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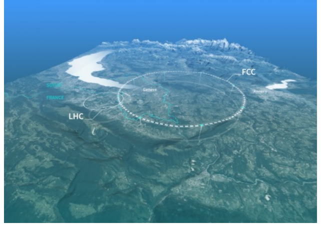

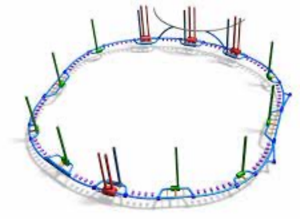

# Status of the drift chamber project for the IDEA detector proposal for FCC-ee


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Sezione di Bari

**Nicola De Filippis**
Politecnico and INFN Bari

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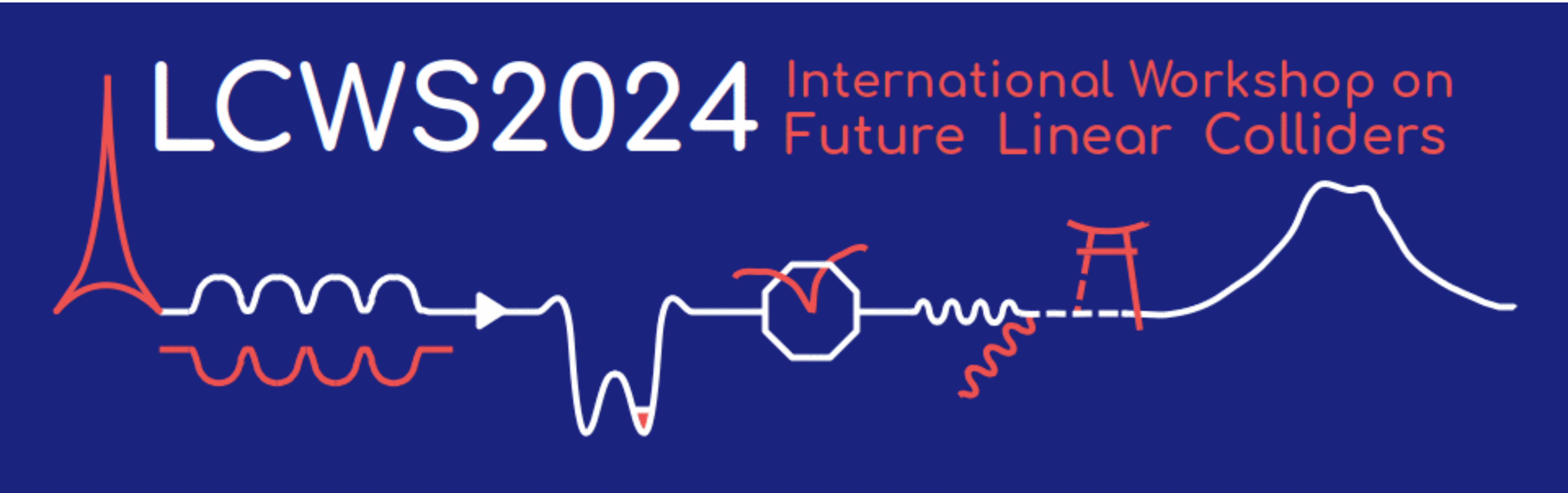
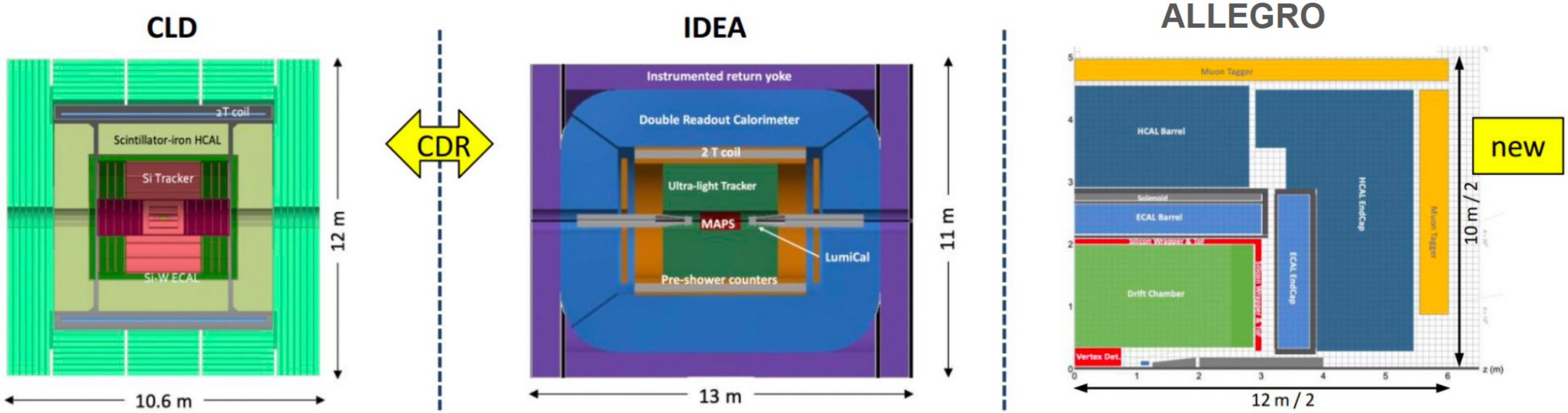


# FCC-ee detector benchmarks




**Imported from CLIC**

- Full Si tracker
- SiW Ecal HG
- SciFe Hcal HG
- Large coil outside

**FCCee specific design**

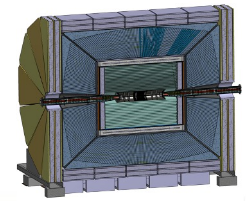
- Si Vtx + wrapper (LGAD)
- Large drift chamber (PID)
- DR calorimeter
- Small coil inside

**FCCee specific design**

- Tracker as IDEA
- LAr EM calorimeter
- Coil integrated
- Hcal not specified

- High luminosity required for the physics → constraints on the design of the detectors close to the machine components, in particular the LumiCal and VTX detectors

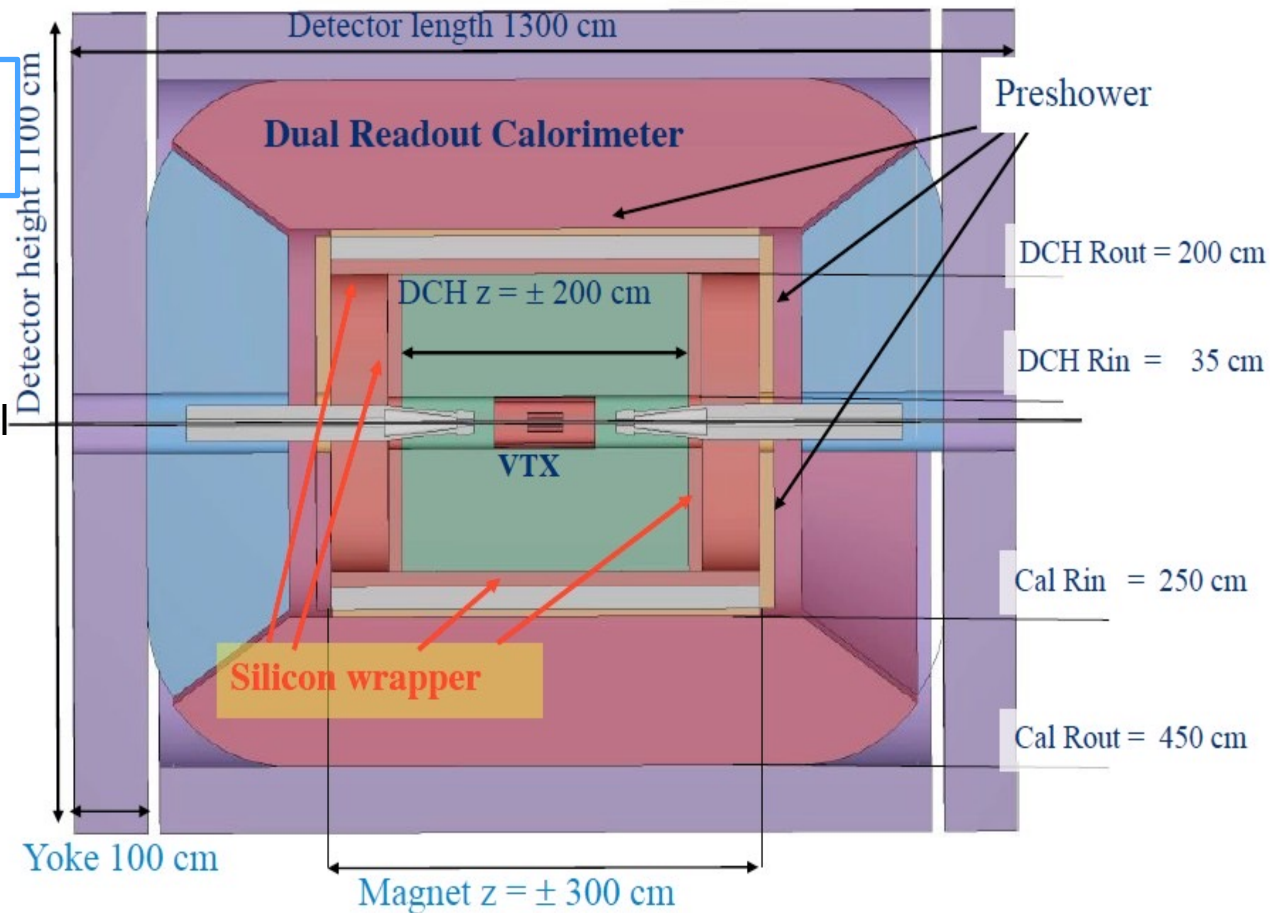
# The IDEA detector at $e^+e^-$ colliders



