FCC-ee Tracker Full Simulation : Detailed Vertex Digitization Studies and Outlook

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- **Context and Motivation**
- CLD Detector Concept and All Silicon tracker
- Silicon sensor digitization: Our Module *VTXDigiDetailed*
- Tracking Performance and validation against the parametric reference

Introduction - Full Simulation for FCC-ee

❖ **Motivation for a Precise Digitiser** :

- ➢ **From Ideal to Real**: We need to simulate realistic detector response to validate model capabilities
- ➢ **Physics Scope:** Essential for studying detector performance in high-occupancy environments
- ➢ **Broader Integration**: To build a robust, parameter-based tool that can easily be adapted to test other detector geometries

❖ **From Software R&D**:

- ➢ **New *VTXdigiDetailed* Module**: Developed by IP2I team (**MR**, officially merged) and previously presented by Jessy Daniel (9th FCC Physcis Workshop 2026)

❖ **To Physics & Performance Validation**:

- ➢ **Objective**: Transition from idealized parametric smearing to a physics-driven response (Integrated in key4hep)
- ➢ **R&D Feedback Loop**

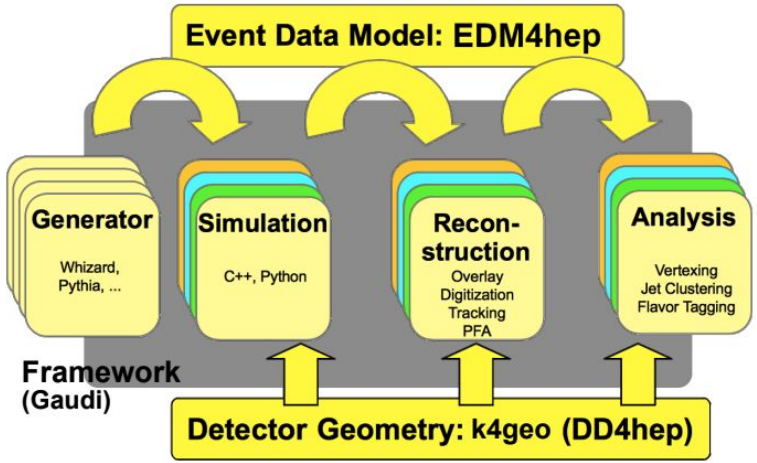
Introduction - Key4Hep framework

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**

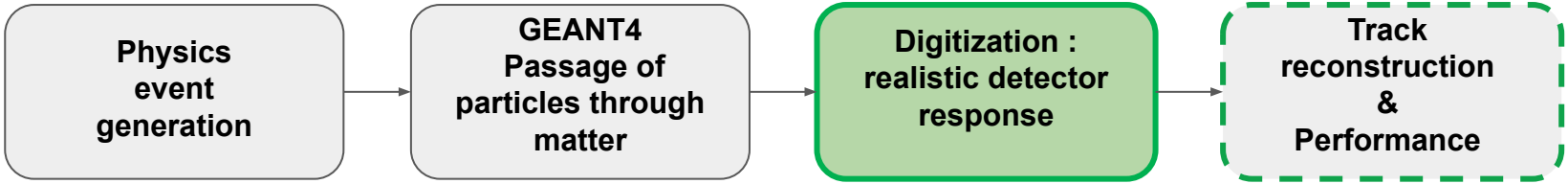
❖ **Common effort** from FCC, CLIC/ILC, EIC, CEPC, Muon Collider etc.
- ➢ **Preserves** and **adds** existing functionality from iLCSoft, FCCSW, CPECSW…
- ➢ **Builds on top of the experience** from LHC and **results of R&D**

❖ Having **common building blocks** enables **synergies** across f**uture 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**

➢ Diagram of the full simulation chain



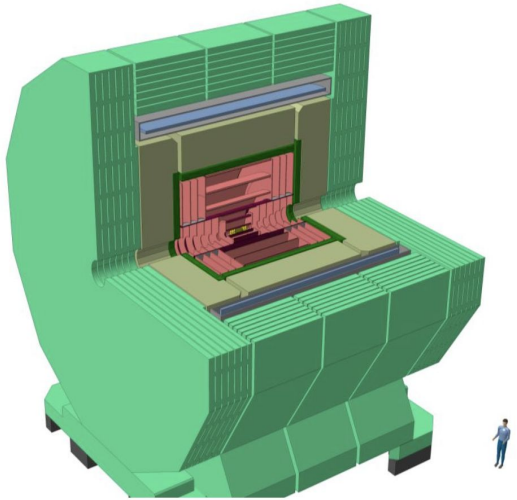
➢ **Digitization** translates the energy deposited in the silicon into realistic electronic signals. It is the step that determines how faithfully the simulation reproduces the real performance expected from a sensor.

