Cluster counting algorithms for particle identification at future colliders

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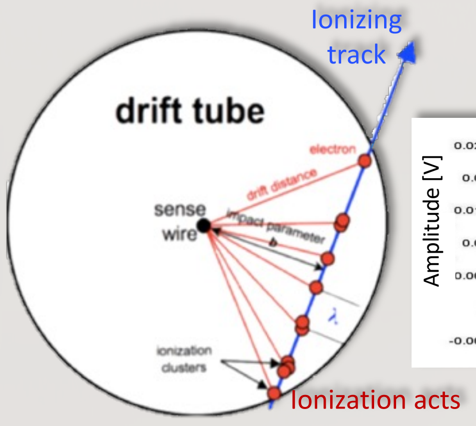
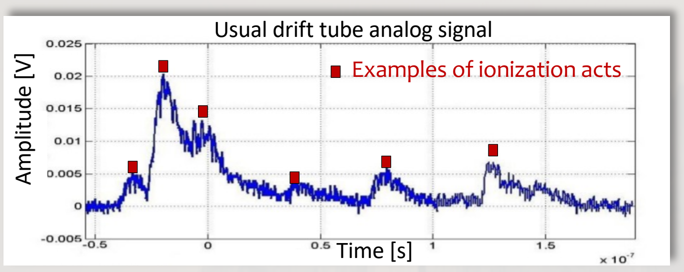
INTRODUCTION

The large statistical fluctuations in the **ionization energy loss (dE/dx)** by charged particles in **gaseous detectors** implies that many measurements are needed along the particle track to get a precise mean, and this represent a limit to the **particle separation capabilities** that should be overcome in the design of future colliders [1]. The **cluster counting technique (dN/dx)** represents a valid alternative which takes advantage of the **Poisson nature** of the **primary ionization process** and offers a more statistically robust method to infer mass information.

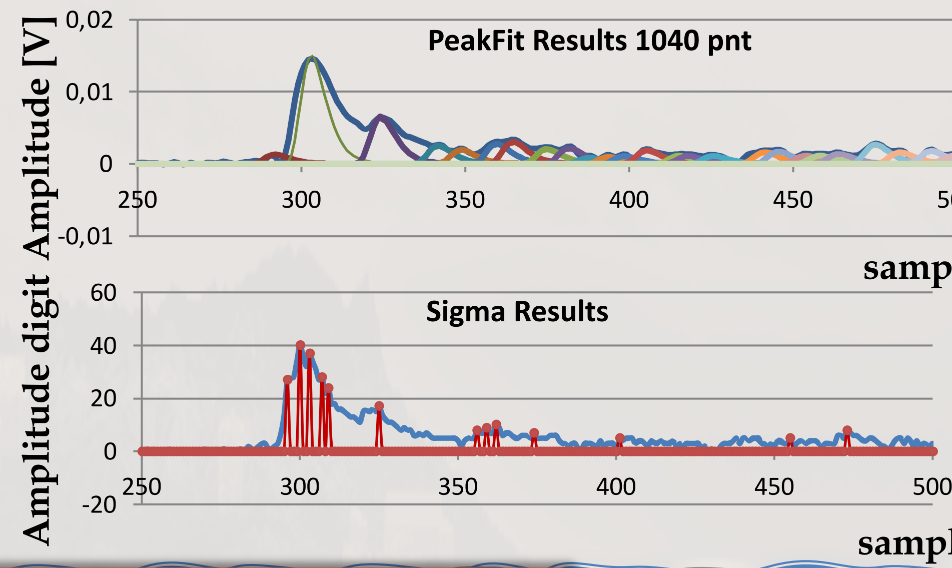




It consists in **singling out**, in ever recorded detector signal, the **electron peak structures** related to the arrival of the electrons belonging to a **single primary ionization act** (cluster) on the anode wire.

A CHALLENGES

The search for $\sim O(100)$ **electron peaks** and the **cluster recognition** in real waveform signals is extremely challenge because of their **superimposition in the time scale** even in low-noise conditions:



B DATA SAMPLES AND ELECTRON FIND PEAK ALGORITHMS

To apply the cluster counting technique successfully:

1. Pulses associated to **electrons from different clusters** must have a little probability of overlapping in time.
2. The time distance between **electrons coming** from the **same cluster** must be small enough to **prevent overcounting**.