**Innovative Detector for E+e- Accelerator**

**IDEA** consists of:

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




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

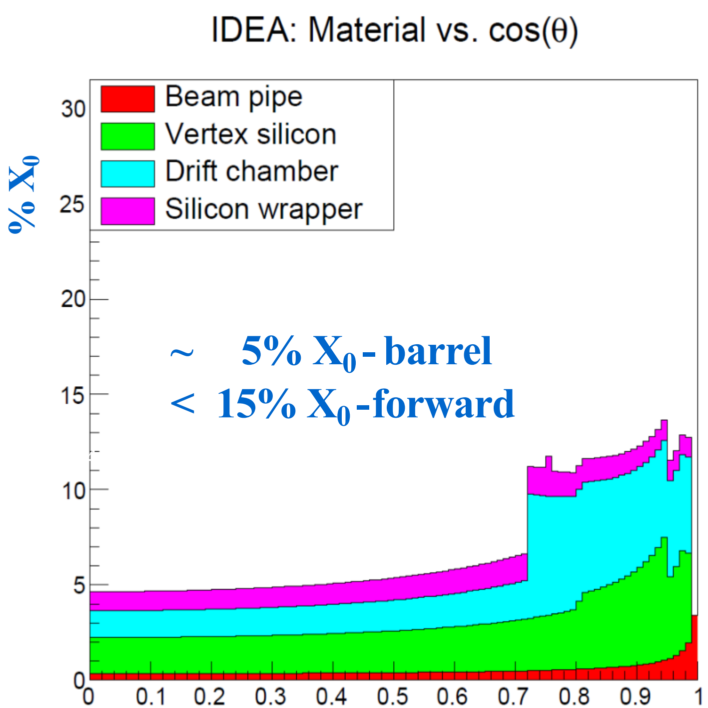
→ optimized at 2 T

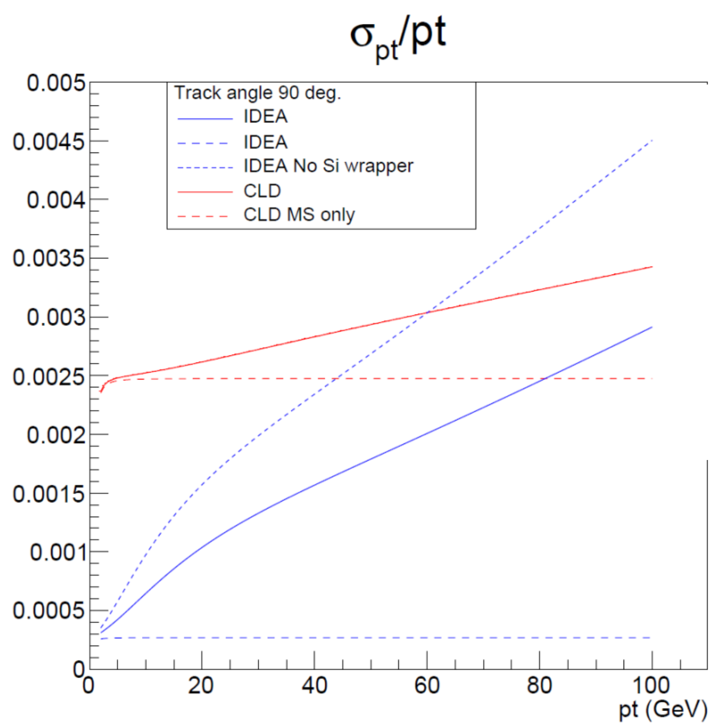
→ large tracking radius needed to recover momentum resolution

# Design features of the IDEA Drift Chamber

For the purpose of tracking and ID at low and medium momenta mostly for heavy flavour and Higgs decays, the IDEA drift chamber is designed to cope with:

- transparency against multiple scattering, more relevant than asymptotic resolution
- a high precision momentum measurement
- an excellent particle identification and separation




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 Drift Chamber of IDEA

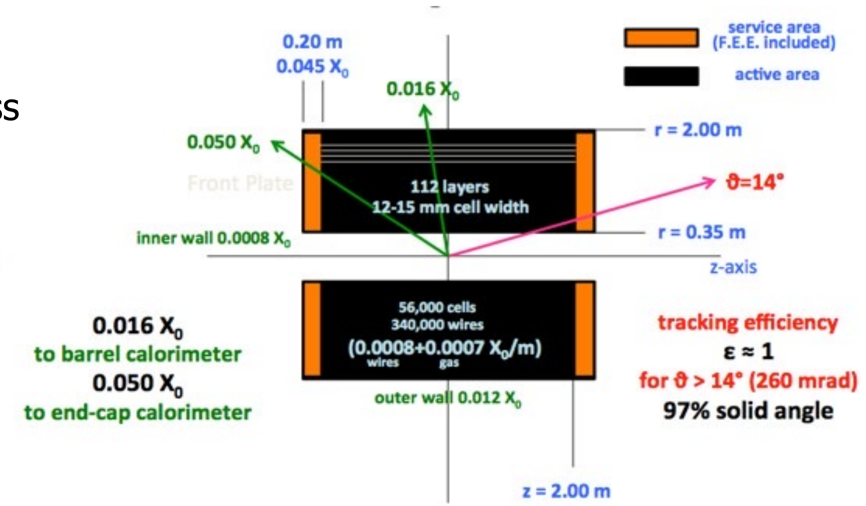
The DCH is:

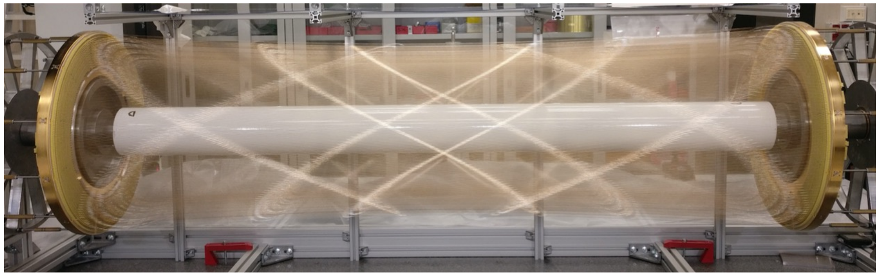
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - $iC_4H_{10}$ 10%
- inner radius $R_{in}$ = 0.35m, outer radius $R_{out}$ = 2m
- length L = 4m
- drift length ~1 cm
- drift time ~150ns
- $\sigma_{xy}$ < 100 μm, $\sigma_z$ < 1 mm
- 12÷14.5 mm wide square cells, 5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

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

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

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



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

- thin wires → increase the chamber granularity → reducing both multiple scattering and the overall tension on the endplates

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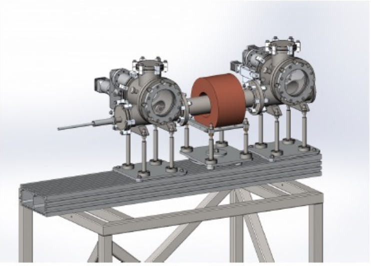
# Challenges for large-volume drift chambers

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

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

The proposed drift chambers for FCC-ee and CEPC have lengths **L = 4 m** and plan to exploit the cluster counting technique, which requires gas gains **~5×10$^5$**.
This poses serious constraints on the drift cell width (**w**) and on the wire material (**YTS**).

