Progress on cluster counting for the 4th concept DC

Guang Zhao
for DC PID Group
zhaog@ihep.ac.cn

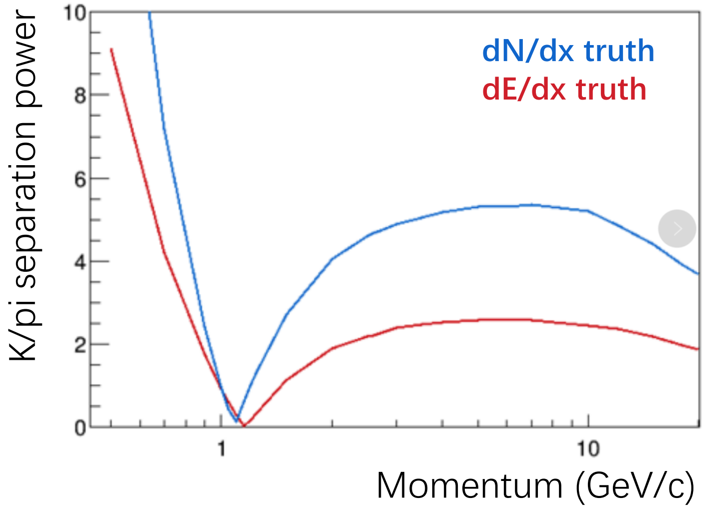
CEPC Physics and Detector Meeting
Jan. 11, 2023

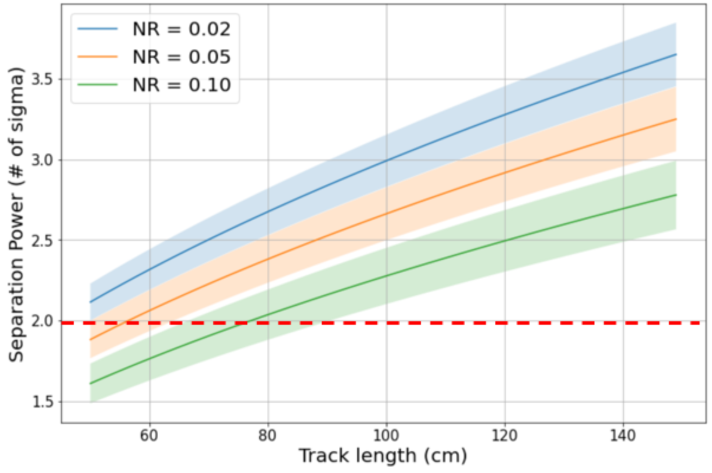
Motivation

- **Excellent PID is required for CEPC physics programs**
  - Preliminary requirement: > 2σ for 20 GeV/c pion/kaon separation
- **The cluster counting (dN/dx) is the most promising breakthrough in PID**
  - Resolution has, potentially, a factor of 2 better than the dE/dx
- **Drift chamber with cluster counting can provide sufficient PID power while keeping a reasonable detector size**

Recaps of simulation

- **Ideal simulation (truth):**
  - K/pi separation with dN/dx is x2 better than dE/dx
- **Full simulation (more realistic, w/ electronics/noises/reconstruction):**
  - 2σ K/pi separation at 20 GeV/c
- **Determine DC parameters with full simulation**





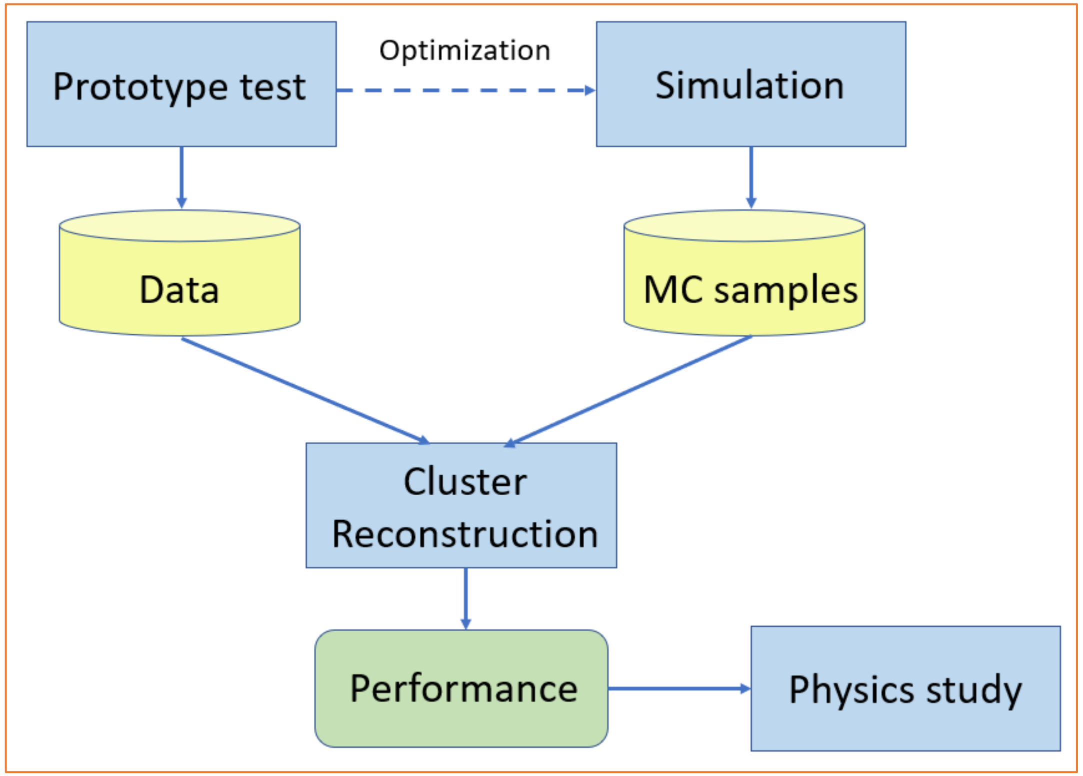
The resolution scales with $L^{-0.5}$
(Noise ratio in beam-test is close to 10%)

