Drift chamber with cluster counting technique at FCC-ee

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on behalf of IDEA DC group

Gaseous trackers - applications and advantages

- **Gaseous detectors** have been used in experiments for **tracking** applications for the last ~50y.
  - MWPC, **Drift chambers**, TPCs, Straw tubes
- Tracking system should be as light as possible
  - **Momentum resolution** dominated by multiple scattering at low momentum.
  - **Particle Flow** requires as little material as possible in front of ECAL.
  - **PID** capabilities, over wide momentum range.
- **The Drift Chamber** widely used in past and present particle colliders and are planned to be essential components in future colliders.

Past

Facility	Experiment	Detector type
SPEAR	MARK2	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CESR	CLEO1,2,3	Drift Chamber
VEPP2/4M	CMD-2	Drift Chamber
	KEDR	Drift Chamber
	NSD	Drift Chamber
PETRA	CELLO	MWPC + Drift Ch.
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Ch.
	TASSO	MWPC + Drift Ch.
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC
PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

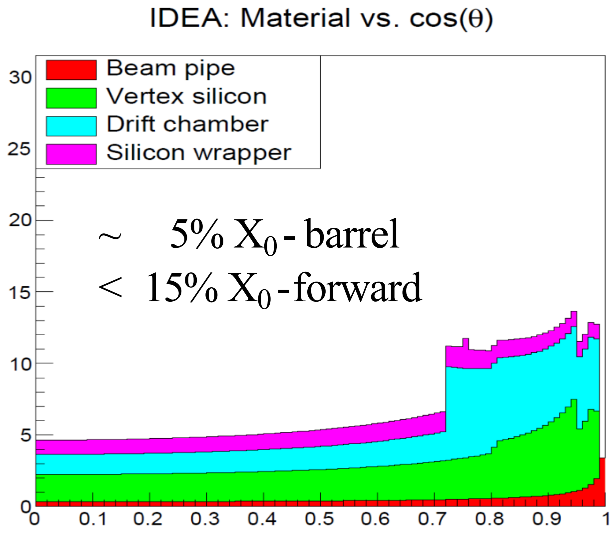
Present & future

Facility	Experiment	Detector type
VEPP2000	CMD-3	Drift Chamber
	KEDR	Drift Chamber
BEPC2	BES3	Drift Chamber
S.KEKB	Belle2	Drift Chamber
LHC	ALICE	TPC
	ATLAS	Straw tubes
	LHCb	Straw tubes
CERN SPS	COMPASS	Drift Chamber + Straw
	NA35	TPC
	NA49	TPC
RHIC	STAR	TPC
	PHENIX	Drift Chamber
PSI	MEGII	Drift Chamber
ILC	ILD	TPC
	SiD	Si
FCC-ee	CLD	Si or TPC
	IDEA	Drift Chamber
	ALLEGRO	Drift Chamber, Straw
SCTF	BINP	Drift Chamber
	HIEPA	Drift Chamber

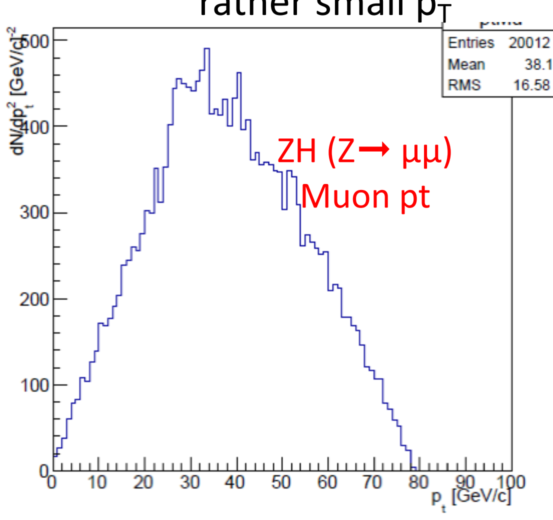
*not an exhaustive list

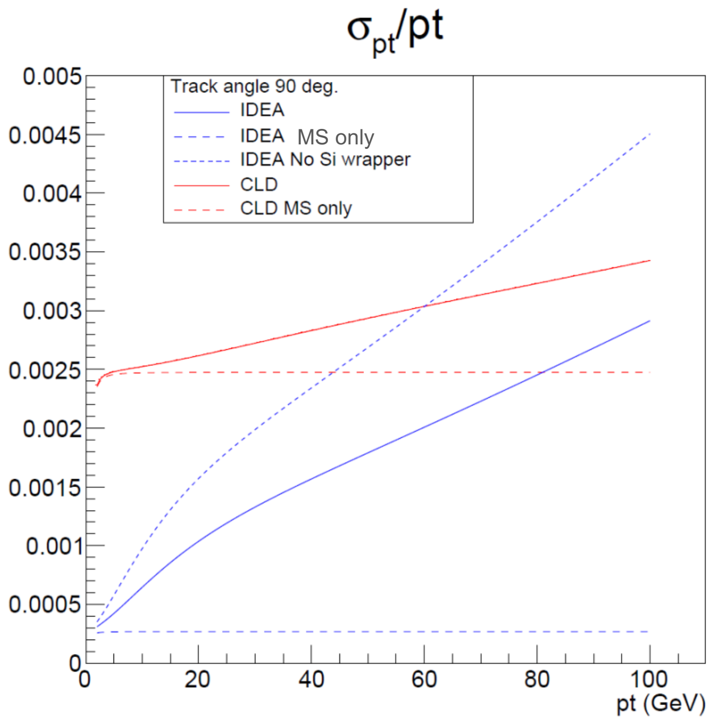
Design features of the IDEA Drift Chamber

- IDEA DCH designed to provide efficient tracking, high precision momentum measurement and excellent particle identification for particles of low and medium momenta. Main features:
  - High granularity.
  - Transparency against multiple scattering.
  - An excellent particle identification and separation.



muons in ZH events have rather small p_T

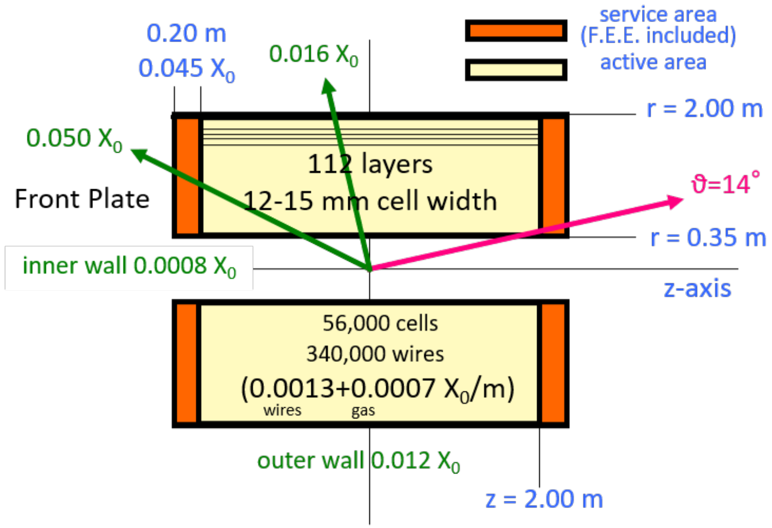


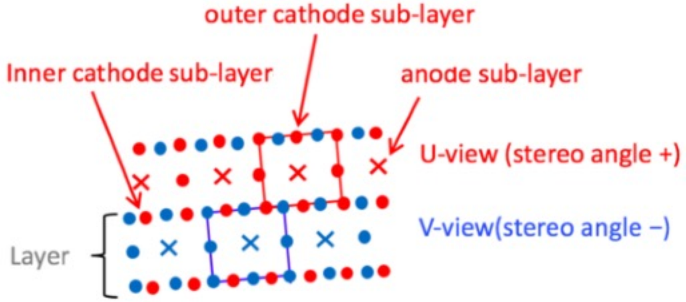


- Due to the minimization of the multiple scattering contribution, the IDEA tracking system performs better, over almost the entire momentum range of interest, than an alternative tracking system based only on Si detectors (CLD).
  - For 10 GeV (50 GeV) **μ** emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is about 0.05 % (0.15%) with the very light IDEA DCH.

The Drift Chamber of IDEA

- Dimensions: 4 m long (active volume), 35cm to 2m radius
- Low material budget
  - Barrel: ~ 1.6% X_0
  - Forward directions: ~ 5% X_0
- Stereo layout
  - 112 layers ranging from 50 to 250 mrad
- Operating gas mixture: He + 10% iC4H10
  - Average drift velocity of ~ 2 cm/μs → drift time t_D < 400 ns
  - Number of cluster (per m.i.p.) ~ 12.5 cm^{-1} avg. with ~ 1.6 electrons/cluster).
- Sense (anode): 20μm W(Au) → 56448 total
- Field (cathode): 40μm Al(Ag) → 285504 total
- Guard (cathode): 50μm Al(Ag) → 2016 total
- Active volume: 56448 almost squared drift cells (12 ÷ 14.5 mm), with a 5: 1 field-to-sense wire ratio for simpler time-to-distance relations
- Overall expected resolution: σ_{xy} ~ 100 μm and σ_z ~ 1 mm



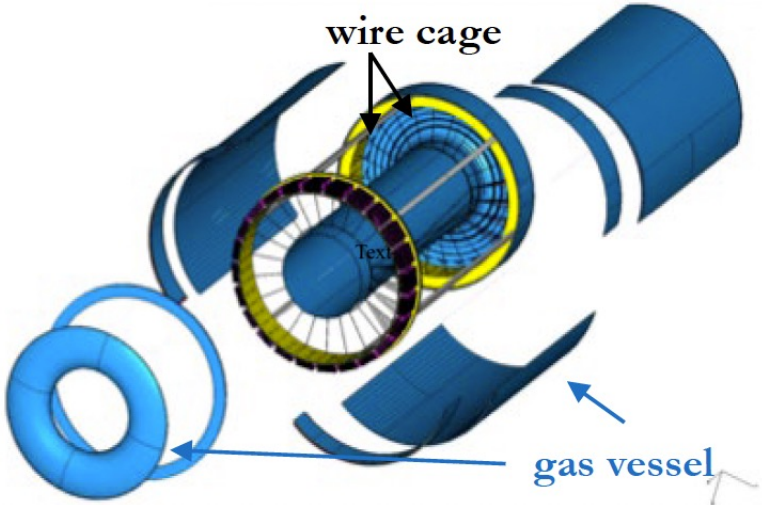


5 : 1 field-to-sense wire ratio

Mechanical structure of the DCH

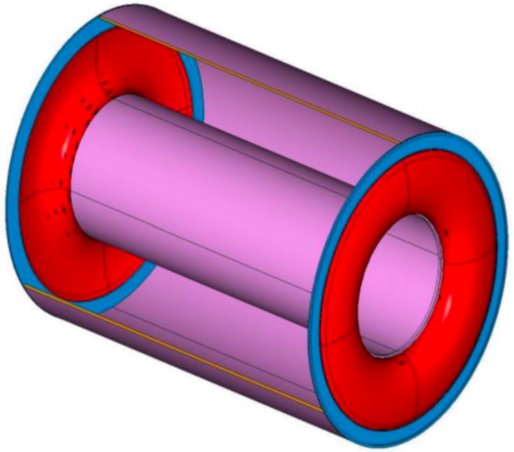
- The mechanical design of the drift chamber is driven by two main objectives:
  - ✓ Maximizing its transparency in terms of radiation length.
  - ✓ Maximizing its mechanical stability by reducing to acceptable limits the deformations of the endplates under the total load of the wires.
- A significant reduction in the amount of material at the end plates is obtained by separating the gas containment function from the wire tension support function.

- New concept of construction allows to reduce material to ≈ 10^{-3} X_0 for the barrel and to a few x 10^{-2} X_0 for the end-plates.