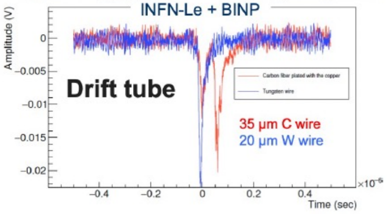
**⇒ new wire material studies**



- **Non-flammable gas / recirculating gas systems**

Safety requirements (**ATEX**) demands stringent limitations on flammable gases;
Continuous increase of **noble gases cost**

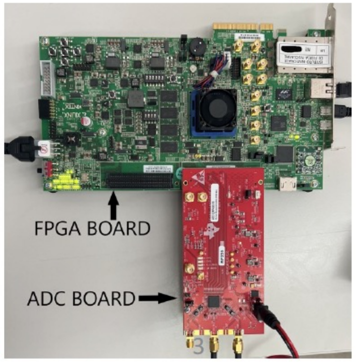
**⇒ gas studies**



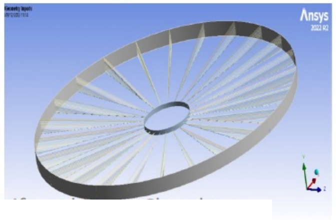

- **Data throughput**

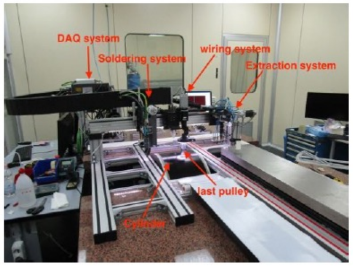
Large number of channels, high signal sampling rate, long drift times (slow drift velocity), required for cluster counting, and high physics trigger rate ($Z_0$-pole at FCC-ee) imply data transfer rates in excess of **~1 TB/s**

**⇒ on-line real time data reduction algorithms**




- **New wiring systems for high granularities / / new end-plates / new materials**



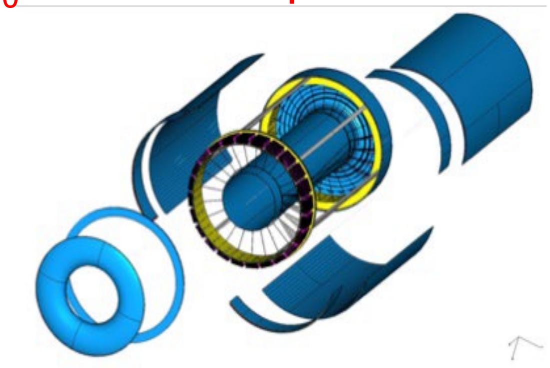



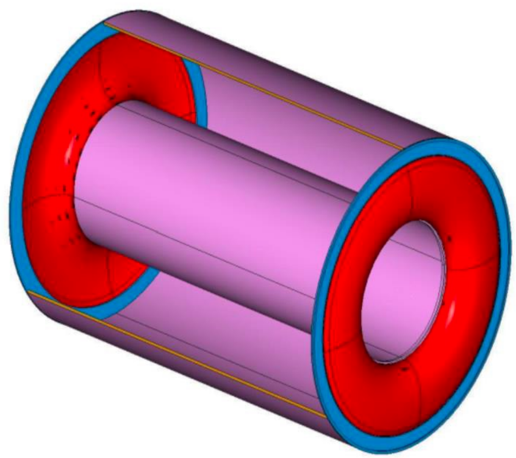
# Mechanical structure of the DCH

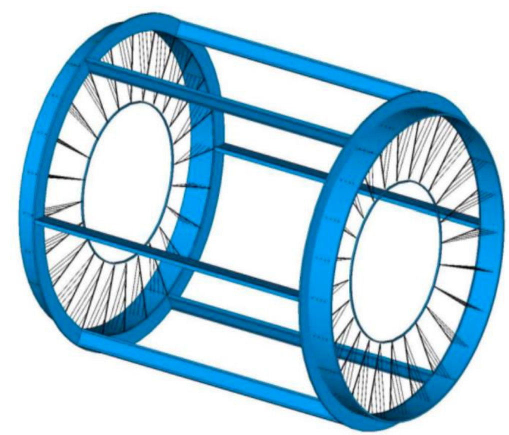
New concept of construction allows to reduce material to ≈ $10^{-3}$ $X_0$ for the barrel and to a few x $10^{-2}$ $X_0$ for the end-plates.

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

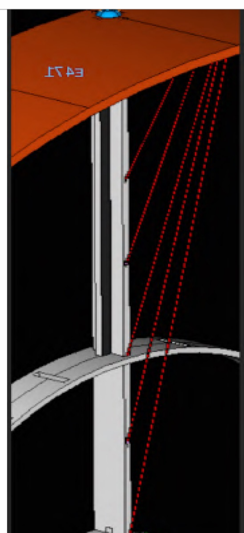
**Wire cage**
Wire support structure not subject to differential pressure can be light and feed-through-less

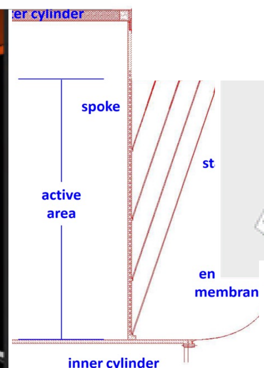


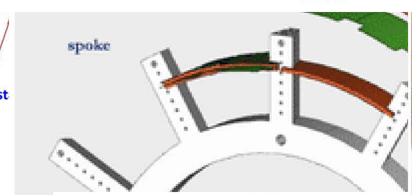


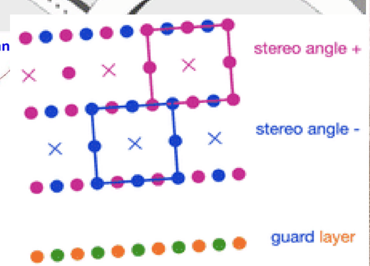


- New tension recovery schema
- Experience inherited from the MEG2 DCH



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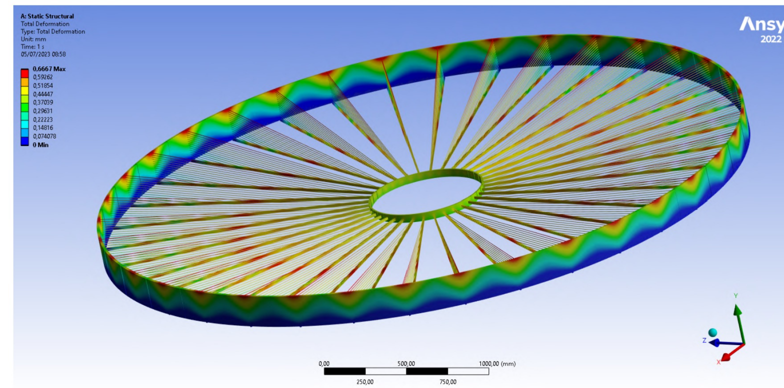
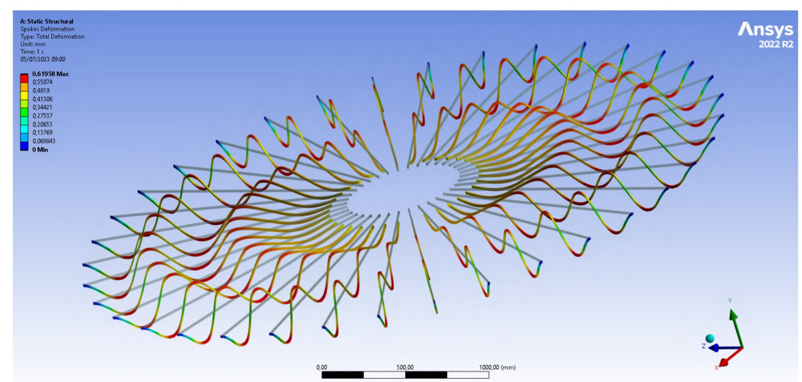
# Mechanical structure with FEM: prestressing

Goal: minimizing the deformation of the spokes using prestressing force in the cables

Finding the correct prestressing force in 14 cables → solving 15 dimensional optimization problem




| Total deformation (mm) of the drift chamber with the edge of the outer cylinders fixed | | | |
|---|---|---|---|
| No prestress | | Prestress in the cables | |
| Spokes | Outer cylinder | Spokes | Outer cylinder |
| 14.099 | 0.63 | 0.62 | 0.67 |




N.B.

- Prestressing not yet optimized
- 24 → 36 spokes considered for this study

The structure exhibited a deformation of 600 μm but our goal was to limit the deformation of the spokes to 200 μm while ensuring the structural integrity.

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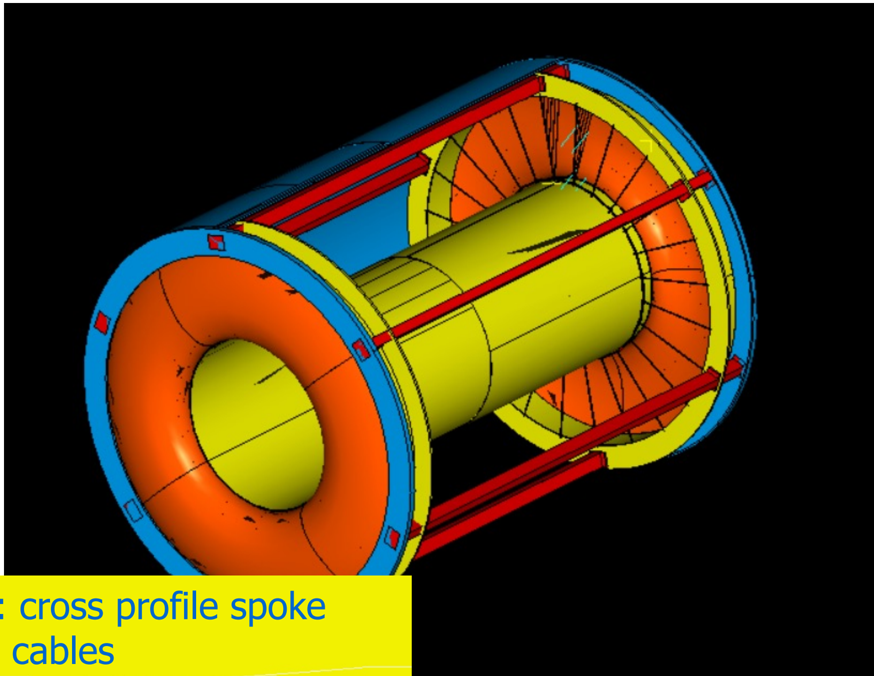
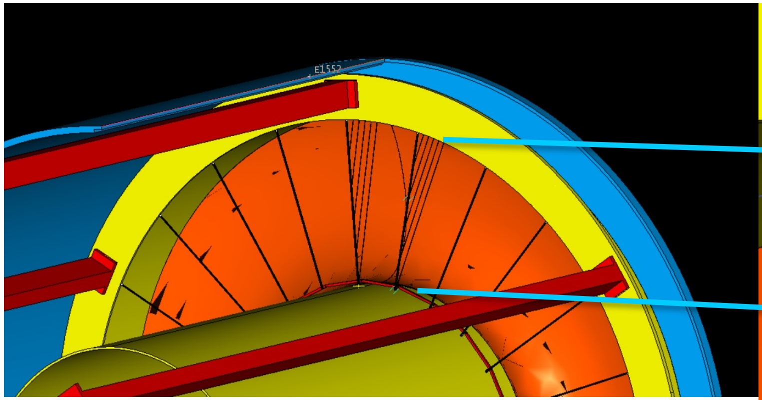
# Mechanical structure: a complete model