★ Our work :

- **Developing the full simulation chain -** in particular by designing a detailed digitization for the silicon tracker sensors of the FCC-ee and assessing its impact on performance.

★ Why CLD ?

- **CLD** - **CLIC- like detector concept -** is built on a fully silicon tracker, which makes it a natural testbed to develop and validate our chain ⇒ but remain a detector-independent method



Ref : CLD Detector Concept

Outline

- Context and Motivation
- **CLD Detector Concept - All-Silicon tracker and vertex detector**
- Silicon sensor digitization: VTXDigiDetailed
- Tracking Performance and validation against the parametric reference

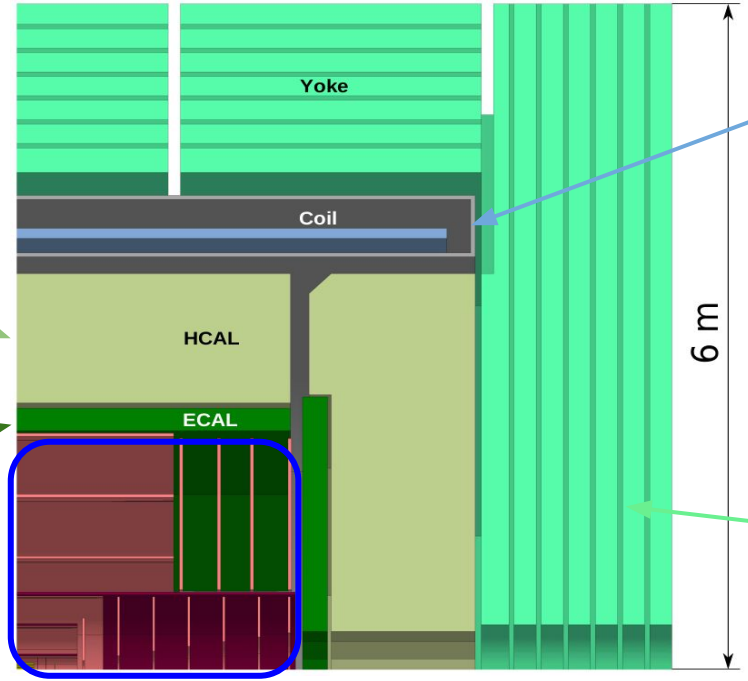
CLD Detector Concept

- 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

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

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

Vertex Detector and Tracker (Today's focus)

