Institute of High Energy Physics
Chinese Academy of Sciences

PID performance study with Drift Chamber at IHEP

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For CEPC the 4th conceptual drift chamber working group

The 2022 International Workshop on the High Energy Circular Electron Positron Collider
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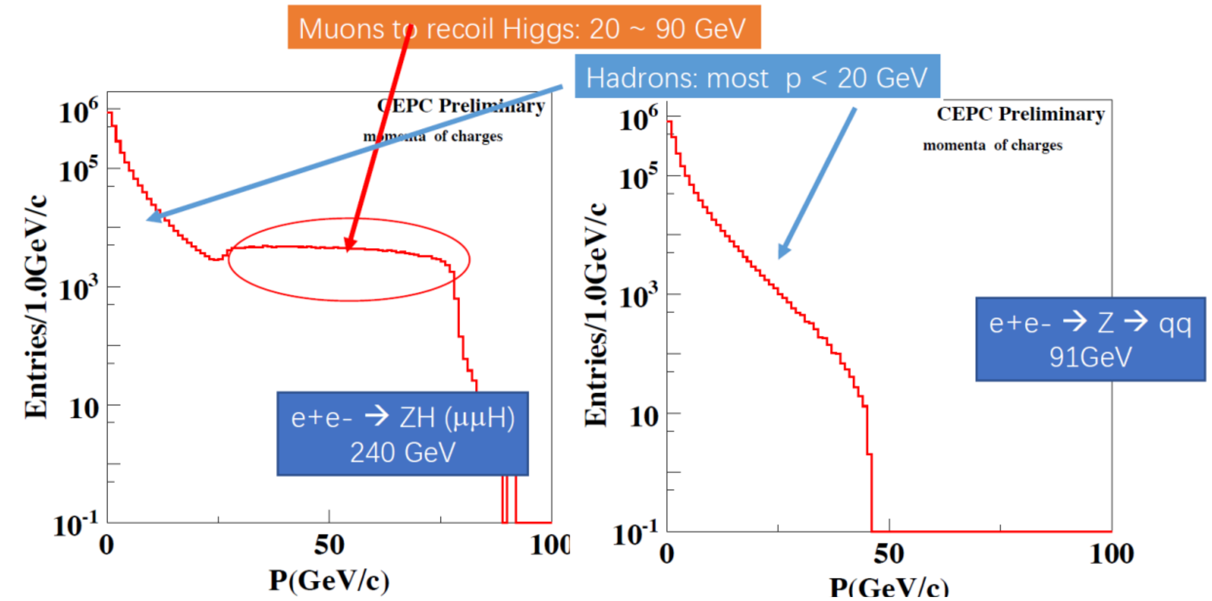
Motivations

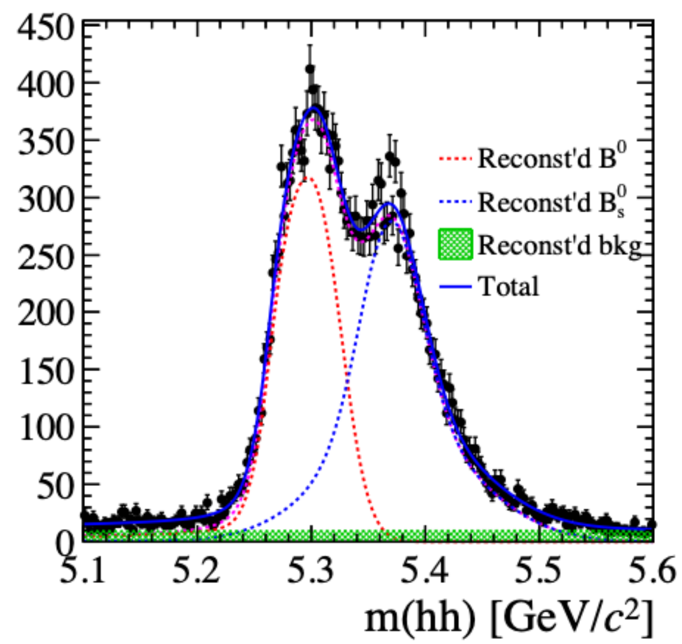
- CEPC is proposed as not only a Higgs, but also a W/Z factory.
- Especially at Z-pole, ~10^{12} Z bosons offer great opportunity for flavor physics and jet study etc.
- Giving the fact that produced charged hadrons are concentrated on low momentum region, particle identification (PID) would be critical.

Operation mode	Z factory	WW threshold scan	Higgs factory
$\sqrt{s}$ (GeV)	91.2	158 – 172	240
Running time (years)	2	1	7
L (10^{34} cm^{-2}s^{-1})	17 – 32	10	3
Integrated Luminosity (ab^{-1})	8 – 16	2.6	5.6
Higgs yield	–	–	10^6
W yield	–	10^7	10^8
Z yield	10^{11-12}	10^8	10^8

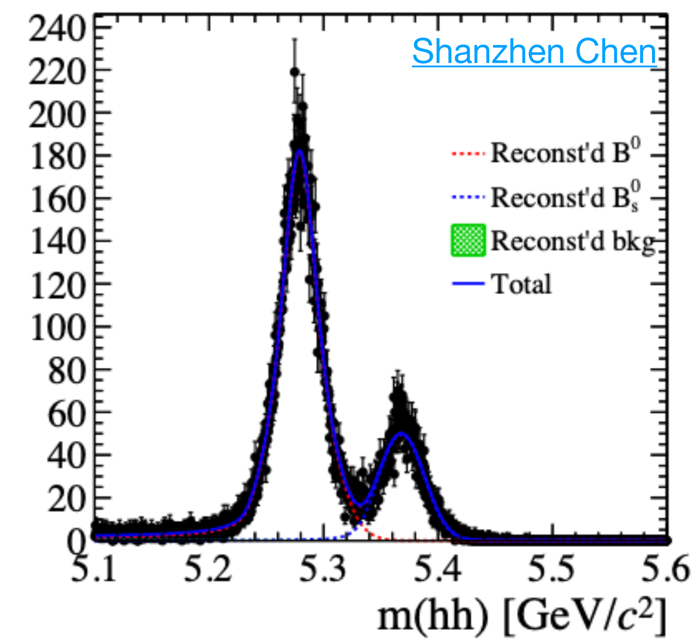


Example of the impact of PID in heavy flavor decay reconstruction

Disentangle the various $B_s^0(B^0) \to h^-h^+$ in same topology final-states.



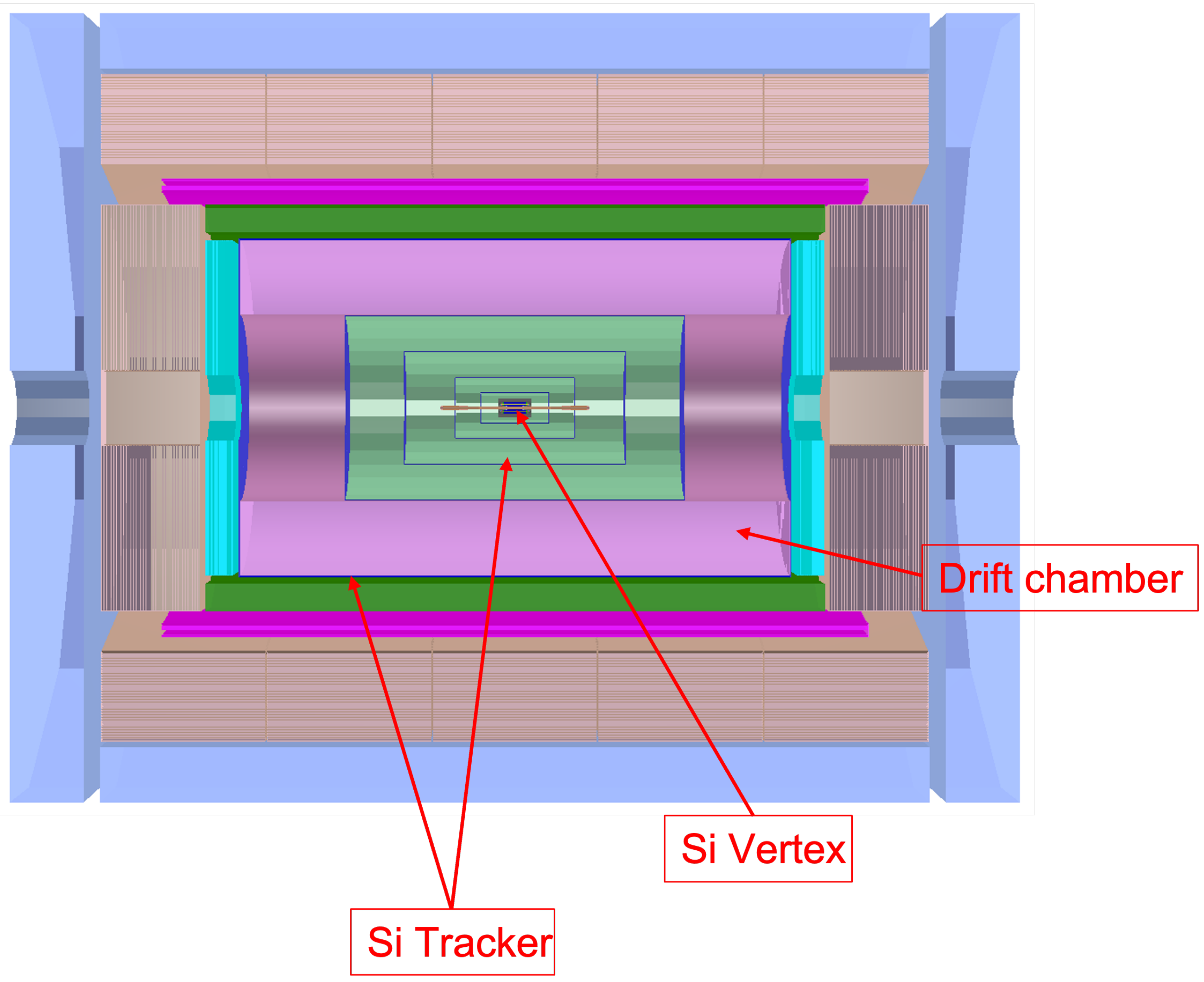
Assuming 50% PID efficiency



Assuming 100% PID efficiency

Motivations for Drift Chamber

- Drift Chamber is a design in 4th conceptual detector at CEPC.
  - between the Full Silicon Tracker layers for particle identification (PID).
  - optimized for PID by applying the cluster counting technique.



<u>cluster counting technique</u>: measuring the clusters directly allows a significant improvement with respect to dE/dx method

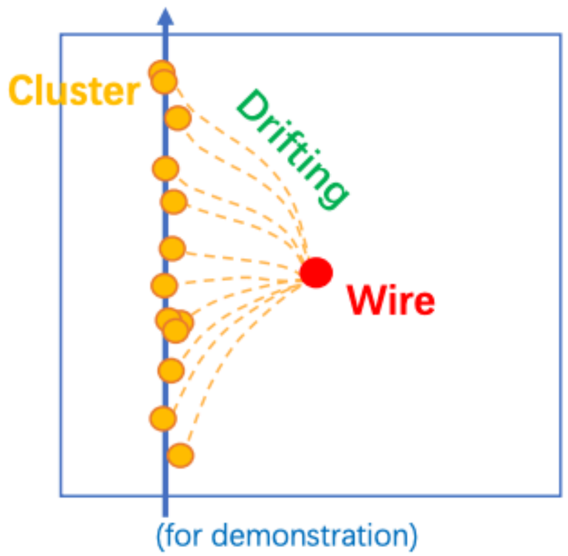
- Main goals are to provide
  - sufficient PID separation power for hadron momentum up to 20 GeV/c
  - good tracking performance combined with silicon tracker

Contents

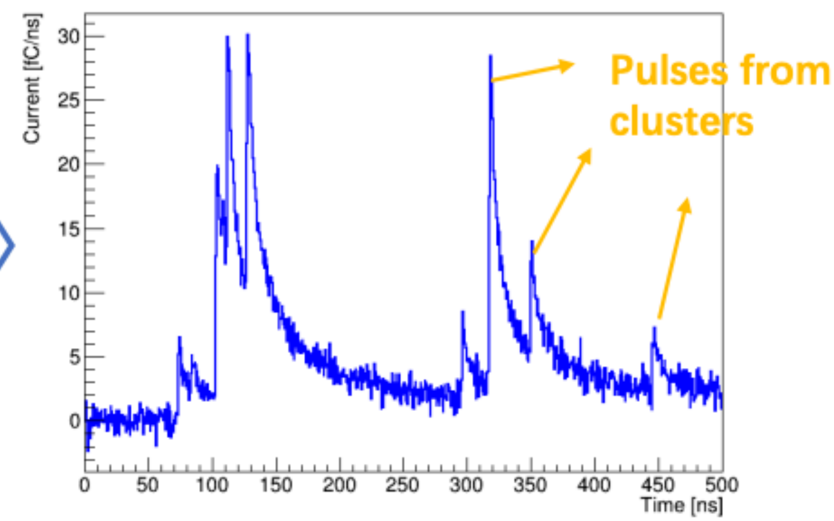
- Energy loss and cluster counting
- Simulation study and expected performance
- Counting algorithm with machine Learning

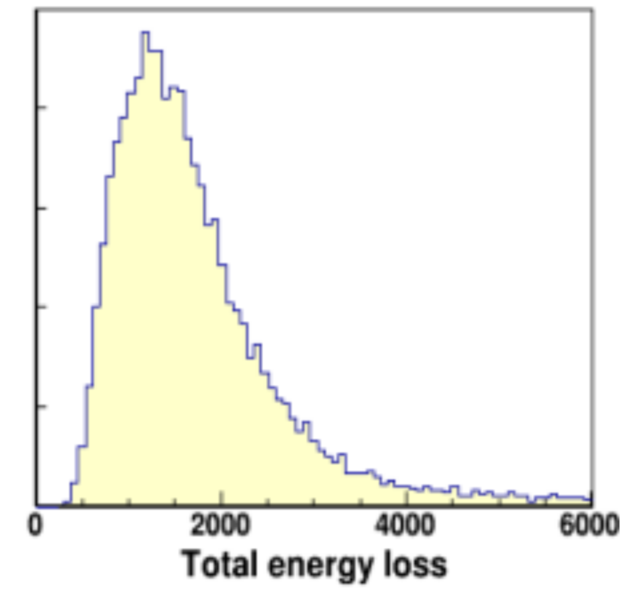
Ionization measurement: dE/dX and dN/dX

DC cell

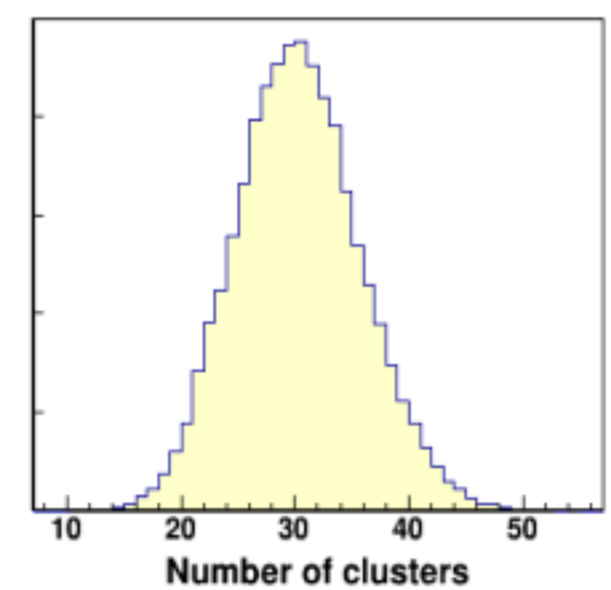


Induced current





dE/dx



dN/dx

For demonstration

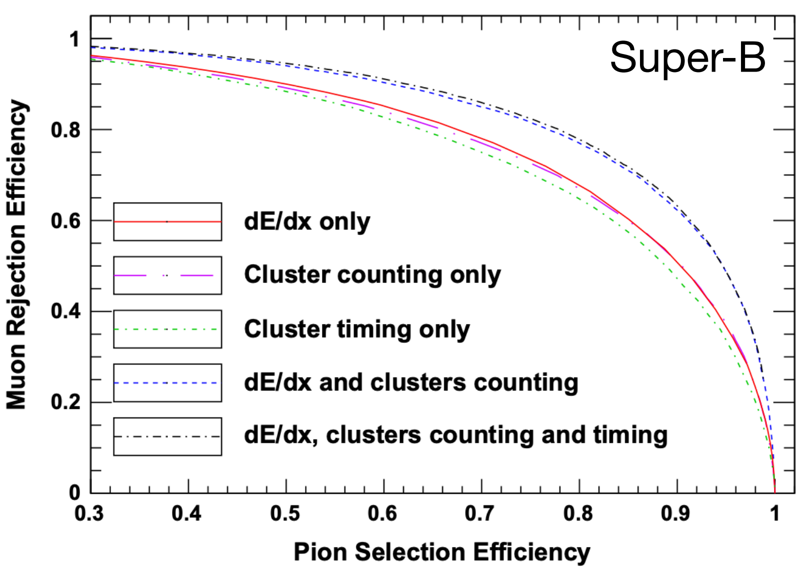
- Energy loss (dE/dx):
  - Fluctuations of number of clusters (N_p) + transferred energy result in Landau distribution.
  - Lost information due to mean truncation.
- Cluster counting (dN/dx): Measure number of clusters
  - Clean in statistics, only depends on N_p :

