Progress and Developments on the IDEA Drift Chamber

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On behalf of the IDEA DCH community

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eurizon
European network
for developing new horizons for RIs

The IDEA detector at the e^+e^- colliders

IDEA → Innovative Detector for Electron-positron Accelerators (more details in the F. Bedeschi's talk in this Workshop):

Vertex:
- 5 Monolitic silicon pixel (MAPS) layers
- R=1.2 – 34 cm

Drift chamber:
- **4 m long, R = 35-200 cm**
- **He-iC_4H_{10} gas mixture**
- **All stereo wires**
- **PId with Cluster counting technique**

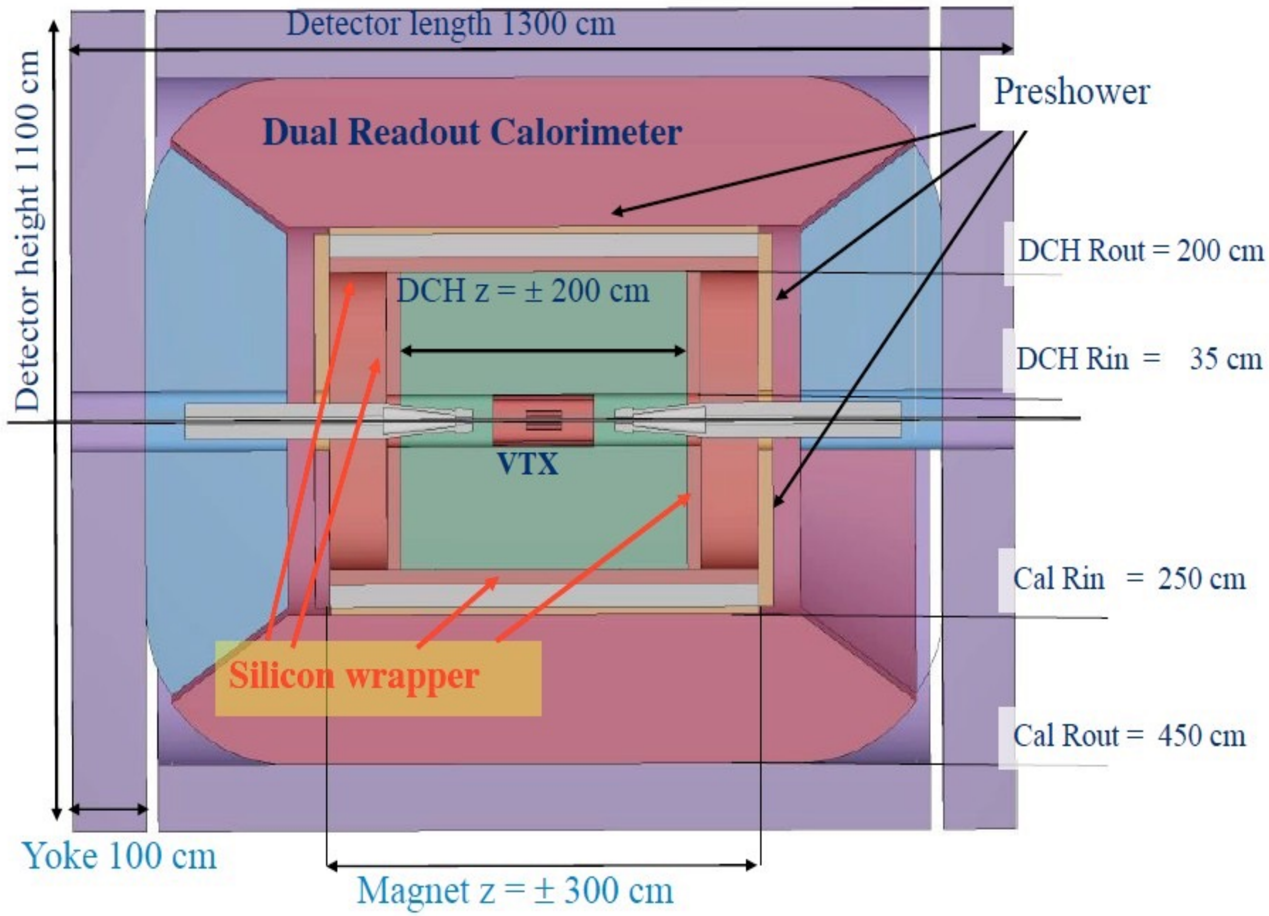
Si Wrapper:
- 2 layers of μ-strips in both barrel and forward regions

Superconducting solenoid:
- 5 m long, R = 2.1-2.4, 2T B field
- Thin low-mass → 0.74 X_0, 0.16 λ @ 90º

Pre-shower:
- 2 layers of μ-Rwell

Calorimetry :
- Dual readout calorimeter 2m deep/8 λ

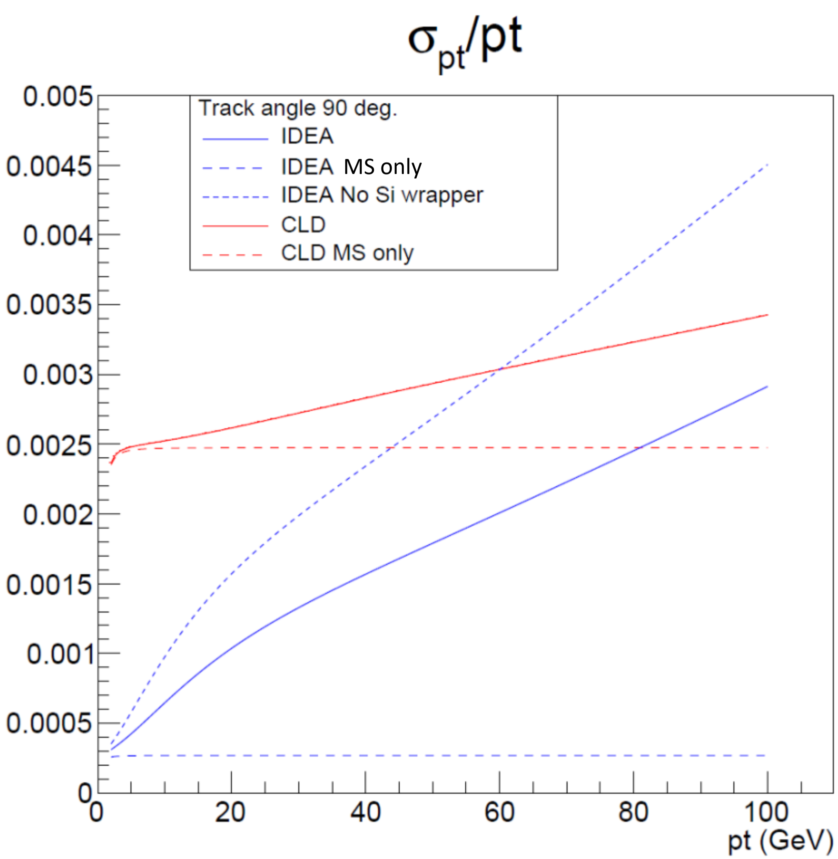
Muon chambers:
- 3 μ-Rwell stations embedded in the magnet return yoke

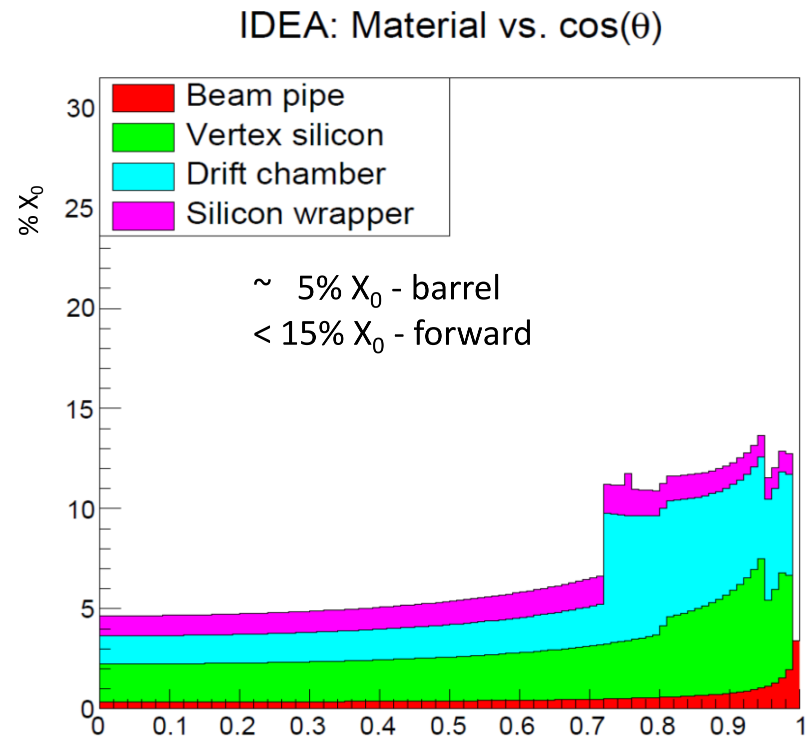


Main features of DCH design

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*
- *Cluster counting technique*





Particle momentum range far from the asymptotic limit where MS is negligible

$$\frac{\Delta p_T}{p_T}\Big|_{res.} \approx \frac{12\,\sigma_{r\phi}\,p_T}{0.3\,B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

Drasal, Riegler,
https://doi.org/10.1016/j.nima.2018.08.078

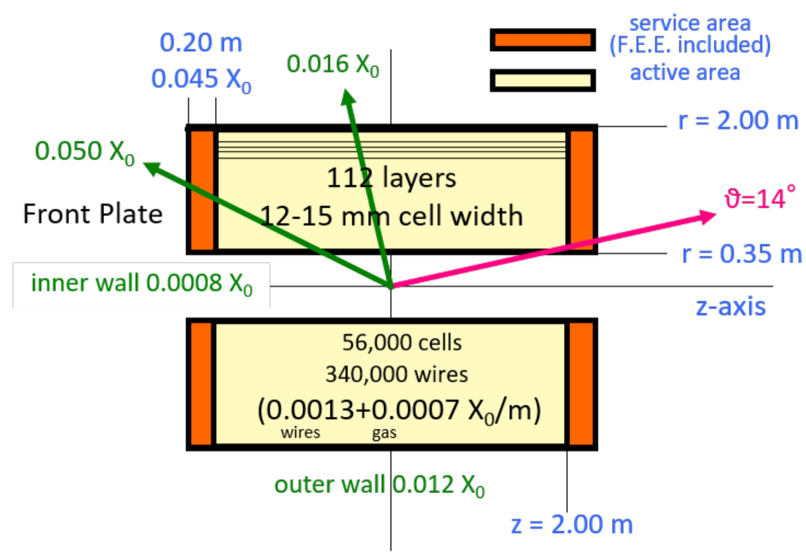
The IDEA DCH

- Large volume: R_{in} = 0.35 m, R_{out} = 2 m, L = 4 m, Inner wall = 200 μm thick Carbon fiber, Outer wall = 2cm thick composite material sandwich
- Operating gas: He 90% - iC_4H_{10} 10%
- Full stereo: 112 co-axial layers, arranged in 24 (15°) identical azimuthal sectors, at alternating-sign stereo angles ranging from 50 to 250 mrad
- Granularity: 12÷14.5 mm (at z=0) wide square cells, 5 : 1 field to sense wires ratio
- drift length ~1 cm, drift time ~350-400 ns
- Expected resolution σ_{xy} < 100 μm, σ_z < 1 mm
- **56,448 cells and** 343968 wires in total:

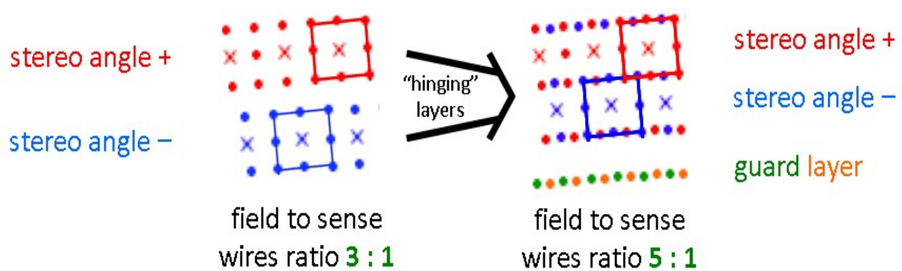
sense wires → 20 μm diameter W(Au) => 56448 wires
(**thin!!**) field wires → 40 μm diameter Al(Ag) => 229056 wires
Field between sense and guard wires → 50 μm diameter Al(Ag) => 58464 wires

tracking efficiency ε ≈ 1 for ϑ > 14° (260 mrad)
97% solid angle

0.016 X_0 to barrel calorimeter
0.050 X_0 to end-cap calorimeter

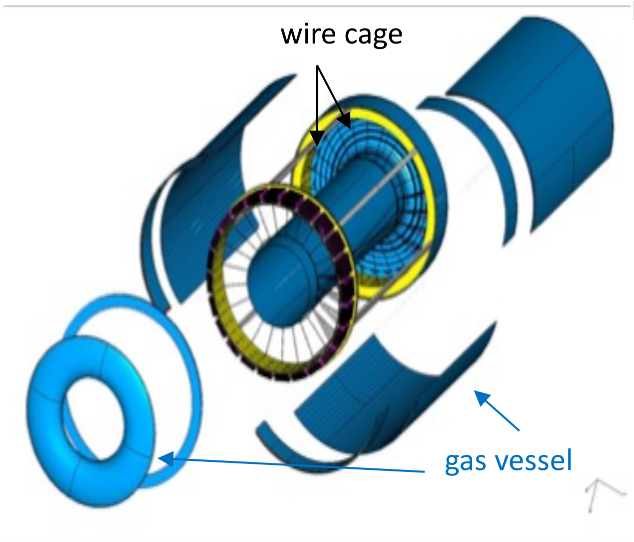


combination of + and –wire orientation produces a more uniform equipotential surface → better E-field isotropy and smaller E×B asymmetries)



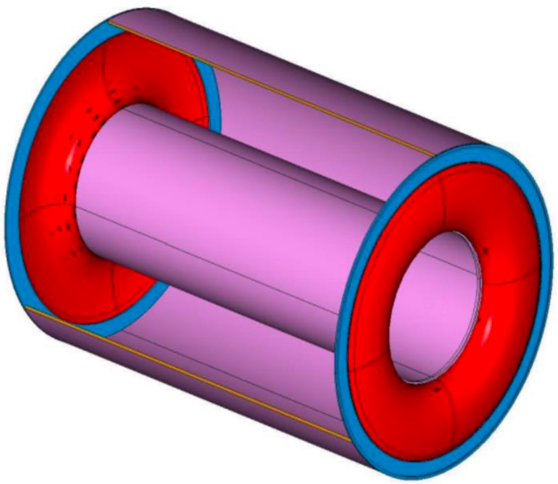
IDEA DCH: mechanical structure/1

Thin wires+separation gas envelope/wire supporting structure ("feed-through-less") → increase chamber granularity but reducing material, multiple scattering and total tension on end plates



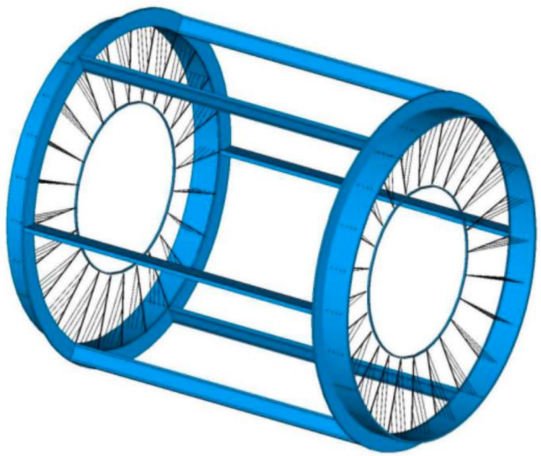
Gas containment

Gas vessel can freely deform → no impact on the internal wire position and mechanical tension.



Wire cage

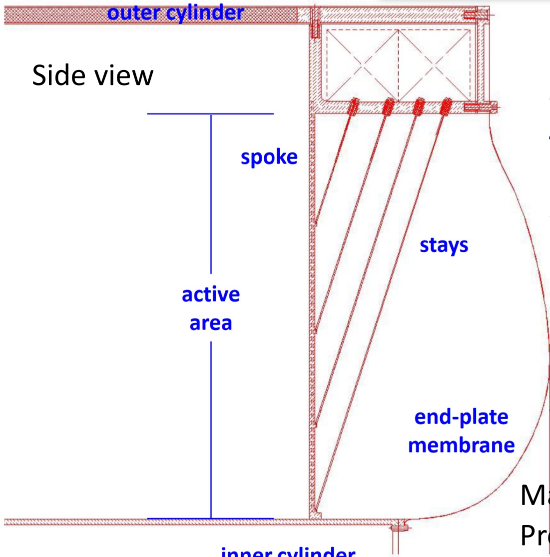
Wire support structure not subject to differential pressure can be light and feed-through-less



Challenges:

- the accuracy of the position has to be in the range of 100-200 µm
- the position of the anodic wire in space must be known with an accuracy better than 50µm at most
- the anodic and cathodic wires should be parallel in space to preserve the uniformity of the electric field
- a 20µm tungsten wire, 4m long, will bow about 400 µm at its middle point, if tensioned with a load of approximately 30gr → 30gr tension for each wire → 10 tons of total load on the endcap

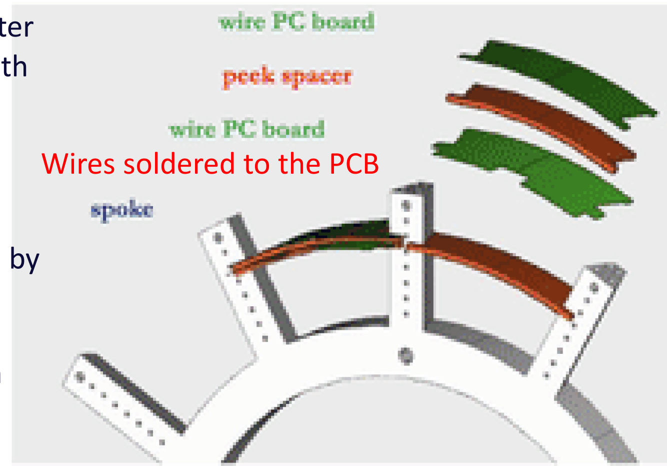
IDEA DCH: mechanical structure/2



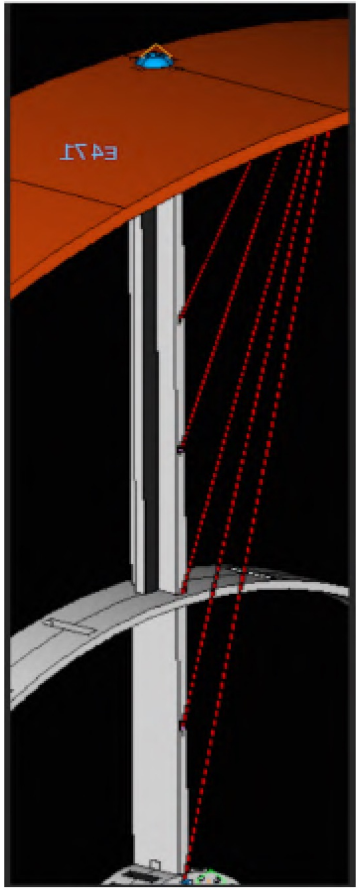
Inner cylinder and Outer cylinder connected with 48 Spokes (24 per Each side) forming 24 azimuthal sectors.

Each spoke supported by 15 Cables/Stays.

Spoke length = 160cm



Material: Epoxy Carbon Prepeg for cylinders and spokes, Structural steel for the cables.



FEM Parametric Design exploration → varying input parameters in some possible ranges in order to see how the system responds - Response Surface Methodology (RSM) is used.

The input parametric variables are:

1. Height and thickness of the outer (cage) cylinder;
2. Dimensions (breadth and depth) of the spokes;
3. Dimensions (radius) of the cables;
4. Thickness of the inner (cage) cylinder.

