The IDEA drift chamber

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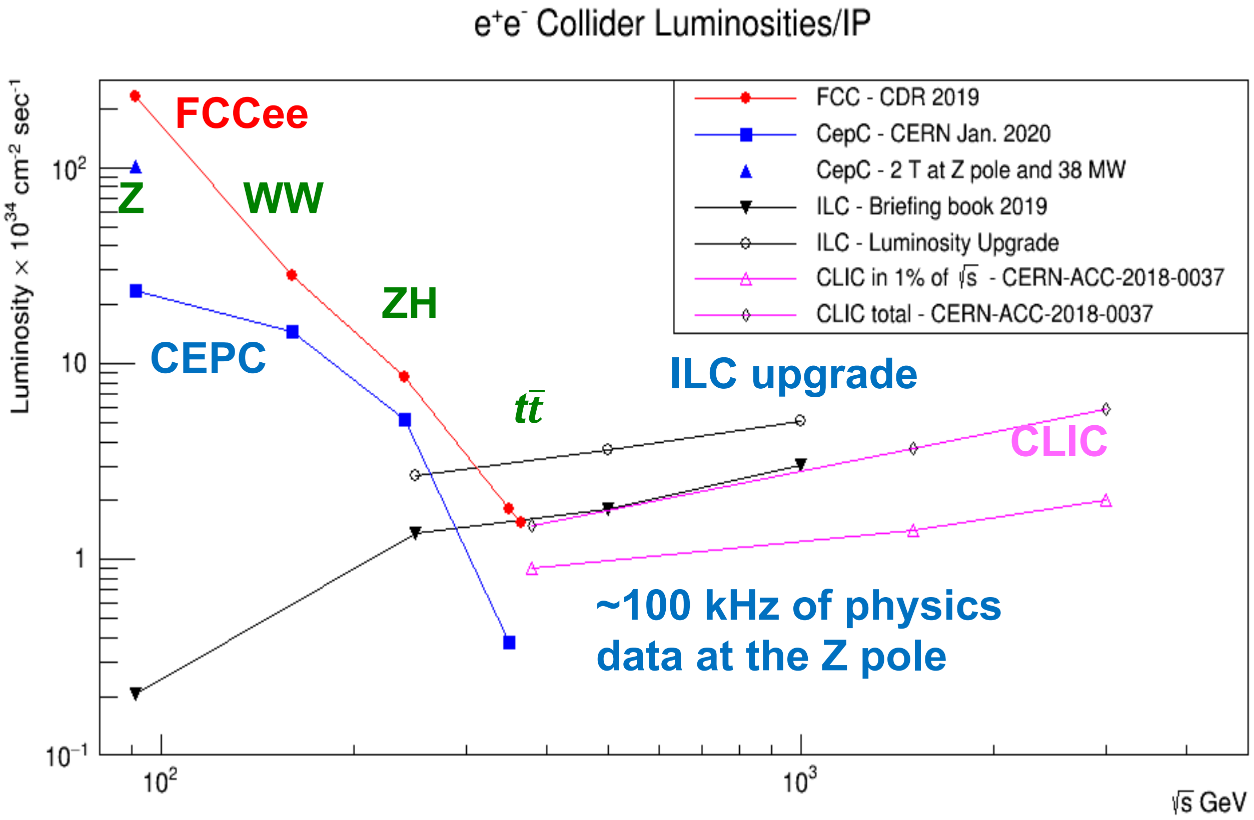
Politecnico and INFN Bari
on behalf of the IDEA DCH community

The 2022 international workshop on the high energy Circular Electron-Positron Collider (CEPC)

Nanjing University and IHEP, October 24-28, 2022

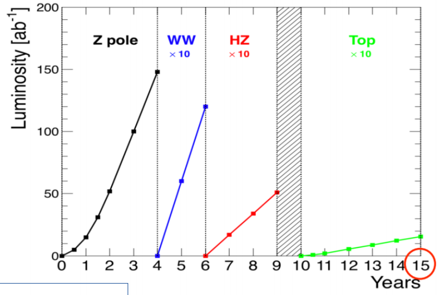
Machine luminosity for physics at e^+e^- colliders



~100 kHz of physics data at the Z pole

Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})	Event Statistics
FCC-ee-Z	4	88-95	150	3×10^{12} visible Z decays
FCC-ee-W	2	158-162	12	10^8 WW events
FCC-ee-H	3	240	5	10^6 ZH events
FCC-ee-tt	5	345-365	1.5	10^6 $t\bar{t}$ events

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



$$\approx \frac{\Delta_{LEP,Stat}}{500}$$

Physics requirements: Higgs, EWK and Heavy Flavour

- Tracking:
  - Momentum resolution for Z recoil (and H→$\mu\mu$)
    - 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

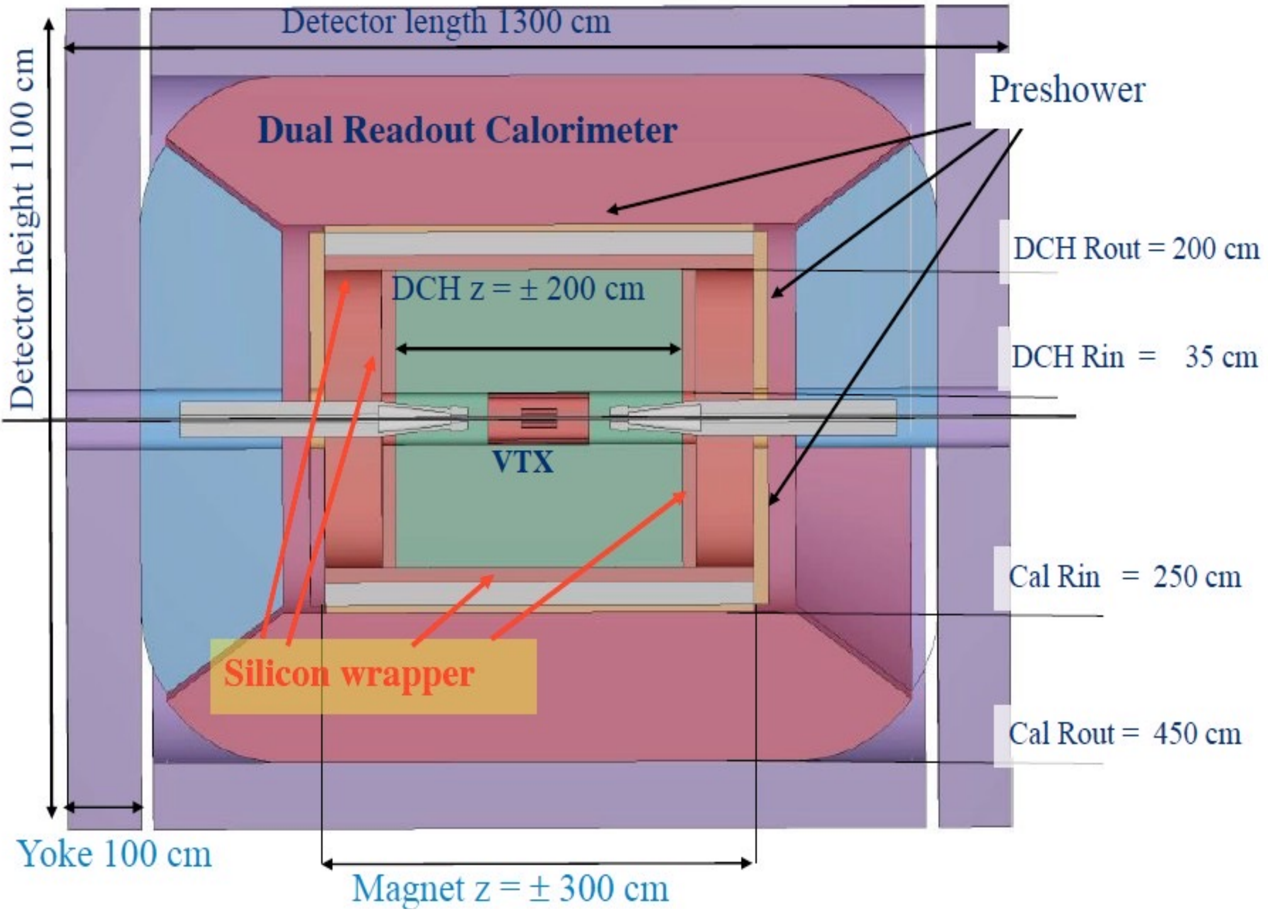
EWK and Heavy Flavour

The IDEA detector at e^+e^- colliders (1)