$$P(N_P, k) = \frac{N_P^k}{k!} e^{-N_P}$$

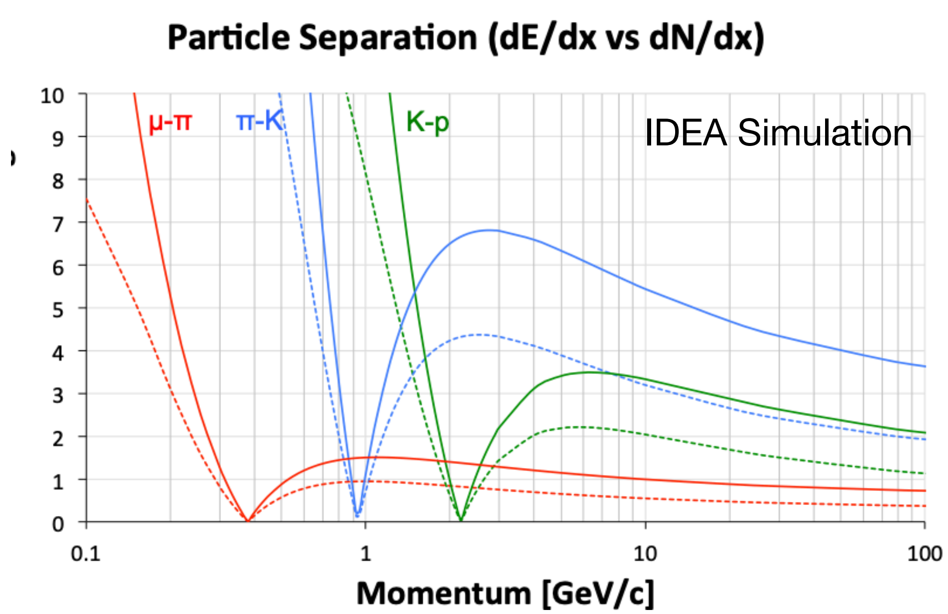
  - Theoretical resolution: $\frac{1}{\sqrt{N_P}}$ potential gain of a factor of 2

Researches on cluster counting

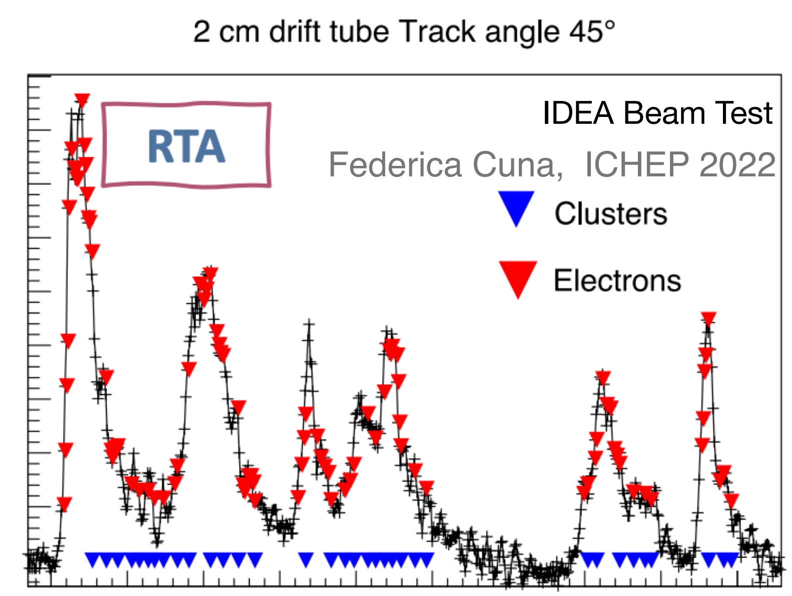
- Proposals for e^+e^- colliders:
  - Detector for Super-B
    - Done with full track length drift chamber prototype. 90% He 10% iC4H10 gas.
  - IDEA detector for FCC-ee or CEPC
    - Assuming 80% counting efficiency and 4.2% dE/dx resolution
    - Beam test work are undergoing.



J-F Caron,https://doi.org/10.1016/j.nima.2013.09.028

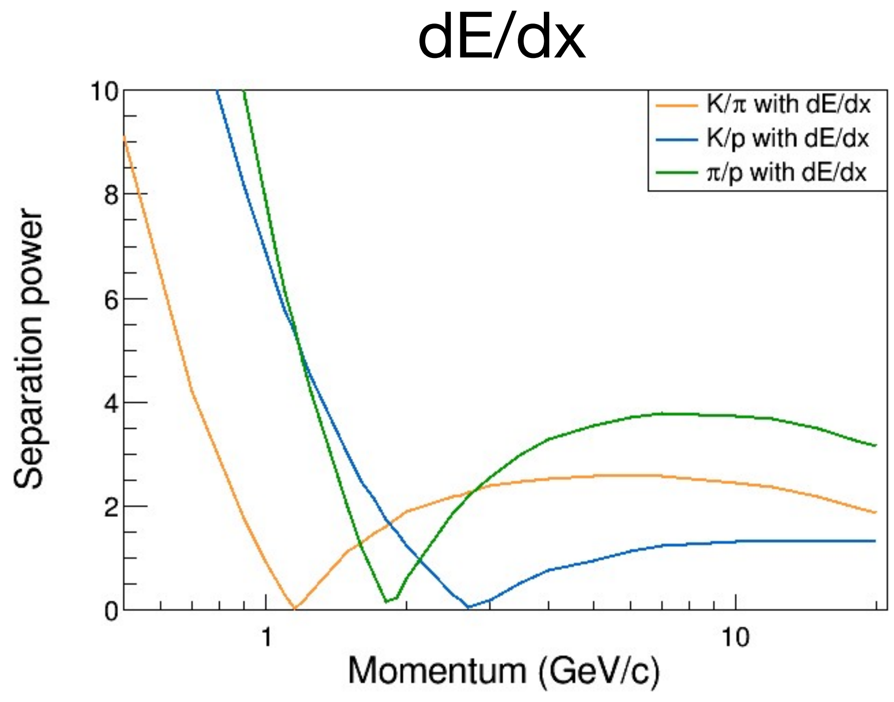


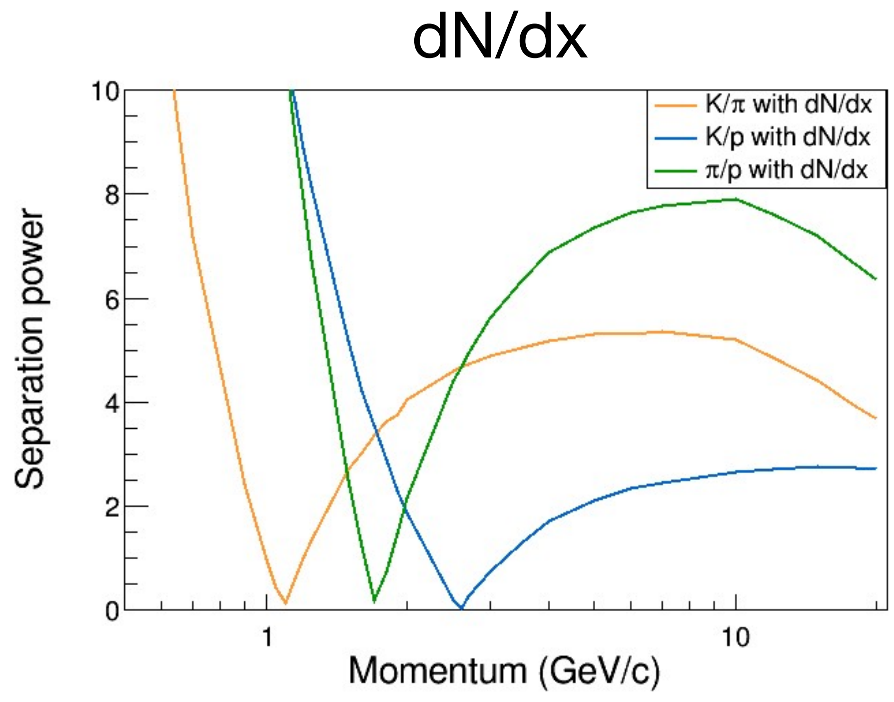
G. Chiarello et. al, NIM A 936 (2019) 503-504



PID with ionization simulation

- The theoretical results are obtained from Garfield++ simulation.
  - The dE/dx applies a truncated mean, the dN/dx counts all the primary ionizations.

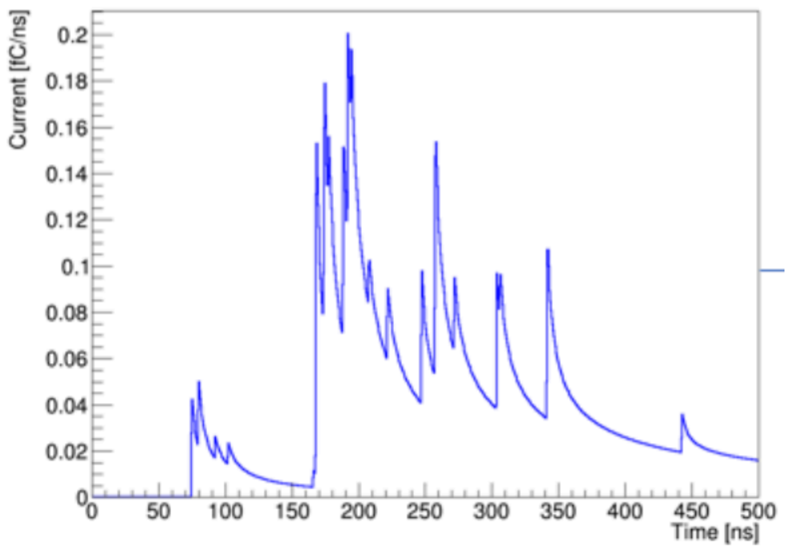


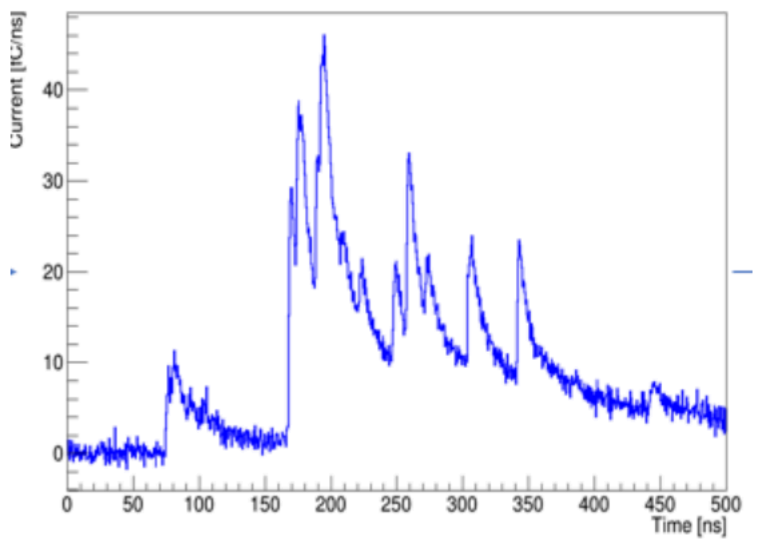


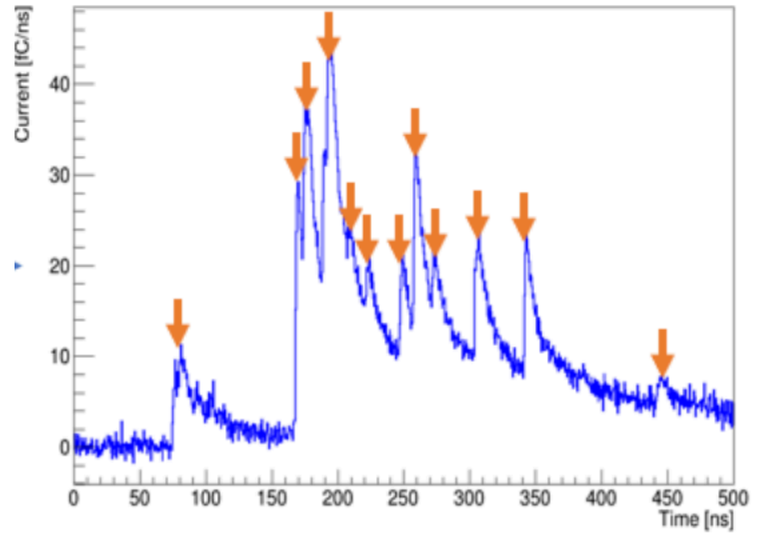
- Cluster counting delivers better PID performance than dE/dx.
- However, we need to consider the effect of electronics, noises etc. more importantly , the efficiency of counting algorithm.
- To simulate/control those factors, a waveform simulation is studied.

Waveform-based simulation

- The critical content of cluster counting is the waveform processing, an end-to-end workflow composes simulation, digitization and reconstruction steps.







Simulation

Signal generator (Garfield++)

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

Digitization

Electronics

- Preamplifier
- Noise
- ADC: sampling rate

Reconstruction

Peak finding algorithm

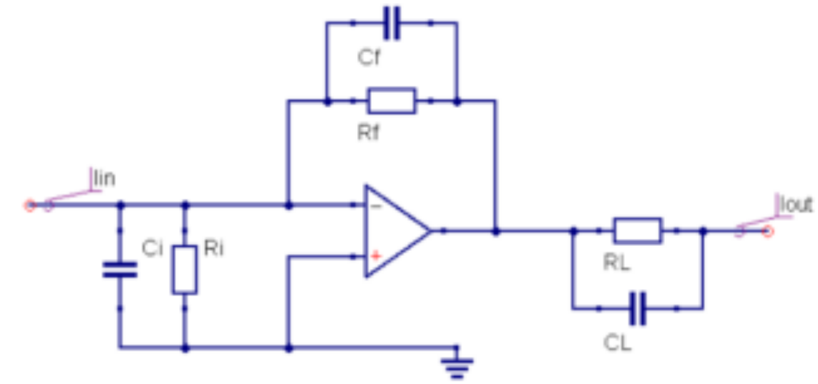
- Second derivative
- Machine Learning

Digitization

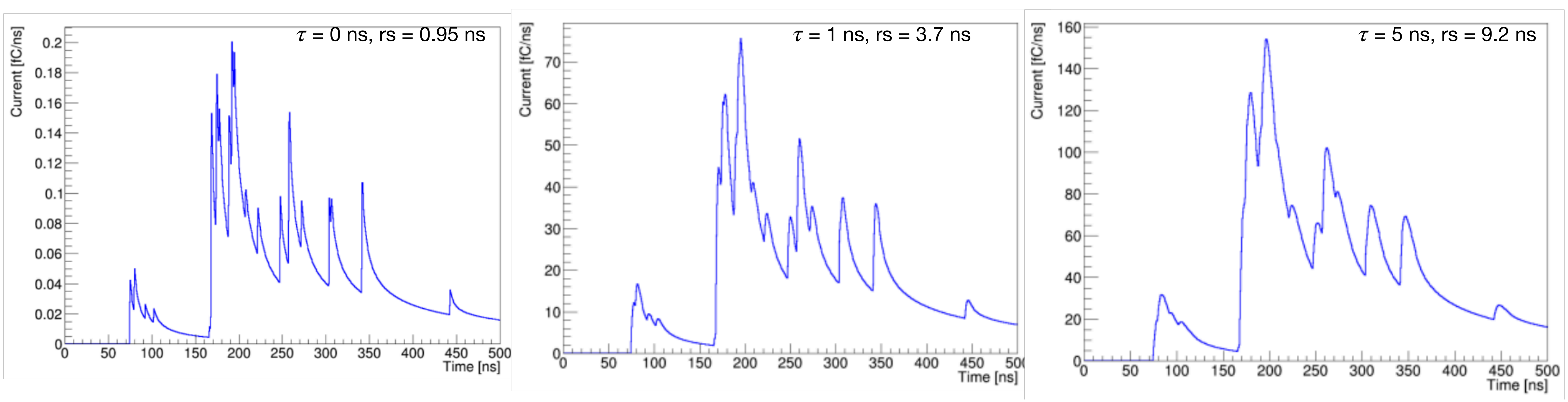
- A simple current-sensitive pre-amplifier is assumed.
  - A transform function is convoluted to raw signal:
  - Impulse response in time domain:

$$h(t) = 1/\sqrt{R_f C_f} \times e^{-t/R_f c_f}, R_f C_f = \tau \text{ (time const)}$$

