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Cluster counting algorithms for PID at future colliders

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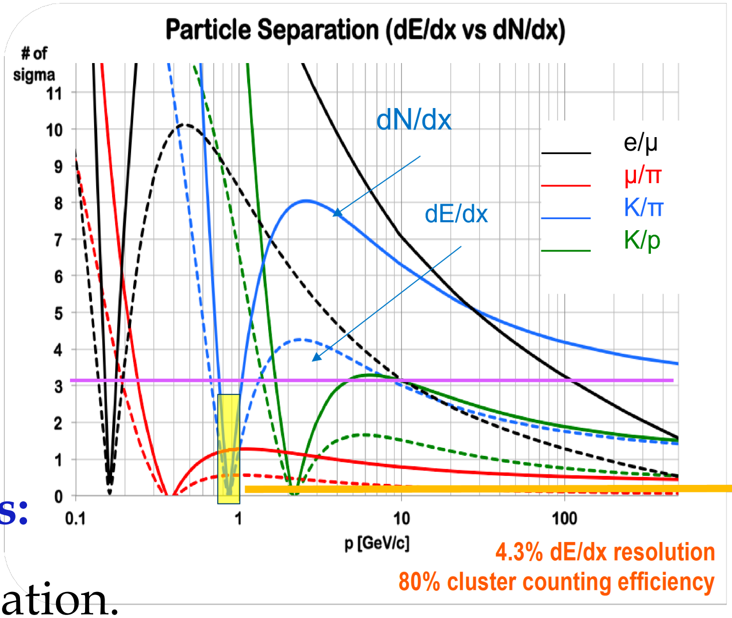
on behalf of cluster counting test beam team

Second ECFA Workshop, Paestum
10-13 Oct 2023

Why Cluster counting?

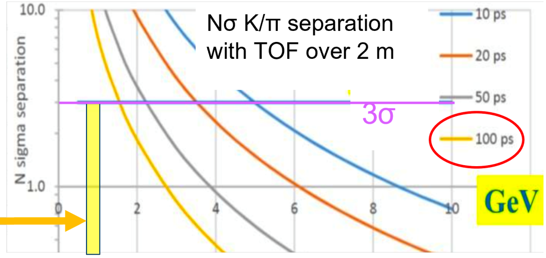
➢ **We deal with a Poissonian physics process:**

- independent from cluster size fluctuations
- insensitive to highly ionizing δ-rays
- independent from gas gain fluctuations



Analytical Results :

dN/dx performance is 2 times better than dE/dx in a wide transverse momentum range with He:IsoB 90/10

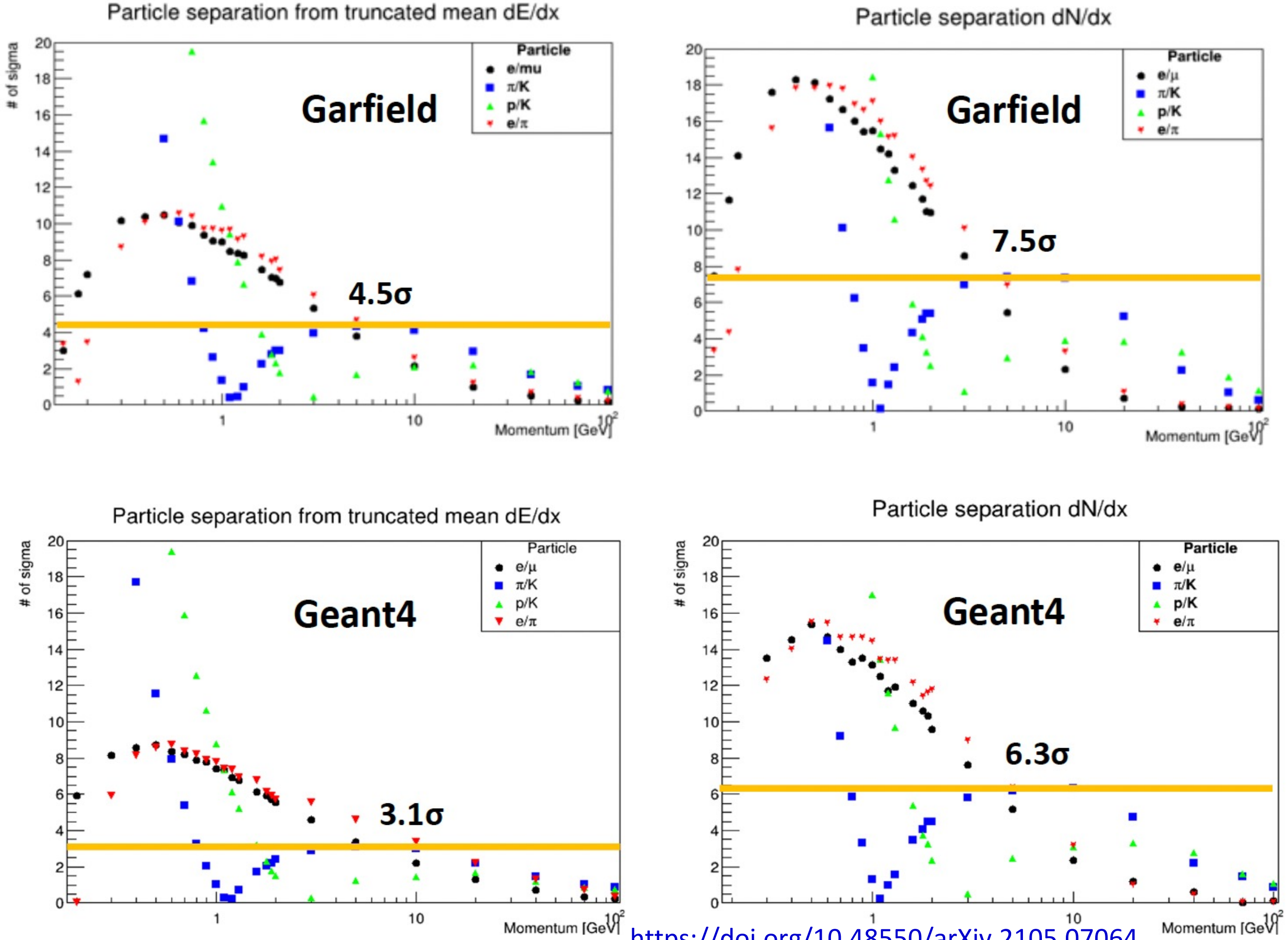


➢ **The choice of a He-based gas mixture implies:**

- low primary ionization density ⇨ large time separation.
- low drift velocity ⇨ even larger time separation (v_{drift} ~ 2.5 cm/μs)
- low average cluster size (< $N_{electrons}$/cluster> ~ 1.6)
- low single electron diffusion (< 110 μm for 0.5 cm drift, or < 4.5 ns)

The simulation of the cluster counting

We have developed an algorithm, which uses the energy deposit information provided by Geant4, to reproduce, in a fast and convenient way, the clusters density and the cluster size distributions predicted by Garfield++.



https://doi.org/10.48550/arXiv.2105.07064

Garfield++ in reasonable agreement with analytical calculations up to 20 GeV/c momentum, then falls much more rapidly at higher momenta.

Despite Geant4 uses the cluster density and the cluster size distributions from Garfield++, it disagrees from Garfield++ and, therefore, from the analytical calculations also.

See this talk in the coming session for more information about this algorithm.

Beam test motivation

1. Lack of experimental data on cluster density and cluster population for He based gas. Particularly in the relativistic rise region to compare predictions.

2. 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++?

3. Despite a higher value of the dNcl/dx Fermi plateau with respect to dE/dx, why this is reached at lower values of $\beta\gamma$ with a steeper slope?

- These questions are crucial for establishing the particle identification performance at FCCee, CEPC and SCTF.
- The only way to ascertain these issues is an experimental measurement!

Beam test goals

Need to demonstrate the **ability to count clusters** at a **fixed βγ** (e.g. muons at a fixed momentum – 165 GeV, 180 GeV) by changing:

- track length (different cell size - 1 cm, 1.5 cm and 2 cm) and changing the track angle (0° to 60°);
- gas mixture (He:IsoB 90/10, 80/20, 85/15).

Establish **the limiting parameters** for an efficient cluster counting:

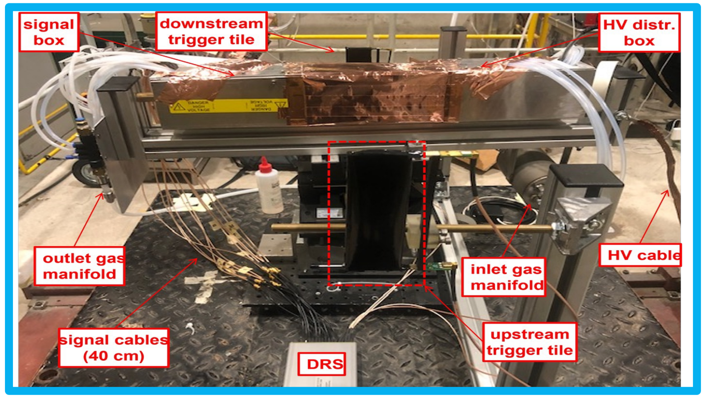
- cluster density (by changing **the gas mixture**).
- space charge (by changing **gas gain**, **sense wire diameter**, **track angle**).
- gas gain saturation.

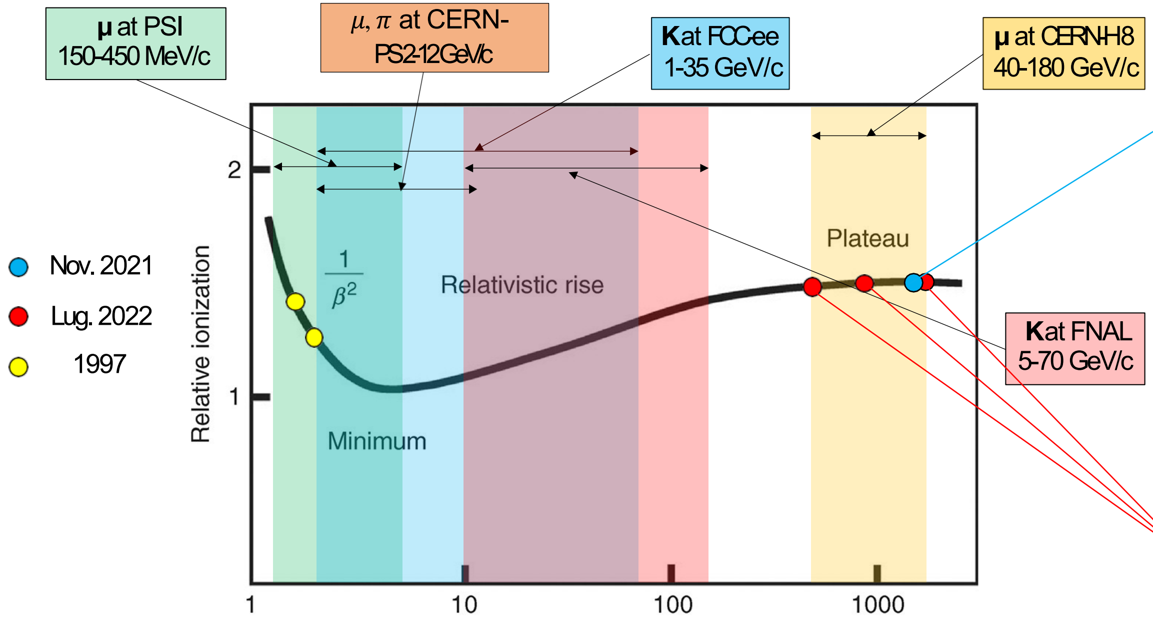
For the Future data taking campaigns: In optimal configuration, **measure the relativistic rise as a function of βγ**, both in dE/dx and in $dN_{cluster}/dx$, by scanning the muon momentum from the lowest to the highest value (from **a few GeV/c** to about **250 GeV/c**).

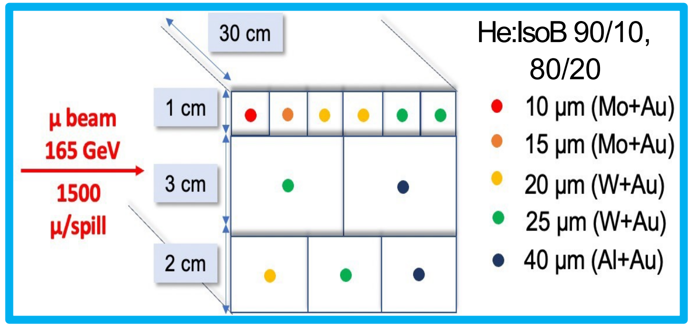
Beam Tests in 2021 & 2022

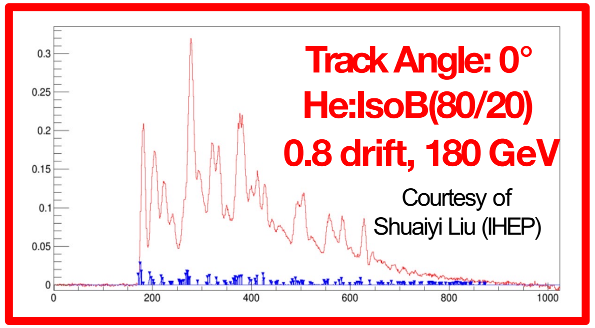
Beam tests to experimentally asses and optimize **the performance of the cluster counting/timing** techniques in strict collaboration with the IHEP Beijing group:

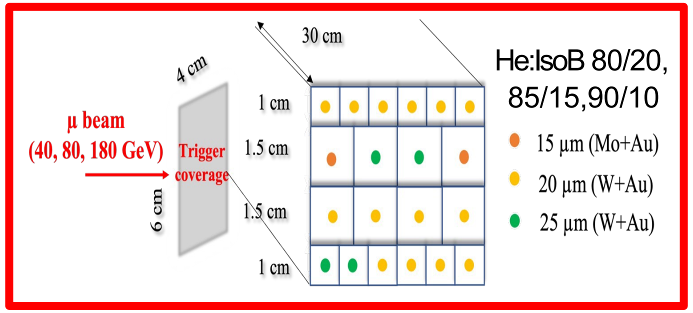
- Two muon beam tests performed at CERNH8($\beta\gamma > 400$) in Nov. 2021 and July 2022.
- Another **muon beam test** is done in Jul 2023 at **CERN** using μ beam (1-12 GeV).
- Another test is planed to be done at FNAL-MT6 with $\boldsymbol{\pi}$ and K ($\beta\boldsymbol{\gamma} = 10-140$) to fully exploit the relativitic rise.