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

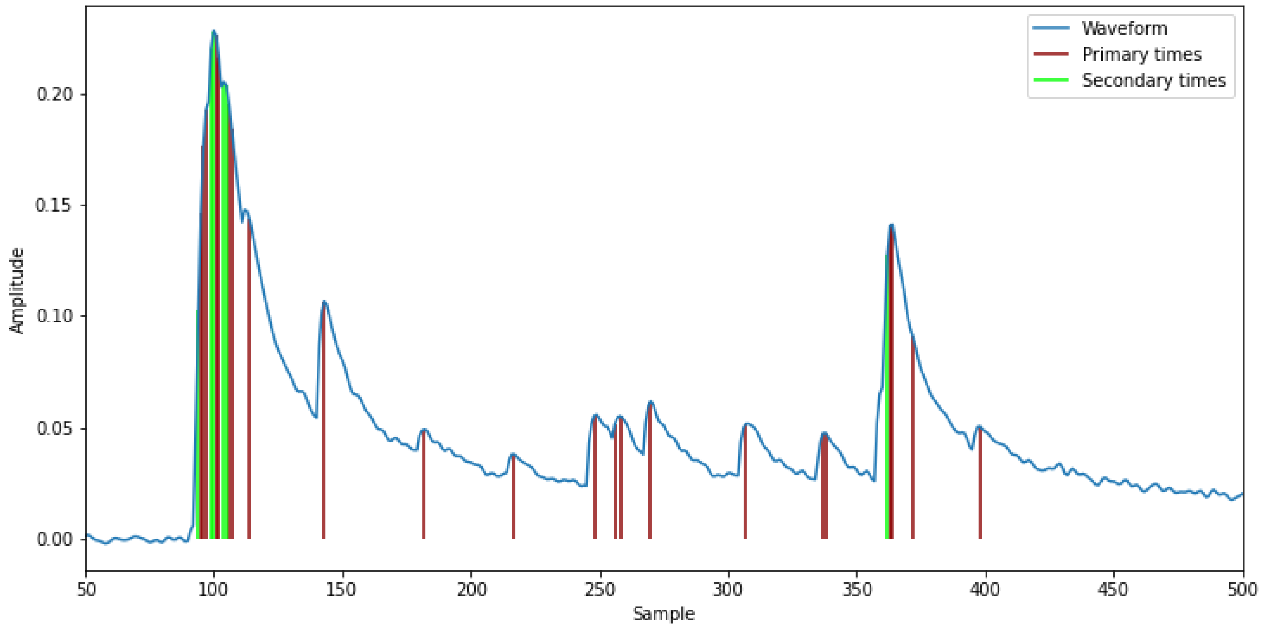
Major efforts in this talk

- Reconstruction algorithm
- Understanding beam test data

Cluster counting workflow



Reconstruction algorithm



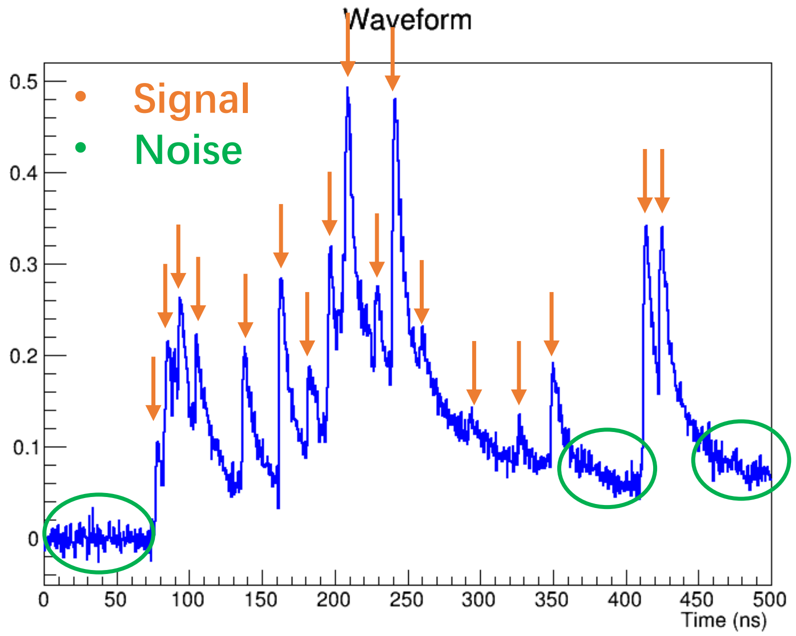
- **Task:**
  - Both **primary electrons** and **secondary electrons** contribute peaks on the waveform
  - Find the number of peaks from **primary electrons**

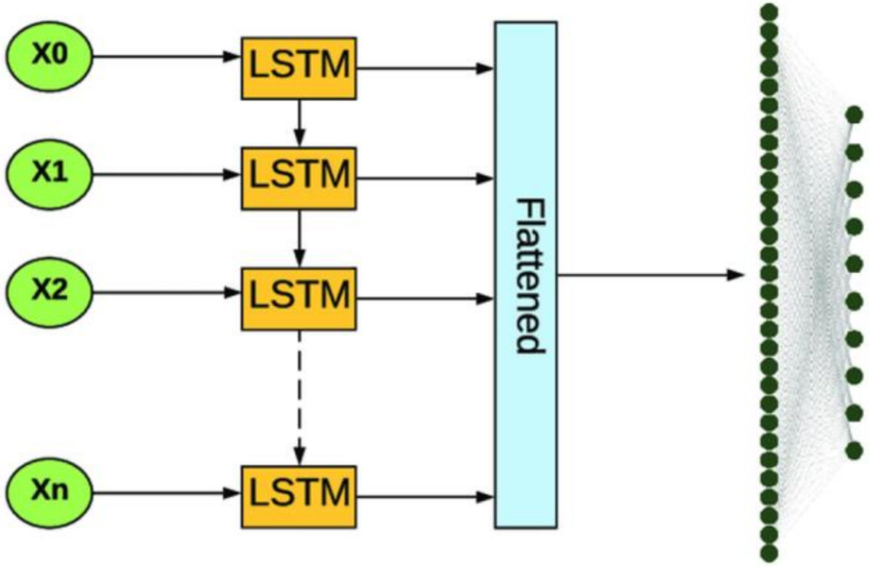
- **Difficulties**
  - High pile-up
  - Could be noisy

- **Machine learning** can make full use of the waveform information, could be effective

Step 1: Peak finding

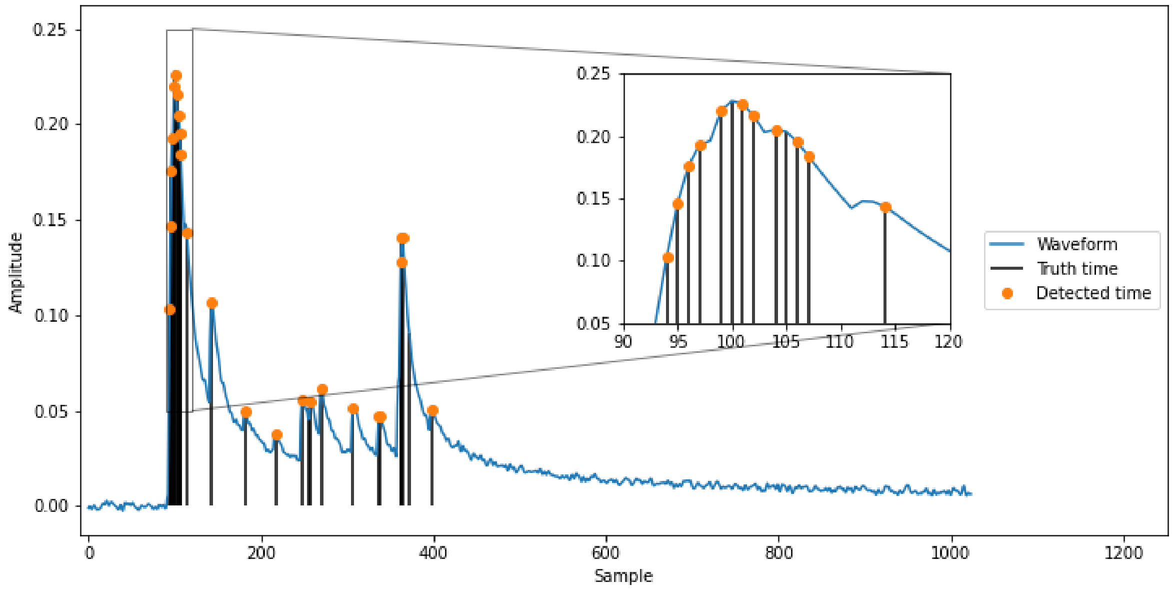
- To detect all peaks from the waveform
- Classification for “signals” and “noises”
- Architecture: Recurrent Neural Network (RNN)





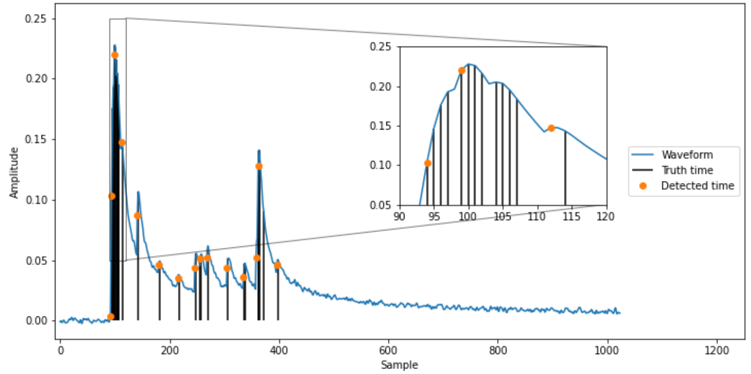
Compare to the derivative algorithm

Neural Network

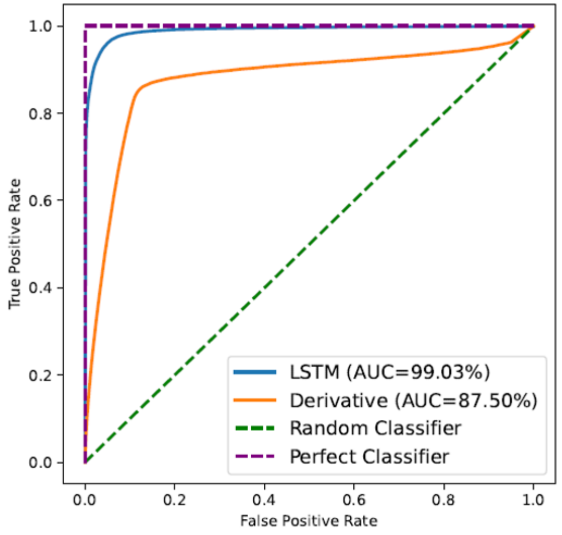


The NN can find the peaks more effective!