  - Preliminary assumption, need further studies to align with experimental electronics.
  - Different τ will smooth waveform

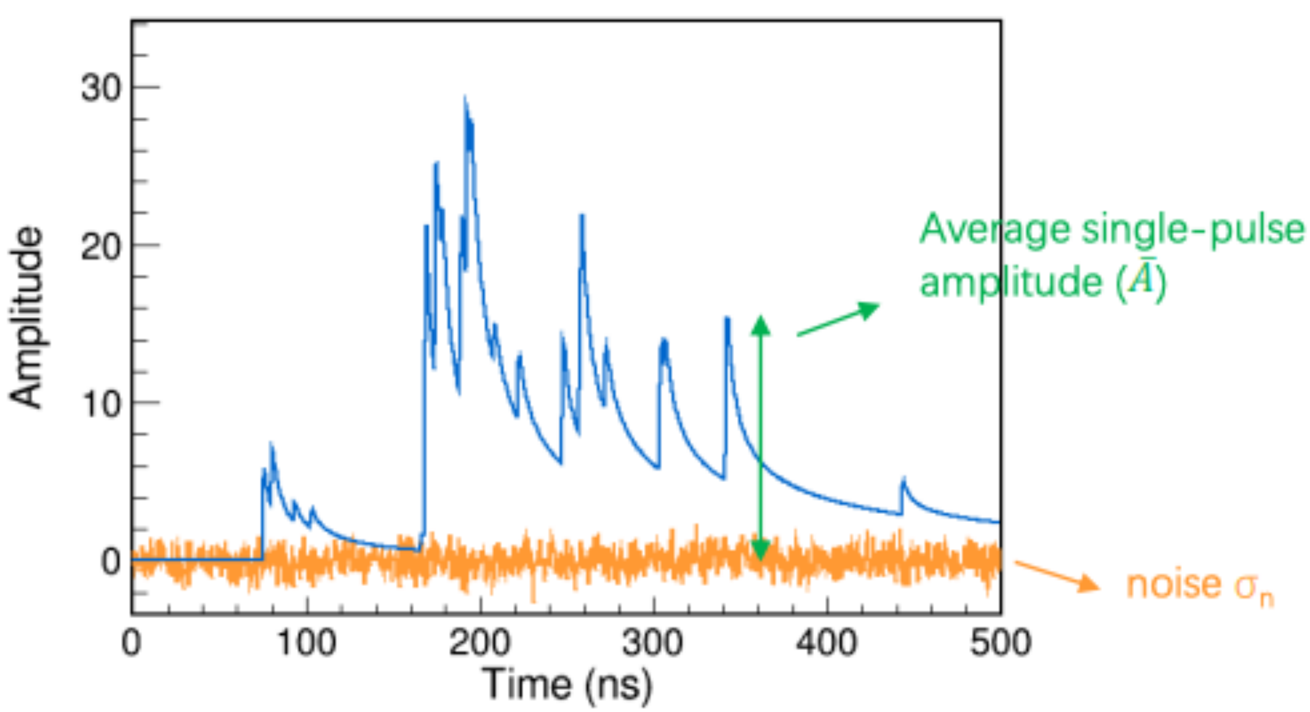


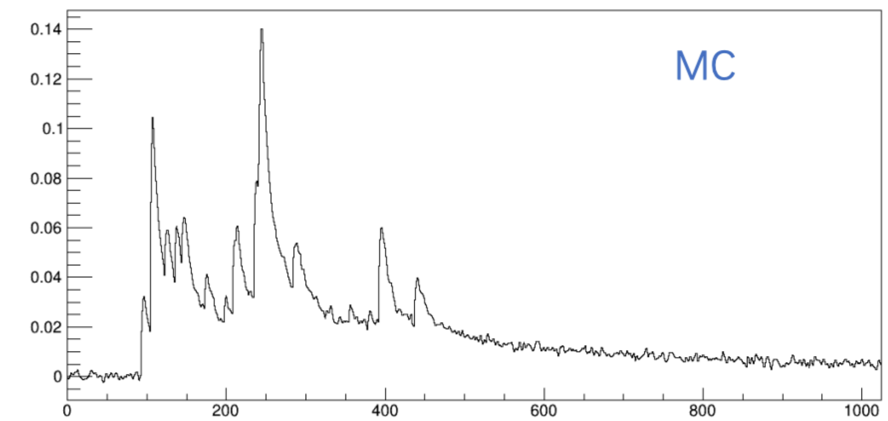
$Ri \parallel Ci \gg Rf \parallel Cf$ and $CL = 0$

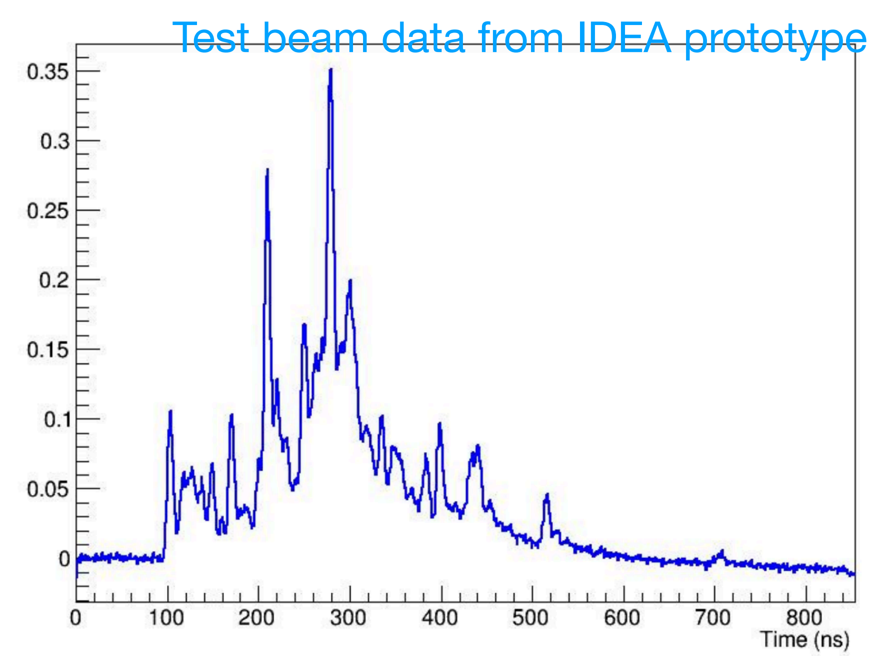


Digitization

- Noise simulation
  - Extract frequency spectra from experimental waveform using FFT.
  - Generate noise by performing iFFT with a random phase
  - Noise ratio definition: $\sigma_{Noise}/A_{signal}$

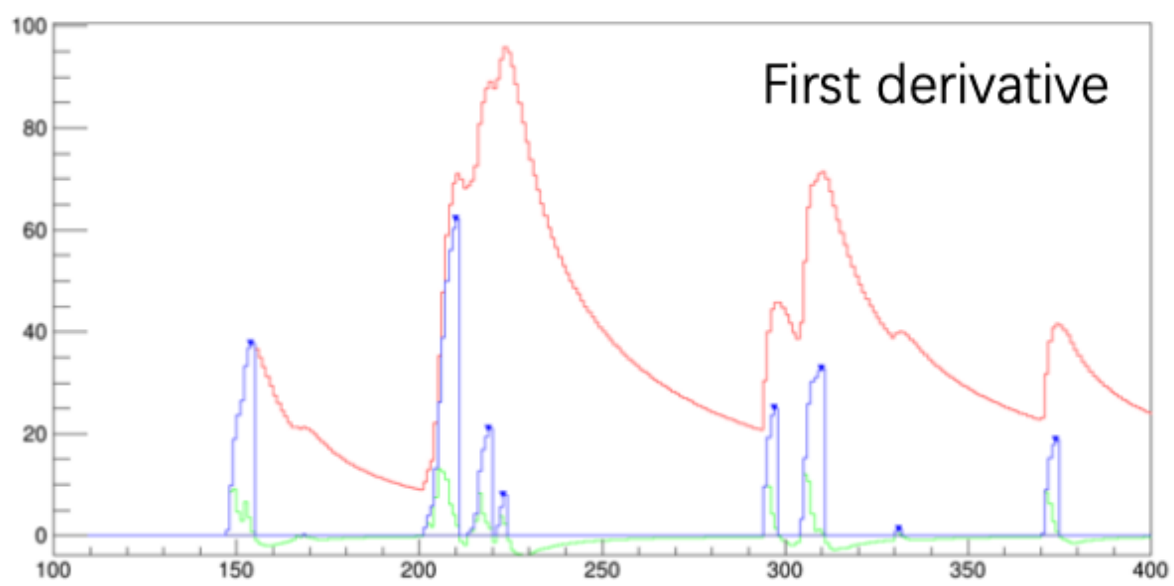


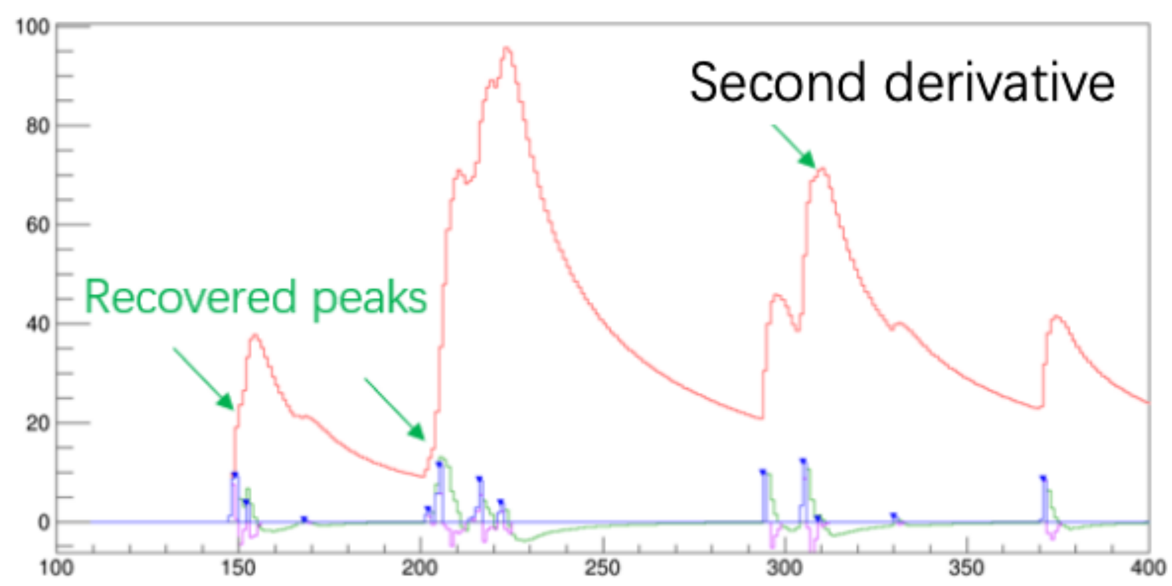




Reconstruction

- Looking for fast and efficient peak find algorithms
- Derivative: The start of a peak will be determined by a change in the derivative
  - Not sensitive to baseline
  - Can be easy to implement in hardware



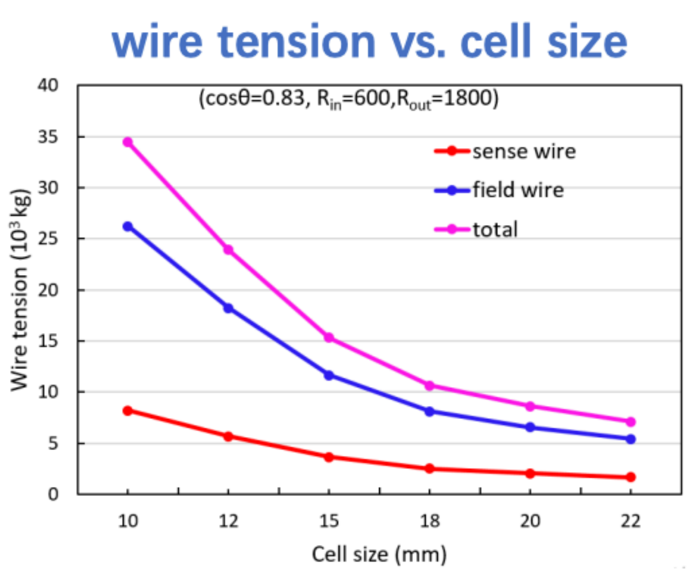


- Pile-up on the failing edge is easier to recover but not for the case on the rising edge
- Will show machine learning solution in a few coming slides

Detector preliminary design

- The separation depends on cluster density, track length, efficiency, etc.
- Gas mixture
  - Prefer smaller cluster density, slower drift velocity, smaller longitudinal diffusion
  - He/iC4H10 is selected from a branch of mixtures => Guang Zhao's talk.

- Cell size
  - In principle, the cell size would't affect too much PID.
  - Has impact on engineering. Prefer less wire tension, reduced number of wires => larger cell