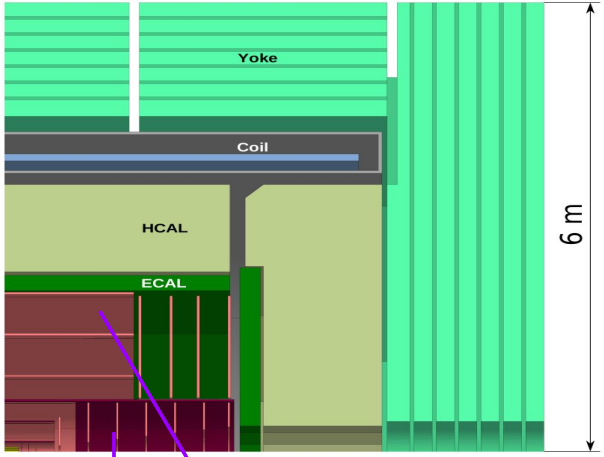


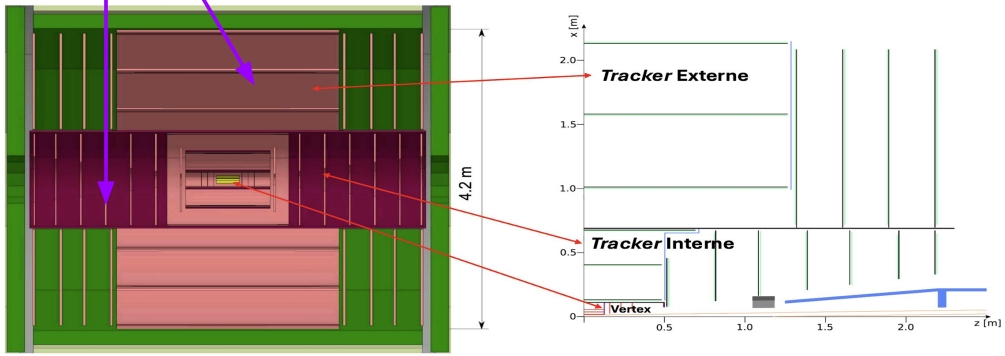
SuperConducting 2T solenoid

Yoke + Muon detector RPCs

More details in : CLD Detector Concept

CLD - Focus on All Silicium Tracker and Vertex detector





Sub-detector	Technologies	Resolution
Vertex	Pixels MAPS 25x25 μm^2	***~3 μm***
Inner Tracker **except 1st endcap**	Bandes Si (pitch 50 μm) Pixels MAPS 50x50 μm^2	***~7x90 μm*** ***~5×5 μm***
Outer Tracker	Bandes Si (pitch 50 μm)	***~7x90 μm***

❖ **Modifications** made to the vertex detector **:**

- ➢ Pixels : **25×25 *μm*^{2}→20×20 *μm*^{2} (configurable in the module)**
- ➢ Sensitive Layer : 50 μm → 10 μm thickness
- ➢ Goal : Represent a MAPS sensor with a greater fidelity (Monolithic Active Pixel Sensor)

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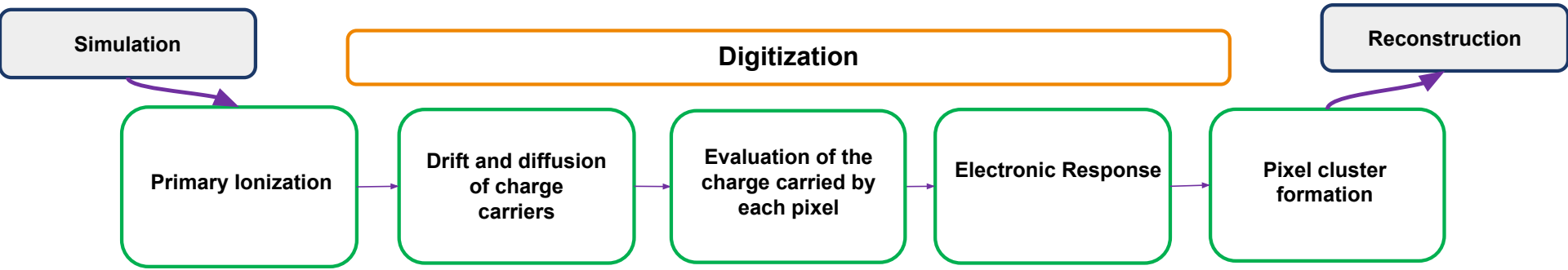
❖ **Sensor response (*VTXDigiDetailed module*, developed at IP2I) :**

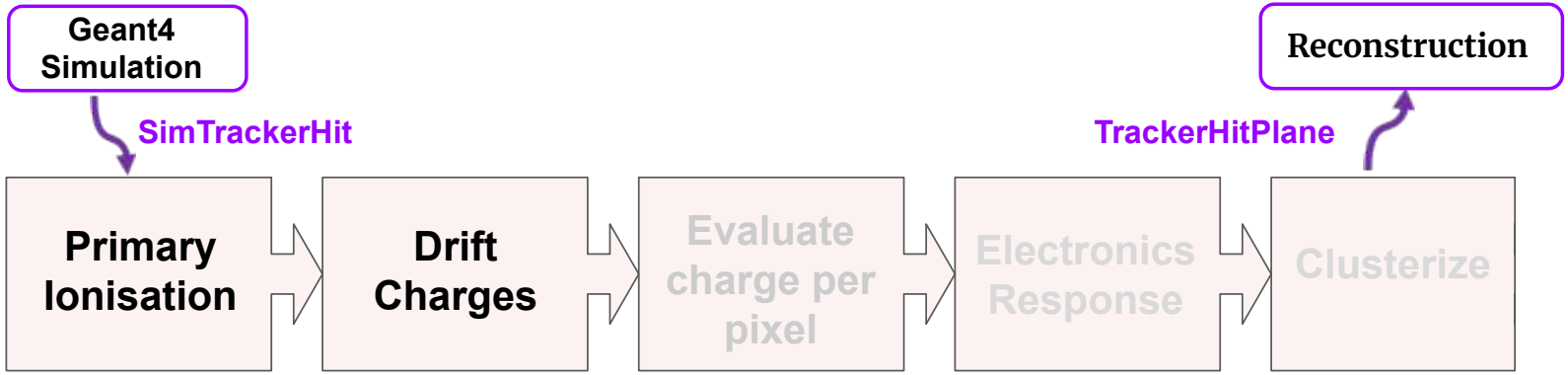


★ **Generic & reusable:** one module → all silicon subdetectors (VT, IT, OT, barrel & endcap)