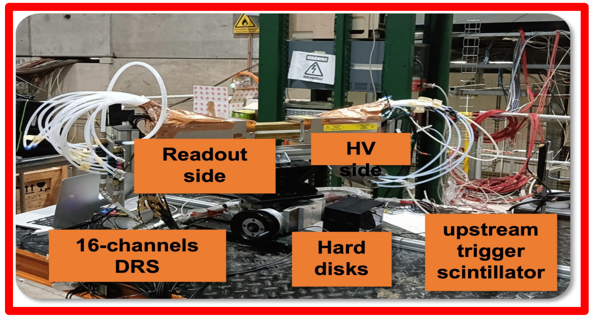












Find Electron peaks Algorithms (Bari & Lecce)

Derivative Algorithm (DERIV)

Find good electron peak candidates at position bin n and amplitude A_n :

- **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.

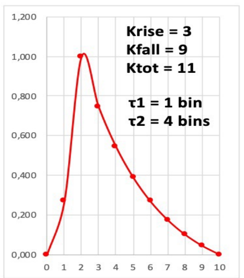
- Require that the amplitude at the peak candidate position is greater than a r.m.s. signal-related small quantity and the amplitude difference among the peak candidate and the previous (next) signal amplitude is greater (less) than a r.m.s. signal-related small quantity.

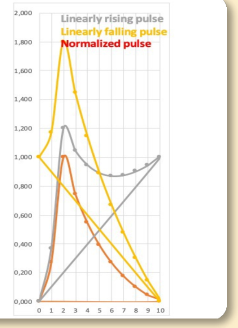
- NOTE: r.m.s. is a measurements of the noise level in the analog signal from first bins.

Running Template Algorithm (RTA)

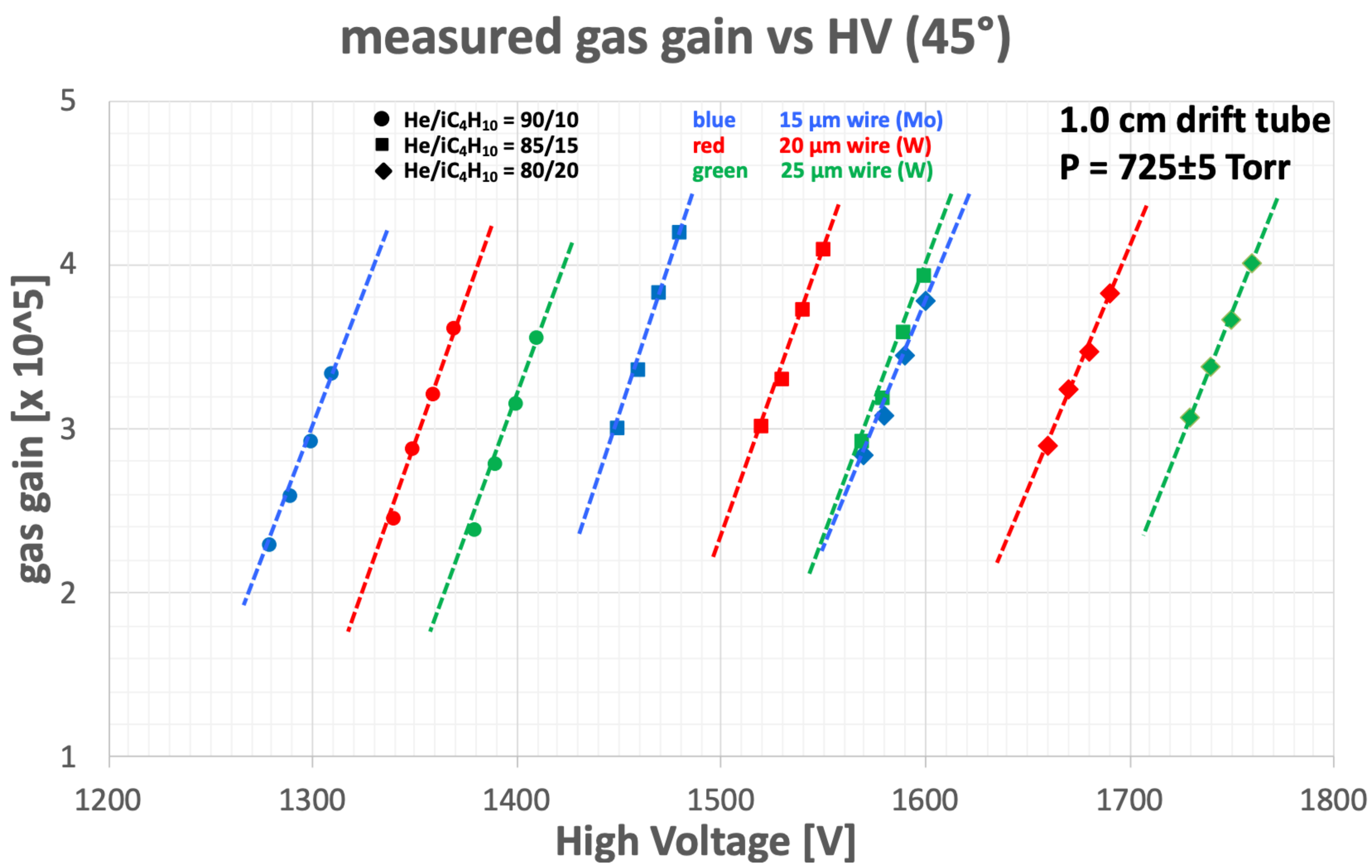
- Define an electron pulse template based on experimental data.
- Raising and falling exponential over a fixed number of bins (Ktot).
- Digitize it (A(k)) according to the data sampling rate.
- The algorithm scan the wave form and run over Ktot bins by comparing it to the subtracted and normalized data (build a sort of χ^2).
- Define a cut on χ^2.
- Subtract the found peak to the signal spectrum.
- Iterate the search.
- 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



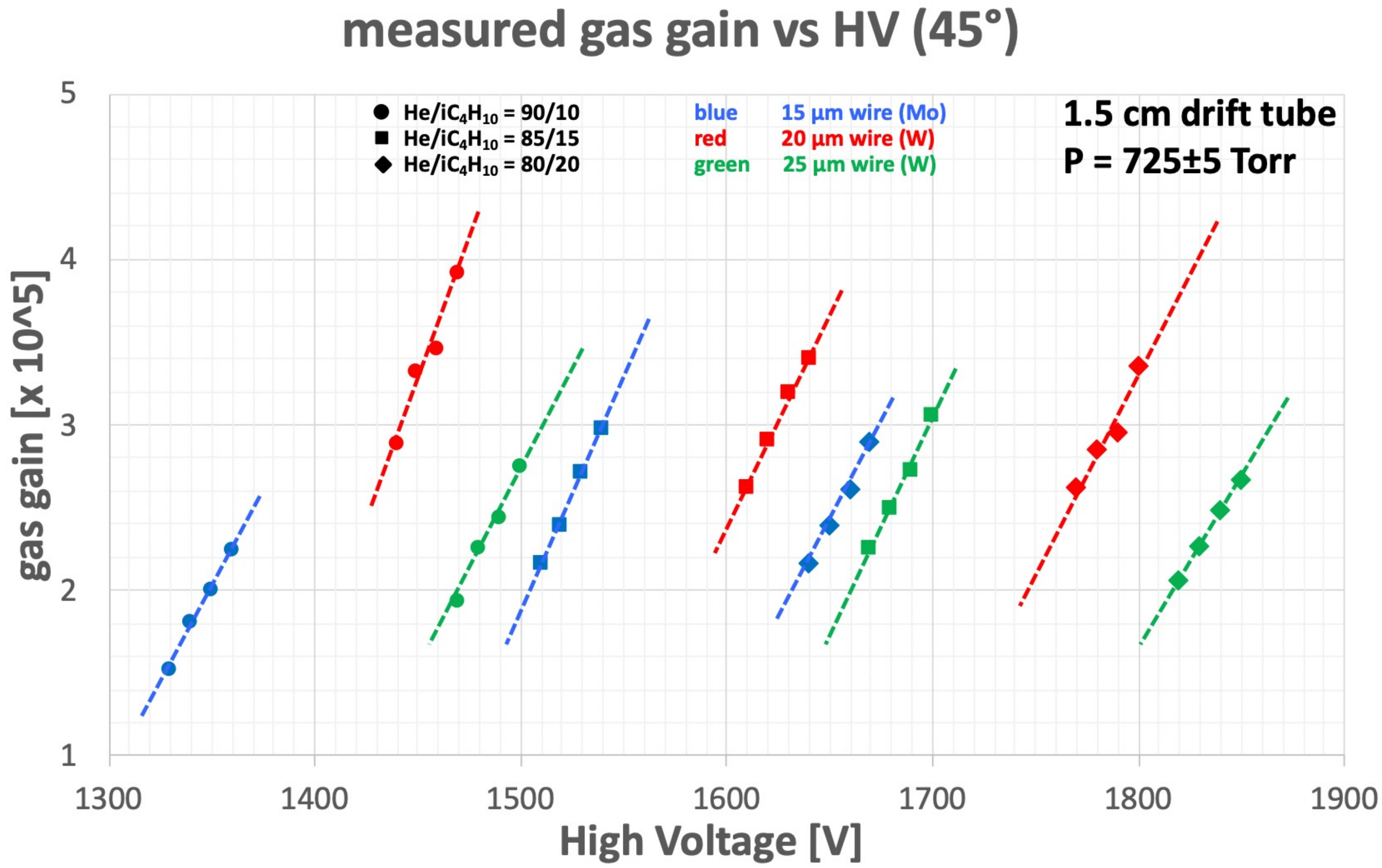


Gas gain (Test Beam Jul 2022)



25µm wire He:IsoB 85/15 has the same gain of 15µm wire He:IsoB 80/20

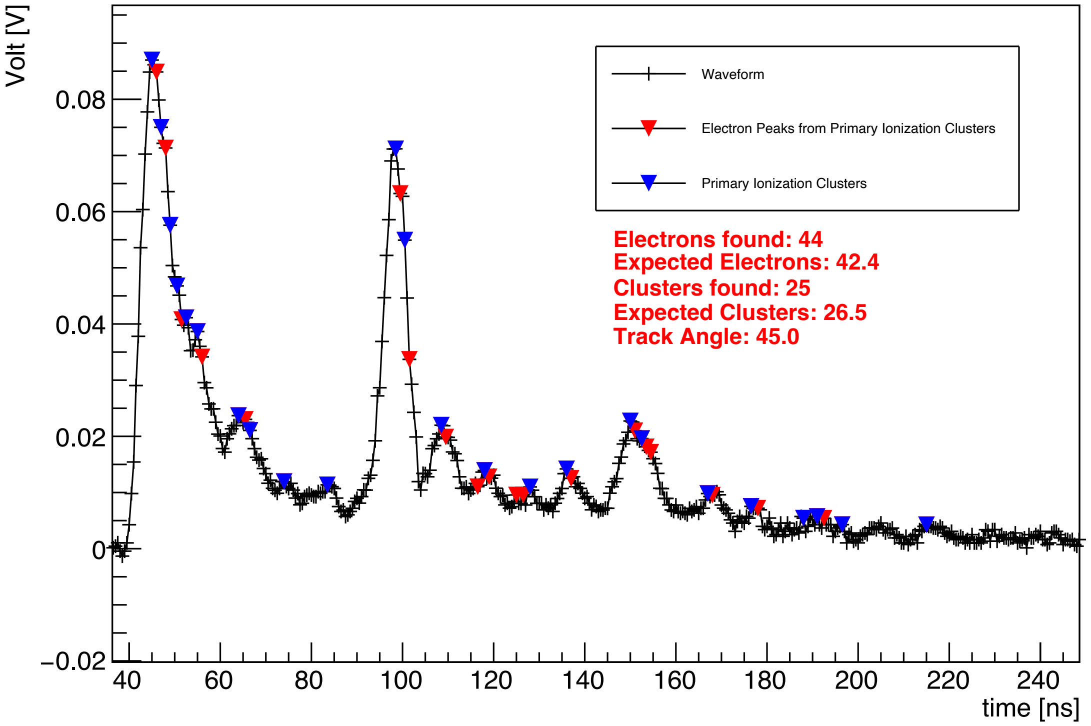
Gas gain (Test Beam Jul 2022)



