# Simulation of particle identification with cluster counting technique

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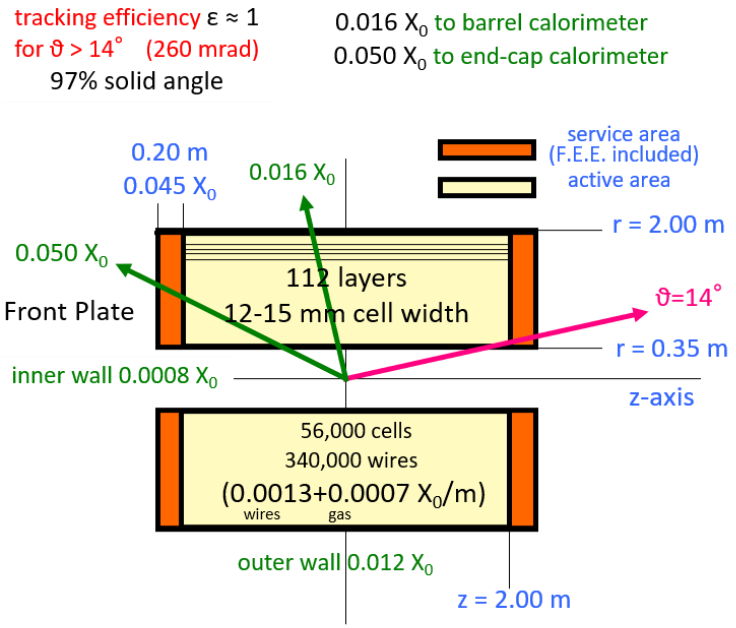
# IDEA DRIFT CHAMBER

The IDEA drift chamber (DCH) is the tracker of FCC-ee and CEPC.
It is designed to provide efficient tracking, high precision momentum measurement and excellent particle identification by exploiting the application of the cluster counting technique.




- **He based gas mixture** (90% He – 10% i-$C_4H_{10}$)
- **Full stereo configuration** with alternating sign stereo angles ranging from 50 to 250 mrad
- 12÷14.5 mm wide square cells 5 : 1 field to sense wires ratio
- 56,448 cells
- 14 co-axial super-layers, 8 layers each (112 total) in 24 equal azimuthal (15°) sectors

**MORE INFORMATION:**
*https://indico.cern.ch/event/656491/contributions/2939121/attachments/1629781/2597342/IDEA-CDCH_FCCweek18.pdf*

## MAIN GOALS

- Gas containment – wire support functions separation:

  the total amount of material in radial direction, towards the barrel calorimeter, is of the order of 1.6% X0, whereas in the forward and backward directions it is equivalent to about 5.0% X0, including the endplates instrumented with front end electronics.
- Feed-through-less wiring:

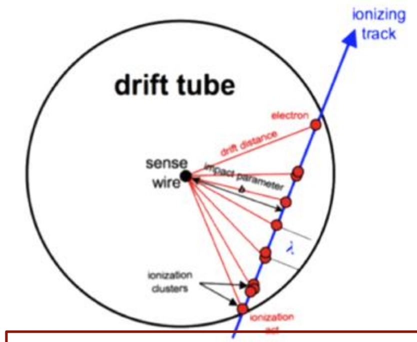
  allows to increase chamber granularity and field/sense wire ratio to reduce multiple scattering and total tension on end plates due to wires by using thinner wires
- **Cluster timing**:

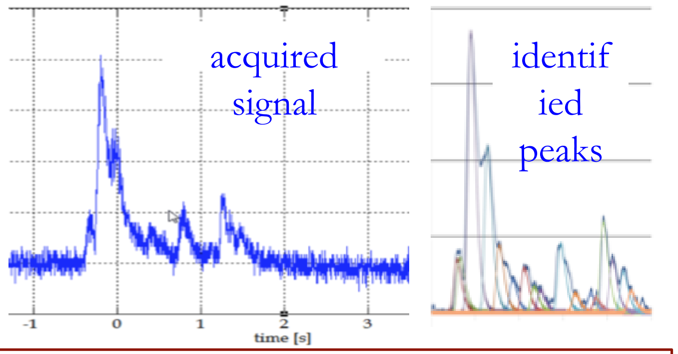
  allows to reach spatial resolution < 100 μm for 8 mm drift cells in He based gas mixtures (such a technique is going to be implemented in the MEG-II drift chamber under construction)
- **Cluster counting**:

  allows to reach $dN_{cl}/dx$ resolution < 3% for particle identification (a factor 2 better than dE/dx as measured in a beam test)

# 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).

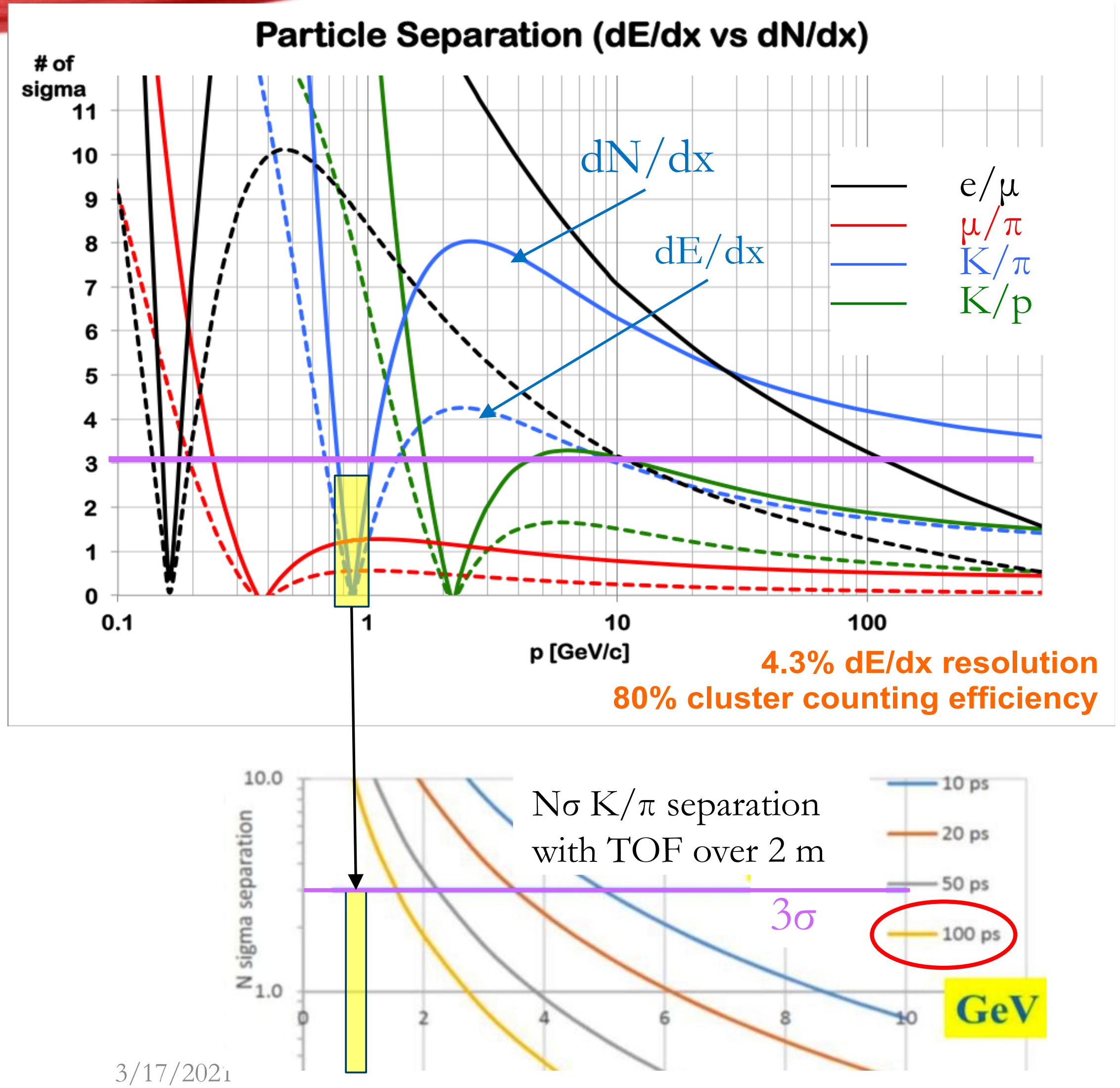


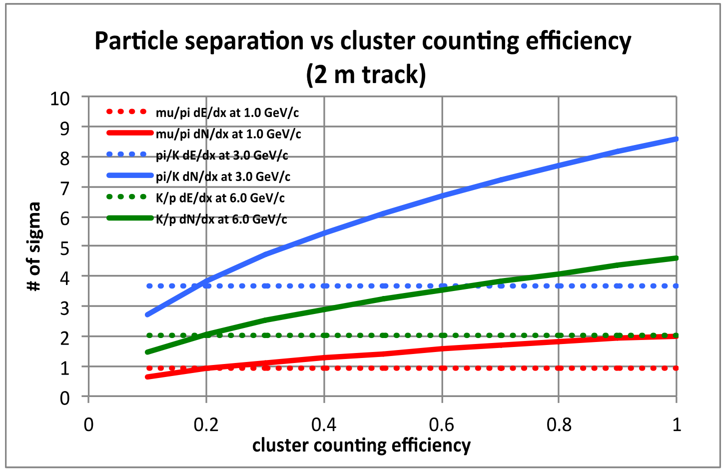

| dE/dx | $dN_{cl}/dx$ |
| --- | --- |
| Truncated mean cut (70-80%) reduces the amount of collected information n ≈ 100 and a 2m track at 1 atm give **σ ≈ 4.3%** | $\delta_{cl}$ = 12.5/cm for He/$iC_4H_{10}$=90/10 and a 2m track give **σ ≈ 2.0%** |

*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

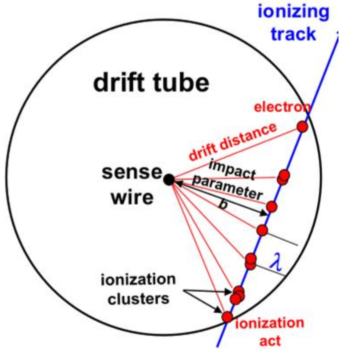



- 80% cluster counting efficiency.
- Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)
- Could recover with timing layer




*Analytic evaluation, prof F.Grancagnolo*
*To be checked with test beam and simulations*

# Drift Chamber simulation - Cluster Counting/Timing simulation

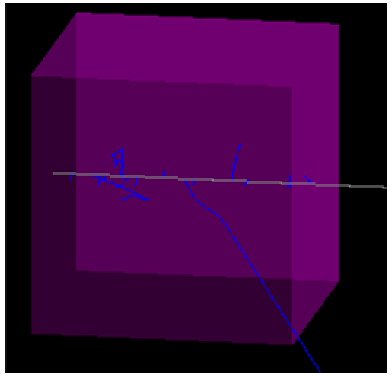



To investigate the potential of the Cluster Counting technique (for He based drift chamber) on physics events a reasonable simulation/parameterization of the ionization clusters generation in Geant4 is needed.

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.



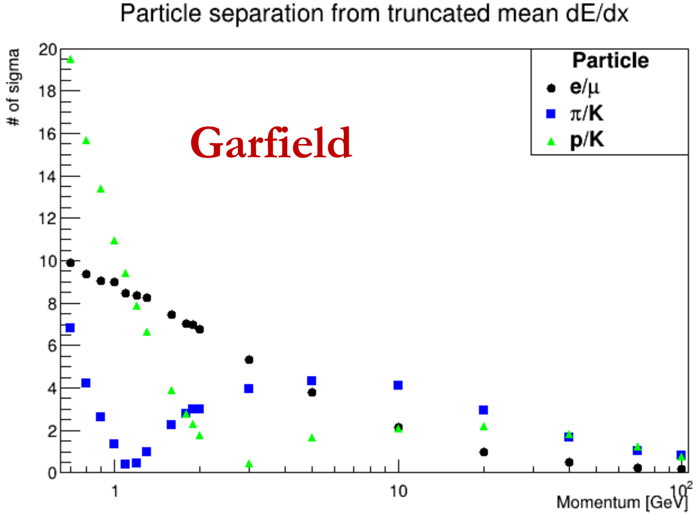
Geant4:

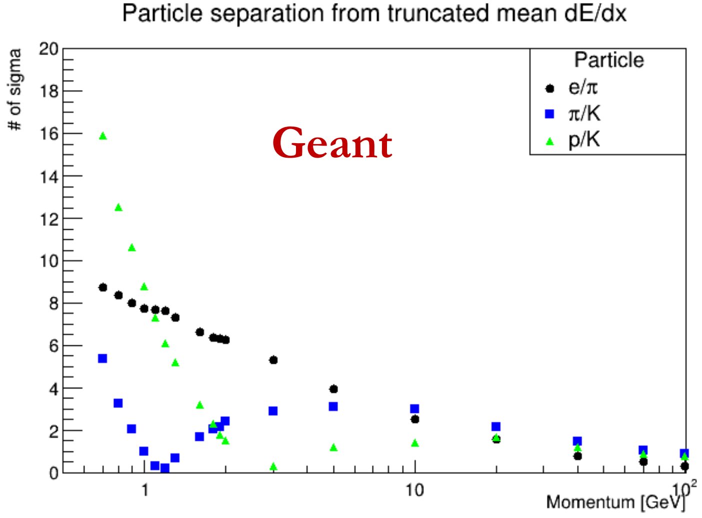
- Simulates the elementary particle interaction with material of a full detector
- Studies colliders events
- It doesn't simulate (normally) the ionization clustering process
- It doesn't simulate (normally) the free charges movements and collections on the electrodes.

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.

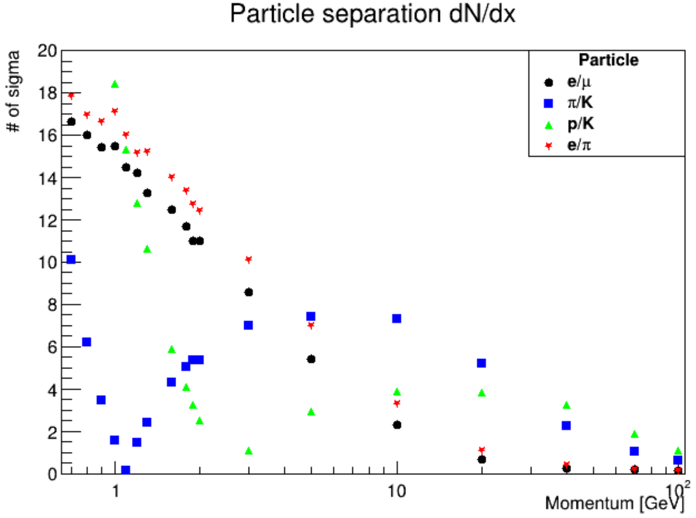
# Drift Chamber simulation - Cluster Counting/Timing simulation-PID

We are simulating tracks crossing 200 cell (1 cm long side) of 90% He and 10% $iC_4H_{10}$ with Garfield and Geant




Truncated mean at 70%




$$n_\sigma = \frac{\Delta_A - \Delta_B}{\langle \sigma_{A,B} \rangle}$$

$<\sigma_{A,B}>$ is the average of the two resolutions.

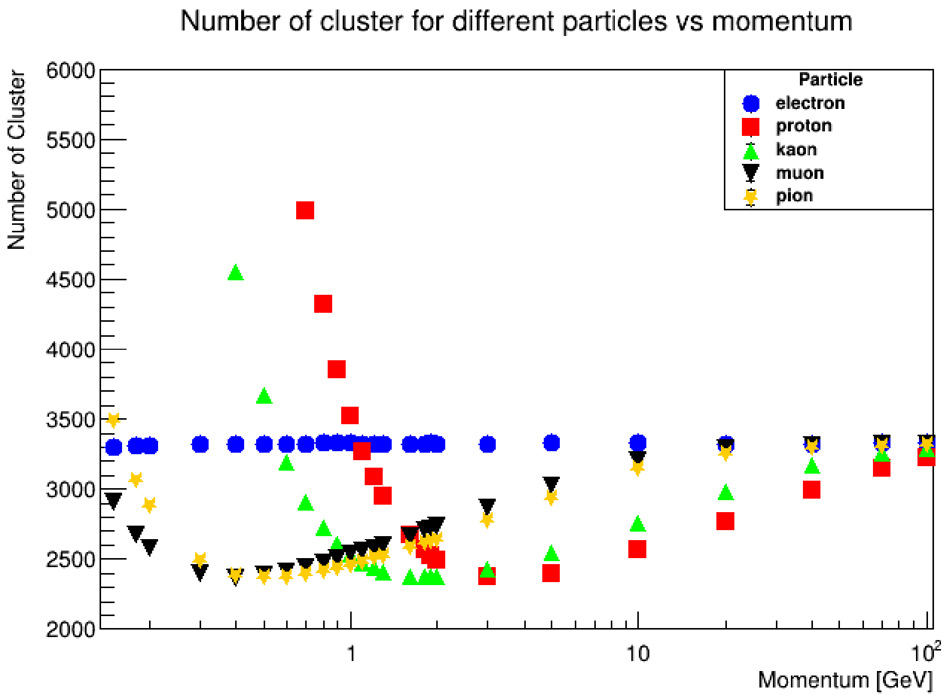
Cluster counting leads to an **improvement** on particle separation power. As example, around 5 GeV the power separation of a pion from kaon obtained with traditional method is about 4, the one obtained with cluster counting is around 8.

