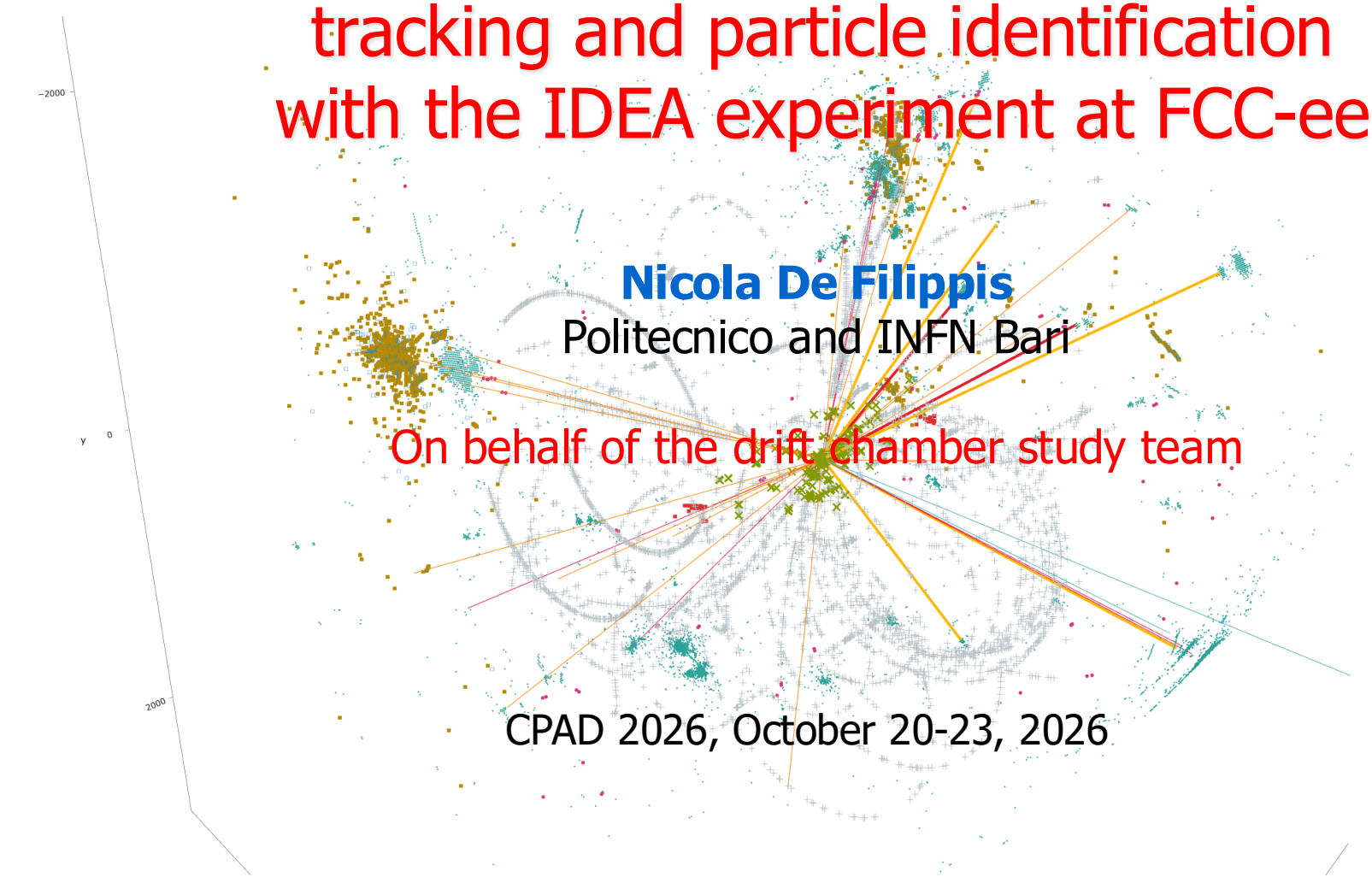
An ultra-light drift chamber for tracking and particle identification with the IDEA experiment at FCC-ee

Nicola De Filippis
Politecnico and INFN Bari

On behalf of the drift chamber study team



CPAD 2026, October 20-23, 2026

European Strategy 2020

*"**An electron-positron Higgs factory is the highest priority next collider**. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy."*

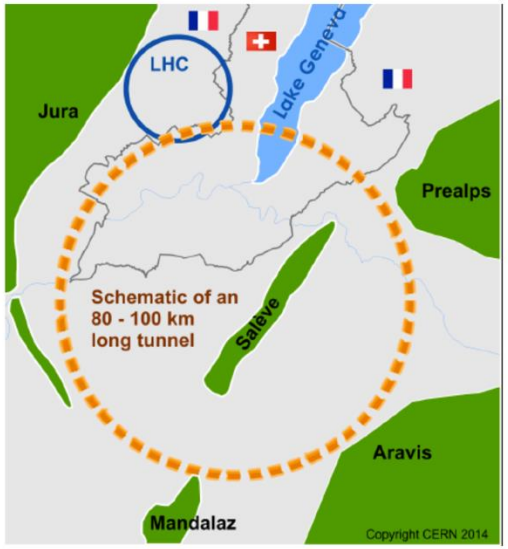
"Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update."

FCC project @ CERN: a new 100 km tunnel in the Geneva region, for two complementary machines covering the largest phase space in the high energy frontier:

- **extreme precision circular e+e-collider (FCC-ee) with** variable collision energy from 90-360 GeV
- **highest energy reach in pp collisions** (**FCC-hh**): 100 TeV

FCC Feasibility Study (FS) launched in 2021:

- To be carried out in 2021-2025
- Mid-term review in Autumn 2023
- March 2025: documentation submitted to ES committe

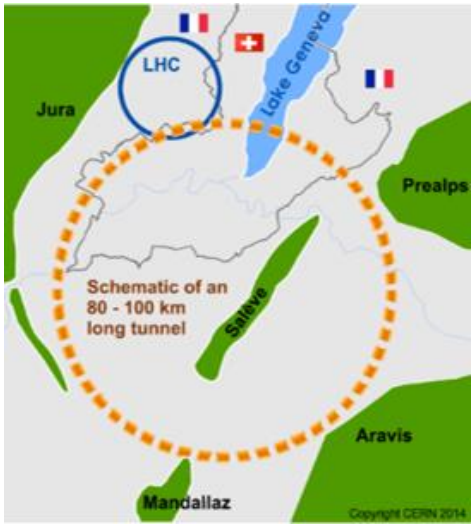


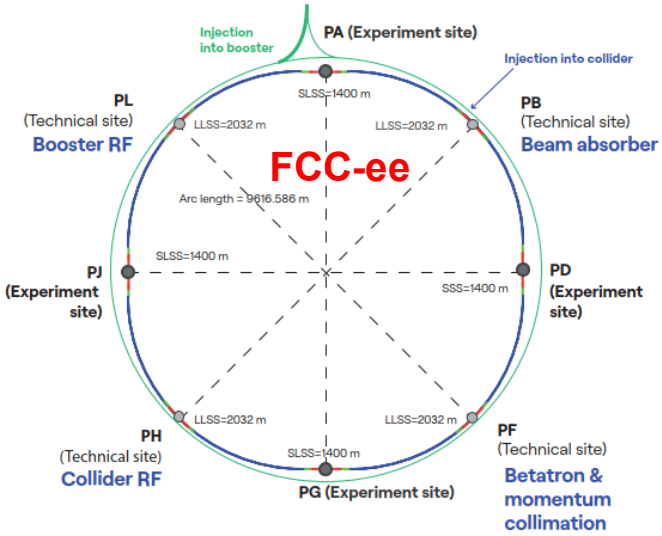


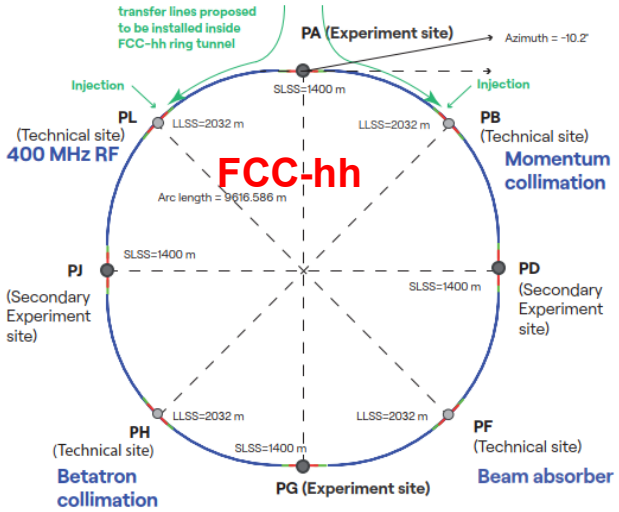
European Strategy 2025 + FCC Week 2026



FCC integrated program - timeline





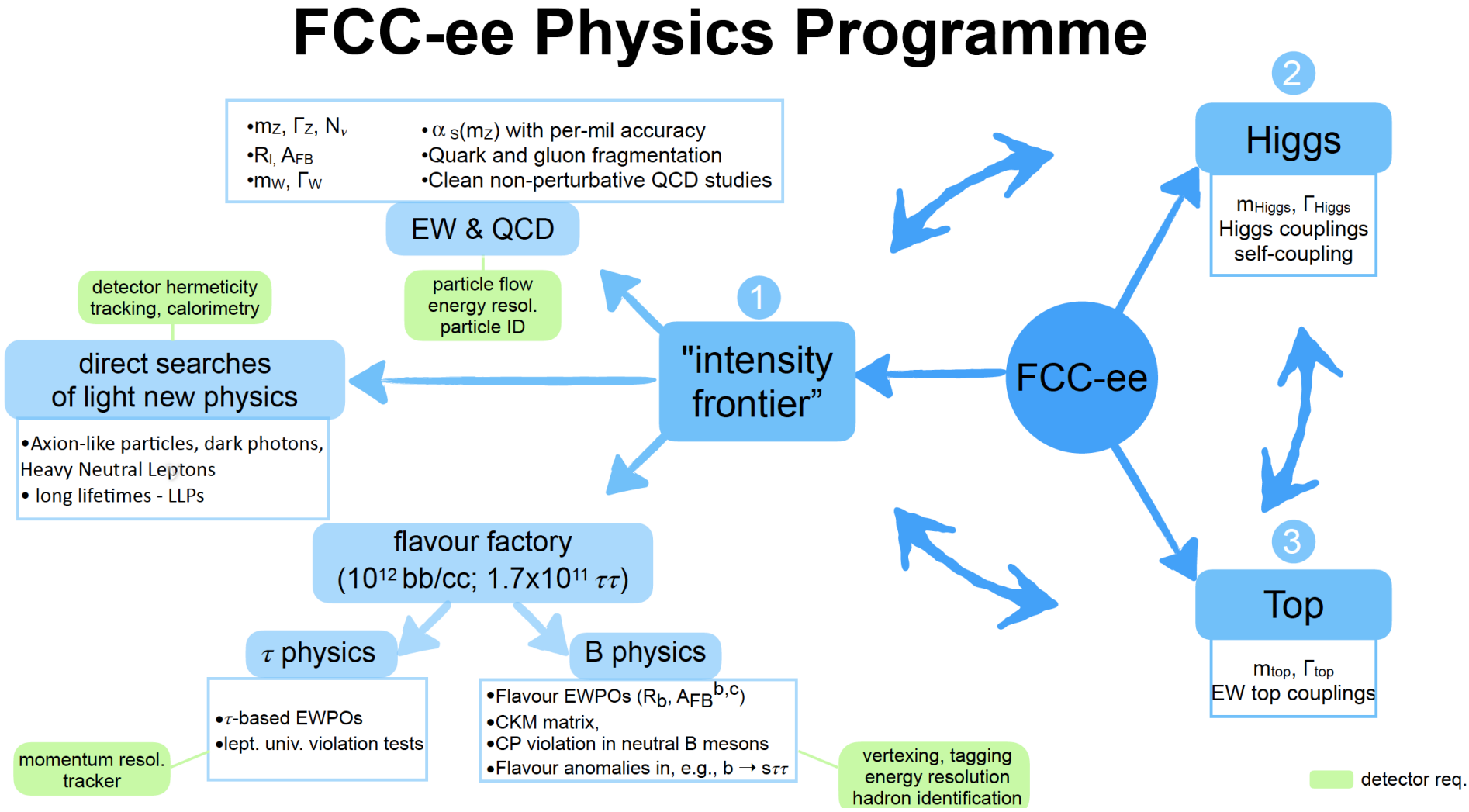


2020 - 2045 | **2048 - 2062** | **2075?**

- **focus on implementation of FCC-ee as first step ; possible pathway to FCC-hh to be decided later**
- **common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure**
- **highly synergetic and complementary physics programme maximising the physics opportunities**
- **FCC-ee project would allow the start of a new, major facility at CERN within a few years of the end of HL-LHC**

Total cost for FCC-ee over ~15 years of about 15 BCHF…

A broad physics program



Physics requirements: Higgs, EWK and Heavy Flavour

- **Tracking:**
  - Momentum resolution for Z recoil (and H→μμ)
    - Comparatively low momenta involved → transparency is important
  - Vertex resolution/transparency to separate g, c, b, τ final states
- **Calorimetry:**
  - Jet-jet invariant mass resolution to separate W, Z, H in 2 jets
  - Good π^0 ID for τ and HF reconstruction

