Drift chamber with cluster counting technique at FCC-ee
Simulation & Reconstruction

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on behalf of IDEA DC group

RD-FCC WP1 - Software & Analysis Meeting

15 Oct 2025

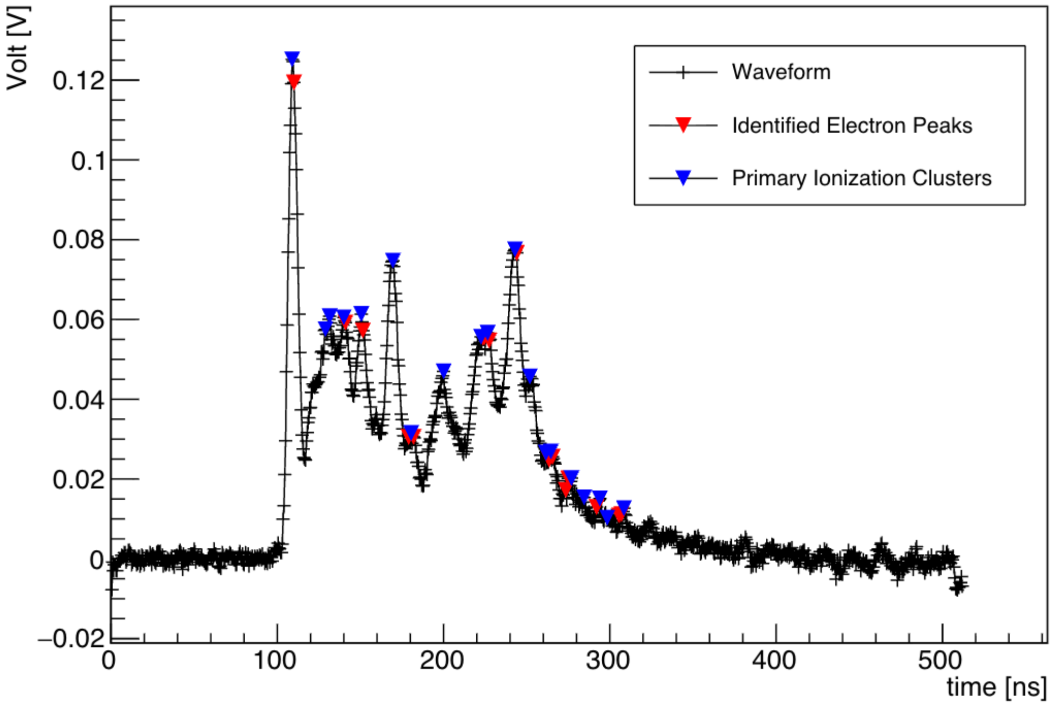
digitization for the IDEA DCH

M. Saiel, N. De Filippis, G. Tassielli

- Result of a hit cell digitization at the **lowest level, L_0**, must be **a waveform**

- At a higher **level, L_1**, results of hit digitization are:
  - list of electron peak positions and relative amplitudes (i.e., ionization electrons after peak finding –red markers in the picture) or
  - list of ionization cluster positions and relative amplitudes (after electrons clusterization algorithm –blue markers in the picture)

- At an even higher **level, L_2**, results of hit digitization are:
  - impact parameter.
  - number of clusters.



Strategy of hit digitization for the IDEA DCH

L_0 digitization: (produce the waveform)

1. Particle–cell intersection → find where the track crosses a drift cell.
2. define the **ionization length ℓ** of the particle track within the cell volume.
3. distribute along ℓ, with an exponential distribution, a number of ionization acts n_{cl} extracted according to a Poisson distribution of peak value $dN_{cl}/dx \times \ell$, where dN_{cl}/dx is a tabulated function only of the particle $\beta\gamma$
   - this function to be provided by beam test experimental results or theory parameterization.
4. for each of the n_{cl} extract, for the given gas mixture, a number of electrons n_{el} according to the experimental distributions given in: H. Fischle, J. Heintze and B. Schmidt, Experimental determination of ionization cluster size distributions in counting gases, NIMA 301 (1991).
5. transport each of the n_{el} electrons to the sense wire (tabulated distance to- time distributions can be used and drift time must be smeared with properly calculated diffusion, according to experimental measurement or in alternative with Garfield).

Strategy of hit digitization for the IDEA DCH

L_0 digitization: (produce the waveform)

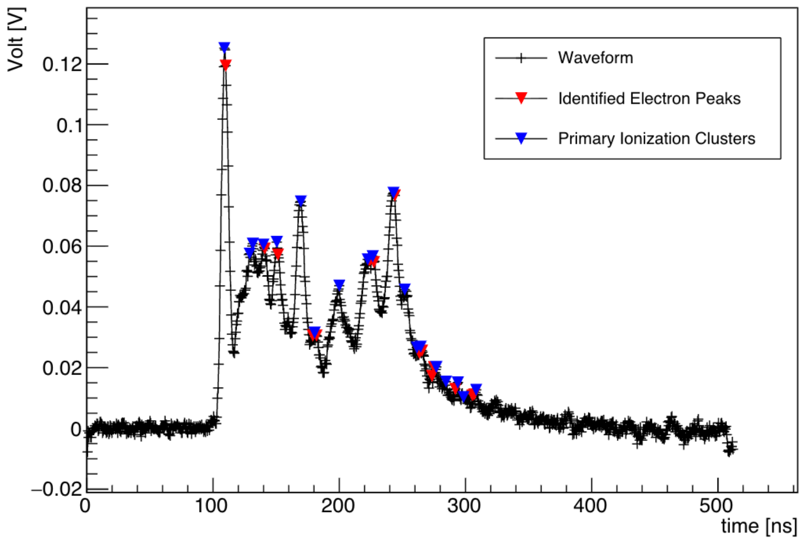
6. Define **the amplitude of the signal** generated by each of the n_{el} electrons according to the gas amplification parameters, using the proper Polya distributions →electron with amplitude and time.
7. Generate the individual **electron pulses** by introducing the rise and fall times derived by experimental measurements.
8. Build **the analog waveform** by summing up the individual contributions of all single electrons.
9. propagate the waveform along the sense wire at both ends, by taking into account the proper transit time (constant transit velocity assumed as a first attempt, ~ 5ns/m) and the signal attenuation along the sense wire, according to experimental measurements;

Strategy of hit digitization for the IDEA DCH

L_0 digitization: (produce the waveform)

10. **Convert the analog waveform into digital** according to the defined time bins (~0.5 ns at 2Gsa/s) and amplitude bits (~10-12 bits);
11. **Apply the preamplifier electronics** transfer functions (taking into account the impedence mismatch for reflection and transmission) and further convoluted with the waveform;
12. **Add the proper noise according** to the frequency response determined experimentally using the fast Fourier transform.

