A beam test for the cluster counting technique

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Advantages

N_{cl} number of primary ionizations

- 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.)**:

  $\sigma_{dNcl/dx}/(dN_{cl}/dx) = N_{cl}^{-1/2} < 2.0\%$ (at 100% counting efficiency)
- potentially, 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 **singe electron diffusion**

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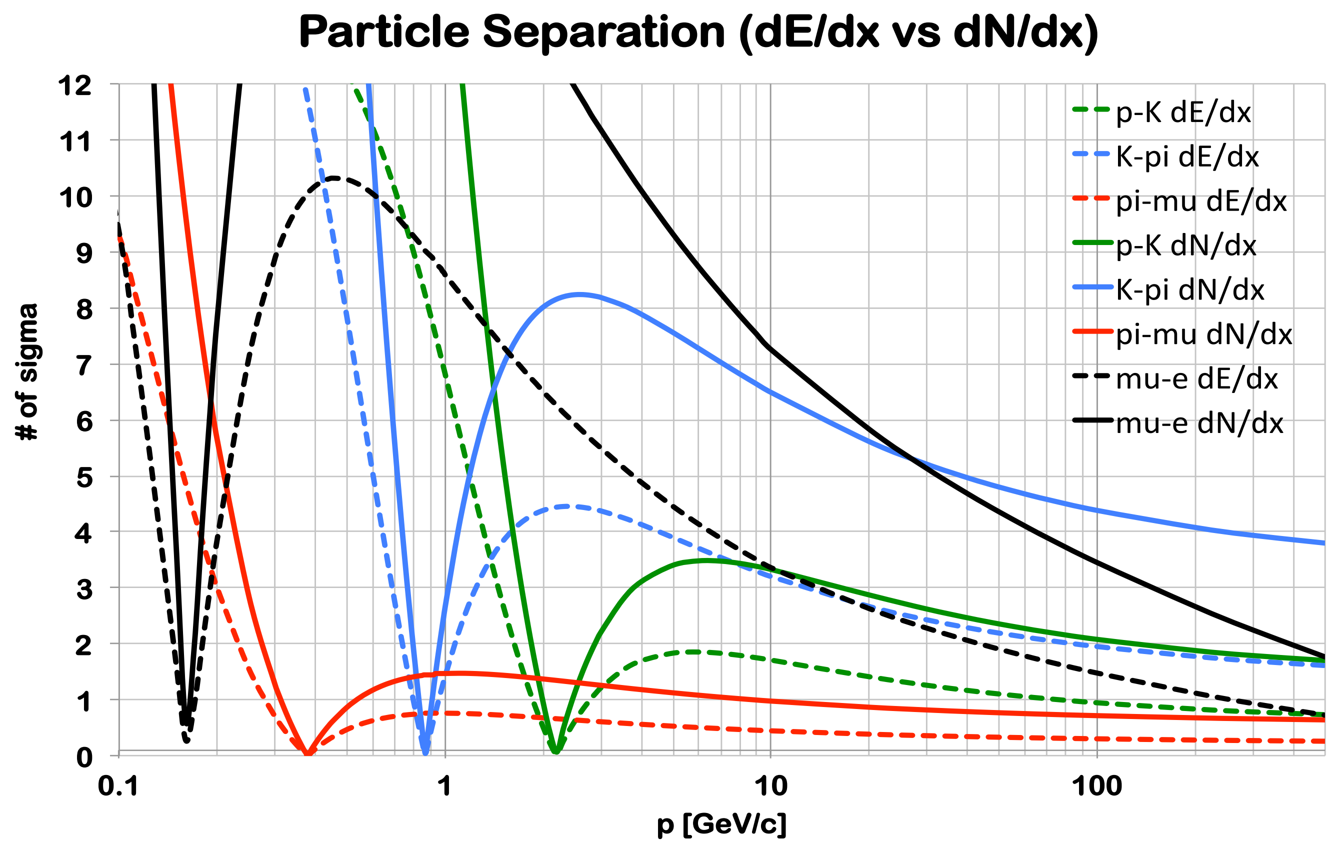
Recipe

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

PID in IDEA drift chamber

Expected from analytical calculations for the IDEA drift chamber

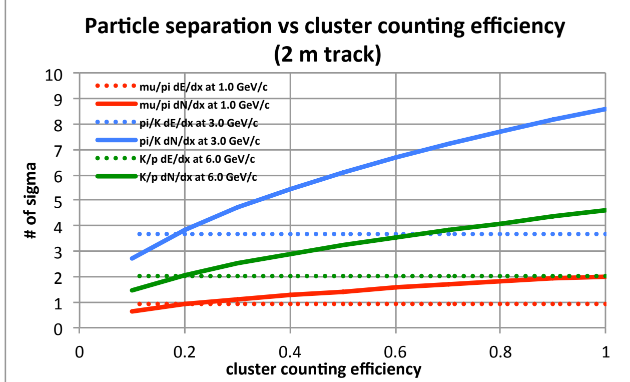


He/iC_4H_{10} = 90/10
$\delta_{cl}=12\ cm^{-1}$

σ(dE/dx)/(dE/dx)
=4.3%

80% cluster
counting efficiency

$\sigma(dN_{cl}/dx)/(dN_{cl}/dx)$
=2.3%



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.

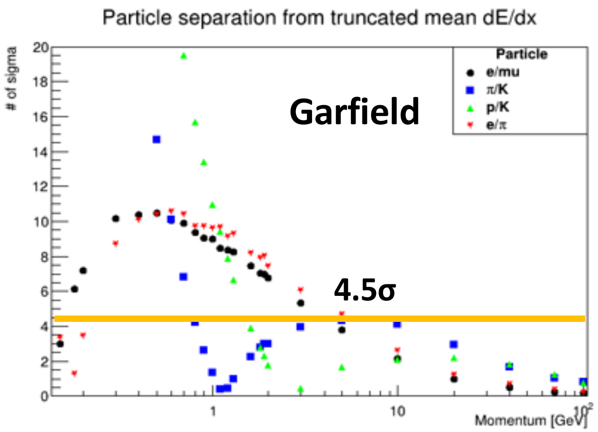
We have developed an algorithm, which uses the **energy deposit** information provided by Geant4, to reproduce, in a fast and convenient way, the **clusters density** and the **cluster size** distributions predicted by Garfield++.

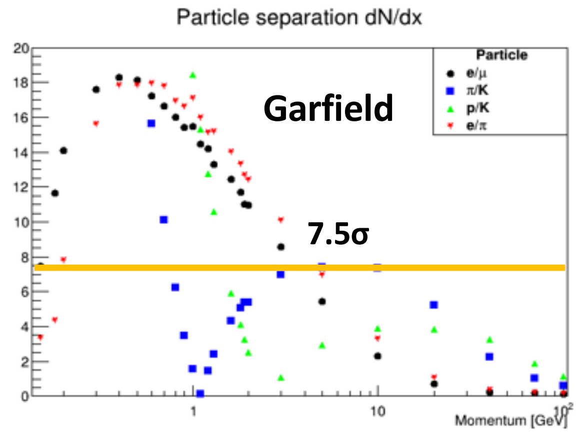
A simulation of the ionization process in 200 drift cells, 1 cm wide, in 90% He and 10% iC_4H_{10} gas mixture has then been performed both in **Garfield++** and in Garfield-modeled **Geant4**.

