Input for the European Strategy: Physics and detector studies

Nicola De Filippis
Politecnico and INFN Bari

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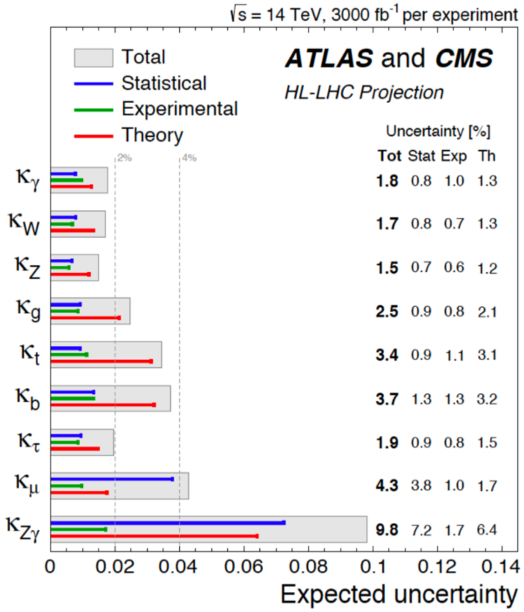
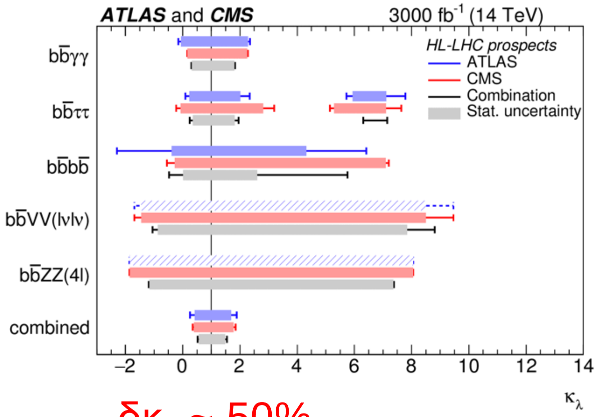
Landscape of the Higgs physics

So far many questions still open for Higgs physics:

- ✓ How well the Higgs boson couplings to fermions, gauge bosons and to itself be probed at current and future colliders?
- ✓ How do precision electroweak observables provide us information about the Higgs boson properties and/or BSM physics?
- ✓ What progress is needed in theoretical developments in QCD and EWK to fully capitalize on the experimental data?
- ✓ What is the best path towards measuring the Higgs potential ?
- ✓ To what extent can we tell whether the Higgs is fundamental or composite?

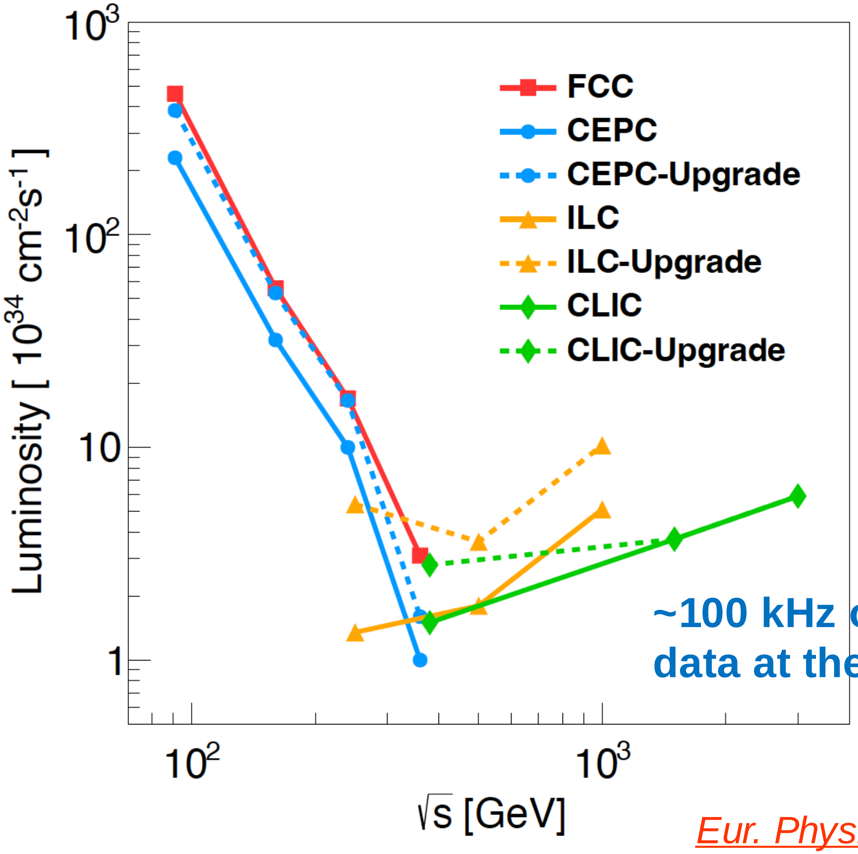
- ➢ **HL-LHC and future colliders would explore in detail the Higgs properties:** understand the deep origin of EWSB
- ➢ **Beyond HL-LHC measurements:**
  - ✓ Couplings to fermions to %-level, to bosons to per-mil
  - ✓ self-coupling
  - ✓ Invisible decays
  - ✓ BSM Higgses





$\delta\kappa_\lambda \sim 50\%$

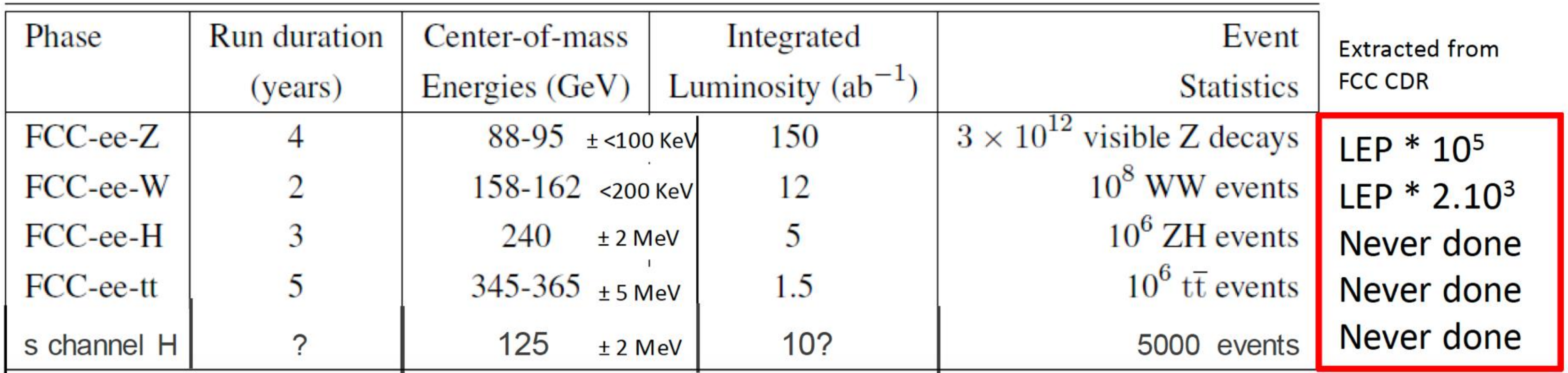
Machine luminosity for physics at e^+e^- colliders



~100 kHz of physics data at the Z pole

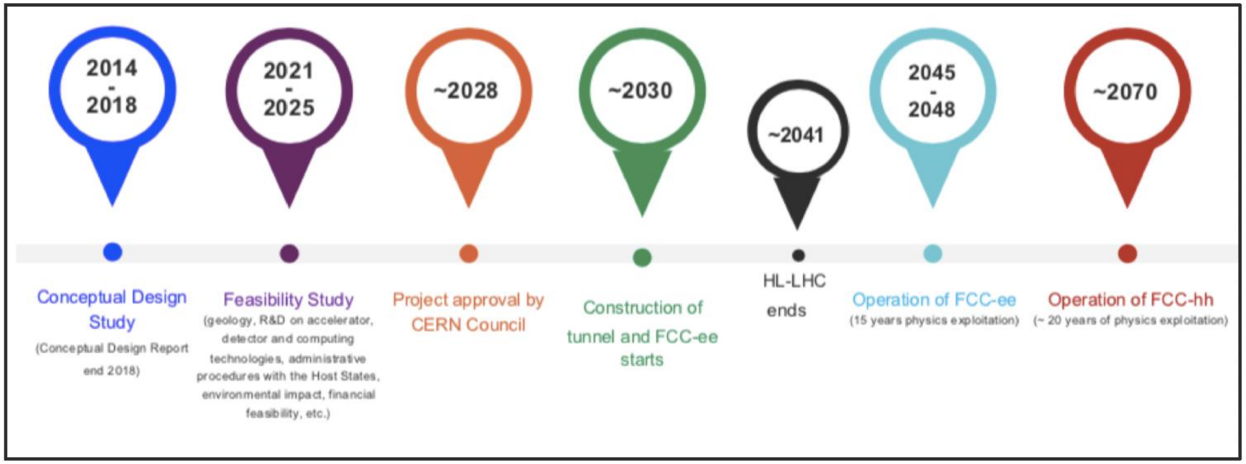
- Higgs factory:
  - 10^6 $e^+e^- \rightarrow HZ$
- EW & Top factory:
  - 3×10^{12} $e^+e^- \rightarrow Z$
  - 10^8 $e+e^- \rightarrow W^+W^-$
  - 10^6 $e^+e^- \rightarrow tt$
- Flavor factory:
  - 5×10^{12} $e^+e^- \rightarrow bb$, cc
  - 10^{11} $e^+e^- \rightarrow \tau^+\tau^-$

Eur. Phys. J. Special Topics volume 228, pages 261–623 (2019)



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics	Extracted from FCC CDR
FCC-ee-Z	4	88-95 ± <100 KeV	150	3×10^{12} visible Z decays	LEP * 10^5
FCC-ee-W	2	158-162 <200 KeV	12	10^8 WW events	LEP * 2.10^3
FCC-ee-H	3	240 ± 2 MeV	5	10^6 ZH events	Never done
FCC-ee-tt	5	345-365 ± 5 MeV	1.5	10^6 $t\bar{t}$ events	Never done
s channel H	?	125 ± 2 MeV	10?	5000 events	Never done

Report by F. Gianotti at the latest FCCweek



1st stage collider FCC-ee:
electron-positron collisions 90-360 GeV:
electroweak and Higgs factory
2nd stage collider FCC-hh:
proton-proton collisions at ~ 100 TeV

"Realistic" schedule taking into account:

- ❑ past experience in building colliders at CERN
- ❑ the various steps of approval process: ESPP update, CERN Council decision
- ❑ HL-LHC will run until ~ 2041

→ ANY future collider at CERN cannot start physics operation before ~ 2045 (but construction will proceed in parallel to HL-LHC operation)

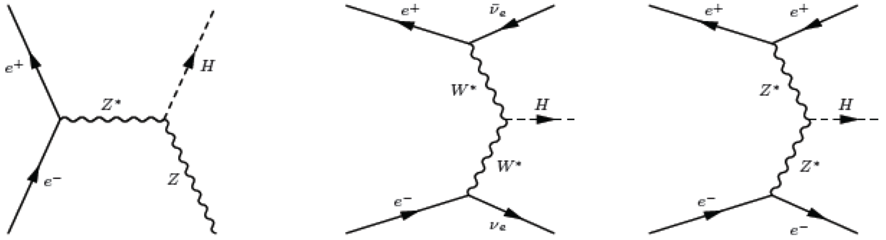
Care should be taken when comparing to other proposed facilities, for which in most cases only the (optimistic) technical schedule is shown. In particular, studies related to **territorial implementation** (surface sites, roads, connection to water and electricty, environmental impact, admin procedures, etc.), which for FCC are being carried out in the framework of the Feasibility Studies, **take years.**

Next steps:

- ❑ Complete Feasibility Study by March 2025
- ❑ ESPP update: process started by Council in March → to be completed in June 2026 → see next slide
- ❑ Preparation for Council decision on FCC end 2027/beg 2028: "pre-TDR phase"

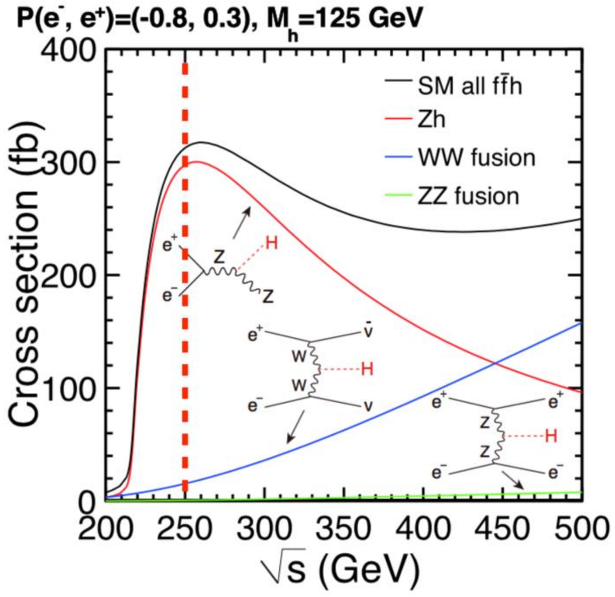
Higgs production at FCC-ee

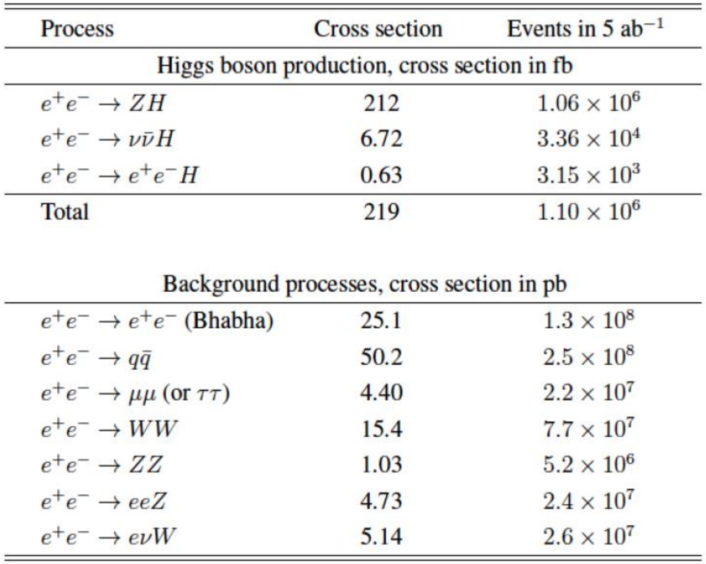
Higgs-strahlung or $e^+e^- \rightarrow ZH$



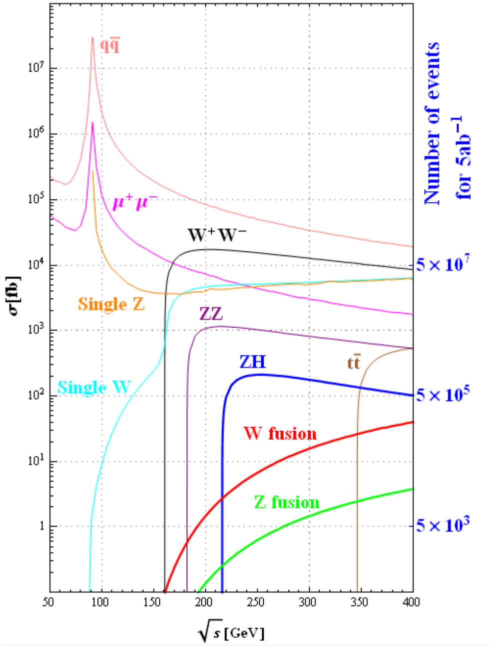
Higgs production @ FCC-ee		
Threshold	ZH production	VBF production
240 GeV / 5 ab^{-1}	1e6	2.5e4
365 GeV / 1.5 ab^{-1}	2e5	5e4

VBF production: $e^+e^- \rightarrow \nu\nu H$ (WW fus.), $e^+e^- \rightarrow He^+e^-$ (ZZ fus.)



