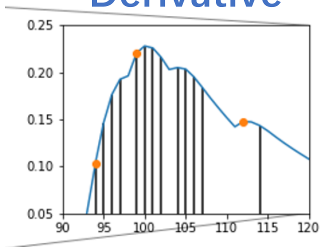
- **Study the PID requirement from physics channels**
  - Physics input to constrain the detector parameters
  - Delphes fast simulation is ongoing

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

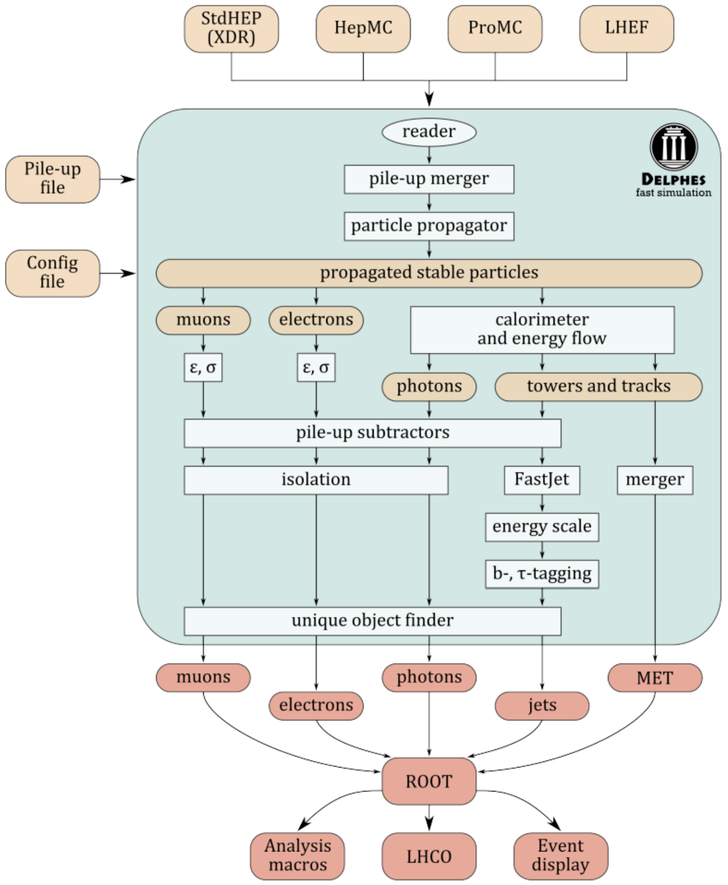
Deep Learning



Derivative