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

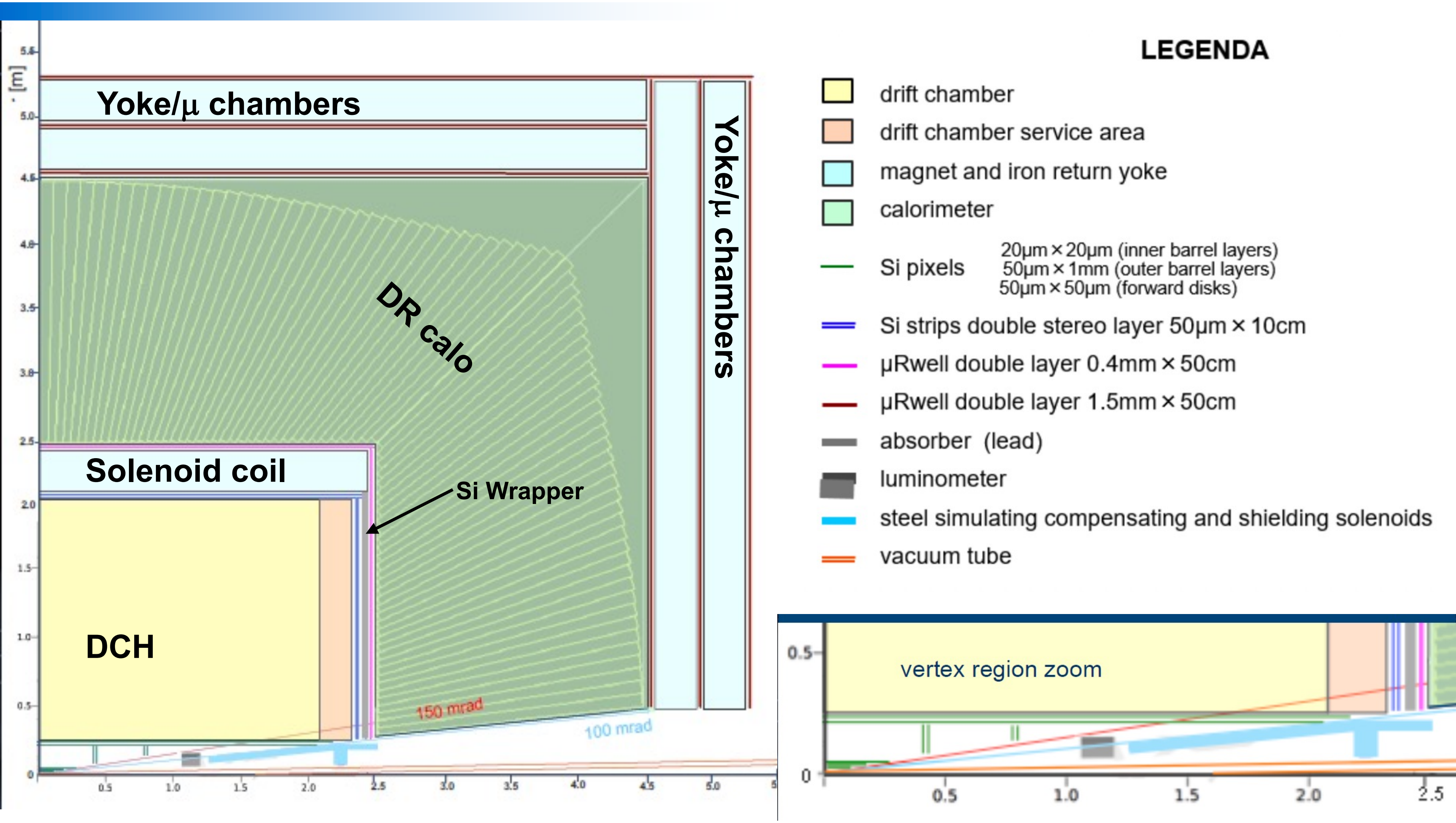


Low field detector solenoid to maximize luminosity (to contain the vertical emittance at Z pole).

→ optimized at 2 T

→ large tracking radius needed to recover momentum resolution

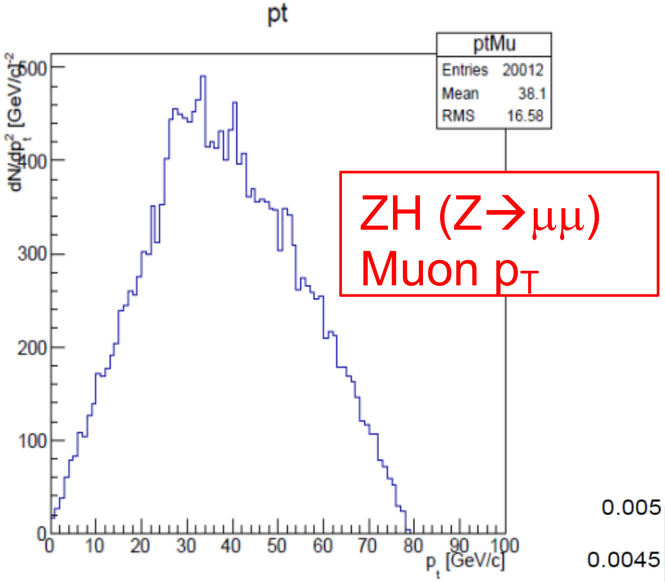
The IDEA detector at e^+e^- colliders (2)



Tracking coverage → 150 mrad → No material in front of luminometer
Calorimetry → 100 mrad

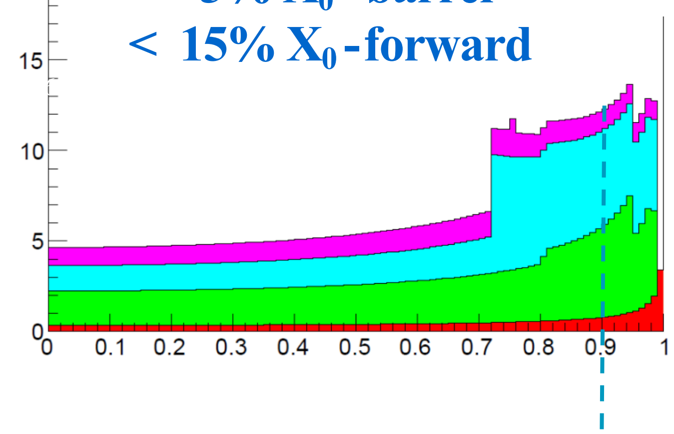
Design guidelines: momentum resolution

- Z or H decay muons in ZH events have rather small/medium p_T
  - **Transparency** (against multiple scattering) more relevant than asymptotic resolution



ZH (Z→μμ) Muon p_T

IDEA: Material vs. cos(θ)