## Drift Chamber simulation - Cluster Counting/Timing simulation-Garfield analysis

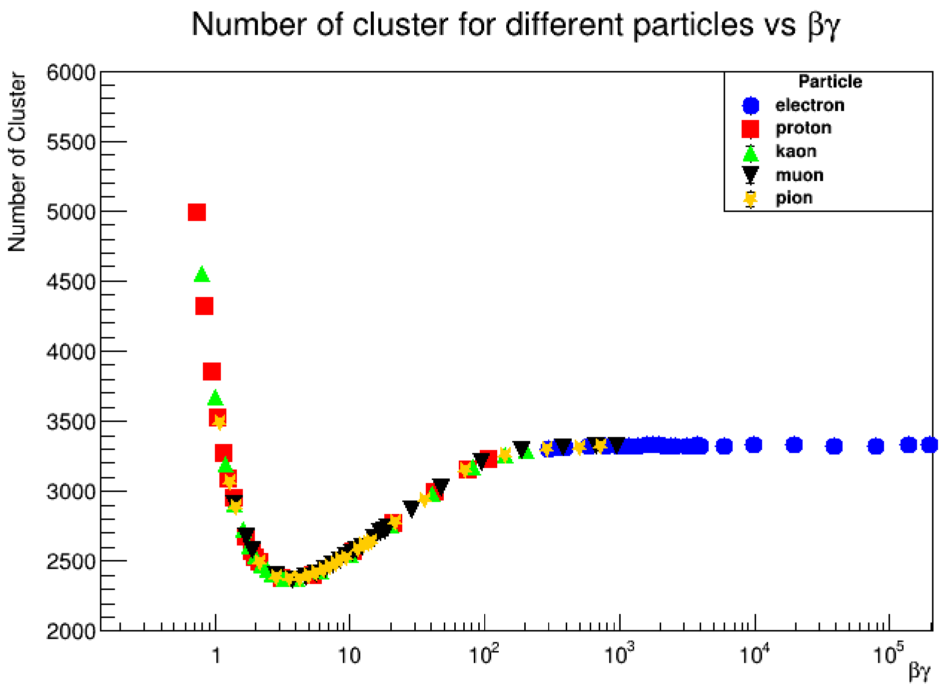
Studying the results from Garfield++ simulations, we can interpret correctly the results obtained from Geant4 simulations with the goal of reconstruct the number of clusters and the cluster size generated from different particles with different momenta passing through the tracker detector.

The goal is to extract from Garfield++ the relevant parameters to create models to convert the energy loss to cluster and then extract them as function of the primary particle βγ.

**Number of cluster from Garfield++**



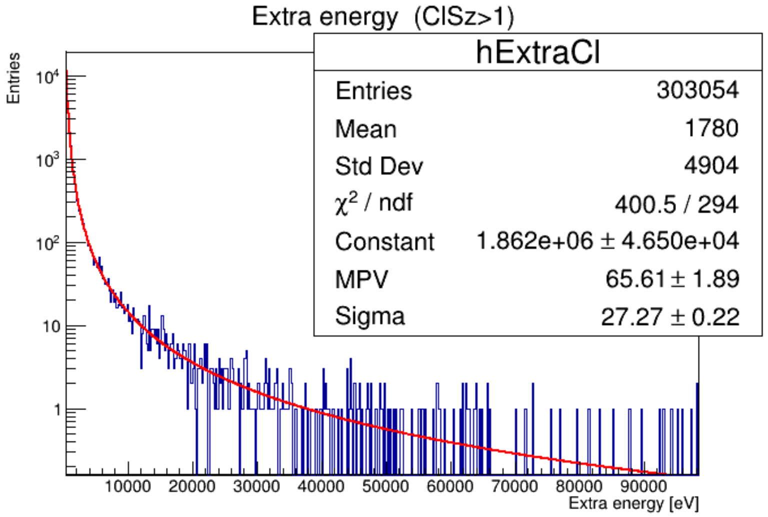

Here the distribution of number of cluster produced by different particle at different momenta, obtained with Garfield++

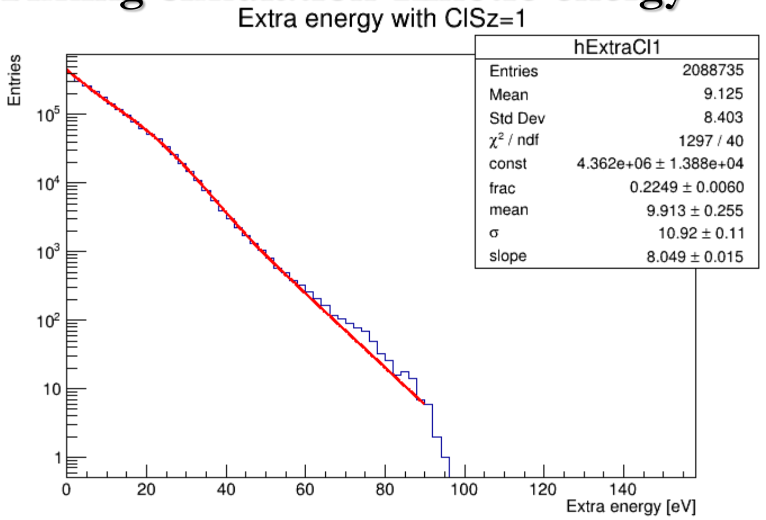


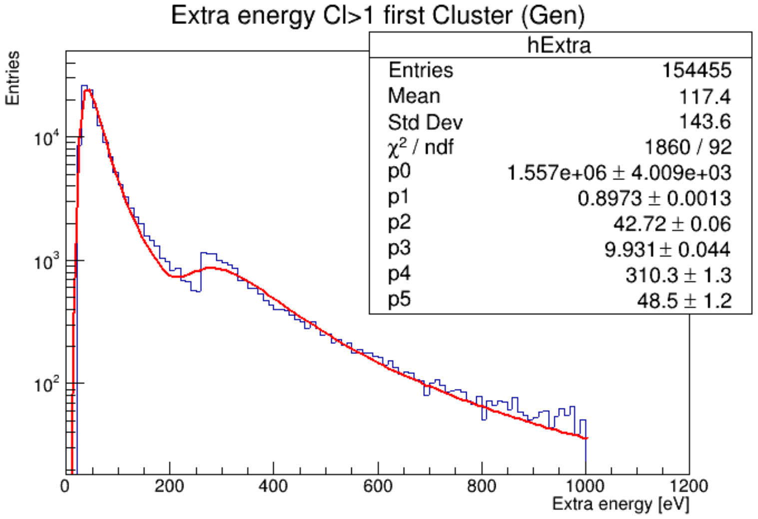
# Drift Chamber simulation - Cluster Counting/Timing simulation-Kinetic energy

Kinetic energy distribution for cluster with cluster size equal to 1.
The fit is the sum of an exponential function plus a Gaussian function.

Kinetic energy distribution for cluster with cluster size higher than 1 (left) and up to 1keV cut (right).
The fits are performed with a Landau functions.



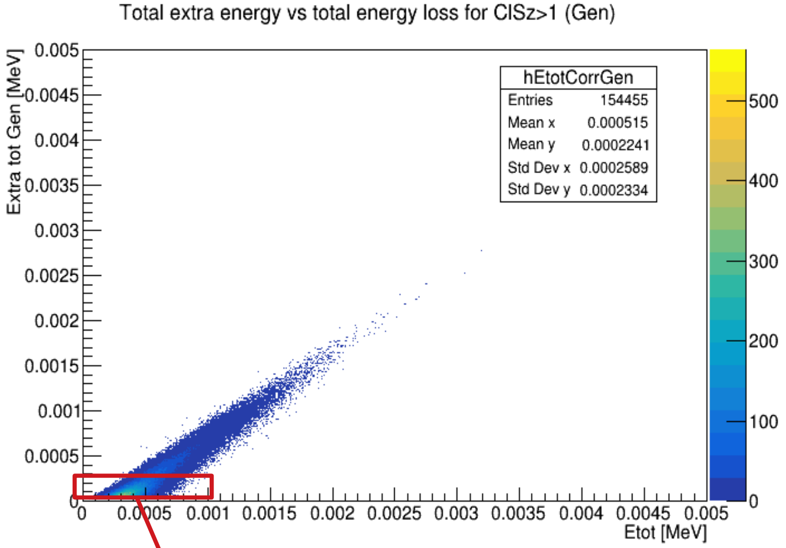



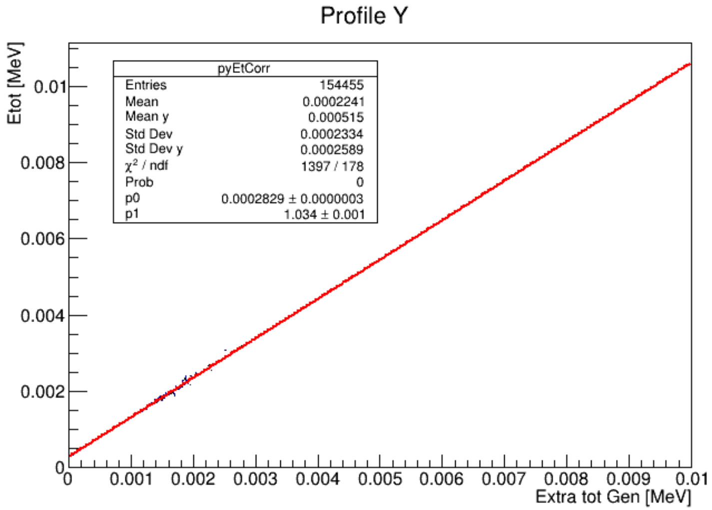



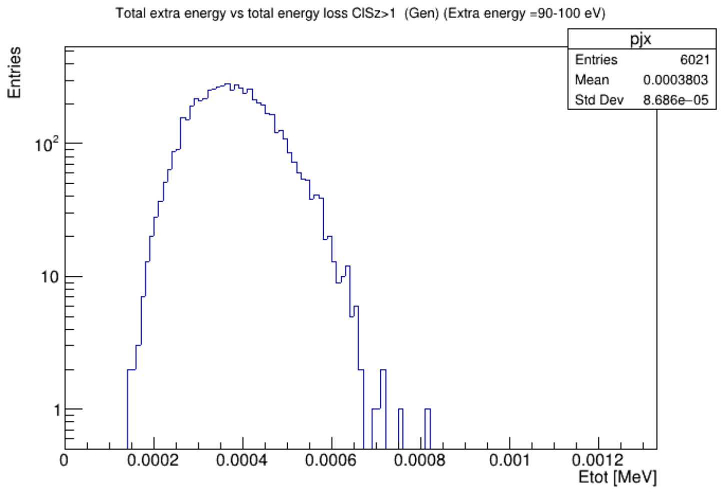

1keV cut is equivalent to the single interaction range cut set (by default) in Geant4

*The **goal** is to create two different models for kinetic energy of clusters with cluster size equal to 1 and higher than 1, to interpret correctly the total energy loss by different particles in a single cell.*

## Drift Chamber simulation - Cluster Counting/Timing simulation-kinetic energy for cluster with cluster size higher than 1




**maxExEcl = total kinetic energy spent to create cluster with cluster size higher than 1**

MaxEx0 is the first parameter of the linear fit

MaxExSlp is the second parameter of linear fit

ExSgm is the average of the sigma of each point in the correlation trend.

$$maxExECl = \frac{\left(Etot - maxEx0 + gRandom \rightarrow Gaus(0, ExSgm)\right)}{maxExSlp}$$

The figure shows an example of distribution of total energy loss for extra energy between 90 and 100 eV for cluster with cluster size higher than one.

## Drift Chamber simulation - Cluster Counting/Timing simulation- The algorithms

We implemented seven different algorithms trying to reproduce the number of cluster and the cluster size.
The first step common to all algorithm is the evaluation of the total kinetic energy for cluster with cluster size higher than one (maxExEcl) event by event.

1) The first algorithm uses a reference value of the ratio between clusters containing a single electron and clusters containing more than one electron (Rt). Using the Rt value, the algorithm chooses to create cluster with cluster size one or higher. Then, it assigns the kinetic energy to each cluster by using the proper distributions. If the cluster has more than one electron, a check on the total kinetic energy is performed and its cluster size is evaluated. The procedure is repeated until the sum of primary ionization energy and kinetic energy per cluster saturate the energy loss of the event.

**2) The second algorithm, if maxExEcl is higher than zero, generates the kinetic energy for clusters with cluster size higher than one by using its distribution and evaluates 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.**
**The reconstruction of clusters with cluster size equal to one remains the same for all next algorithms.**

**3) The third algorithm (similar to the previous), during the generation of cluster with cluster size higher than one, assigns the kinetic energy to them, choosing the best over five extractions that makes the total kinetic energy for cluster with cluster size higher than one approximating better the maxExEcl.**
**To correct a systematic underestimation of the mean number of clusters, an additional correction to the residual energy for generating cluster with cluster size equal to one can be used**.

## Drift Chamber simulation - Cluster Counting/Timing simulation- The algorithms

4)The fourth algorithm (similar to the previous), during the generation of cluster with cluster size higher than one, assigns (by extracting from the proper distribution) the kinetic energy to them, until the total kinetic energy better approximates the maxExEcl.

5)The fifth algorithm is similar to the fourth with almost differences in the technical implementation.

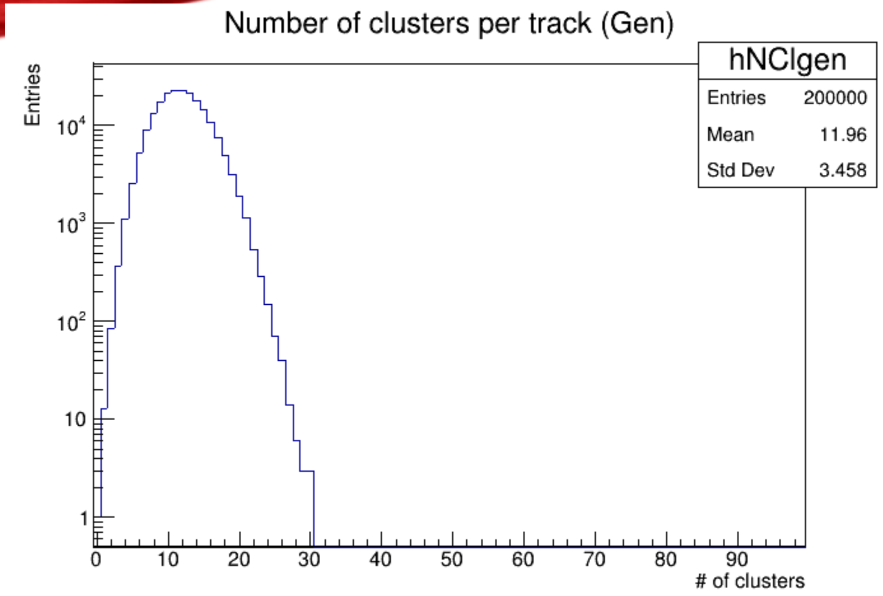
**6)The sixth algorithm follows a different methodology. Indeed it uses the total kinetic energy of the event to evaluate a priori the number of cluster, applying the most likelihood criterium.**

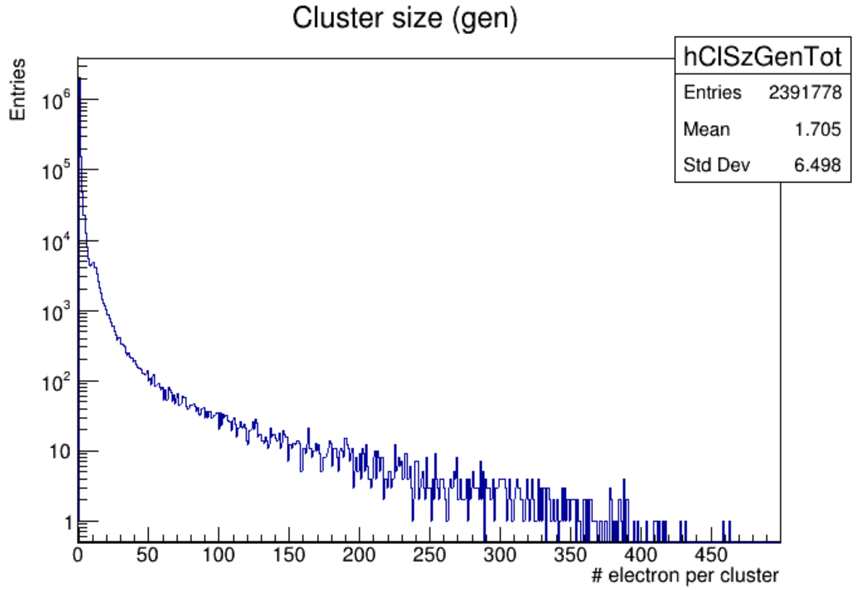
7)The last algorithm is similar to the second algorithm but generates the kinetic energy for cluster with cluster size higher than one by using the fit of kinetic energy distribution.

