Full simulation of the FCC-ee tracker: progress in the Digitisation

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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 ?
    → Need rough and quick simulations.
- **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

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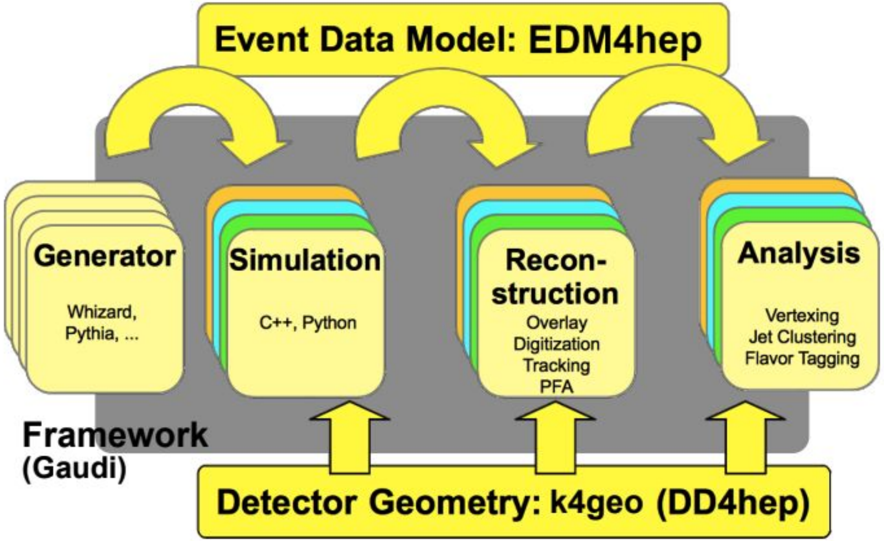
Towards a Turnkey Software Stack :

- **Software initiative** created in **2019** to optimise efforts in the context of **future colliders studies**.
  ⇒ Aims to **connect** and **extend** the individual packages towards a **complete data processing framework**

❖ **Common effort** from FCC, CLIC/ILC, EIC, CEPC, Muon Collider....
  ➢ **Preserves** and **adds** existing functionality from iLCSoft, FCCSW, CPECSW...
  ➢ **Builds on top of the experience** from LHC and **results of R&D**

❖ Having **common building blocks** enables **synergies** across **future collider communities**



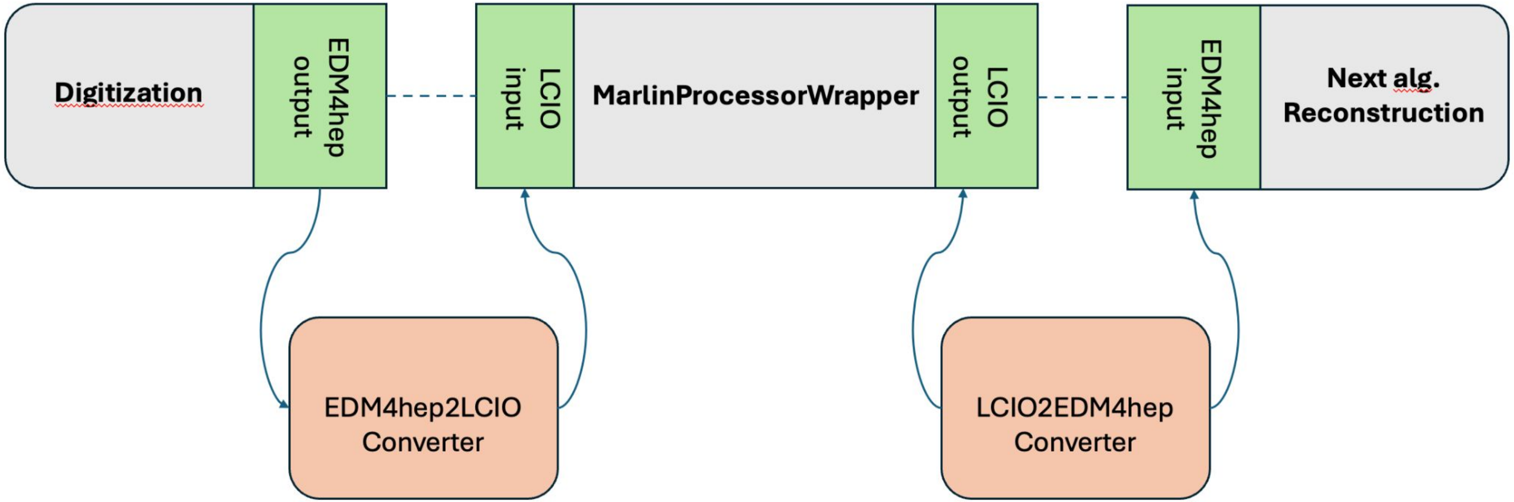
★ **Main ingredients :**
- **Event data model : EDM4hep**, based on **PODIO, AIDA** project
- **Event processing framework : Gaudi**, used in LHCb, ATLAS...
- **Detector description : DD4hep, AIDA** project
- **Package Manager : Spack**

