Istituto Nazionale
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Sezione di Bari

Cluster counting with IDEA drift chamber

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on behalf of the DCH community

ECFA Higgs Factories: 2nd Topical Meeting on Reconstruction

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eurizon
European network
for developing new horizons for RIs

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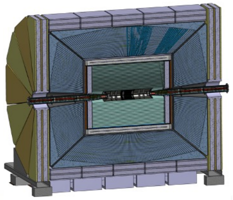
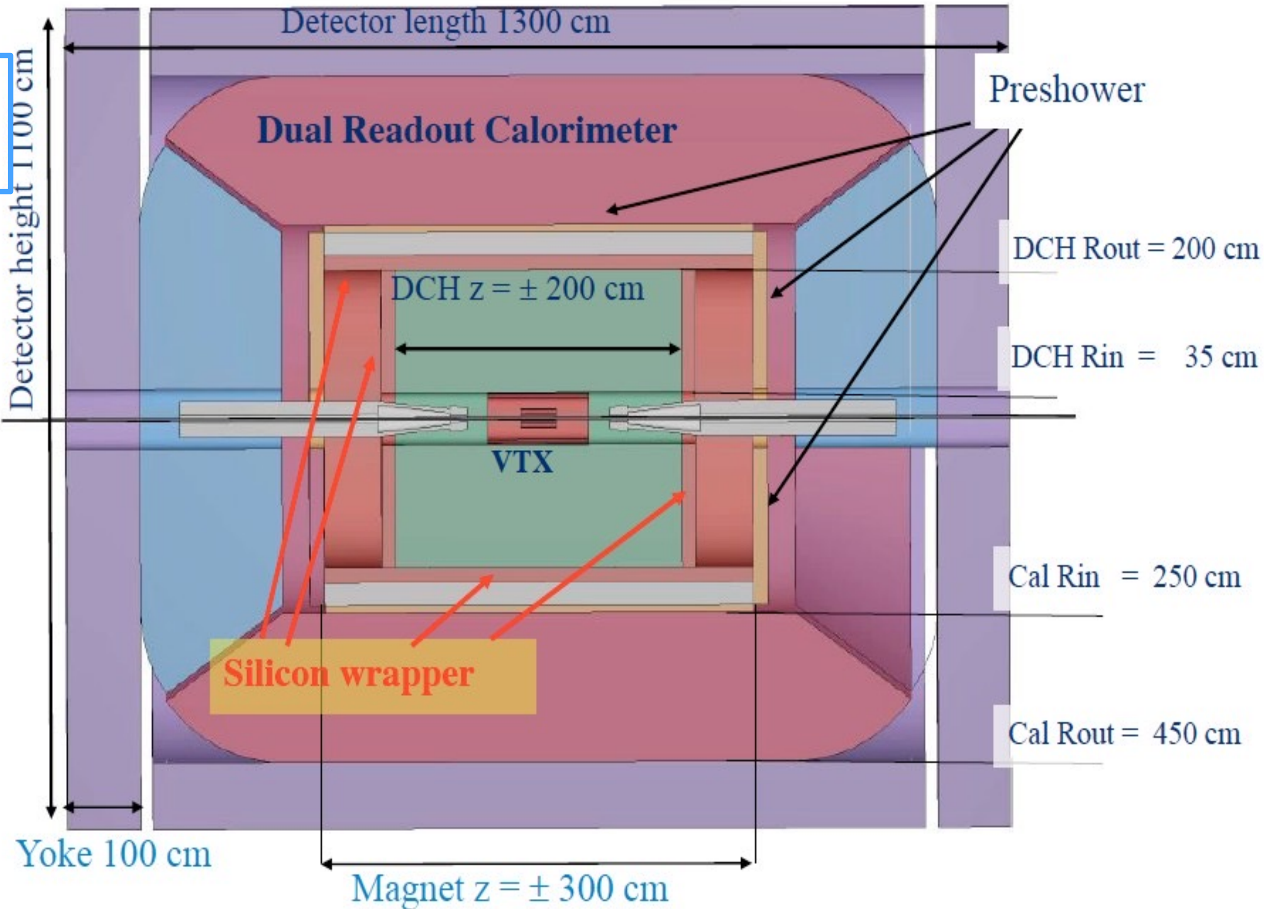
The IDEA detector at e^+e^- colliders

Innovative Detector for E+e- Accelerator

IDEA consists of:

- a silicon pixel vertex detector
- a large-volume extremely-light **drift chamber**
- surrounded by a layer of silicon micro-strip detectors
- a thin low-mass superconducting solenoid coil
- a preshower detector based on **μ-WELL technology**
- a dual read-out calorimeter
- muon chambers inside the magnet return yoke, based on **μ-WELL technology**





Low field detector solenoid to maximize luminosity (to contain the vertical emittance at Z pole).

→ optimized at 2 T

→ large tracking radius needed to recover momentum resolution

The Drift Chamber

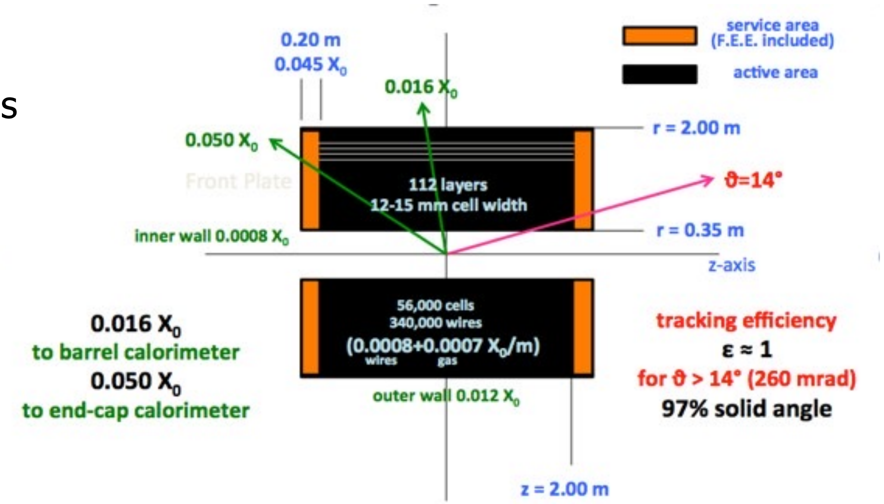
The DCH is:

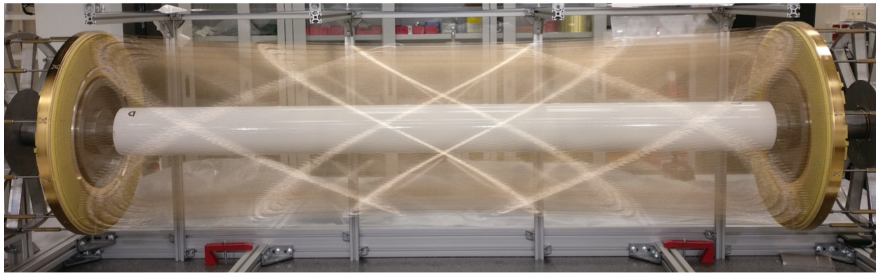
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m
- drift length ~1 cm
- drift time ~150ns
- $\sigma_{xy} < 100\ \mu m$, $\sigma_z < 1$ mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires ratio
- 112 co-axial layers, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors, with frontend electronics
- 343968 wires in total:

  sense vires: 20 μm diameter W(Au) => 56448 wires

  field wires: 40 μm diameter Al(Ag) => 229056 wires

  f. and g. wires: 50 μm diameter Al(Ag) => 58464 wires





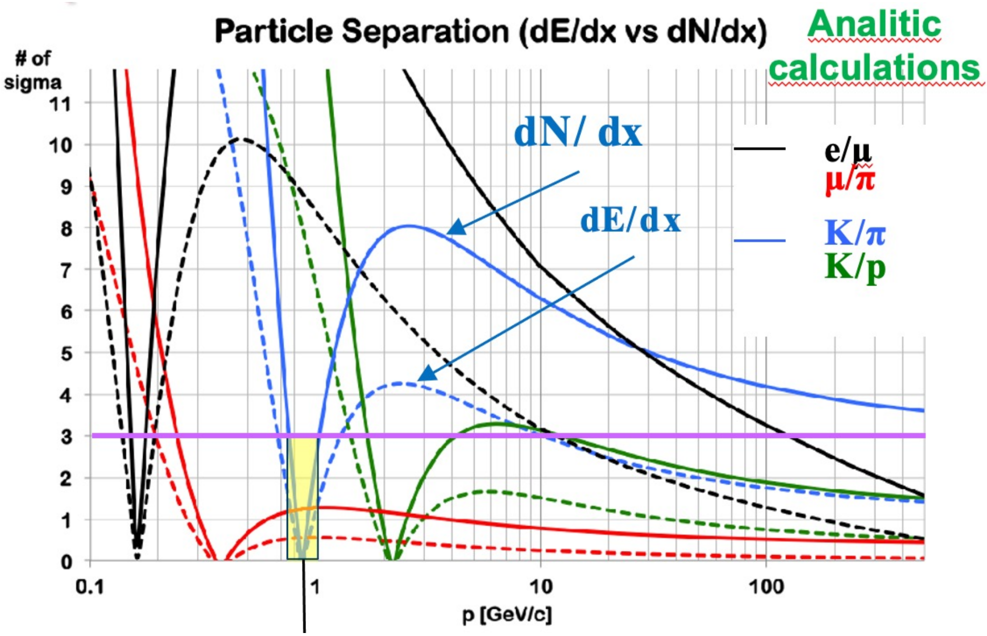
- the wire net created by the combination of + and – orientation generates a more uniform equipotential surface → better E-field isotropy and smaller ExB asymmetries)