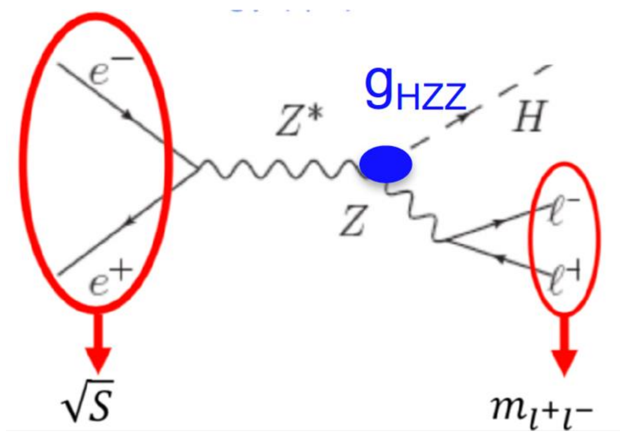


Process	Cross section	Events in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \rightarrow ZH$	212	1.06×10^6
$e^+e^- \rightarrow \nu\bar{\nu}H$	6.72	3.36×10^4
$e^+e^- \rightarrow e^+e^-H$	0.63	3.15×10^3
Total	219	1.10×10^6
Background processes, cross section in pb		
$e^+e^- \rightarrow e^+e^-$ (Bhabha)	25.1	1.3×10^8
$e^+e^- \rightarrow q\bar{q}$	50.2	2.5×10^8
$e^+e^- \rightarrow \mu\mu$ (or $\tau\tau$)	4.40	2.2×10^7
$e^+e^- \rightarrow WW$	15.4	7.7×10^7
$e^+e^- \rightarrow ZZ$	1.03	5.2×10^6
$e^+e^- \rightarrow eeZ$	4.73	2.4×10^7
$e^+e^- \rightarrow e\nu W$	5.14	2.6×10^7



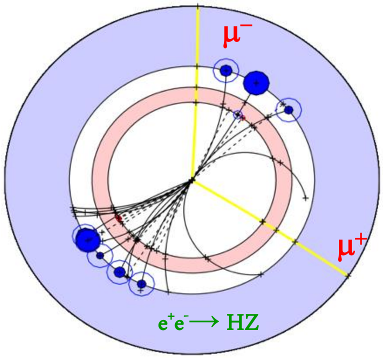
N. De Filippis

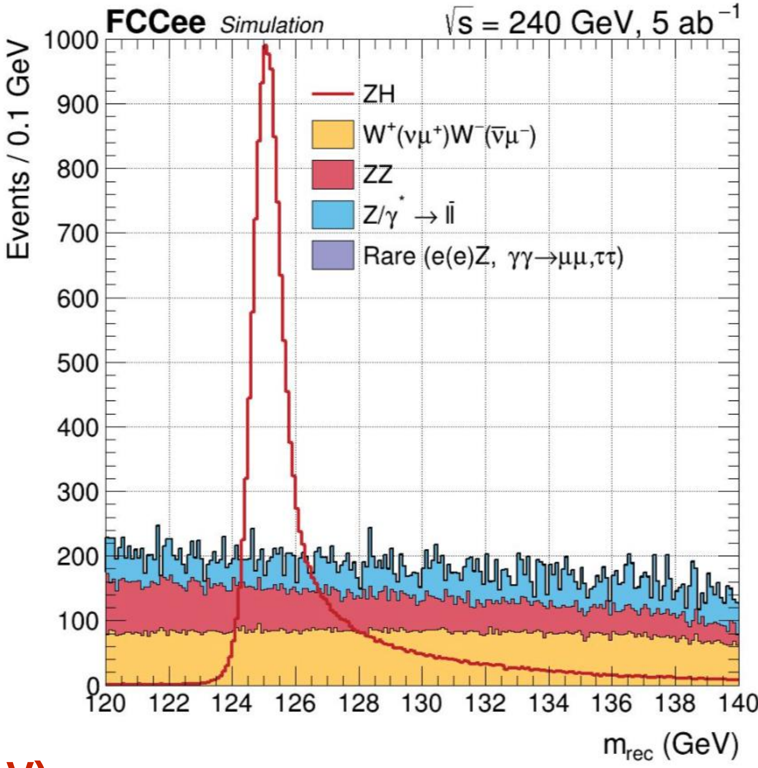
Global strategy for Higgs studies



$\sigma(e^+e^- \to HZ)\ \alpha\ g^2_{HZZ}$

ZH events tagged by the Z, without reconstructing the Higgs decay. Unique to lepton colliders.





e.g. when Z → leptons :

$$m^2_{\text{recoil}} = s + m^2_{\ell\ell} - 2\sqrt{s}(E_{\ell^+} + E_{\ell^-})$$

A fit to the recoil mass distribution allows:

- measurement of σ(ZH) independent of the Higgs decay mode with O(%) uncertainty. Hence an absolute determination on g_{HZZ}

  → **$\delta g_{HZZ}/g_{HZZ}$ ~ 0.2 %** (also including Z→had)

- a precise meas. of the **Higgs mass → $\delta m_H/m_H$ ~ O(MeV)**

Easiest case: Z → lep.

• Z → had: more careful design of the analysis

Model-independent Higgs couplings measurements

Known g_{HZZ} it is possible to measure σ x BR for specific Higgs decays

$$\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H}\to \mathrm{X}\overline{\mathrm{X}}) \propto \frac{g^2_{\mathrm{HZZ}}\times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$

- H → ZZ* provides Γ_H
- H → XX provides g_{HXX}

H → ZZ* provides Γ_H :

$$\frac{\sigma(e^+e^-\to ZH)}{\mathrm{BR}(H\to ZZ^*)} = \frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{\mathrm{SM}}\times\Gamma_H$$

→ **$\delta\Gamma_H/\Gamma_H$ ~ several %**

Select events with H → bb, cc, gg, WW, tt, γγ, μμ, Zγ, …

Deduce g_{Hbb} , g_{Hcc} , g_{Hgg} , g_{HWW} , g_{Htt} , $g_{H\gamma\gamma}$, $g_{H\mu\mu}$, $g_{HZ\gamma}$, …

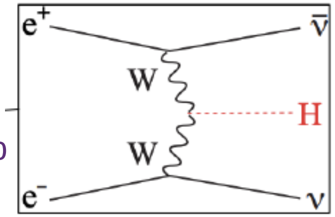
Select events with H → “nothing” → deduce Γ(H→invisible)

→ **$\delta g_{XX}/g_{XX}$ ~ 1 %**

a model-indep determination of Higgs couplings.

Data at higher energy bring important additional observables:

$$\sigma_{\mathrm{H}\nu_e\bar{\nu}_e} \times \mathcal{B}(\mathrm{H}\to \mathrm{X}\overline{\mathrm{X}}) \propto \frac{g^2_{\mathrm{HWW}}\times g^2_{\mathrm{HXX}}}{\Gamma_{\mathrm{H}}}$$



First vvH → vvbb ~ $g_{HWW}^2\, g_{Hbb}^2 / \Gamma_H$

- vvbb / (ZH(bb) ZH(WW) ~ g_{HZZ}^4 / Γ_H = R → Γ_H precision at 1%

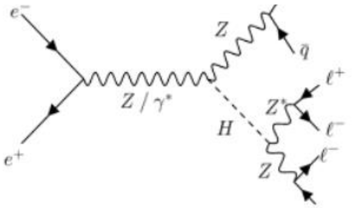
Then do vvH →vvWW ~ g_{HWW}^4 / Γ_H

- R / vvWW ~ g_{HWW}^4 / g_{HZZ}^4
- g_{HWW} precision to few permil

At the end: Higgs couplings and Γ_H extracted from a global fit to all σ x BR (Kappa framework, SMEFT framework)

ZH, Z→(qq/νν) H→ZZ*→4l studies

Yehia Mahmoud and Nicola De Filippis



Samples:

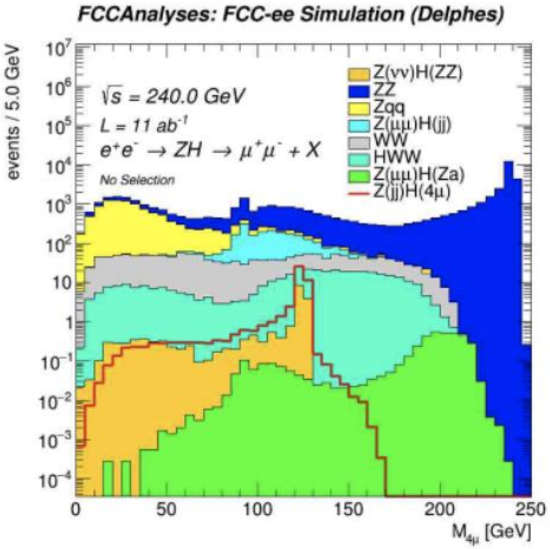
Produced by WHIZARD+PYTHIA for event generation and Delphes (IDEA detector card) for detector simulation. FCCee Winter 2023 Samples. Events produced at $\sqrt{s} = 240$ GeV and L = 10.8 ab^{-1}.

Backround -> ZZ/ WW/ Zqq/ HWW/ Hjj/ HZa

Lepton Selection criteria (Same for hadronic and invisible channels):

- First pair of leptons (From On-shell Z)
  - Oppositely charged leptons
  - The pair which minimises $|M_{ll} - M_Z|$
- Second Pair of leptons (From off-shell Z)
  - Oppositely charged leptons
  - Highest momentum oppositely charged pair of the remaining

- Additional cut for 2e2mu: On-shell Z mass > 60 GeV. This is to remove contribution from Off-Shell Z leptons.


FCCAnalyses: FCC-ee Simulation (Delphes)

Analysis cuts:

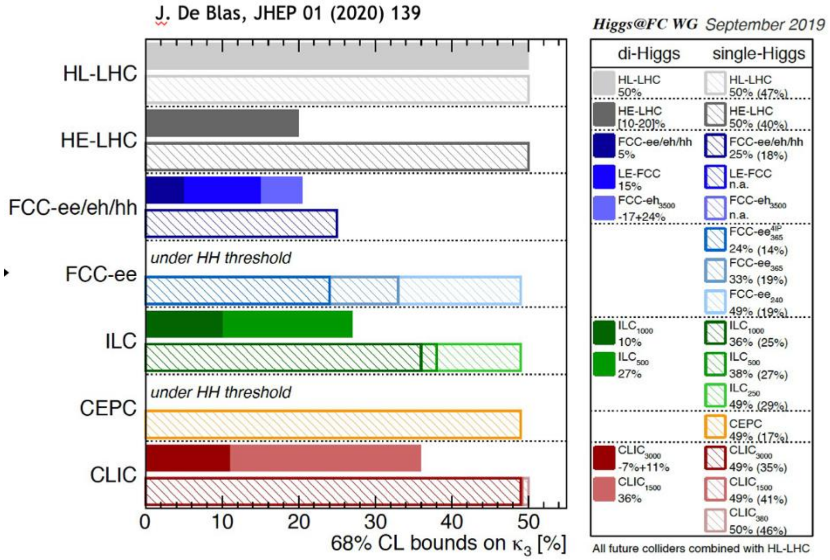
- Momentum of the softest lepton (
  P_{min} > 5 GeV.
- Missing momentum cut:
  P_{miss} < 40 GeV for Z(jj), P_{miss} > 100 GeV for Z(νν)
- Visible energy of all the reconstructed particles excluding the 4 leptons
  E_{vis} > 30 GeV
- Invariant mass of dimuon pair from the Off-shell Z*
  10 < M_{Z^*} < 65 GeV
- Invariant mass of the 4 leptons:
  124 < M_{4l} < 125.5 GeV

Channel	**Signal yield**	**Total Bckg**	**s/√(s+b)**
Z(jj)H(4μ)	26	3	4.82
Z(jj)H(4e)	19	8	3.6
Z(jj)H(2e2μ)	20	5	4.0
Z(νν)H(4μ)	9	4	2.496
Z(νν)H(4e)	6	2	2.12
Z(νν)H(2e2μ)	7	3	2.21

Higgs self couplings at FCC-hh

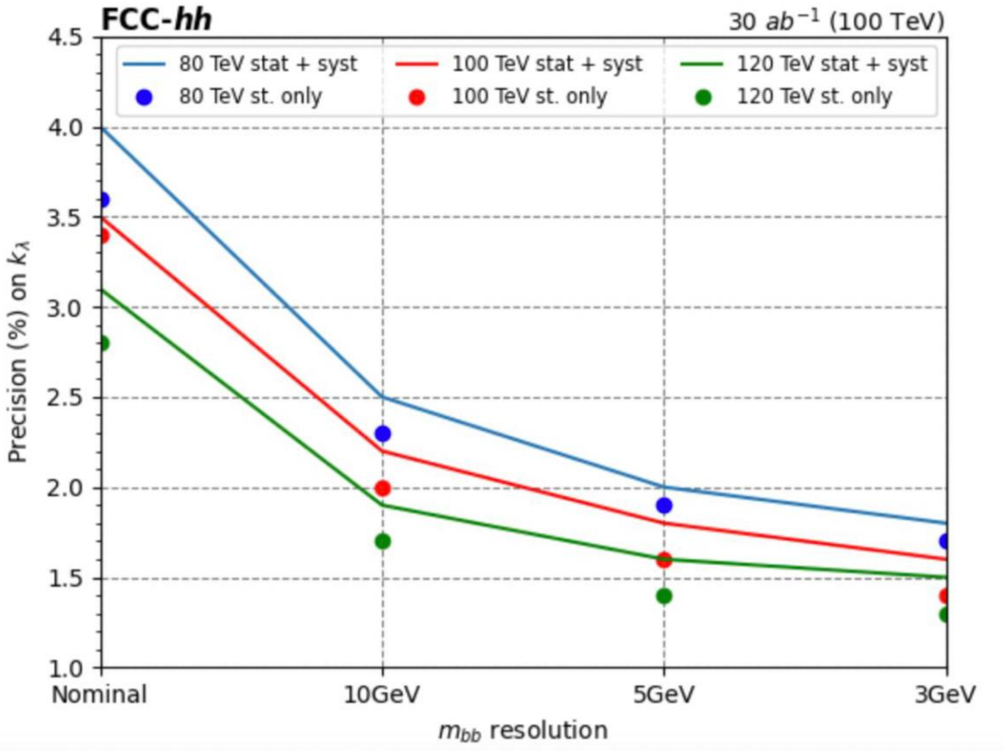
A, Taliercio, N. De Filippis

Future



Future limits on k_λ

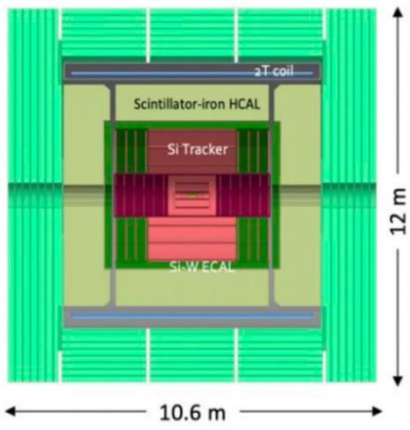
$b\bar{b}\gamma\gamma$ analysis: center of mass energy scan



Detector studies

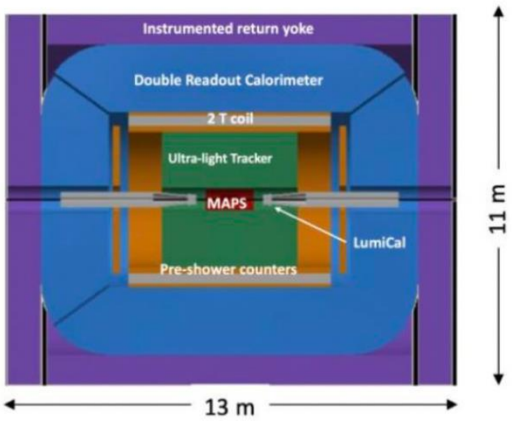
FCC-ee detector concepts

CLD

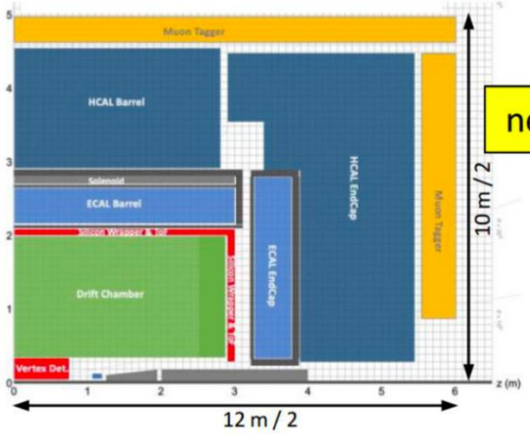


CDR

IDEA



ALLEGRO



new

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

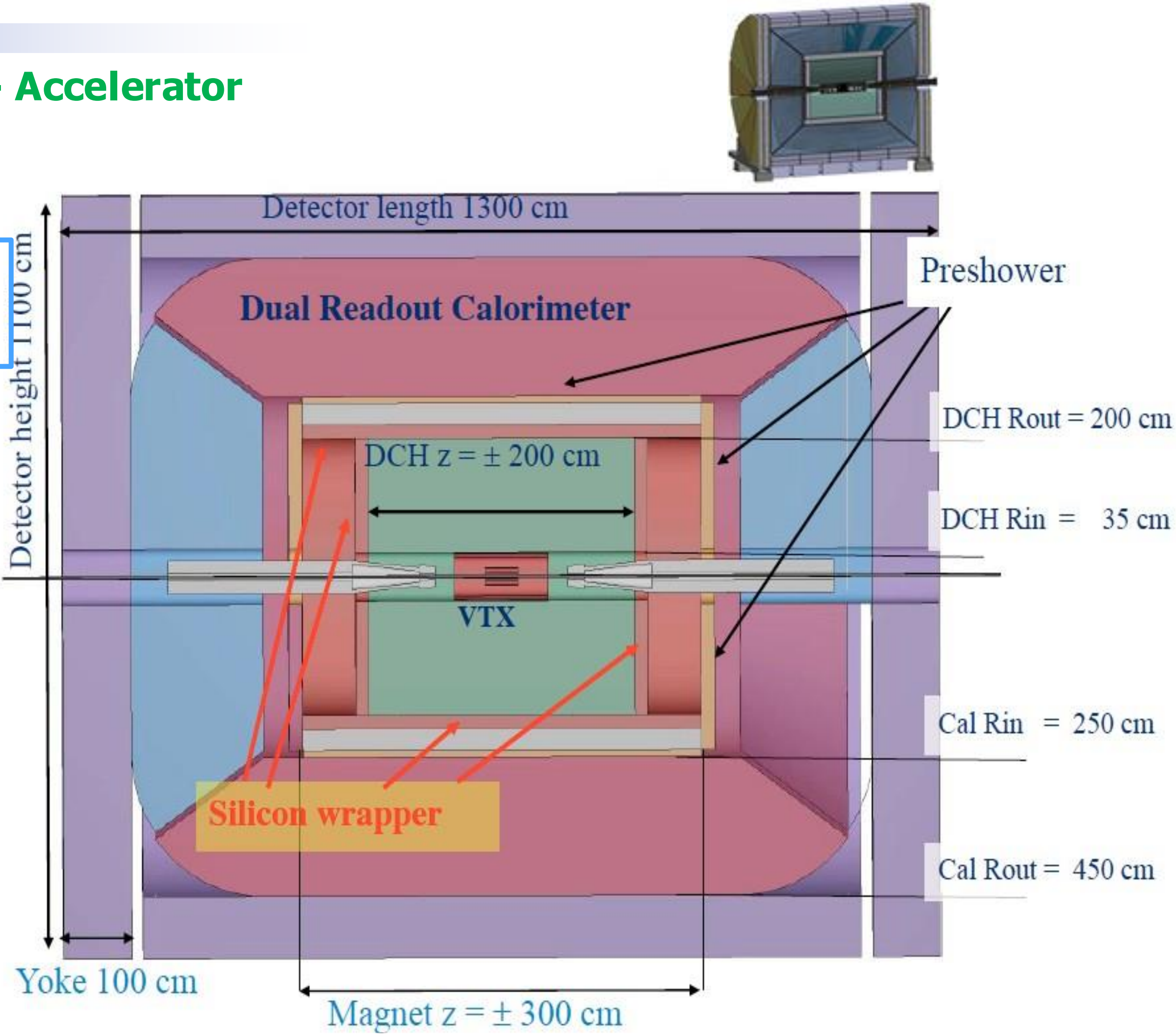
- High luminosity required for the physics → constraints on the design of the detectors close to the machine components, in particular the LumiCal and VTX detectors

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).