Nothing is written in stone, **opportunities ahead** :
⇒ **Multithreading**
⇒ **Framework homogenization**
⇒ .....

Difficulties in combining algos from several experiments, in particular ILC (LCIO-based Marlin software) :

-> MarlinWrapper to use ILC SW processors within EDM4HEP

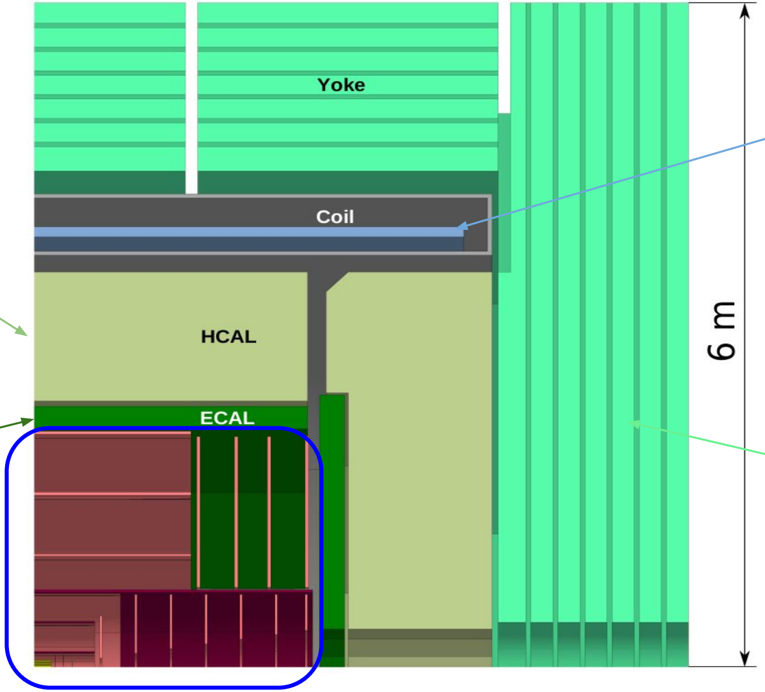
-> LCIO ↔ EDM4HEP Converters



CLD Detector Concept

- 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



Fe-Scintillator sandwich structure (44 layers) 3×3cm^2 cells

Si-W sandwich structure (40 layers) – 5×5mm^2 cells

SuperConducting 2T solenoid

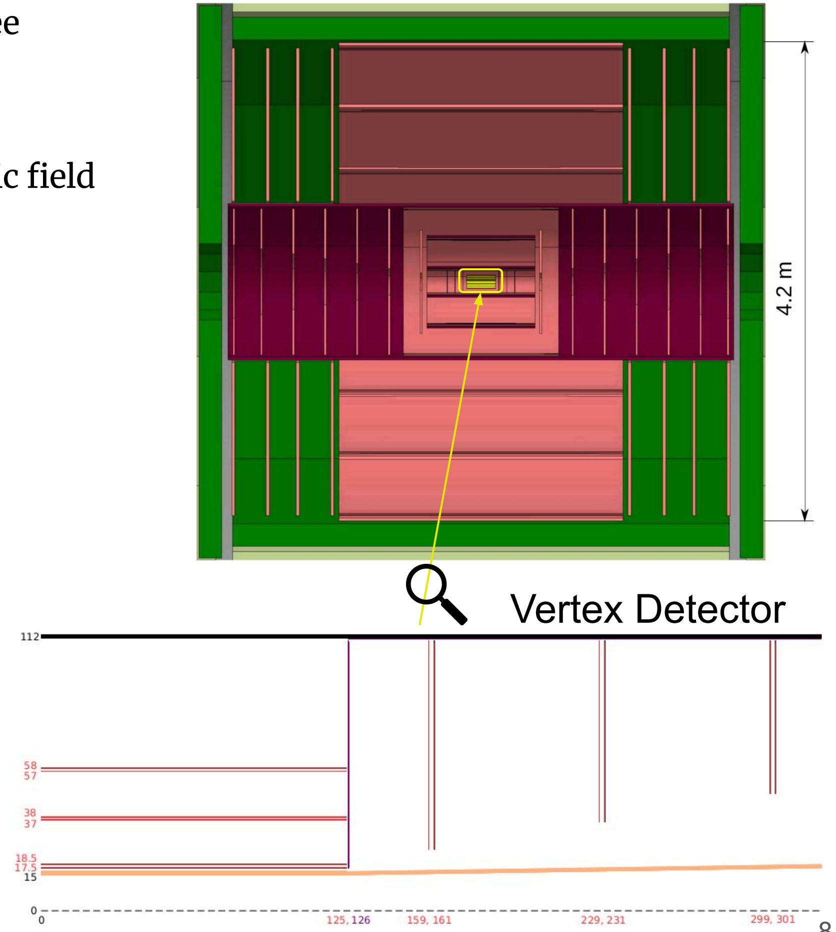
Yoke + Muon detector RPCs

Vertex Detector and Tracker

CLD Detector Concept

- 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
    - 25×25 μm^2 monolithic silicon pixels – 50 μm thick
