# Cluster Counting Algorithms and Results from beam test

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# Advantages of $dN_{cl}/dx$

## $N_{cl}$ number of primary ionizations follows Poisson statistics

- 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.)**:

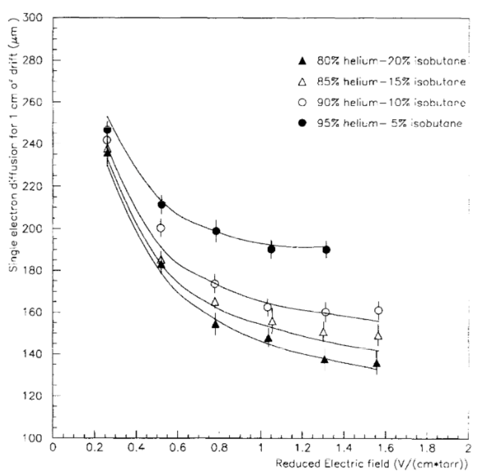
  $$\sigma_{dNcl/dx}/(dN_{cl}/dx) = N_{cl}^{-1/2} < 2.0\%$$

  potentially, a **factor > 2 better** than **dE/dx**
- resolution scales with $\mathbf{L^{-0.5}}$ (not $\mathbf{L^{-0.37}}$ as in dE/dx)

## Further advantages of Helium

- low **primary ionization density** → **large time separation** (**λ ~ 800 μm** in 90%He, or ~ **30 ns**)
- low **drift velocity** → **even larger time separation** (**$v_{drift}$ ~ 2.5 cm/μs**)
- low average **cluster size** (**< $N_{electrons}$/cluster> ~ 1.6**)
- low **singe electron diffusion** (**< 110 μm for 0.5 cm drift**, or **< 4.5 ns**)

V. Golovatyuk et al. / Nucl. Instr. and Meth. in Phys. Res. A 394 (1997) 97–102



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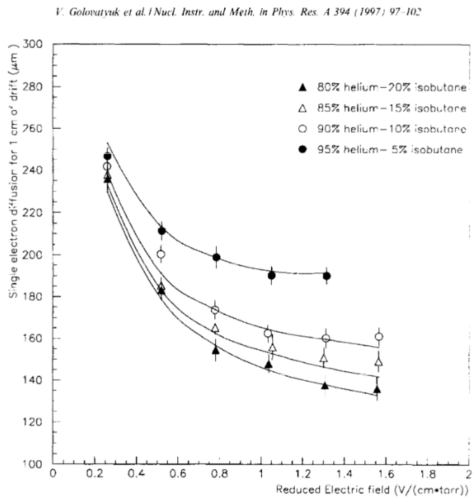
### Simple recipe

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



# PID: analytical calculations vs full simulation

## Which simulation?

**Garfield++** can describe in detail the properties and the performance of a drift chamber single cell, but it is not suitable to simulate a large-scale detector and to study collider events.

**Geant4** can simulate elementary particle interactions with the material of a complex detector and study collider events, but the fundamental properties and the performances of the sensible elements, like the drift cells, have to be parameterized or "ad-hoc" physics models have to be implemented.

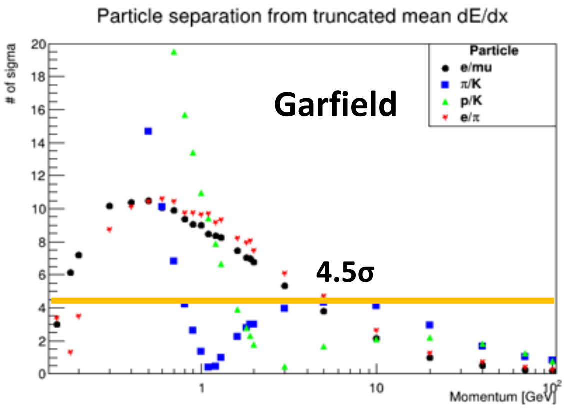
We have developed an algorithm, which uses the **energy deposit** information provided by Geant4, to reproduce, in a fast and convenient way, the **clusters density** and the **cluster size** distributions predicted by Garfield++.

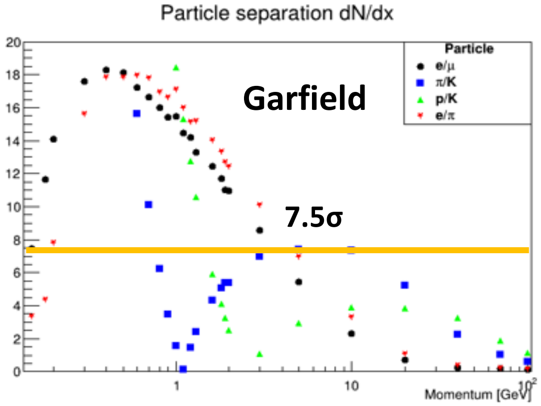
A simulation of the ionization process in 200 drift cells, 1 cm wide, in 90% He and 10% $iC_4H_{10}$ gas mixture has then been performed both in **Garfield++** and in Garfield-modeled **Geant4**.

Do the simulations confirm the prediction?

*F. Cuna, N. De Filippis, F. Grancagnolo, G. Tassielli, Simulation of particle identification with the cluster counting technique, arXiv:2105.07064v1 [physics.ins-det] 14 May 2021*

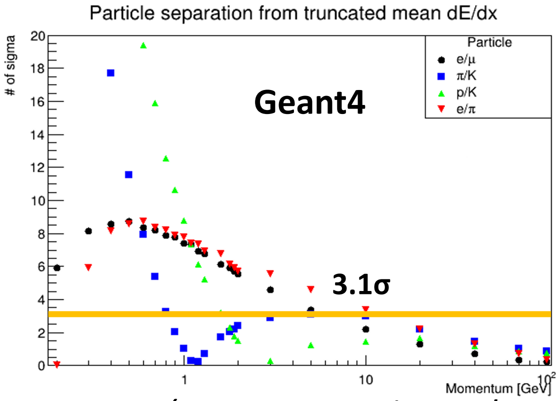
# PID: full simulation vs analytical calculations

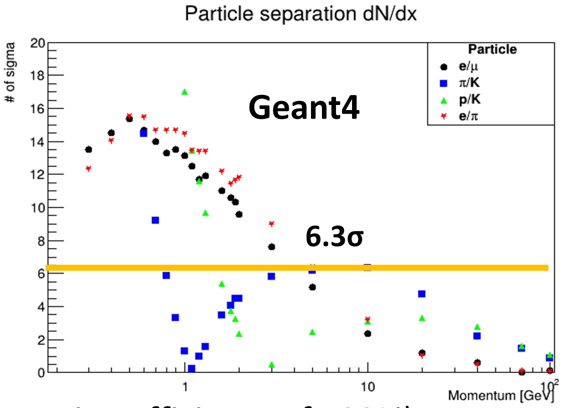



**dN/dx: consider π/K separation:**

Garfield++ in reasonable **agreement with analytical calculations up to 20 GeV/c** momentum, then **falls much more rapidly at higher momenta**.




*(We are assuming a cluster counting efficiency of 100%).*

Despite **Geant4** uses the cluster density and the cluster size distributions from Garfield++, it **disagrees** from **Garfield++** and, therefore, from the **analytical calculations** also.

# PID full simulation with cluster counting

## Open questions:

1. **Lack of experimental data** on cluster density and cluster population for He based gas. Particularly in the relativistic rise region to compare predictions.
2. Despite the fact that the Garfield++ model in GEANT4 reproduces reasonably well the Garfield++ predictions, why particle separation, both with dE/dx and with $dN_{cl}/dx$, **in GEANT4 is** considerably **worse than in Garfield++**?
3. Despite a higher value of the $dN_{cl}/dx$ Fermi plateau with respect to dE/dx, why this is reached at **lower values of βγ with a steeper slope**?
4. These questions are crucial for establishing the particle identification performance at **FCCee**, **CEPC** and **SCTF**
5. However, **the only way to ascertain these issues is an experimental measurement!**

# beam test objectives

## Beam test plans (two phases):

1. Establish the **limiting parameters** for an efficient cluster counting:
   - gas gain saturation
   - cluster density (by changing the gas mixture)
   - space charge (by changing gas gain, sense wire diameter, track angle)
2. Demonstrate the **ability to count clusters**:
   at a fixed βγ (muons at a fixed momentum) count the clusters by
   - doubling and tripling the track length and changing the track angle;
   - changing the gas mixture.

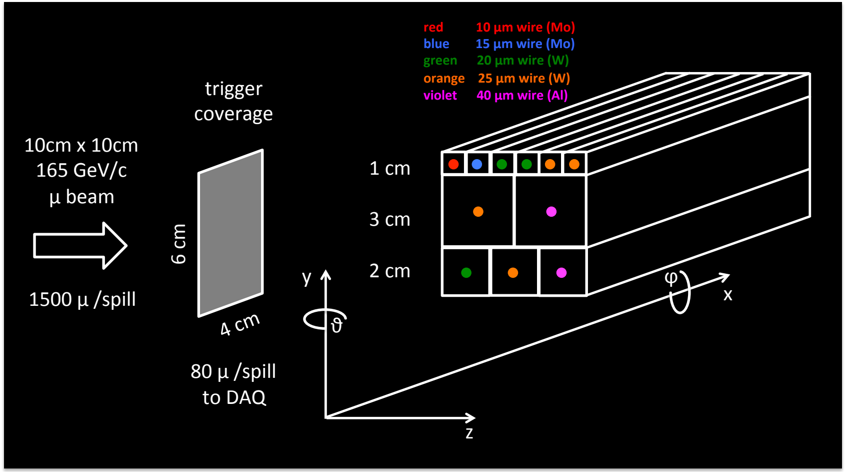
**test done**

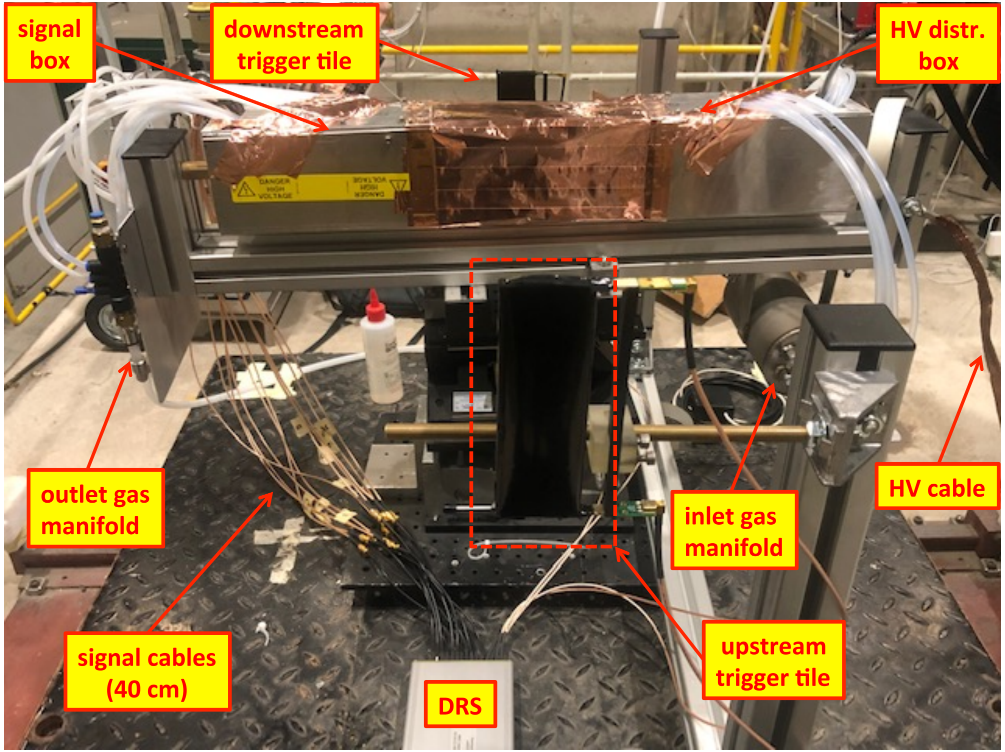
3. In optimal configuration, **measure the relativistic rise as a function of βγ**, both in **dE/dx** and in **$dN_{cl}/dx$**, by scanning the muon momentum from the lowest to the highest value (from a few GeV/c to about 250 GeV/c at CERN/H8).
4. Use the experimental results to fine tune the predictions on performance of **cluster counting** for **flavor physics** and for **jet flavor tagging** both in **DELPHES** and in **full simulation**