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

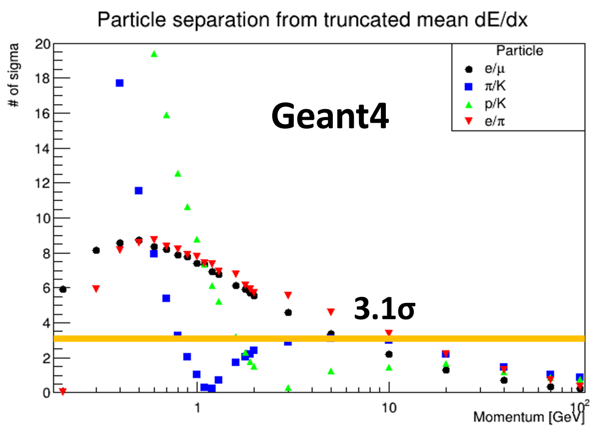
PID: full simulation vs analytical calculations

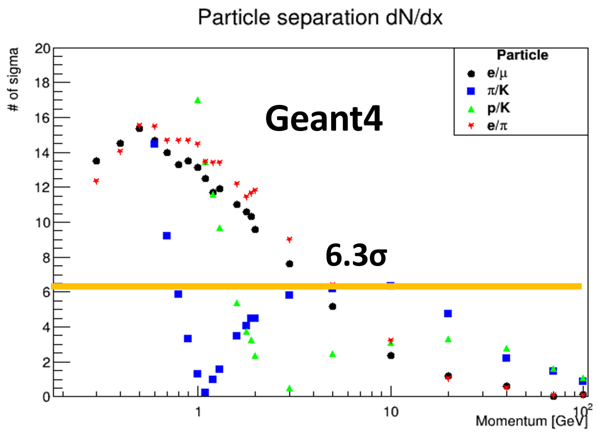




dN/dx: consider π/K separation at 5 GeV/c:

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



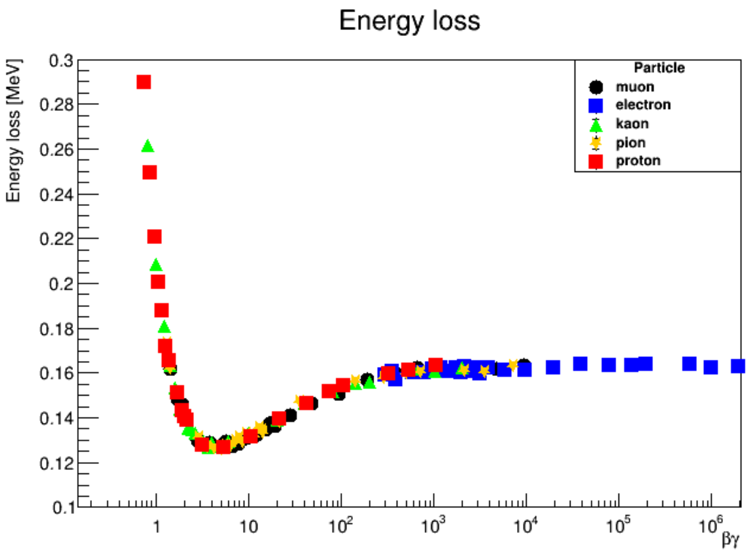


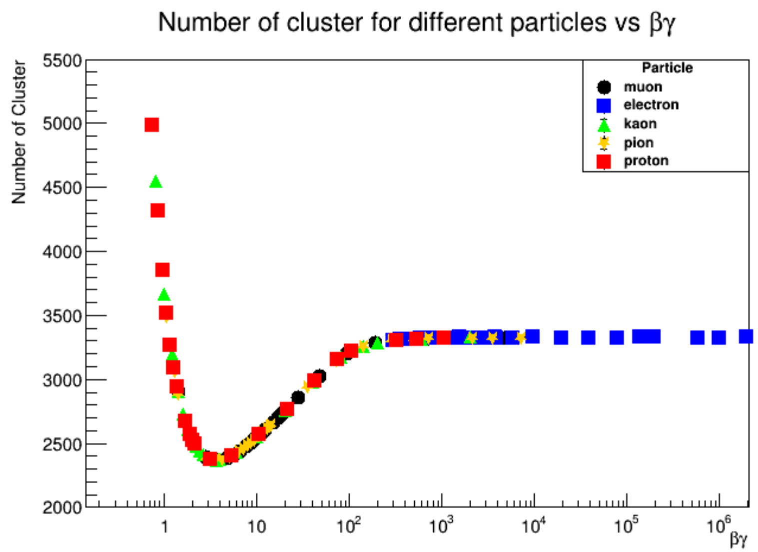
Despite **Geant4** uses the cluster density and the cluster size distributions from Garfield++, it **disagrees** from **Garfield++** and, therefore, from the **analytical calculations** also.

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

PID full simulation with cluster counting

dE/dx and dN/dx vs βγ





PID full simulation with cluster counting

Open questions:

1. There exists limited **experimental data** on cluster density and cluster population for He based gas. Particularly in the relativistic rise region, in order to compare predictions.
2. Is the theoretical model derived by Garfield++ correct to describe the phenomenon, given the limited amount of experimental data?
3. 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++**?
4. Despite a higher value of the Fermi plateau (1.38 × m.i.p.) for **dN_{cl}/dx** with respect to **dE/dx** (1.26 × m.i.p.), why it is reached at **lower values of βγ** (250 vs 600) **with a steeper slope**?
5. These questions are crucial for establishing the particle identification performance at **FCCee** and at **CEPC**
6. However, **the only way to ascertain these issues is an experimental measurement!**

beam test objectives

Beam test plans:

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

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test done, analysis in progress