List of variables
maxExEcl : total kinetic energy spent to create clusters with cluster size higher than 1
ExECl : kinetic energy generated per cluster
Ncl1 : number of clusters with cluster size equal to one
Nclp : number of clusters with cluster size higher than one
maxCut : energy value equivalent to the range cut set in Geant4
totExECl : total kinetic energy reconstructed to create clusters with cluster size higher than one
Eloss : energy loss from a track passing through the cell
ClSz : cluster size
Eizp : primary ionization energy, 15.8 eV
Eizs : secondary ionization energy, 25.6 eV

# Drift Chamber simulation - Cluster Counting/Timing simulation-Results

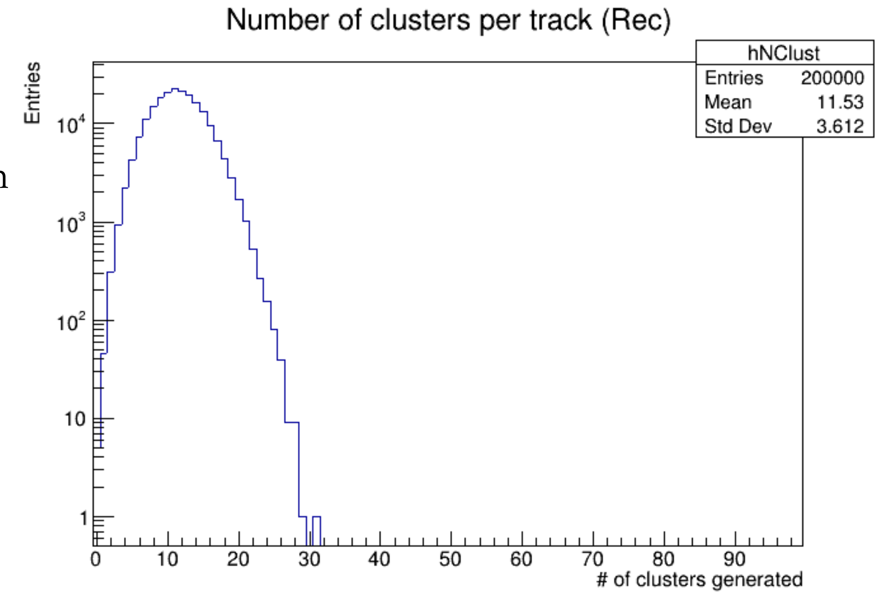
MC Truth

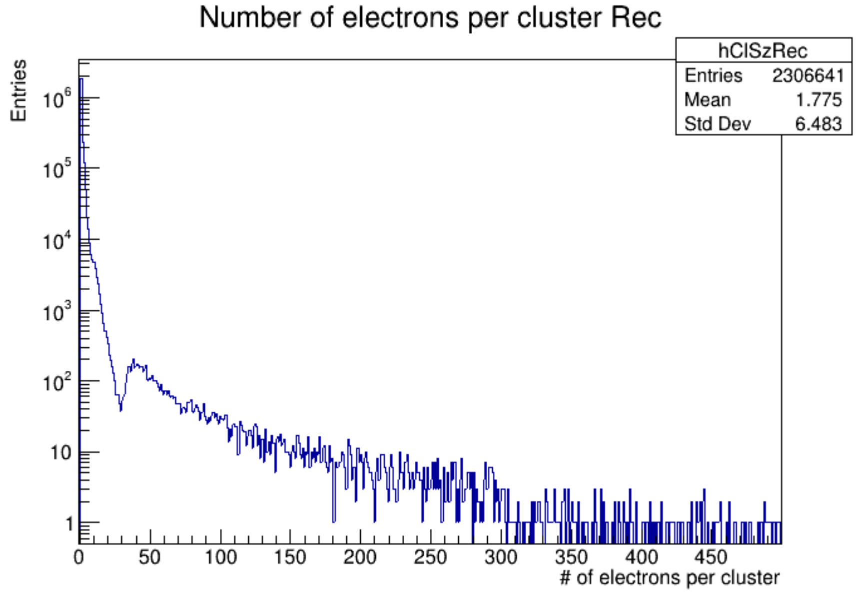



Case of study:
muon at 300 MeV

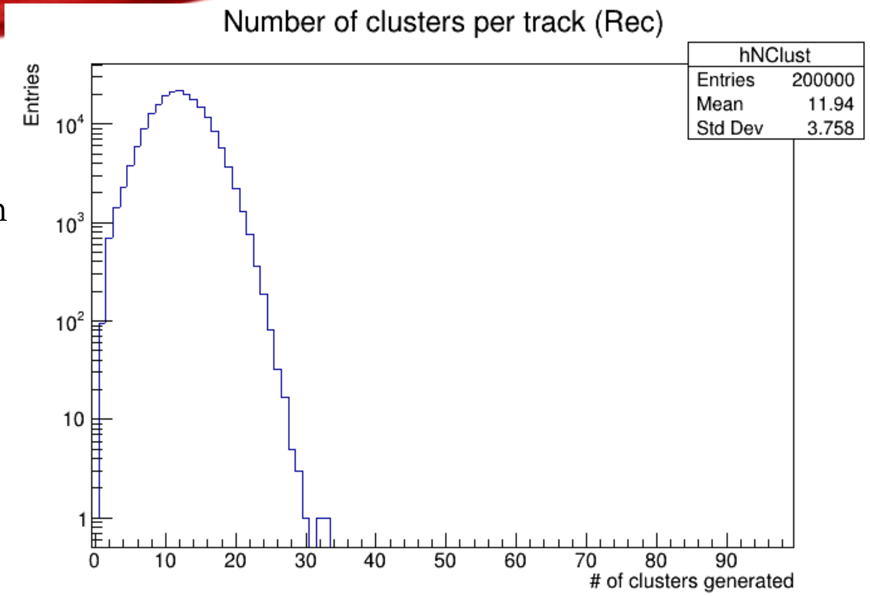
2st algorithm

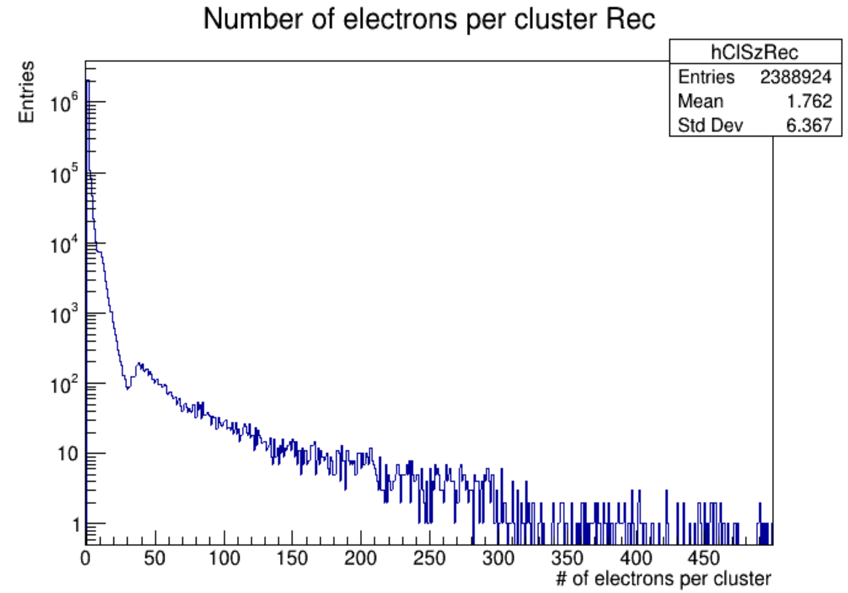


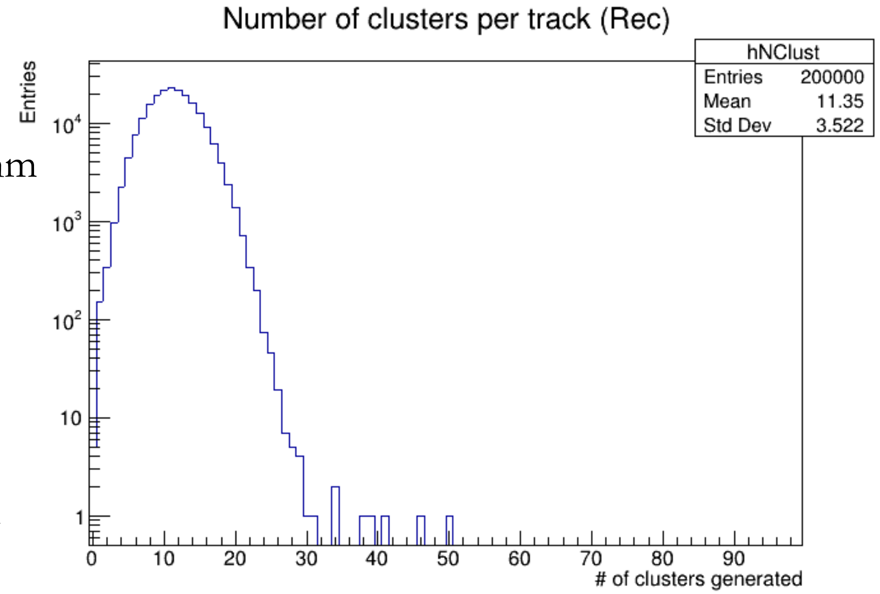
# Drift Chamber simulation - Cluster Counting/Timing simulation-Results

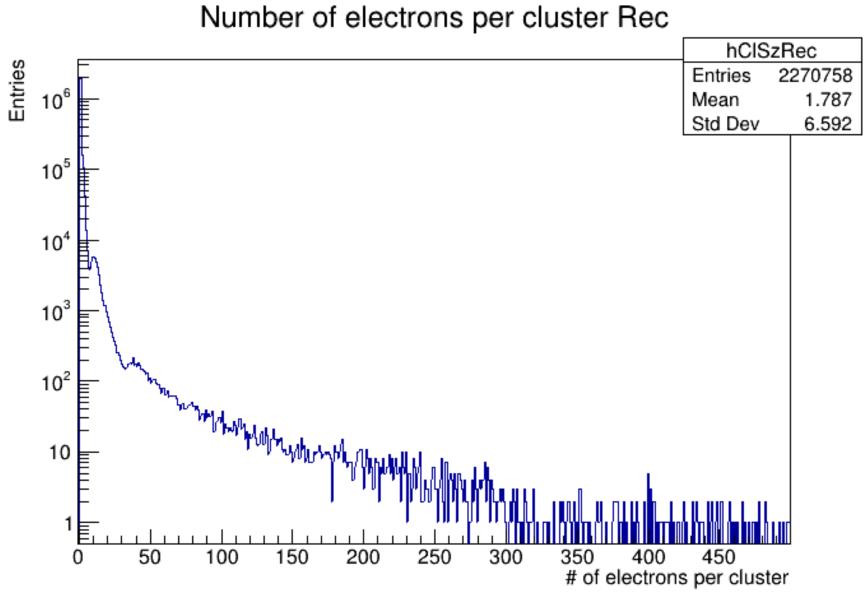
3st algorithm



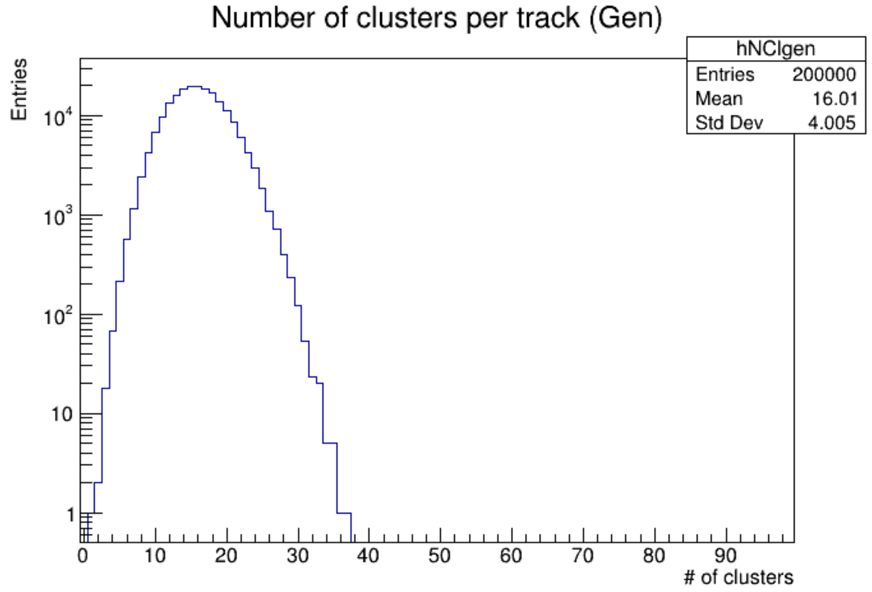



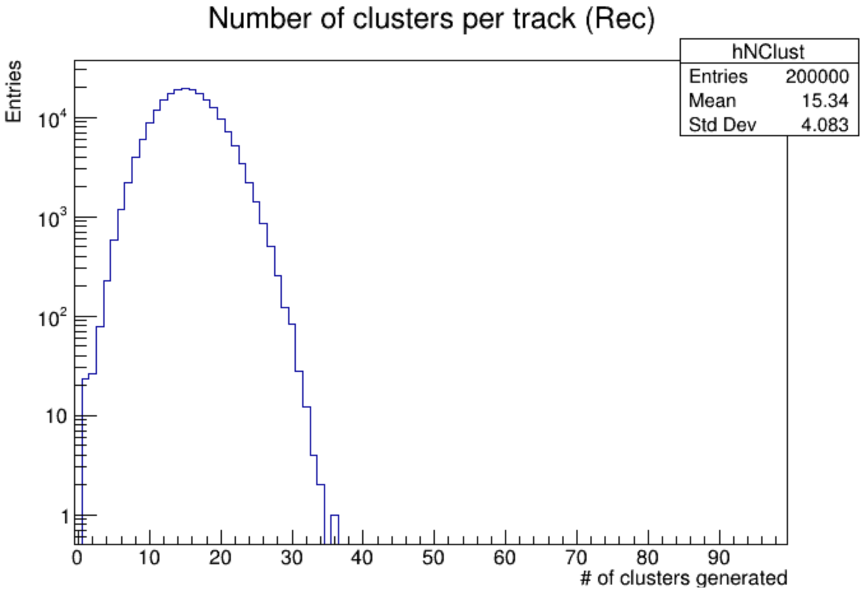

6st algorithm



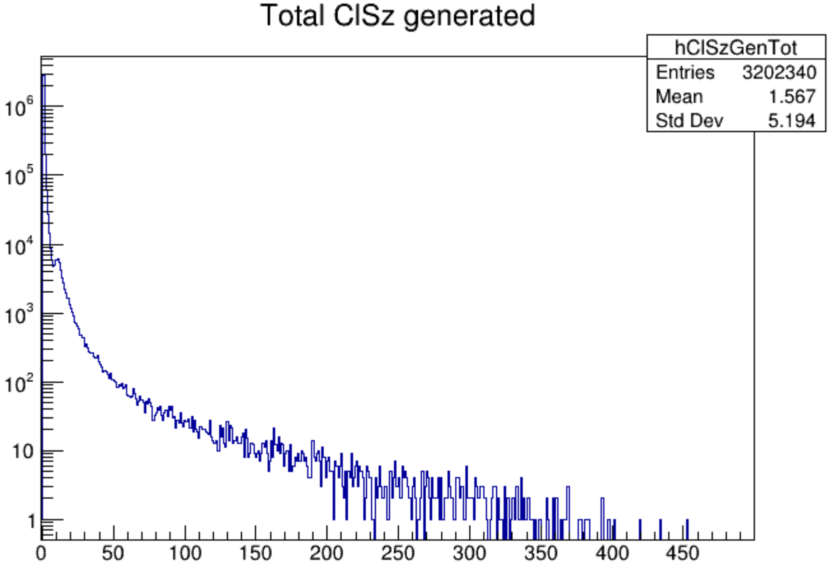



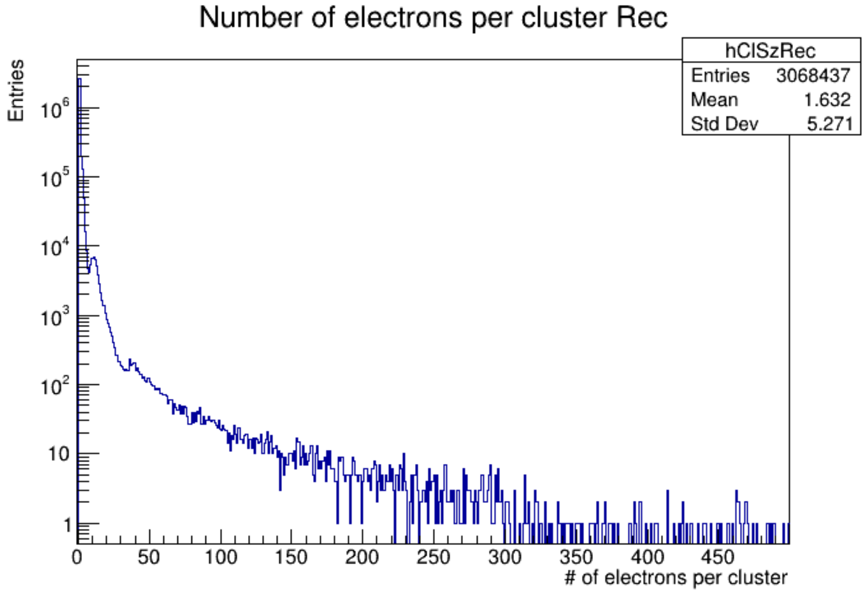
# Drift Chamber simulation - Cluster Counting/Timing simulation-Test on different momenta and different particles