**new beam test July 2022**

# Test setup

## schematic



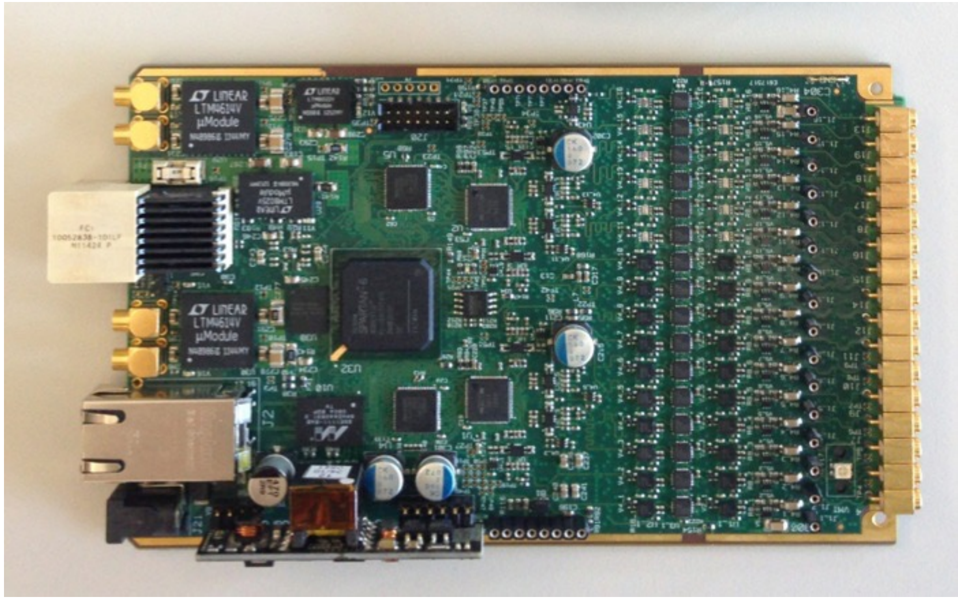

The test was performed during November 2021 at CERN on the H8 beam line in a **parasitic mode**. Main users on the same beam line was a team testing a tile calorimeter and, therefore, requesting for **large part of the time, beams of electrons and hadrons, at various energies,** needed for their calibration, but **useless for our purposes**. Only **sporadically**, a beam of **165 GeV/c muons** was available for us.

# Test setup: advantages

- no need of **external trackers**: only interested in **path length** inside the drift tube active volume
- no need to convert **time to distance** (just count clusters in the **time domain**)
- no need of **internal tracking** (time-to-distance and $t_0$ **calibrations**, alignment, track finding and fitting algorithms, ...)
- no worry of **multiple scattering** (irrelevant for path length differences)
- no need of **particle tagging** in hadron beams: use only **muon beams** at different momenta (**different βγ**)
- use selected **commercial amplifiers** neglecting **power consumption**
- use only **fully integrated digitizers** (**WDB**) for ease of readout

# Test setup: hardware

## DAQ

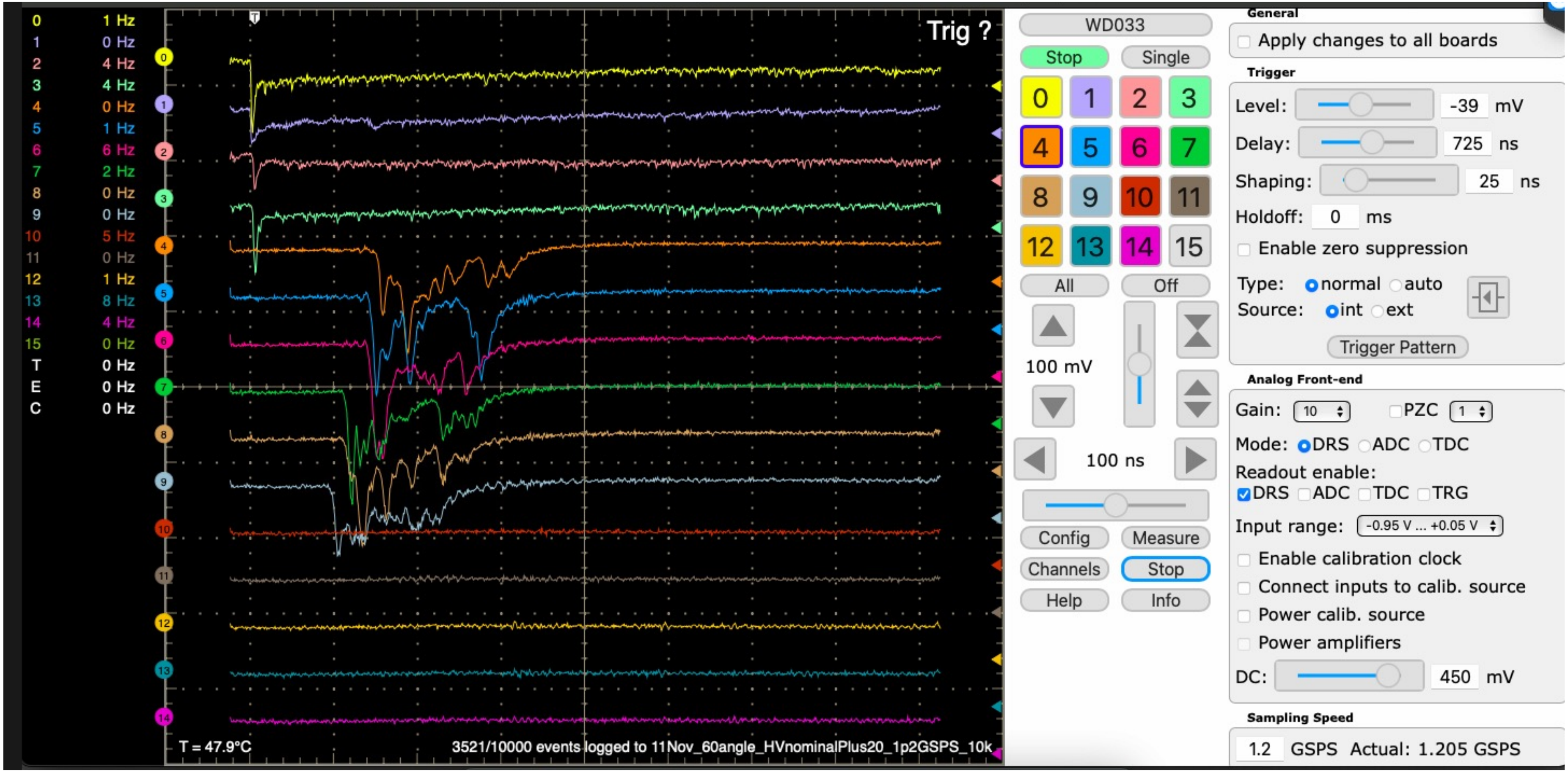


16 channels data acquisition board designed and used by the MEG2 experiment at PSI ($\mu \rightarrow e + \gamma$)
(credit to S. Ritt, Paul Sherrer Institute, Zurich, Switzerland)

## Trigger

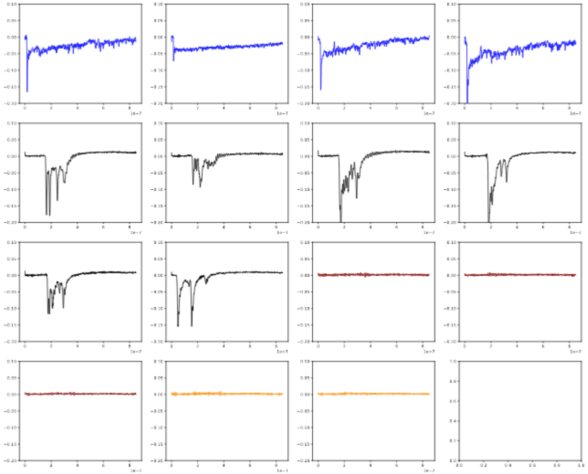
12cm x 6cm upstream and downstream scintillator tiles (designed and used as timing counter of the MEG2 experiment at PSI) used in coincidence and readout by SiPM

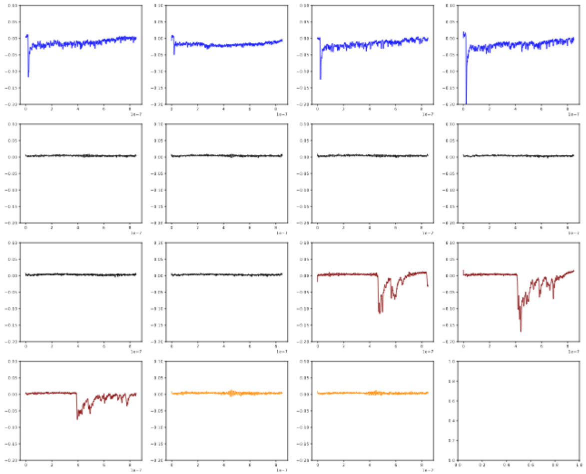
# Test setup: event display

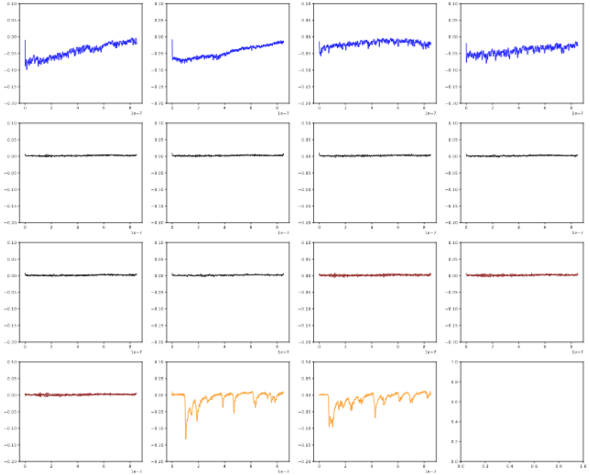


# event display

top 4 channels trigger scintillators







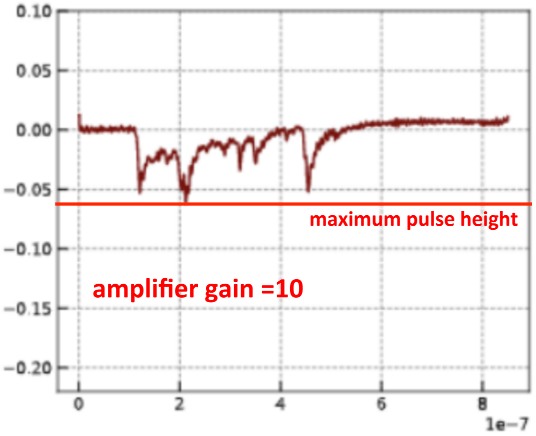
6 drift tubes (1 cm)