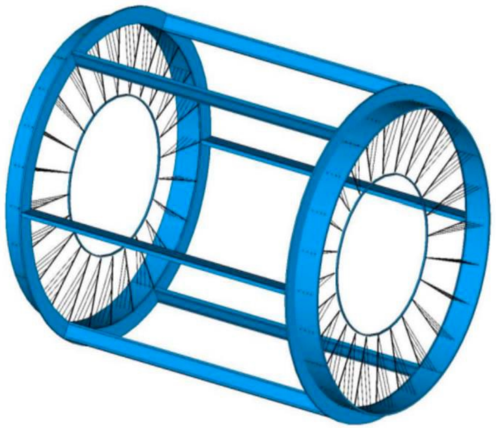
Gas containment

Gas vessel can freely deform without affecting the internal wire position and mechanical tension.



Wire cage

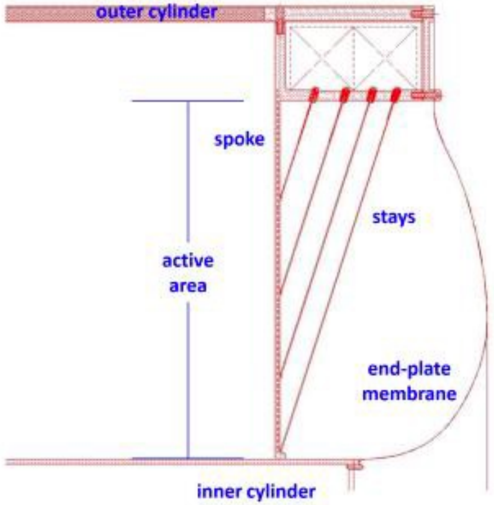
Wire support structure not subject to differential pressure can be light and feed-through-less

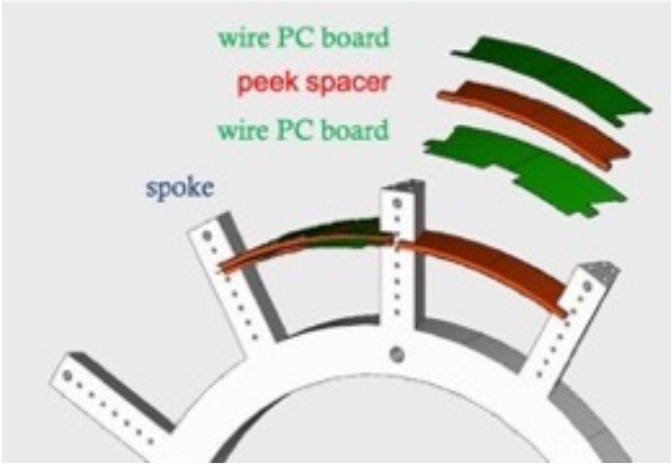


Mechanical structure of the DCH

New tension recovery schema

- Experience inherited from the **MEG2 DCH**
- inner and outer cylinder connected to 48 spokes, forming 24 identical sectors.
- To minimize the deformations due to the wire load, it is necessary to create a system of adjustable stays that steers the wire tension to the outer end plate rim .



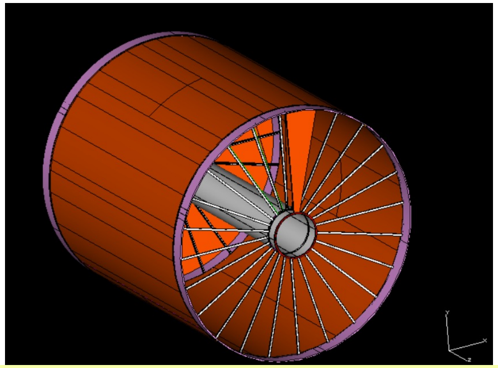


FEM simulation studies:

- **Our main goal** is to minimize the deformation of the spokes using prestressing force in the cables, while ensuring the structural integrity.
- varying input parameters in some possible ranges in order to see how the system responds.

A realistic complete model ready:

- mechanically accurate.
- precise definition of the connections of the cables on the structure.
- connections of the wires on the PCB.
- location of the necessary spacers.
- connection between wire cage and gas containment structure.



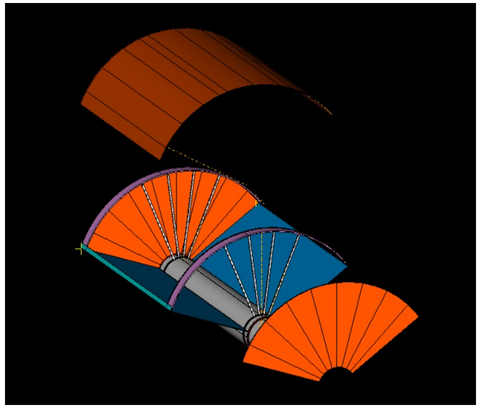
More information in Nicola's talk tomorrow

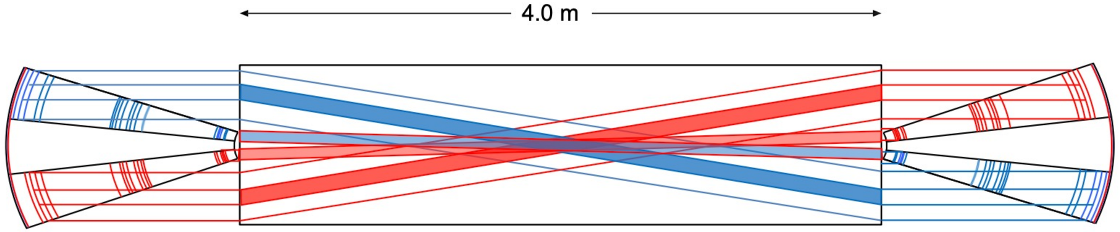
DCH full length prototype

- Optimize the wiring strategy, the High Voltage and signal distribution, test performance of different versions of front-end, digitization and acquisition chain.
- Check the limits of the wires' electrostatic stability at full length and at nominal stereo angles.
- Test different wires: uncoated Al, C monofilaments, Mo sense wires, …, of different diameters
  - Test different wire anchoring procedures (soldering, welding, gluing, crimping, …) to the wire PCBs
  - Test different materials and production procedures for spokes, stays, support structures and spacers
  - Test compatibility of proposed materials with drift chamber operation (outgassing, aging, creeping, …)
- Validate the concept of the wire tension recovery scheme with respect to the tolerances on the wire positions

More information in Nicola's talk tomorrow

ELECTRONICS COVERAGE





Minimum stereo angle	50 mrad
Maximum stereo angle:	250 mrad

TOTAL LAYERS: 8

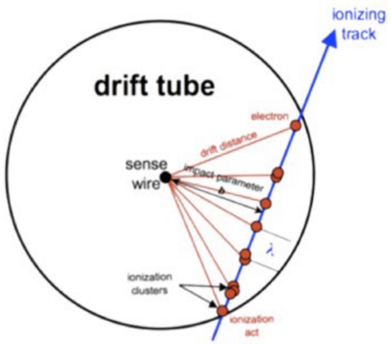
Type	Wires	Wire Boards
Sense	168	8
Field	965	22
Guard	264	12
Total	1397	42

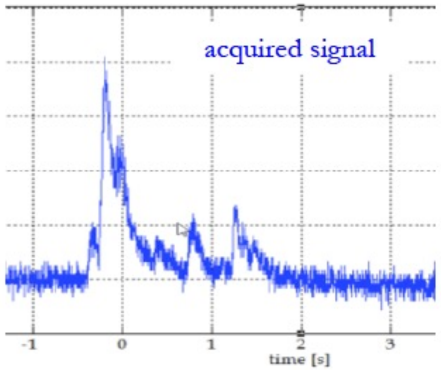
Readout channels: 8+8 +16+16+16+16 + 16+16 = 112

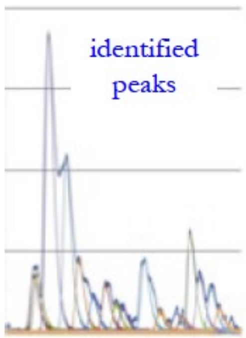
PID with Cluster Counting Technique

- **Principle:** In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently.

- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.

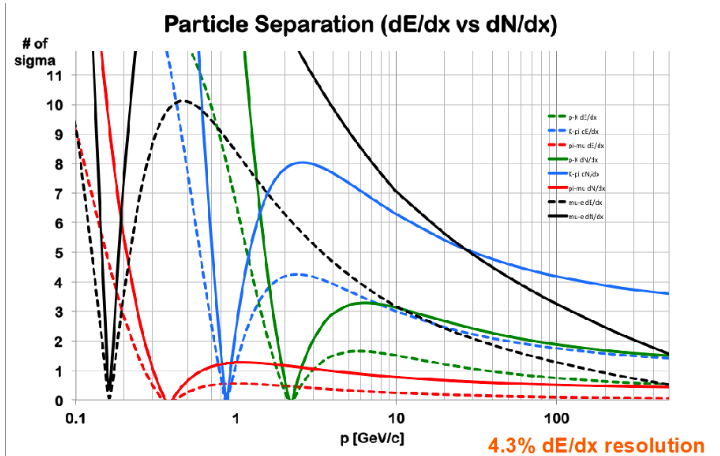






▶Backup

dE/dx	dN_{cl}/dx
Truncated mean cut (70-80%) reduces the amount of collected information. n = 112 and a 2m track at 1 atm give **σ ≈ 4.3%**	δ_{cl}= 12.5/cm for He/iC4H10 = 90/10 and a 2m track give **σ ≈ 2.0%**



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

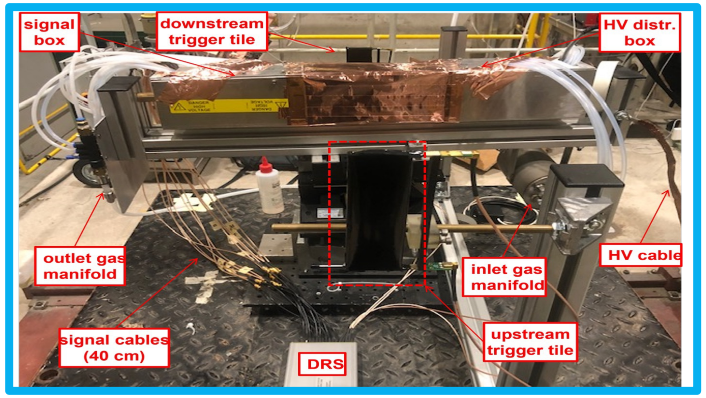
- Despite the fact that the Garfield++ model in GEANT4 reproduces reasonably well the Garfield++ predictions, why particle separation, both with dE/dx and with dNcl/dx, in GEANT4 is considerably worse than in Garfield++? ▶Backup

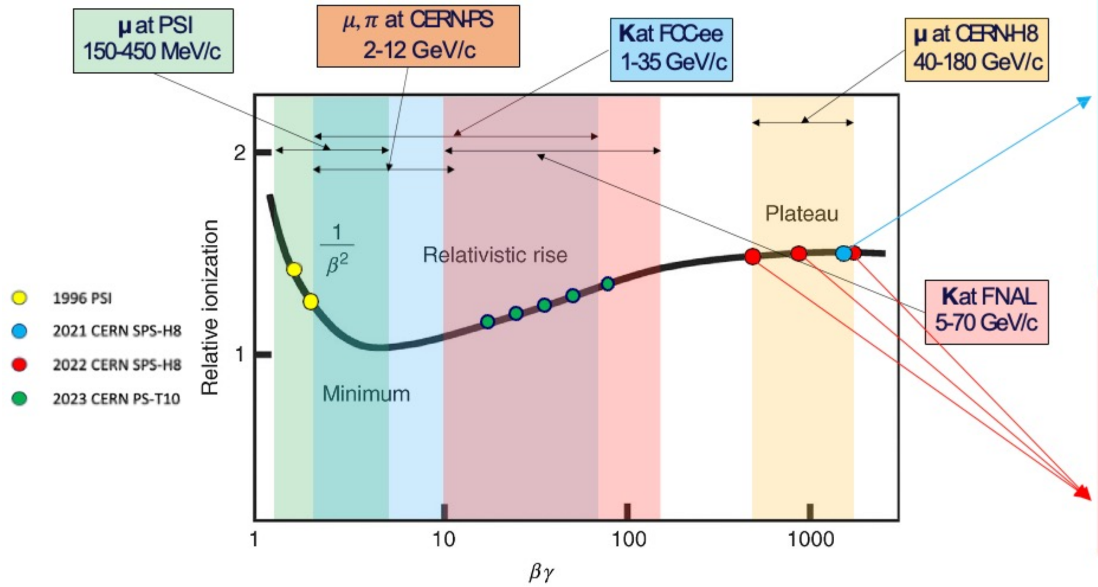
- Despite a higher value of the dN_{cl}/dx Fermi plateau with respect to dE/dx, why this is reached at lower values of βγ with a steeper slope?