The output for the L_0 digitization ⇨

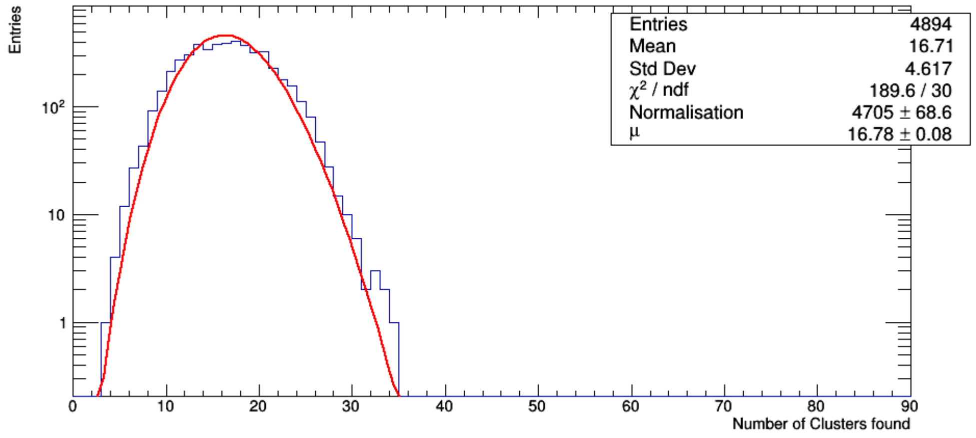


Strategy of hit digitization for the IDEA DCH

L_1 digitization:

- Once the L_0 digitized waveform in a hit cell has been produced, the application of any cluster counting algorithm **(RTA, DERIV, ML, …)** will give rise to the:
  - ✓ list of electron peak positions (time) with their relative amplitudes
  - ✓ list of ionization cluster positions (time) with their relative amplitudes

Example of the reconstructed clusters using RTA algorithm



Strategy of hit digitization for the IDEA DCH

L_2 digitization:

1. impact parameter:

- The impact parameter can be obtained with the application of a ML algorithm, trained on samples of simulated clusters sequences at known impact parameters, thus exploiting the knowledge of the full waveform (instead of relying only on the timing of the first cluster)

N. B. A considerable reduction of the impact parameter bias at short drift distances is expected because of the use the full waveform information (all the clusters)

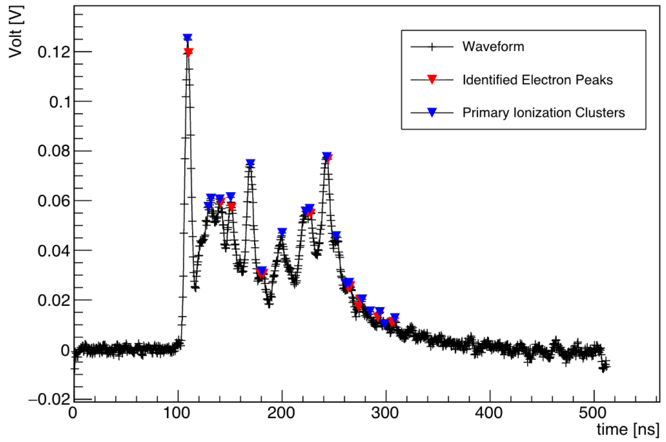
2. particle identification :

- n_{cl} of a hit cell is the relevant parameter for particle identification.
- the sum of number of clusters found on all hit cells belonging to the particle trajectory, divided by the total length of the track, measured from the track fit, provides the dN_{cl}/dx of the particle (care must be given to treating hit rejection and hit sharing)

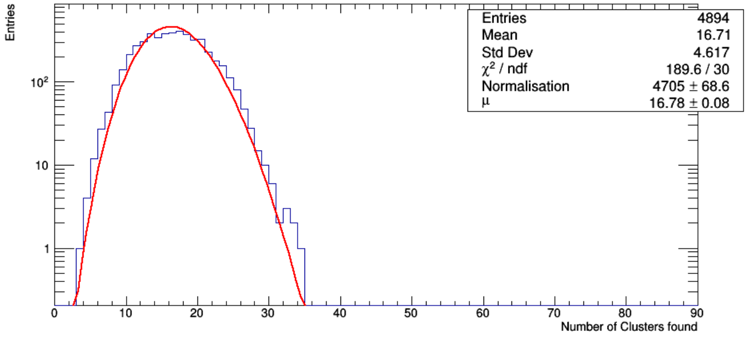
⇨ a comparison of this value against different particle type hypothesis provides the particle mass assignment

Cluster counting using RTA algorithm

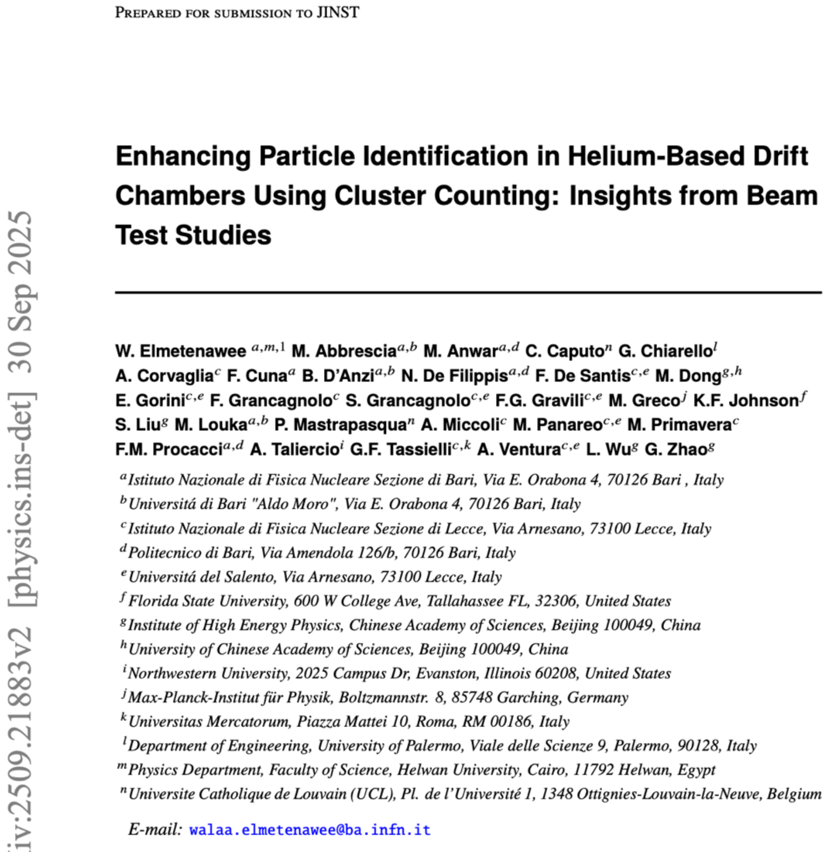
- **Finding peaks algorithms:**
  - to accurately identify electron peaks, we developed and tested two distinct algorithms:
    - ✓ Running Template Algorithm (RTA) "W. Elmetenawee"
    - ✓ Derivative Algorithm (DERIV). "M. Louka"
- **Clusterization:**
  - Merges electron peaks in consecutive bins from a single electron to reduce fake electron counts.
- **Performance scans:**
  - We evaluated algorithm performance under varying conditions:: gas mixture, gain, geometrical configuration (cell size, sense wires size), sampling rate, HV, and track angle.
- **Resolution study: dN/dx vs dE/dx:**
  - comparative analysis of the resolution in: the number of clusters per unit length (dN/dx) and the ene[rgy] loss per unit length (dE/dx).



Poissonian distribution for the number of clusters.



Paper submitted to JINST
https://arxiv.org/abs/2509.21883



Prepared for submission to JINST

arXiv:2509.21883v2 [physics.ins-det] 30 Sep 2025

Enhancing Particle Identification in Helium-Based Drift Chambers Using Cluster Counting: Insights from Beam Test Studies