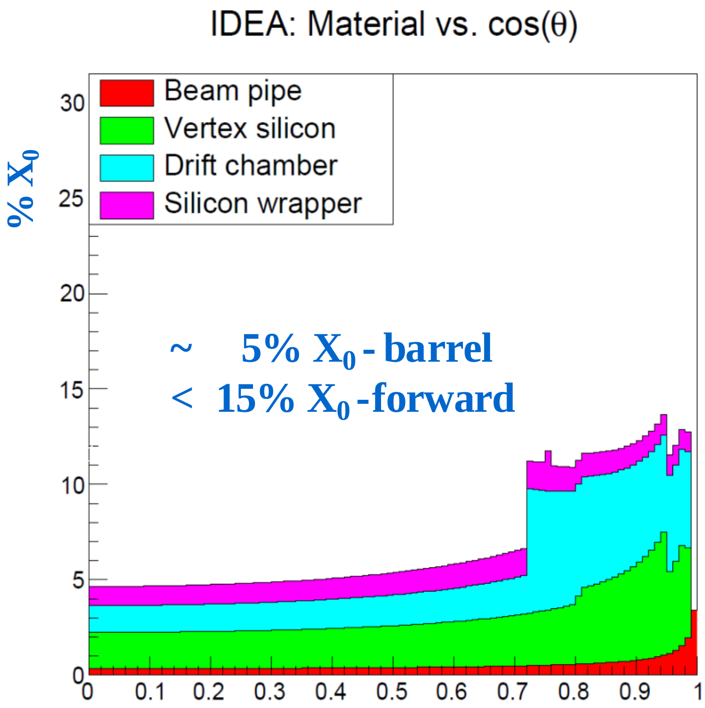
→ optimized at 2 T

→ large tracking radius needed to recover momentum resolution

Design features of the IDEA Drift Chamber

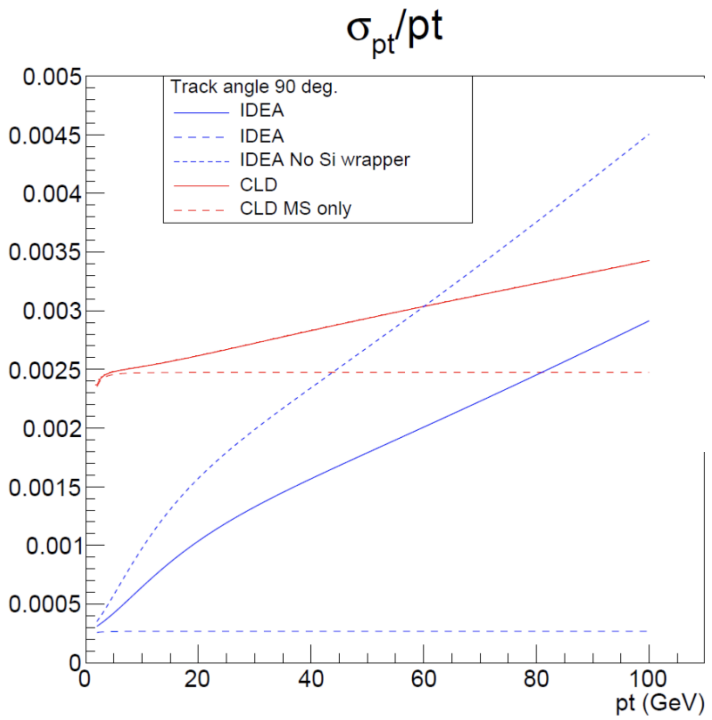
For the purpose of tracking and ID at low and medium momenta mostly for heavy flavour and Higgs decays, the IDEA drift chamber is designed to cope with:

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



~ 5% X_0 - barrel

< 15% X_0 -forward



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

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

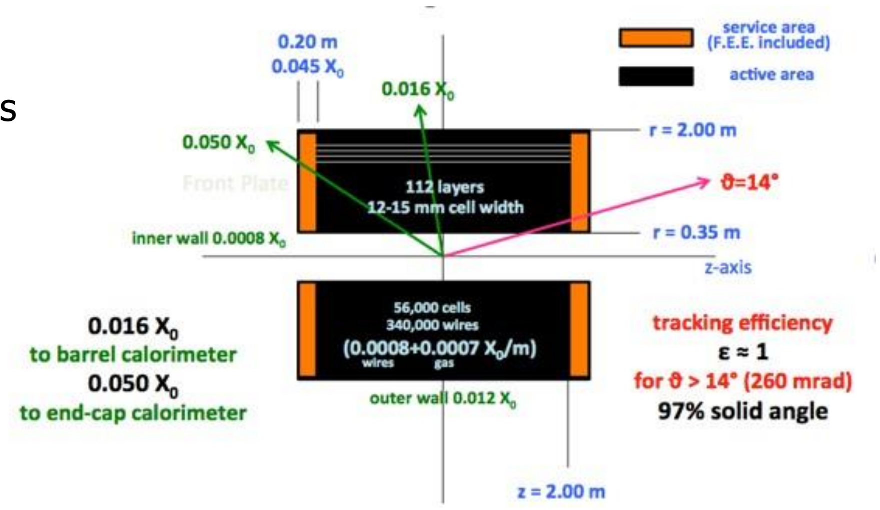
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\,B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}$$

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

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

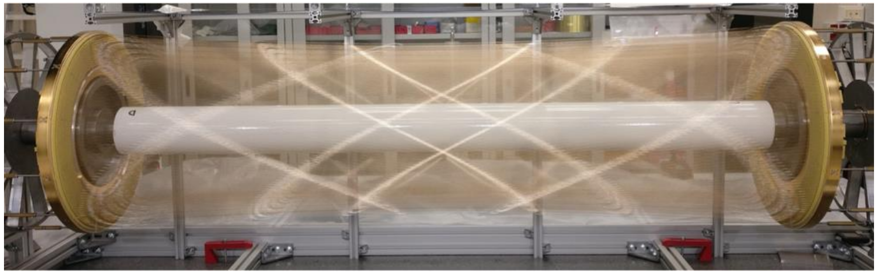
The Drift Chamber of IDEA



The 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
- $\sigma_{xy} < 100\ \mu m$, $\sigma_z < 1$ 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:

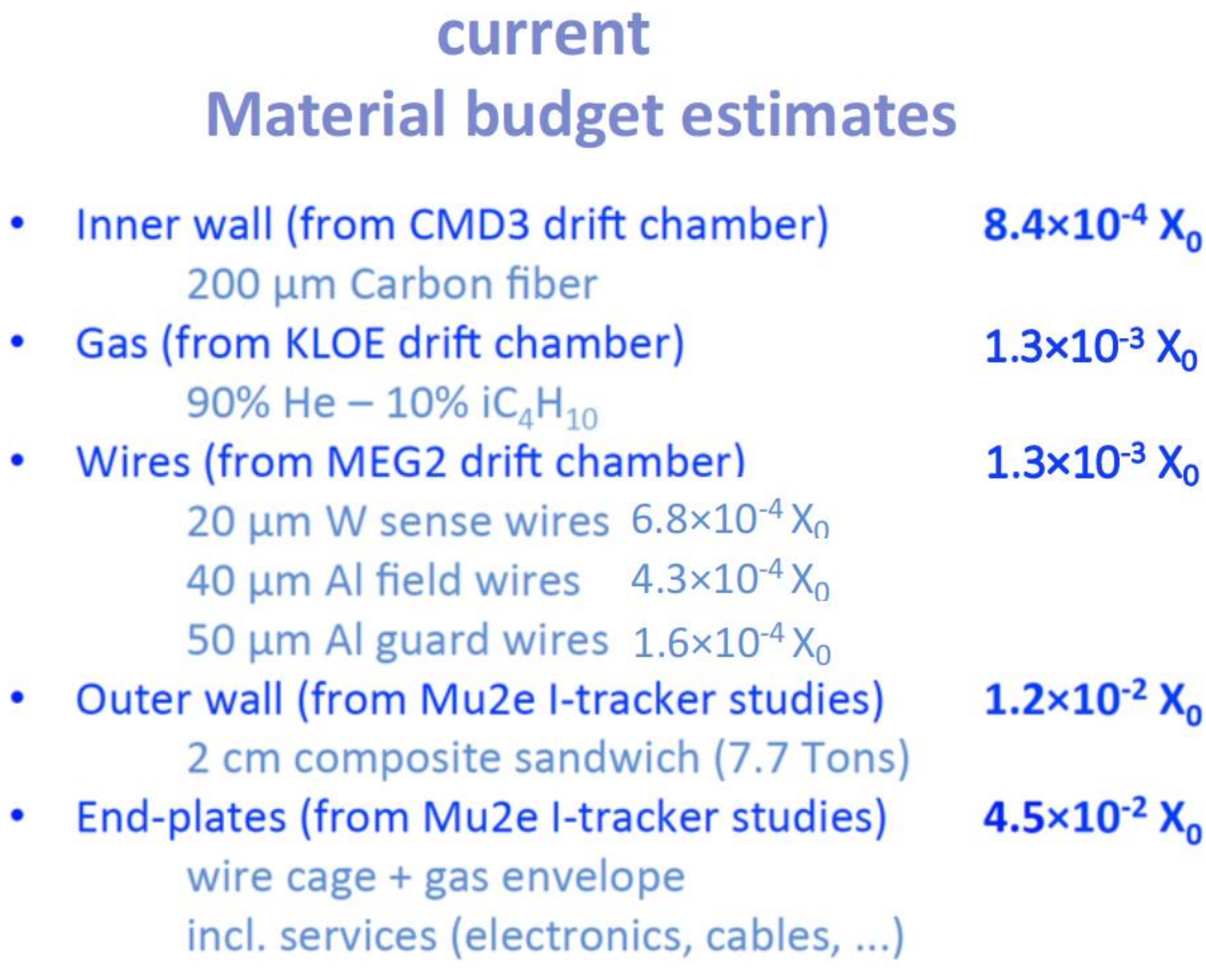
  sense vires: 20 μm diameter W(Au) => 56448 wires
  field wires: 40 μm diameter Al(Ag) => 229056 wires
  f. and g. wires: 50 μm diameter Al(Ag) => 58464 wires



- 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

Challenges: minimization of the material budget

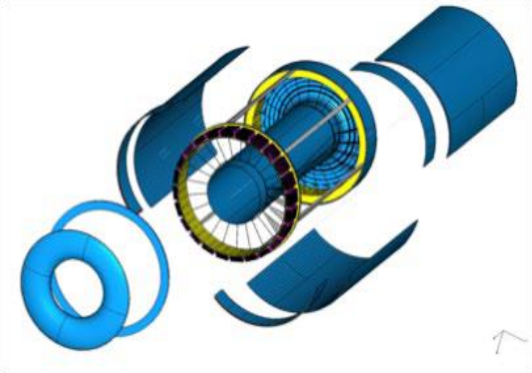


current
Material budget estimates

- 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, ...)

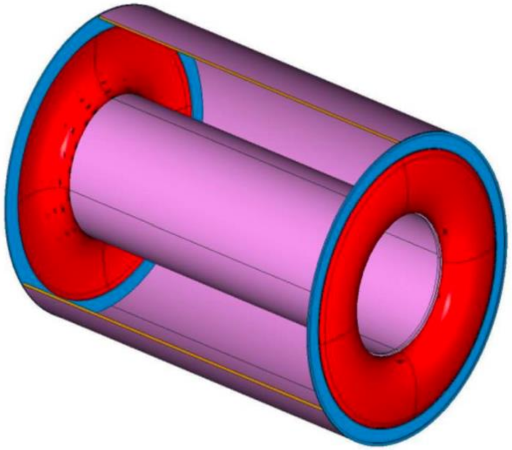
Mechanical structure of the DCH

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.



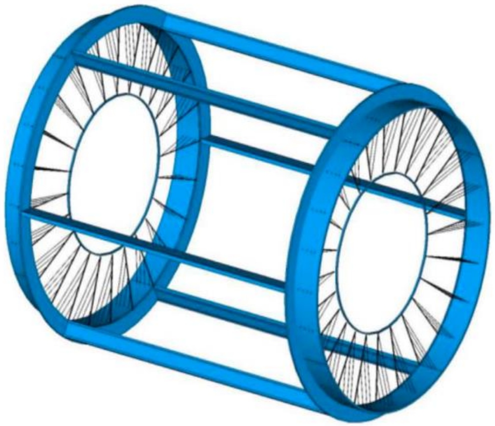
Gas containment

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



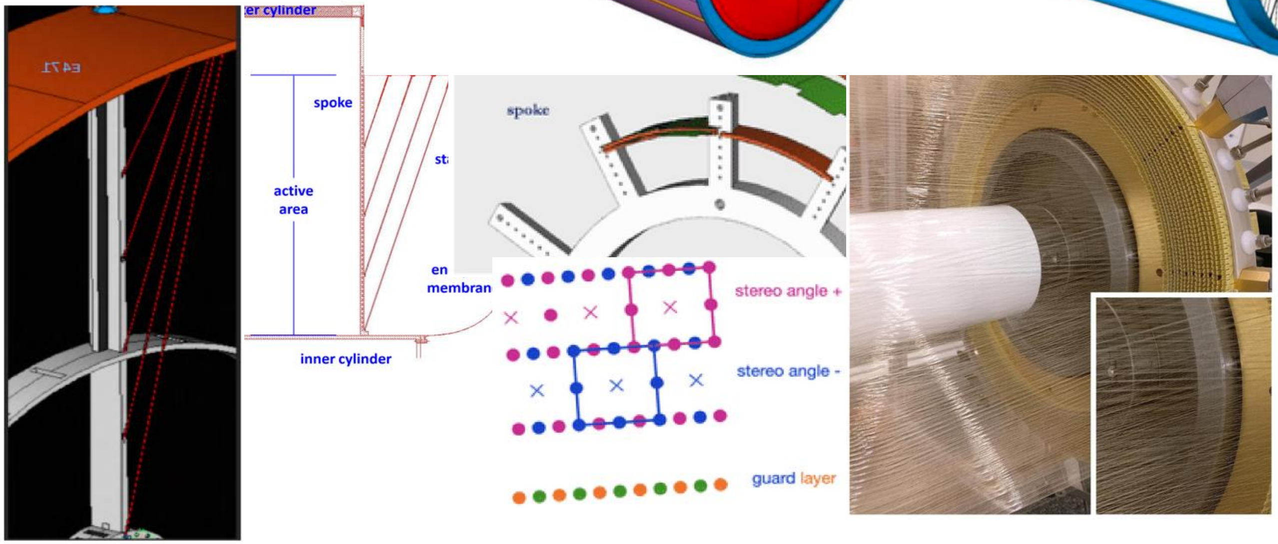
Wire cage

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



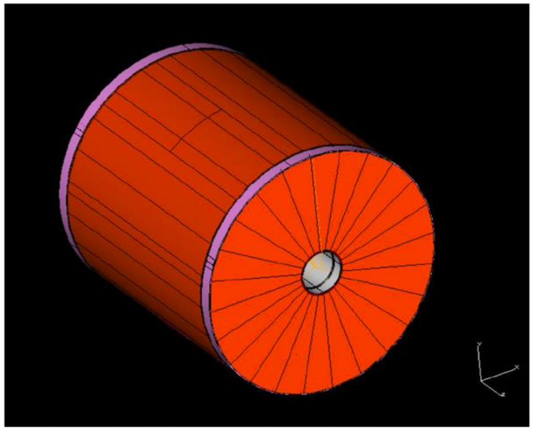
- New tension recovery schema

- Experience inherited from the MEG2 DCH



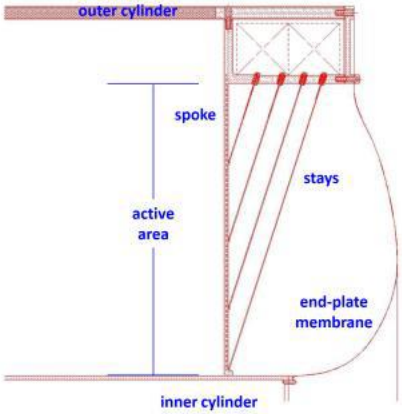
Mechanical structure of the DCH

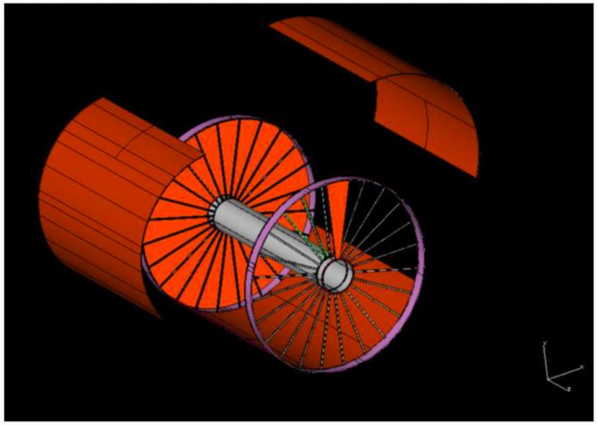
IDEA Drift Chamber



- Inner radius $\mathbf{R_{in}}$ **= 35 cm**, outer radius $\mathbf{R_{out}}$ **= 200 cm**
- Length **L = 400 cm**
- Inner wall thickness **200 μm** Carbon fiber
- Outer wall thickness **2cm** composite material sandwich (honeycomb structure)

tension recovery system



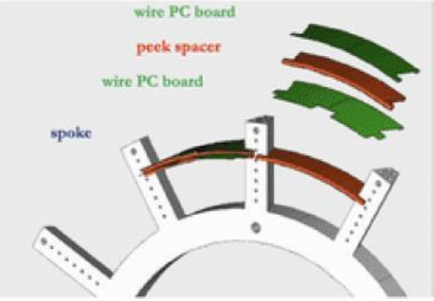


- **Inner cylinder** and **Outer cylinder** are connected with 48 **Spokes** (24 per endcap) forming 24 azimuthal sectors.
- Each spoke is supported by 15 **Cables.**
- Spoke length **l =** 165cm

IDEA Drift Chamber: wire cage

- **343968 wires** in total:
  - 56448 sense wires – 20 μm diameter W(Au)
  - 229056 field wires – 40 μm diameter Al(Ag)
  - 58464 field and guard wires – 50 μm diameter Al(Ag)

- The **Wires** are soldered to the PCB and inserted between the spokes.
- **112 co-axial layers** (grouped in 14 superlayers of 8 layers each) **of para-axial wires**, at alternating-sign stereo angles, arranged in 24 identical azimuthal sectors.
- **Stereo configuration:** one sector is connected with the second corresponding sector in the opposite endcap (hyperbolic profile).