Derivative



ROC

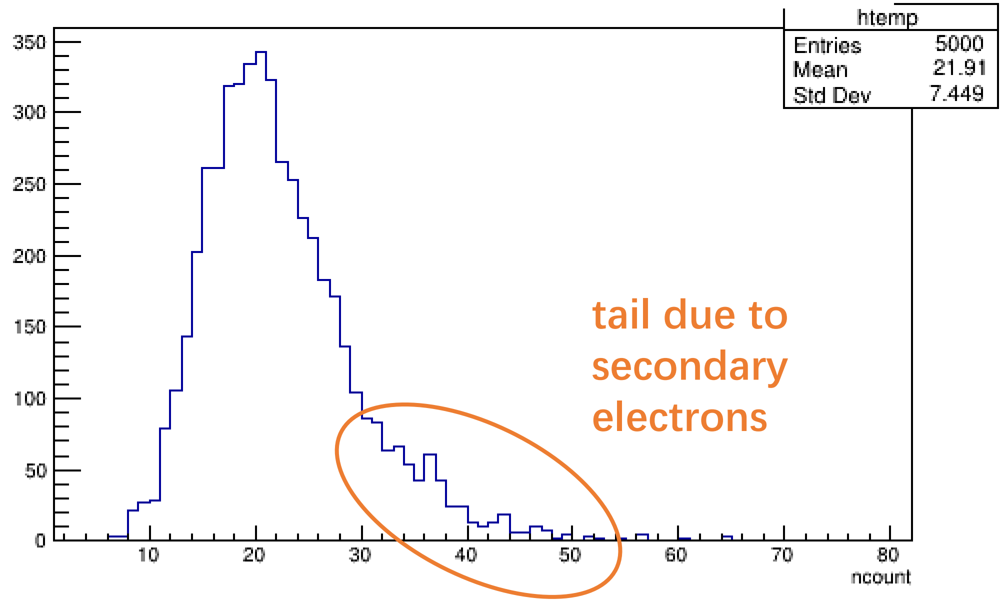


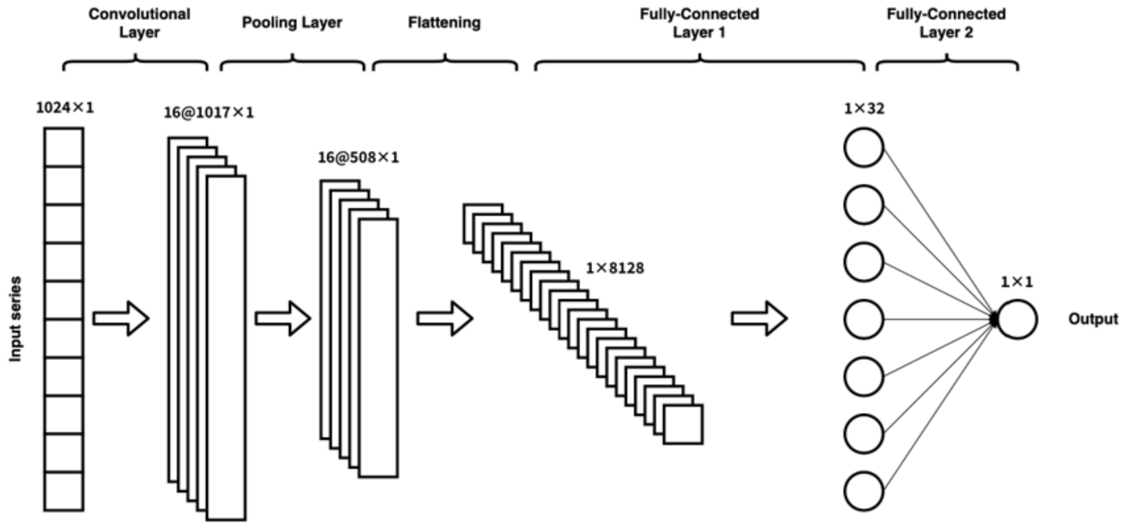
- RNN
- Derivative

Step 2: Discrimination of the primaries

- To discriminate primary peaks from the secondary ones
- Regression problem
- Architecture: 1D Convolutional Neural Network (CNN)

