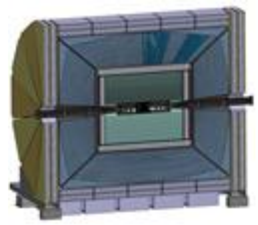

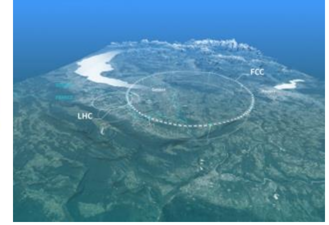
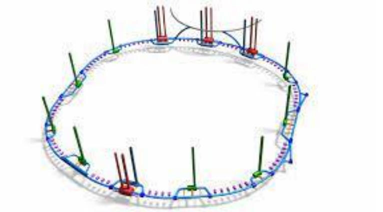

IDEA Drift Chamber digitization

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Politecnico and INFN Bari

Franco Grancagnolo
INFN Lecce

8th FCC Physics workshop
January 13-16 2025

Strategy of measurement of particle coordinates in a traditional DCH

1. Measurement of the drift time:
   - known the drift velocity of the ionization electrons along their drift trajectory → distance along the drift trajectory between the wire and the track
2. Measurement of the pulse-height ratios at the two ends of the wire:
   - charge division because of the damping of the pulse as it propagates along the wire
3. Measurement of the difference of arrival times at the two ends of a wire:
   - time propagation of the signal on the wire

Method 1 measures the coordinate in the drift direction

Method 2 and 3 provide the coordinate along the wire direction

N.B. We assume that «technical problems» are already solved such as:

- wire position under control
- drift velocity known well enough (well known distorsion of the E and B)
- electronics capable to measure the drift time
- etc.

Strategy of measurement of particle coordinates in **IDEA DCH**

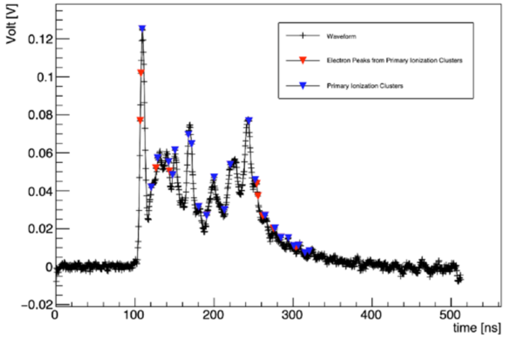
The following strategy:

- ❑ is specifically designed for a **cluster counting drift chamber** in the intent of exploiting all peculiar features of the:
  - cluster timing technique for improving the impact parameter measurement
  - cluster counting technique for particle identification
- ❑ is aimed at minimizing simulation complexity and time
- ❑ uses, as much as possible, tabulated distributions of relevant complex functions, relying on experimental measurements
  - ❑ however, any step in the sequence can, alternatively, be elaborated with these on *ad hoc* simulation packages (Garfield, Heed, …)

N.B. Measurement of the drift time, the pulse-height ratios and the difference of arrival times at the two ends of a wire to be done **for each cluster**

Strategy of hit digitization for the IDEA DCH

- Result of a hit cell digitization at the lowest level, L_0, must be a **waveform**



- Parameters of the waveform are:
  - time bin size
  - amplitude bit size
- At a higher level, L_1, results of hit digitization are:
  - list of electron peak positions and relative amplitudes (i.e., ionization electrons after peak finding – red markers in the picture) or
  - list of ionization cluster positions and relative amplitudes (after electrons clusterization algorithm – blue markers in the picture)
- At an even higher level, L_2, results of hit digitization are:
  - impact parameter d_{DCA}
  - number of clusters n_{cl}