MEG2 drift chamber

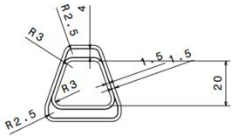
Mechanical structure with FEM

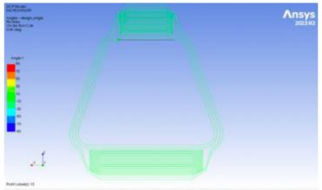
Big Problems to manage!

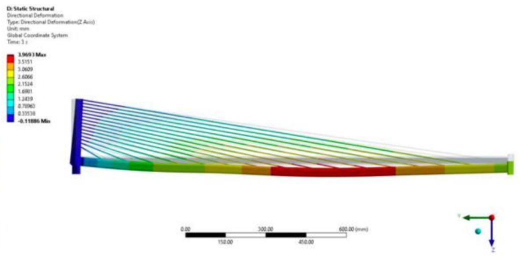
- σ_{xy} < **100 μm** → accuracy on the position of the anodic wires < **50 μm**.
- The anodic and cathodic wires should be parallel in space to preserve the constant electric field.
- A 20 μm tungsten wire, 4 m long, will bow about 400 μm at its middle point, if tensioned with a load of approximately 30 grams.

30 gr tension for each wire → **10 tonnes** of total load on the **endcap**

Simulation studies: progress about the final design of the cross section of the spoke







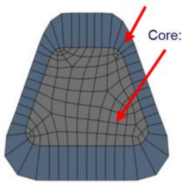
Statical structural simulation: deformation along z

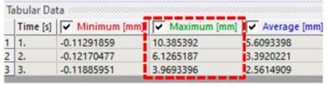
Miccoli (INFN Lecce)

F. Procacci (Poliba e INFN Bari)

Skin: Layered Shell Elements SHELL181

Core: Brick Elements SOLID185





Tabular Data

	Time [s]	☑ Minimum [mm]	☑ Maximum [mm]	☑ Average [mm]
1	1.	-0.11291859	10.385392	5.6093398
2	2.	-0.12170477	6.1265187	3.3920221
3	3.	-0.11885951	3.9693396	2.5614909

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

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 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)

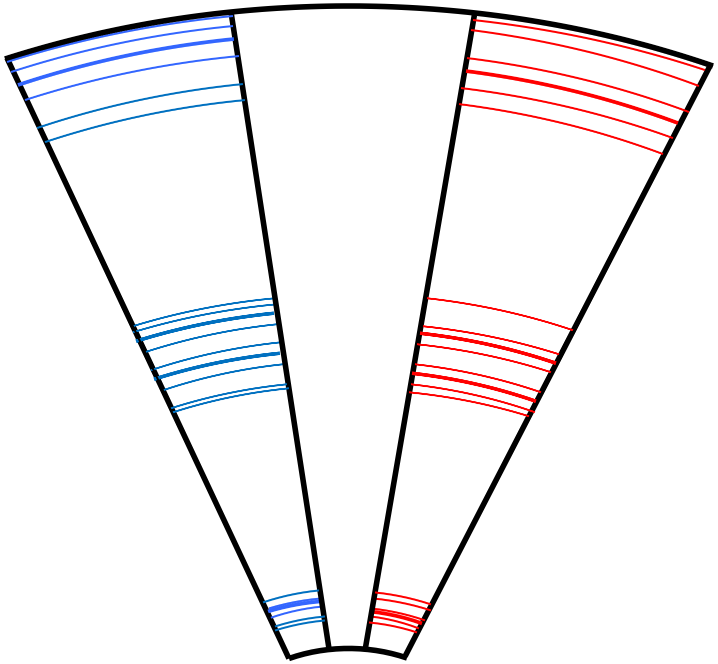
- Test performance of **different versions of front-end, digitization and acquisition chain**

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

2025 full-length prototype: Wiring

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



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

N. De Filippis

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 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 renovate a **clean room at INFN-BA**
- Wiring and assembling operations would occur during second half of 2025
- Prototype built by end of 2025/beginning 2026 and ready to be tested during 2026

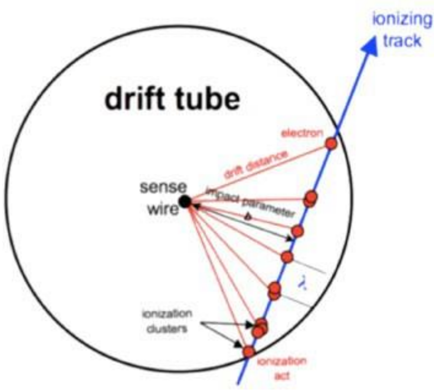
N. B. Aggressive schedule strongly depending on the funding

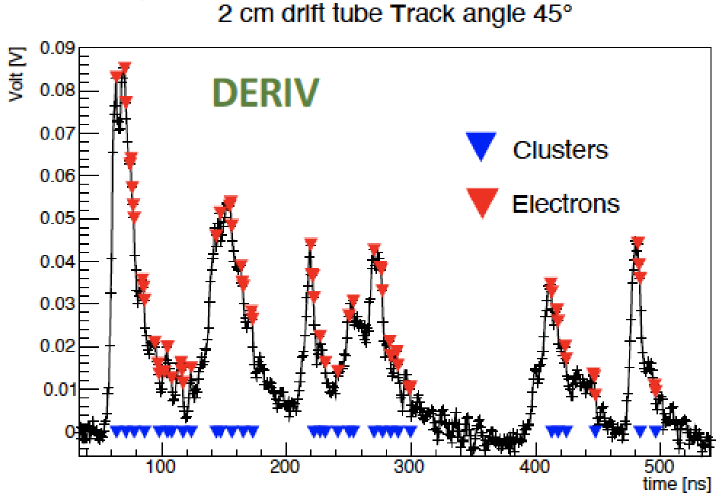
Testbeam data analysis

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

Requirements
fast front-end electronics
(**bandwidth ~ 1 GHz**)
high sampling rate digitization
(**~ 2 GSa/s, 12 bits, >3 KB**)

- 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

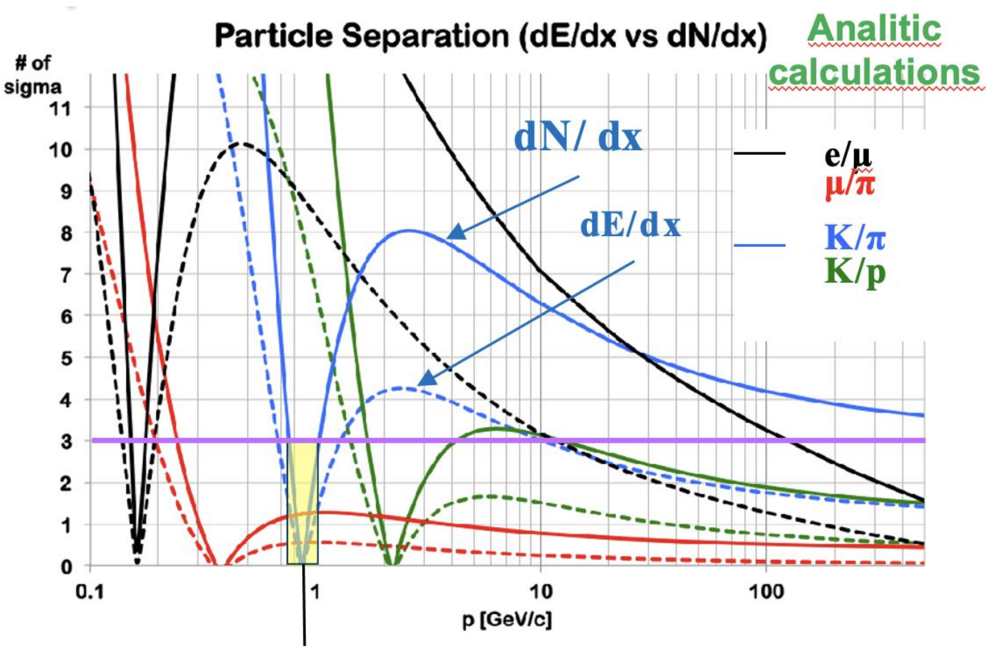
- The cluster counting is based on replacing the measurement of an ANALOG information (the [truncated] mean dE/dX) with a DIGITAL one, the number of ionisation clusters per unit length:

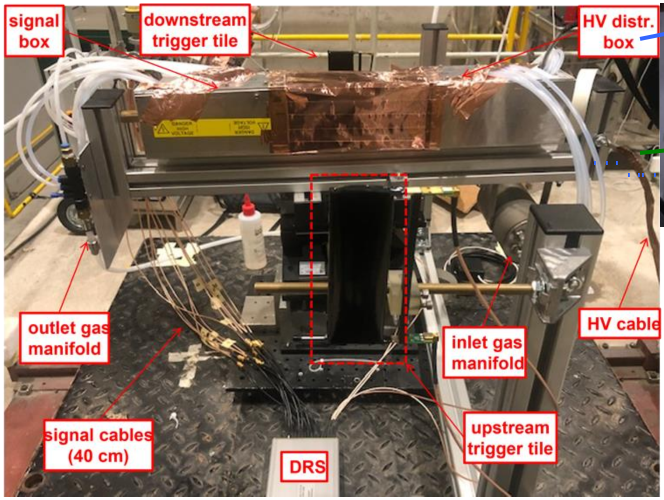
dE/dx: truncated mean cut (70-80%), with a 2m track at 1 atm give $\sigma \approx 4.3\%$

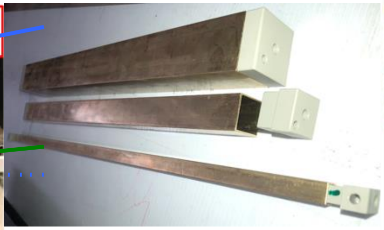
dN_{cl}/dx: for $He/iC_4H_{10}=90/10$ and a 2m track gives $\sigma_{dN_{cl}/dx} / (dN_{cl}/dx) < 2.0\%$

The Drift Chamber: Cluster Counting/Timing and PID

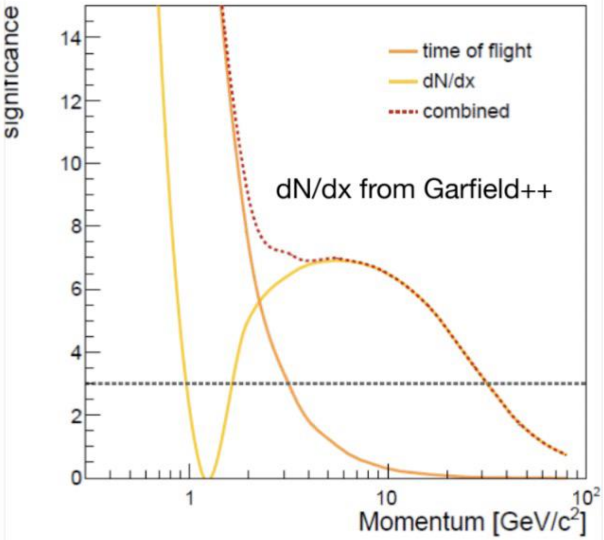
- Analitic calculations: Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)
- Simulation with Garfield++ and with the Garfield model ported in GEANT4:
  - the particle separation, both with dE/dx and with dN_{cl}/dx, in GEANT4 found considerably worse than in 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







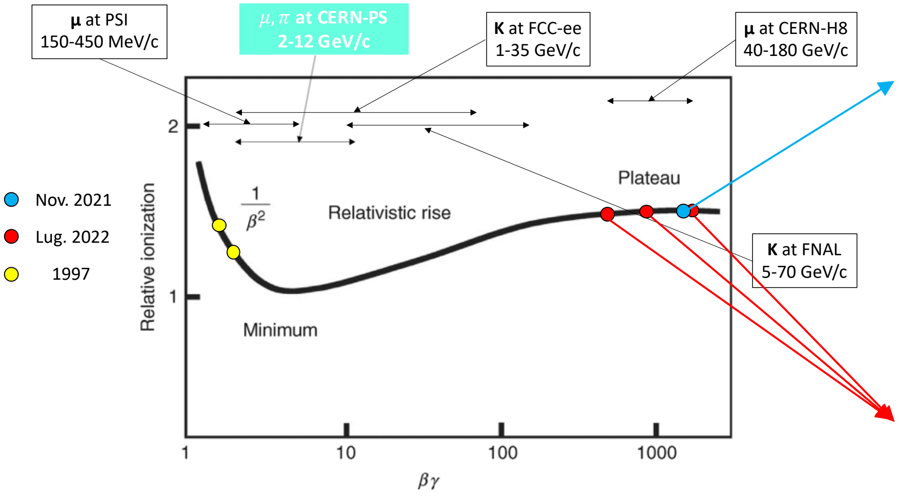
90%He-10%iC$_4$H$_{10}$
nominal HV+20, 45°,
Gas gain ~ $2 \cdot 10^5$,
165 GeV/c

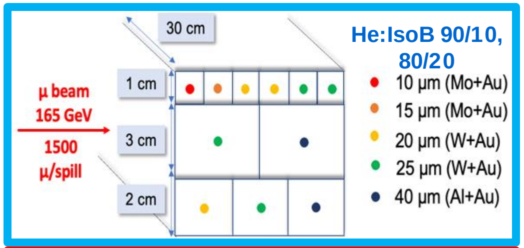


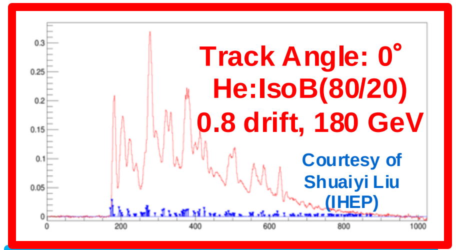
Beam tests in 2021,2022, 2023 and 2024

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).
- A **muon beam test** (from 4 to 12 GeV momentum) in 2023 performed at **CERN**. A new testbeam with the same configuration done on July 10, 2024
- Ultimate test at **FNAL-MT6** in 2025 with □ and **K (βγ = 10−140)** to fully exploit the relativitic rise.

