Particle identification for the IDEA drift chamber using the cluster counting technique

Walaa Elmetenawee (INFN Bari (IT))

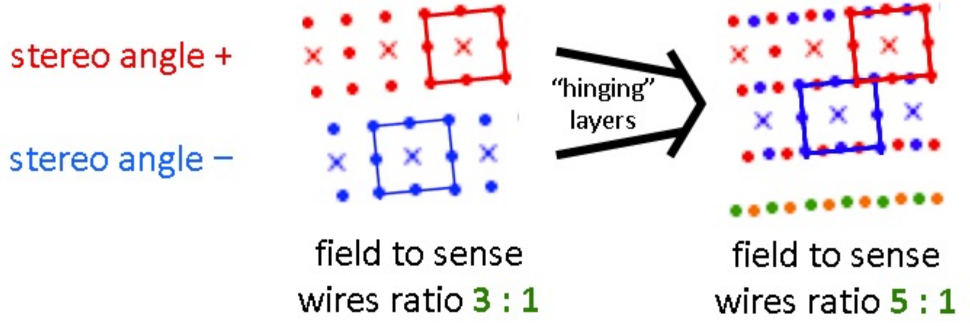
on behalf of IDEA DCH group

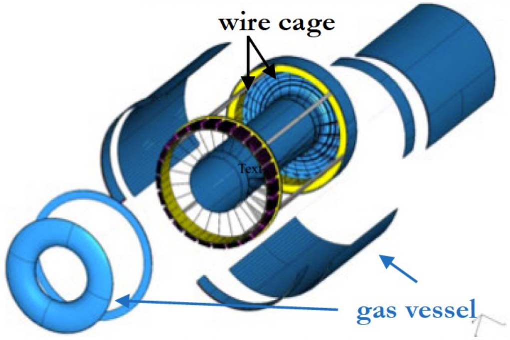
Second ECFA Workshop, Paestum
10-13 Oct 2023

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 871072

The IDEA drift chamber

The IDEA detector concept for a future e+e− collider adopts an ultra-low mass drift chamber as a central tracking system. The He-based ultra-low mass drift chamber is designed to provide efficient tracking, a high-precision momentum measurement, and excellent particle identification by exploiting the cluster counting technique.





- **He based gas mixture** (90% He – 10% i-C_4H_{10})
- **Full stereo configuration**

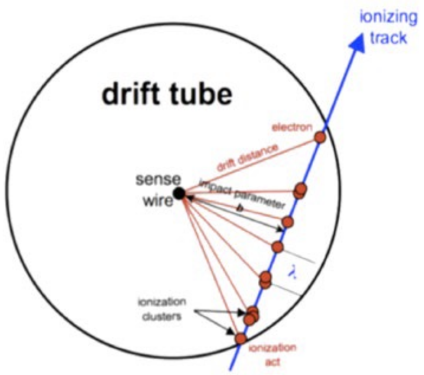
Main Features:

- Gas containment – wire support functions separation: allows to reduce material to ≈ 10^{-3} X_0 for barrel and a few x 10^{-2} X_0 for the end-plates.
- Feed-through-less wiring: allows to increase chamber granularity and field/sense wire ratio to reduce multiple scattering and total tension on end plates due to wires by using thinner wires.
- **Cluster timing: allows to reach spatial resolution < 100 μm for 8 mm drift cells in He based gas mixtures**
- **Cluster counting: allows to reach dN_{cl}/dx resolution < 3% for particle identification (a factor 2 better than dE/dx).**

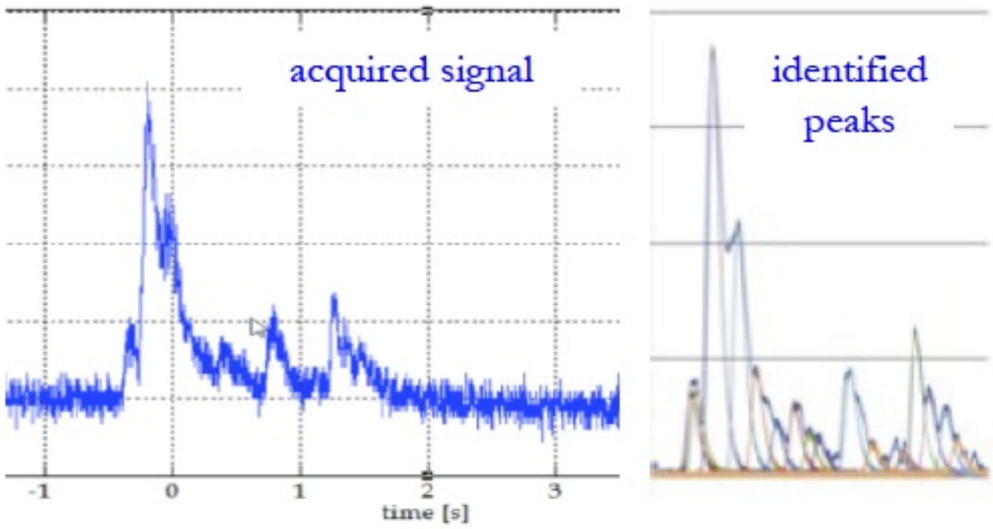
For more information about the IDEA DCH, see the previous talk by Francesco.