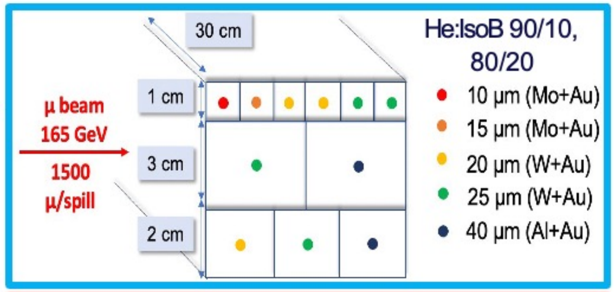
finding answers by using real data from beam tests!!

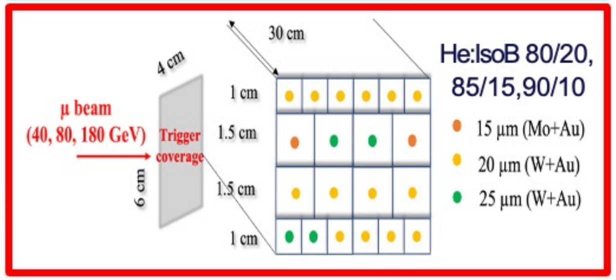
Main Beam Test setup & goals

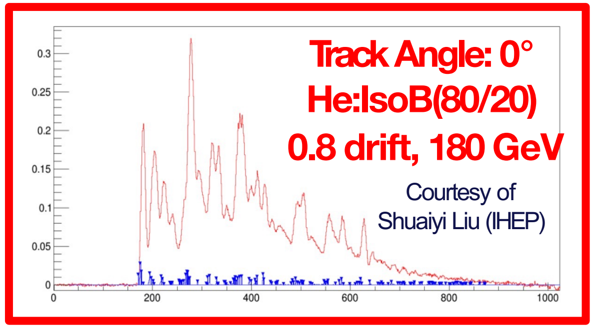
- **Beam tests to experimentally assess and optimize the performance of the cluster counting/timing techniques.**
  - Two muon beam tests performed at CERN H8(βγ > 400) in Nov. 2021 and July 2022.
  - Two muon beam tests performed at CERN T10 in Jul 2023 and Jul 2024 using μ beam (1-12 GeV).
  - Another test is planed to be done at FNAL-MT6 with π and K ($\beta\gamma$ = 10−140) to fully exploit the relativistic rise.

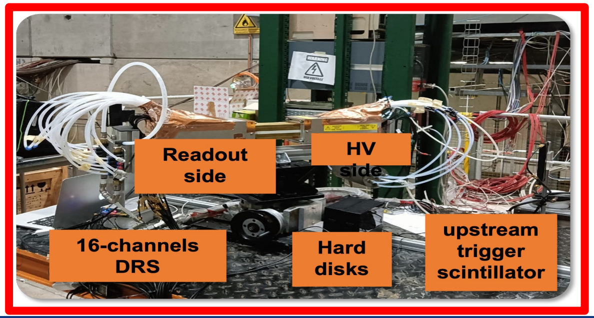












Analysis strategy

Finding peaks algorithms:

- To accurately identify electron peaks, we have developed and tested Three distinct algorithms:
  - ✓ Derivative Algorithm (DERIV)
  - ✓ Running Template Algorithm (RTA)
  - ✓ NN- based approach (developed by IHEP)

Today talk

Clusterization:

- Merging of electron peaks in consecutive bins in a single electron to reduce fake electrons counting.

Different scans done:

- Using the test beam data we evaluated the performance of our algorithms across various conditions: gas mixture, gain, geometrical configuration (cell size, sense wires size), sampling rate, HV, and track angle.

Resolution study: dN/dx vs dE/dx:

- Investigated the resolution of the number of detected clusters per unit length (dN/dx) versus the energy loss per unit length (dE/dx).

Documentation: Analysis Note is done!

Beam Test Results on Cluster Counting for IDEA Drift Chamber

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Find Electron peaks Algorithms

Derivative Algorithm (DERIV)

- Compute the first and second derivative from the amplitude average over two times the timing resolution and require that, at the peak candidate position, they are less 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.

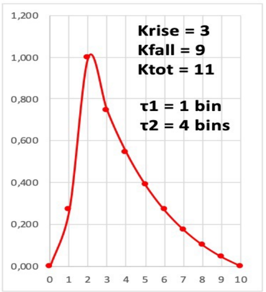
- Require that the amplitude at the peak candidate position is greater than a r.m.s. signal-related small quantity and the amplitude difference among the peak candidate and the previous (next) signal amplitude is greater (less) than a r.m.s. signal-related small quantity.

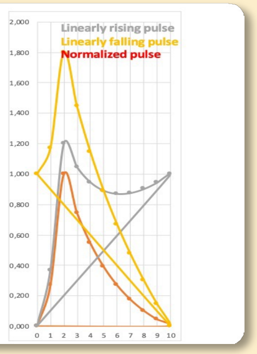
- NOTE: r.m.s. is a measurements of the noise level in the analog signal from first bins.

Running Template Algorithm (RTA)

- Define an electron pulse template, characterized by rising and falling exponentials, over a fixed number of bins derived from experimental data.
- Digitize it according to the data sampling rate.
- The algorithm scans the wave form, comparing the normalized electron pulse template to the data within a search window.
- It evaluates the agreement between the template and the data, applying a cut-off to identify peaks.
- Subtract the found peak to the signal spectrum.
- Iterate the search and stop when no new peak is found.

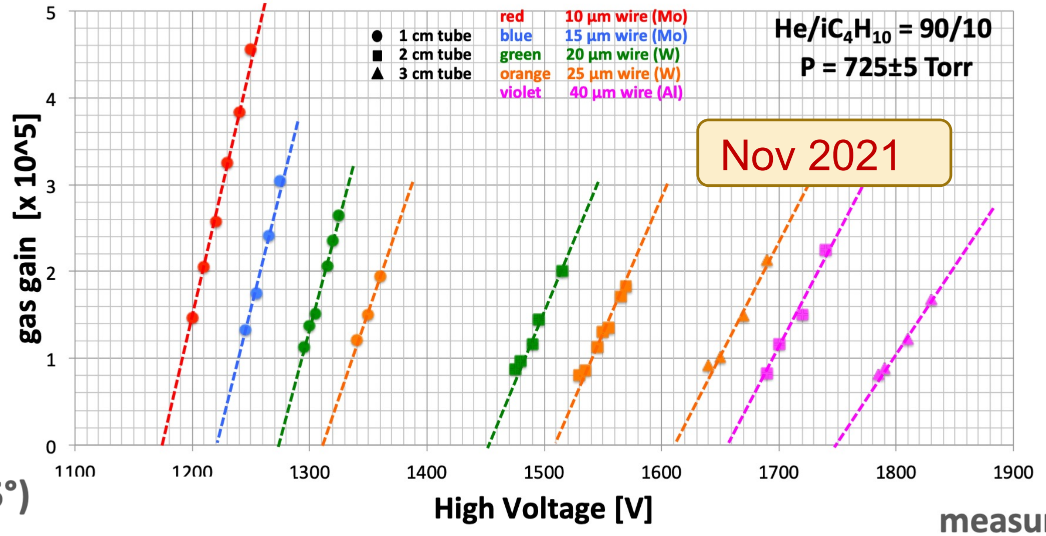
k	A(k)
0	0.0
1	0.269
2	1.0
3	0.744
4	0.545
5	0.390
6	0.269
7	0.175
8	0.102
9	0.044
10	0.0



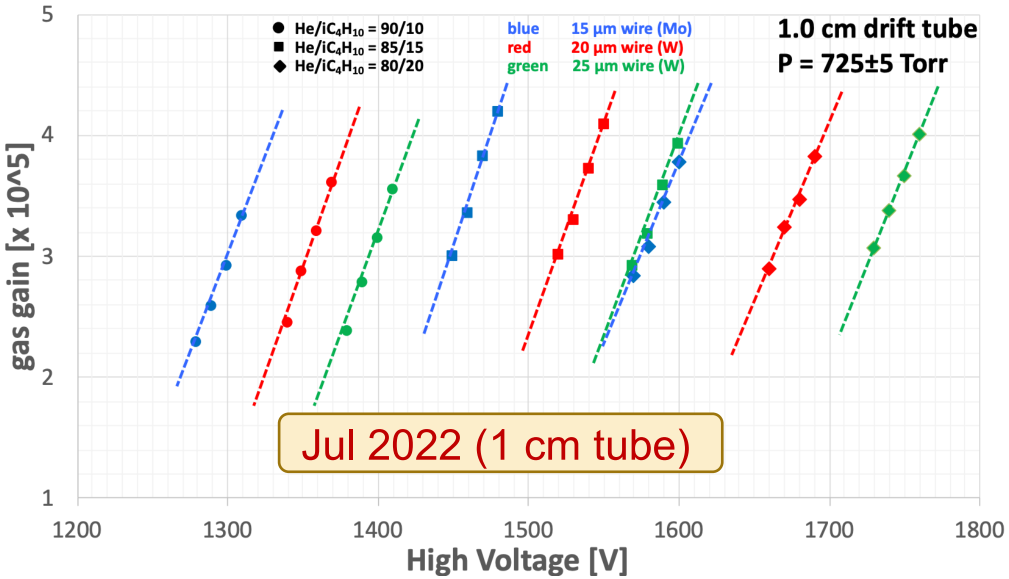


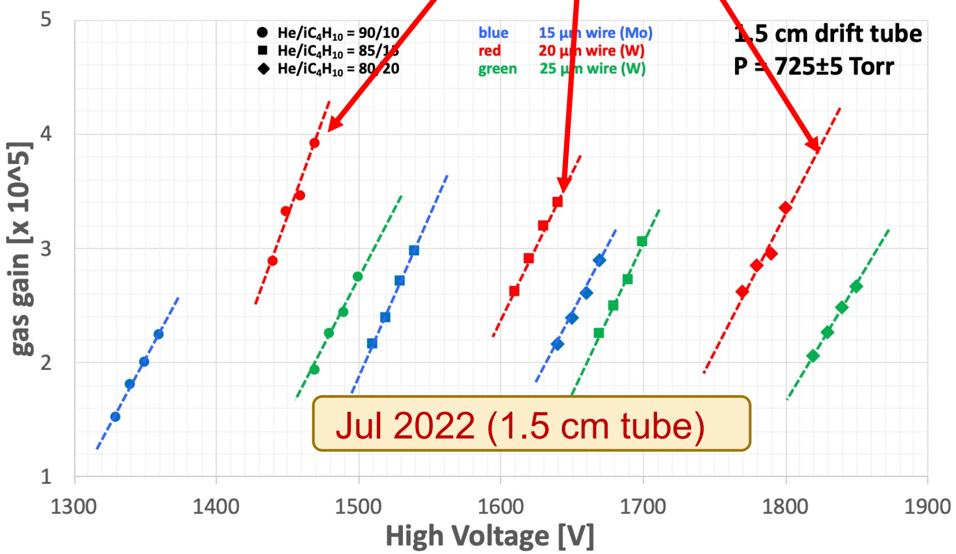
Gas gain scan

The range of gas gain, independently of the drift tube configuration (drift length, sense wire diameter, gas mixture), lies within 1×10^5 and 5×10^5.



