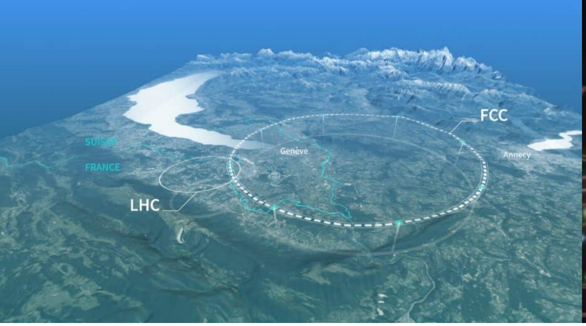
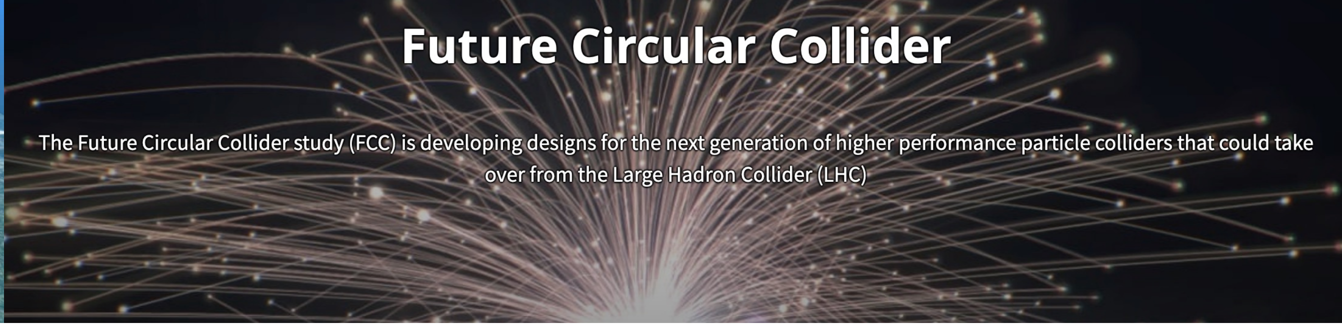




Tracking at the Future Circular Collider

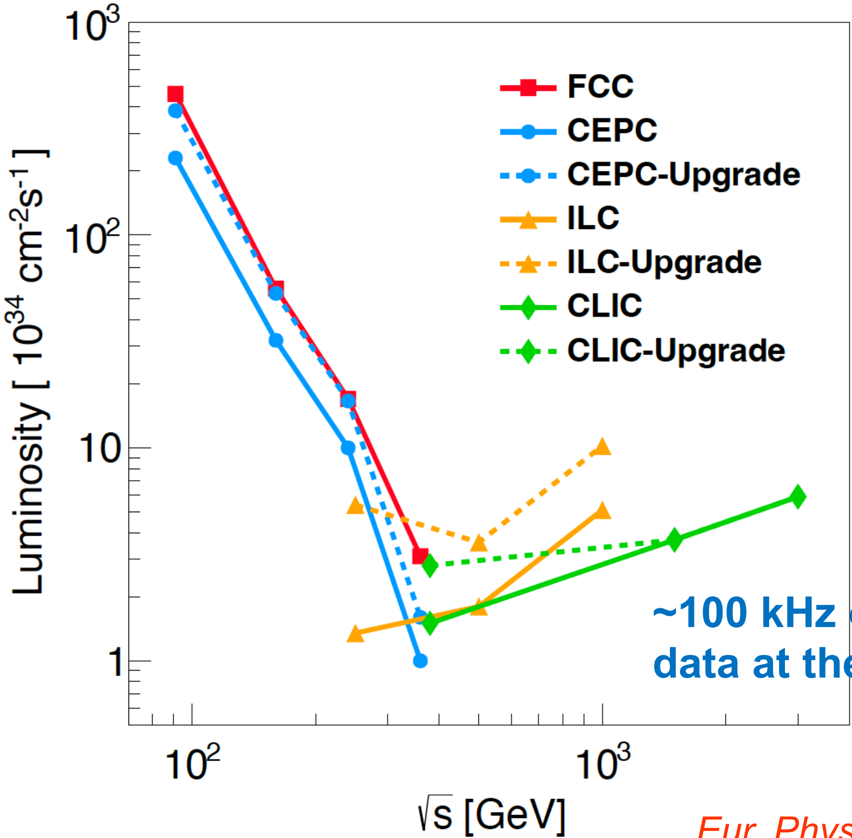
Nicola De Filippis
Politecnico and INFN Bari

Innovative Detector Technologies and Methods (IDTM)

LIP Lisbon, September 12-14, 2023

eurizon
European network
for developing new horizons for RIs

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



- 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} $e^+e^- \to bb, cc$
  - 10^{11} $e^+e^- \to \tau^+\tau^-$

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

Requirements of tracking system for an experiment at a leptonic collider

Central tracker system:

- state-of-the-art momentum and angular resolution for charged particles;
- B field limited to ~ 2 T to contain the vertical emittance at Z pole. Large tracking radius needed to recover momentum resolution.
- High transparency required given typical momenta in Z, H decays (far form the asymptotic limit where the Multiple Scattering contribution is negligible).
- Particle ID is a valuable additional ability.

Vertexing:

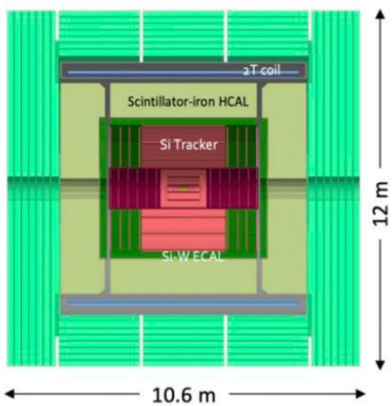
- excellent b- and c-tagging capabilities : few µm precision for charged particle origin;
- small pitch, thin layers, limited cooling, first layer as close as possible to IP.

Challenges:

- Physics event rates up to 100 kHz (at Z pole) → strong requirements on sub-detectors and DAQ systems

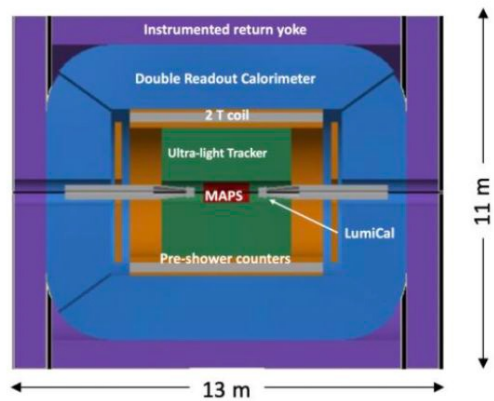
Detector concepts for experiments @ **FCCee**

CLD



- Well established design
  - ILC -> CLIC detector -> CLD
- Full Si vtx + tracker;
- CALICE-like calorimetry;
- Large coil, muon system
- Engineering still needed for operation with continuous beam (no power pulsing)
  - Cooling of Si-sensors & calorimeters
- Possible detector optimizations
  - σ_p/p, σ_E/E
  - PID ($\mathcal{O}$(10 ps) timing and/or RICH)?
  - …

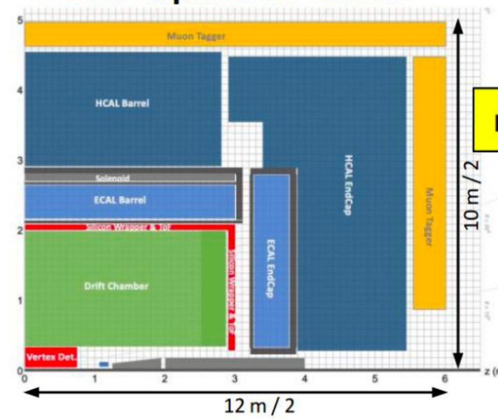
IDEA



- A bit less established design
  - But still ~15y history
- Si vtx detector; ultra light drift chamber w powerful PID; compact, light coil;
- Monolithic dual readout calorimeter;
  - Possibly augmented by crystal ECAL
- Muon system
- Very active community
  - Prototype designs, test beam campaigns, …

Noble Liquid ECAL based

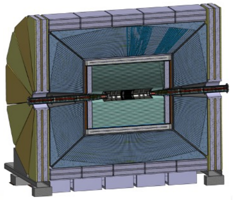
new



- A design in its infancy
- Si vtx det., ultra light drift chamber (or Si)
- High granularity Noble Liquid ECAL as core
  - Pb/W+LAr (or denser W+LKr)
- CALICE-like or TileCal-like HCAL;
- Coil inside same cryostat as LAr, outside ECAL
- Muon system.
- Very active Noble Liquid R&D team
  - Readout electrodes, feed-throughs, electronics, light cryostat, …
  - Software & performance studies