Cluster Counting/Timing and P.Id. expected performance

- Gaseous counters provide signals with pulse height **proportional to the numbers of electron** liberated during the ionization process along the track length inside the sensitive volume and **proportional to the energy deposit** .
- Using the information about energy deposit particle identification can be performed but, **the large and inherent uncertainties in total energy deposition represent a limit to the particle separation capabilities.**
- **Cluster counting technique** can improve the particle separation capabilities.
- The method consists in singling out, in ever recorded detector signal, the isolated structures related to the arrival on the anode wire of the electrons belonging to a single ionization act (dN/dx).



▶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

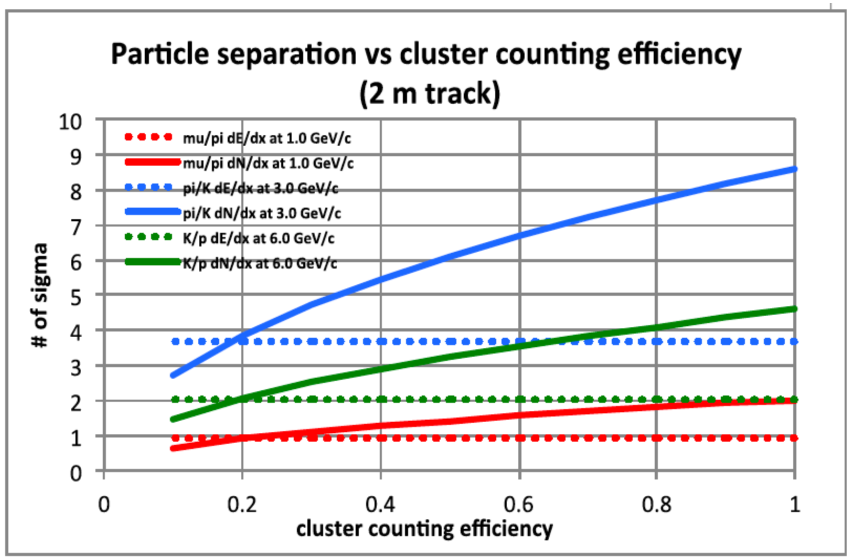
σ ≈ 2.0%

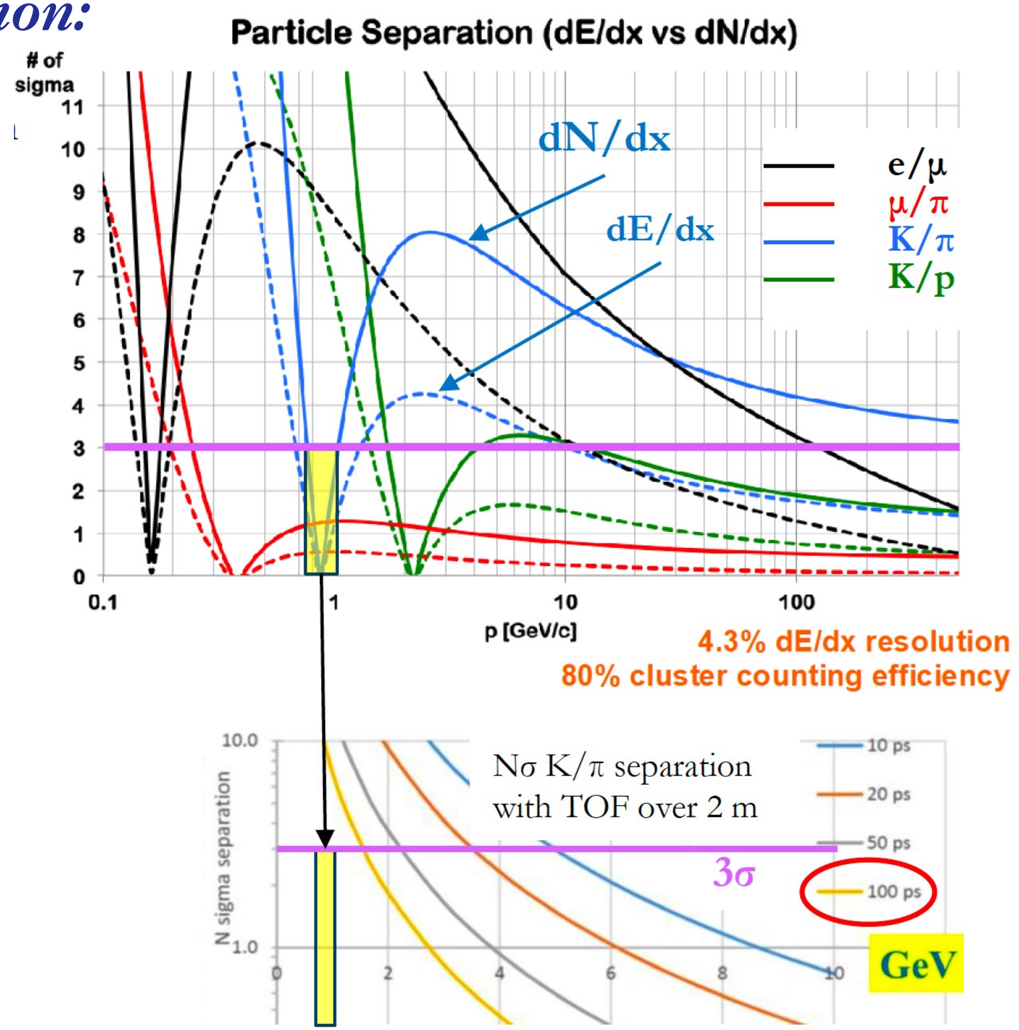
Moreover, C.C. may improve the spatial resolution < 100 μm for 8 mm drift cells in He based gas mixtures

