The 2022 international workshop on the high energy Circular Electron-Positron Collider

PID performances study with the IDEA Drift Chamber

F. Cuna for the cluster counting team

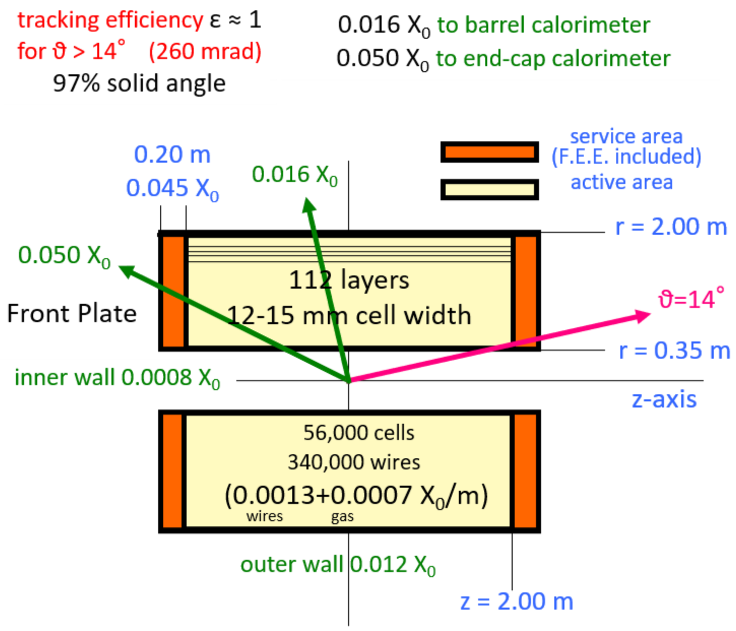
Outline

- The IDEA drift chamber in a nutshell
- Physics motivations for the particle identification
- Particle identification with the dE/dx technique
- Particle identification with the cluster counting technique
- The simulation of the particle identification performances with Garfield++ and Geant4

The 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

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)

MORE INFORMATION:
"The IDEA drift chamber", prof. Nicola De Filippis

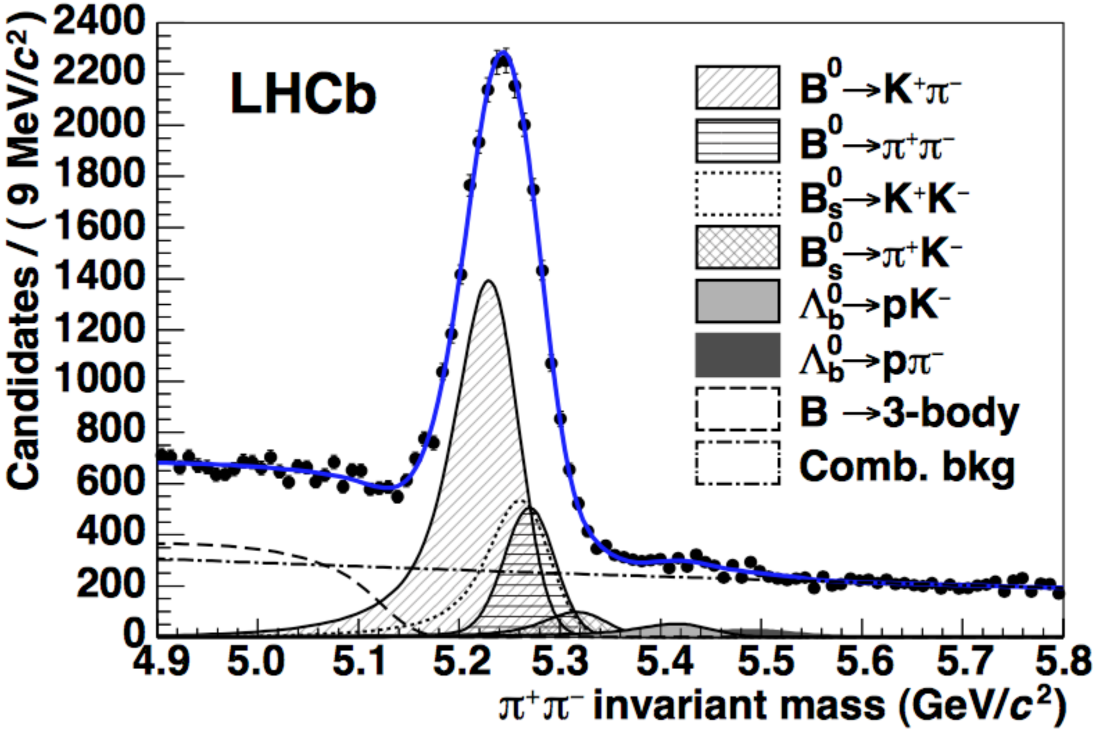
Physics motivations: B decays

Example: 2-prongs B-decays

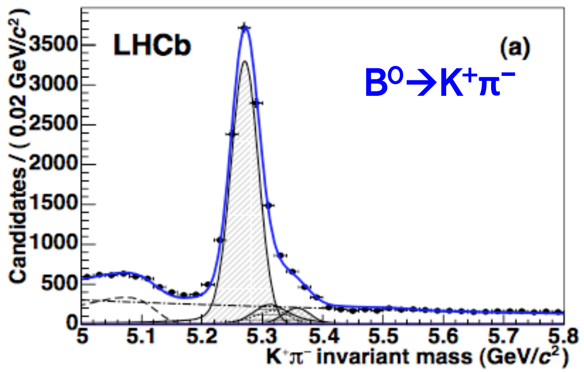
LHCb - JHEP 10 (2012) 037

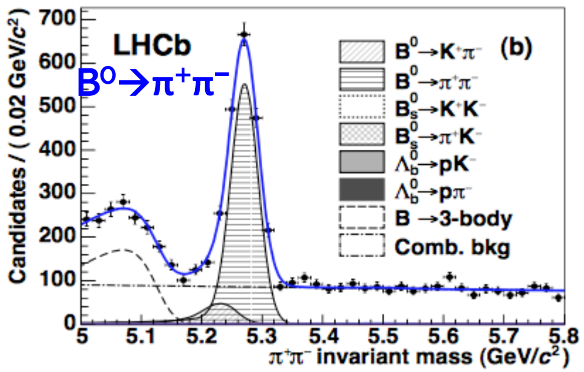
Particle identification mandatory to disentangle different fina states.

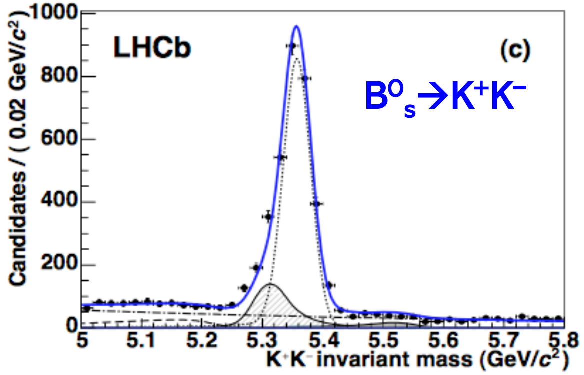
Before PId

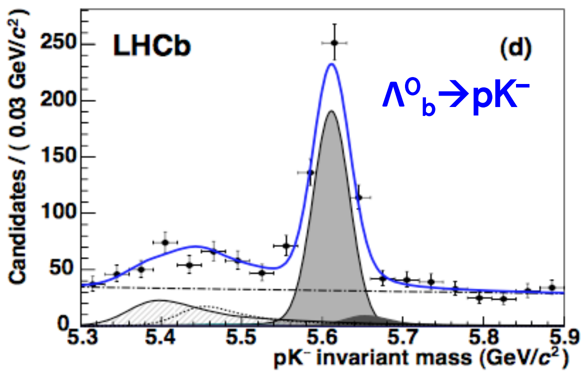


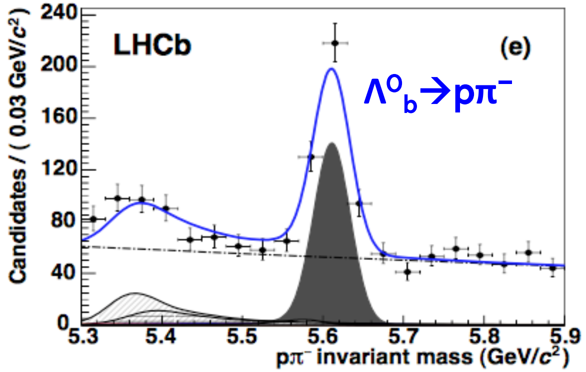
After PId











PId cut efficiencies and misidentifications	$\pi^+\pi^-$	K^+K^-	$K^+\pi^-$	$p\pi^-$	pK^-
$B^0 \to \pi^+\pi^-$	43.1	0.33	28.6	1.53	0.13
$B^0_s \to K^+K^-$	0.05	55.0	15.4	0.05	1.63
$B^0_{(s)} \to K^+\pi^-$	1.40	4.17	67.9	0.72	0.06
$\bar{B}^0_{(s)} \to \pi^+K^-$	1.40	4.17	2.09	0.02	0.85
$\Lambda^0_b \to p\pi^-$	1.93	0.92	16.8	35.4	3.16
$\bar{\Lambda}^0_b \to \pi^+\bar{p}$	1.93	0.92	0.95	0.03	0.18
$\Lambda^0_b \to pK^-$	0.06	12.2	1.92	1.18	40.2
$\bar{\Lambda}^0_b \to K^+\bar{p}$	0.06	12.2	4.51	0.03	0.18

