IDEA Drift Chamber

1st IDEA Study Group meeting
October 15th 2024

M. Primavera (INFN Lecce) on behalf of Bari and Lecce Groups:

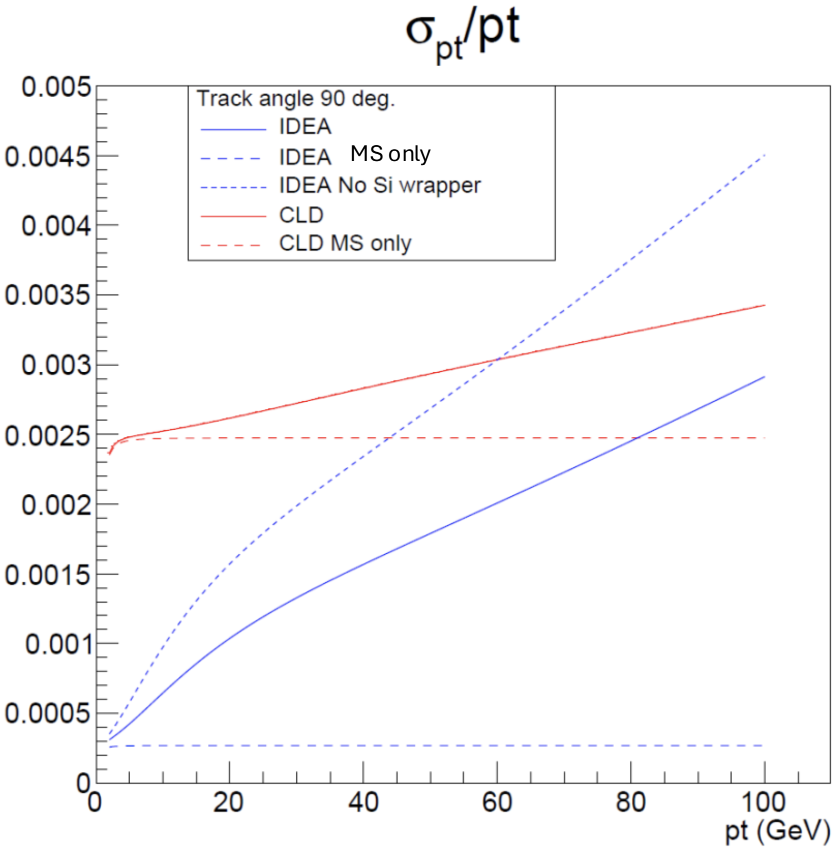
Bari: M. Abbrescia , M. Numan Anwar , N. De Filippis, W. Elmetenawee, M. Louka, F.M. Procacci
Lecce: A. Corvaglia, F. De Santis, E. Gorini, F. Grancagnolo, S. Grancagnolo, F.G. Gravili, A. Miccoli, F. Paladini, M. Panareo, A. Ventura, C. Veri

Other collaborators expressed their interest in joining the project

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 against multiple scattering
- Cluster counting technique for PId

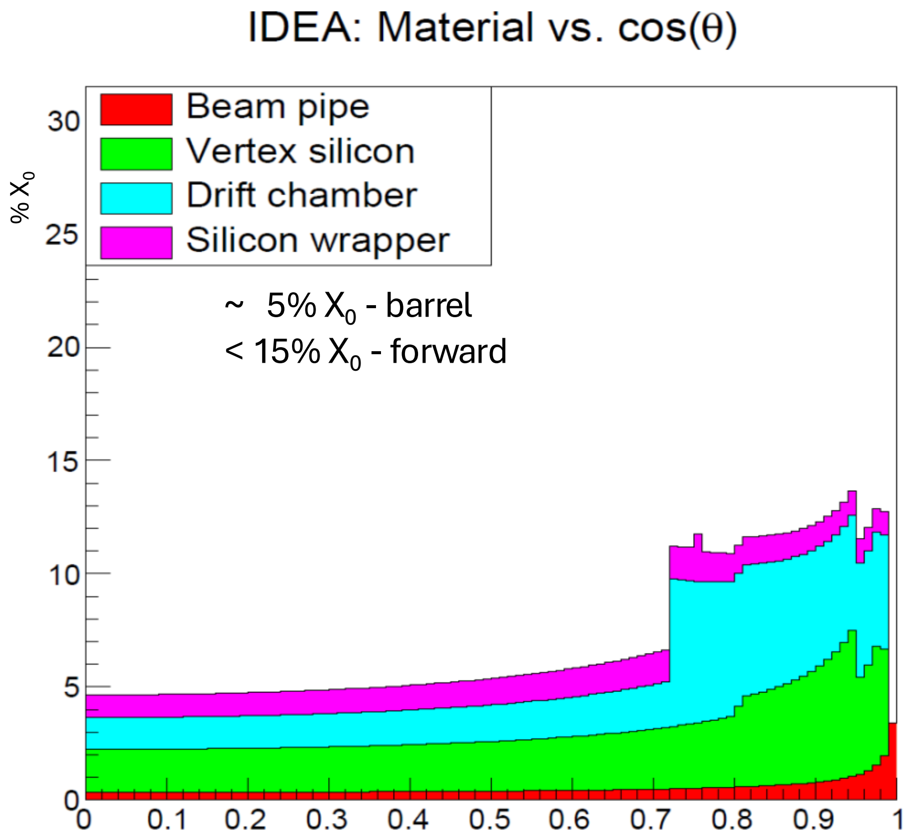


Particle momentum range far from the asymptotic limit where MS is negligible

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

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

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

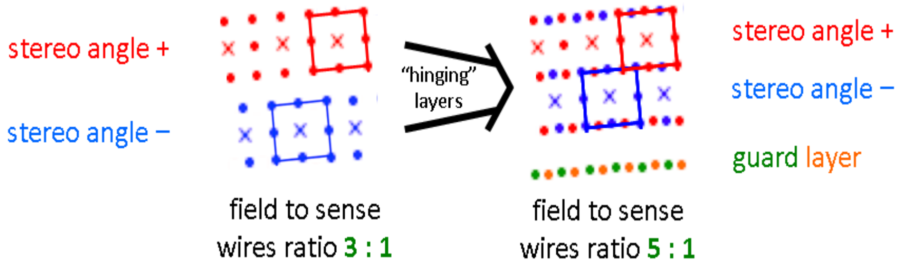


The IDEA DCH

- Large volume: **R_{in} = 0.35 m, R_{out} = 2 m, L ength= 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 **$\sigma_{xy} < 100\ \mu m$, $\sigma_z < 1$ mm**
- **56,448 cells and 343968 wires** in total:

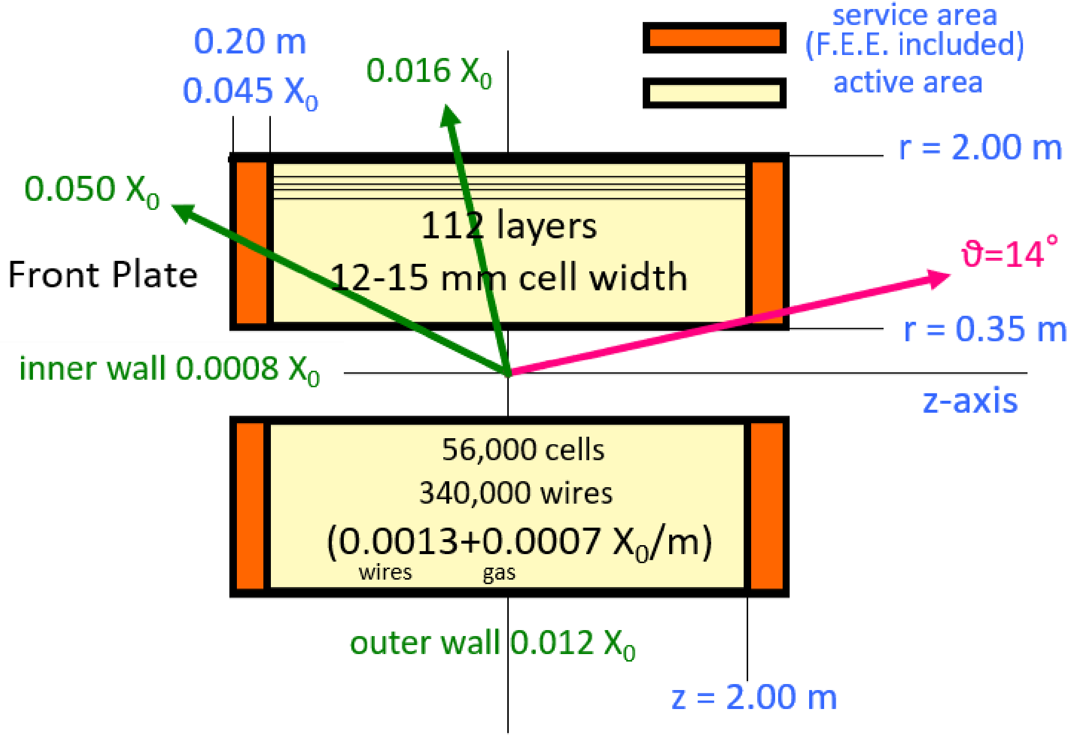
sense wires → 20 μm diameter W(Au) => 56448 wires
(**thin!!**) field wires → 40 μm diameter Al(Ag) => 229056 wires
Field between sense and guard wires → 50 μm diameter Al(Ag) => 58464 wires