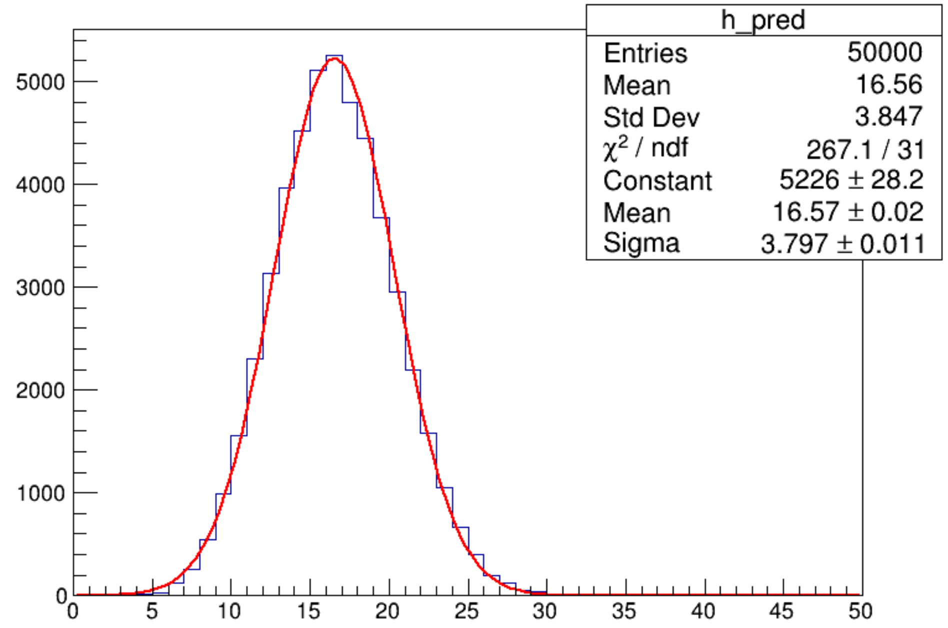
Detected peaks from the peak finding





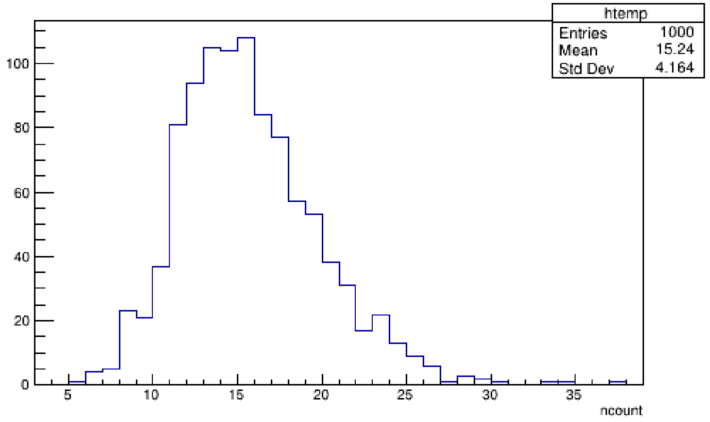
N_{cls} distributions

ML



Resolution ~23%

Derivative

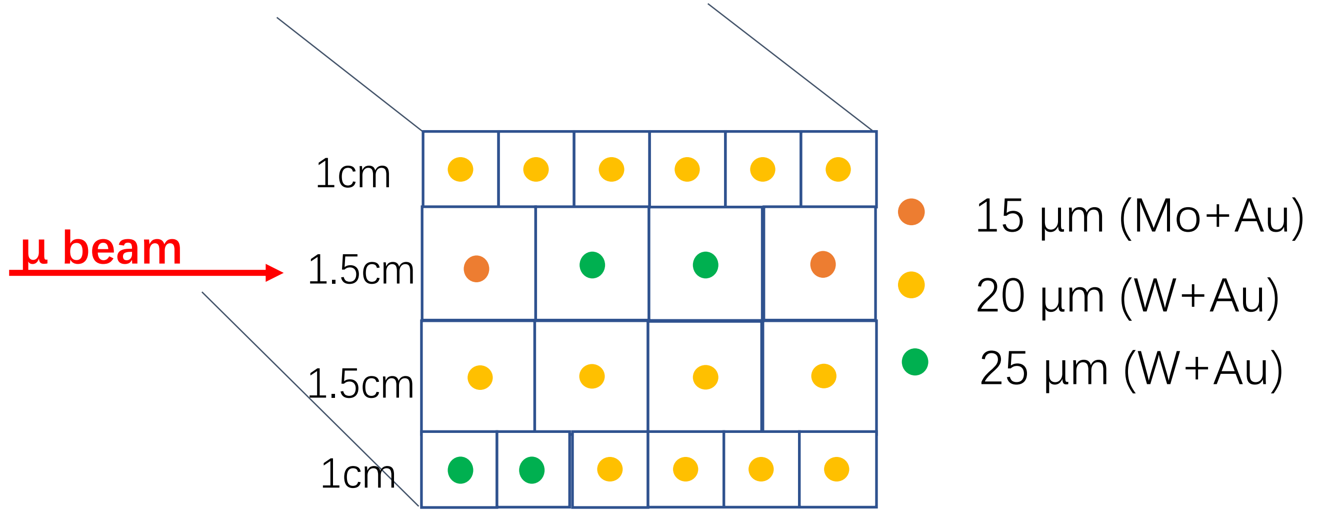


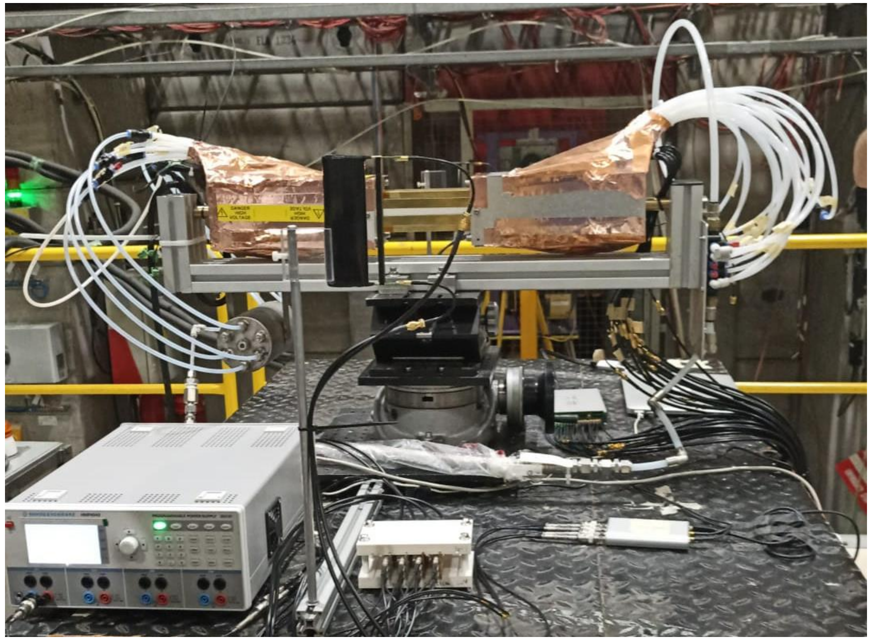
✓ RMS/MEAN ~ 27%

- ✓ Very good Gaussian-like distribution
- ✓ The resolution is very close to the truth value (~21%), which implies possible improvement on PID

Beam test

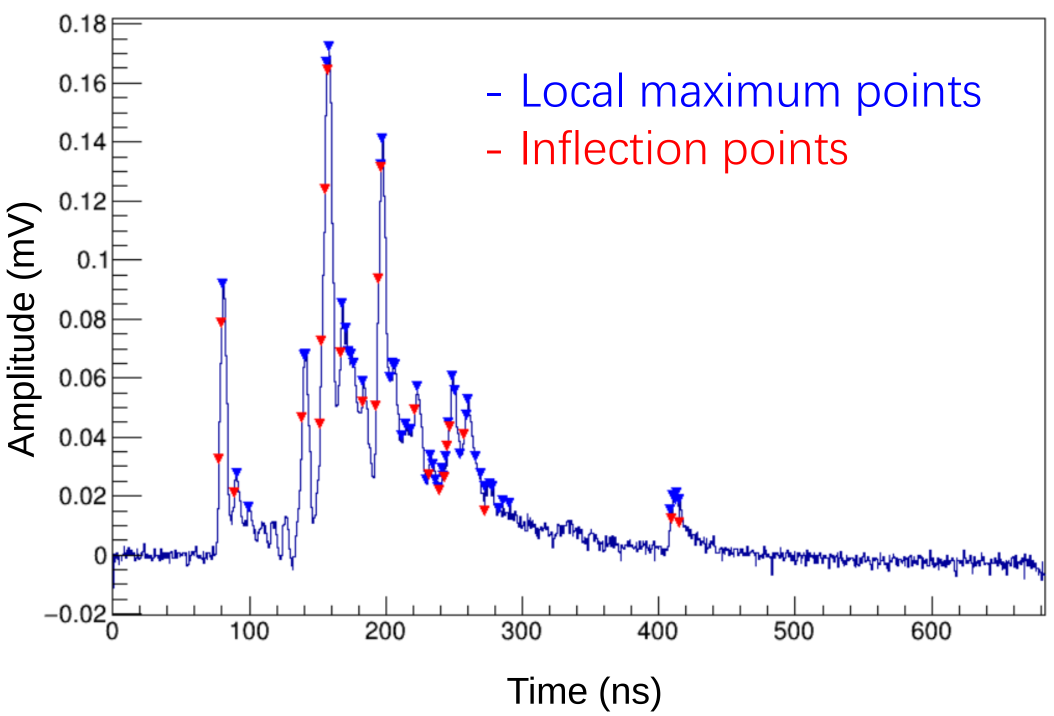
- **Two rounds of beam test organized by INFN group**
  - First round: Nov. 2021 (Shuiting joined)
  - Second round: July 2022 (Shuaiyi joined)
- **Cooperation between INFN and IHEP on data analysis is ongoing**