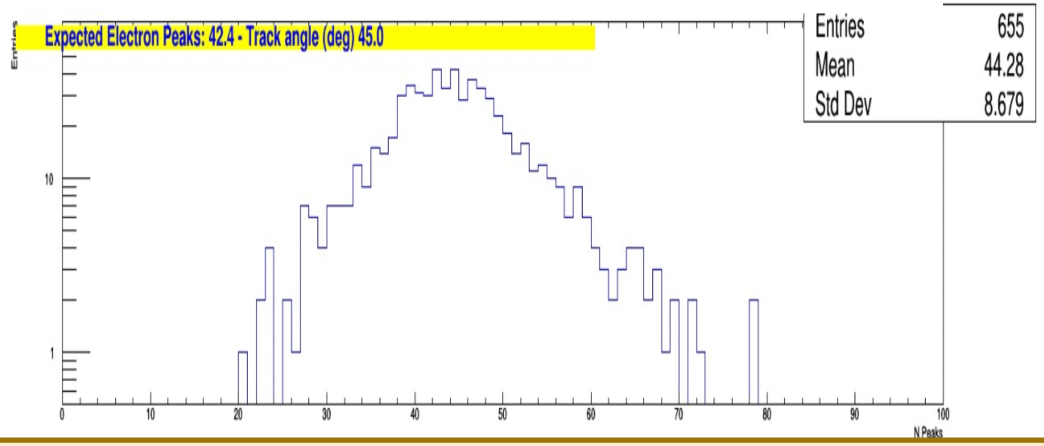
20µm wire excluded from physical quantities mean computation

Reconstruction of Electron Peaks (RTA Algorithm)

Sense Wire Diameter 15 μm; Cell Size 1.0 cm; Track Angle 45; Sampling rate 2 GSa/s; Gas Mixture He:IsoB 80/20



Electron Peaks distribution



Expected number of electron =
δ cluster/cm (M.I.P.) * drift tube size [cm] * 1.3 (relativistic rise)* 1.6 electrons/cluster * 1/cos(α)

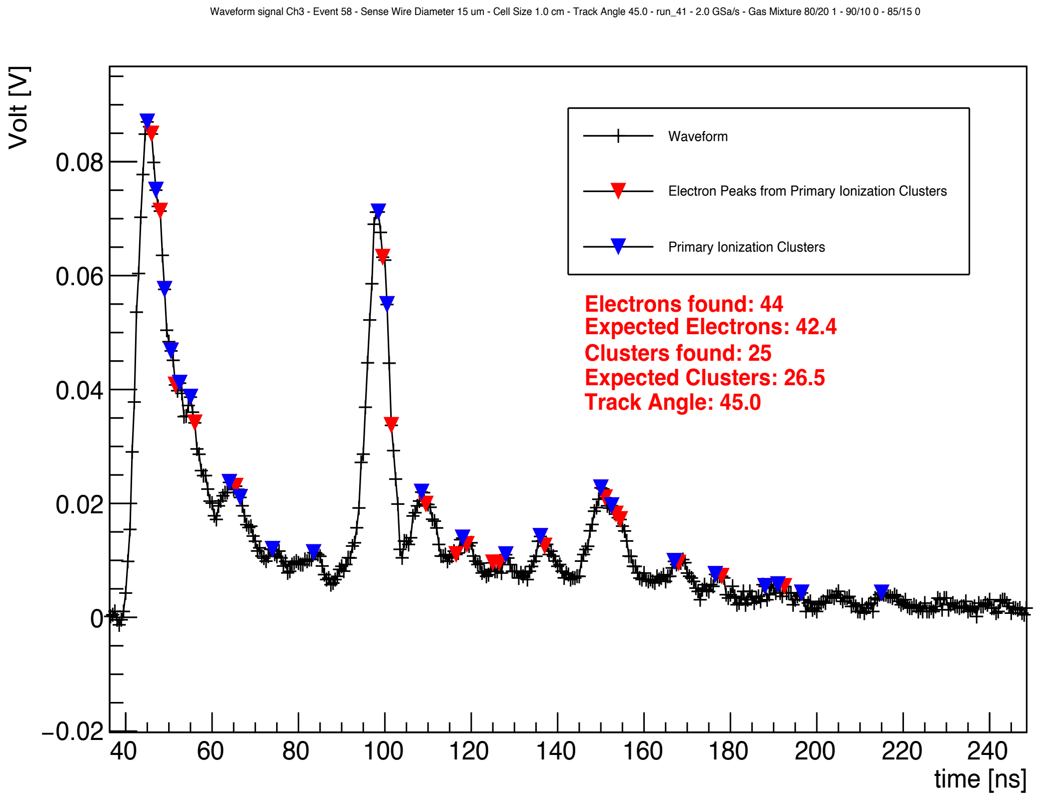
α = angle of the muon track w.r.t. normal direction to the sense wire.
δ cluster/cm (mip) changes from 12, 15, 18 respectively for He:IsoB 90/10, 85/15 and 80/20 gas mixtures.
drift tube size are 0.8, 1.2, and 1.8 respectively for 1 cm, 1.5 cm, and 2 cm cell size tubes

[1] H. Fischle, J. Heintze and B. Schmidt, Experimental determination of ionization cluster size distributions in counting gases, NIMA 301 (1991)

Reconstruction of Primary Ionization Clusters

Sense Wire Diameter 15 μm; Cell Size 1.0 cm; Track Angle 45; Sampling rate 2 GSa/s; Gas Mixture He:IsoB 80/20

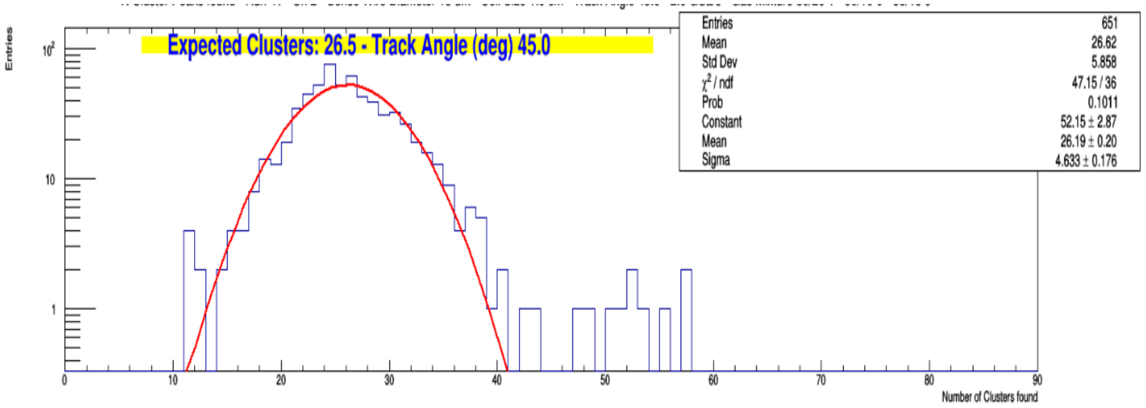
- ***Merging of electron peaks*** *in consecutive bins in a single electron to reduce fake electrons counting.*
- ***Contiguous electrons peaks*** *which are compatible with the electrons' diffusion time (it has a* $\sim\sqrt{t}_{ElectronPeak}$ *dependence, different for each gas mixture) must be considered 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!***



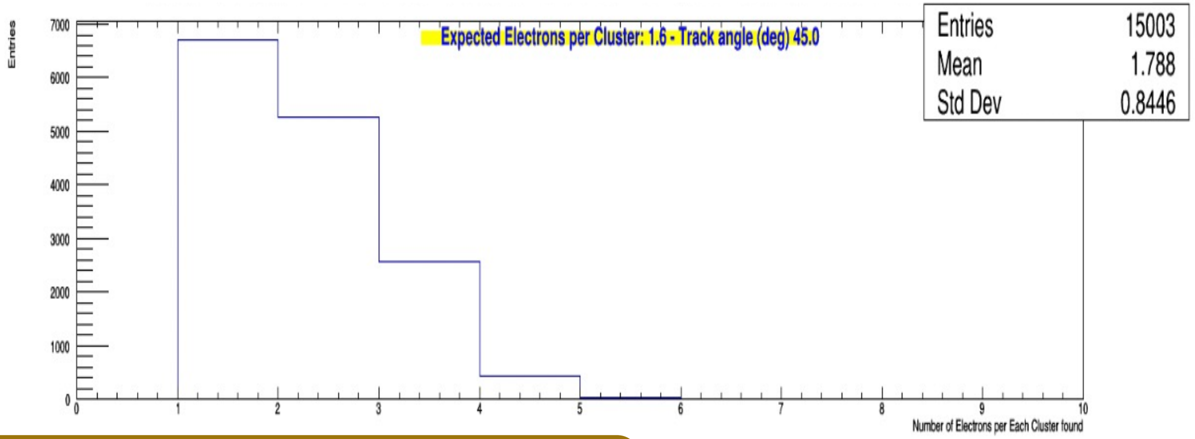
Reconstruction of Primary Ionization Clusters

Sense Wire Diameter 15 µm; Cell Size 1.0 cm; Track Angle 45; Sampling rate 2 GSa/s; Gas Mixture He:IsoB 80/20

Poissonian distribution for the number of clusters



Electrons per cluster distribution



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.

Poissonian distribution of the number of clusters and cluster size in acceptance with the expectation

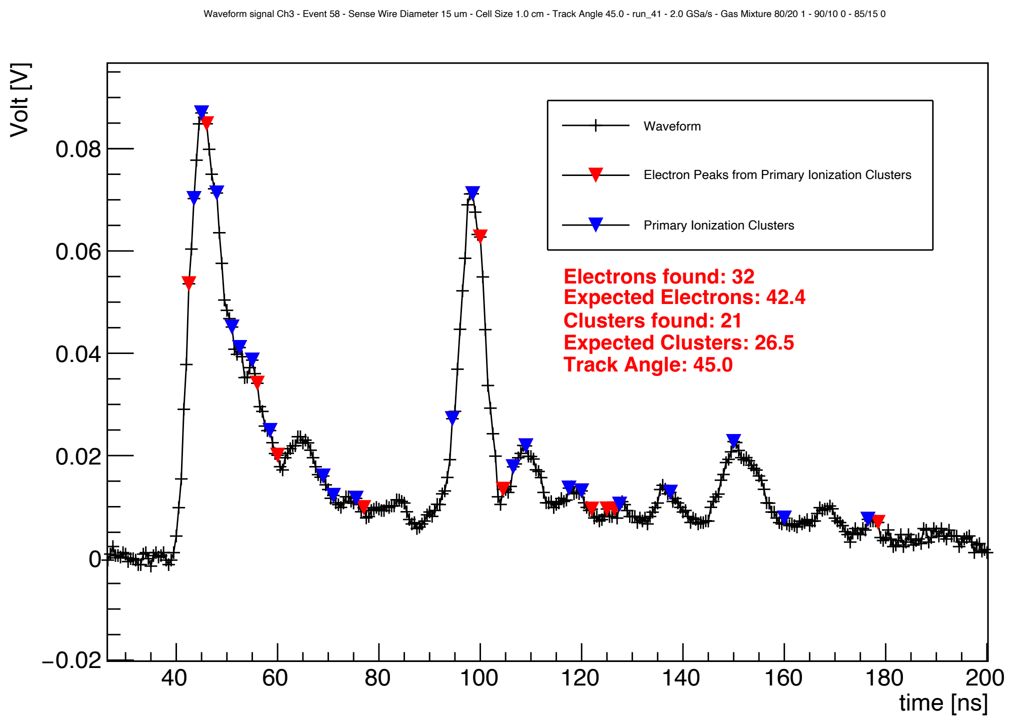
Comparison between DERV and RTA algorithm

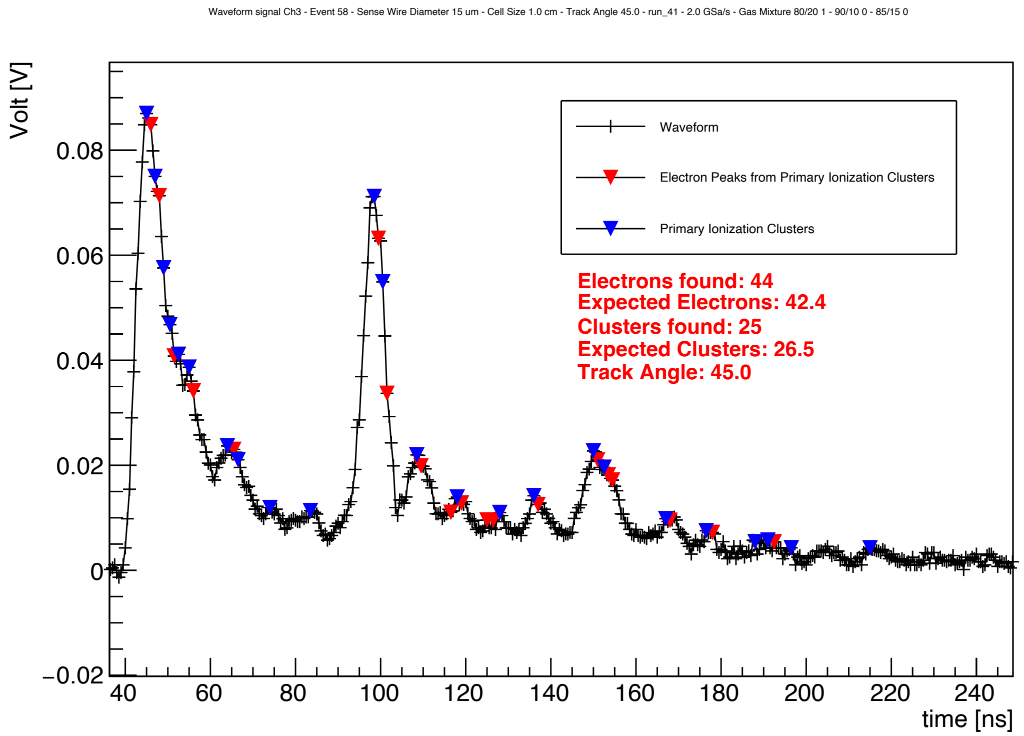
1 cm drift tubes

Run: 41; Track angle: 45^0; Gas mixture: 80% He 20% iC_4H_{10} ; HV = Nominal Sampling rate= 2 Gsa/s