★ **Fully steerable:** pixel pitch, threshold, smearing etc. in the config file - no recompilation

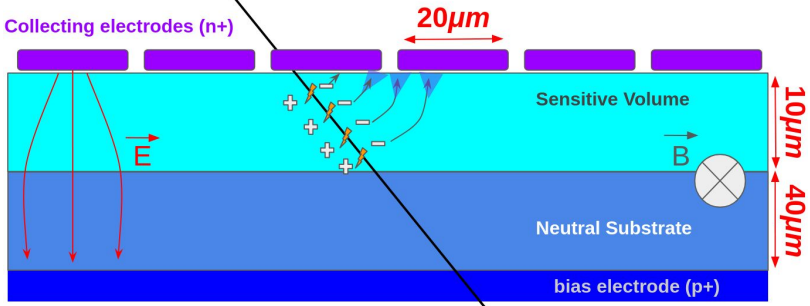
★ **Geometry-aware:** thickness & sensor dimensions read directly from DD4hep → automatically follows geometry updates

Detailed VTX Digitizer : A Quick Refresher



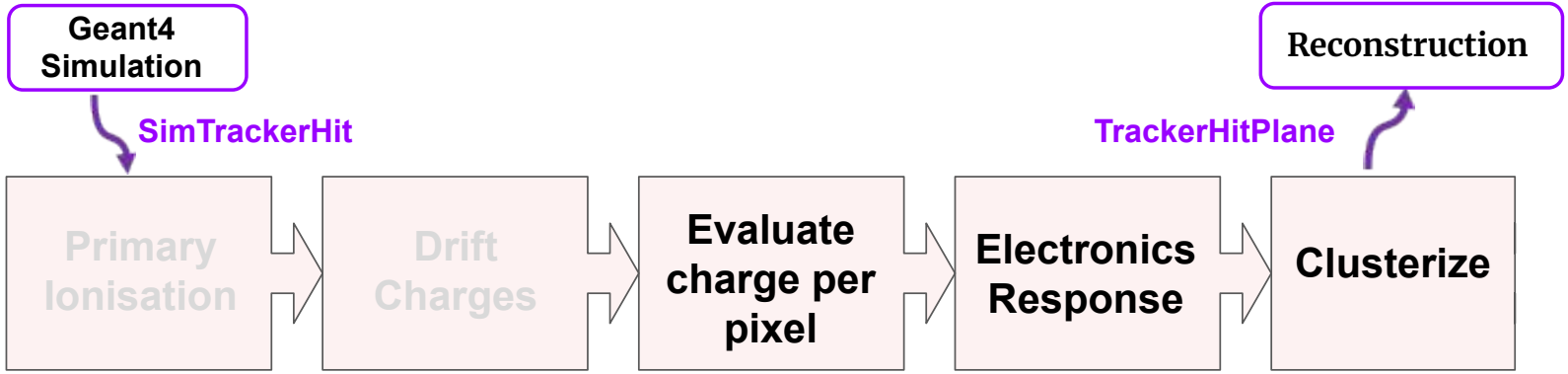
- Geant4 gives the path of the particle, the deposited energy, and hit position and time
  - The path of the particle is divided into **segments**
  - The energy deposited is divided uniformly into each segment and converted into **number of electrons**

- Drift each charge in the depletion area according to magnetic and electric fields + Consider thermal diffusion
  - Drift from **Lorentz Angle** and **E field** considered **uniform**
  - Thermal diffusion is considering by creating a **charge cloud**

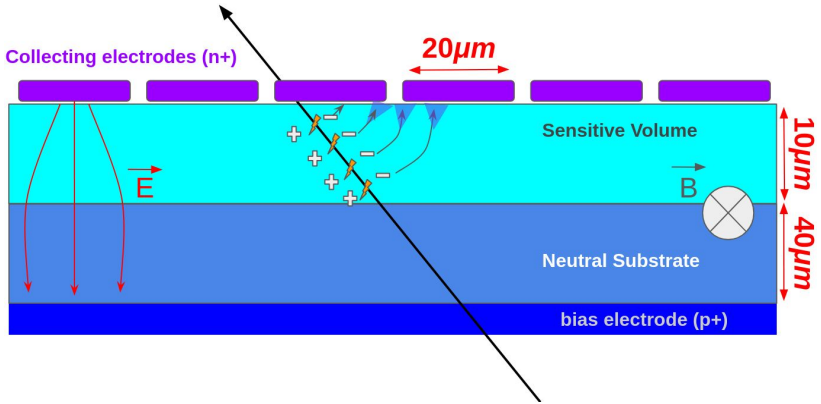


* Thanks to Jessy Daniel's **Merge Request** and already presented in previous talks (ie, 9th FCC Physcis Workshop 2026)