3 drift tubes (2 cm)

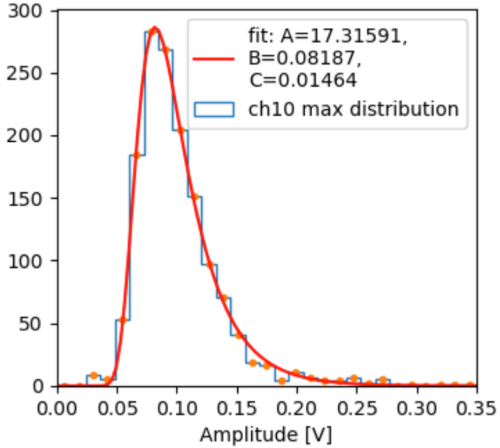
2 drift tubes (3 cm)

vertical full scale 30 mV (gain 10) – horizontal scale 800 ns

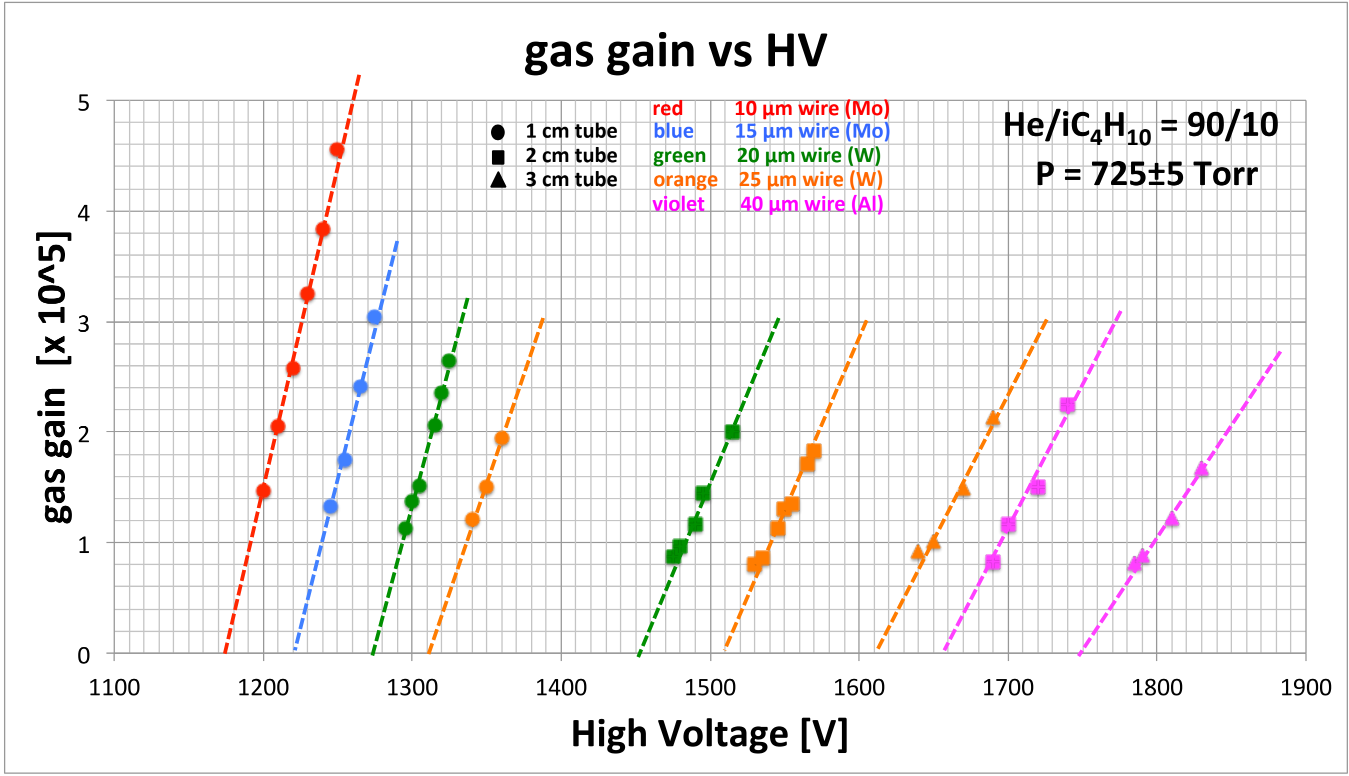
# gas gain



0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
0
2
4
6
8
1e−7
maximum pulse height
amplifier gain =10

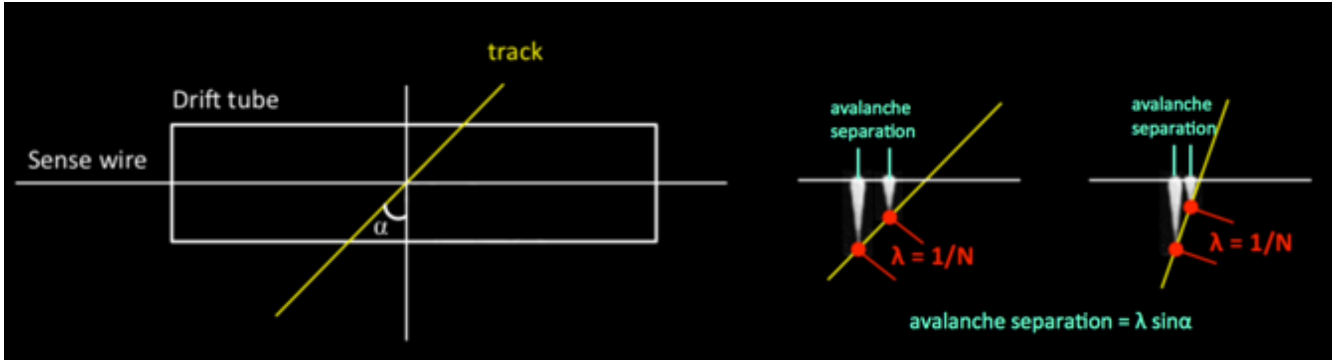



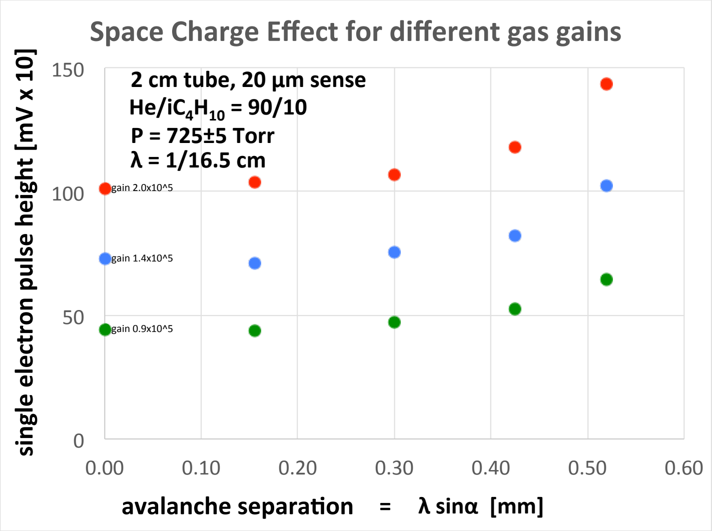
fit: A=17.31591,
B=0.08187,
C=0.01464
ch10 max distribution
Amplitude [V]

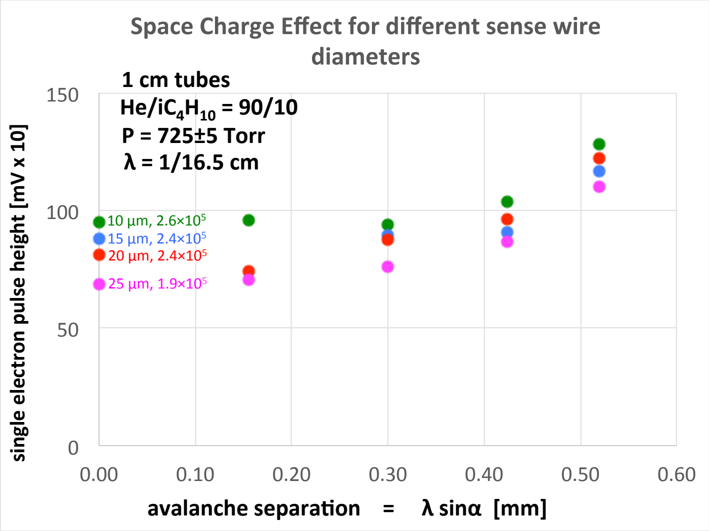



gas gain vs HV
1 cm tube
2 cm tube
3 cm tube
red 10 μm wire (Mo)
blue 15 μm wire (Mo)
green 20 μm wire (W)
orange 25 μm wire (W)
violet 40 μm wire (Al)
He/iC4H10 = 90/10
P = 725±5 Torr
gas gain [x 10^5]
High Voltage [V]

# space charge




**no dependence of space charge effects from the gas gain, no dependence of space charge effects from the sense wire diameter** at least in this range of gas gain values

The **space charge effect** for this gas mixture, results in approximately **≈ 30% avalanche suppression, at α=0°**.

A **naive model** based on **spherical avalanche profile** gives, for these particular configurations, an **avalanche radius $r_{av}$ ≈ 450 μm**.

The condition of **no avalanche overlap: $\lambda \sin\alpha \geq 2\, r_{av}$**, in this case, is met for $1/\lambda$ = **N ≤ 11/cm**. Any helium/isobutane gas mixture richer than 10% isobutane (corresponding to N = 12/cm for a m.i.p.) will, therefore, **necessitates space charge effects corrections**, which may affect an efficient application of the cluster counting techniques.

# Electron peak finding strategy based on derivatives of spectral function

Please, see details of the used algorithm in

B. D'Anzi
March 17, 2022, IHEP-INFN joint Meeting on cluster counting in drift chambers:
[https://indico.ihep.ac.cn/event/16376/](https://indico.ihep.ac.cn/event/16376/)

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

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

α = angle of the muon track w.r.t. normal to sense wire
δ cluster/cm (mip) = 12 for 90He (18 for 80He) gas mixtures
drift tube size = 0.8 for 1 cm (1.8 for 2 cm) drift tube