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



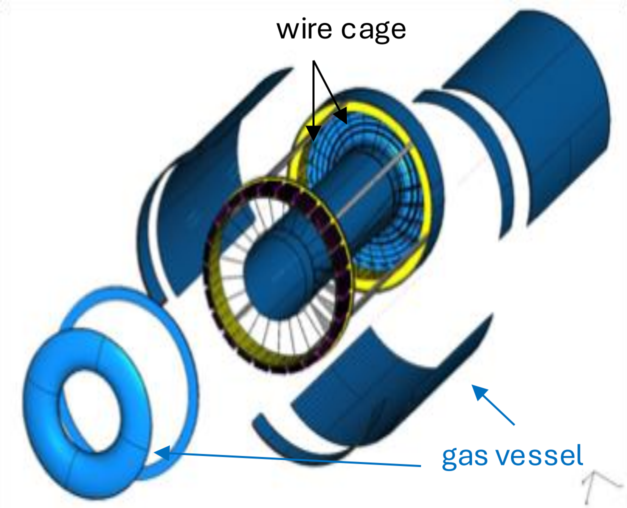
tracking efficiency ε ≈ 1
for ϑ > 14° (260 mrad)
97% solid angle

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



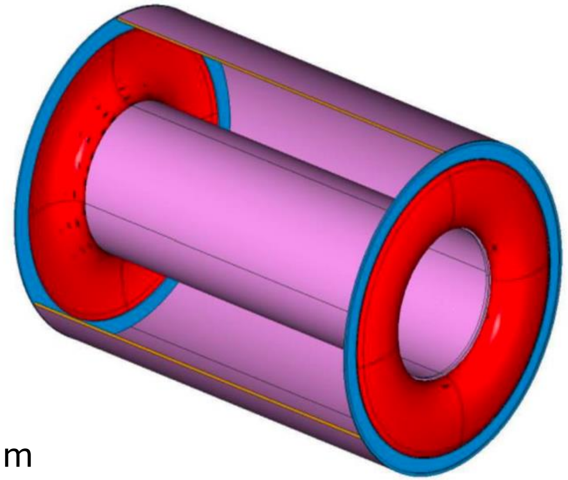
DCH design

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



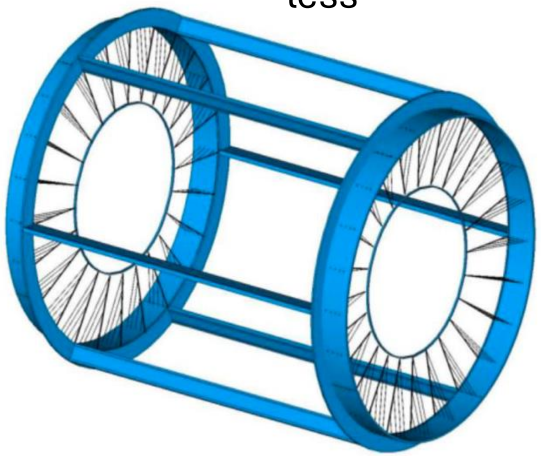
Gas containment

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:

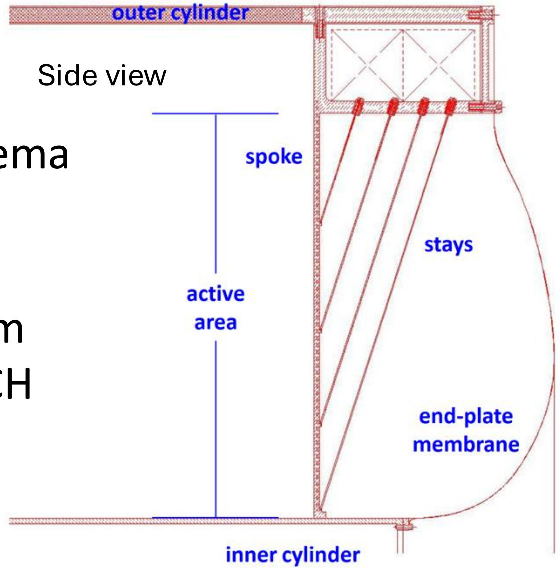
- the accuracy of the position has to be in the range of 100-200 μm
- the position of the anodic wire in space must be known with an accuracy better than 50μm at most
- the anodic and cathodic wires should be parallel in space to preserve the uniformity of the electric field
- a 20μm tungsten wire, 4m 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

In addition:

- Given the requests on gas gain for cluster counting (~5×10^5) and on the chamber length, the electrostatic stability condition sets serious constraints on the cell width and on the wire materials
- Safety requirements demands stringent limitations on flammable gases
- Large number of channels, high signal sampling rate, low drift velocity required for cluster counting, and the high trigger rate at the Z pole at FCCee imply data transfer rates ~1TB/s

DCH mechanical structure

- New tension recovery schema
- Experience inherited from the MEG2 DCH

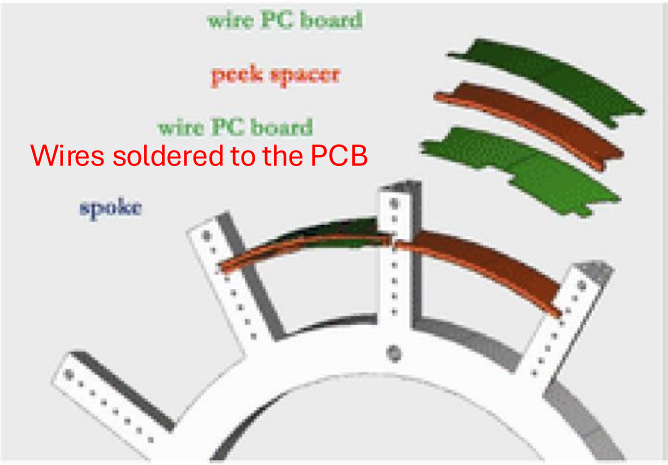


Inner cylinder and Outer cylinder connected with 48 Spokes (24 per Each side) forming 24 azimuthal sectors.

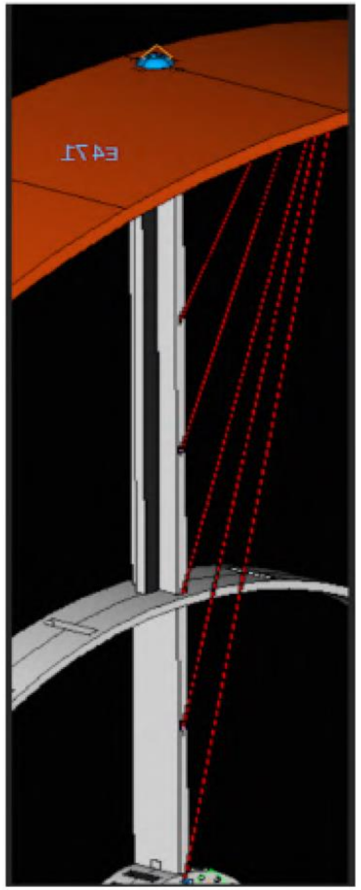
Each spoke supported by 15 Cables/Stays.