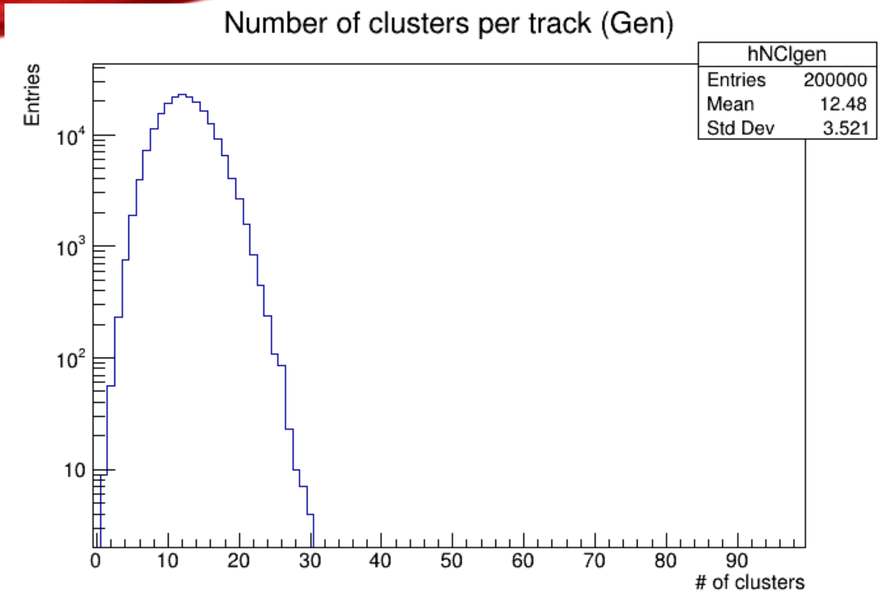



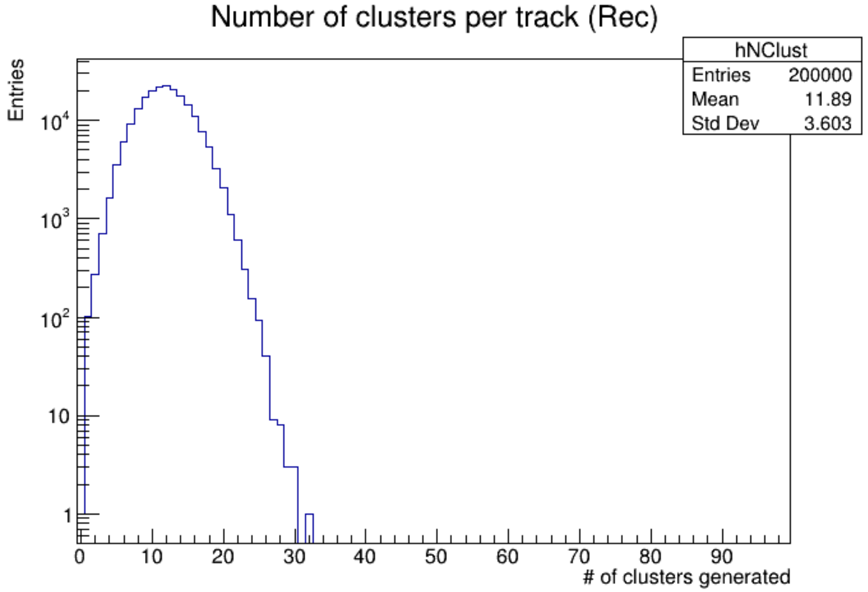

Case of study:
muon at 10 GeV



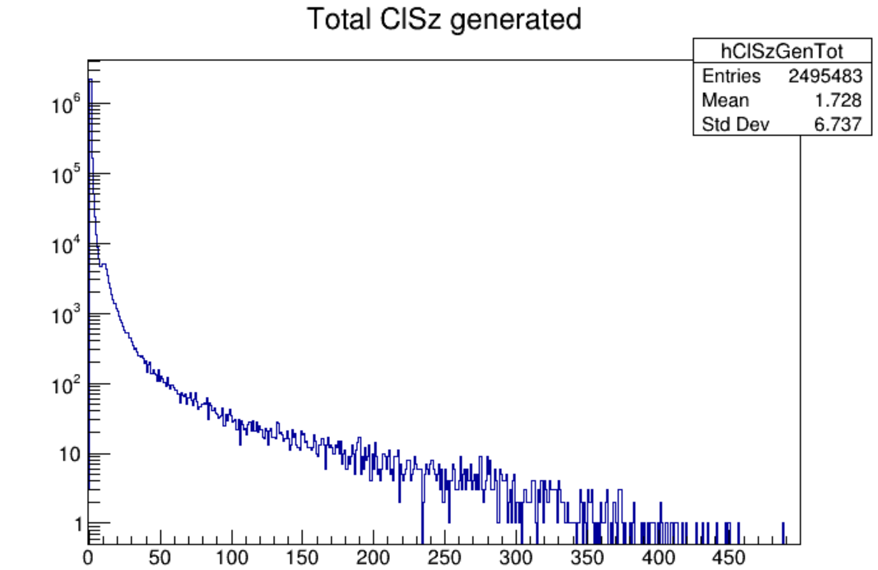



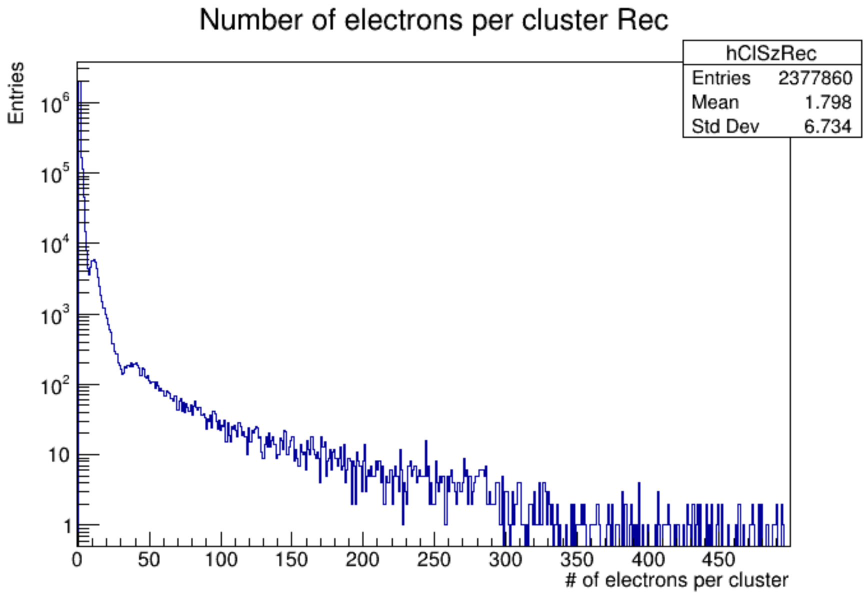
# Drift Chamber simulation - Cluster Counting/Timing simulation-Test on different momenta and different particles




Case of study:
pion at 300 MeV

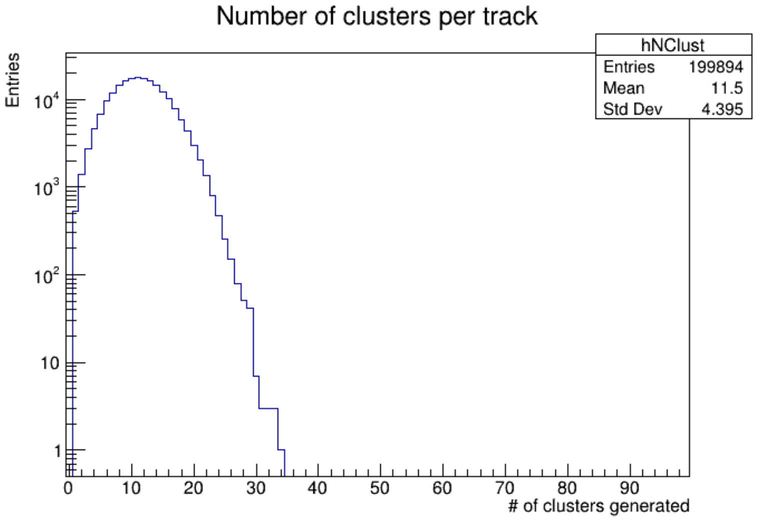


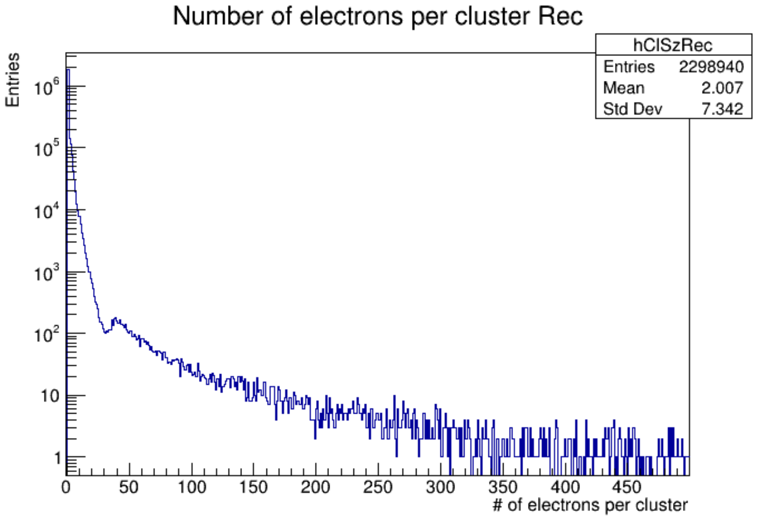



## Drift Chamber simulation - Cluster Counting/Timing-Geant4

The algorithm is tested with Geant4 simulations and the results obtained are compatible with the ones obtained with Garfield++.