Parameters:	
Height:	200 mm
Innerthickness:	10 mm
Outerthickness:	14.4 mm
Rectangle_B:	9.6 mm
Rectangle_H:	16.6 mm
Circle_R:	1.5 mm

Total deformation along the chamber axis of the model

If no optimization of the spoke cross section, and no prestressing force in the cables

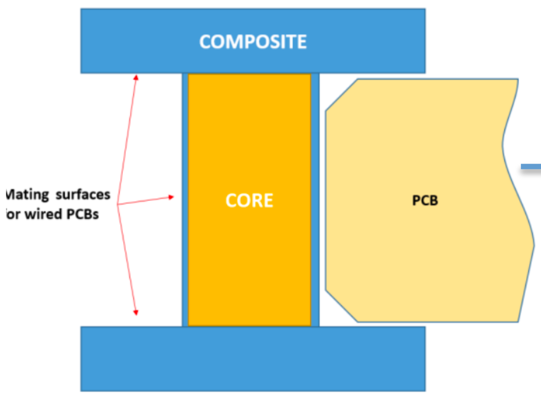
Responses:	
Maximum_Deformation:	22.995 mm (Linear Analysis)
Maximum_Deformation:	21.643 mm(Non-Linear Analysis)
Total_Mass:	2.6269 kg per sector
Total_Deformation_Load_Multiplier:	2.2068

IDEA DCH: mechanical structure/3

- FEM analysis: single endcap simulation → Spokes and cables behaviour under wires pressure

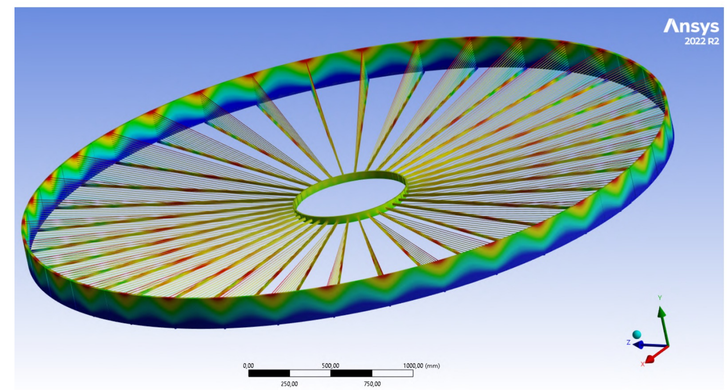
- Goals: minimizing the deformation of the spokes using prestressing force in the cables

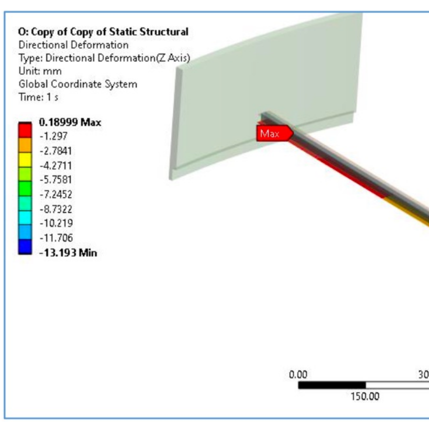
Finding the correct prestressing force in 15 cables → solving 15 dimensional optimization problem
Limit the deformation of the spokes to **200 μm** while ensuring the structural integrity
→ few μm error on the sagitta



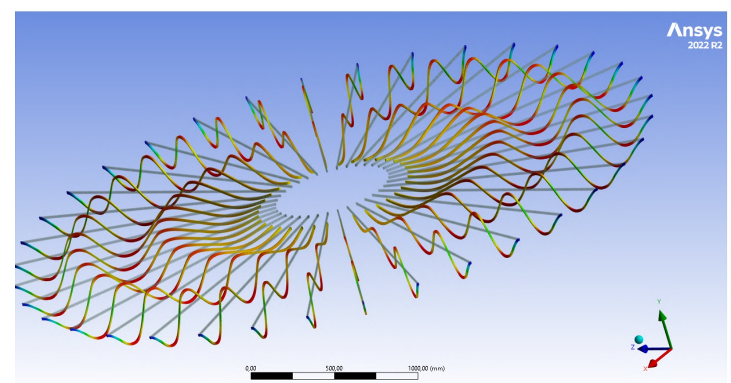
ENGINSOFT

"optimized" layout of the spoke + prestressing force

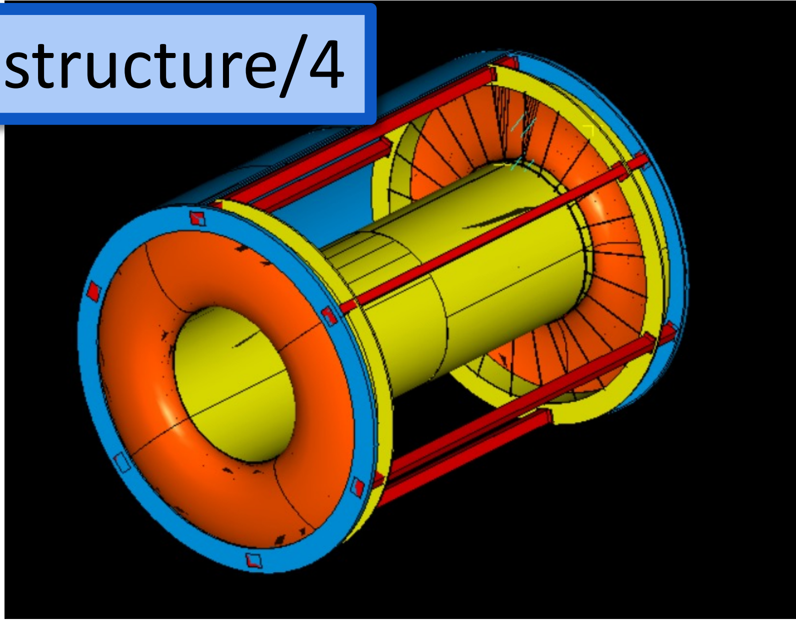




Max deformation along the chamber axis ~ 190 μm



IDEA DCH: mechanical structure/4



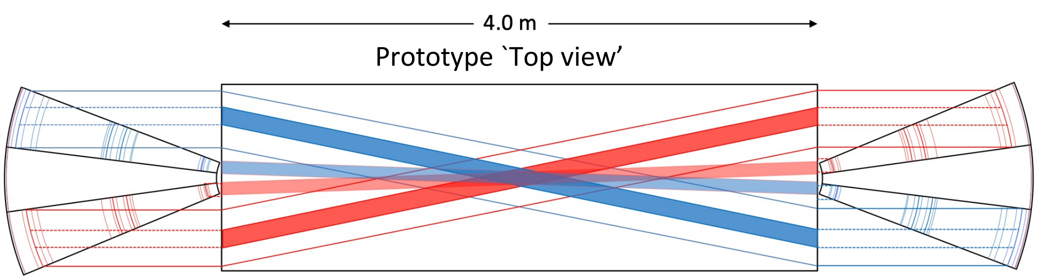
A complete, mechanically accurate model definition ongoing (ENGINSOFT), with:

- location of the necessary spacers
- definition of the connections of:
  - cables on the structure
  - wires on the PCB
  - wire cage and gas containment structure

Design and construction of the mold for the spokes and the inner ring are now starting, with the model as input (CETMA)

Aiming to realize a DCH prototype full lenght:

- to check electrostatic stability
- to test materials (wires, spokes,…), techniques (soldering, glueing, …), front-end, digitization, etc.
- Enough layers to be effective, but limit # of wires and complexity
- Close to the most updated design



Minimum stereo angle	50 mrad
Maximum stereo angle:	250 mrad

Cell size 1.2 - 1.4 cm

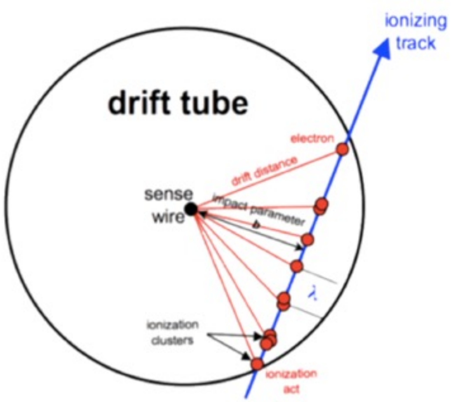
TOTAL LAYERS: 10
Sense wires: 168
Field wires: 965
Guard wires: 264

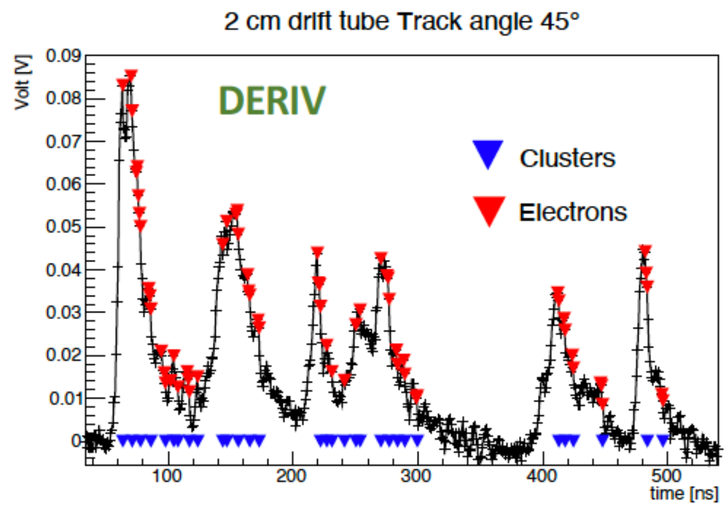
PCBoards wire layers: 42
Sense wire boards: 8
Field wire boards: 22
Guard wire boards: 12

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

IDEA DCH: Particle Identification/1

- He based gas mixtures → signals from ionization acts are spread in time to few ns
- Fast read-out electronics (~GHz sampling) → efficiently identify them
- Counting dN_{cl}/dx (# of ionization acts per unit length) → make possible to identify particles (P.Id.) with a better resolution than dE/dx





- Collect signal and identify peaks
- record the arrival time of the clusters generated in every ionisation act (≈12cm^{-1})
- reconstruct the trajectory at the most likely position

dE/dx

- Requires high stability on HV and gas parameters and electronics calibration
- truncated mean cut (70-80%) reduces the amount of information. For n = 112 and a 2m track at 1 atm → **σ ≈ 4.3%**

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

Empirical parametrization

P. Reak and A.H. Walenta, IEEE Trans. Nucl. Sci. NS-27 (1980) 54

dN_{cl}/dx

- Requires fast electronics and sophisticated counting algorithms
- Less dependent on gain stability issues
- δ_{cl} = 12./cm for He/iC_4H_{10}=90/10 and a 2m track → **σ ≈ 2.0%**

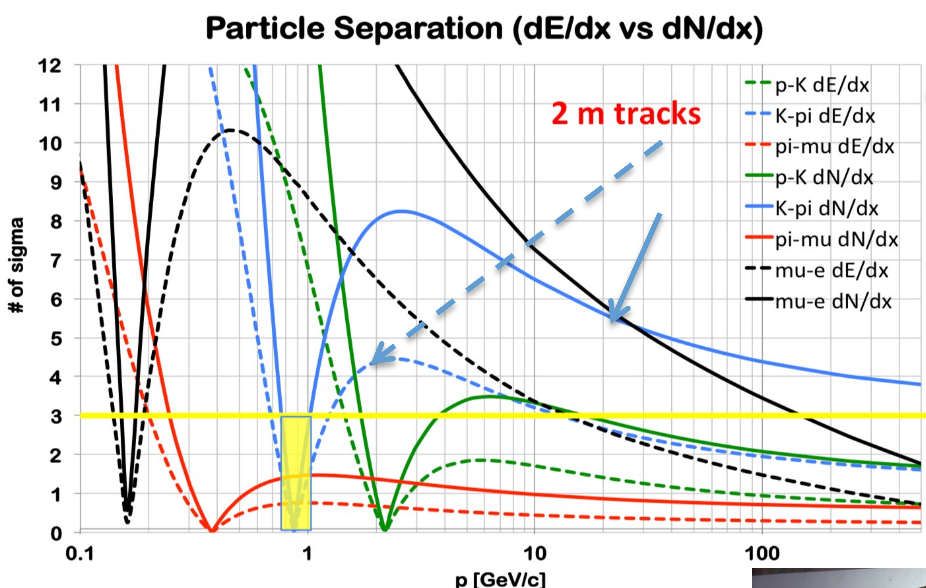
$$\frac{\sigma_{dN_{cl}/dx}}{(dN_{cl}/dx)} = \left(\delta_{cl} \cdot L_{track}\right)^{-1/2} = N_{cl}^{-1/2}$$

