Particle identification with the cluster counting technique in the IDEA drift chamber

F. Cuna for the cluster counting team

Istituto Nazionale di Fisica Nucleare

International Conference of High Energy Physics

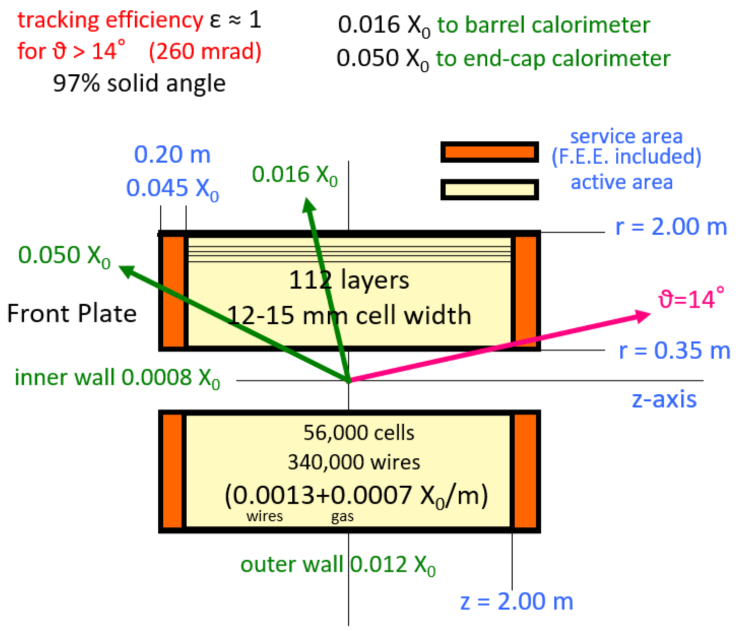
Outline

- The IDEA drift chamber: an innovative and high-performing tracker
- The cluster counting technique: a promising method for the particle identification
- The simulations results with Garfield++ and Geant4: first hint of great results
- A test beam for the validation of the great expectations
- Preliminary results: the algorithms to count clusters

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)

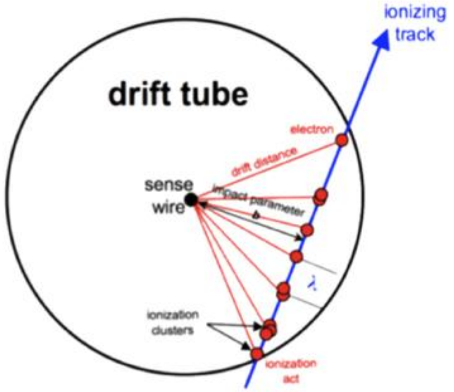
MORE INFORMATION:
https://indico.cern.ch/event/656491/contributions/2939121/attachments/1629781/2597342/IDEA-CDCH_FCCweek18.pdf

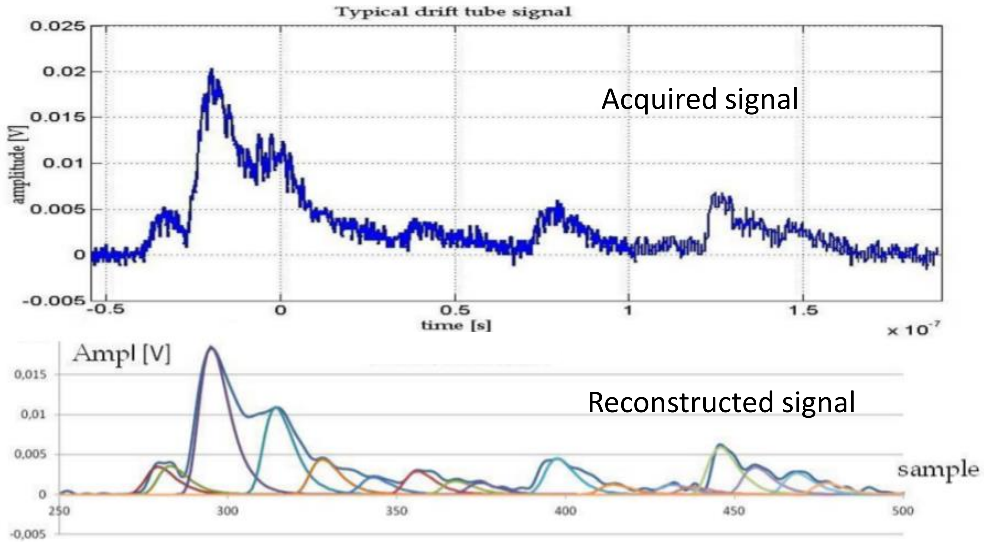
The cluster counting technique

Using the information about energy deposit by a track in a gaseous detector, particle identification can be performed.
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!!!

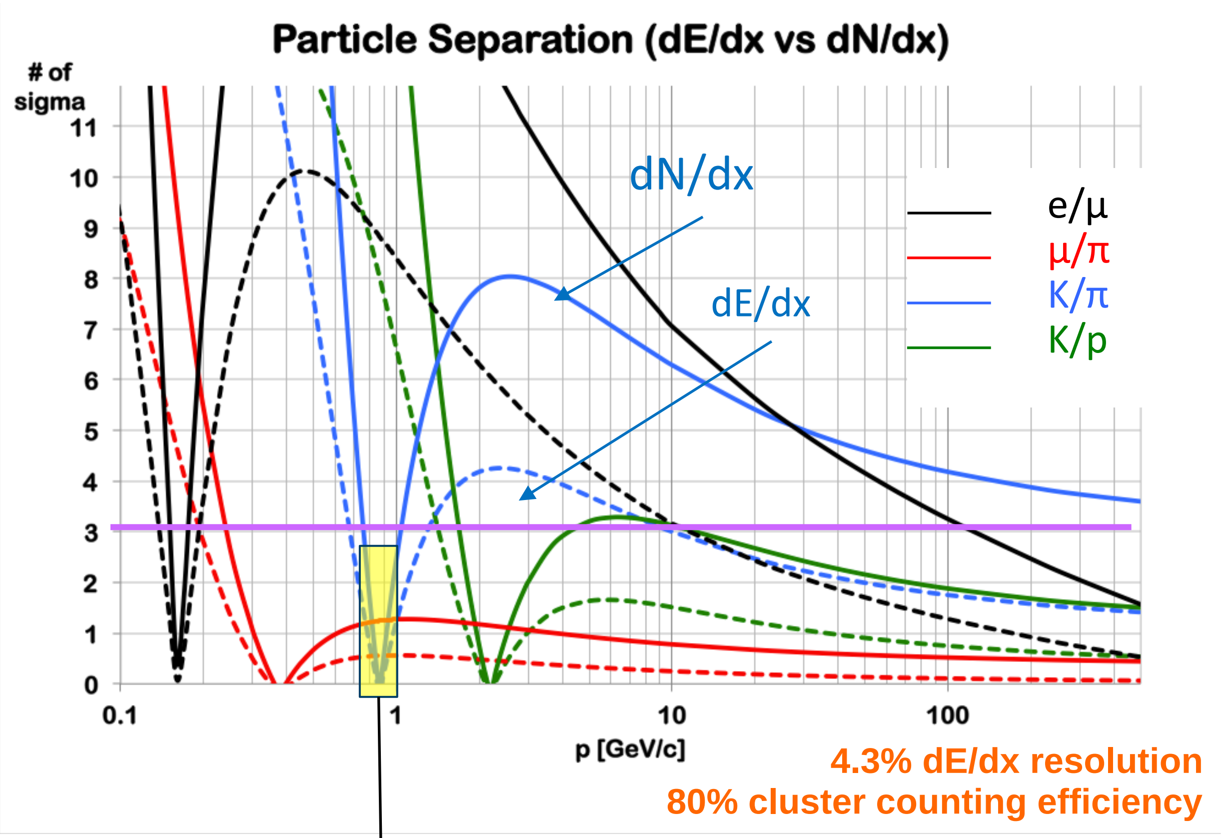
The method consists in singling out, in ever recorded detector signal, the isolated structures related to the arrival on the anode wire of the electrons belonging to a single ionization act (dN/dx).

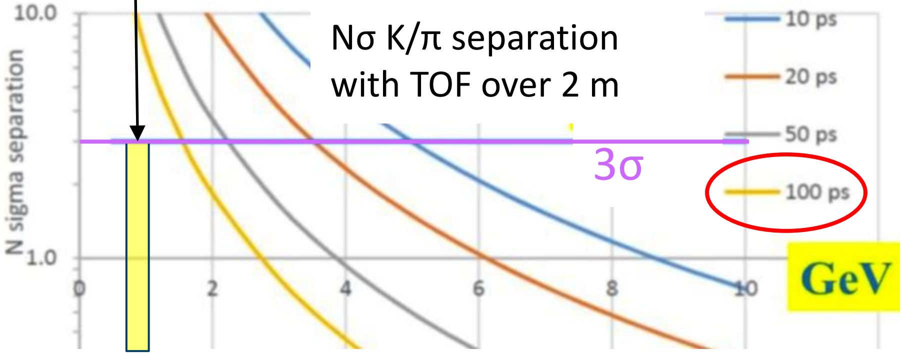




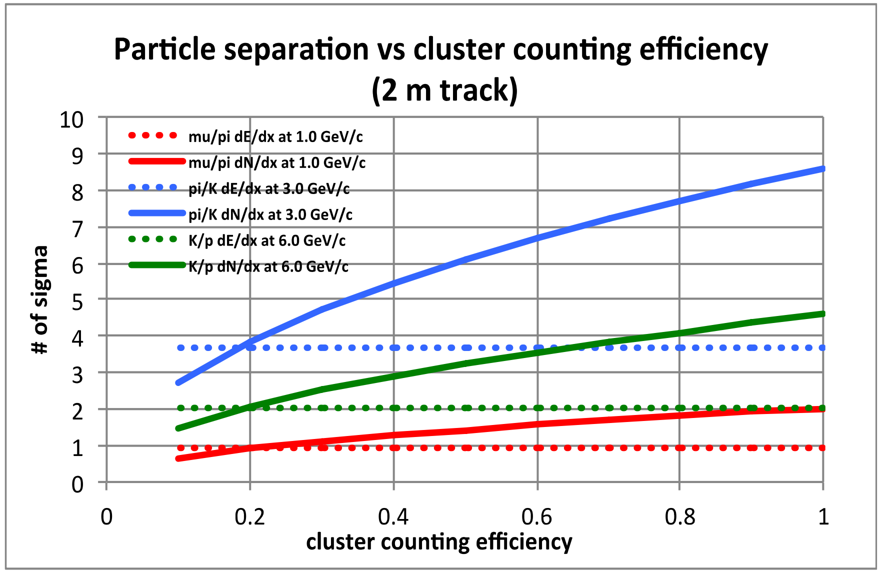
dE/dx	dN_{cl}/dx
Truncated mean cut (70-80%) reduces the amount of collected information n ≈ 100 and a 2m track at 1 atm give **σ ≈ 4.3%**	δ_{cl} = 12.5/cm for He/iC_4H_{10}=90/10 and a 2m track give **σ ≈ 2.0%**