# Fermi plateau in He = 1.3 x m.i.p.

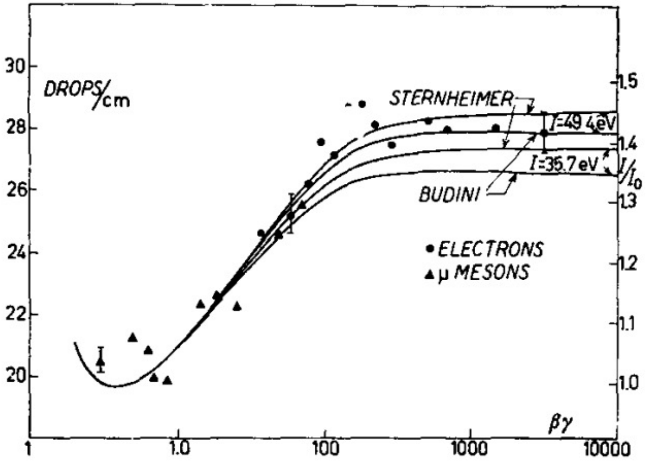
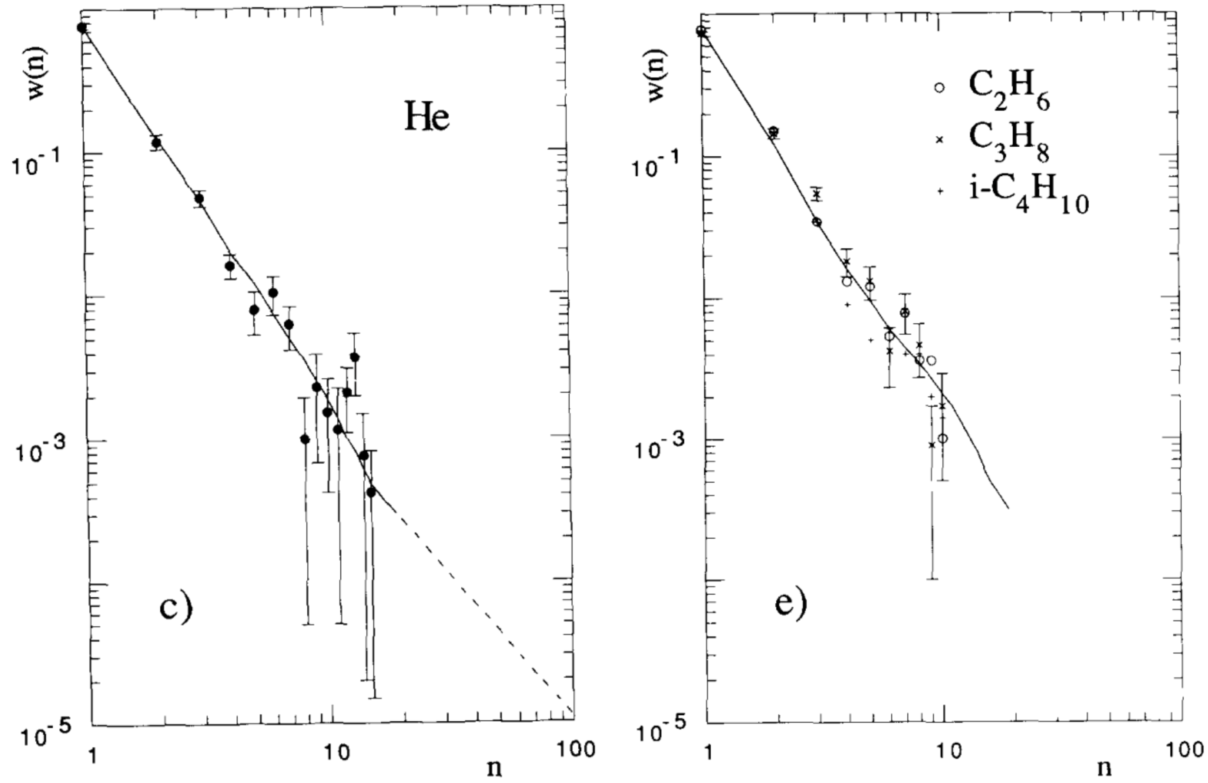



Fig. 1. – Ionization loss in helium. The theoretical curves are normalized to the $\mu$-mesons with $\beta\gamma < 30$, and are calculated for different values of the average ionization potential for the mixture of gases in the cloud chamber. Standard deviations are indicated for a few of the experimental points.

**R. G. KEPLER, C. A. D'ANDLAU, W. B. FRETTER and L. F. HANSEN**
*Relativistic Increase of Energy Loss by Ionization in Gases*
IL NUOVO CIMENT0 VOL. VII, N. 1 - 1 Gennaio 1958

# <$N_{electrons}$/cluster> = 1.6

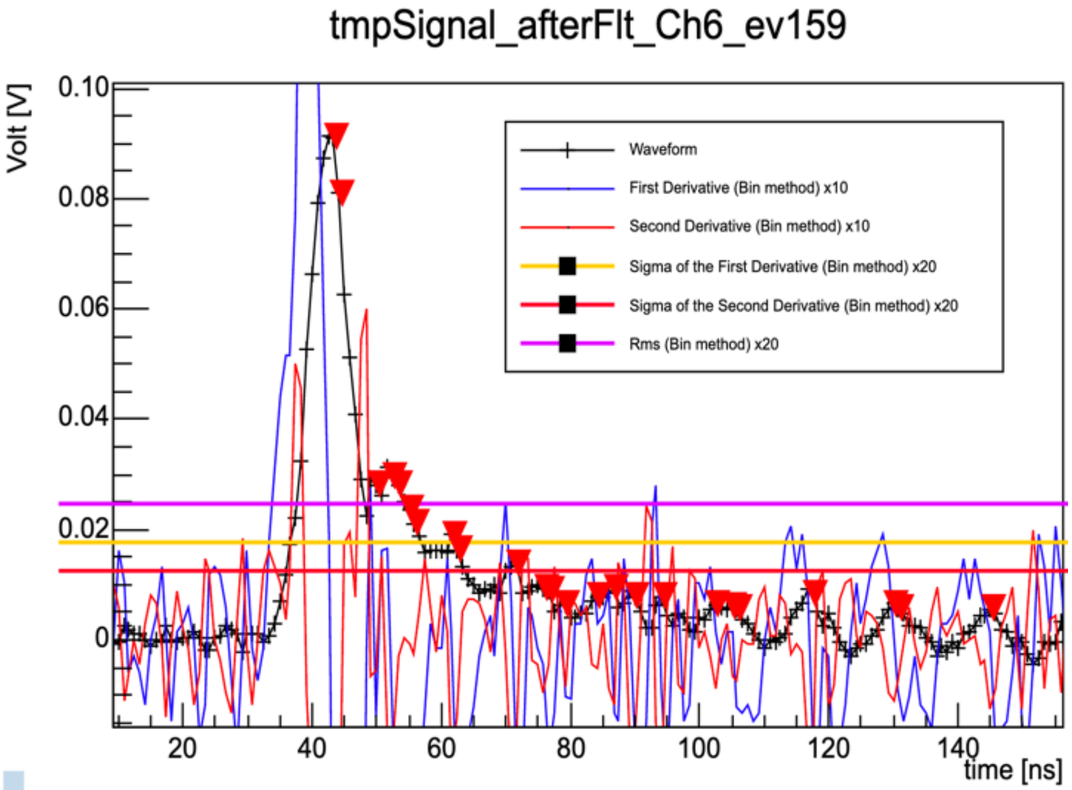


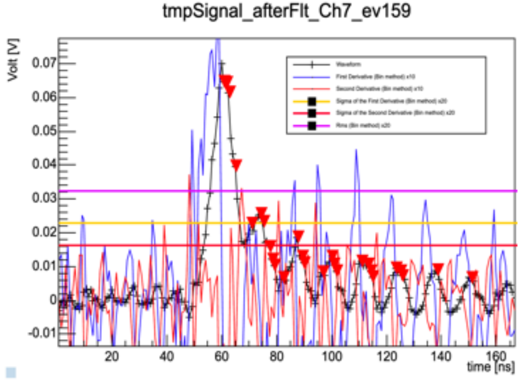

**H. Fischle , J. Heintze and B. Schmidt**
*Experimental determination of ionization cluster size distributions in counting gases*
Nuclear Instruments and Methods in Physics Research A301 (1991) 202-214

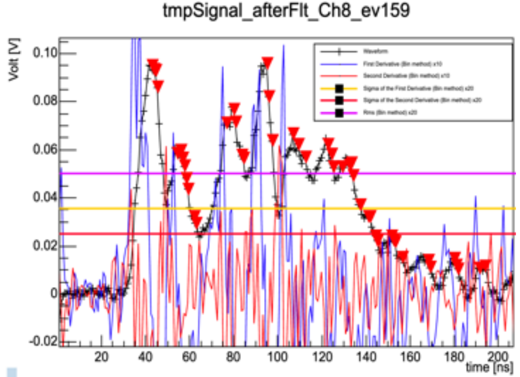
# Electron peaks counting

1 cm drift tubes

Run: run_99.root; Track angle(deg): 0° ; Gas mixture: $90\%He10\%iC_4H_{10}$ ; HV = +20