Higgs boson sector

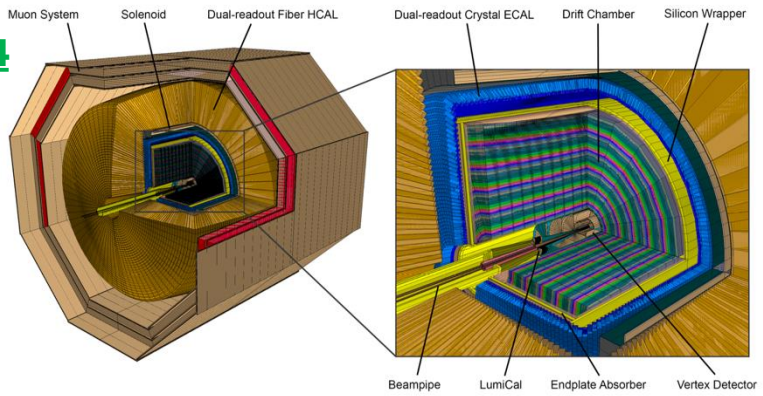
- **EWK:**
  - Extreme definition of detector acceptance
  - Extreme EM resolution (crystals) under study
    - Improved π^0 reconstruction
    - Physics with radiative return
- **Heavy Flavour:**
  - PID to accurately classify final states and flavor tagging

EWK and Heavy Flavour

The IDEA Drift Chamber @ FCC-ee: new concepts

IDEA detector consists of: [arXiv:2502.21223v4]

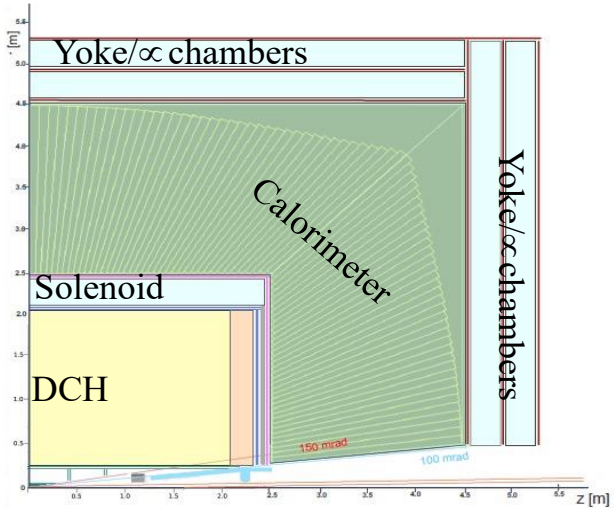
- a silicon pixel vertex detector
- a large-volume extremely-light **drift chamber**
- surrounded by a layer of silicon micro-strip detectors
- a dual-redout crystal ECAL
- a thin low-mass superconducting solenoid coil
- a dual read-out calorimeter HCAL
- muon chambers inside the magnet return yoke,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



drift chamber evolution

KLOE (1998) ⟹ **CMD-2** (2006) ⟹ **MEG2** (2014) ⟹ **IDEA** (2017)

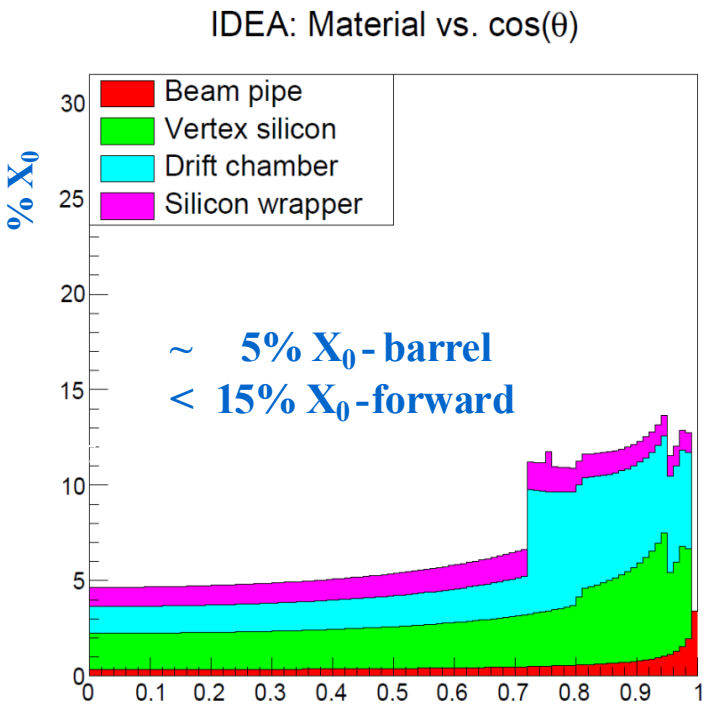
- New mechanical assembly procedure by separating the gas containment from the wire support functions
- New concepts for wire tension compensation resulting in end caps with a 5% X_0 (including front end electronics and cables) and 1.6% X_0 in the radial direction
- A larger number of thinner and lighter wires resulting in less total stress on end plates
- No use of massive feed-through → Feed-through-less wiring
- Use of cluster counting for particle identification
- Use of cluster timing for improving spatial resolution

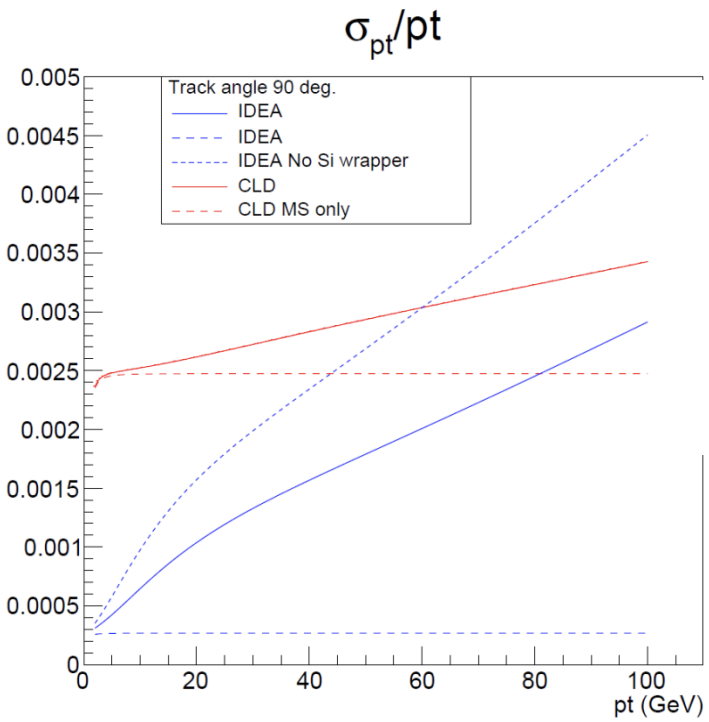


Design features of the IDEA Drift Chamber

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

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

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

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

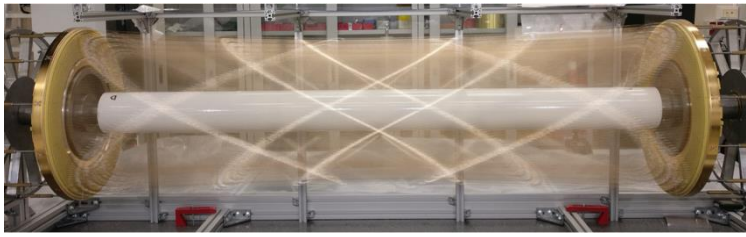
For 10 GeV (50 GeV) μ emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is

- about 0.05 % (0.15%) with the very light IDEA DCH

The Drift Chamber of IDEA

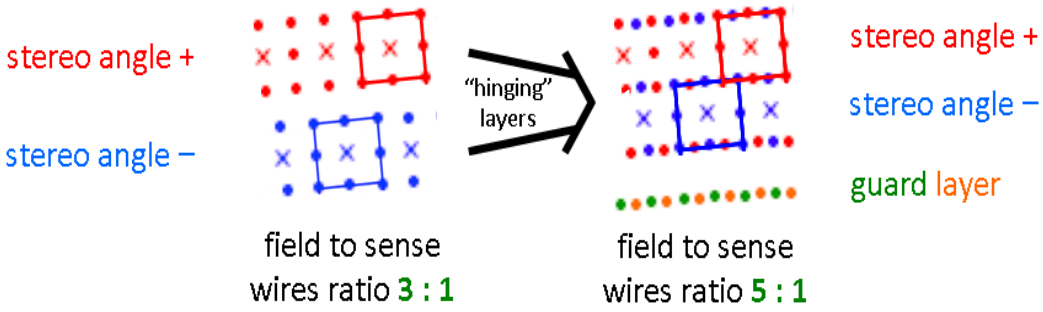
The IDEA DCH is:

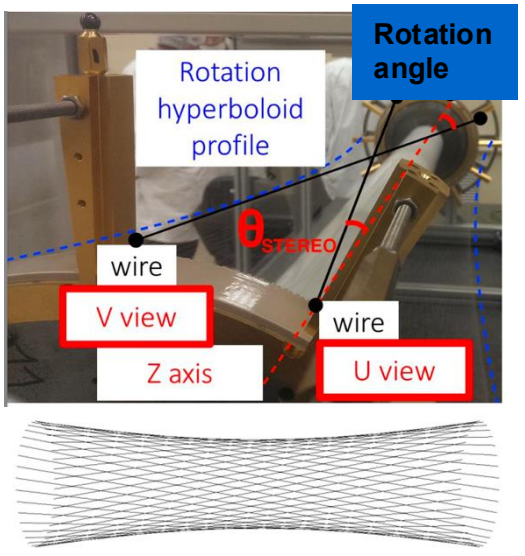
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m
- drift length ~1 cm, drift time up to 400ns
- ➢ σ_{xy} < 100 μm, σ_z < 1 mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires ratio
- 112 co-axial layers (grouped in 14 superlayers of 8 layers), at alternating-sign stereo angles, in 24 azimuthal sectors



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

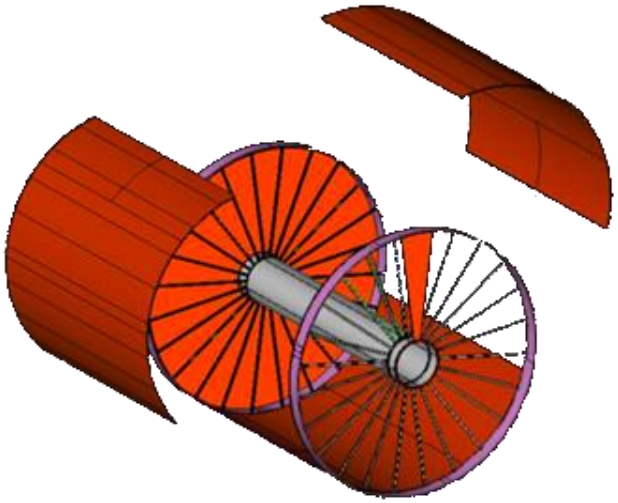




The wire net created by the combination of + and – orientation generates a more uniform equipotential surface

One sector is connected with the first sector next to the corresponding one on the opposite endcap (hyperboloid envelope of stereo wires)

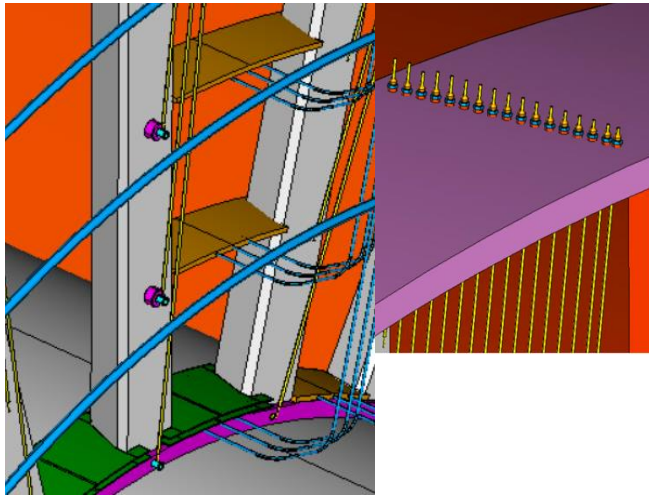
Mechanics for the IDEA DCH



- Outer cylinder made of 3 panels 2 cm thick made of 3 layers (2 monolithic CF with Al honeycomb structure in the middle)
- External and internal ring in monolithic CF
- Endplates made of 48 Spokes (24 per endcap), defining 24 azimuthal sectors.
- Each spoke (length l = 165 cm) is supported by 15 Stays.
- **10 tonnes** of total load on the endcap (30 gr per wire):
  - Load on spokes: 416 kg/spoke → 2.5 kg/cm average
  - Load on stays (14 stays/spoke): ~ 200 kg/stay
- Inner cylinder thickness 200 μm CF – not **structural**

The spoke deformation (due to wires tension) recovery system:

- loading is made with 15 stays;
- the first stay, from the bottom, is anchored directly to the inner ring;
- each stay is anchored to the spoke with a self-adjusting angle system;
- the stay tensioning system is achieved by moving a sphere glued directly onto the CF wire;
- the sphere is moved by a screw-insert system anchored directly into the outer ring.