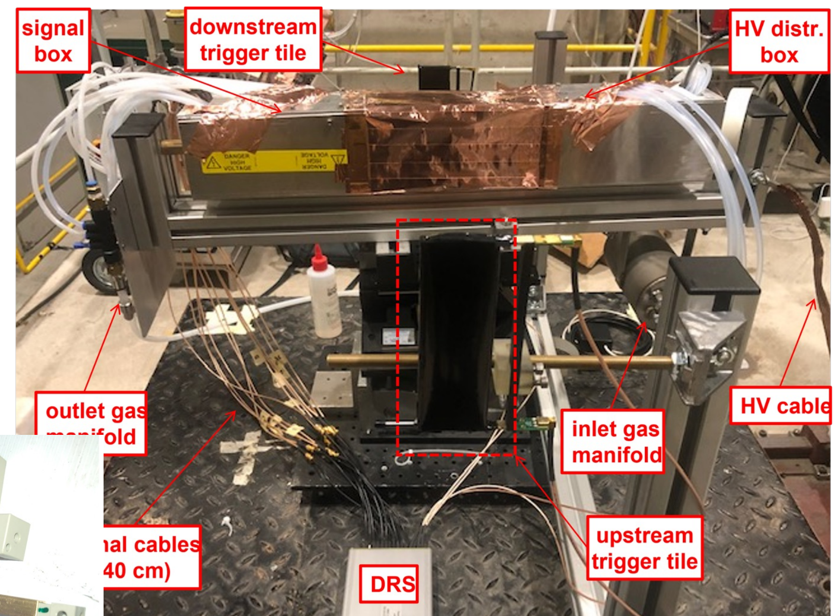
Poisson

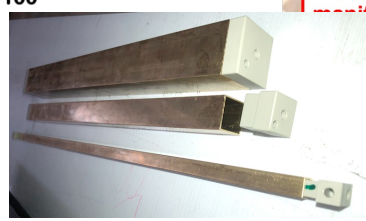
IDEA DCH: Particle Identification/2

- Analytical calculations → predict excellent K/π separation over the full range of momenta except 0.85<p<1.05 GeV

Analitic calculations:
He/iC_4H_{10} 90/10 δ_{cl}=12 cm^{-1}
$\sigma(dE/dx)/(dE/dx)$ =4.3%
80% cluster counting efficiency





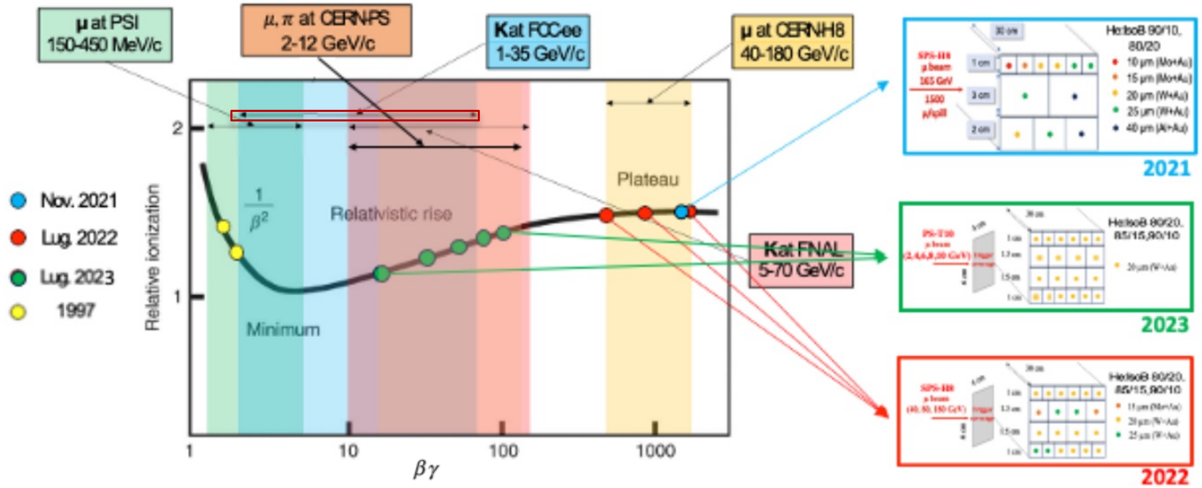


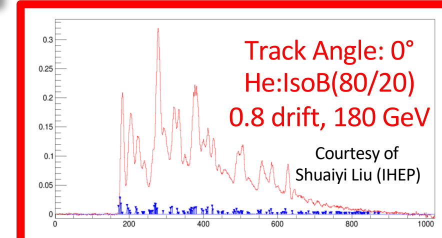
Simulation with Garfield++ and with the Garfield model ported in GEANT4:

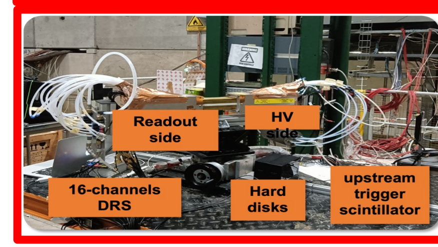
- the particle separation, both with dE/dx and with dN_{cl}/dx, in GEANT4 found considerably worse than in Garfield
- the dN_{cl}/dx Fermi plateau with respect to dE/dx is reached at lower values of $\beta\gamma$ with a steeper slope
- Results on real data from beam tests are crucial

- Two **muon beam tests** performed at **CERN-H8 ($\beta\gamma$ > 400)** in Nov. 2021 and July 2022.
- A **muon beam test** (from 4 to 12 GeV momentum) in 2023 performed at **CERN PS**
- test at **FNAL-MT6** with **π** and **K ($\beta\gamma$ = 10–140)** could be important to fully exploit the relativitic rise.

IDEA DCH: Particle Identification/3



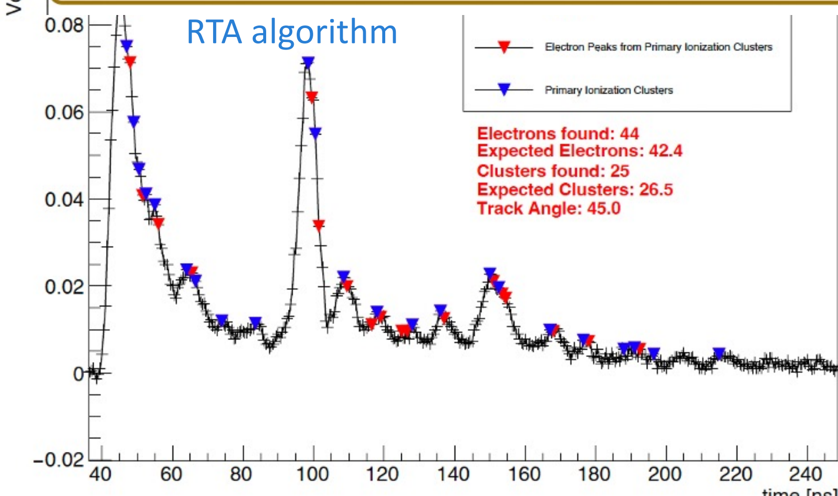


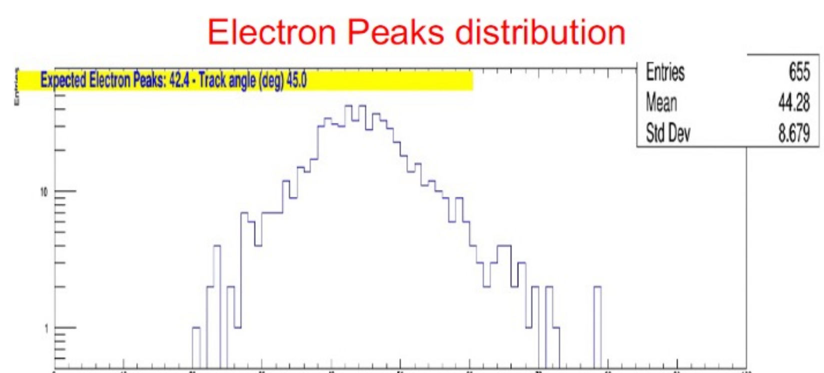


- Different **electron peak finding** algorithms used in analizing 2021/2022 data
  - First and Second Derivative (DERIV)
  - Running Template Algorithm (RTA)
  - RNN-based Machine Learning Algorithm (developed at IHEP)

Result compatible within errors

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





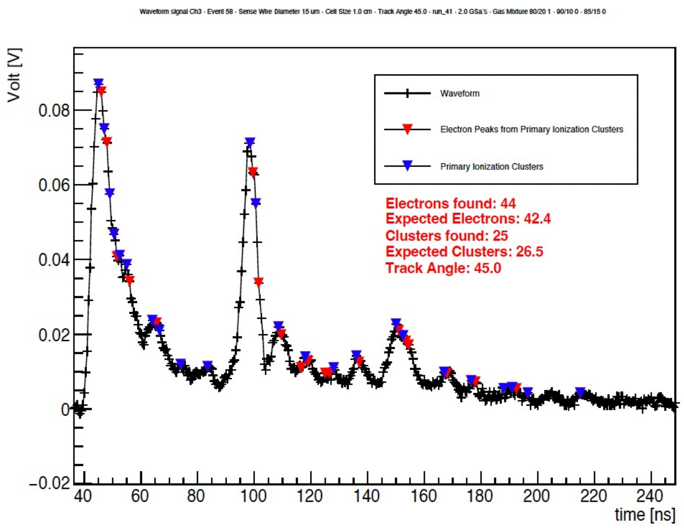
Expected number of electron =
δ cluster/cm (M.I.P.) * drift tube size [cm] * 1.3 (relativistic rise)* 1.6 electrons/cluster * 1/cos(α)