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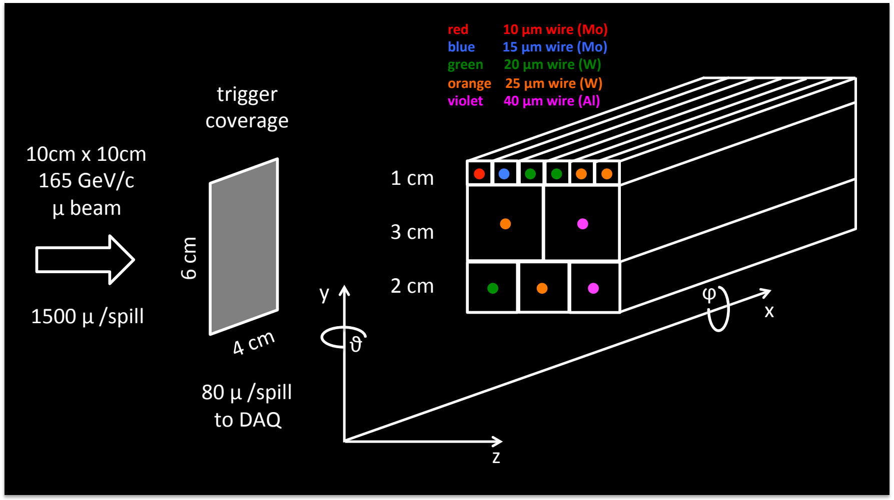
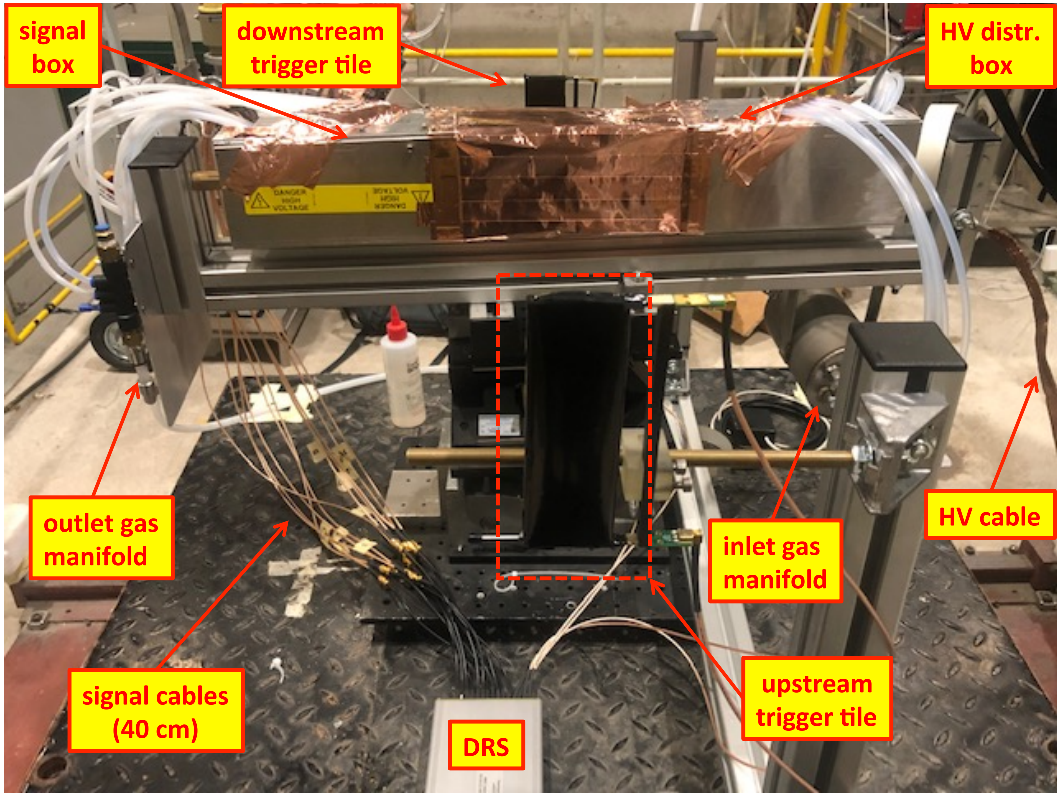
beam test in June 2022

Test setup

schematic





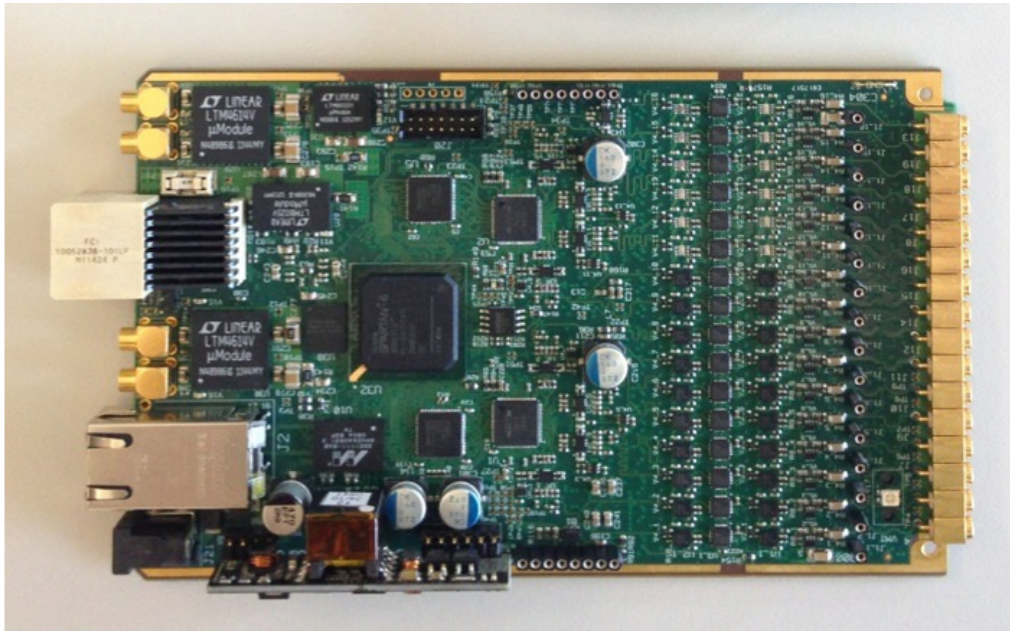
The test was performed during November 2021 at CERN on the H8 beam line in a **parasitic mode**. Main users on the same beam line was a team testing a tile calorimeter and, therefore, requesting for **large part of the time, beams of electrons and hadrons, at various energies,** needed for their calibration, 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 of **internal tracking** (time-to-distance and t_0 **calibrations**, alignment, track finding and fitting algorithms, ...)
- no need to correct for ambient conditions (very little effect of **pressure** and **temperature** on peak counting)
- no need to convert **time to distance** (just count clusters in the **time domain**)
- 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