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}

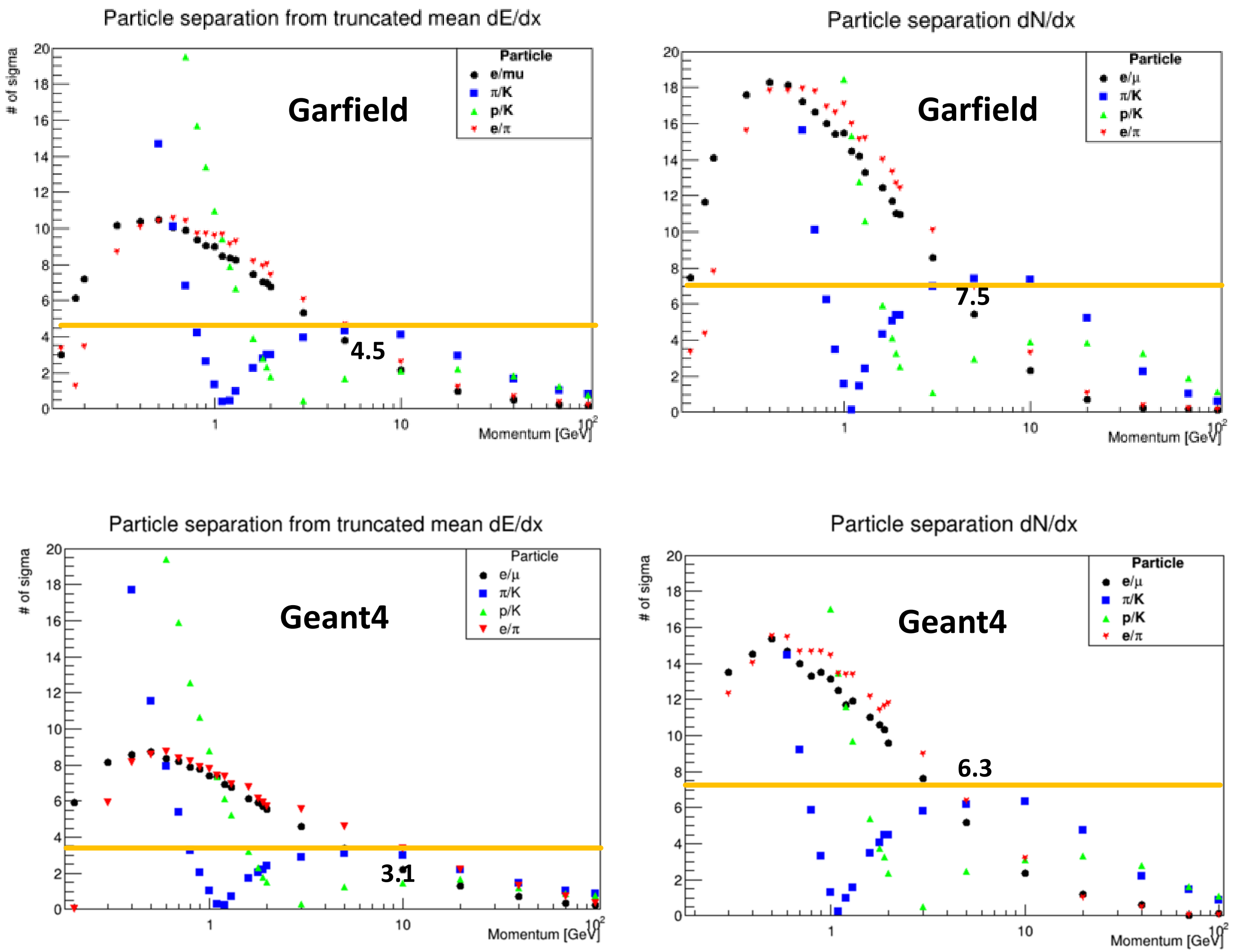
has been performed in **Garfield++** and **Geant4**.

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.

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.

The simulations confirm the predictions: a factor 2 better than dE/dx !

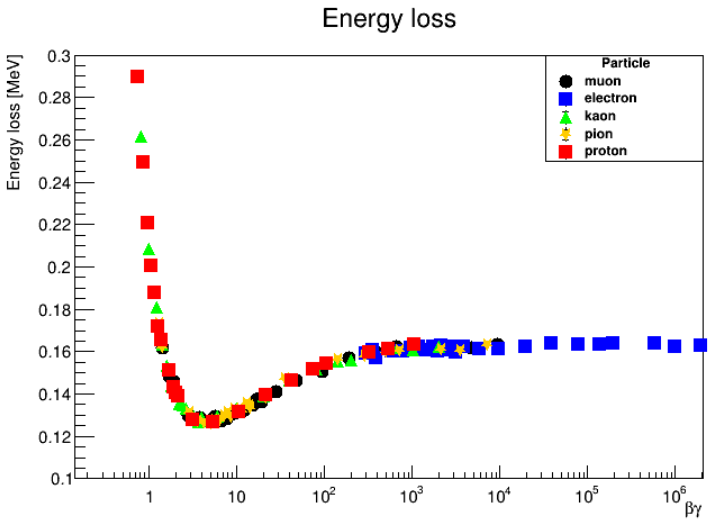
But…

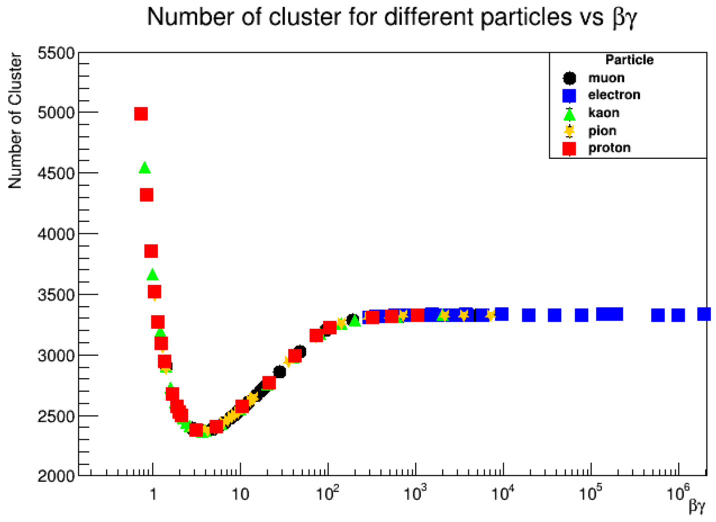


We are assuming a cluster counting efficiency of 100%.

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 dN/dx, in GEANT4 is considerably worse than in 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.

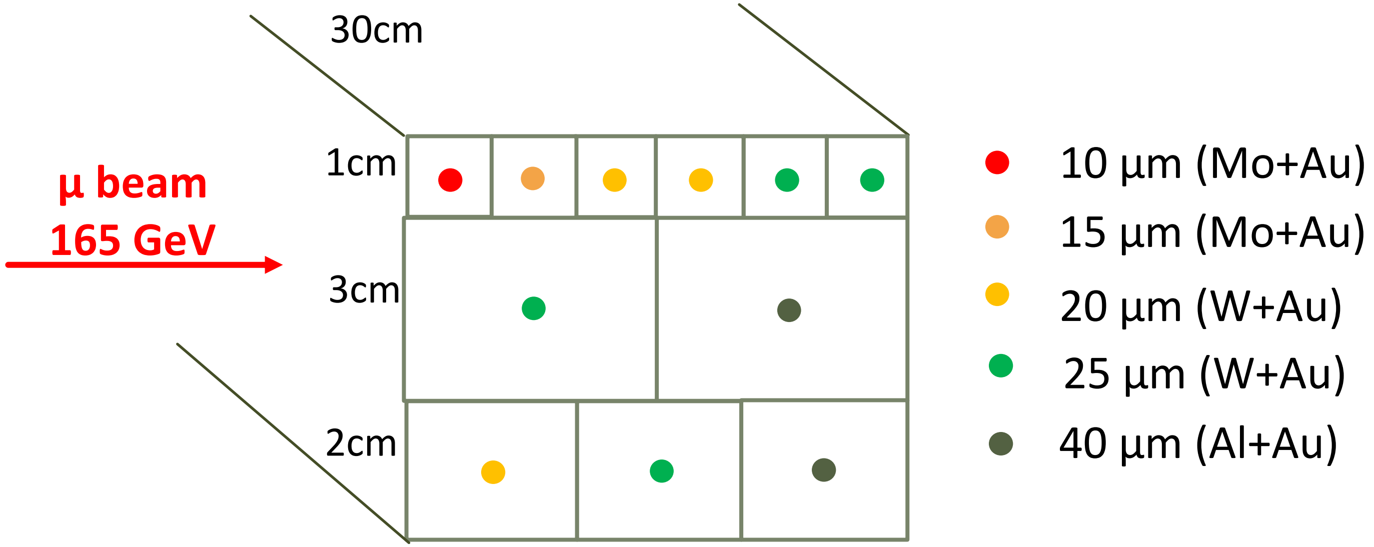
The only way to solve these issues is an experimental measurement! So we planned a test beam in 2 part:

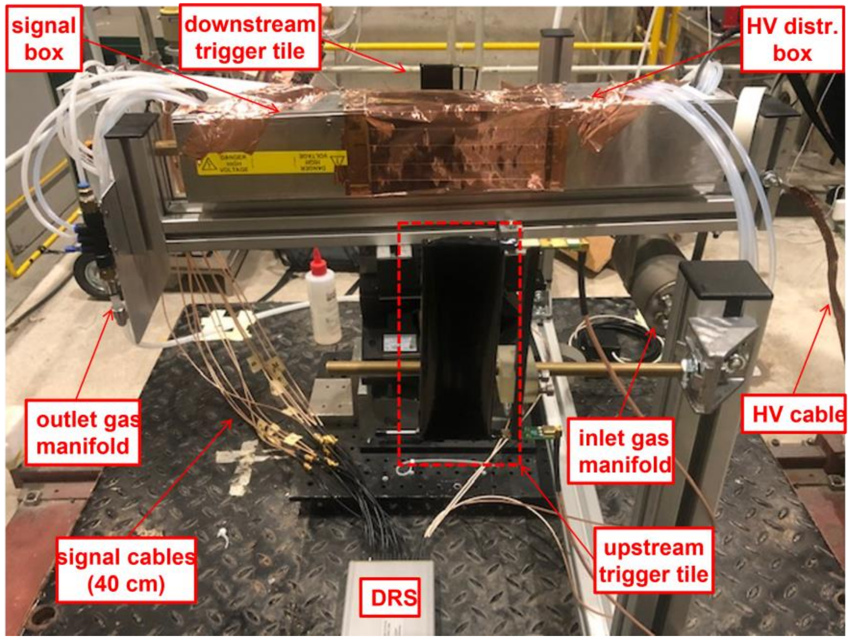
1) **November 2021**: demonstrate the ability to count clusters at different gas mixtures and with different drift cell size, different wire material and different wire diameter.
2) **July 2022:** measure the relativistic rise as a function of βγ, both in dE/dx and in dN/dx, by scanning the muon momentum from the lowest to the highest value (from 40 GeV/c to about 180 GeV/c at CERN/H8).

Experimental set up

Keep it simple!

11 drift tubes with different cell size and different material wires and diameter wires, to test different configurations.





The set up consists of:

- **6 drift tubes 1 cm × 1 cm × 30 cm**
  - **1 with 10 μm sense wire, 1 with 15, 2 with 20 μm, 2 with 25 μm**
- **3 drift tubes 2 cm × 2 cm × 30 cm**
  - **1 with 20 μm sense wire, 1 with 25 μm, 1 with 40 μm**
- **2 drift tubes 3 cm × 3 cm × 30 cm**
  - **1 with 20 μm sense wire, 1 with 40 μm**
- DRS for data acquisition
- Gas mixing, control and distribution (only He and iC_4H_{10})
- 2 trigger scintillators

The connecting scheme

SY 1527 Mainframe | 1535P 24ch | CAEN A996 Radiall 691803004 | 24 leads HV cable | HV distribution board | connecting pin | drift tube end cap | connecting pin | HV decoupling board

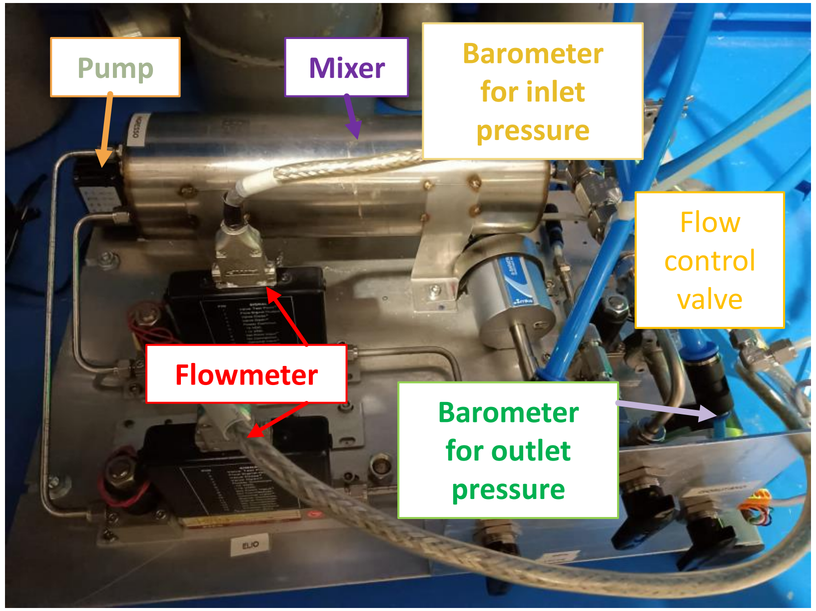
Trigger scintillator

Two scintillator tiles (12 cm x 4 cm), placed upstream and downstream of the drift tubes pack, instrumented with SiPM.

The gas system :

- sets the needed gas mixture
- checks the gas pressure at the entrance and at the exit of the tubes
- maintains constant the gas pressure inside the tubes, by using a proportional valve and a pump.

Portable gas system

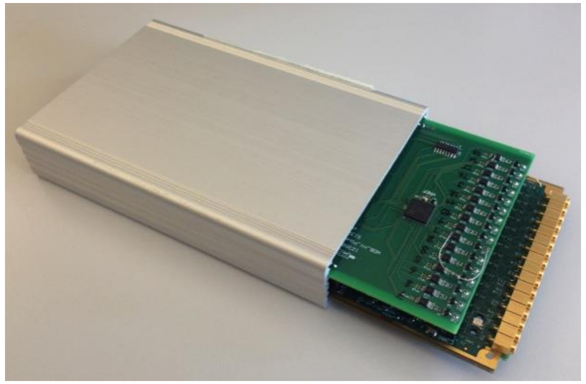


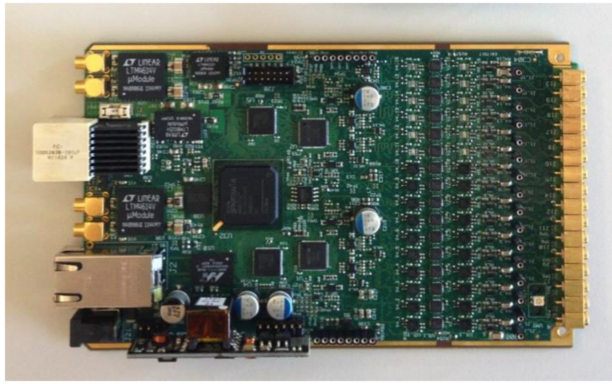
The DAQ system: WDB wave dream board

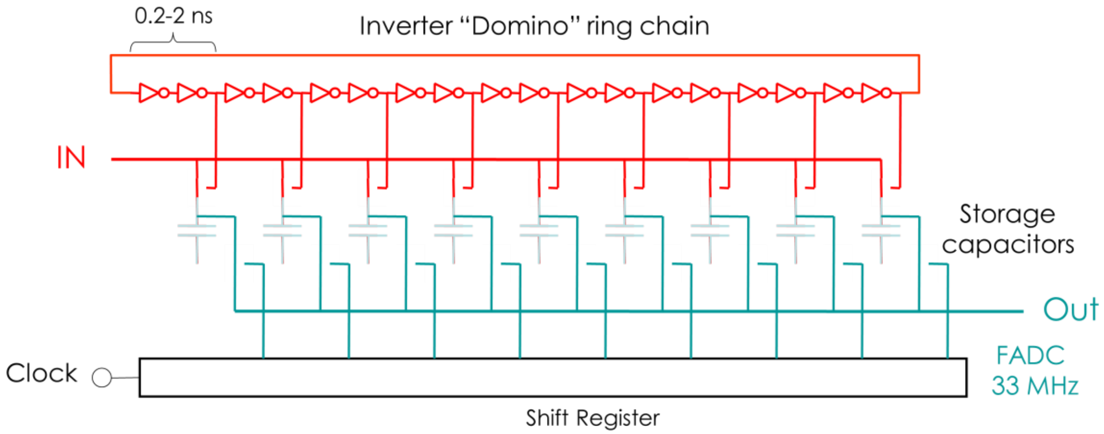
16 ch **D**rs4 **REA**dout **M**odule

Special thanks to the MEG collaboration

16 channels data acquisition board designed and used by the MEG2 experiment at PSI ($\mu \rightarrow e + \gamma$)







- **Analog switched capacitor array**: analog memory with a depth of 1024 sampling cells, perform a "**sliding window**" sampling.