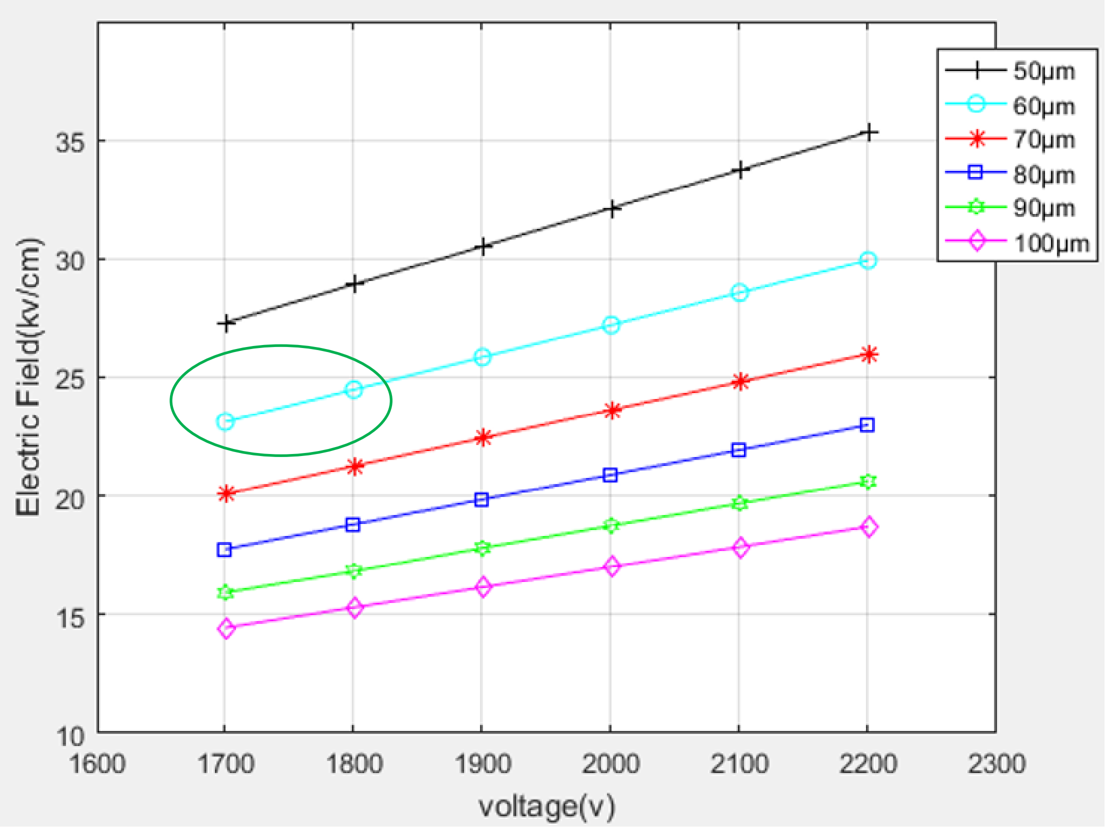


Delphes

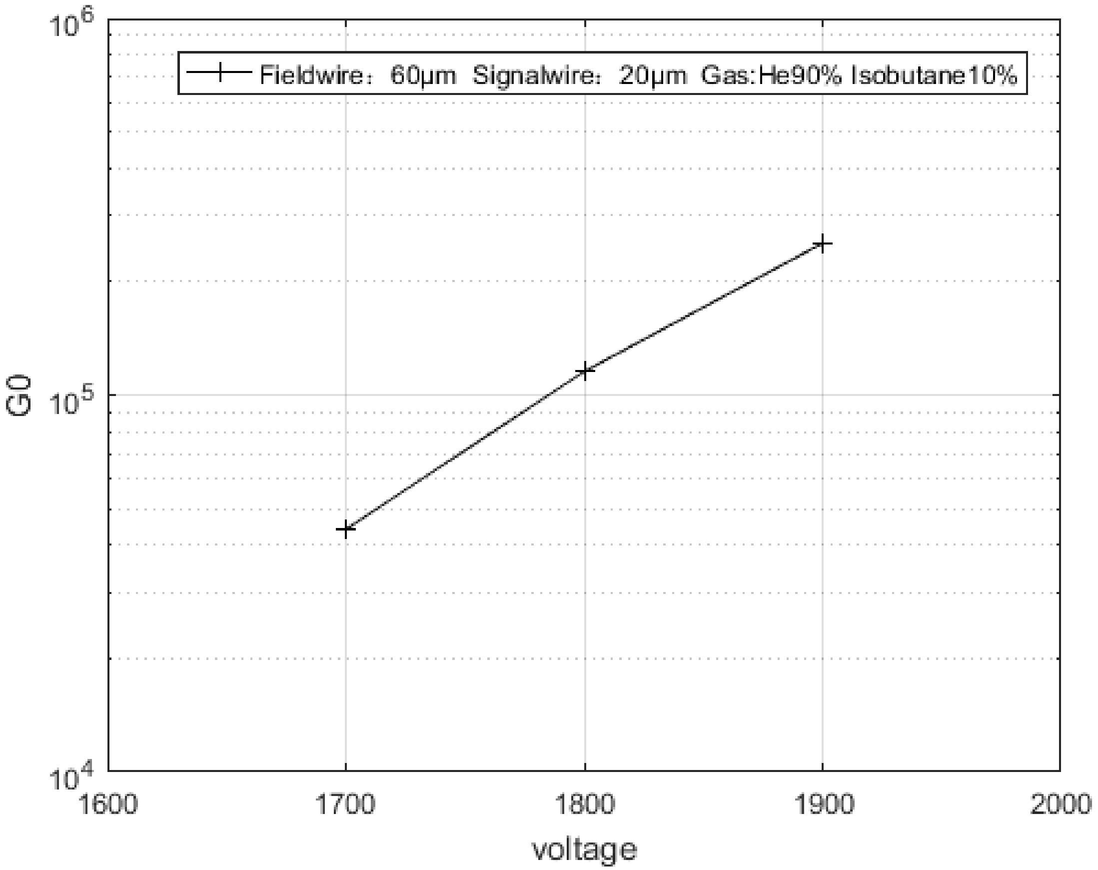


Backup

Field and gain

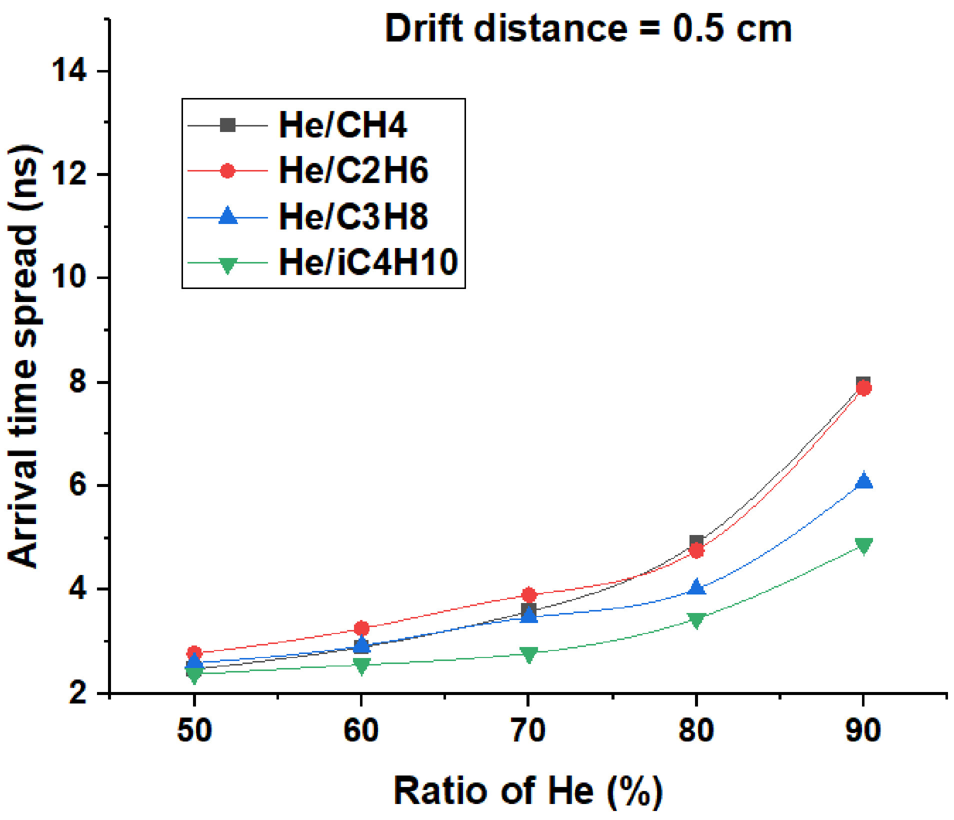