~ 5% X_0 - barrel

< 15% X_0 - forward

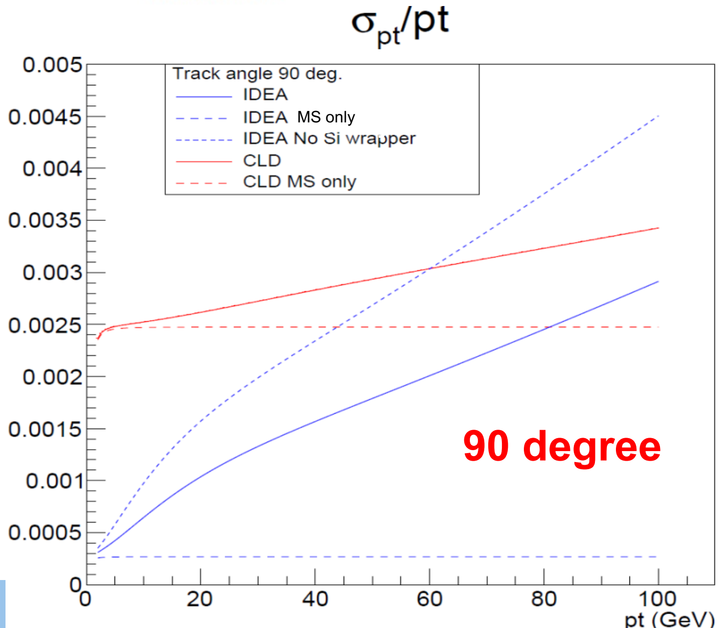
The IDEA drift chamber is designed to be transparent

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



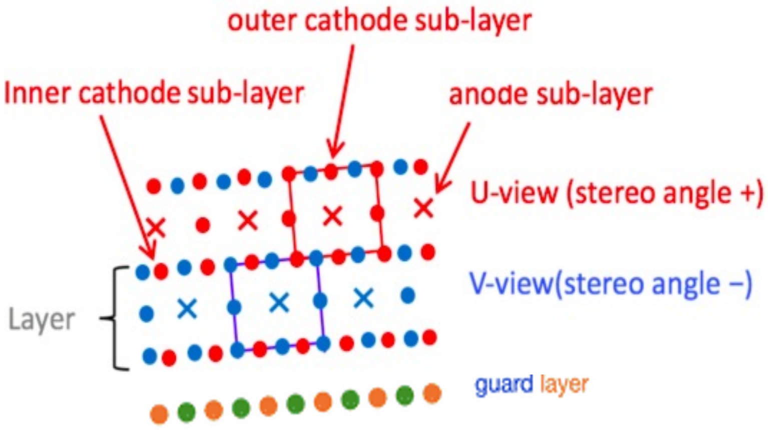
Design features: the Drift Chamber

The IDEA drift chamber is designed to provide:

- an efficient tracking, a high precision momentum measurement
- an excellent particle identification and separation

The IDEA Central Drift Chamber 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
- 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.



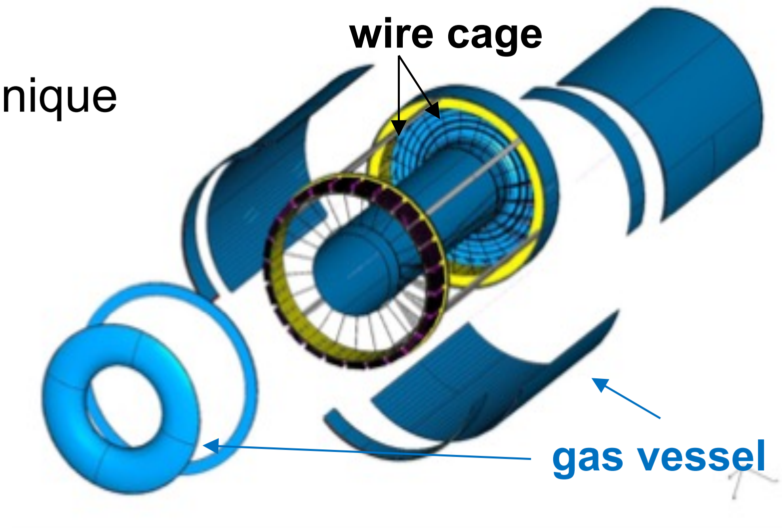
The wire net created by the combination of + and – orientation generates **a more uniform equipotential surface** → better E-field isotropy and smaller ExB asymmetries

- High wire number requires a non standard wiring procedure and needs a feed-through-less wiring system.
- A novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber

sense wires:	20 mm diameter W(Au) =>	56448 wires
field wires:	40 mm diameter Al(Ag) =>	229056 wires
f. and g. wires:	50 mm diameter Al(Ag) =>	58464 wires
	343968 wires in total	

Design features: the Drift Chamber

Novel approach at construction technique of high granularity and high transparency Drift Chambers

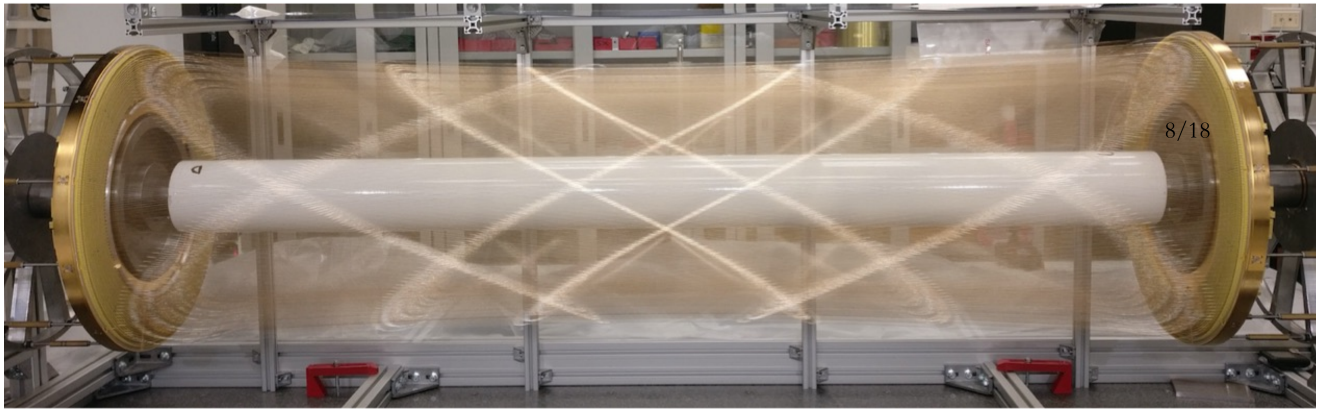


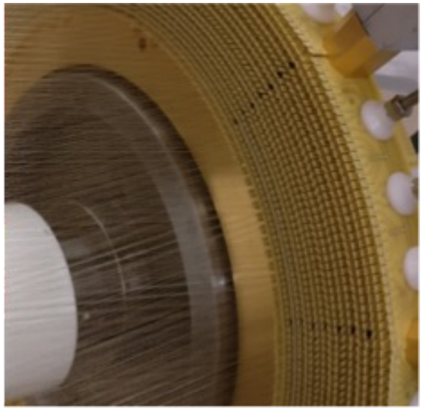
Based on the MEG-II DCH new construction technique the IDEA DCH can meet these goals:

- Gas containment – wire support functions separation:

  allows to reduce material to ≈ 10^{-3} X_0 for the inner cylinder and to a few x 10^{-2} X_0 for the end-plates, including FEE, HV supply and signal cables
- Feed-through-less wiring:

  allows to increase chamber granularity and field/sense wire ratio to reduce multiple scattering and total tension on end plates due to wires by using thinner wires