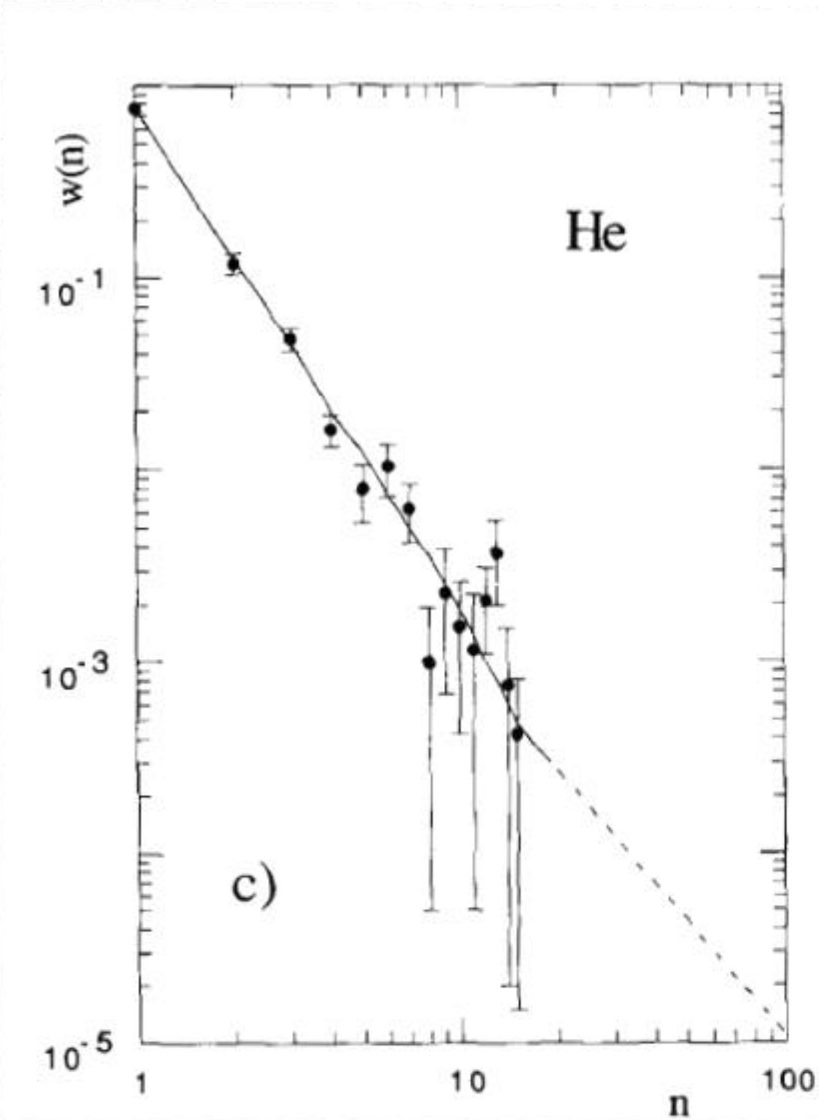
N. De Filippis

Sequence of steps for the simulation

1. Intersect the physical particle trajectory with the space volume defined by the fired cell;
2. define the ionization length ℓ of the particle track within the cell volume;
3. distribute along ℓ, with an exponential distribution, a number of ionization acts n_d extracted according to a Poisson distribution of peak value $dN_d/dx \times \ell$, where dN_d/dx is a tabulated function only of the particle $\beta\gamma$.
   - this function to be provided by **beam test experimental results**
   - in absence of that we rely on Bethe-Block / theory paramterization
4. for each of the n_d extract, for the given gas mixture, a number of electrons n_{el} according to the experimental distributions given in: *H. Fischle, J. Heintze and B. Schmidt*, *Experimental determination of ionization cluster size distributions in counting gases, NIMA 301 (1991)*
5. transport each of the n_{el} electrons to the sense wire (tabulated distance to-time distributions can be used and drift time must be smeared with properly calculated diffusion, according to experimental measurement or in alternative with Garfield)

Cluster size distribution

H. Fischle, J. Heintze and B. Schmidt, Experimental determination of ionization cluster size distributions in counting gases, NIMA 301 (1991)



	CH_4	Ar	He	CO_2
k				
1	78.6	65.6	76.60	72.50
2	12.0	15.0	12.50	14.00
3	3.4	6.4	4.60	4.20
4	1.6	3.5	2.0	2.20
5	0.95	2.25	1.2	1.40
6	0.60	1.55	0.75	1.00
7	0.44	1.05	0.50	0.75
8	0.34	0.81	0.36	0.55
9	0.27	0.61	0.25	0.46
10	0.21	0.49	0.19	0.38
11	0.17	0.39	0.14	0.34
12	0.13	0.30	0.10	0.28
13	0.10	0.25	0.08	0.24
14	0.08	0.20	0.06	0.20
15	0.06	0.16	0.048	0.16
16	(0.050)	0.12	(0.043)	0.12
17	(0.042)	0.095	(0.038)	0.09
18	(0.037)	0.075	(0.034)	(0.064)
19	(0.033)	(0.063)	(0.030)	(0.048)
≥ 20	$(11.9/k^2)$	$(21.6/k^2)$	$(10.9/k^2)$	$(14.9/k^2)$

Sequence of steps for the simulation

6. Define the amplitude of the signal generated by each of the n_{cl} electrons according to the gas amplification parameters, using the proper Polya distributions → electron with amplitued and time

7. Generate the individual electron pulses by introducing the rise and fall times derived by experimental measurements (spatial charge effect not considered here);

8. Build the analog waveform by summing up the individual contributions of all single electrons;

9. propagate the waveform along the sense wire at both ends, by taking into account the proper transit time (constant transit velocity assumed as a first attempt, ~ 5ns/m) and the signal attenuation along the sense wire, according to experimental measurements;

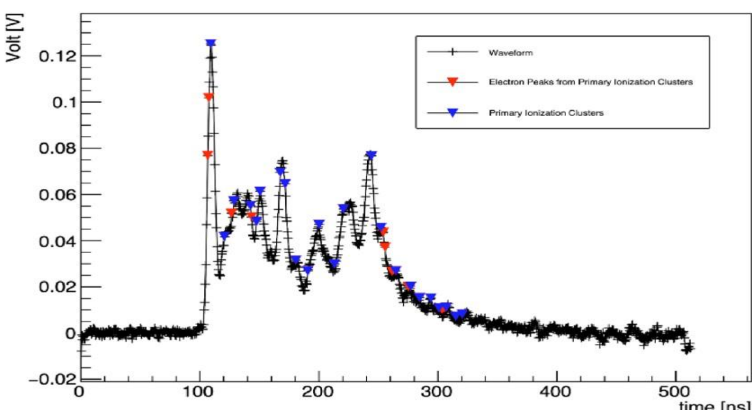
Sequence of steps for the digitization

9. convert the analog waveform into digital according to the defined time bins (~0.5 ns at 2Gsa/s) and amplitude bits (~10-12 bits);