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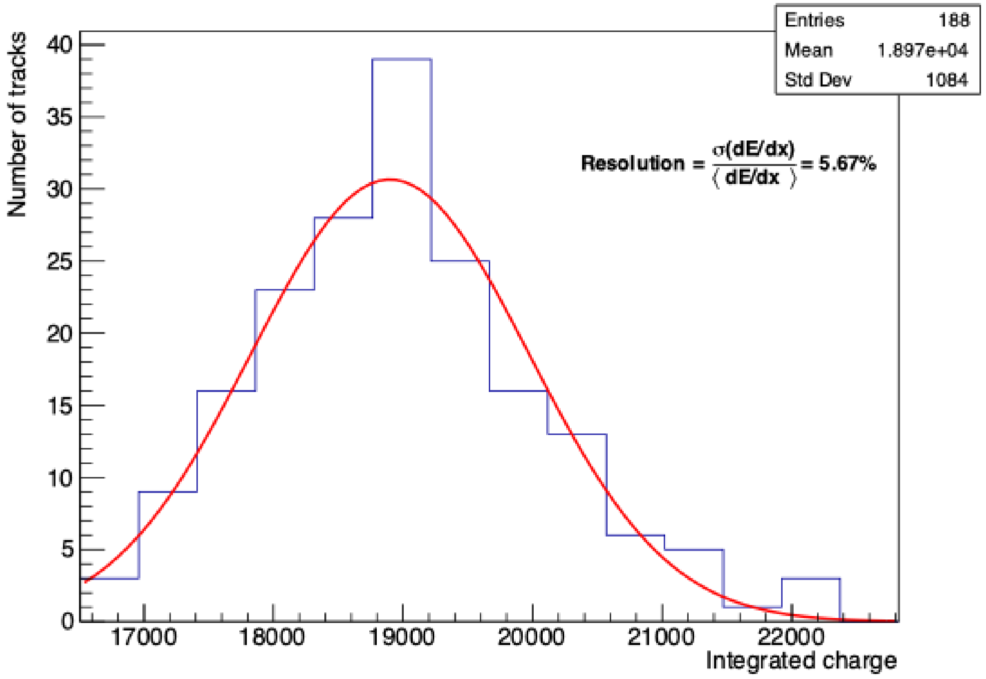
Resolution study

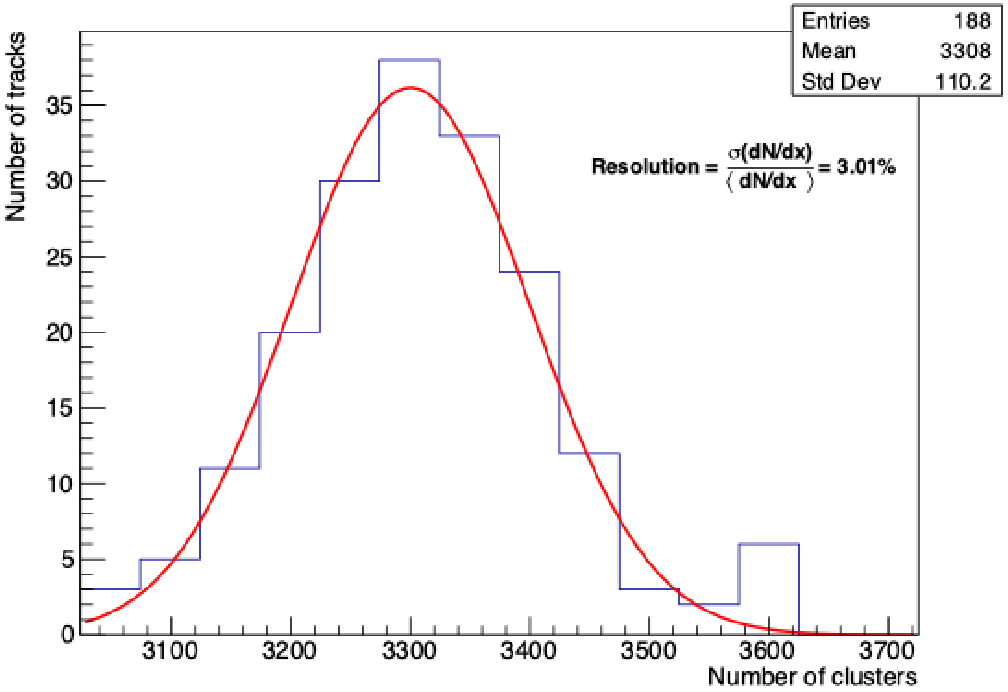
Study done using same tracks (2 m track length) made of the same hits.

dE/dx Resolution (remove 20% higher charges)



@2m long track we have dE/dx resolution 5.7%

dN/dx Resolution



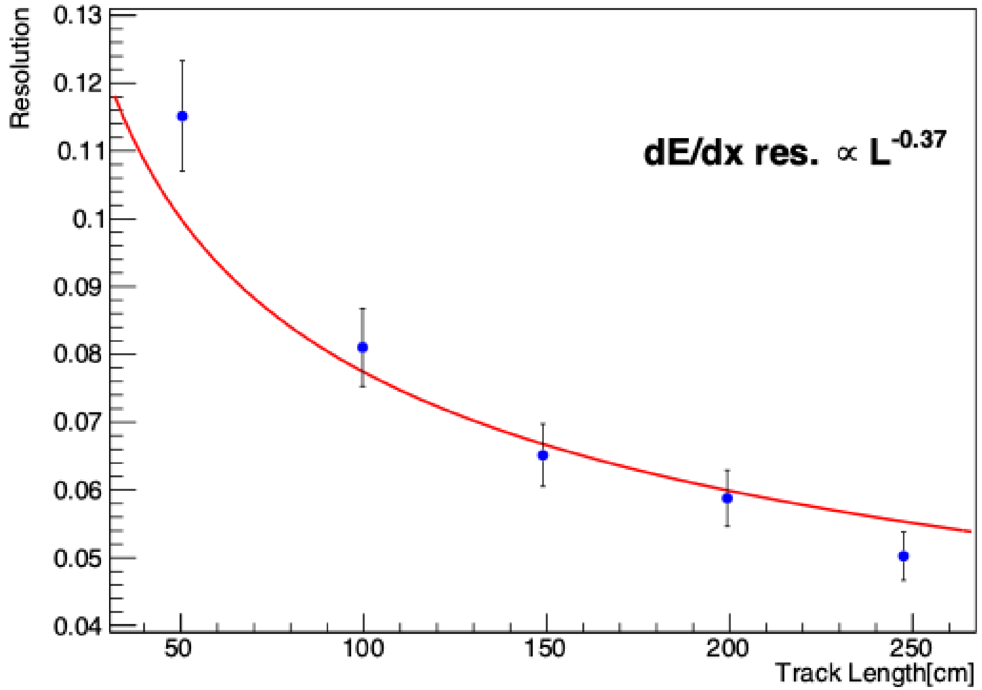
@2m long track we have dN/dx resolution 3%

~ **2 times** improvement in the resolution using dN/dx method (Preliminary results)