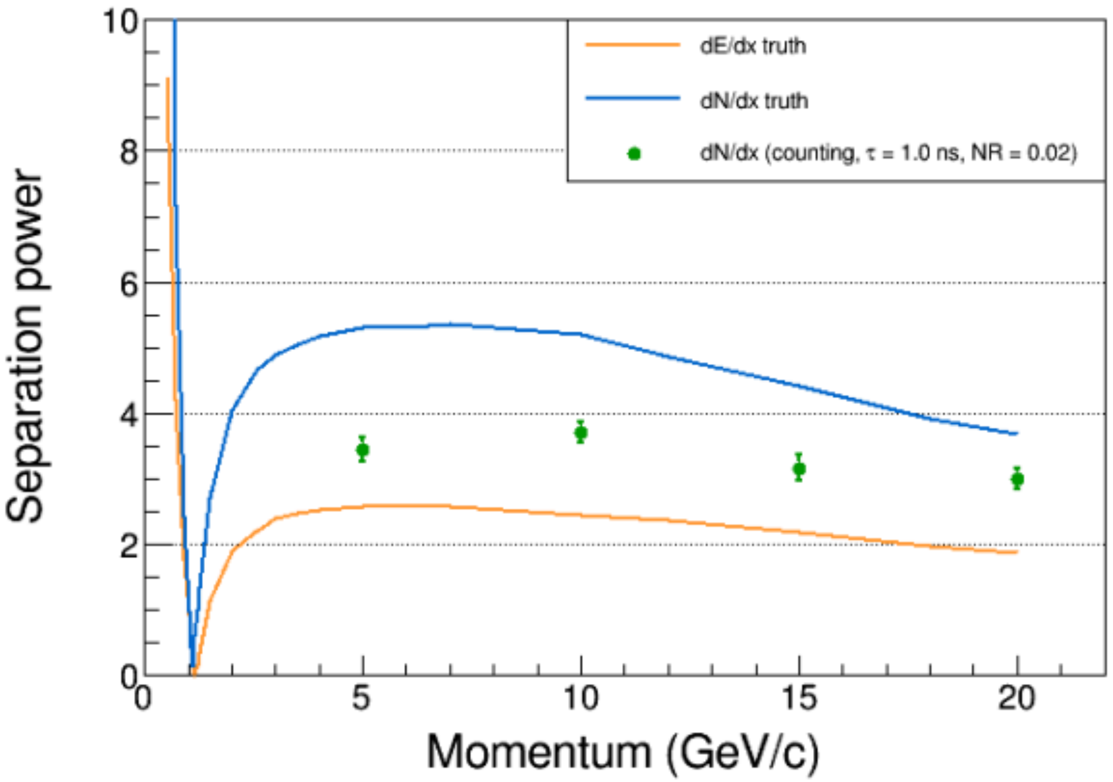
DC parameters

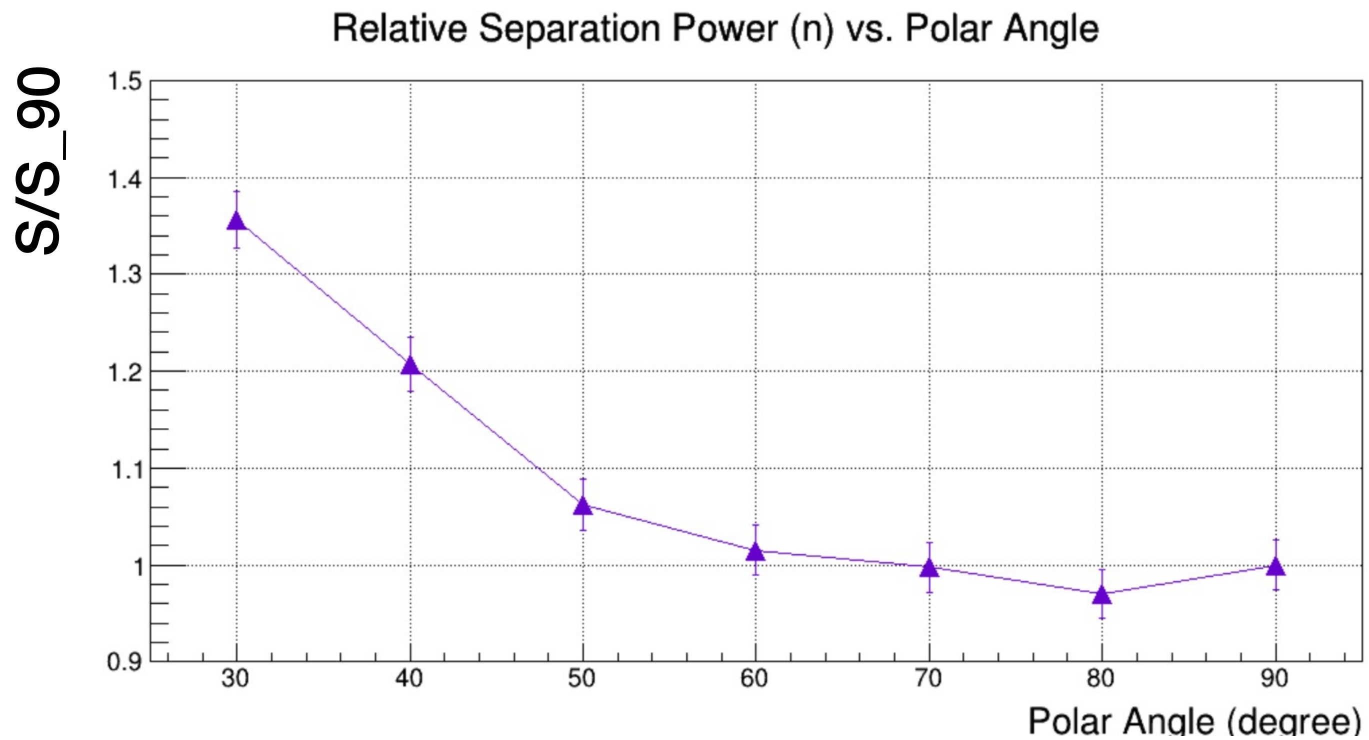
R extension		800 mm - 1800 mm
Length of outmost wires	$\cos\theta = 0.82$	5143 mm
Cell size		18 mm x 18 mm
Gas mixture		He/iC4H10 = 90:10

Expected performance with cluster counting

$$S = \frac{(dN/dx)_\pi - (dN/dx)_K}{(\sigma_\pi + \sigma_K)/2}$$

K/π separation vs momentum at 90 degree

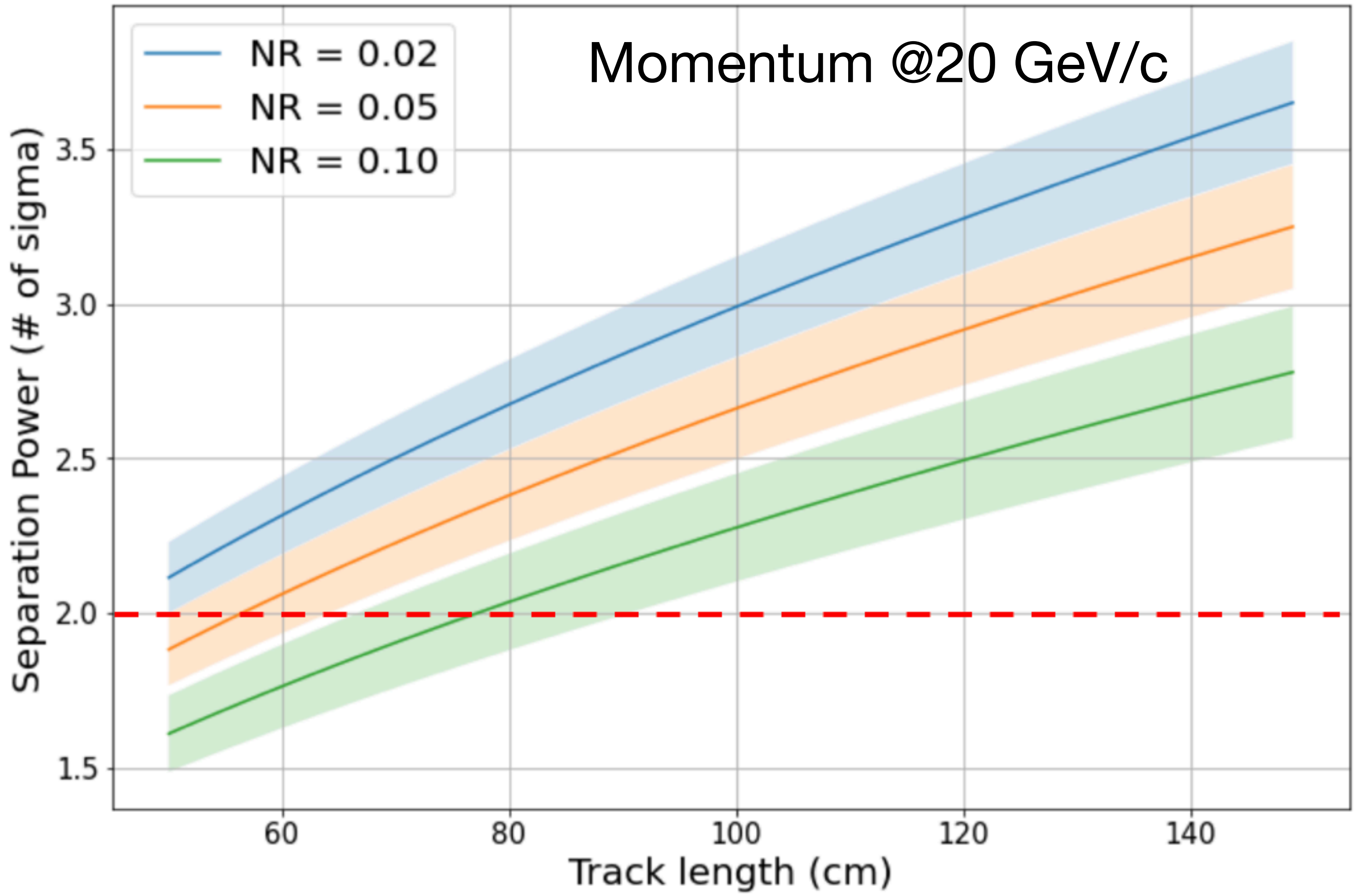




- 90 degree performance with 1m tracking length with noise: 1.5 better than dE/dx truth
- Polar angle scan: long track length allows better separation.

Expected performance with cluster counting

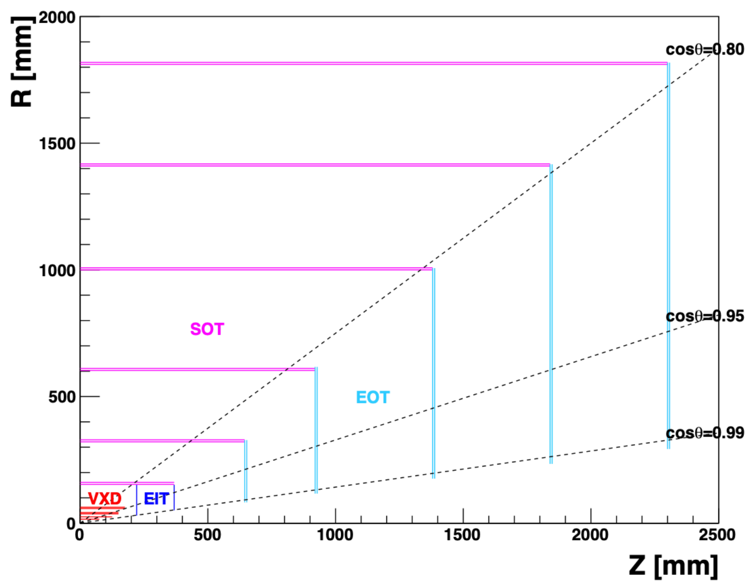
- A $2\sigma\ K/\pi$ separation at 20 GeV/c is achieved within 1m track length in 10% noise ratio.
- The requirement of separation power needs further studies with physics channels.
  - Some studies in physics channels considering dN/dx is ongoing.



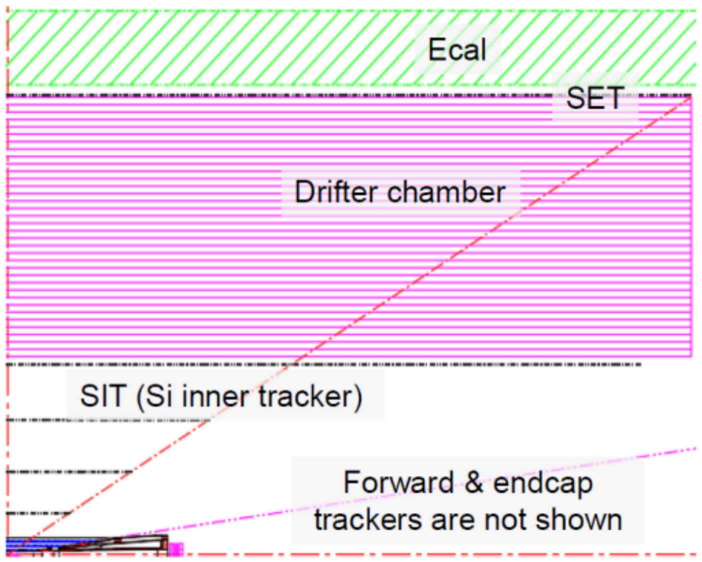
Resolution is scaled by $\sqrt{L}$

Momentum performance

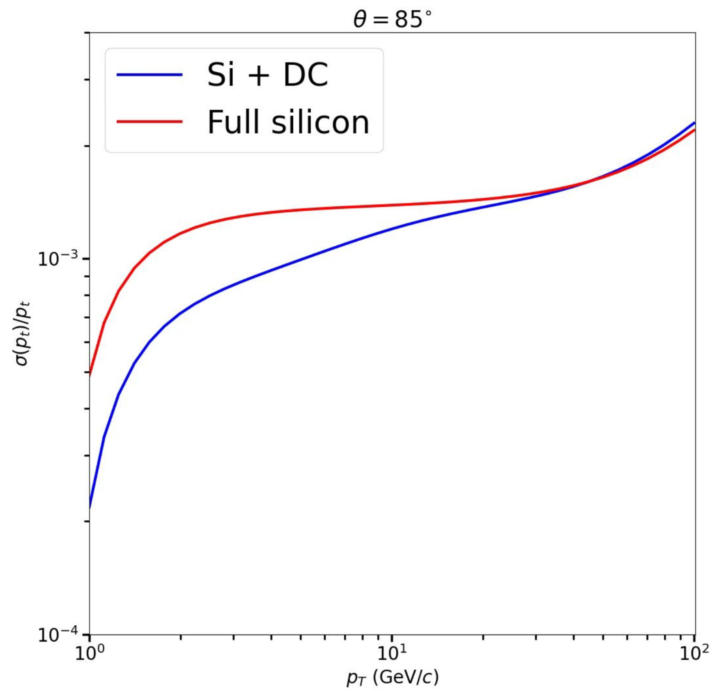
- High resolution and low budget Si system is required, such as silicon inner tracker, silicon external tracker for precise measurement.



Full Silicon Tracker (FST) from CDR



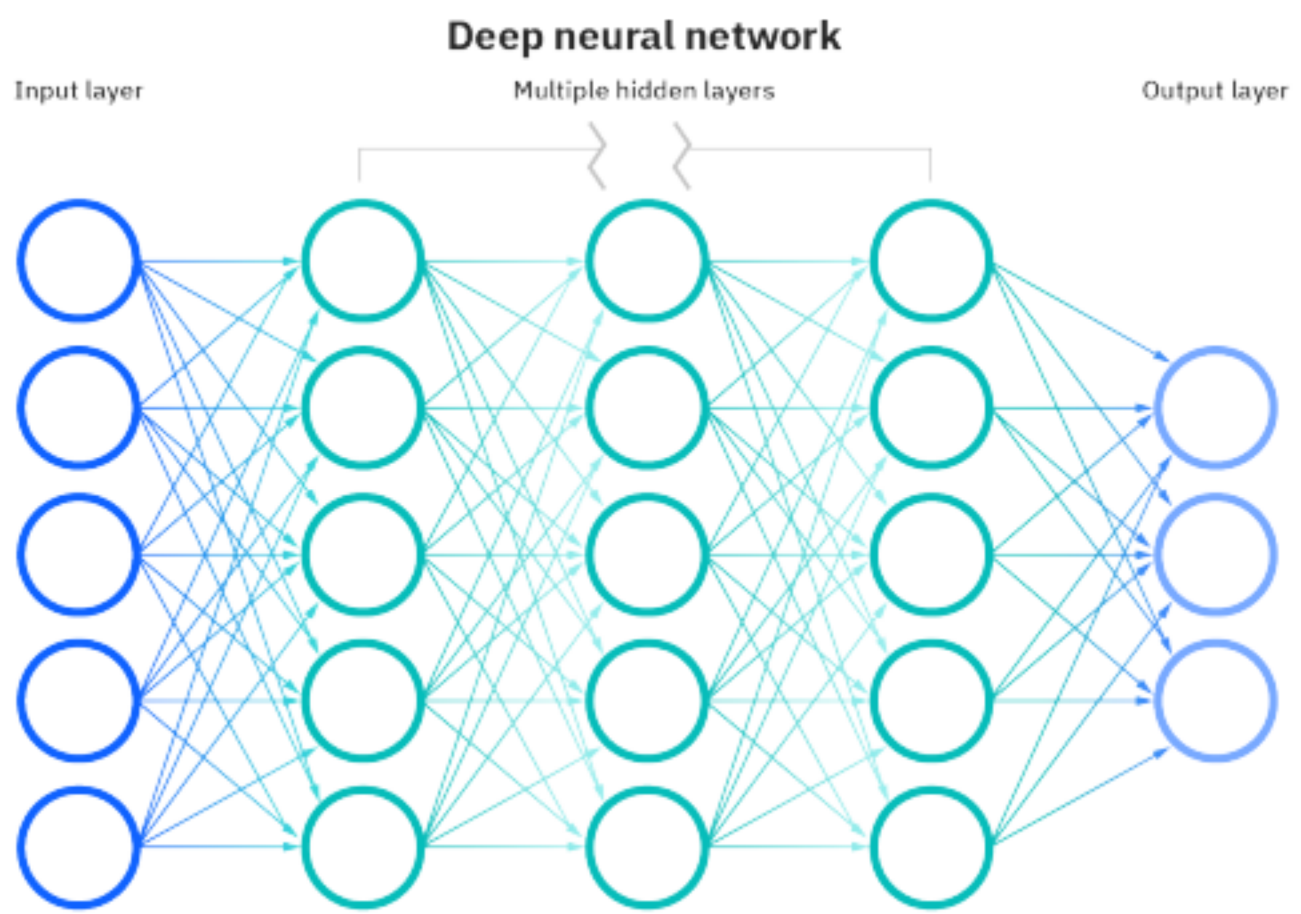
Si + DC



- The change of drift chamber is significant to low momentum measurement.
- Si + DC design gives better momentum resolution than FST design ~ Pt < 50 GeV/c.

counting algorithm based on Machine Learning

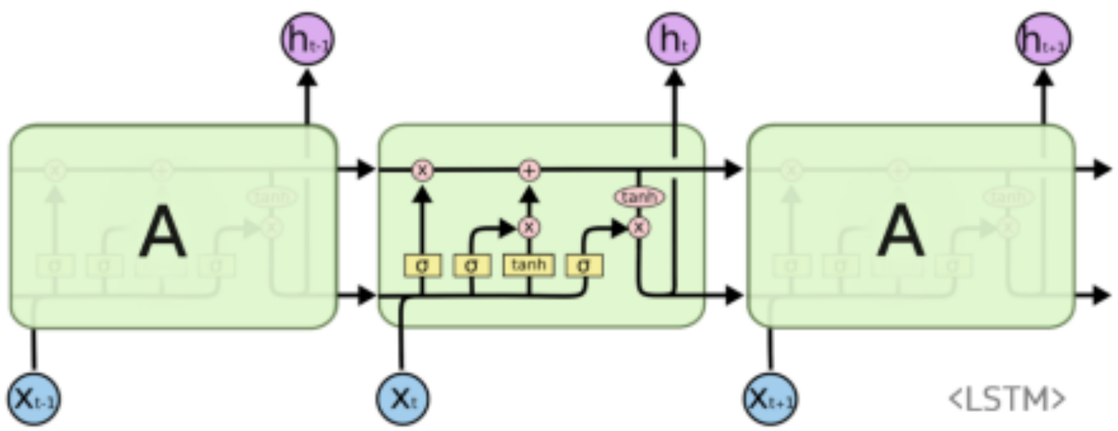
- The counting algorithm is the essential for the success of cluster counting
- Derivative peak finding algorithm recap:
  - Only use slope of the raising-edge information.
  - Not effective in high pile-up region and sensitive to noise.
- Machine learning: extract complex & nonlinear relationship of the input data
  - What architecture of ML can be a solution for cluster counting?