10. apply the preamplifier electronics transfer functions (taking into account the impedence mismatch for reflection and transmission) and further convoluted with the waveform;

11. add the proper noise according to the frequency response determined experimentally using the fast Fourier transform and added to the signal using the inverse fast Fourier transform

The digitization output/result is the L_0 digitized waveform whiich must be validated with experimental data



Sequence of steps for the simulation of isolated hits

Hits due to photon interactions must be treated in a different way:

- lacking experimental measurements in this particular gas mixture, one has to cope with the reliability of the GEANT4 simulations.
- in most cases the interaction will result in a single Compton electron which produces a **single electron/peak** and, therefore, easily distinguishable from a hit due to an ionizing track;
- however, the final results of the hit cell digitization will still be a waveform (with just a single peak)

Level L_1 digitization

Once the L_0 digitized waveform in a hit cell has been produced, the application of any cluster counting algorithm (RTA, DERIV, IHEP ML, …) will give rise to the:

- list of electron peak positions (time) with their relative amplitudes

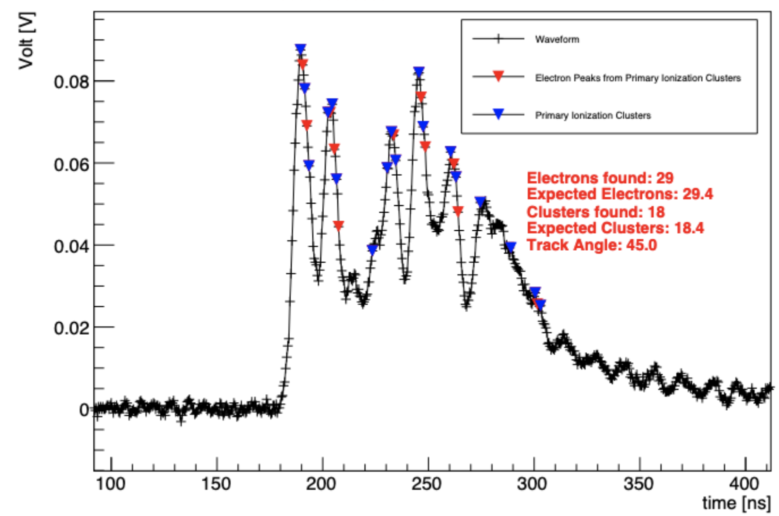
$$\{el_i\ ,\ A_{el,i}\}\ ,\ i = 1,\ n_{el}$$

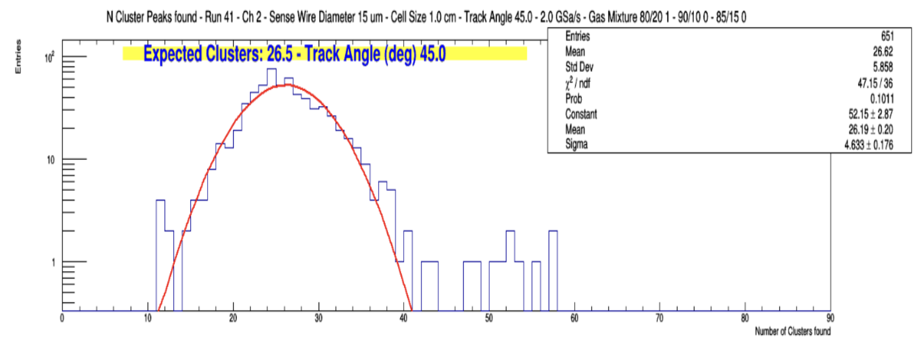
and, after the electrons clusterization algorithms, to the

- list of ionization cluster positions (time) with their relative amplitudes

$$\{cl_j\ ,\ A_{cl,j}\}\ ,\ j = 1,\ n_{cl}$$

Sense Wire Diameter 15 μm; Cell Size 1.0 cm
Track Angle 45; Sampling rate 2 GSa/s
Gas Mixture He:IsoB 80/20





Level L_2 digitization: impact parameter

Once the lists below are derived:

$\{el_i, A_{el,i}\}$, $i = 1, n_{el}$ $\{cl_j, A_{cl,j}\}$, $j = 1, n_{cl}$

the impact parameter d_{DCA} can be obtained with the application of a **ML algorithm**, trained on samples of simulated $\{cl_j\}$ sequences at known impact parameters, thus exploiting the knowledge of the full waveform (instead of relying only on the timing of the first cluster)