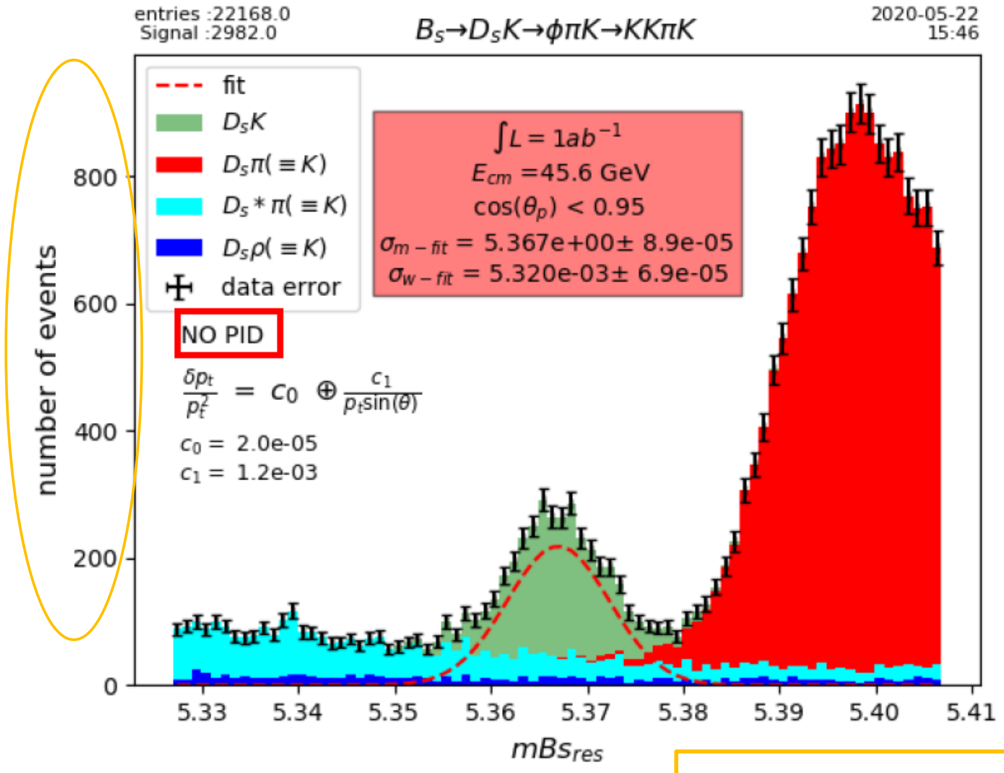
Physics motivations: $B_s \to D_s K$

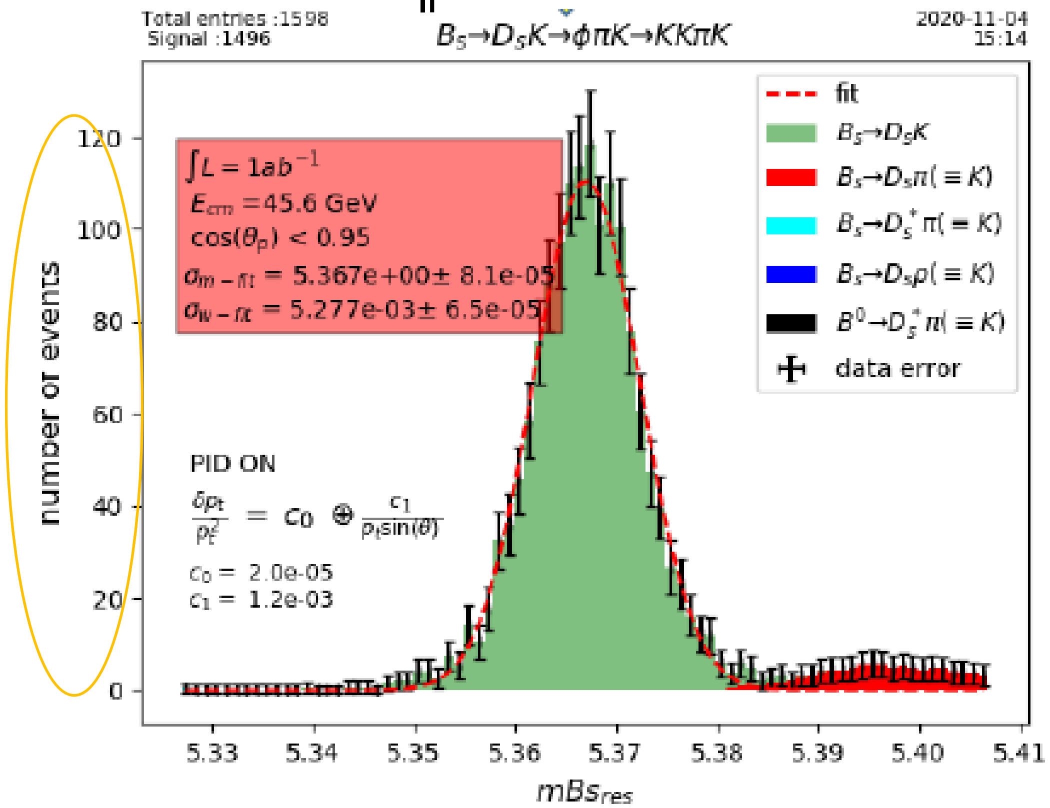
A golden channel to observe the effect of the particle identification.

Without particle identification, great contribution from pion and kaon misidentification.

With a modest PID: ToF + dE/dx

σ(dE/dx)=5%
σ(ToF)=20ps
ToF Detector location : 2m from IP





Note: the number of events is strongly reduced. A σ(dE/dx)~2% will increase this number. Cluster counting will provide a valid alternative

Prof. R.Aleksan talk

Particle identification with the traditional method of dE/dx

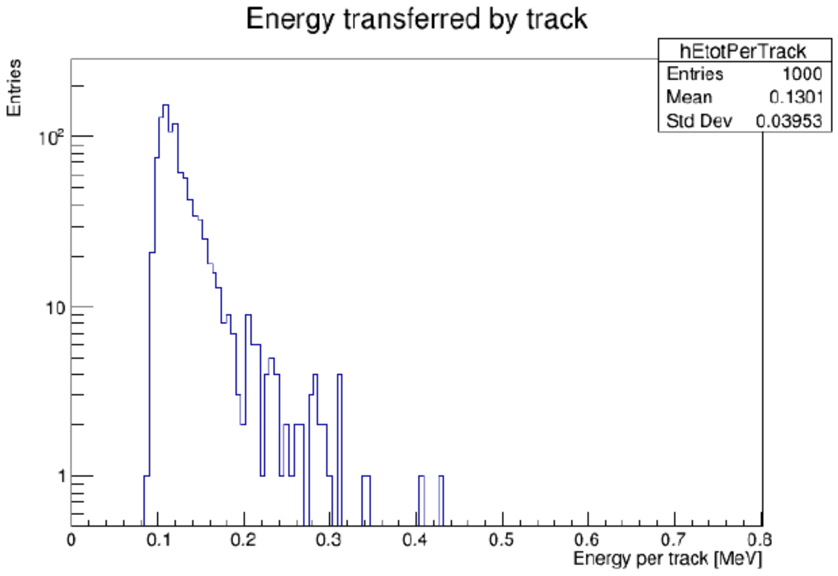
A particle passing through a material undergoes a series of inelastic collisions with the atomic electrons of the material.

As a result, each atom could be excited or ionised, while the particle loses a small fraction of its kinetic energy.

Measurements of the deposited energy are widely used for particle identification.

Gaseous counters provide signals whose pulse height is proportional to the number of electrons produced in the ionization process along the track length inside the detector and thus proportional to the deposit energy.

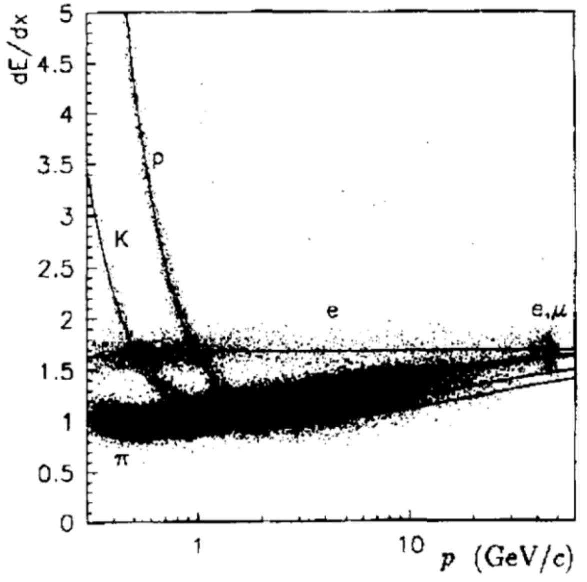
The distribution of the deposit energy follows the *Landau* distribution, since it allows the possibility of large energy transfers in single collisions that add a long tail (*Landau* tail) to the high energy side, resulting in a asymmetric shape whose mean value is significantly higher than the most probable value.