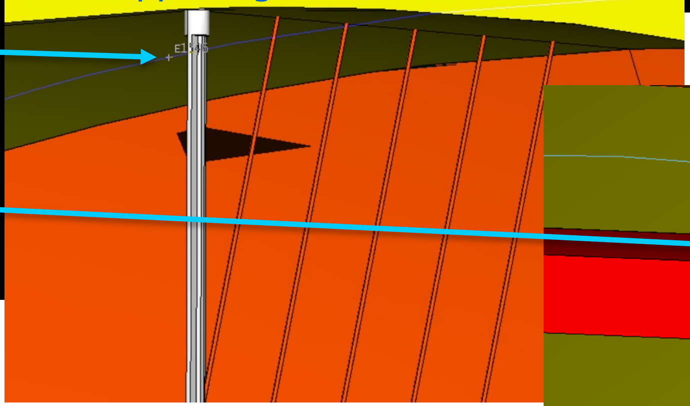
A realistic complete model almost ready:

- 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

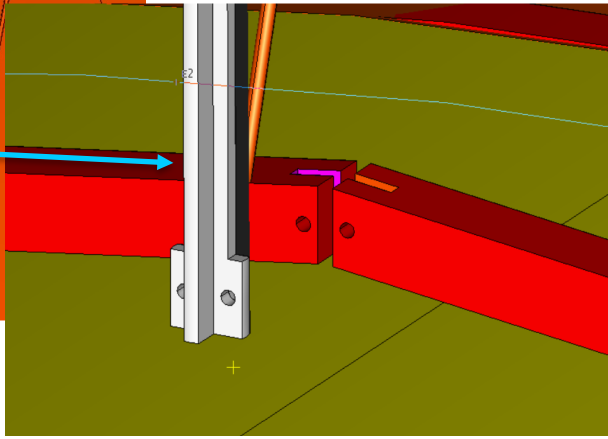
→ the final project ready







Upper junction: cross profile spoke and supporting cables



Lower junction: joint design

Plan to start the construction of a DCH prototype full lenght, one sector, next year.

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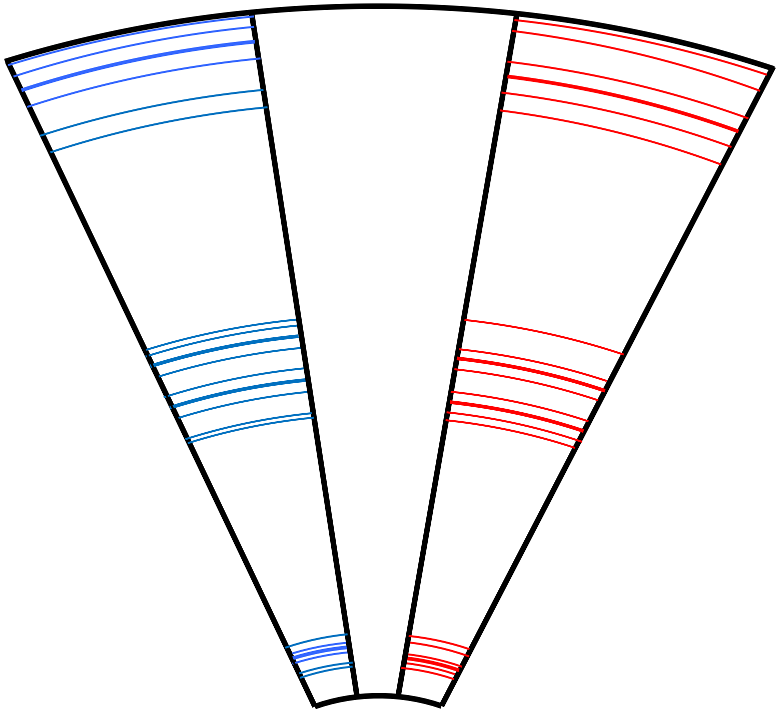
# 2025 full-length prototype: Goals

- 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
  - 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
- Starting from the new concepts implemented in the MEG2 CDCH robot, optimize the wiring strategy, by taking into account the 4m long wires arranged in multi-wire layers
- Define and validate the assembly scheme (with respect to mechanical tolerances) of the multi-wire layers on the end plates
  - Define the front-end cards channel multiplicity and their location (cooling system necessary?)
- Optimize the High Voltage and signal distribution (cables and connectors)
- Test performance of different versions of front-end, digitization and acquisition chain

# 2025 full-length prototype: Wiring



**First two layers of superlayer #1**
- V and U guard layers (2 x 9 guard wires)
- V and U field layers (2 x 18 field wires)
- U layer (8 sense + 9 guard)
- U and V field layers (2 x 18 field wires)
- V layer (8 sense + 9 guard)
- V and U field layers (2 x 18 field wires)
- V and U guard layer (2 x 9 guard wires)

**Last two layers of superlayer #7**
- V and U guard layers (2 x 21 guard wires)
- V and U field layers (2 x 42 field wires)
- U layer (20 sense + 21 guard)
- U and V field layers (2 x 42 field wires)
- V layer (20 sense + 21 guard)
- V field layer (42 field wires)

**First two layers of superlayer #8**
- U field layer (46 field wires)
- U layer (22 sense + 23 guard)
- U and V field layers (2 x 46 field wires)
- V layer (22 sense + 23 guard)
- V and U field layers (2 x 46 field wires)
- V and U guard layer (2 x 23 guard wires)

**Last two layers of superlayer #14**
- V and U guard layers (2 x 35 guard wires)
- V and U field layers (2 x 70 field wires)
- U layer (34 sense + 35 guard)
- U and V field layers (2 x 70 field wires)
- V layer (34 sense + 35 guard)
- V and U field layers (2 x 70 field wires)
- V and U guard layer (2 x 35 guard wires)