DERIV Algorithm

RTA Algorithm





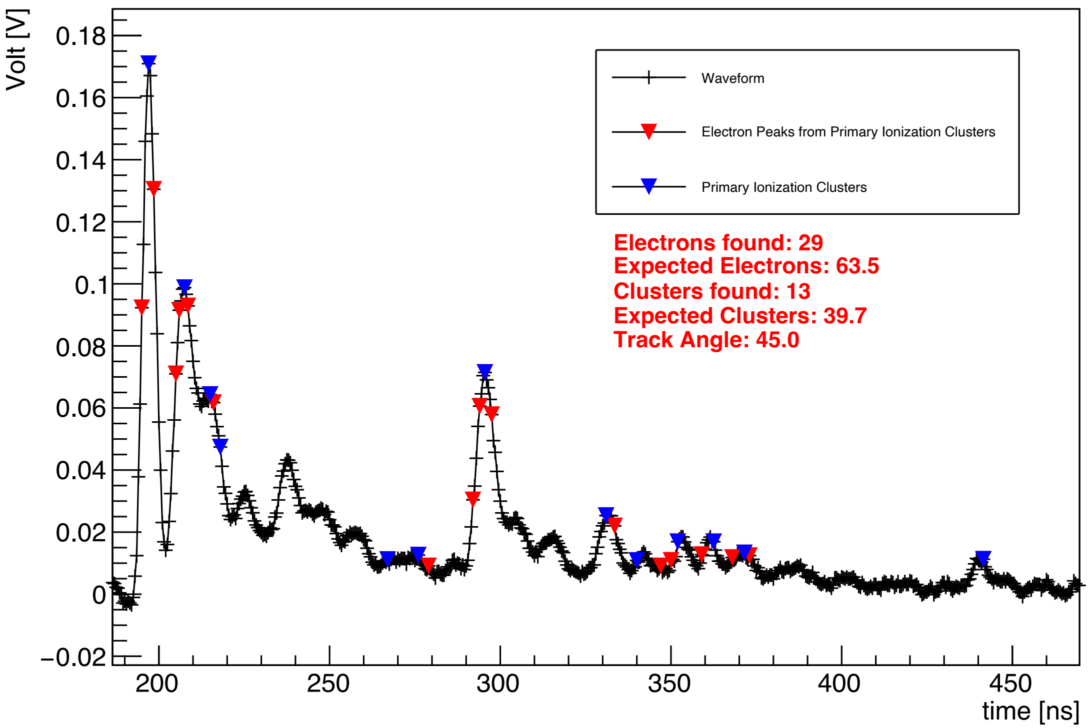
Comparison between DERV and RTA algorithm

1.5 cm drift tubes

Run: 41; Track angle: 45^0; Gas mixture: 80% He 20% iC_4H_{10} ; HV = Nominal Sampling rate= 2 Gsa/s

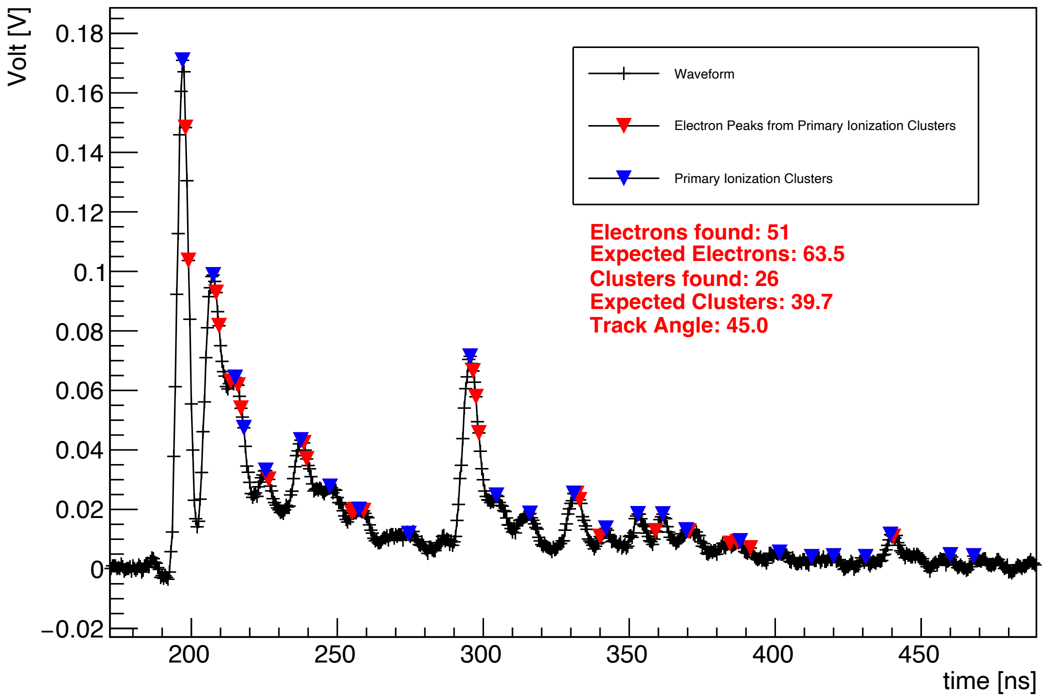
DERIV Algorithm

Waveform signal Ch7 - Event 0 - Sense Wire Diameter 15 um - Cell Size 1.5 cm - Track Angle 45.0 - run_41 - 2.0 GSa/s - Gas Mixture 80/20 1 - 90/10 0 - 85/15 0



RTA Algorithm

Waveform signal Ch7 - Event 0 - Sense Wire Diameter 15 um - Cell Size 1.5 cm - Track Angle 45.0 - run_41 - 2.0 GSa/s - Gas Mixture 80/20 1 - 90/10 0 - 85/15 0

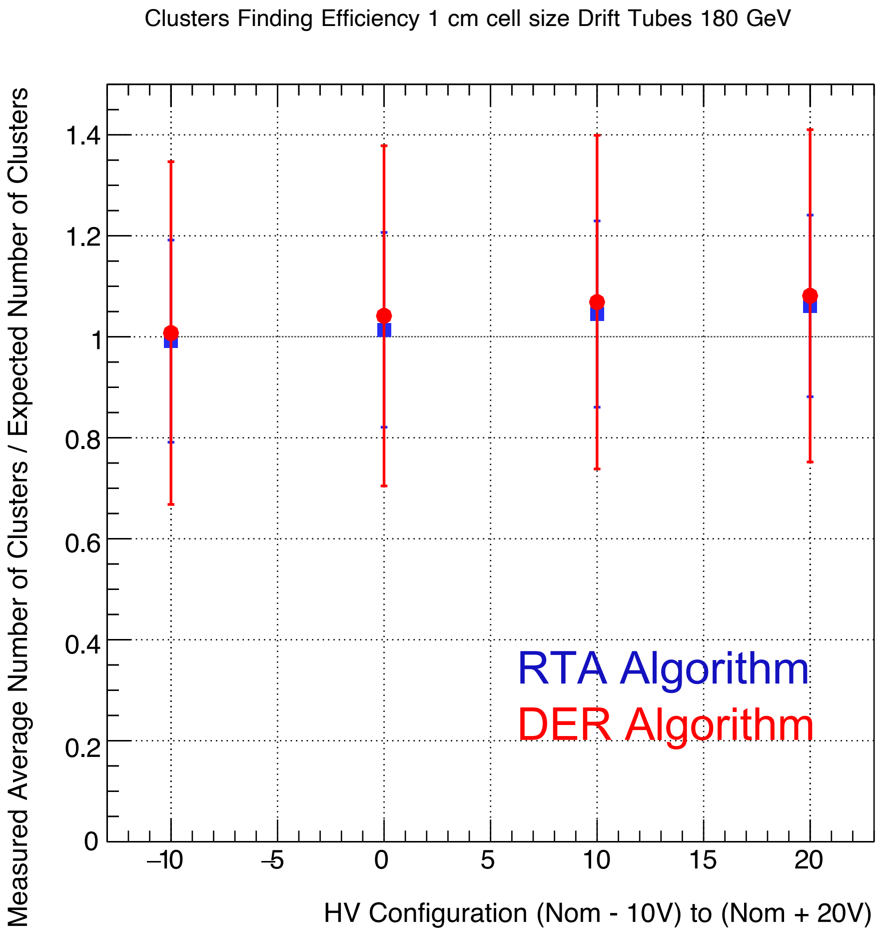


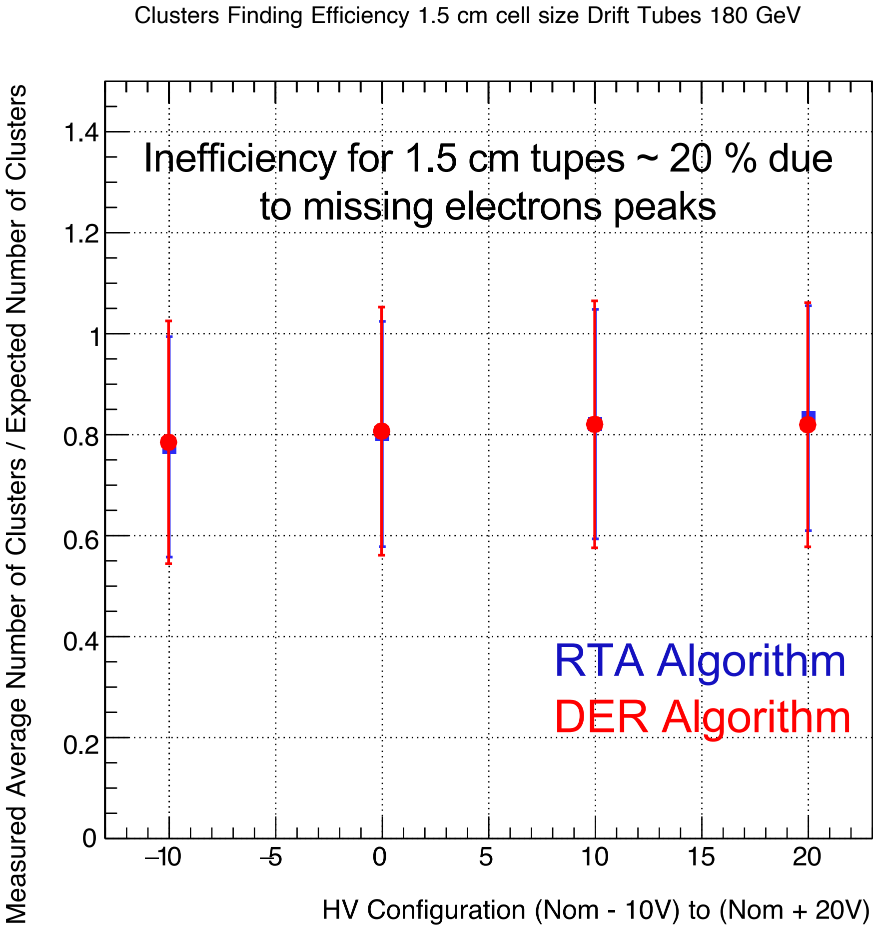
Comparison between DERV and RTA algorithm