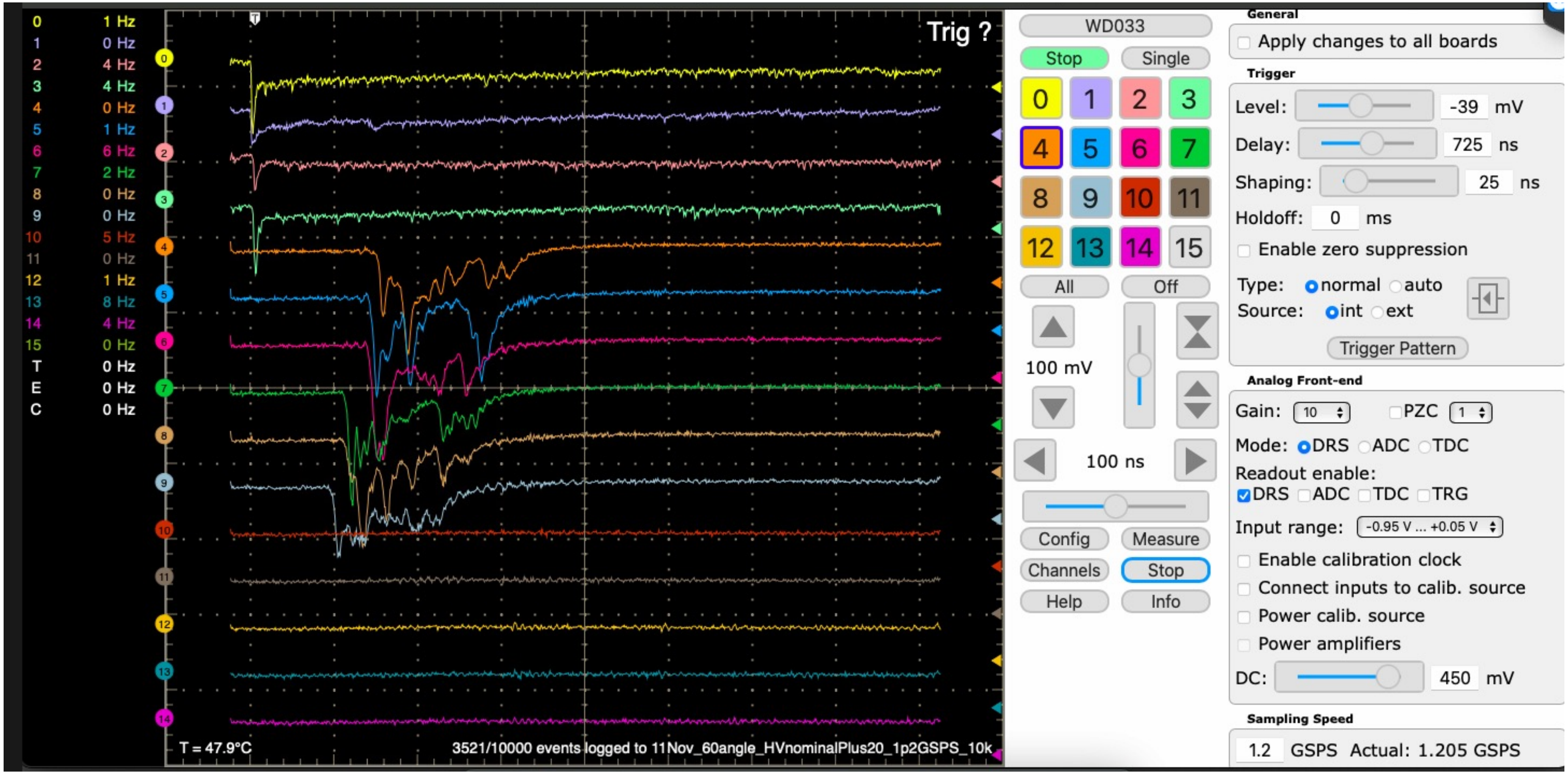


16 channels data acquisition board designed and used by the MEG2 experiment at PSI ($\mu \rightarrow e + \gamma$)
(credit to S. Ritt, Paul Sherrer Institute, Zurich, Switzerland)

Trigger

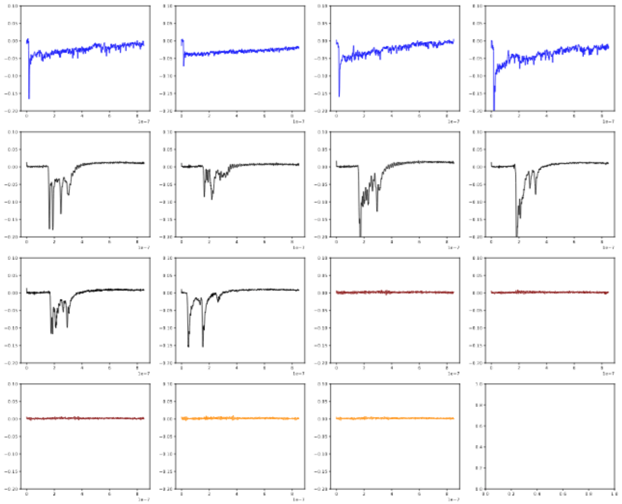
12cm x 6cm upstream and downstream scintillator tiles (designed and used as timing counter of the MEG2 experiment at PSI) used in coincidence and readout by SiPM

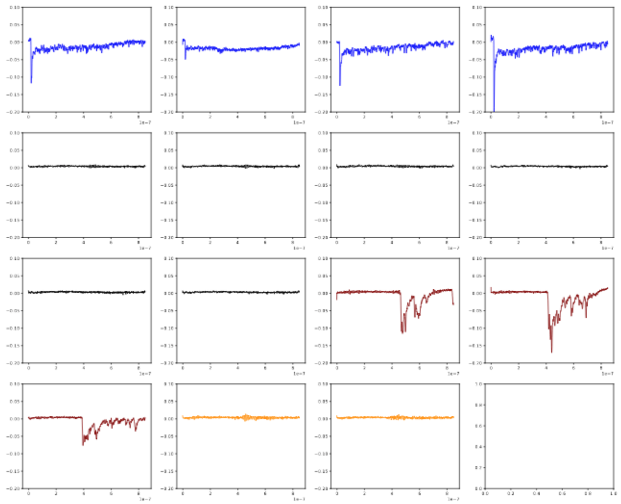
Test setup: event display

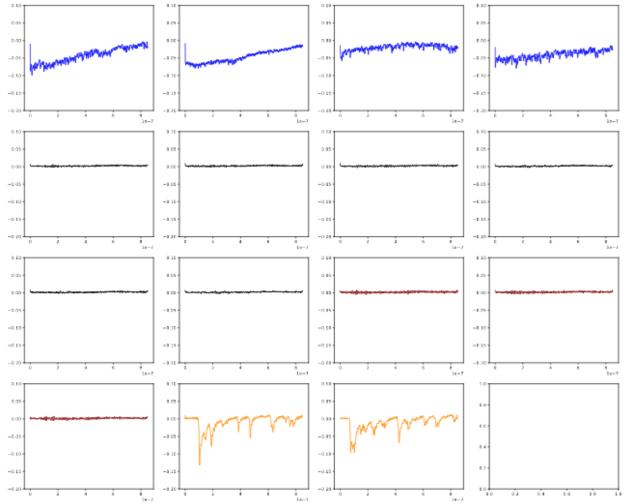


event display

top 4 channels trigger scintillators







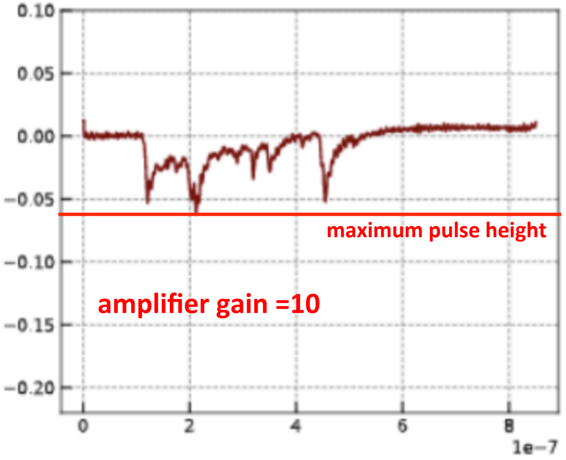
6 drift tubes (1 cm)

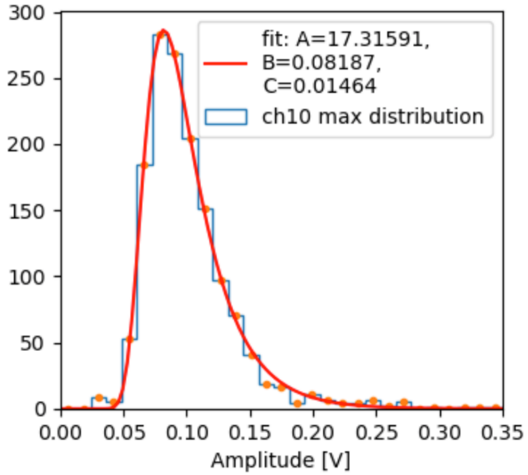
3 drift tubes (2 cm)