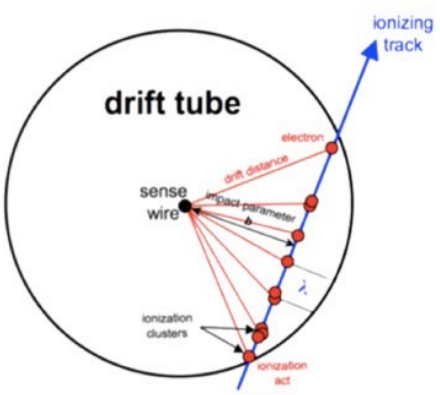
- a large number of wires requires a non standard wiring procedure and needs a feed-through-less wiring system → a novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber

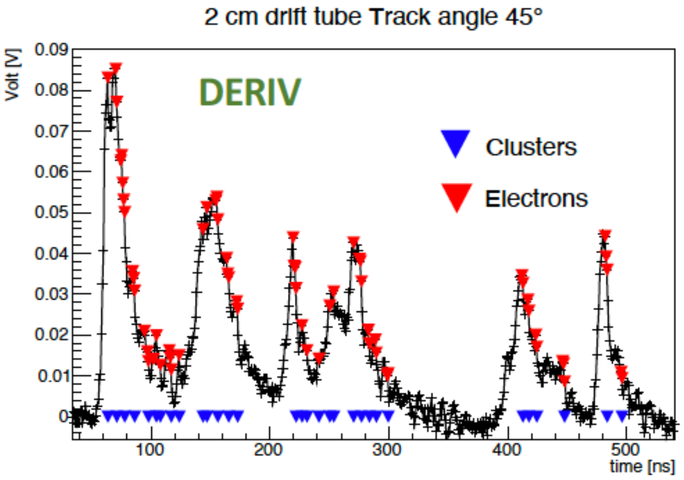
The Drift Chamber: Cluster Counting/Timing and PID

- Analitic calculations: Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)

- Simulation with Garfield++ and with the Garfield model ported in GEANT4:
  - the particle separation, both with dE/dx and with dN_{cl}/dx, in GEANT4 found considerably worse than in Garfield
  - the dN_{cl}/dx Fermi plateau with respect to dE/dx is reached at lower values of βγ with a steeper slope
  - finding answers by using real data from beam tests at CERN in 2021, 2022 and 2023







Cluster counting method:

- collect signal and identify peaks

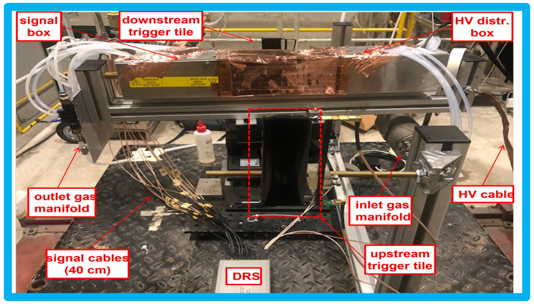
- record the time of arrival of electrons generated in every ionisation cluster

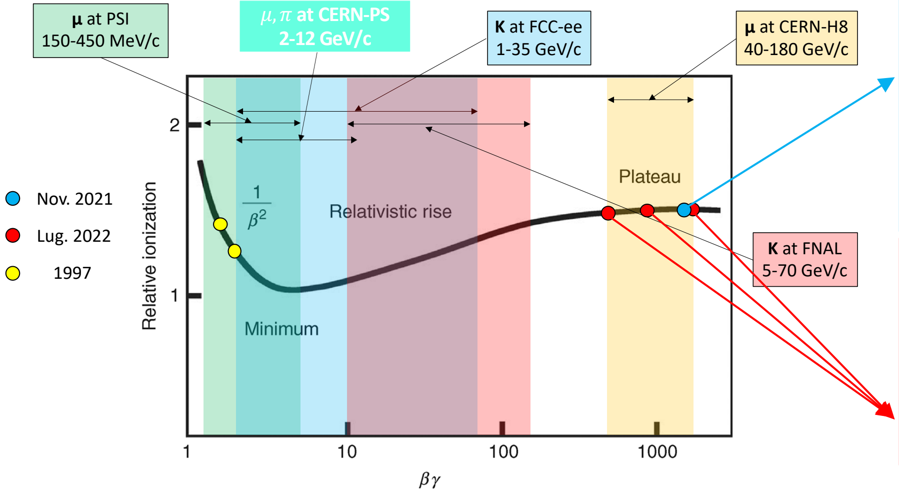
- reconstruct the trajectory at the most likely position

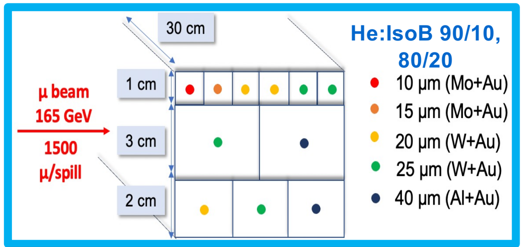
Beam tests in 2021,2022 and 2023

Beam tests to experimentally asses and optimize the **performance of the cluster counting/timing** techniques in strict collaboration with the IHEP Beijing group:

- two **muon beam tests** performed at **CERN-H8 (βγ > 400)** in Nov. 2021 and July 2022.
- a **muon beam test** in 2023 on going at **CERN**.
- ultimate test at **FNAL-MT6** in 2024 with π and **K (βγ = 10−140)** to fully exploit the relativitic rise.

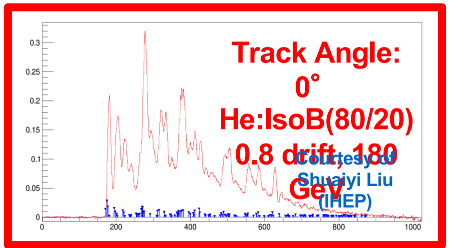






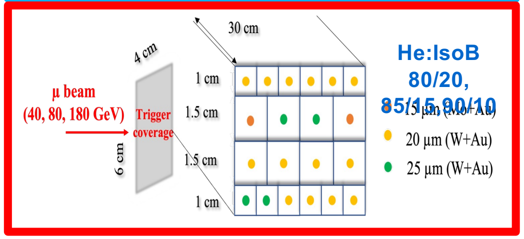
He:IsoB 90/10, 80/20

- ● 10 μm (Mo+Au)
- ● 15 μm (Mo+Au)
- ● 20 μm (W+Au)
- ● 25 μm (W+Au)
- ● 40 μm (Al+Au)



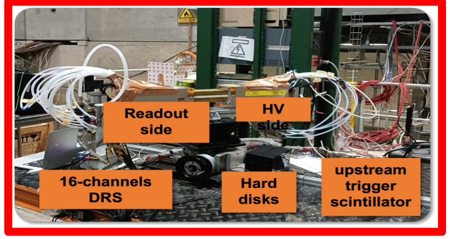
Track Angle: 0°
He:IsoB(80/20)
0.8 drift, 180 GeV

Courtesy of Shuaiyi Liu (IHEP)