Cluster Counting/Timing and P.Id. expected performance

analytic evaluation:

- ✓ Cluster Counting/Timing in DCH for good P.Id. Performance.
- ✓ Expected **excellent K/π separation** over the entire range except 0.85<p<1.05 GeV (blue lines).
- ✓ Could recover with timing layer.





Drift Chamber simulation: Cluster Counting/Timing simulation

To investigate the potential of the Cluster Counting technique (for He based drift chamber) on physics events a reasonable simulation/parameterization of the ionization clusters generation in Geant4 is needed.

Garfield/Garfield++:

- (Heed) simulates the ionization process in the gasses (not only) in a detailed way.
- (Magboltz) computes the gas properties (drift and diffusion coefficients as function of the fields value)
- solves the electrostatic planar configuration and simulates the free charges movements and collections on the electrodes.

So Garfield can study and characterize the properties and performance of single cell or drift chamber with simple geometry, but it is not designed to simulate a full detector neither study collider events.

Geant4:

- Simulates the elementary particle interaction with material of a full detector
- Studies colliders events
- It doesn’t simulate (normally) the ionization clustering process
- It doesn’t simulate (normally) the free charges movements and collections on the electrodes.

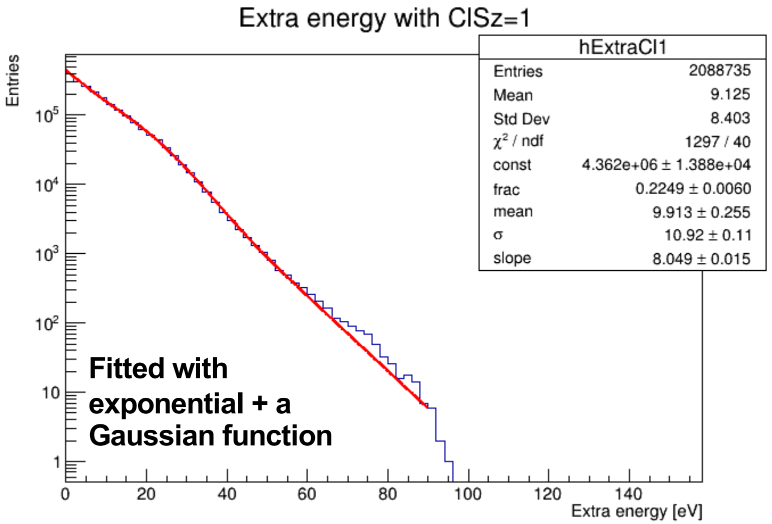
It is very useful to simulate the elementary particle interaction with the material of a full (complex) detector and to study collider events. The fundamental properties and performance of the sensible elements (drift cells) have to be parametrized or ad-hoc physics models have to be defined.

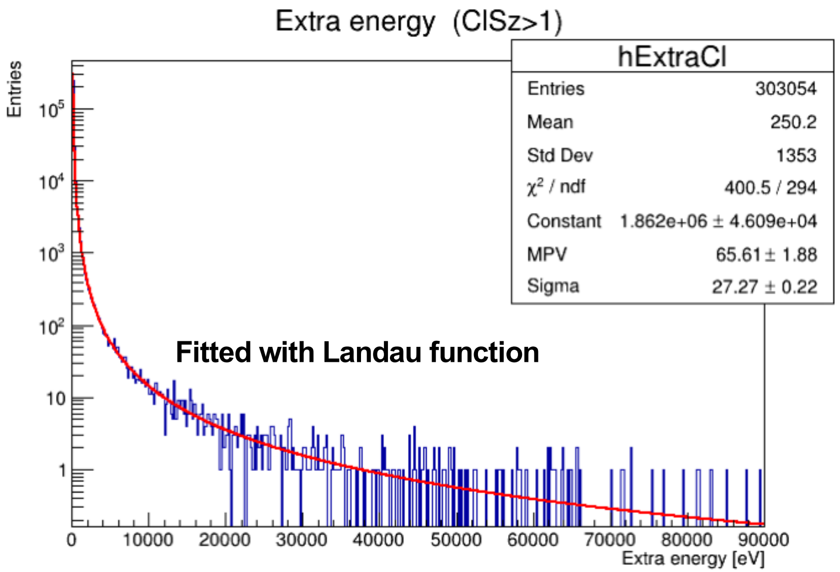
Drift Chamber simulation: Cluster Counting/Timing simulation