Recipe in Helium-based drift chambers:

- High front end bandwidth (≈ 1 GHz), S/N ratio > 8
- High sampling rate (> 2 GSa/s), ≥ 12 bit

Data sests available (Beam Tests at CERN H8):

- **Nov. 2021:** 1.2 **GSa/s**, 1 cm, 2 cm and 3 cm **drift-tube size cells**, 15-30 μm **wire diameter**, 90/10 and 80/20 **$He:iC_4H_{10}$ gas mixtures**, 10 bit, $O(10^5)$ **gas gain**, 165 GeV/c **muon momentum**, 15°, 30°, 45° and 60° between the anode wire direction and the ionizing tracks (α)
  $\sim 100k$ events, on-going analysis with promising results!
- **July 2022:** 1.2, 1.5, 2.0 **GSa/s**, 1 cm and 1.5 cm **drift-tube size cells**, 90/10, 80/20 and 85/15 **$He:iC_4H_{10}$ gas mixtures**, 10 bit, $O(10^5)$ **gas gain,** 40 and 180 GeV/c **muon momenta,** 15°- 60° α
  $\sim 700k$ events, offline analysis just started!

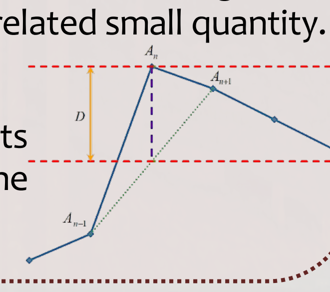
Find good electron peak candidates at position bin n and amplitude A_n:

DERIVATIVE ALGORITHM

- Compute the first and second derivative from the **amplitude average** over **two consecutive bins (1.6 ns for 1.2 GSa/s)** 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:

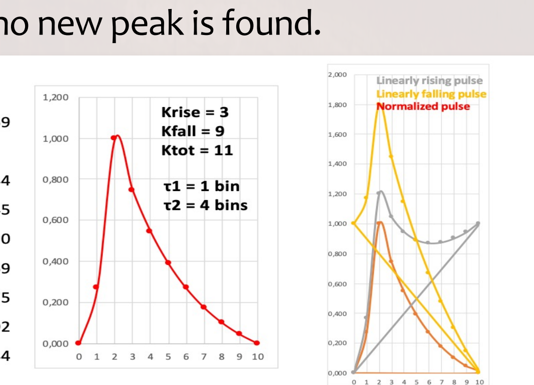
- R.m.s. is a measurements of the **noise level** in the analog signal



RUNNING TEMPLATE ALGORITHM

- Define an **electron pulse template** based on experimental with a **raising** and **falling exponential** over a fixed number of bins (K_{tot}) and **digitized (A(k))** according to the data sampling rate.
- Run over **K_{tot} bins** by comparing it to the subtracted and normalized data **(build a sort of χ^2 and define a cut on it).**
- **Subtract the found peak** to the signal spectrum and **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

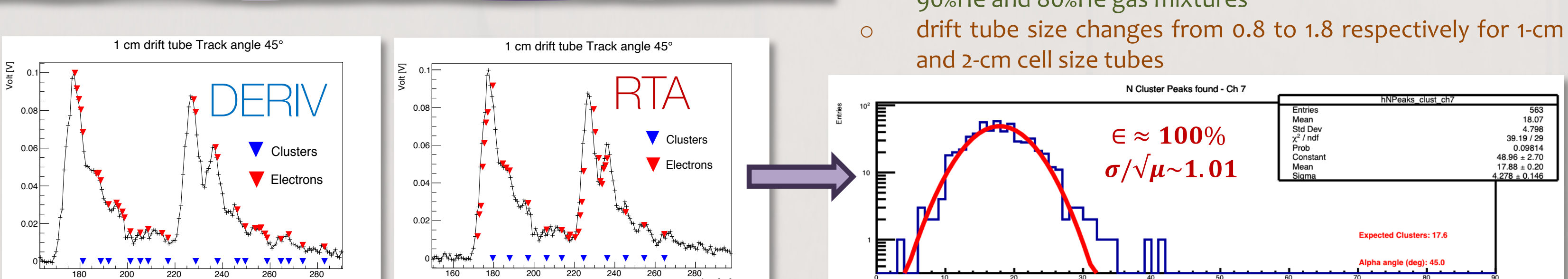


C CLUSTERIZATION STRATEGY AND RESULTS

1) **Association of electron peaks** in consecutive bins (difference in time 0.833 ns == 1 bin) electrons to **a single electron** to remove **fake electrons.**
2) **Contiguous electrons peaks** which are compatible with the electrons diffusion time (2.5 ns) must be considered belonging to the **same ionization cluster.** For them, a counter for electrons per each cluster is incremented.
3) **Position of the clusters** corresponds to the position of the **last electron** in the cluster.
4) We expect a **Poissonian distribution for the number of cluster distributions [2]!** It tends to a gaussian when the mean value tends to values higher than 20.