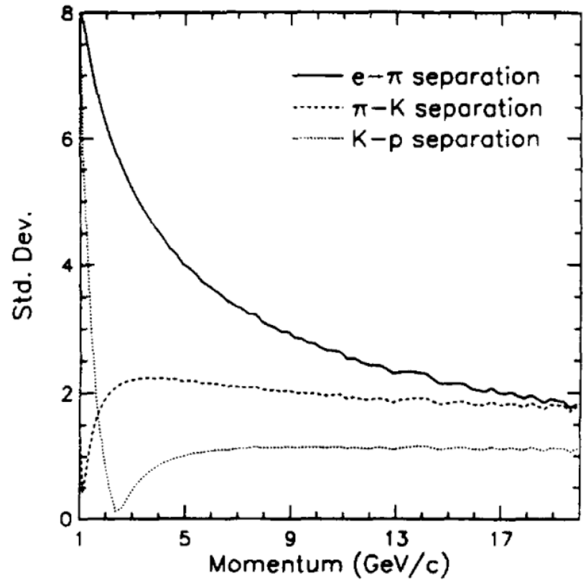


Energy loss distribution of a muon traversing 200 cells, 1 cm per side, filled with 90 % He and 10% iC_4H_{10} simulated by Garfield++.

The **mean value** is not a good estimator for the energy deposition and usually a truncated mean (typically from 40 % up to 80 %) is used.

ALEPH





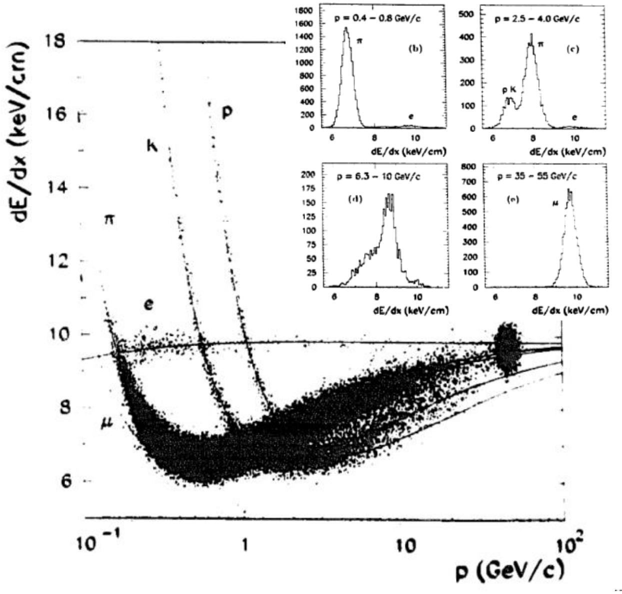
TPC (Argon based gas mixture)

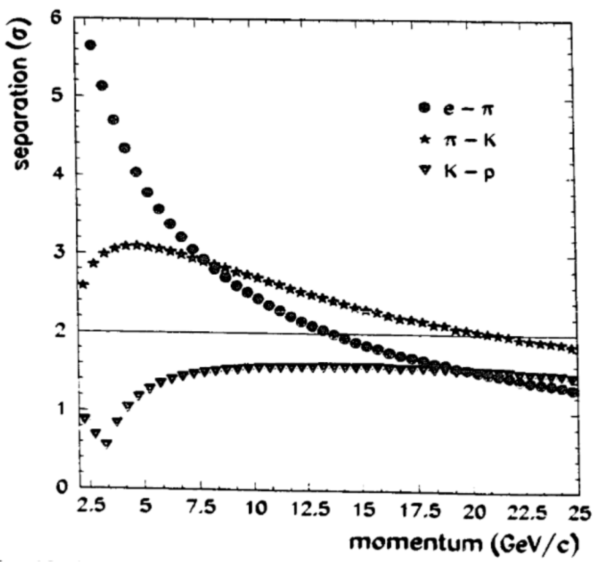
two-sided truncated mean:
discard lowest 8% and largest 40%

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 1.19 N^{-0.5} (dx/w_0)^{-0.4} \left[(dE/dx)/(dE/dx)_{mip}\right]^{-0.4}$$

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 4.5\%$$

OPAL





Drift Chamber (Argon based gas mixture at 4 bar)

hit quality cuts and truncated mean:
discard largest 30%

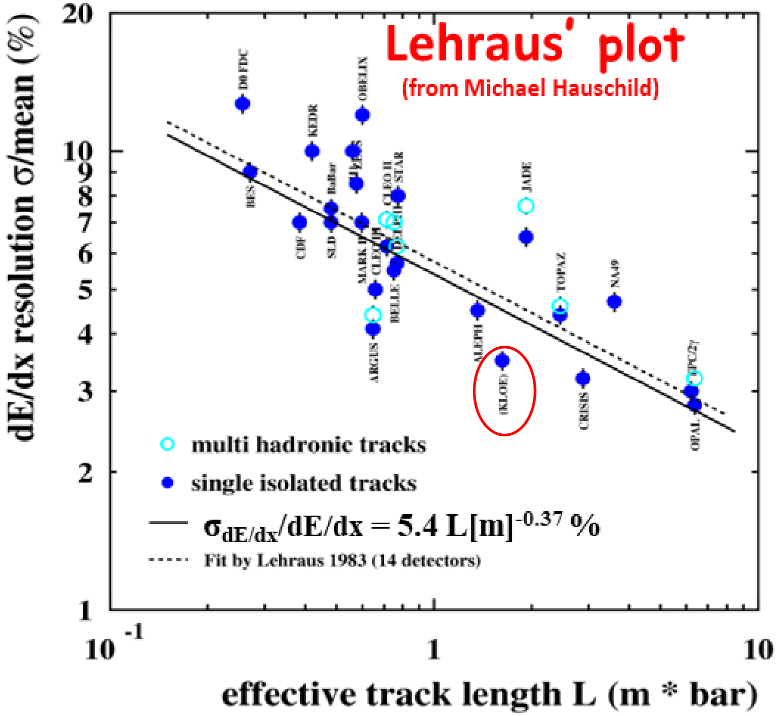
$$\frac{\sigma_{dE/dx}}{(dE/dx)} \propto N^{-0.43}$$

$$\frac{\sigma_{dE/dx}}{(dE/dx)} = 3.1\% \text{ (dimuons)},\ 3.8\% \text{ (m.i.p.)}$$

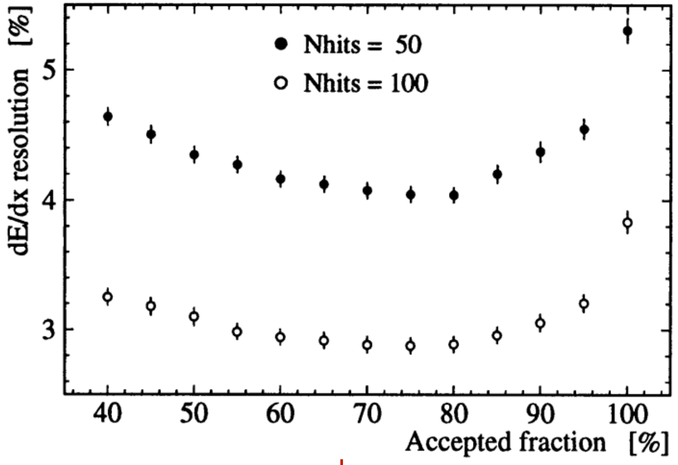
But… the use of a pressure at 4 bar is not suitable for efficient tracking performances

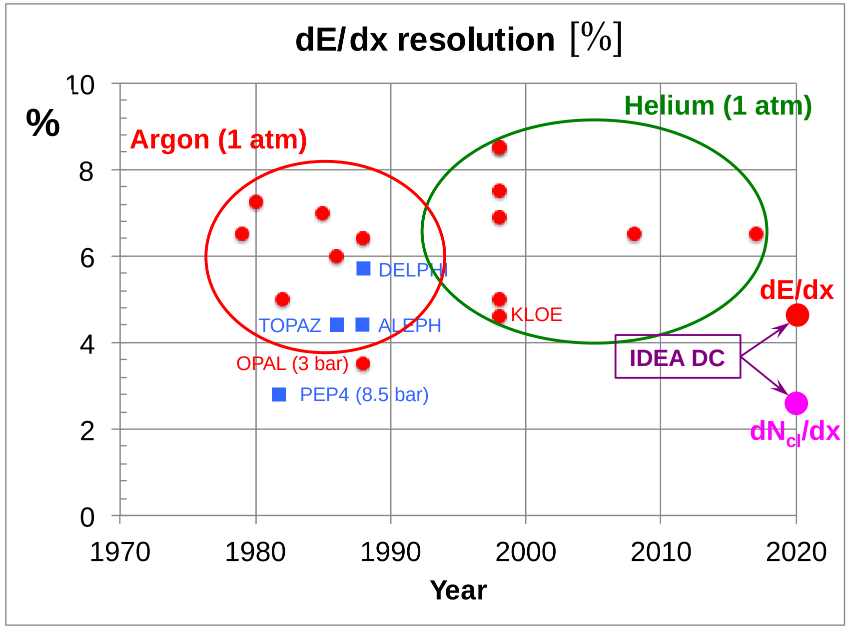
Historical evolution of the particle identification with dE/dx

First attempt by Ivan Lehraus in 1983 to connect dE/dx resolution and detector size (effective detector length L = track length * pressure)



Dependence of dE/dx resolution vs. truncated mean fraction and number of samples (KLOE: He mix.)