- **500MSPS ↔ 5GSPS sampling speed** with 11.5 bit signal-noise ratio
  - 8 analog channels + 1 clock-dedicated channel for sub 50ps time alignment

- Pile-up rejection O(~10 ns)
- Time measurement O(10 ps)
- Charge measurement O(0.1%)

The data files have been converted in root format to accomplish the data analysis.
Data at different configuration have been collected:

- 90%He-10%iC_4H_{10}
- 80%He-20%iC_4H_{10}
- HV nominal (+10,+20,+30,-10,-20,-30)
- Angle 0° ,30 °,45 °,60 °

Details at: Application of the DRS chip for fast waveform digitizing, Stefan Ritt, Roberto Dinapoli, Ueli Hartmann, *Nuclear Instruments and Methods in Physics Research A 623 (2010) 486–488*

The DAQ system: an oscilloscope interface

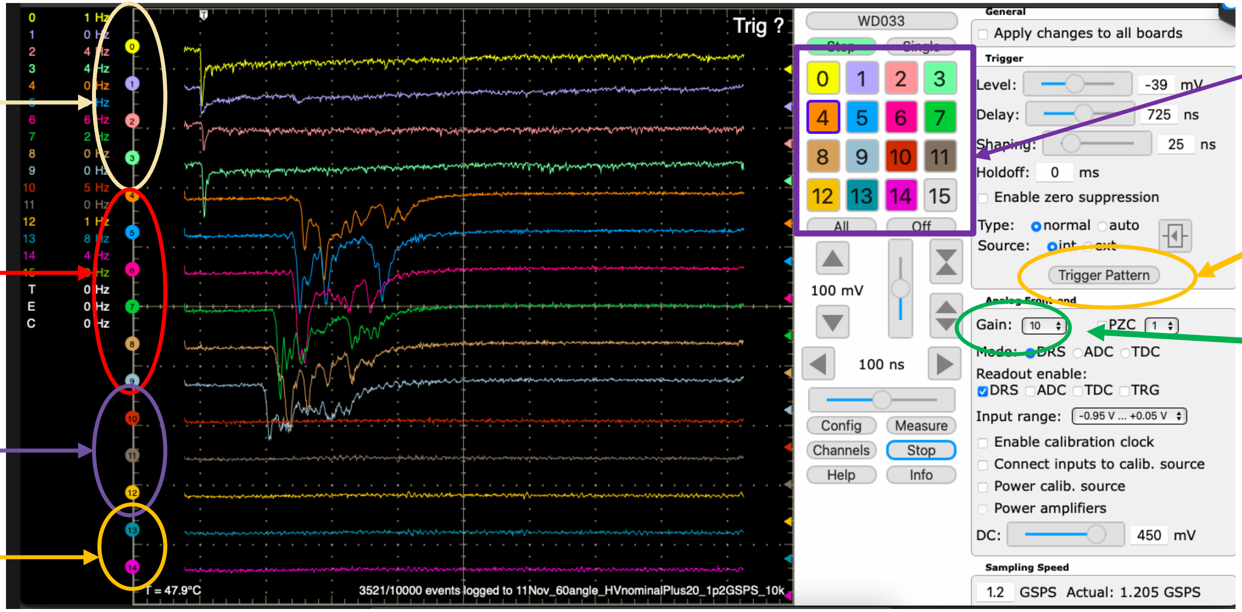
WDB interface is similar to the interface of an oscilloscope with 16 channels

4 trigger channels

6 tubes 1 cm cell size with typical event

3 tubes 2 cm cell size

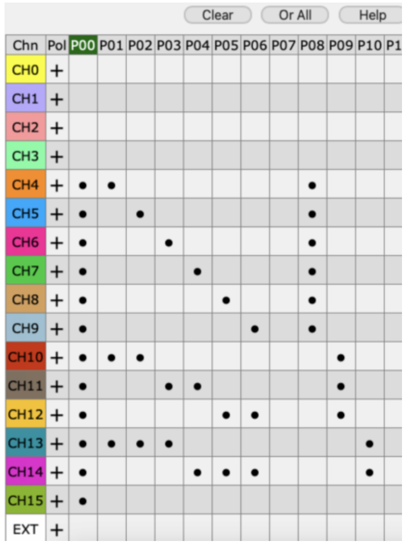
2 tubes 3 cm cell size



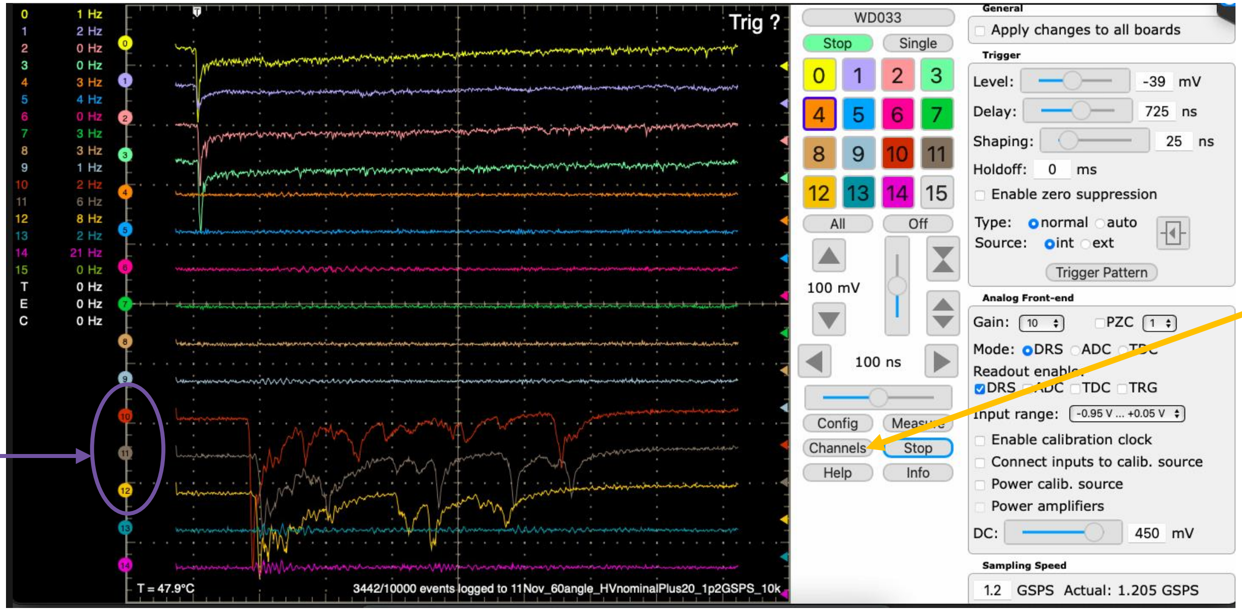
Channel selection panel

Trigger selection pattern

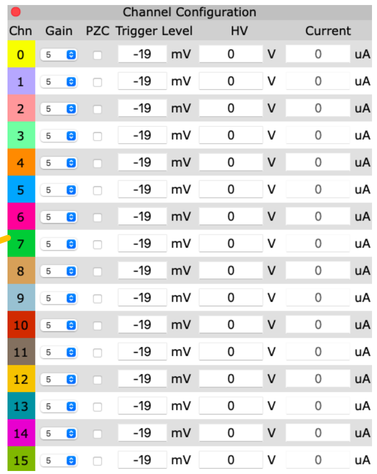
Gain selection



typical event



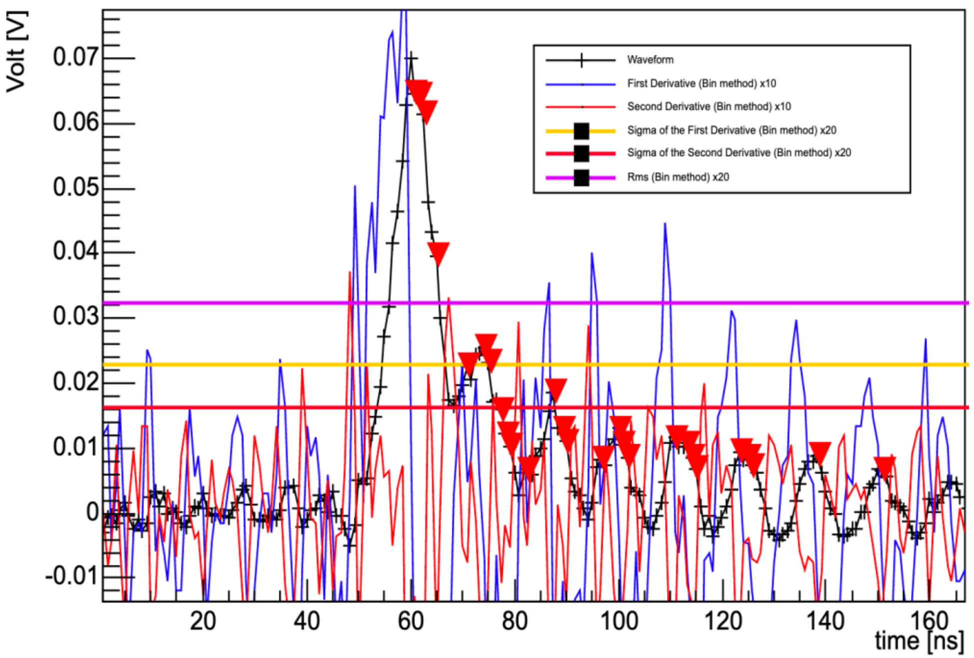
Channels setting



Preliminary results: an efficient algorithm to count electrons

The first and second derivative algorithm (DERIV)

0°, nominal HV+20, 90%He-10%iC_4H_{10}
Tube with 1 cm cell size and 20 μm diameter