IDEA DCH: Particle Identification/4

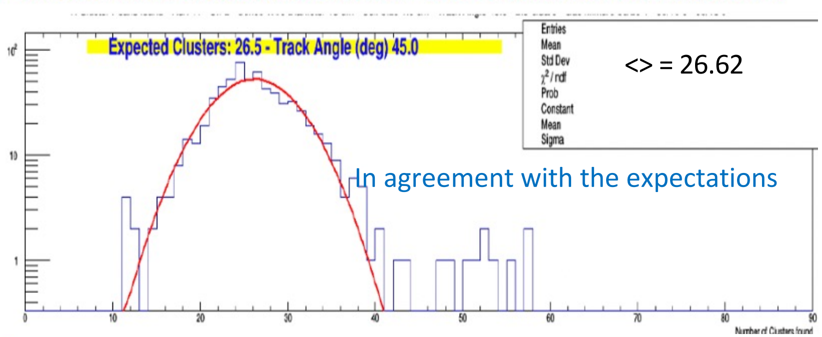
- **Clusterization (merging electron peaks)** in 2021/2022 data

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

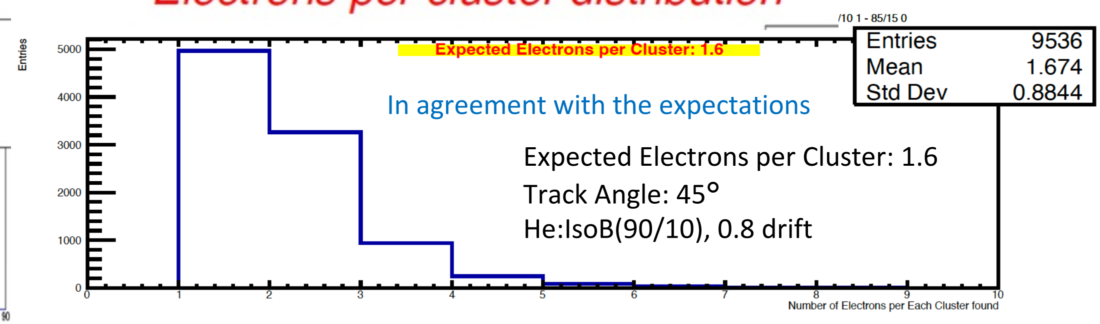
- ***Merging of electron peaks*** *in consecutive bins in a single electron to reduce fake electrons counting.*
- ***Contiguous electrons peaks*** *which are compatible with the electrons' diffusion time (it has a* $\sim\sqrt{t_{ElectronPeak}}$ *dependence, different for each gas mixture) must be considered 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!***



Poissonian distribution for the number of clusters



Electrons per cluster distribution



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

E-field suppression due to space charge effects + attachment + recombination affect the cluster counting efficiency → corrections (depending on the drift length) applied

IDEA DCH: data reduction and signal pre-processing

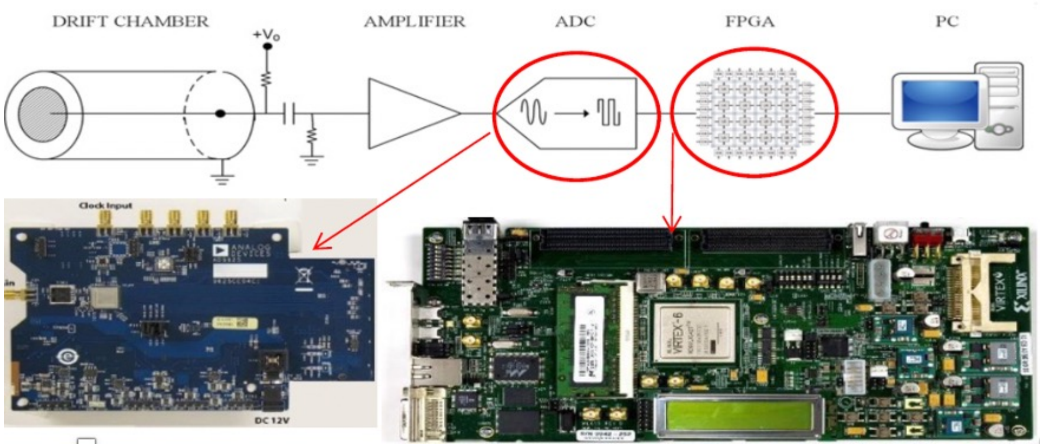
(further details in the F. Bedeschi's talk)

High speed digitization (2 GSa/s) for CC $\Rightarrow$ Transfer rate of TB/s

Data reduction strategy: transfer, for each hit drift cell, only the minimal information relevant to apply the **Cluster Counting/Timing (CCT) techniques**, i.e. the **amplitude** and the **arrival time of each peak** associated with **each individual ionisation electron** $\Rightarrow$ **CCT algorithms!**

Use of a **FPGA** for the **real-time data analysis** of drift chamber signals **digitized by an ADC.**

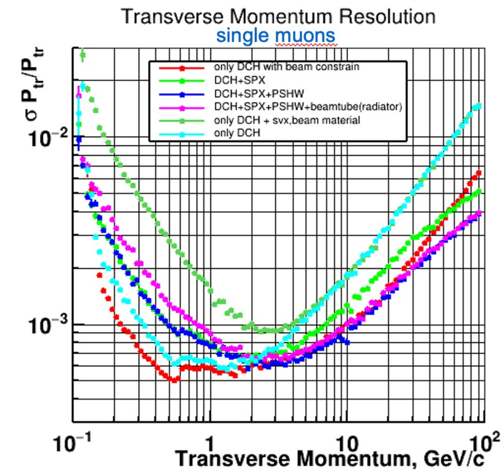
Goal: implement on a single FPGA more sophisticated peak finding algorithms for the parallel pre-processing of many ADC channels



- Completed bench tests with **ASoCv3 chip** (4 channels) from **NALU SCIENTIFIC**. Next step is to readout drift tube signals and to process them on-line.
- Received **NALU SCIENTIFIC HDSoC** (32 channels test board). Evaluation tests with drift tubes and cosmic rays are starting
- **CAEN** provided us the **VX2740** digitizer (a lower performance version of the **VX2751**, suitable for cluster counting) →becoming familiar with the **openFPGA SCICompiler** software
- Also exploiting the possibility of implementing the **CAEN FERS-5200** platform using the **Citiroc-1A** chip, with proper ASIC and digitizer, as a modular, scalable platform for the high readout density of a large volume drift chamber instrumented with cluster counting.

Moreover, needed to understand how to implement the data transfer to the DAQ via Optical fibers within the 10Gbit/s standard

IDEA DCH: simulation



Geant4 and DD4HEP simulations of the IDEA geometry are available:

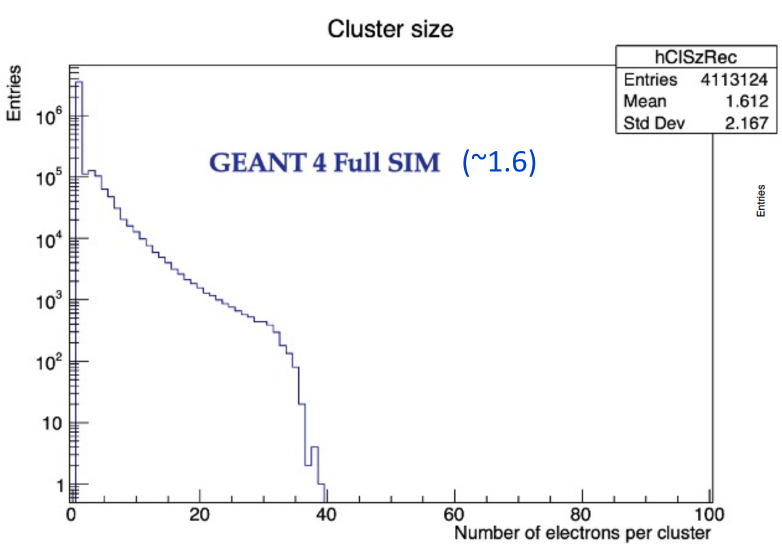
- The DCH is simulated at a good level of geometry details, including detailed description of the endcaps; hit and digi creation (while track reconstruction code available in Geant4)

$\sigma(p_t)/p_t$ (100 GeV) = 3×10^{-3}

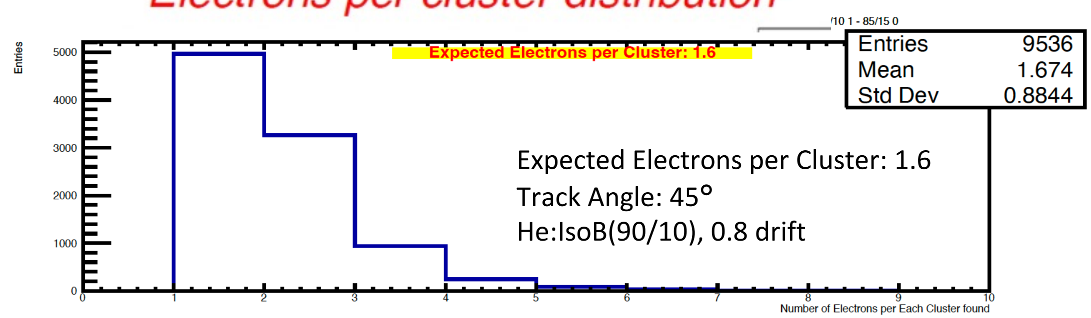
but new studies ongoing!

- Cluster Counting/Timing simulation:
  - ➢ Rather simple algorithm which use the energy deposit information provided by Geant4 to reproduce, in a fast way, the clusters number distribution and the cluster size distribution (starting from the cluster kinetic energy in Garfield++ simulations)
  - ➢ The algorithm has been implemented successfully in the IDEA full SIM (GEANT4 and Key4HEP)

Cluster size distribution, for a muon at 10 GeV



Electrons per cluster distribution



The results obtained form the **GEANT 4 Full Simulation framework** for the cluster population (~1.6) is in a good agreement with **Garfield++ expectation (~1.56)**, the results from the **test beam analysis(~1.7)**, and with the **analytic evaluations (~1.6)**.

Conclusion

Progress and developments on the IDEA DCH reported on:

- Mechanical structure → under definition (design, materials, component optimization)
- Cluster counting technique → under study on test beam data analysis (efficiency, electron peaks and cluster density as a function of gas mixture, gain, cell size, sense wire diameter, sampling rate, track angle)
- Data reduction and pre-processing → electronics components under test
- Simulation → geometry, performance, cluster counting

Thank you for your attention!

Backup slides

Challenges

- Extremely high luminosities:
  large statistics (high statistical precision) - control of systematics (@10^{-5} level)
- Large beam crossing angle (30mrad)
  very complex MDI
  emittance blow-up with detector solenoid field (< 2T)
- Physics event rates up to 100 kHz (at Z pole)
  strong requirements on sub-detectors and DAQ systems
- Bunch spacing down to 20 ns (at Z pole)
  "continuous" beams (no power pulsing)
- More physics challenges at Z pole:
  - luminosity measurement at 10^{-5} - luminometer acceptance ≈1-2 μm
  - detector acceptance definition at <10^{-5} - detector hermeticity (no cracks!)
  - stability of momentum measurement - stability of magnetic field wrt E_{cm} (10^{-6})
  - b/c/g jets separation - flavor and τ physics - vertex detector precision
  - particle identification (preserving hermeticity) - flavor physics (and rare processes)

- The maximum drift time (400ns) will impose an overlap of some (20 at Z pole) bunch crossings bringing the hit occupancy to ~ 10% in the inner-most drift cells. Based on MEG-II experience, this occupancy, which allows over 100 hits to be recorded per track on average in the DCH, is deemed manageable.