    - <u>Goal</u> : 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



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

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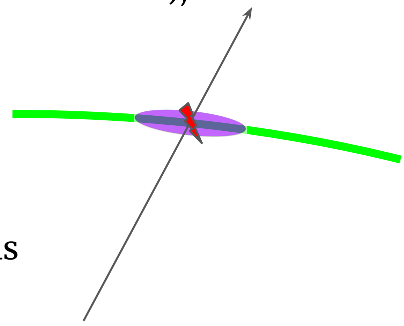

- **Previous version :**
  - Digitisation using **ILC soft** (Marlin)
  - Did a simple **smearing of the hit position and time** according to expected resolutions

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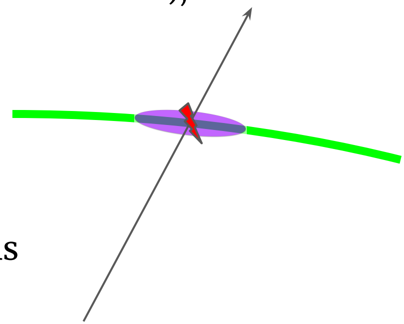

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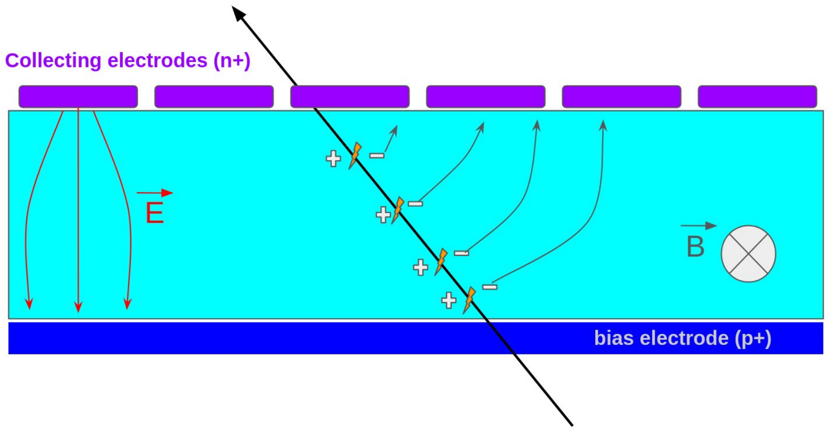
  - Digitisation using **ILC soft** (Marlin)
  - Did a simple **smearing of the hit position and time** according to expected resolutions

- **<u>Goals</u>** : 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)