1 cm drift tubes

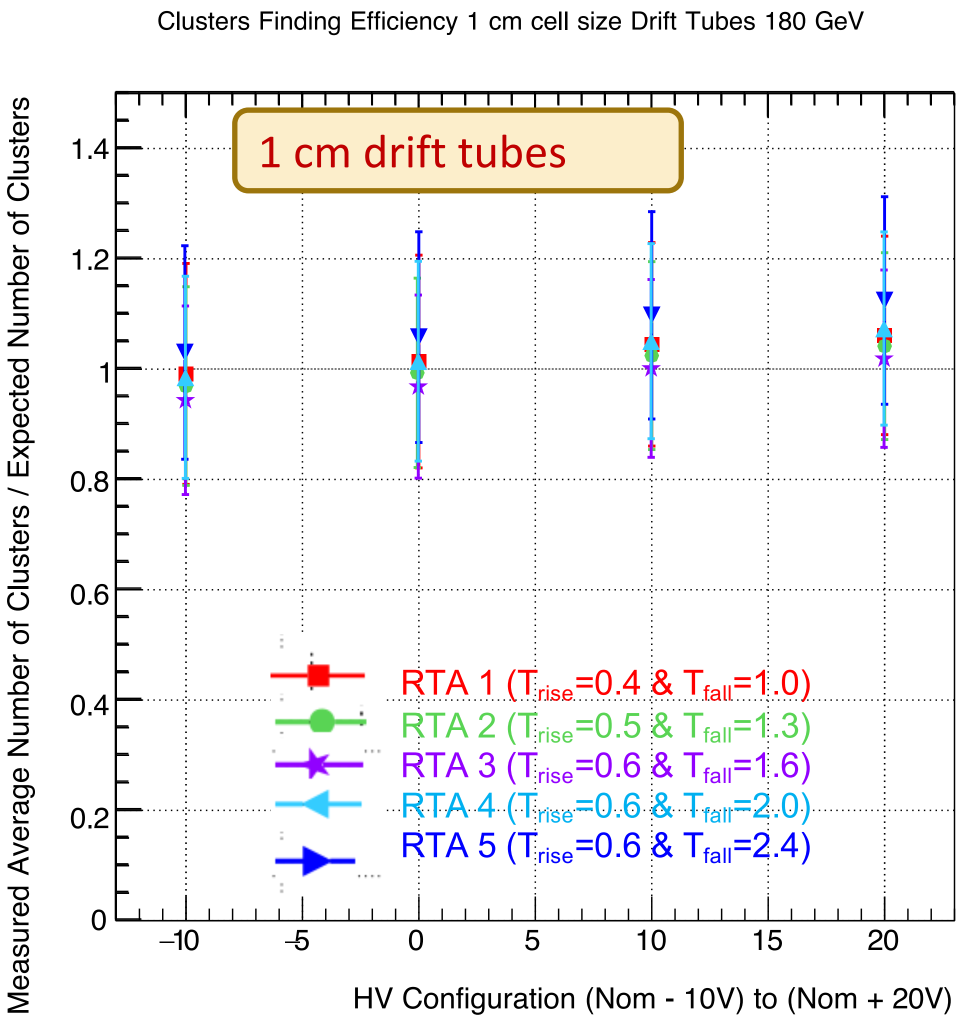
HV scan

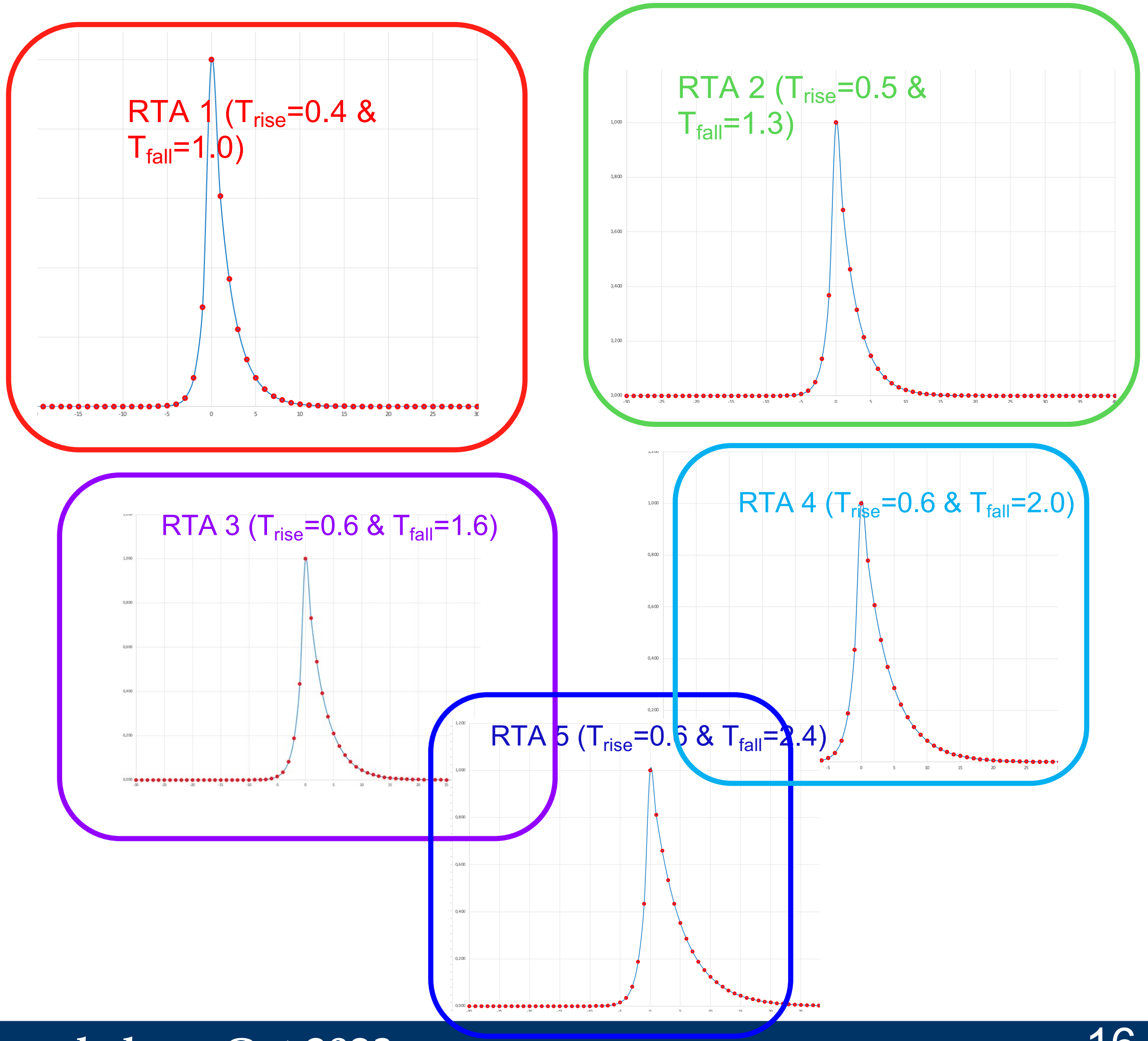
1.5 cm drift tubes



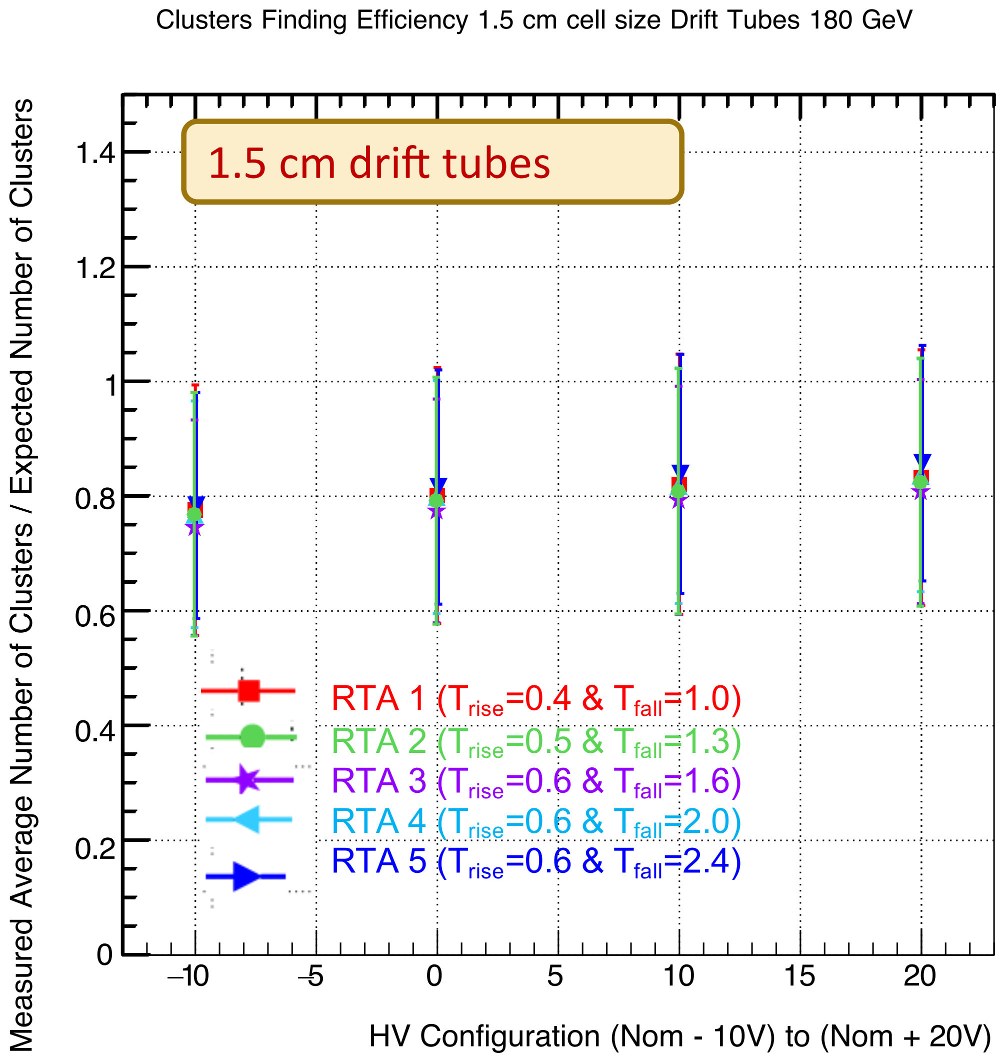


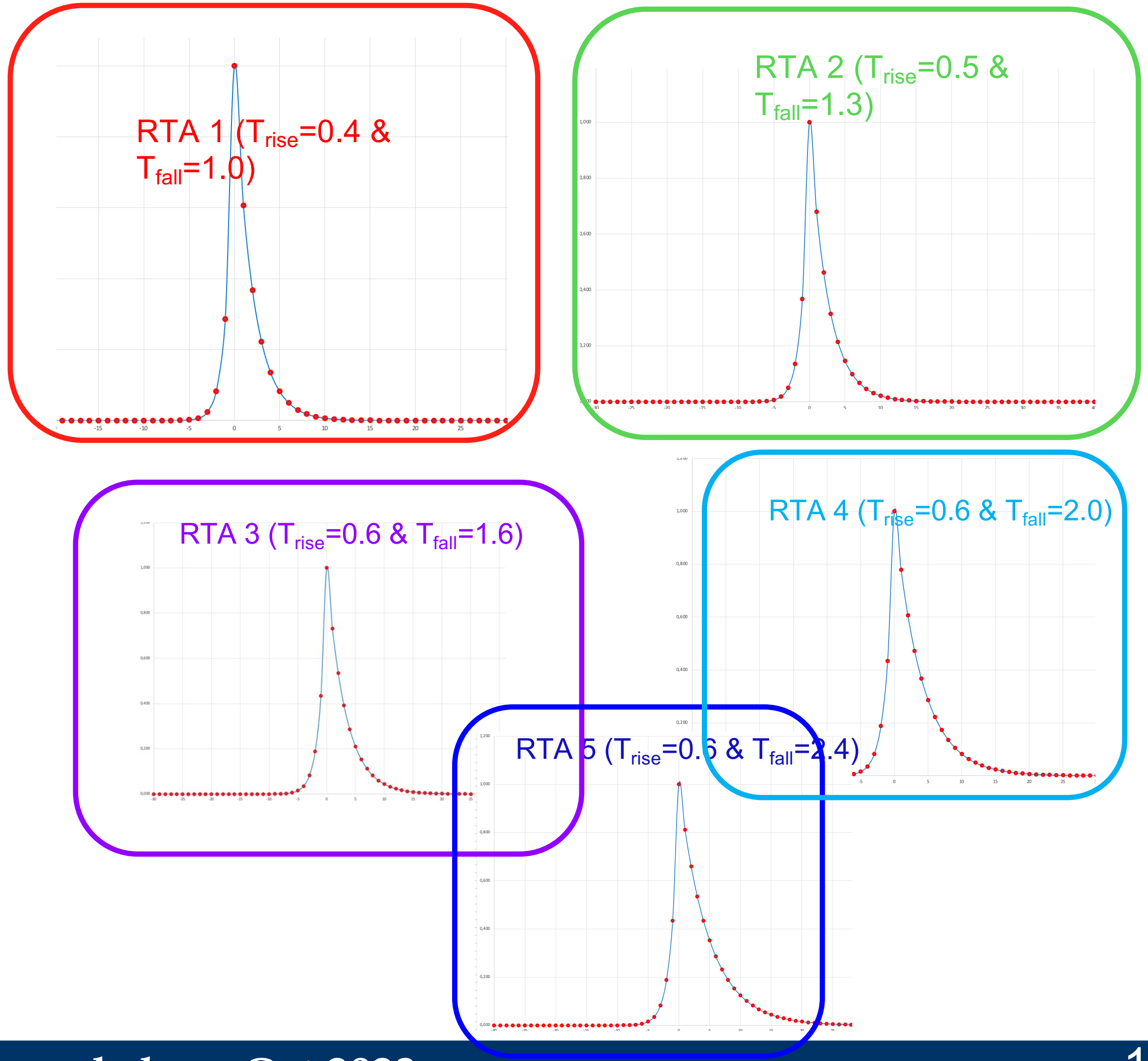
RTA Templates scan





RTA Templates scan

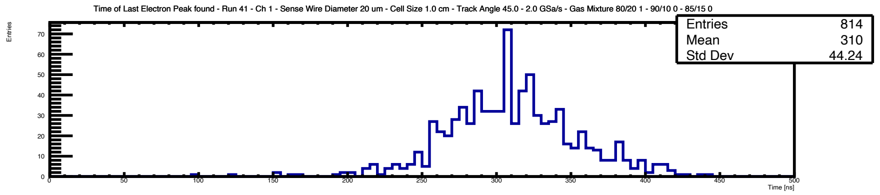


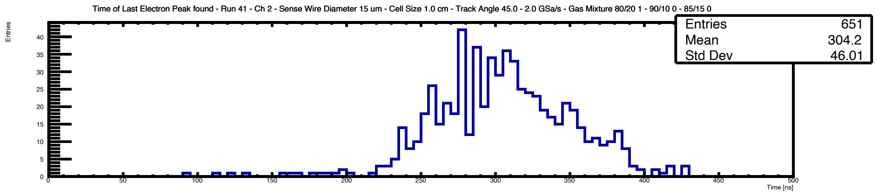


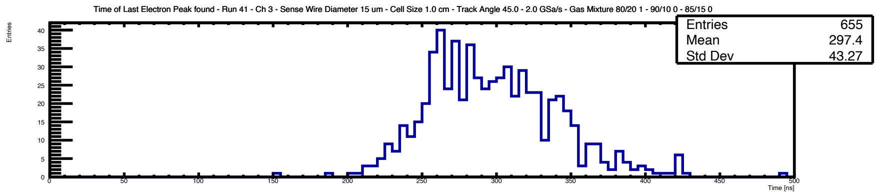
Time of the last electron peak

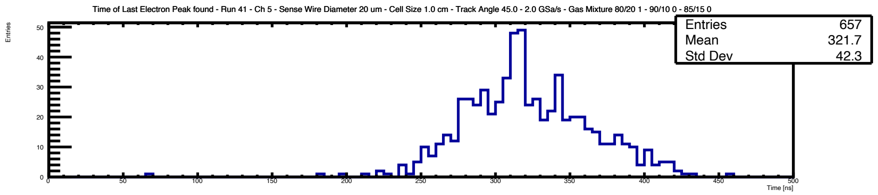
Time of the last electron peak 1 cm tupes

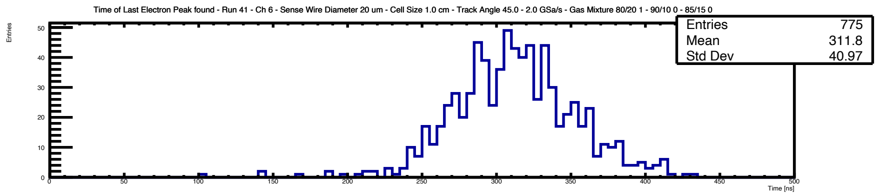
Track Angle 45; Sampling rate 2 GSa/s; Gas Mixture He:IsoB 80/20

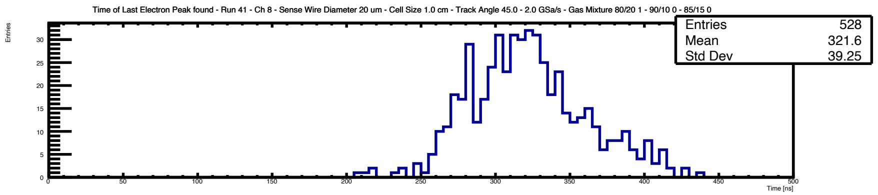


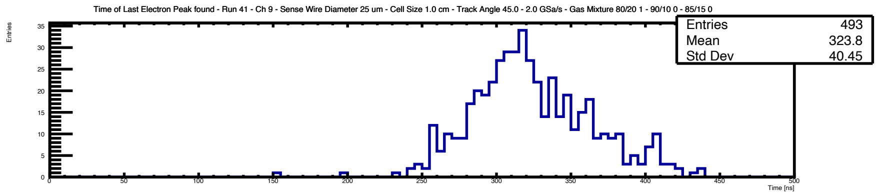


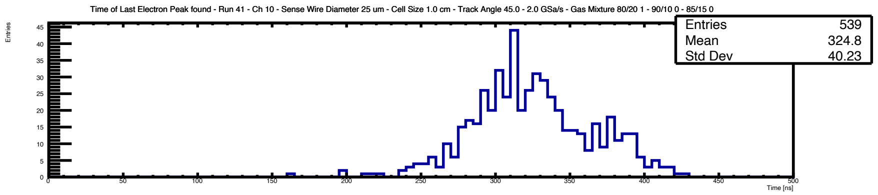