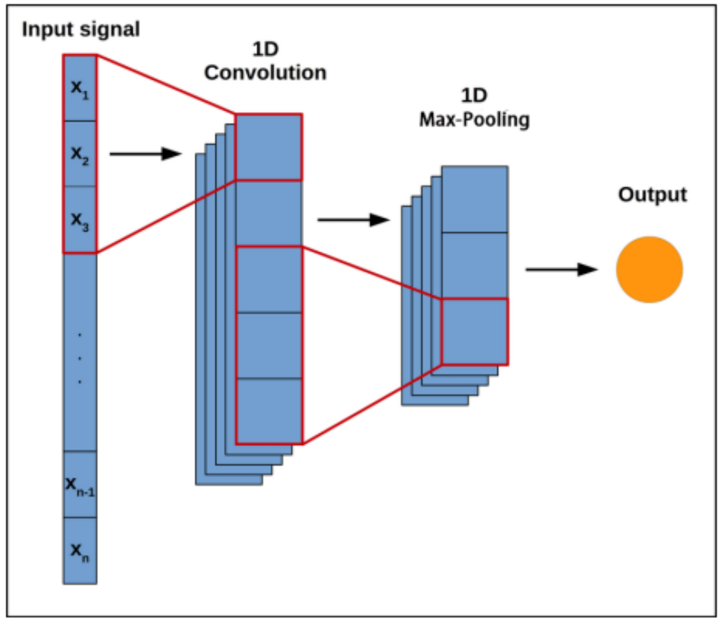


[Zhefei Tian's poster]

Machine Learning counting algorithm

- In practice, we treat the cluster counting as a classification and a regression problem in two steps:
  - **Peak finding**: find primary and secondary ionization peaks with the sequence information
  - N_{cluster} **determination**: group electron peaks to clusters

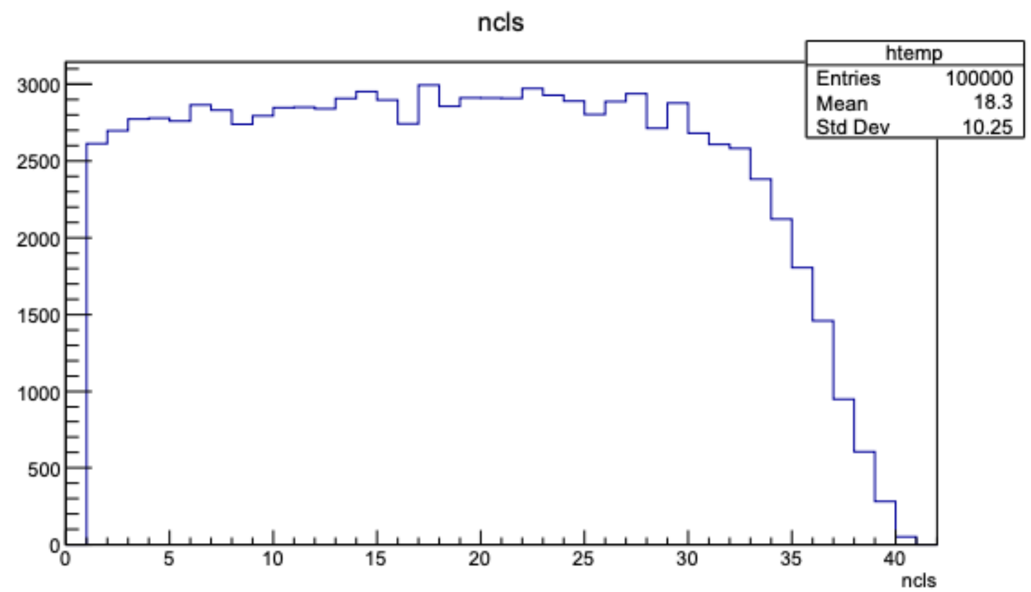


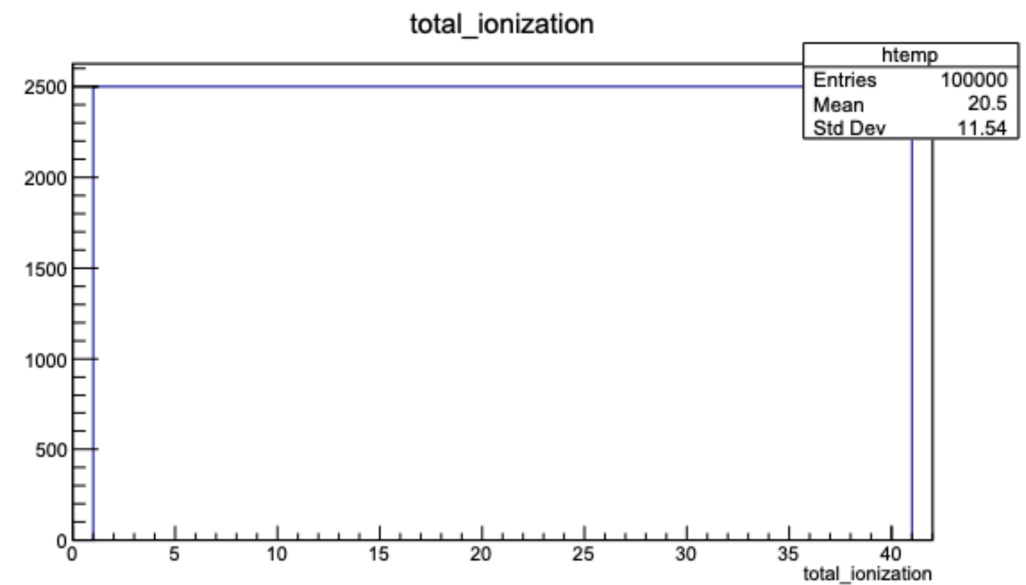


- "LSTM" = long short-term memory
  - Can retain contextual information from previous samples
  - Good for time series datasets for which the order of the events matters
- CNN:
  - Detect distinct features without any human intervention.
  - Provide an efficient dense network for identification

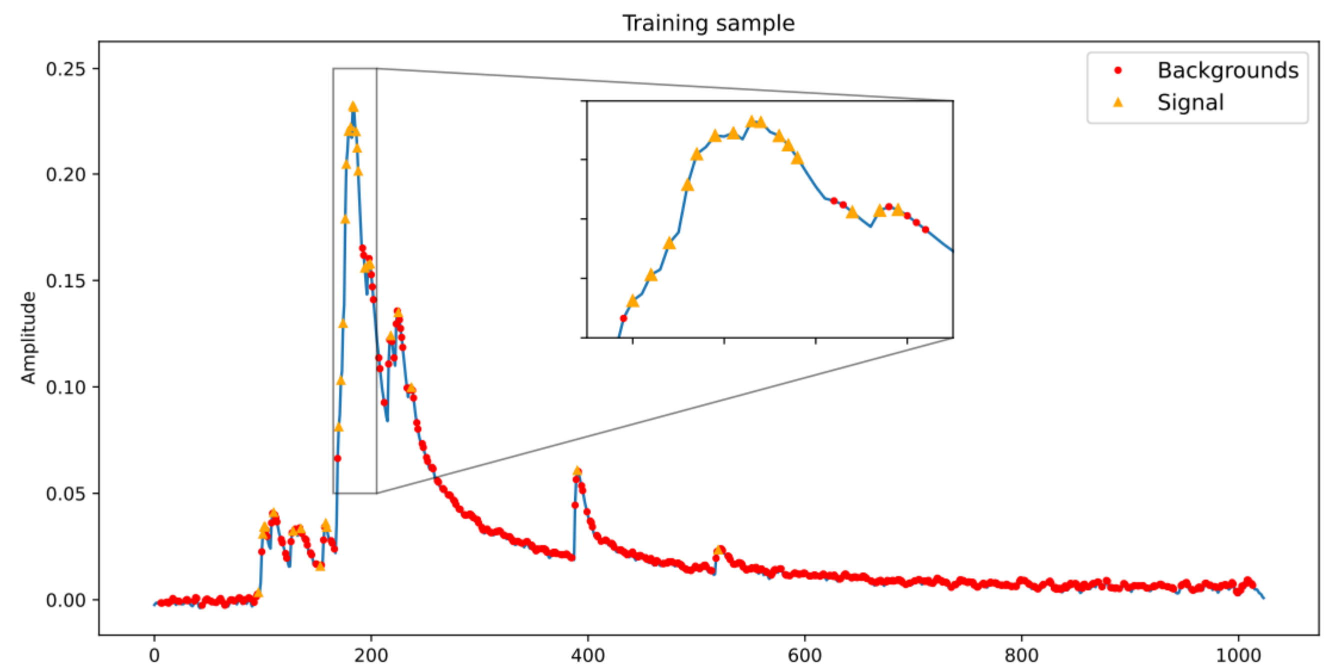
Data preparation

- A set of Monte-Carlo sample was generated as training sample
- The number of total ionization is 1 to 40, where the number of clusters are sampled from certain distribution.





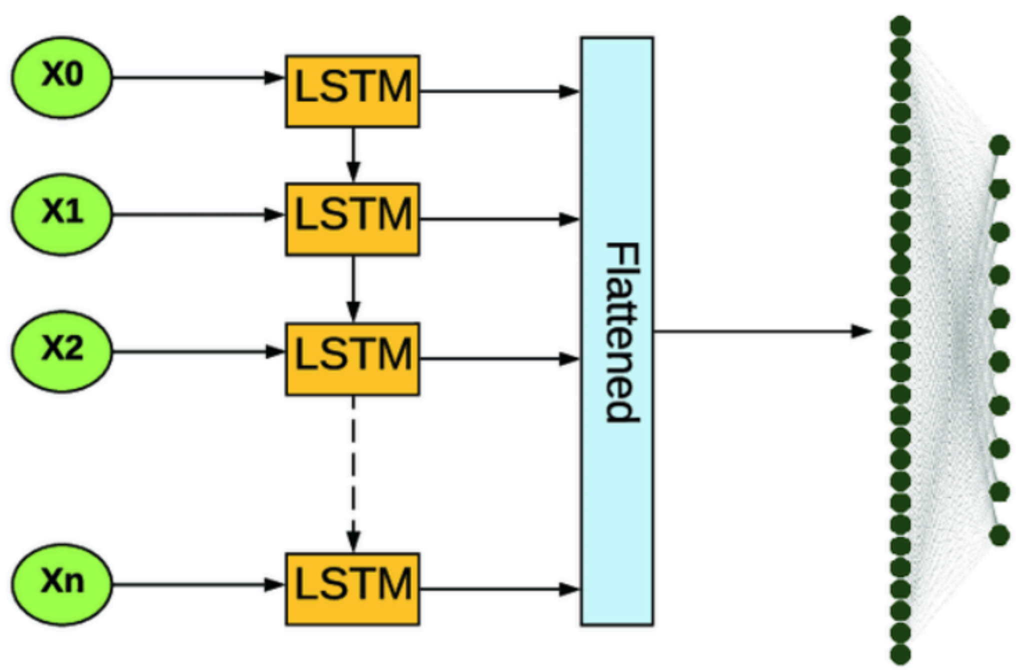
- Use slice windows of the waveform as the inputs
  - Label is added to match the signal/background
  - Balancing signal/background sample

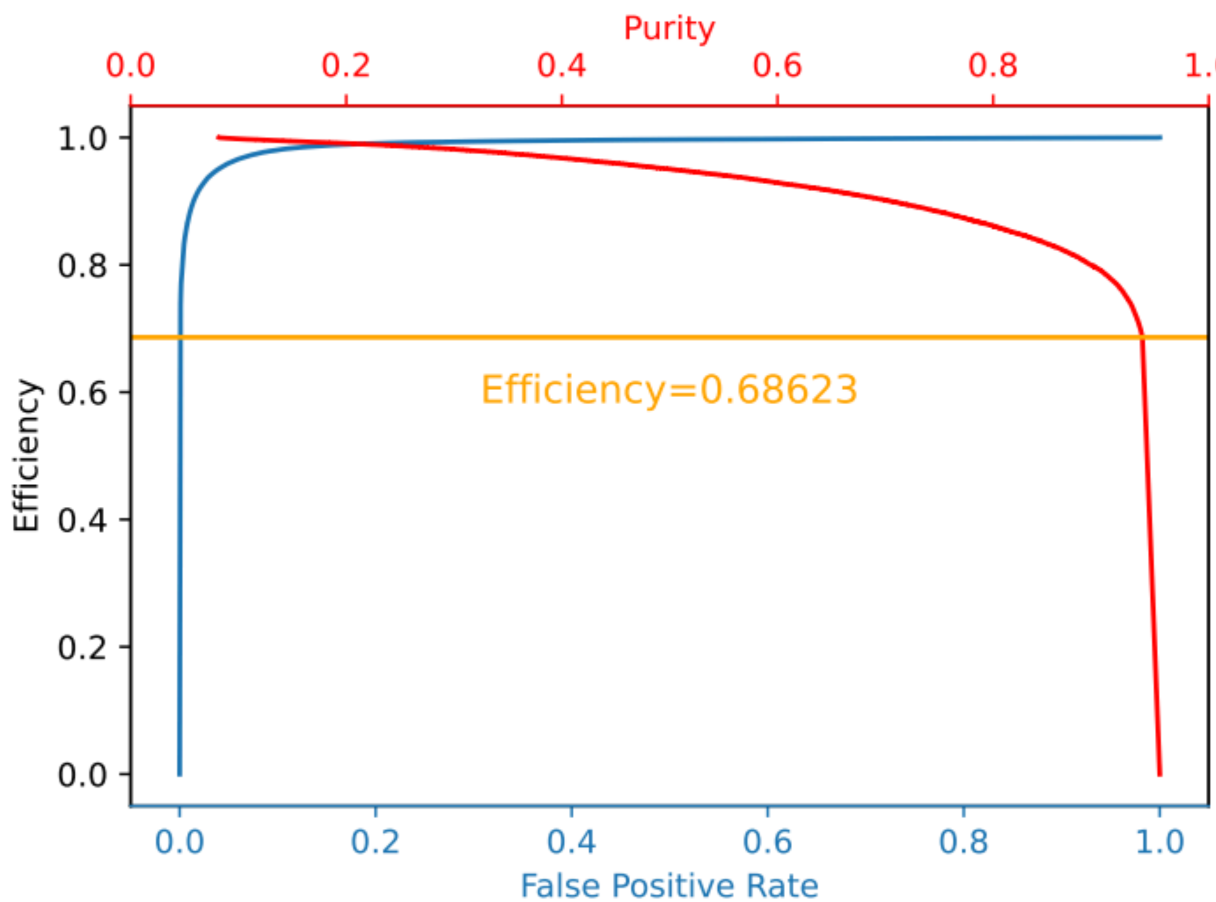


Training model- LSTM

- **Step1: peak finding: find all ionization peaks from current waveform.**
- Purity of detected signal peaks, efficiency of detected signal peaks and other metrics are used to evaluate the model:
  - Purity (Precision) = TP / (TP + FP) = 0.892
  - Efficiency (Recall) = TP / (TP + FN) = 0.686
  - False Positive Rate = FP/(FP+TN) = 0.0005