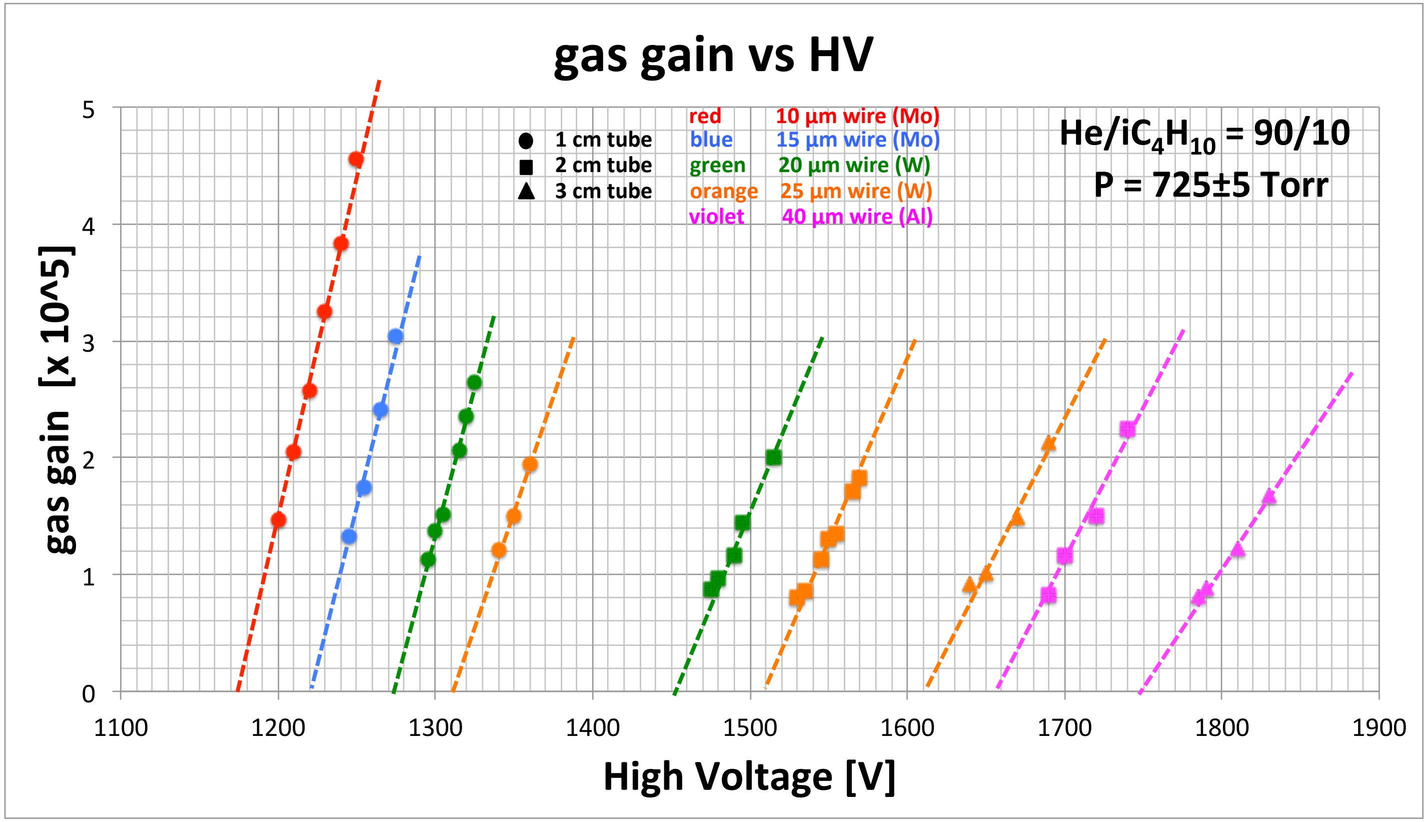
2 drift tubes (3 cm)

vertical full scale 300 mV (gain 10) – horizontal scale 800 ns

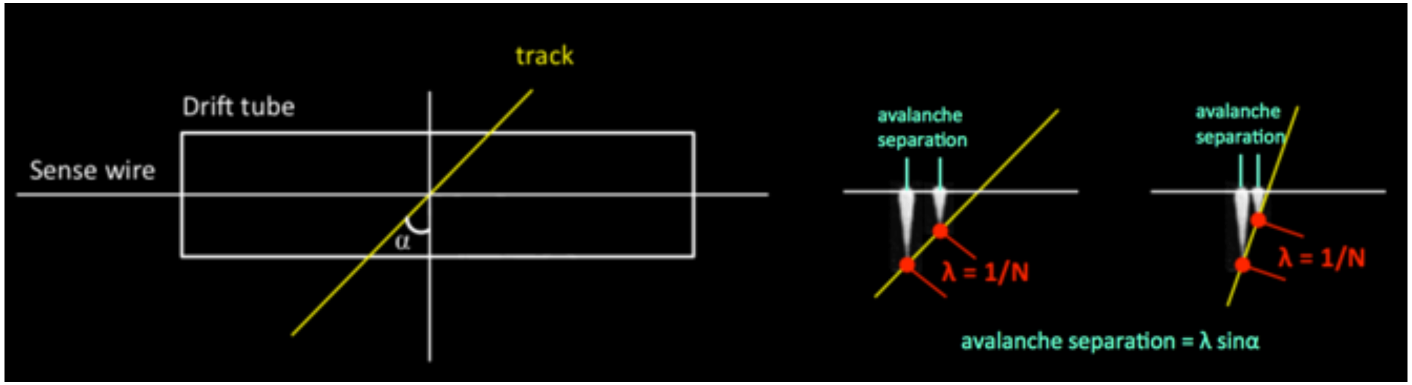
gas gain

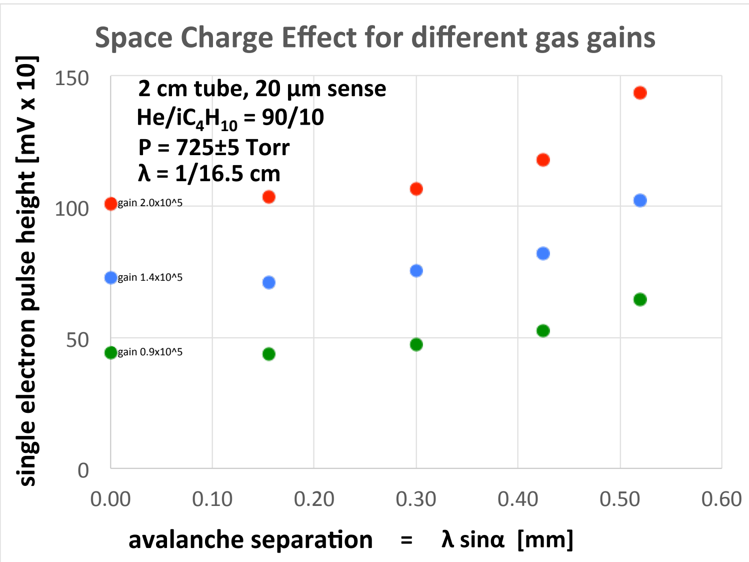

maximum pulse height
amplifier gain =10
1e−7

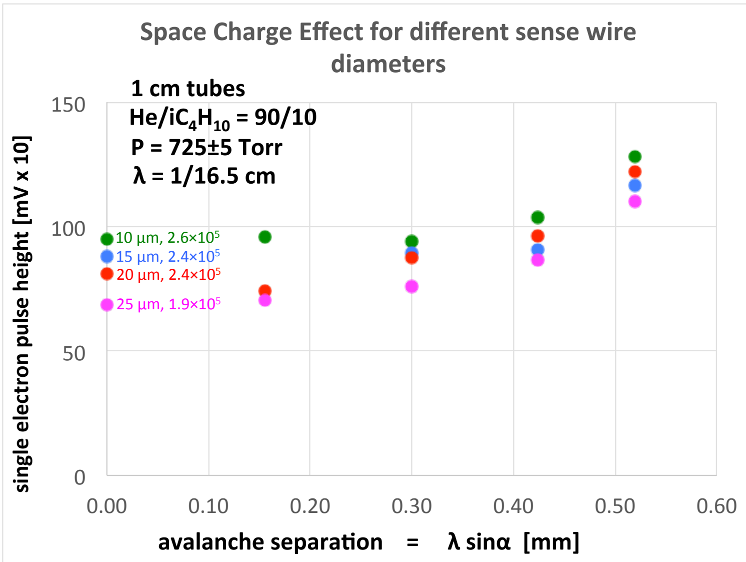

fit: A=17.31591,
B=0.08187,
C=0.01464
ch10 max distribution
Amplitude [V]