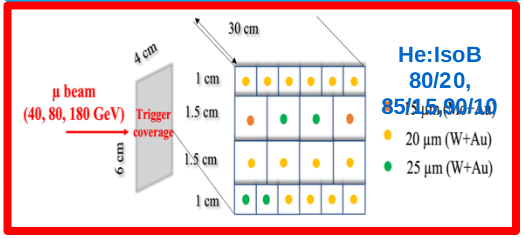


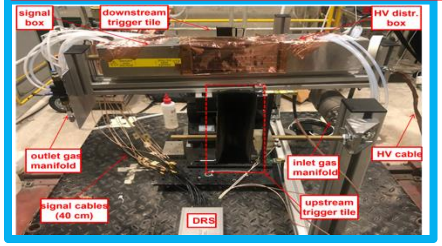




Track Angle: 0°
He:IsoB(80/20)
0.8 drift, 180 GeV

Courtesy of
Shuaiyi Liu
(IHEP)





N. De Filippis

2021/2022 beam test results: performance plots

- Several algorithms developed for electron peak finding:

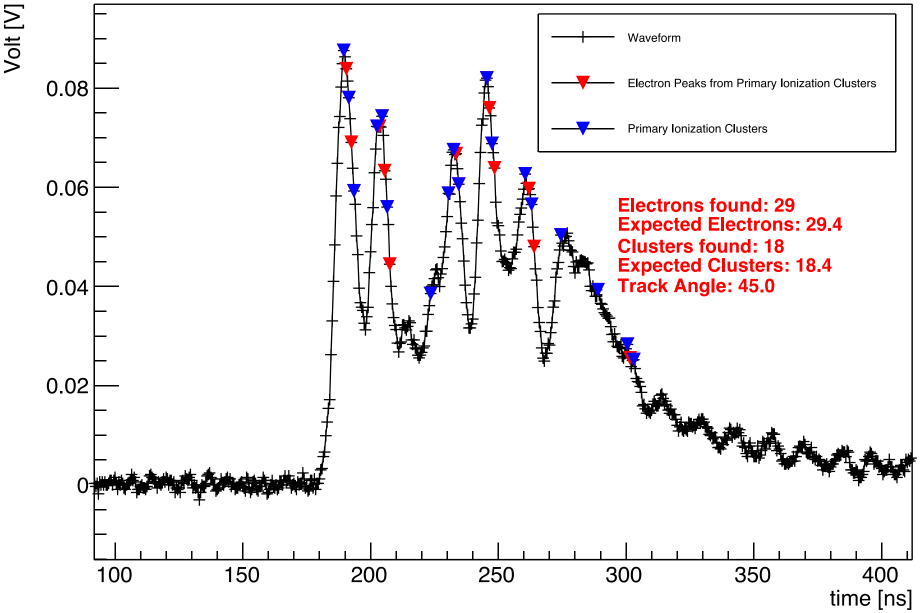
✓ Derivative Algorithm (DERIV)

✓ 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)

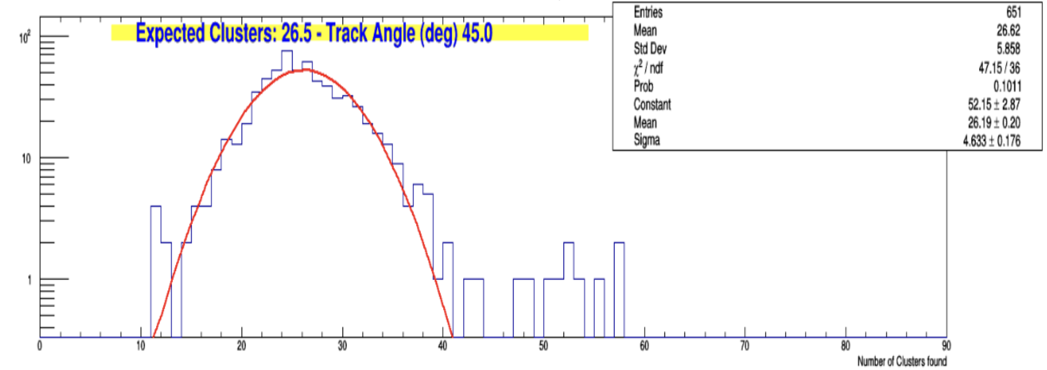
Sense Wire Diameter 15 µm; Cell Size 1.0 cm
Track Angle 45; Sampling rate 2 GSa/s
Gas Mixture He:IsoB 80/20



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

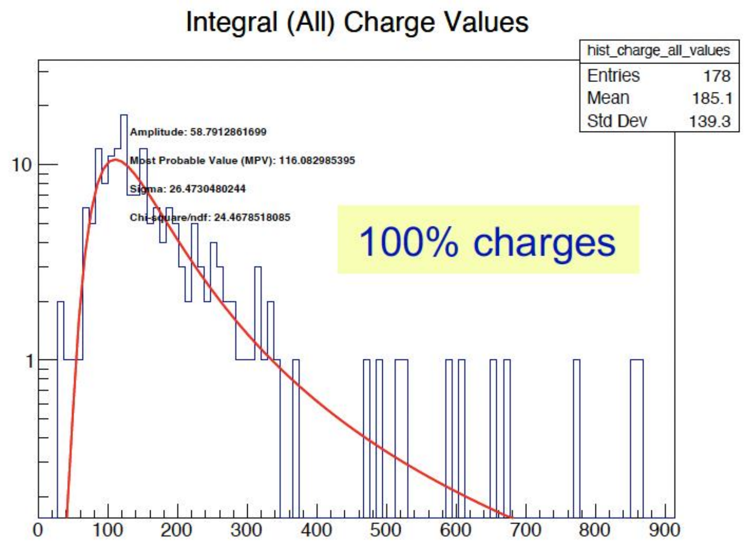


[1] H. Fischle, J. Heintze and B. Schmidt, Experimental determination of ionization cluster size distributions in counting gases, NIMA 301 (1991)

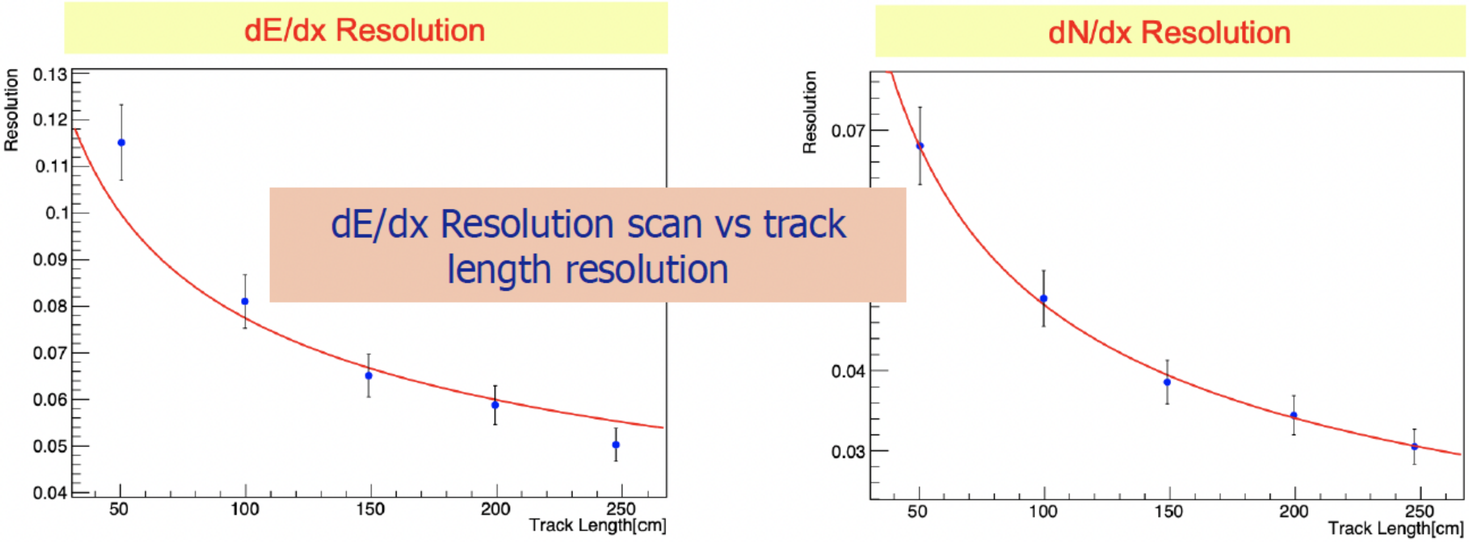
N. De Filippis

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**



100% charges



dE/dx Resolution scan vs track length resolution

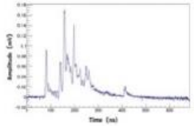
dE/dx resolution dependence on the track length $L^{-0.37}$

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

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

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**

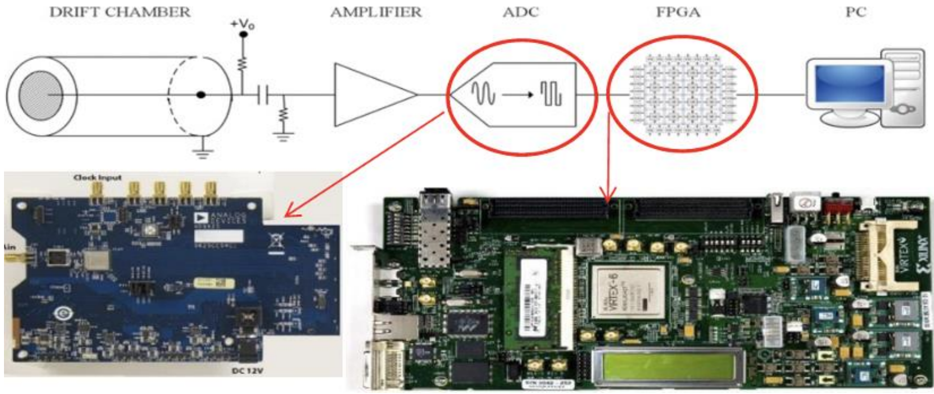
- 100 KHz of Z decays with 20 charged tracks/event multiplicity
- 30 KHz of $\gamma\gamma \longrightarrow$ hadrons with10 charged tracks/event multiplicity
- 2.5% occupancy due to beam noise
- 2.5% occupancy due to hits with isolated peaks

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.



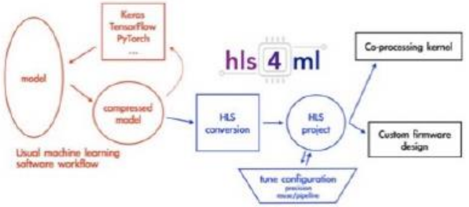
Single channel solution has been successfully verified.

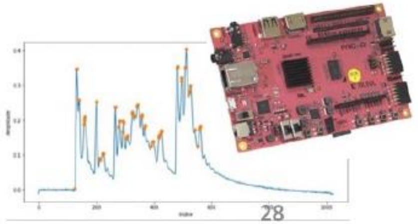
G. Chiarello et al., The Use of FPGA in Drift Chambers for High Energy Physics Experiments May 31, 2017 DOI: 10.5772/66853

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

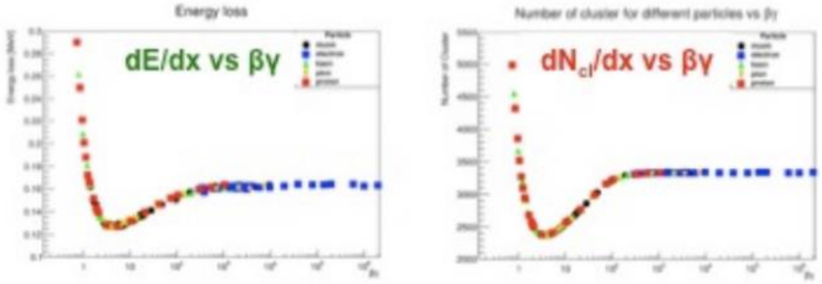


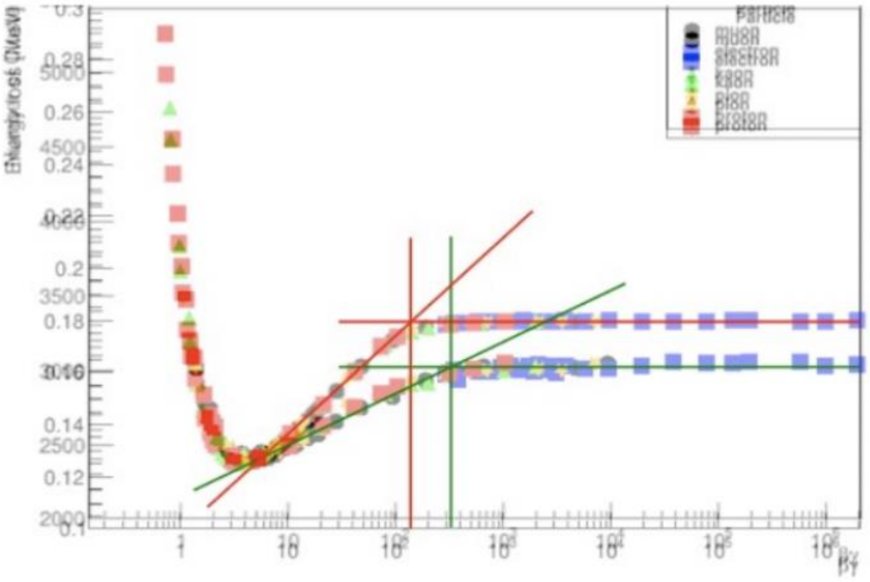


Full simulation

Simulation of Cluster Counting/Timing and PID: GARFIELD

GEANT4 with **HEED** clusterization model





F. Cuna, N. De Filippis, F. Grancagnolo, G. Tassielli, Simulation of particle identification with the cluster counting technique, arXiv:2105.07064v1 [physics.ins-det] 14 May 2021

Higher values of Fermi plateau for **dN$_{cl}$/dx** w.r.t. **dE/dx**,
yet
reached at lower $\beta\gamma$ values
and with a steeper slope

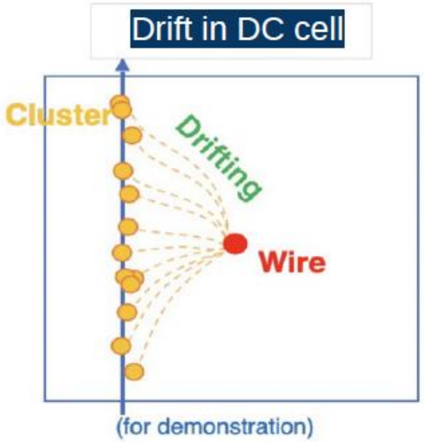
due to a choice of **E$_{cut}$** (the maximum energy of an electron still associated to a track in the simulation) parameter?

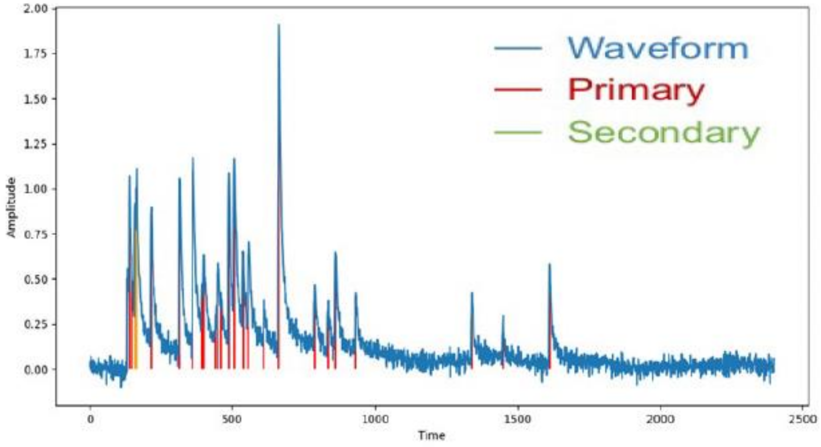
⇩

Experimental beam test campaign needed

Simulation of Cluster Counting: GARFIELD + NN

IHEP + M. Anwar (Bari Politecnico)





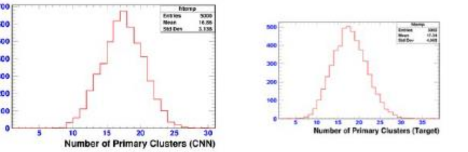
Digitizer in place → to be exported in Key4HEP

- A muon particle is passed through mixture of gases (90% He and 10% C_4H_{10}) generate electron-ion pairs causing a read out signal (induce current). The simulation package creates analog induced current waveforms from ionizations (HEED). The digitization package incorporates electronics responses taken from experimental measurements and generates realistic digital waveforms

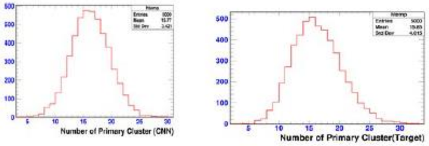
• Two Step Reconstruction Algorithm:

- **Peak finding: Find all peaks (primary and secondary) in the waveform**
- **Clusterization: Determine the primary peaks from the founded peaks in step 1**

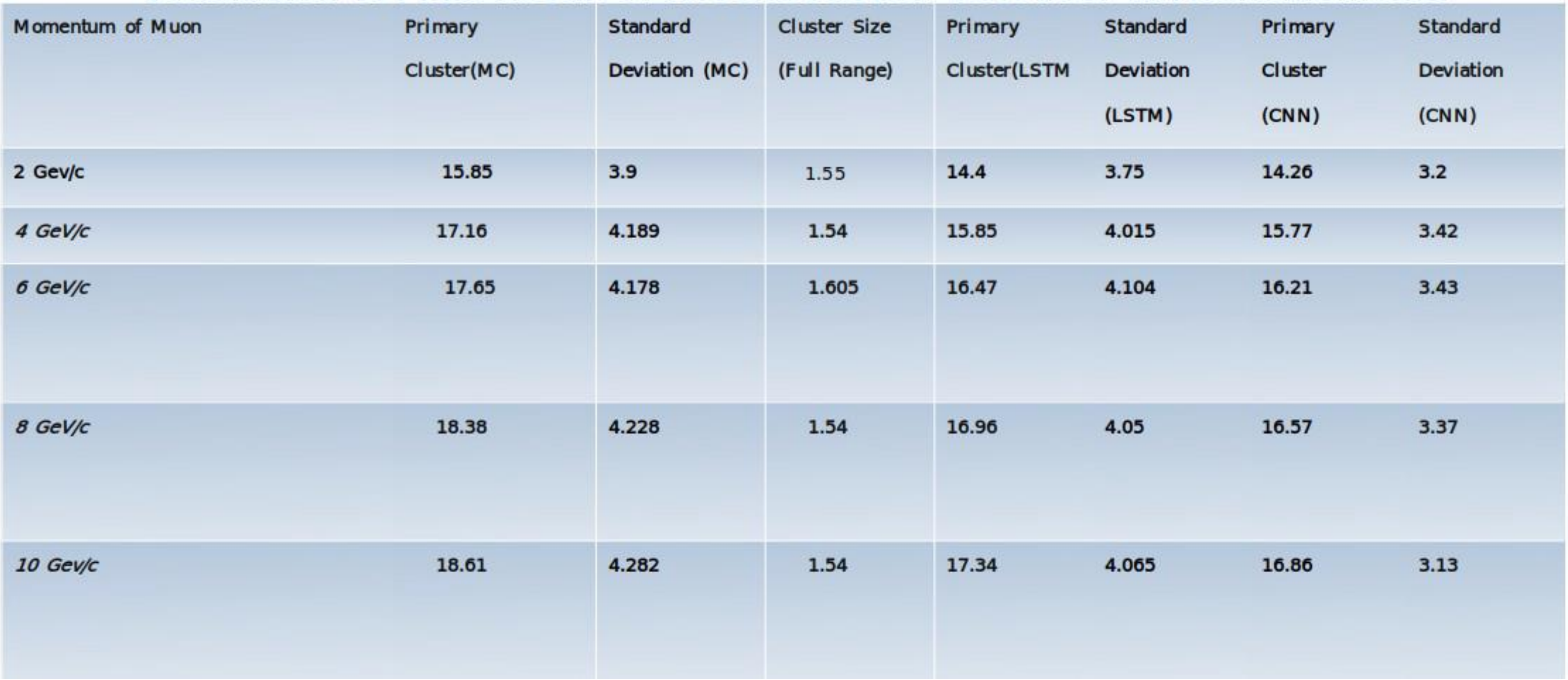
Simulation of Cluster Counting: GARFIELD + NN