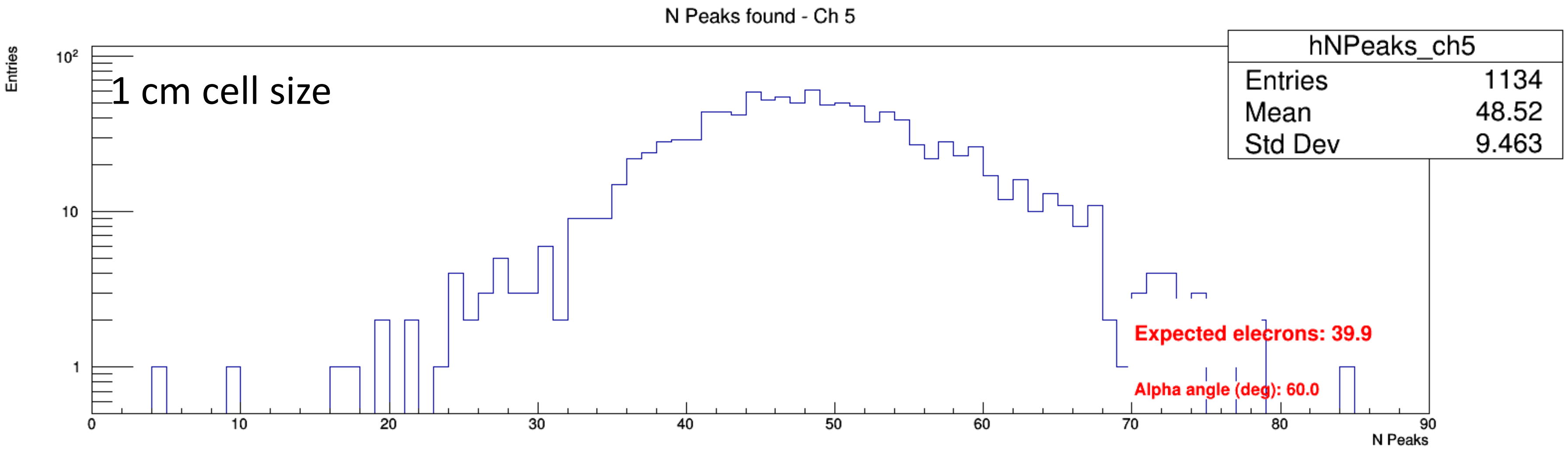
Requirements for a good peak candidate in the bin position [ip]:

1. Amplitude constraint:
   - Amplitude[ip]>4*rms
   - Amplitude[ip]- Amplitude[ip-1]>rms || Amplitude[ip+1]-Amplitude[ip-1]>rms
2. First derivative constraint:
   - Fderiv[ip]<$\sigma_{der1}/2$
   - Fderiv[ip-1]> σ_{der1} ||Fderiv[ip+1]<- σ_{der1}
3. Second derivative constraint:
   - Sderiv[ip]<0

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

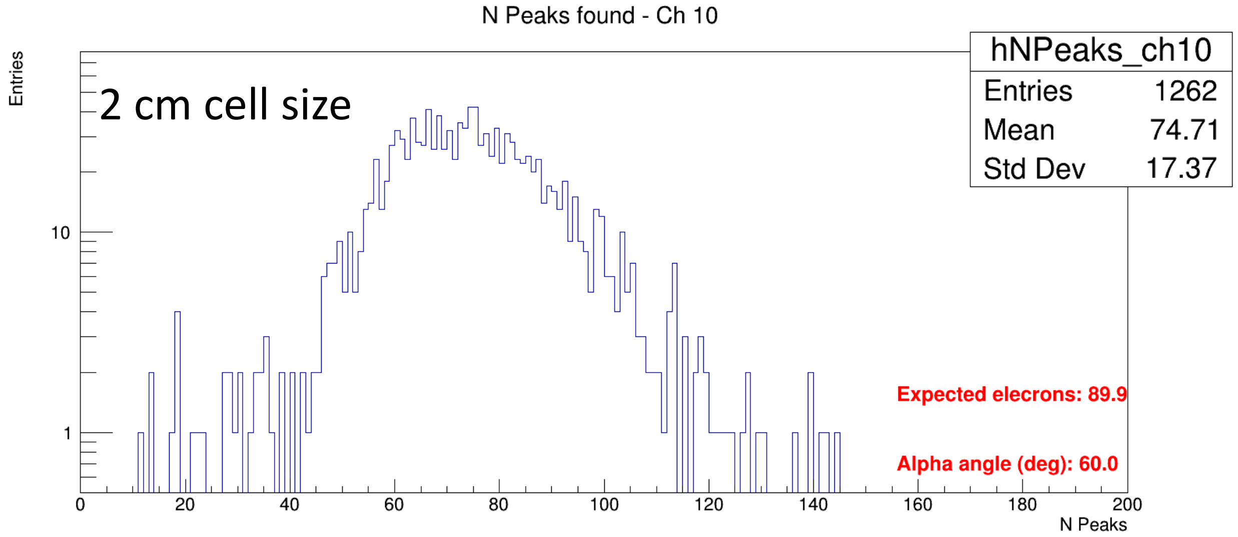
- δcluster/cm(M.I.P.) changes from 12 to 18 respectively for 90%He and 80%iC_4H_{10}
- Drift tube size changes from 0.8 to 1.8 respectively for 1 cm and 2 cm cell size tube.
- α is the angle of the muon tracks to the detector

The first and second derivative algorithm: results



90%He-10%iC_4H_{10}
60°
nominal HV+20

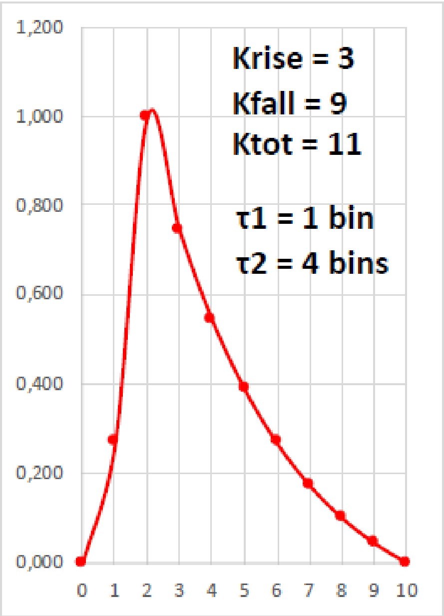
The mean values are compatible with the ones expected!

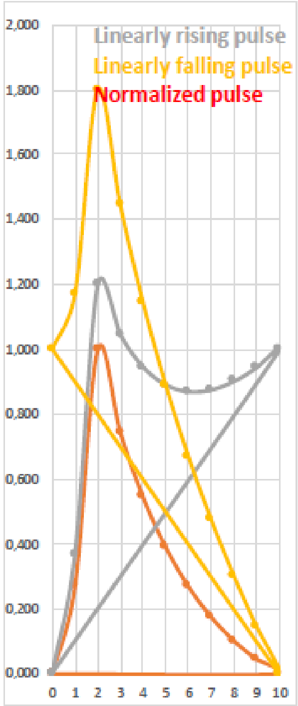


The running template algorithm (RTA)

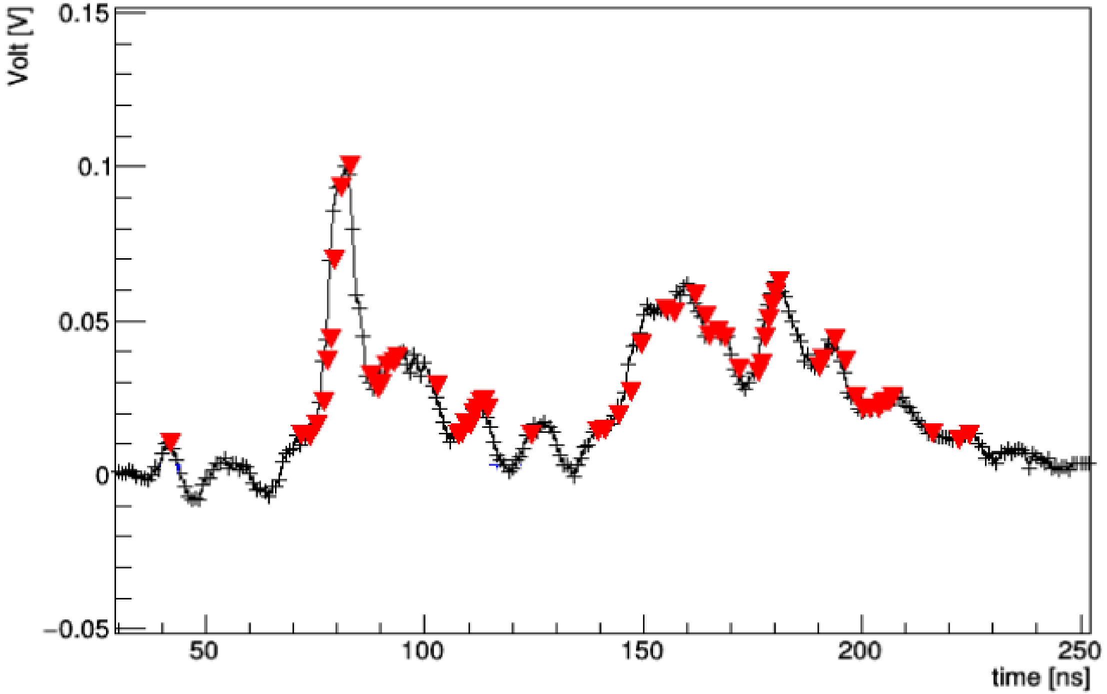
- Define an electron pulse template based on experimental data.
- Raising and falling exponential over a fixed number of bins (Ktot).
- Digitize it (A(k)) according to the data sampling rate.
- Run over Ktot bins by comparing it to the subtracted and normalized data (build a sort of $\chi 2$).
- Define a cut on $\chi 2$.
- 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