N. B. A considerable reduction of the impact parameter bias at short drift distances is expected because of the use the full waveform information (all the clusters)

→ Estimation of the uncertainty on the measurement of the d_{DCA}

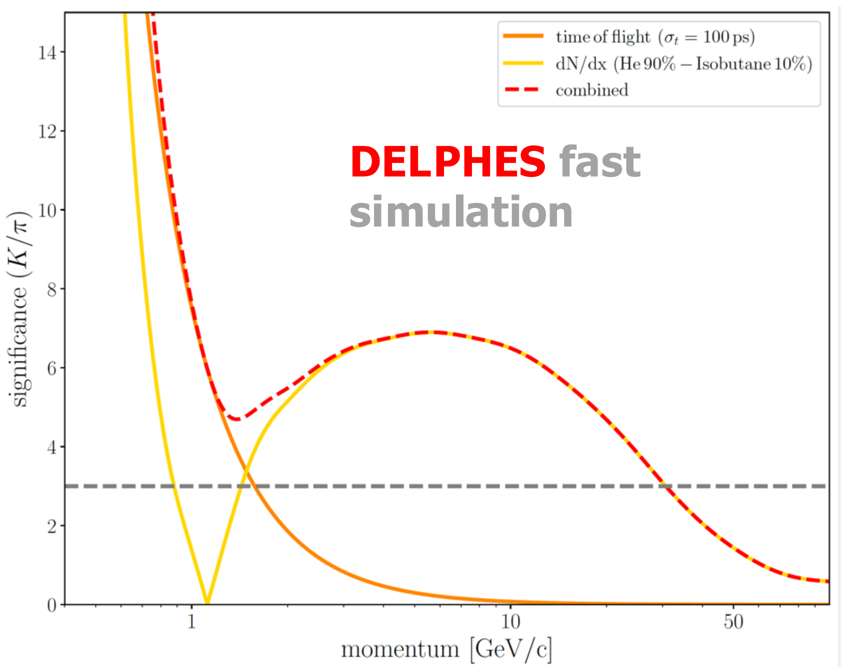
Level L_2 digitization: particle identification

n_{cl} of a hit cell is the relevant parameter for particle identification

the sum of number of clusters found on all hit cells belonging to the particle trajectory, divided by the total length of the track, measured from the track fit, provides the dN_{cl}/dx of the particle (care must be given to treating hit rejection and hit sharing) →

→ a comparison of this value against different particle type hypothesis provides the particle mass assignment

K/π separation in number of a σ



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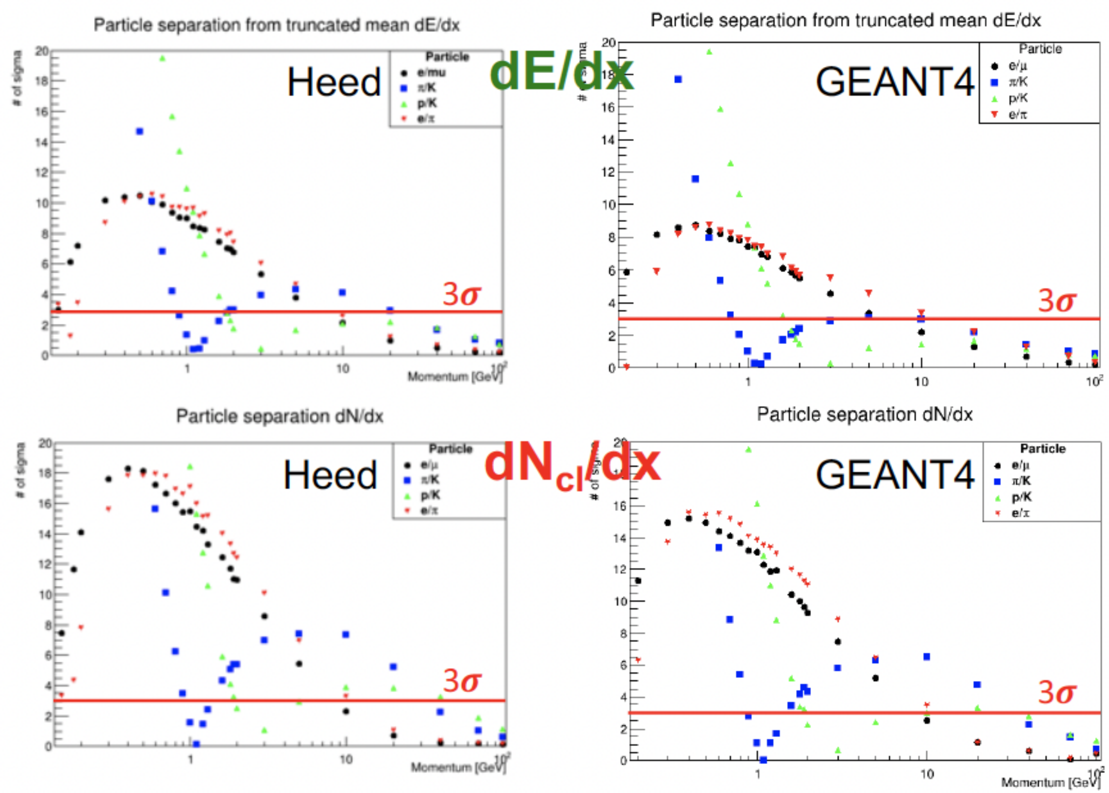
Existing studies: Geant4/Garfield++ simulation