Spoke length = 160cm

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



Wires soldered to the PCB



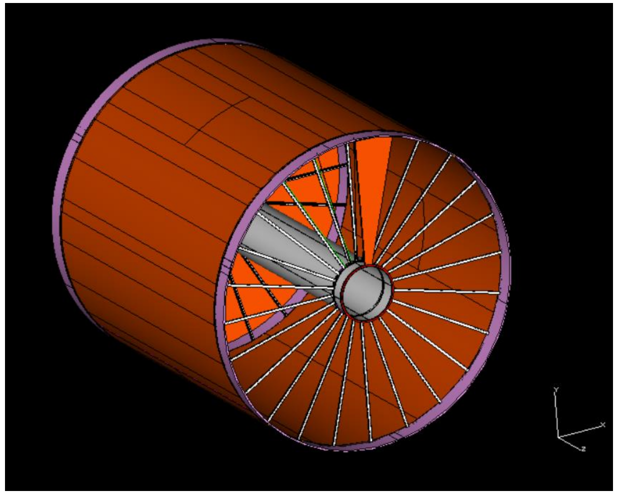
FEM Parametric Design exploration → varying input parameters in some possible ranges in order to see how the system responds - Response Surface Methodology (RSM) is used.

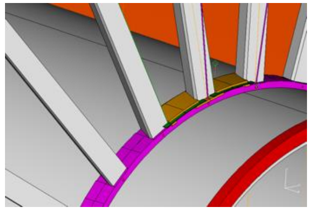
Our **main goal** was to limit the deformation of the spokes to **200 μm** while ensuring the structural integrity.

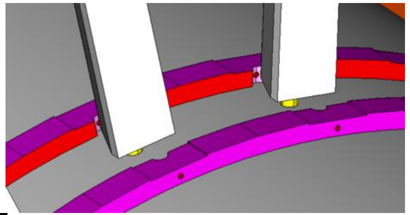
A realistic complete model ready:

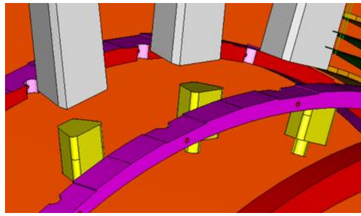
- mechanically accurate
- precise definition of the connections of the cables on the structure
- connections of the wires on the PCB
- location of the necessary spacers
- connection between wire cage and gas containment structure

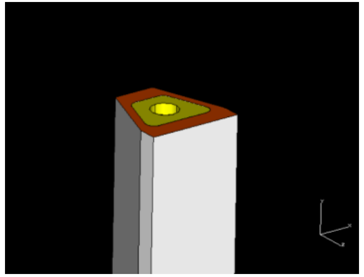
Plan to start the construction of a DCH prototype full lenght, three sectors per EC

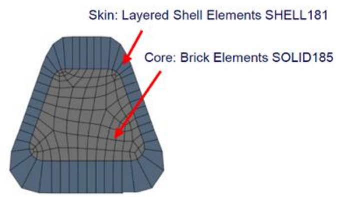


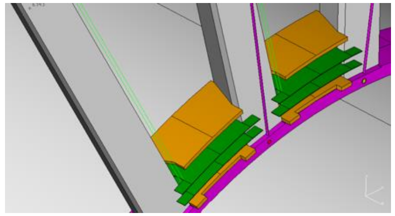


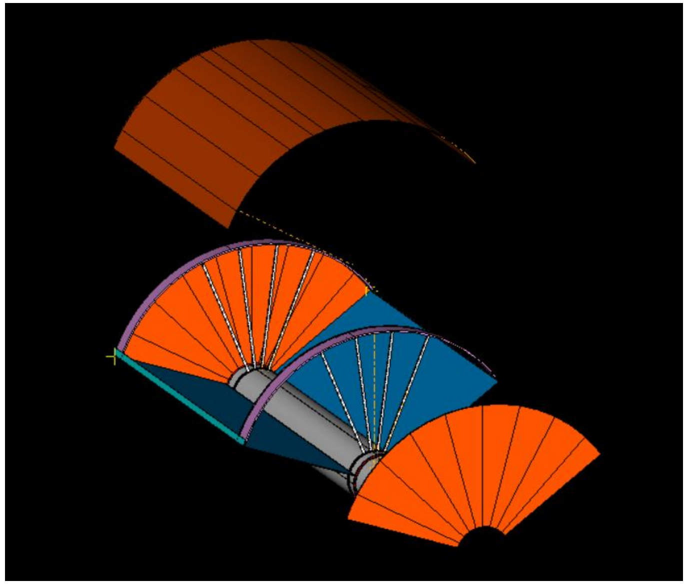








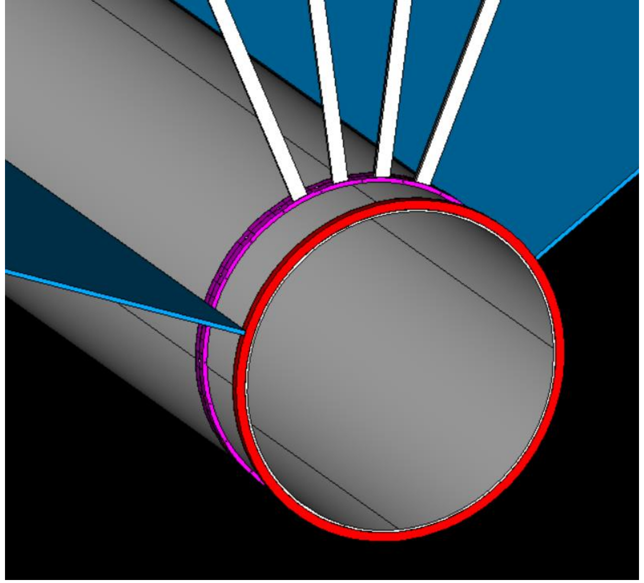




DCH full length prototype

- 8 spokes (4 per endcap)
- Internal ring
- part of the outer ring
- part of the cylindrical panels

TOTAL LAYERS: 8
Sense wires: 168
Field wires: 965
Guard wires: 264

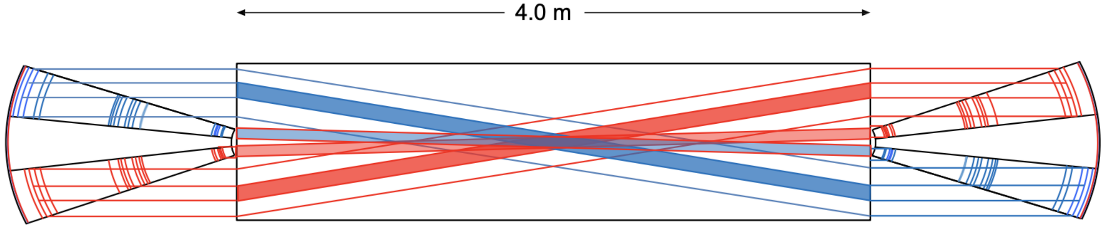


PCBoards wire layers: 42
Sense wire boards: 8
Field wire boards: 22
Guard wire boards: 12
HV values: 14

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

- ➢ Check the limits of the wires' electrostatic stability at full length and at nominal stereo angles
- ➢ Test different wires, different wire anchoring procedures (soldering, welding, gluing, crimping, …) to the wire PCBs, different materials and production procedures for spokes, stays, support structures and spacers, 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, optimize the layout of the wires' PCBs (sense, field and guard), according to the wire anchoring procedures, with aim at minimizing the end-plate total material budget
- ➢ optimize the wiring strategy, the High Voltage and signal distribution, test performance of different versions of front-end, digitization and acquisition chain