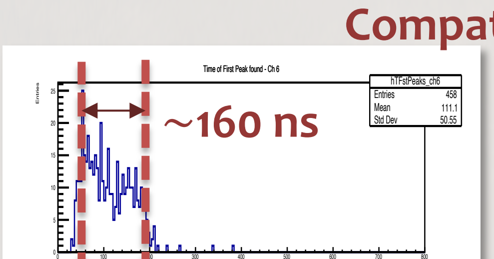
NCluster (Expected number of cluster= δ cluster/cm (M.I.P.) * drift tube size [cm] * 1.3 (relativistic rise [3])* 1/cos(α)

- α corresponds to the angle of the muon track w.r.t. drift tube direction
- δ cluster/cm (mip) changes from 12 to 18 respectively for 90%He and 80%He gas mixtures
- drift tube size changes from 0.8 to 1.8 respectively for 1-cm and 2-cm cell size tubes

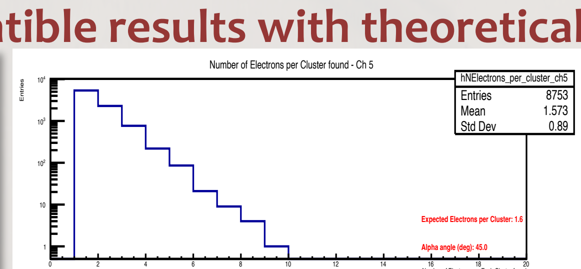


Experimental Electrons Drift velocity for 1cm (2cm) cell drift tubes = maximum impact parameter/drift time ~ 2.5 $cm/\mu s$ (2.2 $cm/\mu s$) ; **Cluster population** = 1.6 electrons/cluster

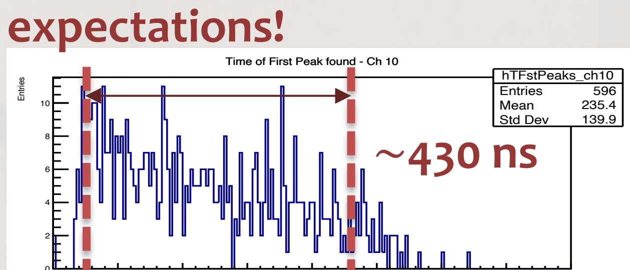
Compatible results with theoretical expectations!



Maximum impact parameter for 1-cm cell drift tubes = 0.4 cm

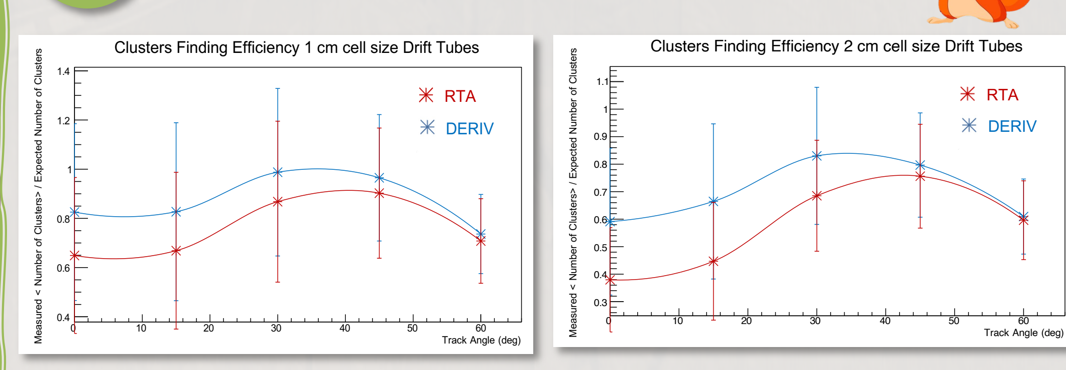


<Measured Electrons/cluster> = 1.573



Maximum impact parameter for 2-cm cell drift tubes is 0.9 cm

D WORK IN PROGRESS



- Investigate the inefficiency at high Track angle (first hypothesis: **space charge + attachment + recombination effects**).
- Optimization of variable cuts for **2-cm** (1-cm drift) **drift tubes** Nov2021 Beam Test data set against **undercounting** (overcounting).
- Apply the algorithms to new test beam data with cuts' dependence (**rms, derivatives** for **DERIV** and **χ2** for the **RTA**) on the sampling rate and the ADC resolution.

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