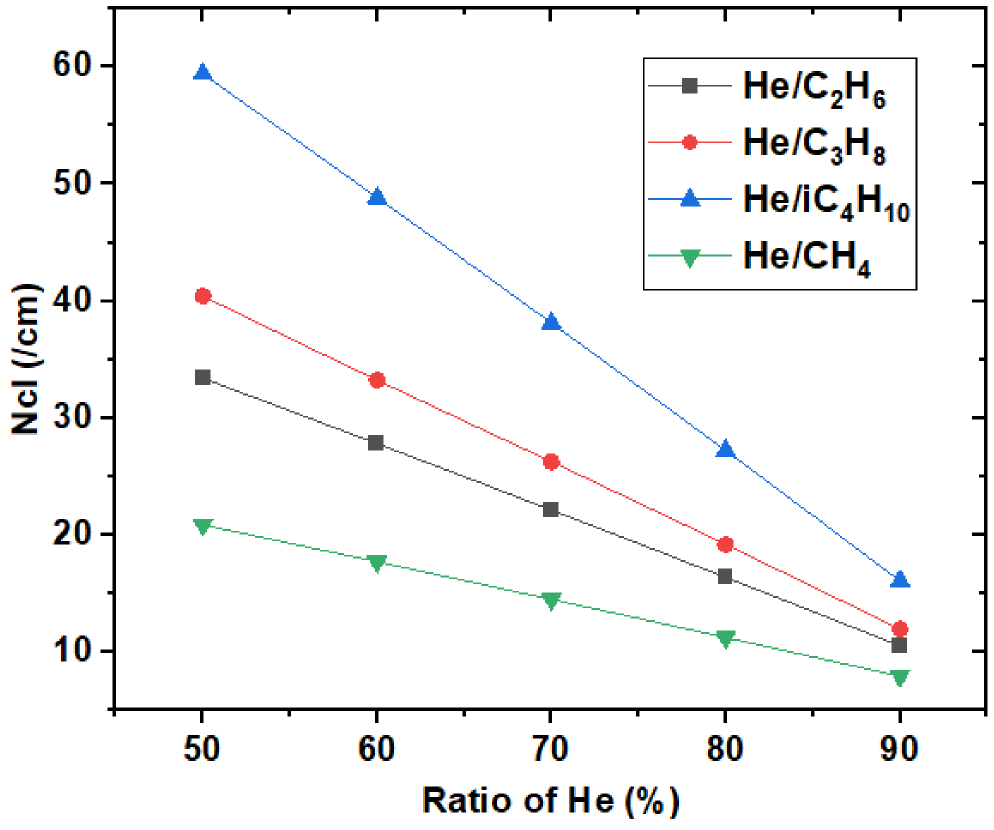
Electric field of field wires



Gain

Property for more gas mixtures



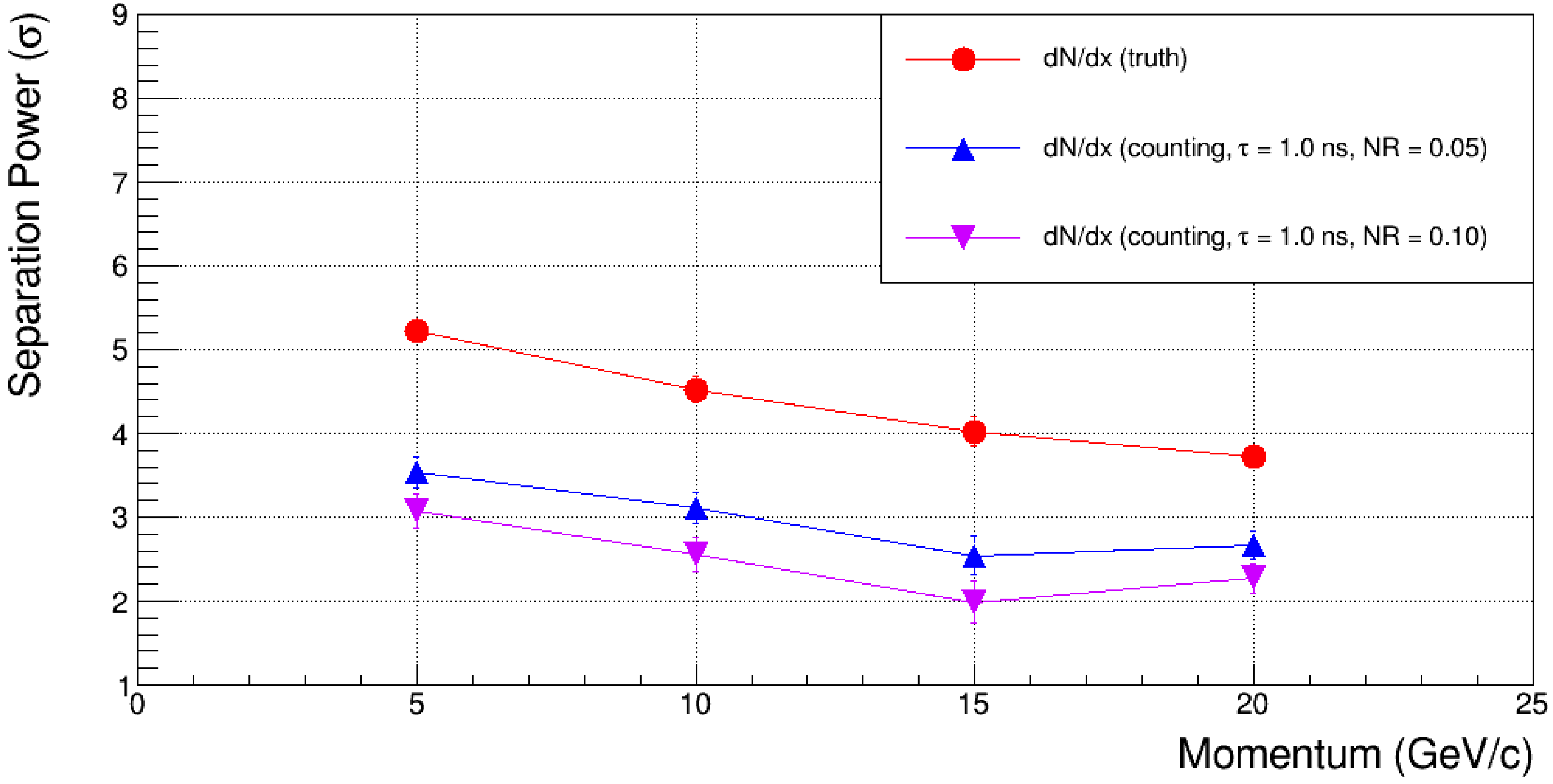