- The above distrubitions shows us the number of primary clusters detected by CNN and Target(LSTM) for 10 GeV Momentum



- The above distrubitions shows us the number of primary clusters detected by CNN and Target(LSTM) for 4 GeV Momentum



Momentum of Muon	Primary Cluster(MC)	Standard Deviation (MC)	Cluster Size (Full Range)	Primary Cluster(LSTM	Standard Deviation (LSTM)	Primary Cluster (CNN)	Standard Deviation (CNN)
2 Gev/c	15.85	3.9	1.55	14.4	3.75	14.26	3.2
4 GeV/c	17.16	4.189	1.54	15.85	4.015	15.77	3.42
6 GeV/c	17.65	4.178	1.605	16.47	4.104	16.21	3.43
8 GeV/c	18.38	4.228	1.54	16.96	4.05	16.57	3.37
10 Gev/c	18.61	4.282	1.54	17.34	4.065	16.86	3.13

N. De Filippis

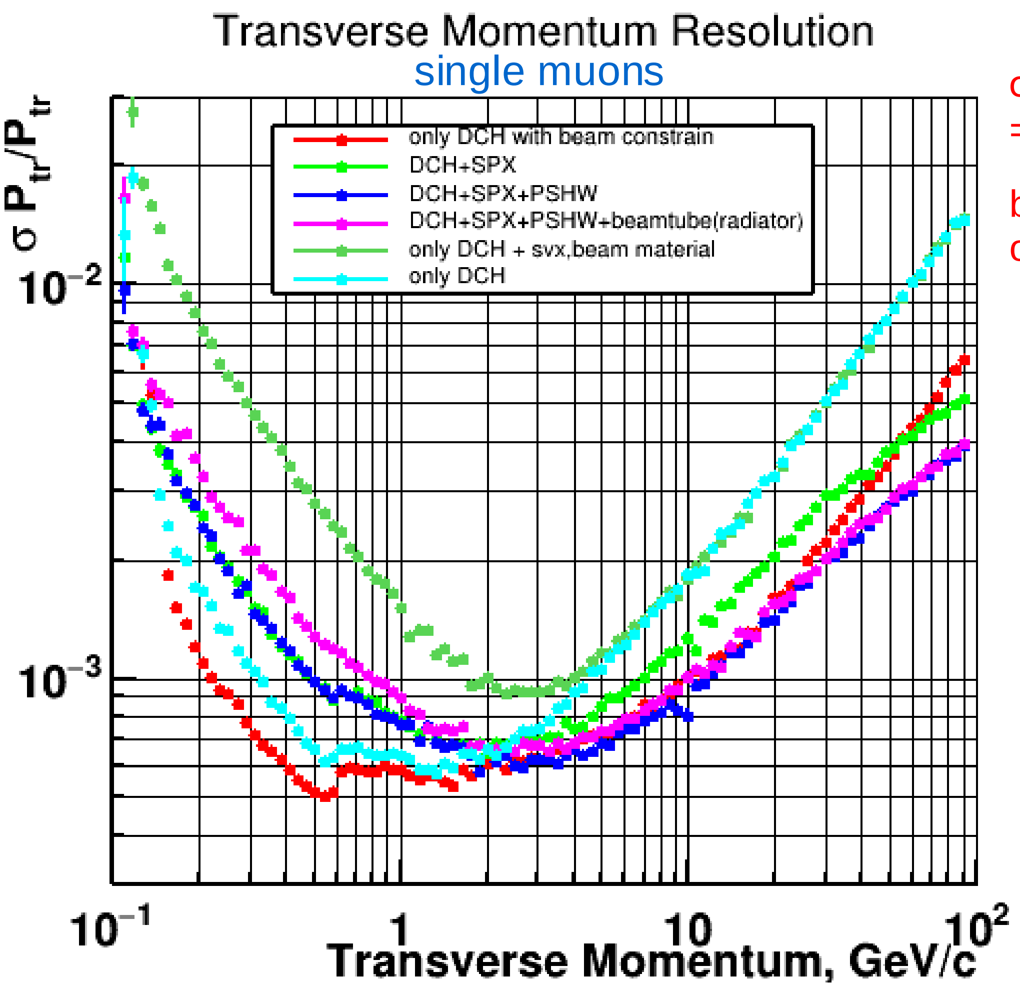
Full simulation of IDEA: performance of the IDEA (old) + tracking + background studies

For the Geant4 based simulation framework code:

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

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

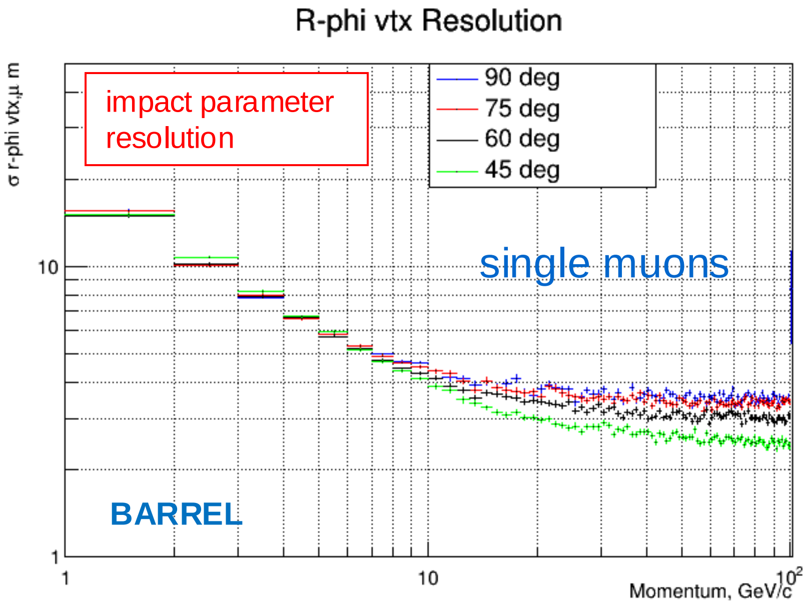
$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{N}{\sqrt{(N+1)(N-1)}}\,\frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}\left(1+0.038\ln\frac{d}{X_0\,\sin\theta}\right)$$



single muons

$\sigma(p_t)/p_t$ (100 GeV) $= 3\times10^{-3}$

but new studies ongoing



impact parameter resolution

single muons

BARREL

$\sigma(d_0)$ (100 GeV) = 2μm

International collaboration

INFN Bari + Lecce

INFN Pisa joining with MEG DCH experts

INFN Perugia joining for tracking studies

G. Iakovidis group from BNL (US): wire procurement

A. Jung group from Purdue U. (US):

- coating / manufacturing facility at composite center Purdue would allow manufacturing all kinds of materials
- existing supported R&D on US side
  - composite R&D for thicker high TC / electric C CFs
  - reconstruction / tracking for FCC folded GEANT work of implementing CF into sim
  - prototype of CF and reference of tungsten being constructed in lab

G. Charles group from IJCLAB (France)

- any test with wire material, choice for the prototype chosen but new ones could be tested. Produce charaterization of strength, maybe with a micrometric motor. Test different kind of wires
- test also of anchoring the wire (crimp, gluing, soldering)
- activity on mechanical design and realization of prototypes
- Garfield simulation studies, participation to testbeam campaigns
- Activity on electronics to be verified with IN2P3

IHEP (China): Effort to build a international collaboration enforced

- ➢ well established collaboration with IHEP for NN-based cluster counting algorithm

Summary/Conclusions

Good progress reported on:

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

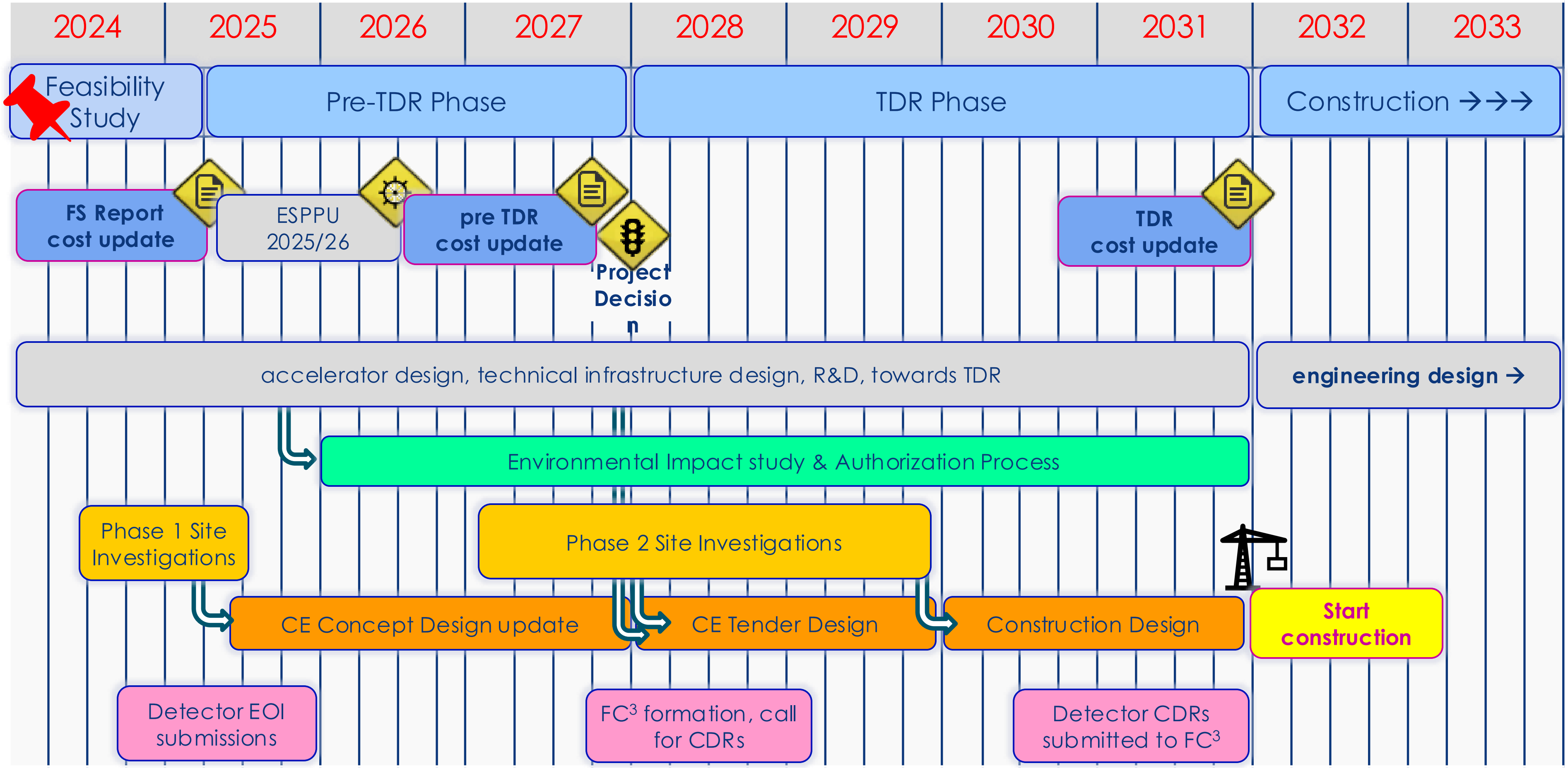
Plenty of areas for collaboration (also in the context of DRD1 WP2):

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

Effort to build a international collaboration enforced

Backup

Possible timeline till start of construction



2024 2025 2026 2027 2028 2029 2030 2031 2032 2033

Feasibility Study

Pre-TDR Phase

TDR Phase

Construction →→→

FS Report cost update

ESPPU 2025/26

pre TDR cost update

Project Decision

TDR cost update

accelerator design, technical infrastructure design, R&D, towards TDR

engineering design →

Environmental Impact study & Authorization Process

Phase 1 Site Investigations

Phase 2 Site Investigations

CE Concept Design update

CE Tender Design

Construction Design

Start construction

Detector EOI submissions

FC^3 formation, call for CDRs

Detector CDRs submitted to FC^3

FUTURE CIRCULAR COLLIDER

FCC-ee main machine parameters

Parameter	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1270	137	26.7	4.9
number bunches/beam	11200	1780	440	60
bunch intensity [10^{11}]	2.14	1.45	1.15	1.55
SR energy loss / turn [GeV]	0.0394	0.374	1.89	10.4
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.1/0	2.1/9.4
long. damping time [turns]	1158	215	64	18
horizontal beta* [m]	0.11	0.2	0.24	1.0
vertical beta* [mm]	0.7	1.0	1.0	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.71	1.59
vertical geom. emittance [pm]	1.9	2.2	1.4	1.6
vertical rms IP spot size [nm]	36	47	40	51
beam-beam parameter ξ_x / ξ_y	0.002/0.0973	0.013/0.128	0.010/0.088	0.073/0.134
rms bunch length with SR / BS [mm]	5.6 / 15.5	3.5 / 5.4	3.4 / 4.7	1.8 / 2.2
luminosity per IP [10^{34} cm^{-2}s^{-1}]	140	20	≥5.0	1.25
total integrated luminosity / IP / year [ab^{-1}/yr]	17	2.4	0.6	0.15
beam lifetime rad Bhabha + BS [min]	15	12	12	11

4 years
5 x 10^{12} Z
LEP x 10^{5}

2 years
> 10^{8} WW
LEP x 10^{4}

3 years
2 x 10^{6} H

5 years
2 x 10^{6} tt pairs

Design and parameters to maximise luminosity at all working points:

- allow for 50 MW synchrotron radiation per beam.
- **Independent vacuum systems for electrons and positrons**
- **full energy booster ring with top-up injection, collider permanent in collision mode**

- ☐ x 10-50 improvements on all EW observables
- ☐ up to x 10 improvement on Higgs coupling (model-indep.) measurements over HL-LHC
- ☐ x10 Belle II statistics for b, c, τ
- ☐ indirect discovery potential up to ~ 70 TeV
- ☐ direct discovery potential for feebly-interacting particles over 5-100 GeV mass range

Up to 4 interaction points → robustness, statistics, possibility of specialised detectors to maximise physics output

F. Gianotti

On going Higgs analyses so far

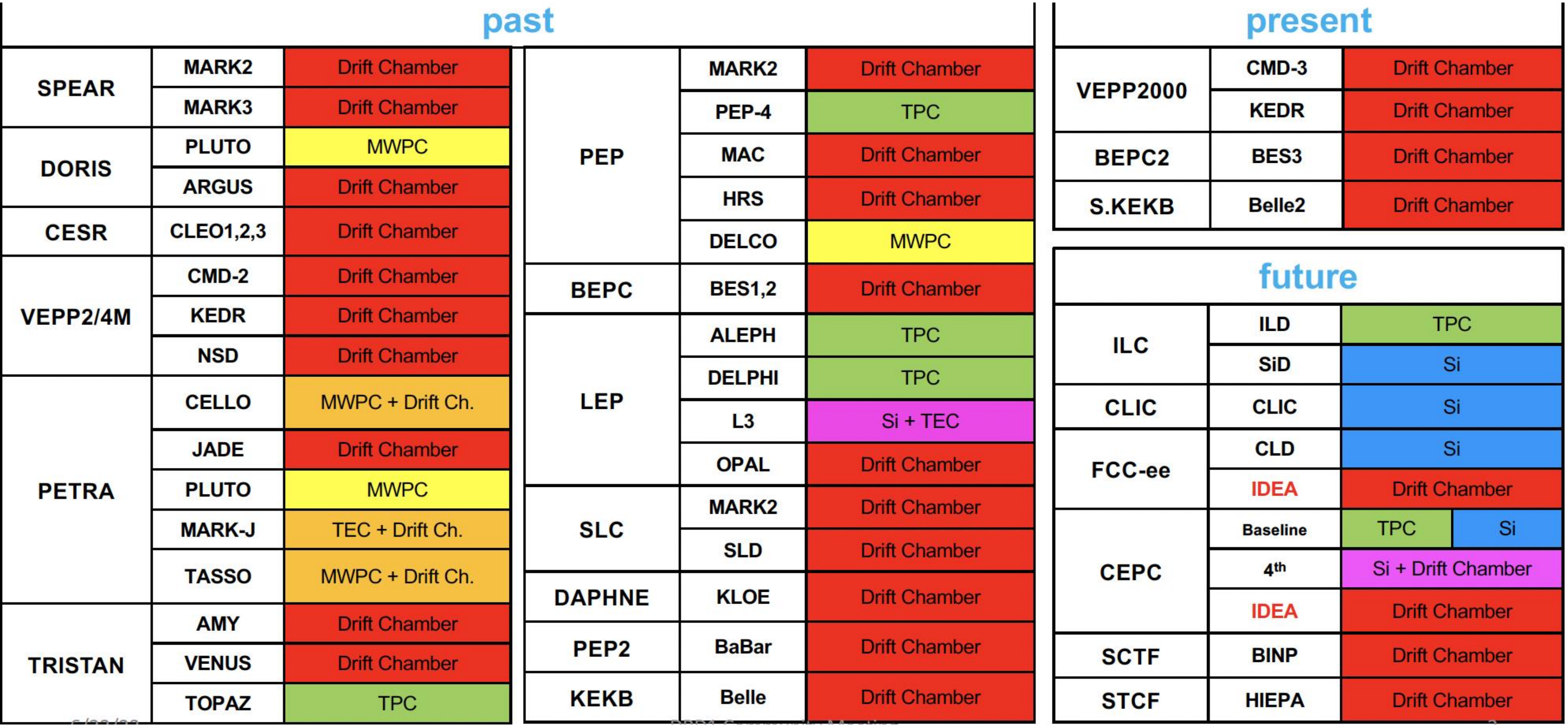
FCC-ee:

- ZH cross section and Higgs mass measurement
- Higgs couplings in fully hadronic final state (Z → jj, H → jj and Z → νν, H → jj)
- Higgs CP studies
- Higgs Width Determination Using ZHZZ* Events (N. De Filippis, Y. Mahmoud)
- Light Yukawas and FCNCs in the ZH →vvjj channel
- Higgs boson self-coupling
- Study of Electron Yukawa via s-channel Higgs Production at FCC-ee (ee->H->WW*)
- Higgs to invisible analysis

FCC-hh:

- Higgs self-coupling measurements at the FCC-hh (N. De Filippis, A. Taliercio et al.)