Resolution study

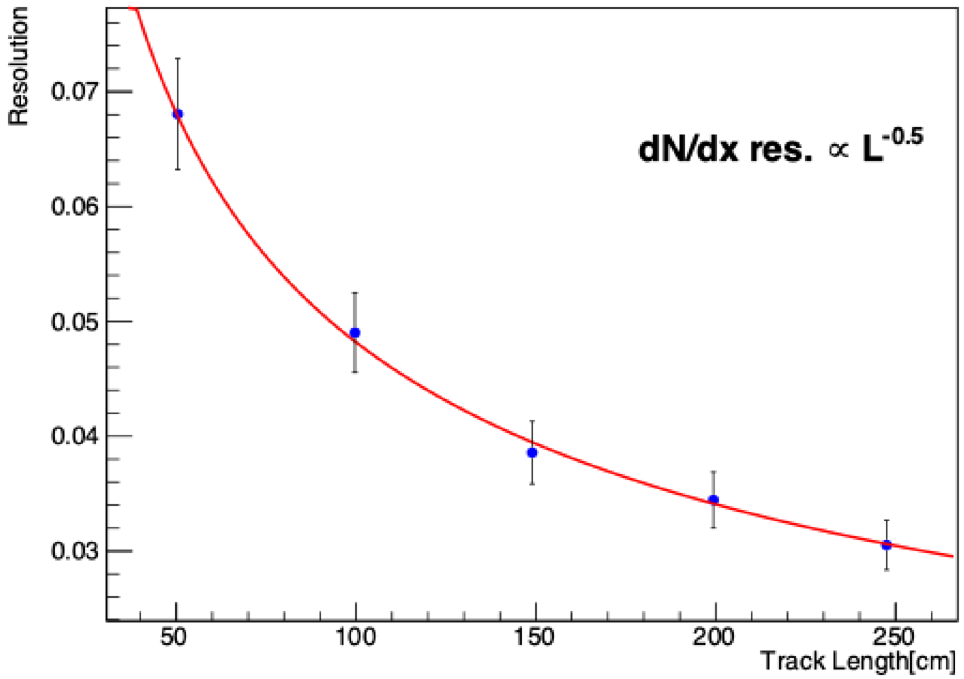
2m tracks length

dE/dx Resolution



dE/dx resolution dependence on the track length $L^{-0.37}$

dN/dx Resolution



dN/dx resolution dependence on the track length $L^{-0.5}$

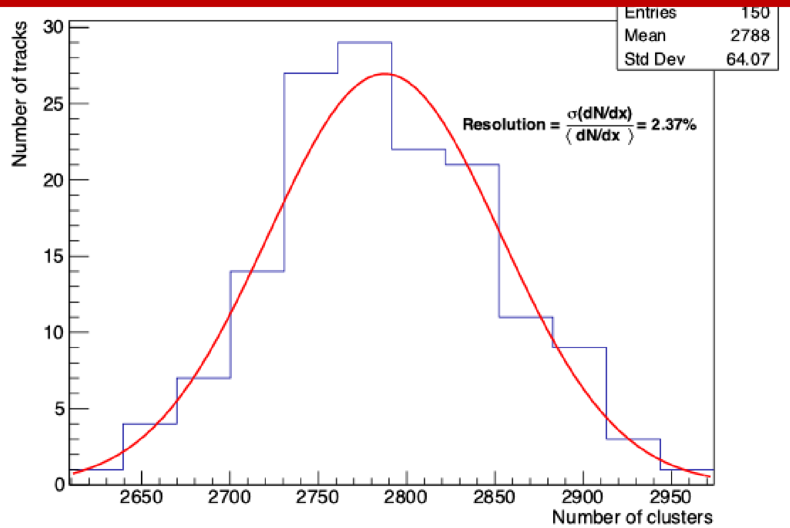
~ **2 times** improvement in the resolution using dN/dx method (Preliminary results)

Improved dN/dx Resolution

Waveform Cleaning for Improved dN/dx Resolution:

- Applied cleaning criteria to reject distorted or incomplete waveforms
- Required cluster time span to stay within a physically reasonable range
- Suppressed tracks with wide or noisy signals

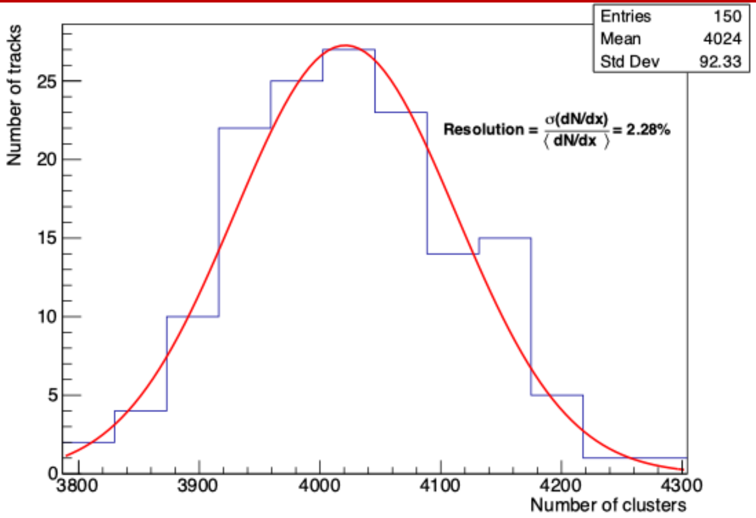
Resulted in improved dN/dx resolution: from 3.00% to 2.38% for 2-meter tracks



Correction for Recombination and Attachment Effects

- Ionization electrons can be lost due to recombination or attachment during drift
- Applied a time-based correction to compensate for cluster loss:
  - Derived from the trend of cluster count vs. time
  - Used 2D histograms (clusters vs. time)
  - Fitted time profiles with a linear (first-order) function
- Correction applied event-by-event to account for spatial variations.

Resulted in improved dN/dx resolution: from 2.38% to 2.28% for 2-meter tracks



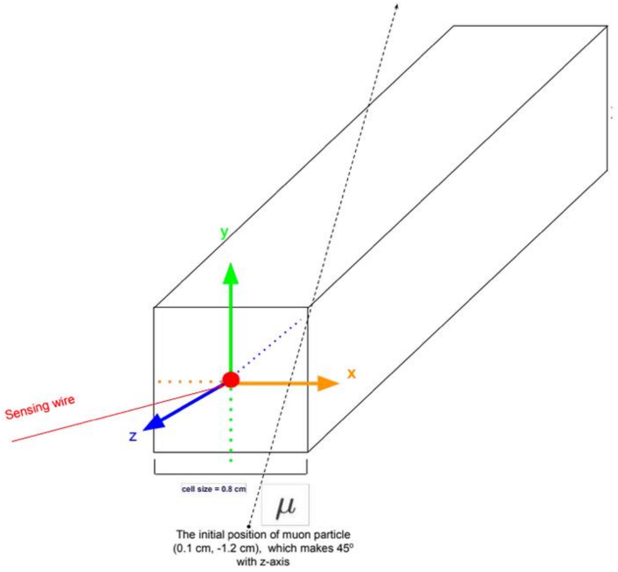
~ **2.5 times** improvement in the resolution using dN/dx method (Final results)

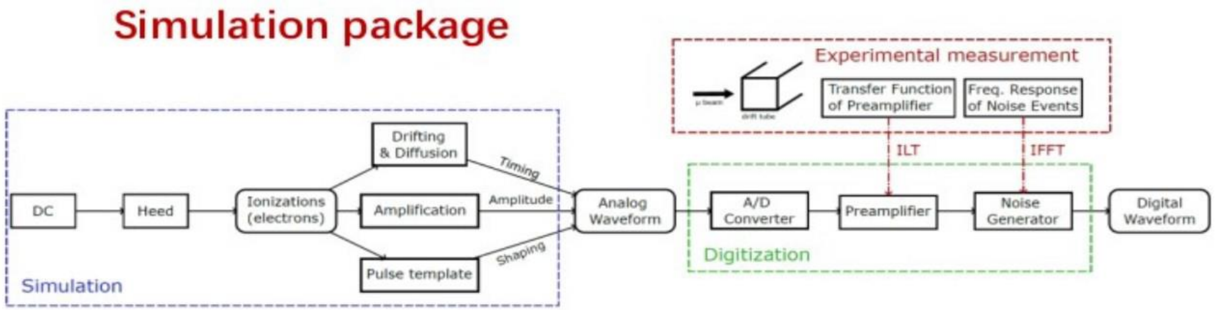
Peak finding algorithm with LSTM

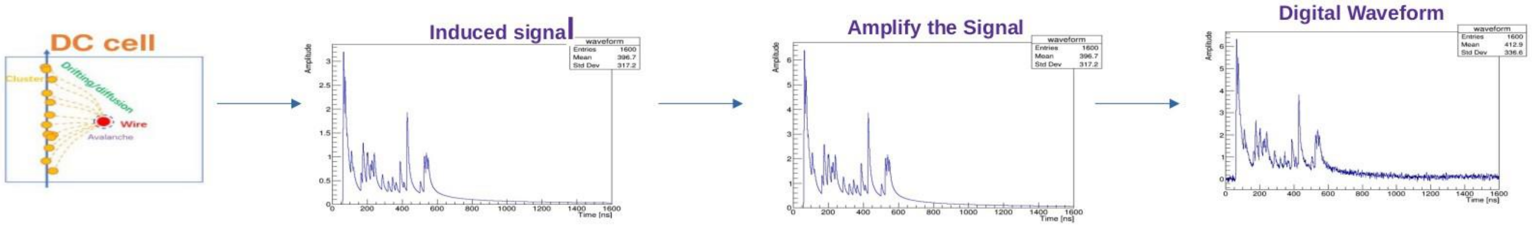
M. Anwar, N. De Filippis

Simulation chain based on Garfield ++

A muon passing through a given gas-mixture (90% He and 10% C_4H_{10}) generates electron-ion pairs that drift towards opposite charge and induce current, thereby generating signal. The simulation package creates analog induced current waveforms from ionizations (HEED). The digitization package incorporates electronics responses taken from experimental measurements and generates realistic digital waveforms