- However, signals from photons can be effectively suppressed at the data acquisition level by requiring that at least three ionization clusters appear within a time window of 50 ns.

- In addition, cluster signals separated by more than 100 ns are not from the same signals, this effectively bring the BXs pile-up from 20 to 4

Tracking at future e^+e^- colliders

High Lumi e^+e^- colliders:

- EW factories (3×10^{12} $e^+e^- \rightarrow Z$, 10^8 $e^+e^- \rightarrow W^+W^-$)
- $t\bar{t}$ and Higgs boson factories (10^6 $e^+e^- \rightarrow t\bar{t}$, 10^6 $e^+e^- \rightarrow HZ$)
- flavor factories (5×10^{12} $e^+e^- \rightarrow b\bar{b}$, $c\bar{c}$, 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$)

FCC-ee parameters		Z	W^+W^-	ZH	ttbar
$\sqrt{s}$	GeV	91.2	160	240	350-365
Luminosity / IP	10^{34} cm^{-2} s^{-1}	230	28	8.5	1.7
Bunch spacing	ns	19.6	163	994	3000
"Physics" cross section	pb	35,000	10	0.2	0.5
Total cross section (Z)	pb	40,000	30	10	8
Event rate	Hz	92,000	8.4	1	0.1
"Pile up" parameter [μ]	10^{-6}	1,800	1	1	1

Physics rates up to 100 kHz (at Z pole,challenging)→ fast detectors and FE electronic and DAQ

Tracker:

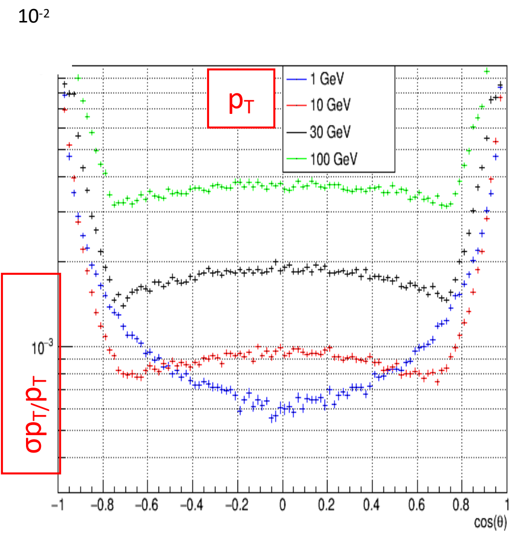
- High momentum ($\delta p/p^2 \leq$ few x 10^{-5}) and angular resolution $\Delta\vartheta \leq 0.1$ mrad (to monitor beam spread) for charged particle momenta ranging at the Z pole from a few hundred MeV/c to several tens of GeV/c
- Large angular coverage
- Large tracking radius to recover momentum resolution since magnetic field is limited to ~ 2 T to contain the vertical emittance at Z pole
- High transparency due to the low momentum particles from Z, H decays → Multiple Scattering (MS) contribution to the resolution is not negligible!
- Particle identification to distinguish identical topology final states → flavour and τ physics, rare processes

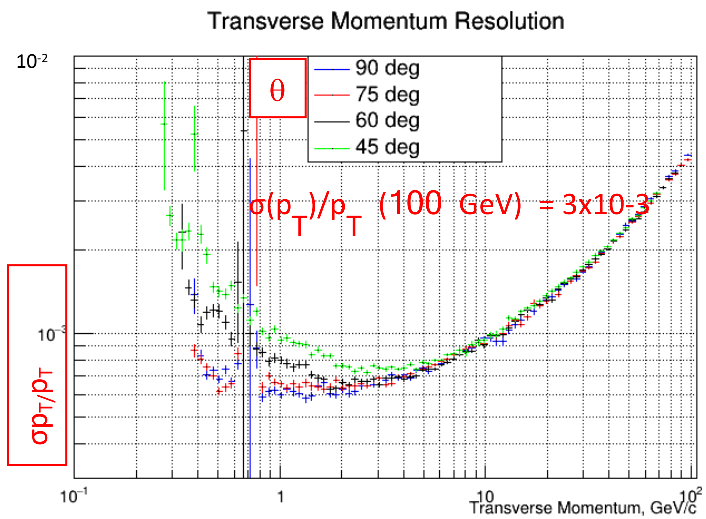
Vertexing:

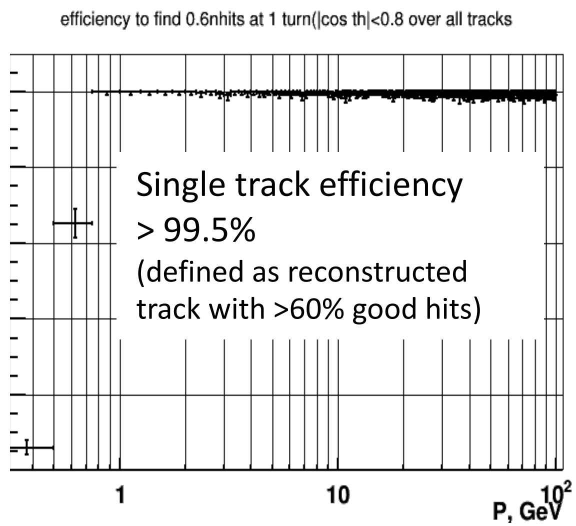
- Few μm track impact parameter resolution
- High transparency

IDEA drift chamber: expected tracking performance

- Full Geant4 standalone simulation of the IDEA tracking system →drift chamber simulated at a good level of geometry details
- Vertex detector and Si wrapper included in the track fit taking into account material contributions
- A preliminary Vertex detector and Drift Chamber description implemented inside the FCC-sw



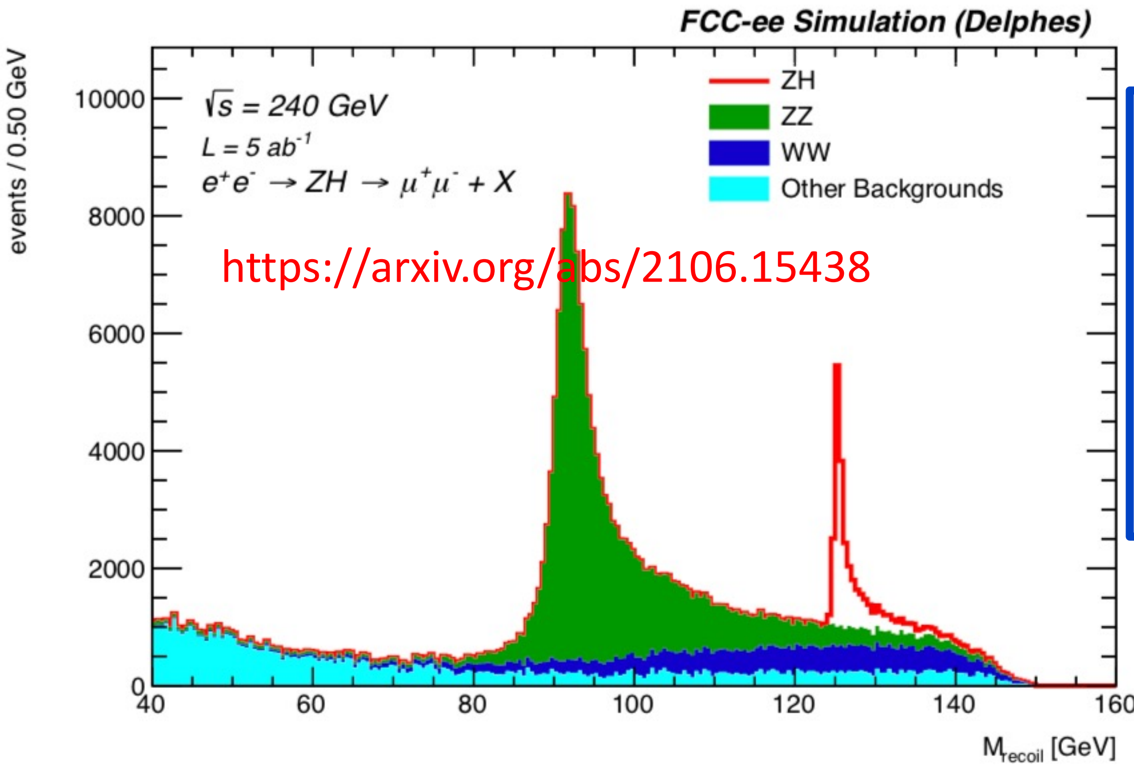




single muons, p_T resolutions as function of ϑ and p_T assuming σ_d = 100 µm and (conservative for Si) σ_{Si} = pitch/√12 µm

IDEA drift chamber: expected performance on physics events

- IDEA Fast simulation (Delphes) → Parameterized response of the detector + covariance matrix description for tracks