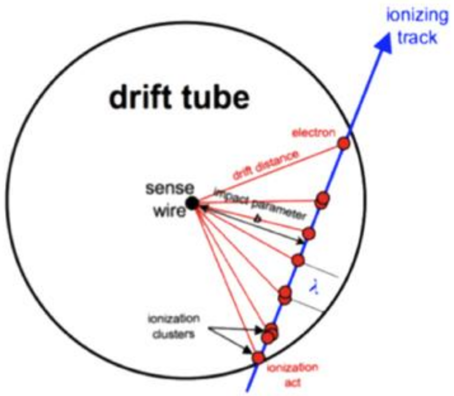
ELECTRONICS COVERAGE

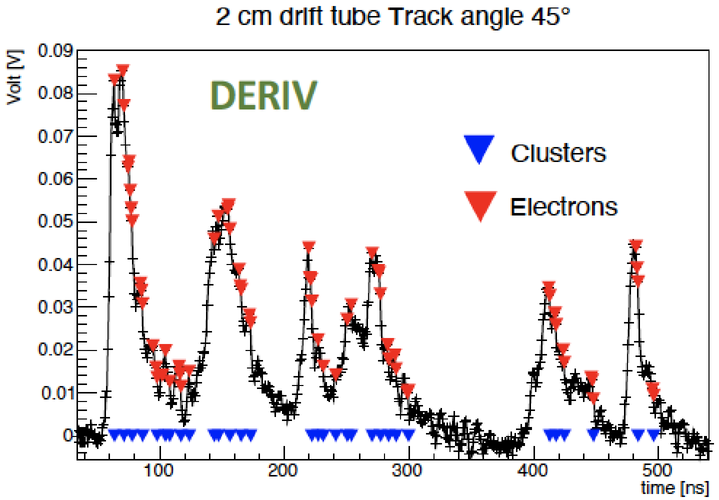


Minimum stereo angle 50 mrad
Maximum stereo angle: 250 mrad

DCH particle identification

- 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

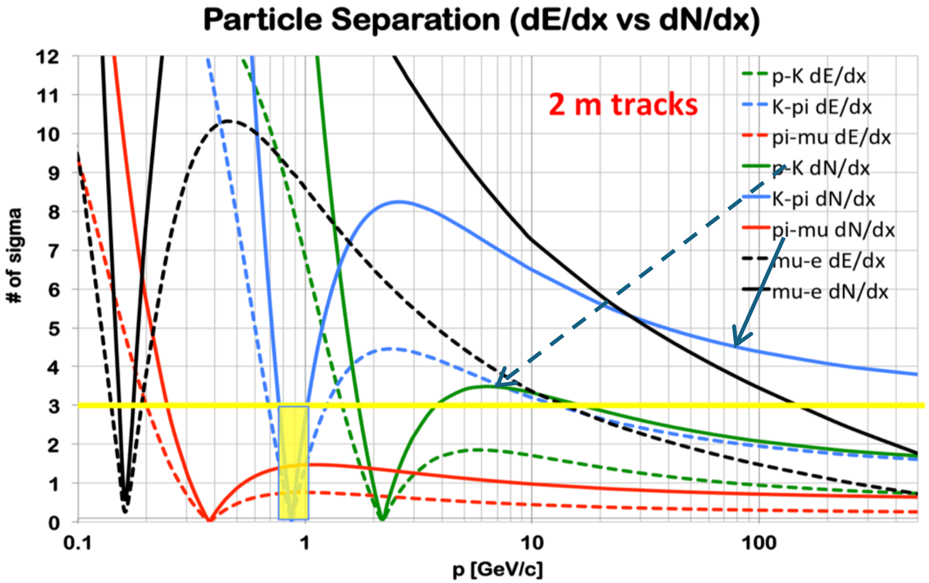
- Requires fast electronics and sophisticated counting algorithms
- Less dependent on gain stability issues
- δ_{cl}= 12./cm for He/iC_4H_{10}=90/10 and a 2m track → **σ ≈ 2.0%**

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

Poisson

DCH particle identification

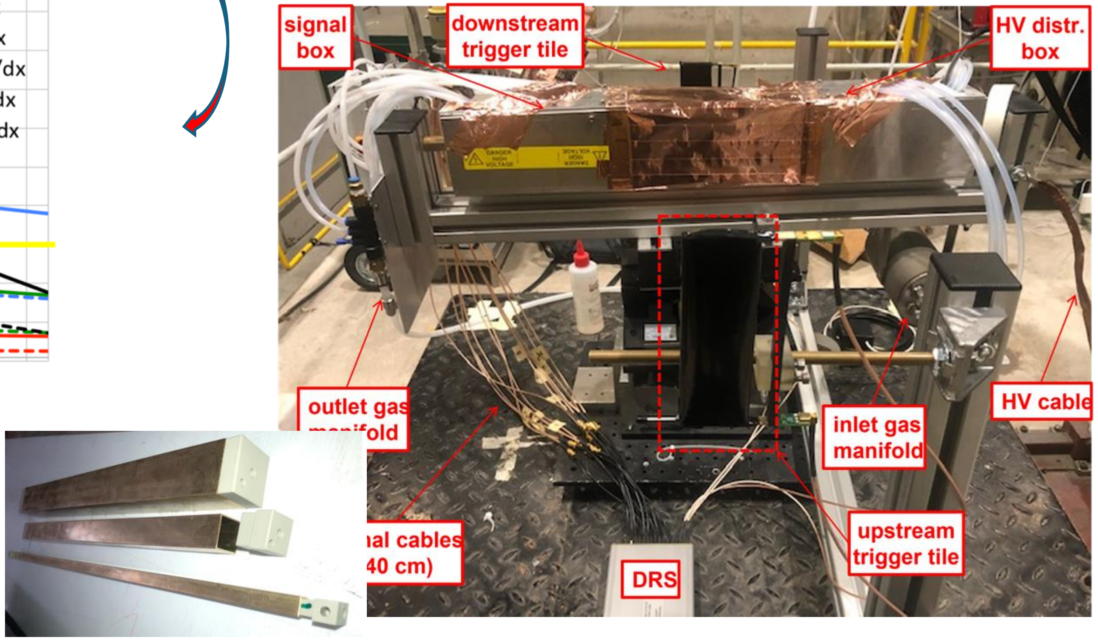
- Analytical calculations → predict excellent K/π separation over the full range of momenta except 0.85<p<1.05 GeV



Analitic calculations:
He/iC$_4$H$_{10}$ 90/10 δ_{cl}=12 cm^{-1}
σ(dE/dx)/(dE/dx) =4.3%
80% cluster counting efficiency

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

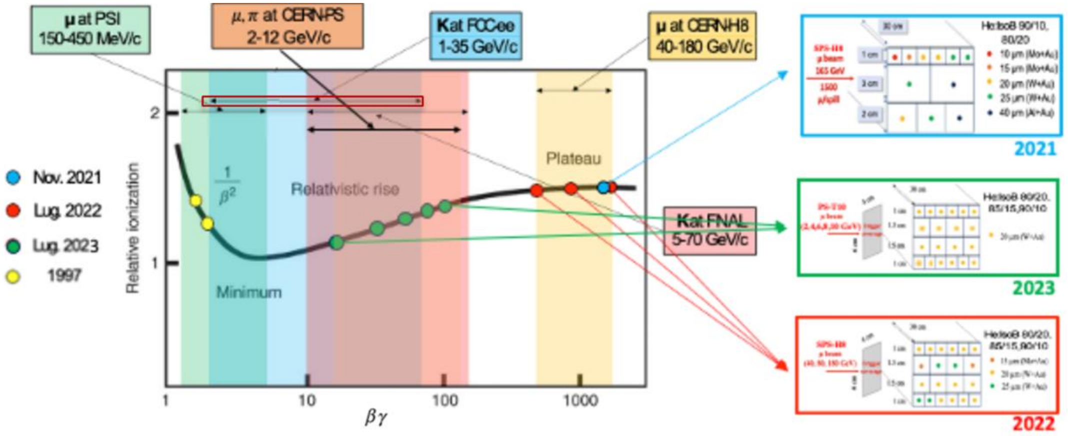
- the particle separation, both with dE/dx and with dN$_{cl}$/dx, in GEANT4 found considerably worse than in Garfield
- the dN$_{cl}$/dx Fermi plateau with respect to dE/dx is reached at lower values of βγ with a steeper slope
- Results on real data from beam tests are crucial



- Two **muon beam tests** performed at **CERN-H8 (βγ > 400)** in Nov. 2021 and July 2022.
- **Muon beam tests** performed in 2023 (from 4 to 12 GeV momentum) and in 2024 (1-12 GeV) at **CERN PS**
- test at **FNAL-MT6** with **π** and **K (βγ = 10−140)** could be important to fully exploit the relativitic rise.