Detailed VTX Digitizer : A Quick Refresher

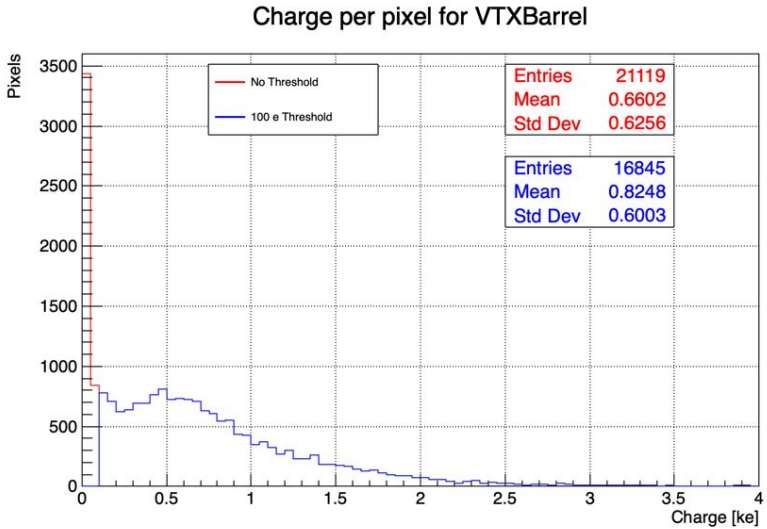


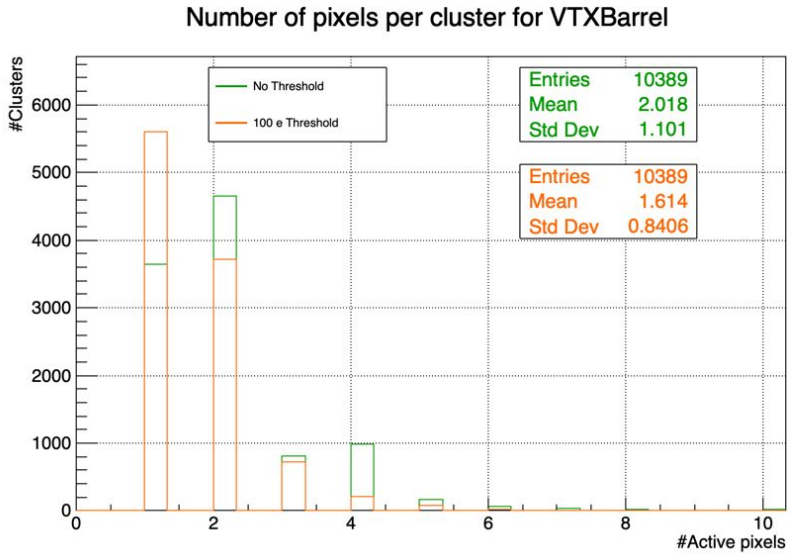
- Deduce the **energy deposited** in each pixel/strip
- Consider **electronic response** (Only Threshold for now) :
- **Clusterization**
  - Get the central position of the clusters with a weighted average
- Return a TrackerHitPlane to reconstruction containing per hit :
  - Position + uncertainty
  - Time + uncertainty
  - Total recorded energy