Z recoil mass

Z → μμ final state

Nominal Higgs mass → 125 GeV

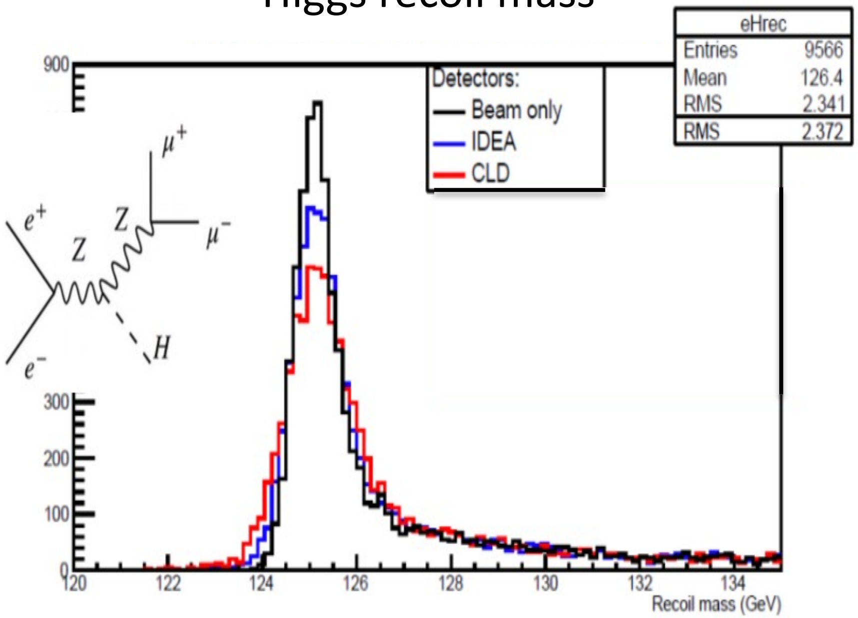
Events with

- $15 < p_T(\mu\mu) < 70$ GeV
- $|M_{\mu\mu} - M_Z| < 20$ GeV

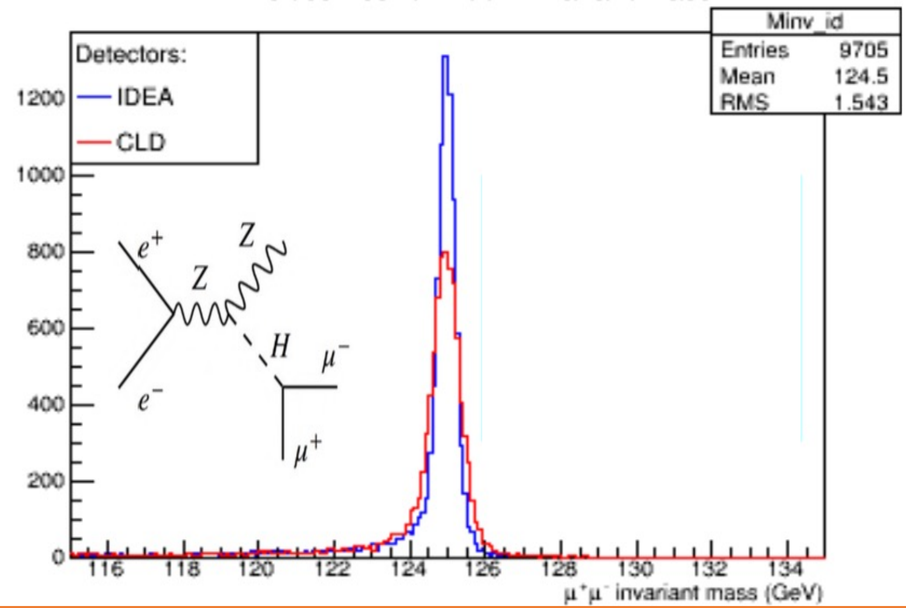
DCH muon momentum resolution (in clean events) → 1% stat. unc. on inclusive σ_{ZH}
→ ~6MeV on m_H

Expected performance: compare IDEA and CLD

Higgs recoil mass



Di-muon invariant mass



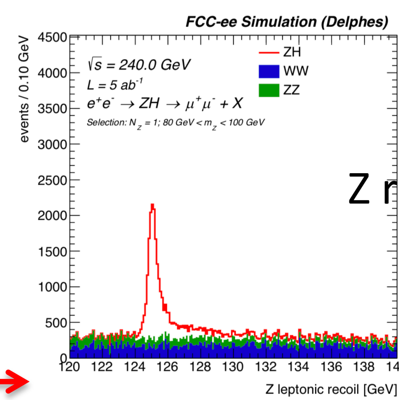
Beam only→ assumes 0.136% beam spread and an ideal detector
IDEA → Fast simulation studies
CLD → full Si-tracker system

Transparency ensures a better resolution!

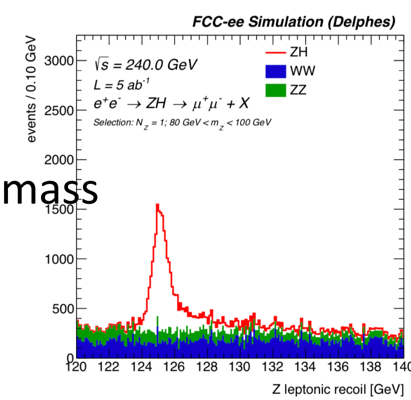
Ang LI, Gregorio Bernardi, FCCee Physics and Performance Meeting, January 18th 2021

Comparison of IDEA and CLD Simulation of the $e^+e^- \rightarrow ZH \rightarrow \mu^+\mu^- + X$

Z recoil mass



IDEAtrkCov

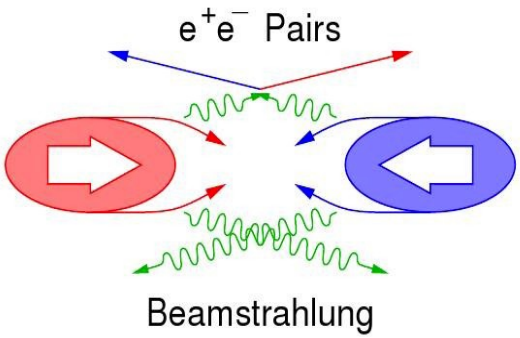


CLDtrkCov

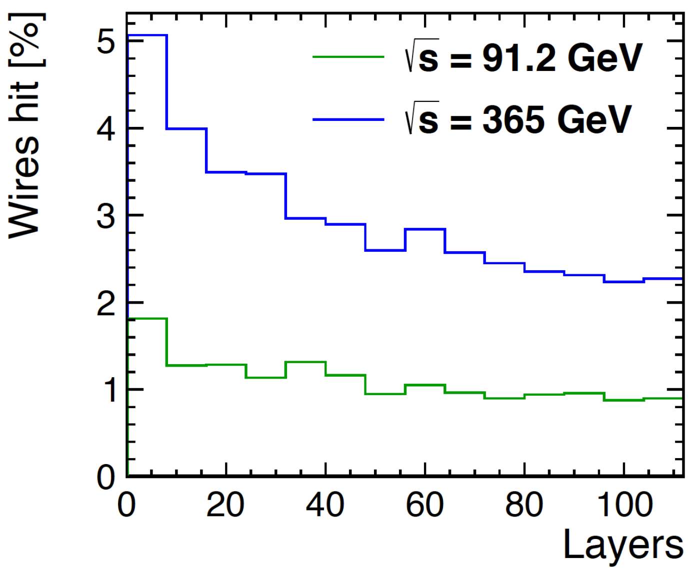
Zoom in on the ZH peak region
CLD has larger width and lower peak

Machine background

- Machine background → preliminary study of the induced occupancy show that it will be not an issue



Background	Average occupancy	
	$\sqrt{s}$ = 91.2 GeV	$\sqrt{s}$ = 365 GeV
e^+e^- pair background	1.1%	2.9%
$\gamma\gamma \to$ hadrons	0.001%	0.035%
Synchrotron radiation	negligible	0.2%



IDEA DCH geometry

Material budget estimates extrapolated from already built chambers or studies

Conservative estimates:

- Inner wall (from CMD3 drift chamber) **$8.4\times10^{-4}\ X_0$**
  200 µm Carbon fiber
- Gas (from KLOE drift chamber) **$7.1\times10^{-4}\ X_0/m$**
  90% He – 10% iC_4H_{10}
- Wires (from MEG2 drift chamber) **$1.3\times10^{-3}\ X_0/m$**
  20 µm W sense wires $4.2\times10^{-4}\ X_0/m$
  40 µm Al field wires $6.1\times10^{-4}\ X_0/m$
  50 µm Al guard wires $2.4\times10^{-4}\ X_0/m$
- Outer wall (from Mu2e I-tracker studies) **$1.2\times10^{-2}\ X_0$**
  2 cm composite sandwich (7.7 Tons)
- End-plates (from Mu2e I-tracker studies) **$4.5\times10^{-2}\ X_0$**
  wire cage + gas envelope
  incl. services (electronics, cables, ...)

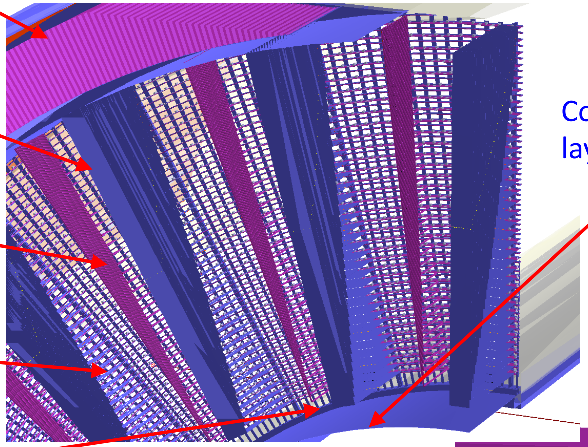
Electronics boards: 12 cm x 6 cm x 3mm G10 (FR4);

signal cables:
2.032 cm x 25 µm Kapton
+ 40 µm 16 pairs of Copper wires;

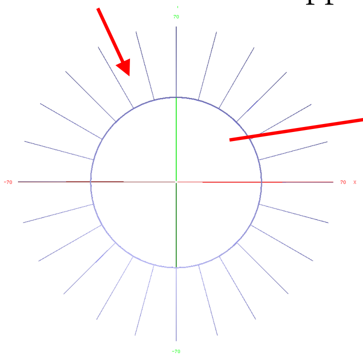
HV cables:
500 µm Copper wire
+ 500 µm Teflon insulation;

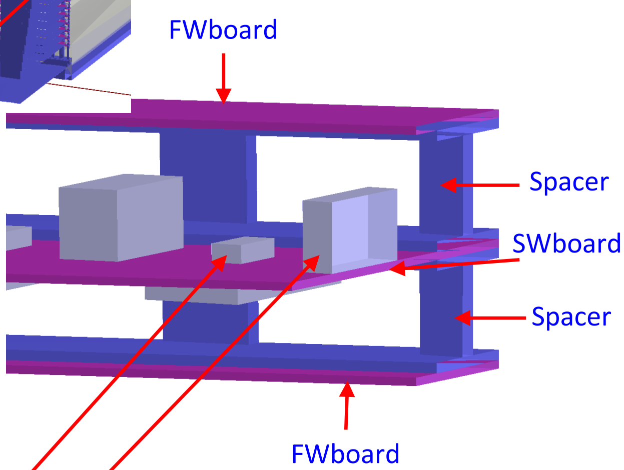
Wire anchoring;

Carbon fiber wire support.