Tracker parameters

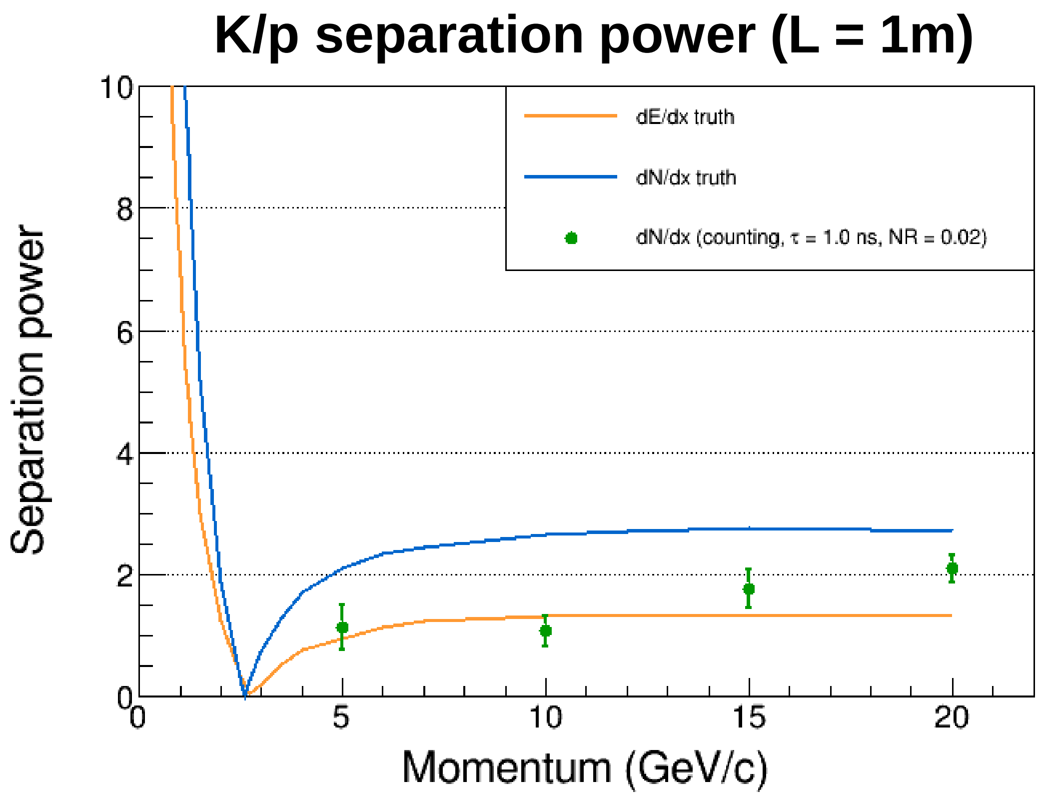
Gang Li's talk: https://indico.ihep.ac.cn/event/16011/session/2/contribution/12/material/slides/0.pdf