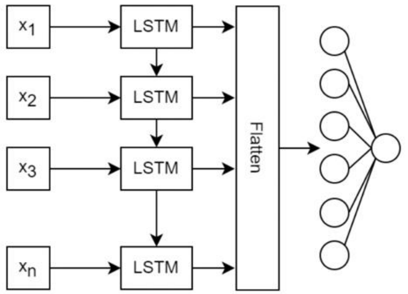


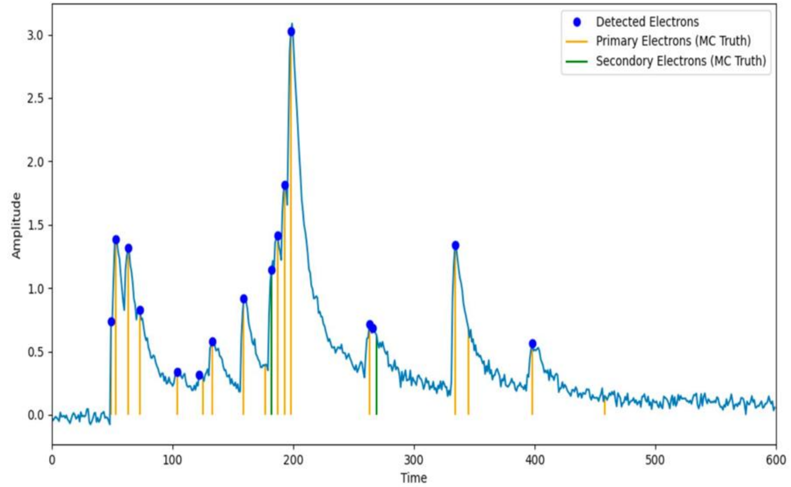
Peak finding algorithm with LSTM

Peak finding with LSTM(*)

Why LSTM? Waveforms are time series

- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

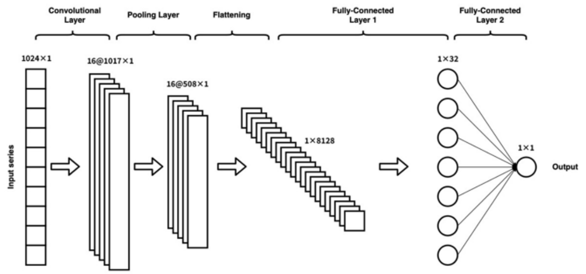


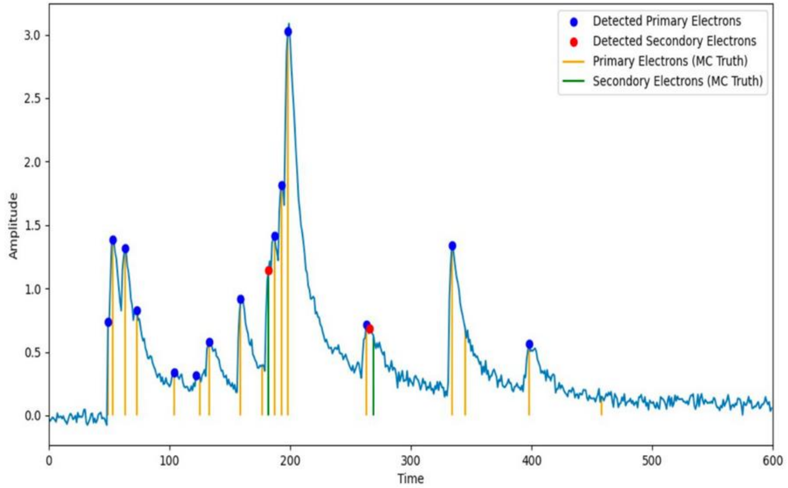


Clusterization with DGCNN(**)

Why DGCNN? Locality of the electrons in the same primary cluster, perform message-passing through neighbour nodes in GNN.

- Architecture: DGCNN (GNN-based)
- Method: Binary classification of primary and secondary electrons





(*) LSTM: Long Short-Term Memory

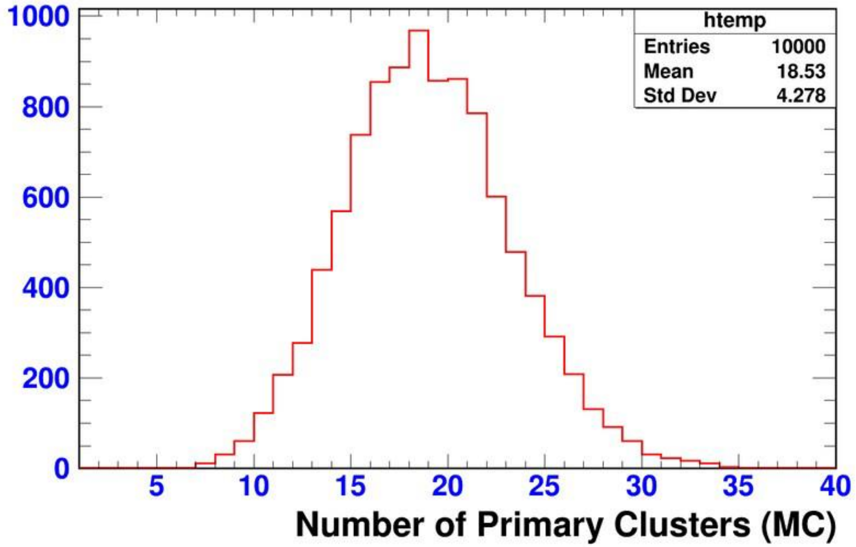
(**) DGCNN: Dynamic Graph Convolutional neural networks

Peak finding algorithm with LSTM

Different Momenta of Muon (GeV)	2	4	6	8	10	180
Monte Carlo (MC)						
Primary Cluster (MC)	15.89	16.99	17.81	18.28	18.53	19.10
Std. Deviation (MC)	4.01	4.10	4.12	4.30	4.20	4.30
LSTM Model						
Primary Cluster (LSTM)	14.45	15.37	16.06	16.34	16.49	17.30
Std. Deviation (LSTM)	3.77	3.84	3.90	3.90	3.90	4.02
CNN Model						
Primary Cluster (CNN)	14.38	15.00	15.38	15.77	16.29	16.76
Std. Deviation (CNN)	3.37	3.20	3.20	3.10	3.30	3.20

Table 1: Primary cluster means and standard deviations from MC, LSTM, and CNN across different muon momenta.

Mean number of primary clusters at 10 GeV muon momentum



Peak finding algorithm with Transformer

A. Asief, N. De Filippis, W. Elmetenawee

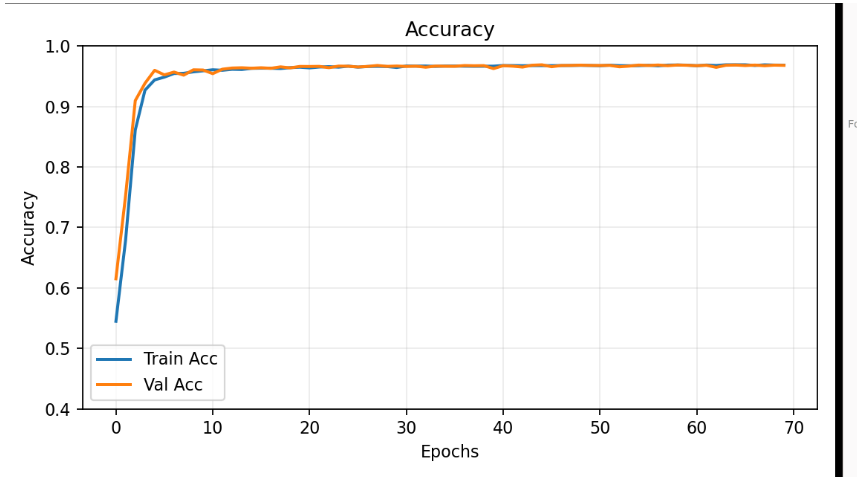
Better at resolving overlapping peaks due to attention to multiple context points simultaneously.