Some results: Pixel and Cluster

- 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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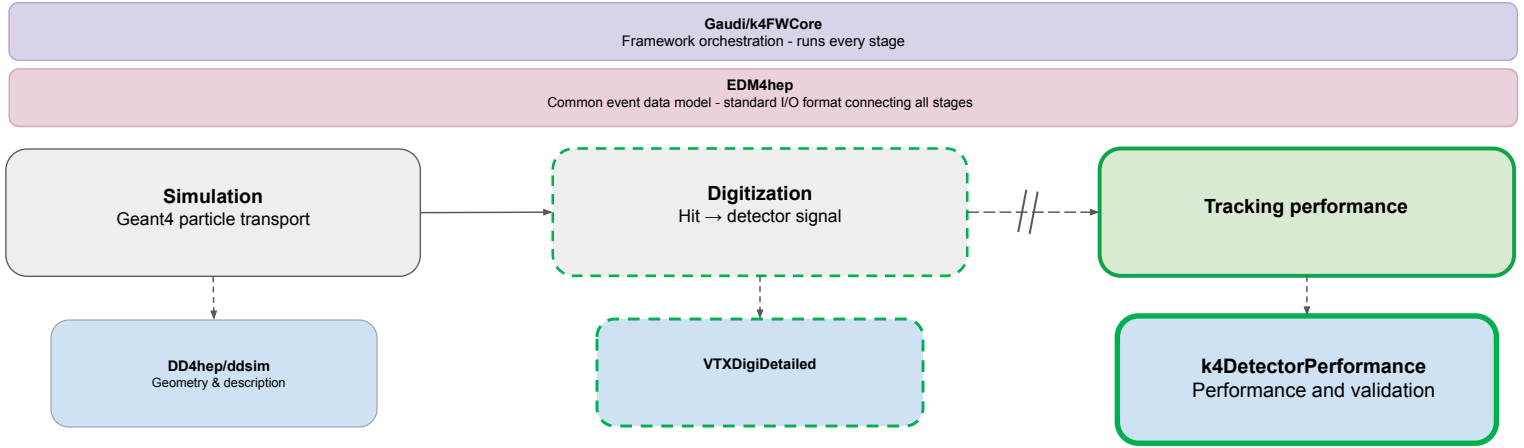
Tracking Performance Framework - Overview



❖ **k4DetPerformance - Inherited validation framework**

➢ Tracking performance suite from G. Sadowski (IPHC IN2P3) PhD Thesis. Runs on the Key4hep stack

Track-truth matching

- Reco tracks associated to true "MC" (simulated) particles via shared hits

Track parameters

- For the five perigee/helix parameters :
  a. Curvature **Ω**
  b. Azimuthal Angle φ_0
  c. Impact Parameter d_0
  d. Z - position z_0
  e. Slope $\tan\lambda$

Residuals

- For each fitted track, the residual is **Δ = reco - true**
- the resolution is its width **σ (Δ)** extracted per **(θ, p) configuration**

My setup - benchmarking detailed digitization against the baseline

❖ **Objective** : Quantify the benefit of a realistic digitization (VTXDigiDetailed) on tracking performance, *via* a direct comparison with the parametric Gaussian-smearing baseline

➢ **Two digitization models compared:**

Baseline (reference) - *Gaussian Smearing*

- Hit position smeared according to a Gaussian of fixed width
- Fast, but less realistic

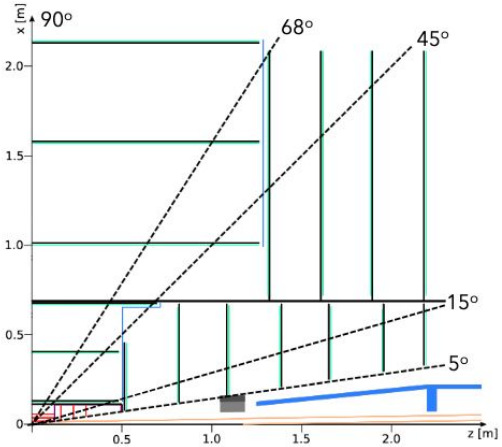
Detailed digitizer (our model) - *VTXDigiDetailed*

- Accounts for the fine effects of the particle-matter interaction: creation, transport and diffusion of charge carriers
- More computationally expensive, but more realistic

➢ **Analysis chain** (built on *TrackerPerformanceScripts*, inherited from G. Sadowski (IPHC IN2P3)) **:**

- Particle-gun scan: polar angle **θ ∈ [10°, 90°] and momentum p ∈ [1, 100] GeV, 2000 single muons per (θ,p) point.**
- Resolutions are extracted from the width of the Gaussian fit
- detailed-vs-parametric overlay **with ratio panel** + theoretical resolution curves