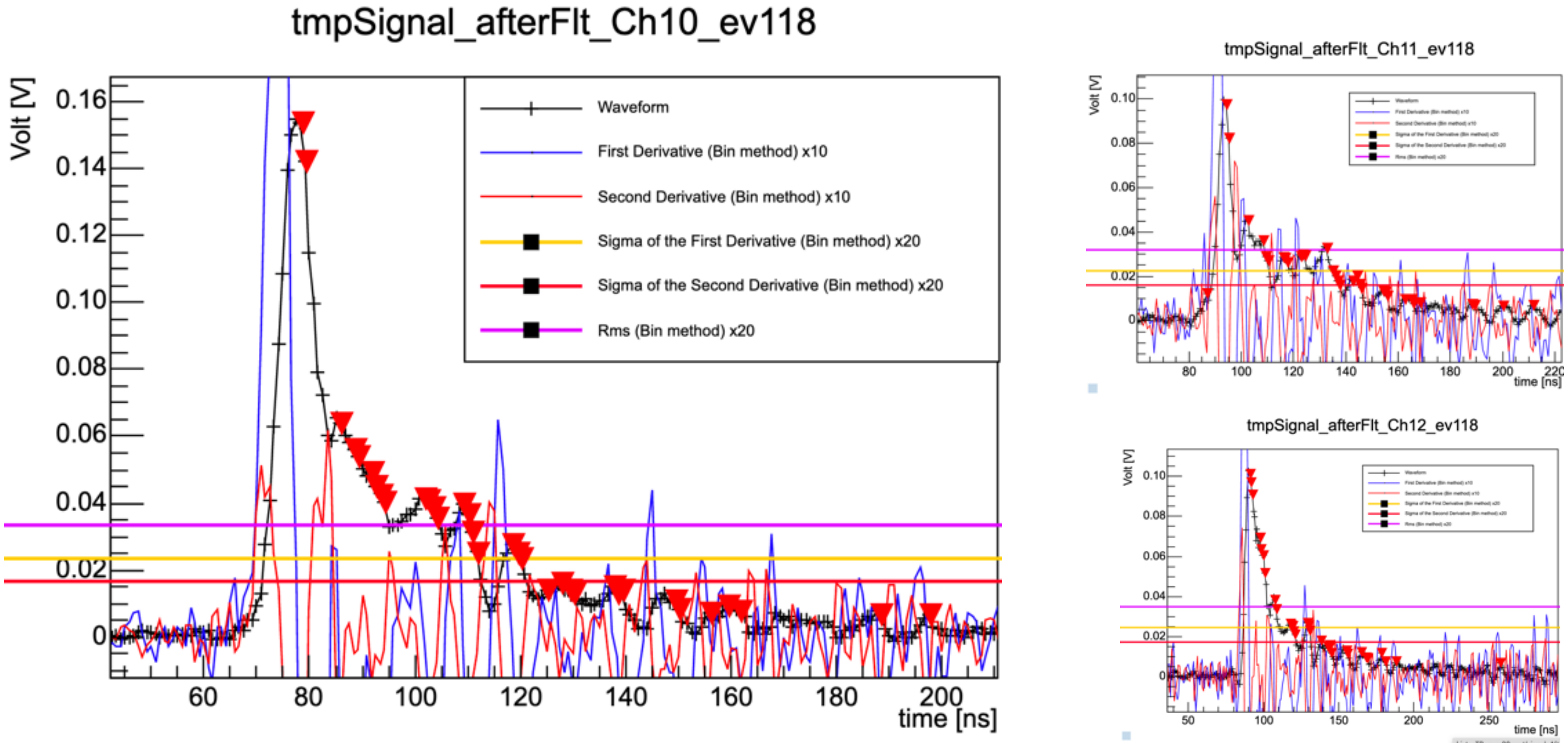



# Electron peaks counting

2 cm drift tubes

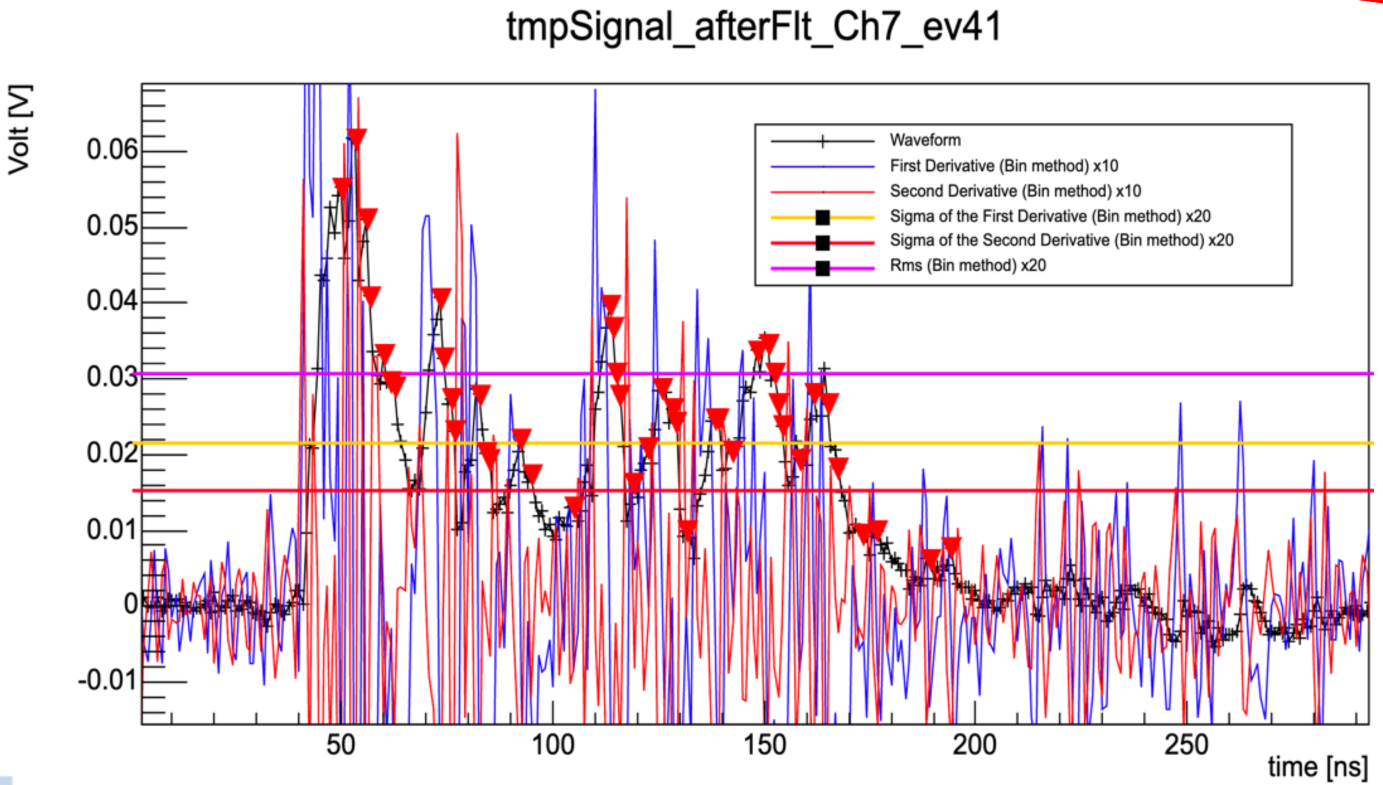
Run: run_99.root; Track angle(deg): 0° ; Gas mixture: $90\%He10\%iC_4H_{10}$ ; HV = +20



# Electron peaks counting

1 cm drift tubes

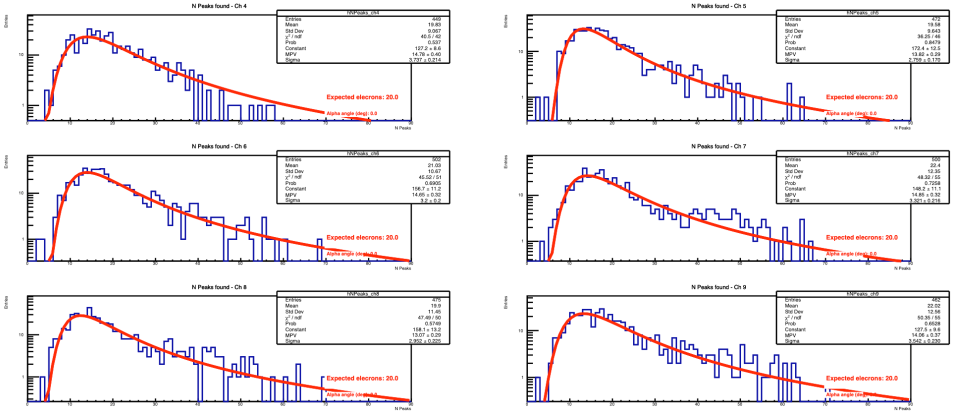
Run: run_127.root; Track angle(deg): 60° ; Gas mixture: 80%He20%$iC_4H_{10}$ ; HV = +20



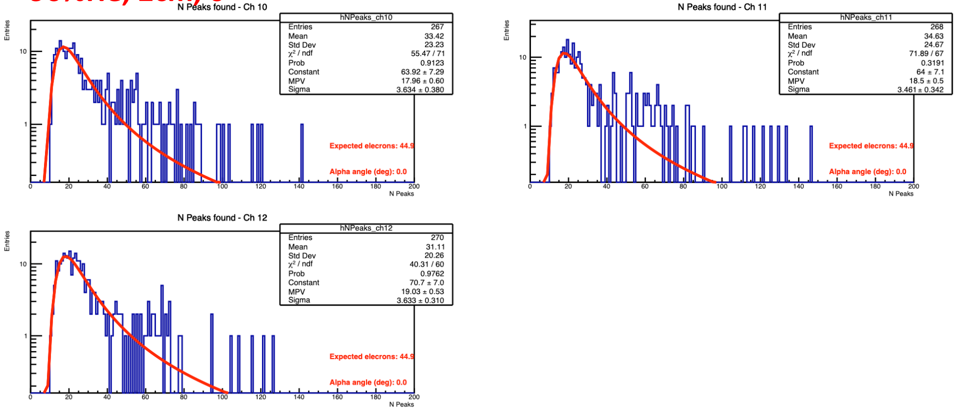

Expected 50% more clusters (and electrons) with respect to 90%He - 10%$iC_4H_{10}$

# Electron peaks counting

90%He, 1cm, 0°

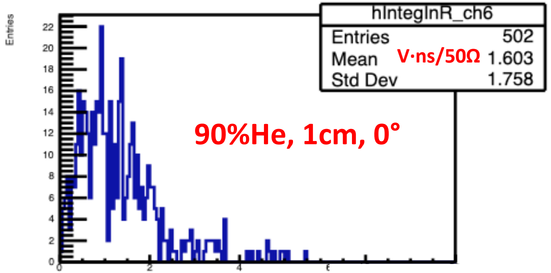



90%He, 2cm, 0°




$\langle N_{electrons} \rangle$
**= 20.8**
(expected 20.0)

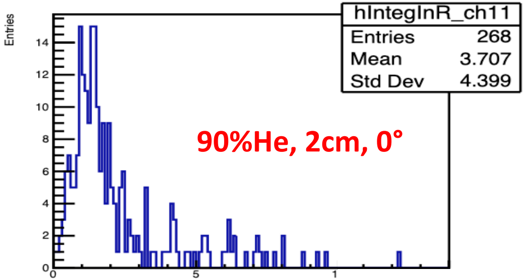
$\langle N_{electrons} \rangle$
**= 33.1**
(expected 45.0)



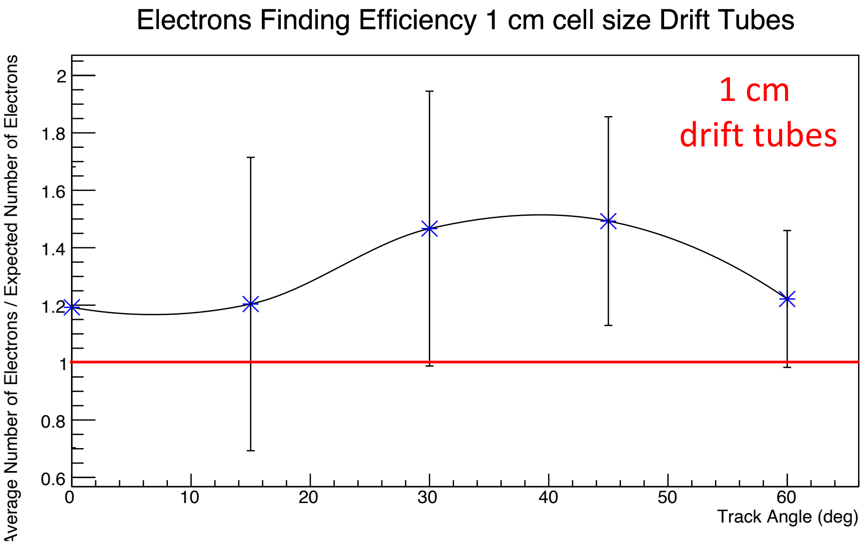

Charge integral = 32 pCoul

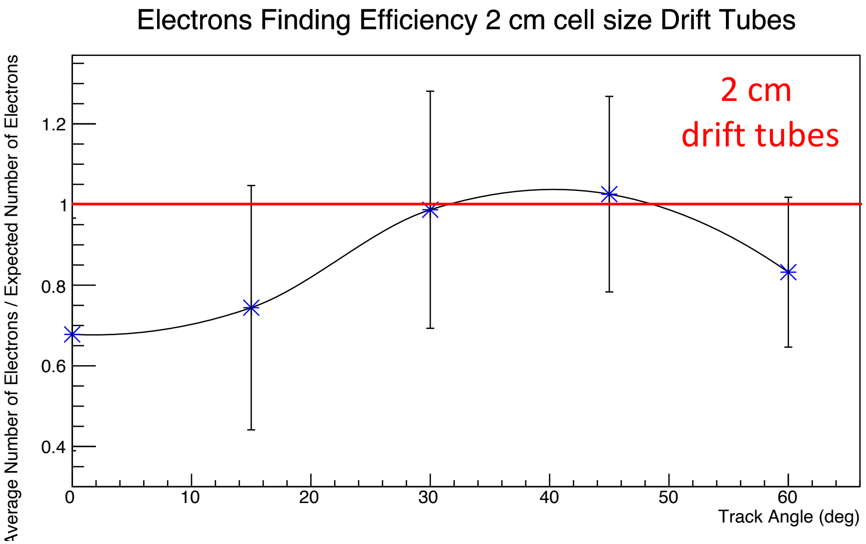
32/74 ≈ 0.8/1.8

Charge integral = 74 pCoul



# Electron peaks counting




- Electrons **overcounting** due to fake electron peaks in adjacent bins (easily corrected in the clusterization algorithm)
- **Inefficiency** for 2 cm drift tubes under investigation
- **Undercounting** for $\alpha < 30°$ due to space charge effects
- **Undercounting** for $\alpha > 45°$ due to high electron peaks density (average 5 bins at 60°) → **real inefficiency** (can be corrected)

# Electron clustering

1. Association of electron peaks in consecutive bins (difference in time == 1 bin)
2. Contiguous electrons peaks compatible with the electrons diffusion time (2.5 ns or 3 bins) are considered belonging to the same ionization cluster.