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







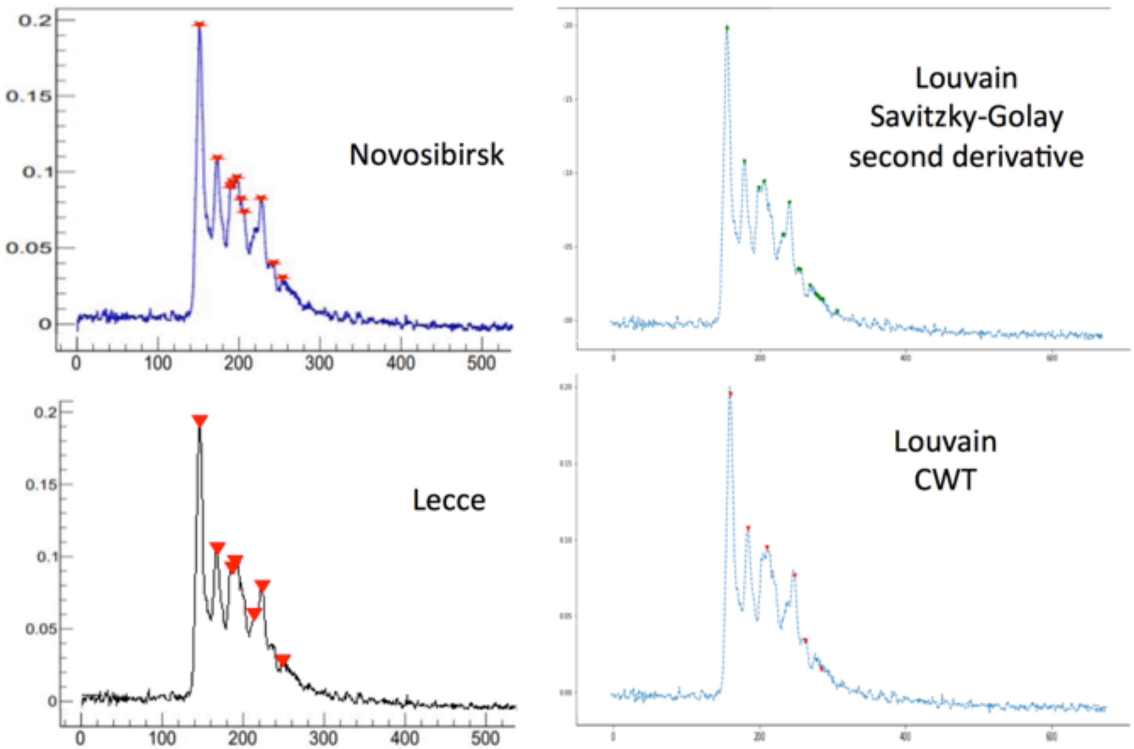
no dependence of space charge effects from the gas gain, **no dependence of space charge effects from the sense wire diameter** at least in this range of gas gain values

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

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

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

counting peaks



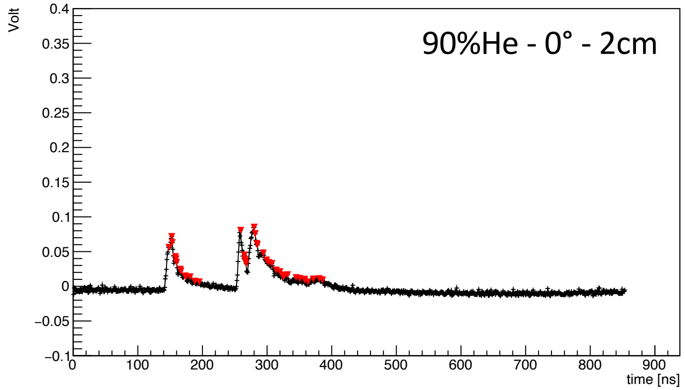
First attempts at applying different algorithms.

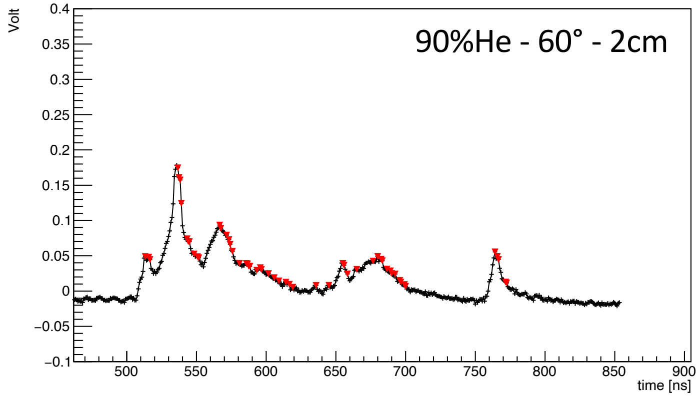
No optimization of parameters and cuts here.

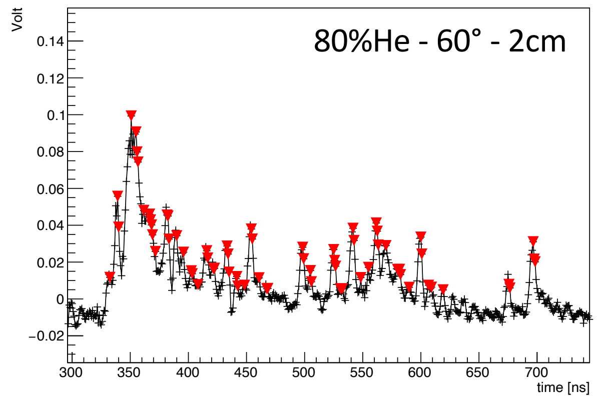
Concentrating on machinery to speed up comparisons among different algorithms.

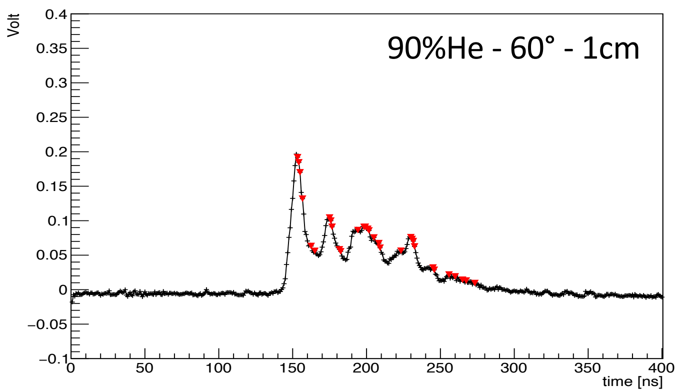
Other algorithms (IHEP) welcome in the game.