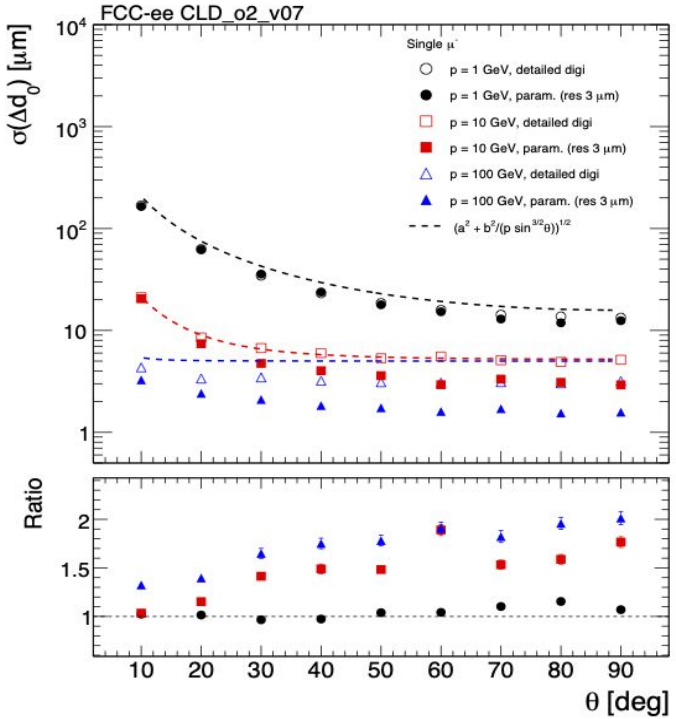
➔ **Result**: **resolution vs (θ,p)**, **detailed vs parametric**, quantifying where realistic digitization matters.



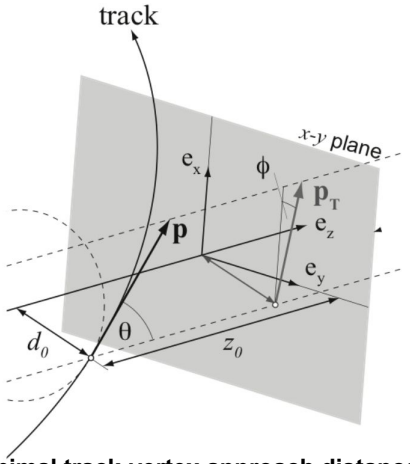
CLD (o2_v07) Detector Layout

Result: Transverse Impact Parameter Resolution

- **σ(d₀)** compared across 3 approaches : **Detailed module (IP2I)**, **Baseline module** and the **analytical CLD model** taken as reference
- Lower panel — **Detailed VTXDigiDetailed / Baseline ratio**



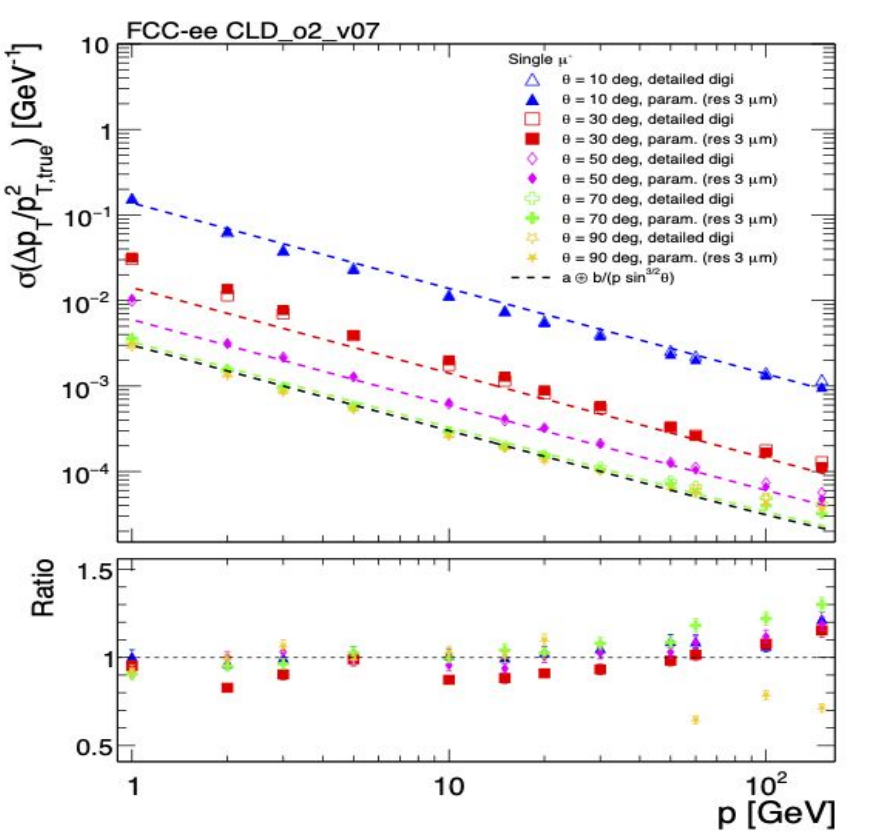
Values and formula are taken from CLD Detector Concept ref. paper



d₀ : minimal track-vertex approach distance in the transverse plane

- **Good agreement** of the detailed module with the analytical reference
- **Discrepancy between the 2 module as expected:** our module reproduces realistic sensor effects that the baseline module idealizes