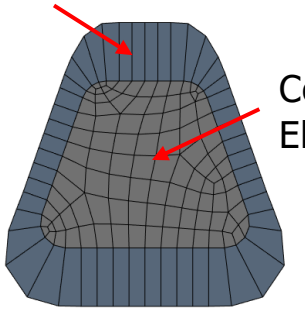


Mechanics for the IDEA DCH: spoke mock-up

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

- Goals: minimizing the deformation of the spokes using prestressing force in the cables.
  - Limit the deformation of the spokes to 200 μm while ensuring the structural integrity → few mm error on the sagitta
- Optimization of spoke cross section: investigated different shapes, finally:

Skin: Layered Shell Elements

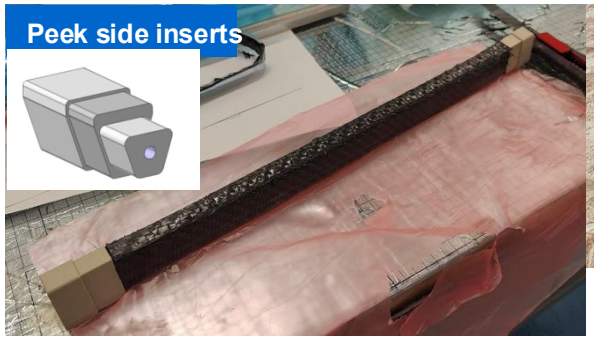


Core: Brick Elements

Carbon foam core 6x lighter than aluminum (FOAM ROHACELL® 35 HTC)

Item	Prepreg Tissue	CPT (mm)	Layup	T (mm)
Internal wrapping	430g/m^2	0.5	(0)3	1.5
Longitudinal reinforcement	800g/m^2	0.86	(0)4	4
External wrapping	430g/m^2	0.5	(0)3	1.5

- Production of a spoke prototype (50 cm long):
- The core was milled with a numerically controlled machine.
- The winding foils were manually cut into strips of the sizes in figure
- The PEEK side inserts were glued with acrylic adhesive





IDEA 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 DCH 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?)

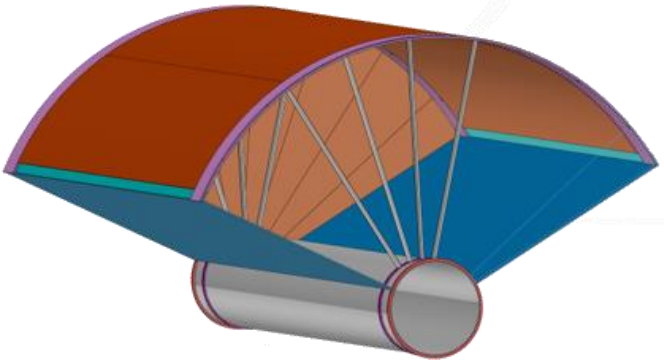
- **Optimize the High Voltage and signal distribution** (cables and connectors)

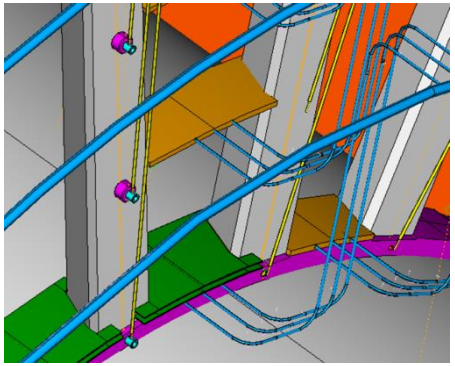
- Test performance of **different versions of front-end, digitization and acquisition chain**

- ***Full-length prototype necessary***
  - ***Can be done in parallel on small prototypes***

IDEA full-length prototype

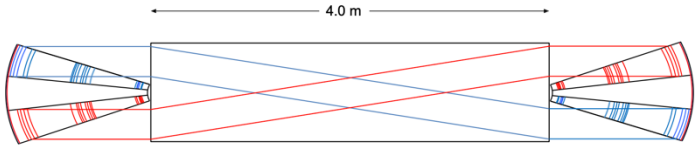
Target: a full length DCH prototype with 3 sectors per endcap

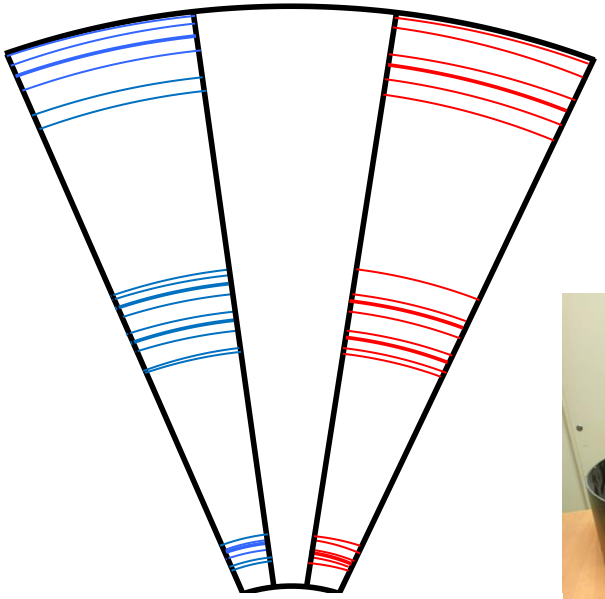




- 8 spokes (4 per endcap)
- Internal ring
- part of the outer ring
- part of the cylindrical panel

MAX COVERAGE





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

Internal ring and a spoke delivered recently → mechanical test will start soon





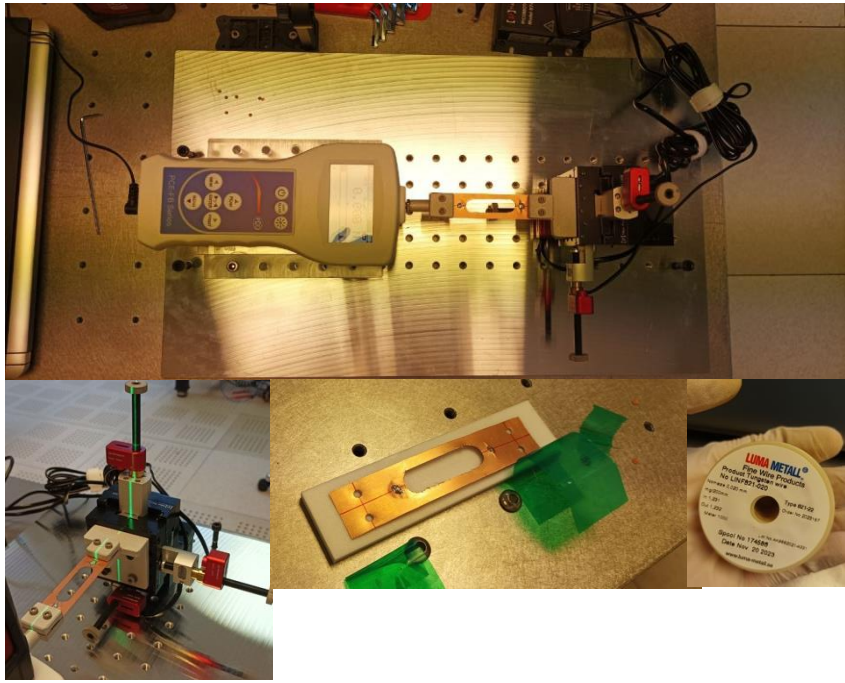
Wire tests with standard protocol

Tests made in a clean room at INFN Bari:

- 20 μm diameter tungsten wire coated with gold
- 20 μm diameter molibdenum coated with gold
- 33.5 μm diameter carbon monofilament
- 40 μm aluminium field wires tested but the wire is slipping at the glued point → new glue

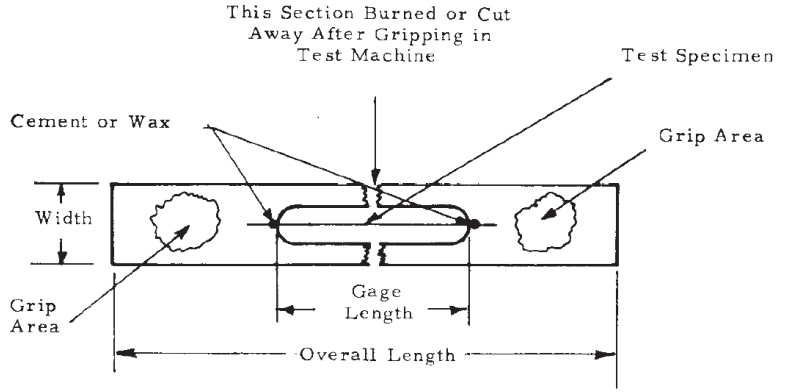
Setup:

- 3 axis picometer slides (30nm step)
- digital dynamometer (acc. 0.001N)



Protocol for measurements (ASTM D 3379 – 75):

- **Scope**: Tensile Strength and Young's modulus for High-Modulus (>21 GPa) Single-Filament Materials (gauge length > 2000*wire diameter)
- **Summary**:
- the filaments are center-line mounted on special slotted tabs.
- the tabs are gripped so that the test specimen is aligned axially in the jaws of a constant-speed movable-crosshead test machine.
- the filaments are stressed to failure

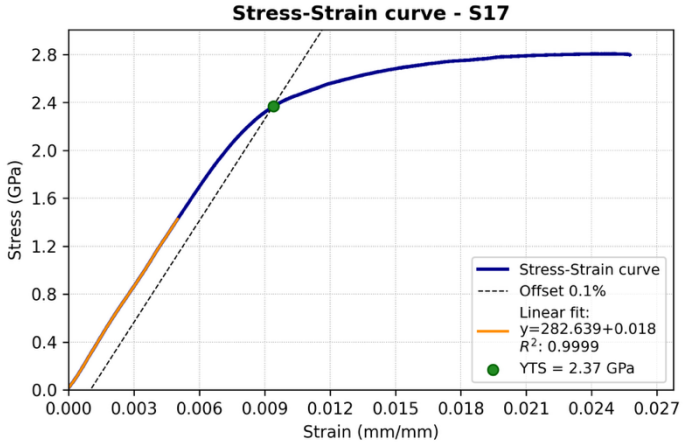


Full report at the last DRD1 coll. meeting:
https://indico.cern.ch/event/1632132/contributions/6923854/

Wire tests: curves

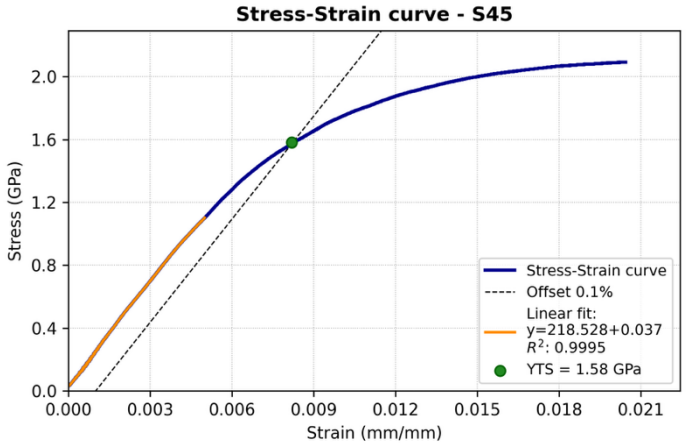
W (Z=74)+Au wire test

- conductive, easy to solder
- Wire diameter: 20 µm, filaments (S#) 40-60 mm long



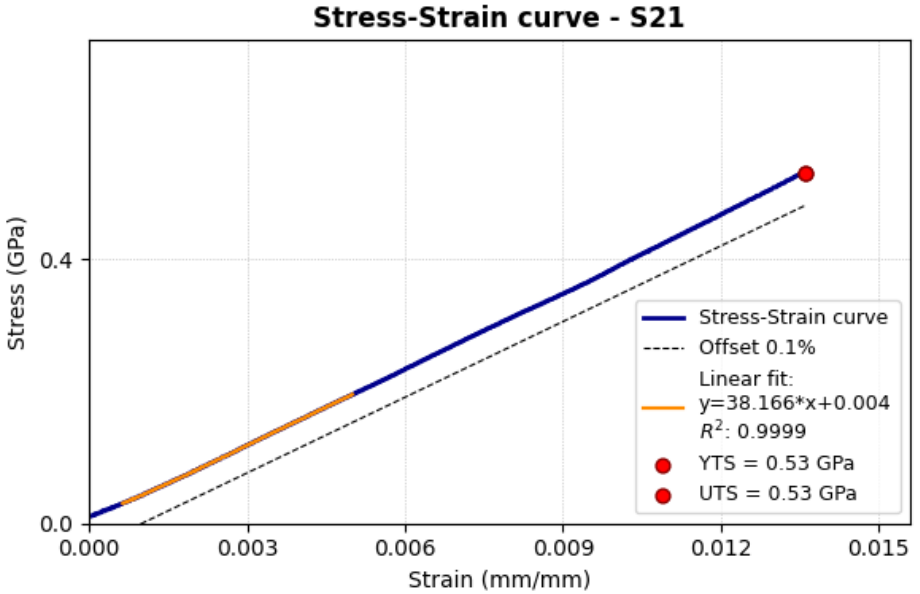
Mo (Z= 42)+Au wire test

- conductive, easy to solder
- Wire diameter: 20 µm, filaments (S#) 50 mm long



Monofilament C (Z=6) wire test

- Not conductive (requires coating)
- Wire diameter: 33.3 µm, filaments (S#) 40 mrn long