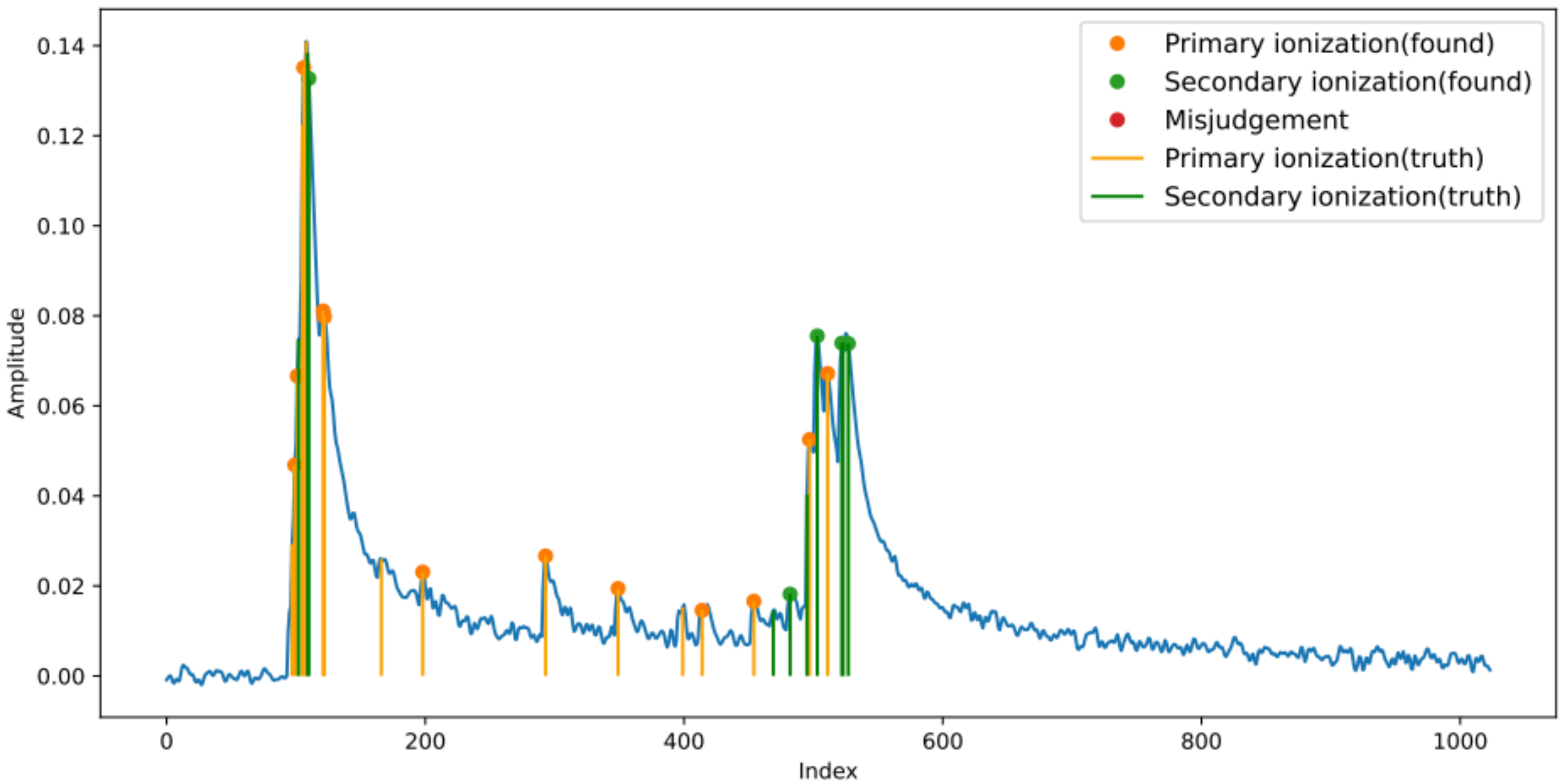
		Prediction	
		Signal	Noise
Truth	Signal	TP	FN
	Noise	FP	TN

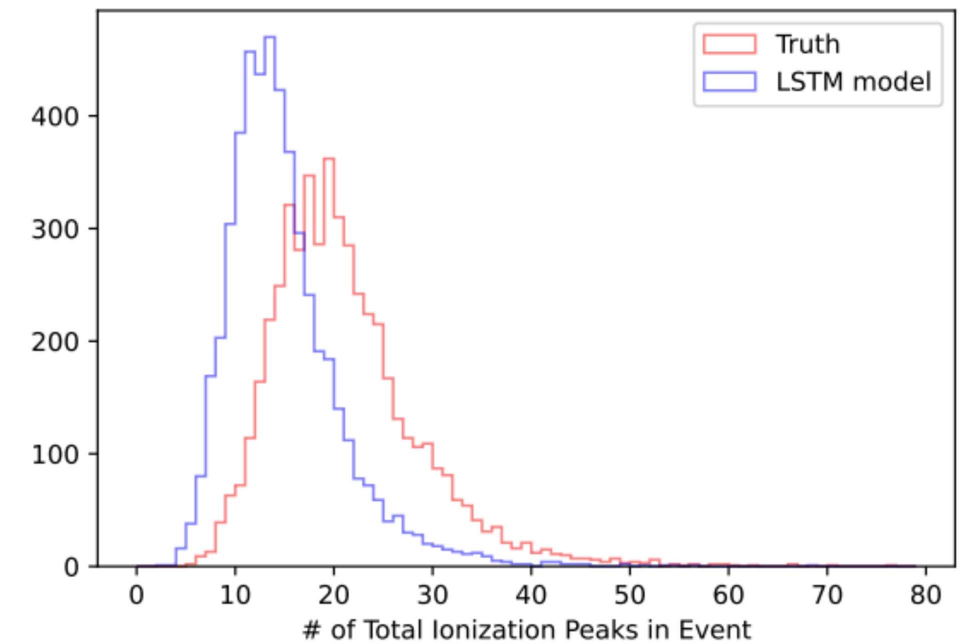




Peak finding model testing

- Test the training model on a separate datasets
- Peak finding result:
  - Moderate counting efficiency and tiny fake rate.

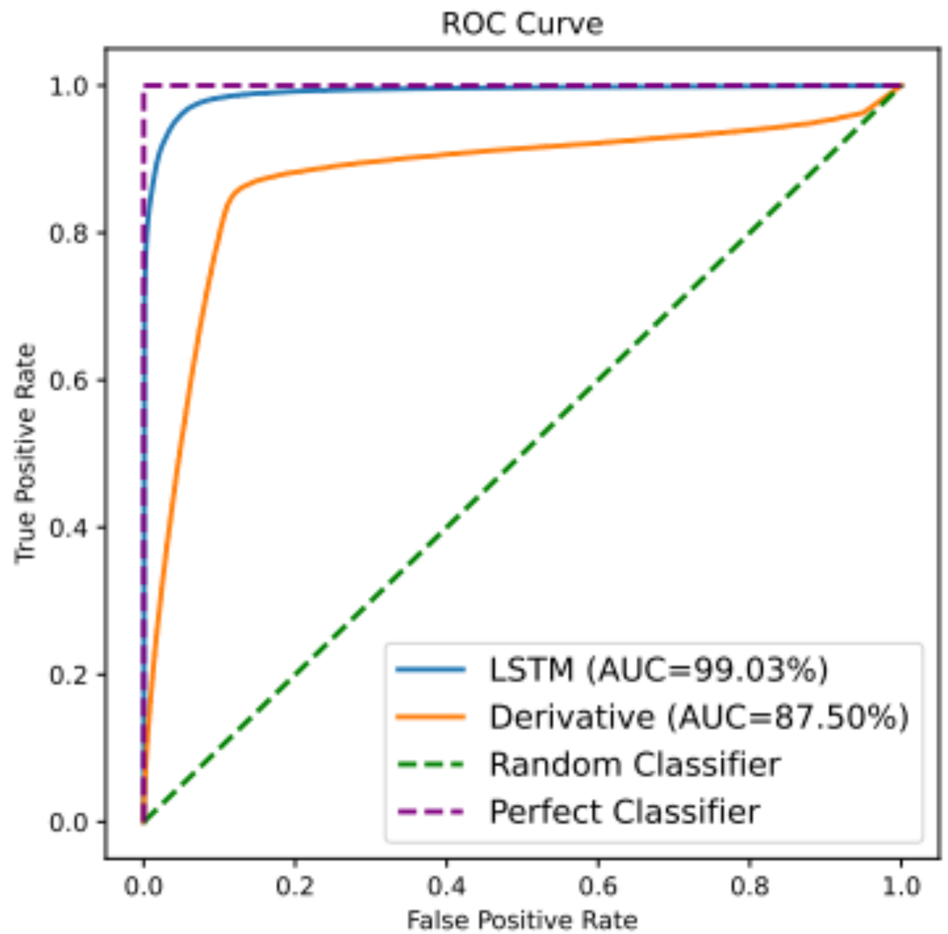


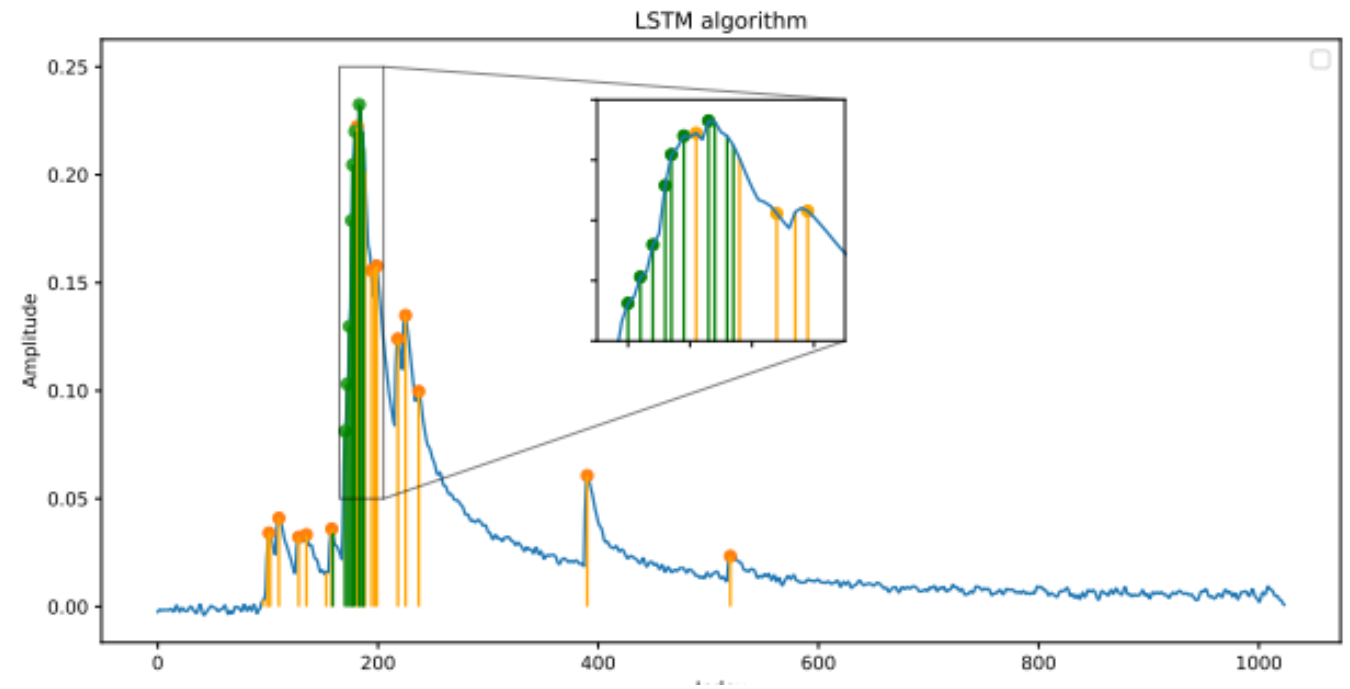


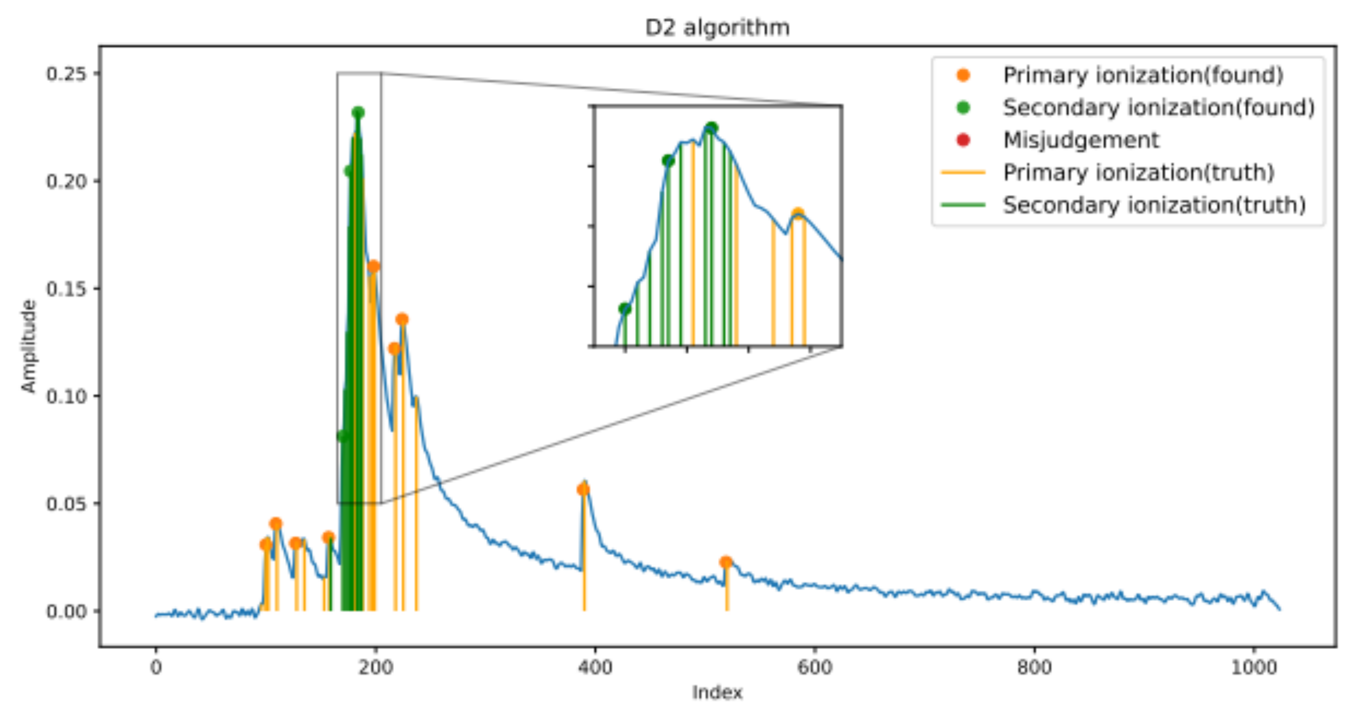
  - The lost peaks mostly come from pileup regions.

Comparison of two algorithms

- ROC curve is frequently used for evaluating the performance of binary classification algorithms. ROC curve with lager area under-curve (AUC) is better.