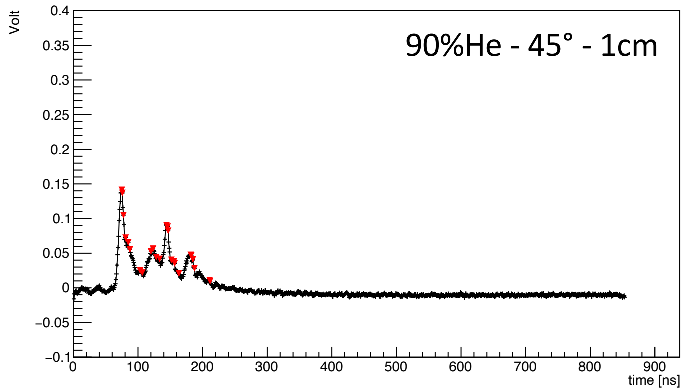
counting peaks (tuning the Lecce algorithm)

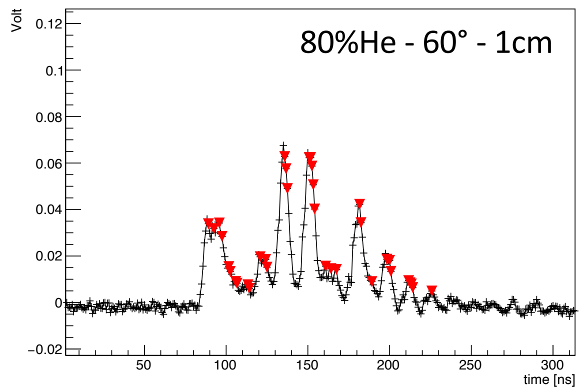








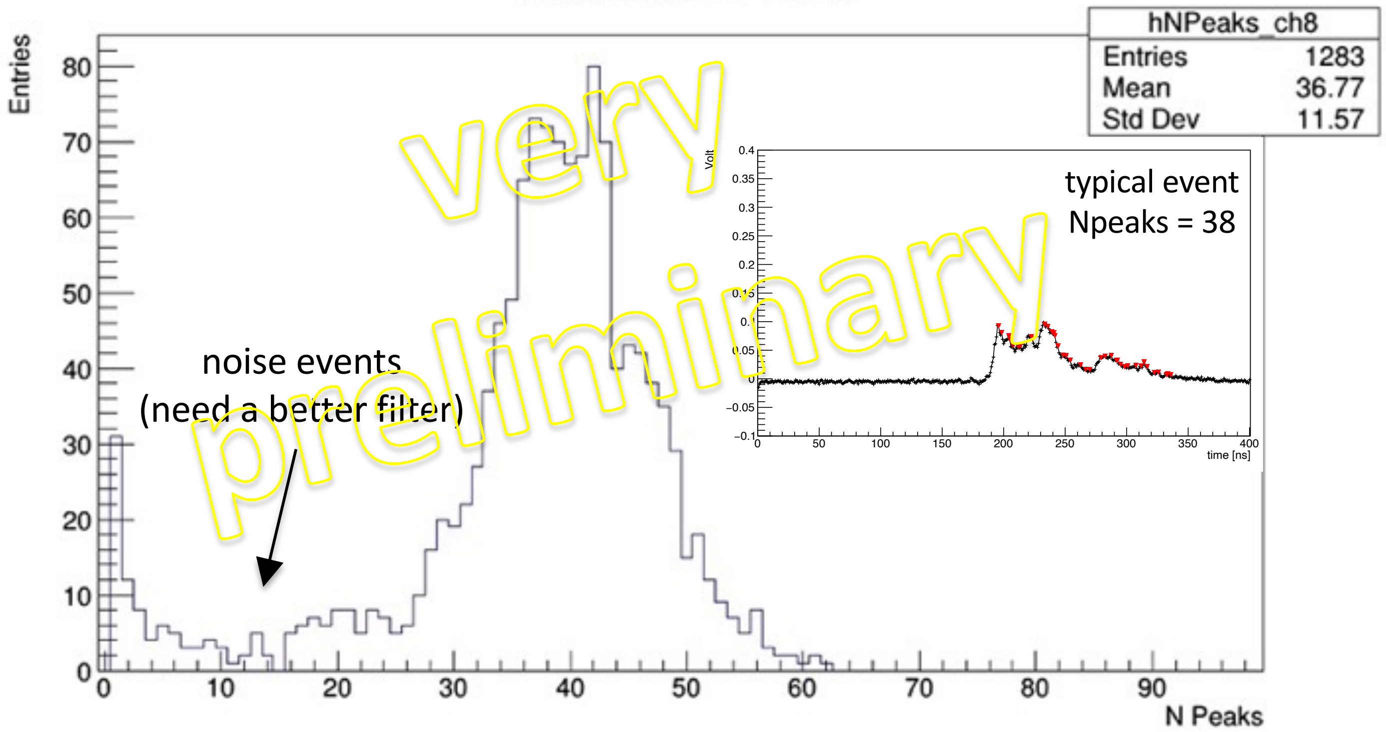




counting peaks

Expected number of electron peaks:

δ clusters/cm (m.i.p.) × 1.3 (rel. rise) × 1.6 electrons/cluster × tube size [cm] × 1/cosα