Tracker detectors at e^+e^- collider



past

SPEAR	MARK2	Drift Chamber
	MARK3	Drift Chamber
DORIS	PLUTO	MWPC
	ARGUS	Drift Chamber
CESR	CLEO1,2,3	Drift Chamber
VEPP2/4M	CMD-2	Drift Chamber
	KEDR	Drift Chamber
	NSD	Drift Chamber
PETRA	CELLO	MWPC + Drift Ch.
	JADE	Drift Chamber
	PLUTO	MWPC
	MARK-J	TEC + Drift Ch.
	TASSO	MWPC + Drift Ch.
TRISTAN	AMY	Drift Chamber
	VENUS	Drift Chamber
	TOPAZ	TPC

PEP	MARK2	Drift Chamber
	PEP-4	TPC
	MAC	Drift Chamber
	HRS	Drift Chamber
	DELCO	MWPC
BEPC	BES1,2	Drift Chamber
LEP	ALEPH	TPC
	DELPHI	TPC
	L3	Si + TEC
	OPAL	Drift Chamber
SLC	MARK2	Drift Chamber
	SLD	Drift Chamber
DAPHNE	KLOE	Drift Chamber
PEP2	BaBar	Drift Chamber
KEKB	Belle	Drift Chamber

present

VEPP2000	CMD-3	Drift Chamber
	KEDR	Drift Chamber
BEPC2	BES3	Drift Chamber
S.KEKB	Belle2	Drift Chamber

future

ILC	ILD	TPC
	SiD	Si
CLIC	CLIC	Si
FCC-ee	CLD	Si
	IDEA	Drift Chamber
CEPC	Baseline	TPC Si
	4th	Si + Drift Chamber
	IDEA	Drift Chamber
SCTF	BINP	Drift Chamber
STCF	HIEPA	Drift Chamber

Activities discussed in the framework of:

- FCC-ee collaboration
- DRD1 Gaseous Detector – collaboration
  - WP2 - Inner and central tracking with PID (Drift Chambers)

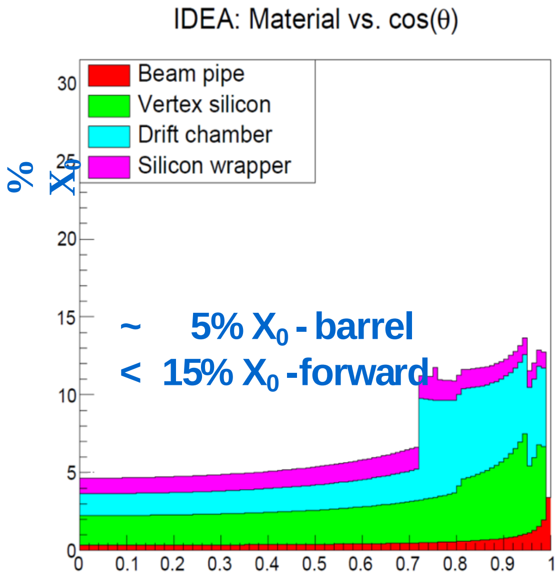
Requirements on track momentum resolution

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

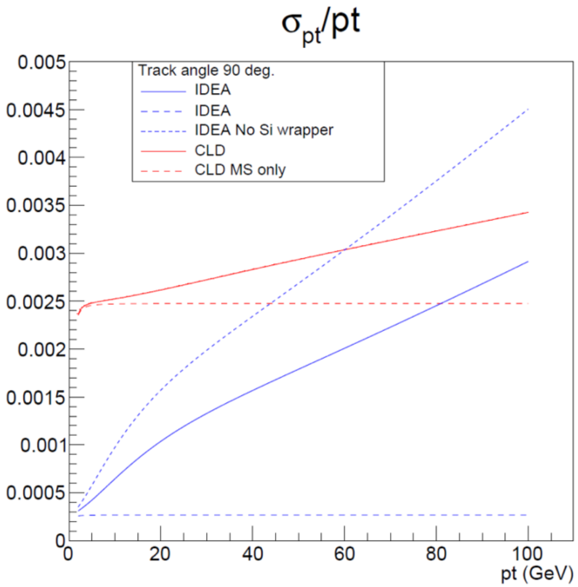
The CLD silicon tracker is made of:

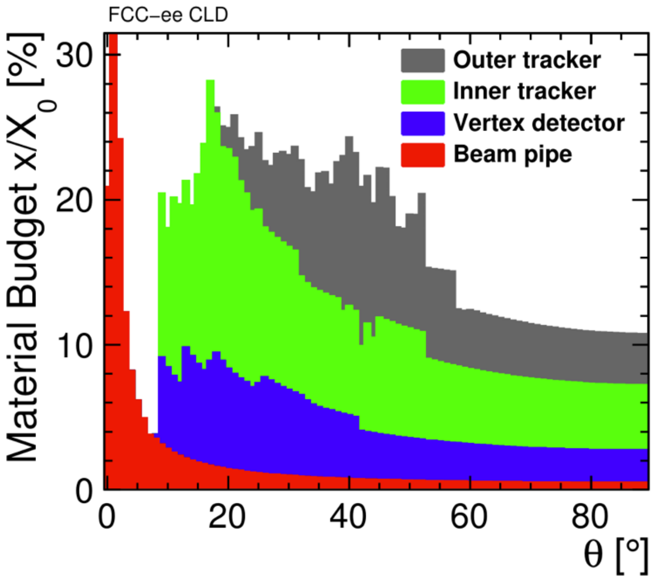
- six barrel layers, at radii ranging between 12.7 cm and 2.1 m, and of eleven disks.
- the material budget for the tracker modules is estimated to be 1.1 − 2.1% of a radiation length per layer



~ 5% X_0 - barrel

< 15% X_0 -forward





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
- about 0.25% (0.3%) with the CLD full silicon tracker, being dominated by the effect of MS

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 **~5×10^5**.
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**

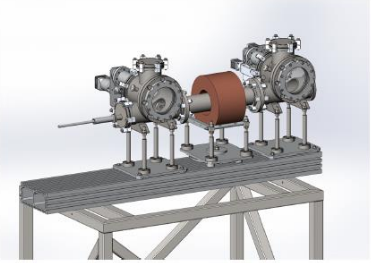
⇒ gas studies

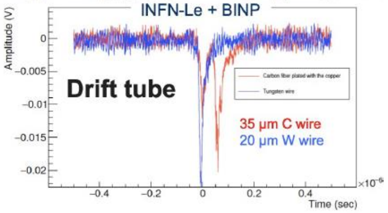
- **Data throughput**

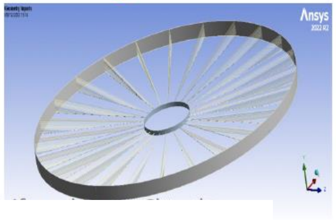
Large number of channels, high signal sampling rate, long drift times (slow drift velocity), required for cluster counting, and high physics trigger rate (Z_0-pole at FCC-ee) imply data transfer rates in excess of **~1 TB/s**

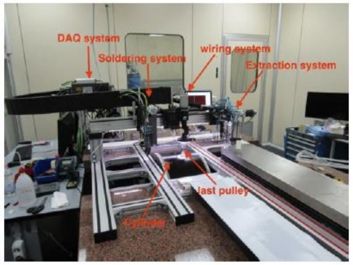
⇒ on-line real time data reduction algorithms

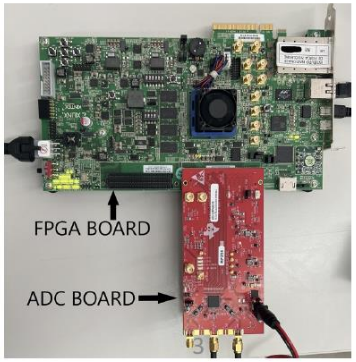
- **New wiring systems for high granularities / / new end-plates / new materials**





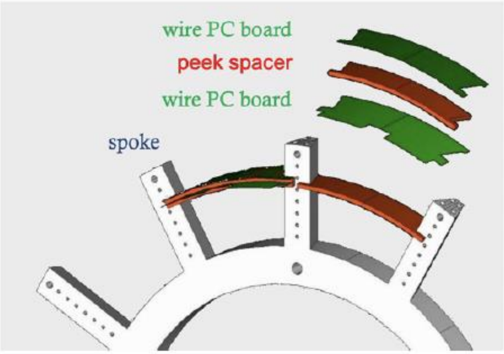


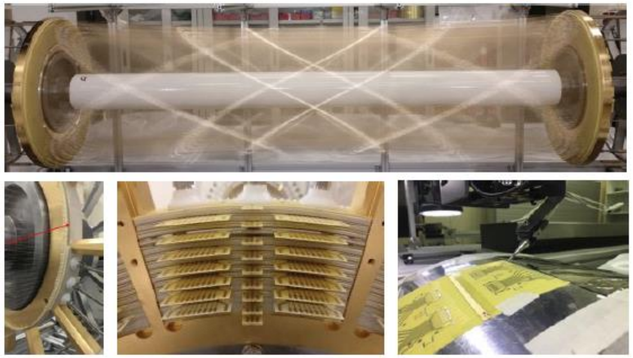


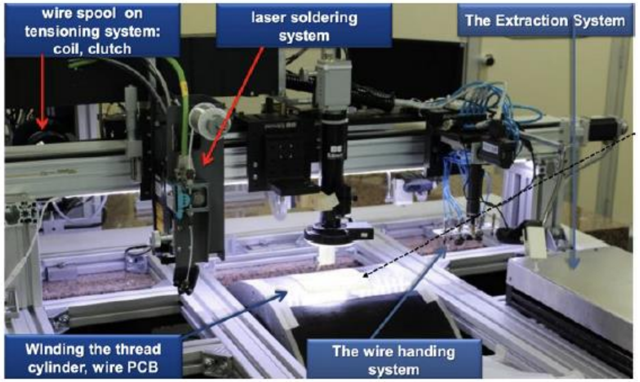


2nd CHALLENGE: 350,000 wires!

Evolution of the MEG2 drift chamber wiring





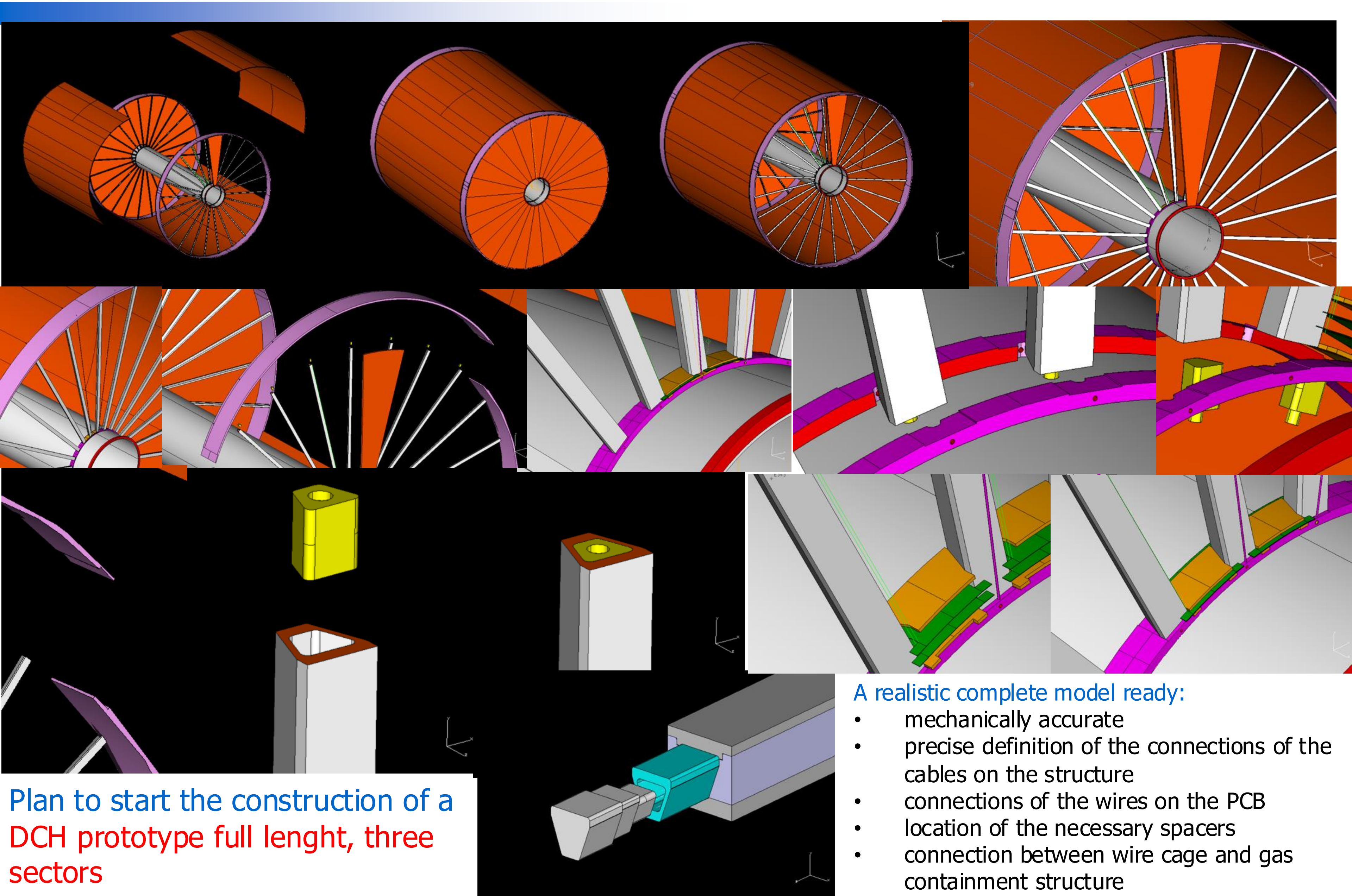


Wiring robot at INFN Lecce:
32 wires at once

MEG2: 12 wires/cm^2
IDEA: 4 wires/cm^2

Very different dimensions!
+ tension recovery scheme

Mechanical structure: a complete model

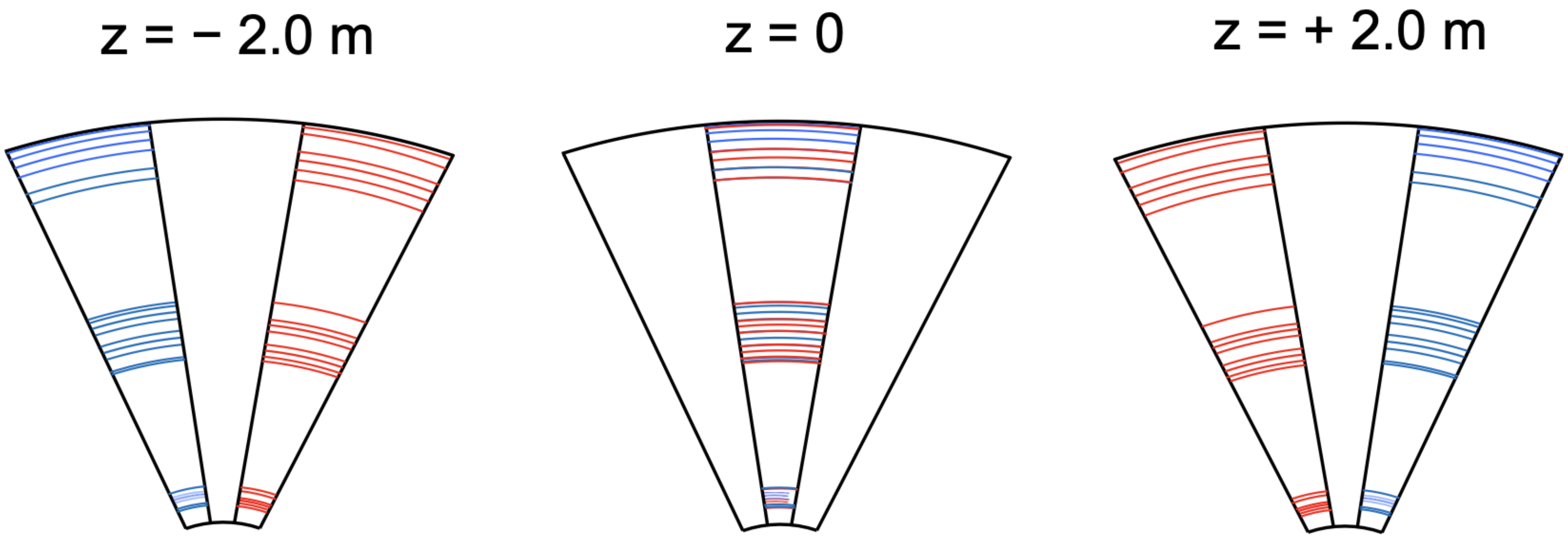


Plan to start the construction of a DCH prototype full lenght, three sectors

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

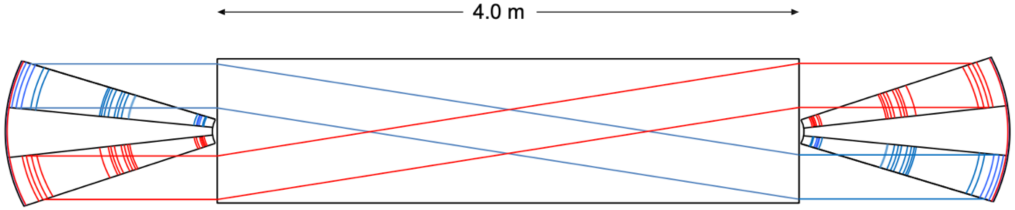
2025 full-length prototype: Coverage


z = − 2.0 m

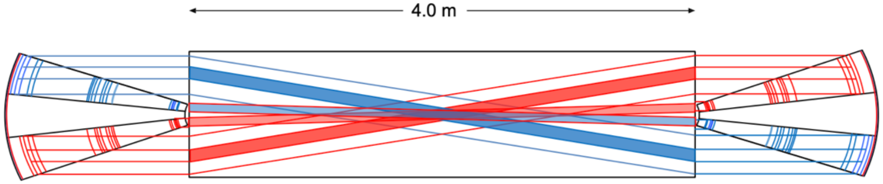
z = 0

z = + 2.0 m

MAX COVERAGE



ELECTRONICS COVERAGE



Minimum stereo angle	50 mrad
Maximum stereo angle:	250 mrad

2025 full-length: some arguments

- 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 a coverage of about 2 dm^2 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