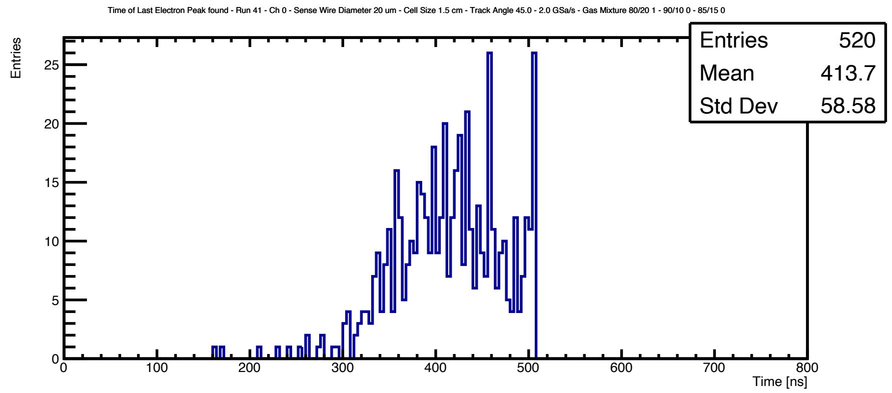


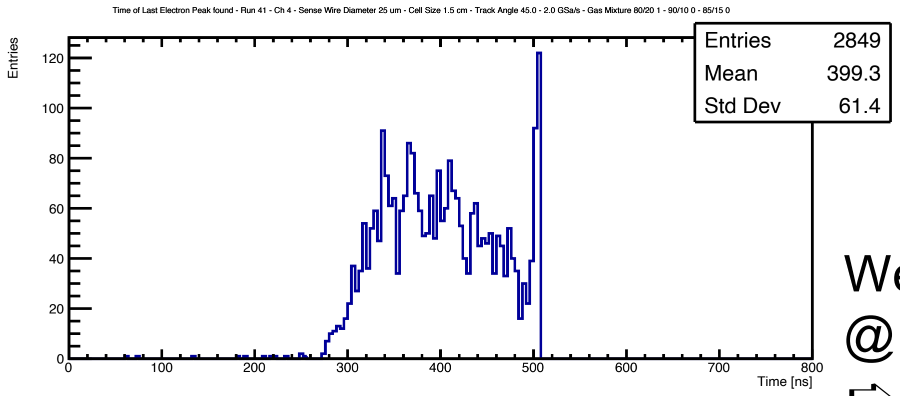


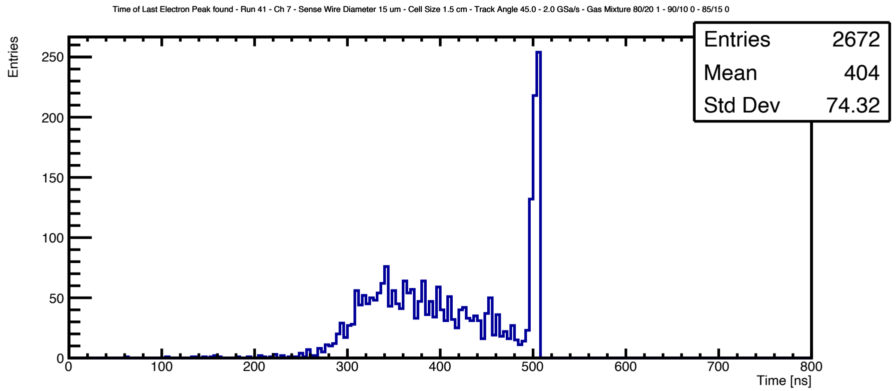
Time of the last electron peak

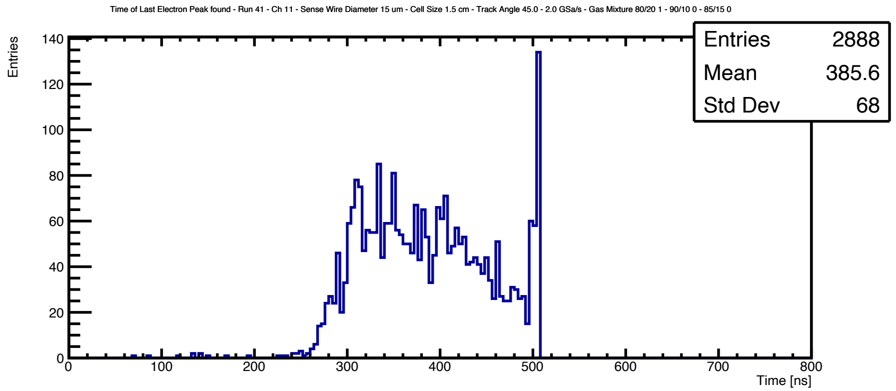
Time of the last electron peak 1.5 cm tupes
Track Angle 45; Sampling rate 2 GSa/s; Gas Mixture He:IsoB 80/20

Issue in 1.5 cm tubes due to 512 ns don't cover the full range.







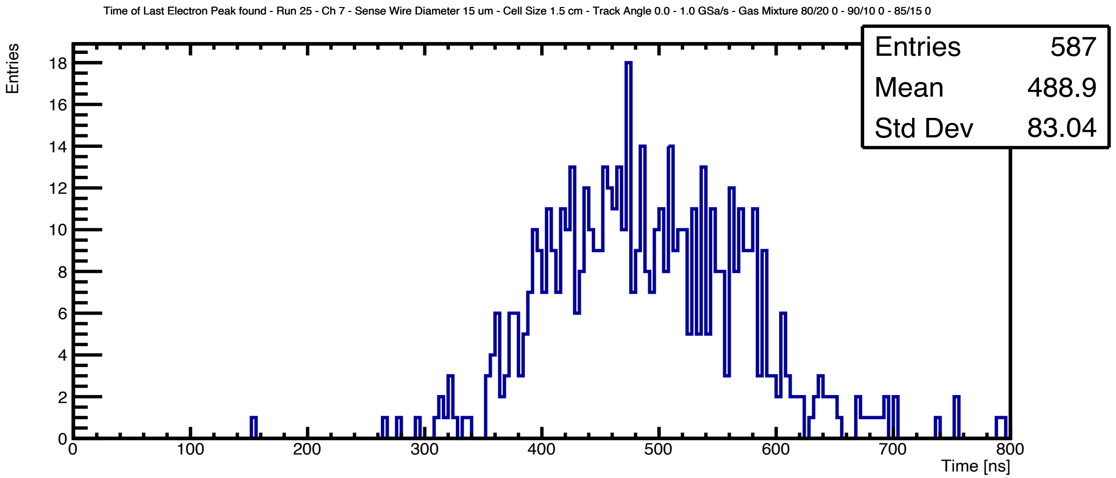


We have 1024 bins,
@ 2GSa ➪ 1/2 ns/bin
➪ 512 ns.

Time of the last electron peak

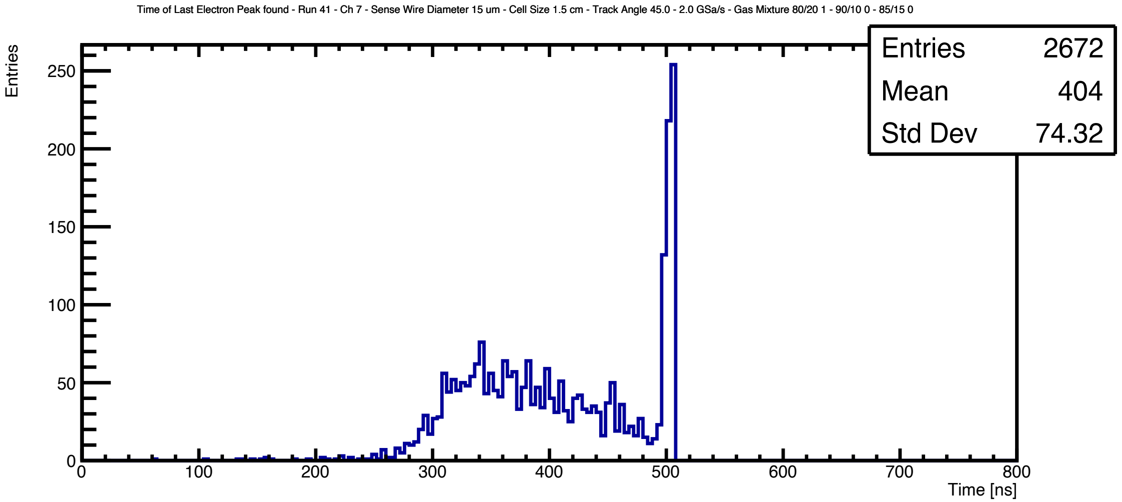
Time of the last electron peak 1.5 cm tupes, Track Angle 45; Gas Mixture He:IsoB 80/20

Sampling rate 1 GSa/s;



We have 1024 bins,
@ 1GSa ➪ 1 ns/bin ➪ 1024 ns.