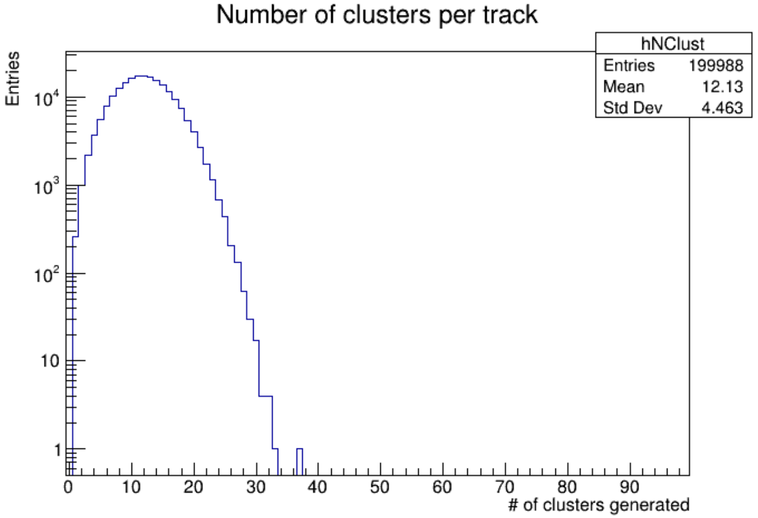
2st algorithm

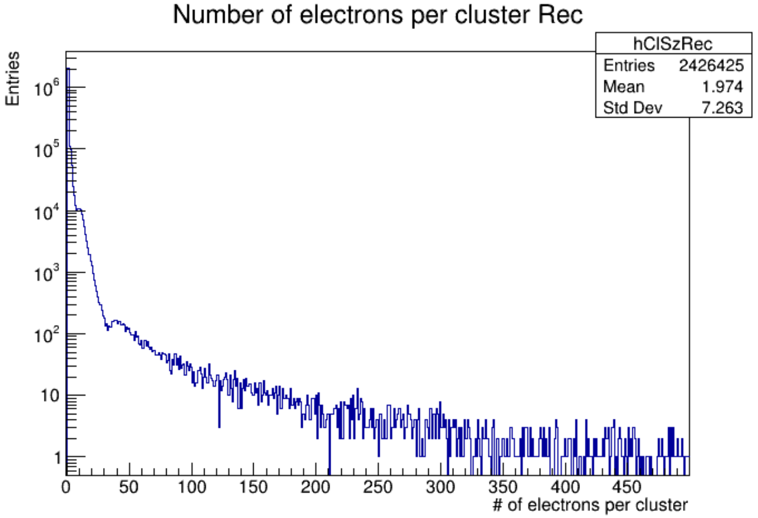


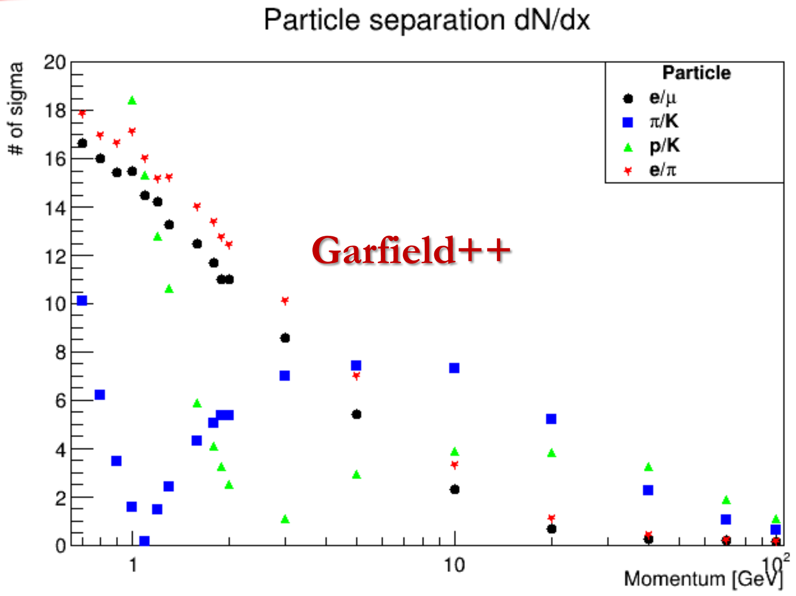

Case of study:
muon at 300 MeV

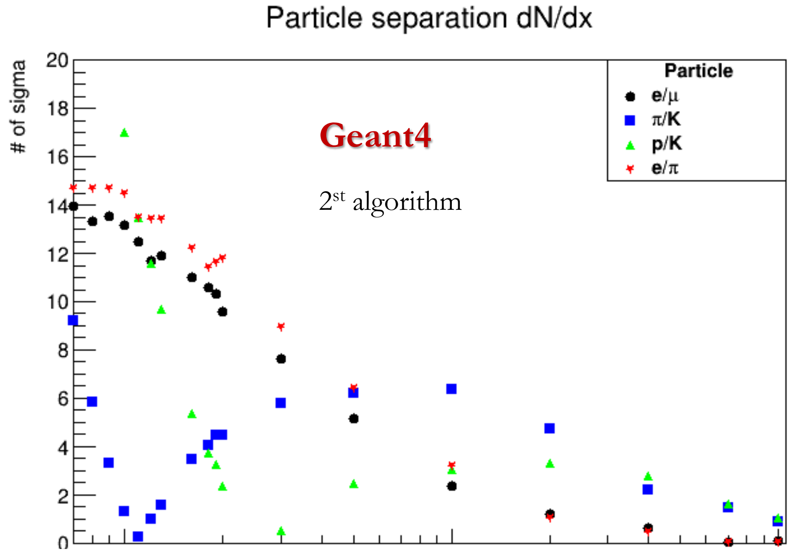
3st algorithm

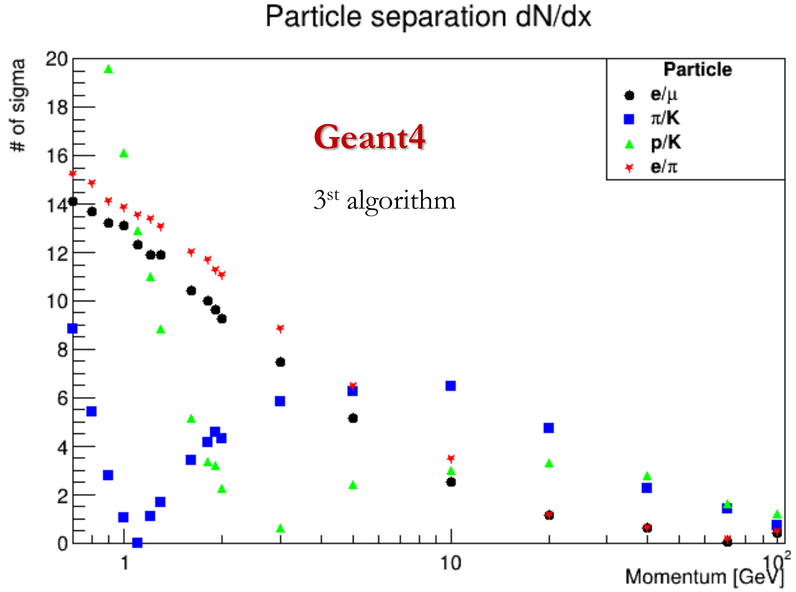


# Drift Chamber simulation - Cluster Counting/Timing-PID in Geant4




We are simulating tracks crossing 200 cell (1 cm long side) of 90% He and 10% $iC_4H_{10}$ with Garfield and Geant.

We are assuming a cluster counting efficiency of 100%.

## Conclusions

- Cluster counting improves particle separation capabilities respect to the traditional dE/dx method.
- Reasonable algorithms to simulate the Ionization Clusters by using the Geant4 data are developed.
- The algorithm was tested on different cell size, providing consistent results.
- A first fast Cluster Finder algorithm was developed, implemented on an FPGA and tested on a test bench.
- We are working on importing the algorithm in the drift chamber full simulation.

To do list

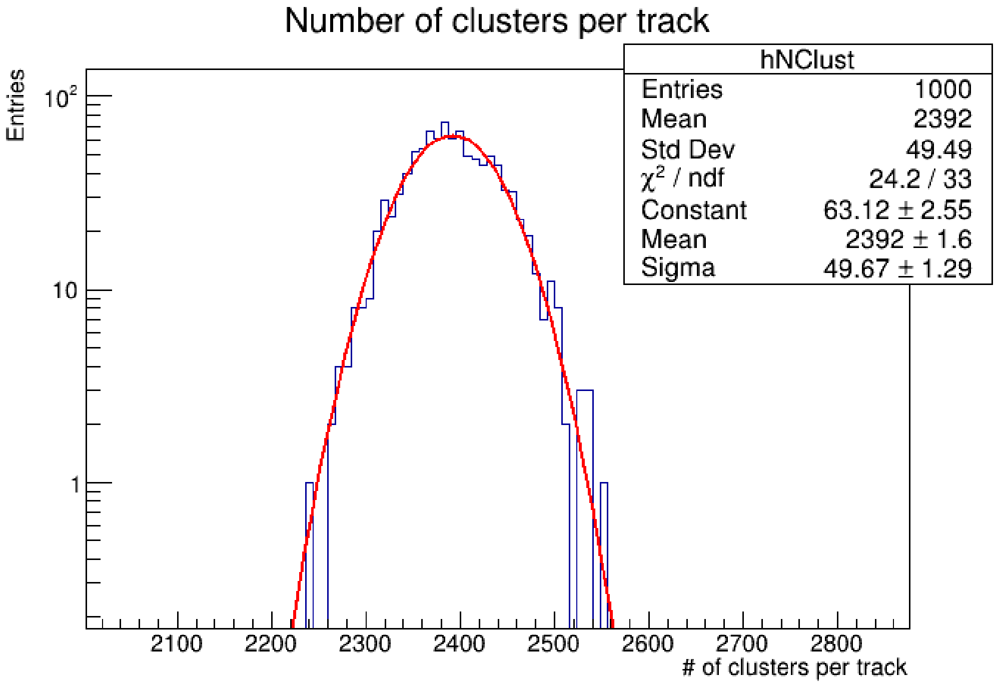
- Continue to develop the full simulation and perform physics studies
- Perform PID studies with the full detector simulation
- Improve Clustering algorithm validation with measurements
- Continue to develop the DAQ prototype and test it
- Construct the monitor chamber and ad hoc prototypes

**Thanks for your attention**

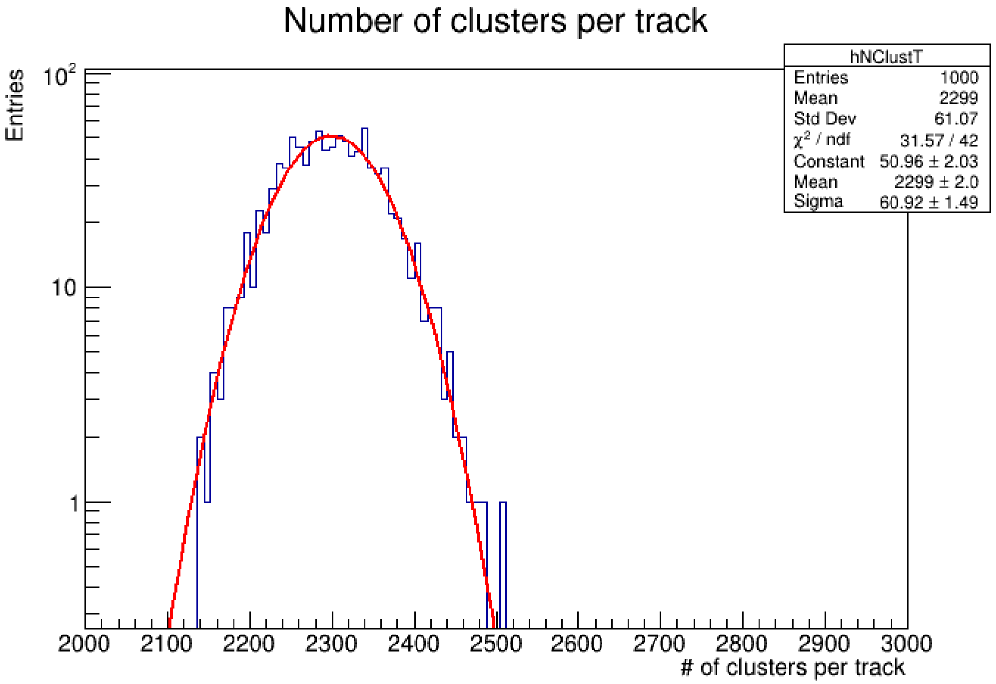
# BACKUP

Number of cluster for muon 300 MeV in 200 cells

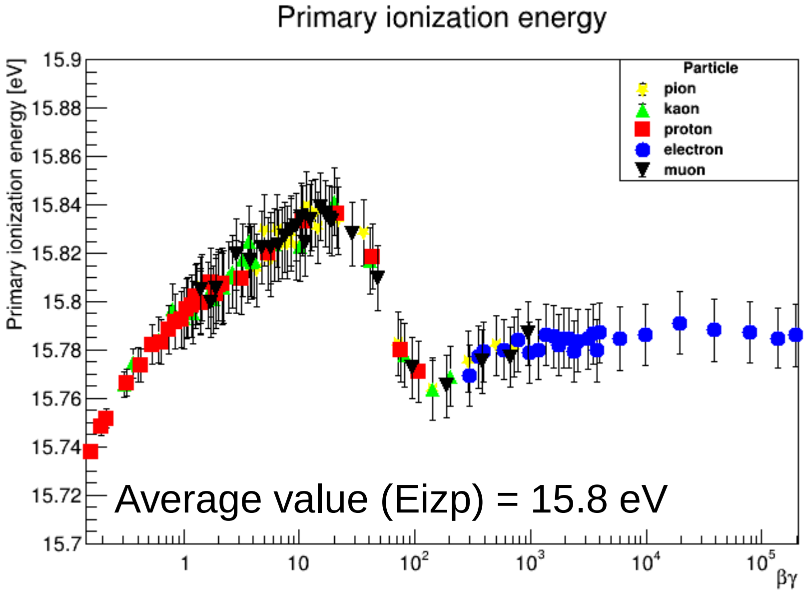
**Geant4**

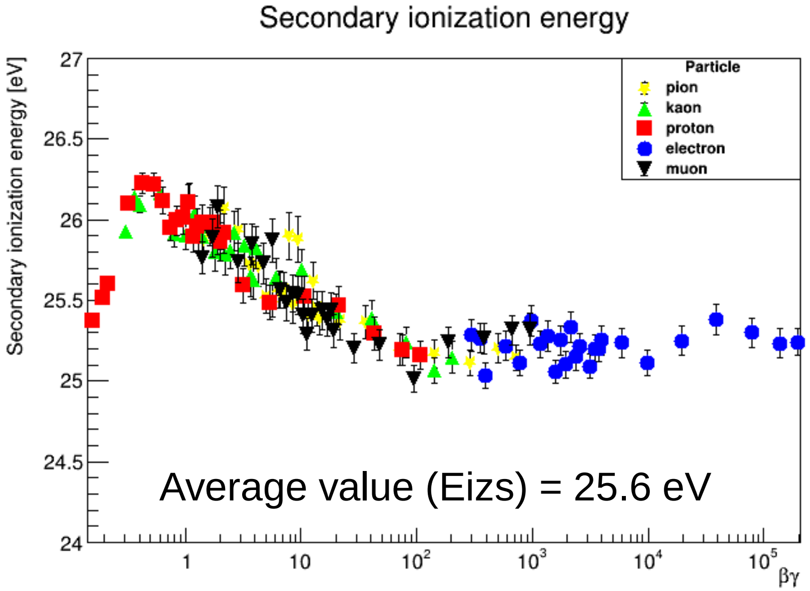


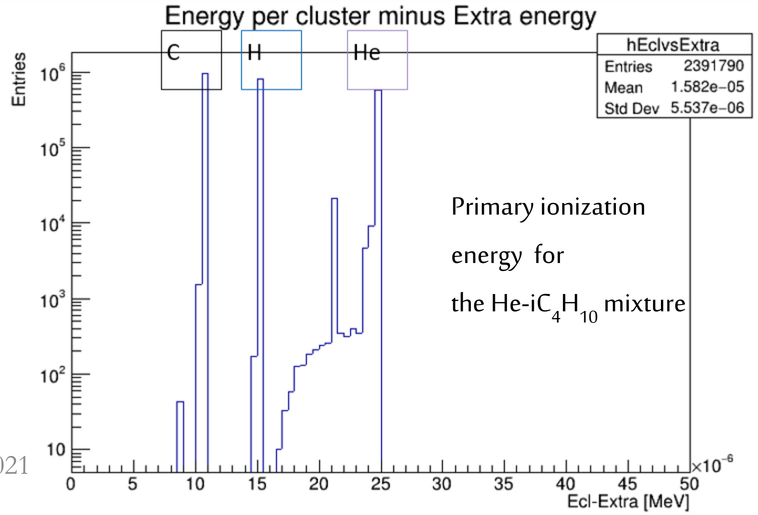

**Garfield++**



# Drift Chamber simulation - Cluster Counting/Timing simulation



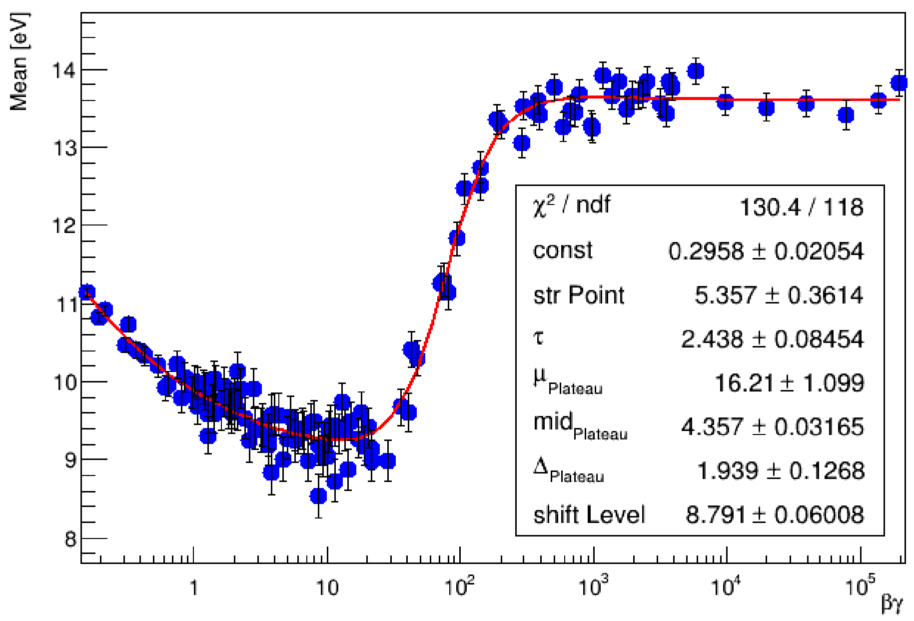




Primary ionization energy for the He-i$C_4H_{10}$ mixture

First step to the algorithm implementation is the evaluation of primary and secondary ionization energy

## Fit parameters for kinetic energy distribution for cluster with cluster size equal to 1

Mean from gaus+exp fit of Extra Energy with ClSz=1




Here the distribution of mean value (top left) and sigma value (bottom right) for different particles with different momenta.

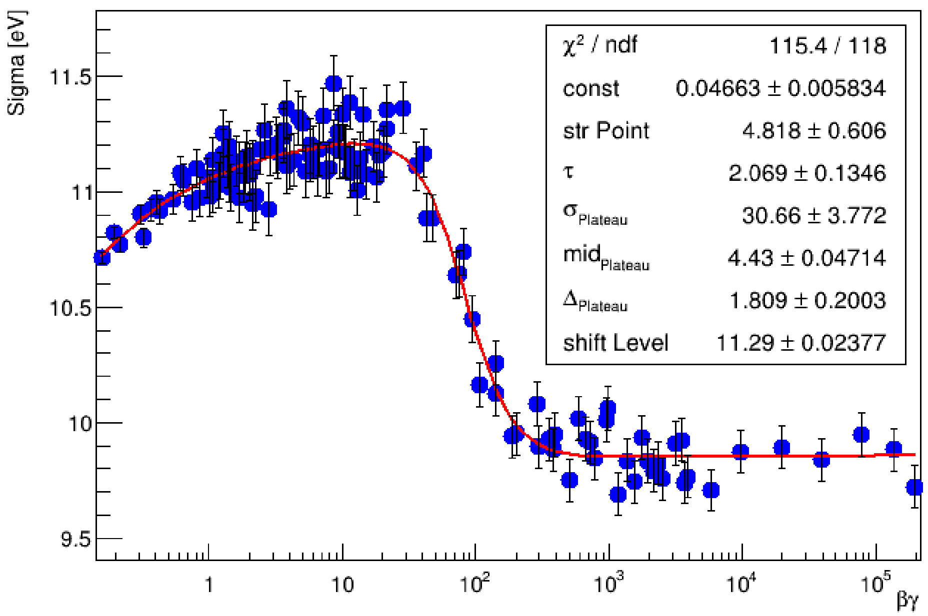
The distributions are fitted with an exponential function plus an efficiency function.