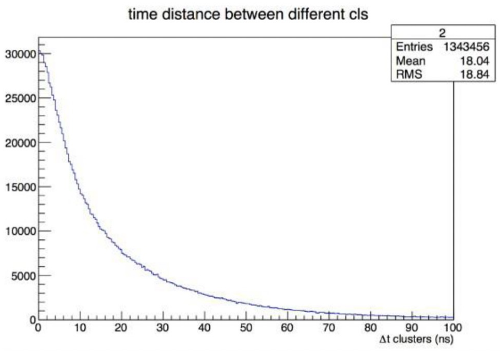
   For them, a counter for electrons per cluster is incremented.

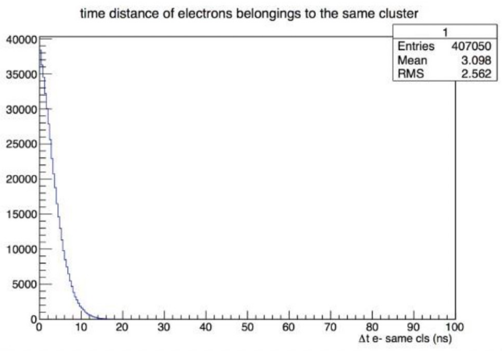
   (Next, consider this cut a function of the first cluster drift time, according to the electron diffusion)

1. Position of the clusters is taken as the position of the last electron in the cluster.

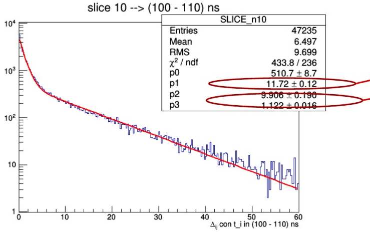
   (Next, position the cluster at the time of the electrons charge weighted average)

2. The distributions of the number of clusters must follow a Poisson distribution!




## Garfield simulation

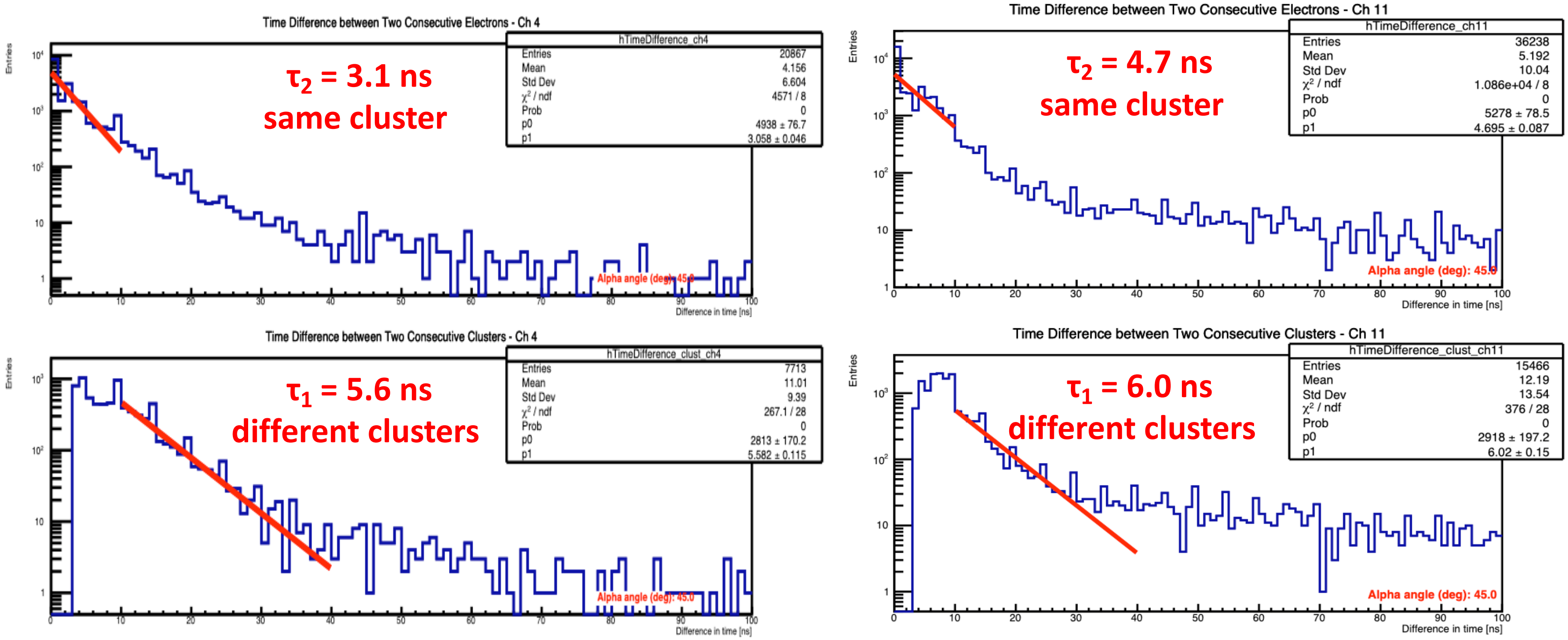



$f(t) = Ae^{-t/\tau 1} + \text{B}\, e^{-t/\tau 2}$

τ1 describes time distance for different clusters

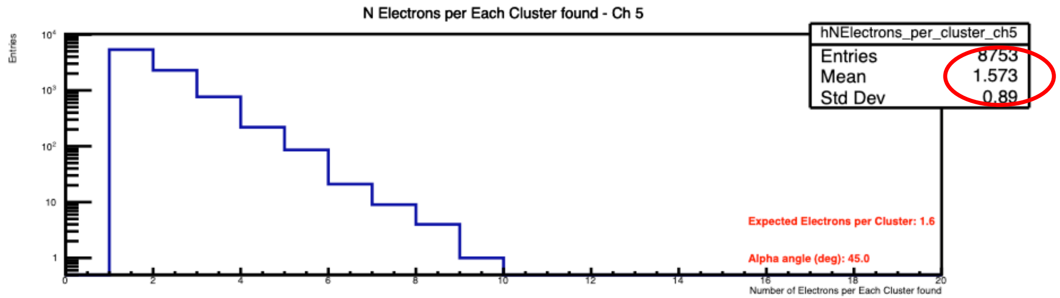
τ2 describes time distance for same cluster

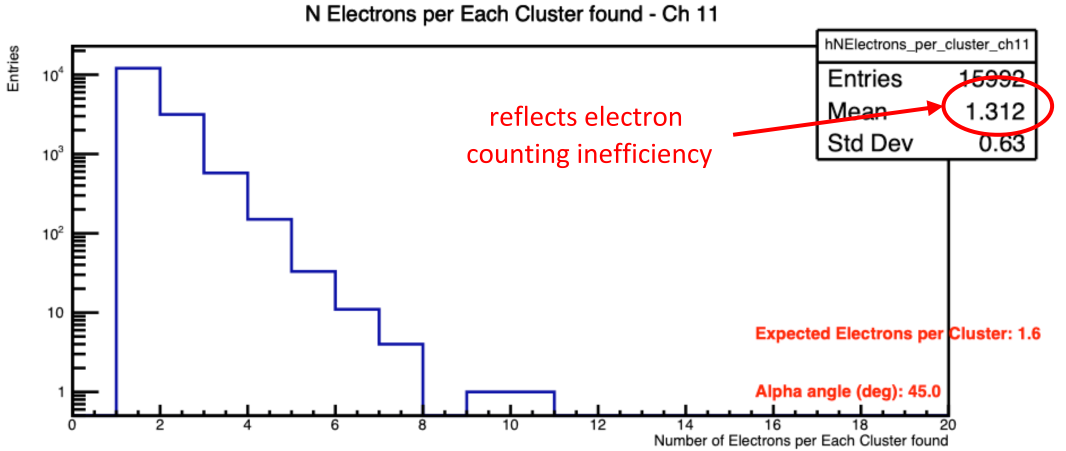
# Electron clustering



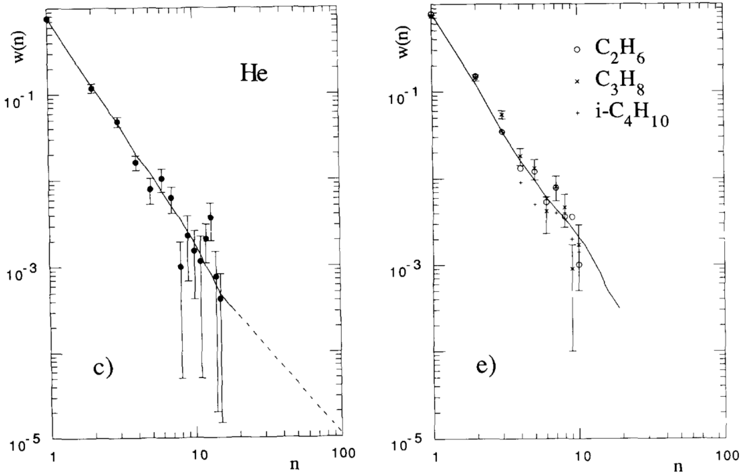

**1 cm drift tubes** **2 cm drift tubes**

# Electrons cluster density (90%He)




## $<N_{electrons}/cluster> = 1.6$

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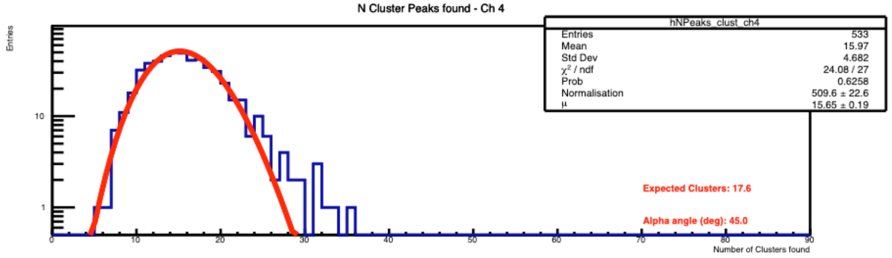
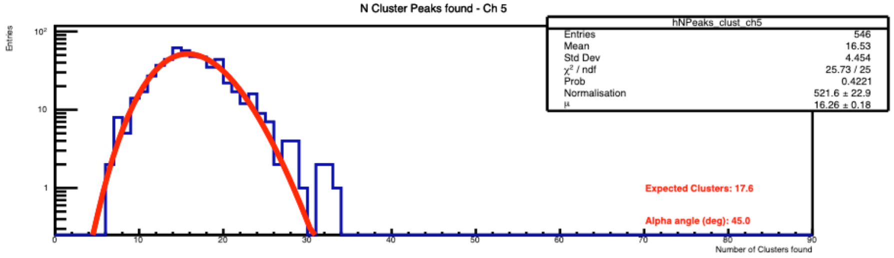
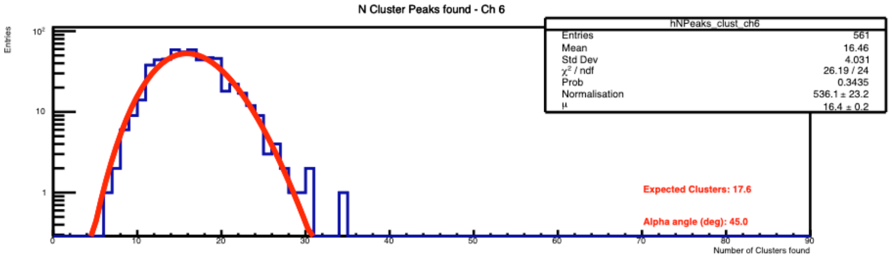
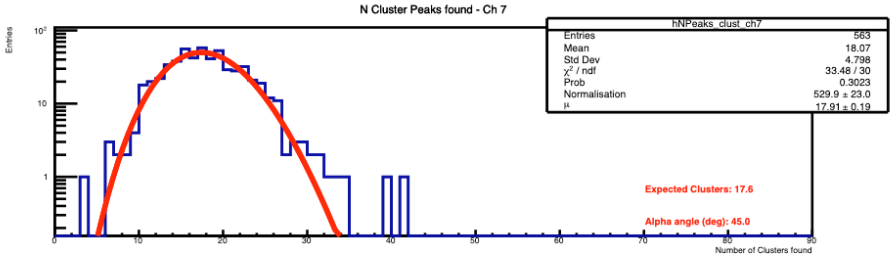
**No recent experimental measurement**