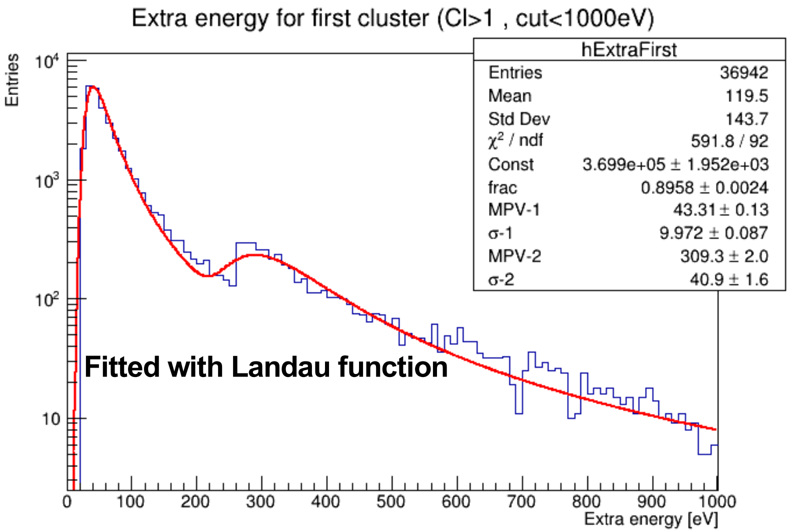
https://doi.org/10.48550/arXiv.2105.07064

The basic idea is to develop an algorithm which can use the energy deposit information provided by Geant4 to reproduce, in a fast and convenient way, the clusters number distribution and the cluster size distribution.

- The algorithm starts from Garfield++ simulations.
- Firstly, we analyse the distribution of the kinetic energy for clusters that have a cluster size equal to 1(left), and clusters that have cluster size higher than 1 (middle) and the distribution of clusters with a cluster size higher than 1 up to a 1 keV, which is a cut equivalent to the single interactions range cut set by default in Geant4.







Drift Chamber simulation: Cluster Counting/Timing simulation

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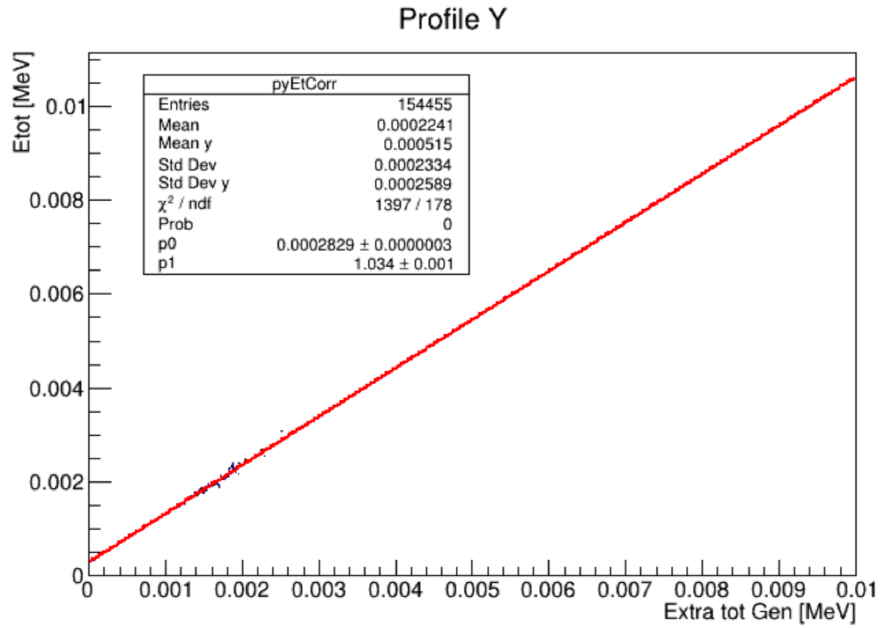
Then we focused on the evaluation of the maximum kinetic energy spent to create clusters with cluster size higher than one. (maxExEcl).