KLOE DRIFT CHAMBER: helium based gas mixture

- Helium mixtures (less multi-electron clusters) need less truncation than Argon mixtures
- Resolution obtained is slightly above 2% by using 100 sample, an accepted fraction of 70% and helium based gas mixture.

Particle identification with the cluster counting technique

The large and intrinsic uncertainties in the total energy deposition represent a limit to the particle separation capabilities.
Cluster counting technique can improve the particle separation capabilities!!!

The advantages of cluster counting with helium based gas mixture

Ncl number of primary ionizations is:

- independent from cluster size fluctuations
- insensitive to highly ionizing δ-rays
- independent from gas gain fluctuations
- a 2 m track in a He – mix gives Ncl > 2400 (for a m.i.p.):
  $\sigma_{dNcl/dx}/(dNcl/dx) = Ncl^{-1/2} < 2.0\%$ (at 100% counting efficiency)
- a factor > 2 better than dE/dx
- resolution scales with $L^{-0.5}$ (not $L^{-0.37}$ as in dE/dx)

Advantages of Helium

- low primary ionization density → large time separation
- low drift velocity → even larger time separation
- low average cluster size
- low single electron diffusion

Recipe

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

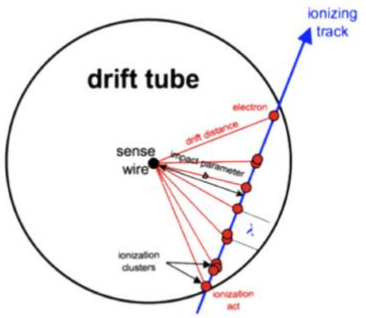
In order to apply the cluster counting technique, two main requirements have to be met:

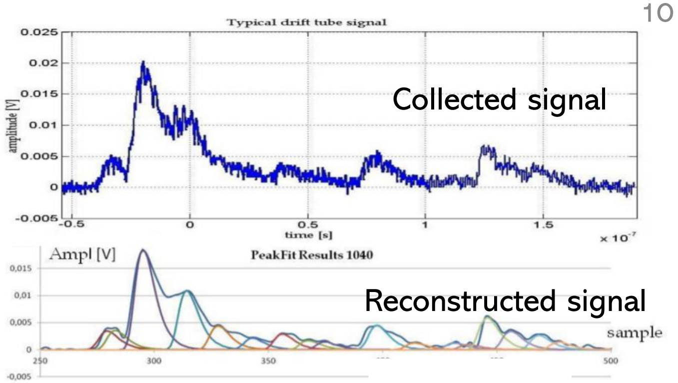
1. Pulses from electron belonging to different clusters must have a little chance of overlapping in time,
2. The time distance between electrons coming from the same cluster must be small enough to prevent overcounting.

Particle identification with the cluster counting technique

A conceptually simply procedure

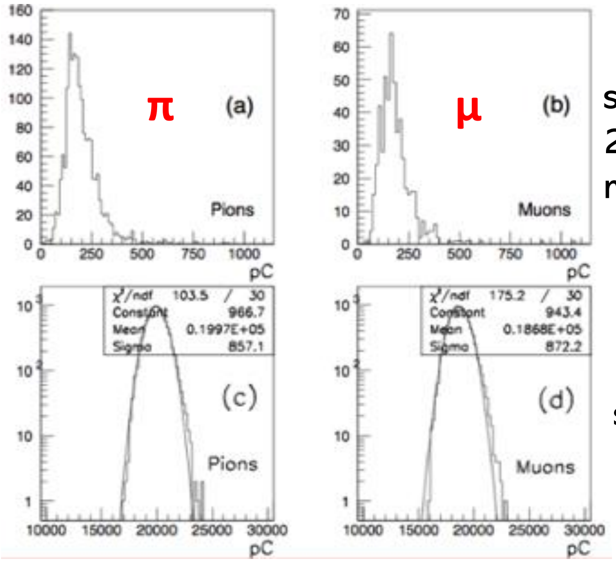
Singling out, in ever collected detector signal, the isolated structures related to the arrival on the anode wire of the electrons belonging to a single ionization act (dN/dx).





A first test beam was performed at the PSI of Villigen to prove the feasibility of a primary cluster counting measurement in a conventional drift detector filled with helium based gas mixture.

μ/π separation at 200 MeV/c in He/iC_4H_{10} – 95/5 100 samples 3.7 cm gas gain 2×10^5, 1.7 GHz – gain 10 amplifier, 2GSa/s – 1.1 GHz – 8 bit digitizer