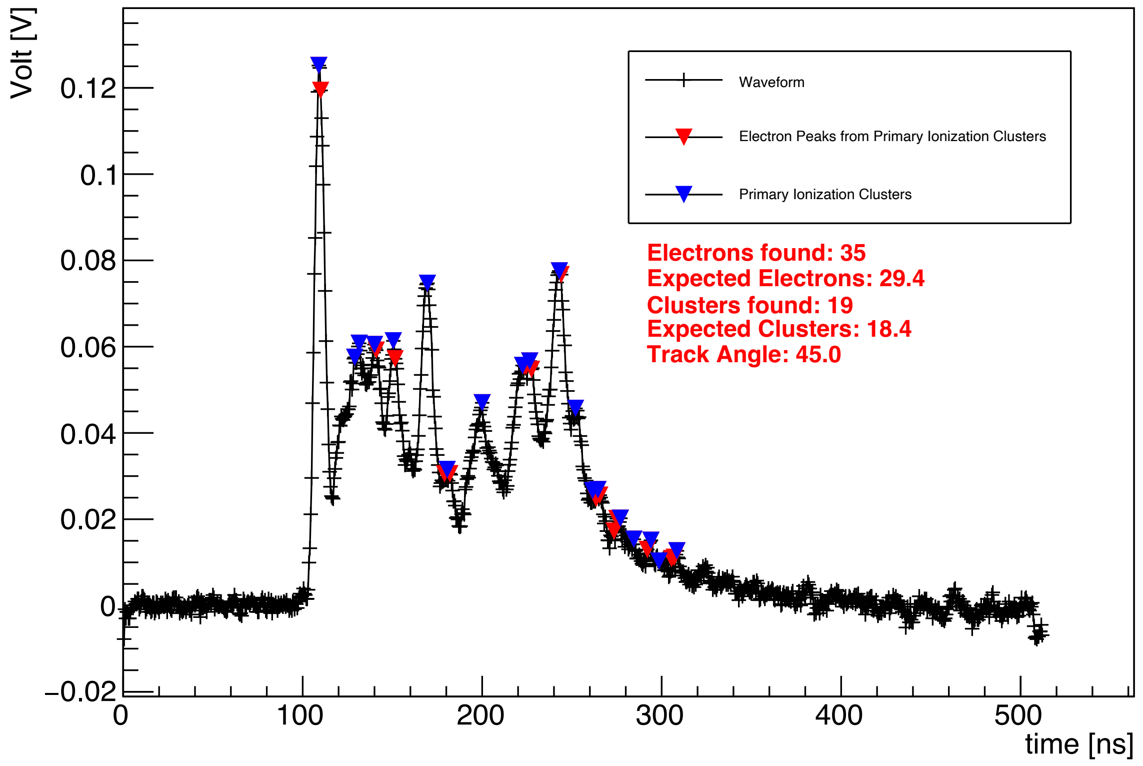
20µm wire excluded from physical quantities mean computation



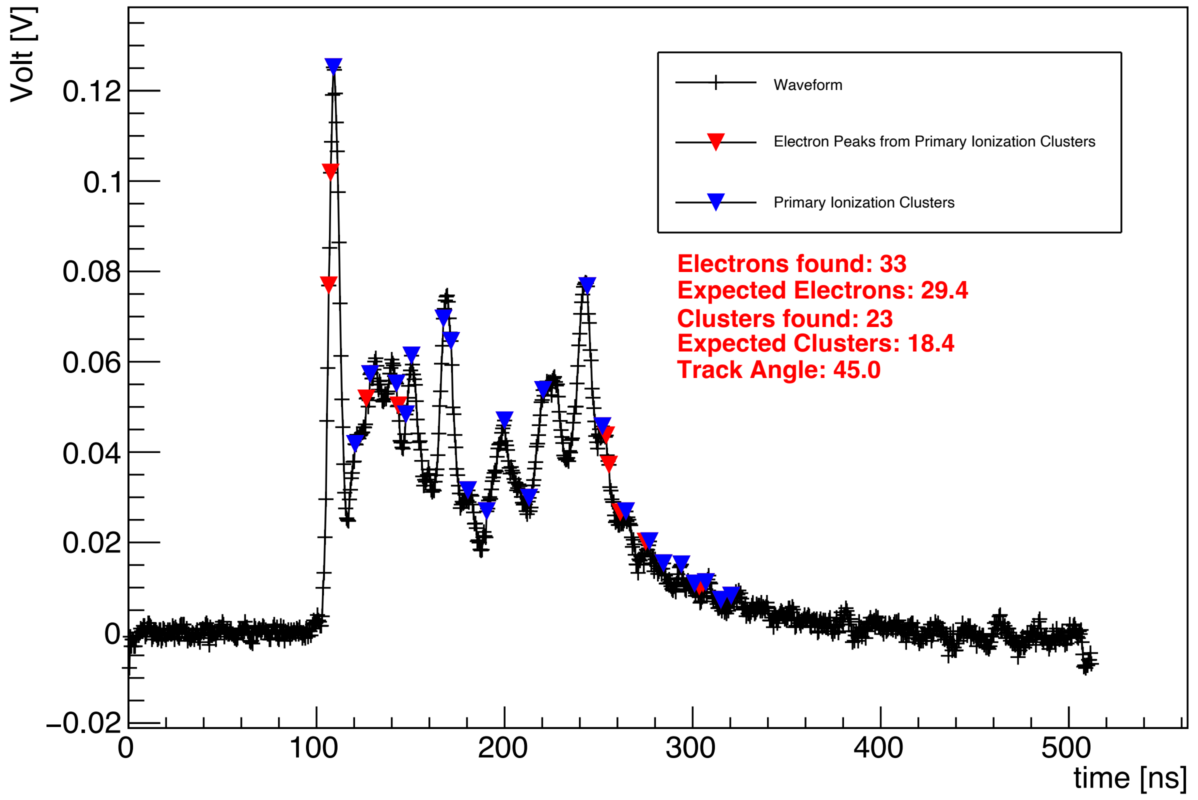


Electron peaks Finding

Peaks found by the RTA algorithm



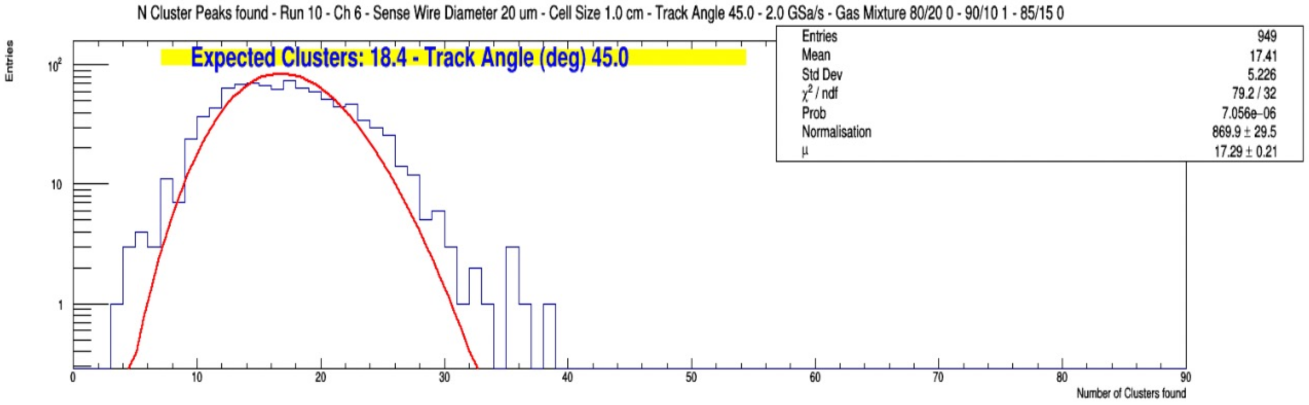
Peaks found by the DERIV algorithm

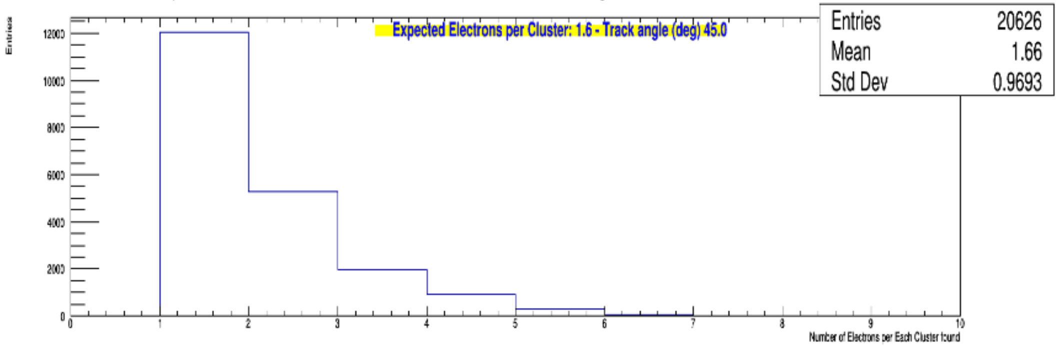


Reconstruction of Primary Ionization Clusters

Clusterization algorithm

- 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 $\sim\sqrt{tElectronPeak}$ 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!



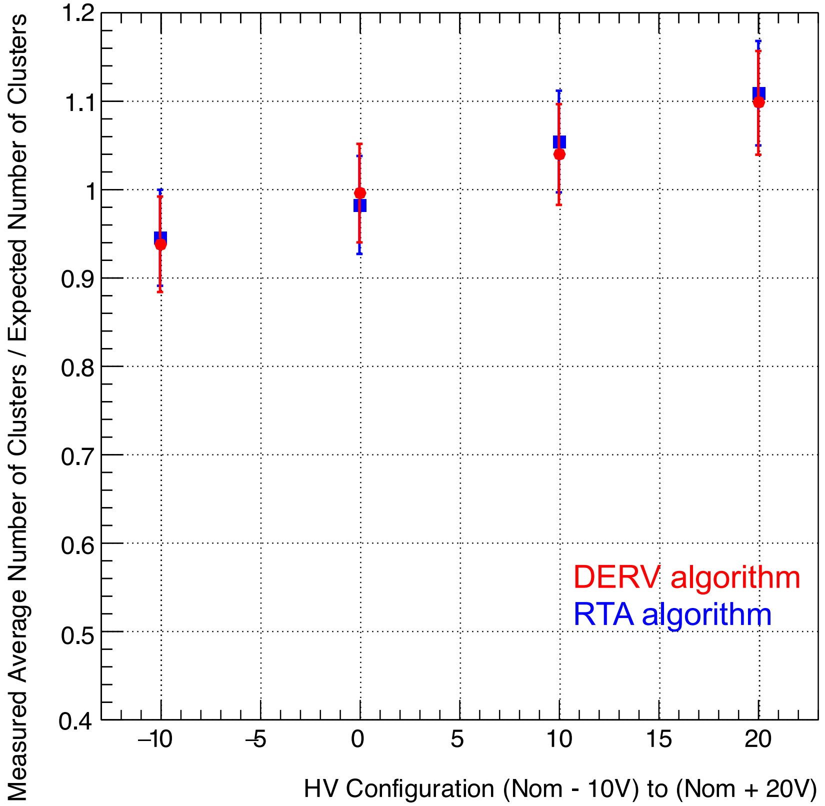


Expected number of cluster = δ cluster/cm (M.I.P.) * drift tube size [cm] * 1.3 (relativistic rise)* 1/cos(α)