Enconder-Only Transformer

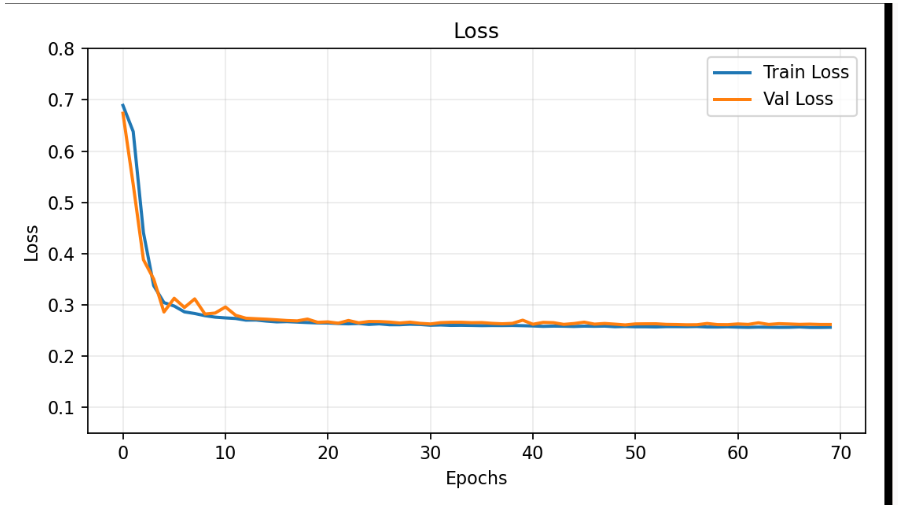
Reason:

- ✓ Our task is **peak finding**, not sequence generation.
- ✓ Encoder is sufficient for per-bin classification (peak / no peak).
- ✓ Simpler, faster, and fewer parameters.
- ✓ Better suited for waveform analysis.

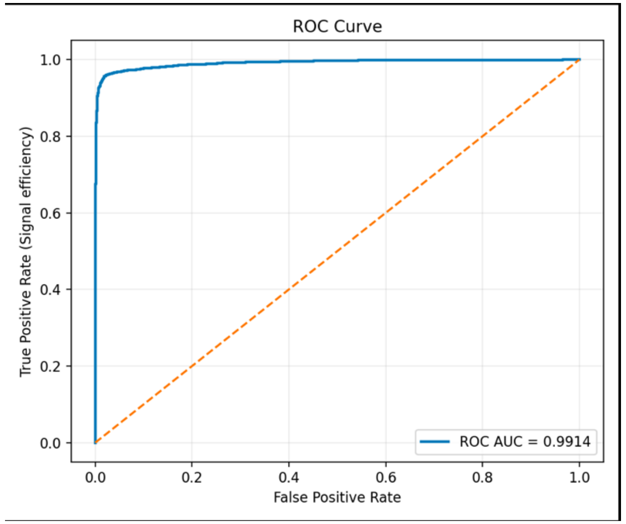
Aspect	**LSTM**	**Transformer**
toprule Parallelism	Low	High
Long-range capture	Weak	Strong
Training speed	Slow	Fast
Per-bin output	Limited	Excellent



Accuracy: ≈ 0.97 — rapid convergence and strong generalization



Loss: ≈ 0.26 — smooth and stable learning curve



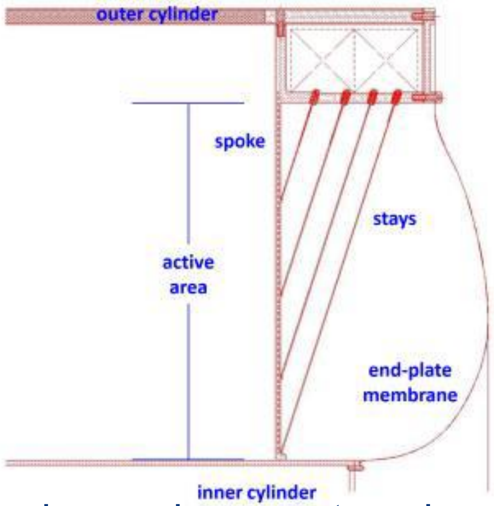
ROC AUC: 0.9914 — excellent separation of signal vs background

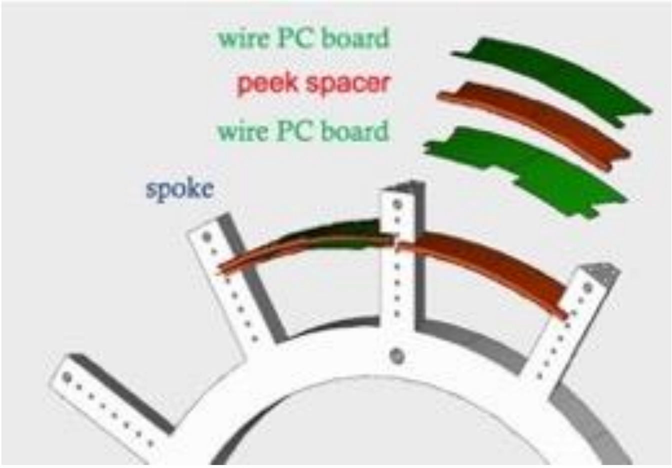
Mechanical simulation studies of the DCH

F. Procacci, A. Miccoli,……

New tension recovery schema

- Experience inherited from the **MEG2 DCH**
- inner and outer cylinder connected to 48 spokes, forming 24 identical sectors.
- To minimize the deformations due to the wire load, it is necessary to create a system of adjustable stays that steers the wire tension to the outer end plate rim .



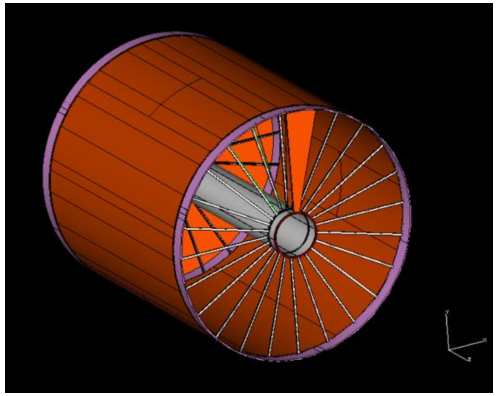


FEM simulation studies:

- **Our main goal** is to minimize the deformation of the spokes using prestressing force in the cables, while ensuring the structural integrity.
- varying input parameters in some possible ranges in order to see how the system responds.

A realistic complete model ready:

- mechanically accurate.
- precise definition of the connections of the cables on the structure.
- connections of the wires on the PCB.
- location of the necessary spacers.
- connection between wire cage and gas containment structure.



Summary

- The strategy for the digitization of the signals in the IDEA drift chamber has been defined, profiting from the information of all the ionization clusters along the track.
- The procedure relies primarily more on experimental information
  - it is fundamental to derive as many results as possible from testbeam analysis
- Different algorithms have been tested to be used in L1 digitizer (**RTA, DERIV, LSTM, Transformer**)
- The development of different algorithms enabled accurate electron peak detection, with performance validated using test beam data.
- Resolution studies done with RTA algorithm showed that the dN/dx method achieves **a resolution 2.5 times** better than the traditional dE/dx approach.
- These results highlight the strong potential of cluster counting for future detector technologies.
- A realistic complete model of Mechanical simulation of the DCH is ready.