Disclaimer: the study has not been updated recently

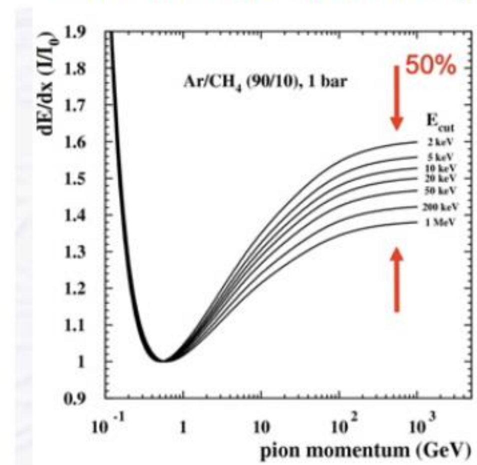
2.0 m long tracks in 90/10 He/iC_4H_{10}

full simulation



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

Geant4 uses the cluster density and the cluster size distributions derived from **Heed**, however, they **disagree**, most likely, due to a different choice of the E_{cut} parameter (the maximum energy of an electron still associated to a track in the simulation)



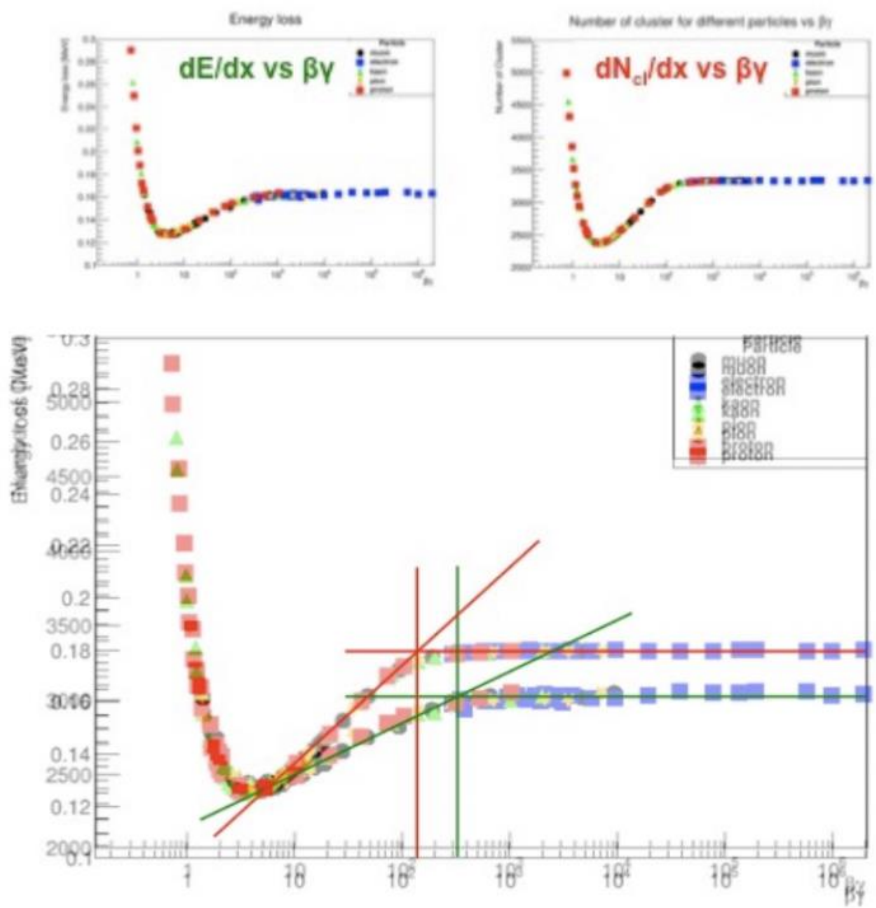
M. Hauschild Progress in dE/dx techniques used for particle identification NIM A379(1996) 436

N. De Filippis

Existing tools: Geant4/Garfield++ simulation

Disclaimer: the study has not been updated recently

GEANT4 with **HEED** clusterization model



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

Higher values of Fermi plateau for **dN_{cl}/dx** w.r.t. **dE/dx**, yet reached at lower $\beta\gamma$ values and with a steeper slope

due to a choice of **E_{cut}** (the maximum energy of an electron still associated to a track in the simulation) parameter?

⇩

Experimental beam test campaign needed

→ **Simulation NOT RELIABLE, many paramenters to tune looking at data!**

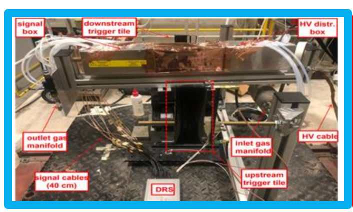
Existing studies: Testbeam data analysis

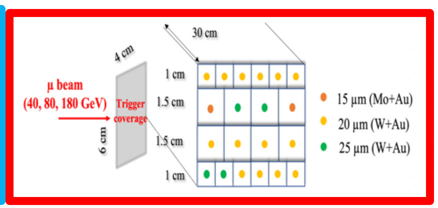
W. Elmetenawee (INFN Bari), M. Louka (Ph.D. Poliba and INFN Bari)

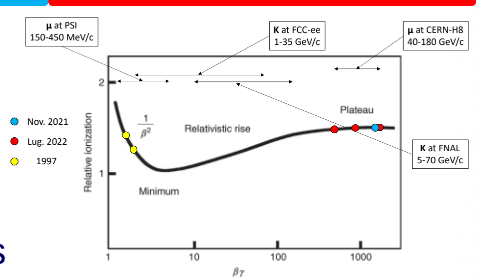
Beam tests to experimentally asses and optimize the **performance of the cluster counting/timing** techniques:

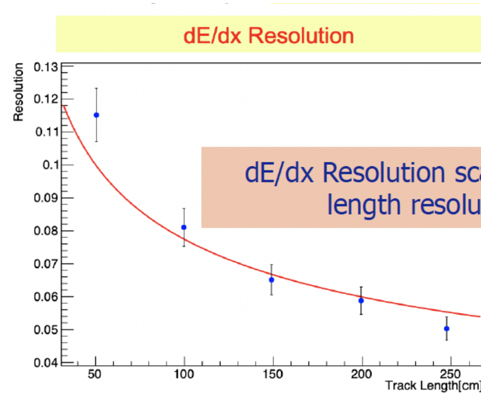
- Two **muon beam tests** performed at **CERN-H8 (βγ > 400)** in Nov. 2021 and July 2022 (p_T = 165/180 GeV).
- A **muon beam test** (from 4 to 12 GeV momentum) in 2023 performed at **CERN**. A new testbeam with the same configuration done on July 10, 2024
- Ultimate test at **FNAL-MT6** in 2025 with □ and **K (βγ = 10−140)** to fully exploit the relativitic rise.

Results with **muon beam tests at CERN (βγ > 400)** in Nov. 2021+July 2022 (p_T =165/180 GeV)

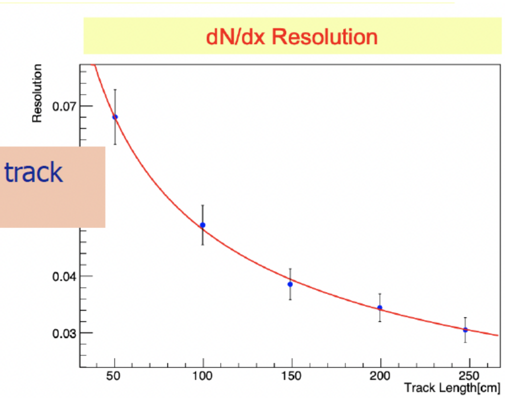








dE/dx Resolution scan vs track length resolution



dE/dx resolution dependence on the track length $L^{-0.37}$

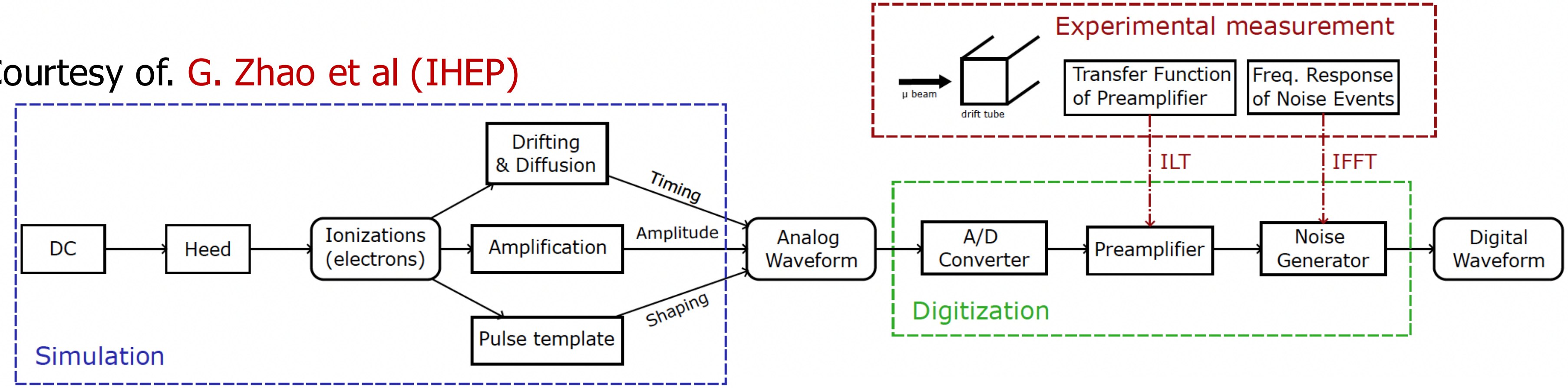
dN/dx resolution dependence on the track length $L^{-0.5}$

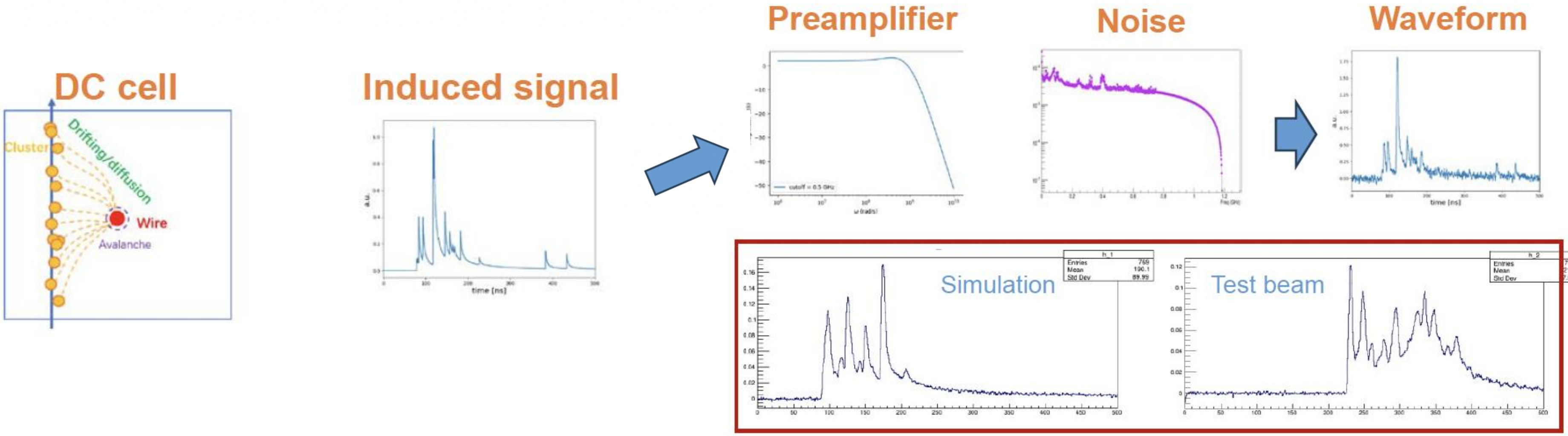
~ 2 times improvement in the resolution using dN/dx method

N. De Filippis

Existing studies: waveform-based full simulation chain

Courtesy of. G. Zhao et al (IHEP)





"Peak finding algorithm for cluster counting with domain adaptation"

Comp. Phys. Comm., 300, 2024, 109208, https://doi.org/10.1016/j.cpc.2024.109208

Existing studies: DCH hit digitizer by A. Tolosa-Delgado

- New Drift chamber digitizer available from k4Rectracker, which handles:
  - Hit position projection and smearing.
    - Each simulated hit is transformed into a digitized hit. The digitized hit position is the projection of the simulated hit position onto the sense wire (at the center of the cell)
    - Smearing of the digitized hit position along the wire and radially is done according to the input parameter values
    - Debug histograms are created if `create_debug_histograms` option is enabled
    - It requires that the cellID contain the layer and number of cell within the layer (nphi). It does not matter if the segmentation comes from geometrical segmentation by using twisted tubes and hyperboloids (and the cellID is created out of volume IDs), or the segmentation is virtual DD4hep segmentation
    - Data extension has now the functionalities to calculate the required quantities
  - Adds dN/dx information: number of clusters and their size, which are derived from precalculated distributions contained in an input file specified by the parameter `fileDataAlg`. The method and distributions corresponds to the option 3 described in F. Cuna et al, arXiv:2105.07064
- New digitized hit class is used as an EDM4hep data extension, to be integrated into EDM4hep
- Random number generator uses the seeds calculated on an event basis by the UID service, from the podio header information (run/event number)

See details at link: *https://indico.cern.ch/event/1483862/#57-update-on-drift-chamber-sim*

Summary and to do List

- the strategy for the digitization of the signals in the IDEA drift chamber has been defined, profiting from the information of **all the ionization clusters along the track**
- **3 digitization levels** defined
- the procedure relies primarily more on **experimental** information
  - it is fundamental to derive as many results as possible from testbeam analysis
- in alternative and waiting for data-based parameterizations, simulations programs inputs from Geant4/Garfield could be used but being aware that the tuning of the parameters of the model could produce unreliable predictions
- let's coordinate with the software experts for the **code implementation** of the strategy

Backup

Distributions

Probability distribution (Poissonian) of the number of encounters along any length L has a mean of L/ λ

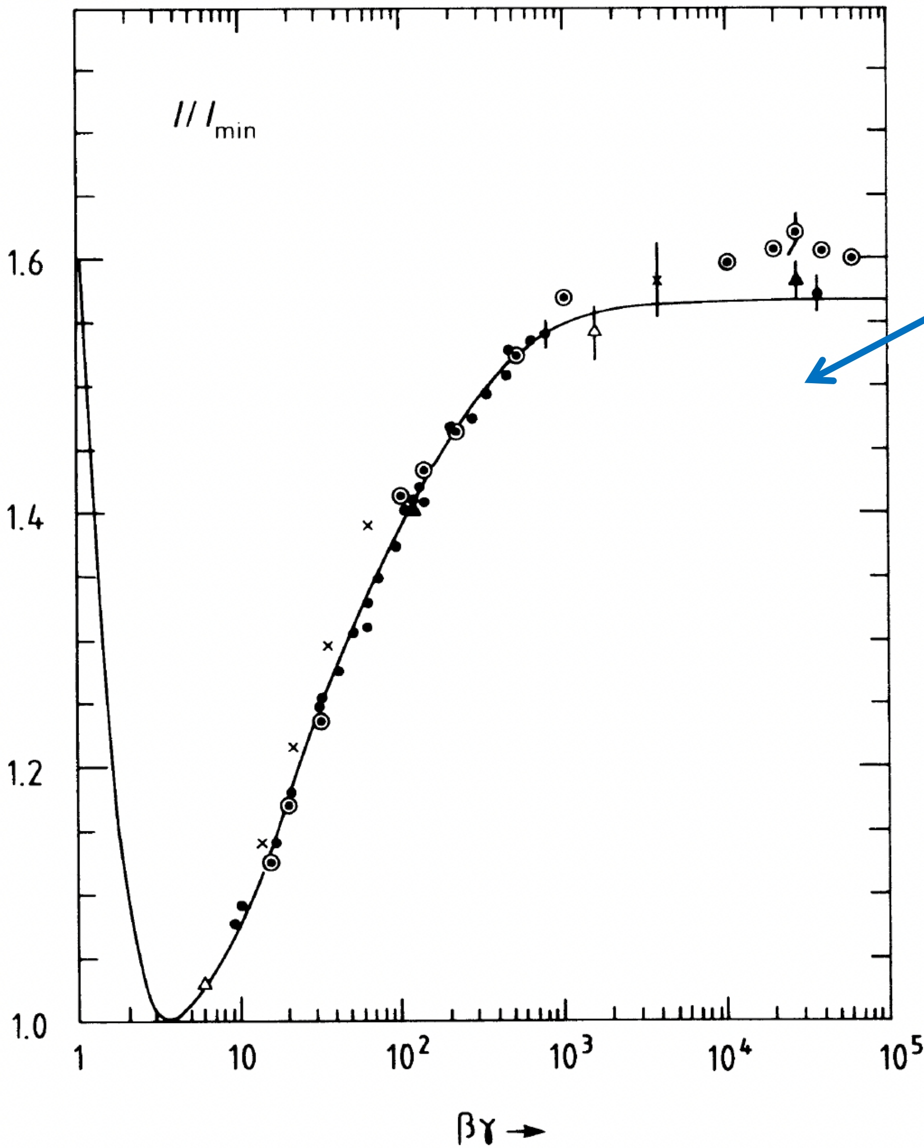
$$P(L/\lambda, k) = \frac{(L/\lambda)^k}{k!} \exp(-L/\lambda)$$

λ = mean free flight path

$$f(l)\mathrm{d}l = P(1/\lambda, 0) P(\mathrm{d}l/\lambda, 1) = (1/\lambda) \exp(-l/\lambda)\mathrm{d}l.$$

Probability distribution (exponential) f(l)dl of the free flight paths l between encounters

Most probable/Average energy loss



Measured values of the most probable energy loss in an Ar + methane mixture as a function of βγ, compared with the photo-absorption model of Allison and Cobb (**PAI**)

Average energy loss by **Bethe-Block**:

$$\frac{dE}{dx} = \frac{4\pi N e^4}{mc^2}\frac{1}{\beta^2}z^2\left(\ln\frac{2mc^2}{I}\beta^2\gamma^2 - \beta^2 - \frac{\delta(\beta)}{2}\right)$$

Existing studies: Waveform-based full simulation chain (IHEP)

Simulation package consists of two components:

- **Simulation:**
  - the geometry of drift chamber cells is constructed
  - ionizations of charged particles are generated by the Heed package.
  - the transportation, amplification and signal creation processes for each electron are **parameterized according to the Garfield++ simulation results**, which outputs analog waveforms for drift chamber cells

Reference: D. Pfeiffer, L. De Keukeleere, C. Azevedo et al., «*Interfacing Geant4, Garfield++ and Degrad for the simulation of gaseous detectors*», Nucl. Instr. and Meth. A 935, 121-134 (2019). doi: 10.1016/j.nima.2019.04.110.

- **Digitization:** data-driven electronics responses and noise
  - the impulse response of the preamplifier and further convoluted with the waveform
  - the noise extracted from the experimental data using the fast Fourier transform and added to the signal using the inverse fast Fourier transform
  - the digitization outputs realistic digitized waveforms with good agreement with experimental data in terms of rise time of the peak and noise level
  - according to testbeam data the waveform has a single-pulse rise time of 4 ns, a noise level of 5% and a roughly sampling rate of 1.5 GHz