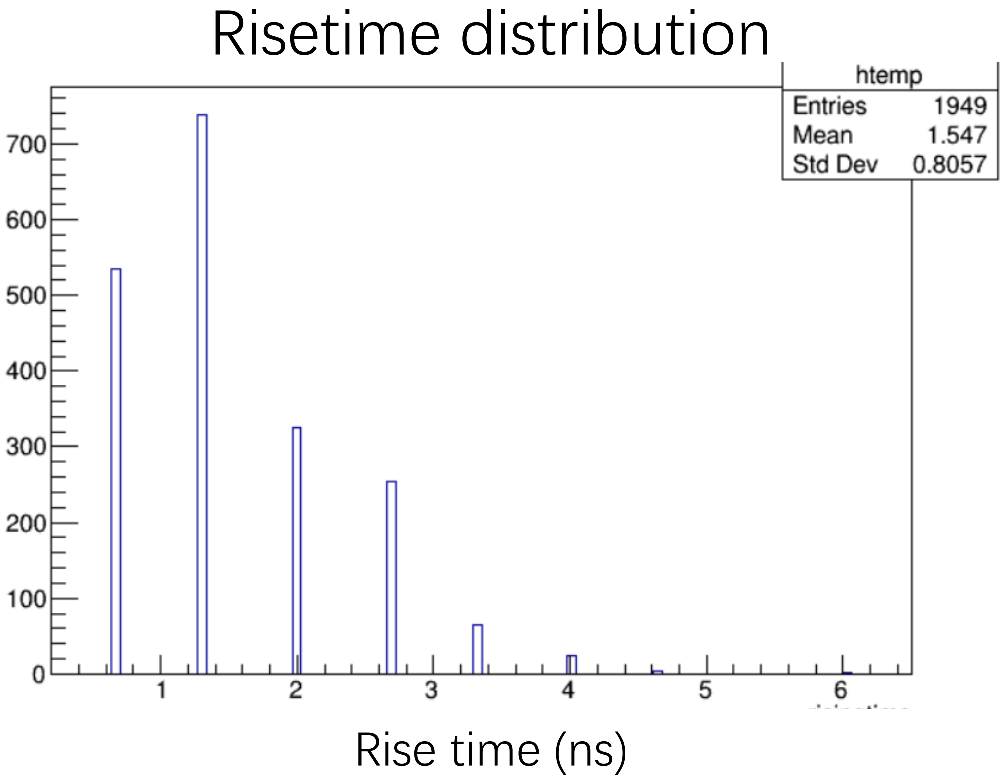




2nd round of test beam:
Federica's talk in Meeting on cluster counting in drift chambers, Jul 28, 2022
https://indico.ihep.ac.cn/event/16837/

Peak risetime estimation



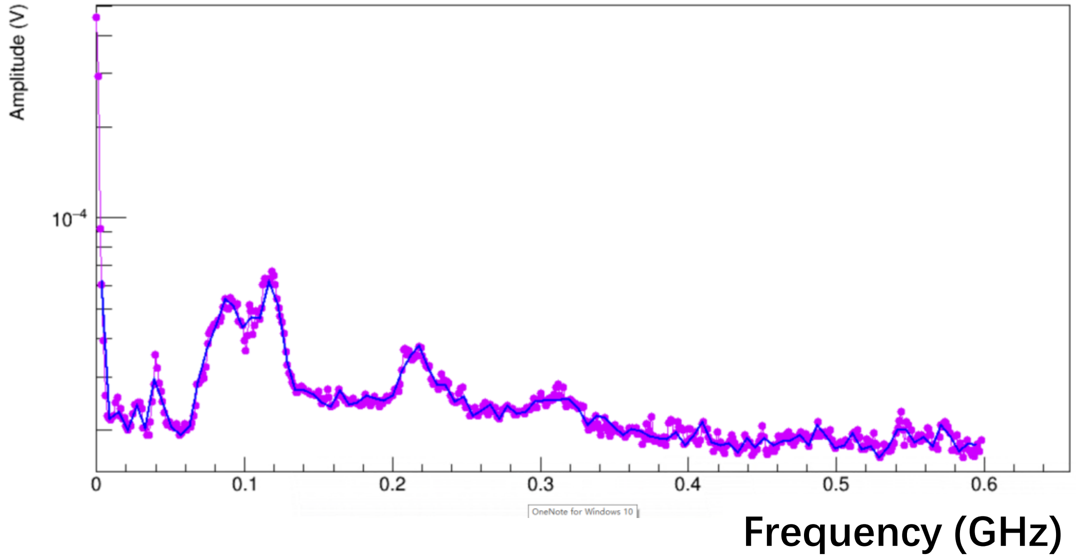


- Require local maximum >0.015mV
- For each local maximum points, find the nearest early point, whose slope starts to decrease (inflection point)
- The time distance between the local maximum and the inflection points is recorded as the risetime.

- Each bin is around 0.67 ns
- Averaged risetime is **1.55 ns**
- 95% of the risetimes less than 2.67 ns

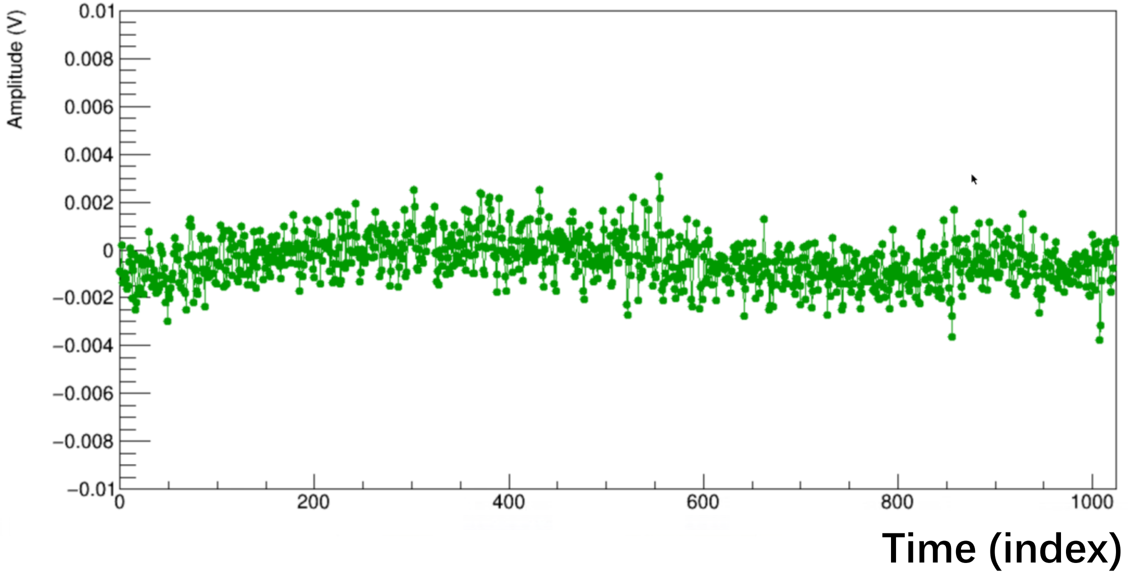
Noise extraction

Data (frequency domain)



IFFT

Simulation (time domain)