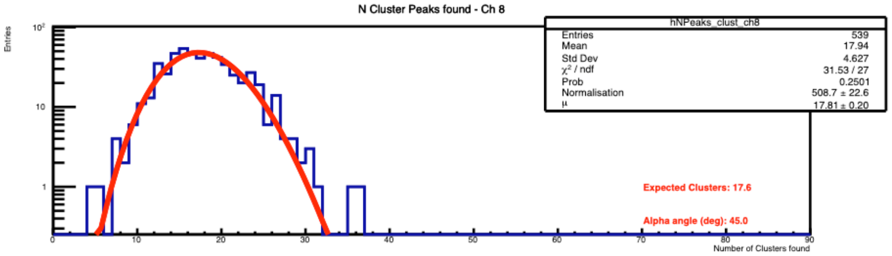
# Cluster counting (Poisson fits) – 1 cm, 45°

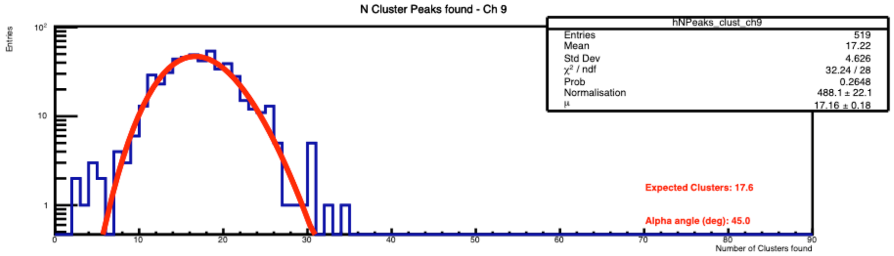


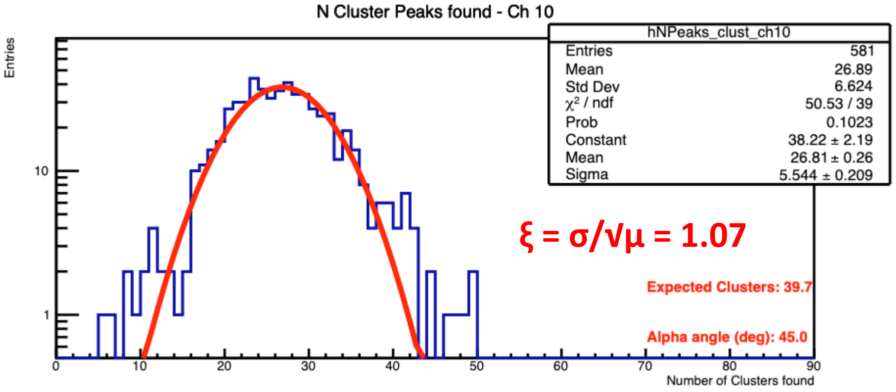



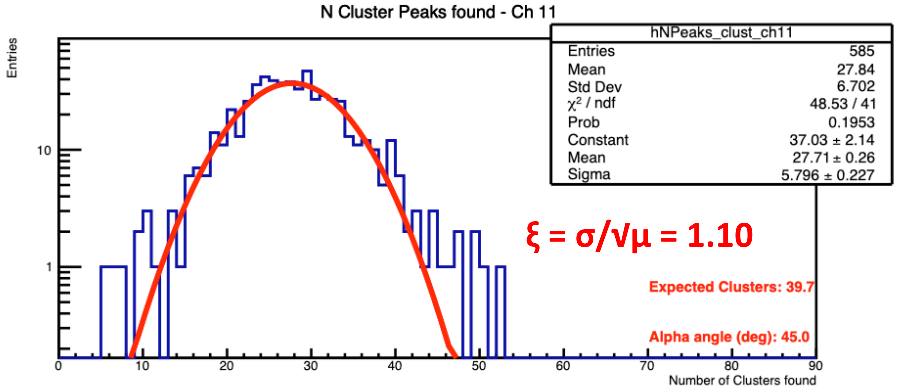



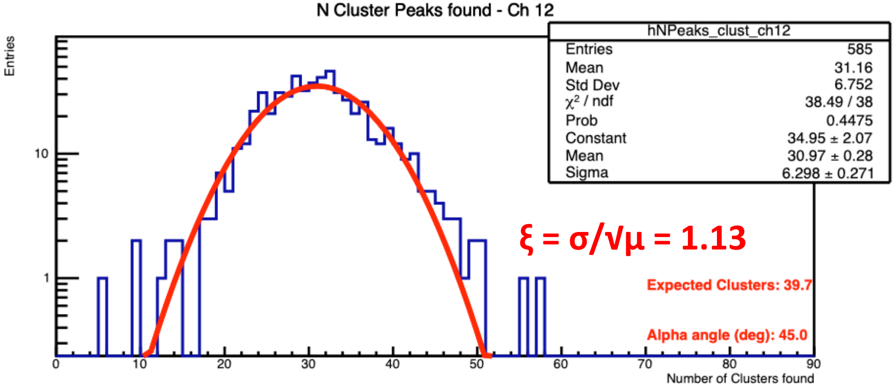



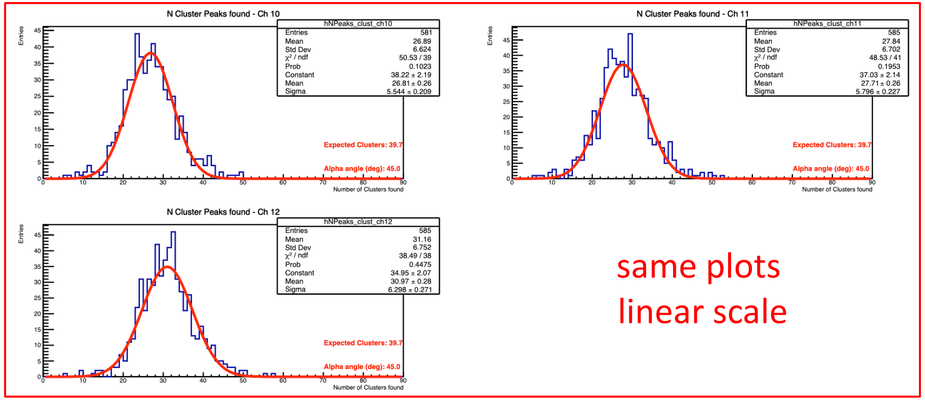



# Cluster counting (Gauss fits) – 2 cm, 45°

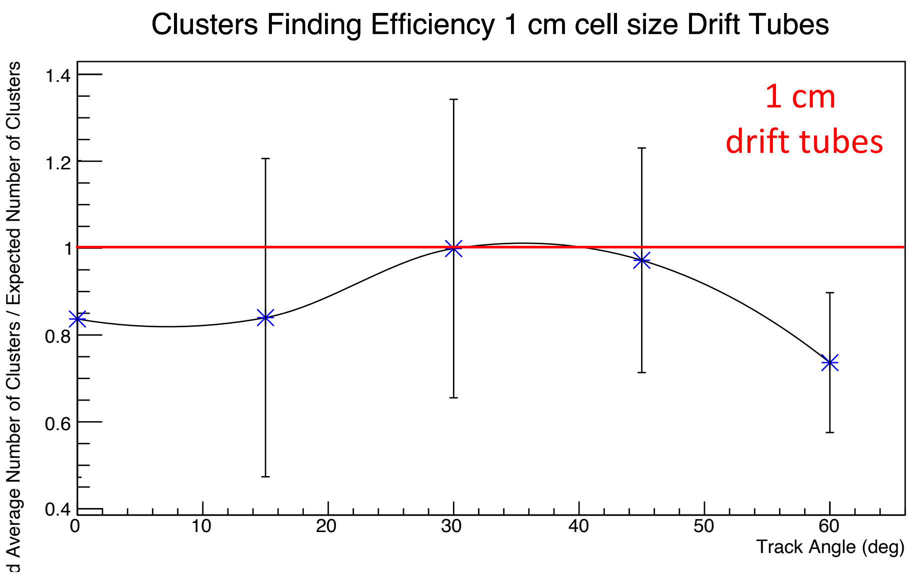


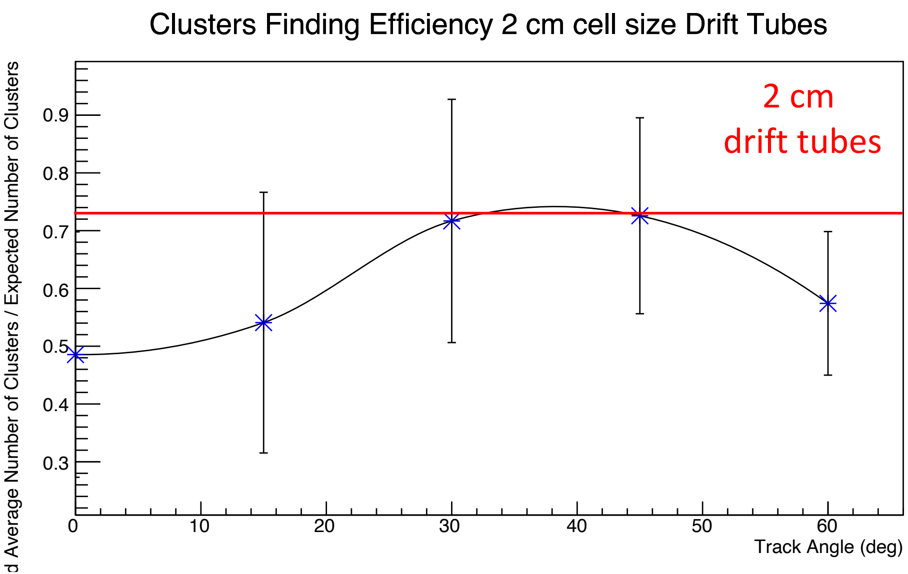



# Cluster counting




- Same effects seen in the electron peaks counting (**space charge** and high **electron peaks density**)
- **Full efficiency** and **Poisson distribution** for 1 cm drift tubes
- **25-30% average inefficiency** for 2 cm drift tubes (electron inefficiency)
- **Inefficiency** may be cured by increasing the sampling rate (more bins per peak)

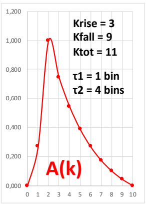
# Alternative counting algorithms

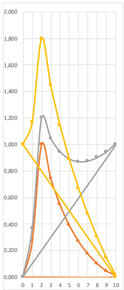
# Running Template Algorithm (at debugging stage)

- 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

Example 1

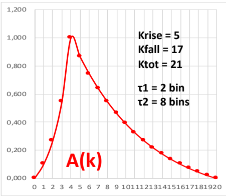
| k | A(k) |
|---|---|
| 0 | 0.0 |
| 1 | 0.269 |
| 2 | 1.0 |
| 3 | 0.744 |
| 4 | 0.545 |
| 5 | 0.390 |
| 6 | 0.269 |
| 7 | 0.175 |
| 8 | 0.102 |
| 9 | 0.044 |
| 10 | 0.0 |