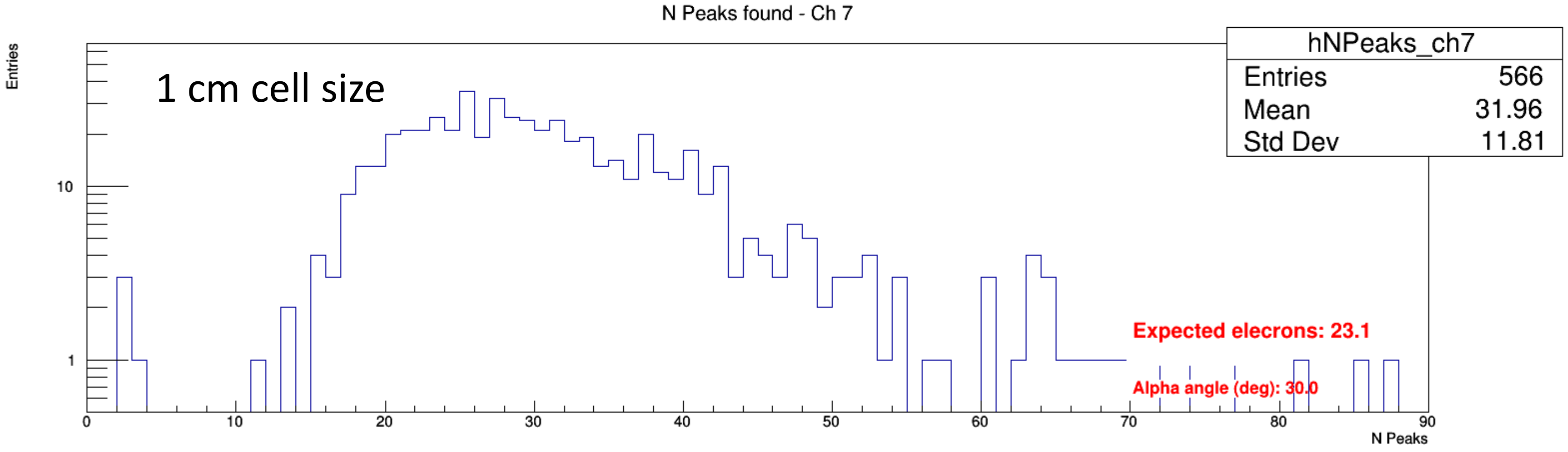




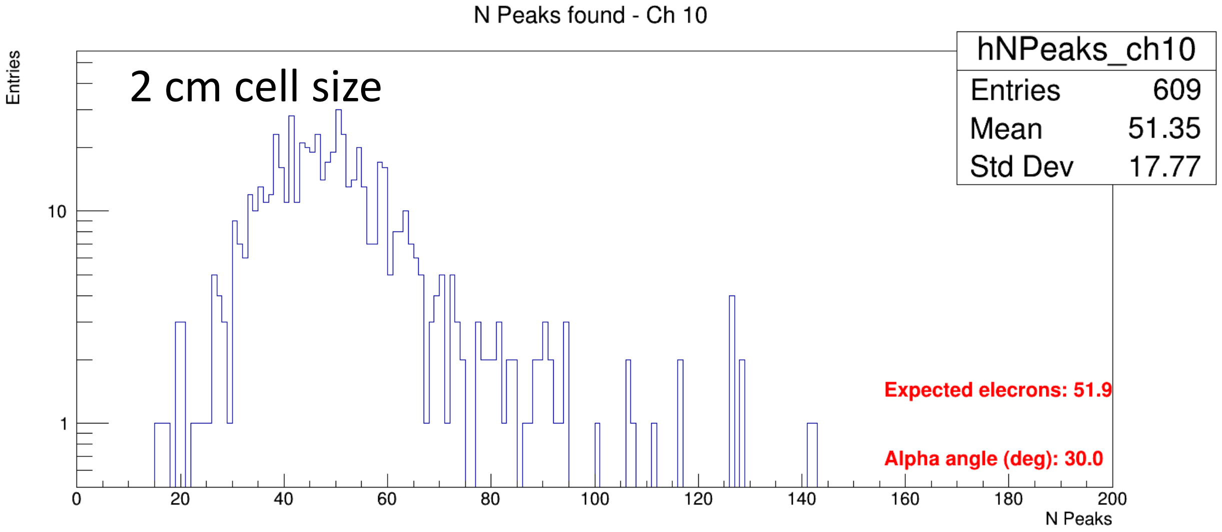
30°, nominal HV+20, 90%He-10%iC_4H_{10}
Tube with 1 cm cell size and 20 μm diameter



The running template algorithm (RTA): results



90%He-10%iC_4H_{10}
30°
nominal HV+20

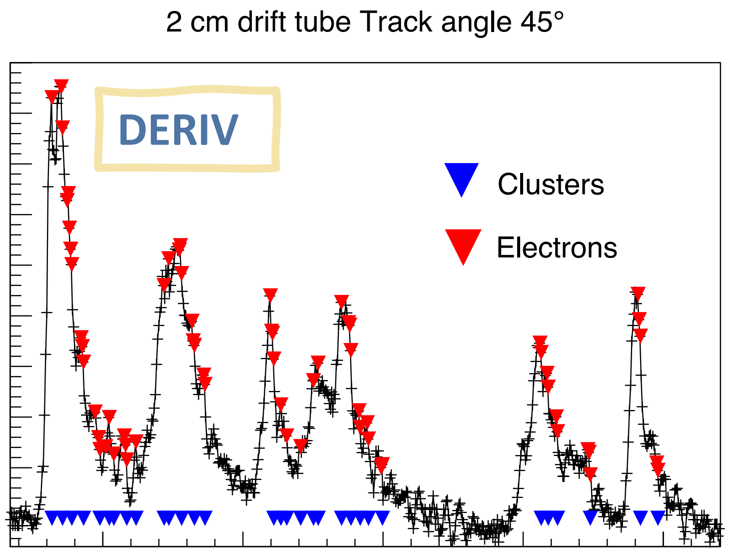


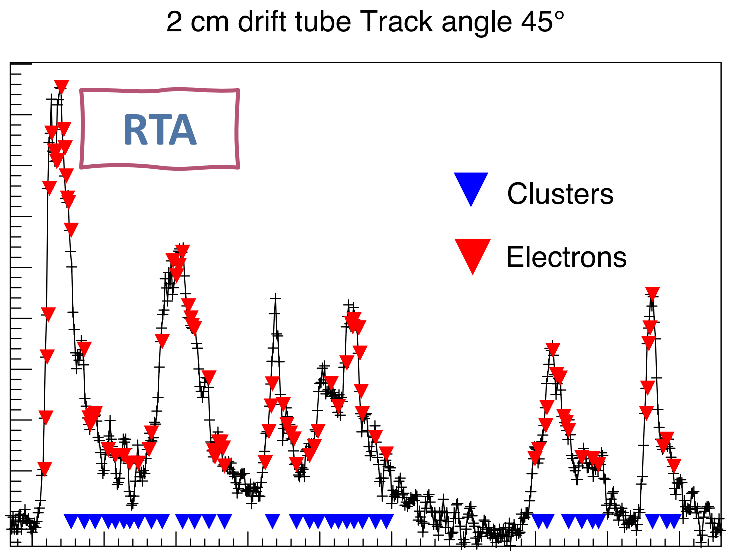
The mean values are compatible with the ones expected!

A single clusterization algorithm

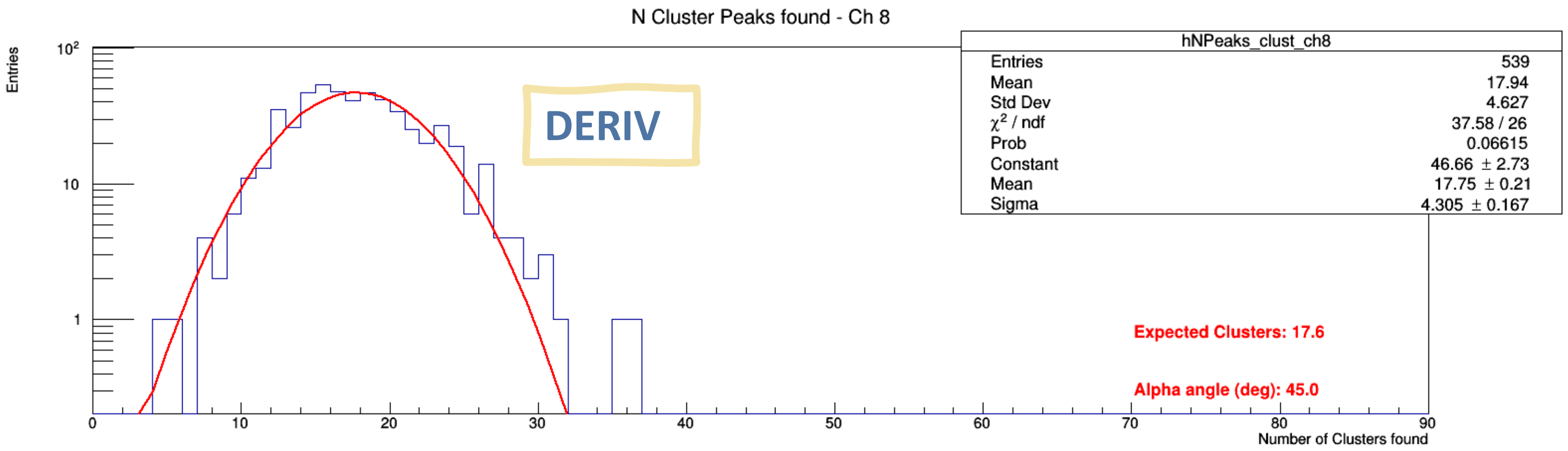
Once find the electron peaks, clusterization of the electron peaks into ionization clusters has been implemented:

1) Association of electron peaks consisting in consecutive bins (difference in time == 1 bin) electrons to a single electron in order to eliminate fake electrons.
2) Contiguous electrons peaks which are compatible with the electrons diffusion time (2.5 ns or 3 bins) must be considered belonging to the same ionization cluster.
3) Position of the clusters is taken as the position of the last electron in the cluster.