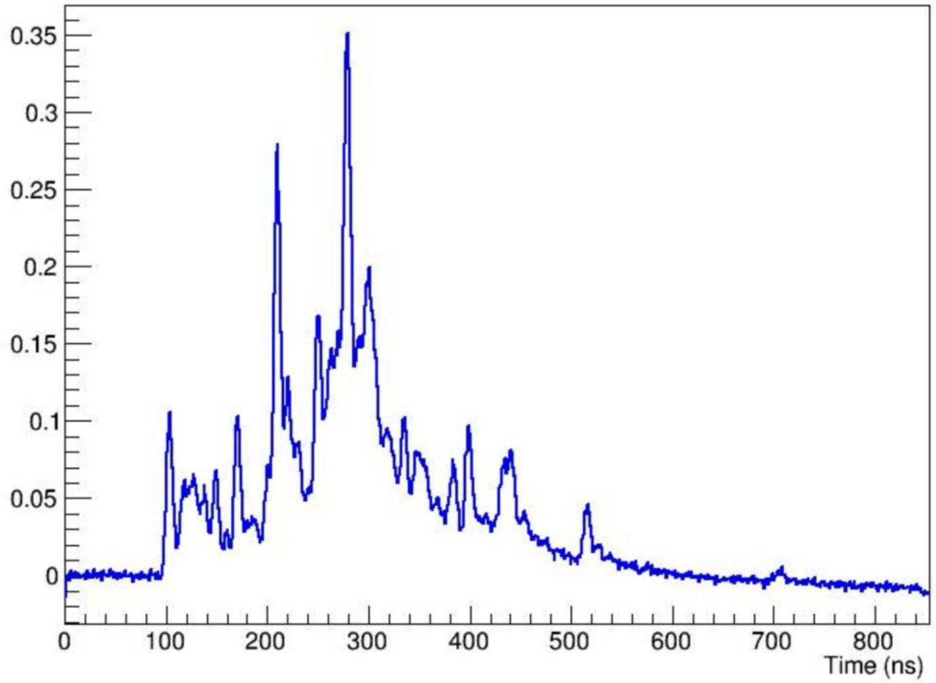


Noise distribution

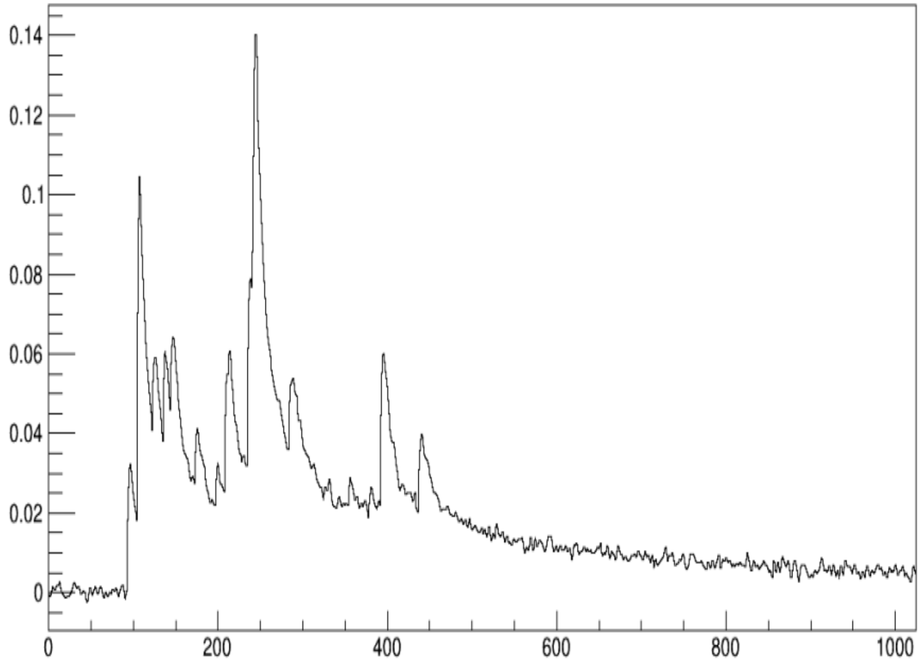
	Data	Simulation
Mean	0.00019	0.00058
RMS	0.00125	0.00125

MC tuning with data

Data

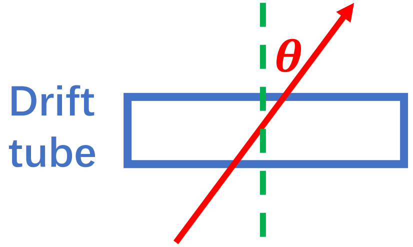


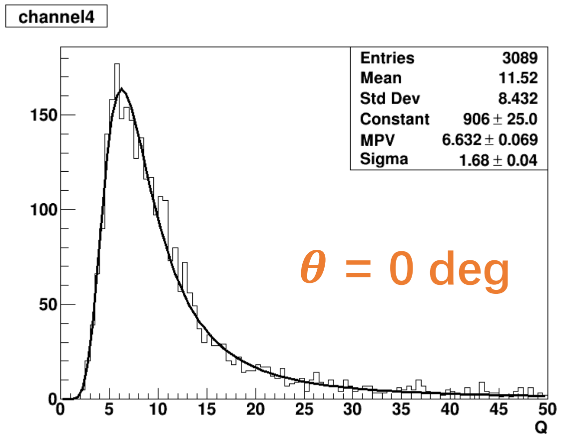
Simulation

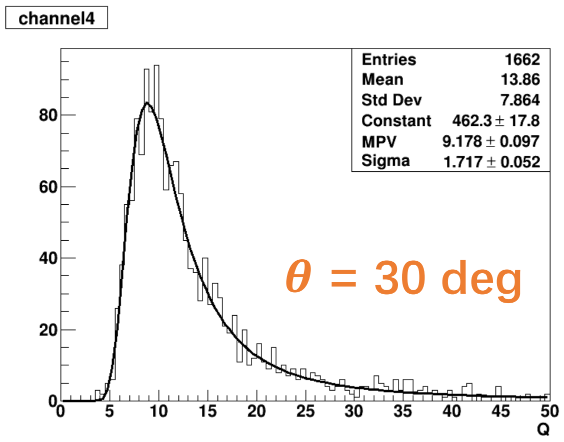


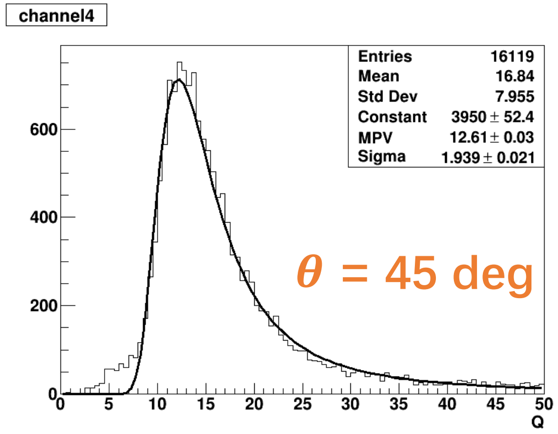
Tuning MC with data: (1) Rise-time, (2) Noise, (3) Amplitude
➔ Better data/MC consistency