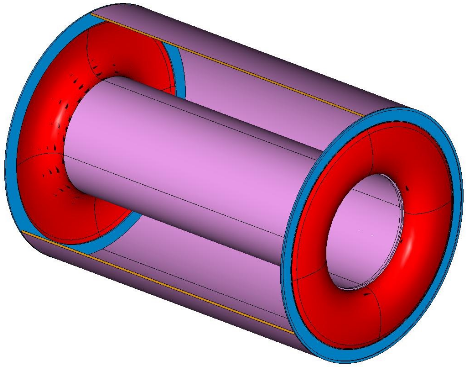


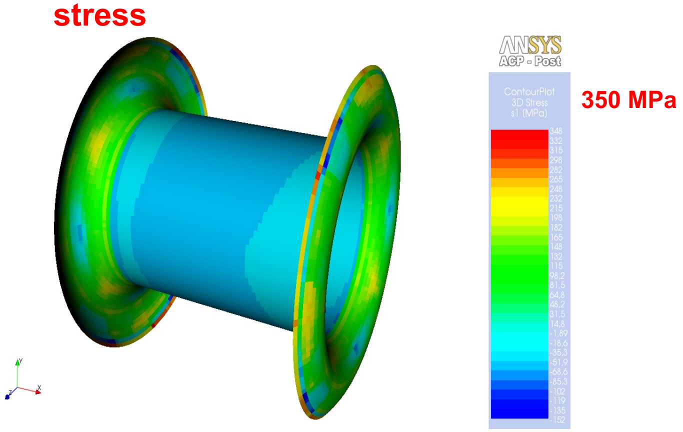
Mechanical construction scheme

On going: Finite element analysis in collaboration with a company (EnginSoft) and Politecnico Un. in Bari and Turin

Gas containment

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





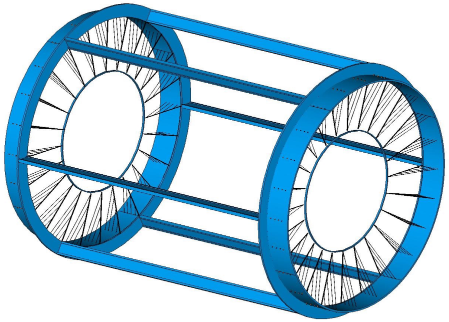
Static solution

Inner cylinder sandwich:
2 C-fiber skins, 2-ply each,
HM M30S 53 ET443 51%
+ C-foam core, 5 mm total
Grafoam® FPA-10
(0.100 g/cm² total)

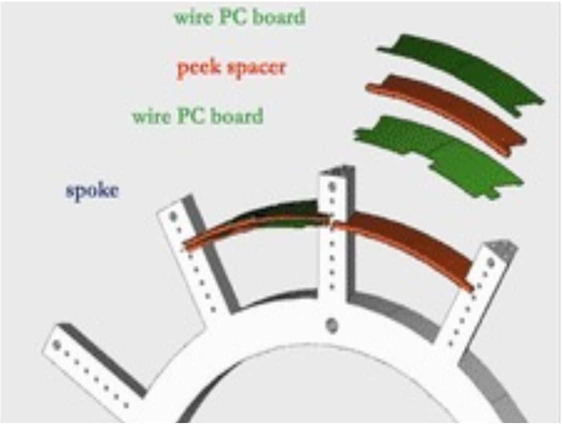
End plates: 4-ply
orthotropic (0-90-90-0)
HM M30S 53 ET443 51%
60 µm/ply - 0.0053 g/cm²
(0.021 g/cm² total)

Wire support

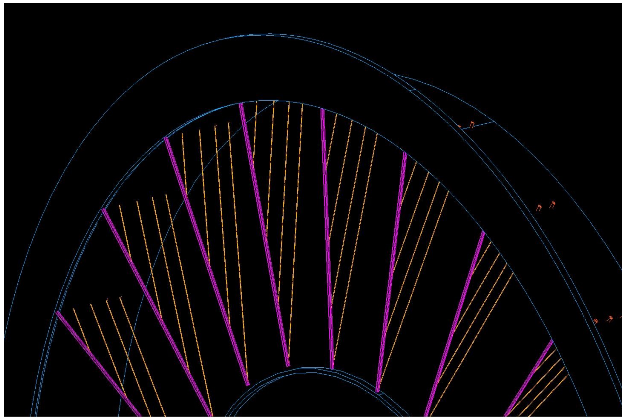
Wire support structure not subject to differential pressure can be light and feed-through-less.



Analogy with MEG2 drift chamber



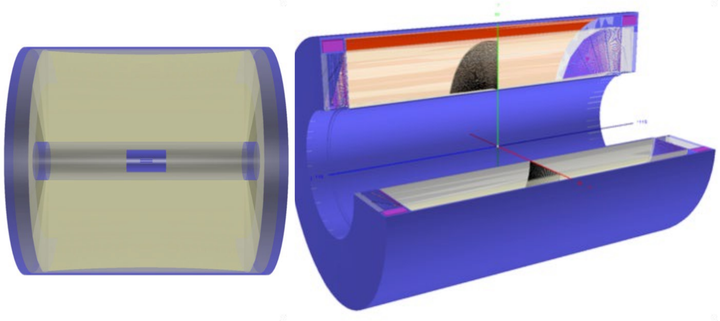
Wire tension recovery scheme



Plan for 2023/2024:

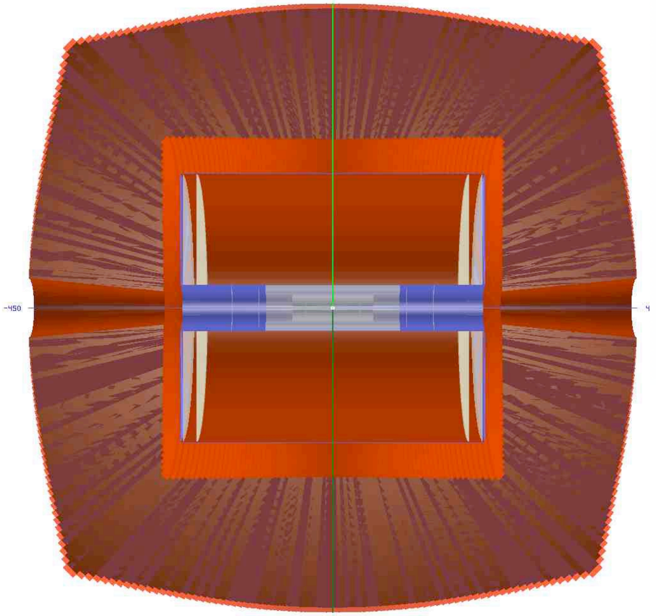
- construct a full-size prototype (4m long) to test different wire choices and the relative electrostatic stability and to validate the proposed tension recovery scheme of the endplates.

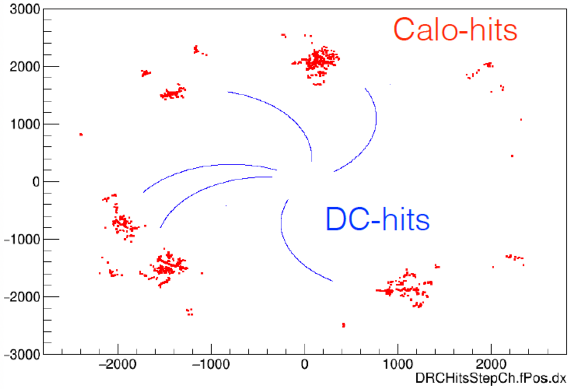
Geant4 simulation of the drift chamber

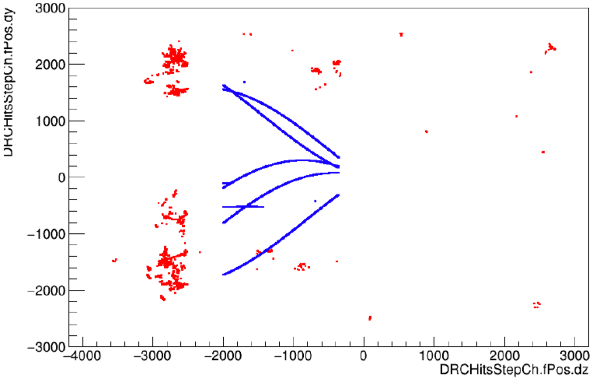


A full standalone geant4 simulation of the IDEA **Silicon Vertex (and Si wrapper), DriftChamber, DR Calorimeter (and Muon)**