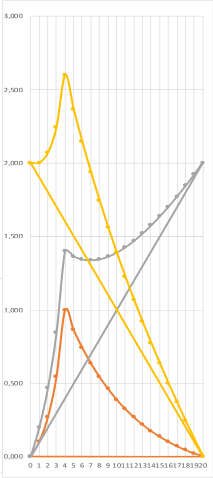


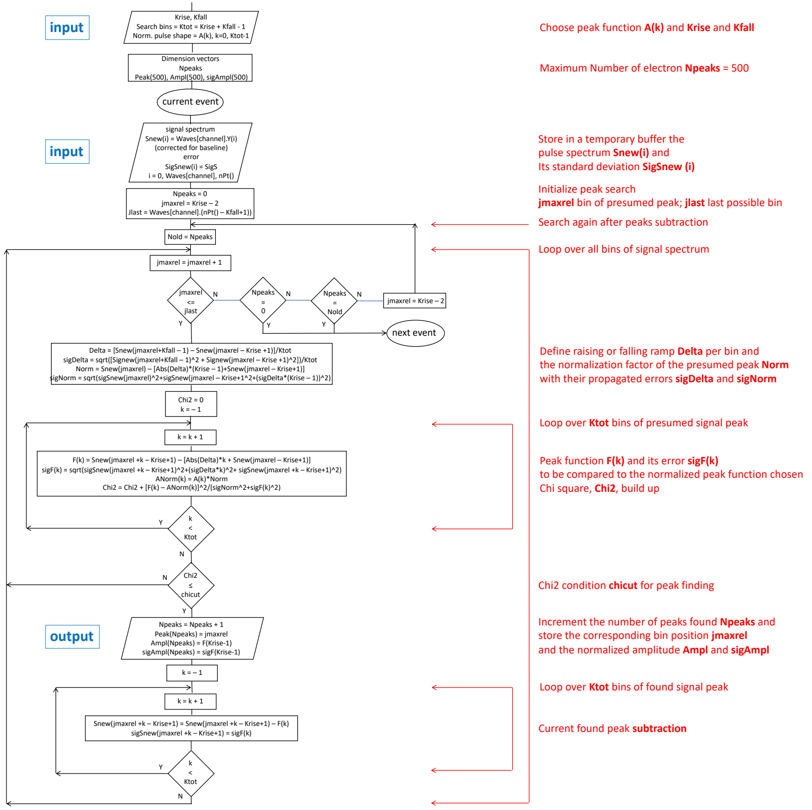




Example 2

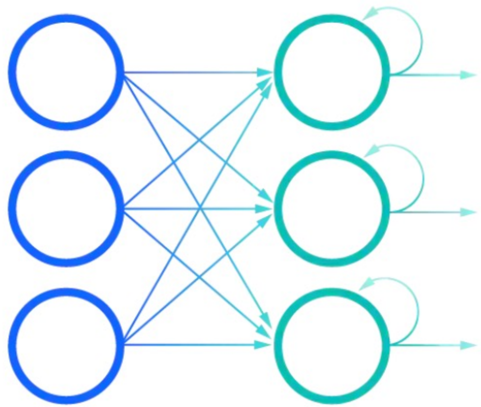
| k | A(k) |
|---|---|
| 0 | 0,000 |
| 1 | 0,102 |
| 2 | 0,269 |
| 3 | 0,545 |
| 4 | 1,000 |
| 5 | 0,864 |
| 6 | 0,744 |
| 7 | 0,638 |
| 8 | 0,545 |
| 9 | 0,463 |
| 10 | 0,390 |
| 11 | 0,326 |
| 12 | 0,269 |
| 13 | 0,219 |
| 14 | 0,175 |
| 15 | 0,136 |
| 16 | 0,102 |
| 17 | 0,071 |
| 18 | 0,044 |
| 19 | 0,021 |
| 20 | 0,000 |





# Peak finding with deep learning



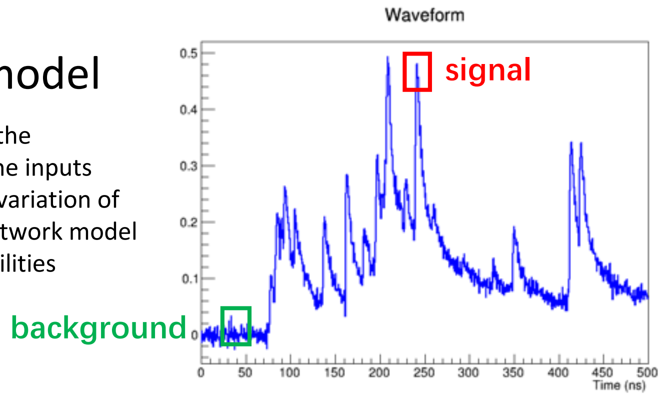
**Machine Learning:**
- Powerful: "Learn" the characteristics of data automatically by the machine

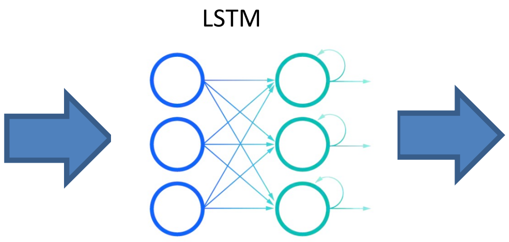
**Recurrent Neural Network (RNN):**
- Internal loops ➔ "memories"
- Powerful to handle time-sequence problems

**Waveform Peak Finding:**
- Can be adapted to a machine learning problem:
  - Binary classification: "peaks" vs. "noises"
  - Time-sequence data structure: appropriate for RNN
- Advantage and challenge by using ML
  - Advantage: Make fully use of the waveform information, while derivative only rely on the rising-edge
  - Challenge: Require excellent data/MC consistency

## Training model

- Using slices of the waveform as the inputs
- Using LSTM (a variation of RNN) as the network model
- Output probabilities

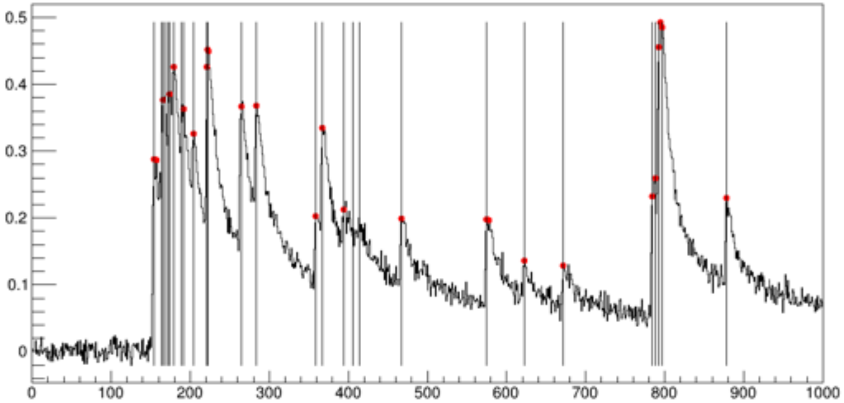


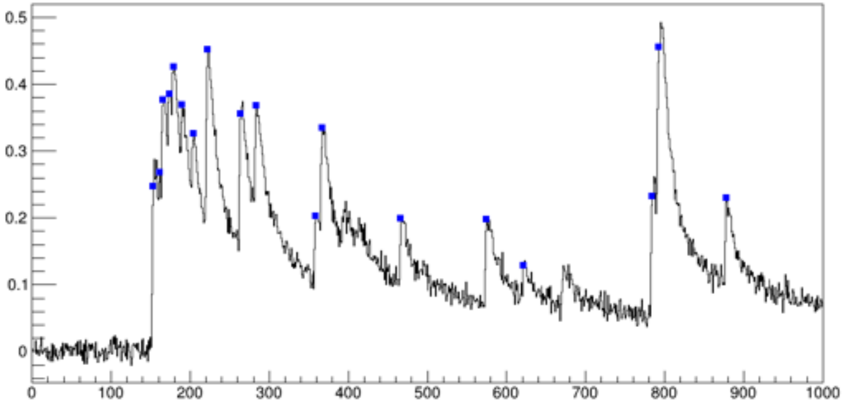

**Output probability (classifier)**

# Peak finding example with deep learning (toy MC)

RNN (LSTM)




Derivative




Black line: truth times (primaries and secondaries)

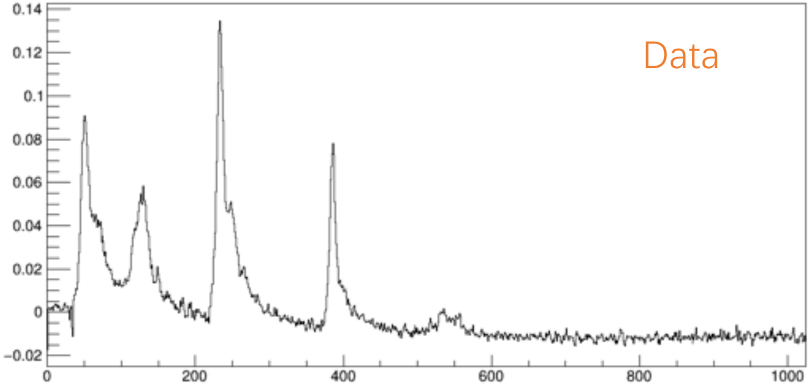
**Peak detection ability with RNN is better than that with derivative**

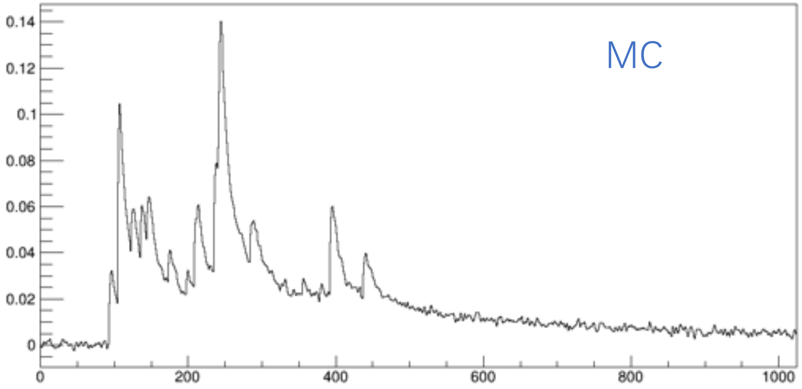
# Efforts on improving data/MC consistency

(1) **MC tuning:**

- Noise model
- Amplitude
- Peak rising-time

(1) Tune MC base on Data → (2) Train network with MC → (3) Apply to Data




**MC is more consistent with data. But some effects are still need to be investigated (e.g., space-charge).**

# Conclusions

- **Particle identification** via **dE/dx** has essentially made **no progress since over 40 years**.
- **Cluster counting** may provide the long sought jump in performance.
- Both analytical and montecarlo simulations suggest an **improvement of a factor 2 of dN/dx versus dE/dx**.
- Byproduct of the **cluster counting** technique is the **cluster timing** technique, which offers **improvements in the impact parameter resolution** (directly coupled to transverse momentum resolution) and allows for **a precise event time-stamping**.
- 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. So far, we have concentrated our efforts in successfully demonstrating the **ability to efficiently count ionization clusters**.
- Next step will be the experimental measurement of the **cluster density** and **cluster size distributions over the relativistic rise region**, which will begin this coming summer at CERN H8.