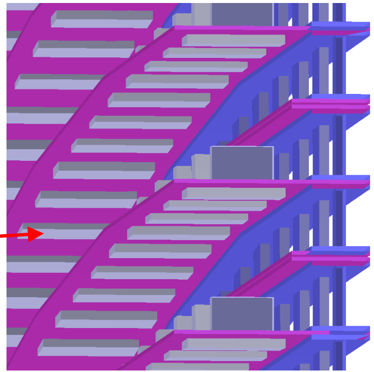
Connecting ring is described as a circular layer: 0.5 cm x 1.5 cm Carbon fiber





The wire anchoring system:

- Field wire board: 4 mm x 200 µm G10(FR4);
- Spacer: made of polycarbonate, instead of holes it is drawn with spokes but with the same area ratio.
- Sense wire board: 1 cm x 200 µm G10(FR4) plus components:
  1) termination resistance: 1.6 mm x 800 µm x 450 µm Aluminum;
  2) HV Capacitance: 3.17 mm x 1.57 mm x 1.7 mm Aluminum;
  3) HV resistance (only downstream): 5 mm x 2.5 mm x 550 µm Aluminum.



dE/dx and dN_{cl}/dx

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

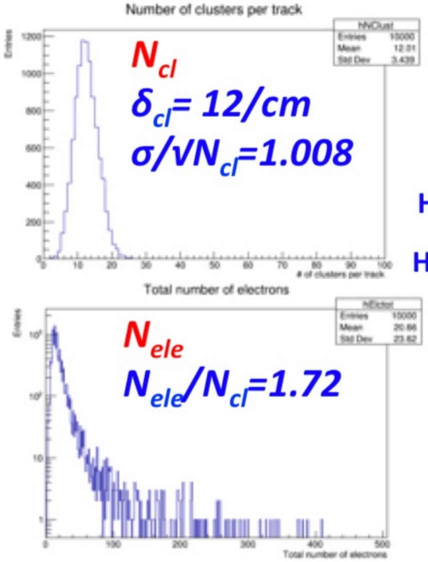
Walenta

Empirical parameterization of dE/dx resolution in gas (limited by Landau fluctuations)

"It has been experimentally confirmed that the relativistic rise is mainly due to the increased number of the primary clusters, rather than due to the energy of clusters."

P. Reak and A.H. Walenta, IEEE Trans. Nucl. Sci. NS-27 (1980) 54

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



HEED simulation
1 cm
He/iC_4H_{10} - 90/10

dE/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%

Increasing ***P*** to 2 atm improves resolution by 20% (σ ≈3.4%) but at a **considerable** cost of multiple scattering contribution to momentum and angular resolutions.

dN_{cl}/dx

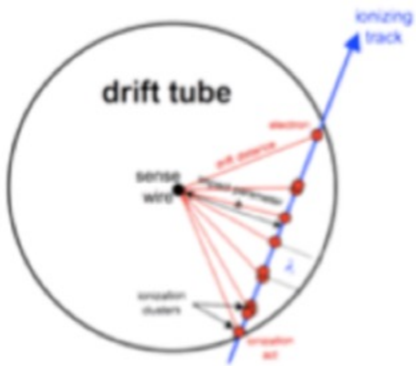
δ_{cl} = 12.5/cm for He/iC_4H_{10}=90/10 and a **2m track** give

σ ≈ 2.0%

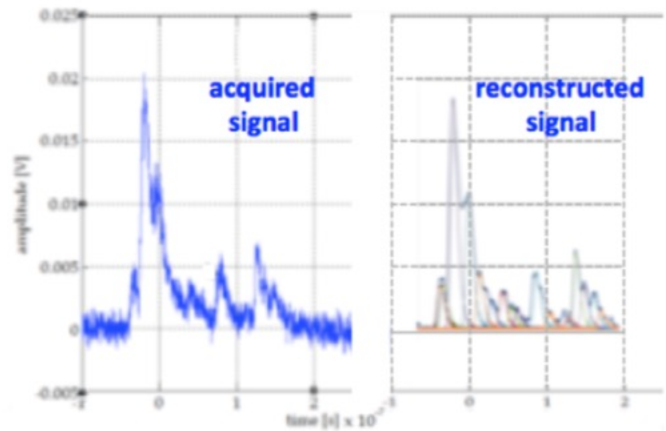
A small increment of iC_4H_{10} from 10% to 20% (δ_{cl} = 20/cm) improves resolution by 20% (σ ≈1.6%) at only a **reasonable** cost of multiple scattering contribution to momentum and angular resolutions.

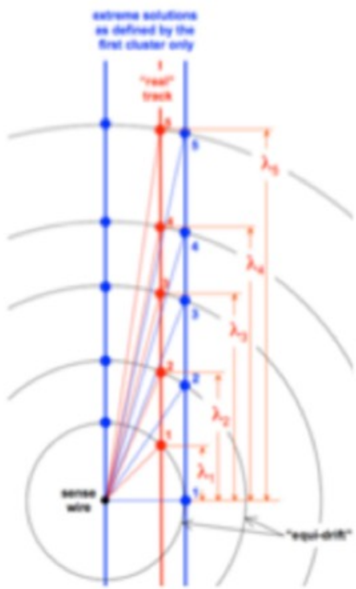
Conditions to be satisfied for cluster counting→ pulses from electrons belonging to different clusters must have a little chance of overlapping in time and, at the same time, the time distance between pulses generated by electrons coming from the same cluster must be small enough to prevent over-counting. **The optimal counting condition can be reached only as a result of the equilibrium** between the fluctuations of those processes which forbid a **full cluster detection efficiency** and of the ones enhancing the **time separation among different ionization events**. *(F. Grancagnolo - PId with dE/dx, IAS Program on High Energy Physics (HEP 2021), Hong Kong, 15 January 2021)*

Cluster timing

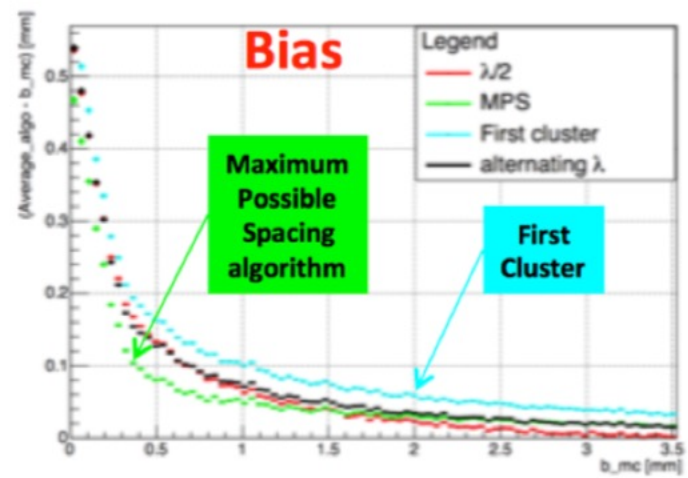


From the **ordered sequence of the electrons arrival times**, considering the average time separation between clusters and their time spread due to diffusion, **reconstruct the most probable sequence of clusters drift times:** $\{t_i^{cl}\} \quad i=1,N_{cl}$





For any given first cluster (**FC**) drift time, the **cluster timing technique** exploits the drift time distribution of all successive clusters $\{t_i^{cl}\}$ to determine the most probable impact parameter, thus reducing the **bias** and the average **drift distance resolution** with respect to those obtained from with the FC method alone.



Spatial resolution could be improved → < 100 µm for 8 mm drift cells in He based gas mixtures

Electron peak finding algorithms

Derivative Algorithm (DERIV)

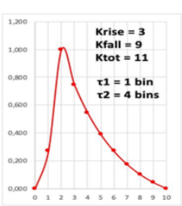
Find good electron peak candidates at position bin n and amplitude A_n :

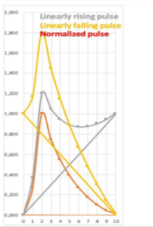
- **Compute the first and second derivative from the amplitude average over two times the timing resolution** and require that, at the peak candidate position, they are less than a r.m.s. signal-related small quantity and they increase (decrease) before (after) the peak candidate position of a r.m.s. 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 based on experimental data.
- Raising and falling exponential over a fixed number of bins (Ktot).
- Digitize it (A(k)) according to the data sampling rate.
- The algorithm scan the wave form and run over Ktot bins by comparing it to the subtracted and normalized data (build a sort of χ^2).
- Define a cut on χ^2.
- Subtract the found peak to the signal spectrum.
- Iterate the search.
- 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

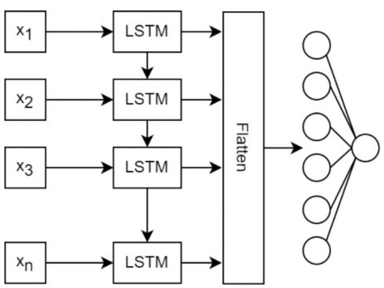




Cluster counting with machine learning

Peak finding with LSTM

Why LSTM? Waveforms are time series

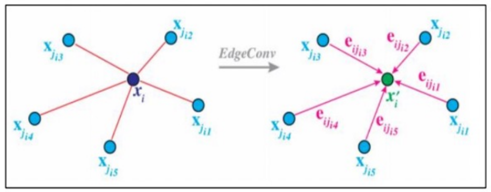


- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

LSTM: Long Short-Term Memory

Clusterization with DGCNN

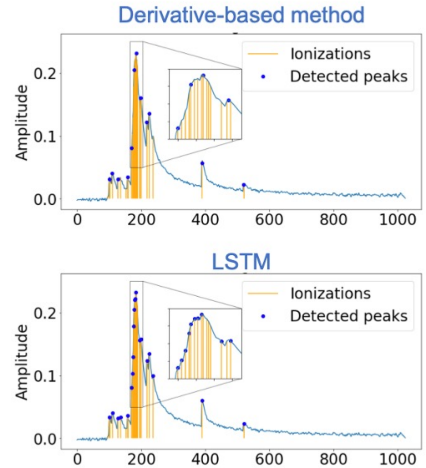
Why DGCNN? Locality of the electrons in the same primary cluster, perform massage passing through neighbour nodes in GNN

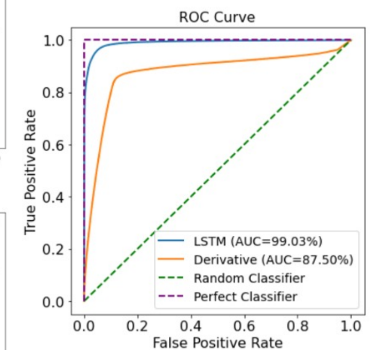


arXiv: 1801.07829

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

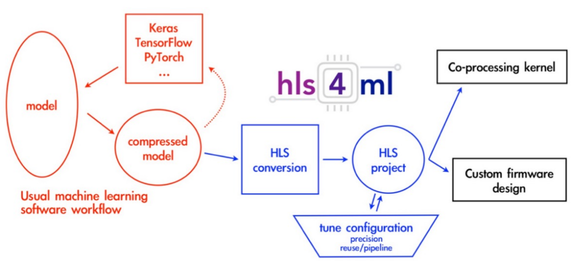
DGCNN: Dynamic Graph Convolutional neural networks





LSTM model is better classifier compared to derivative-based model

Board for cluster counting: new idea ML algorithm



The first step required for the implementation of the neural network on the FPGA is the conversion of the high-level code used for the creation of the network (QKeras) into an High-Level Synthesis (HLS)

To accomplish this task, the hls4ml package will used.

A schematic workflow of hls4ml is illustrated in the figures.

1. The parts red indicates the usual software steps required to design a neural network for a specific task.
2. The blue section of the workflow is the task done by hls4ml, which translates the model into an HLS project that can be synthesised and implemented to run on an FPGA.