Also:

- Aluminium wire: mechanical studies ongoing for the best gripping system.
- Steel wire: other candidate under study with diameter of 30µm and 50µm

Wire tests: results

- Gold-plated Tungsten (20 µm)
  - UTS ≈ 2.80 Gpa
  - Young's Modulus ≈ 285.5 GPa
  - Very stable elastic behavior

Statistics	Ultimate Tensile Strength - UTS (GPa)	Effective time test (s)	Total wire elongation (mm)	Elongation (%)	Elastic limit strain (mm/mm)	Yield Tensile Strength - YTS (GPa)	Young module - E (GPa)
Mean	2.80	63.13	1.26	2.53	0.0092	2.34	285.51
Std. Dev.	0.01	1.70	0.03	0.06	0.0002	0.02	6.04

- Gold-plated Molybdenum (20 µm)
  - UTS ≈ 2.11 Gpa
  - Young's Modulus ≈ 219.2 GPa
  - Slightly lower stiffness compared to W

Statistics	Ultimate Tensile Strength - UTS (GPa)	Effective time test (s)	Total wire elongation (mm)	Elongation (%)	Elastic limit strain (mm/mm)	Yield Tensile Strength - YTS (GPa)	Young module - E (GPa)
Mean	2.11	51.08	1.02	2.04	0.0084	1.61	219.17
Std. Dev.	0.01	1.03	0.02	0.04	0.0003	0.03	7.62

- Carbon Monofilament (33.5 µm)
  - UTS ≈ 0.69 Gpa
  - Young's Modulus ≈ 0.69 GPa.
  - Brittle behavior (no plastic region)
  - Requires coating and further optimization

Plan: long-term load-bearing test for 4m wire (+ aging)

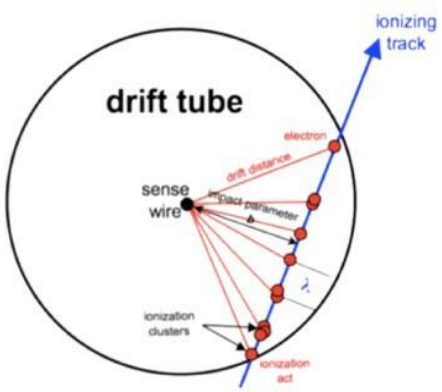
Statistics	Ultimate Tensile Strength - UTS (GPa)	Strain at UTS (mm/mm)	Young module - E (GPa)	Yield Tensile Strength - YTS (GPa)	Elastic limit strain (mm/mm)	Effective time test (s)	Total wire elongation (mm)	Elongation (%)
Mean	0.69	0.0176	38.24	0.69	0.0176	35.12	0.70	1.75
Std. Dev.	0.12	0.0028	0.53	0.12	0.0028	5.67	0.11	0.29

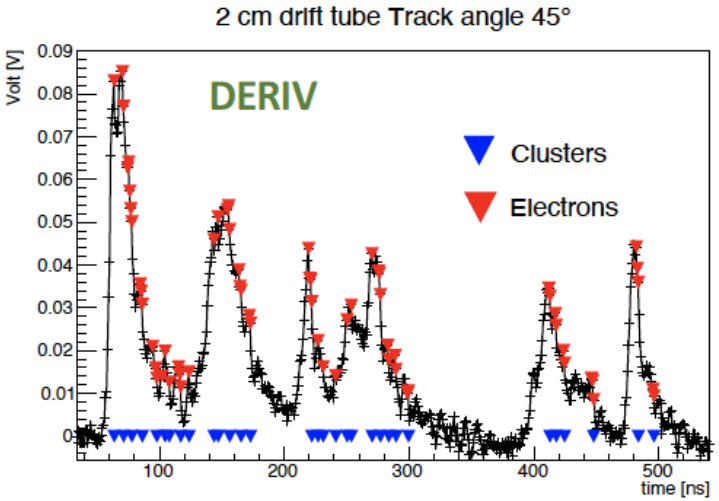
Testbeam activities

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:

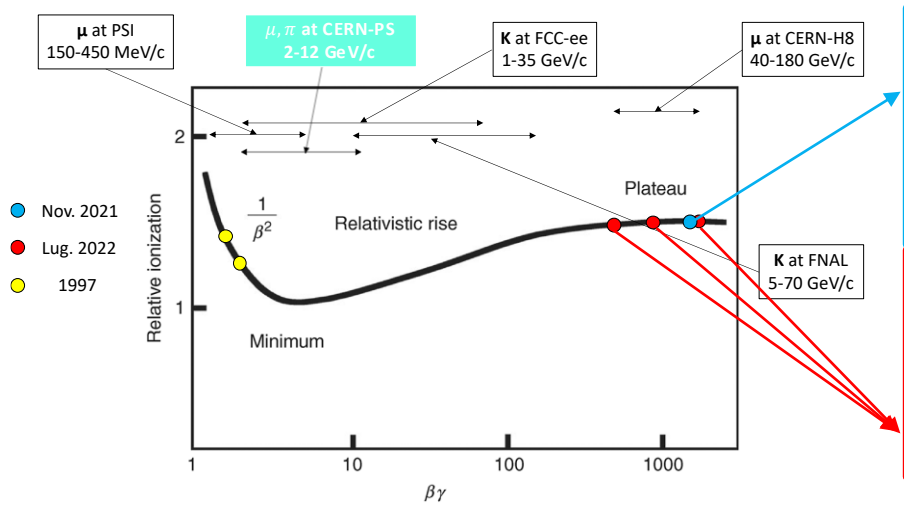
dE/dx: truncated mean cut (70-80%), with a 2m track at 1 atm give $\sigma \approx 4.3\%$

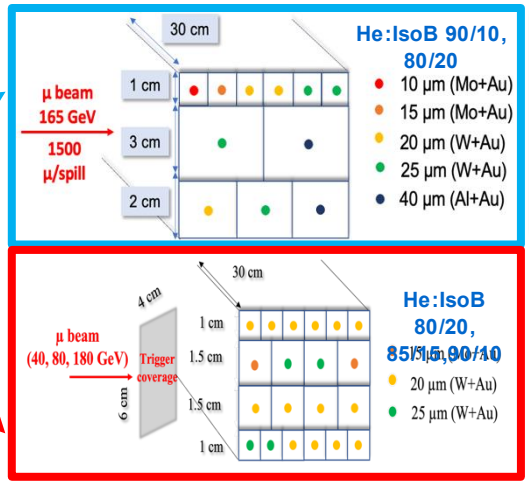
dN_{cl}/dx: for He/iC_4H_{10}=90/10 and a 2m track gives $\sigma_{dNcl/dx}$ **$/(dN_{cl}/dx)$** < 2.0%

Testbeam campaigns

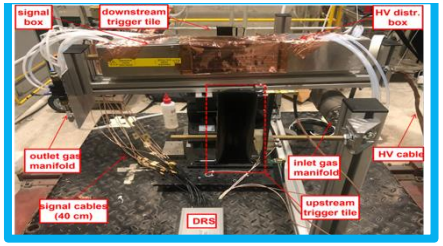
Beam tests to experimentally asses and optimize the **performance of the cluster counting/timing** techniques:

- two **muon beam tests** performed at **CERN-H8** **(βγ > 400)** in Nov. 2021 and July 2022 (p_T = 165/180 GeV) → **publication in next slide**
- a **muon beam test** (from 4 to 12 GeV momentum) in 2023 and 2024 performed at **CERN T10** – **analysis under finalization**
- test at **CERN T9** made on **May 27-June 10, 2026** with □ , **K** and μ at low momenta (2-16 GeV) to exploit the relative rise and the **particle separation with the cluster counting (for the first time)**



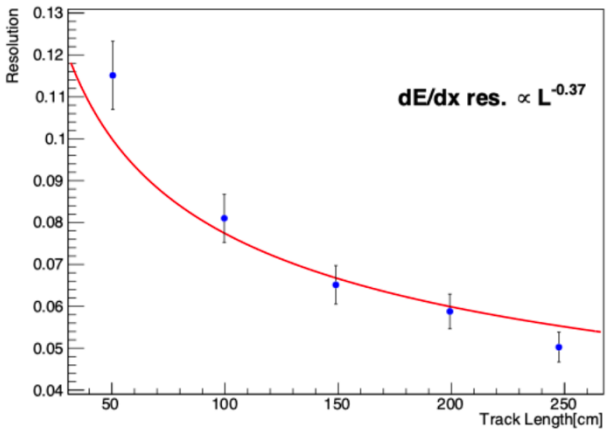


90%He-10%iC$_4$H$_{10}$
nominal HV+20, 45°,
Gas gain ~ 2 · 10^5,
165 GeV/c



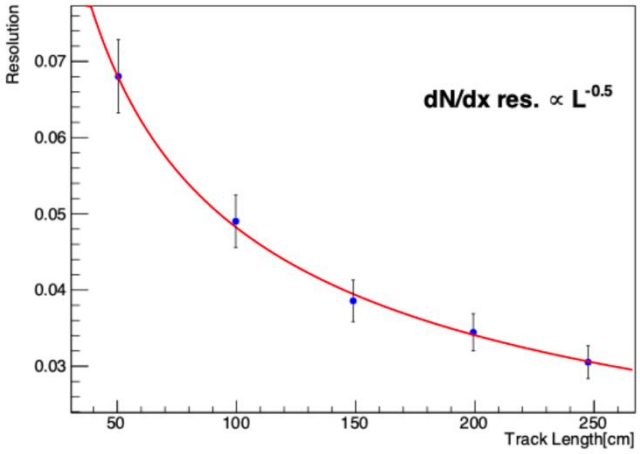
2021/2022 beam test results: performance plots

dE/dx Resolution



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

dN/dx Resolution



W. Elmetenawee *et al* 2025 *JINST* 20 P11019

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Enhancing particle identification in helium-based drift chambers using cluster counting: insights from beam test studies

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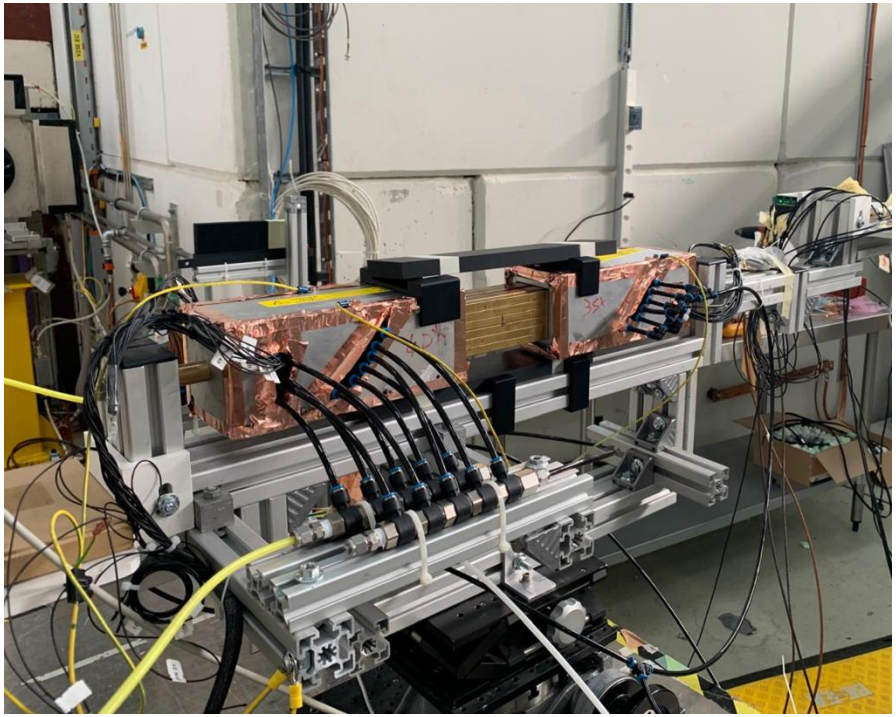
Abstract: Particle identification in gaseous detectors traditionally relies on energy loss measurements (dE/dx); however, uncertainties in total energy deposition limit its resolution. The cluster counting technique (dN/dx) offers an alternative approach by exploiting the Poisson-distributed nature of primary ionization, providing a statistically robust method for mass determination. Simulation studies with Garfield++ and Geant4 indicate that dN/dx can achieve twice the resolution of dE/dx in helium-based drift chambers. However, experimental implementation is challenging due to signal overlap in the time domain, complicating the identification of electron peaks and ionization clusters. This paper presents novel algorithms and modern computational techniques to address these challenges,

2025 JINST 20 P11019

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

Beam test at CERN T9 in 2026

Both the IDEA and IHEP CEPC team joined the test and work together





Box with 20 drift tubes:

- 1(effective 0.8) and 1.5(effective 1.1) cm cell size
- 20μm Au-plated tungsten

Drift chamber prototype:

- 10 layers, 6 cells/layer, 60 cells
- Cell size: 12 mm × 12 mm
- Length of protopype: 530 mm
- Sense wire: 20 μm Au-plated tungsten
- Field wire: 70 μm Aluminum
- Length of wire: 250 mm

Shared gas mixture and distribution system, shared trigger signal, different readout electronics

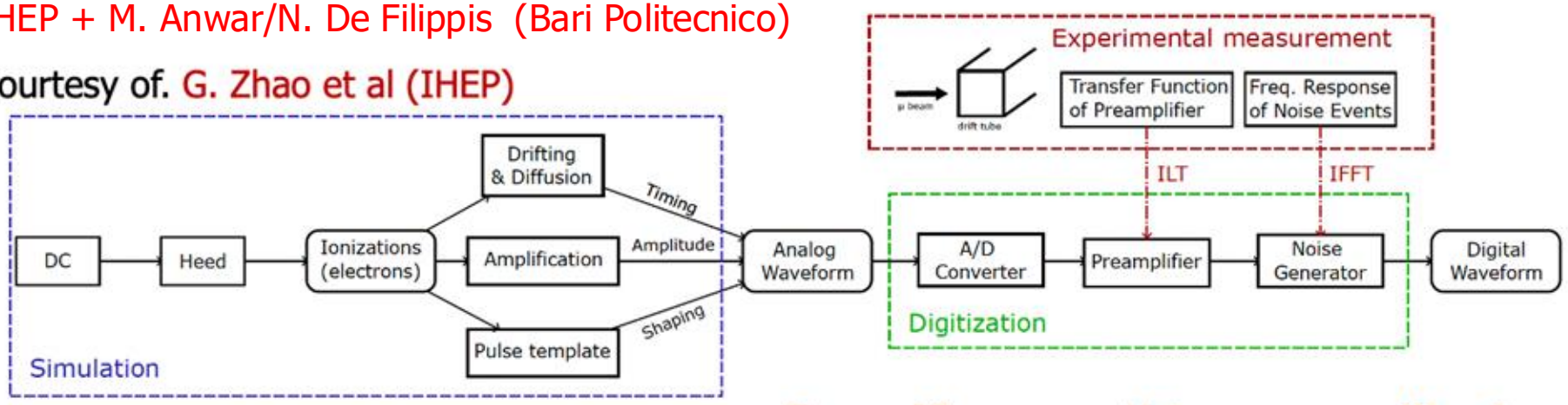
Collected data for muon in the momentum range 2-12 GeV, negative pions (95% pure) and kaons in the momentum range 6-15 GeV

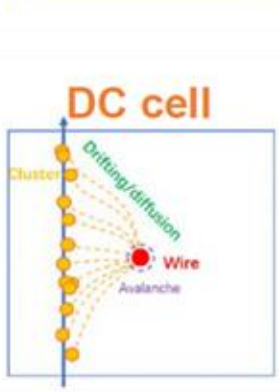
Software development

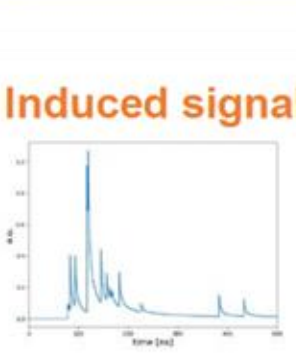
CEPC/IDEA: Garfield fast/full simulation chain

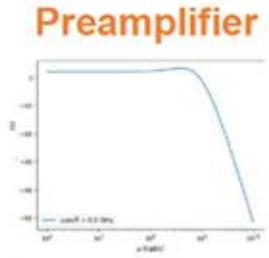
IHEP + M. Anwar/N. De Filippis (Bari Politecnico)

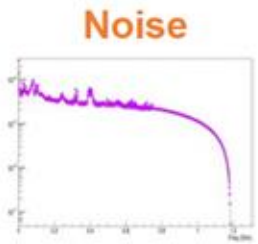
Courtesy of. G. Zhao et al (IHEP)

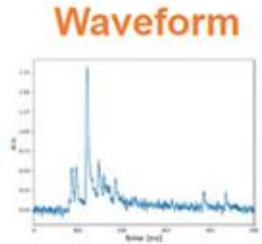


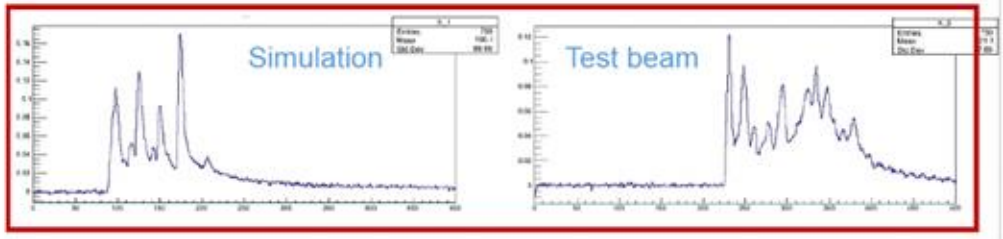










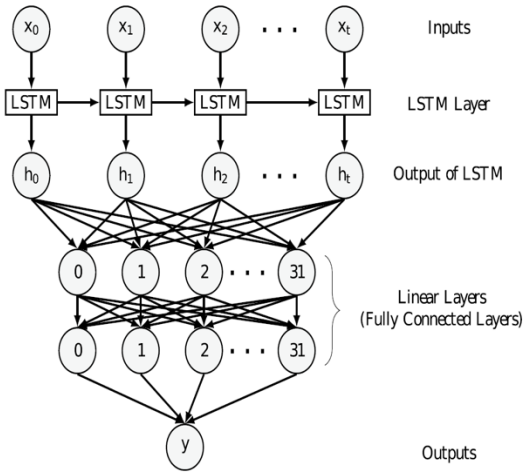


"Peak finding algorithm for cluster counting with domain adaptation"
Comp. Phys. Comm., 300, 2024, 109208, https://doi.org/10.1016/j.cpc.2024.109208

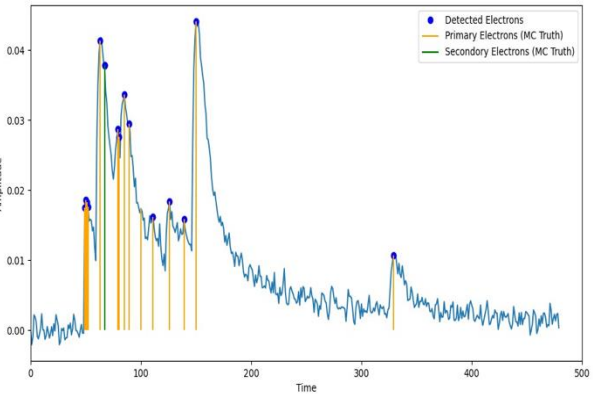
CEPC/IDEA: Reconstruction with Deep Learning

- Two DL models have been developed:
  - Simulated samples (Nucl. Sci. Tech. 36, 113)
    - Supervised model: LSTM peak-finding + DGCNN clusterization
  - Test beam samples (Comp. Phys. Comm. 300, 109208)
    - Simi-supervised domain adaptation: DNN + Optimal Transport
- Collaboration between IHEP and INFN group on 2021/2022 test beam analysis
  - MC fine tuning to match real data
  - Trained LSTM + CNN with MC, and apply on test beam 2022 data

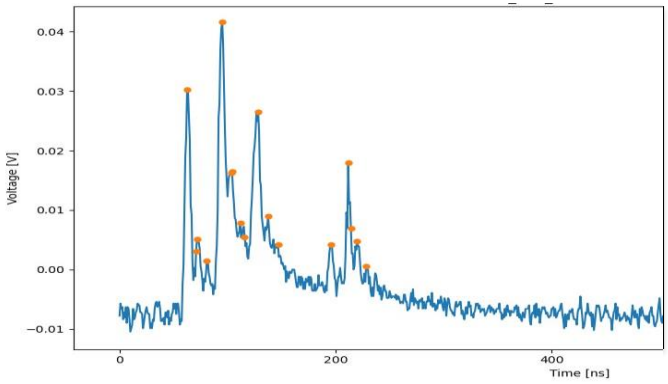
LSTM Peak-Finding Model



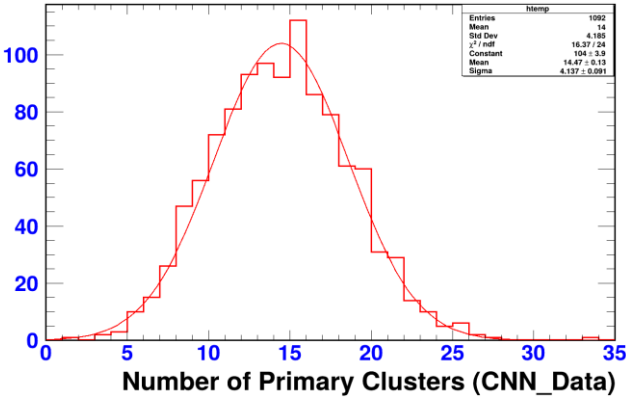
Tuned MC Waveform



Read Data Waveform



of Clusters in Data



CEPC/IDEA: PID with Deep Learning

muons

Momentum	Monte Carlo Mean / Std	Peak Finding Mean / Std	Clusterization Regression Mean / Std	Clusterization Classification Mean / Std
10 GeV	17.74/4.22	16.48/3.92	16.43/3.32	16.54/3.82
8 GeV	17.33/4.19	16.10/3.89	16.15/3.32	16.27/3.79
6 GeV	16.95/4.05	15.93/3.83	16.04/3.33	16.20/3.82
4 GeV	16.33/4.01	15.37/3.81	15.61/3.35	15.81/3.80
2 GeV	15.18/3.93	14.34/3.72	14.68/3.38	15.10/3.83

pions

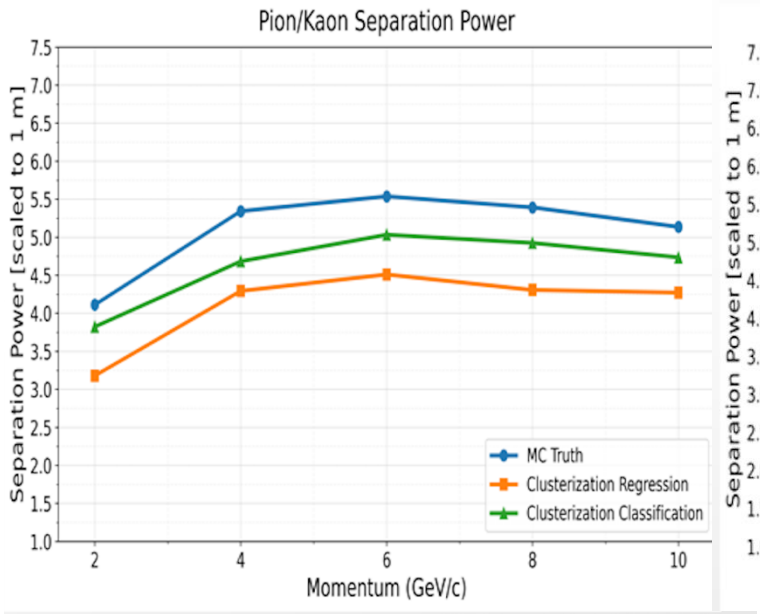
Momentum	Monte Carlo Mean / Std	Peak Finding Mean / Std	Clusterization Regression Mean / Std	Clusterization Classification Mean / Std
10 GeV	17.32/4.18	16.03/3.86	15.87/3.30	16.12/3.76
8 GeV	17.02/4.12	15.76/3.82	15.64/3.32	15.95/3.79
6 GeV	16.57/4.04	15.52/3.78	15.48/3.33	15.80/3.77
4 GeV	15.85/4.01	14.86/3.79	14.98/3.37	15.32/3.82
2 GeV	14.61/3.82	13.75/3.61	13.96/3.28	14.44/3.70

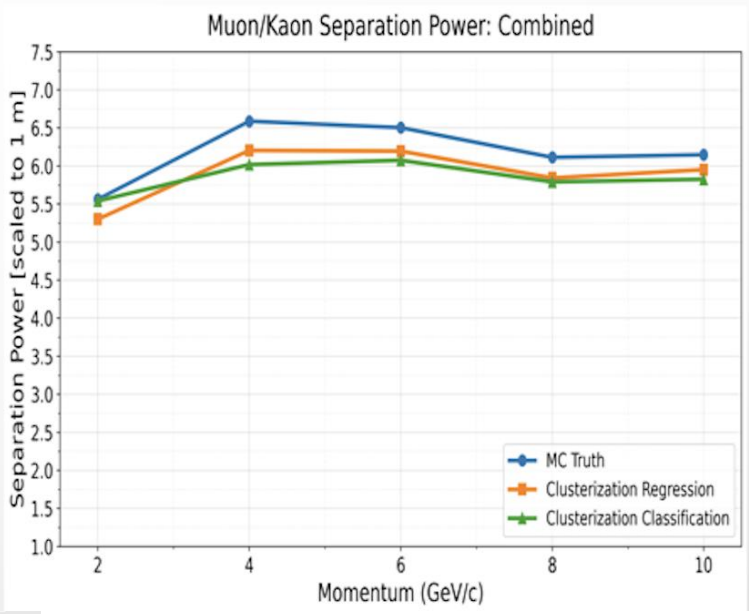
CEPC/IDEA: PID with Deep Learning

Kaons

Momentum	Monte Carlo Mean / Std	Peak Finding Mean / Std	Clusterization Regression Mean / Std	Clusterization Classification Mean / Std
10 GeV	15.25/3.88	14.17/3.61	14.46/3.30	14.37/3.63
8 GeV	14.86/3.89	13.82/3.62	14.21/3.32	14.13/3.60
6 GeV	14.41/3.76	13.52/3.55	13.98/3.32	13.94/3.62
4 GeV	13.79/3.70	12.99/3.51	13.55‘/3.29	13.58/3.61
2 GeV	13.08/3.62	12.35/3.43	12.92/3.26	13.05/3.57

$$S = \frac{|\mu_A - \mu_B|}{(\sigma_A + \sigma_B)/2}$$



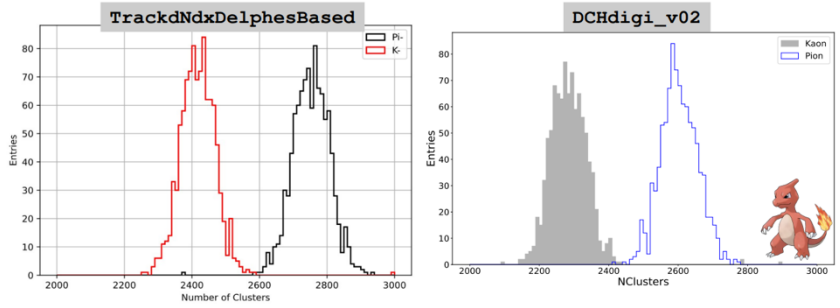


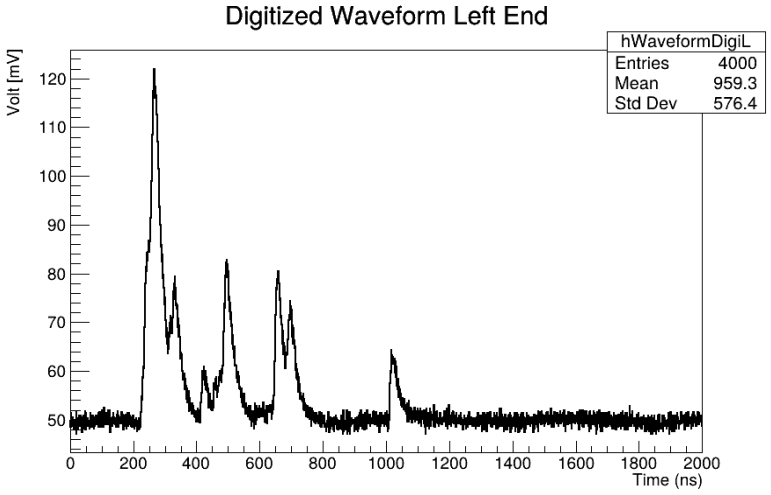
IDEA: Digitization for the drift chamber in FCCSW

Complete strategy at link:
https://indico.cern.ch/event/1439509/contributions/6289570/attachments/2997087/5280386/DeFilippis_Digitizer_v1.pdf

DCHdigi_v02 - Andreas Loeschcke Centeno

- Ncluster comparison between 1k Pions and Kaons @ 10GeV
- Use the TrackdNdxDelphesBased and new DCHdigi_v02 to compute Nclusters





N. De Filippis

DCHdigi_v0X - Muhammad Saiel

Intersect the physical particle trajectory with the space volume defined by the fired cell (input to digitization).

1. Define the ionization length L (Geant4 weighted step length) of the particle track within the cell volume.
2. Extract a number of ionization acts n_{cl} according to a Poisson distribution with peak value $(dN_{cl}/dx) \times L$, and distribute them along L using exponential spacings with a mean free path $1/(dN_{cl}/dx)$.
   dN_{cl}/dx is a tabulated function only of the particle $\beta\gamma$
   I. This function can be provided by the test beam Experimental result.
   II. At the moment we are relying on the Bethe-Bloch parameterization.





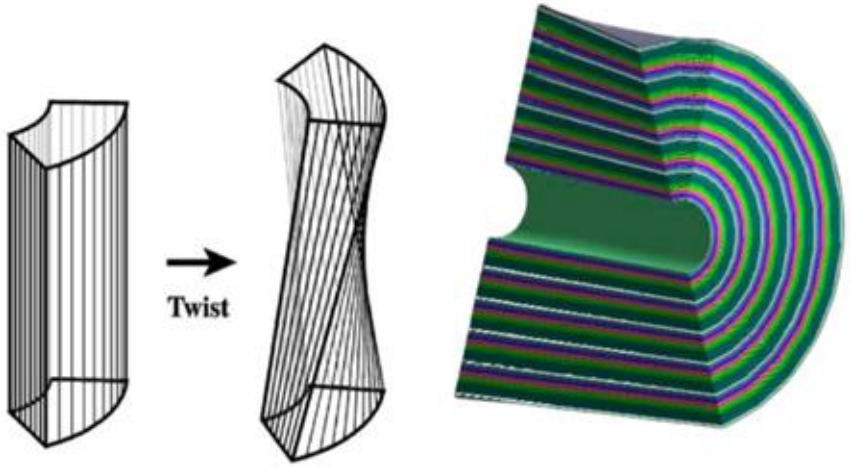
- ☐ Starting from **Geant4 simulated hits** and producing realistic **digitized waveforms (L_0)**.
- ☐ Ionization is modeled through **cluster generation and electron multiplication**, using **βγ-dependent dNcl/dx**, experimental cluster-size distributions.
- ☐ Electron drift times are computed using **tabulated X–T relations (2D LUT)** with **diffusion smearing**, ensuring a fast yet realistic transport to the sense wire.
- ☐ Each **drifting electron** is assigned an **avalanche charge (gain)**.
- ☐ Individual electron pulses are shaped using **measured rise/fall times**, summed to form the **analog waveform**, propagated along the wire, and processed through **electronics response and FFT-based noise injection**.
- ☐ The digitization outputs a **fully realistic waveform**, enabling **cluster counting, peak finding**.

Full simulation of the IDEA drift chamber in DD4HEP

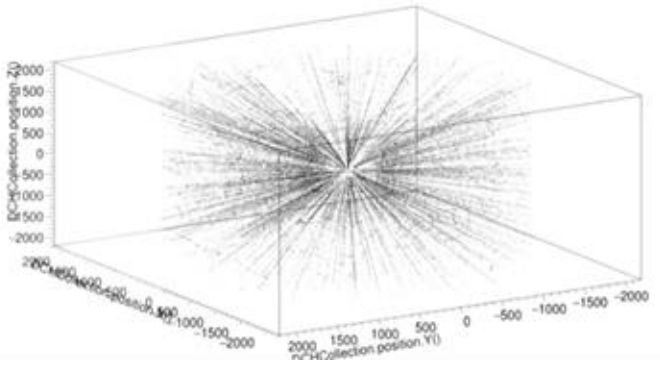
Done by people at CERN

Large-volume extremely light drift wire chamber Evolving from the detectors built for KLOE and MEG2 experiments: is a full-stereo unique volume, co-axial with the 2T solenoid field, with high granularity, low mass and short drift path.

- Cylindrical wall made of carbon fiber
- Cylindrical volume filled of gas mixture.
- 112 hyperboloidal layers filled with gas mix.
- Cells are twisted tubes (twisted tube results from layer segmentation in phi, keeping the twist angle), made of gas mix. These cells are the sensitive volumes!
- Field (x5) and sense (x1) wires inside each cell.
- The new version (v02) is in k4geo.

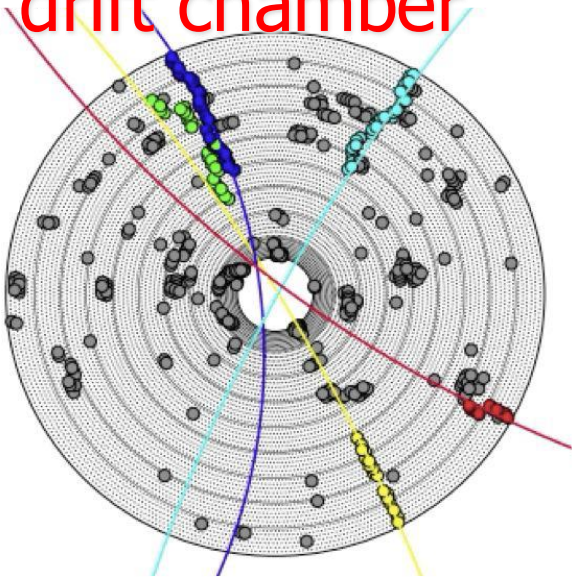


DriftChamber o1_v02 Twisted tubes.

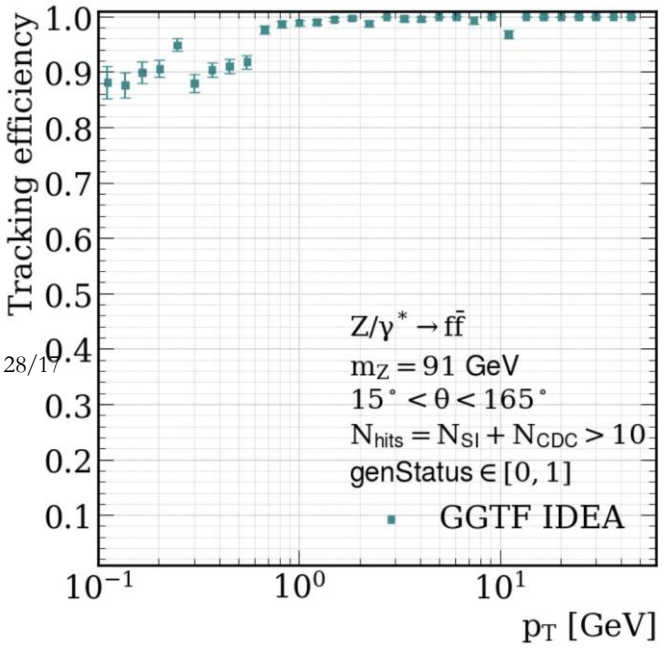


Track reconstruction with the IDEA drift chamber

A. De Vita, P. Azzi (PD)
+CERN+MIT



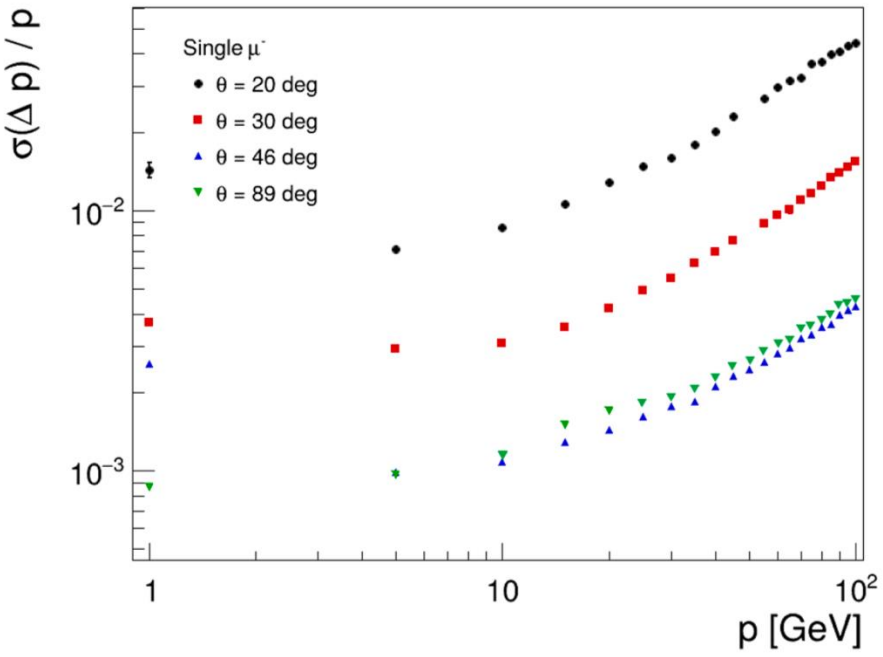
- IDEA DCH performance was studied with a detailed standalone Geant4 simulation;
- Physics studies are on going with DELPHES (performance tuned on Geant4 simulation);
- IDEA DCH DD4HEP description in the FCC framework is done (optimizations are ongoing):
  - Geometry description;
  - Digitization;
  - Track reconstruction:
    - A new ML based Pattern Recognition was developed (Geometric Graph Track Finding);
    - Kalman filter (GENFIT2) implemented;
    - ML Particle Flow.



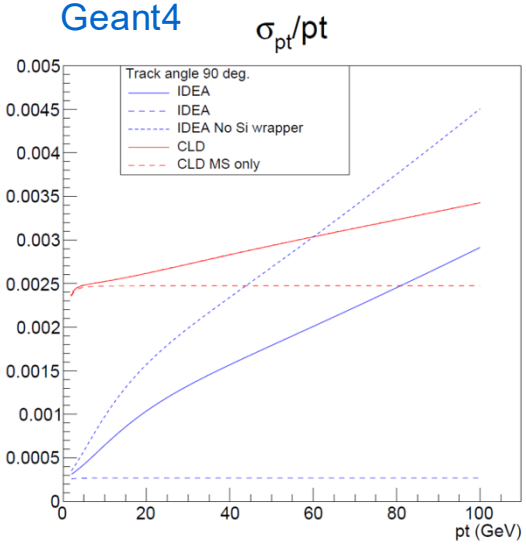
Plan: physics analysis studies for benchmark B and Higgs channels starting with full simulation and reconstruction

Outer tracker: Drift Chamber (IDEA) performance

- **DCH used in conjuction with vertex and silicon medium tracker and/or silicon wrapper**
- NEW FULL simulation based on key4HEP/DD4HEP/Geant4
  - momentum resolution as a function of momentum p, for single muons at different θ
  - below 0.7 GeV/c, particles begin to loop in the magnetic field (2T option), leading to a transition between two distinct regions in the p_T spectrum.



Old simulation based on Geant4



Analytic formula

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

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

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

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

For 10 GeV (**50 GeV**) μ emitted at an angle of 90° w.r.t the detector axis, the p_T resolution is

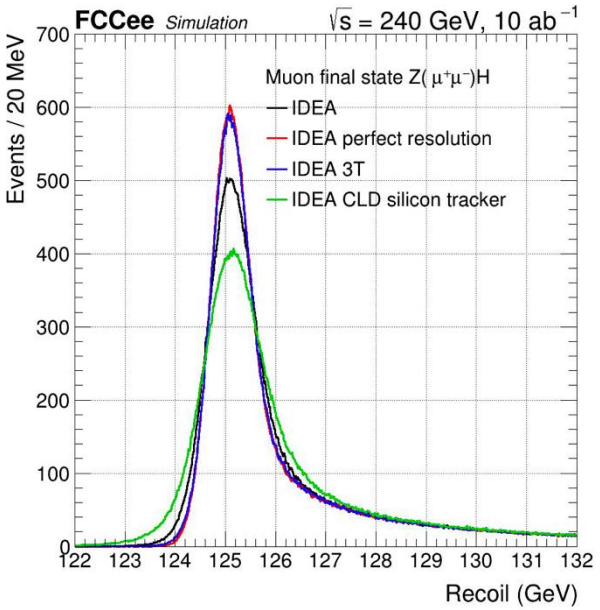
- about 0.05 % (**0.15%**) with the very light IDEA DCH → impact on Higgs mass measurement

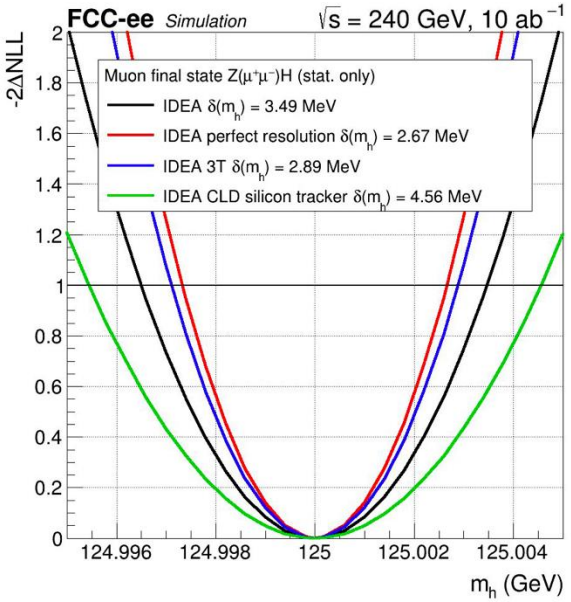
Constraint from Higgs Mass measurement

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 p of O(50) GeV, to be measured with a p_T resolution smaller than the BES in order for the p_T measurement not to limit the mass resolution → σ_{p_T}/p_T ~ 0.15/0.2% @ $\mathcal{O}$(50)GeV

- 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

Conclusions

Good progress by the drift chamber teams on:

- mechanical structure design
- on going effort to build prototypes
- testbeam organization and data analysis → progressing
- software for full simulation, digitization, track reconstruction → in place

Plenty of areas for futher collaboration (also in the context of DRD1 WP2):

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

Backup

Challenges: wire studies

Wire constraints

Electrostatic stability condition

$$T_c \geq \frac{C^2 V_0^2}{4\pi\epsilon w^2} L^2$$

T_c wire tension
w cell width
L wire length
C capacitance per unit length
V_0 voltage anode-cathode

For w = 1 cm, L = 4 m:

T_c > 26 g for 40 μm Al field wires (δ_{grav} = 260 μm)
T_c > 21 g for 20 μm W sense wires (δ_{grav} = 580 μm)

Elastic limit condition

$$T_c < YTS \times \pi \cdot r_w^2$$

YTS = 750 Mpa for W, *290 Mpa for Al*

T_c < 36 g for 40 μm Al field wires (δ_{grav} = 190 μm)
T_c < 24 g for 20 μm W sense wires (δ_{grav} = 510 μm)

The drift chamber length (**L = 4 m**) imposes
strong constraints on the drift cell size (**w = 1 cm**)
Very little margin left ⇒ increase wires radii or cell size
⇒ use different types of wires

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

Challenges: minimization of the material budget

current
Material budget estimates

- Inner wall (from CMD3 drift chamber) **8.4×10^{-4} X_0**
  - 200 µm Carbon fiber
- Gas (from KLOE drift chamber) **1.3×10^{-3} X_0**
  - 90% He – 10% iC_4H_{10}
- Wires (from MEG2 drift chamber) **1.3×10^{-3} X_0**
  - 20 µm W sense wires 6.8×10^{-4} X_0
  - 40 µm Al field wires 4.3×10^{-4} X_0
  - 50 µm Al guard wires 1.6×10^{-4} X_0
- Outer wall (from Mu2e I-tracker studies) **1.2×10^{-2} X_0**
  - 2 cm composite sandwich (7.7 Tons)
- End-plates (from Mu2e I-tracker studies) **4.5×10^{-2} X_0**
  - wire cage + gas envelope
  - incl. services (electronics, cables, ...)

Helium used because of:

- Low primary ionization density implies a large time separation
- low drift velocity means larger time separation (v_{drift} ≈ 2.5 cm/µs)
- low average cluster size $\langle N_{electrons}/cluster \rangle$ ≈ 1.6
- low single electron diffusion (< 110 µm for 0.5 cm drift, or < 4.5 ns)

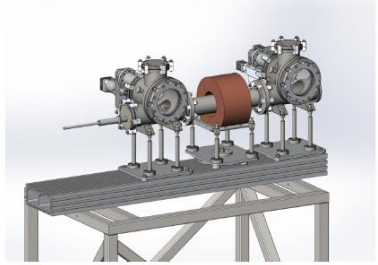
Challenges for large-volume drift chambers

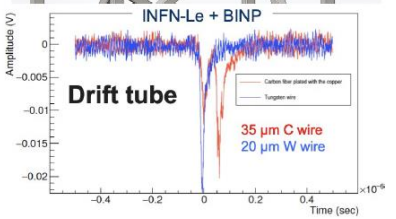
- **Electrostatic stability** condition: $\frac{\lambda^2}{4\pi\varepsilon}\frac{L^2}{w^2} < wire\ tension < YTS \cdot \pi r_w^2$

λ = 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 **~5×10⁵**.
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**

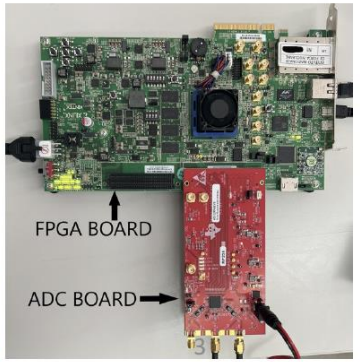
Safety requirements (**ATEX**) demands stringent limitations on flammable gases;
Continuous increase of **noble gases cost**

⇒ **gas studies**

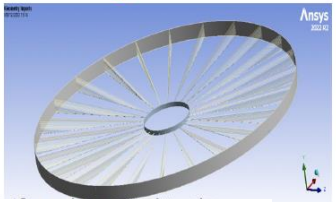
- **Data throughput**

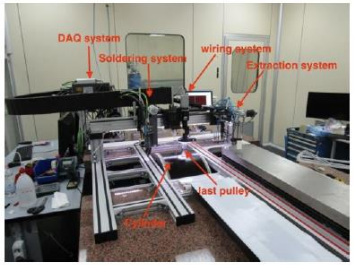
Large number of channels, high signal sampling rate, long drift times (slow drift velocity), required for **cluster counting**, and high physics trigger rate (Z_0-pole at FCC-ee) imply data transfer rates in excess of **~1 TB/s**

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



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



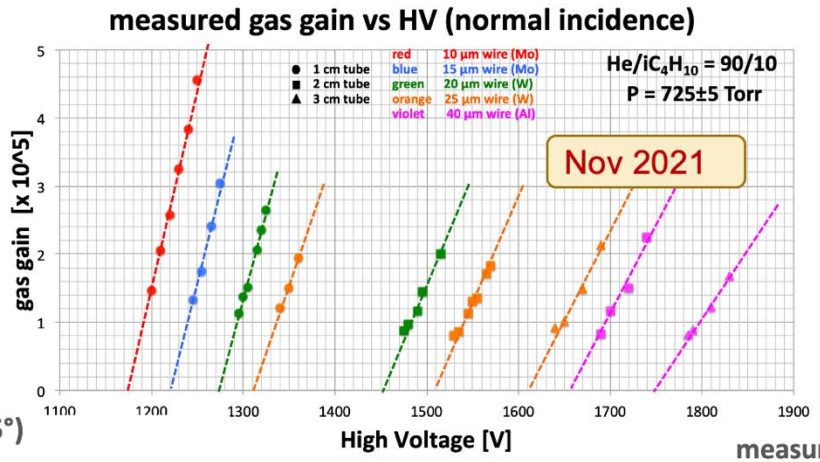


Wire tests: definitions and procedures

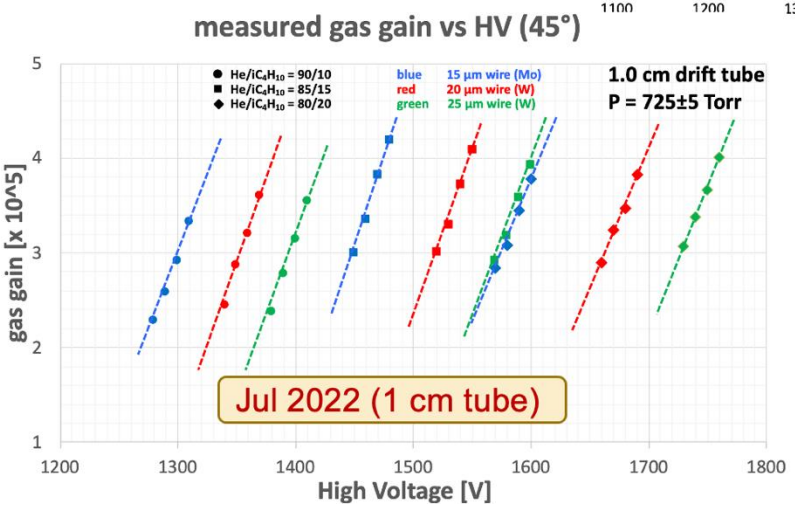
- L = load (in N) measured with the dynamometer
- t = time (in s) measured with the slider
- A = filament area (m^2)
- v = picomotor velocity (in μm/s)
- D = displacement (in mm) = v*t
- SS = stress (in Gpa) = L/A
- GL = gauge length (mm)
- ST = strain (in %) = D/GL
- TS = Tensile Strength (in GPa) = Max(SS)
- Y = Young module (Gpa) from the slope of the elastic part of Stress-Strain curve
- R^2= correlation coefficient
- Effective test time (s) = the time up to the break
- TWE Total wire elongation (mm) = the elongation up to the break
- Elongation (%) = TWE/GL*100
- Fracture strain - εf (%), value of the strain at the break point
- Elongation at break (%) = εf *100
- Elastic limit strain - εy(%), value of the strain at the end of elastic part
- Yield Tensile Strength - YTS (GPa) = Y* εy

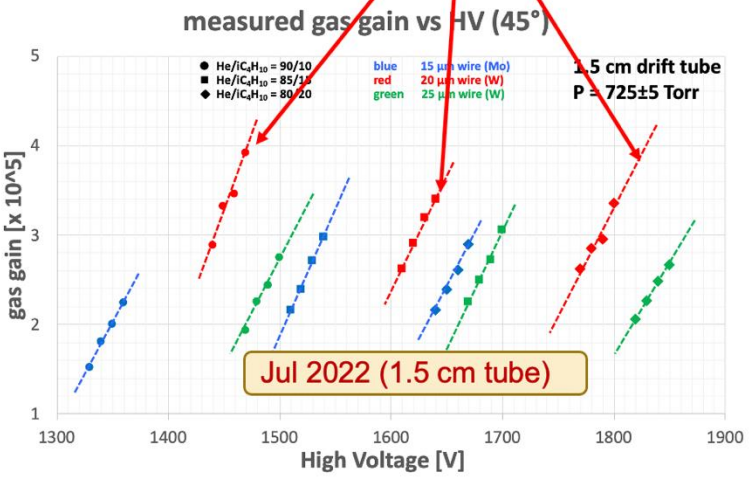
2021/2022 beam test results: gas gain scan

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



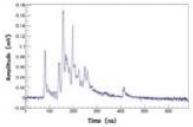
20µm wire excluded from physical quantities mean computation





Challenge: Data reduction and pre-processing

The excellent performance of the **cluster finding** algorithms in offline analysis, relies on the assumption of being able to transfer the full spectrum of the digitized drift signals.
However …



according to the **IDEA drift chamber operating conditions**:

- 56448 drift cells in 112 layers (~130 hits/track)
- maximum drift time of 500 ns
- cluster density of 20 clusters/cm
- signal digitization 12 bits at 2 Gsa/s

… and to the **FCC-ee running conditions at the Z-pole**

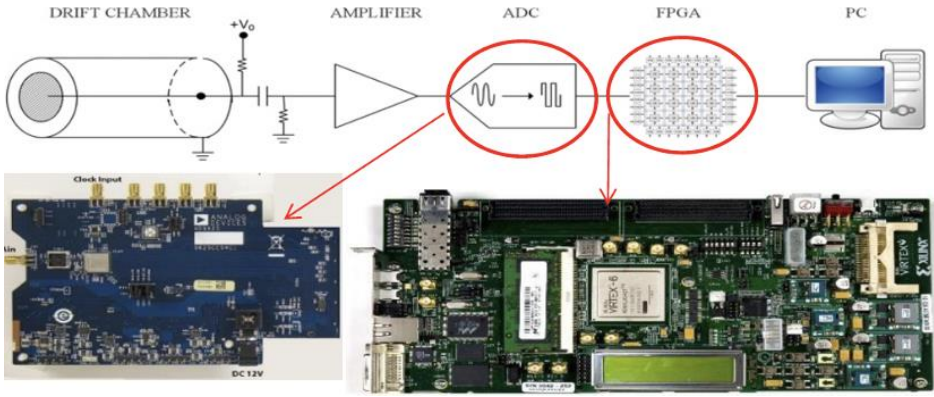
- 100 KHz of Z decays with 20 charged tracks/event multiplicity
- 30 KHz of $\gamma\gamma \longrightarrow$ hadrons with10 charged tracks/event multiplicity
- 2.5% occupancy due to beam noise
- 2.5% occupancy due to hits with isolated peaks

Reading both ends of the wires, ⇨ data rate ≥ 1 TB/s !

Solution consists in transferring, for each hit drift cell, instead of the **full signal spectrum**, only the **minimal information** relevant to the application of the **cluster timing/counting techniques**, i.e.:

the amplitude and **the arrival time** of each peak associated with each individual ionisation electron.

This can be accomplished by using a **FPGA** for the **real time analysis** of the data generated by the drift chamber and successively digitized by an ADC.

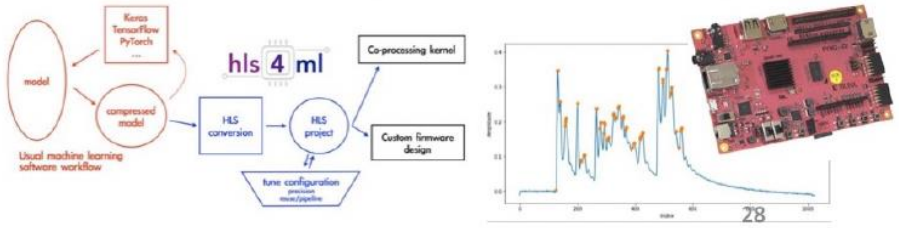


Single channel solution has been successfully verified.

G. Chiarello et al., The Use of FPGA in Drift Chambers for High Energy Physics Experiments May 31, 2017
DOI: 10.5772/66853

With this procedure **data transfer rate is reduced to ~ 25 GB/s**
Extension to a 4-channel board is in progress. Ultimate goal is a multi-ch. board (128 or 256 channels) to **reduce cost** and complexity of the system and to gain flexibility in determining the **proximity correlations** between hit cells for track **segment finding** and for **triggering** purposes.

Implementing ML algorithms on FPGA for peak finding



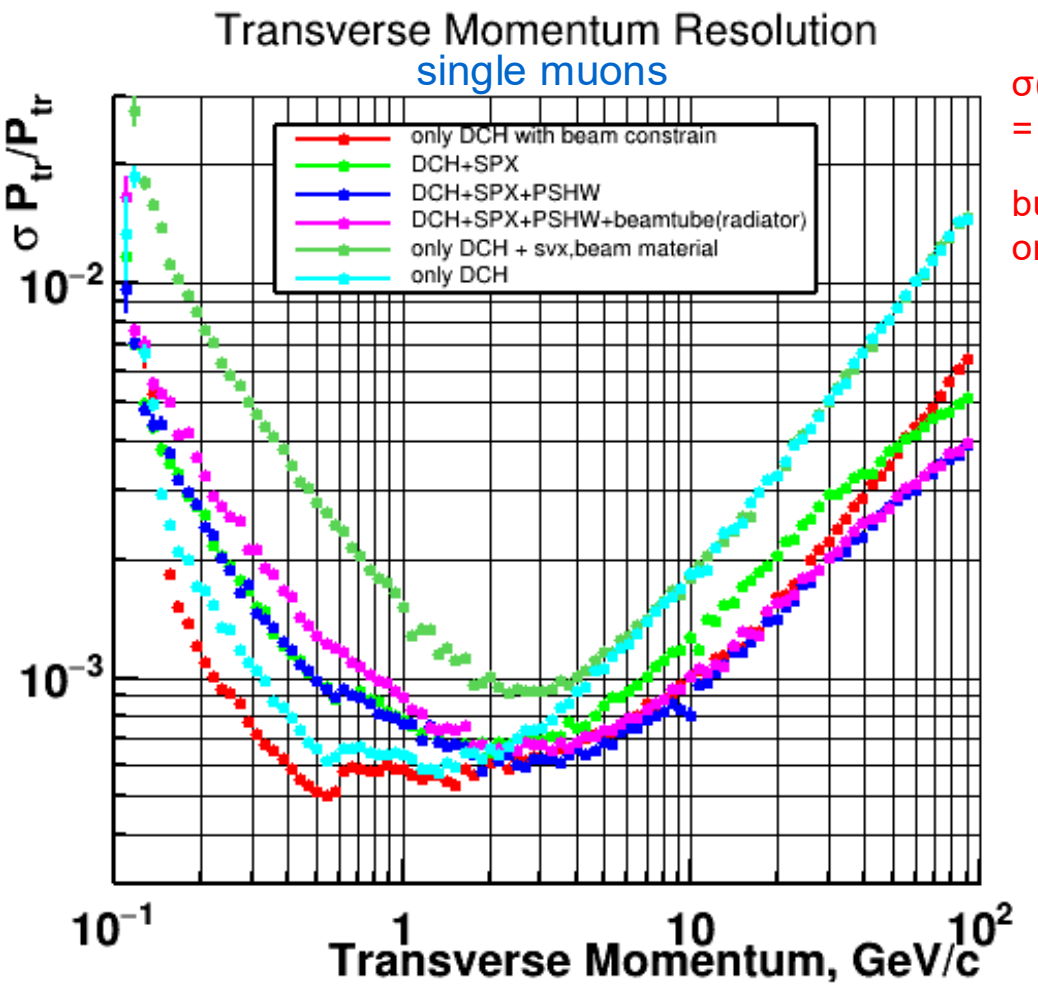
New developments on going !

Track finding: performance of the current IDEA

For the Geant4 based simulation framework code:

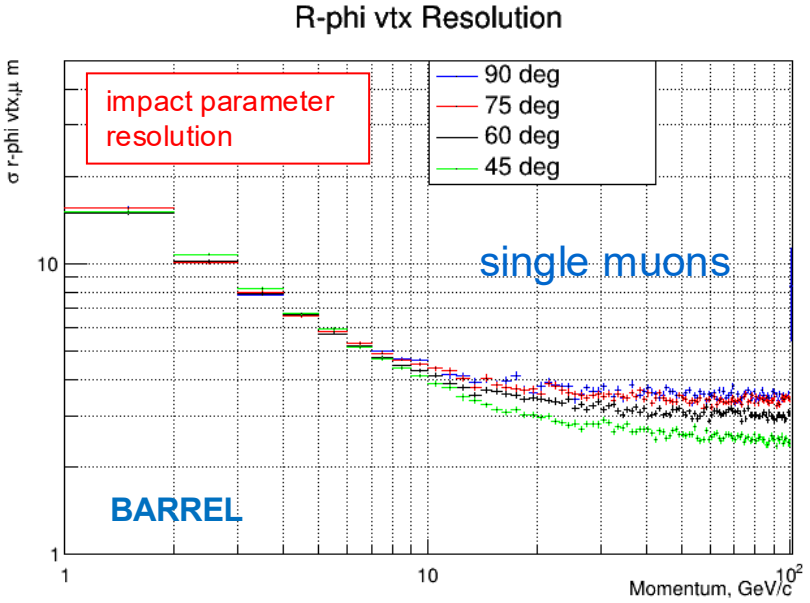
$$\frac{\Delta p_T}{p_T}|_{res.} = \frac{\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}|_{m.s.} = \frac{N}{\sqrt{(N+1)(N-1)}}\,\frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0 \sin\theta}}\left(1+0.038\ln\frac{d}{X_0\sin\theta}\right)$$



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

but new studies ongoing



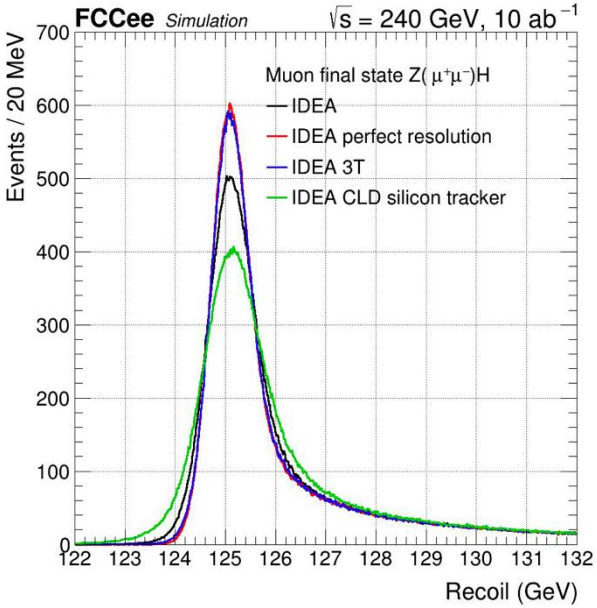
$\sigma(d_0)$ (100 GeV) = 2μm

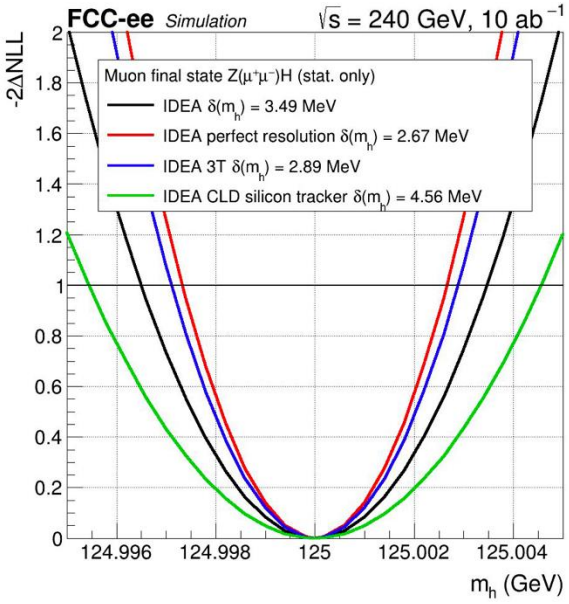
Constraint from Higgs Mass measurement

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

Most recent References

Old References

G. Cataldi, F. Grancagnolo, S. Spagnolo, Cluster counting in helium based gas mixtures, Nuclear Insmtments end Methods in Physics Research A 386 (1997) 458-469.

M. Benedikt et al., FCC-ee The Lepton Collider : Future Circular Collider Conceptual Design-Report Volume 2. Eur. Phys. J. Spec. Top.228(2019) 261{623}.

F.Bedeschi, A detector concept proposal for a circular e+e- collider,Vol. ICHEP2020, PoS. (2021) 819

G.F. Tassielli on behalf of the IDEA Collaboration, A proposal of a drift chamber for the IDEA experiment for a future e+e- collider, Vol. ICHEP2020, PoS. (2021) 877.

F.Cuna, N.De Filippis, F.Grancagnolo, G.F.Tassielli, Simulation of particle identification with the cluster counting technique, proceeding at LCWS2021.

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H. Fischle , J. Heintze and B. Schmidt Experimental determination of ionization cluster size distributions in counting gases, Nuclear Instruments and Methods in Physics Research A301 (1991) 202-214.