DCH particle identification: new results

- ➢ New results from the 2021/2022 beam tests at CERN H8 ($\beta\gamma > 400$) [ICHEP 2024]

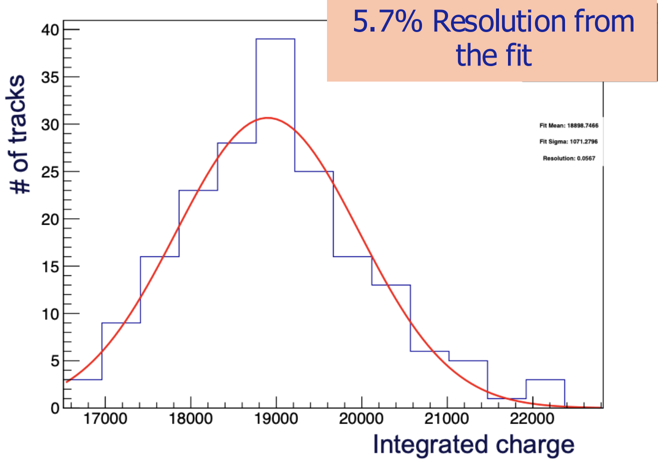


- ➢ Landau distribution for the charge along a track
- ➢ Selected the distribution with 80% of the charges for the dE/dx truncation to be compared with dN/dx. There is still margin for improvements in CC efficiency!

- ➢ Data analysis of the two test beams at CERN T10 performed in July 2023 and July 2024 with muons (1-12 GeV) ongoing

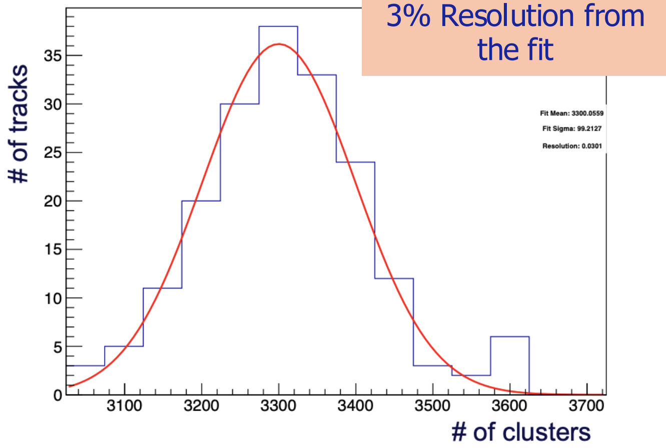
Study done using same tracks (2 m track length) made of the same hits. 180 GeV/c muons

dE/dx Resolution (remove 20% higher charges)


5.7% Resolution from the fit

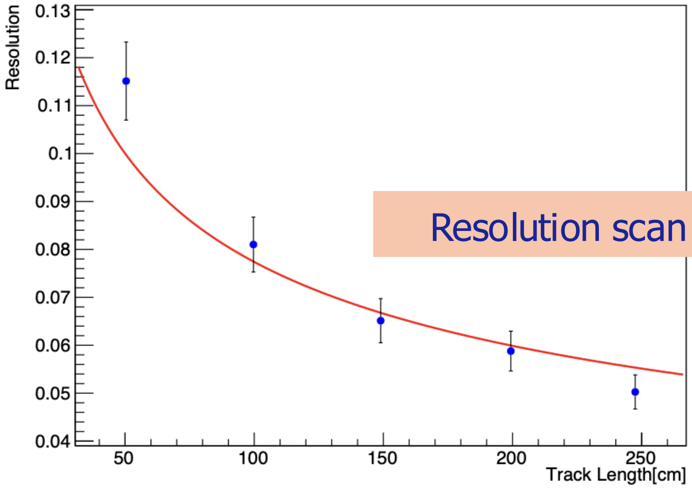
@2m long track we have dE/dx resolution 5.7%

dN/dx Resolution

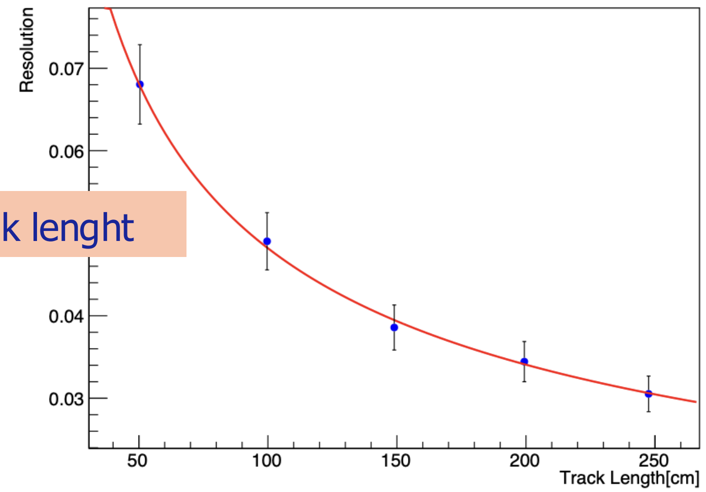

3% Resolution from the fit

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

dE/dx Resolution



dN/dx Resolution



Resolution scan vs track lenght

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

Effort to build a **international collaboration** enforced

- well established collaboration with **IHEP** for NN-based cluster counting algorithms
- started to collaborate with US colleagues from **BNL**
- relevant contribution from IHEP and BNL in July 2024 test beam!
- Areas for collaboration → detector design, construction, beam tests, performance, reconstruction, full simulation, physics performance

2025-2026 **plans**

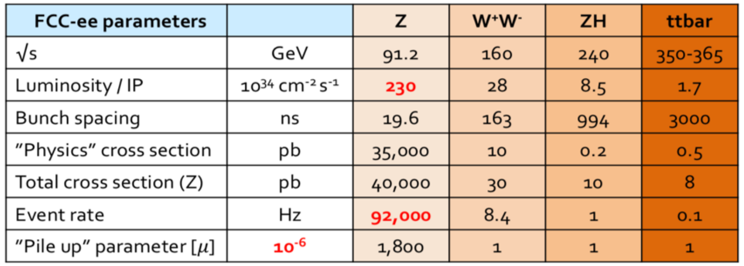
- Test beams: **2023-2024 test beam data analysis**, 2025 test beam at **FNAL-MT6** with **π** and **K ($\beta\gamma$ = 10–140)** → important to fully exploit the relativitic rise.
- DCH prototype: activities to start the construction of a **full-scale prototype** → to test the chamber mechanical and electrostatic stability (a clean room is needed for wiring!)
- **full simulation** (digi+ tracking algorithms) of the chamber

Backup slides

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 $e^+e^-\rightarrow tt$, 10^6 $e^+e^-\rightarrow HZ$)
- flavor factories (5×10^{12} $e^+e^-\rightarrow bb$, cc, 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 $\Delta\theta \leq 0.1$ 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

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)