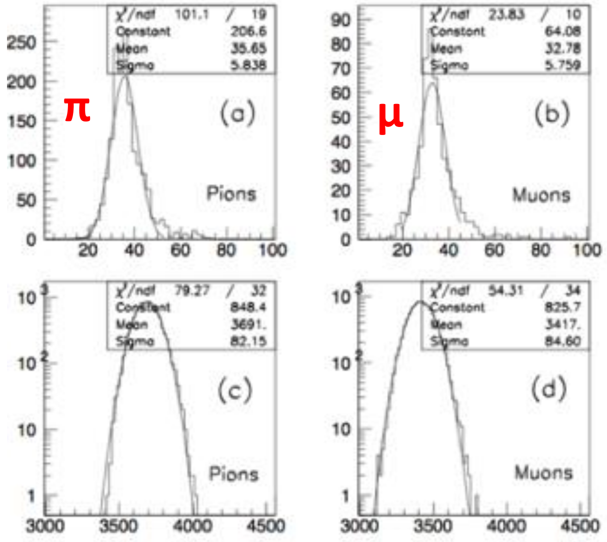
single sample 20% truncated mean

sum over 100 samples

integrated charge

expected 2.0 σ separation

measured 1.4 σ separation



single sample

π: σ/√N_cl=0.978

μ: σ/√N_cl=1.006

sum over 100 samples

π: σ/√N_cl=1.35

μ: σ/√N_cl=1.45

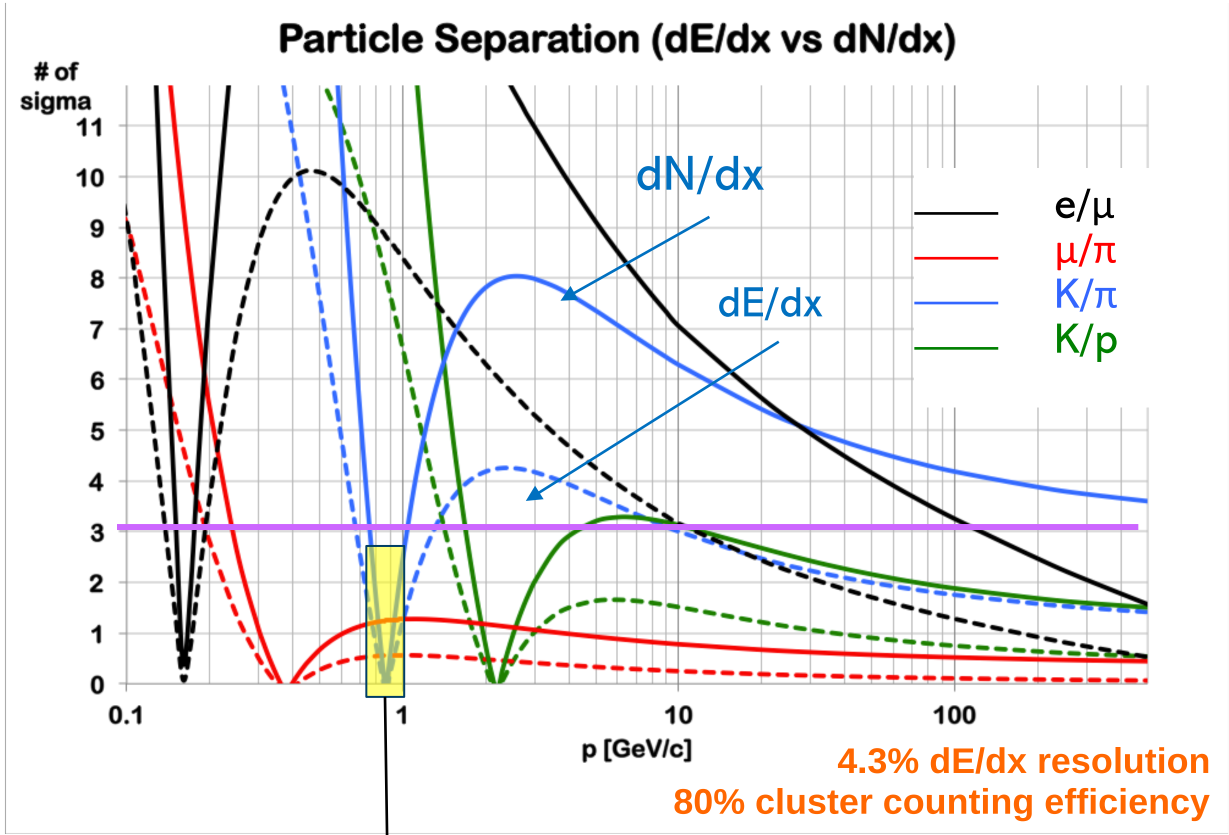
cluster counting

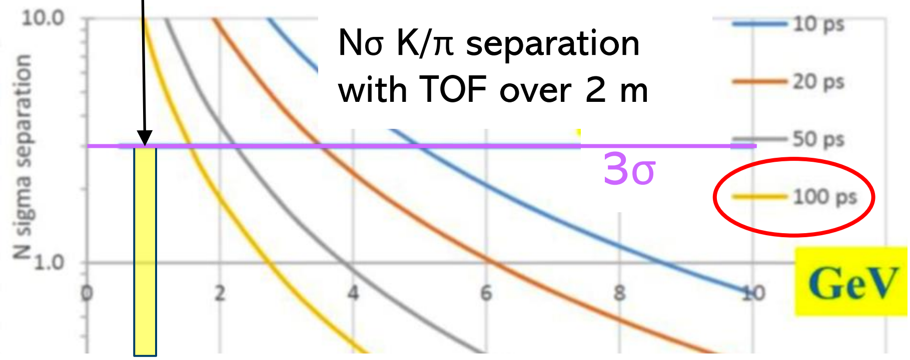
expected 5.0 σ separation

measured 3.2 σ separation

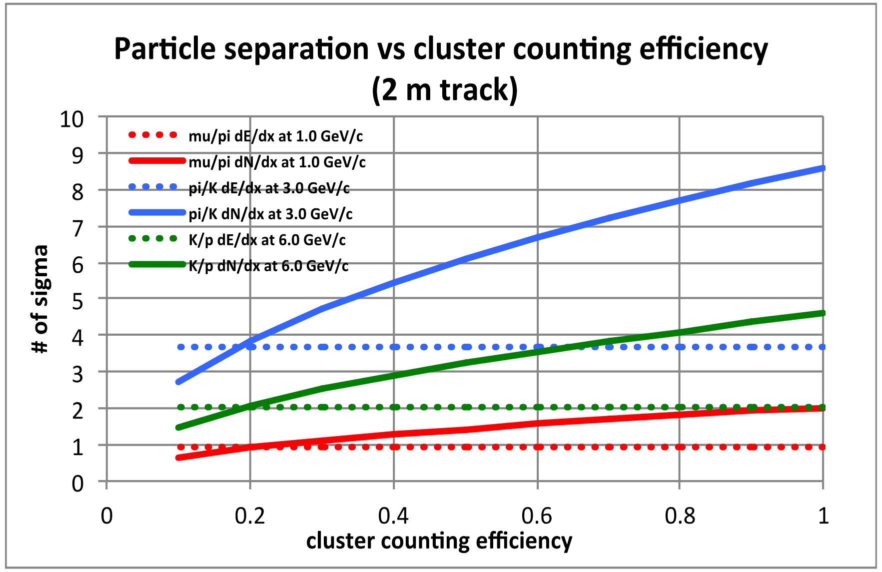
Cluster Counting/Timing Techniques for drift chambers, M. Cascella, F. Grancagnolo, G. Tassielli, Nuclear Physics B-Proceedings Supplements

The cluster counting technique: expected performances





- 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

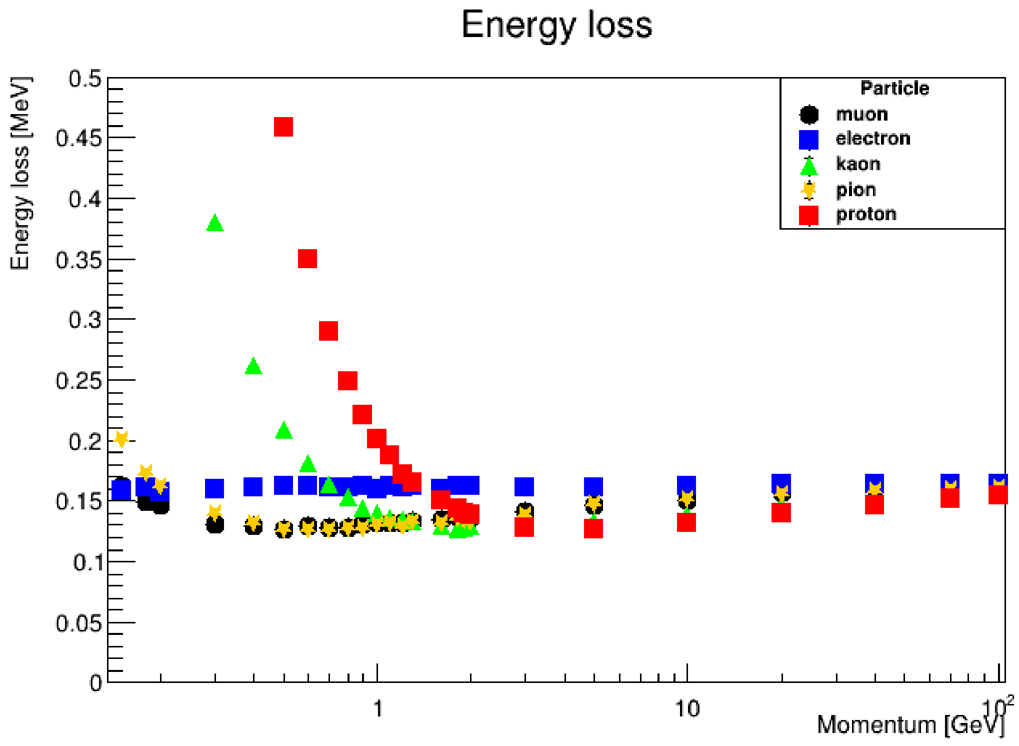


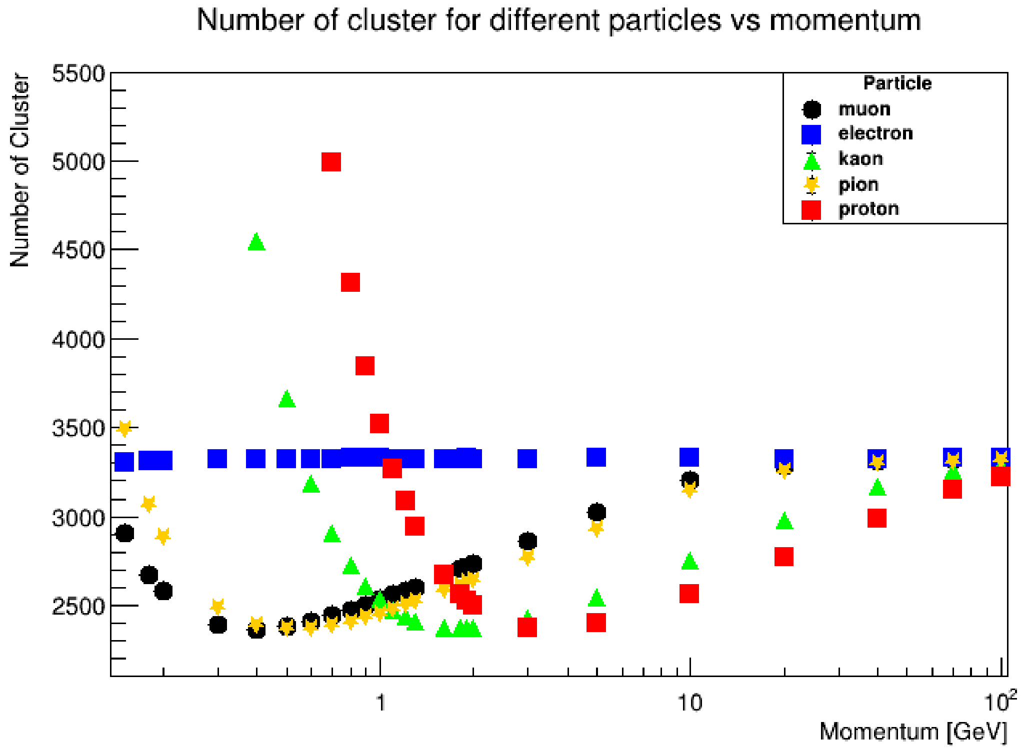
Analytic evaluation, prof F.Grancagnolo
To be checked with simulations and experimental data

Cluster counting for particle identification: simulation results

A simulation of the ionization process in 1 cm long side cell of 90% He and 10% iC_4H_{10} has been performed in **Garfield++** and **Geant4**.
Geant4 software can simulate in detail a full-scale detector, but the fundamental properties and the performances of the sensible elements have to be parameterized or an "ad hoc" physics model has to be implemented.