- To extract this parameter, named maxExEcl, we studied the correlation plot, between the total energy loss by particles traversing the gas mixture and the total kinetic energy of clusters with cluster size higher than 1; moreover we evaluated the parameter named ExSgm to take into account the smearing around the mean value of the total energy loss. The profile plot is fitted with a linear function and the formula for evaluating the maxExEcl is :

$$maxExEcl = \frac{E_{tot} - p0 + Random(Gaus(0, ExSgm))}{p1}$$

where p0 and p1 are the fit parameters of the linear fit and E_{tot} is the total energy loss by the particles traversing the 200 cells of gas.



Drift Chamber simulation: Cluster Counting/Timing simulation

The Algorithm implementation:

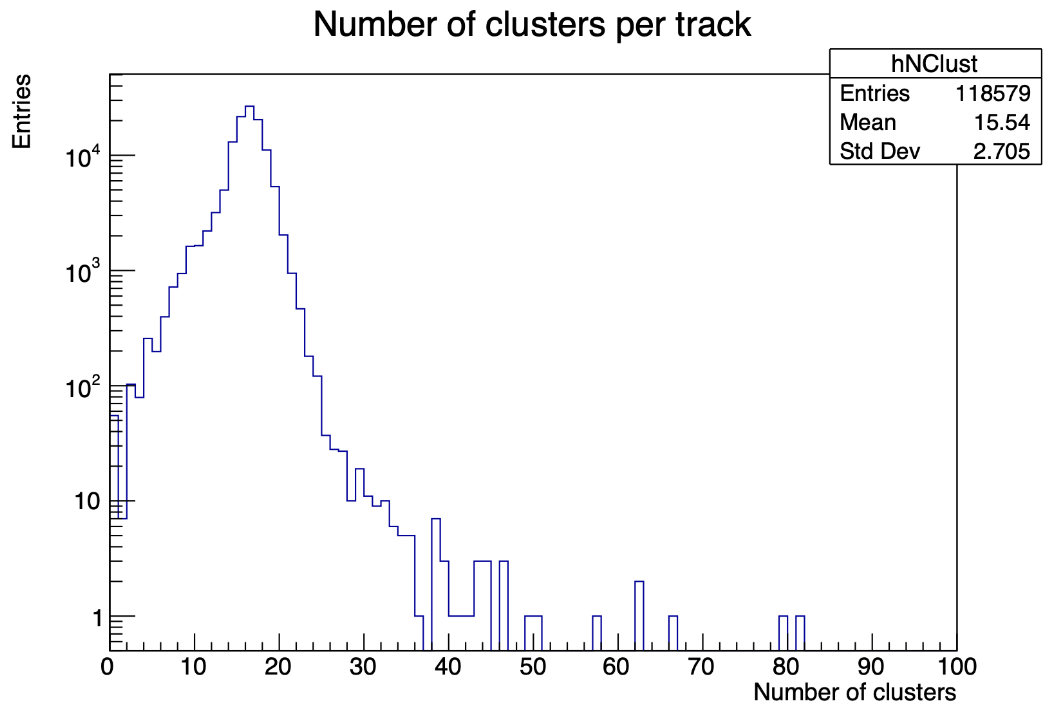
- Using the results from the **Garfield++ analysis** described in the previous slides, and after testing several algorithms for the cluster counting in **GEANT 4** (the detailed study are available here:https://doi.org/10.48550/arXiv.2105.07064).

- We selected the one with more consistent results and implemented it in the simulation of the Drift Chamber of IDEA detector in both: the **GEANT 4 Full Simulation framework & Key4HEP Full Simulation framework**

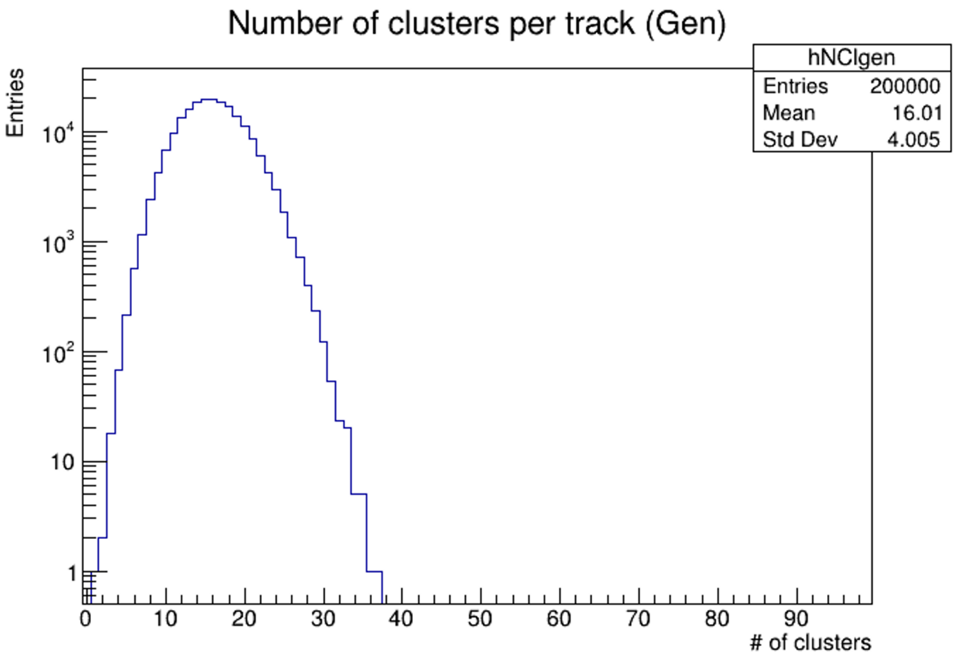
- we started to implement the algorithm as following:

  - **If maxExEcl is higher than zero**, generates the kinetic energy for clusters with **cluster size higher than one** by using its distribution and evaluates the cluster size.
  - This procedure is repeated until **the sum of primary ionization energy and kinetic energy** per cluster saturate the maxExEcl of the event.
  - Then, using the remaining energy **(Eloss-maxExEcl),** the algorithm creates clusters **with cluster size equal to one** by assigning their kinetic energy according to the proper distribution.

Drift Chamber simulation: Cluster Counting/Timing simulation



Clusters number distribution, for a muon at 10 GeV traversing as simulated with **GEANT 4 IDEA full SIM framework.**



Clusters number distribution, for a muon at 10 GeV traversing 200 cells, 1 cm per side, filled with 10% He and 90 % iC4H10, simulated **with Garfield ++.**

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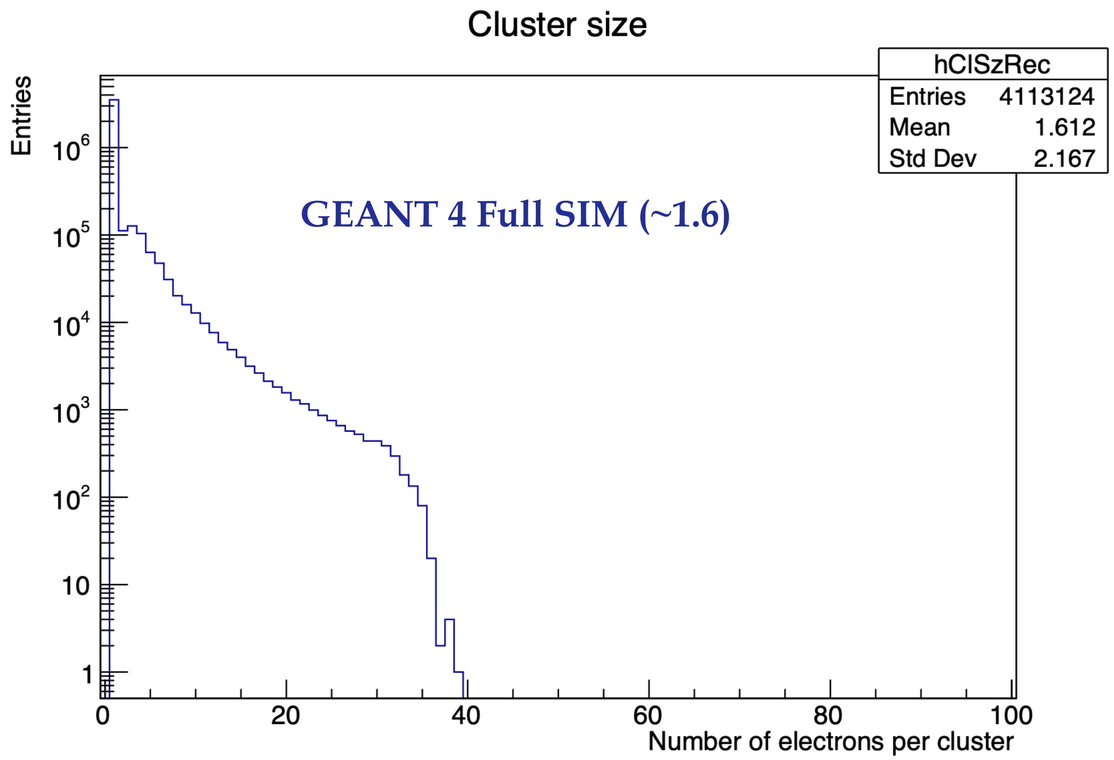
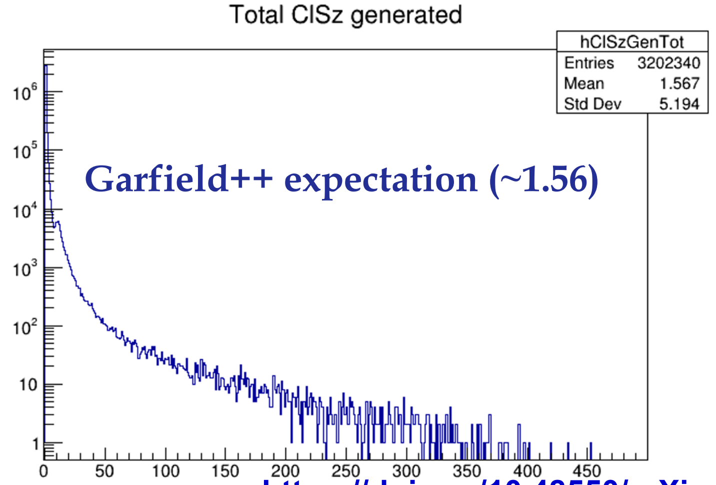
Drift Chamber simulation: Cluster Counting/Timing simulation