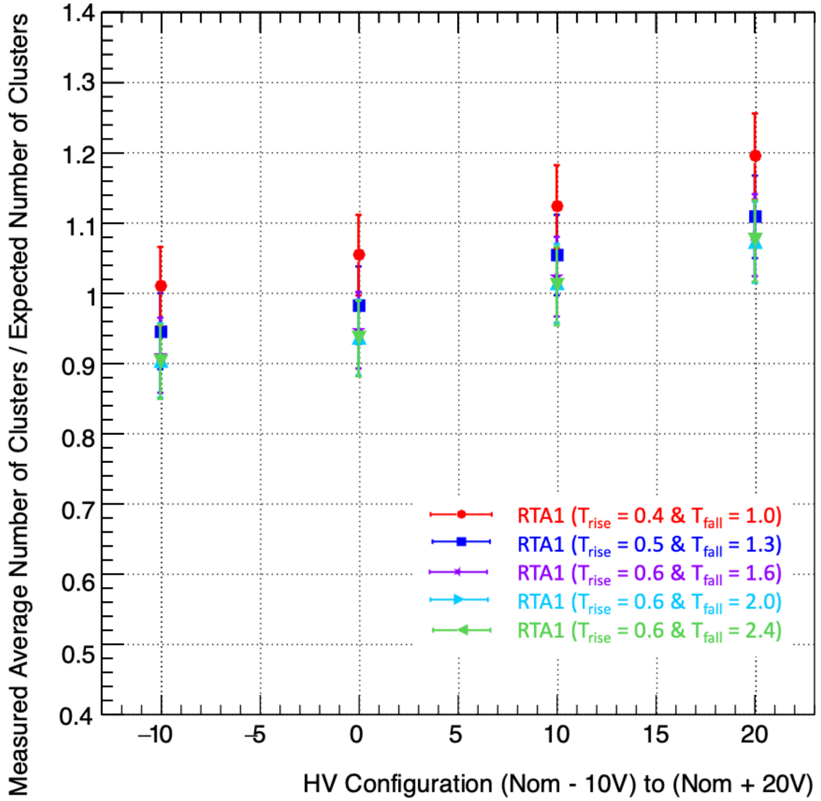
α = angle of the muon track w.r.t. normal direction to the sense wire.
δ cluster/cm (mip) changes from 12, 15, 18 respectively for He:IsoB 90/10, 85/15 and 80/20 gas mixtures.
drift tube size are 0.8, 1.2, and 1.8 respectively for 1 cm, 1.5 cm, and 2 cm cell size tubes.

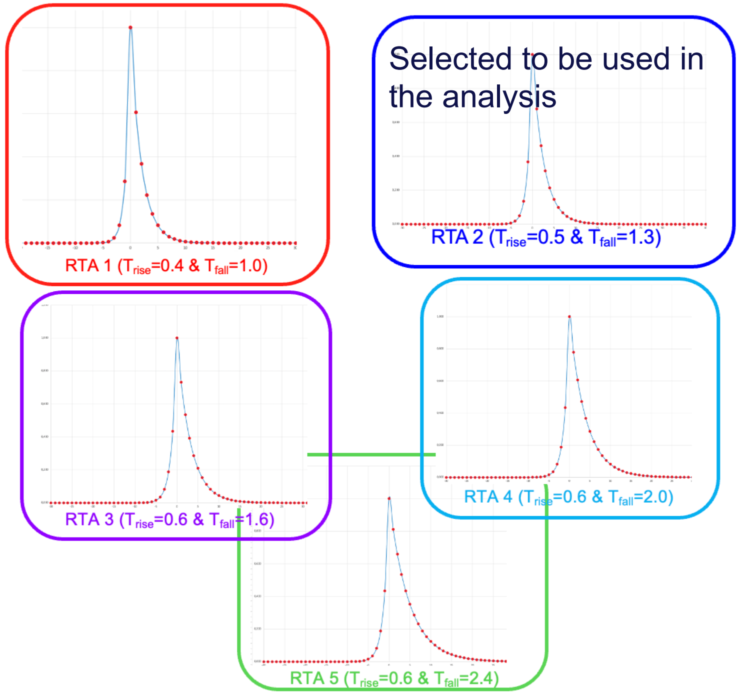
Electron peaks Finding Algorithms (DREV vs RTA algorithm)