Layers	Radius(mm)	$\sigma_{R\phi}$(mu)	σ_Z(mu)	Thickness(1%/X_0)
Beam Pipe	14.5	-	-	0.15
VTX	16/18/37/39/58/60	2.8/6/4/4/4/4	2.8/6/4/4/4/4	0.15
VTX-shell	65.0	-	-	0.15
SITs	80/253/600	7.2/7.2/7.2	86.6/86.6/86.6	0.65
DC inner shell	798	-	-	0.104
DC wires (20*20mm) and gas	800 -- 1800	100	2828	0.0108+0.0031
DC outer shell	1803.0	-	-	1.346
SET (HV-CMOS 25x300 μm^2)	1811.0	11.5	138.5	0.65

K/π separation with more noise levels

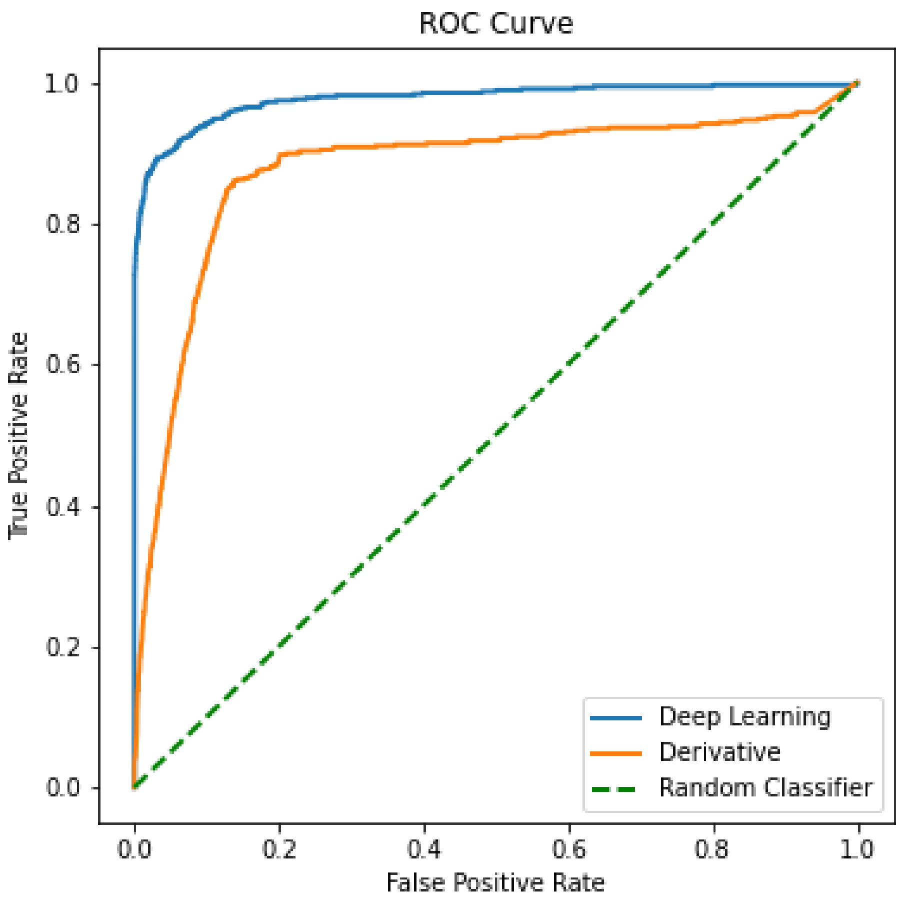


K/π separation for proton



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

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