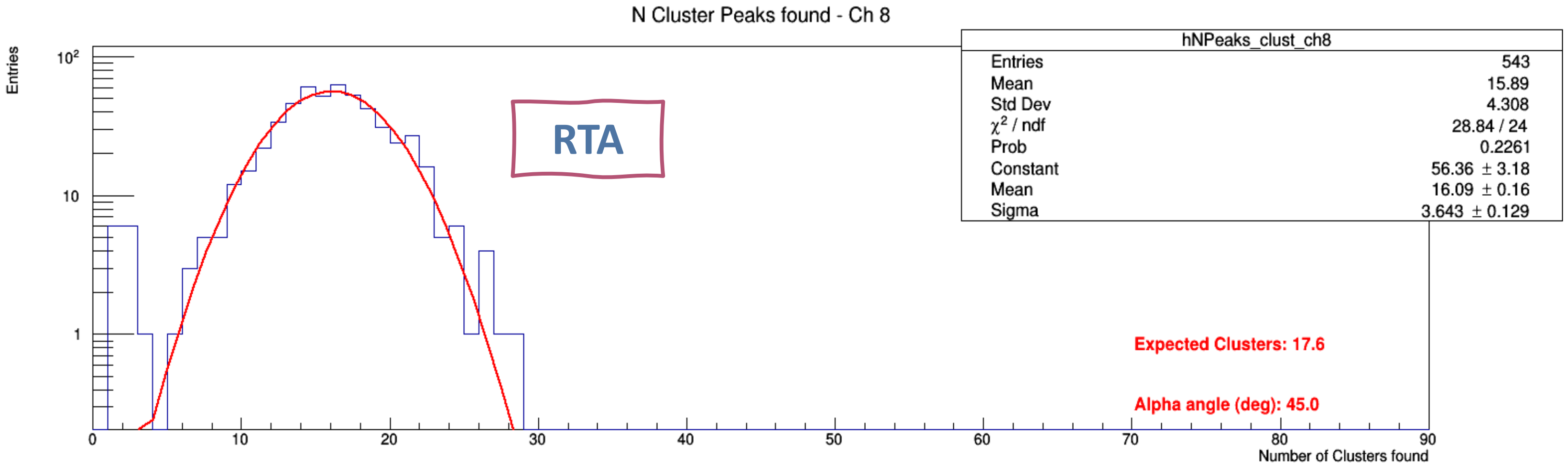




Comparison between the two algorithms

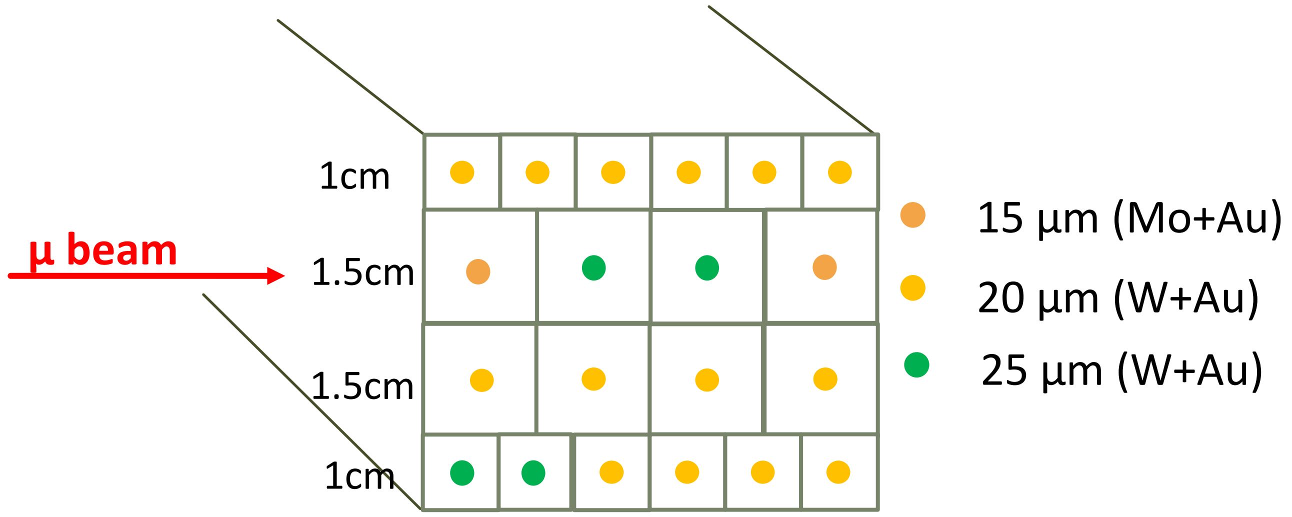


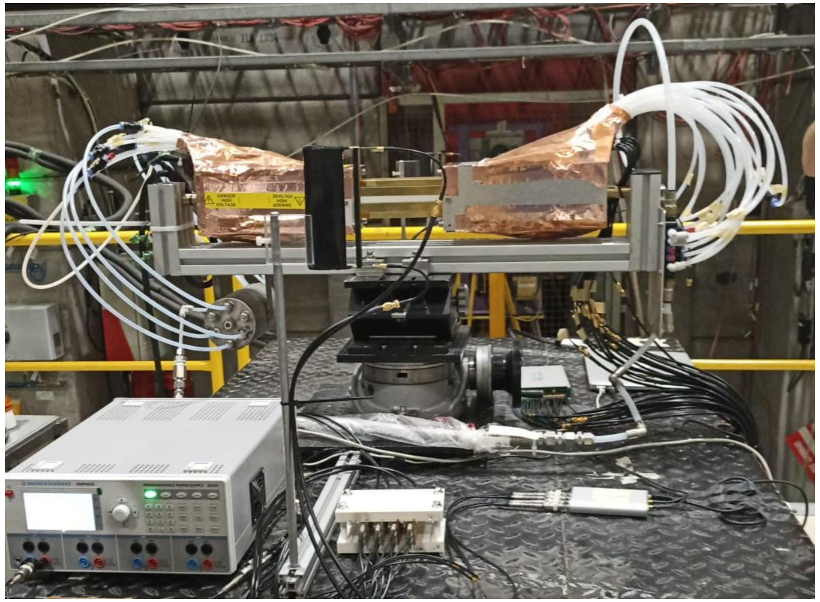
POISSONIAN DISTRIBUTION!



Some news about the ongoing test

The second part of the test is ongoing during these days.





We plan to collect data at different percentages of helium and isobutane:

- 90-10
- 85-15
- 80-20

Some news about the ongoing analysis

An interesting test bench to exploit the cluster counting technique potential in particle ID is the decay of $\boldsymbol{B_s \rightarrow D_s K}$.
We are performing an analysis which intend to compare the particle identification performance with dE/dx method and dN/dx method.
Currently, we are using the fast simulation in Delphes, then we will implement al the tools in the full sim.

Conclusion

Cluster counting technique is a promising method to improve particle separation capabilities. Analytical results and simulations results confirm the expectations, and the test beam plays a key role in this scenario to fine tuning the predictions on the performance of cluster counting for flavor physics and for jet flavor tagging.

Next steps:

- Complete the second part of the test beam!
- Optimize the two cluster counting algorithms and exploit the possibility of using neural networks or AI and apply them on the new collected data
- Complete the B_s analysis

THANK YOU!

The test beam crew

C. Caputo[1], G. Chiarello[2], A. Corvaglia[3], F. Cuna[3,4], B. D’Anzi[5,6], N. De Filippis[6,7], F. De Santis[3,4], W. Elmetenawee[6], E. Gorini[3], F. Grancagnolo[3], M. Greco[3,4], S. Gribanov, K. Johnson[8], A. Miccoli[3], M. Panareo[3], A. Popov, M. Primavera[3], A. Taliercio[1], G. F. Tassielli[3], A. Ventura[3], S. Xin[9]

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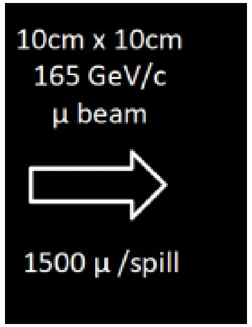
[2]Istituto Nazionale di Fisica Nucleare, Pisa, Italy
[3]Istituto Nazionale di Fisica Nucleare, Lecce, Italy
[4]Università del Salento, Italy
[5]Università degli Studi di Bari »Aldo Moro», Italy

Back-up

Context

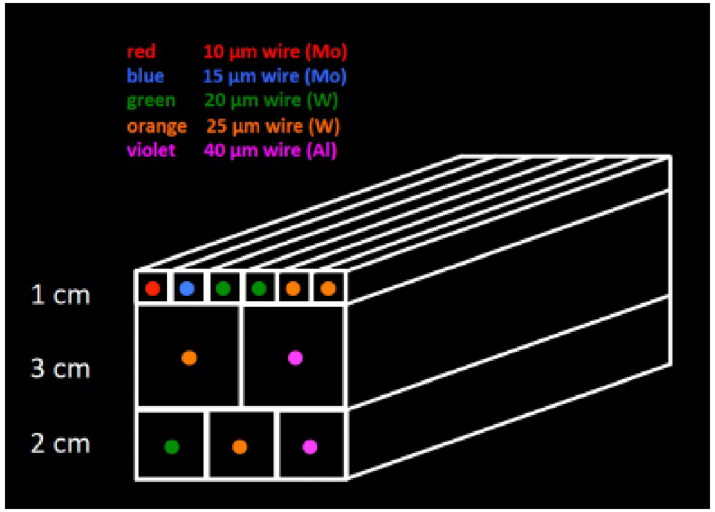
- ❑ Offline analysis on November test beam data taken with 165 GeV/c muons beams from 11st November
- ❑ Dealing with 11 drift tubes having cell sizes of 1-cm,2-cm and 3-cm:



- ➢ **Channels 0,1,2,3** are Trigger Counters

- ➢ **Channels 4,5,6,7,8,9** are the 6 Drift Tubes of 1 cm cell size respectively:
  - Channel 4 with a wire diameter of 10 micrometer
  - Channel 5 with a wire diameter of 15 micrometer
  - Channel 6 and 7 with a wire diameter of 20 micrometer
  - Channel 8 and 9 with a wire diameter of 25 micrometer

- ➢ **Channels 10,11,12** are the 3 Drift Tubes of 2 cm cell size respectively:
  - Channel 10 with a wire diameter of 20 micrometer
  - Channel 11 with a wire diameter of 25 micrometer
  - Channel 12 with a wire diameter of 40 micrometer



- ➢ **Channels 13,14** are the 2 Drift Tubes of 3 cm cell size respectively:
  - Channel 13 with a wire diameter of 25 micrometer
  - Channel 14 with a wire diameter of 40 micrometer

Signal acquisition window is out of the signal range

NOTE:

fderiv[ip] = (Waves_normalized.Y[ip+1]-Waves_normalized[ip-1])/2

sderiv[ip] = (fderiv[ip+1]-fderiv[ip-1])/2

sigd1 = rms/sqrt(2)

sigd2 = rms/2

NOTE: r.m.s. has been defined over the first 30 bins as the $r.m.s. = \sqrt{\frac{\sum_{i=0}^{30}(Wave\_normalized[channel].Y - bsln)^2}{30}}$

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

from *Walenta parameterization (1980)*

L_{track} = 0.6 m
P = 1 atm
n = 64

$$\frac{s_{dE/dx}}{(dE/dx)} = 8.1\%$$

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

from *Poisson distribution*

L_{track} = 0.6 m
δ_{cl} = 12.5/cm

$$\frac{s_{dN_{cl}/dx}}{(dN_{cl}/dx)} = 3.6\%$$

A new Switch capacitors array(SCA), called the Domino Ring Sampler(DRS)

The recent version, DRS4, is capable of digitizing 9 differential input channels at sampling rates of up to 6 Giga-samples per second(GSPS) with an analogue bandwidth of 950MHz(3 dB).

The channel depth can be configured between 1024 and 8192 cells, and the signal-to-noise ratio allows a resolution equivalent to more than 11 bits.

The high bandwidth, low power consumption and short readout time make this chip attractive for many experiments, replacing traditional ADCs and TDCs.

The DAQ system: binary format file

- Header relating to the board consisting of the words:
  DRS8
  TIME
  B#XXX (XXX represents the card number and changes according to the WDB, in this case 033)
  Calibration information

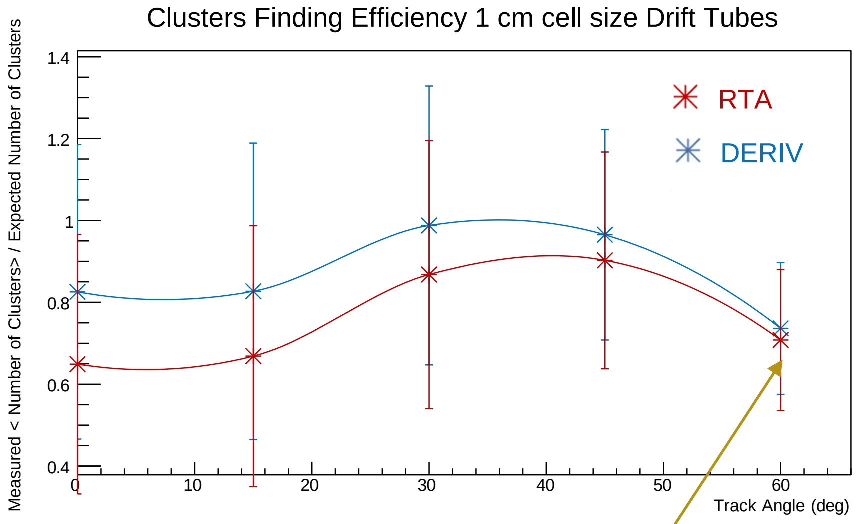
- Header EVENT
  Serial. Number
  Time information
  Channel Information

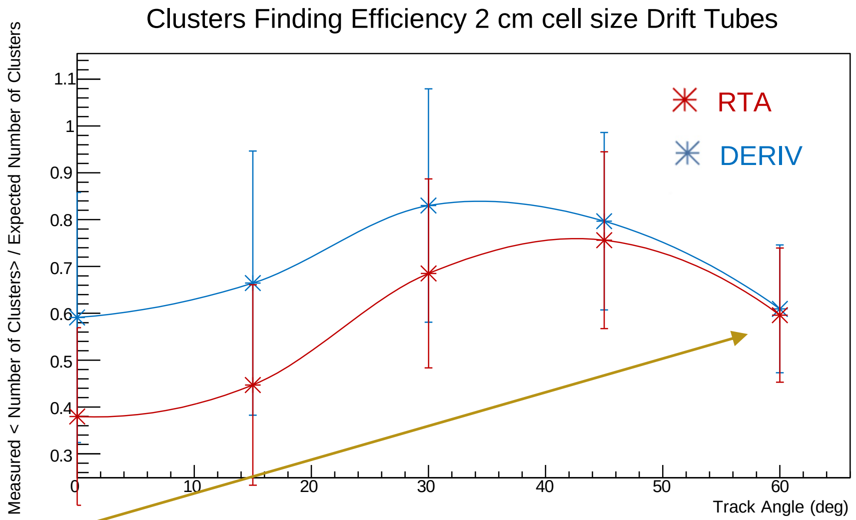
The data files have been converted in root format to accomplish the data analysis.
Data at different configuration have been collected:

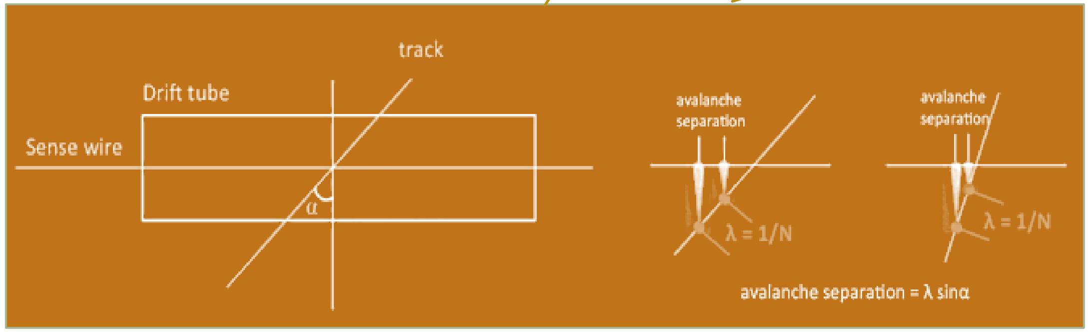
- 90%He-10%iC_4H_{10}
- 80%He-20%iC_4H_{10}
- HV nominal (+10,+20,+30,-10,-20,-30)
- Angle 0° ,30 °,45 °,60 °

Word	Byte 0	Byte 1	Byte 2	Byte 3	Contents
0	‘D’	‘R’	‘S’	‘8’	File header, Byte 3 = version
1	‘T’	‘I’	‘M’	‘E’	Time Header
2	‘B’	‘#’	Board number		Board serial number
3	‘C’	‘0’	‘0’	‘0’	Channel 0 header
4	Time Bin Width #0				Effective time bin width in ns for channel 0 encoded in 4-Byte floating point format
5	Time Bin Width #1				
…	…				
1027	Time Bin Width #1023				
1028	‘C’	‘0’	‘0’	‘1’	Channel 1 header
1029	Time Bin Width #0				Effective time bin width in ns for channel 1 encoded in 4-Byte floating point format
1030	Time Bin Width #1				
…	…				
2052	Time Bin Width #1023				
2053	‘E’	‘H’	‘D’	‘R’	Event Header
2054	Event Serial Number				Serial number starting with 1
2055	Year		Month		Event date/time 16-bit values
2056	Day		Hour		
2057	Minute		Second		
2058	Millisecond		Range		Range center (RC) in mV
2059	‘B’	‘#’	Board number		Board serial number
2060	‘C’	‘0’	‘0’	‘0’	Channel 0 header
2061	Scaler #1				Scaler for channel 0 in Hz
2062	‘T’	‘#’	Trigger cell		Channel 0 first readout cell
2063	Voltage Bin #0		Voltage Bin #1		Channel 0 waveform data encoded in 2-Byte integers. 0=RC-0.5V and 65535=RC+0.5V. RC see header.
2064	Voltage Bin #2		Voltage Bin #3		
…	…		…		
2574	Voltage Bin #1022		Voltage Bin #1023		
2575	‘C’	‘0’	‘0’	‘1’	Channel 1 header
2576	Scaler #2				Scaler for channel 1 in Hz
2077	‘T’	‘#’	Trigger cell		Channel 1 first readout cell
2578	Voltage Bin #0		Voltage Bin #1		Channel 1 waveform data encoded in 2-Byte integers. 0=RC-0.5V and 65535=RC+0.5V. RC see header.
2579	Voltage Bin #2		Voltage Bin #3		
…	…		…		
3089	Voltage Bin #1022		Voltage Bin #1023		
3090	‘E’	‘H’	‘D’	‘R’	Next Event Header
…					

Comparison between the two algorithms







Space charge, attachment and recombination effects affect the experimental cluster counting efficiency