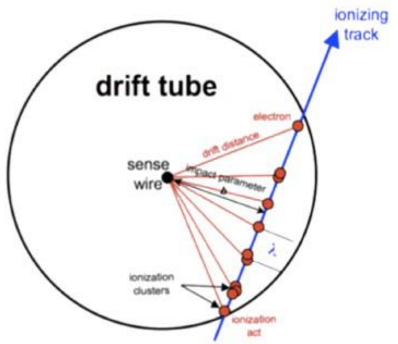
Backup

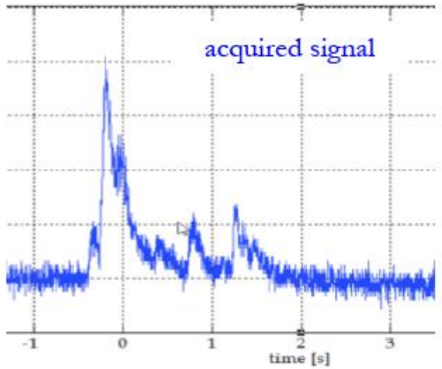
PID with Cluster Counting Technique

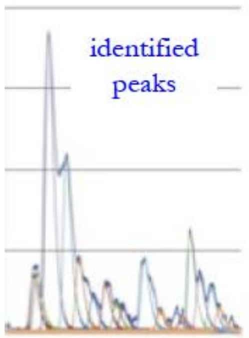
- **Principle:** In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently.

- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.

▶Backup







dE/dx

Truncated mean cut (70-80%) reduces the amount of collected information. n = 112 and a 2m track at 1 atm give

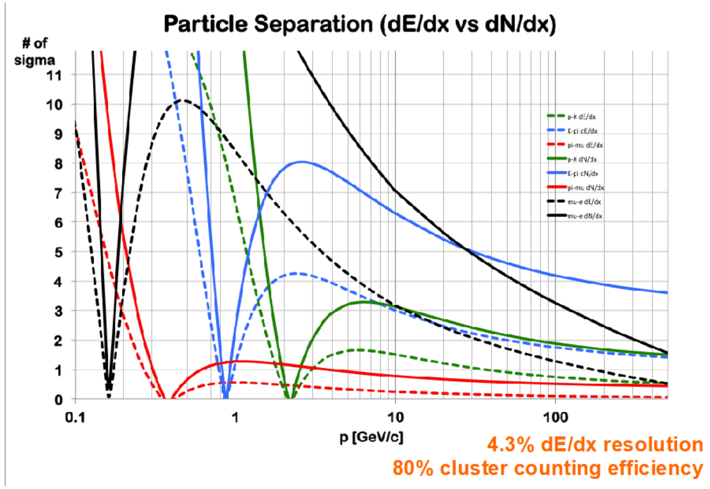
σ ≈ 4.3%

dN_{cl}/dx

δ_{cl}= 12.5/cm for He/iC4H10 = 90/10 and a 2m track give

σ ≈ 2.0%

- **Analytic calculations:** Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines).



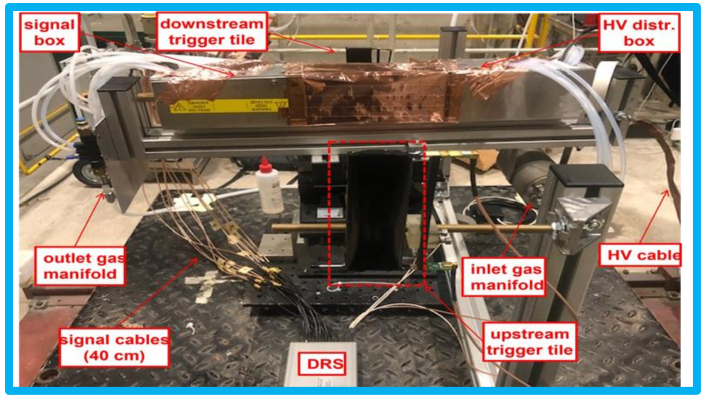
- Despite the fact that the Garfield++ model in GEANT4 reproduces reasonably well the Garfield++ predictions, why particle separation, both with dE/dx and with dNcl/dx, in GEANT4 is considerably worse than in Garfield++? ▶Backup

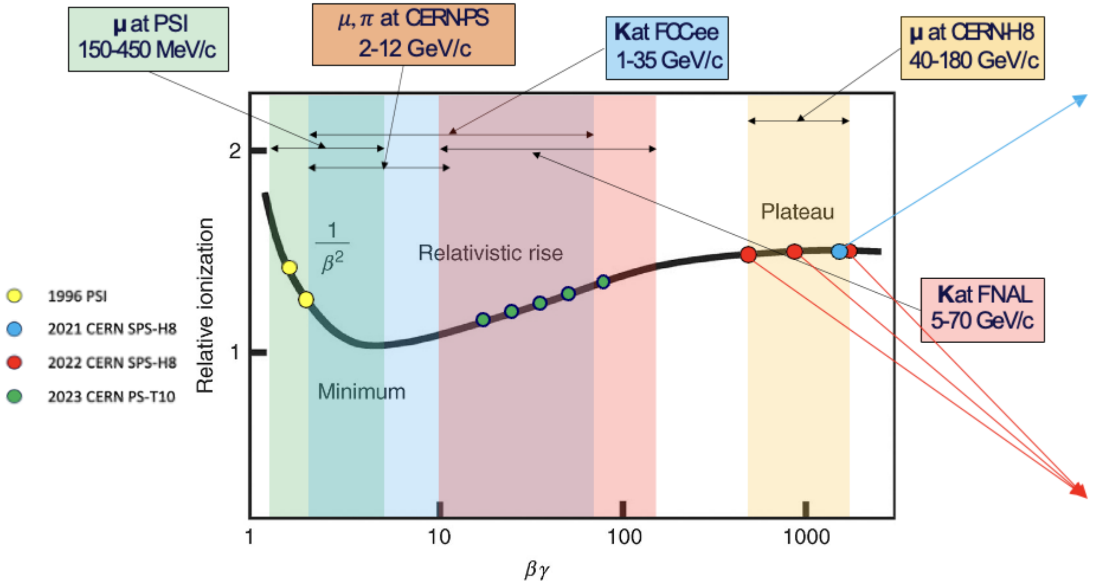
- Despite a higher value of the dN_{cl}/dx Fermi plateau with respect to dE/dx, why this is reached at lower values of βγ with a steeper slope?

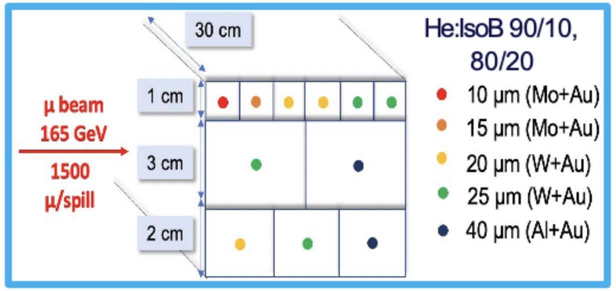
finding answers by using real data from beam tests!!