Detailed tracking digitizer

- <u>Strategy for new digitizer</u> **inspired by CMS digitizer (work in progress...) :**
    - **Set primary ionisation** : divide particle path in segments and deposit energy (charges) in each segment
    - **Drift each charge** in the depletion area according to magnetic and electric fields (2nd order Lorentz force used) + **Consider diffusion** (the charge is expanded to a 2D Gaussian cloud)
    - **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** (Thresholds, signal shape, noise, radiation damage, etc) — In a second phase
    - **Clusterize and fit** the central position of the hit and resolution (**for now weighted average**)
    - Return the hit collection to the next step (Tracks reconstruction) as a EDM4HEP **TrackerHitPlaneCollection**
    - ***<u>Note</u>*** : must find a way to consider time

All Steps are done (but the timing)
Caveat : Realistic Parameters should be however better defined



Detailed tracking digitizer : Technical Implementation

- **What has been done so far :**
  - Sensor pixels were not considered -> Pixels segmentation has been added **to the DD4Hep geometry** (necessary to get the charge per pixel and do a proper clusterisation)
  - **Creation of** a new class VTXDigitizerDetailed according to previous slide description:
    - Can be used for whether the vertex detector or tracker (Inner/Outer)
    - **First simple version implemented without considering time (still simple time smearing)**
    - Note **:** Parameters for diffusion and mobility are currently taken as default from CMS

      → Need to adapt for MAPS or other type of sensors
  - CLDConfiguration adapted **to use VTXDigitizerDetailed** instead of Marlin digitizer and **use a EDM4Hep->LCIO converter** on VTXDigitizer output for compatibility with Marlin reconstruction

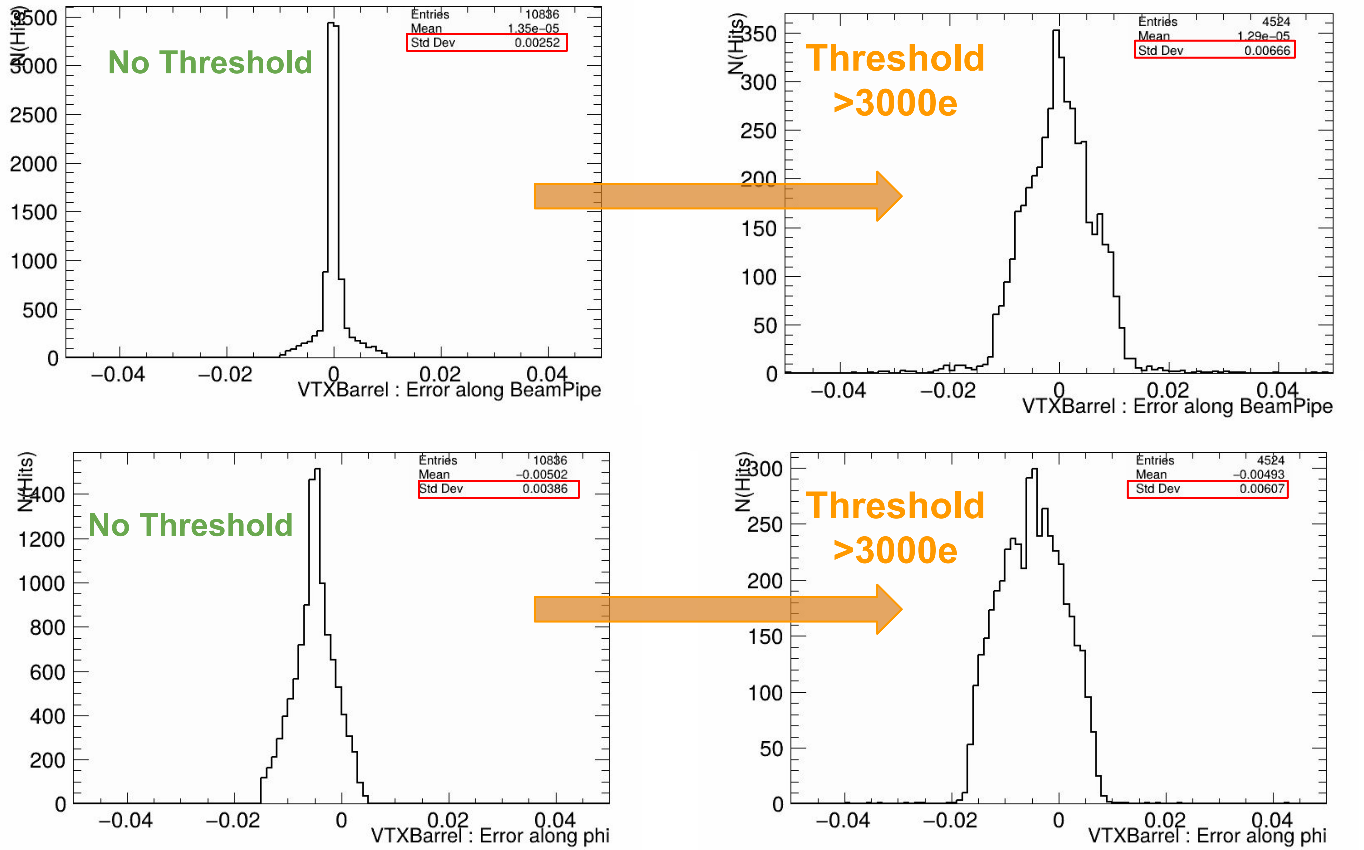
- Next Steps :
  - Consider **time** (through signal shape ?)
  - **Adapt parameters** to real sensors (Geometry, mobility, diffusion, thresholds, etc)
  - Consider electronics **noise and/or radiation damage**
  - Develop a fancier clusterizer