DERIV vs RTA algorithm



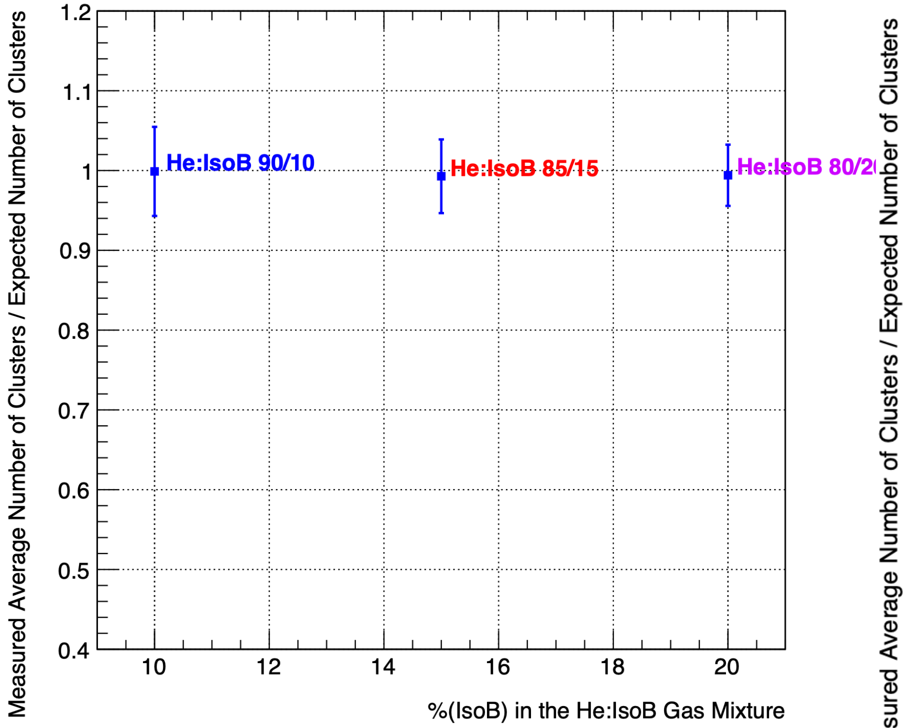
RTA Templates scan



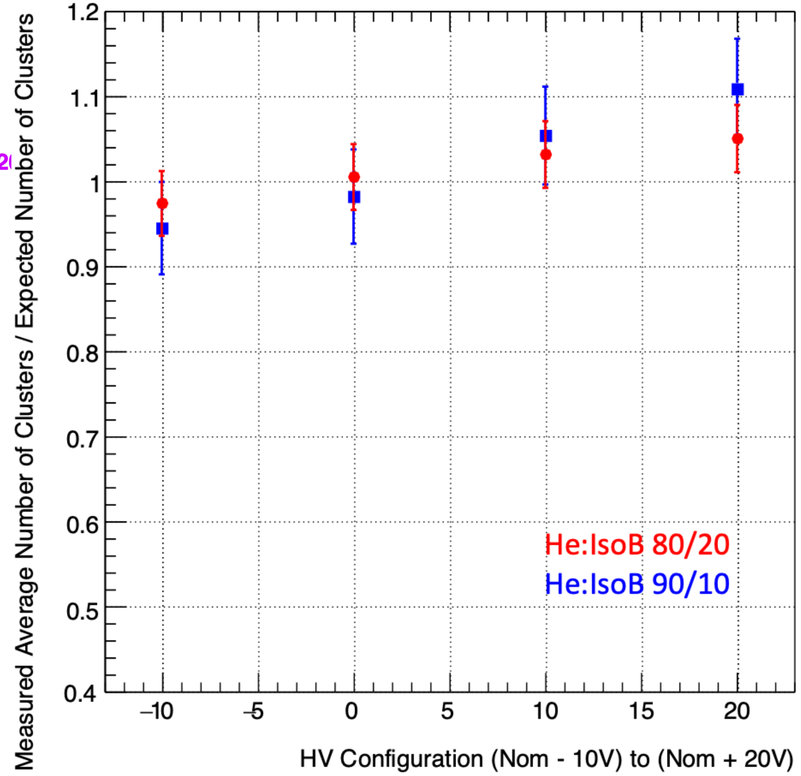


Gas mixture & HV & angle scans

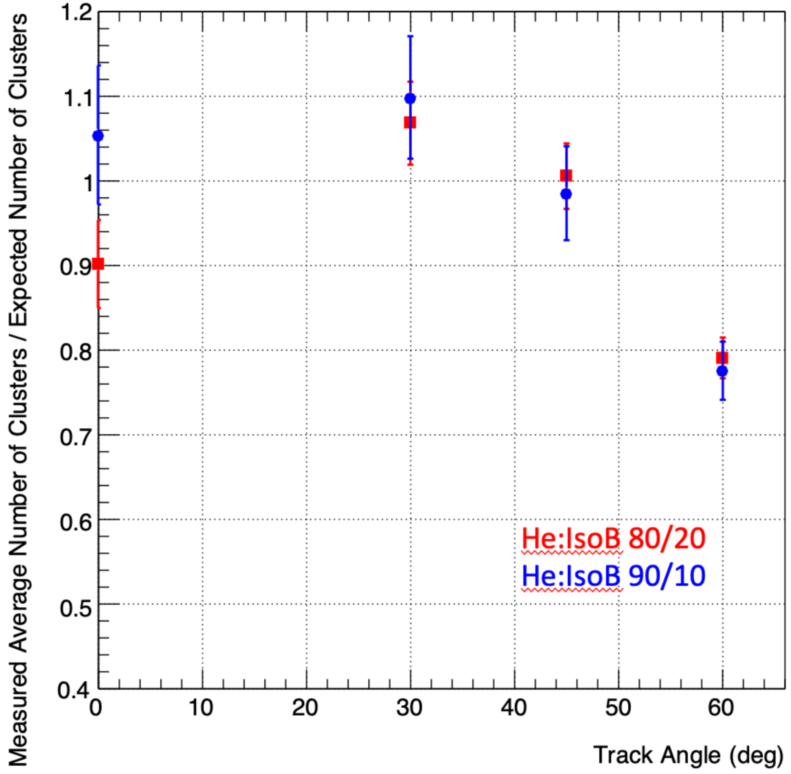
Gas Mix scan



HV scan



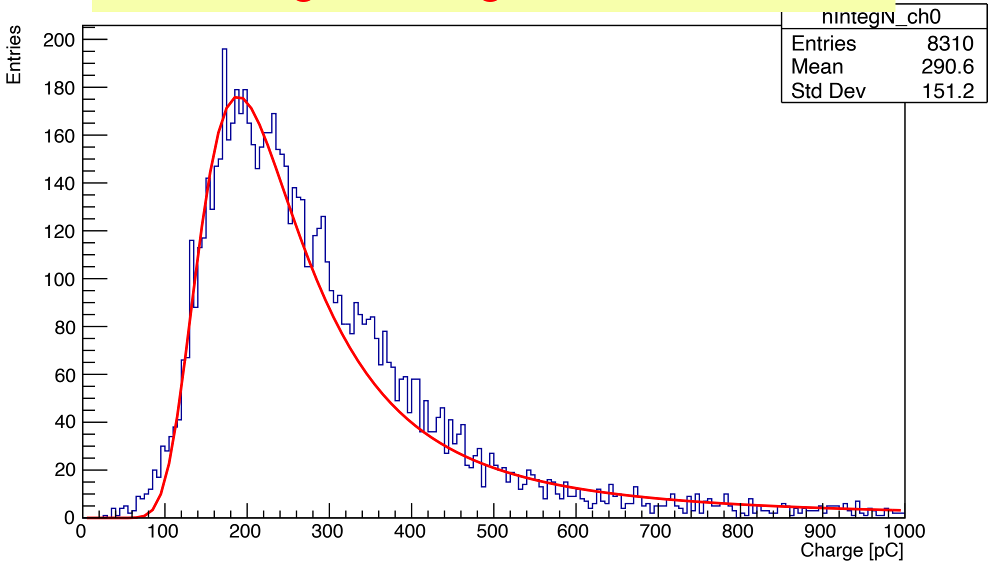
Angle scan



Resolution study

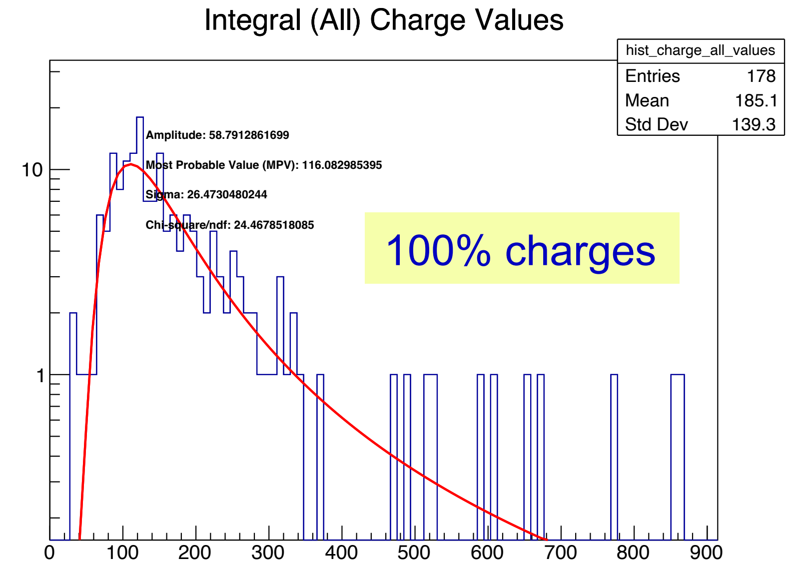
- **dE/dx Resolution study:**
  - Landau distribution for the charges.
  - Measure charge of many samples (cells) along track.
  - Get ”mean" charge over samples = dE/dx.
  - Simple “mean” charge subject to large fluctuations ⇨“Truncated Mean” (robust).
  - Reject samples with highest charge (typically) 20-30% and calculate mean (“truncated” mean) of remaining samples.
  - Optimize truncation empirically (⇨best dE/dx resolution).

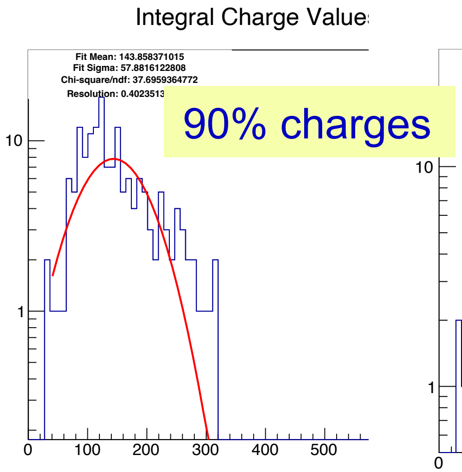
Integral charge distribution

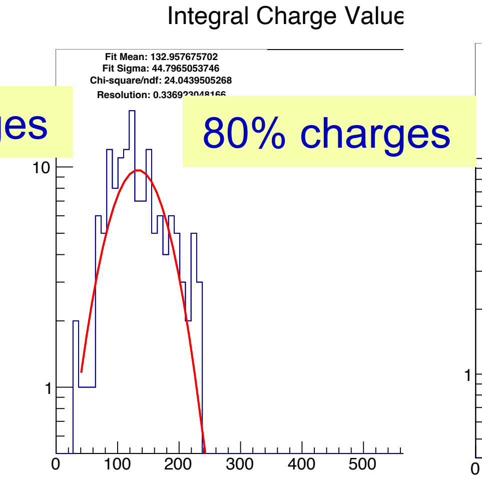


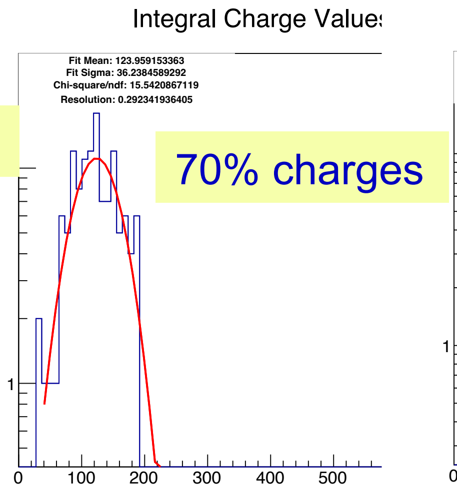
Resolution study

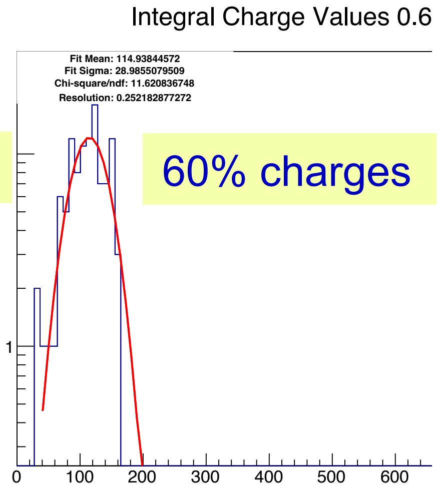
- **dE/dx Resolution study:**
  - 2m track length.
  - Landau distribution for the charges.
  - Optimize truncation empirically (⇨best dE/dx resolution).
  - Tested the resolution for each.
  - Selected the distribution with 80% of the charges to be compared with dN/dx.

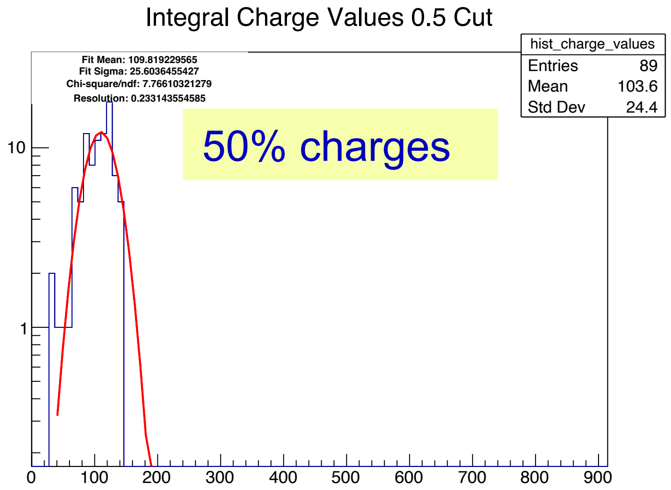






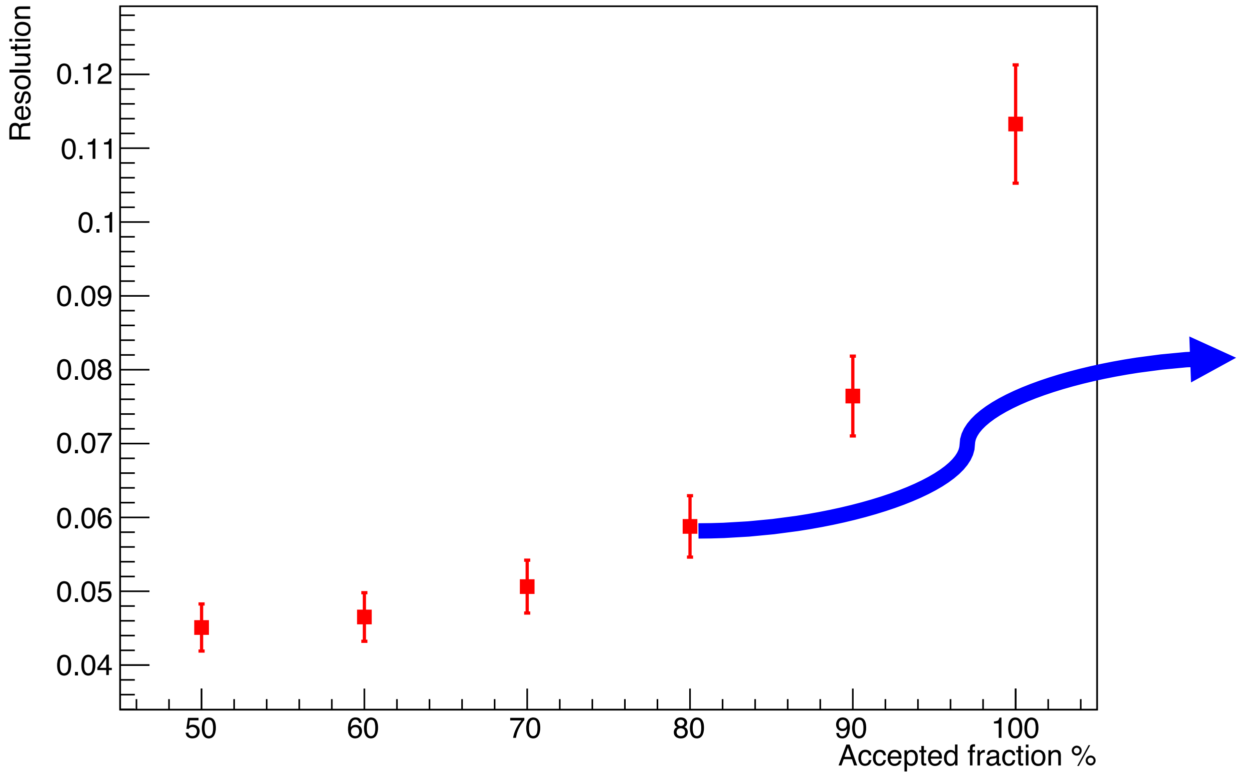




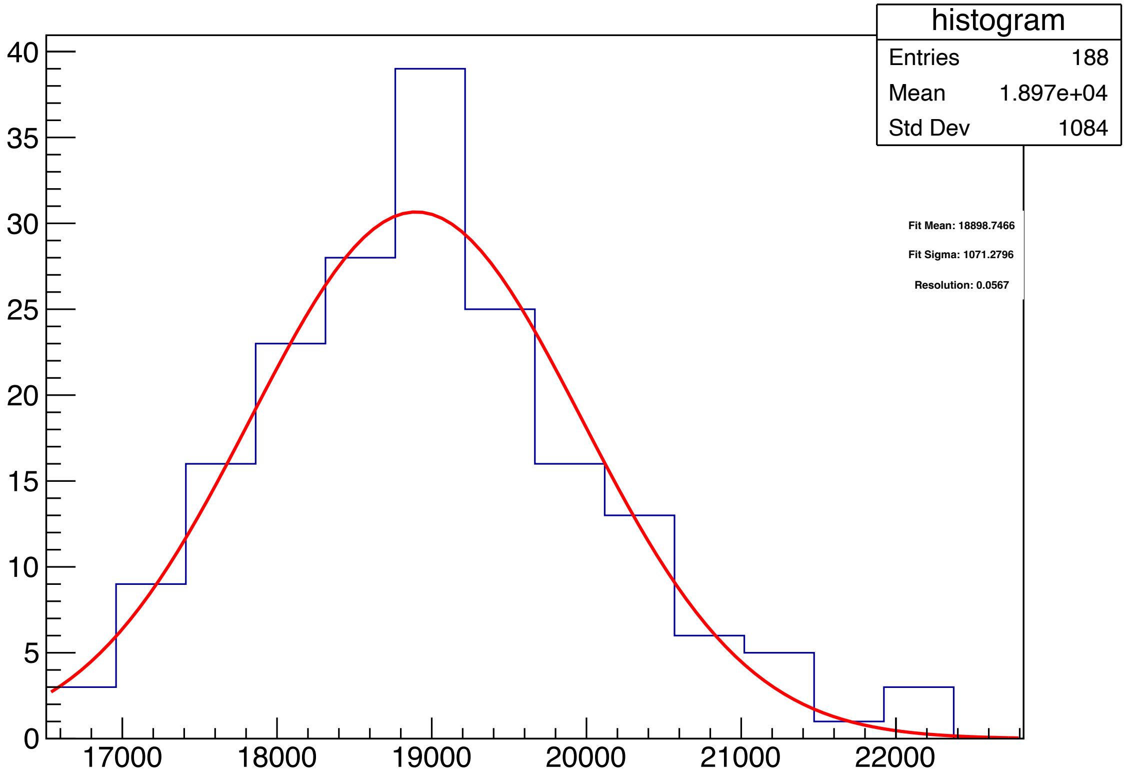


Resolution study

dE/dx Resolution Scan Vs accepted fraction of charge



dE/dx Resolution (remove 20% higher charges for each track)