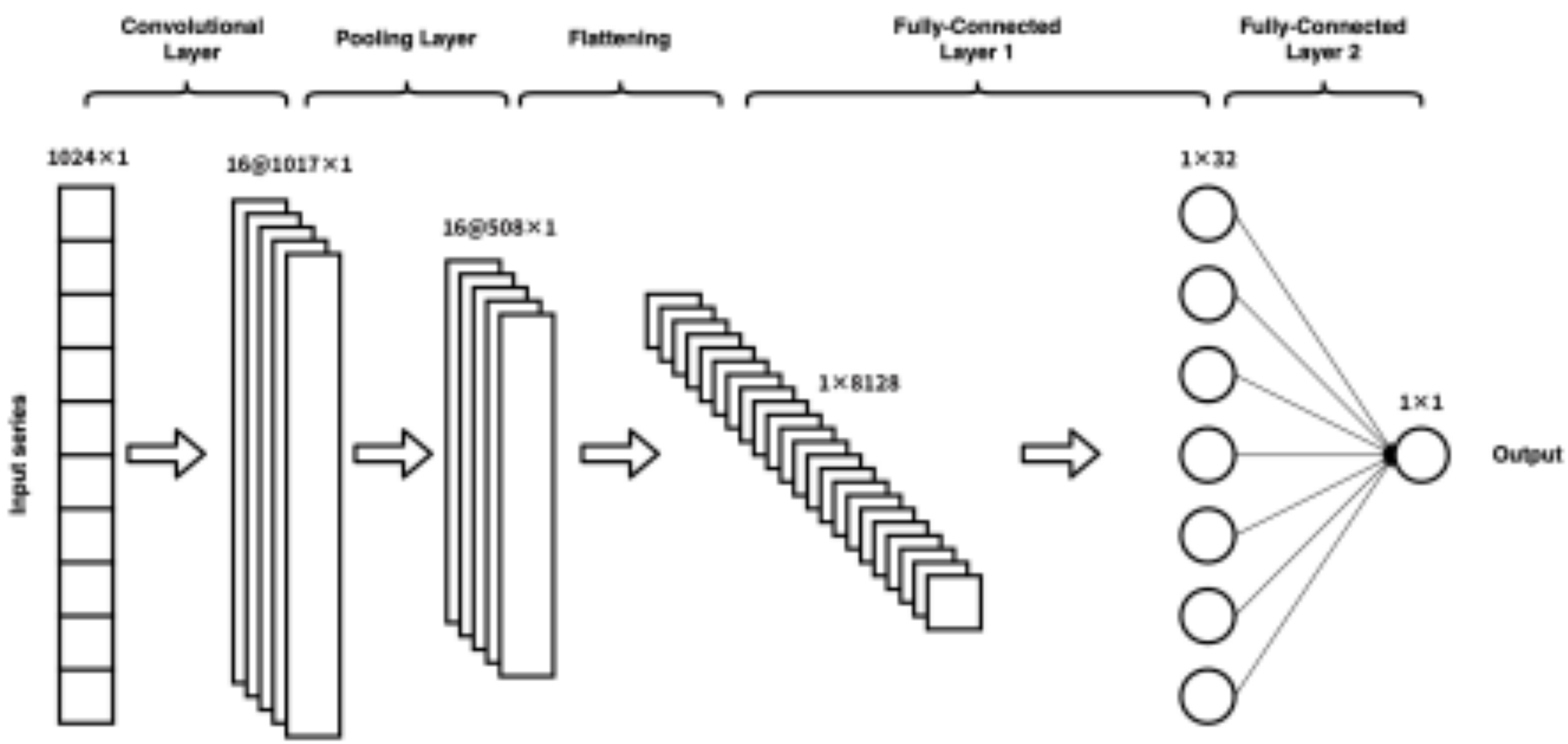






N_{cluster} determination training

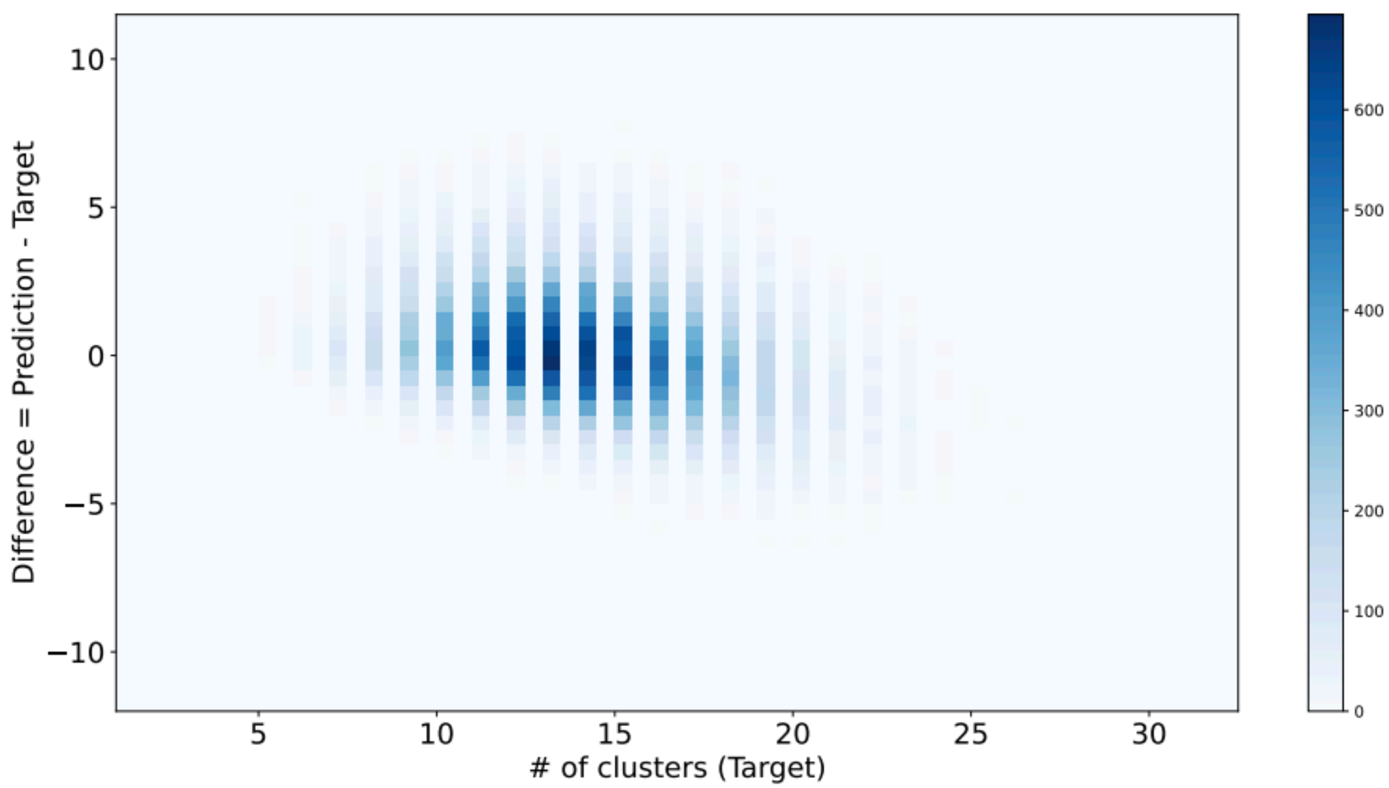
- **Step2: Determine the number of clusters according to the ionization peaks found by peak finding algorithm.**
- Regression problem to predict number of clusters
- The features are detected time (from first step), labels are number of clusters.

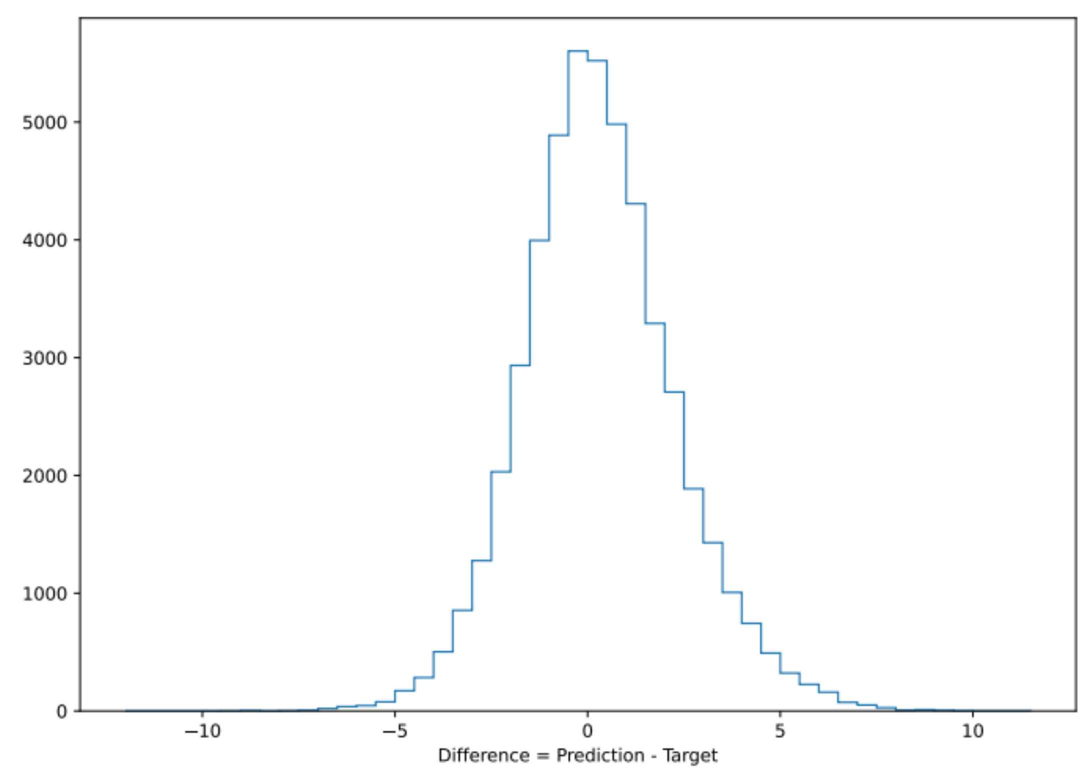


- 1D CNN to handle sequence data

N_{cluster} determination testing

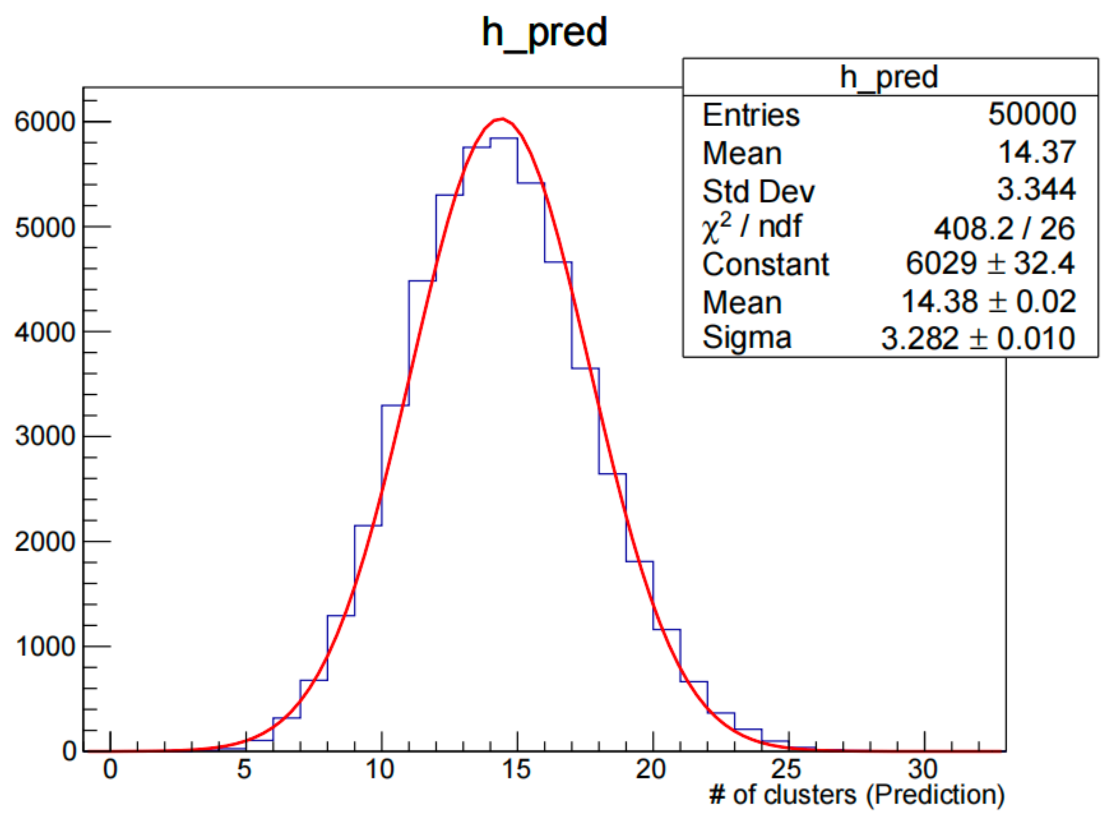
- Test samples with Poisson distribution (μ = 20) processed by peak finding model was used to test the Cluster determination model.
- The difference between predicted and target values are small and reminds stable.

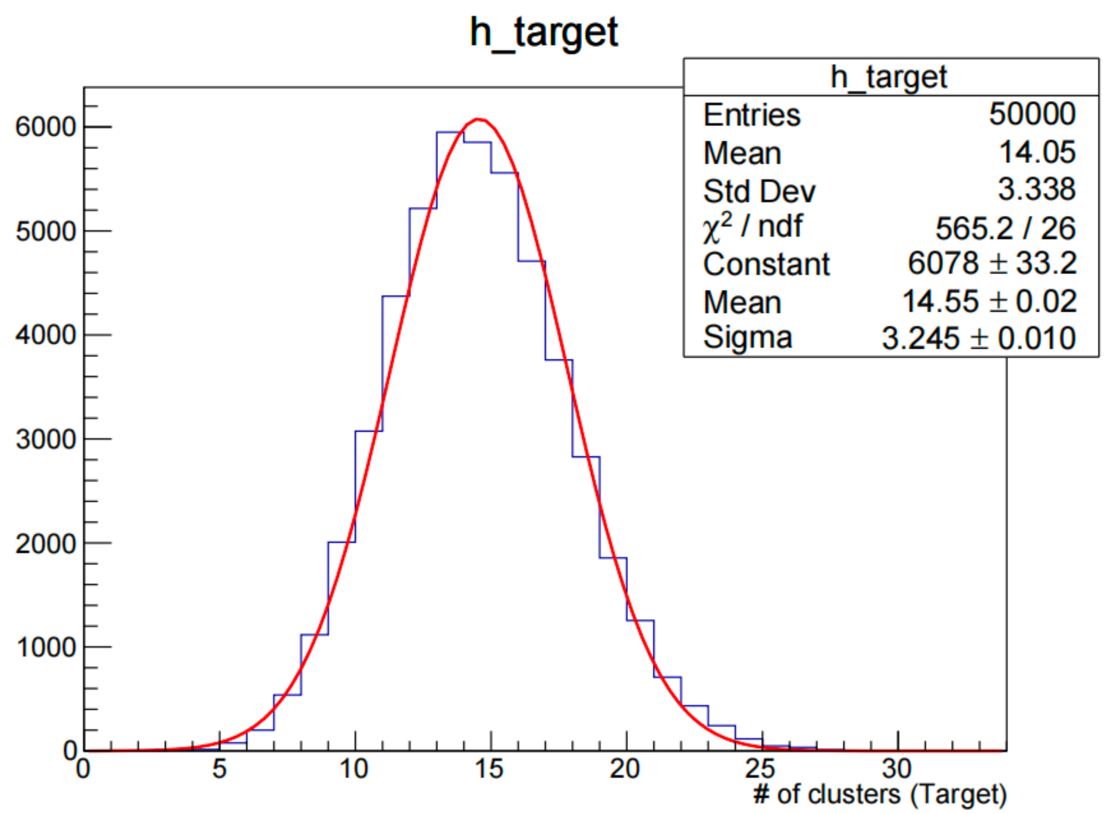




N_{cluster} determination testing

- Single cell resolution (σ/μ) ~ 22.8% (22.3 % in truth)
- Very good Gaussian distribution
- The relative error is quite similar to the truth value. Which implies stable efficiency.





Summary

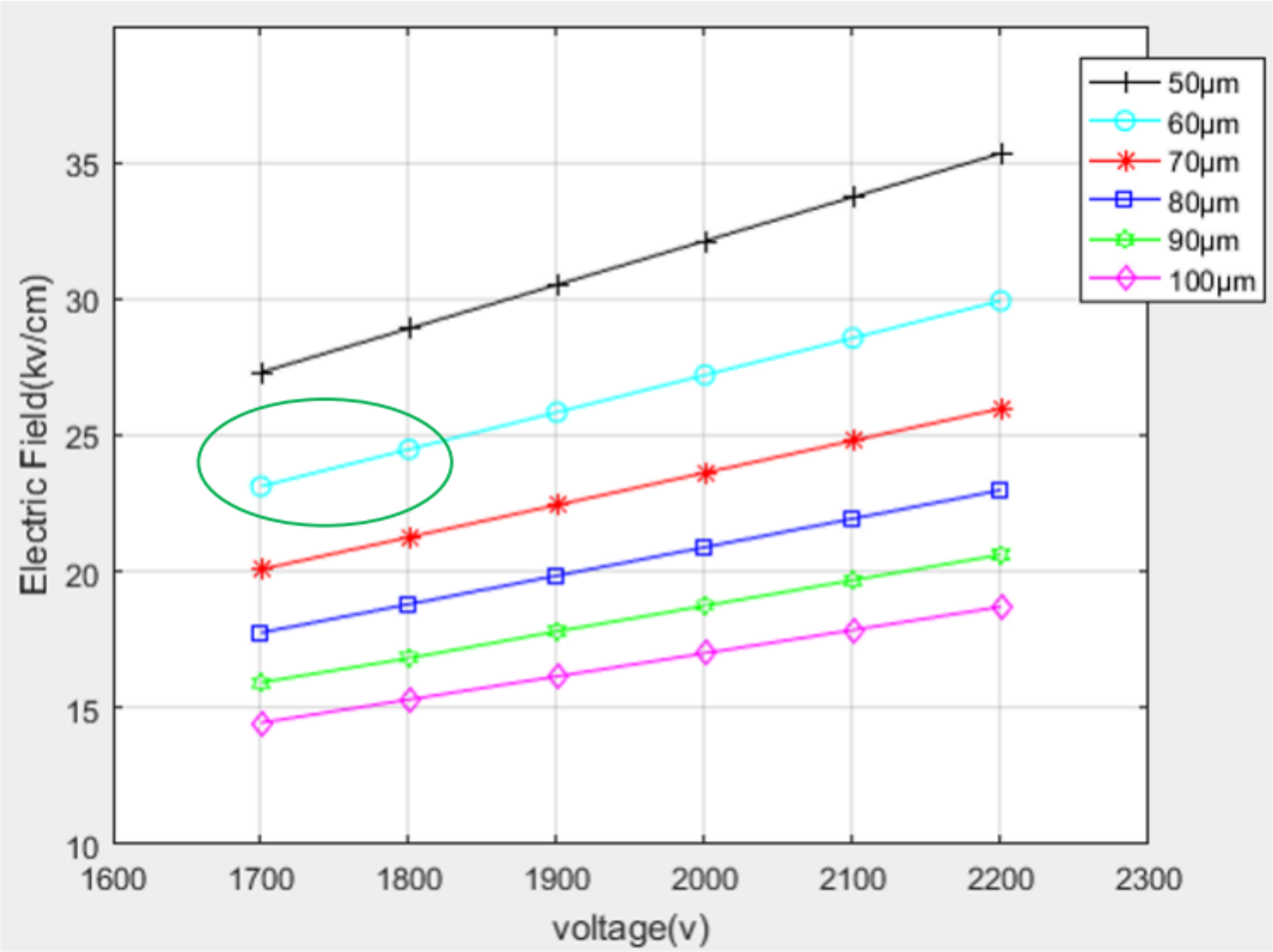
- A tracker with silicon layers and a drift chamber is proposed for CEPC, simulation study and expected PID performance are presented.
  - K/π separation reaches to 2σ up to 20 GeV/c for 1m track length under certain noises.
  - The momentum resolution of low momentum is benefited.
- A machine learning based cluster counting algorithm is developed.
- Result with the ML algorithms shows promising performance for MC samples.