Some Preliminary results : Barrel resolution

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

VTX Barrel

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



→ Without threshold : Single hit resolution of **~2.5µm** along beampipe and **3.8µm** orthogonal, **close to the expected 3µm**

→ **With threshold : worse spatial resolution** → should consider this in threshold parameterisation !

→ A shift of ~5.5µm along ϕ
-> Compatible with charge drift in magnetic field !

Some Preliminary results : Endcap resolution

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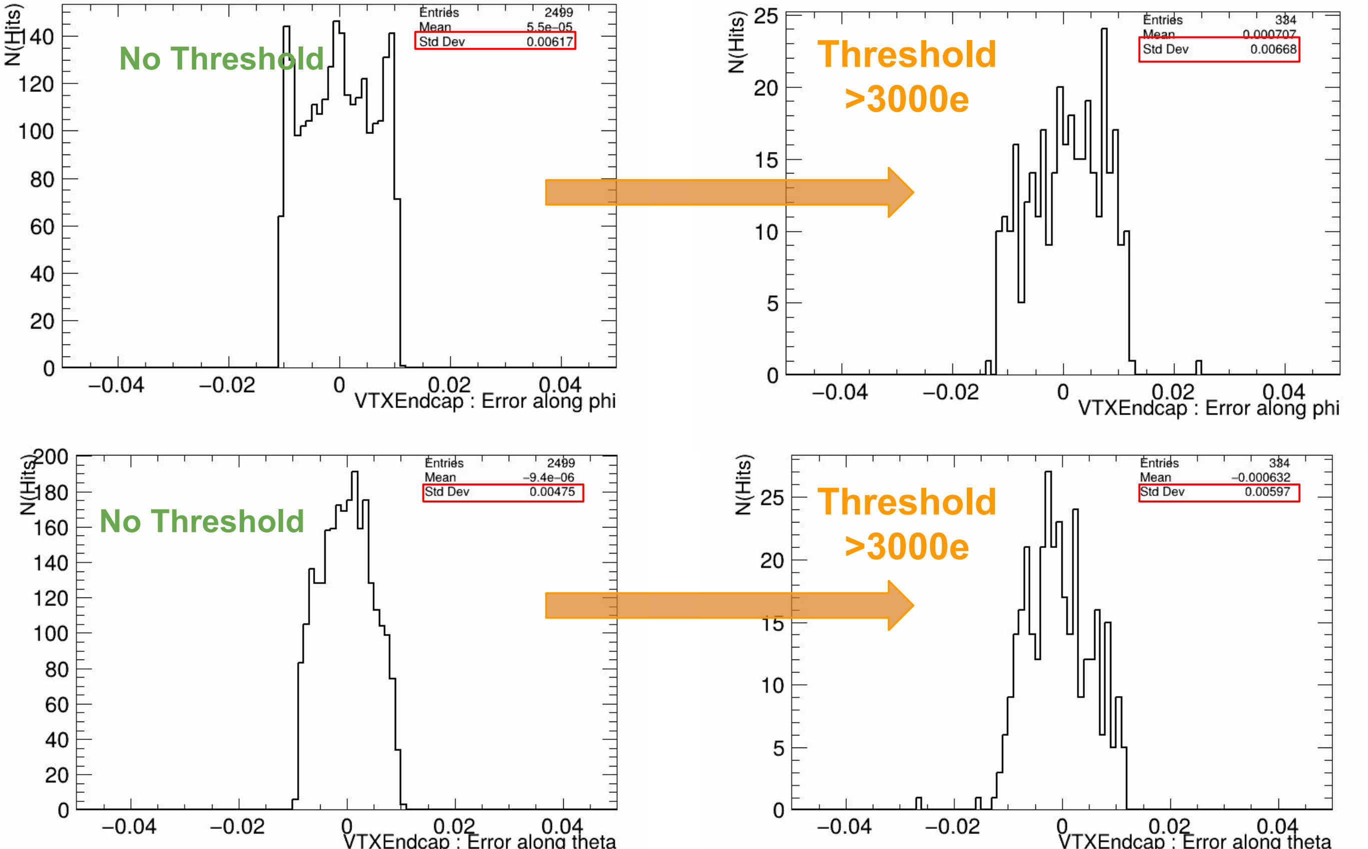
VTX
ENDCAP