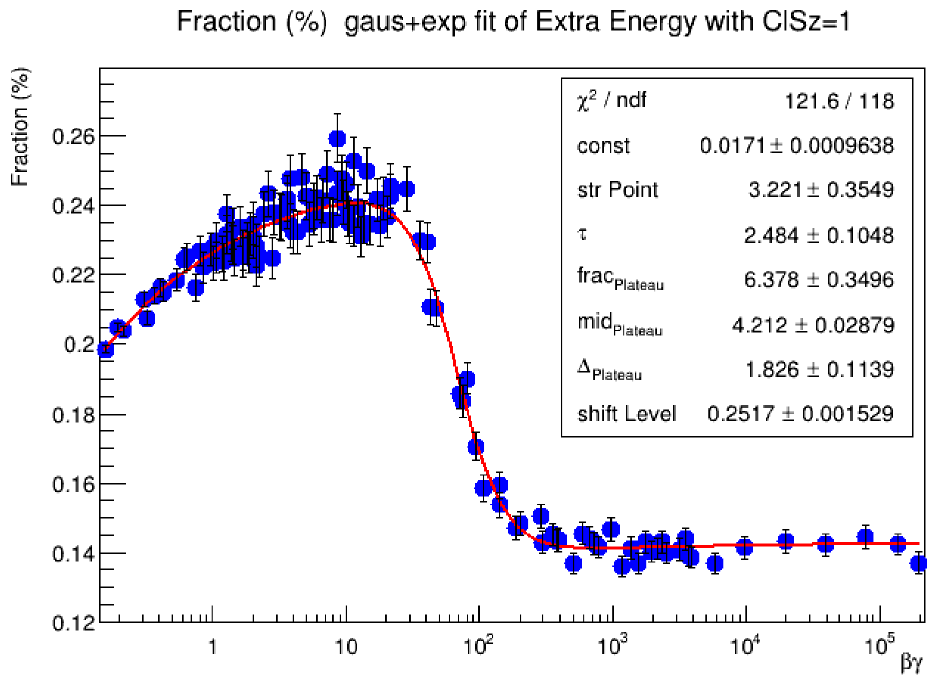
$$Eff = \frac{Eff_{plateau}}{1 + 81^{\frac{V_{1/2} - V}{\Delta^{90\%}_{10\%}}}}$$

Other parameters studied are:

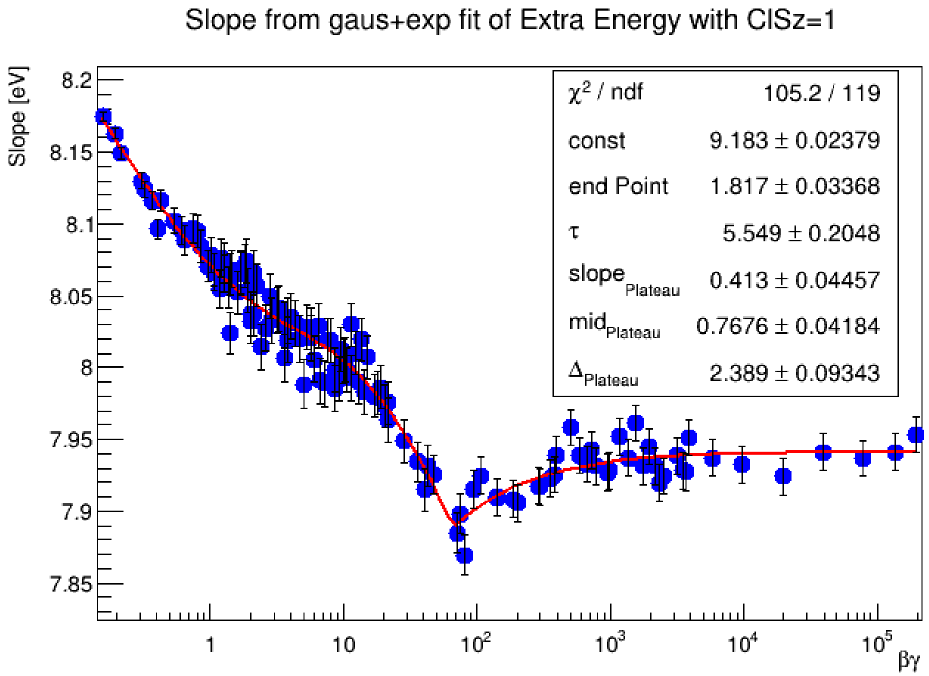
- Slope and fraction for exp+gaus fit
- Most probable value and sigma for landau fit
- The two MPV and sigma for double landau fit

Sigma from gaus+exp fit of Extra Energy with ClSz=1

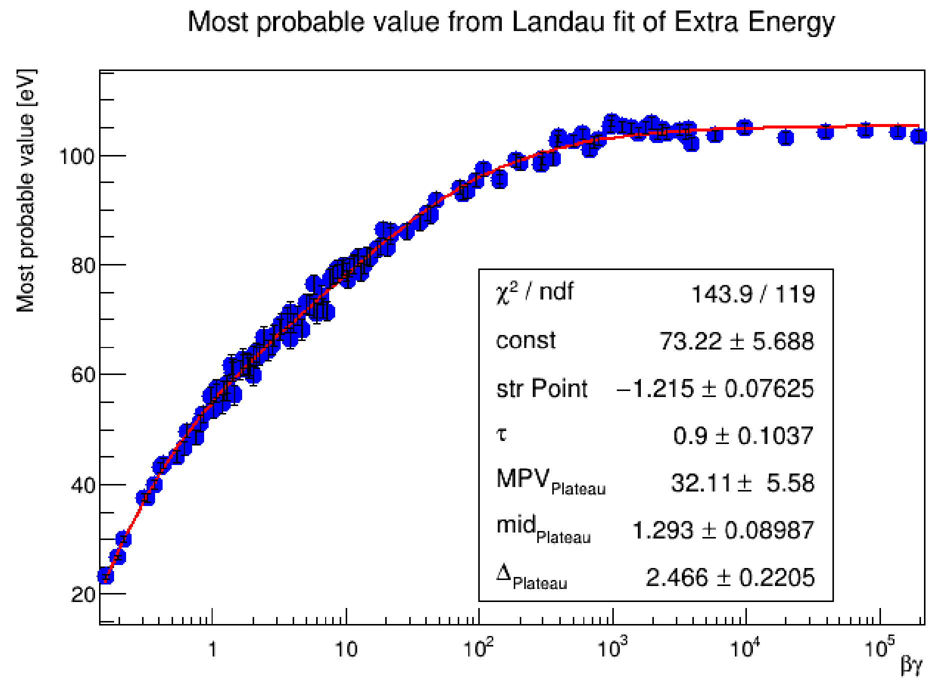





Here the distribution of the fraction value from fit,
fitted with a decreasing exponential function plus an efficiency function.

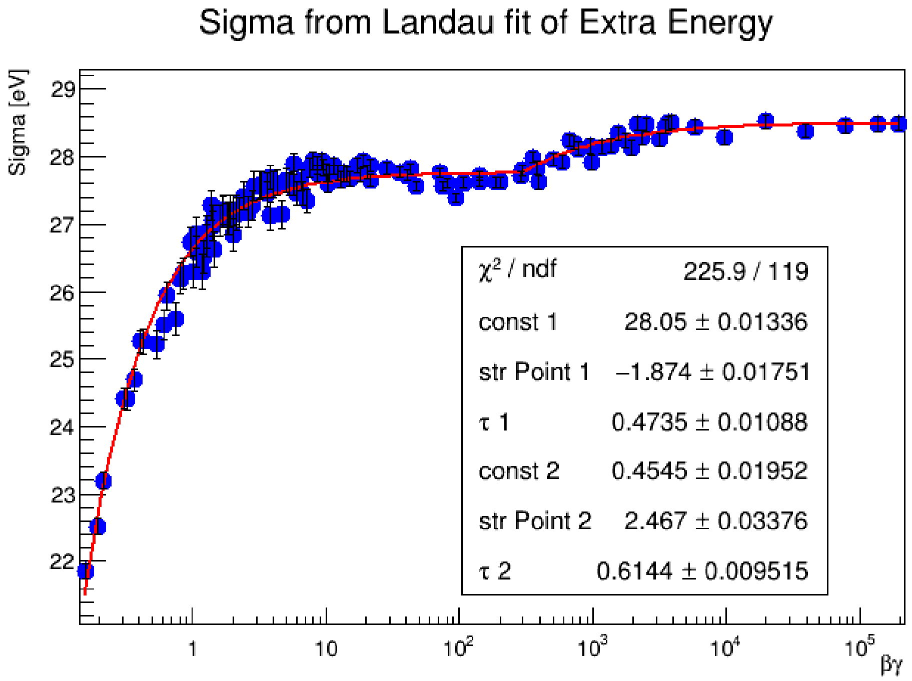



Here the distribution of the slope value of fit,
fitted with a 1-exponential function plus an efficiency function.



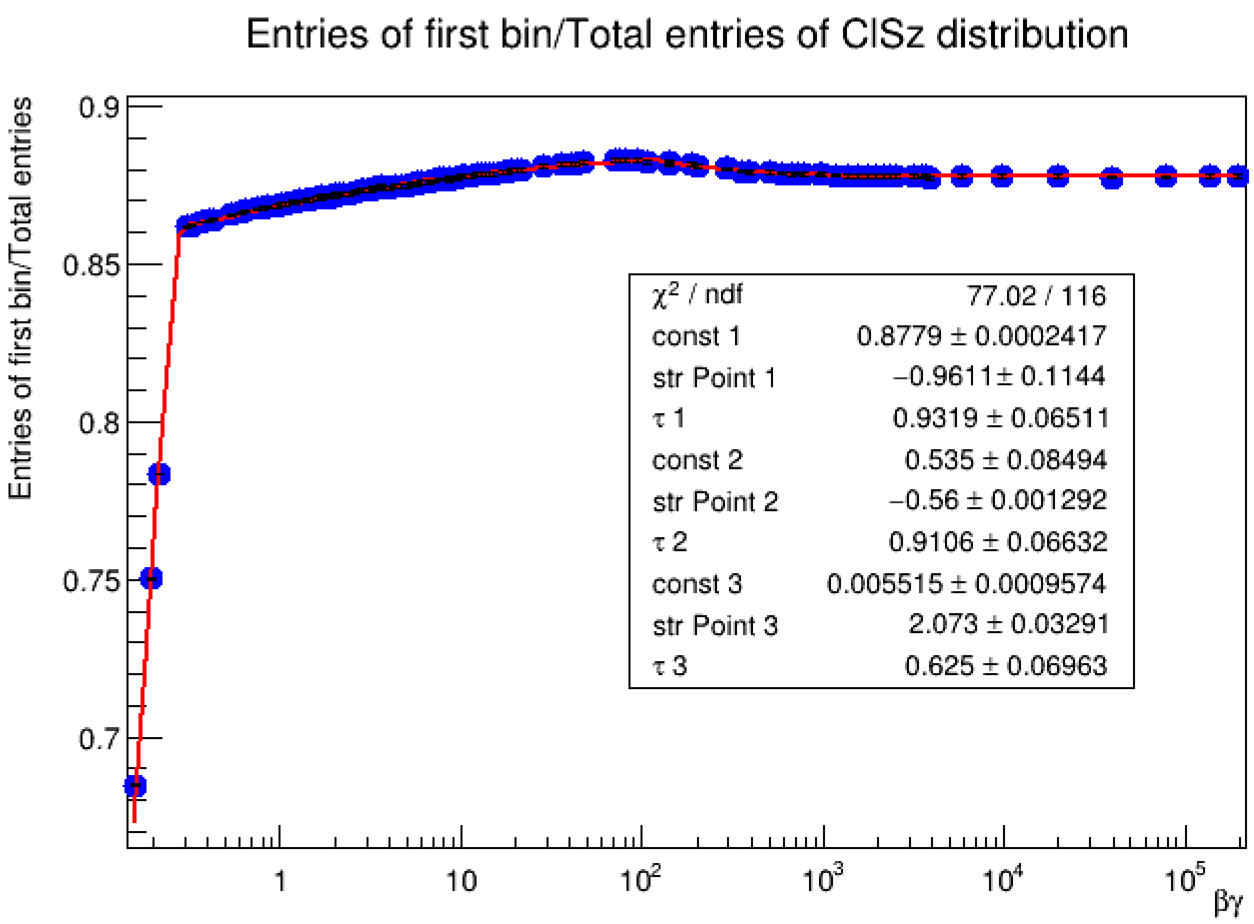

**Fit parameters for kinetic energy distribution for cluster with cluster size higher than 1**

Here the distribution of the most probable value, fitted with 1- decreasing exponential function plus an efficiency function.




Here the distribution of the sigma value, fitted with 1- decreasing exponential function plus an efficiency function.