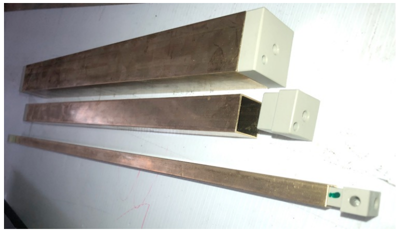
He:IsoB 80/20, 85/15,90/10

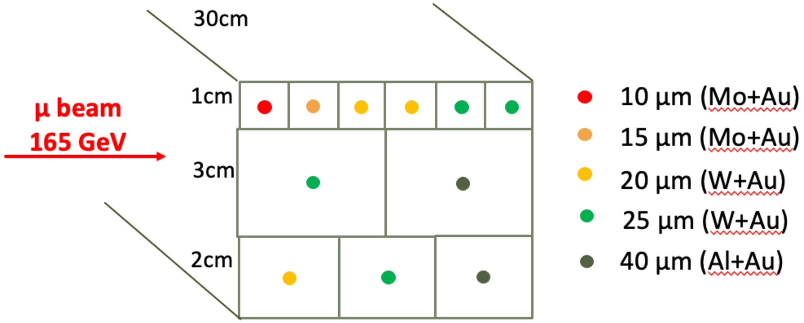
- ● 15 μm (Mo+Au)
- ● 20 μm (W+Au)
- ● 25 μm (W+Au)

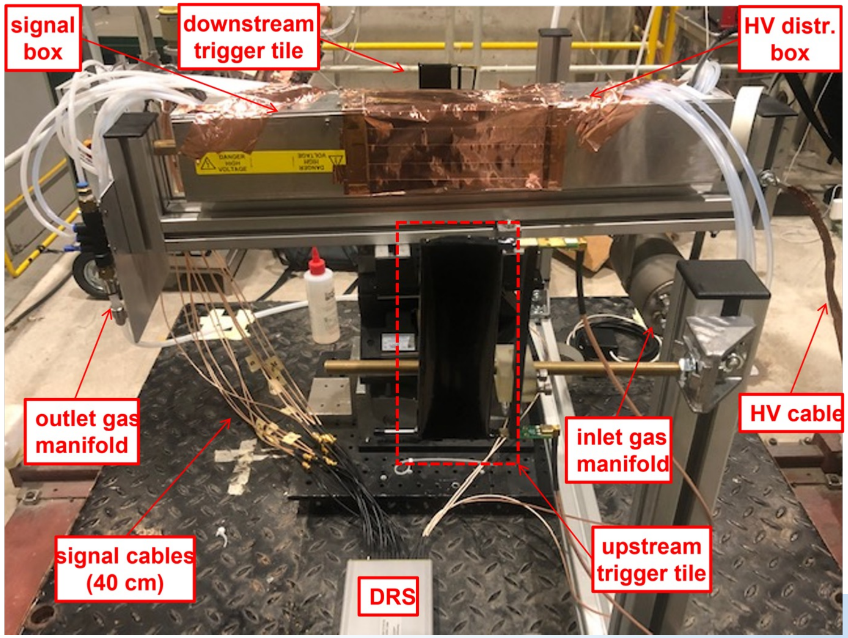


Beam test setup at H8/CERN in 2021

11 drift tubes with different cell size and different material wires and diameter wires







The setup consisted of:

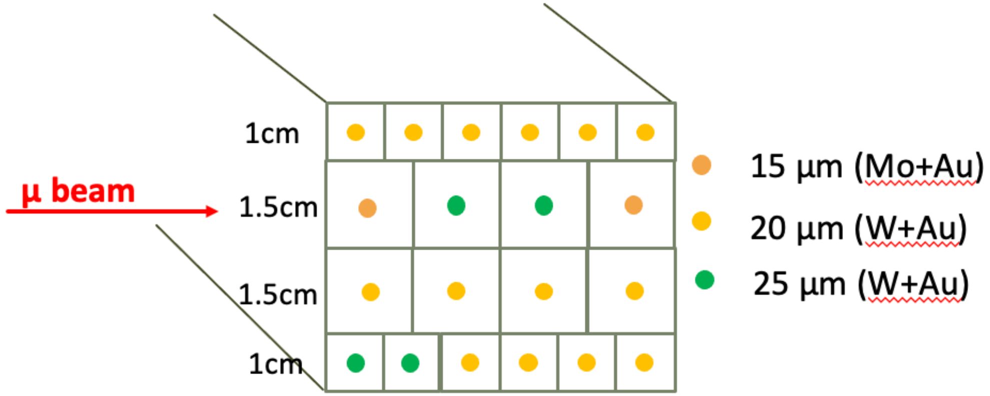
- 6 drift tubes 1 cm × 1 cm × 30 cm
    - 1 with 10 μm sense wire, 1 with 15μm, 2 with 20 μm, 2 with 25 μm
- 3 drift tubes 2 cm × 2 cm × 30 cm
    - 1 with 20 μm sense wire, 1 with 25 μm, 1 with 40 μm
- 2 drift tubes 3 cm × 3 cm × 30 cm
    - 1 with 20 μm sense wire, 1 with 40 μm
- DRS board for data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

Helium used because of:

- Low primary ionization density implies a large time separation
- low drift velocity means larger time separation ($v_{drift} \approx 2.5$ cm/μs)
- low average cluster size $\langle N_{electrons}/cluster \rangle \approx 1.6$
- low single electron diffusion (< 110 μm for 0.5 cm drift, or < 4.5 ns)

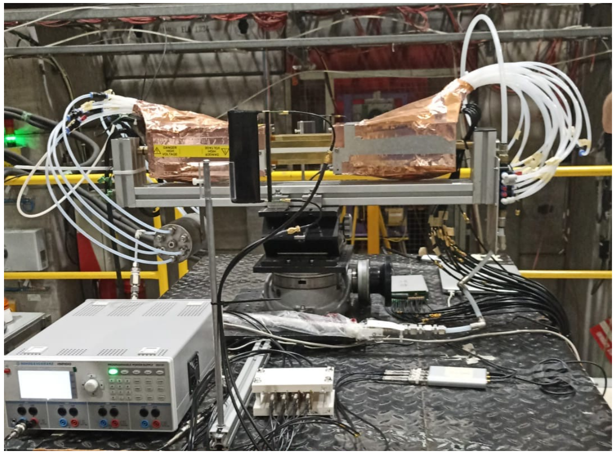
Beam test setup at H8/CERN in 2022

- 20 tubes with different wires (different material and diameter) and different cell size.
- 1 16-channel DRS
- 3 4-channel DRS
- the portable gas system
- custom PCBs for the 2 trigger scintillators.
- two external hard disk to store the data collected



- Data collected at different percentages of helium and isobutane: 90-10. , 85-15, 80-20.

- Data collected with muon beam with 180, 80 and 40 GeV momentum



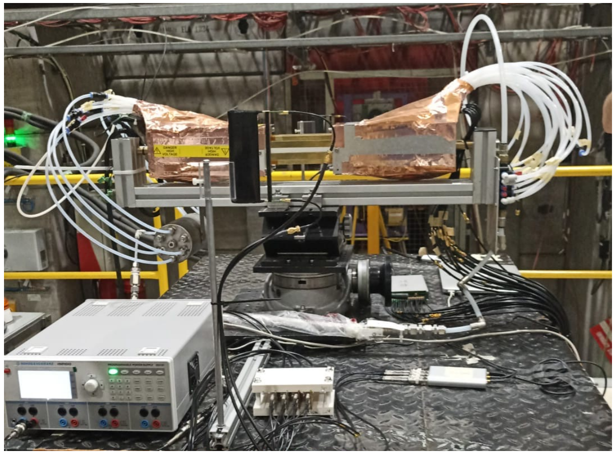
NEW CONNECTION SCHEME

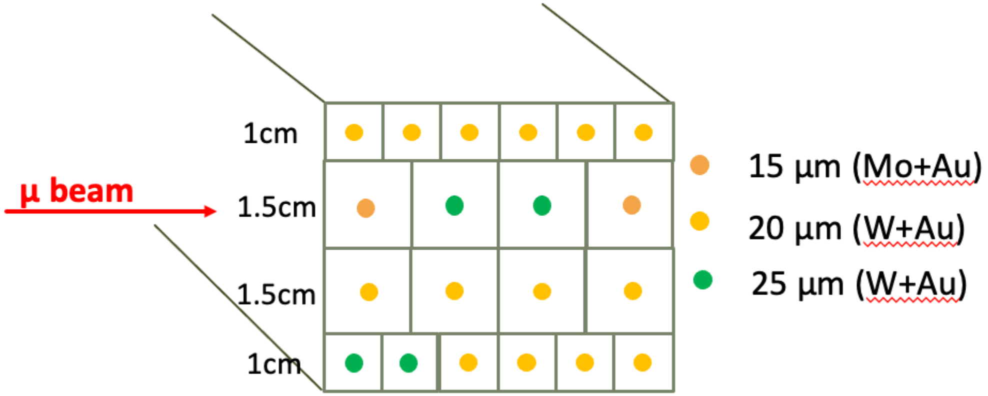
- Connect the 2 trigger scintillators to a 4-channels DRS
- Propagate the trigger signal to the 4-channel DRS and 16-channel DRS, where the tube are connected.