FCC-ee CDR: https://link.springer.com/article/10.1140/epjst/e2019-900045-4

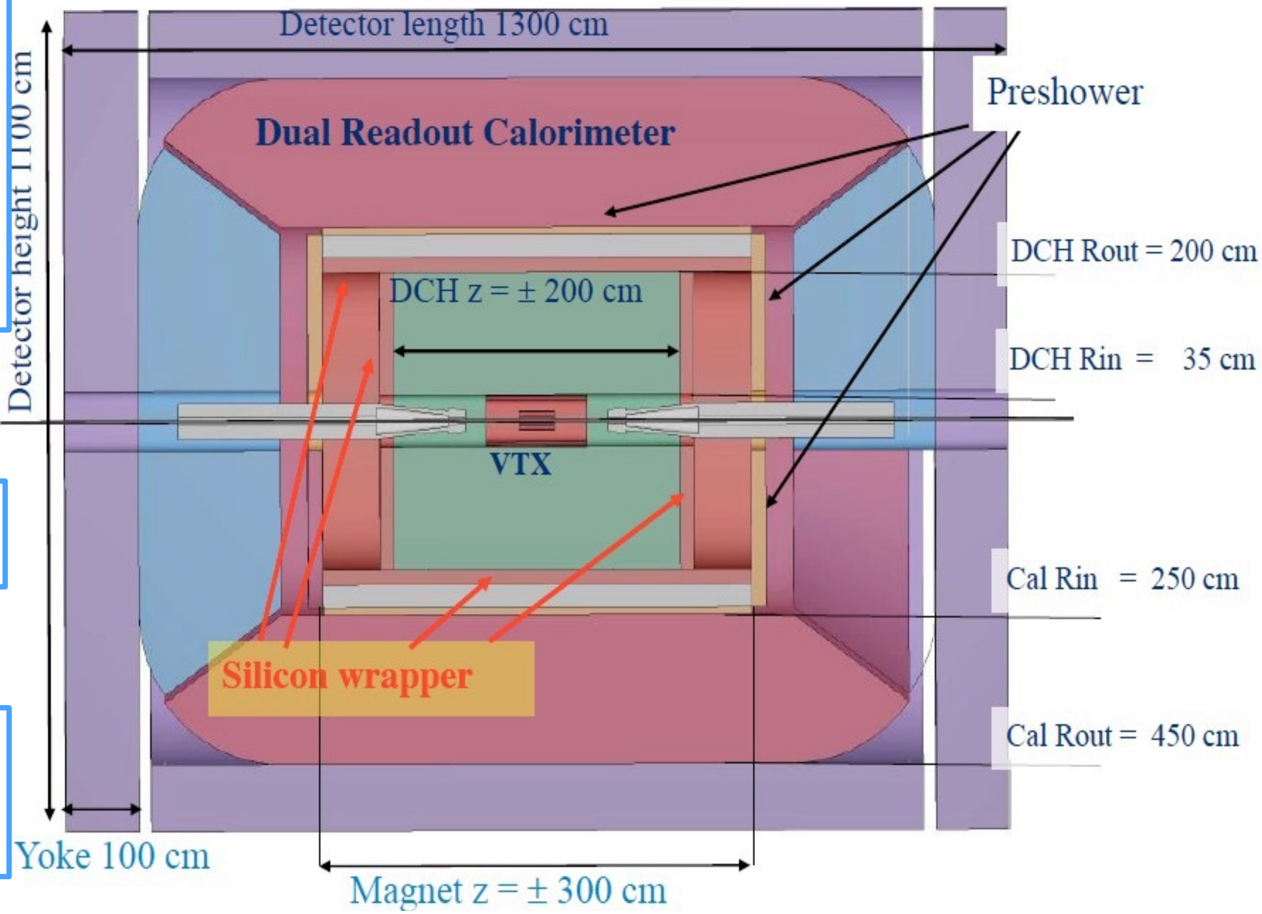
The IDEA detector at e^+e^- colliders



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**



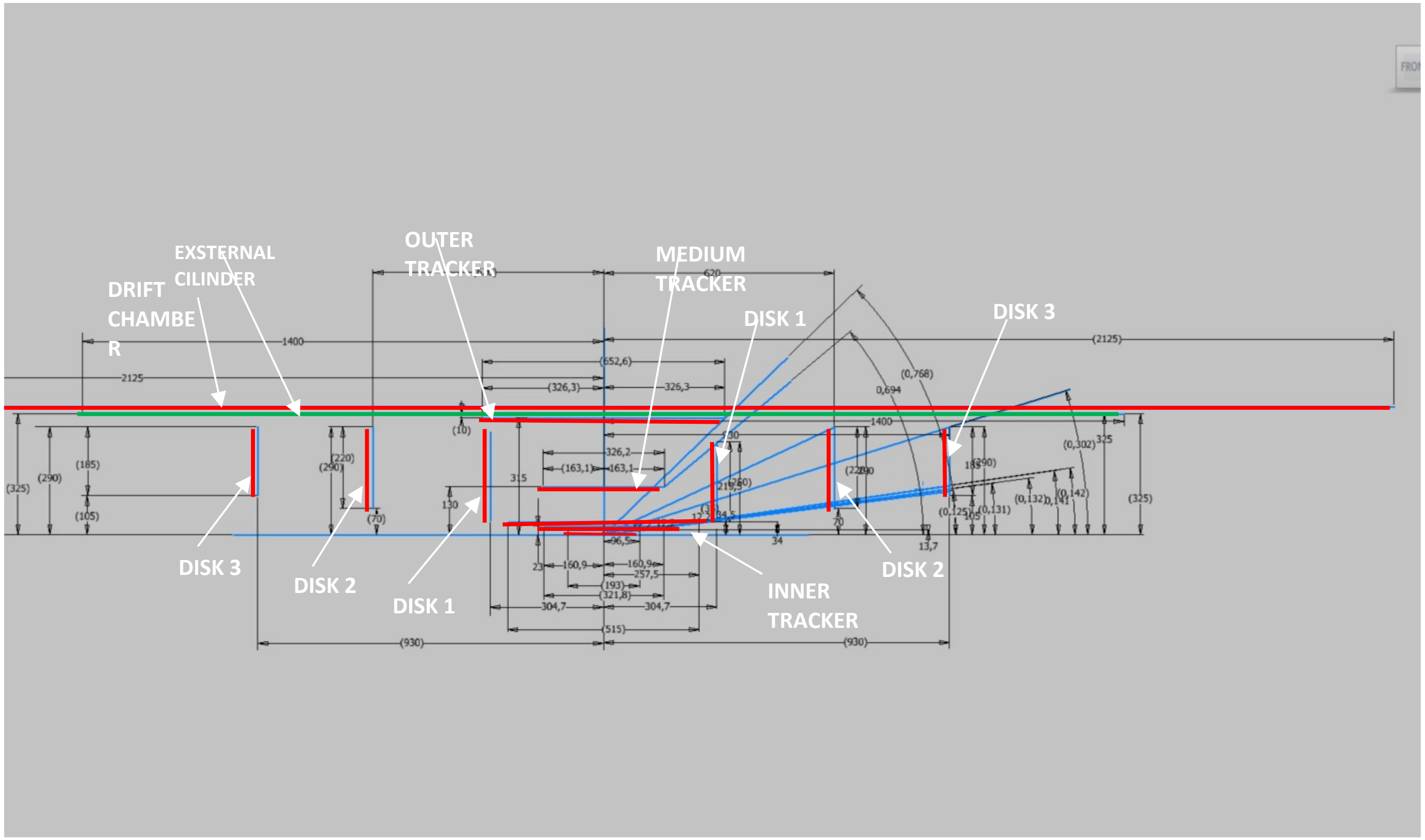
Low field detector solenoid to maximize luminosity (to contain the vertical emittance at Z pole).

→ optimized at 2 T

→ large tracking radius needed to recover momentum resolution

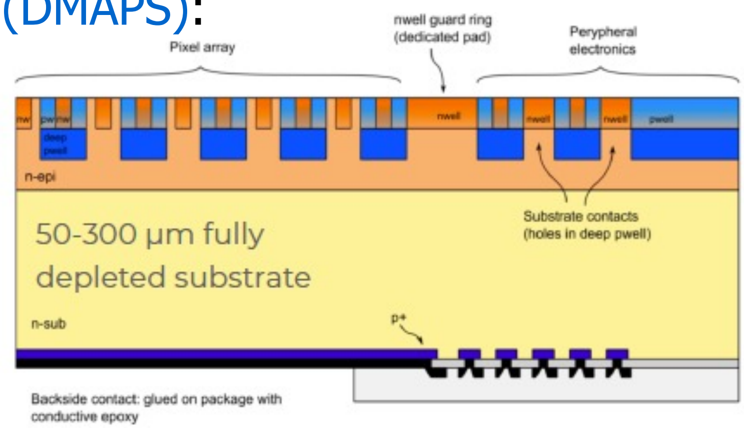
Silicon detectors for precision measurements:

- vertex detector/inner tracker (VTX)
- silicon medium & outer tracker
- silicon wrapper (SET)



Vertex detector Insubria U.+ Milano U.

ARCADIA INFN prototype



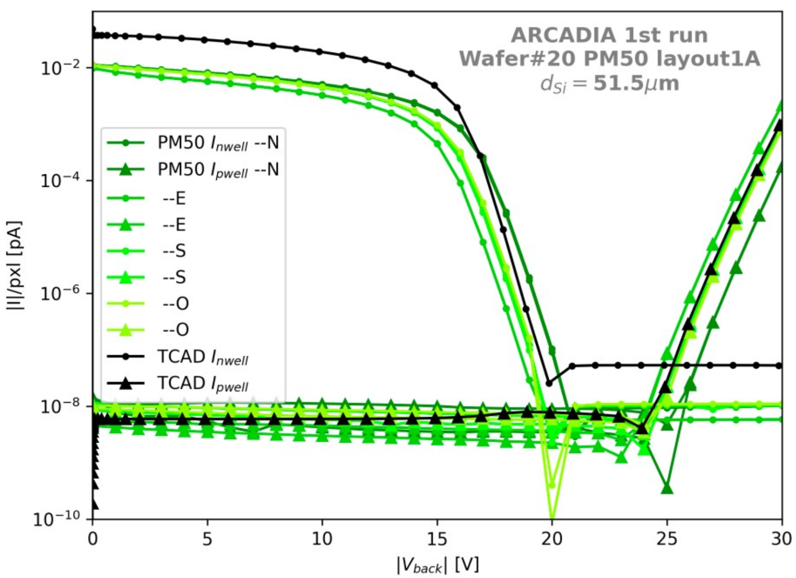
Technology: Depleted Monolithic Active Pixel Sensors (DMAPS):

- 25 x 25μm^2 pixel size for hit resolution ~ 3 μm
- 5 μm shown by ALICE ITS (30 μm pixels)
- prototype with thickness ~ 200 μm down to 50μm
- low power consumption (< 20 mW/cm^2)

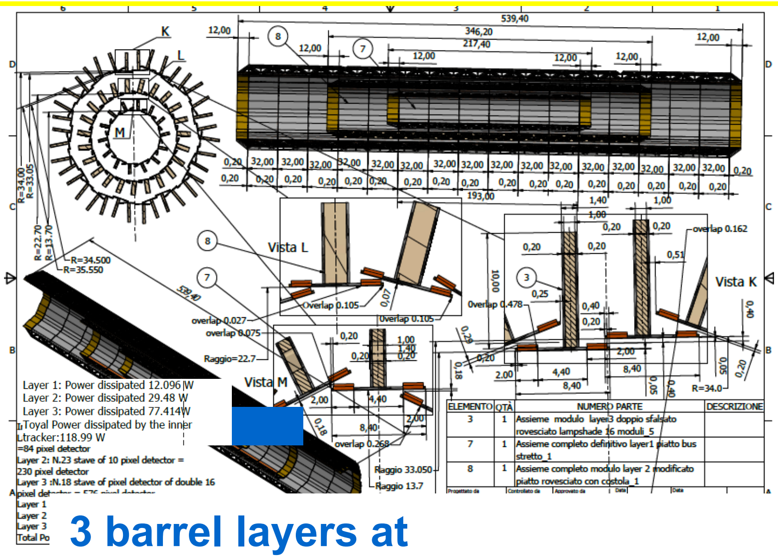
Tests of different design options:

- IV and CV measurements of test-structures from the first and second production run: proven functionality, stable operation at full depletion, and good agreement with TCAD simulations

A 2nd iteration prototype is working and will be tested soon at a test beam area



VTX mechanical strcture

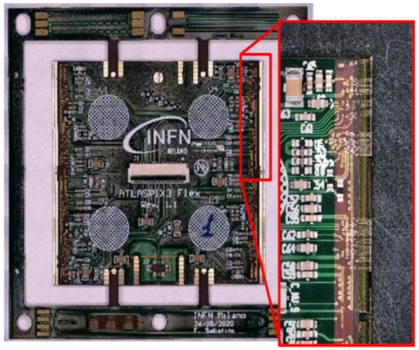


3 barrel layers at - 13.7, 23.7 and 34-35.4 mm radius

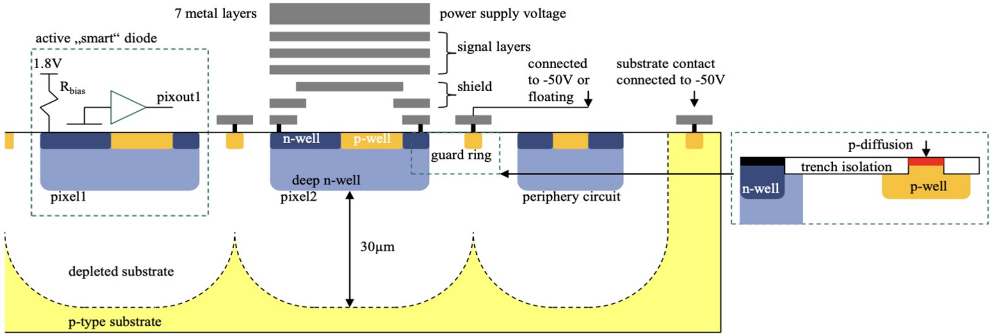
Silicon medium and outer tracker KIT+UK+IHEP+INFN

ATLASPIX3 modules: a full-size system on chip, targeting the outer tracker

- Intermediate barrel at 15 cm radius
- Outer barrel at 31.5 cm radius

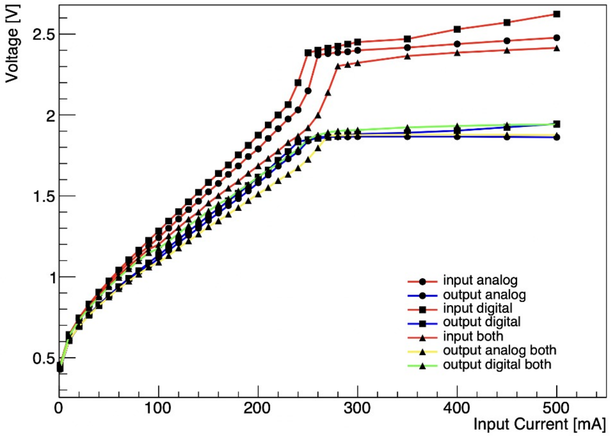


- quad module, inspired by ATLAS ITk pixels
- pixel size 50×150 μm^2
- TSI 180 nm process on 200 Ωcm substrate
- 132 columns of 372 pixels



Power consumption:

- ATLASPIX3 power consumption 100-150 mW/cm^2



Complete system consists of 900'000 cm^2 area / 4 cm^2 chip = 225k chips (56k quad-modules)

Data rate constrained by the inner tracker:

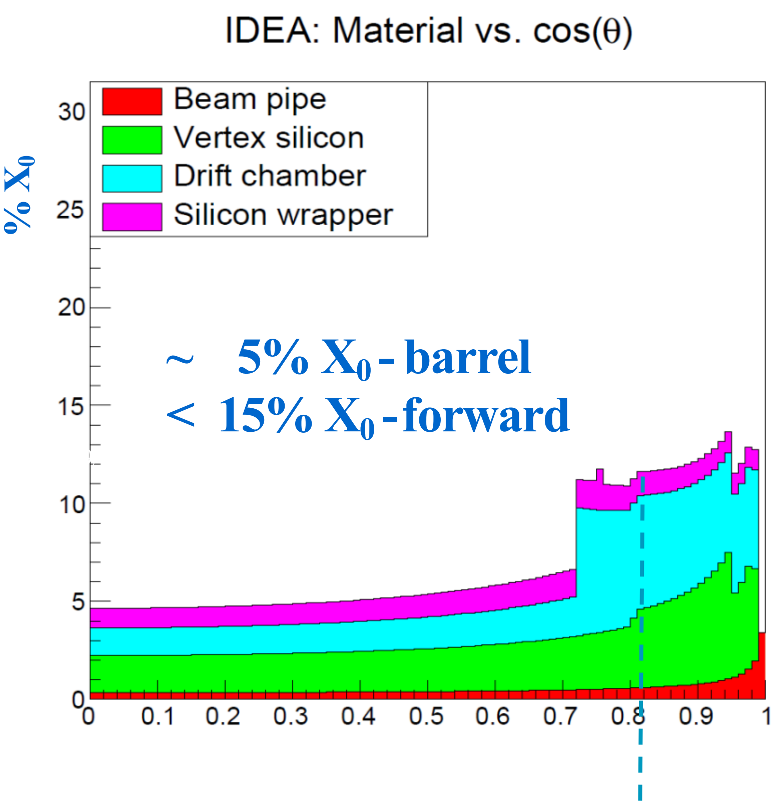
- average rate 10^{-4} - 10^{-3} particles cm^{-2} $event^{-1}$ at Z peak
- assuming 2 hits/particle, 96 bits/hit for ATLASPIX3
- 640 Mbps link/quad-module provides ample operational margin
- 16 modules can be arranged into 10 Gbps fast links: 3.5k links
- can also assume 100 Gbps links will be available: 350 links