1 cm tube

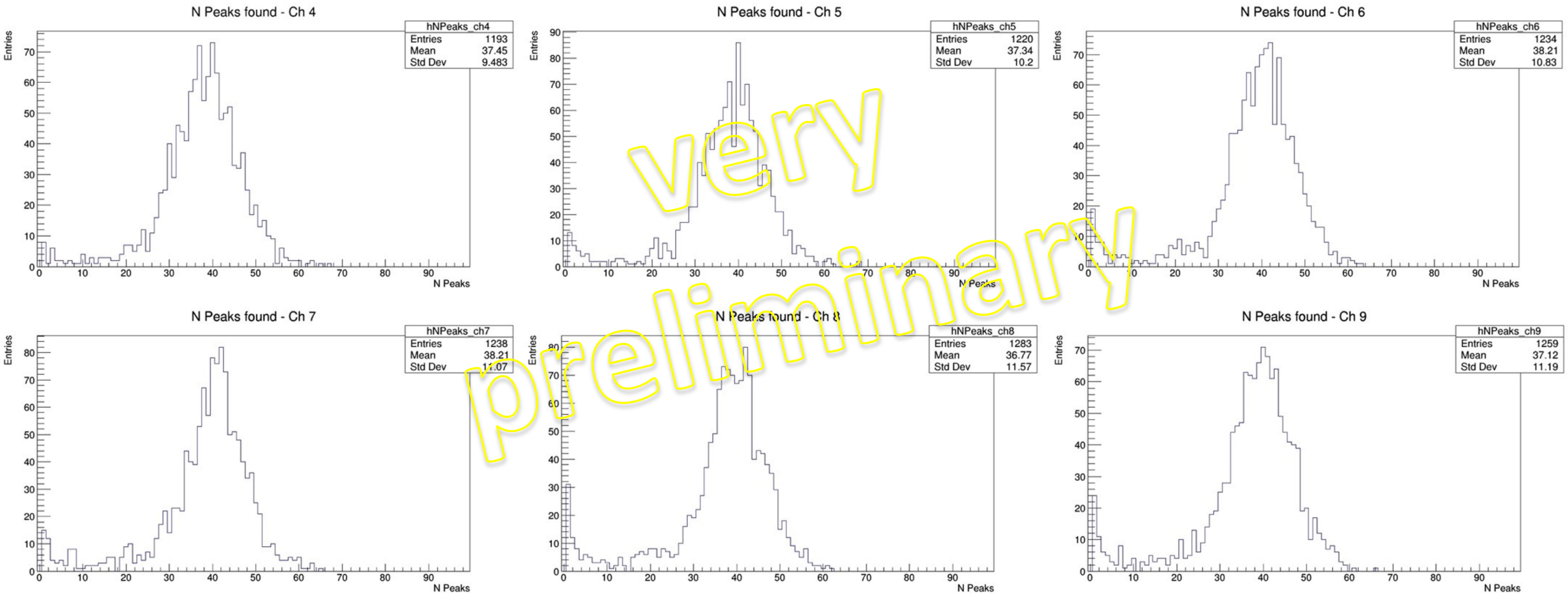
0.8 cm gas
90% He, δ=12/cm
α = 60°

Expected
Nelectrons = **40**
Nclusters = **25**

Association of electrons in clusters still missing

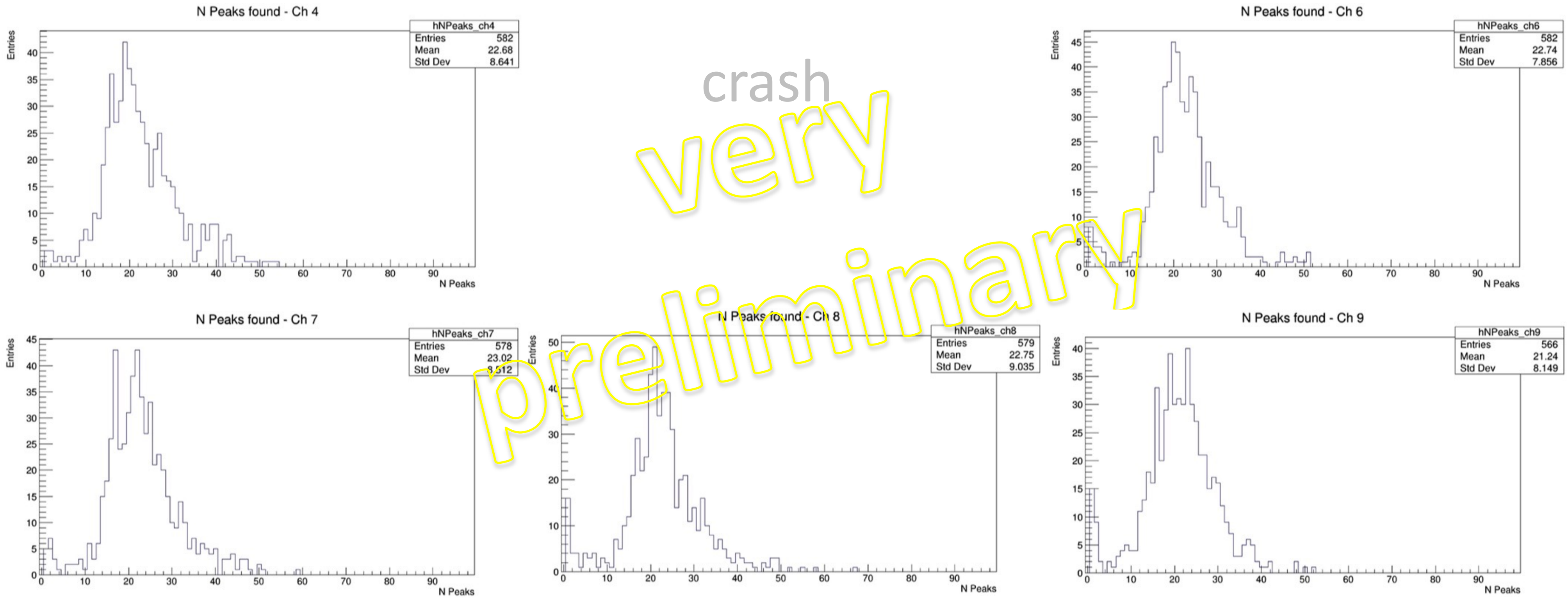
counting peaks

1 cm tubes – **different sense wires** – 90%He – **α = 60°** – **expected Npeaks = 40**



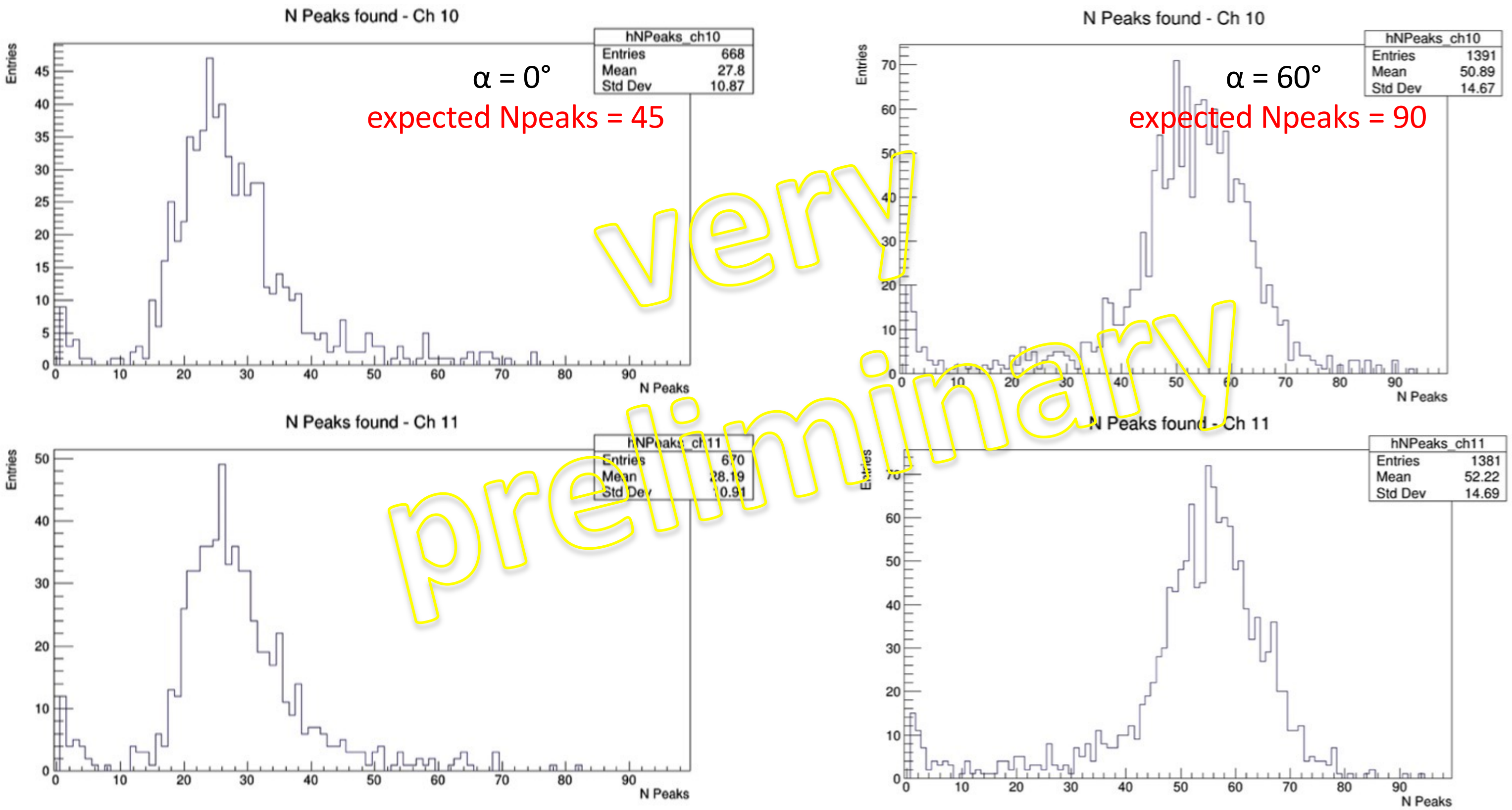
counting peaks

1 cm tubes – **different sense wires** – 90%He – **α = 0°** – **expected Npeaks = 20**



counting peaks

2 cm tubes – **different sense wires** – 90%He



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.
- 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**.
- 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** and we are very close to accomplish this task.
- Next step will be the experimental measurement of the **cluster density** and **cluster size distributions on the relativistic rise region**, which will begin this coming summer.