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







- The full simulation for the IDEA detector ported in the FCC framework.
- A first implementation of DCH with DD4HEP completed
- More details in the talk by L. Lavezzi on Saturday

Performance of the tracking drift chamber

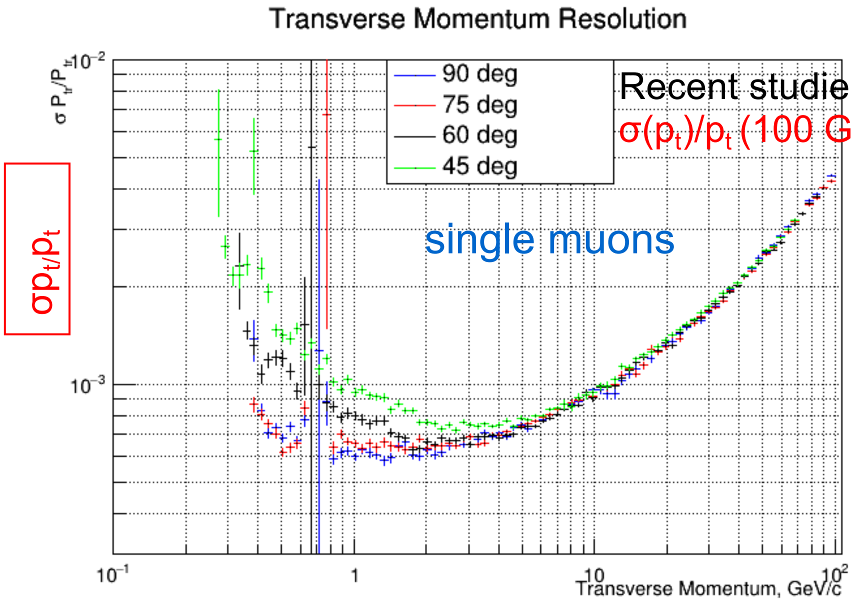
Expected:

$\sigma_{pt} / p_t = (0.7 p_t + 8.3) \times 10^{-4}$

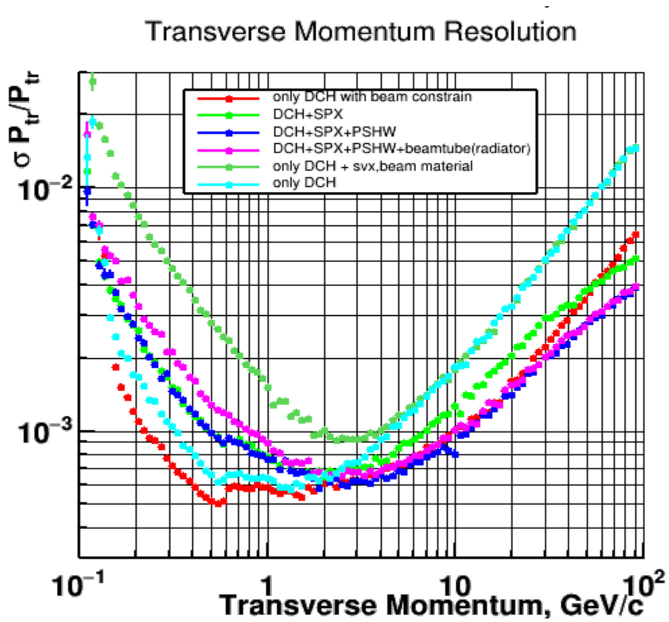
$\sigma_{\vartheta} = (1.1 + 9.4/p) \times 10^{-4}$ rad

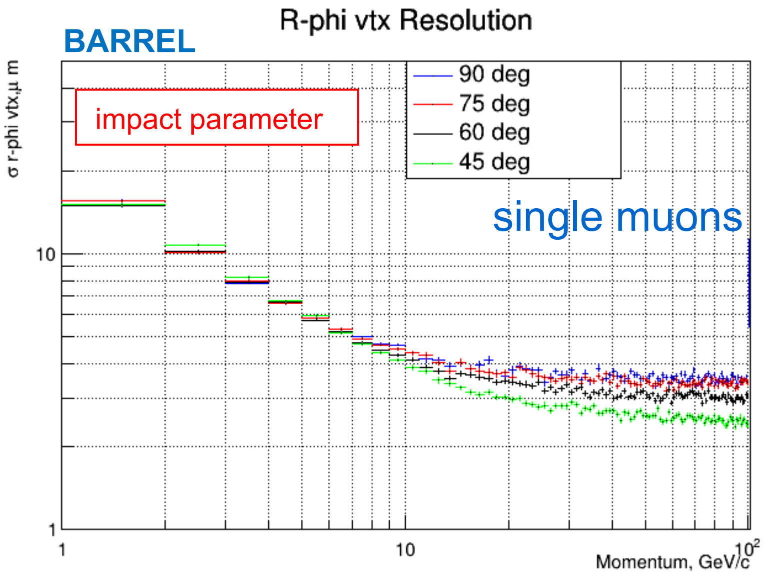
$\sigma_{\varphi} = (0.33 + 9.4/p) \times 10^{-4}$ rad

BARREL (DCH + SVTX + SiWrapper)



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



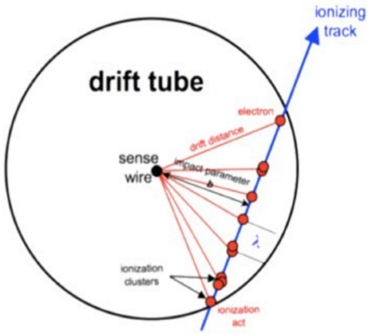


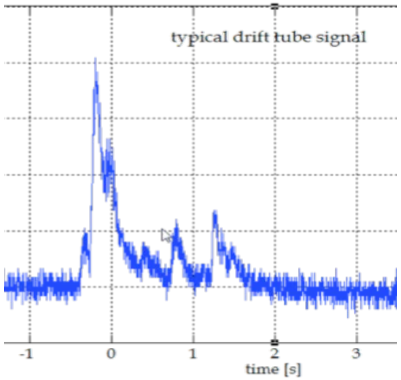
Performance of the particle identification

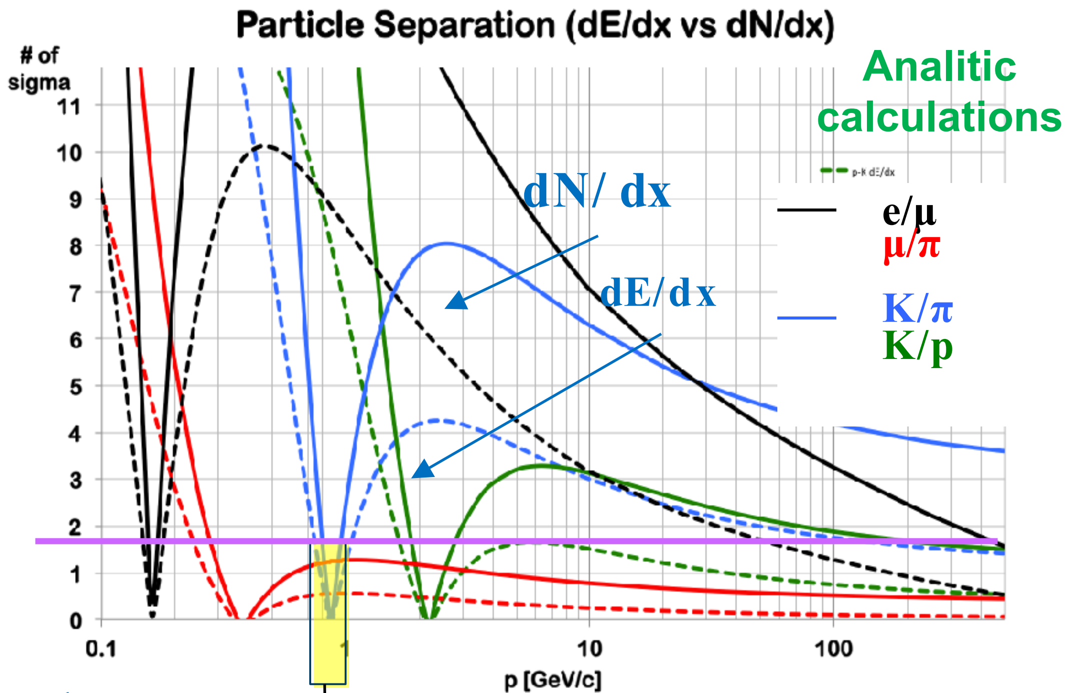
Expected:

$\sigma_{dE/dx}$ = 4.3 %

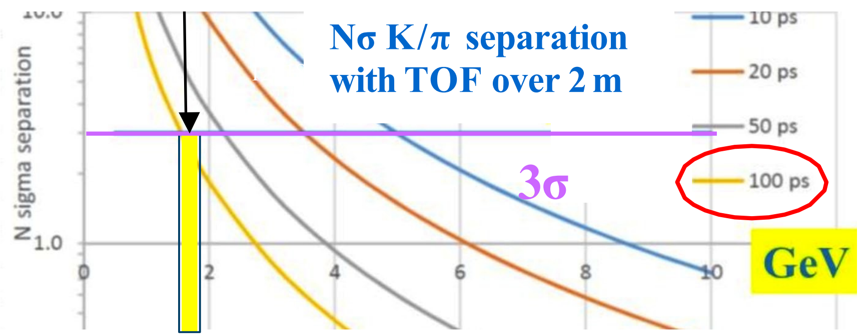
$\sigma_{dN/dx}$ = 2.2 % (at ε_N = 80 %)







- Expected excellent K/π separation over the entire range except 0.85<p<1.05 GeV (blue lines)
- Could recover with timing layer



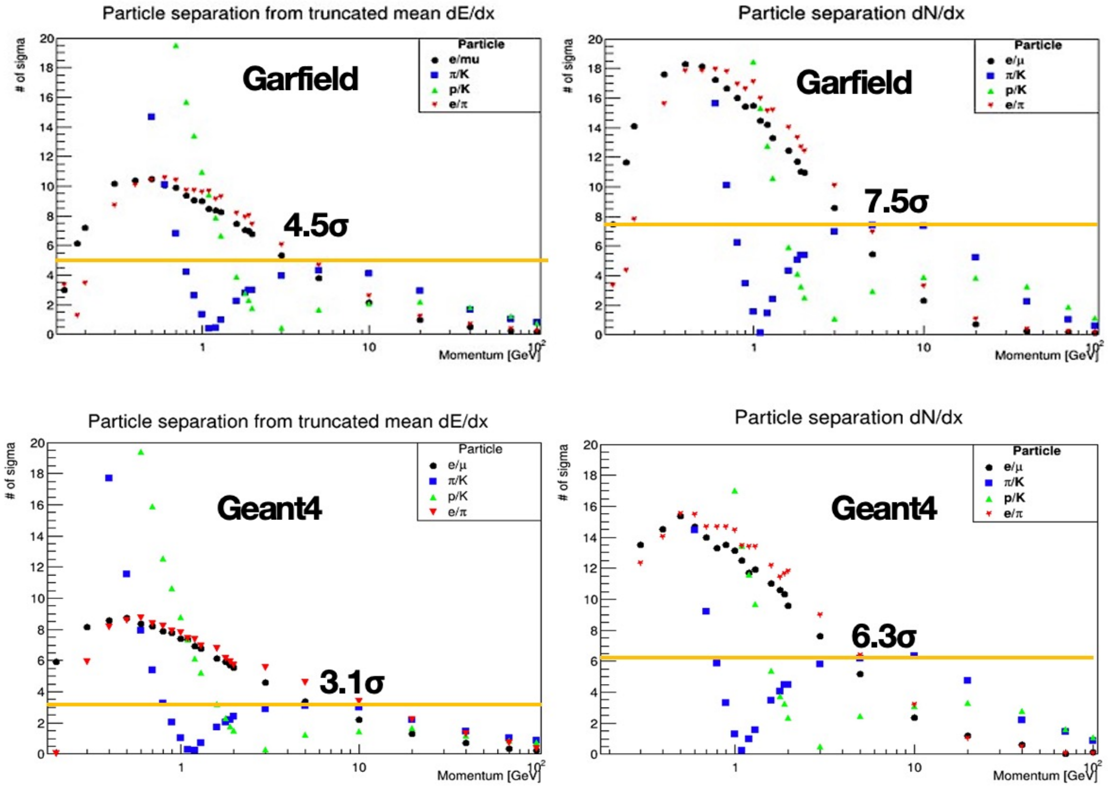
- In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently
- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles with a better resolution w.r.t the dE/dx method.
- N_d= 12.5/cm for He/iC_4H_{10}=90/10 and a 2m track gives $\sigma \approx$ 2.0%

Cluster timing allows to reach spatial resolution < 100 μm for 8 mm drift cells in He

PID full simulation with cluster counting

- **Garfield++ (Heed)** simulates in deep detail the ionization processes in the gas, but it would be extremely cumbersome to follow an ionization particle inside the large volume of a tracking detector.
- **GEANT4** simulates the interaction of a particle with all the materials of a large detector but it doesn't simulate the ionization clustering process which is essential for cluster counting.
- **Define a** model for a fast simulation of the cluster density and the cluster size distribution according to the predictions of Heed, to be used taking into account the results of the particle interactions calculated by **GEANT4**.

A simulation of the ionization process in 200 drift cells, 1 cm wide, in 90% He and 10% iC_4H_{10} gas mixture performed both in Garfield++ and in Garfield-modeled Geant4

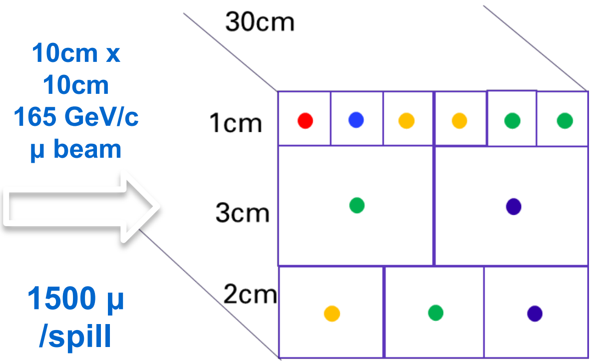


- Garfield++ in agreement with analytical calculations up to 20 GeV/c, then falls much more rapidly at higher momenta
- The Garfield++ model in GEANT4 reproduces reasonably well the Garfield++ predictions, but the particle separation, both with dE/dx and with dN_{cl}/dx, in GEANT4 is considerably worse than in Garfield++. Why?
- Why the dN_{cl}/dx Fermi plateau with respect to dE/dx is reached at lower values of βγ with a steeper slope?
- More details in the talk by F. Cuna later today