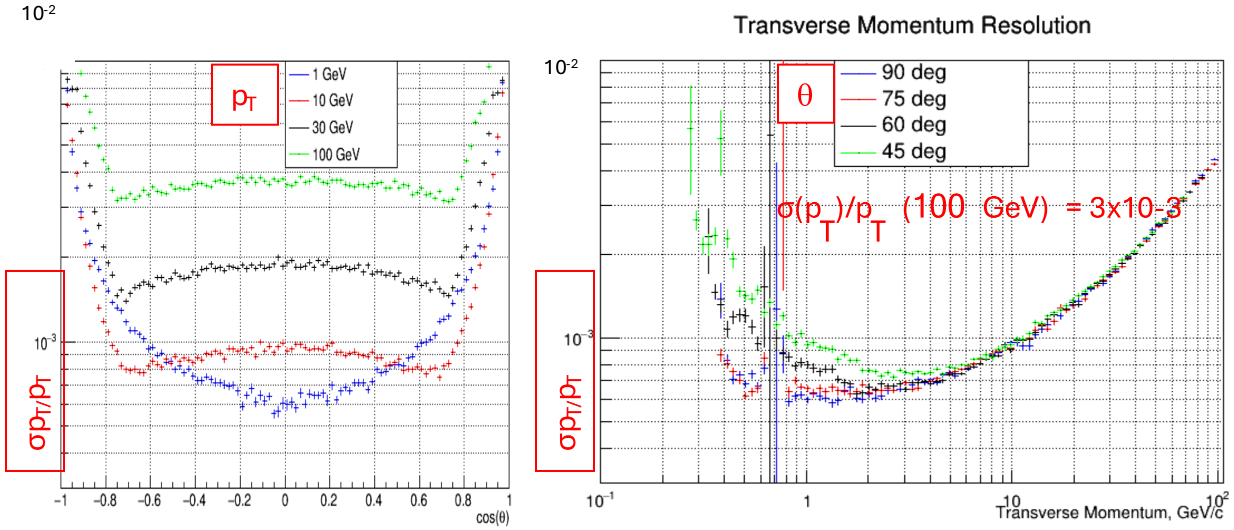
- The maximum drift time (400ns) will impose an overlap of some (20 at Z pole) bunch crossings bringing the hit occupancy to ~ 10% in the inner-most drift cells. Based on MEG-II experience, this occupancy, which allows over 100 hits to be recorded per track on average in the DCH, is deemed manageable.

- 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.

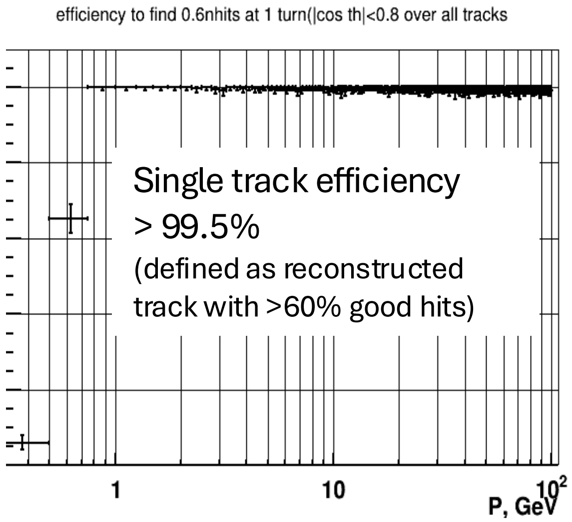
- In addition, cluster signals separated by more than 100 ns are not from the same signals, this effectively bring the BXs pile-up from 20 to 4

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



$\sigma(p_T)/p_T$ (100 GeV) = 3x10-3

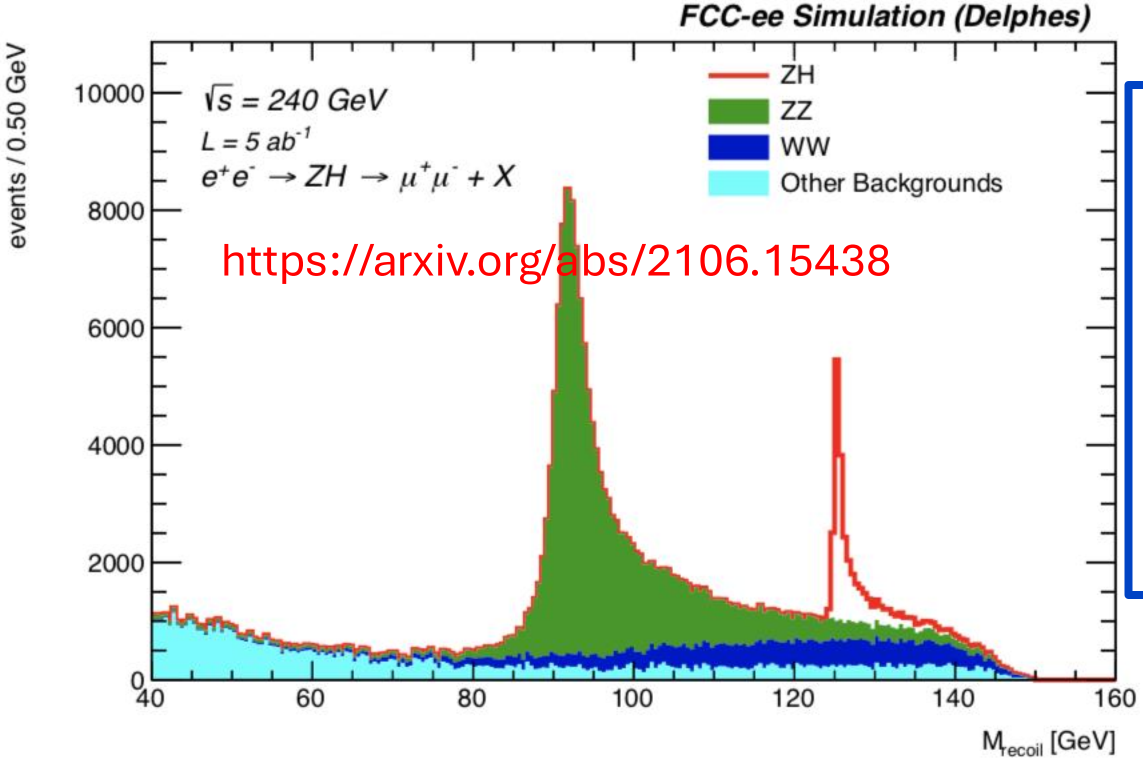


Single track efficiency > 99.5%
(defined as reconstructed track with >60% good hits)

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



https://arxiv.org/abs/2106.15438

Z recoil mass

Z → μμ final state

Nominal Higgs mass → 125 GeV

Events with

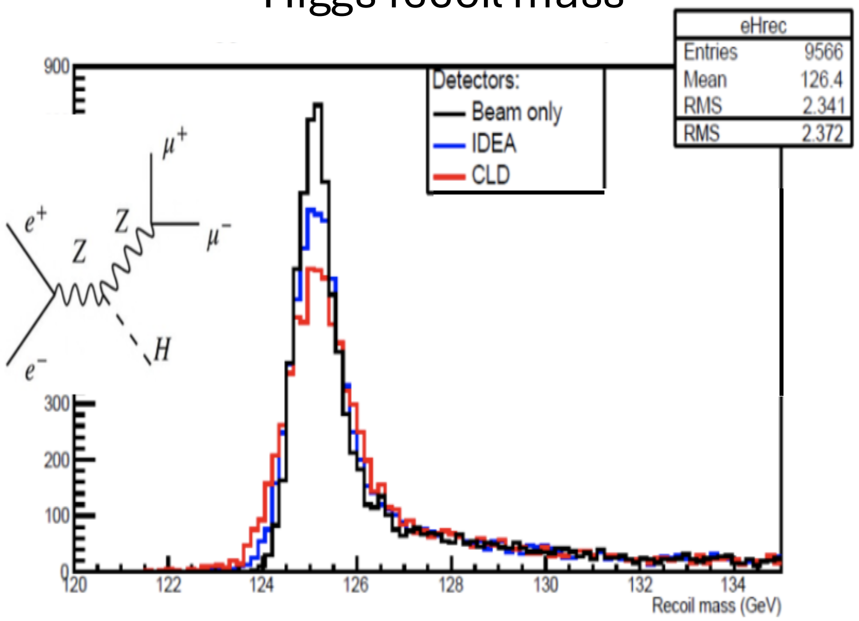
- $15 < p_T(\mu\mu) < 70$ GeV
- $|M_{\mu\mu} - M_Z| < 20$ GeV