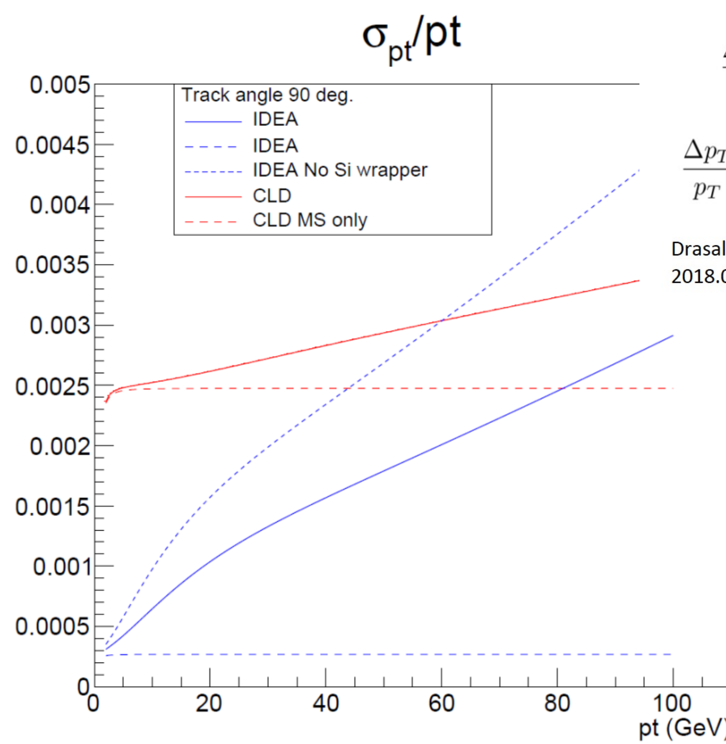
Design features of the IDEA Drift Chamber

INFN Bari and Lecce, IHEP + contributions from UCL, NWU and FSU

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

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





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

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

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

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

The Drift Chamber

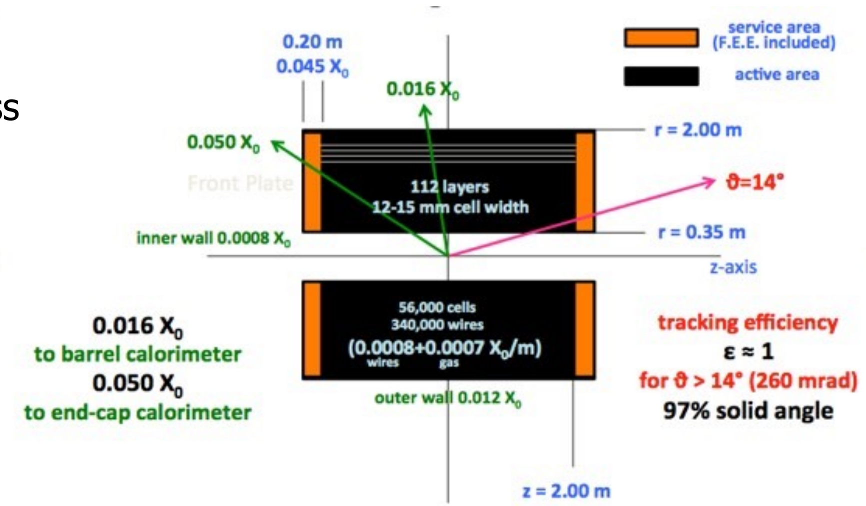
The DCH is:

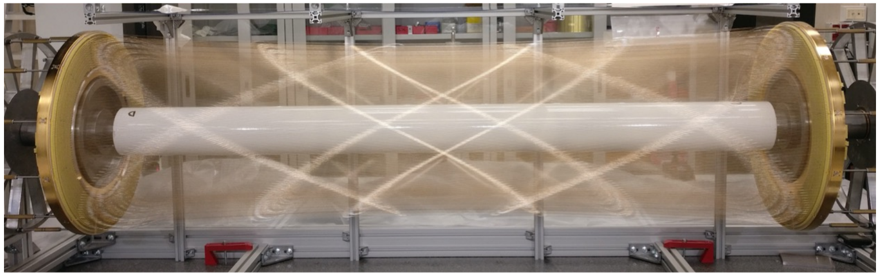
- a unique-volume, high granularity, fully stereo, low-mass cylindrical
- gas: He 90% - iC_4H_{10} 10%
- inner radius R_{in} = 0.35m, outer radius R_{out} = 2m
- length L = 4m
- drift length ~1 cm
- drift time ~150ns
- σ_{xy} < 100 μm, σ_z < 1 mm
- 12÷14.5 mm wide square cells, 5 : 1 field to sense wires ratio
- 112 co-axial layers, 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





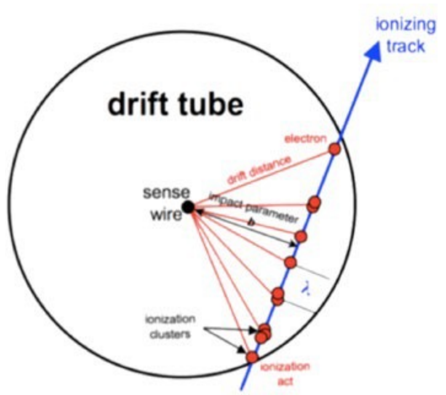
- the wire net created by the combination of + and – orientation generates a more uniform equipotential surface → better E-field isotropy and smaller ExB asymmetries)

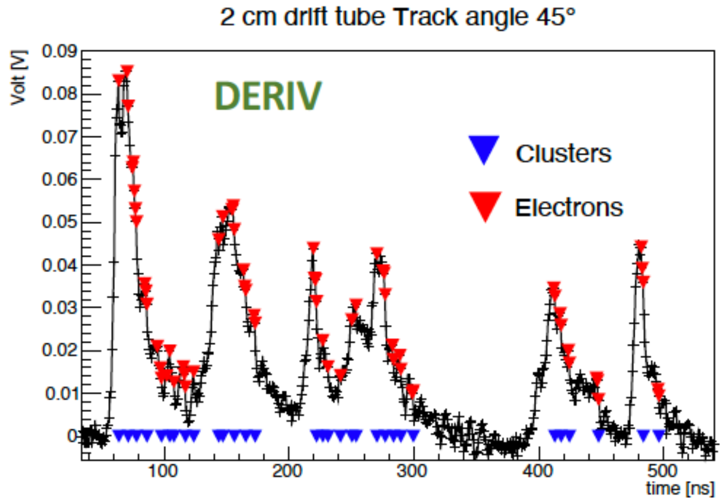
- a large number of wires requires a non standard wiring procedure and needs a feed-through-less wiring system → a novel wiring procedure developed for the construction of the ultra-light MEG-II drift chamber

The Drift Chamber: Cluster Counting/Timing and PID

Principle: In He based gas mixtures the signals from each ionization act can be spread in time to few ns. With the help of a fast read-out electronics they can be identified efficiently.

- By counting the number of ionization acts per unit length (dN/dx), it is possible to identify the particles (P.Id.) with a better resolution w.r.t the dE/dx method.





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

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

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

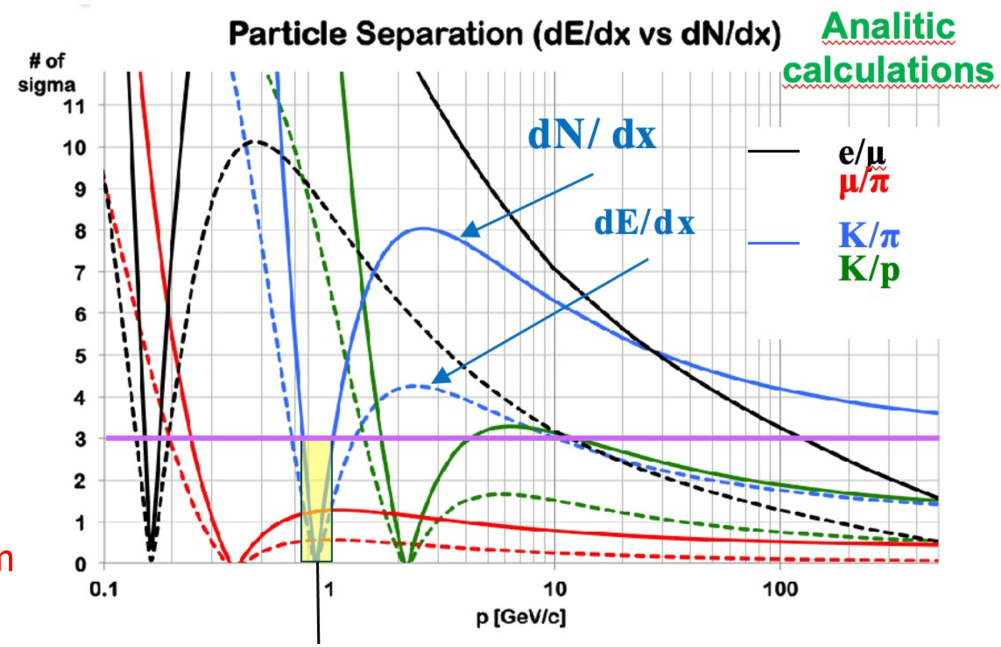
dE/dx: truncated mean cut (70-80%), with a 2m track at 1 atm give $\sigma \approx 4.3\%$

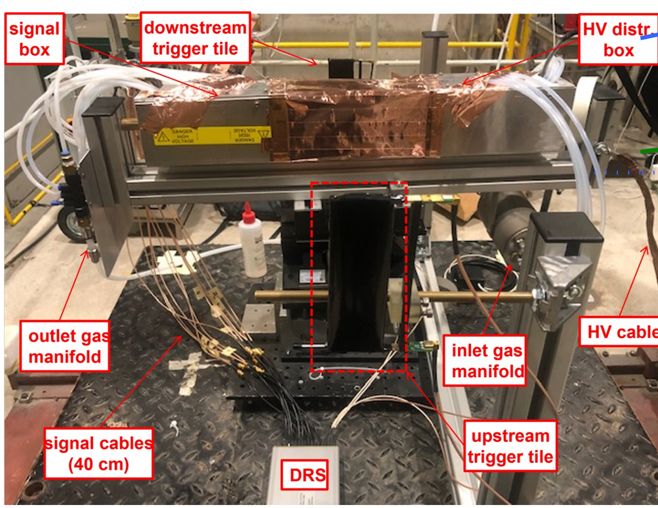
dN_{cl}/dx: for $He/iC_4H_{10}=90/10$ and a 2m track gives $\sigma_{dNcl/dx}$ **$/(dN_{cl}/dx)$** $< 2.0\%$

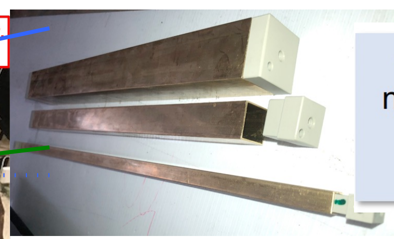
The Drift Chamber: Cluster Counting/Timing and PID

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

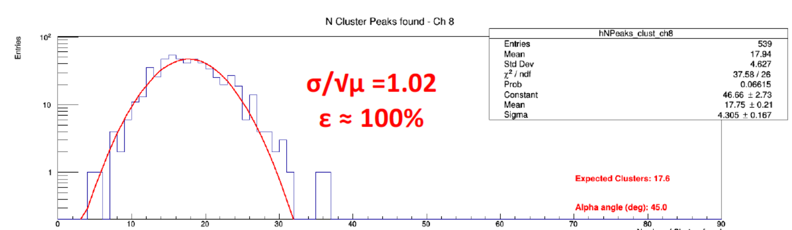
- Simulation with Garfield++ and with the Garfield model ported in GEANT4:
  - the particle separation, both with dE/dx and with dN_{cl}/dx, in GEANT4 found considerably worse than in Garfield
  - the dN_{cl}/dx Fermi plateau with respect to dE/dx is reached at lower values of βγ with a steeper slope
  - finding answers by using real data from beam tests at CERN in 2021 and 2022





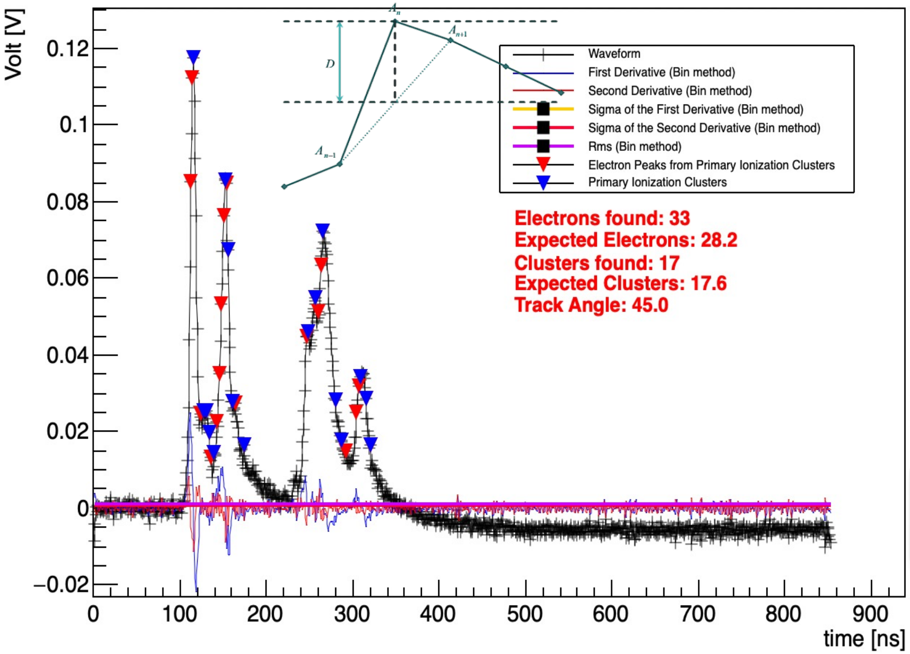


90%He-10%iC_4H_{10}
nominal HV+20, 45°,
Gas gain ~ $2 \cdot 10^5$,
165 GeV/c



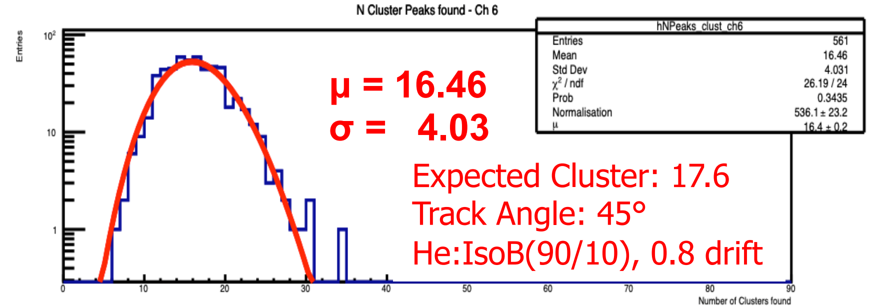
- Poissonian behaviour of the number of clusrers
- Meaurements vs predictions about the number of clusters are in very good agreement
- Same results in independent drift tubes

2021/2022 testbeam: number of clusters



Sense Wire Diameter 10 um – Cell Size 1.0 cm – Track Angle 45° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV

Number of Cluster Distribution



Expected number of cluster = δ cluster/cm (MIP) x drift tube size [cm] x 1.3 (relativistic rise) x 1/cos(α)

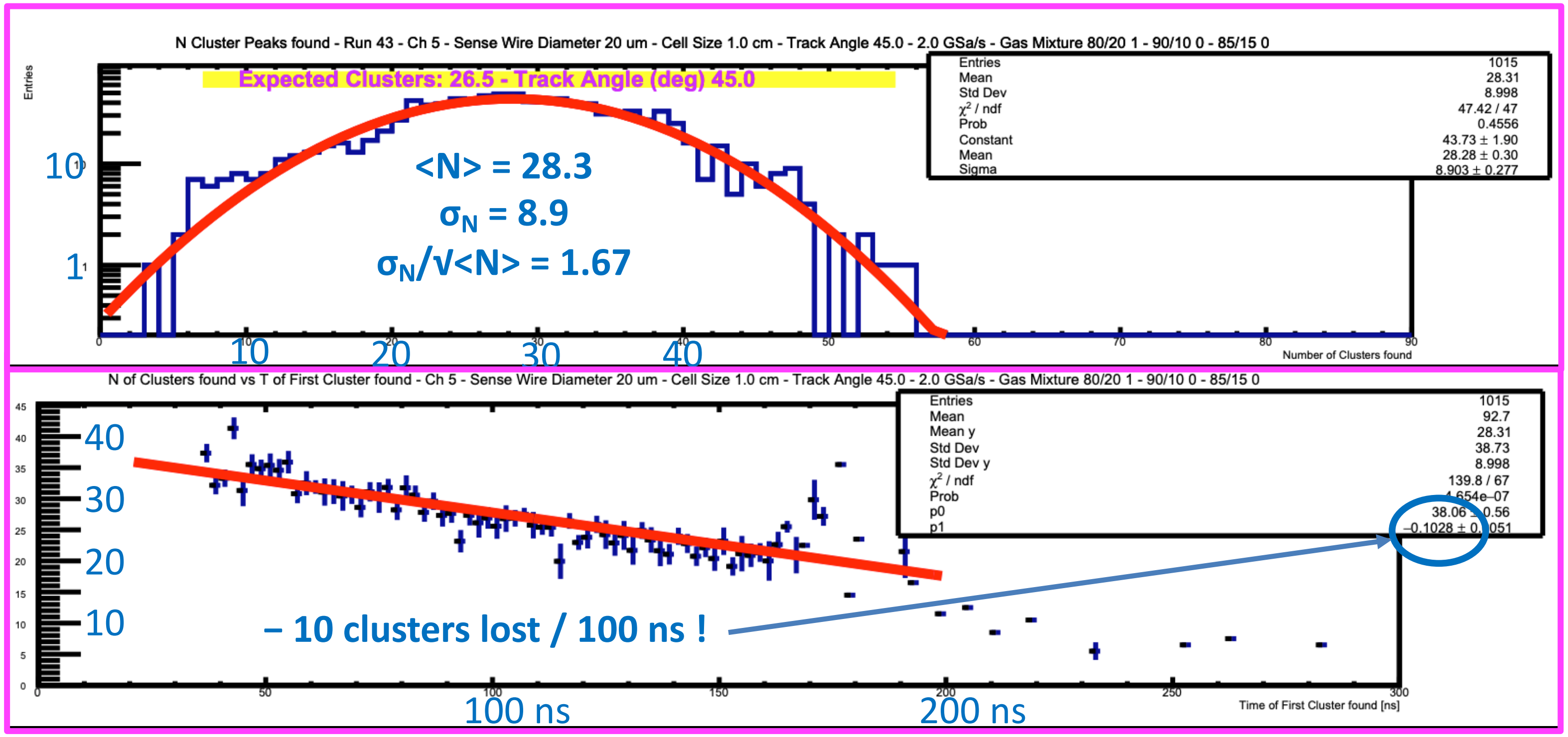
- α is the angle of the muon track w.r.t. normal direction to the sense wires
- δ cluster/cm (mip) changes from 12, 15, 18 respectively for He:IsoB 90/10, 85/15 and 80/20 gas mixtures
- Actual drift tube size are 0.8, 1.2, and 1.8 respectively for 1 cm, 1.5 cm, and 2 cm cell size tubes

- Poissonian behaviour
- Meaurements and predictions about the number of clusters are in very good agreement, with 1cm cell size

Beam test results: recombination and attachment

Space charge + attachment + recombination effects affect the experimental CC efficiency!

- The **loss of efficiency at small angles** is due to the partial shielding of the electric field due to the space charge.
- The **loss of efficiency at large angles** is partially due to the fact that increasing the number of clusters in the same drift time, increases the probability of pileup, then decreasing the counting efficiency.
- The **lower counting efficiency in 2cm** tubes compared to 1cm ones is only partially explained by the effects of recombination and attachment; other possible effects under investigation



Number of Clusters found by DERIV+CLUSTER algorithms

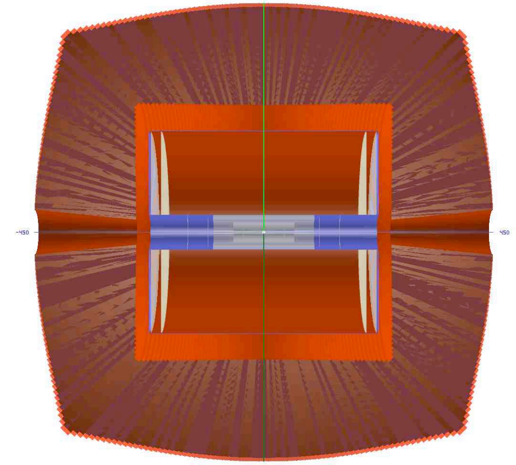
Average Number of Clusters found(@drift time) vs drift time

Combined action of recombination, electron attachment and E-field suppression due to space charge

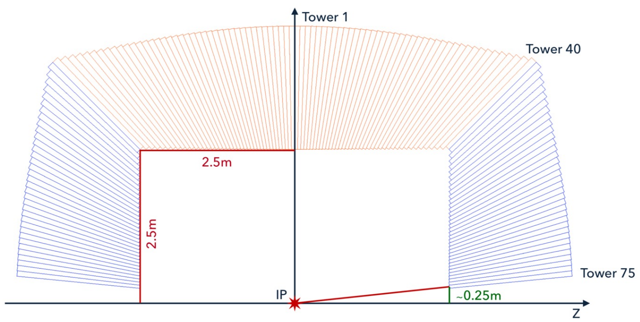
Detector simulation and reconstruction

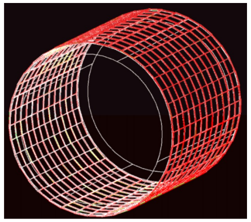
Detector simulation for IDEA

Geant4 and DD4HEP simulations of the IDEA geometry are available



- The DCH is simulated at a good level of geometry details, including detailed description of the endcaps; hit creation and track reconstruction code available
- SVX and Si wrapper are simulated too
- solenoid is also simulated in a simple way
- Dual readout calorimenter simulated combining DR fibers and crystals (in a fully compensating segmented calorimeter)
- Muon detector: simulated with a cylindrical geometry





Track reconstruction for IDEA

Working in Geant4 based simulation framework code.

- Track fitting
  - based on the Kalman Filter
  - specific implementation aspects
- Track finding (Pattern Recognition)
  - general aspects
  - useful options for IDEA case
  - some details on current IDEA PR

Track reconstruction: track fitting

Working in Geant4 based simulation framework code.

- Track fitting
  - based on the Kalman Filter
    - 1960: R. Kalman, "A New Approach to Linear Filtering and Prediction Problems", **Trans. ASME (J. Basic Engineering), 82 D, 35-45, 1960**

      One of the first applications: guiding Apollo 13 to the moon

      Now widely used: in just about every inertial navigation system(GPS, gyro systems), radar tracking
    - First paper in HEP with equivalent equations:
      1984: P. Billoir, "Track Fitting With Multiple Scattering: A New Method," **NIM A (1984) 352**
    - Classic author of Kalman Filter for HEP:
    - 1987: R. Fruhwirth, "Application of Kalman filtering to track and vertex fitting", **NIM A 262 (1987) 444**
  - peculiarities of the Kalman Filter:
    - recursive least-squares estimation;
    - suitable for combined track finding and fitting;
    - mathematically equivalent to least squares fit;
    - avoids time-consuming large matrix inversion inherent in least-squares fits;
    - straightforward to take into account material effects in extrapolation step.

Track fitting: implementation aspects

Many software packages implement KFs :

- **genFit2**: https://github.com/GenFit/GenFit (arXiv:1410.3698 , NIN A620(2010)518–525) used by:
  - PANDA
  - Belle II
  - ...

For the Geant4 based simulation framework code, the track fitting based on Kalman Filter is simulated by using the genFit2 package

- **ACTS**: http://acts.web.cern.ch/ACTS/index.php
  - ATLAS
  - FCC software would use ACTS interfaced to DD4HEP

Track fitting: implementation aspects

What do we need to do?

- pass measurement points with their proper description
  - 3D (2D) point (pixel)
  - 1D point (strip)

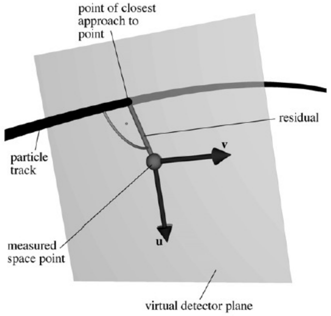


Fig. 2. Virtual detector plane (spanning vectors $\vec{u}$ and $\vec{v}$) for a space-point hit.

  - Drift distance

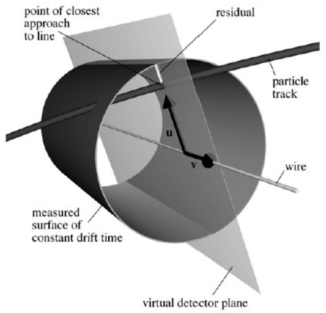


Fig. 3. Virtual detector plane (spanning vectors $\vec{u}$ and $\vec{v}$) for a wire-based drift detector.