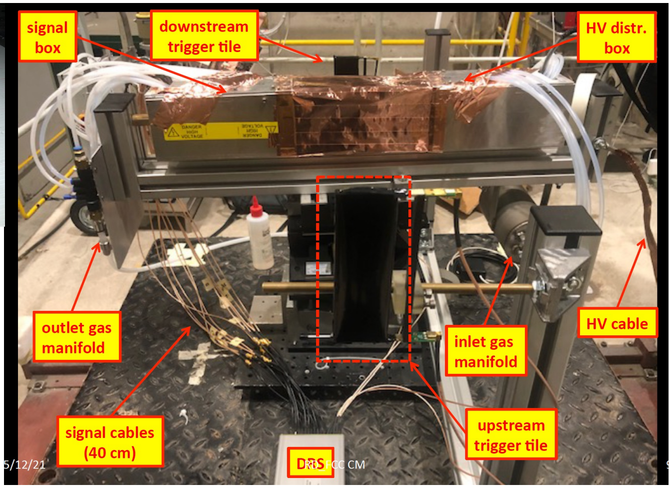
PID with the cluster counting/timing

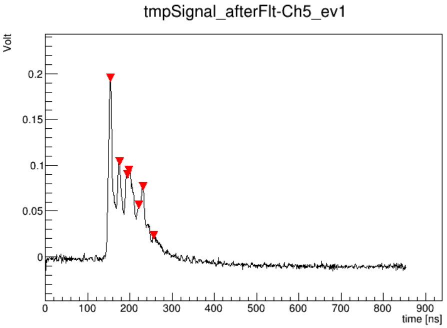
Beam test at H8/CERN in 2021 and 2022 to test the “cluster counting”:

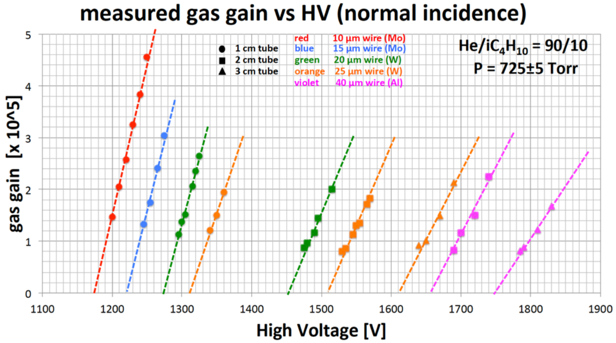
- Need to demonstrate the ability to count clusters:
  at a fixed βγ (e.g. muons at a fixed momentum)
  count the clusters by
  - doubling and tripling the track length and changing the track angle;
  - changing the gas mixture.
- Establish the limiting parameters for an efficient cluster counting:
  - cluster density (by changing the gas mixture)
  - space charge (by changing gas gain, sense wire diameter, track angle)
  - gas gain saturation
- In optimal configuration, measure the relativistic rise as a function of βγ, both in dE/dx and in dN_{cl}/dx, by scanning the muon momentum from the lowest to the highest value (from a few GeV/c to about 250 GeV/c at CERN/H8).

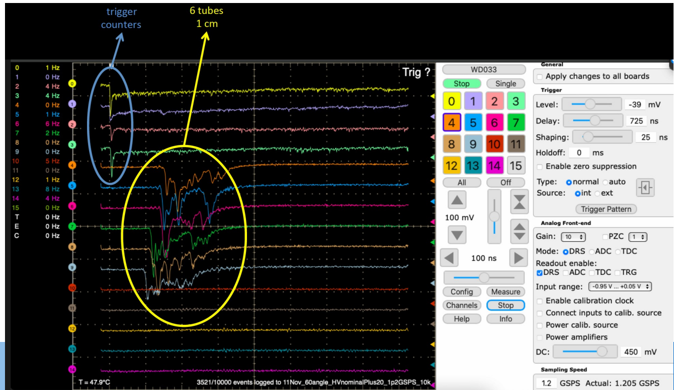


red	10 μm wire
blue	15 μm wire
green	20 μm wire
orange	25 μm wire
violet	40 μm wire









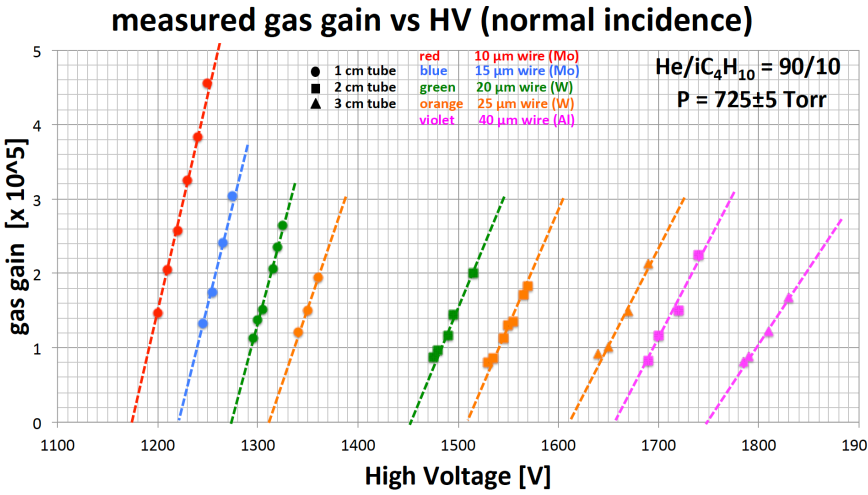
General
☐ Apply changes to all boards
Trigger
Level: -39 mV
Delay: 725 ns
Shaping: 25 ns
Holdoff: 0 ms
☐ Enable zero suppression
Type: ● normal ○ auto
Source: ● int ○ ext
100 mV
100 ns
Analog Front-end
Gain: 10 ☐ PZC 1
Mode: ● DRS ○ ADC ○ TDC
Readout enable:
☑ DRS ☐ ADC ☐ TDC ☐ TRG
Input range: -0.95 V ... +0.05 V
☐ Enable calibration clock
☐ Connect inputs to calib. source
☐ Power calib. source
☐ Power amplifiers
DC: 450 mV
Sampling Speed
1.2 GSPS Actual: 1.205 GSPS
T = 47.9°C
3521/10000 events logged to 11Nov_60angle_HVnominalPlus20_1p2GSPS_10k

0	1 Hz
1	0 Hz
2	4 Hz
3	4 Hz
4	0 Hz
5	1 Hz
6	6 Hz
7	2 Hz
8	0 Hz
9	0 Hz
10	5 Hz
11	0 Hz
12	1 Hz
13	8 Hz
14	4 Hz
15	0 Hz
T	0 Hz
E	0 Hz
C	0 Hz

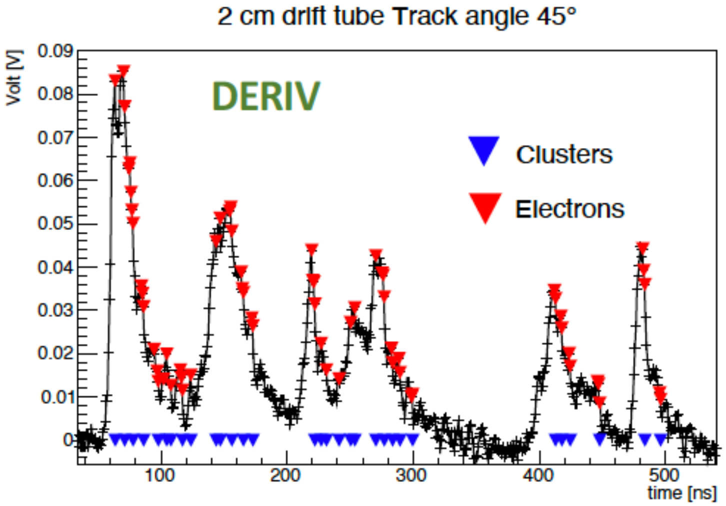
Beam test at H8/CERN in 2021: results

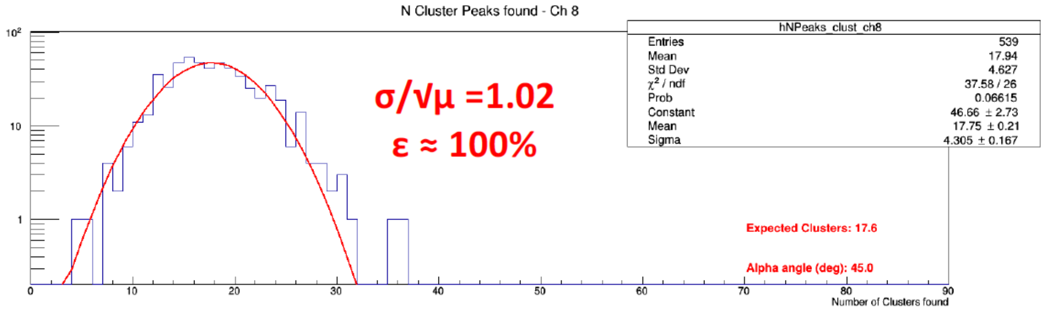
Data collected for different configurations:

- 90%He-10%iC_4H_{10}
- 80%He-20%iC_4H_{10}
- HV nominal (+10,+20,+30,-10,-20,-30)
- Angle 0° , 30 ° , 45 ° , 60 °



Peak finding algorithms for cluster counting





- Poissonian behaviour
- Meaurements and predictions about the number of clusters are in very good agreement

More details in the talk by B. D’Anzi later today

Data reduction and pre-processing of drift chamber signals

Issue: with about 60000 drift cells, assuming to digitise the signal at 12 bits and 2 GS/s, a throughput of about 1 Tb/s is hardly sustainable by modern equipment → is necessary to transfer all the data.