Sampling rate 2 GSa/s;



We have 1024 bins,
@ 2GSa ➪ 1/2 ns/bin ➪ 512 ns.

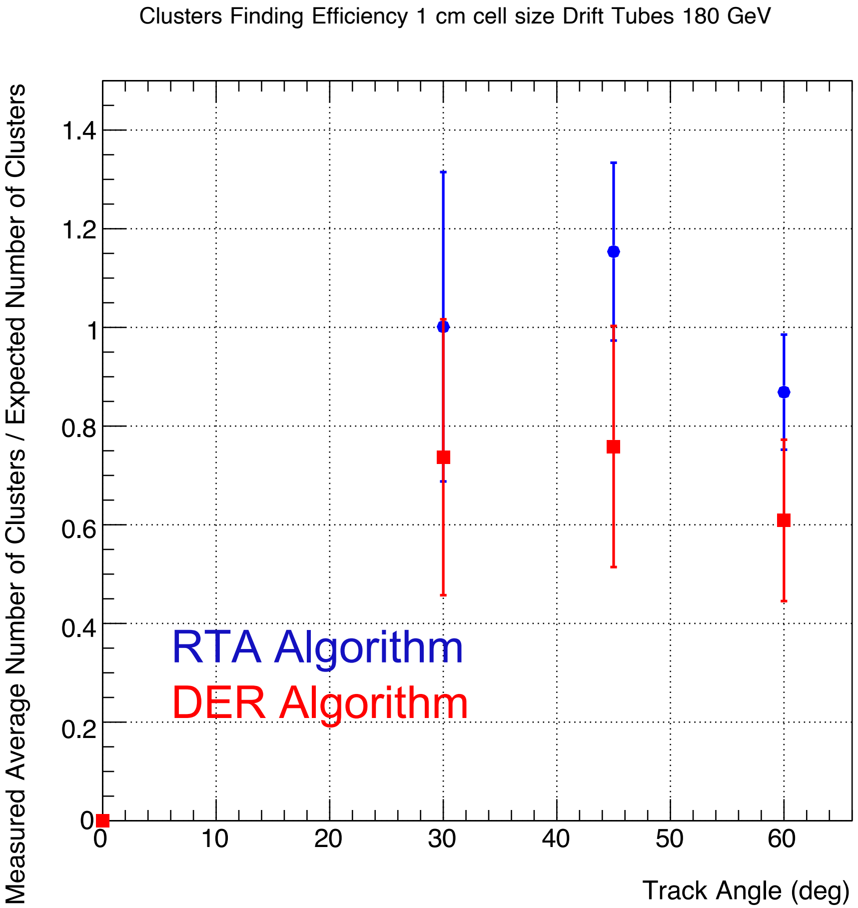
Issue in 1.5 cm tubes when using sampling rate 2GSa/s due to 512 ns don't cover the full range.

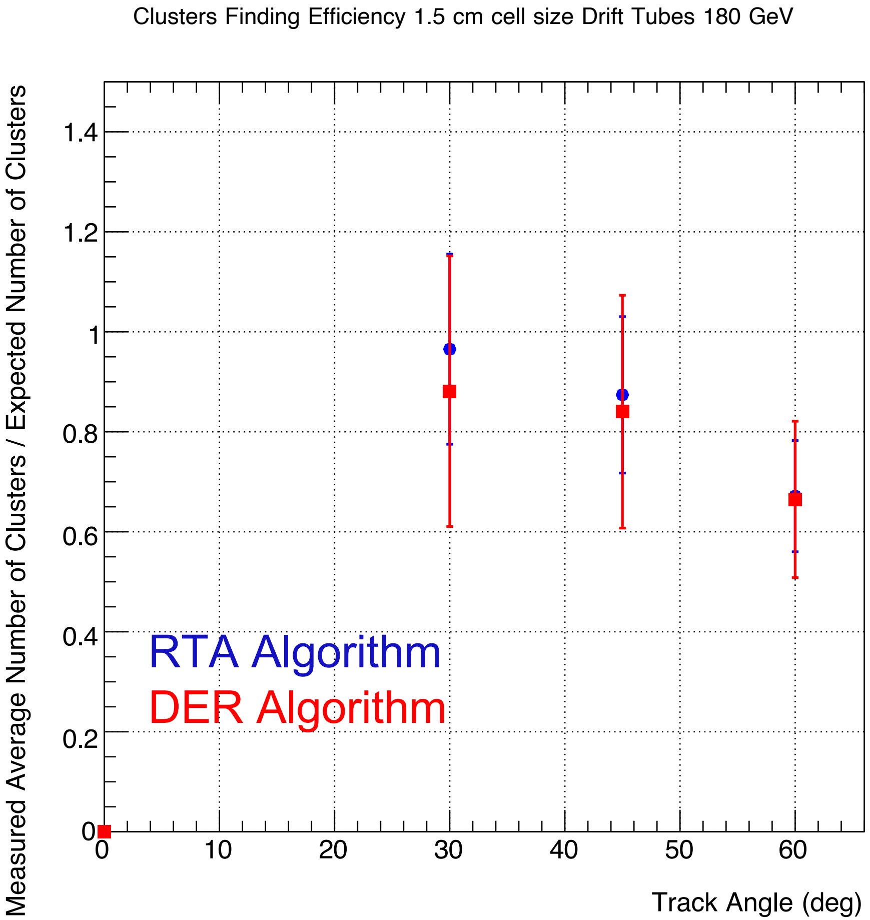
Comparison between DERV and RTA algorithm

1 cm drift tubes

Sampling rate 1 GSa/s;

1.5 cm drift tubes





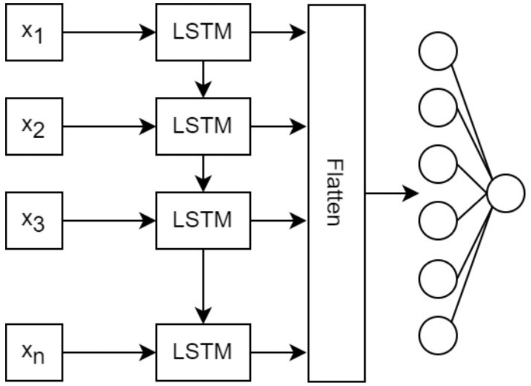
- Undercounting at $\alpha > 45^0$ due to high electron peaks density.

Peak finding algorithm with LSTM

The algorithm is under development in IHEP, for more information see **this talk** by **Guang ZHAO.**

Peak finding with LSTM

Why LSTM? Waveforms are time series

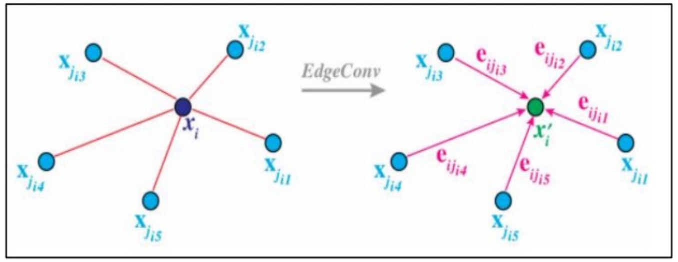


- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

LSTM: Long Short-Term Memory

Clusterization with DGCNN

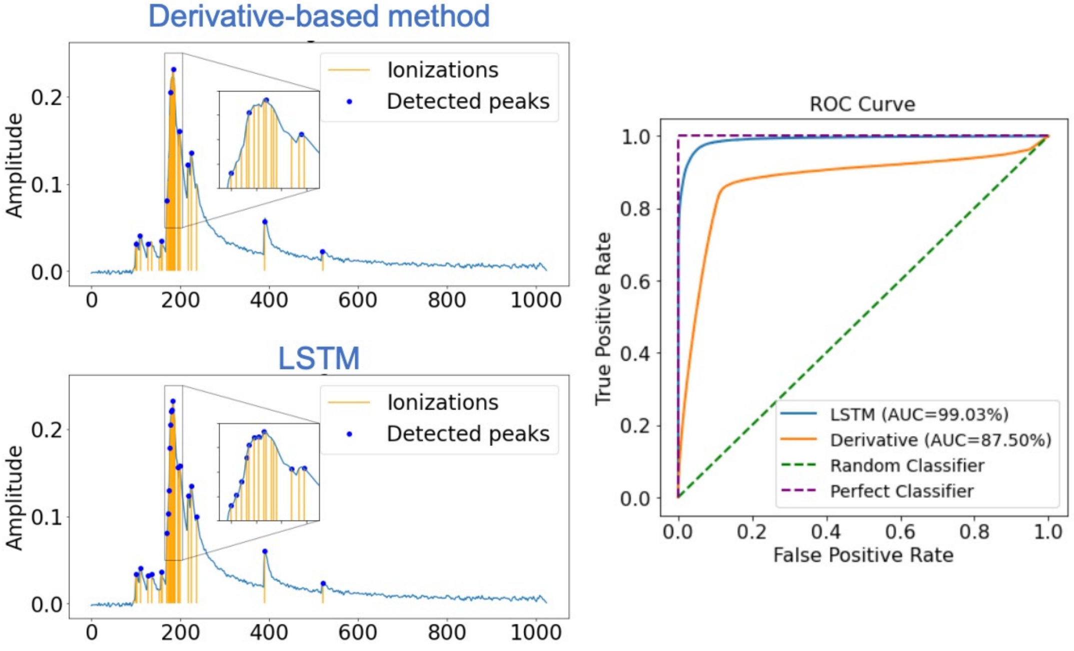
Why DGCNN? Locality of the electrons in the same primary cluster, perform massage passing through neighbour nodes in GNN



arXiv: 1801.07829

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

DGCNN: Dynamic Graph Convolutional neural networks



LSTM model is better classifier compared to derivative-based model

Summary

- The cluster counting technique is a high powerful method to improve the particle identification capabilities: analytic evaluation and simulation confirm its potentials.
- Using the test beam data, we studied the counting efficiency, electron peaks and cluster density as a function of gas mixture, gain, geometrical configuration (cell size, sense wires size), sampling rate, and track angle.
- Two different promising algorithms have been developed and used for finding the electron peaks (DERV & RTA algorithms).
- There is a good agreement between the results from the two algorithms and the expectation.
- The application of the two different algorithms will be very useful for understanding the pathologies of both algorithms, *therefore, it will be extremely useful to have a third algorithm like the one being developed at IHEP with NN.*

Stay tuned for the new results from 2023 test beam!