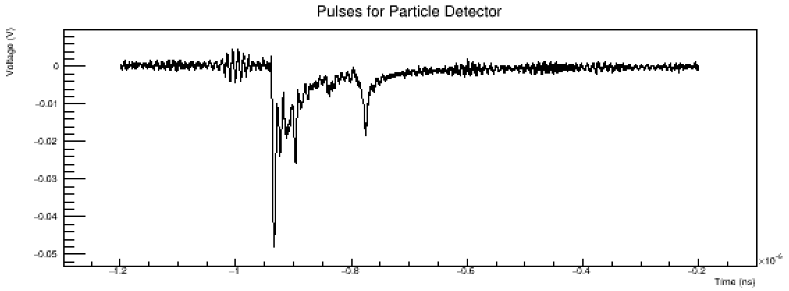
Data analysis in progress

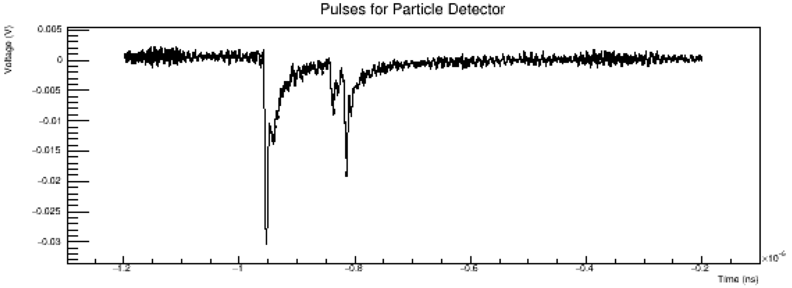
Beam test setup at T10/CERN in 2023

- 20 tubes with different wires (different material and diameter) and different cell size.
- 1 16-channel DRS
- 2 4-channel DRS
- custom PCBs for the 2 trigger scintillators.
- two external hard disk to store the data collected









- Data to be collected at different percentages of helium and isobutane: 90-10. , 85-15, 80-20.

- Data to be collected with muon beam momentum between **1 and 12 GeV**

2021/2022 testbeam: find electron peaks algorithms

Find good electron peak candidates at position bin *n* and amplitude A_n:

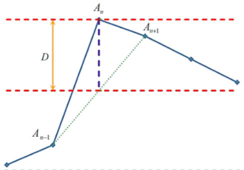
FIRST AND SECOND DERIVATIVE (DERIV) ALGORITHM

- ✦ Compute the first and second derivative from the amplitude average over two consecutive bins (1.6 ns for 1.2 GSa/s) and require that, at the peak candidate position, they are smaller than a r.m.s. signal-related small quantity and they increase (decrease) before (after) the peak candidate position of a r.m.s. signal-related small quantity.

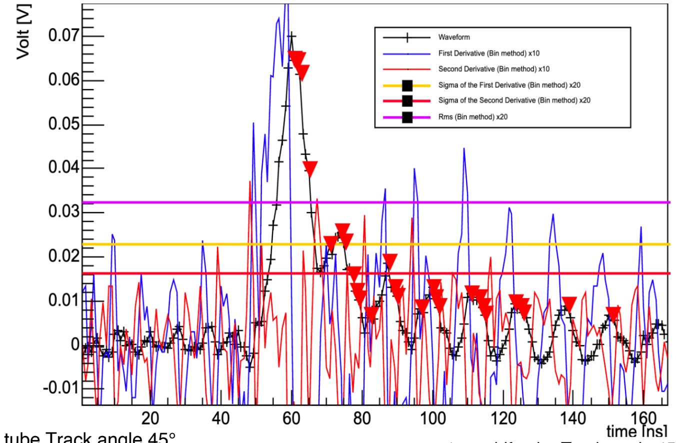
- ✦ Require that the amplitude at the peak candidate position is larger than a r.m.s. signal-related small quantity and the amplitude difference among the peak candidate and the previous (next) signal amplitude is larger (smaller) than a r.m.s. signal-related small quantity.

NOTE:

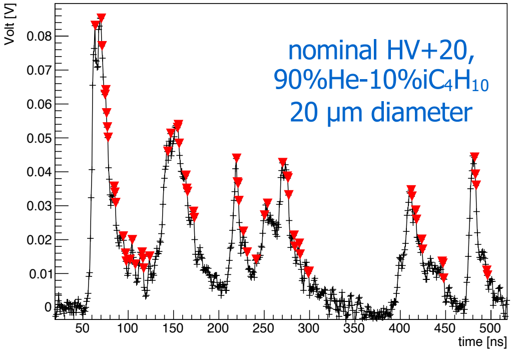
- ✦ R.m.s. is a measurements of the noise level in the analog signal



0°, nominal HV+20, 90%He-10%iC$_4$H$_{10}$
Tube with 1-cm cell size and 20 µm diameter

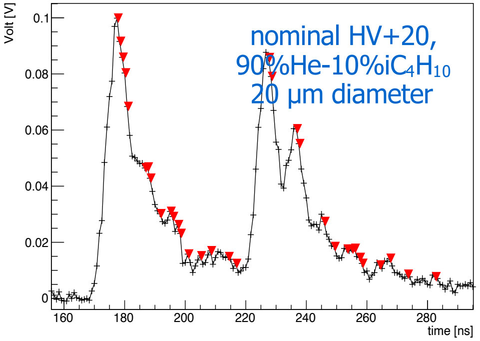


2 cm drift tube Track angle 45°



nominal HV+20,
90%He-10%iC$_4$H$_{10}$
20 µm diameter

1 cm drift tube Track angle 45°



nominal HV+20,
90%He-10%iC$_4$H$_{10}$
20 µm diameter

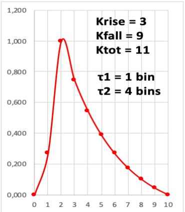
2021/2022 testbeam: find electron peaks algorithms

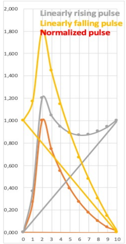
Find good electron peak candidates at position bin *n* and amplitude A_n:

RUNNING TEMPLATE ALGORITHM (RTA)

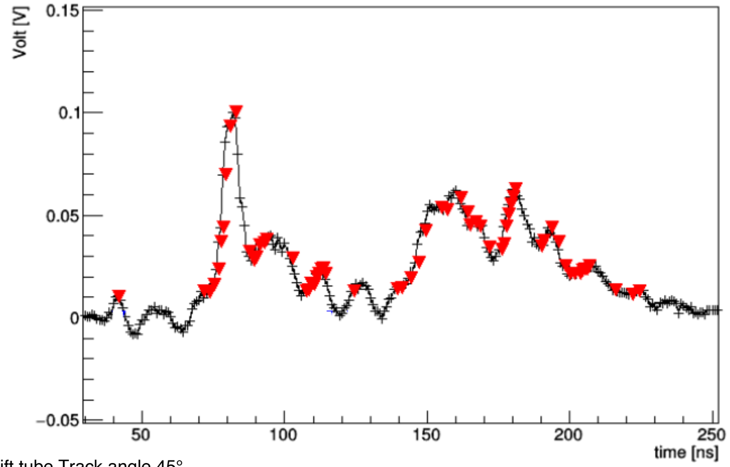
- ✧ Define an electron pulse template based on experimental law with a raising and falling exponential over a fixed number of bins (K_{tot}) and digitized (A(k)) according to the data sampling rate.
- ✧ Run over K_{tot} bins by comparing it to the subtracted and normalized data (build a sort of χ^2 and define a cut on it).
- ✧ Subtract the found peak to the signal spectrum and iterate the search and 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

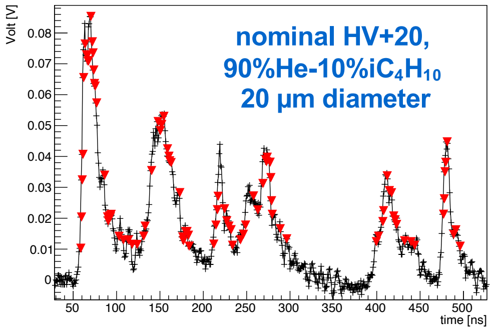




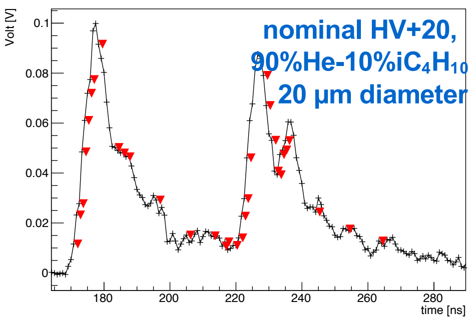
30°, nominal HV+20, 90%He-10%iC$_4$H$_{10}$
Tube with 1 cm cell size and 20 µm diameter



2 cm drift tube Track angle 45°

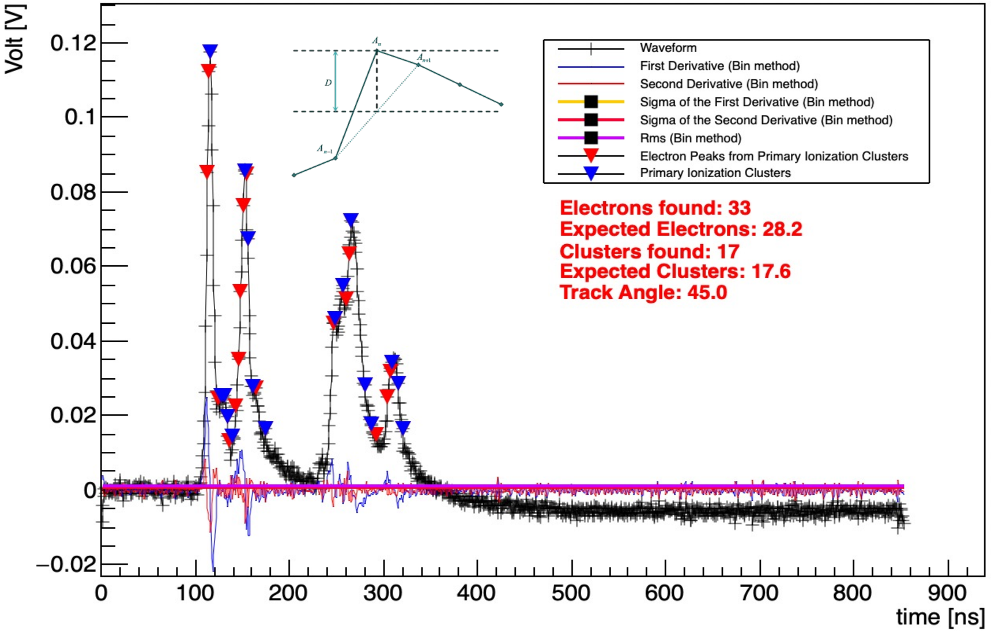


1 cm drift tube Track angle 45°

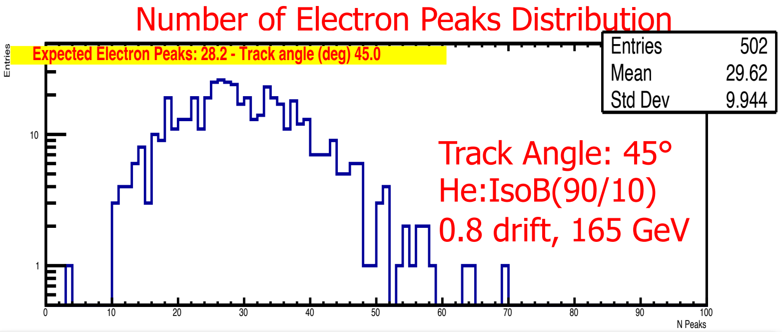


2021/2022 testbeam: number of electron peaks

Reconstruction of Electron Peaks (DERIV Algorithm)



Sense Wire Diameter 10 um – Cell Size 1.0 cm – Track Angle 45° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV



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

- α is the angle of the muon track w.r.t. normal direction to the sense wires
- δ cluster/cm (mip) changes from 12, 15, 18 respectively for He:IsoB 90/10, 85/15 and 80/20 gas mixtures
- Actual drift tube size are 0.8, 1.2, and 1.8 respectively for 1 cm, 1.5 cm, and 2 cm cell size tubes

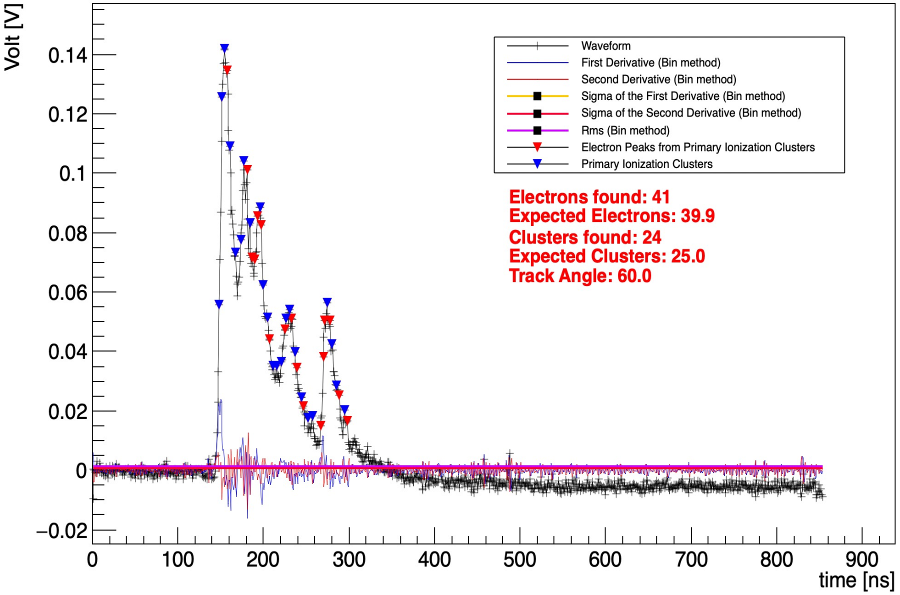
[1] H. Fischle, J. Heintze and B. Schmidt, Experimental determination of ionization cluster size distributions in counting gases, NIM A 301 (1991)

[2] 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

2021/2022 testbeam: clusterization

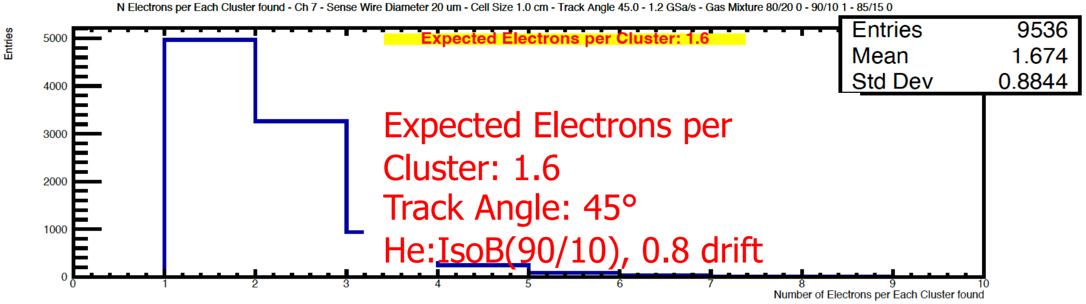
CLUSTERIZATION algorithm: Reconstruction of Primary Ionization Clusters

- Merging of electron peaks in consecutive bins in a single electron to reduce fake electrons counting
- Contiguous electrons peaks which are compatible with the electrons' diffusion time (it has a $\sim\sqrt{t_{ElectronPeak}}$ dependence, different for each gas mixture) must be considered belonging to the same ionization cluster. For them, a counter for electrons per each cluster is incremented.
- Position and amplitude of the clusters corresponds to the position and height of the electron having the maximum amplitude in the cluster. → Poissonian distribution for the number of clusters!



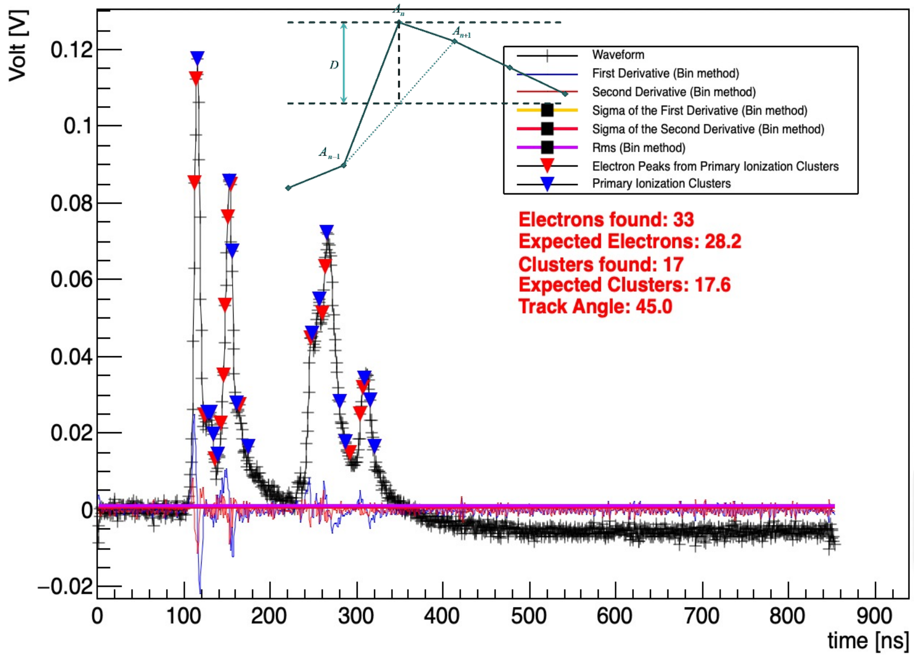
Sense Wire Diameter 20 um – Cell Size 1.0 cm – Track Angle 60° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV

Electron per Clusters Distribution



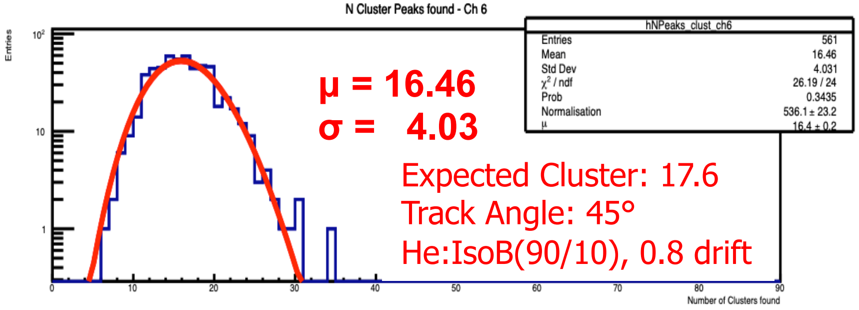
Expected Electrons per Cluster: 1.6
Track Angle: 45°
He:IsoB(90/10), 0.8 drift

2021/2022 testbeam: number of clusters



Sense Wire Diameter 10 um – Cell Size 1.0 cm – Track Angle 45° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV

Number of Cluster Distribution



Expected number of cluster = δ cluster/cm (MIP) x drift tube size [cm] x 1.3 (relativistic rise) x 1/cos(α)

- α is the angle of the muon track w.r.t. normal direction to the sense wires
- δ cluster/cm (mip) changes from 12, 15, 18 respectively for He:IsoB 90/10, 85/15 and 80/20 gas mixtures
- Actual drift tube size are 0.8, 1.2, and 1.8 respectively for 1 cm, 1.5 cm, and 2 cm cell size tubes

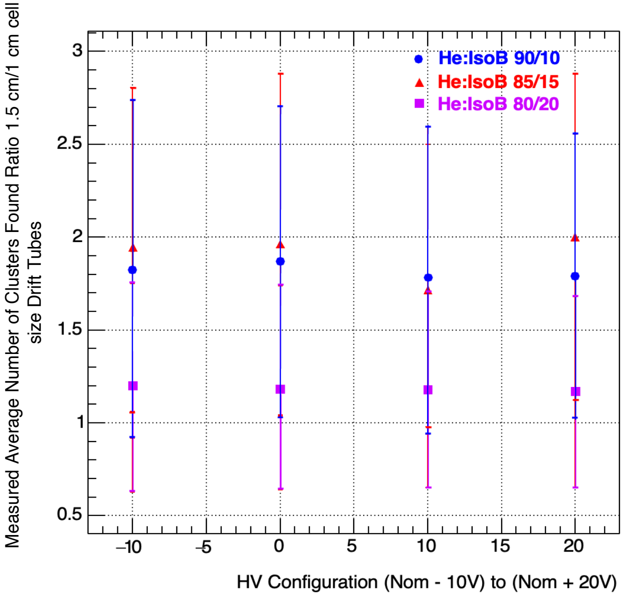
- Poissonian behaviour
- Meaurements and predictions about the number of clusters are in very good agreement, with 1cm cell size

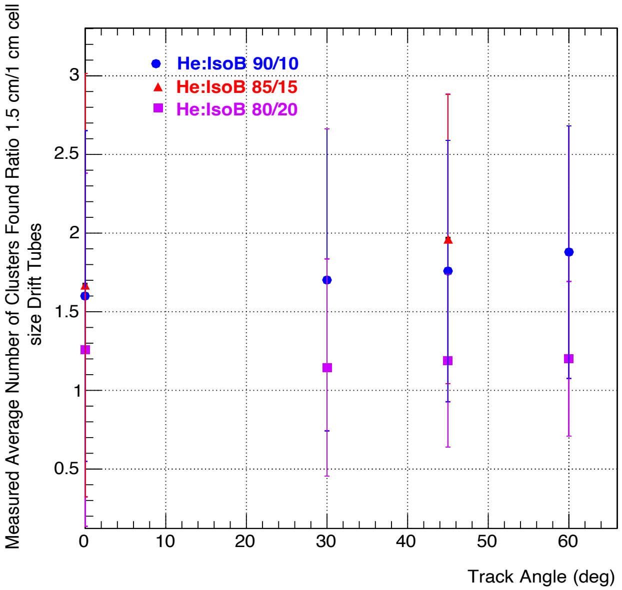
Beam test results: recombination and attachment

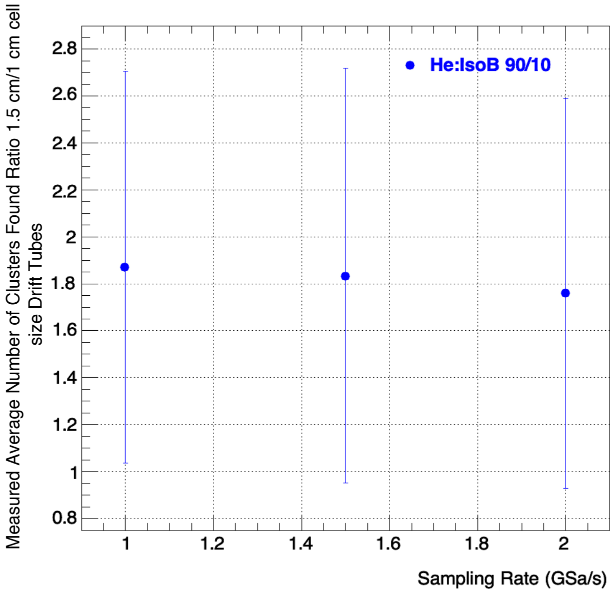
Efficiency w.r.t. Expected Number of Electrons (Clusters) above ~85%. What about being independent from theoretical assumptions?

in Ratios

Expected number of cluster= δ cluster/cm (MIP) x drift tube size [cm] x 1.3 (relativistic rise) x 1/cos(α)



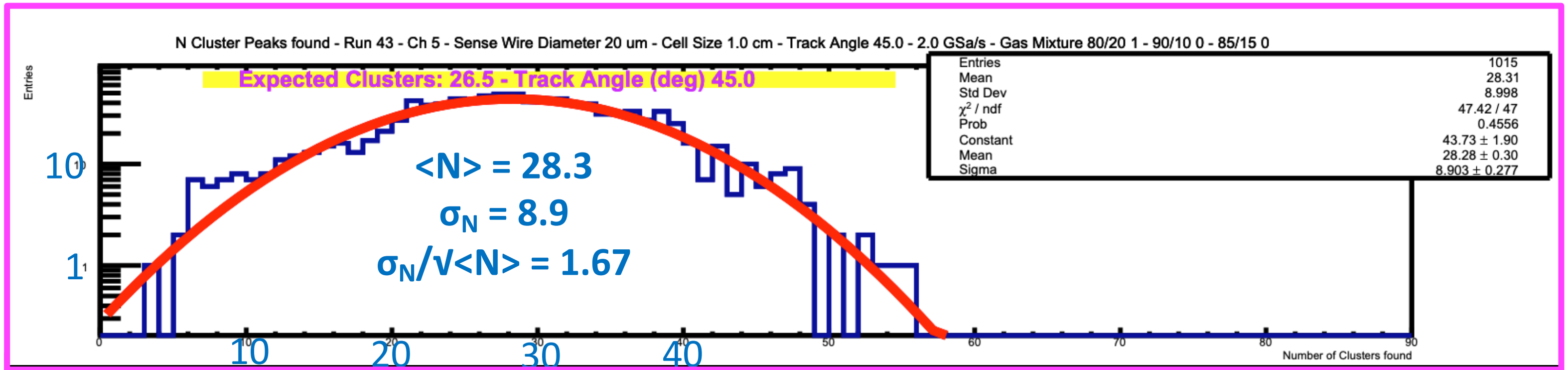




Space charge + attachment + recombination effects affect the experimental CC efficiency!

- The **loss of efficiency at small angles** is due to the partial shielding of the electric field due to the space charge.
- The **loss of efficiency at large angles** is partially due to the fact that increasing the number of clusters in the same drift time, increases the probability of pileup, then decreasing the counting efficiency.
- The **lower counting efficiency in 2cm** tubes compared to 1cm ones is only partially explained by the effects of recombination and attachment; other possible effects under investigation

Beam test results: recombination and attachment



N Cluster Peaks found - Run 43 - Ch 5 - Sense Wire Diameter 20 um - Cell Size 1.0 cm - Track Angle 45.0 - 2.0 GSa/s - Gas Mixture 80/20 1 - 90/10 0 - 85/15 0

Expected Clusters: 26.5 - Track Angle (deg) 45.0

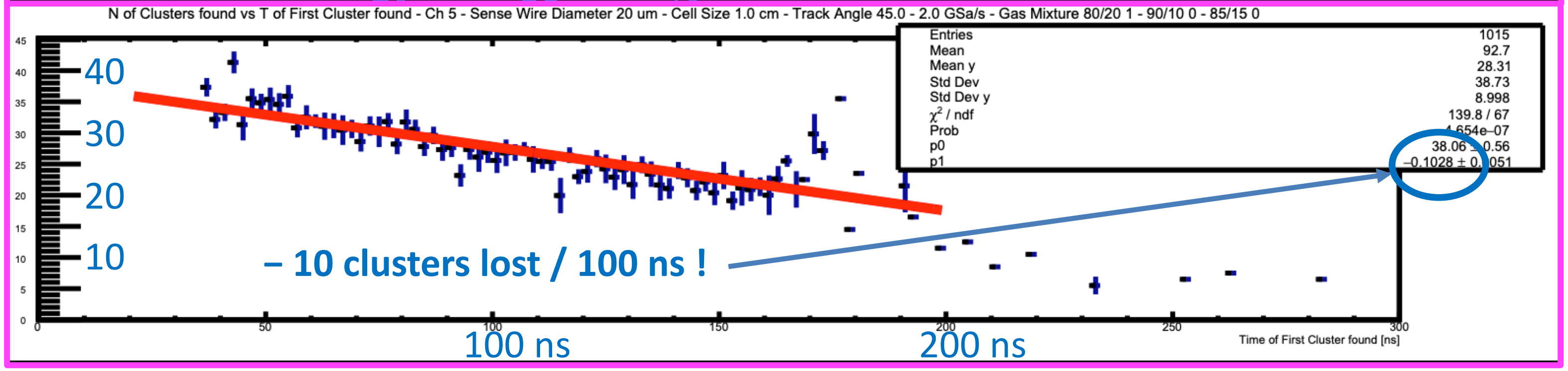
Entries	1015
Mean	28.31
Std Dev	8.998
χ^2 / ndf	47.42 / 47
Prob	0.4556
Constant	43.73 ± 1.90
Mean	28.28 ± 0.30
Sigma	8.903 ± 0.277

$\langle N\rangle = 28.3$

$\sigma_N = 8.9$

$\sigma_N/\sqrt{\langle N\rangle} = 1.67$

Number of Clusters found by DERIV+CLUSTER algorithms



N of Clusters found vs T of First Cluster found - Ch 5 - Sense Wire Diameter 20 um - Cell Size 1.0 cm - Track Angle 45.0 - 2.0 GSa/s - Gas Mixture 80/20 1 - 90/10 0 - 85/15 0

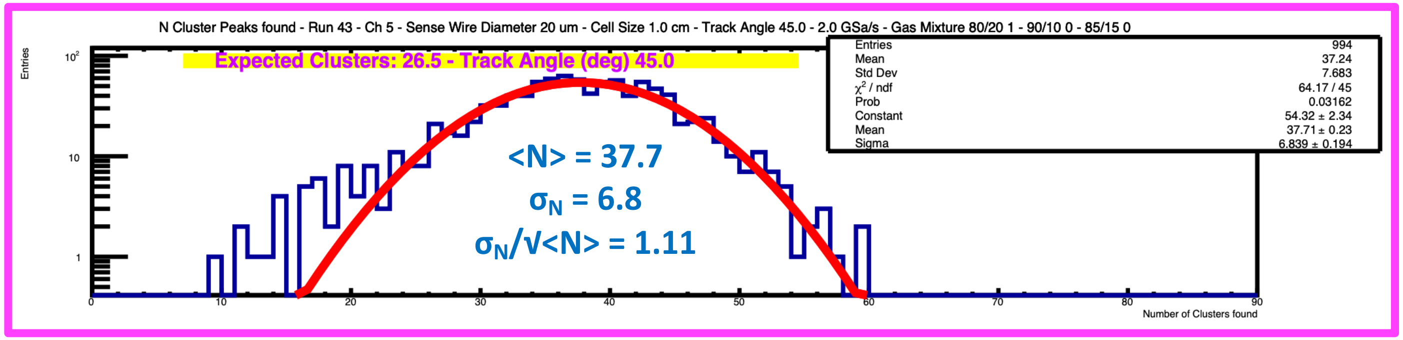
Entries	1015
Mean	92.7
Mean y	28.31
Std Dev	38.73
Std Dev y	8.998
χ^2 / ndf	139.8 / 67
Prob	4.654e−07
p0	38.06 ± 0.56
p1	−0.1028 ± 0.0051

– 10 clusters lost / 100 ns !

Average Number of Clusters found(@drift time) vs drift time

Combined action of recombination, electron attachment and E-field suppression due to space charge

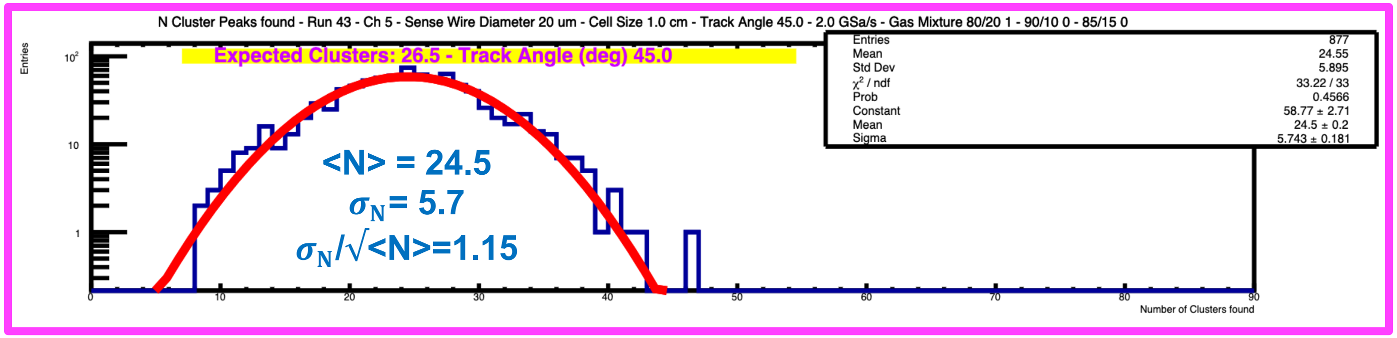
Beam test results: applying corrections



$\langle N \rangle = 37.7$

$\sigma_N = 6.8$

$\sigma_N/\sqrt{\langle N \rangle} = 1.11$



$\langle N \rangle = 24.5$

$\sigma_N = 5.7$

$\sigma_N/\sqrt{\langle N \rangle} = 1.15$

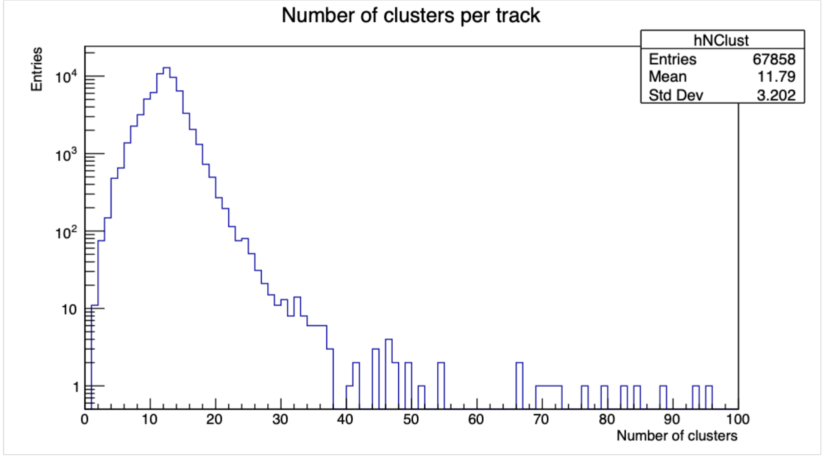
Cuts on the derivative algorithm, which were optimized without including the recombination and attachment effects, need to be reformulated.

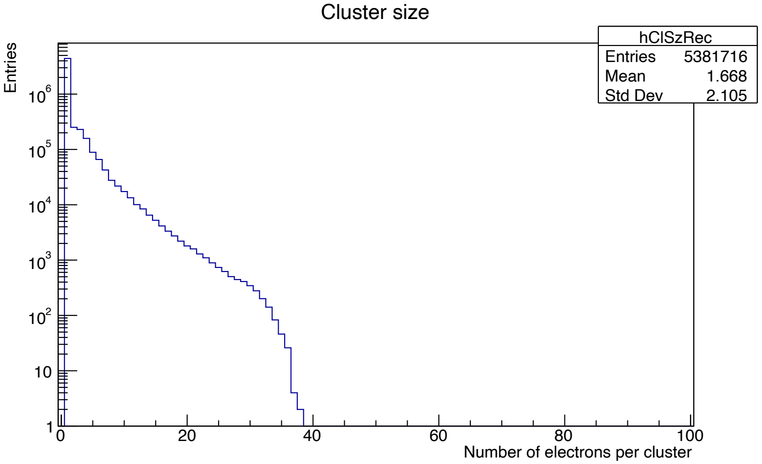
Also, these corrections, strongly depend on the drift length and, therefore, on the drift tube size and must be calculated for each different drift tube configuration.

First attempt of re-tuning cuts on the DERIV algorithm for a 1 cm cell size drift tube

Cluster counting simulated in Geant4

Goal: to implement the cluster counting algorithm for the simulation of the drift chamber in the Geant4 IDEA Full SIM framework. The basic idea is to develop an algorithm which can use the energy deposit information provided by Geant4 to reproduce, in a fast and convenient way, the cluster number distribution and the cluster size distribution. Muons at 300 MeV traversing 200 cells, are used for the validation. The results obtained from Geant4 are in a good agreement with the ones from Garfield and with the expectation.





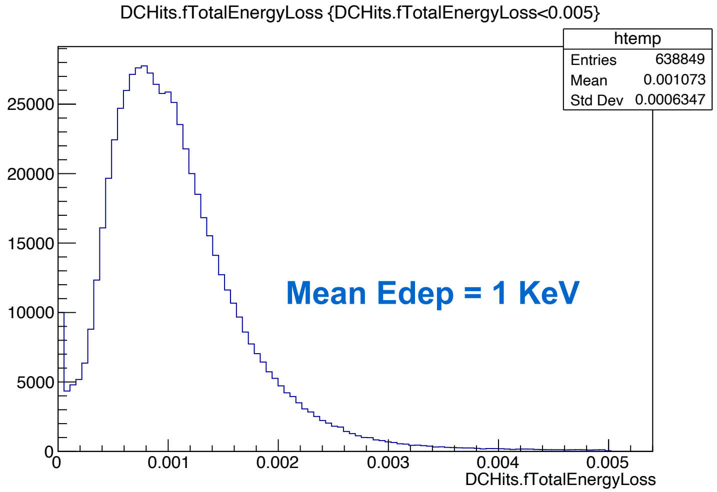
Details at:
https://agenda.infn.it/event/35315/contributions/194914/attachments/103560/144927/IDEA_DC_Mar23.pdf

N:B. The absolute value of the expected energy deposit to be crosschecked

Geant4 vs DD4HEP: comparison

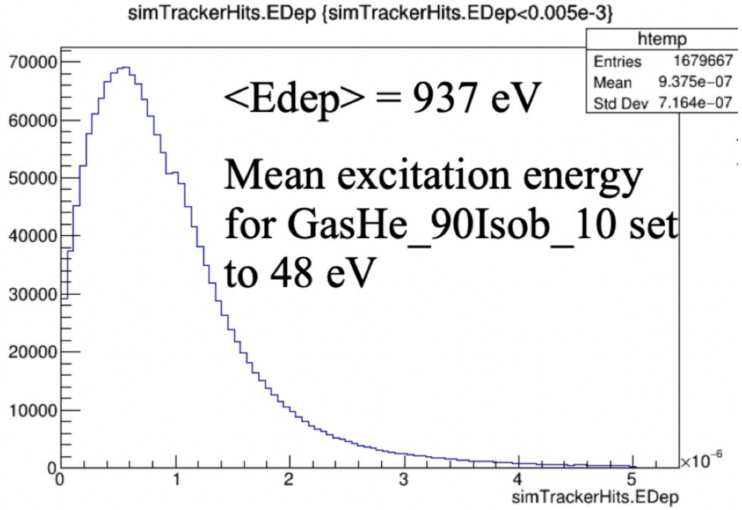
- **Goal:** to validate the implementation of the IDEA drift chamber (DC) geometry and its reconstruction in the DD4hep by doing a comparison with the Geant4 framework. Muons at 10 GeV are used for the validation. Good agreement is observed between the results from the two frameworks.

Geant 4 Framework



Mean Edep = 1 KeV

DD4HEP in Key4Hep Framework



<Edep> = 937 eV

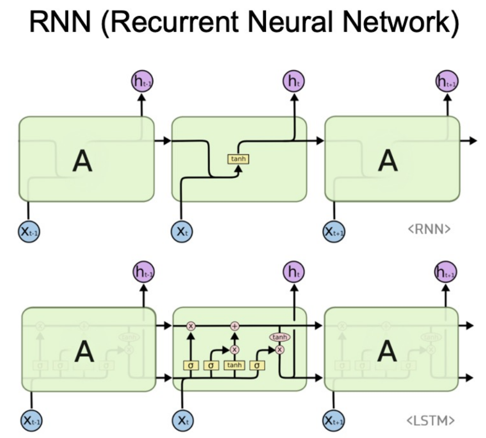
Mean excitation energy for GasHe_90Isob_10 set to 48 eV

Details at:
https://indico.cern.ch/event/1292887/contributions/5433543/attachments/2664039/4615921/Plots_GeantVsKey4Hep.pdf

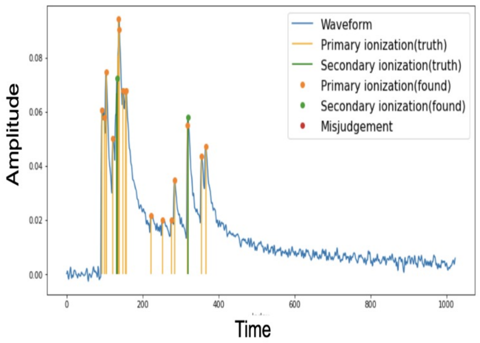
N:B. The absolute value of the expected energy deposit to be crosschecked

Hybrid RNN/CNN for robust PID based on dN/dx cluster counting in drift chambers

A two-step Deep-Learning Reconstruction Algorithm for Cluster Counting



RNN for peak finding



CNN for peak clustering determine the number of clusters per particle trajectory.

- The peak finding algorithm shows better signal purity and efficiency than derivative algorithm
- The clusterization algorithm gives Gaussian distributed number of clusters
- By applying the algorithms, single cell resolution is close to the MC truth level
- Preliminary result with beam test data seems good

https://indico.jlab.org/event/459/contributions/11749/attachments/9370/14005/slides_CHEP2023.pdf

Next plans

Hardware:

- setup of drift tubes for testbeam 2024 at CERN and Fermilab
- construction of a full scale DCH prototype

Simulation and design:

- full simulation (**geometry, hits, digi**) of the DCH and cluster counting
- finalization of the mechanical design of the DCH

Testbeam data analysis:

- finalization of testbeam analysis with 2021, 2022 and 2023 data

Summary and conclusions

- PID with a cluster counting technique is under study by using simulations and beam-test data
- Several algorithms for peak finding under development show agreement in data
- Results demonstrate the capability to count cluster with high efficiency at a fixed βγ
- Limiting conditions for an efficient cluster counting established:
  - gas gain saturation
  - cluster density (by changing the gas mixture)
  - space charge (gas gain, sense wire diameter, track angle)
  - recombination effects and electron attachment

- PID with a cluster counting technique simulated in Geant4/DD4HEP and Delphes

Short term prospects:

- Continuation of Beam Tests
- Construction of a prototype of a full scale wedge of the drift chamber:

Notes in preparation:

- IDEA drift chamber proposal
- Results from cluster counting beam test
- Data acquisition system for cluster counting
- Preliminary studies on the IDEA drift chamber mechanical structure
- Preliminary estimate of the IDEA drift chamber costing

Backup

Cluster counting paramtrized in Delphes

References

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