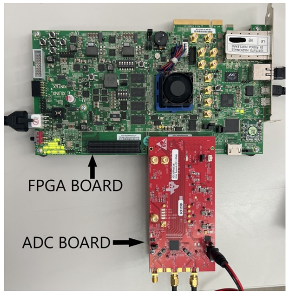
- with the cluster counting algorithms, by transferring only time and amplitude of each electron peak, these rates are reduced to about 60 Gb/s, resulting in a data reduction factor of more than one order of magnitude.

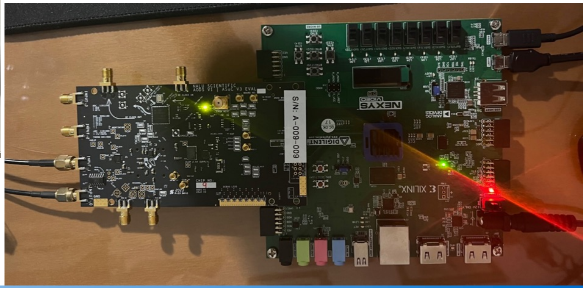
- Applying the cluster counting technique on FPGAs in real time has two main objectives:
  1. reduce transferred data
  2. reduce stored information

- A secondary advantage that allows us to reduce CPU usage during data analysis as the waveforms have already been analyzed in real time, saving only the necessary information

The objective of the new project is to implement, on a single FPGA, cluster counting algorithms for the parallel preprocessing of as many channels as possible in order to reduce the costs and complexity of the system and gain flexibility in determining the proximity correlations between hit cells for track segment search and for triggering purposes.

- For this purpose a card with multichannel reading is under development, testing different digitizers:
  - TEXAS INSTRUMENTS ADC32RF45 → implementation of cluster counting almost complete
  - CAEN digitzer
  - NALU SCIENTIFIC ASoCv3 → test with native acquisition program and then implementation of the cluster counting





Summary/Conclusions

A full-stereo, high momentum resolution ultra-light Drift Chamber accomplishes the requirements for the tracking at FCC-ee/CepC

- the Drift Chamber construction is feasible by adopting the MEG-II Drift Chamber construction technique
- performance studies with Geant4 simulations and analytic calculations performed
- the Cluster Counting technique is expected to give major improvements in PID performance over traditional dE/dx approaches
- Beamtest analysis on going to demonstrate the capability of count clusters and the Poissonian nature of the number of ionization clusters

Thanks to all the contributors

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Chinese Academy of Sciences

Backup

Chamber Layout (the IDEA drift chamber)

Radii (at z = 0)		
Inner Cylinder	350	mm
Guard wires layer	354	mm
First active layer	356	mm
Last (112th) active layer	1915	mm
Guard wires layer	1927	mm
Outer Cylinder	2000	mm

Radii (at end plate)		
Inner Cylinder	350	mm
Guard wires layer	366	mm
First active layer	369	mm
Last (112th) active layer	1982	mm
Guard wires layer	1995	mm
Outer Cylinder	2000	mm

Active length	2000	mm
Number of super-layers (8 layers) Number of sectors	(14x8) = 112 24	
Number of cells per layer / per sector	192÷816 / 16	
Cell size (at z=0)	11.8 ÷ 14.9	mm
2α angle	30°	
Stereo angle	43 ÷ 223	mrad
Stereo drop	12.5 ÷ 68.0	mm

sense wires	56 448
field wires	284 256
guard wires	2 016
Total wires	342 720

Wire Layout (the IDEA drift chamber)

- 112 co-axial layers (grouped in 14 superlayers of 8 layers each) of para-axial wires in 24 azimuthal sectors;
- stereo angles from ±43 mrad to ±223 mrad;
- rotational hyperboloid for each layer
- 192 (at inner layer), 816 (at outer layer) square drift cells (16 per sector);
- cell size ranging from 11.8 mm at the innermost layer, to 14.9 mm at the outermost one;
- ratio of field wires to sense wires = 5 : 1;
- 56 448 sense wires – 284 256 field wires – 2 016 guard wires;
- sense wires 20 µm diameter gold plated Mo (30 g tension);
- field and guard wires, 40 and 50 µm diameter silver plated Al (30 g);
- total wire tension 10 Ton.

Gas Vessel (tentative procedure)

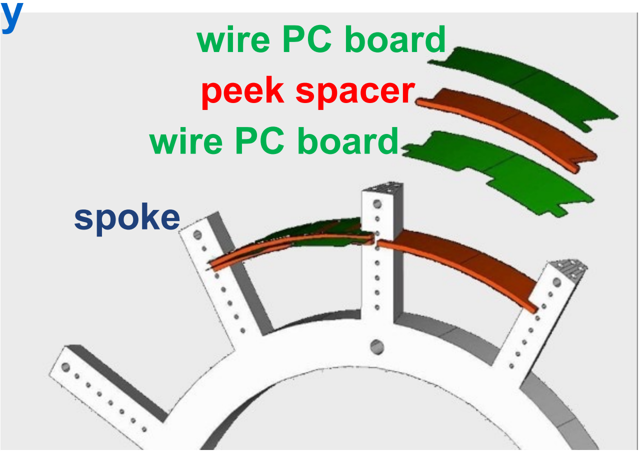
- ☐ **End-plate profile optimization**
  - **Use isotropic material (1 mm thick Aluminum) solid rotational plates + inner cylinder (ideal joints)**
  - **Assume infinitely rigid outer cylinder**
  - **Parameterize geometry by:**
    - **constraining inner cylinder radius**
    - **constraining inner cylinder length**
    - **constraining outer cylinder radius**
    - **varying middle point of a 3 point-spline profile for the end plates**
  - **Optimize dynamic properties:**
    - **minimum stress at inner boundary**
    - **minimum of maximum stress**
    - **maximum safety factor**
  - **Replace isotropic material with light composite material**
  - **Detailed FEM analysis**
- ☐ **Solve buckling instabilities**
- ☐ **Measure mechanical properties of chosen material**
- ☐ **Build a scale model and characterize it**

Design features: the Drift Chamber

Novel approach at construction technique of high granularity and high transparency Drift Chambers

The solution adopted for MEG II:

- end-plates numerically machined from solid Aluminum (mechanical support only);
- Field, Sense and Guard wires placed azimuthally by a Wiring Robot with better than one wire diameter accuracy;
- wire PC board layers (green) radially spaced by numerically machined peek spacers (red) (*accuracy* < *20 μm*);
- wire tension defined by homogeneous winding and wire elongation (*ΔL = 100μm corresponds to ≈ 0.5 g*);
- Drift Chamber assembly done on a 3D digital measuring table;
- build up of layers continuously checked and corrected during assembly;
- End-plate gas sealing done with glue.



(~ 12 wires/cm²) impossible to be built with a conventional technique based on feedthrough: