Towards realistic digitization of silicon tracking detectors for the FCC

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FCC-ee Vertex Detector R&D Workshop
Pisa, Italy - 30 October 2025

Introduction : Full Simulation for FCC-ee detector concepts

A thorough simulation of the detector, capturing all its details, can offer valuable insights to guide the design and optimization process **at each development step**.

- **First ideas about an experiment :**
  - Given physics goals, what kind of detectors to build and what detector performance we need to achieve ?
    → Rough and quick simulations sufficient.
- **Detector concept(s) proposal :**
  - Need of detailed simulation showing physics performance of proposed detector(s).
  - Huge effort by the community to provide full simulation of the proposed concepts → We need this at this stage!
- **R&D and prototype (demonstrator) construction :**
  - Learn from R&D, beam tests, ... enables the improvement of simulation, make it more realistic

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Full simulation steps in a nutshell :

- **Generation :** Generators simulate the needed physics process.
- **Particle-detector interaction (Geant4)** : From detector geometry definition, It produces energy losses for each individual particle in all the crossed material of the detector.
- **Digitisation :** simulates the detector response from energy losses in active detector material
- **Reconstruction** : Track reconstruction uses primarily signals in the tracking detectors to measure tracks of particles.

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This talk

- **Reconstruction** : Track reconstruction uses primarily signals in the tracking detectors to measure tracks of particles.

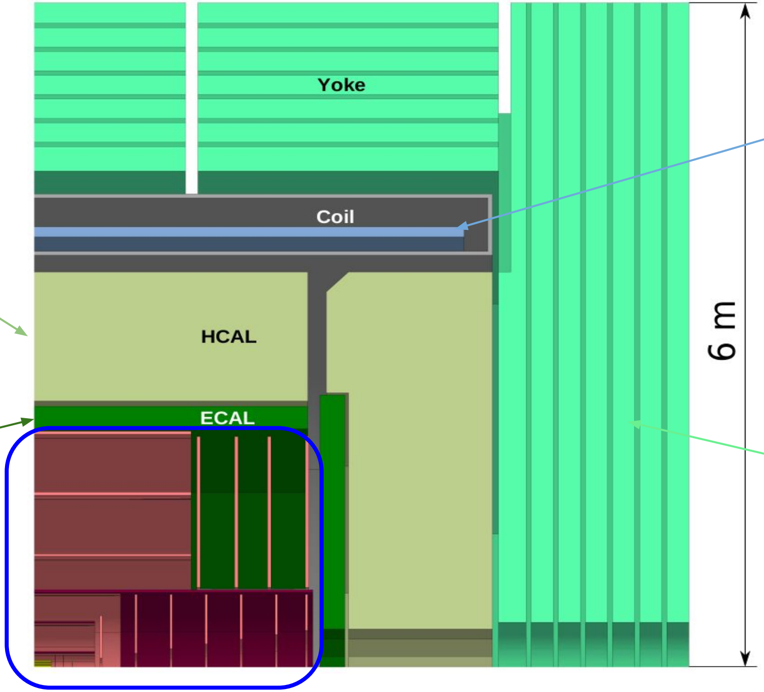
CLD Detector Concept as used in this work

- CLD = **CLIC-like detector** = one of the detector concept for FCC-ee
- General Layout close to CMS but different technology
- **All-Silicon** Vertex detector and Tracker immersed in 2T magnetic field

More details in :
CLD Detector Concept
and Armin Ilg Talk

Fe-Scintillator sandwich structure (44 layers) 3×3cm² cells

Si-W sandwich structure (40 layers) – 5×5mm² cells



SuperConducting 2T solenoid

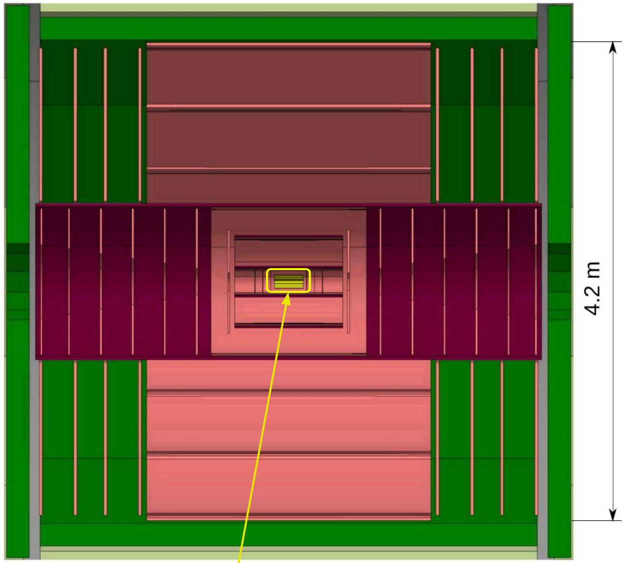
Yoke + Muon detector RPCs

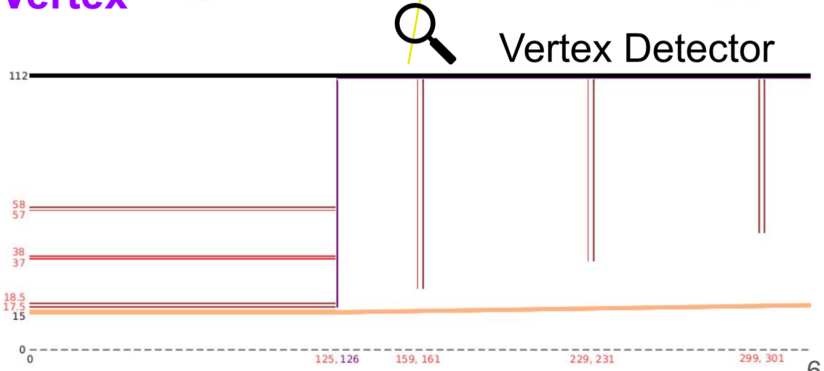
Vertex Detector and Tracker

CLD Detector Concept as used in this work

- CLD = **CLIC-like detector** = one of the detector concept for FCC-ee
- General Layout close to CMS but different technology
- **All-Silicon** Vertex detector and Tracker immersed in 2T magnetic field
  - **Vertex detector**
    - 3 double-layers barrel + 3 double-disks Endcaps
    - **20×20 μm^2** monolithic silicon pixels **MAPS** – 50 μm thick **(only 10 μm active area)**
    - Goal : 3 μm resolution on single hits
  - **Tracker**
    - **Inner** : 3 barrel layers + 7 disks (in petals)
    - **Outer** : 3 barrel layers + 4 disks (in petals)
    - Silicon strips with 50 μm pitch (300 μm length)
      Except first inner disk : 50×50 μm^2 pixel
    - 7×90 μm resolution (resp. 5×5 μm)
  - Material Budget : 1.1-2.2%X_0 per layer

Today : Focus in Vertex





Detailed tracking digitizer

Geant4 Simulation

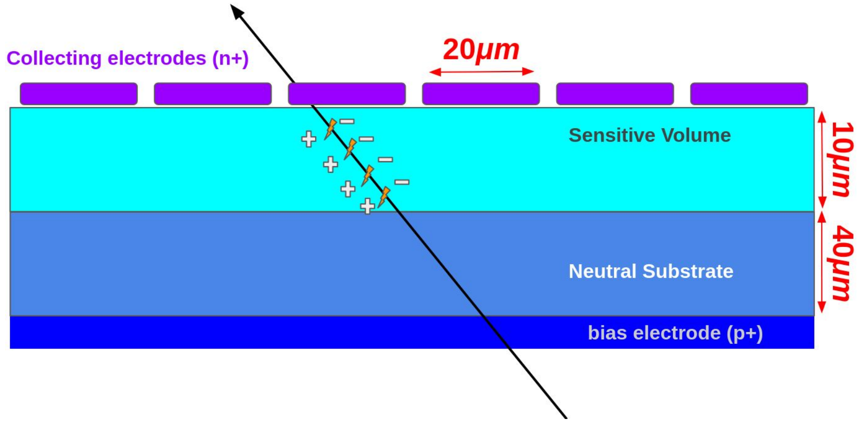
SimTrackerHit

Primary Ionisation → Drift Charges → Evaluate charge per pixel → Electronics Response → Clusterize

TrackerHitPlane

Reconstruction

- Geant4 gives the path of the particle, the deposited energy, and hit position and time
- The path of the particle in sensitive area is **divided into segments**
- **The energy** deposited in the sensitive area (given by Geant4) **is divided uniformly** into each segment and converted into **number of electrons**



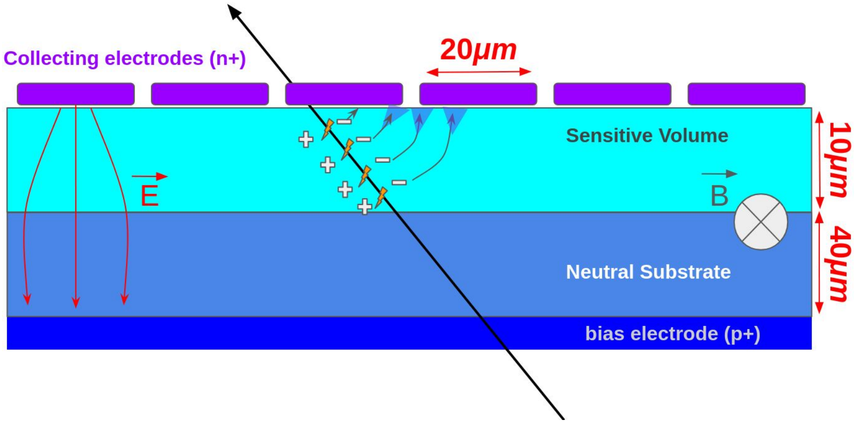
Detailed tracking digitizer

Geant4 Simulation → SimTrackerHit → **Primary Ionisation** → **Drift Charges** → **Evaluate charge per pixel** → **Electronics Response** → **Clusterize** → TrackerHitPlane → **Reconstruction**

- **Drift each charge** in the depletion area according to magnetic and electric fields + **Consider thermal diffusion**

- The **electromagnetic drift** direction is considered from **Lorentz angle** (set to 0.1 per Tesla currently).
  - $\tan(\theta_{Lorentz})/B = 0.1$ (from CMS simulation)
  - E field considered uniform

- **Thermal diffusion** is considered by creating a charge cloud with a width depending on the path distance of the charges
  - Considered as reference a diffusion (σ_50) for 50µm path with σ_50=1.51μm (taken from CMS digitizer)



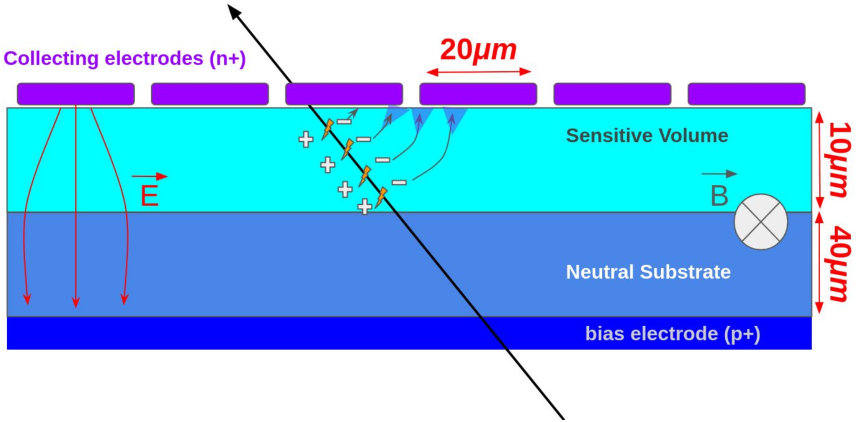
Detailed tracking digitizer

Geant4 Simulation → SimTrackerHit → Primary Ionisation → Drift Charges → **Evaluate charge per pixel** → **Electronics Response** → Clusterize → TrackerHitPlane → **Reconstruction**

- **Deduce the energy deposited in each pixel**/strip
  - Numerical integration over the charge cloud
  - Protection not to consider pixels outside the sensors

- Consider the **electronics response (only Threshold for now)**
  - Threshold value = 100 e- applied to each pixel

- **Up to do** :
  - Electronics noise
  - Radiation damage/ageing
  - Consider Signal Shape (notably for timing)
  - etc



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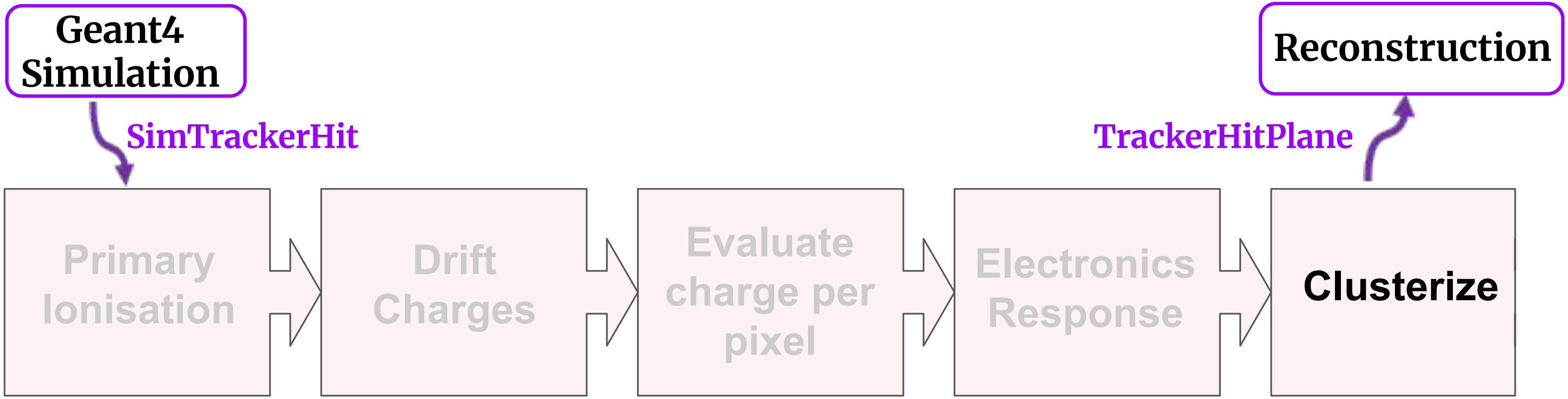
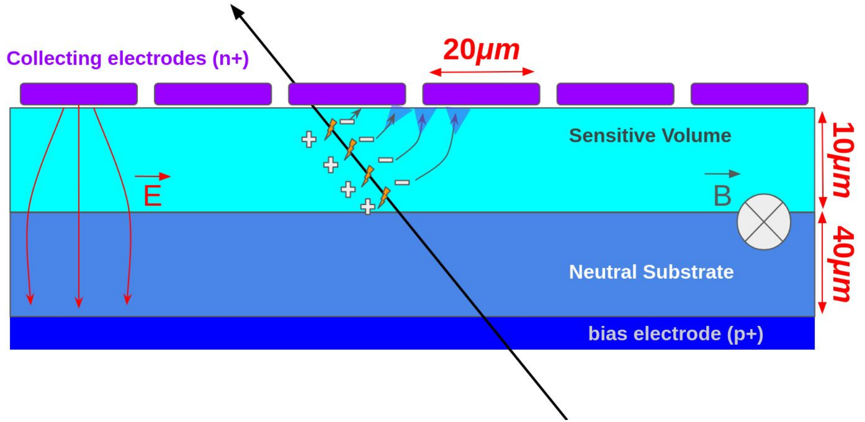


- **Clusterization**
  - Get central position of the clusters with a **weighted average**
  - Translate back the total charge in energy

- Return a TrackerHitPlane to reconstruction containing, per hit:
  - Position + uncertainty
  - Time + uncertainty
  - Total recorded energy



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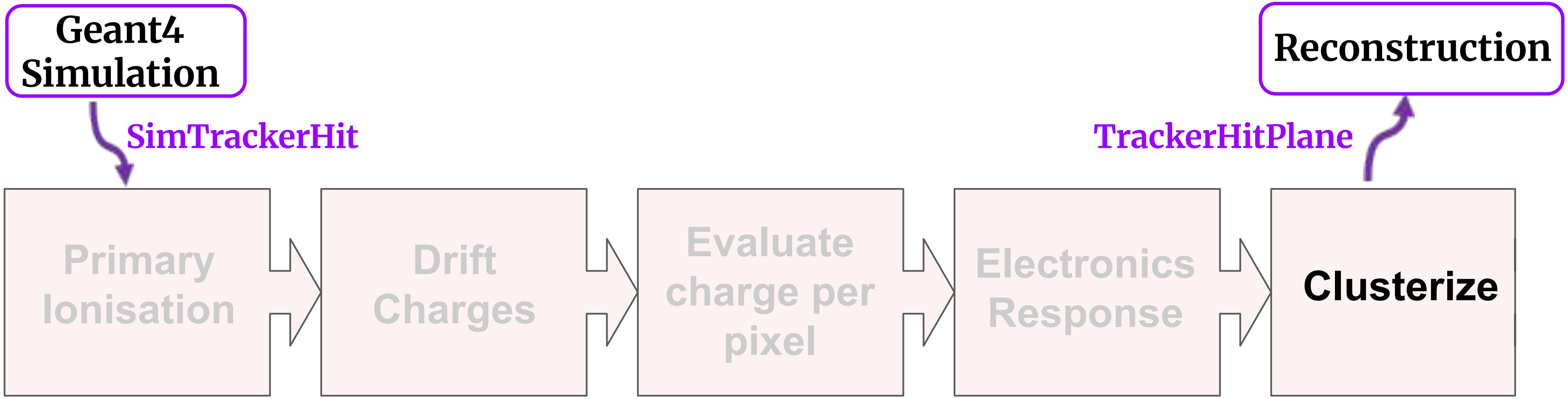

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All Steps are done (but the timing) +Realistic parameters (pixels sizes, threshold, Lorentz Angle, etc) have been discussed with experts from IPHC

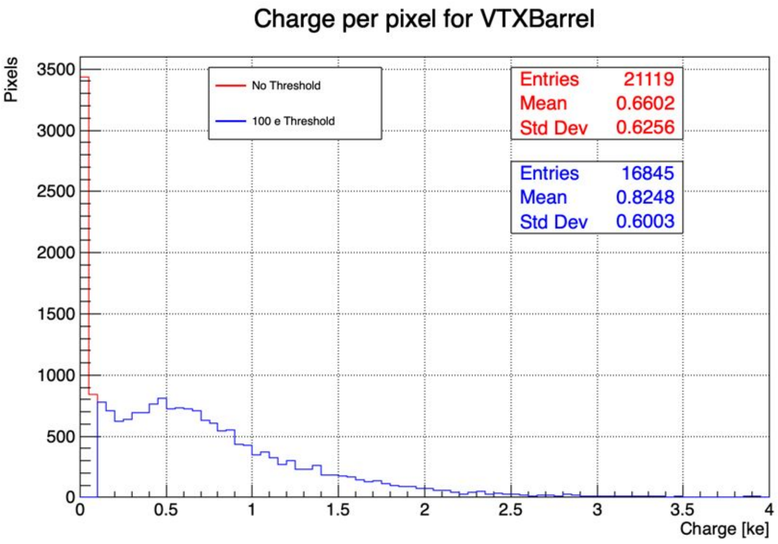
Some results : Pixels and Clusters

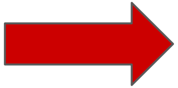
A test have been runned with **2000 muons generated with a 10 GeV energy**

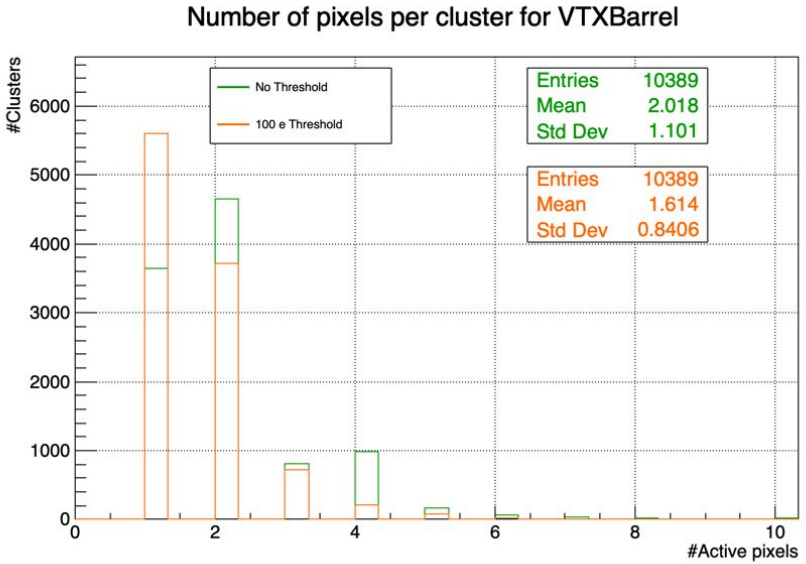
Test the energy per pixel and the number of pixels per cluster : example of VTX Barrel.

→ Before Threshold : ~66 e-/μm, consistent with expectation [2011 JINST 6 P06013]

→ Number of pixels reduced by 20% by threshold
→ Number of clusters stays stable 👍







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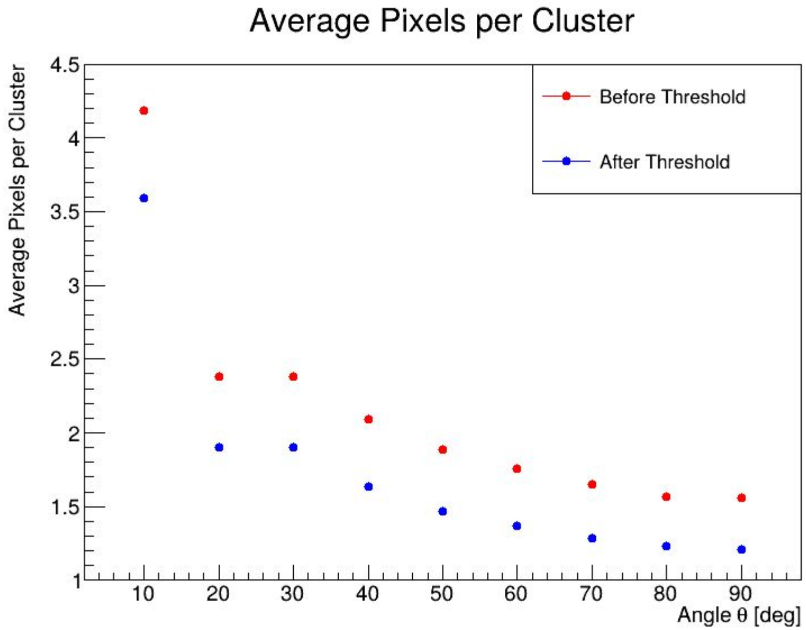
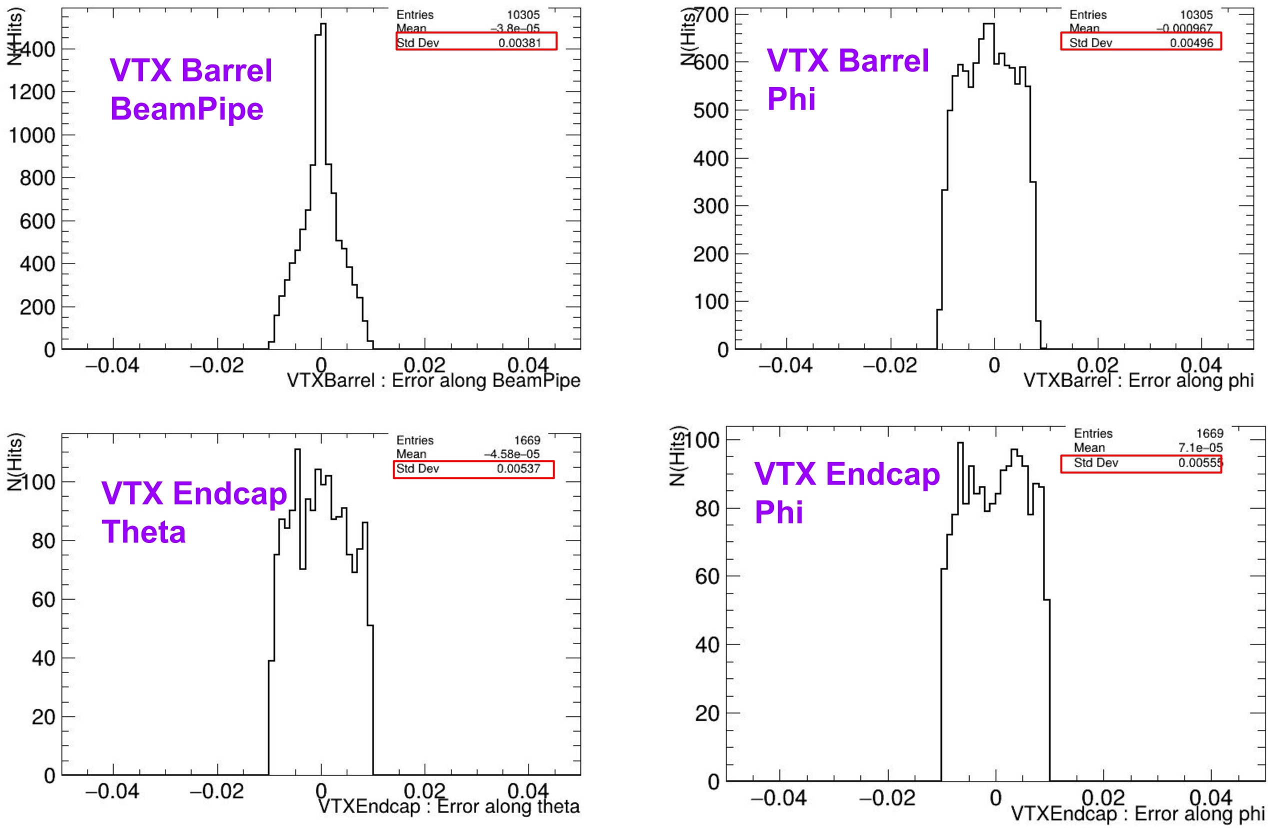
→ As expected, the number of activated pixels decreases at larger angle



Some results : Resolution

A test have been runned with **2000 muons generated with a 10 GeV energy**

Test the distance between the real hit and digitized one, example of Vertex Tracker :



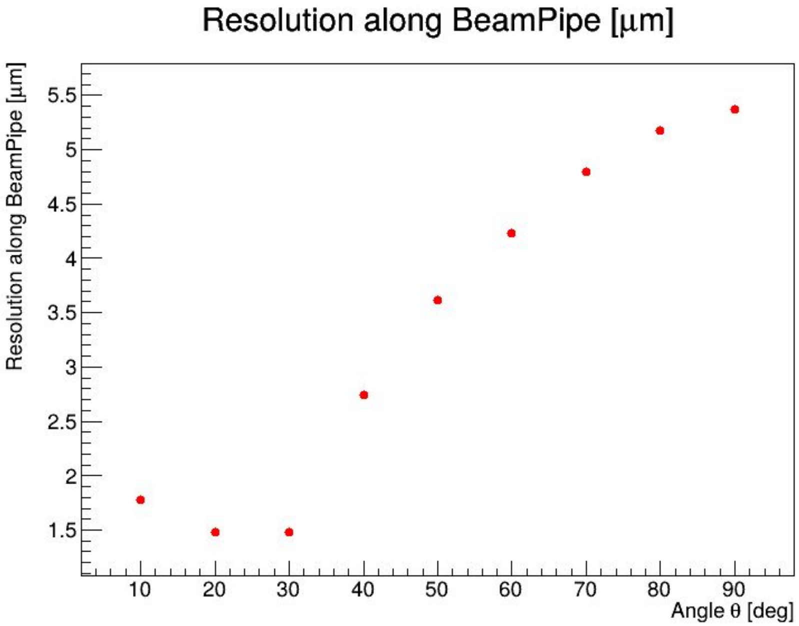
→ Barrel : Single hit resolution of **~3.8*μm*** along beampipe and ~**5.0*μm*** orthogonal→Do not reach the 3*μm* goal
→ A shift of ~1μm along ϕ
= Compatible with charge drift in magnetic field !

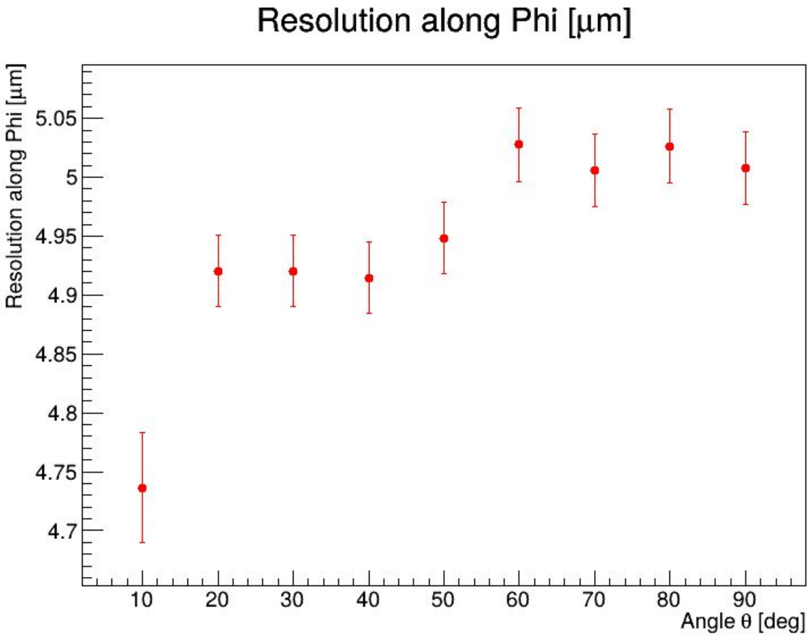
→ Encap : **~5.5*μm*** single hit resolution→Do not reach the 3*μm* goal

Some results : Resolution vs theta

→ We test here the behaviour of the vertex barrel as a function of the particle angle

→ As expected, the number of activated pixels decreases at larger angle → The resolution is then dependent on the angle





→ While the resolution along Z is dependent on the track pseudo-rapidity, the resolution along phi is not, resulting on a asymmetric resolution which were not taken into account by a simple resolution parameterization

Summary

- The **complete simulation** of the detector in all its details is a **key element** to :
  - Derive **realistic performance** studies
  - Guide the **choice between various detector** designs
  - **Optimise layouts**
  - Provide **realistic rates** (Support the electronics R&D)
- **The new detailled digitizer is under development within the Key4Hep framework** and **can later be used for other future detectors** with silicon pixels or silicon micro-strips
- **First version of the digitizer proposed to be implemented in FCCSW (under Merge Request)**
  - Thanks a lot to Brieuc François and the CERN PED software group for invaluable help
- First **results are promising**
- Can be used to **get tracking performances, background studies, etc**
- This digitizer will be improved and tested on other detector concept geometries (SEED, etc)

Thank you for your attention !

FUTURE
CIRCULAR
COLLIDER

BACKUP

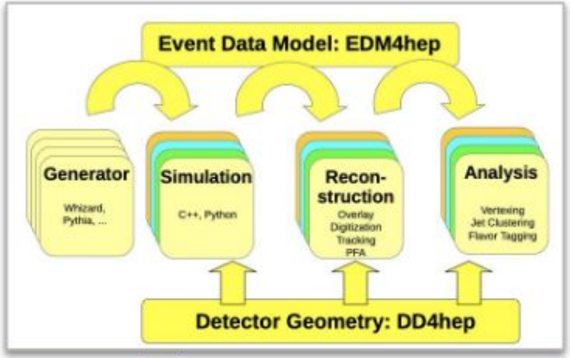
FCC SW : Key4HEP

-> Slide from Brieuc François at FCC workshop

Key4hep, the common software vision

FCC software is part and parcel of **Key4hep**

- Common software initiative created in 2019 to **optimise efforts** in the context of **future colliders studies**
  - Based on the belief that **software commonality between future experiments can be pushed further** than it was so far at LHC
  - **Unify communities**, contributions from CLIC, ILC, FCC, CEPC, EIC, ...
  - Aim at providing a **complete set of tools** supporting generation, simulation, reconstruction, analysis



Current ingredients based on what was available in experiment-free way in 2019

- **Spack** package manager
- **Gaudi** framework, devel/used for (HL-)LHC
- **DD4hep** for geometry, adopted at LHC
- Podio based **EDM4hep** data model

Having common building blocks is a must to leverage synergies and facilitates data openness and preservation!

Opportunities ahead

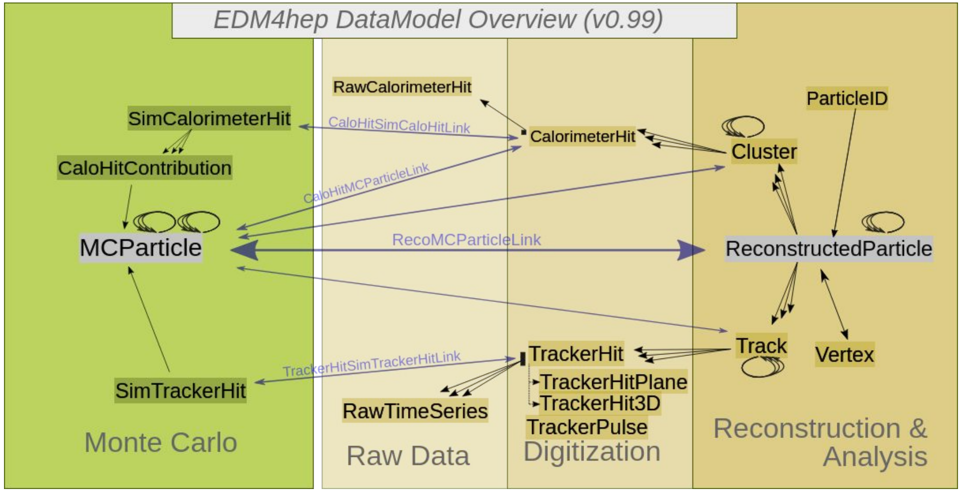
- Multi-threading
- Framework homogenization
- Keep assessing choices made so far
- Monitor and incorporate emerging tools
- ...

Nothing is written in stone! Things can be changed (minimizing disruption)

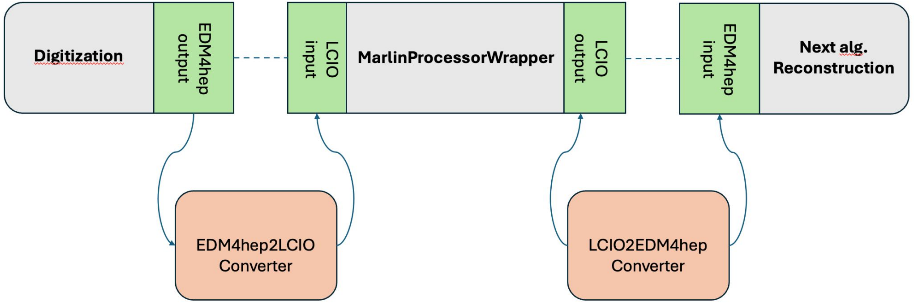
Deliverables already used in large scale productions

The event DATA model : EDM4hep

- **Common language** that all components speak in Key4Hep
- Classes for physics objects like *MCParticle*, with **relations** to other objects
- **Links** between objects
- Objects are grouped in **collections** like *MCParticleCollection*
- **PODIO**(Plain Old Data IO) used to generate EDM4hep code



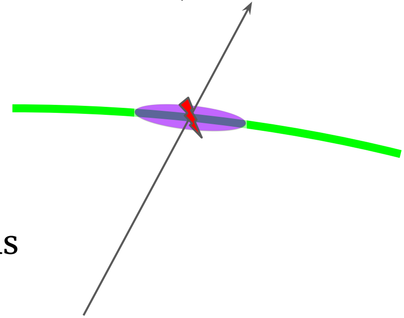
Difficulties in combining algos from several experiments, in particular ILC (LCIO-based Marlin software) :
-> **MarlinWrapper** to use ILC SW processors within EDM4HEP
-> LCIO ↔ EDM4HEP **Converters**



General Ideas for digitizer and previous digitizer version

- **In CLD : Pixel vertex detector and silicon Tracker treated as unified tracking system in simulation and reconstruction**

- **The digitizer**
  - Takes as input an EDM4Hep format SimTrackerHit given by Geant4
  - **Simulates the detector response from energy losses in the active detector material**
  - Returns a TrackerHitPlaneCollection= Collection of digitized hits (position, resolution and time), to be used by track reconstruction algorithm

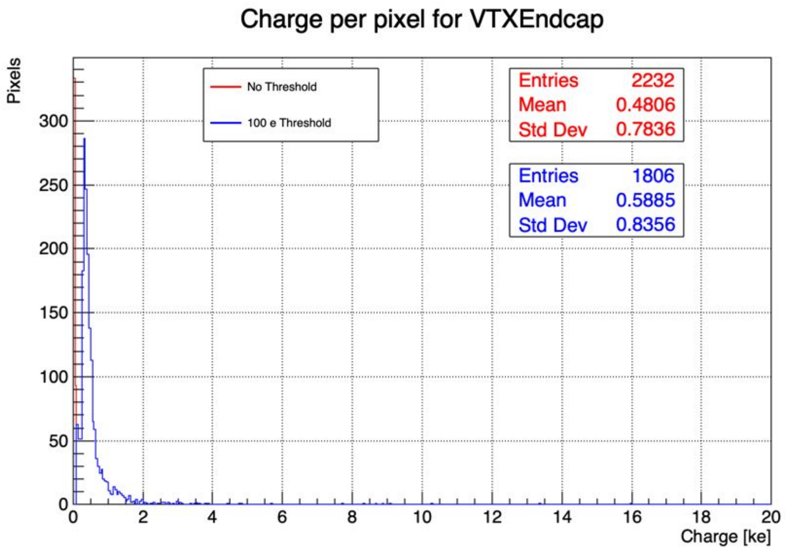


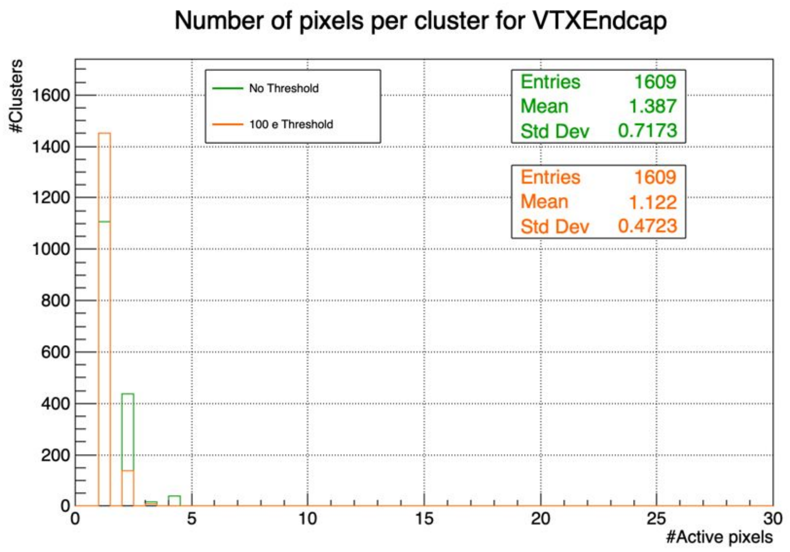
- **Previous version :**
  - Digitisation using **ILC soft** (Marlin)
  - Did a simple **smearing of the hit position and time** according to expected resolutions

- **Goals** : Create more realistic digitizer **within k4Hep software (Get rid of Marlin Wrapper)**
  - **Consider fully simulated charge production, propagation/diffusion and collection**
  - The digitizer is so far developed **using the CLD detector concept**
    → The goal is to be as agnostic as possible of the geometry description and environment
  - New method should stay **generic for any sensor geometry** (pixels, strips)
  - Do a modular software to ease extensions (to include background, variations in energy deposit, etc)

Some Preliminary results : Pixels and Clusters

Test the energy per pixel and the number of pixels per cluster : example of VTX Endcap.





Some Preliminary results : Occupancy

This is just a test plot, no real physics as a muon particle gun is used (not real events)