Cluster size distribution, for a muon at 10 GeV





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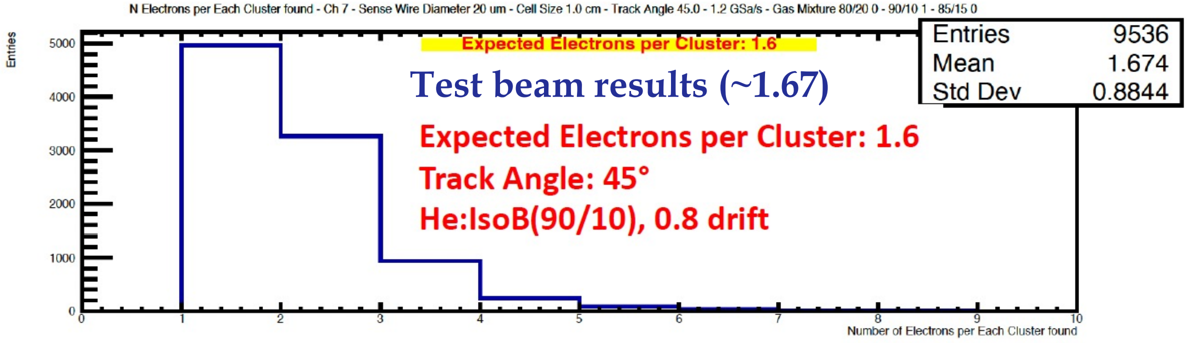
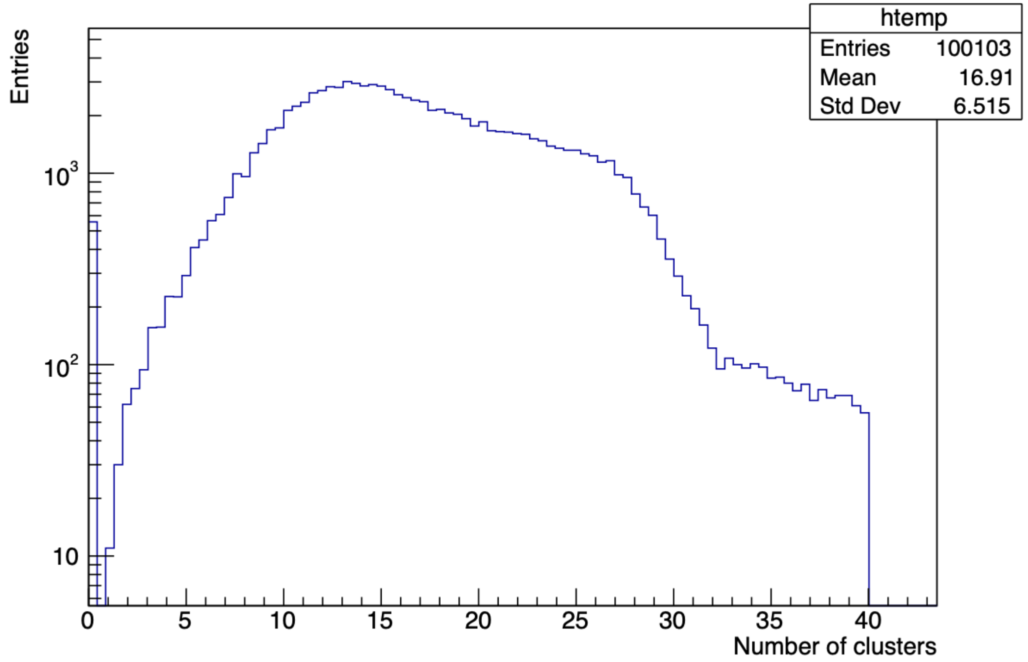
Electron per Clusters Distribution