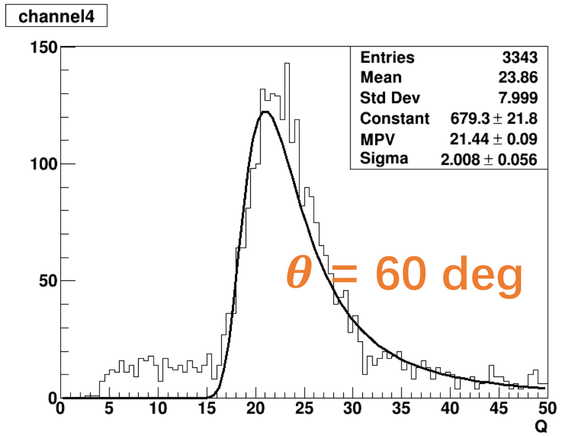
Charge distribution checks



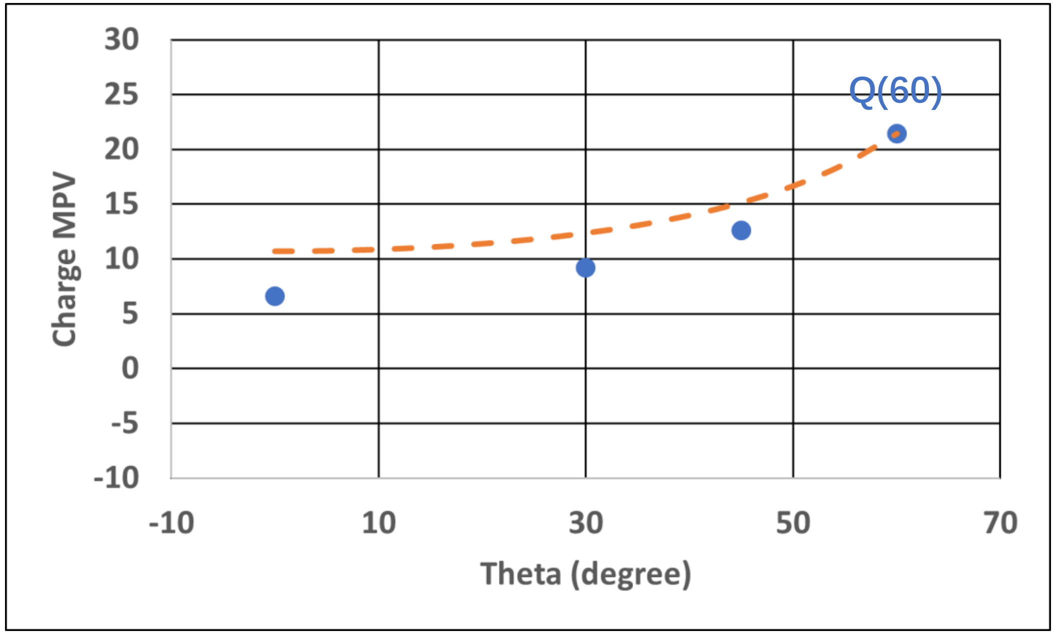








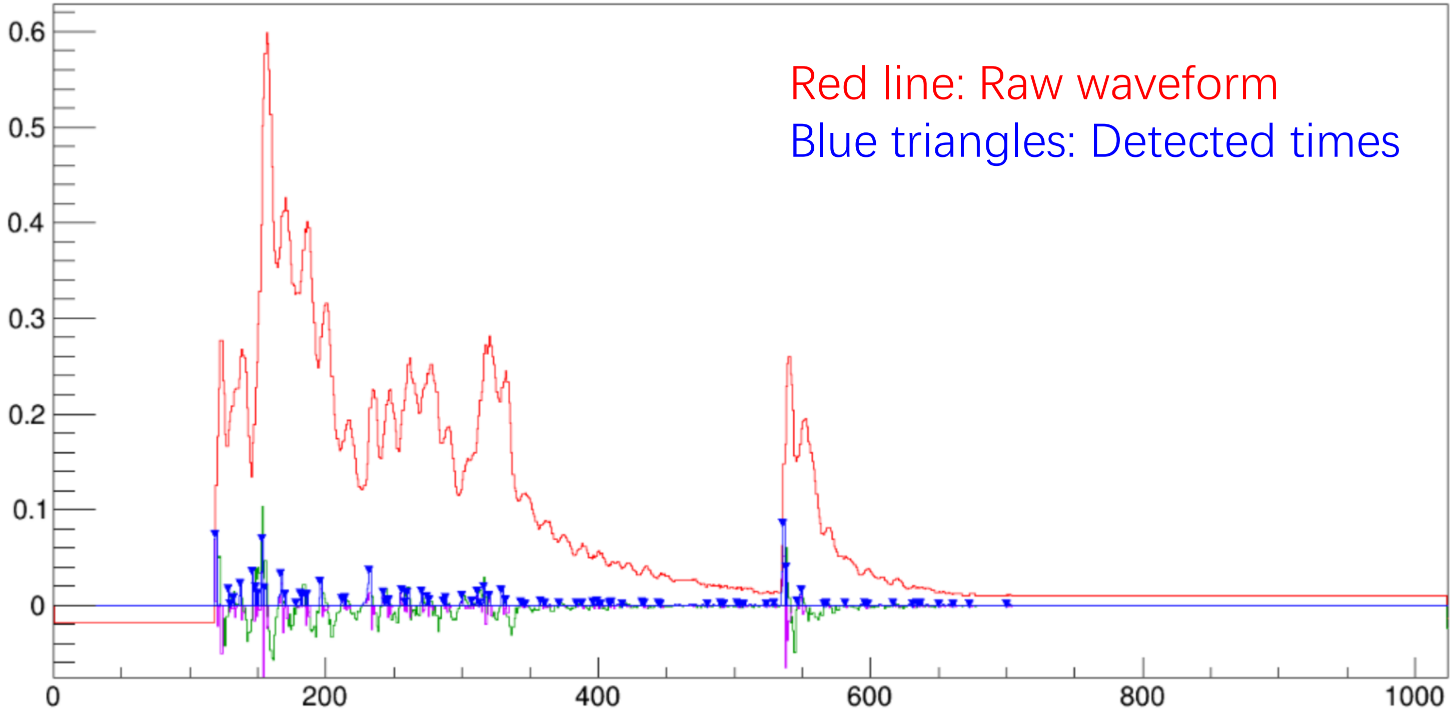
Charge MPV vs. θ



Dashed line: Interpolation from Q(60) by track length
➔ Discrepancies for small θ's due to space charge

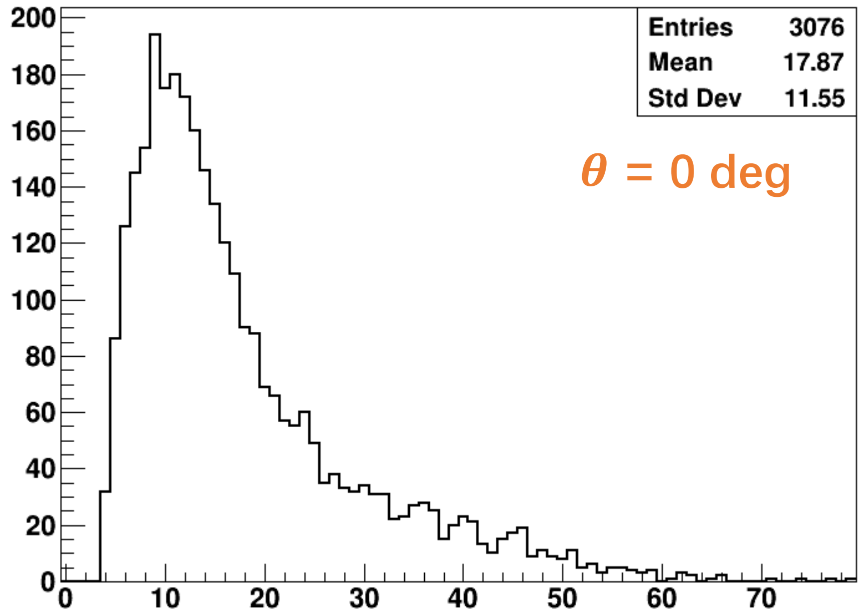
Preliminary peak finding with derivatives

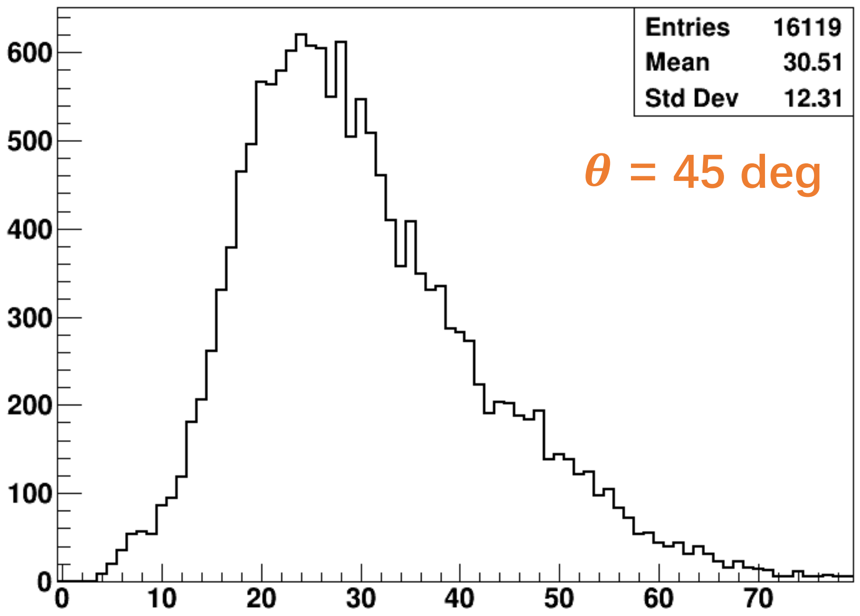
- Apply the algorithm based on 1^{st} and 2^{nd} derivatives on data
- Demonstrated by an example from the 2^{nd} round test beam data



N_{cls} distributions

- A preliminary comparison between $\theta = 0° \ \& \ 45°$
- Next to do
  - Optimize the event selection
  - Optimize the parameters of the algorithm
  - Apply a discrimination algorithm to remove secondary peaks
  - Try ML algorithm