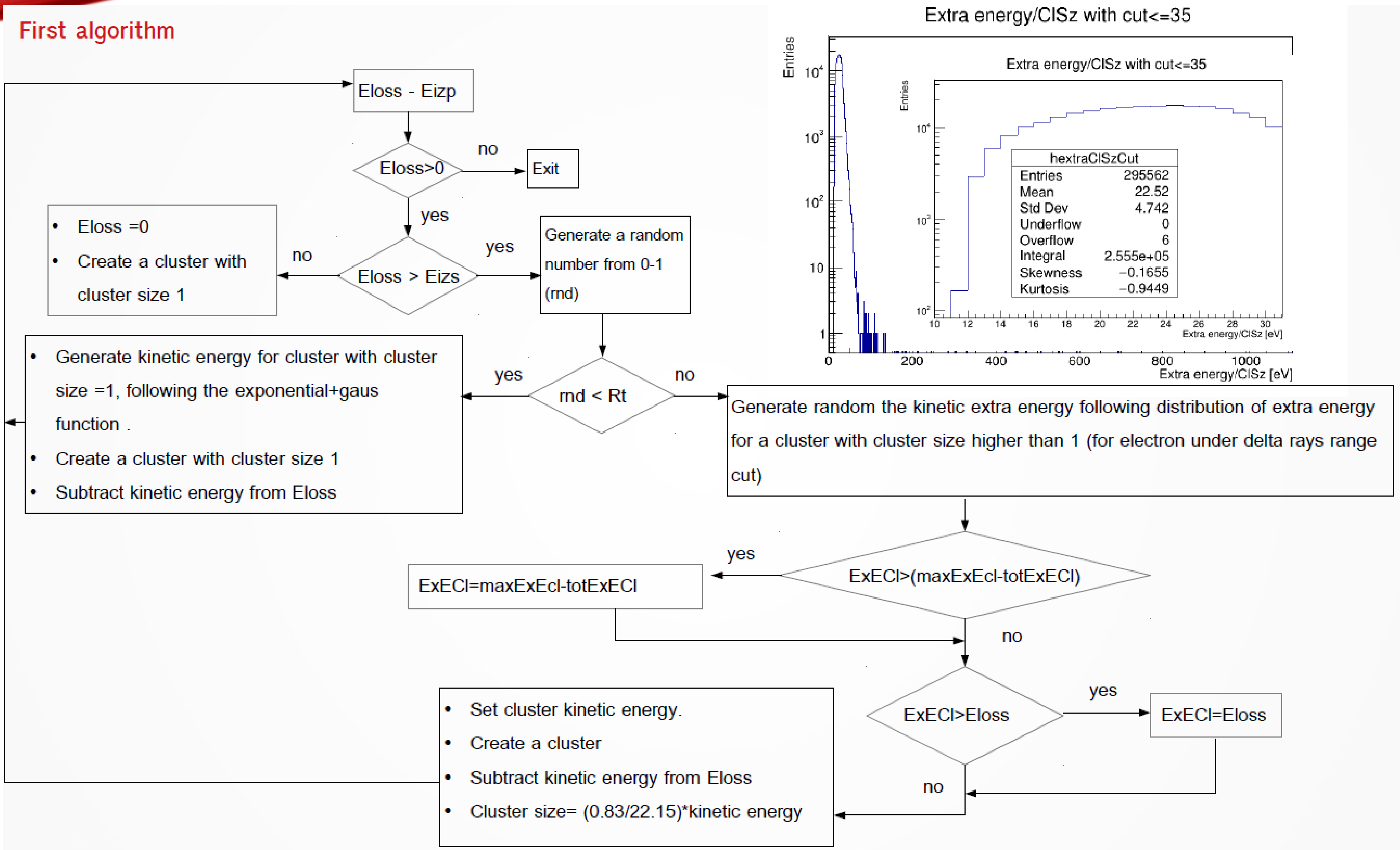
Rt value



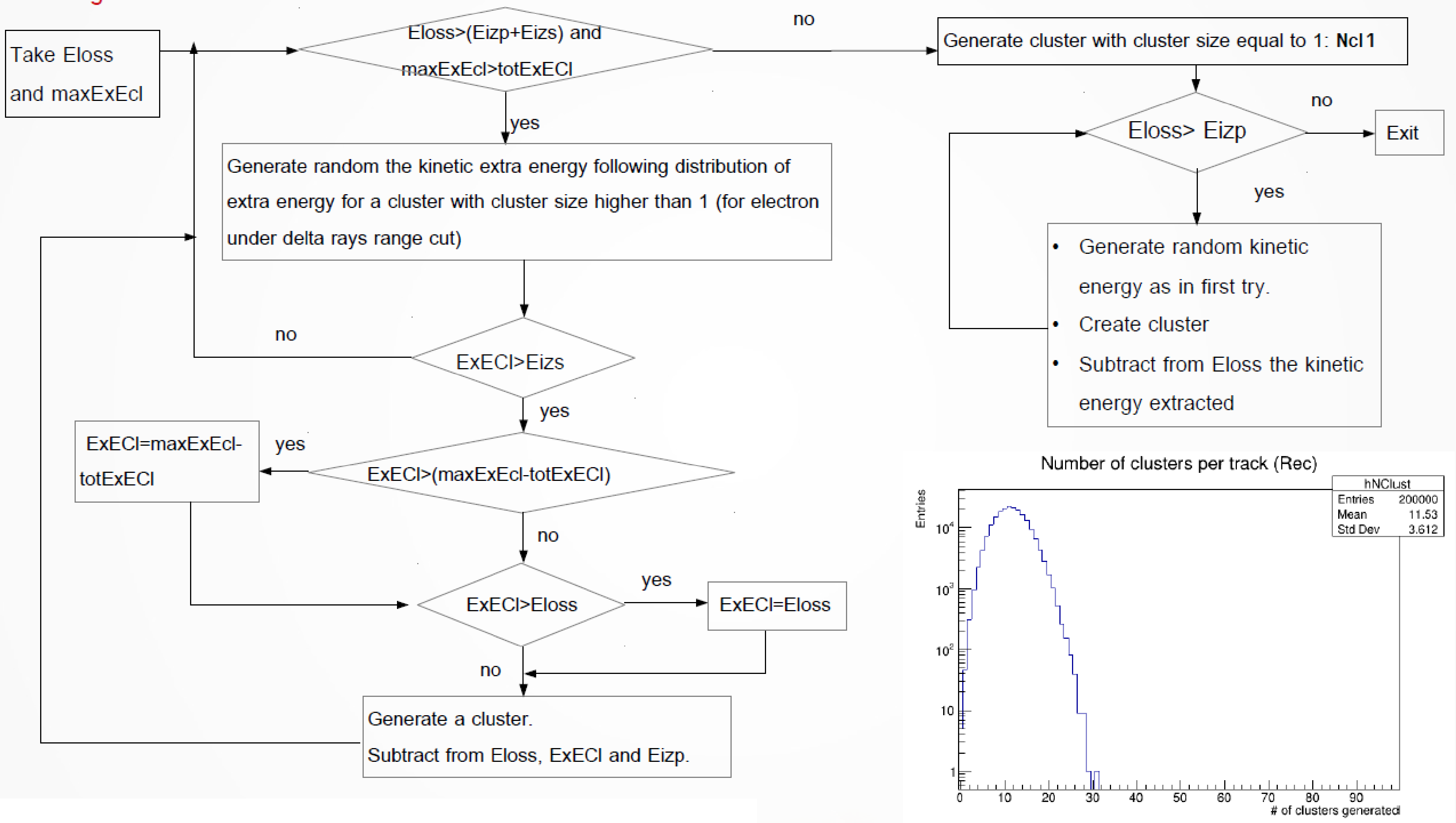

Here the ratio between the cluster containing a single electron and the cluster containing more than an electron.

The distribution is fitted with 1- decreasing exponential function plus two decreasing exponential functions.

# First algorithm

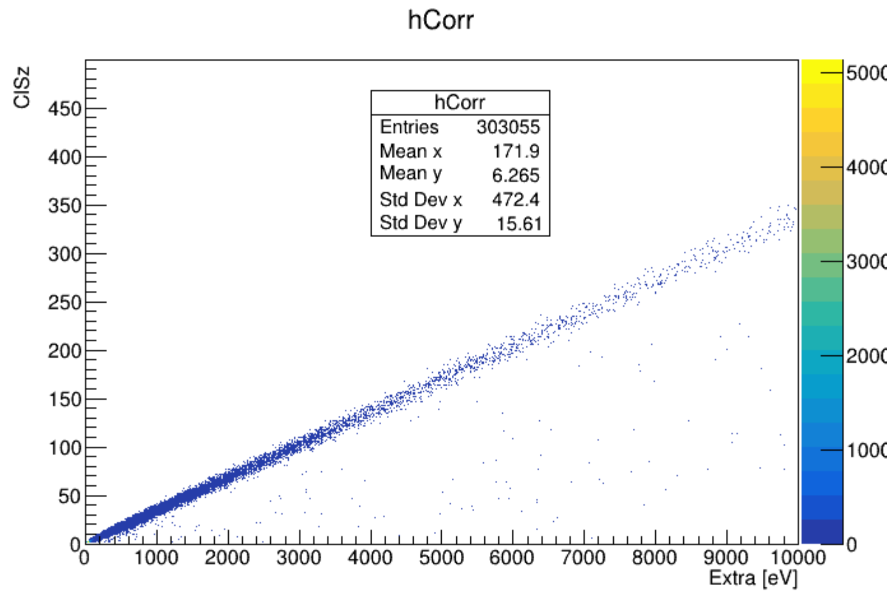


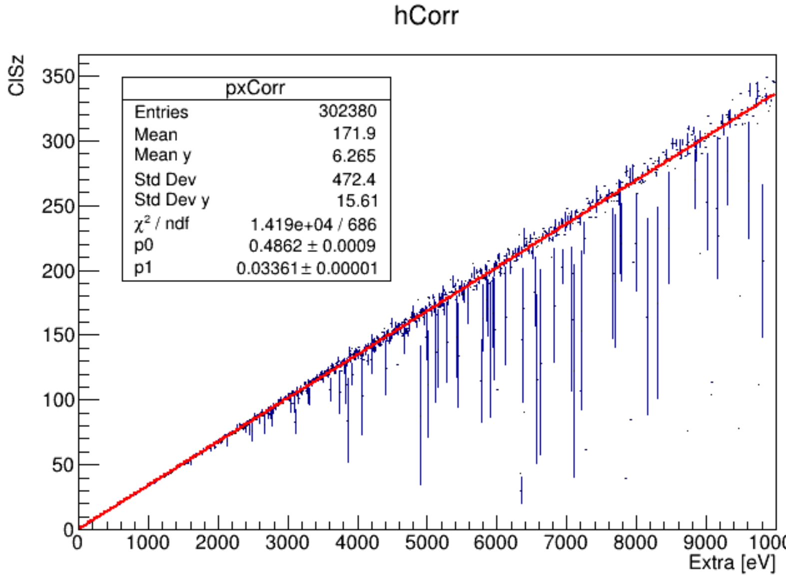
**Second algorithm:** reconstruction of number of cluster



## Second try: reconstruction of cluster size

We studied the relation between extra energy and cluster size for cluster with cluster size higher than 1 (delta rays are included).



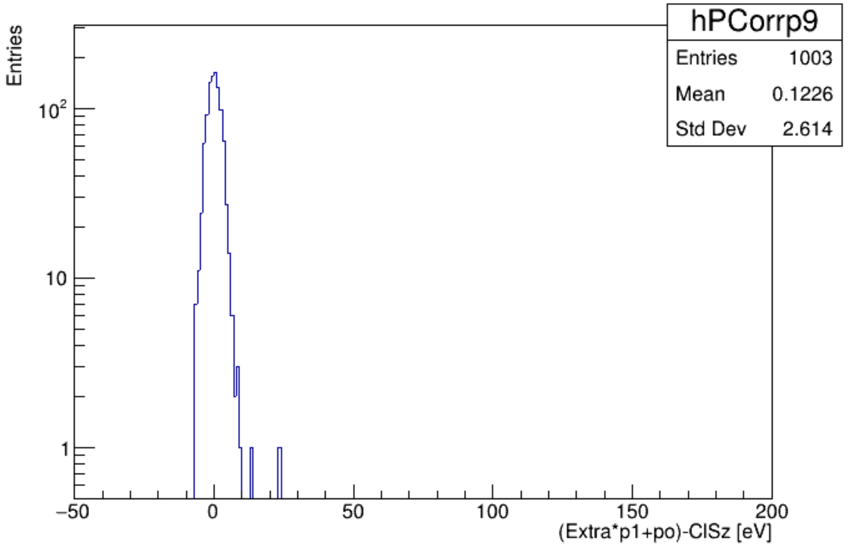




We fit the correlation trend with a first degree polynomial and save the parameter p0 and p1.

To evaluate the cluster size for cluster with more than one electron, we study the dispersion for different slice of extra energy up to delta rays cut range (1000 eV):

(Extra energy*p1+p0)-ClSz.

The figure shows an example for extra energy between 900 and 1000 eV.




At the end, the cluster size is evaluated as :

(Extra energy*p1+p0) minus hPCorrp->GetRandom().

Same evaluation is performed for cluster size generated by delta rays.

We study the dispersion for different slice of extra energy above the value of delta rays cut range (1000 eV):

(Extra energy*p1+p0)-ClSz.

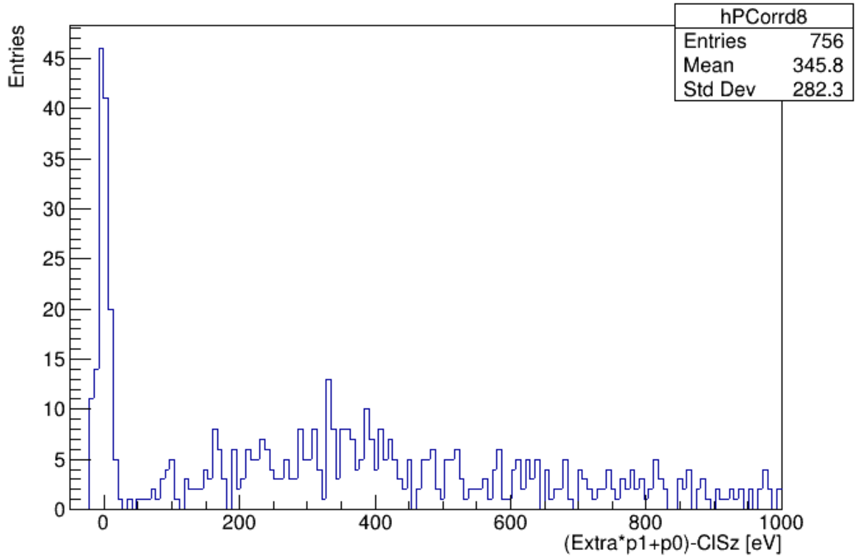
The figure shows a example for extra energy between 9 and 10 keV.

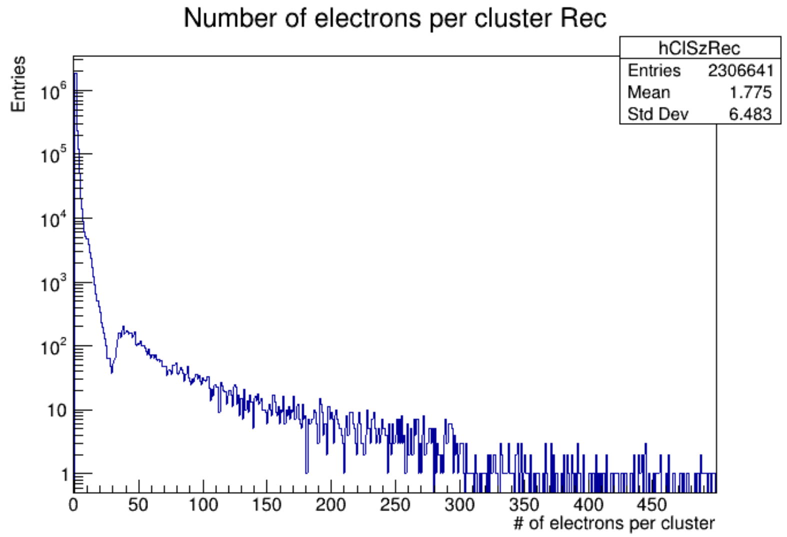
At the end, the cluster size is evaluated as :

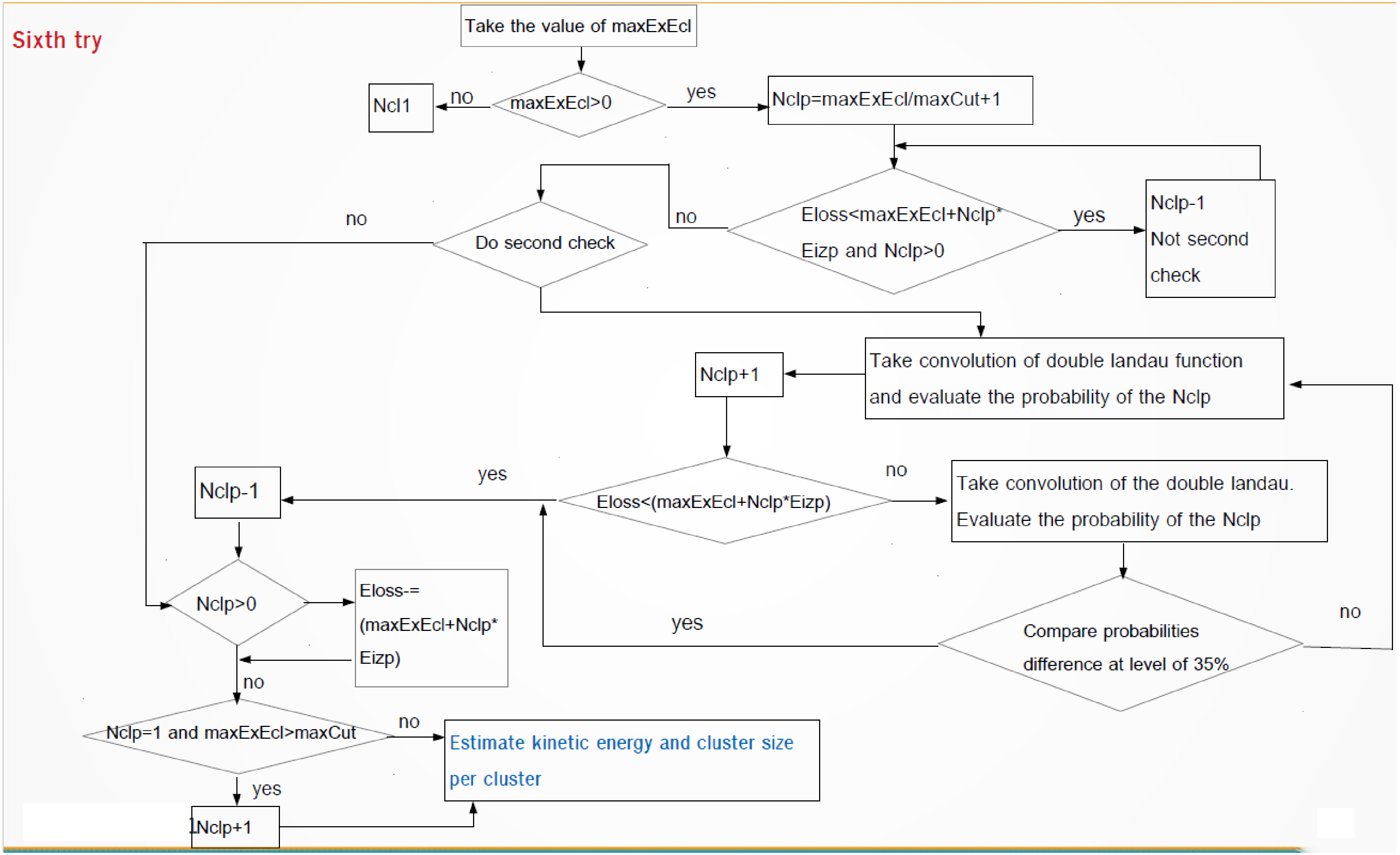
(Extra energy*p1+p0) minus hPCorrd->GetRandom().

The result is better than the first try, besides the depression remains.