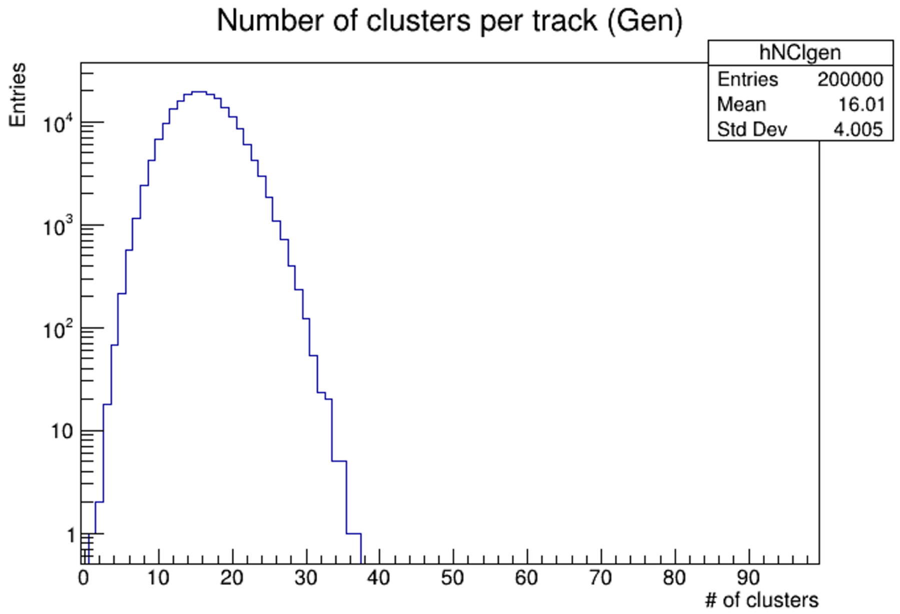


The results obtained form the **GEANT 4 Full Simulation framework** for the cluster population (~1.6) is in a good agreement with **Garfield++ expectation (~1.56),** the results from the **test beam analysis(~1.7),** and with the analytic **evaluations (~1.6)**.

Drift Chamber simulation: Cluster Counting/Timing simulation



Clusters number distribution, for a muon at 10 GeV traversing as simulated with **Key4HEP IDEA full SIM framework.**



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Clusters number distribution, for a muon at 10 GeV traversing 200 cells, 1 cm per side, filled with 10% He and 90 % iC_4H_{10}, simulated **with Garfield ++.**

Summary

- The cluster counting technique is a high powerful method to improve the particle identification capabilities: analytic evaluation and simulation confirm its potentials.
- Reasonable algorithm which can use the energy deposit information provided by Geant4 to reproduce, in a fast and convenient way, the clusters number distribution and the cluster size distribution has been developed.
- The algorithm has been implemented successfully in the two available frameworks for IDEA full SIM (GEANT 4 and Key4HEP).

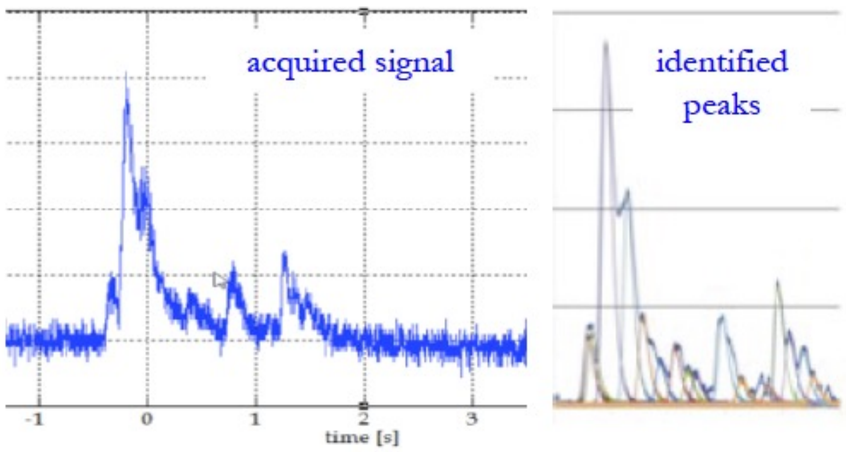
To do list:

- Start validation tests for the results of the algorithm in the Key4Hep famework.
- Implement different algorithms for the cluster count in IDEA DCH simulation (ex: using the Nueral network) and compare the results with the current algorithm.
- Start to do Particle Identification studies using IDEA Full SIM frameworks.

Backup

Cluster Counting/Timing and P.Id. expected performance

From the ordered sequence of the electrons arrival times, considering the average time separation between clusters and their time spread due to diffusion, reconstruct the most probable sequence of clusters drift times: $\{t_i^{cl}\} \qquad i = 1, N_{cl}$



dE/dx

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 0.41 \cdot n^{-0.43} \cdot \left(L_{track}[m] \cdot P[atm]\right)^{-0.32}$$

from *Walenta parameterization (1980)*

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

$\sigma \approx 4.3\%$

Increasing P to 2 atm improves resolution by 20% ($\sigma \approx 3.4\%$) but at a considerable cost of multiple scattering contribution to momentum and angular resolutions.

dN_{cl}/dx

$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2}$$

from *Poisson distribution*

δ_{cl} = 12.5/cm for He/iC_4H_{10}=90/10 and a 2m track give

$\sigma \approx 2.0\%$

A small increment of iC_4H_{10} from 10% to 20% (δ_{cl} = 20/cm) improves resolution by 20% ($\sigma \approx 1.6\%$) at only a reasonable cost of multiple scattering contribution to momentum and angular resolutions.