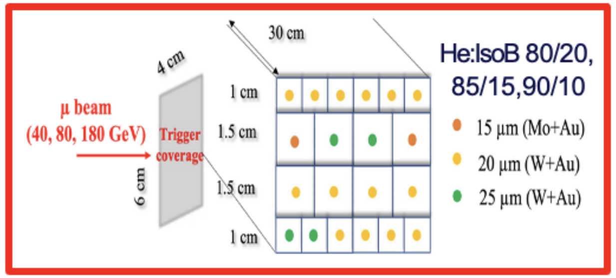
Main Beam Test setup & goals

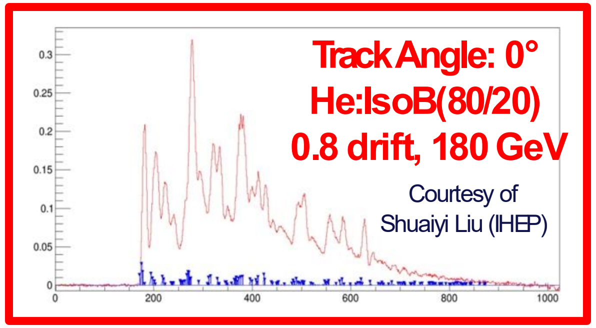
- **Beam tests to experimentally assess and optimize the performance of the cluster counting/timing techniques.**
  - Two muon beam tests performed at CERN H8(βγ > 400) in Nov. 2021 and July 2022.
  - Two muon beam tests performed at CERN T10 in Jul 2023 and Jul 2024 using μ beam (1-12 GeV).
  - Another test is planed to be done at FNAL-MT6 with π and K ($\beta\gamma$ = 10−140) to fully exploit the relativistic rise.

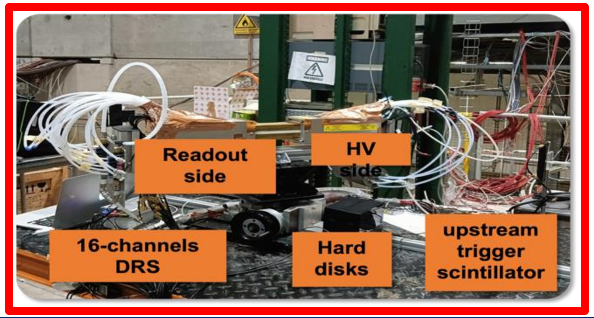












Find Electron peaks Algorithms

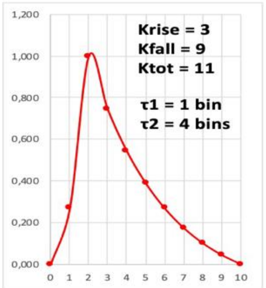
Derivative Algorithm (DERIV)

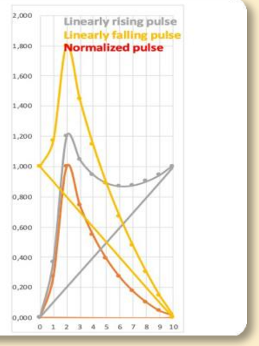
- Compute the first and second derivative from the amplitude average over two times the timing resolution and require that, at the peak candidate position, they are less than a r.m.s. signal-related small quantity and they increase (decrease) before (after) the peak candidate position of a r.m.s. signal-related small quantity.
- Require that the amplitude at the peak candidate position is greater than a r.m.s. signal-related small quantity and the amplitude difference among the peak candidate and the previous (next) signal amplitude is greater (less) than a r.m.s. signal-related small quantity.
- NOTE: r.m.s. is a measurements of the noise level in the analog signal from first bins.

Running Template Algorithm (RTA)

- Define an electron pulse template, characterized by rising and falling exponentials, over a fixed number of bins derived from experimental data.
- Digitize it according to the data sampling rate.
- The algorithm scans the wave form, comparing the normalized electron pulse template to the data within a search window.
- It evaluates the agreement between the template and the data, applying a cut-off to identify peaks.
- Subtract the found peak to the signal spectrum.
- Iterate the search and stop when no new peak is found.

k	A(k)
0	0.0
1	0.269
2	1.0
3	0.744
4	0.545
5	0.390
6	0.269
7	0.175
8	0.102
9	0.044
10	0.0

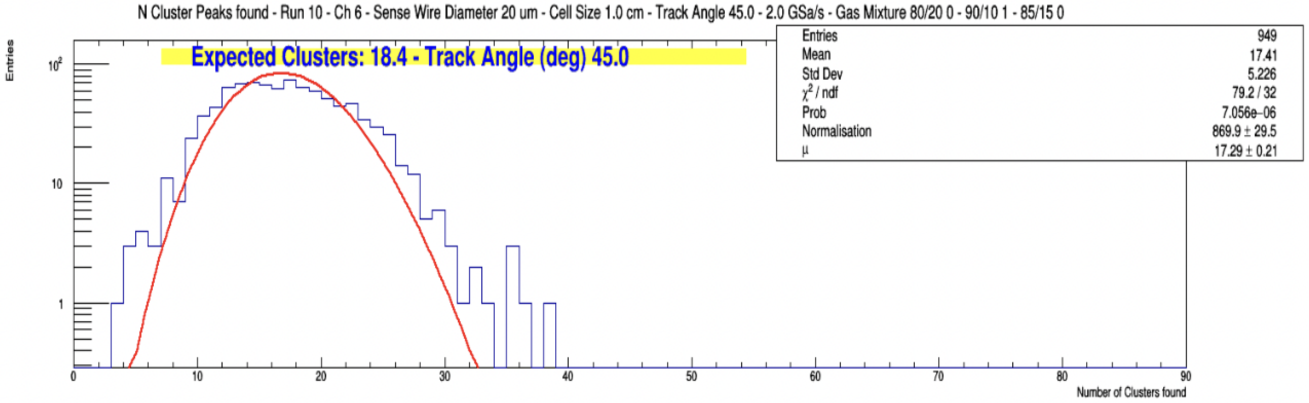


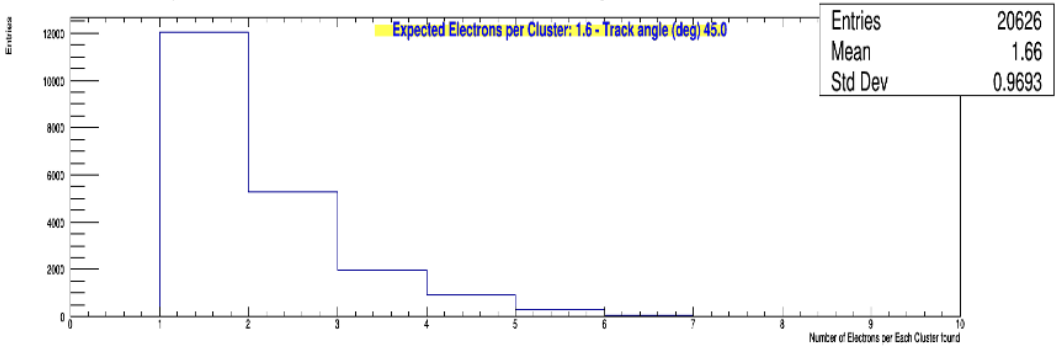


Reconstruction of Primary Ionization Clusters

Clusterization algorithm

- Merging of electron peaks in consecutive bins in a single electron to reduce fake electrons counting.
- Contiguous electrons peaks which are compatible with the electrons' diffusion time (it has a $\sim\sqrt{tElectronPeak}$ dependence, different for each gas mixture) must be considered belonging to the same ionization cluster. For them, a counter for electrons per each cluster is incremented.
- Position and amplitude of the clusters corresponds to the position and height of the electron having the maximum amplitude in the cluster.
- Poissonian distribution for the number of clusters!





Expected number of cluster = δ cluster/cm (M.I.P.) * drift tube size [cm] * 1.3 (relativistic rise)* 1/cos(α)

α = angle of the muon track w.r.t. normal direction to the sense wire.

δ cluster/cm (mip) changes from 12, 15, 18 respectively for He:IsoB 90/10, 85/15 and 80/20 gas mixtures.

drift tube size are 0.8, 1.2, and 1.8 respectively for 1 cm, 1.5 cm, and 2 cm cell size tubes.