**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**

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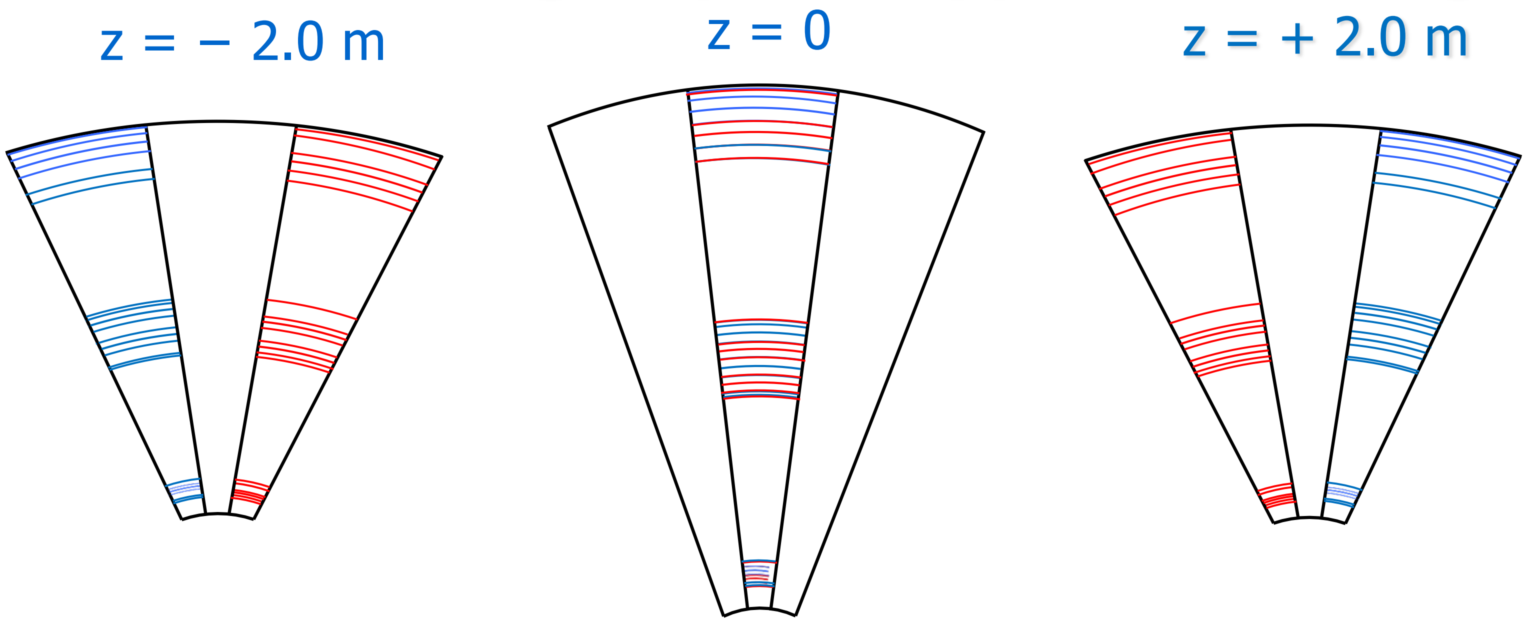
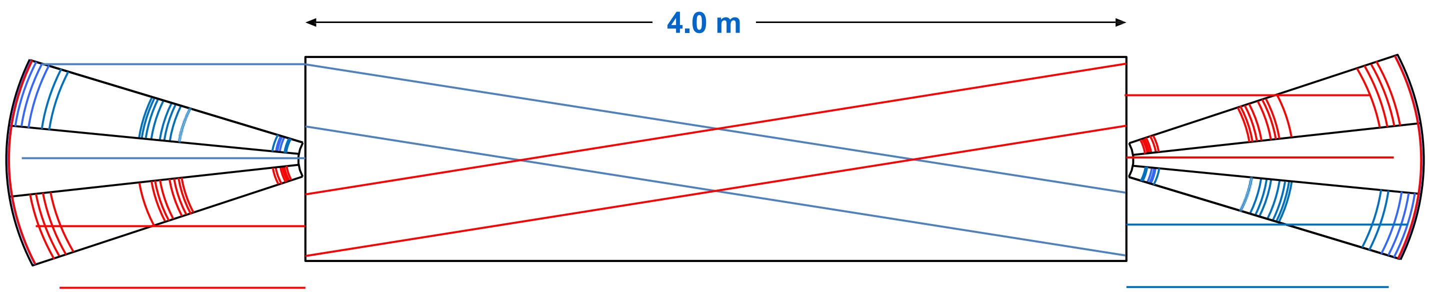
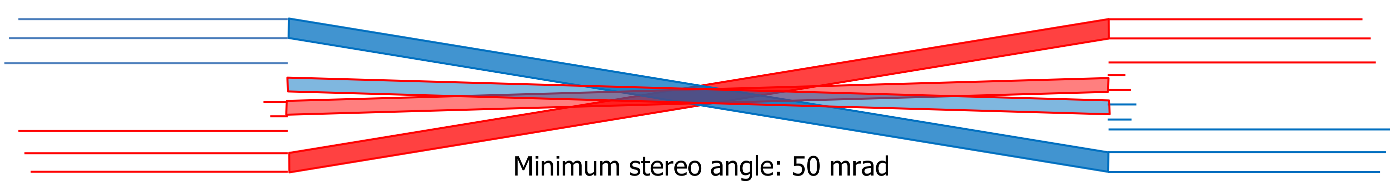
# 2025 full-length prototype: Coverage




## MAX COVERAGE




## ELECTRONICS COVERAGE



Minimum stereo angle: 50 mrad
Maximum stereo angle: 250 mrad

# 2025 full-length prototype: Schedule

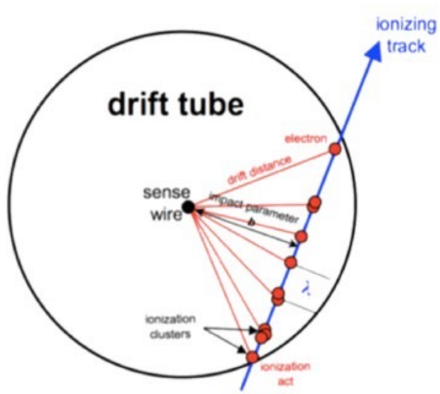
- First phase of conceptual design of full chamber completed as of today by a collaboration of EnginSoft and INFN-LE mechanical service (+ a Master student from Torino Politecnico and a PhD student from Bari Politecnico): final draft of technical report ready
- Full design of full-scale prototype completed by summer 2024 by EnginSoft (purchase order issued) with INFN-LE mechanical service
- Preparation of samples of prototype components (molds and machining) ready by fall 2024 by CETMA consortium
- All mechanical parts (wires, wire PCBs, spacers, end plates) ready by end of 2024
- MEG2 CDCH2 Wiring robot transported from INFN-PI (being used for MEG2 CDCH2 until May 2024) to INFN-LE/BA, refurbished and re-adapted, to be operational by spring 2025
- Wiring and assembling clean rooms:
  - INFN-LE clean room currently occupied by ATLAS ITK assembly (until 2026 ?)
  - Investigating the possibility of using clean rooms at INFN-BA (depending on CMS occupation) or at CNR-LE (subject to agreement between INFN and CNR)
- Wiring and assembling operations would occur during second half of 2025
- Prototype built by end of 2025 (+6 months contingency) and ready to be tested during 2026

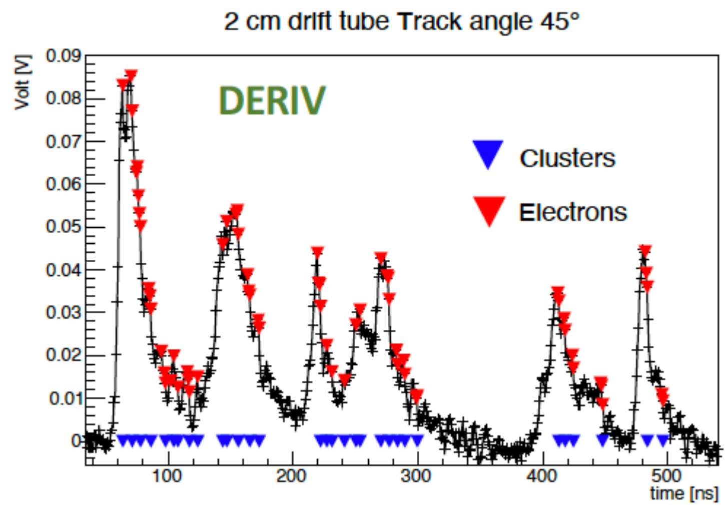
# Testbeam data analysis

# The Drift Chamber: Cluster Counting/Timing and PID

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.




- collect signal and identify peaks
- record the time of arrival of electrons generated in every ionisation cluster
- reconstruct the trajectory at the most likely position

➤ Landau distribution of dE/dx originated by the mixing of primary and secondary ionizations, has large fluctuations and limits separation power of PID → primary ionization is a Poisson process, has small fluctuations

➤ The cluster counting is based on replacing the measurement of an ANALOG information (the [truncated] mean dE/dX ) with a DIGITAL one, the number of ionisation clusters per unit length:

**dE/dx**: truncated mean cut (70-80%), with a 2m track at 1 atm give $\sigma \approx$ 4.3%

**$dN_{cl}/dx$**: for $He/iC_4H_{10}$=90/10 and a 2m track gives $\sigma_{dNcl/dx}$ **$/(dN_{cl}/dx)$** < 2.0%

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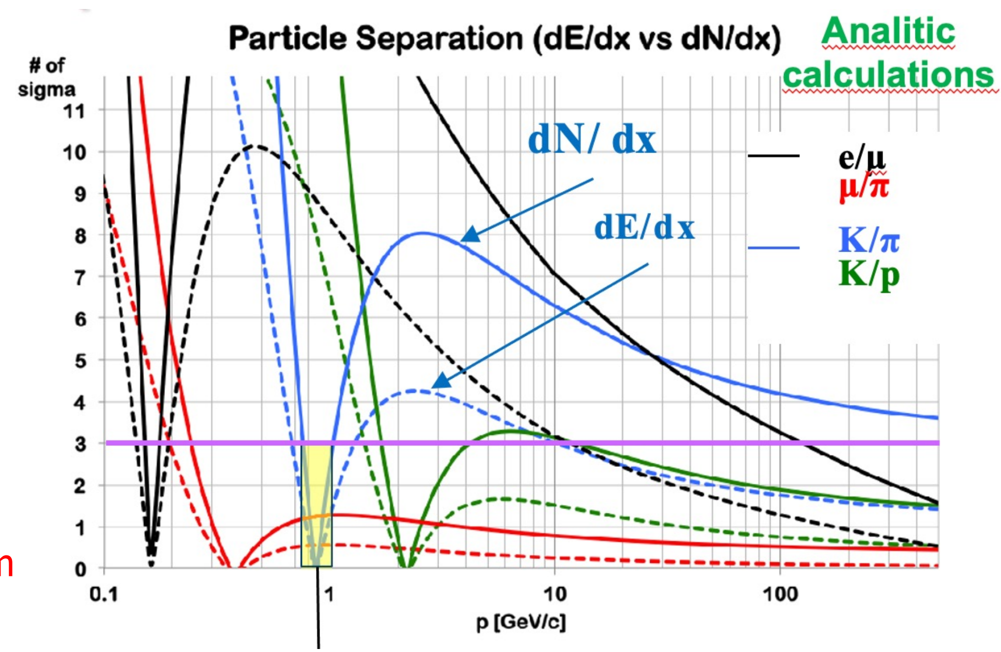
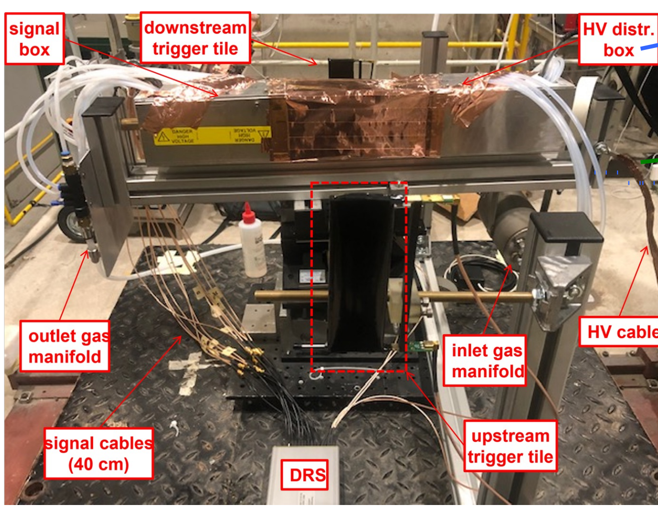
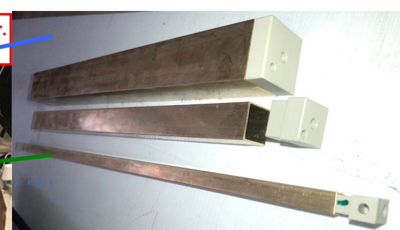
# The Drift Chamber: Cluster Counting/Timing and PID

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

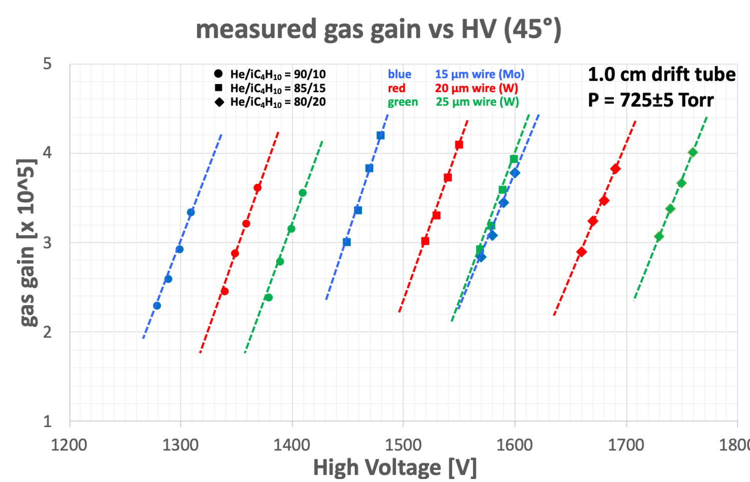
- Simulation with Garfield++ and with the Garfield model ported in GEANT4:
  - the particle separation, both with dE/dx and with $dN_{cl}/dx$, in GEANT4 found considerably worse than in Garfield
  - the $dN_{cl}/dx$ Fermi plateau with respect to dE/dx is reached at lower values of βγ with a steeper slope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



90%He-10%$iC_4H_{10}$
nominal HV+20, 45°,
Gas gain ~ $2 \cdot 10^5$,
165 GeV/c

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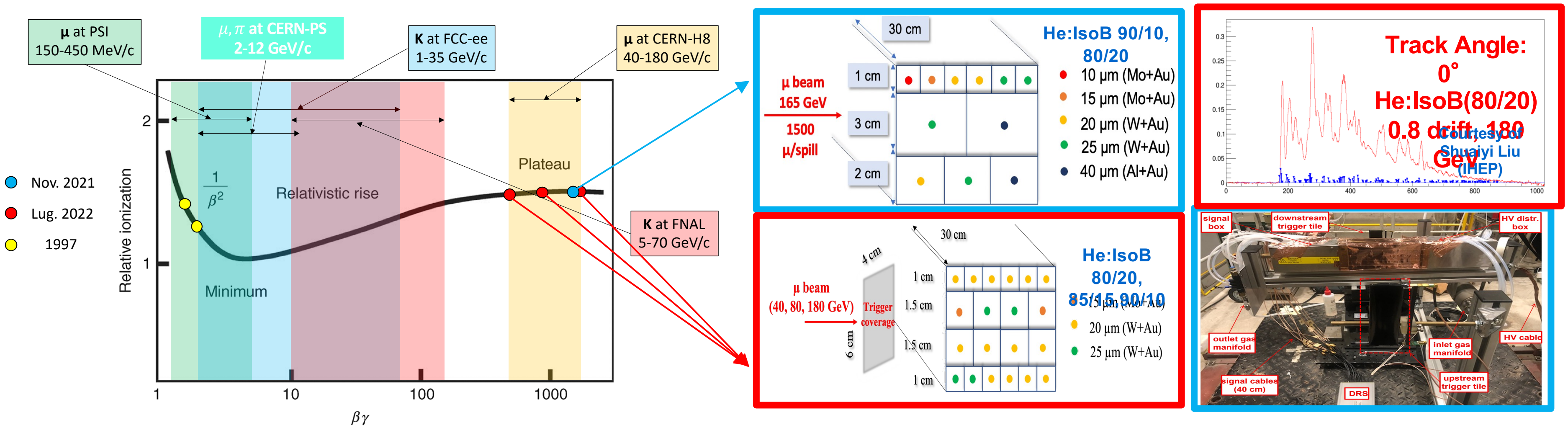
# Beam tests in 2021,2022 and 2023

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

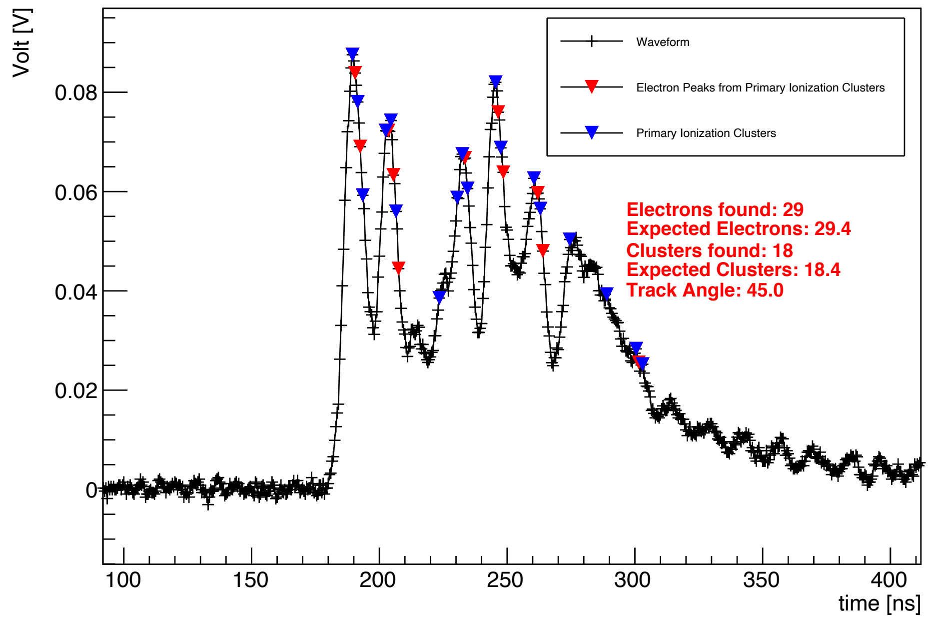
- Two **muon beam tests** performed at **CERN-H8 ($\beta\gamma$ > 400)** in Nov. 2021 and July 2022 ($p_T$ = 165/180 GeV).
- A **muon beam test** (from 4 to 12 GeV momentum) in 2023 performed at **CERN**. A new testbeam with the same configuration starting on July 10, 2024
- Ultimate test at **FNAL-MT6**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



# 2021/2022 beam test results: performance plots

- Several algorithms developed for electron peak finding:
- ✓ Derivative Algorithm (DERIV)
- ✓ and Running Template Algorithm (RTA)
- ✓ NN-based approach (developed by IHEP)
- Clusterization algorithm to merge electron peaks in consecutive bins
- Poissonian distribution for the number of clusters as expected
- Different scans have been done to check the performance: (HV, Angle, gas gain, template scan)