**The evaluation of cluster size remains the same for all next attempts.**

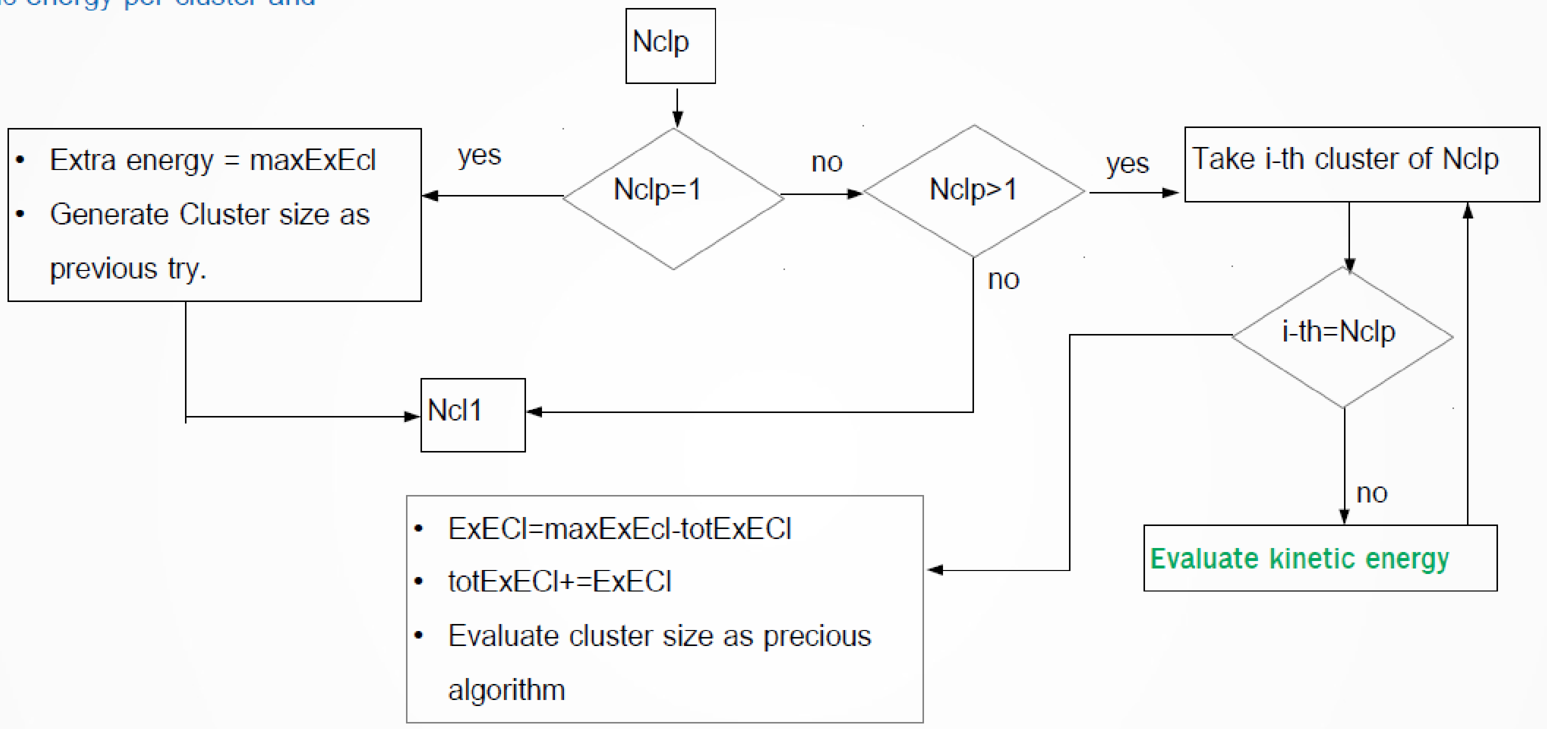



Sixth try
Take the value of maxExEcl
maxExEcl>0
no
Ncl1
yes
Nclp=maxExEcl/maxCut+1
Eloss<maxExEcl+Nclp*
Eizp and Nclp>0
yes
Nclp-1
Not second
check
no
Do second check
no
Take convolution of double landau function
and evaluate the probability of the Nclp
Nclp+1
Eloss<(maxExEcl+Nclp*Eizp)
yes
no
Nclp-1
Take convolution of the double landau.
Evaluate the probability of the Nclp
Compare probabilities
difference at level of 35%
yes
no
Nclp>0
Eloss-=
(maxExEcl+Nclp*
Eizp)
no
Nclp=1 and maxExEcl>maxCut
no
Estimate kinetic energy and cluster size
per cluster
yes
Nclp+1

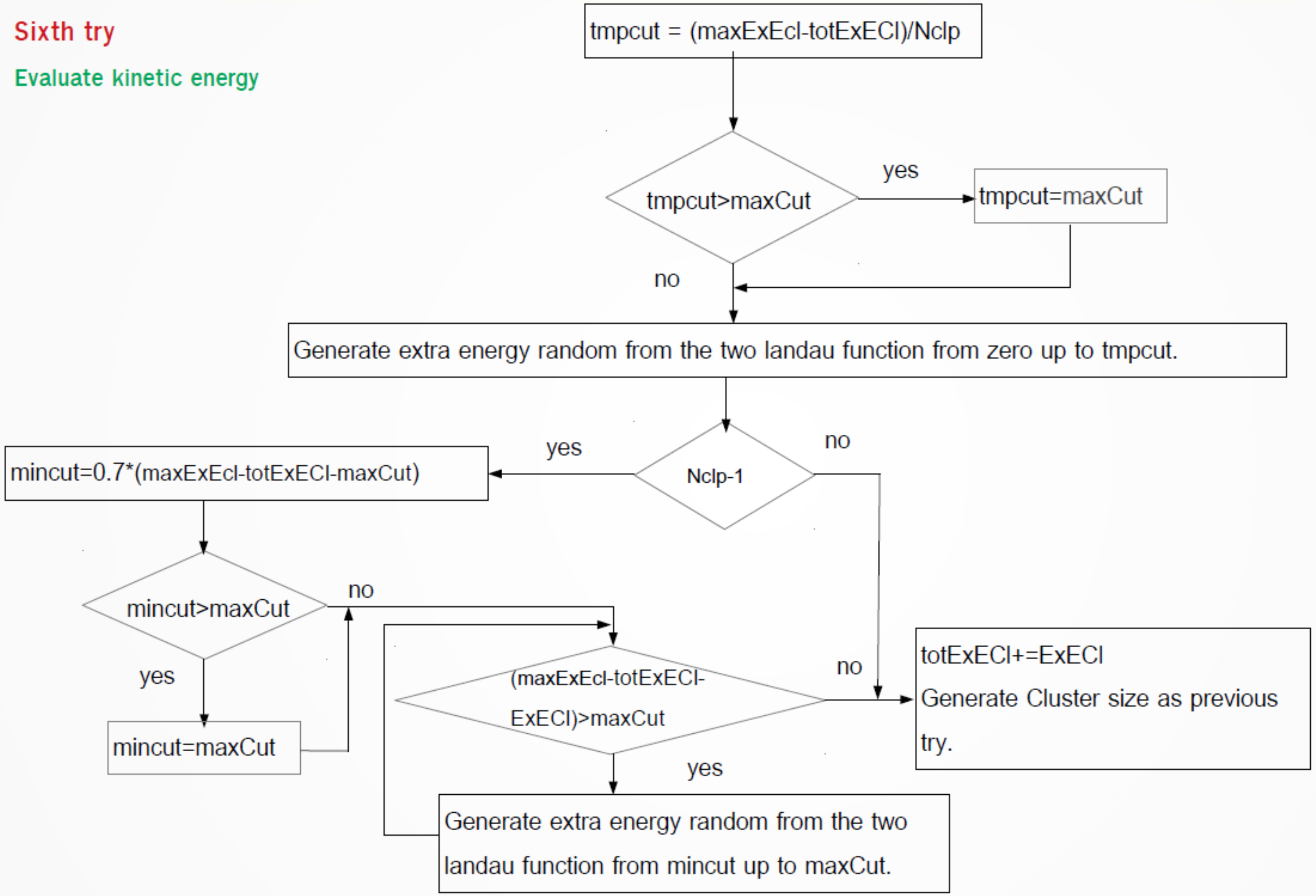
## Sixth try

Estimate kinetic energy per cluster and cluster size



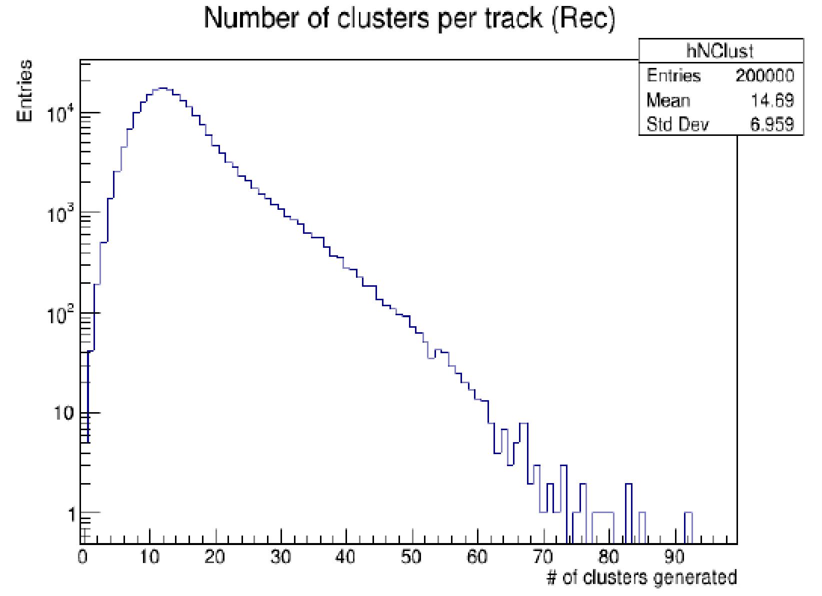
## Sixth try

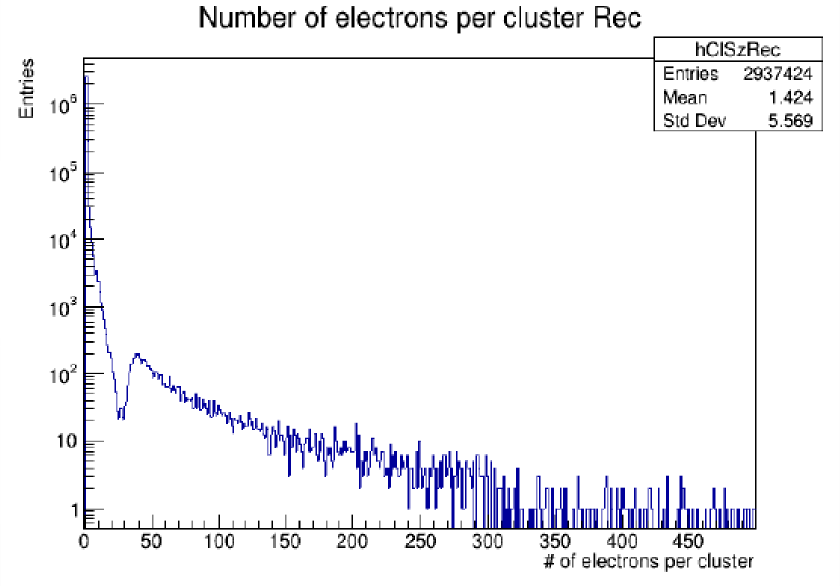
### Evaluate kinetic energy



## First algorithm

The first algorithm uses a reference value of the ratio between clusters containing a single electron and clusters containing more than one electron (Rt). Using the Rt value, the algorithm chooses to create cluster with cluster size one or higher. Then, it assigns the kinetic energy to each cluster by using the proper distributions. If the cluster has more than one electron, a check on the total kinetic energy is performed and its cluster size is evaluated. The procedure is repeated until the sum of primary ionization energy and kinetic energy per cluster saturate the energy loss of the event.




- The peak is almost in agreement with the expected value, but the distribution of number of clusters is not Poissonian, indeed presents a long fake tail.
- The cluster size presents a depression before the value of 50 electrons.

We change the method for algorithm implementation.

## Summary table

| | Ncl | σNcl | Ncl1 | σNcl1 | Nclp | σNclp | maxNclp | #entries of Nclp gen/ #entries of Nclp rec |
|---|---|---|---|---|---|---|---|---|
| expected value | 11.96 | 3.458 | 10.44 | 3.228 | 1.912 | 1.04 | 10.05 | |
| Algorithm | | | | | | | | |
| 1 | 14.69 | 6.959 | 12.85 | 6.426 | 2.157 | 1.25 | 13.5 | 1.082 |
| 2 | 11.53 | 3.612 | 9.225 | 3.633 | 3.448 | 2.602 | 25.5 | 0.899 |
| 3 (without correction) | 10.99 | 3.72 | 9.339 | 3.608 | 2.428 | 1.321 | 14.5 | 0.886 |
| 3 (with correction) | 11.94 | 3.758 | 10.25 | 3.69 | 2.429 | 1.317 | 12.5 | 0.889 |
| 4 | 11.63 | 3.642 | 9.388 | 3.633 | 3.349 | 2.675 | 24.5 | 0.889 |
| 5 | 12.11 | 3.808 | 9.533 | 3.935 | 4.186 | 2.972 | 24.5 | 0.820 |
| 6 | 11.36 | 3.525 | 9.501 | 3.511 | 2.724 | 1.311 | 12.5 | 0.886 |
| 7 | 7.012 | 4.026 | 7.593 | 3.862 | 2.286 | 1.258 | 12.5 | 1.295 |

| | CISz | σCISz |
|---|---|---|
| expected value | 1.705 | 6.498 |
| Algorithm | | |
| 1 | 1.424 | 5.569 |
| 2 | 1.775 | 6.483 |
| 3 (without correction) | 1.828 | 6.695 |
| 3 (with correction) | 1.762 | 6.367 |
| 4 | 1.753 | 6.434 |
| 5 | 1.698 | 6.231 |
| 6 | 1.787 | 6.67 |
| 7 | 2.485 | 9.012 |

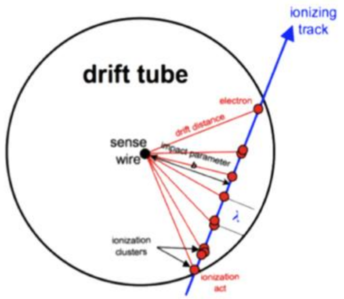
Physics list for geant4

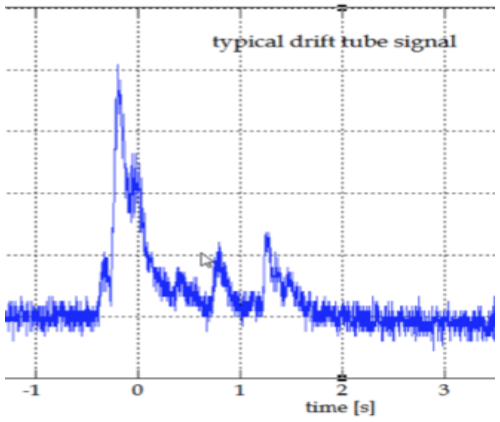
The physics list is “QGSP_BERT” with

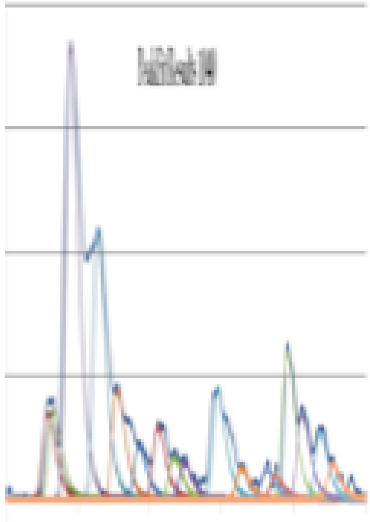
G4EmStandardPhysics_option3(),

G4EmExtraPhysics(), G4DecayPhysics(),G4EmLowEPPhysics().

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: $\{t_i^{cl}\}$ $\quad i = 1, N_{cl}$



## 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

**σ ≈ 4.3%**

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

n=number of sampling layers

## $dN_{cl}/dx$

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

from *Poisson distribution*

$\delta_{cl}$ = 12.5/cm for He/i$C_4H_{10}$=90/10 and a 2m track give

**σ ≈ 2.0%**

A small increment of i$C_4H_{10}$ from 10% to 20% ($\delta_{cl}$ = 20/cm) improves resolution by 20% (σ ≈1.6%) at only a reasonable cost of multiple scattering contribution to momentum and angular resolutions.