Collaborations on MOST-MAECI application

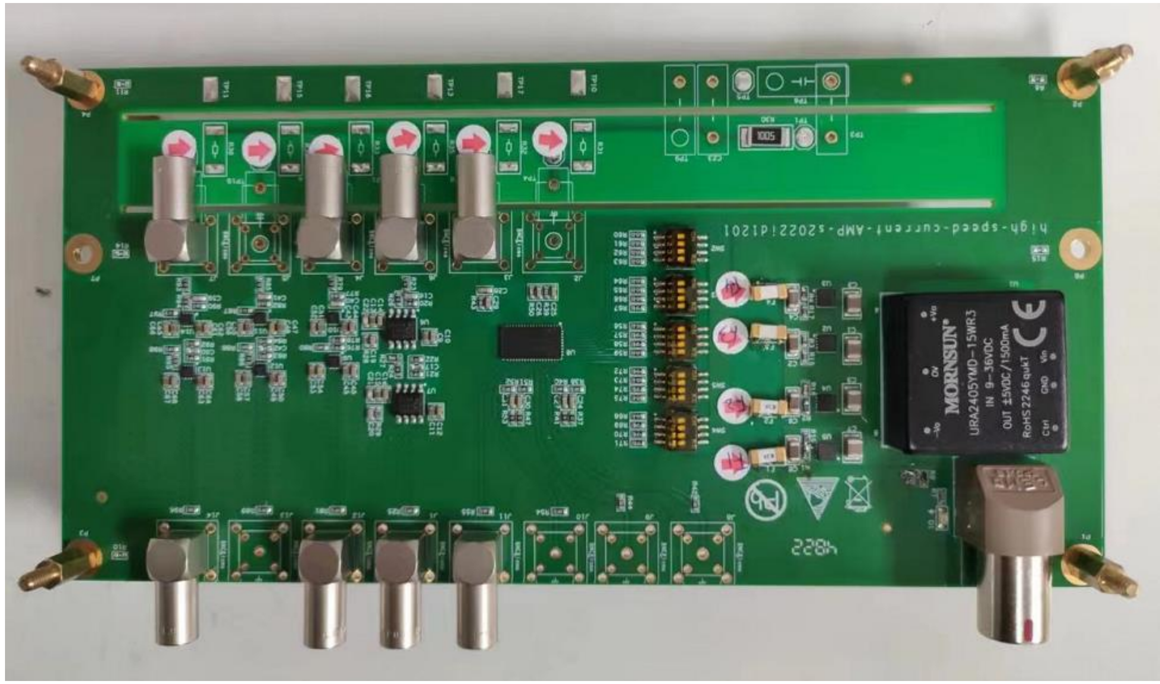
(China-Italy Science and Technology Cooperation)

- **Project: INTRePID (INnovative TRacking and Particle IDentification)**
  - Cluster counting and cluster timing for particle identification and improved spatial resolution in drift chambers at the next generation of lepton colliders

- **Cooperation between INFN and IHEP on**
  - Beam tests for the application of the cluster counting/timing techniques
  - Simulation and reconstruction
  - Design and deployment of real-time ML algorithms on FPGAs

Progress on hardware: new preamplifiers

- High bandwidth current sensitive preamplifiers based on LMH6522 and AD8099 were designed
- Simulation results show the bandwidth and the gain meet the test requirements
- Test is on going. Preliminary tests verify that the gain is big enough, but noise should be further reduced



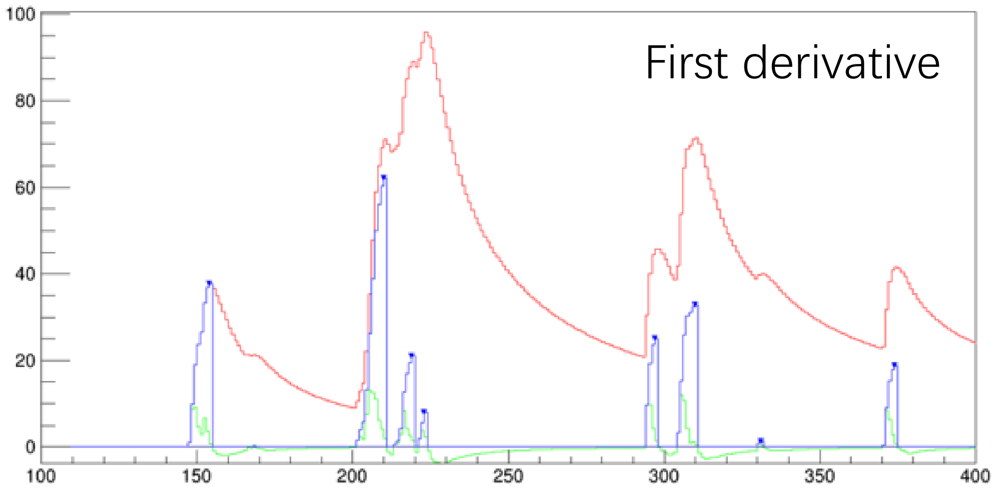
Summary and outlook

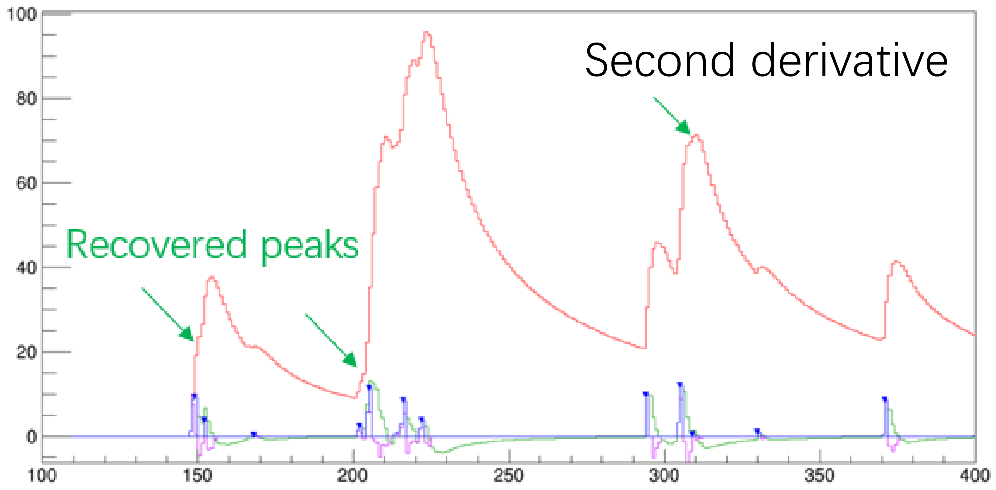
- **A machine learning based reconstruction algorithm is developed**
- **Simulation is tuned with the experimental data**
- **Plans**
  - Better understand the beam test data and fine tuning the MC simulation
  - Optimize the reconstruction algorithm for beam test
  - Extract dN/dx parameters from full simulation and perform physics studies

Backup

Reconstruction algorithm with derivatives

- **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.

Beam test objectives

Beam test plans:

1. First of all, need to demonstrate the **ability to count clusters**:
   at a fixed $\beta\gamma$ (e.g. muons at a fixed momentum) count the clusters by
   - doubling and tripling the track length and changing the track angle;
   - changing the gas mixture.
2. Establish the **limiting parameters** for an efficient cluster counting:
   - cluster density (by changing the gas mixture)
   - space charge (by changing gas gain, sense wire diameter, track angle)
   - gas gain saturation
3. In optimal configuration, **measure the relativistic rise as a function of $\beta\gamma$**, both in **dE/dx** and in **dN_{cl}/dx**, by scanning the muon momentum from the lowest to the highest value (from a few GeV/c to about 250 GeV/c at CERN/H8).
4. Use the experimental results to fine tune the predictions on performance of **cluster counting** for **flavor physics** and for **jet flavor tagging** both in **DELPHES** and in **full simulation**

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