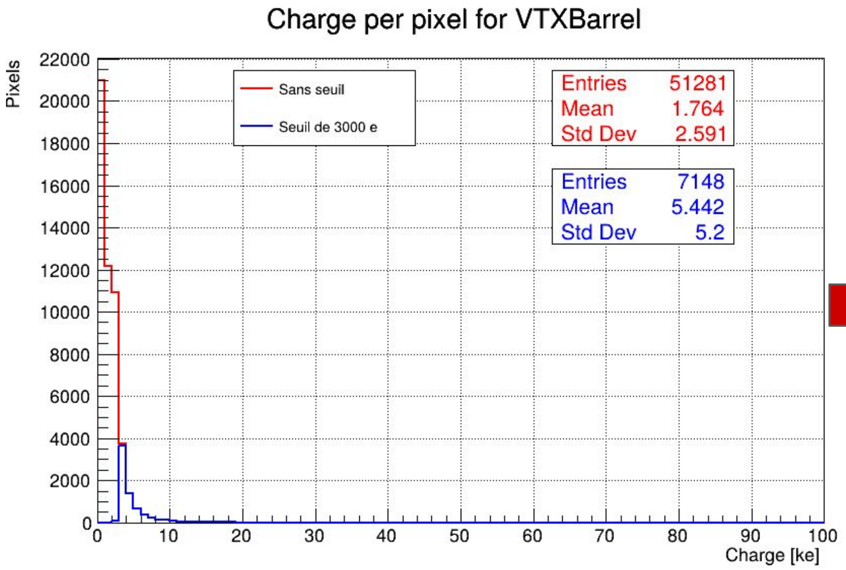


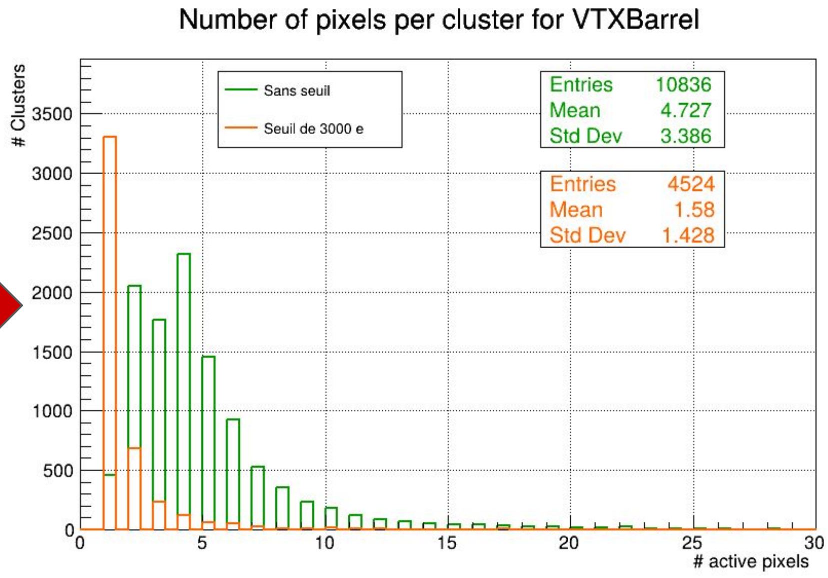
→ Without threshold : Single hit resolution of **~6.2µm** along ϕ and **4.8µm** along ϑ, **close to the expected 3µm**

→ **With threshold : a bit worse spatial resolution** → should consider this in threshold parameterisation !

Some Preliminary results : Pixels and Clusters

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





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)
- A general strategy for digitizer has been thought about, based on what has been done in CMS
- **The new digitizer is under development within the Key4Hep framework** for full compatibility with EDM4Hep data format 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**
  - Thanks a lot to Brieuc François and the CERN PED software group for invaluable help
- First **results promising** and need additional studies
- Will be used to **get tracking performances using tools from Strasbourg group**
- **Should also test this digitizer for other detector concept geometries !**

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FUTURE CIRCULAR COLLIDER

BACKUP

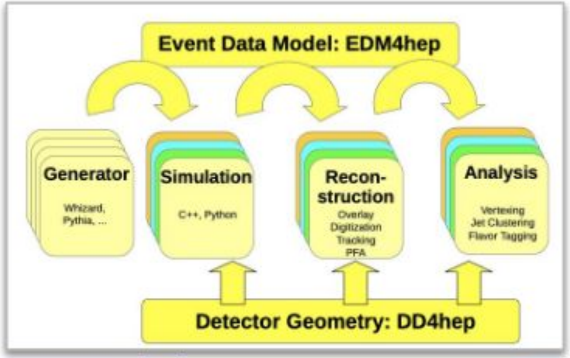
FCC SW : Key4HEP

-> 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!

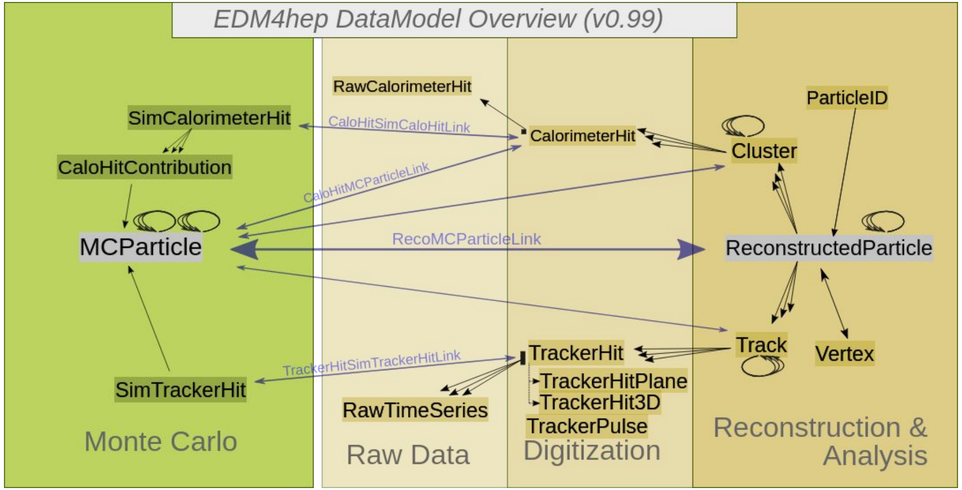
Opportunities ahead
- Multi-threading
- Framework homogenization
- Keep assessing choices made so far
- Monitor and incorporate emerging tools
- ...

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



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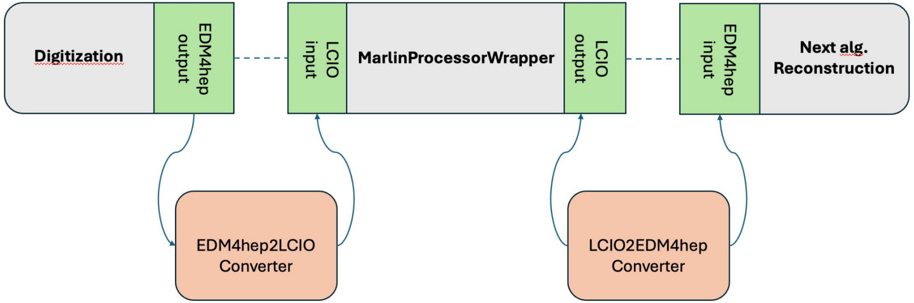
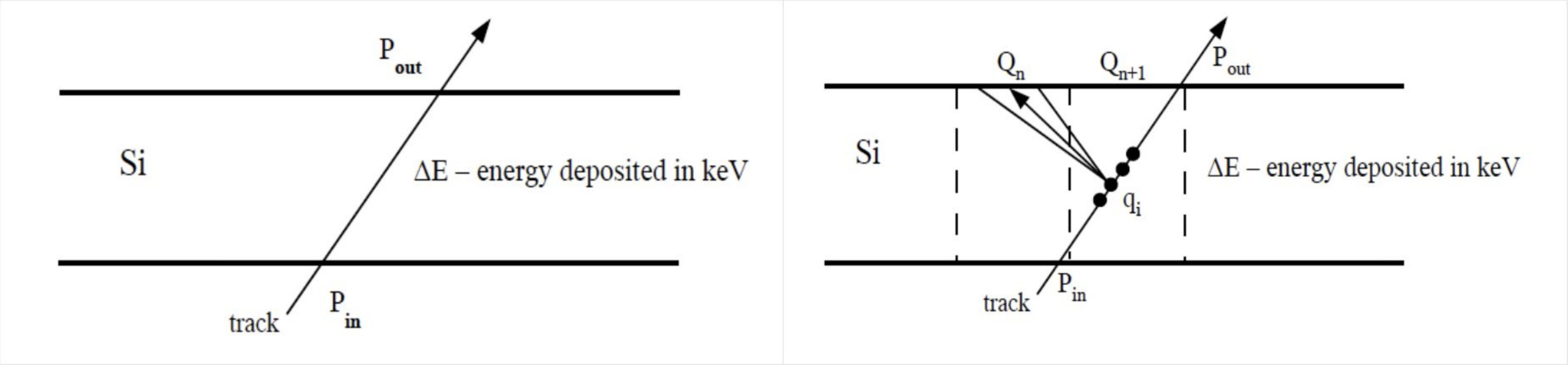


CMS pixel digitizer

- The Pixel digitizer **reads the collection of SimHit** and **writes a collection of Pixel Digi and a collection of links between digi and simhits**.
  - **From Geant-4 simulations we get for each track so called SimHits**: the entrance and exit points and the deposited energy in keV (ΔE).
  - **Only the pixel detector geometry is needed to obtain this.**
  - The pixel digitizer knows **the pixel pitch, signal thresholds, ADC bits, noise, ...**

- The process can logically be split into the **sensor response** and the **readout chip response**, which is also reflected in the structure of the code.



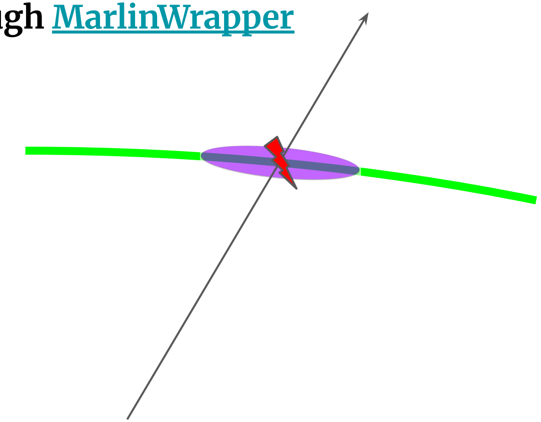
Current status and goals

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

- **Current Status :**
    - Digitization in MarlinTrkProcessor (**from ILC soft**)
        - Input : hit position and time given by Geant4 (EDM4Hep format SimTrackerHit)
        - Output : TrackerHitPlaneCollection = Collection of digitized hits (position, resolution and time)
        - Process : DDPlanarDigiProcessor does a simple **smearing of the hit position and time** according to expected resolutions
        - **Marlin script integrated in EDM4Hep Gaudi based workflow through MarlinWrapper**

    - Existing first version of digitizer within k4RecTracker (VTXDigitizer)
        - **Get rid of Marlin Wrapper** (good data format)
        - Currently not used in CLD Configuration
        - **Problem : Uses the same smearing method**

    Note : DDPlanarDigi also exists in Key4Hep in k4Reco repository



- **Goals** : Create more realistic digitizer **within k4Hep software**
    - **Consider charge production and propagation/diffusion**
    - To be used in other detector concepts with silicon sensors
    - New method should stay **generic for any sensor geometry** (pixels, strips)
    - Should consider **time resolution** too