2025 full-length prototype: Costs

- Drift Chamber conceptual design (20 k€ from EURIZON-LE, invoice paid to EnginSoft)
- Full-Scale Prototype design (20 k€ from EURIZON-LE, purchase order issued to EnginSoft)
- Full-Scale Prototype design and material tradeoffs (molds and machining) (20 k€ from EURIZON-LE, purchase order issued to CETMA)
- Full-Scale Prototype components (inner cylinder and 8 spokes) (20 k€ from EURIZON-LE, purchase order issued to CETMA)
- Wires from CFW: 10 Km of 50 μm Al for field and guard; 1 Km of 20 μm W for sense (15 k€ from EURIZON-BA)
- Wires from Specialty Materials: 900 m of 35 μm C monofilament (5 k€ from EURIZON-LE)
- Wiring robot from MEG2 CDCH CSN1 funds to INFN-LE (estimated 100 k€)

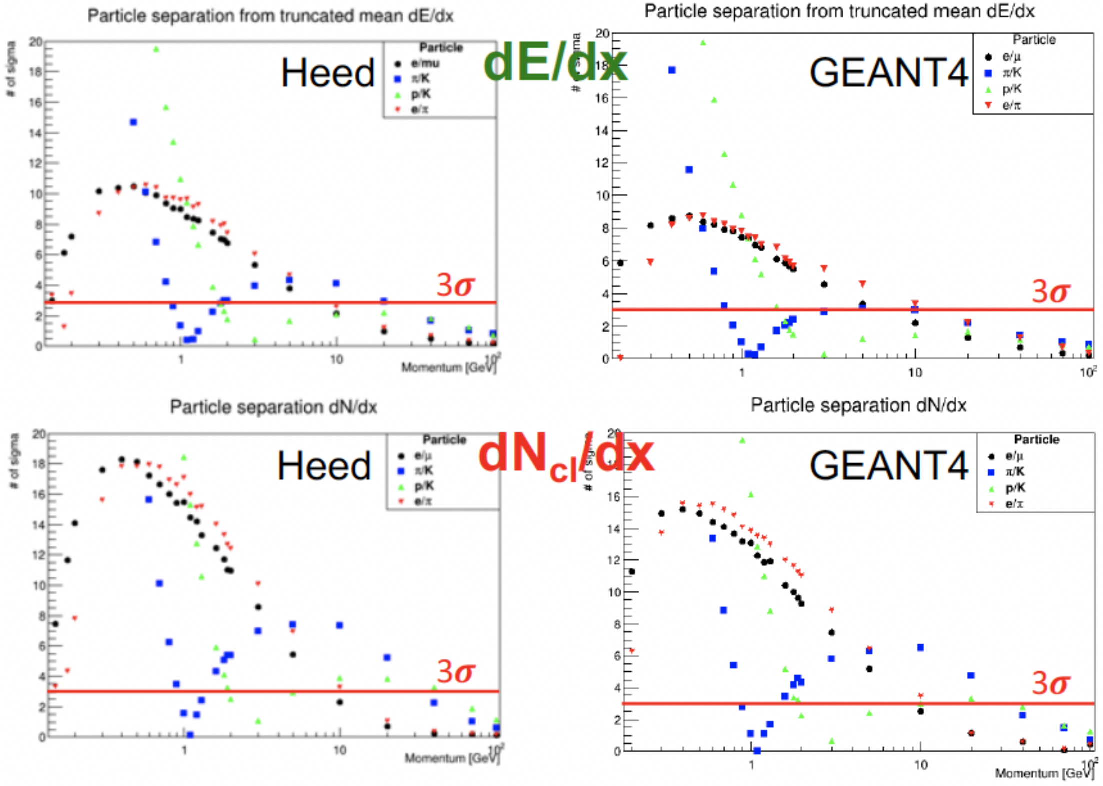
Costs to be borne (late 2024 and 2025)

- Additional wires
- Wire PCBs
- Peek spacer
- Wiring robot refurbishing
- Mechanical support and gas envelope
- Front-end, digitizers and acquisition electronics

Simulation of Cluster Counting/Timing and PID: GARFIELD

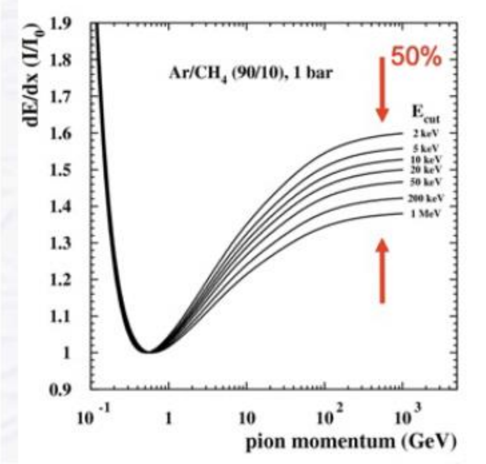
2.0 m long tracks in 90/10 He/iC$_4$H$_{10}$

full simulation



F. Cuna, N. De Filippis, F. Grancagnolo, G. Tassielli, Simulation of particle identification with the cluster counting technique, arXiv:2105.07064v1 [physics.ins-det] 14 May 2021

Geant4 uses the cluster density and the cluster size distributions derived from **Heed**, however, they **disagree**, most likely, due to a different choice of the **E$_{cut}$** parameter (the maximum energy of an electron still associated to a track in the simulation)

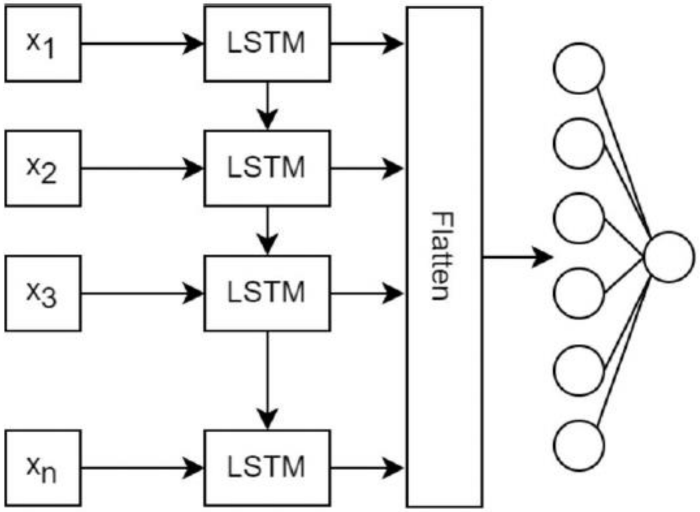


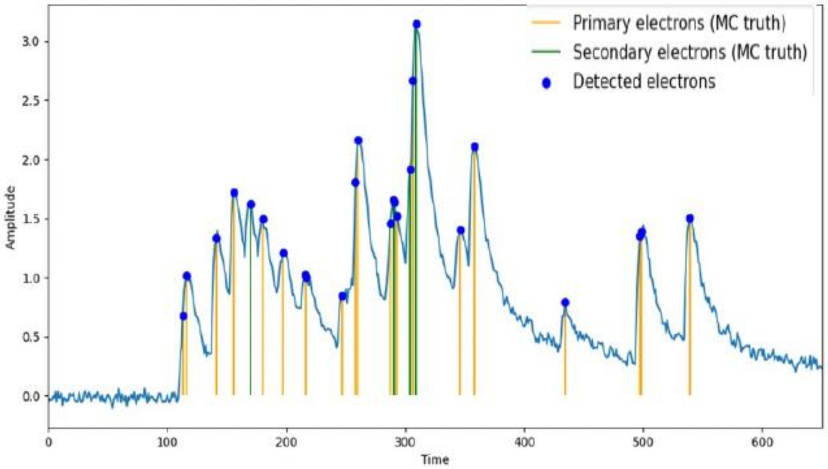
M. Hauschild Progress in dE/dx techniques used for particle identification NIM A379(1996) 436

Simulation of Cluster Counting: GARFIELD + NN

The task of peak finding can be framed as a classification problem in machine learning

- The waveforms are divided into segments, each comprising 15 bins. Each segment can represent either a signal or a noise
- The list of the amplitudes of a segment, subtracted by their mean and normalized by their standard deviation, is served as the input feature for the neural network
- The data of waveform is time sequence data, which suitable for especially Long Short Term Memory Model

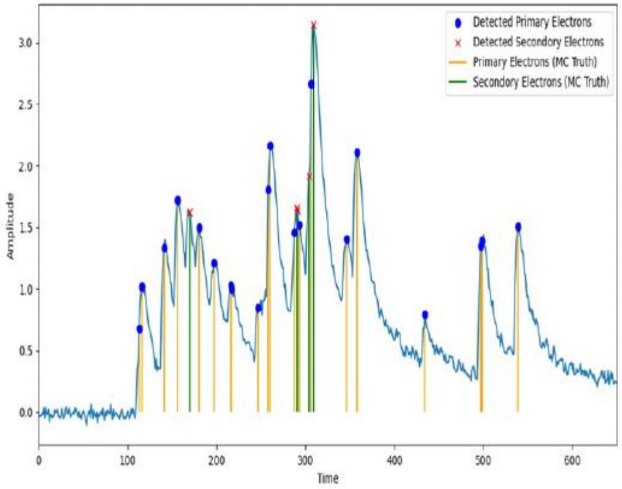


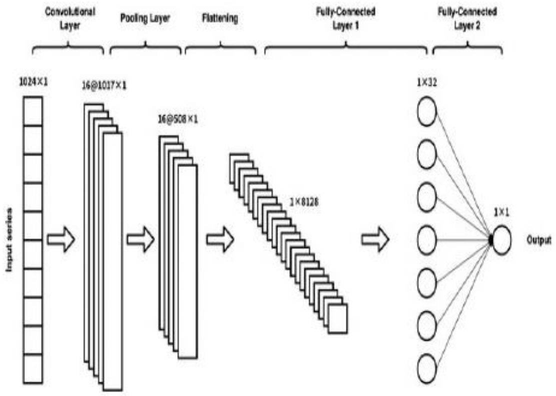


- **We applied a Long Short-Term Memory (LSTM) model to the waveform to classify signals (primary and secondary electrons) from the Noise using a peak-finding algorithm known as classification**

- **Detected peaks from both primary and secondary electrons are shown by blue dots**

Simulation of Cluster Counting: GARFIELD + NN





- A regression problem to predict Number of primary clusters based on the primary detected peaks by using Convolutional Neural Network (CNN) model
- The peaks found by peak finding algorithm would be training sample of this algorithm

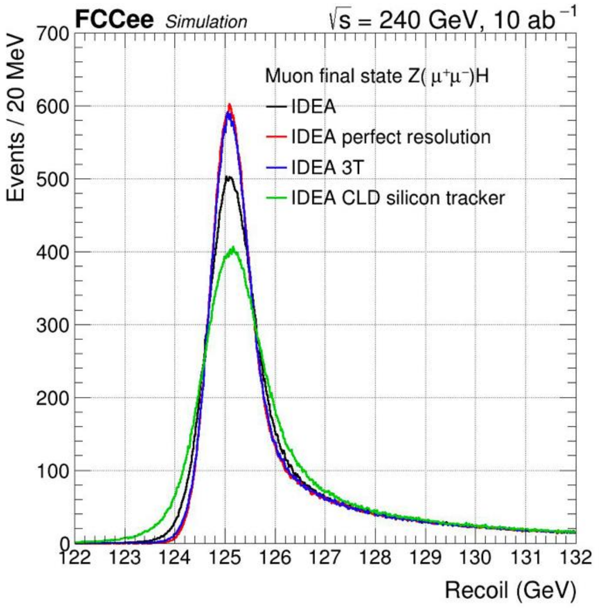
- **Labels: Number of clusters from MC truth**
- **Features: Time list of the detected times in the previous step encoding in an (1024, 1) array.**
- **A regression problem**

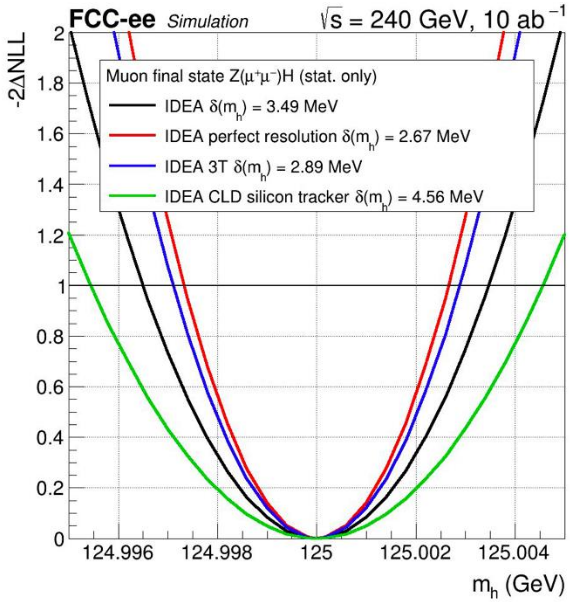
Constraint from Higgs Mass measurement

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

Progress on international collaboration

Joint Statement of Intent between The United States of America and The European Organization for Nuclear Research concerning Future Planning for Large Research Infrastructure Facilities, Advanced Scientific Computing, and Open Science

The United States and CERN intend to:

- Enhance collaboration in future planning activities for large-scale, resource-intensive facilities with the goal of providing a sustainable and responsible pathway for the peaceful use of future accelerator technologies;
- Continue to collaborate in the feasibility study of the Future Circular Collider Higgs Factory (FCC-ee), the proposed major research facility planned to be hosted in Europe by CERN with international participation, with the intent of strengthening the global scientific enterprise and providing a clear pathway for future activities in open and trusted research environments; and
- Discuss potential collaboration on pilot projects on incorporating new analytics techniques and tools such as artificial intelligence (AI) into particle physics research at scale.

Should the CERN Member States determine the FCC-ee is likely to be CERN's next world-leading research facility following the high-luminosity Large Hadron Collider, the United States intends to collaborate on its construction and physics exploitation, subject to appropriate domestic approvals.

26 April 2024

White House Office of Science and Technology Policy Principal Deputy U.S. Chief Technology Officer Deirdre Mulligan signed for the United States while Director-General Fabiola Gianotti signed for CERN.

EU Competitiveness Report

edited by Mario Draghi, and officially handed over to Ursula von der Leyen in September 2024

"One of CERN's most promising current projects, with significant scientific potential, is the construction of the Future Circular Collider (FCC): a 90-km ring designed initially for an electron collider and later for a hadron collider..

Refinancing CERN and ensuring its continued global leadership in frontier research should be regarded as a top EU priority, *given the objective of maintaining European prominence in this critical area of fundamental research, which is expected to generate significant business spillovers in the coming years."*

https://commission.europa.eu/topics/strengthening-european-competitiveness/eu-competitiveness-looking-ahead_en

Supporting statements at CERN’s 70 anniversary

“….No European country alone could have built the world’s largest particle collider. CERN has become a global hub because it rallied Europe and this is even more crucial today.

I am proud that we have financed the feasibility study for CERN’s Future Circular Collider (FCC). This could preserve Europe's scientific edge and could push the boundaries of human knowledge even further. *And as the global science race is on, I want Europe to switch gears. To do so, European unity is our greatest asset. ….”*