- Outlook:
  - Evaluate the full performance of the ML algorithm and apply to the experimental data
  - Study the PID requirement in physics channels using Delphes fast simulation:

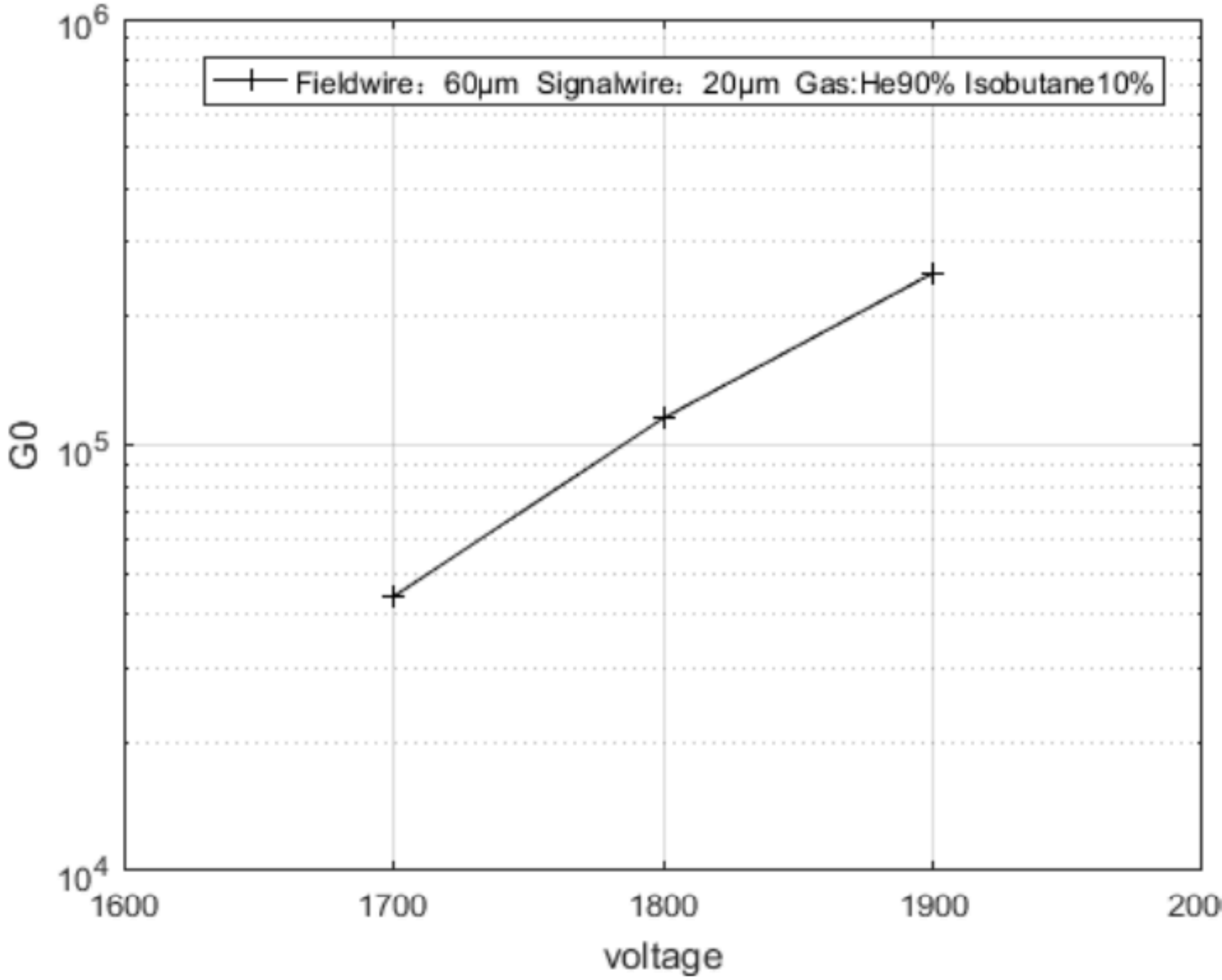
Many thanks to INFN, Jilin University, Wuhan University, Shandong University, Nanjing University and ZhengZhou University for their contributions !

Backup

Field and gain

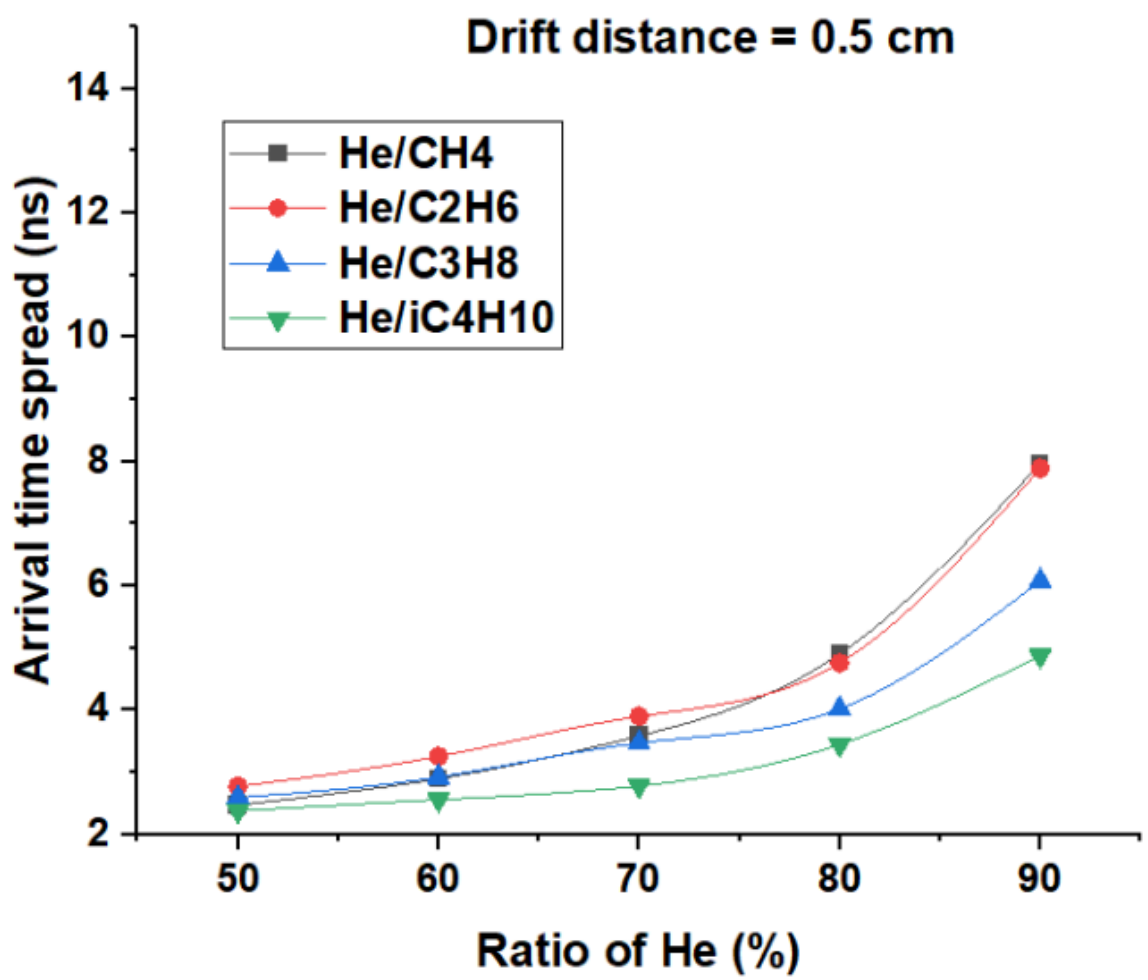


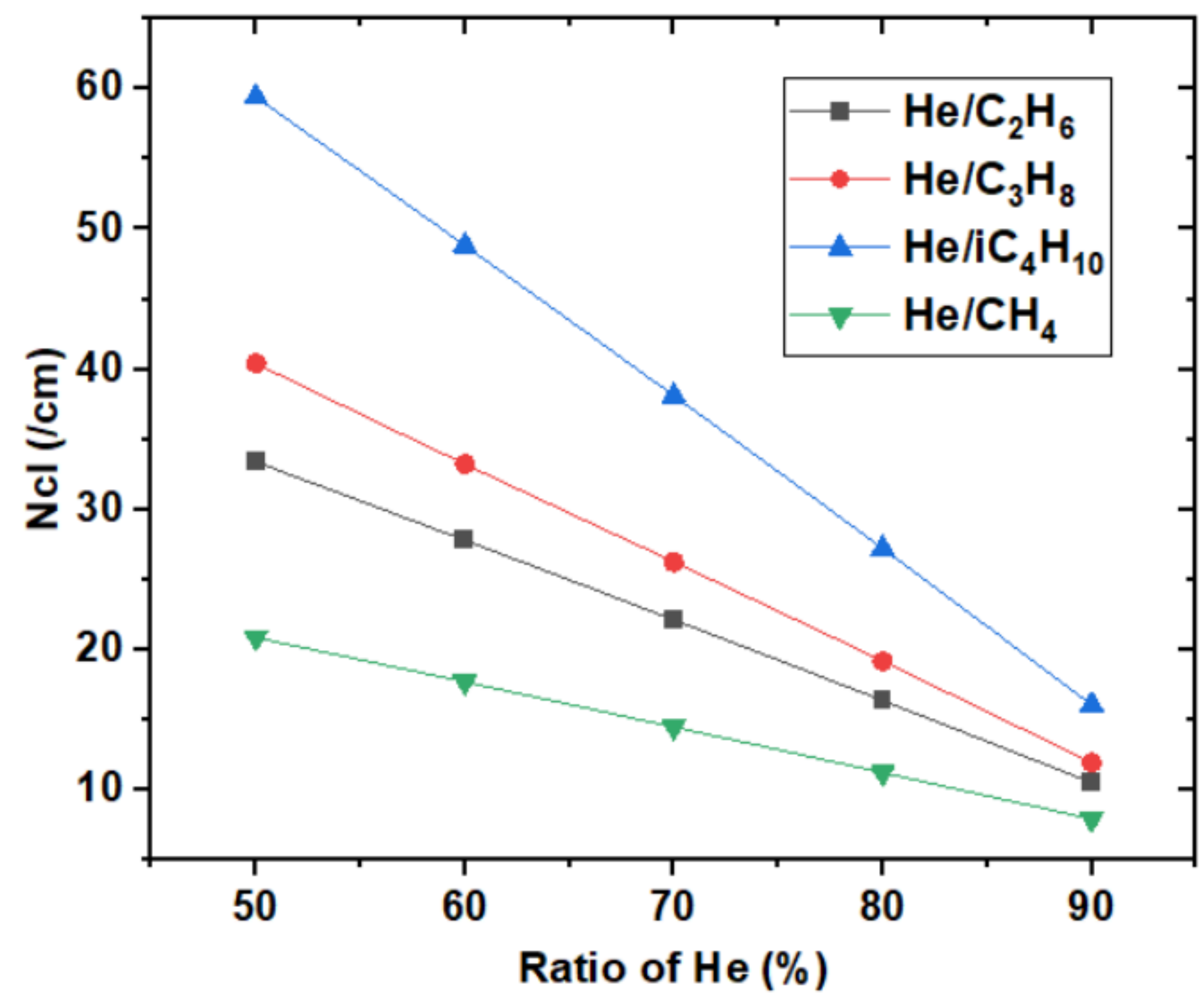
Electric field of field wires



Gain

Property for more gas mixtures



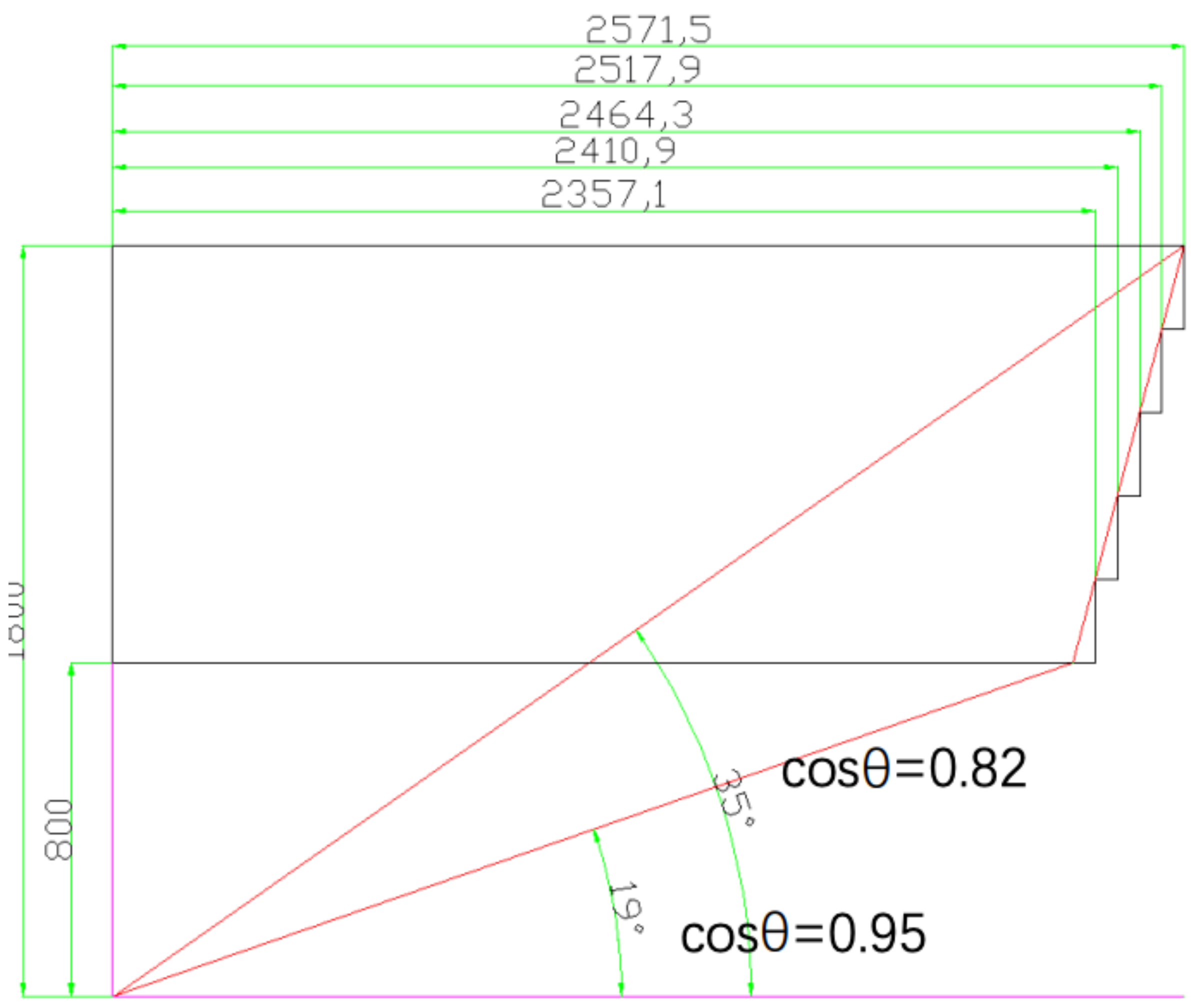


Tracker parameters

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

Drift chamber design with mechanical structures



Total tension: ~9200 kg

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