Starting point: studying the clusters number distribution and the energy loss distribution for muons, pions, electrons, protons and kaons in a range of momentum from 200 MeV up to 1 TeV in Garfield++



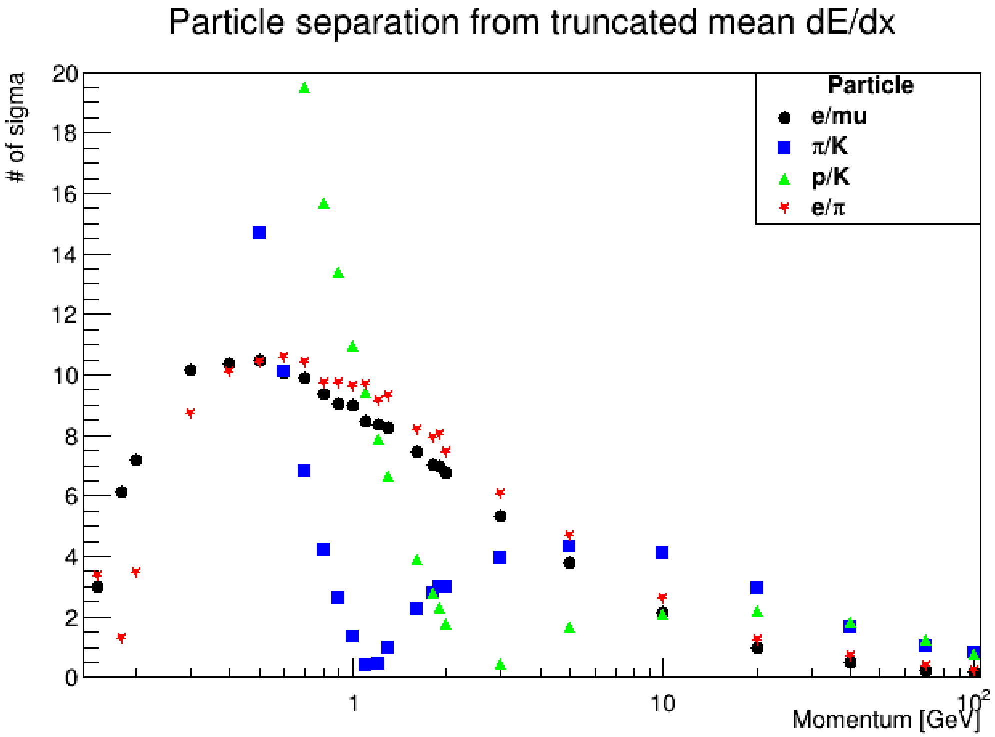


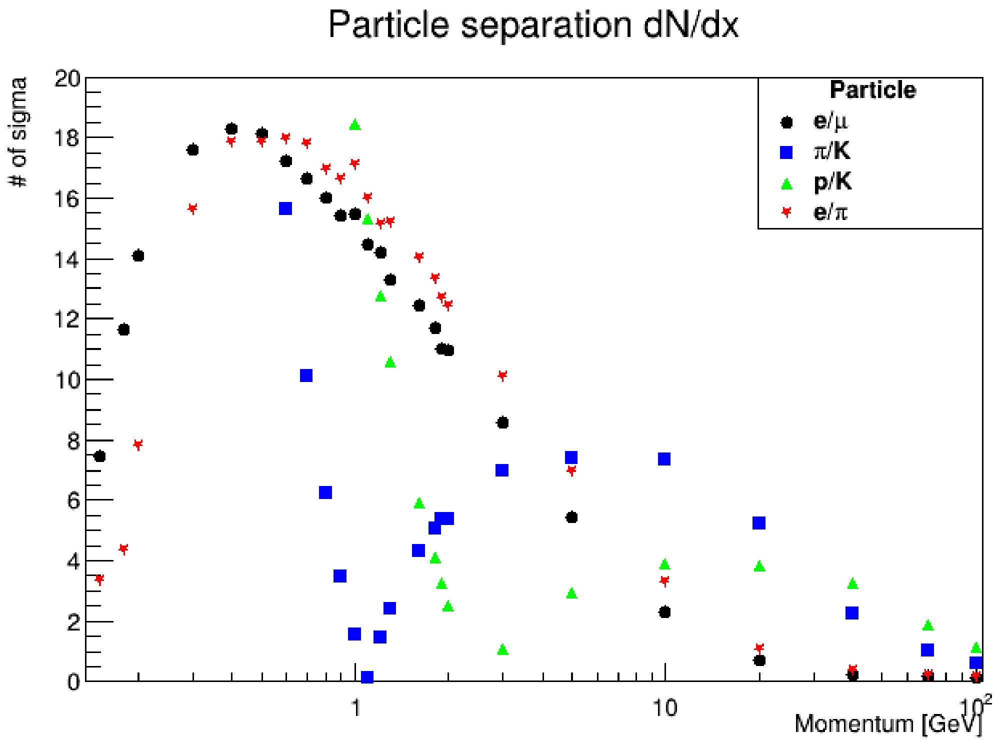
F.Cuna, N.De Filippis, F.Grancagnolo, G.F.Tassielli, **Simulation of particle identification with the cluster counting technique**, proceeding at LCWS2021

Simulations of the particle identification in Garfield++

Then we evaluated the particle separation power implementing both methods:

- the dE/dx with a truncated mean of 70 %
- the dN/dx



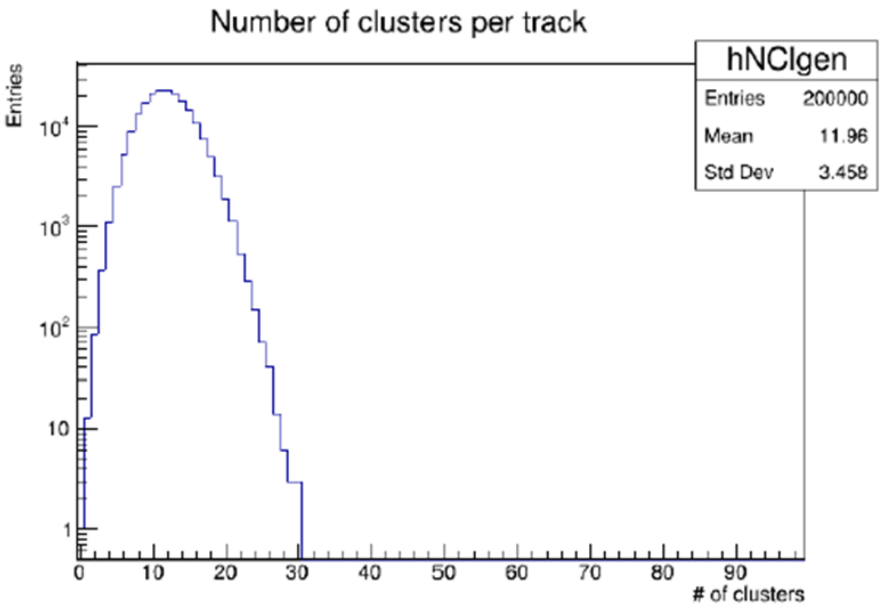


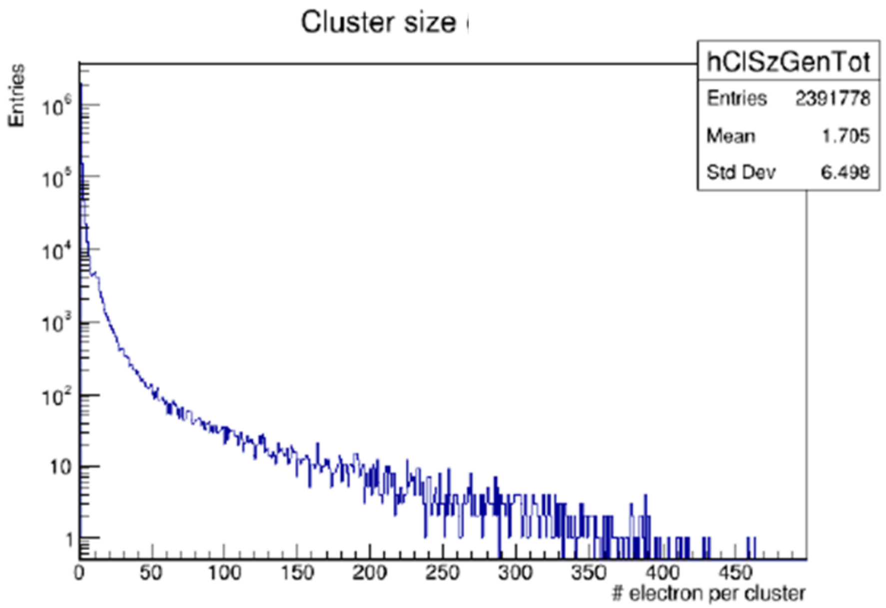
Simulations results confirm that the cluster counting gives better performances than dE/dx.
Our goal is to obtain the same results by using *Geant4.*

Simulations of the particle identification in Geant4: the algorithm

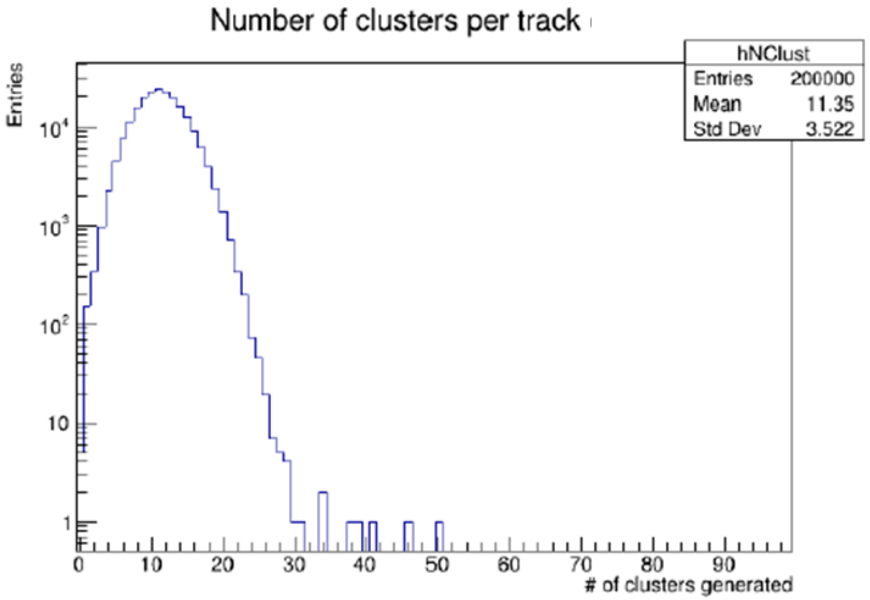
Three different algorithms have been implemented to simulate in Geant4, *in a fast and convenient way*, the number of clusters and clusters size distributions, using the energy deposit provided by Geant4.

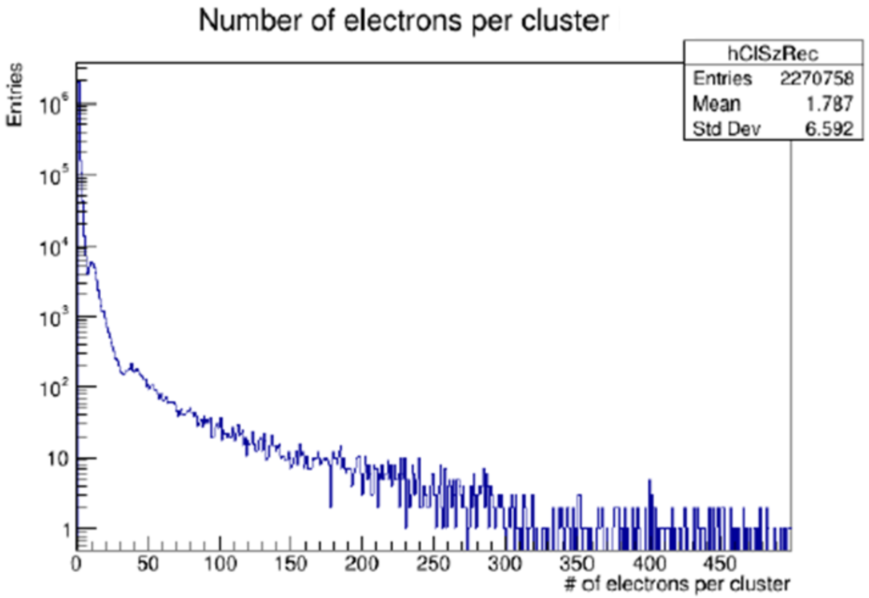
Garfield++ simulation





Example of an algorithm reconstruction

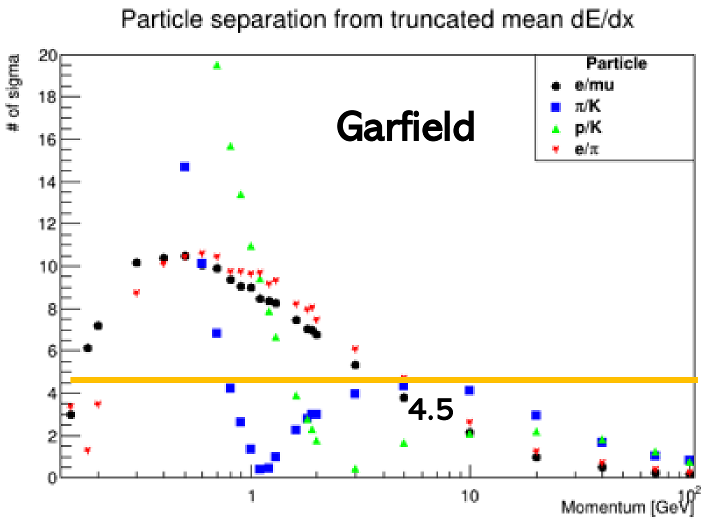


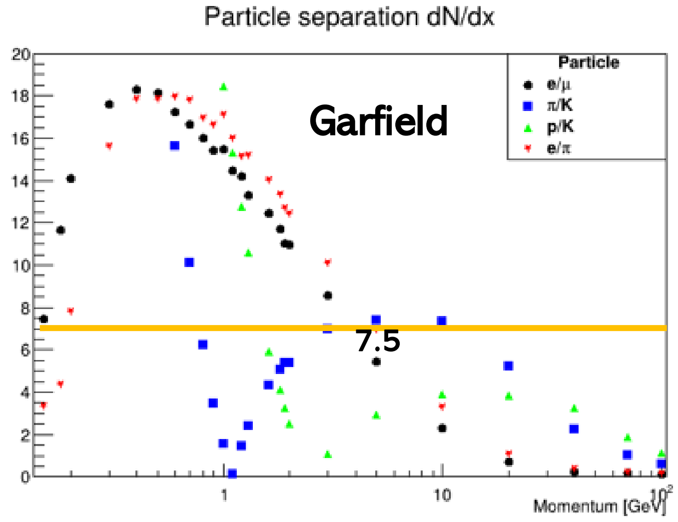


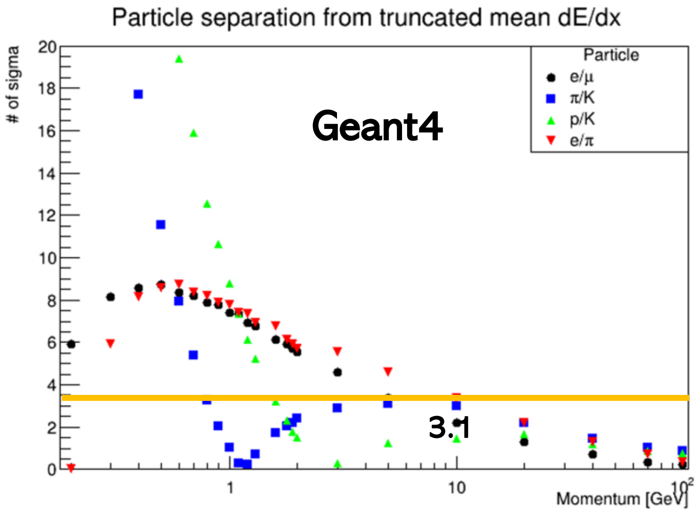
Muon at 300 MeV

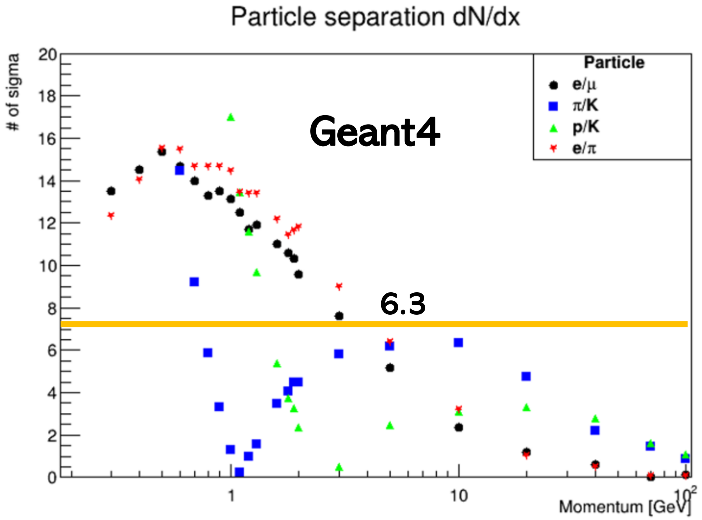
Cluster counting for particle identification: PId results

We implemented in Geant4 one of the three version of the algorithms, which give consistent results with the ones simulated by Garfield++.







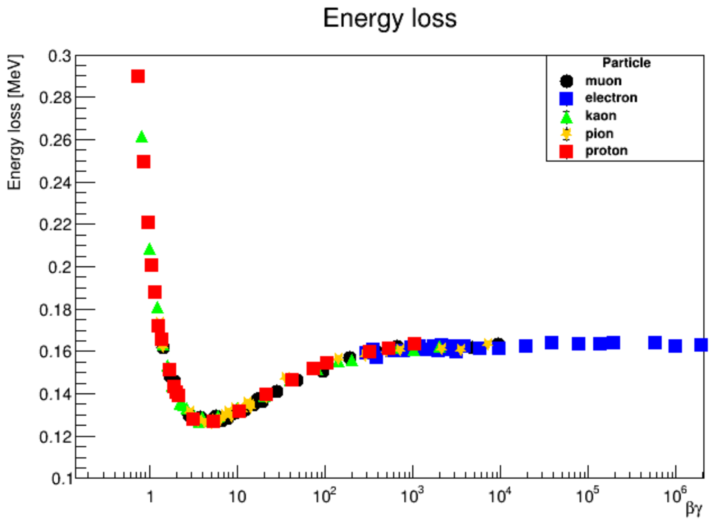


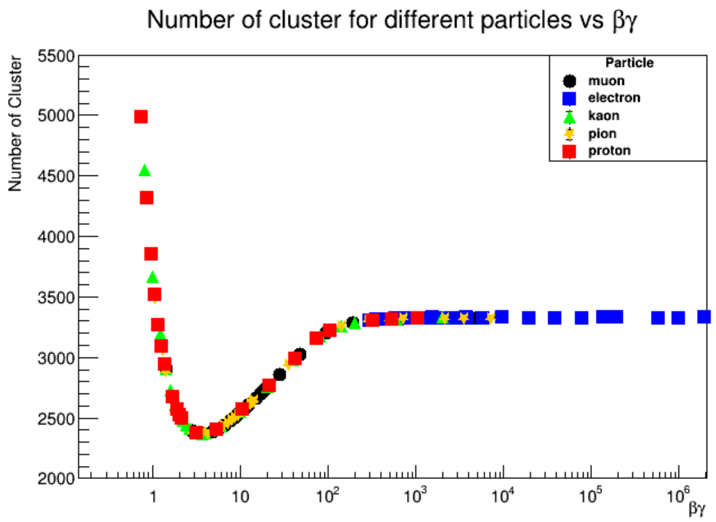
The simulations confirm the factor 2 better than the dE/dx, besides the performances given by Geant4 are slightly different from the ones simulated by Garfield++.

We are assuming a cluster counting efficiency of 100%.

Motivations for a beam test

- Lack of experimental data on cluster density and cluster population for He based gas, particularly in the relativistic rise region to compare predictions.
- Despite the fact that the Heed model in GEANT4 reproduces reasonably well the Garfield predictions, why particle separation, both with dE/dx and with dNcl/dx, in GEANT4 is different from Garfield?
- Despite a higher value of the dNcl/dx Fermi plateau with respect to dE/dx, why this is reached at lower values of βγ with a steeper slope?

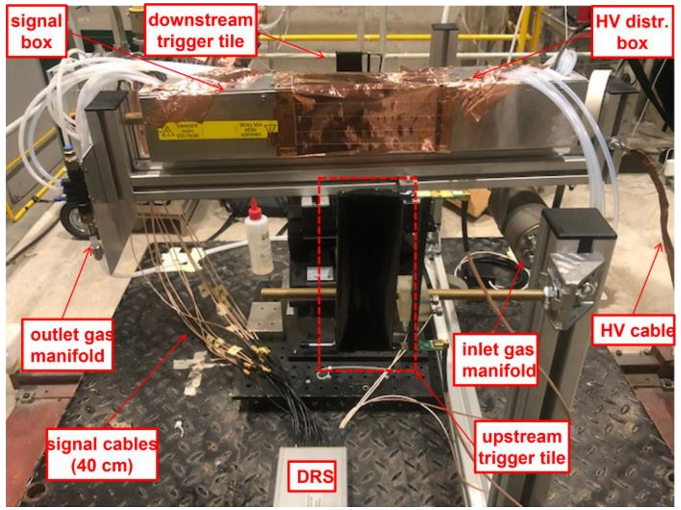


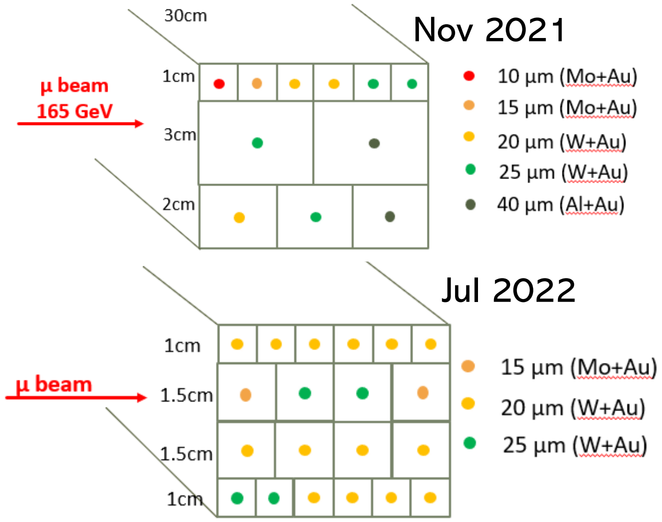


These questions are crucial for establishing the particle identification performance at FCCee, CEPC.

The only way to solve these issues is an experimental measurement!

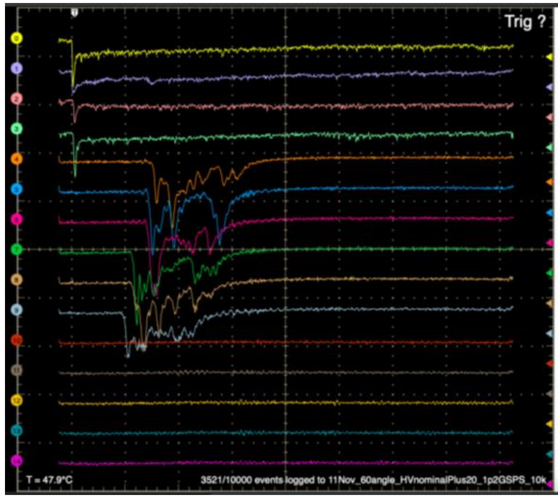
Beam tests to validate the simulations results





A "minimal" setup

- A pack of drift tubes
- DRS for data acquisition
- Gas mixing, control and distribution (He and iC_4H_{10})
- 2 trigger scintillators



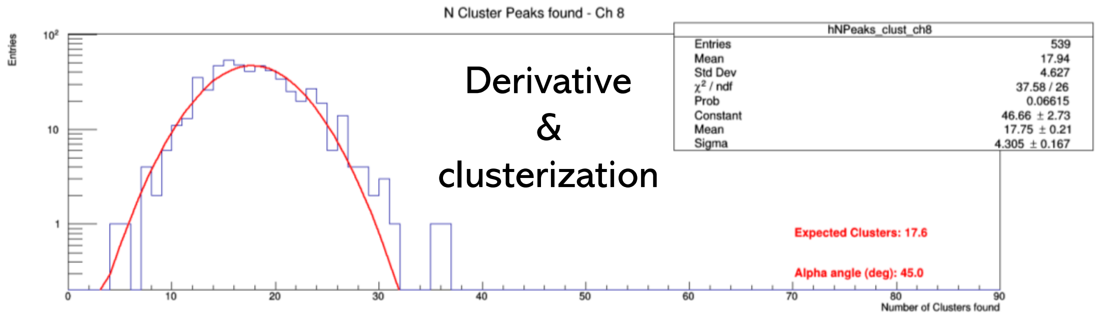
Two algorithms for peaks finding:

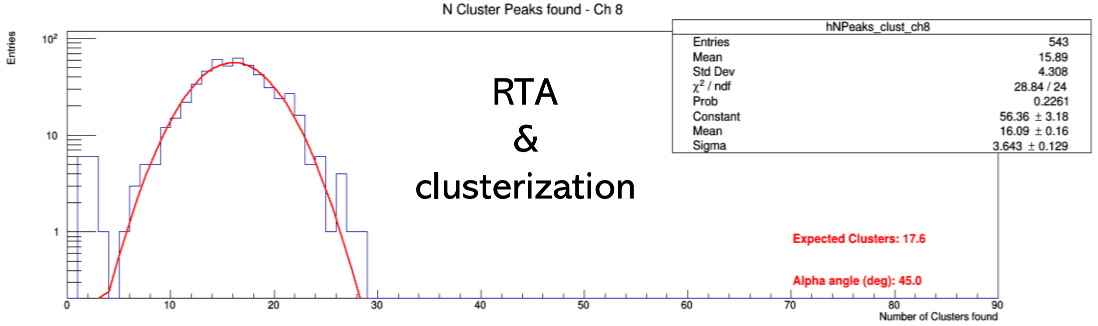
- Derivative algorithm
- Running template algorithm (RTA)

An algorithm to associate the peaks found in clusters:

- Clusterization algorithm

More information:
Beam tests results on cluster counting, Brunella D'Anzi





Poissonian nature

Conclusions

- Particle identification via dE/dx has essentially made no progress since over 40 years.
- Cluster counting could be a valid alternative to improve the PId capabilities
- Both analytical and montecarlo simulations suggest an improvement of a factor 2 of dN/dx versus dE/dx.
- Absolute performance of particle separation power in the relativistic region (crucial for FCC-ee and CEPC) needs to be assessed with experimental measurements.
- A strongly motivated beam test campaign has begun. We are concentrating our efforts in demonstrating the ability to efficiently count ionization clusters. The data analysis is ongoing (see Brunella D'Anzi talk).
- The simulation will be implemented in the full simulation of the IDEA drift chamber.

Thank you

The cluster counting team

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