- delivery a description of the material to allow the MS and ΔE evaluation
  - genFit2: GDML description
  - *ACTS: DD4Hep*

Track finding: general aspects

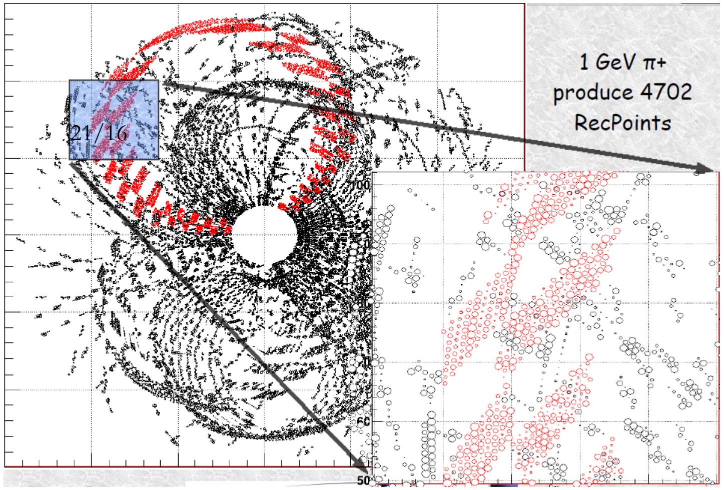
Track finding possible strategies: global vs local methods

- global methods
  - treat hits in all detector layers simultaneously
  - 'find all' tracks simultaneously
  - result independent of starting point or hits order

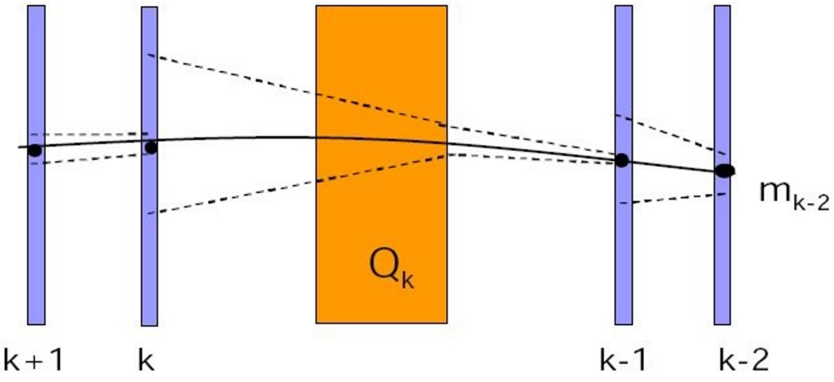
  examples: template matching, Hough transforms (conformal mapping), neural nets, cellular automation, ….
- local methods ('track following')
  - start with construction of track seeds
  - add hits by following each seed through detector layers
  - eventually improve seed after each hits

Stereo Drift Chamber issue for PR:

- Left/Right single cell ambiguity
- Longitudinal position along the wire (in the transverse plane appear two separate circonpherences for the same track before applying a correction for the position along the wire)



Track finding: current IDEA PR (local method)



Follow track candidate iteratively through detection layers

start from an initial track segment ("seed")

requires dedicated algorithm

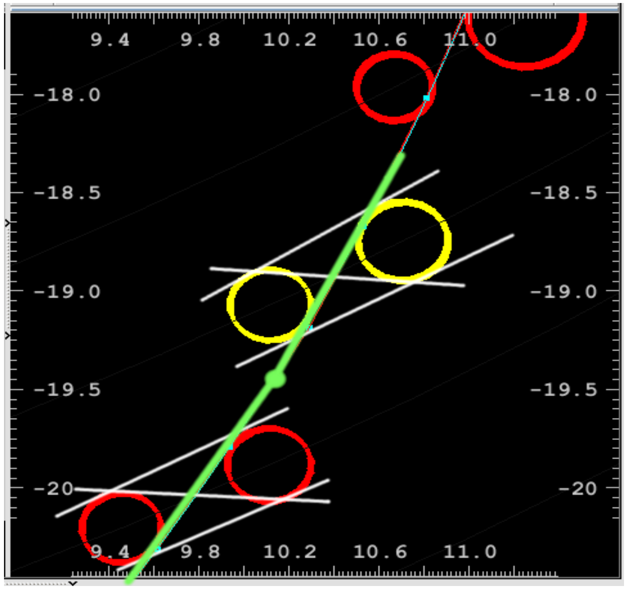
extrapolate: estimate the expected track position in the next detection layer
search: look for hits within a window around the estimated track position
update: if a hit is found inside this search window, add it to the track candidate and update the track parameters
iterate: extrapolate the updated track candidate to the next detection layer

should be broad seeding: track reconstruction efficiency can depend on it, compromise between efficiency and CPU performance
allow for detector inefficiencies: if no hit is found in one layer, continue with the next layer; abandon the candidate if no hits are found in several consecutive layers
allow for combinatorics: if more than one hit is found inside the search window, create a separate "branch" for each candidate; follow all branches concurrently

Track finding: local method for DCH only

Seeding from 2 pairs of hits (each pair on same layer) pointing at the origin

- 2 consecutive hits in same layer
  → 4=2x2(Left-Right) pairs with direction
- 2 pairs from nearest layers compatible:
  |Δcos(φ(direction)-φ(position))|<0.2,
  crossing Z inside DCH
- 1 pair with origin → Pt estimate
  (averaged over 2 pairs)
- Cross Point of 2 opposite stereo pairs give
  Z-coordinate (with Δφ correction from Pt)
- Pz = 0 at beginning
- Z measurement give additional compatibility check
  between 2 hits and between 2 pairs

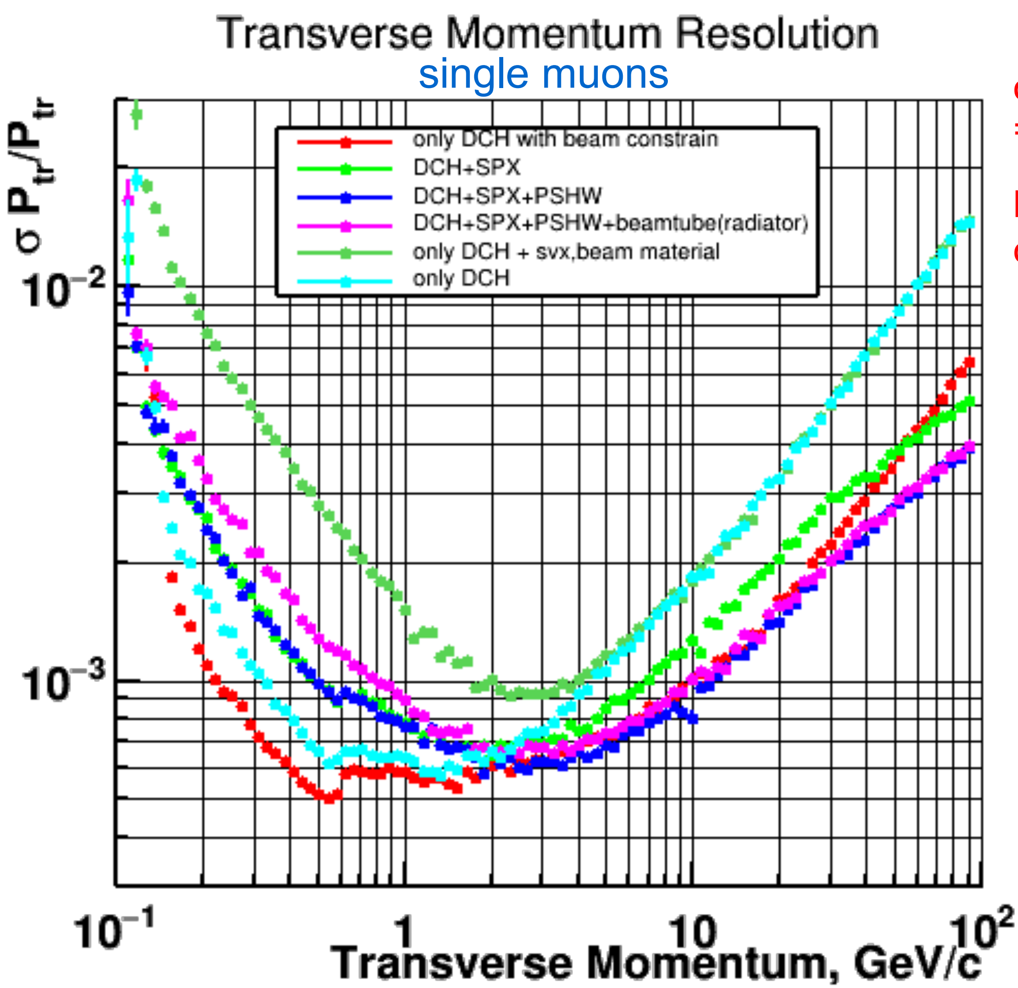


Red hits **projection at z=0 plane**
Yellow **rotated according to φ**

Low combinatory: 2 local compatibilities + 1 from opposite stereo view, but with direction angle check

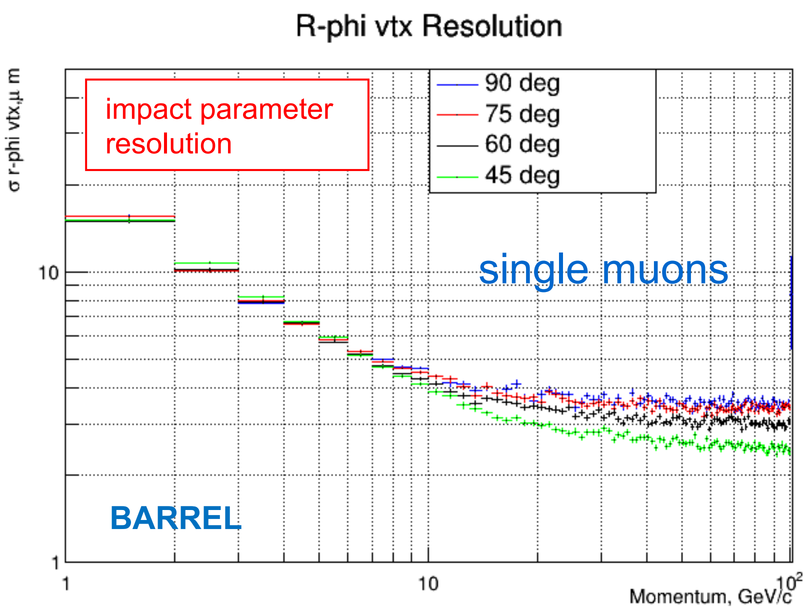
Track finding: performance of the current IDEA PR

For the Geant4 based simulation framework code:



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

but new studies ongoing



$\sigma(d_0)$ (100 GeV) $= 2\mu m$

Summary/Conclusions

Advanced R&D effort on tracking detectors:

- vertex pixel detector, based on ARCADIA
- silicon medium and outer tracker, based on ATLASPIX3
- silicon wrapper, based on ATLASPIX3 (LGAD under evaluation)
- drift chamber design and cluster counting study, sinergy with MEG2
- muon chambers, sinergy with LHCb upgrades

Full simulation of IDEA geometry is available in Geant4 and DD4HEP + hits

- Kalman Filter is currently implemented for the IDEA track reconstruction
- Current PR for the IDEA detectors is developed using a local method approach
- It reached a good performance but need to be tested with jets and with expected background
- Performance expected from simulation to be compared with measurements with beam test data

Plenty of areas for collaboration:

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

Effort to build international collaboration on going (in some areas well advanced) and to be enforced

Manpower, funding under continuous discussion

Backup

FCC-ee Higgs motivation and contacts

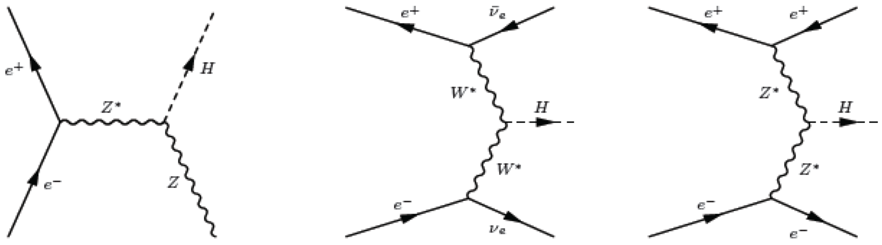
FCC-ee offers broad potential for precision Higgs measurements:

- 5 ab^{-1} integrated luminosity to two detectors over 10 years → 10^6 clean Higgs events
- clean environment
- relative small backgrounds, high S/B

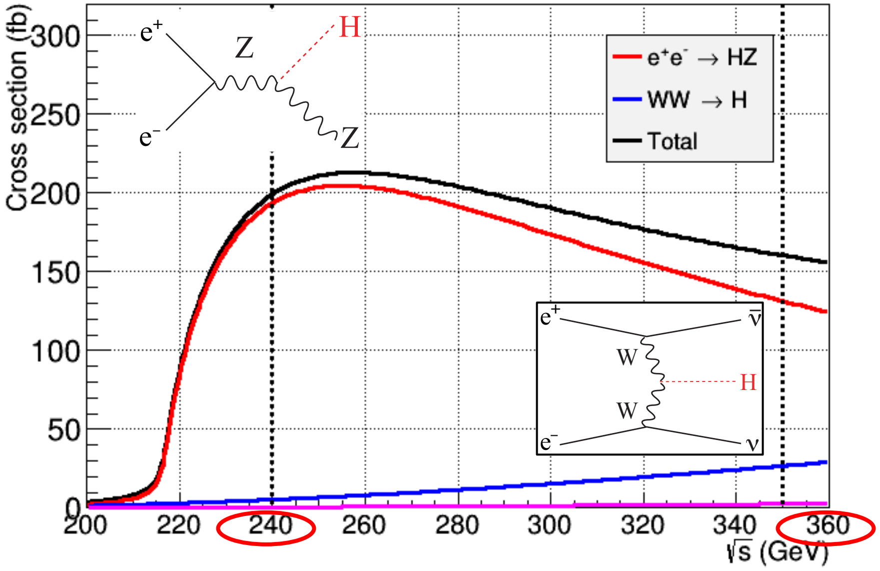
→ FCC-ee can measure the Higgs boson production cross sections and most of its properties with precisions far beyond achievable at the LHC

◆ **Higgs-strahlung (m_H = 125 GeV)**

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

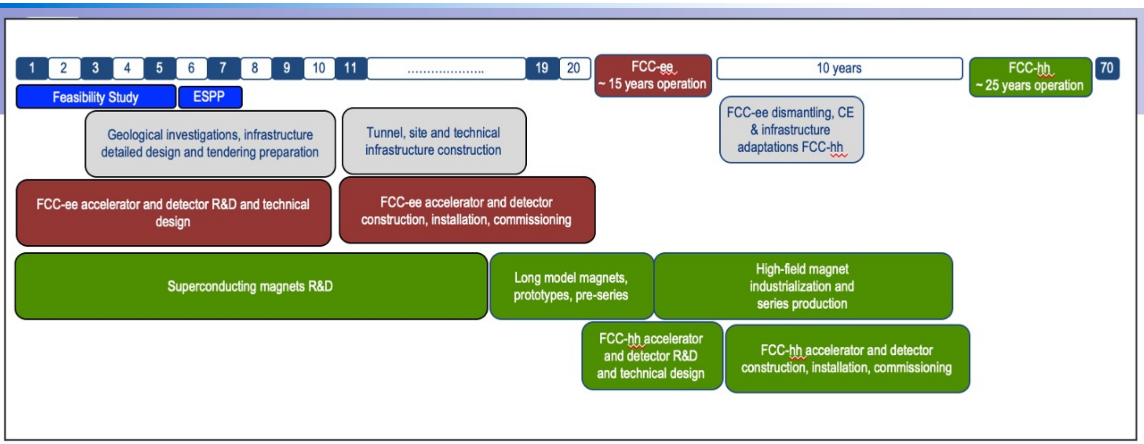


VBF production: $e^+e^- \rightarrow \nu\nu H$ (WW fus.), $e^+e^- \rightarrow He^+e^-$ (ZZ fus.)



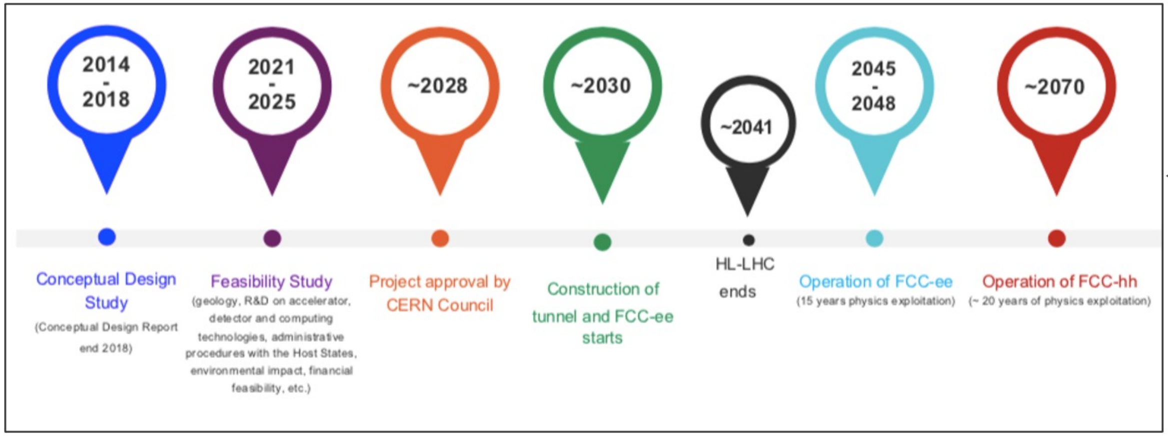
Max. σ at √s = 250 GeV : σ ≈ 200 fb

Report by F. Gianotti at FCCweek@London



FCC estimated timeline

Technical schedule:
FCC-ee could start physics operation **in 2040 or earlier**



"Realistic" schedule takes into account:

- ❑ past experience in building colliders at CERN
- ❑ approval timeline: ESPP, Council decision
- ❑ that 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)

1st stage collider, FCC-ee: electron-positron collisions 90-360 GeV
Construction: 2033-2045 → Physics operation: 2048-2063

2nd stage collider, FCC-hh: proton-proton collisions at ≥ 100 TeV
Construction: 2058-2070 → Physics operation: ~ 2070-2095

Care should be taken when comparing to other proposed facilities, for which in some cases only the (optimistic) technical schedule is shown

2021/2022 testbeam: find electron peaks algorithms

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

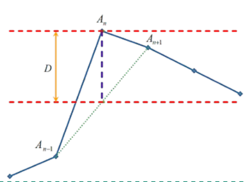
FIRST AND SECOND DERIVATIVE (DERIV) ALGORITHM

- Compute the first and second derivative from the amplitude average over two consecutive bins (1.6 ns for 1.2 GSa/s) and require that, at the peak candidate position, they are smaller than a r.m.s. signal-related small quantity and they increase (decrease) before (after) the peak candidate position of a r.m.s. signal-related small quantity.

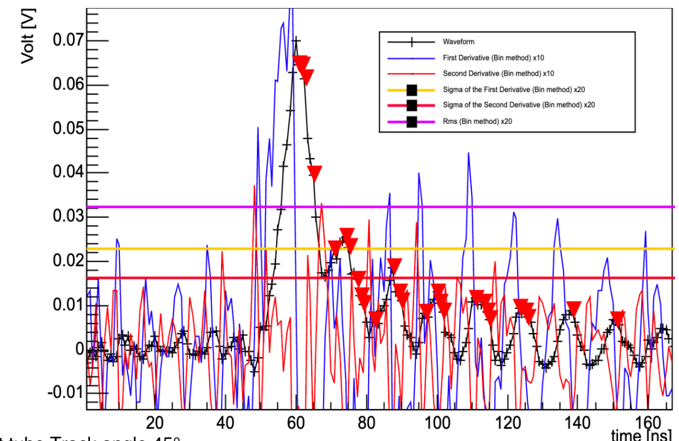
- Require that the amplitude at the peak candidate position is larger than a r.m.s. signal-related small quantity and the amplitude difference among the peak candidate and the previous (next) signal amplitude is larger (smaller) than a r.m.s. signal-related small quantity.

NOTE:

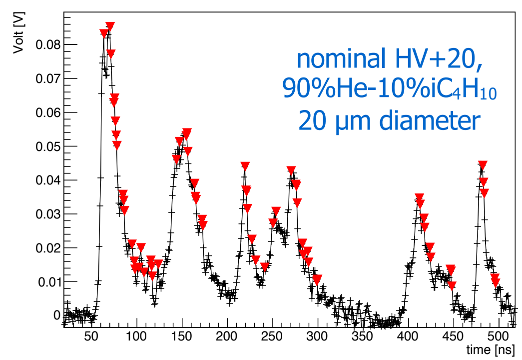
- R.m.s. is a measurements of the noise level in the analog signal



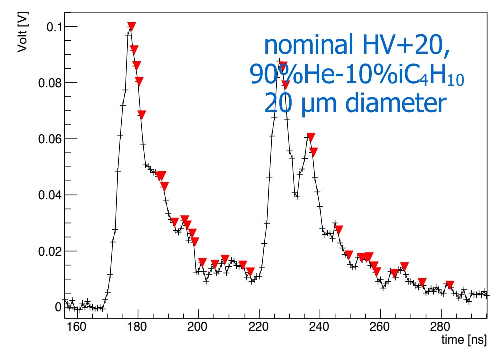
0°, nominal HV+20, 90%He-10%iC_4H_{10}
Tube with 1-cm cell size and 20 μm diameter



2 cm drift tube Track angle 45°



1 cm drift tube Track angle 45°



2021/2022 testbeam: find electron peaks algorithms

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

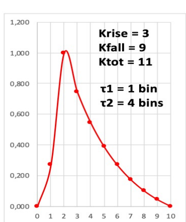
RUNNING TEMPLATE ALGORITHM (RTA)

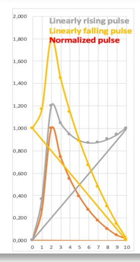
- Define an electron pulse template based on experimental law with a raising and falling exponential over a fixed number of bins (K_{tot}) and digitized ($A(k)$) according to the data sampling rate.

- Run over K_{tot} bins by comparing it to the subtracted and normalized data (build a sort of χ^2 and define a cut on it).

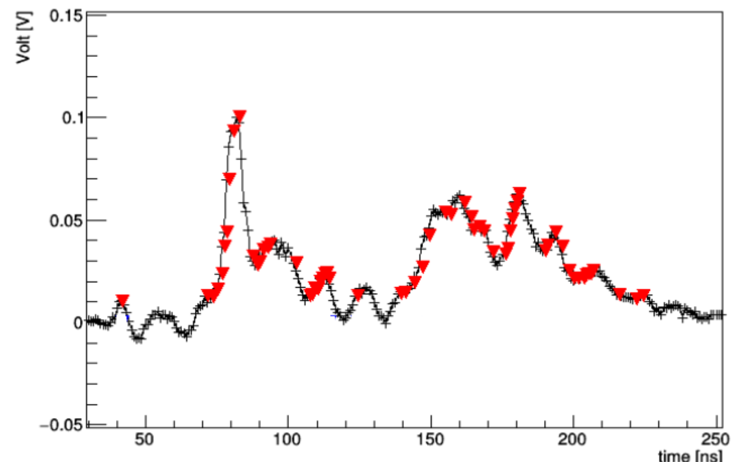
- Subtract the found peak to the signal spectrum and iterate the search and stop when no new peak is found.

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

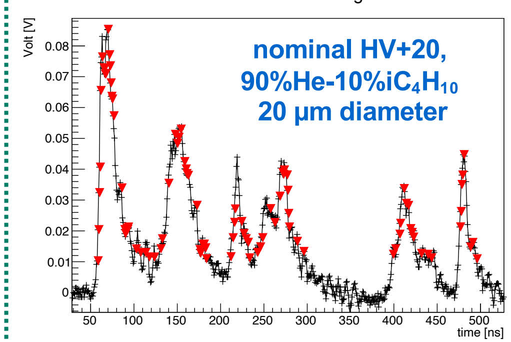




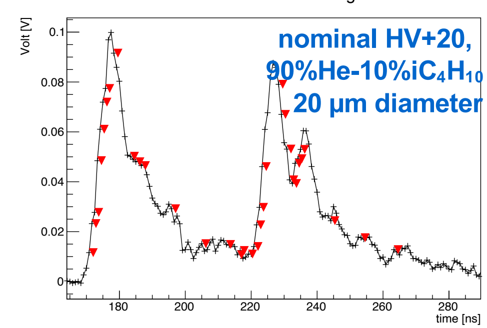
30°, nominal HV+20, 90%He-10%iC_4H_{10}
Tube with 1 cm cell size and 20 μm diameter



2 cm drift tube Track angle 45°

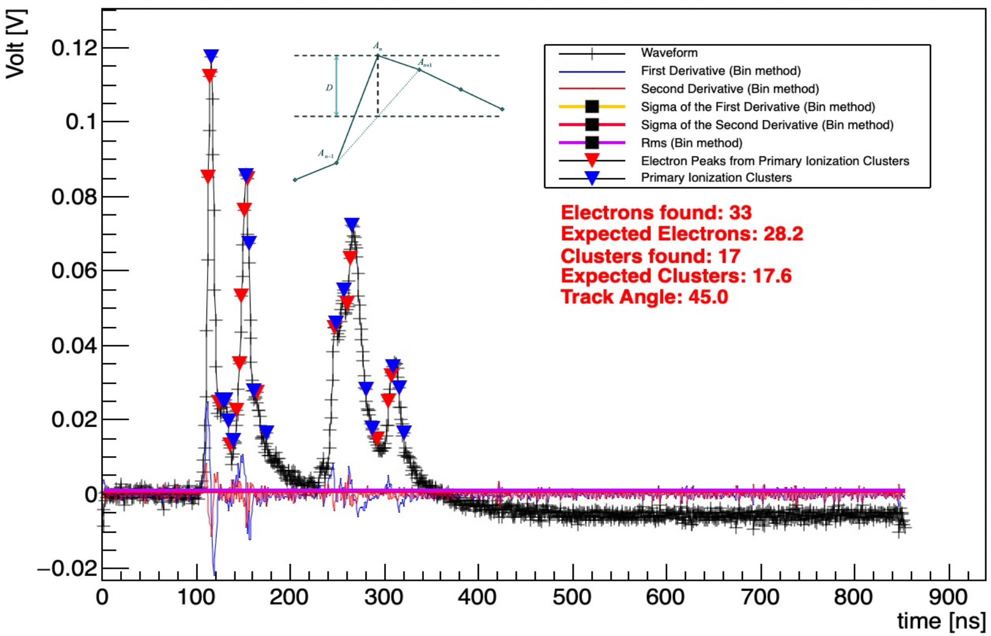


1 cm drift tube Track angle 45°



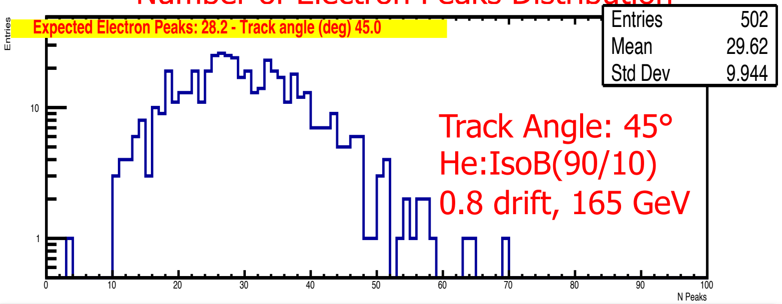
2021/2022 testbeam: number of electron peaks

Reconstruction of Electron Peaks (DERIV Algorithm)



Sense Wire Diameter 10 um – Cell Size 1.0 cm – Track Angle 45° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV

Number of Electron Peaks Distribution



Track Angle: 45°
He:IsoB(90/10)
0.8 drift, 165 GeV

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

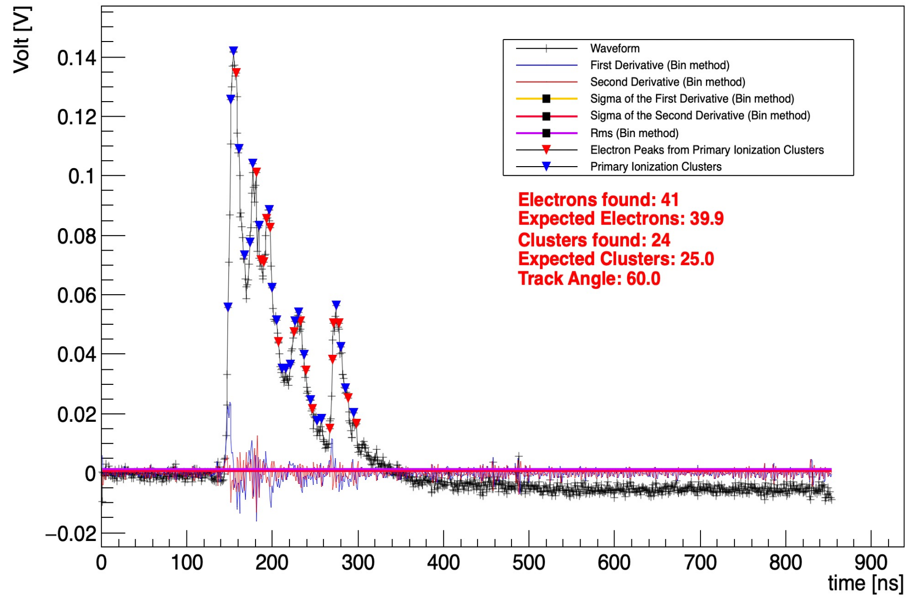
- α is the angle of the muon track w.r.t. normal direction to the sense wires
- δ cluster/cm (mip) changes from 12, 15, 18 respectively for He:IsoB 90/10, 85/15 and 80/20 gas mixtures
- Actual drift tube size are 0.8, 1.2, and 1.8 respectively for 1 cm, 1.5 cm, and 2 cm cell size tubes

[1] H. Fischle, J. Heintze and B. Schmidt, Experimental determination of ionization cluster size distributions in counting gasses, NIM A 301 (1991)
[2] R. G. Kepler, C. A. D'Andlau, W. B. Fretter and L. F. Hansen, Relativistic Increase of Energy Loss by Ionization in Gases, IL NUOVO CIMENT0 VOL. VII, N. 1 - 1 Gennaio 1958

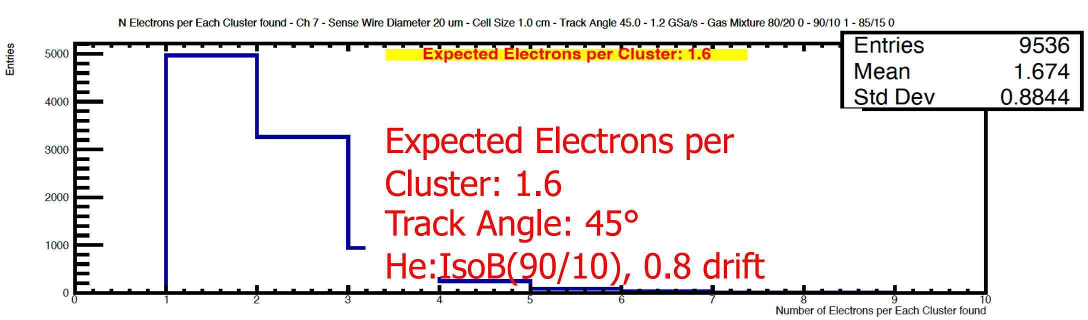
2021/2022 testbeam: clusterization

CLUSTERIZATION algorithm: Reconstruction of Primary Ionization Clusters

- Merging of electron peaks in consecutive bins in a single electron to reduce fake electrons counting
- Contiguous electrons peaks which are compatible with the electrons' diffusion time (it has a $\sim\sqrt{t_{ElectronPeak}}$ dependence, different for each gas mixture) must be considered belonging to the same ionization cluster.
- Position and amplitude of the clusters corresponds to the position and height of the electron having the maximum amplitude in the cluster. → Poissonian distribution for the number of clusters!



Electron per Clusters Distribution



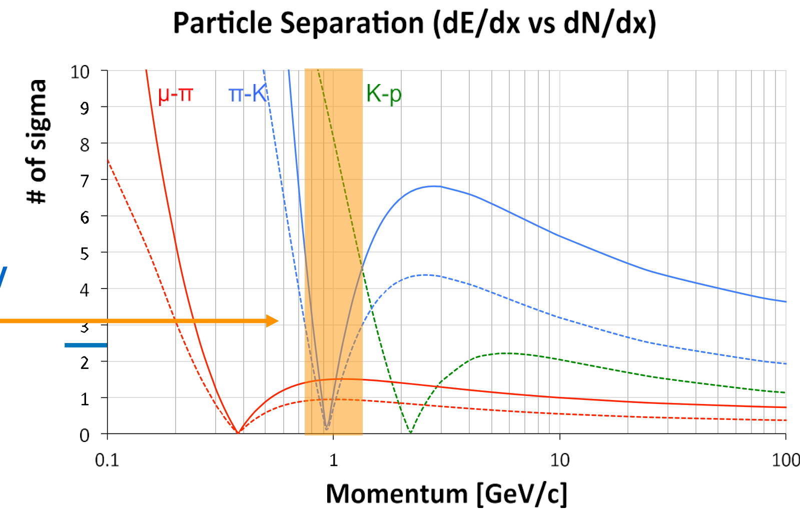
Sense Wire Diameter 20 um – Cell Size 1.0 cm – Track Angle 60° – 1.2 GSa/s – Gas Mixture He:IsoB 90/10 – 165 GeV

Silicon wrapper

INFN Genova

In IDEA concept, tracking and PID provided by the DCH (+ VTX + outer Tracker)

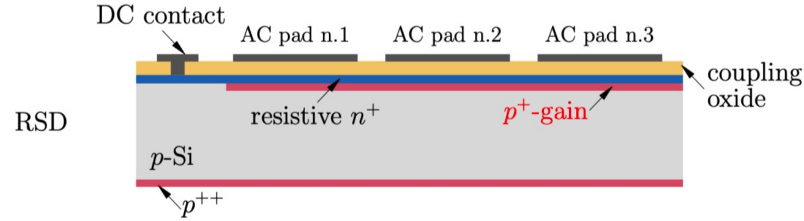
- Silicon wrapper for precise polar angle measurement
- Good K-π separation from dE/dx except for p ~ 1 GeV

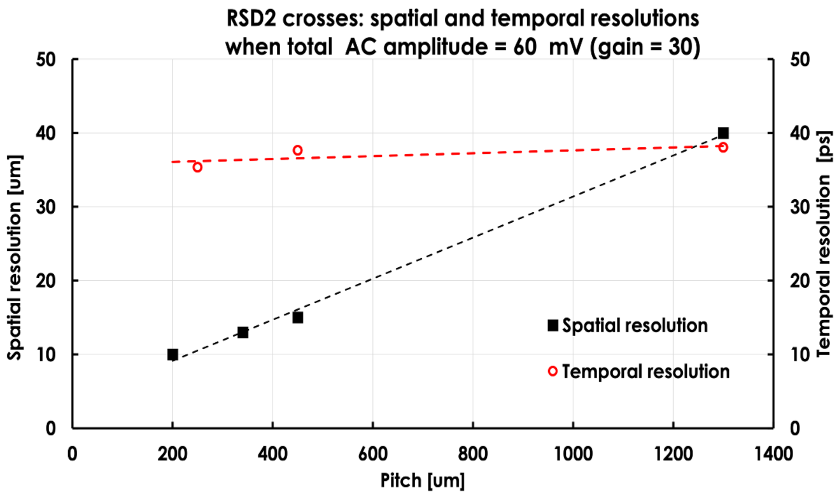


Baseline: ATLASPIX3 modules **BUT**

LGAD (Low-Gain Avalanche Diodes) with RSD (Resistive Silicon Detectors) technology are a possible option:

- TOF with excellent time resolution
- in resistive readout the signal is naturally shared among pads without the need of B field or floating pads





Reconstruction of the position from the signal distribution between contiguous electrodes

Need to show that LGAD could be produced with acceptable cost

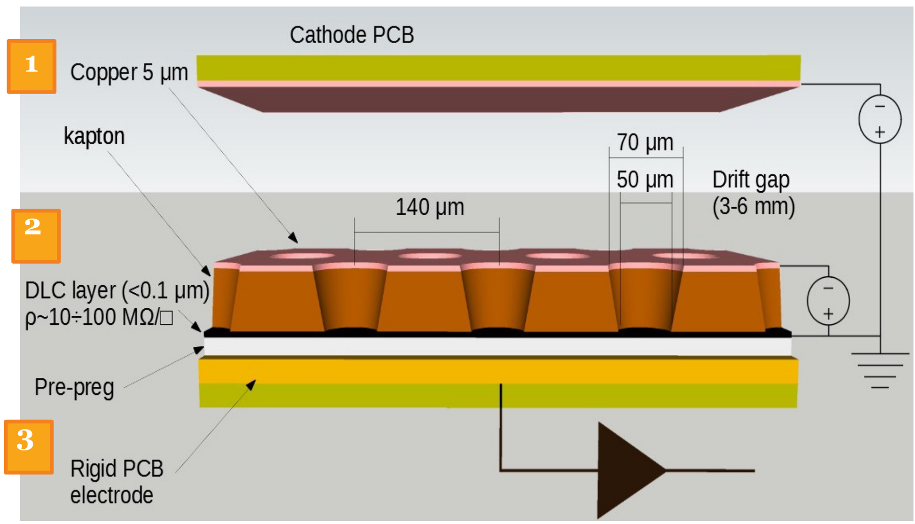
- Technology developed by INFN Turin group, production by FBK
- External funding also (ERC, PRIN)

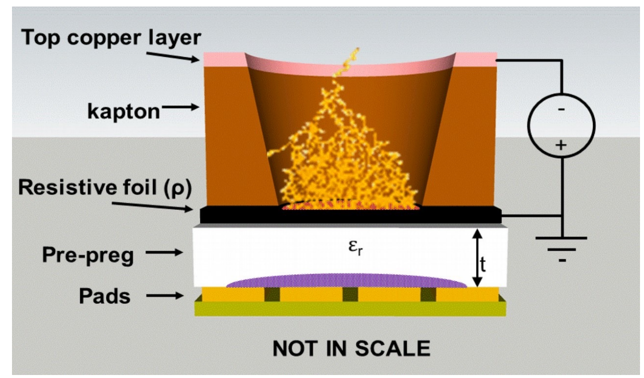
The μ-RWELL detector schema

R&D on μ-RWELL technology mainly motivated by the wish of improving:

- ✓ the stability under heavy irradiation (discharge suppression)
- ✓ the construction technology (simplifying the assembly)
- ✓ the technology transfer to industry (mass production)

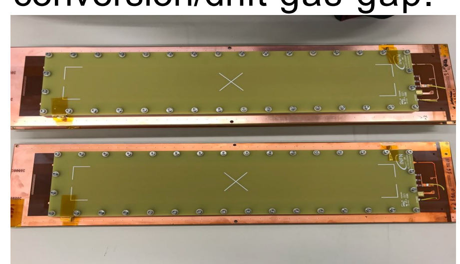
The μ-RWELL is a Micro Pattern Gaseous Detector (MPGD) composed of only two elements: the μ-RWELL_PCB and the cathode.





Applying a suitable voltage between the top Cu-layer and the DLC the WELL acts as a multiplication channell for the ionization produced in the conversion/drift gas gap.

1. A WELL patterned kapton foil acting as amplification stage (GEM-like)
2. a resisitive DLC layer (Diamond Like Carbon) for discharge suppression w/surface resistivity ~ 50÷100 MΩ/sq
3. a standard readout PCB



Test beam at CERN with μ-RWELL prototypes with

- 40cm long strips
- 0.4 mm strip pitch
- 1D readout

Muon detectors for IDEA: guiding principles

INFN Frascati, Ferrara, CERN

Future colliders experiments require extremely large muon detectors :

- ~10000 m^2 in the barrel
- 3-5000 m^2 in the endcap
- 300 m^2 in the very forward region

PRESHOWER requirements:

- high-spatial-resolution layer between magnet and calorimeter
- charge measurement to help discriminating the electromagnetic nature of the clusters
- barrel + two endcaps

MUON CHAMBERS requirements:

- low particle rate
- rough resolution to detect muons behind the calorimeter
- with higher resolution could help detecting secondary vertices from Long-Lived Particles decaying into muons

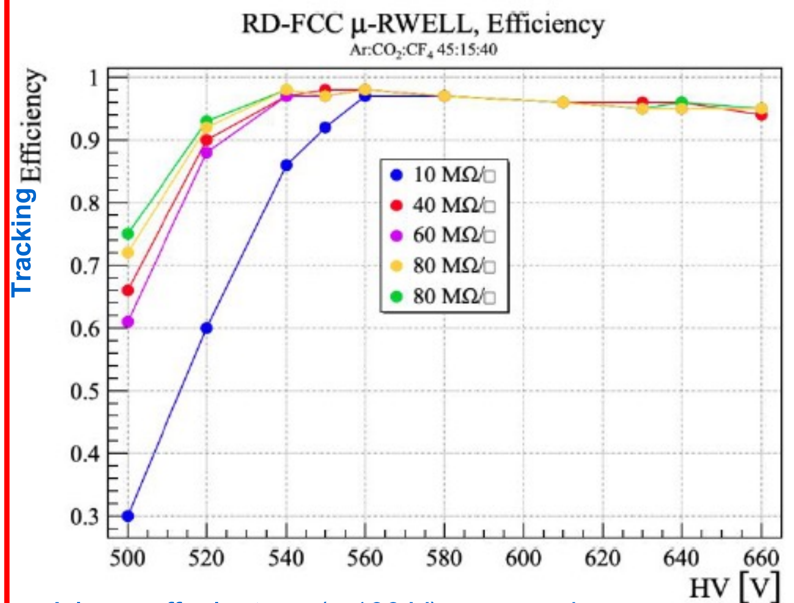
Preshower:

- ✓ Efficiency > 98%
- ✓ Space Resolution < 100 μm
- ✓ Pitch = ~400 μm
- ✓ Strip capacitance ~70 pF
- ✓ 1.5 million channels
- ✓ FEE cost reduction —> custom ASIC
- ✓ Arranged in tiles 50x50 cm^2
- ✓ Mass production —> T.T.

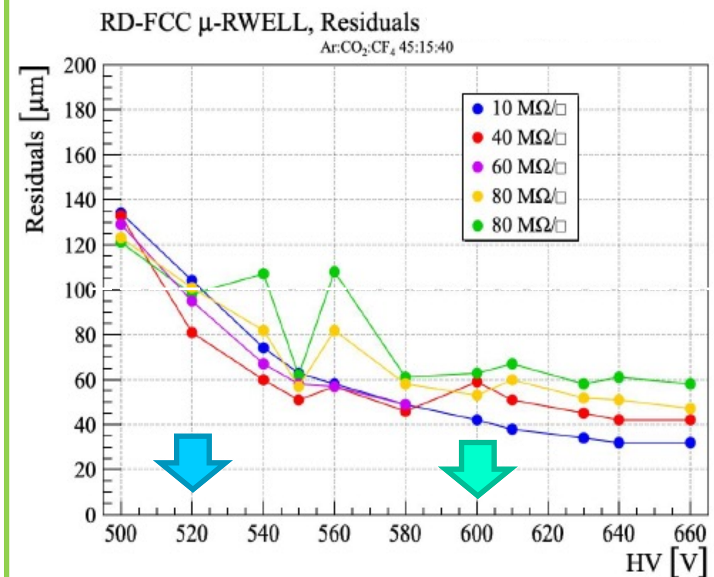
Muon chambers:

- ✓ Efficiency > 98%
- ✓ Space Resolution < 400 μm
- ✓ Pitch = ~1.5 mm
- ✓ Strip capacitance ~270 pF
- ✓ ~5 million channels
- ✓ FEE cost reduction —> custom ASIC
- ✓ Arranged in tiles 50x50 cm^2
- ✓ Mass production —> T.T.

μ-RWELL test beam results and technology transfer



A large eff. pleateau (> 100 V) measured



With a pitch 0.4 mm at HV=520 V and with CL=1.5 → σ < 100 um

Technology transfer with ELTOS/CERN: flow chart

INFN LNF - DDG Istituto Nazionale di Fisica Nucleare

Responsibility:
- Detector design (GERBER);
- Link with ELTOS
- Link with CERN-Rui
- Quality Control detector
- DLC Machine managment (>2023)

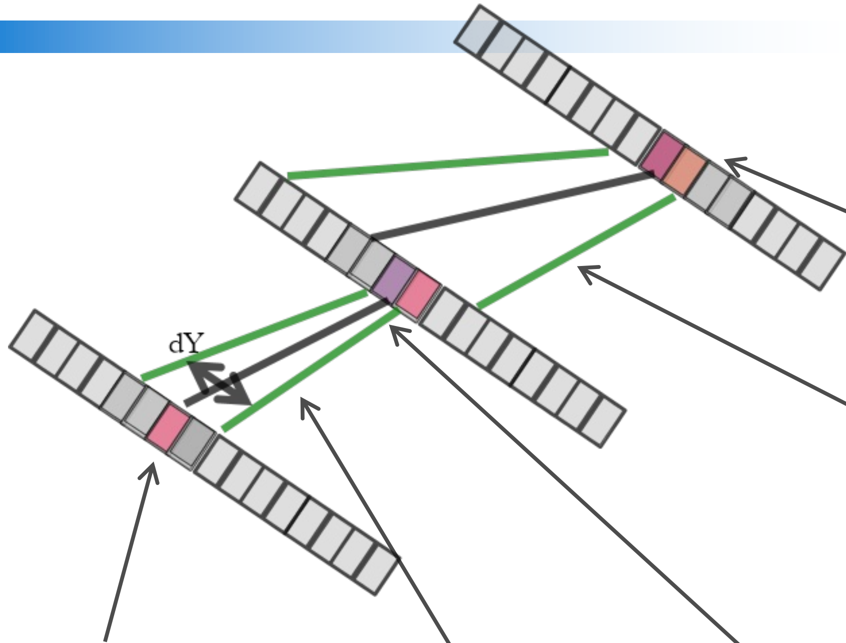
ELTOS

Responsibility:
- PCB RWELL production
- Cathode production
- DLC+PCB RWELL coupling

CERN

Responsibility:
- PCB RWELL finalization
- Hot Electrical Cleaning
- Detector closure

Basic principles of Kalman Filter (1)



parameter vector with error matrix
on the current plane
defined by angle and distance to origin

$$\eta_k^k = \left\{ y, z, \sin(\varphi), \tan(\lambda), \frac{1}{pt} \right\}$$

$$C_k^k = \langle \delta\eta\delta\eta \rangle$$

propagated to next plane

$$\eta_k^{k+1}, C_k^{k+1}$$

updated

propagated
(k+2)

select new hit by chisquare

$$\eta_{k+1}^{k+1}, C_{k+1}^{k+1}$$

Updated by weighted mean of
parameter vector and measurement

Some matrix formalism underlie, but meaning is simple:
recursive usual χ^2 averaging

Prediction

$$\bar{p}_{k|k-1} = \mathbf{F}_k \bar{p}_{k-1|k-1}$$

$$\mathbf{C}_{k|k-1} = \mathbf{F}_k \mathbf{C}_{k-1|k-1} \mathbf{F}_k^T + \mathbf{P}_k \mathbf{Q}_k \mathbf{P}_k^T$$

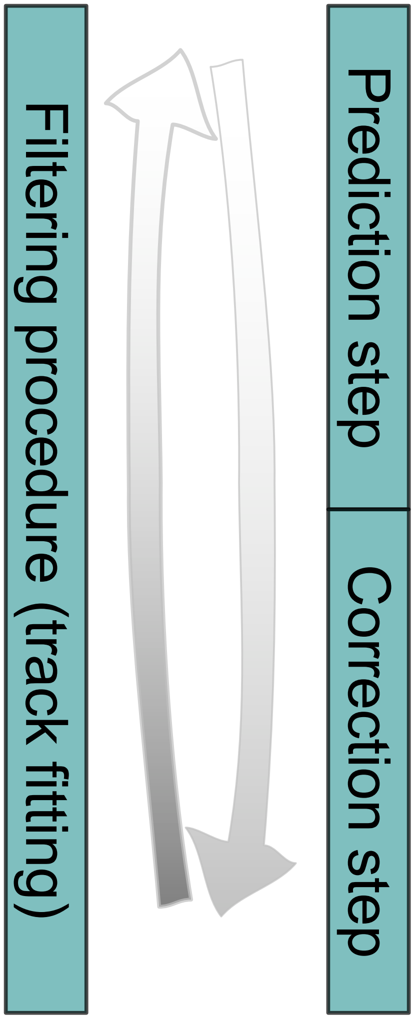
updated step

$$\bar{p}_{k|k} = \bar{p}_{k|k-1} + \mathbf{K}_k (\bar{x}_k - \mathbf{H}_k \bar{p}_{k|k-1})$$

$$\mathbf{K}_k = \mathbf{C}_{k|k-1} \mathbf{H}_k^T (\mathbf{V}_k + \mathbf{H}_k \mathbf{C}_{k|k-1} \mathbf{H}_k^T)^{-1}$$

$$\mathbf{C}_{k|k} = (\mathbf{I} - \mathbf{K}_k \mathbf{H}_k) \mathbf{C}_{k|k-1}$$

Basic principles of Kalman Filter (2)



with equation of motion $\frac{d\vec{v}}{ds} = \frac{kq}{p}\left(\vec{v} \times \vec{B}\right)$

and energy Loss $-\frac{dE}{dx}$

$\rightarrow \eta_k^{k+1}$

with transportation matrix $\frac{\partial \eta_k^{k+1}}{\partial \eta_k^k}$

multiple scattering, energy loss fluctuation

$\rightarrow C_k^{k+1}$

Updated by weighted mean of parameter vector and measurement

$$\eta_{k+1}^{k+1} = C_{k+1}^{k+1}\left[\left(C_k^{k+1}\right)^{-1}\eta_k^{k+1} + H^T V_k^{-1} m_k\right]$$

$$C_{k+1}^{k+1} = \left[\left(C_k^{k+1}\right)^{-1} + H^T V_k^{-1} H_k\right]^{-1}$$

$\rightarrow \eta_{k+1}^{k+1}$

$\rightarrow C_{k+1}^{k+1}$

m_k - measurement with errors = $V_k = \langle \delta m_k \delta m_k \rangle$

H - projection matrix from parameters to measurement

Variations of Kalman Filter

It can be some variations in implementation(most of them just matter of terminology for specific cases) or with extensions

SRKF – Square Root Kalman Filter:

Covariance matrix decompose in square root form
– can give numerical stability

Information Kalman Filter:

rewritten in form of inverse covariance matrix
- useful when some parameters can have infinite sigma

GSF – Gaussian-Sum Filter:

to deal with not gaussian fluctuations - instead of single Gaussian, pdfs modeled by mixture of Gaussians (implemented as a number of Kalman Filters run in parallel)

CKF - The Combinatorial Kalman Filter

Integrate track fitting and pattern recognition
– track splitted in case of few compatible hits

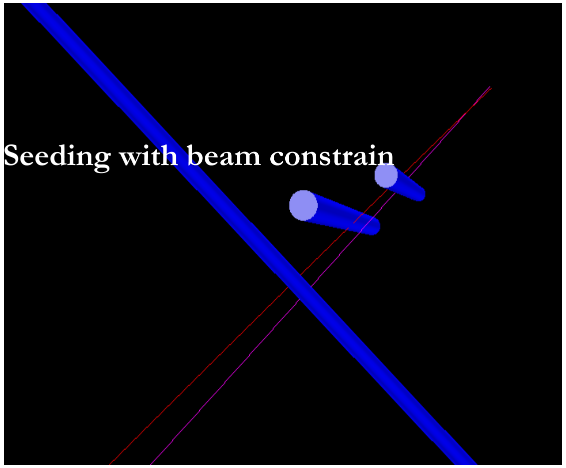
DAF – Deterministic Annealing Filter

On a same surface, several hits may compete for track with different weights
– good for outliers removal

Track finding – local method for DCH only

Seeding from 3 hits in different layers with origin constraint

- Take any 2 free hits from different stereo layers with a gap (4 or 6 layers)
- Cross Point of 2 wires give Z-coordinate
- Select nearest free hits at middle (+-1) layer
- 2 hits from same stereo layer give initial angle in Rphi
- origin added with sigma Rϕ~ 1mm Z ~ 1mm
- Seeds constructed for all 2x2x2=8 combination of Left-Right possibilities
- Checked that at -4 (+-1) layer are available free hits with $\chi^2 < 16$
- Extrapolate and assign any compatible hits (by χ^2) from last to first hits
- Refit segment to reduce beam constraint
- Check quality of track segment:
  - χ^2/NDF < 4
  - number of hits found (>=7)
  - number of shared hits (<0.4Nfound)



Large combinatory:
local compatibility over different layers,
+ 1 from different stereo view