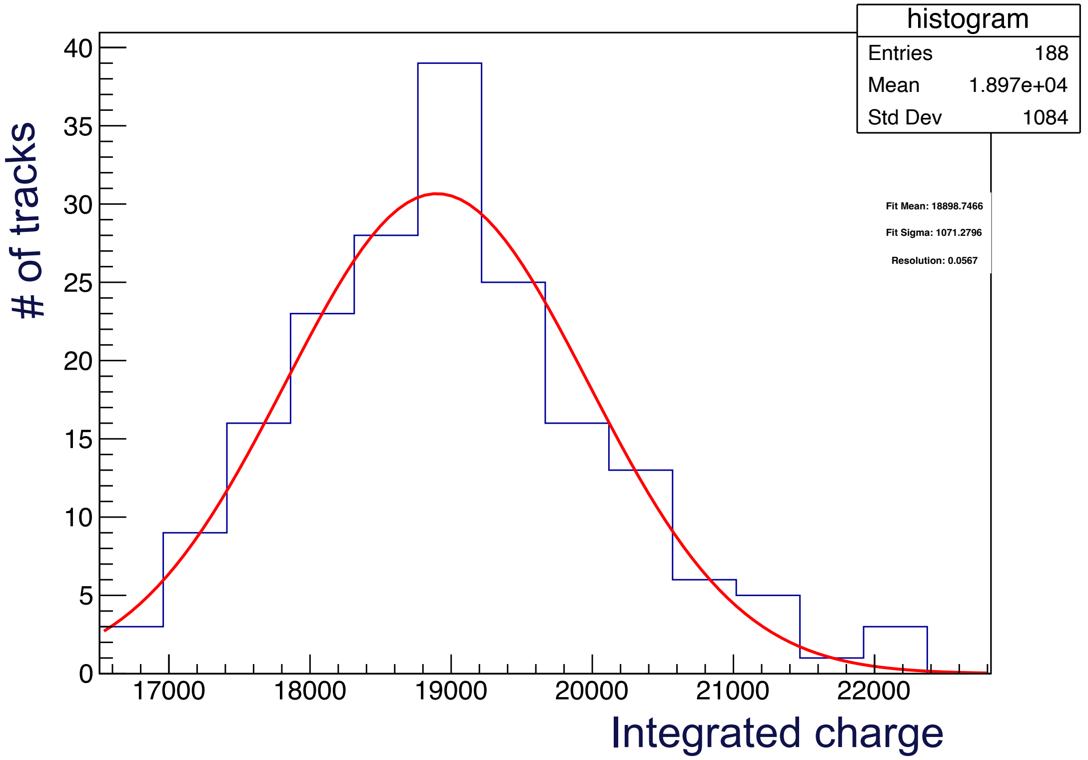
dE/dx resolution varies from 4.5% - 11% for 2 m track length relying on the accepted fraction of the charges.

@2m long track we have dE/dx resolution 5.7%

Resolution study

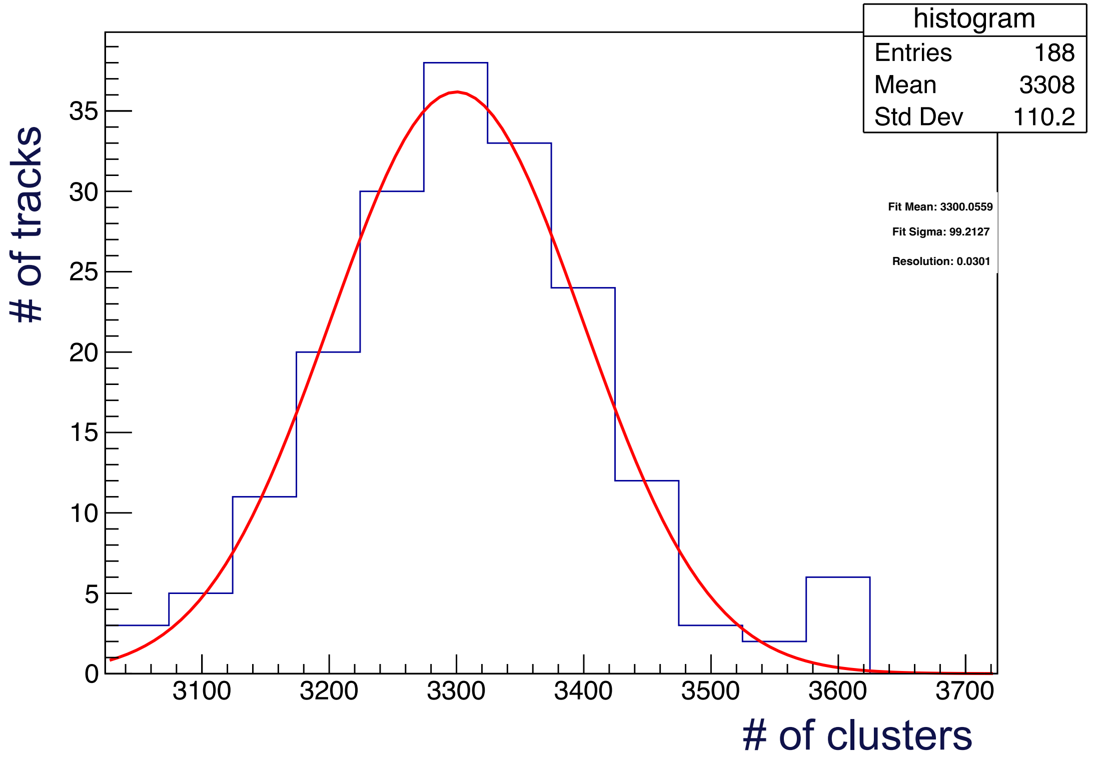
Study done using same tracks (2 m track length) made of the same hits.

dE/dx Resolution (remove 20% higher charges)



@2m long track we have dE/dx resolution 5.7%

dN/dx Resolution



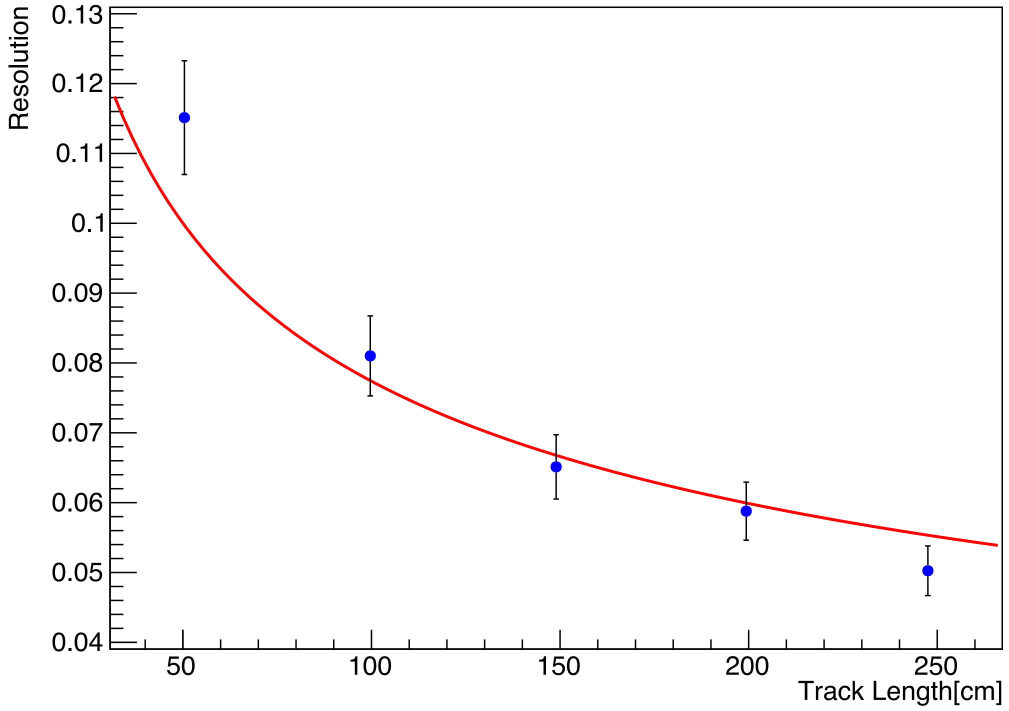
@2m long track we have dN/dx resolution 3%

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

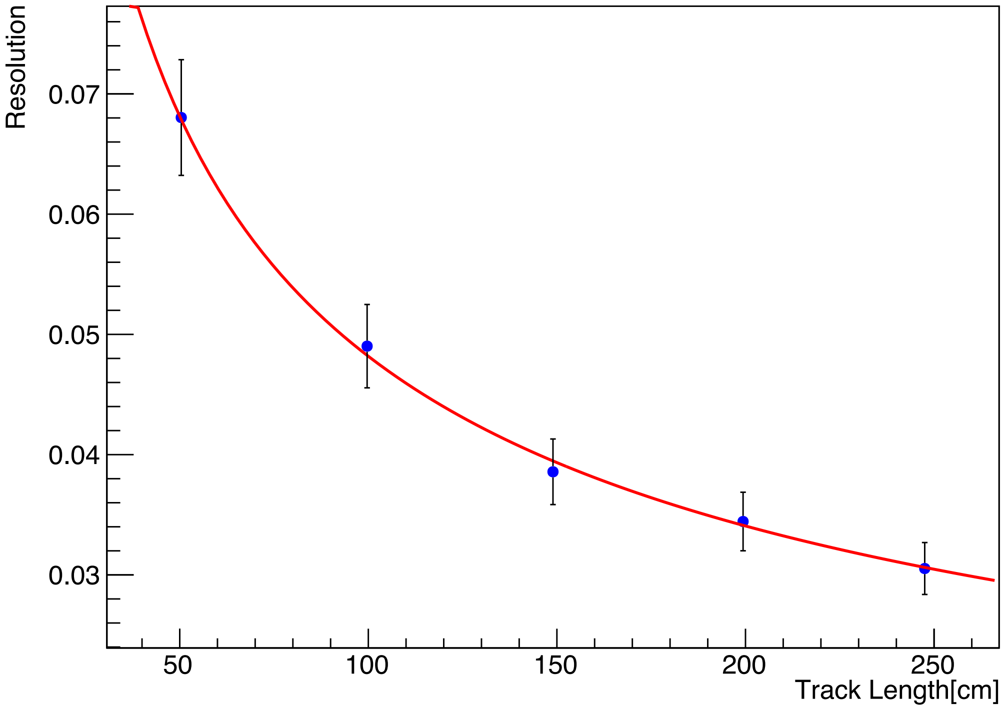
Resolution study

2m tracks length

dE/dx Resolution



dN/dx Resolution



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

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

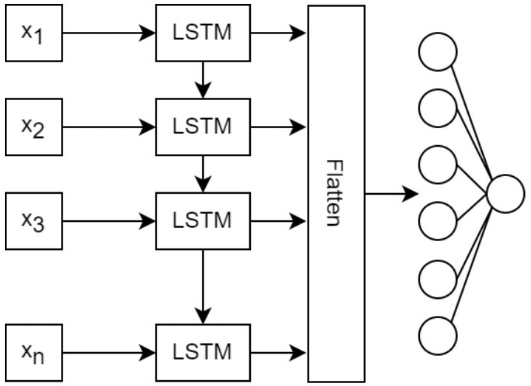
~ **2 times** improvement in the resolution using dN/dx method

Peak finding algorithm with LSTM

The algorithm is developed in IHEP, for more information see **this talk** by **Guang ZHAO.**

Peak finding with LSTM

Why LSTM? Waveforms are time series

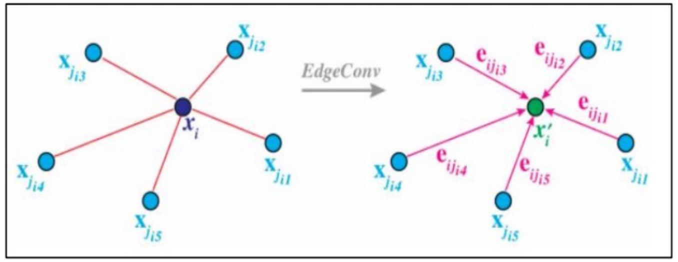


- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

LSTM: Long Short-Term Memory

Clusterization with DGCNN

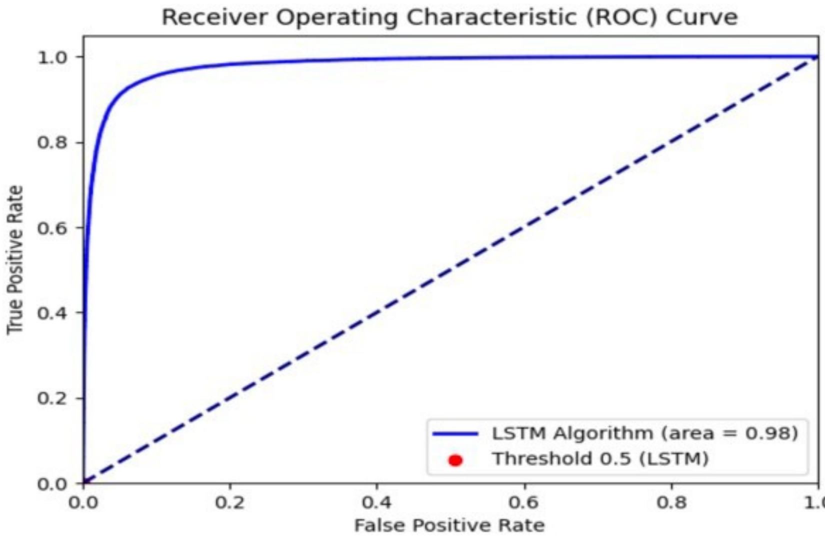
Why DGCNN? Locality of the electrons in the same primary cluster, perform message-passing through neighbour nodes in GNN.



arXiv: 1801.07829

- Architecture: DGCNN (GNN-based)
- Method: Binary classification of primary and secondary electrons

DGCNN: Dynamic Graph Convolutional neural networks



- First results produced by a PhD student from Bari Politecnico "**Muhammad Anwar**"
- Promising results obtained from the simulation.
- Plans to run the algorithm on the data of the test beam and make a direct comparison with the RTA & DERIV algorithm.

Summary

- Good progress reported on:
  - Mechanical structure design
  - on going effort to build a **full-length prototype**.
- The cluster counting technique is a high powerful method to improve the particle identification capabilities: analytic evaluation and simulation confirm its potentials.
- Using the test beam data we evaluated the performance of our algorithms across various conditions: gas mixture, gain, geometrical configuration (cell size, sense wires size), sampling rate, HV, and track angle .
- Using **dN/dx method gives a resolution 2 times better than the dE/dx method** in agreement with the analytical calculation.

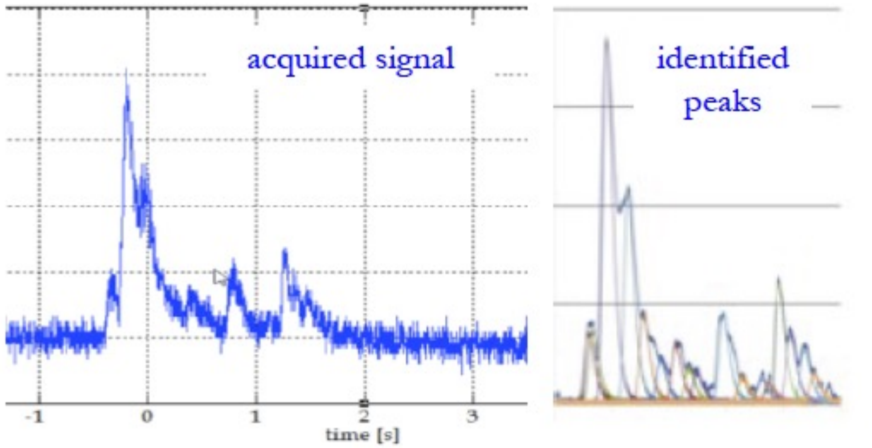
Stay tuned for the new results from 2024 test beam on the relativistic rise region!

Backup

FUTURE CIRCULAR COLLIDER

Cluster Counting/Timing and P.Id. expected performance

From the ordered sequence of the electrons arrival times, considering the average time separation between clusters and their time spread due to diffusion, reconstruct the most probable sequence of clusters drift times: $\{t_i^{cl}\}$ $\quad i = 1, N_{cl}$



dE/dx

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

from *Walenta parameterization (1980)*

truncated mean cut (70-80%) reduces the amount of collected information n = 112 and a 2m track at 1 atm give

$\sigma \approx 4.3\%$

Increasing P to 2 atm improves resolution by 20% ($\sigma \approx 3.4\%$) but at a considerable cost of multiple scattering contribution to momentum and angular resolutions.

dN_{cl}/dx

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

from *Poisson distribution*

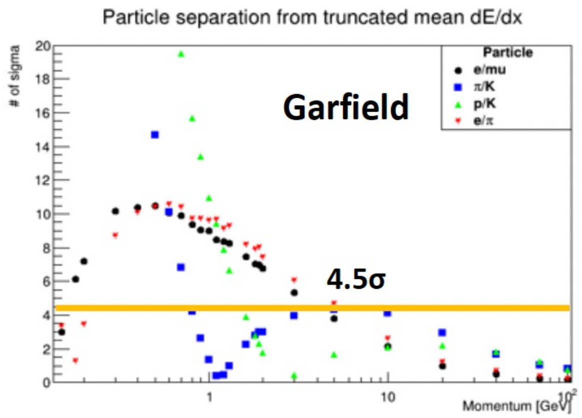
δ_{cl} = 12.5/cm for He/iC_4H_{10}=90/10 and a 2m track give

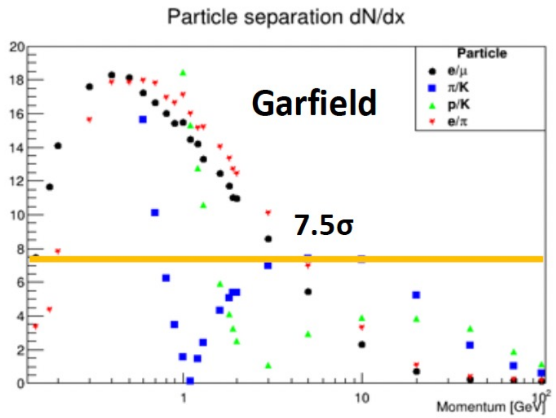
$\sigma \approx 2.0\%$

A small increment of iC_4H_{10} from 10% to 20% (δ_{cl} = 20/cm) improves resolution by 20% ($\sigma \approx 1.6\%$) at only a reasonable cost of multiple scattering contribution to momentum and angular resolutions.

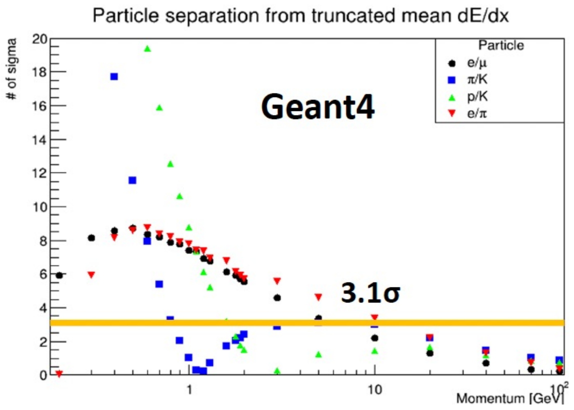
The simulation of the cluster counting

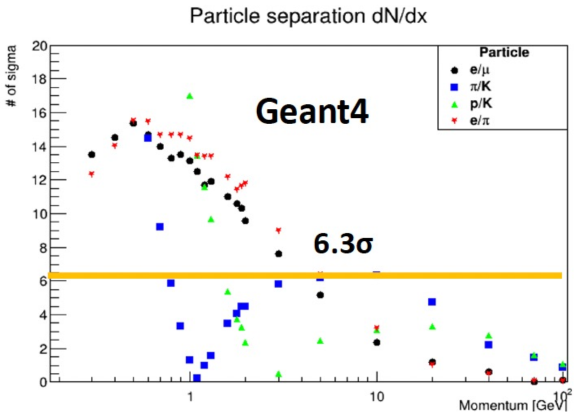
- We have developed an algorithm, which uses the energy deposit information provided by Geant4, to reproduce, in a fast and convenient way, the clusters density and the cluster size distributions predicted by Garfield++.





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



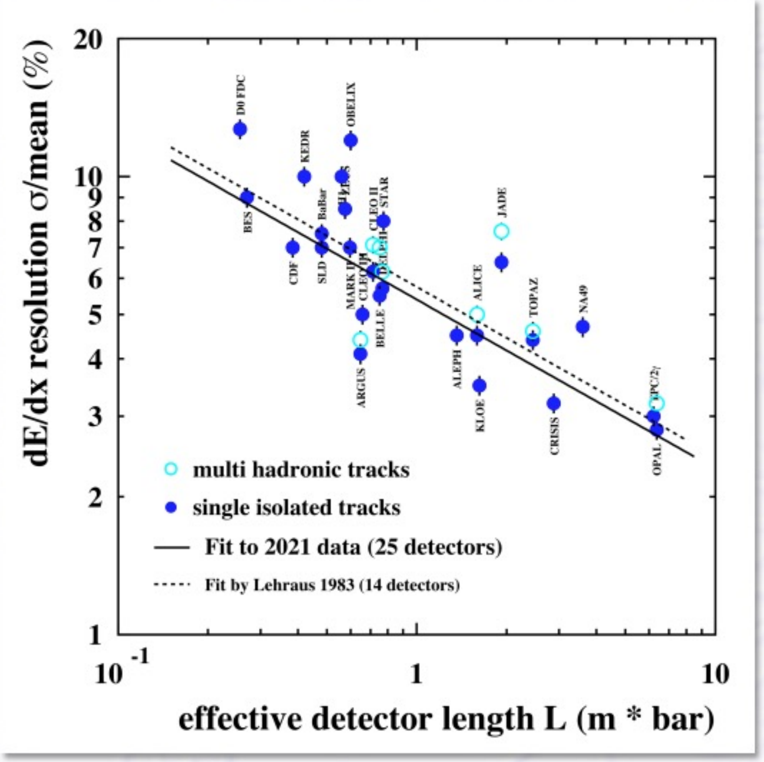


Despite Geant4 uses the cluster density and the cluster size distributions from Garfield++, it disagrees from Garfield++ and, therefore, from the analytical calculations also.

Cluster Counting/Timing and P.Id. expected performance

"Lehraus" Plot 2021

- dE/dx resolution achieved in large detectors, mainly at e^+e^- colliders, at some hadron colliders and fixed target expts.



- Fit by *Lehraus* 1983:

  dE/dx res. = $5.7 * L^{-0.37}$ (%)

- Fit in 2021 (25 large detectors):

  dE/dx res. = $5.4 * L^{-0.37}$ (%)

  - 5.4% typical dE/dx resolution for 1 m track length
  - no significant change to 1983
  - performance of present generation of detectors as predicted ~40 years ago

RD51 Workshop on Gaseous Detector Contributions to PID – 17 February 2021 Michael Hauschild - CERN, page 18