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

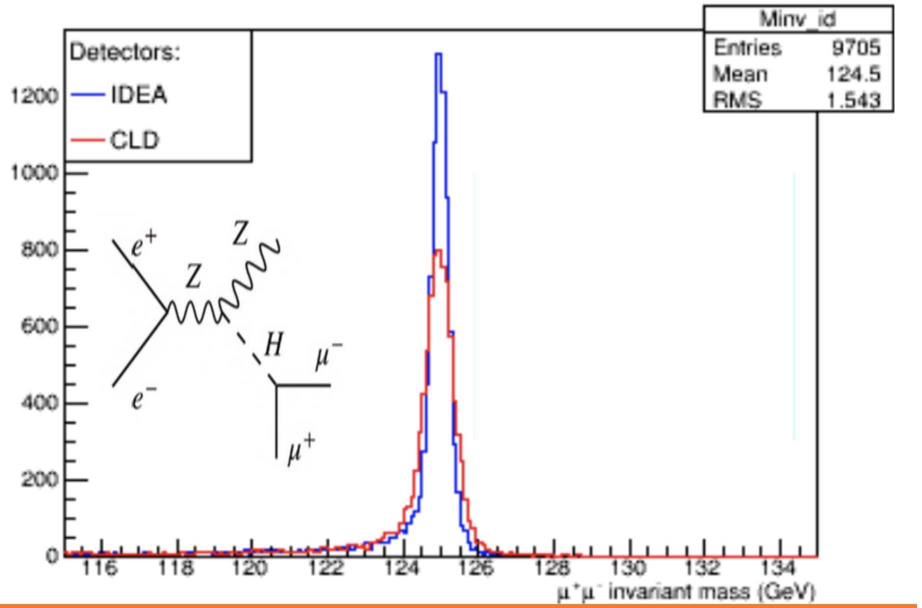
→ ~6MeV on m_H

Expected performance: compare IDEA and CLD

Higgs recoil mass



Di-muon invariant mass



Beam only→ assumes 0.136% beam spread and an ideal detector

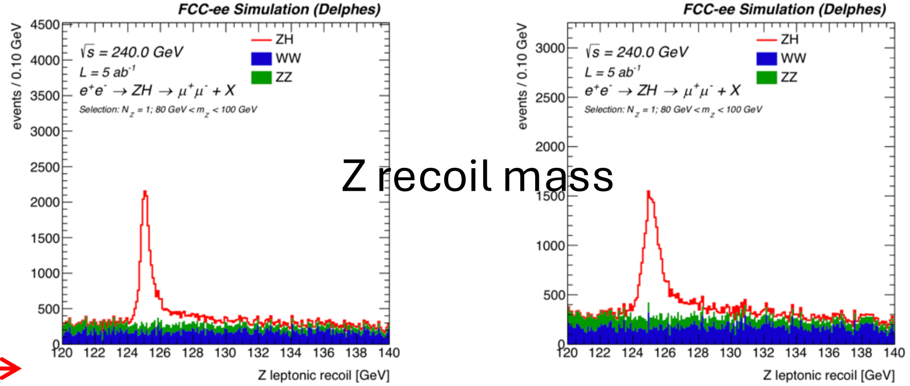
IDEA → Fast simulation studies

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 $e^+e^- \to ZH \to \mu^+\mu^- + X$



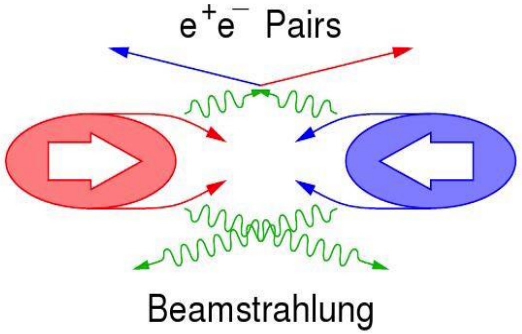
Z recoil mass

IDEAtrkCov CLDtrkCov

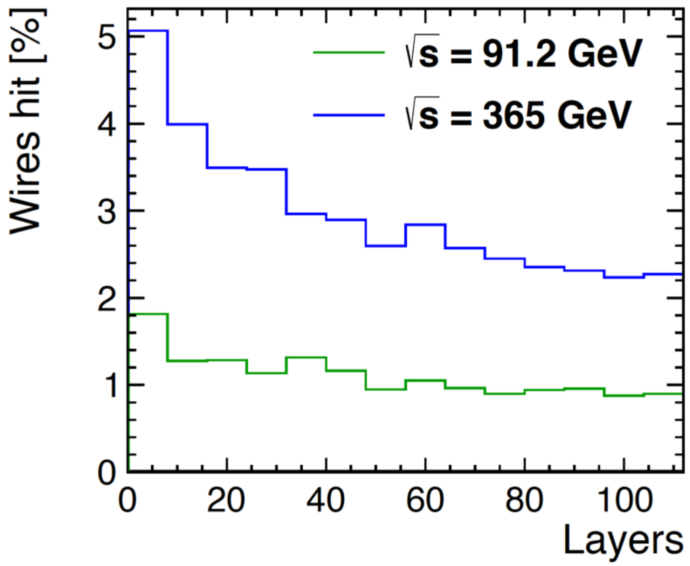
Zoom in on the ZH peak region
CLD has larger width and lower peak

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



IDEA DCH geometry

Electrostatic stability condition: $\frac{\lambda^2}{4\pi\varepsilon}\frac{L^2}{w^2} < \mathit{wire\ tension} < YTS \cdot \pi r_w^2$

λ = linear charge density (gas gain)
L = wire length, r_w wire radius, w = drift cell width
YTS = wire material yield strength

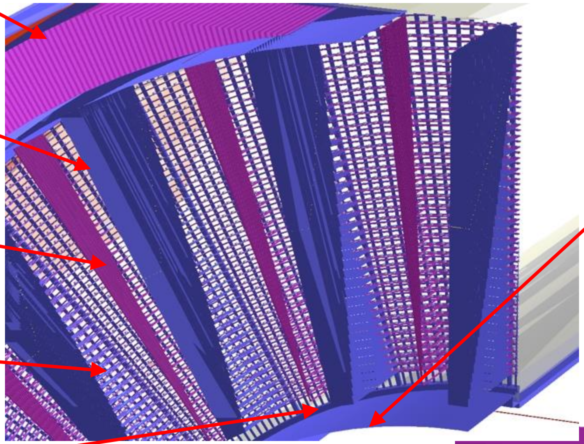
Electronics boards: 12 cm x 6 cm x 3mm G10 (FR4);

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

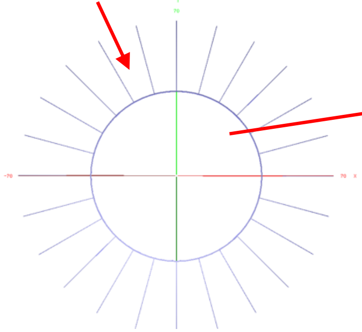
HV cables:
500 μm Copper wire
+ 500 μm Teflon insulation;

Wire anchoring;

Carbon fiber wire support.



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



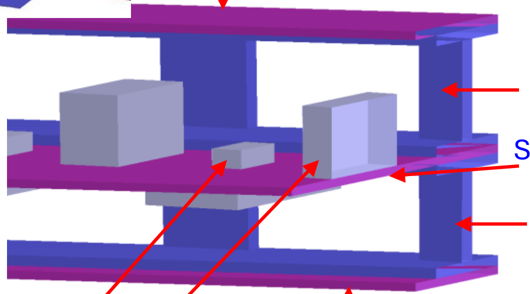
Material budget estimates extrapolated from already built chambers or studies

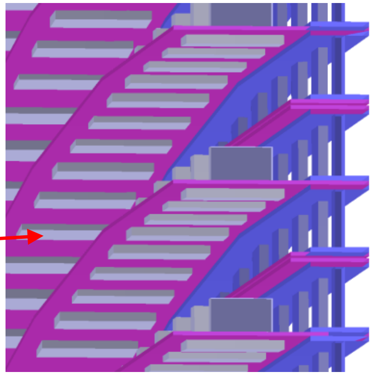
Conservative estimates:

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

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.