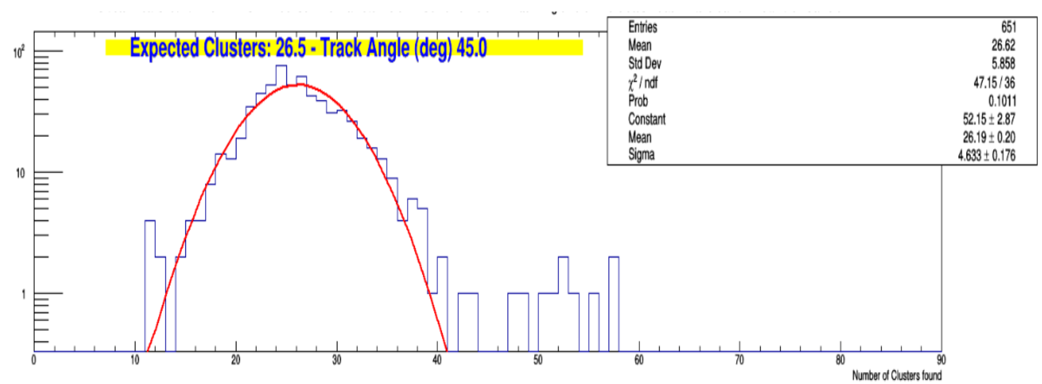
Sense Wire Diameter 15 μm; Cell Size 1.0 cm
Track Angle 45; Sampling rate 2 GSa/s
Gas Mixture He:IsoB 80/20




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

- α = angle of the muon track w.r.t. normal direction to the sense wire
- δ cluster/cm (M.I.P) 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.

## Poissonian distribution for the number of clusters





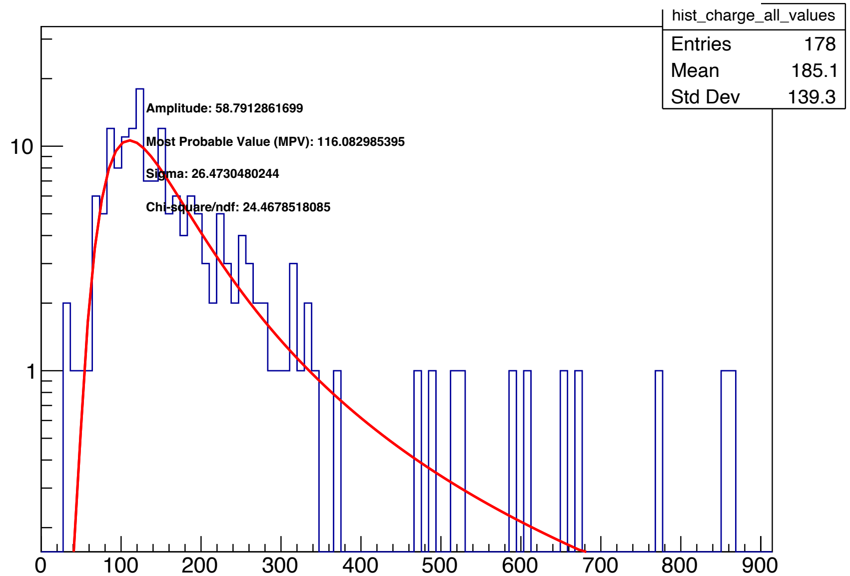
*[1] H. Fischle, J. Heintze and B. Schmidt, Experimental determination of ionization cluster size distributions in counting gases, NIMA 301 (1991)*


N. De Filippis

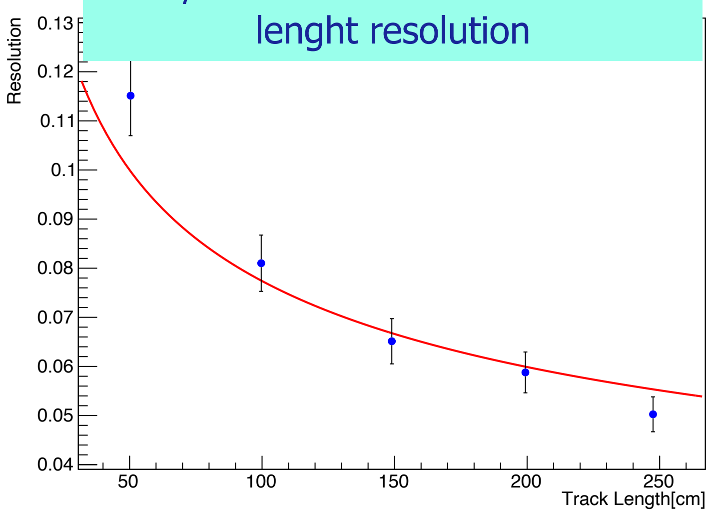
# 2021/2022 beam test results: resolutions

- 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
- NEW results

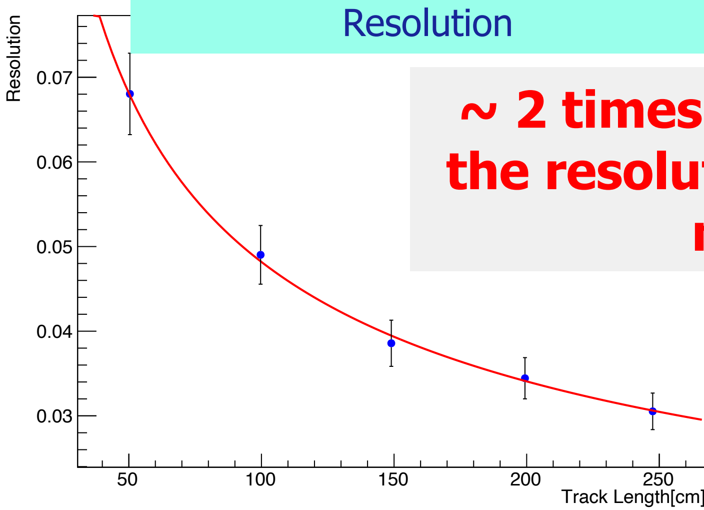
**Integral charges along a 2 m track length**




dE/dx Resolution scan vs track lenght resolution




dN/dx scan vs track lenght Resolution




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

A complete report to be given at ICHEP next week

N. De Filippis

# Summary/Conclusions

Good progress reported on:

- mechanical structure design
- pn going effort to build a full-length prototype next year
- testbeam data analysis → NEW and quite conclusive results

Plenty of areas for collaboration:

- detector design, construction, beam test, performance
- local and global reconstruction, full simulation
- physics performance and impact
- etc.

Effort to build a international collaboration enforced

- well established collaboration with IHEP for NN-based cluster counting algorithms
- started to collaborate with US people from BNL

# Backup

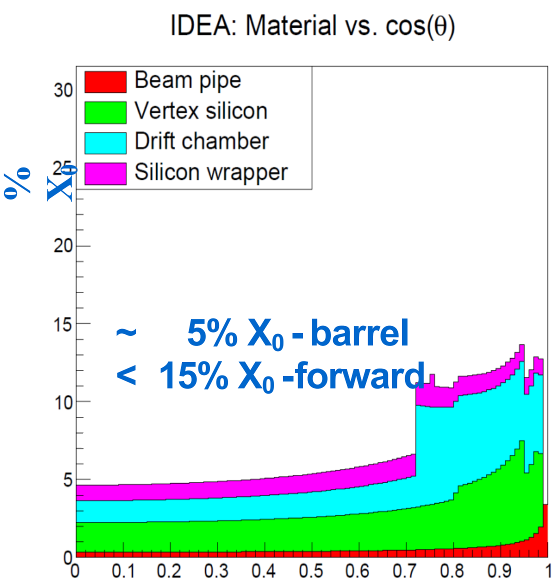
# Requirements on track momentum resolution

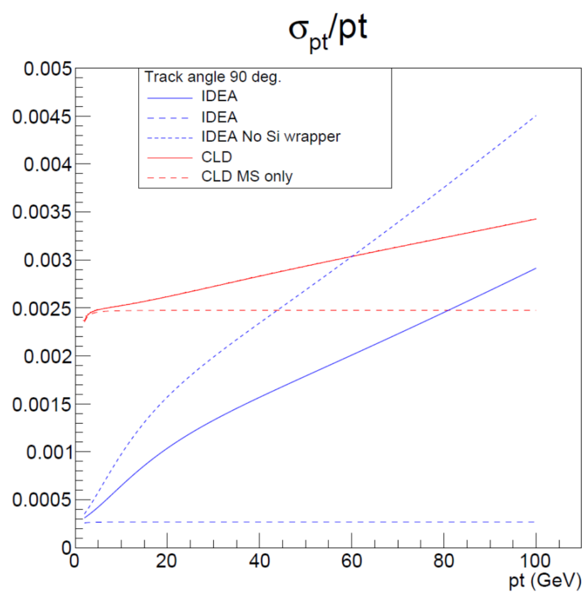
The IDEA Drift Chamber is designed to cope with transparency