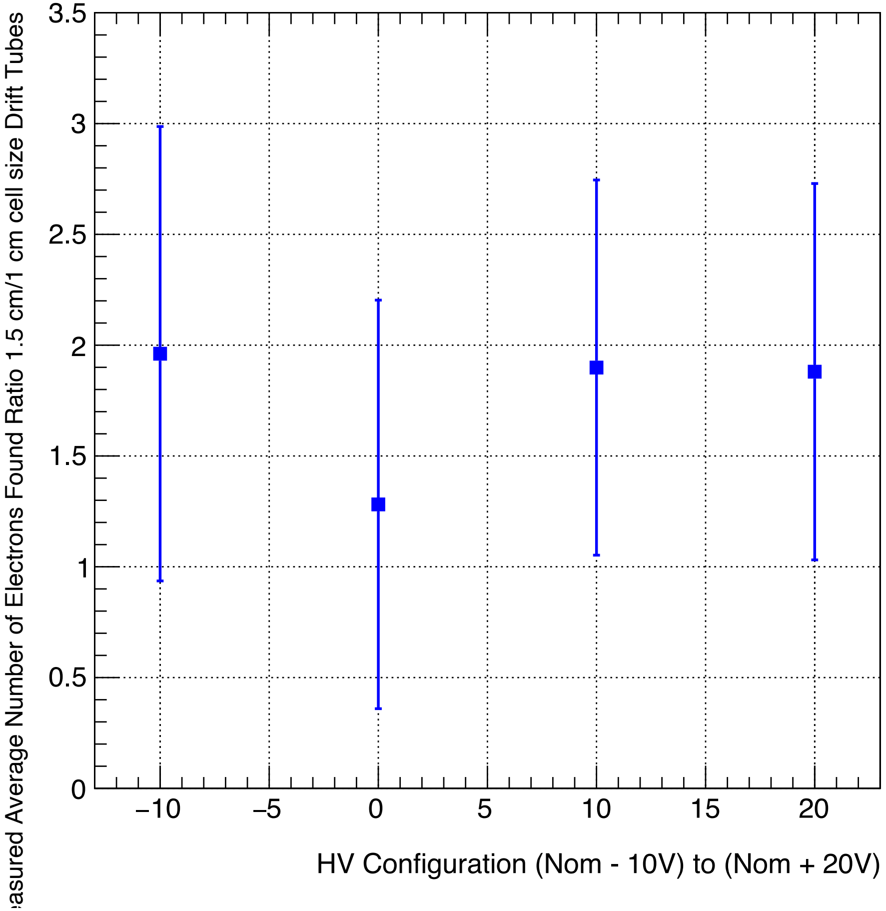
Backup

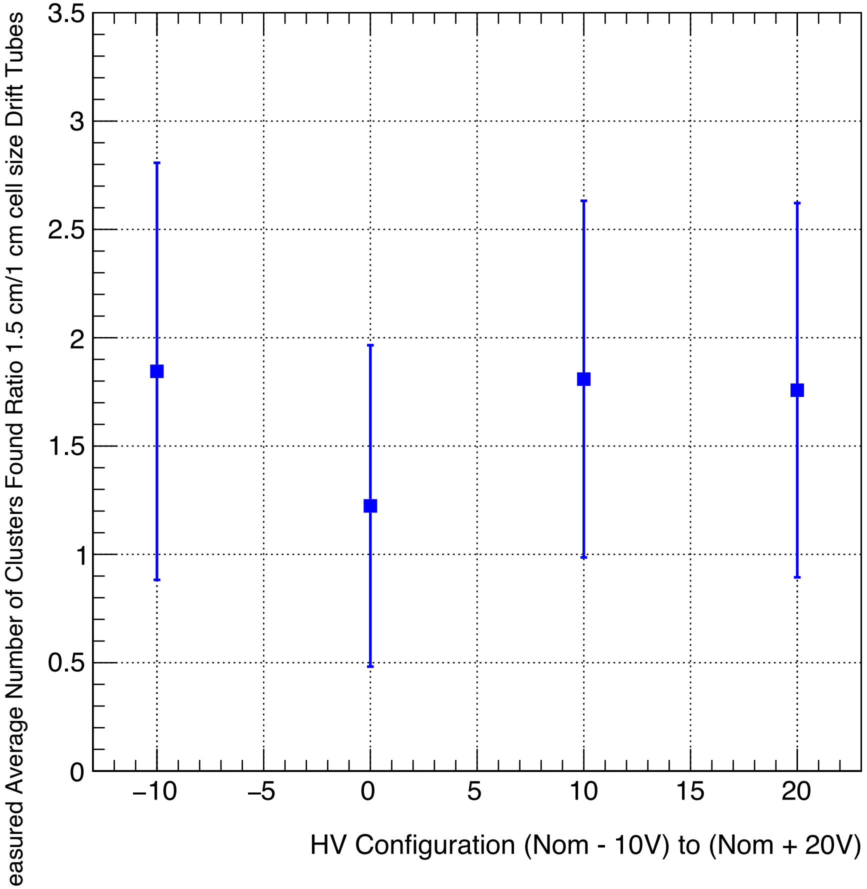
Comparison between DERV and RTA algorithm

Electrons ratio (1.5/1 cm)

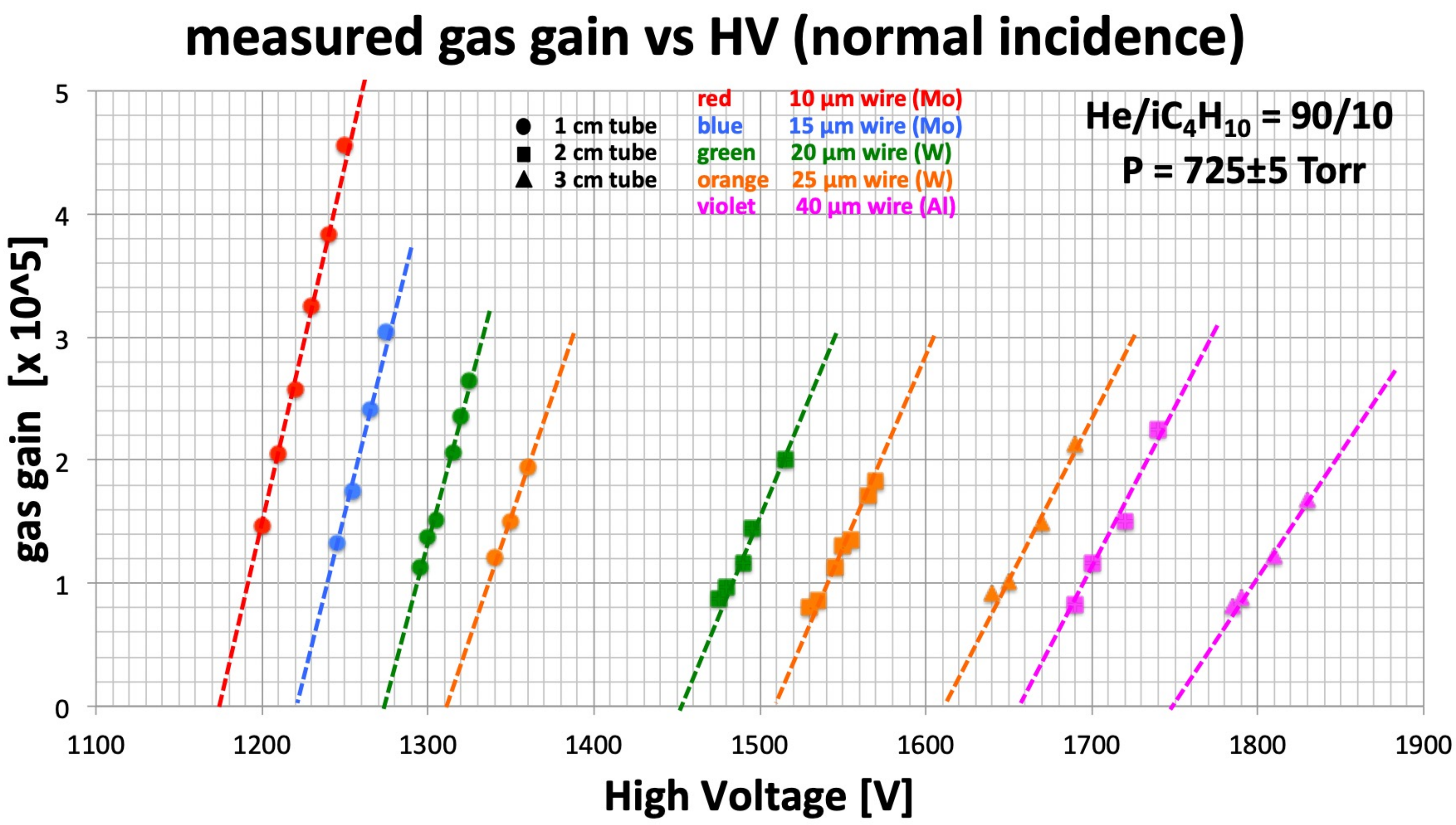
Sampling rate 1 GSa/s;

Clusters ratio (1.5/1 cm)





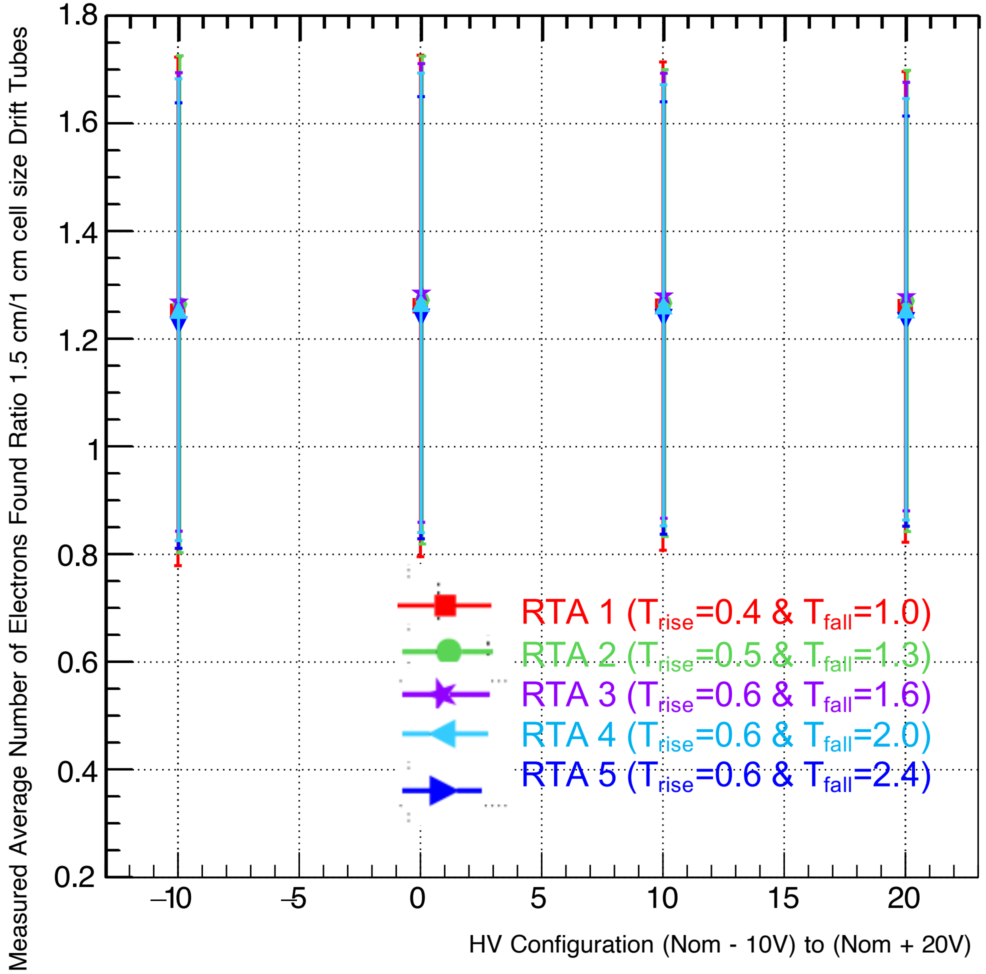
Gas gain (Test Beam Nov 2021)

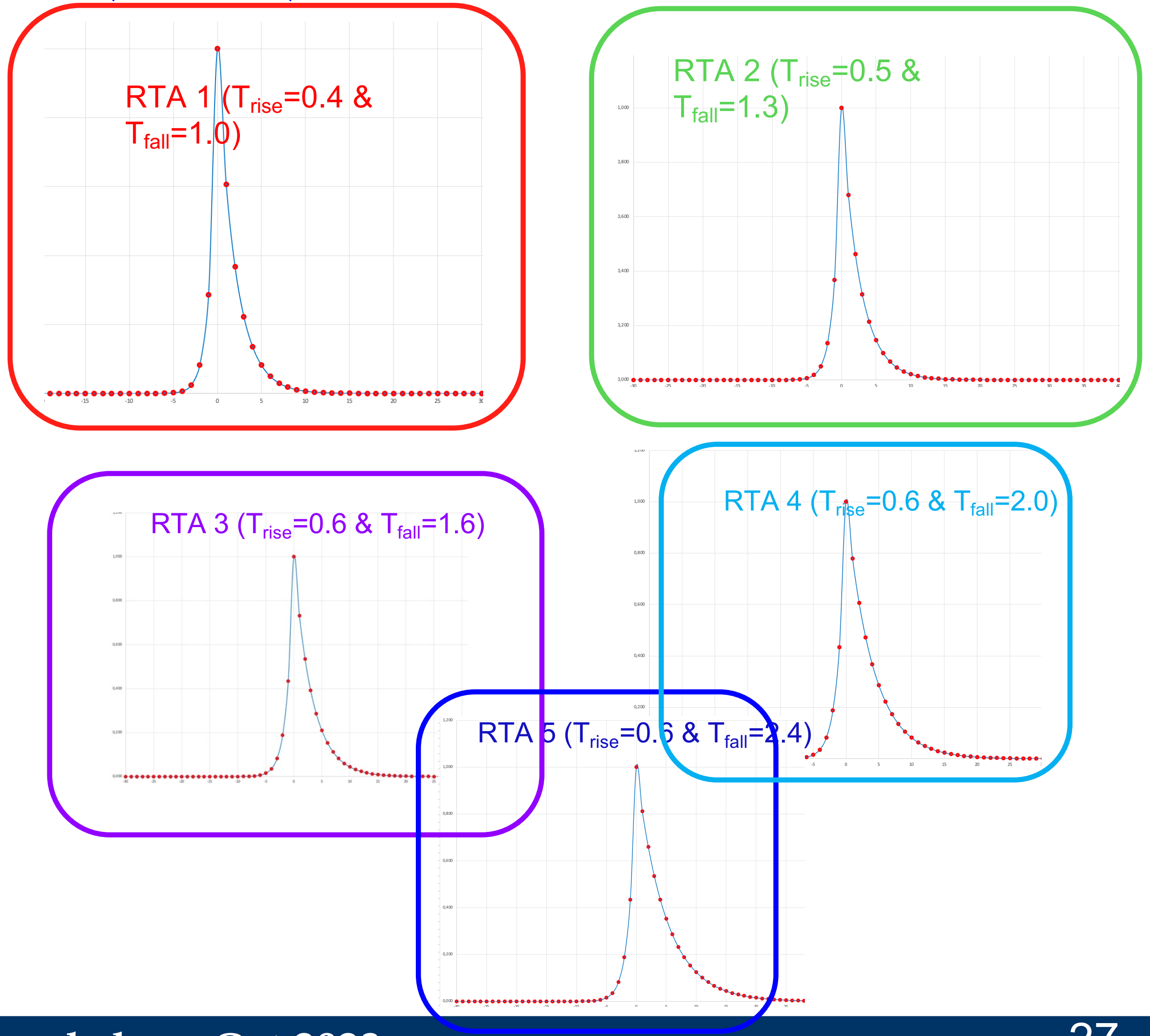


RTA scan ratio (1.5/1 cm tupes)

Ratio of drift tube size (1.2/0.8)

Electrons ratio





RTA scan ratio (1.5/1 cm tupes)

Ratio of drift tube size (1.2/0.8)

Clusters ratio