DCH full length prototype

- Three sectors is the minimum for the two stereo views.

- It is necessary to test the innermost layer, with the smallest cells, the outermost layer with the maximum stereo angle and two intermediate layers at the transition of two superlayers, where the pitch of the wires changes for the increase of cells from one superlayer to the next . So, 4 layers for two views, or 8 layers.

- It is necessary to cover the entire sector in azimuth with the wires to distribute the electric field in order to test the electrostatic stability with stereo configurations. Further reducing the number of field wires would involve the introduction of edge effects that would affect the innermost sense wires.

- It is necessary to cover the entire sector in azimuth with wires to control the spinning on PCBs which become approximately 50 cm long at the outermost layer with obvious difficulties in maintaining geometric tolerances.

- Regarding the number of reading channels, we read the two internal views (all 8+8 channels), the four intermediate views (16+16+16+16 channels on 20+20+22+22 sense wires) and the two external views (16+16 channels on 34+34). All this gives us coverage of a couple of square decimeters for vertical cosmic rays.

- The 112 channels → asked support for the two 64-channel NALU cards in addition to the two 16-channel CAEN VX2751 digitizers for comparison and to test the current division reading and the time difference between the two ends of the wires

Electron peak finding algorithms

Derivative Algorithm (DERIV)

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

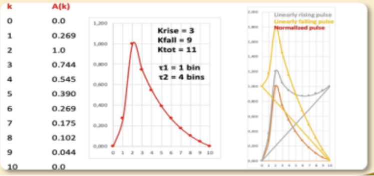
- **Compute the first and second derivative from the amplitude average over two times the timing resolution** and require that, at the peak candidate position, they are less than a r.m.s. signal-related small quantity and they increase (decrease) before (after) the peak candidate position of a r.m.s. 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)

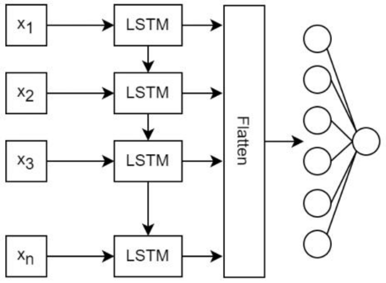
- Define an electron pulse template based on experimental data.
- Raising and falling exponential over a fixed number of bins (Ktot).
- Digitize it (A(k)) according to the data sampling rate.
- The algorithm scan the wave form and run over Ktot bins by comparing it to the subtracted and normalized data (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

Peak finding with LSTM

Why LSTM? Waveforms are time series

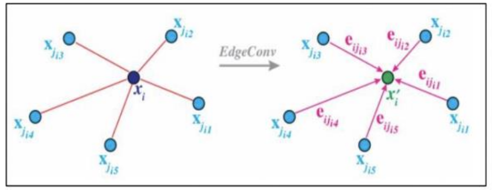


- Architecture: LSTM (RNN-based)
- Method: Binary classification of signals and noises on slide windows of peak candidates

LSTM: Long Short-Term Memory

Clusterization with DGCNN

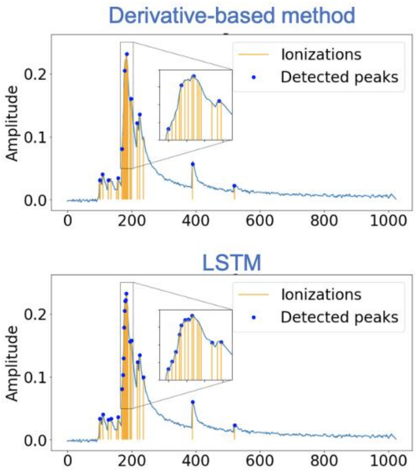
Why DGCNN? Locality of the electrons in the same primary cluster, perform massage passing through neighbour nodes in GNN

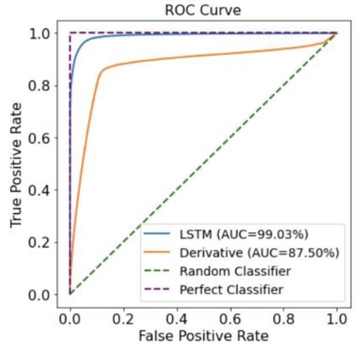


arXiv: 1801.07829

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

DGCNN: Dynamic Graph Convolutional neural networks



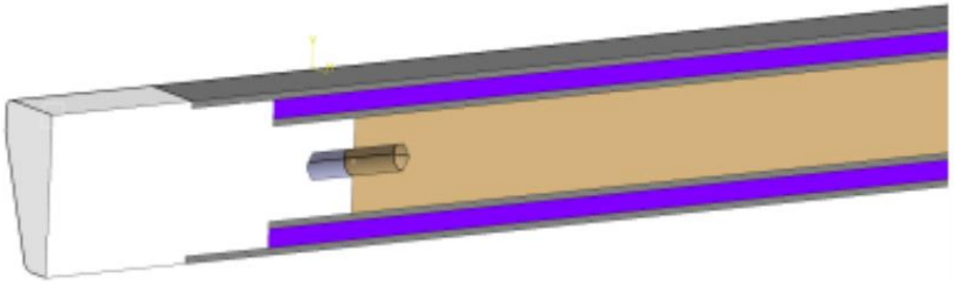


LSTM model is better classifier compared to derivative-based model

Innovative spoke production technique

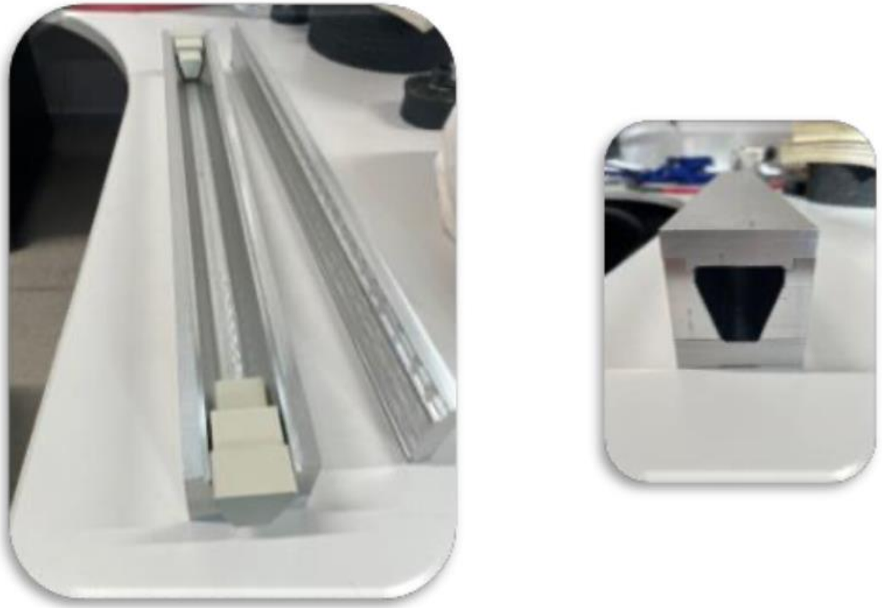
Spoke structure:

- **Carbon foam** core - CFOAM® 35 HTC – brown part
- **PEEK endcaps** with an optimised shape to have greater grip with the internal foam – white part
- The external part is produced with an innovative technique in which a **double layer of carbon fibres** wrap around the foam and a portion of the endcap, improving the grip between the parts – violet and grey parts



Spoke production:

- We have produced an aluminum mold in which the spoke will be formed by wrapping the fibers around the foam and the endcap



Target: Mechanical characterization of the spoke with bending-torsion tests