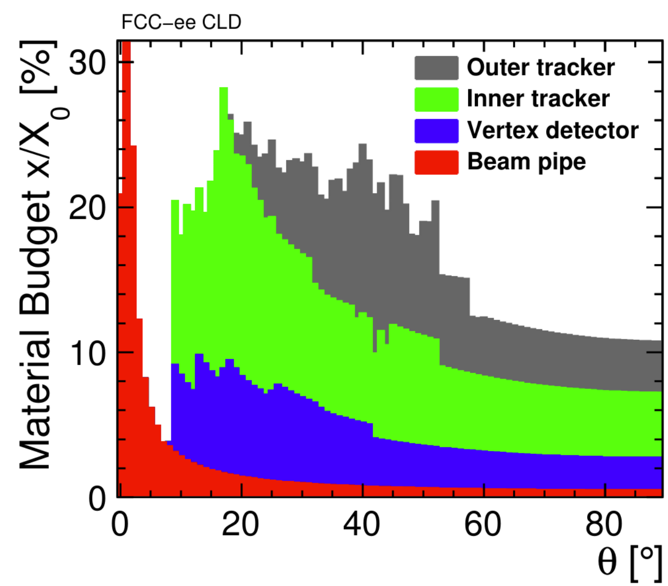
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - $iC_4H_{10}$ 10%
- inner radius 0.35m, outer radius 2m
- length L = 4m

The CLD silicon tracker is made of:

- six barrel layers, at radii ranging between 12.7 cm and 2.1 m, and of eleven disks.
- the material budget for the tracker modules is estimated to be 1.1 − 2.1% of a radiation length per layer




For 10 GeV (50 GeV) $\mu$ 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
- about 0.25% (0.3%) with the CLD full silicon tracker, being dominated by the effect of MS

# Peak finding algos

## Derivative Algorithm (DERIV)

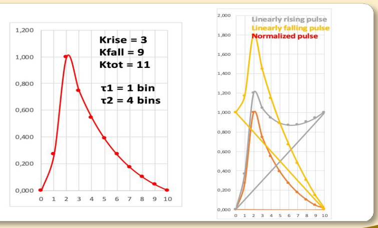
Find good electron peak candidates at position bin n and amplitude $A_n$ :

- 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 $\chi^2$).
- Define a cut on $\chi^2$.
- Subtract the found peak to the signal spectrum.
- Iterate the search.
- Stop when no new peak is found.

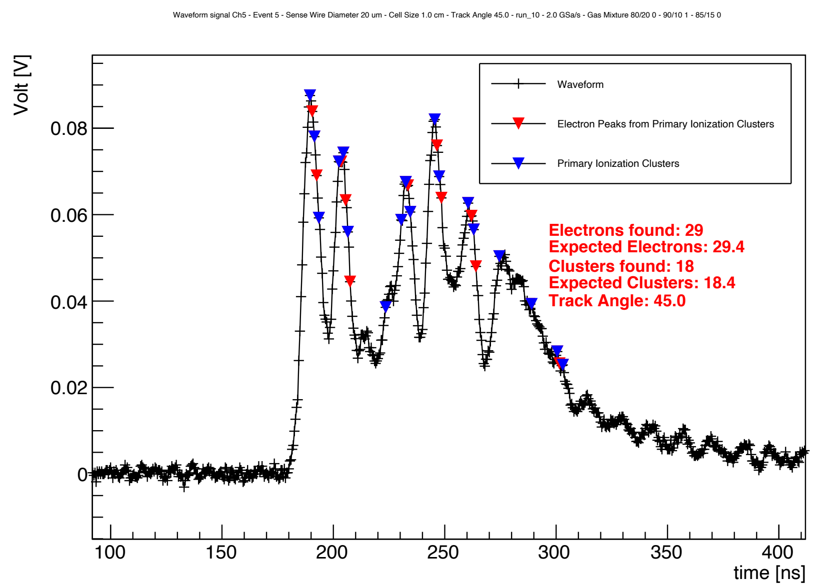
| k | A(k) |
|---|---|
| 0 | 0.0 |
| 1 | 0.269 |
| 2 | 1.0 |
| 3 | 0.744 |
| 4 | 0.545 |
| 5 | 0.390 |
| 6 | 0.269 |
| 7 | 0.175 |
| 8 | 0.102 |
| 9 | 0.044 |
| 10 | 0.0 |



# Peak finding algos

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

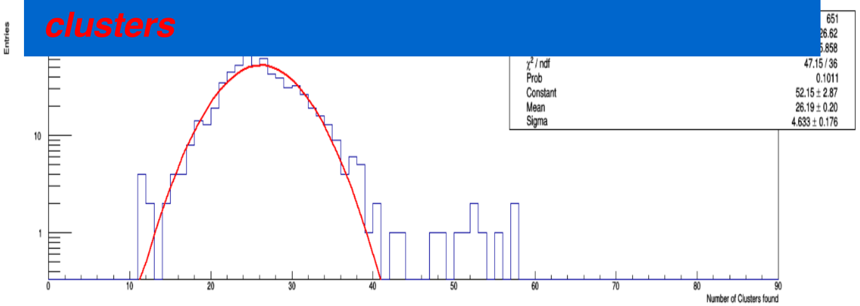
- ***Merging of electron peaks in consecutive bins in a single electron to reduce fake electrons counting.***
- ***Contiguous electrons peaks which are compatible with the electrons' diffusion time (it has a $\sim\sqrt{t_{ElectronPeak}}$ dependence, different for each gas mixture) must be considered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



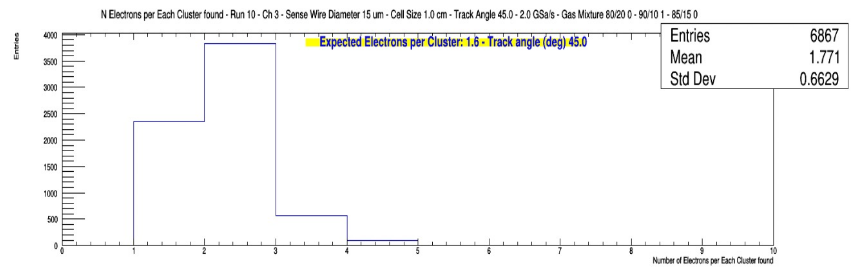
# Reconstruction of primary ionization clusters

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

**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)

**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.

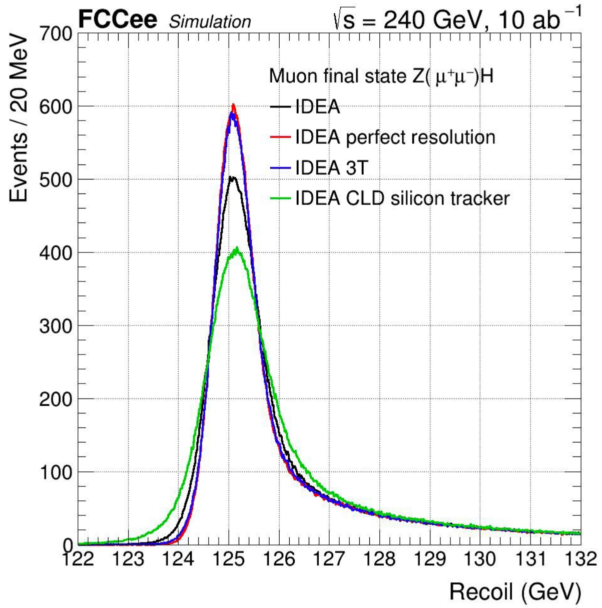
Poissonian distribution of the number of clusters and cluster size in acceptance with the expectation

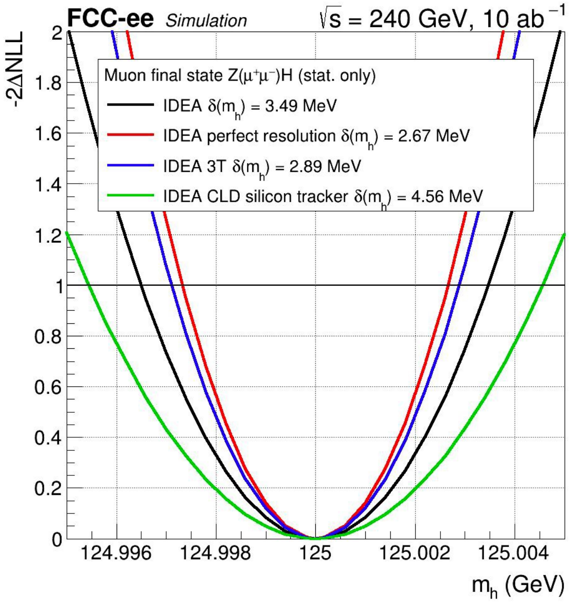
# Constraint from Higgs Mass measurement

Higgs boson mass to be measured with a precision better than its natural width (4MeV), in view of a potential run at the Higgs resonance

Higgs mass reconstructed as the recoil mass against the Z, $M_{recoil}$ , and solely from the Z

$$M^2_{recoil} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$




μ from Z, with momentum of O(50) GeV, to be measured with a $p_T$ resolution smaller than the BES in order for the momentum measurement not to limit the mass resolution

- achieved with the baseline IDEA detector → uncertainty of 4.27 MeV with 10 $ab^{-1}$
- CLD performs less well because of the larger amount of material → larger effects of MS

If the B increased from 2T to 3T → 50% improvement of the momentum resolution
14% improvement on the total mass uncertainty