Results: Momentum Resolution



Values and formula are taken from CLD Detector Concept ref. paper

➢ Momentum resolution is driven by two components: multiple scattering and single-point measurement.

$$\sigma\left(\frac{\Delta p_T}{p_T^2}\right) = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

➢ The spatial resolution provided by pixel clusters does not significantly impact the momentum curvature measurement.

⇒ **Conclusion: Detailed and parametric overlap as expected**

Conclusion

Summary :

- Co-development of a realistic, **fully parameterizable** digitization module for silicon sensors
- A simulation and performance evaluation chain that is **operational** and **validated on the CLD tracker**
- Performance is **consistent** with expectations across all tracking observables, validating our digitizer and **available in Key4Hep for the whole FCC community**

Next steps :

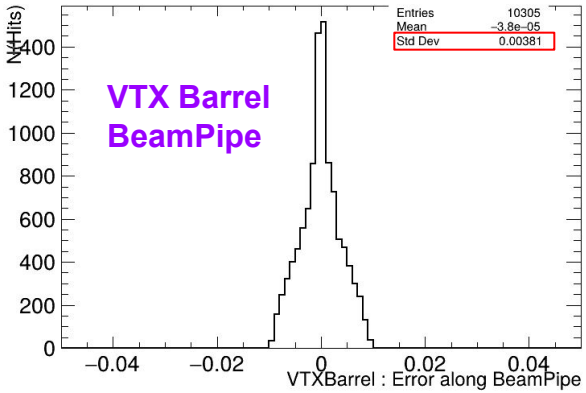
- **Generalize** the chain : other particle types, other detector concepts (ALFA)
- **Broaden** the physics scope: integration of beam-induced background (work in progress)
- **Prepare for the physics**: exploit this framework for tracker sensitive channels such as long-lived particles (**LLPs**)

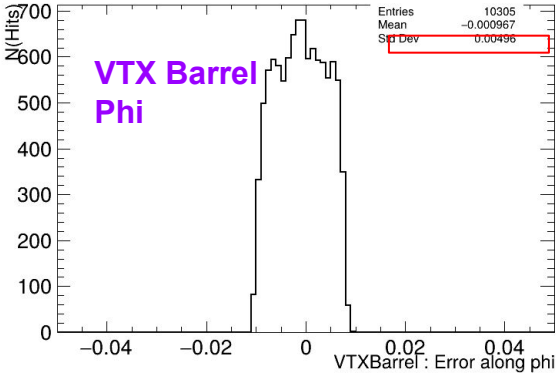
Thanks for your attention !

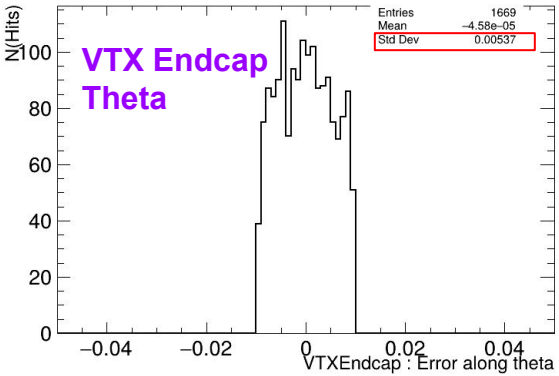
Backup Slides

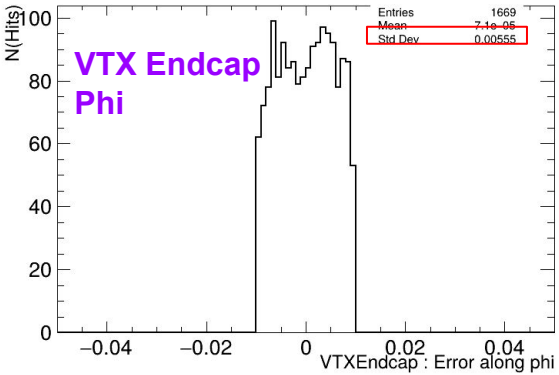
Some results: Hit resolution

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









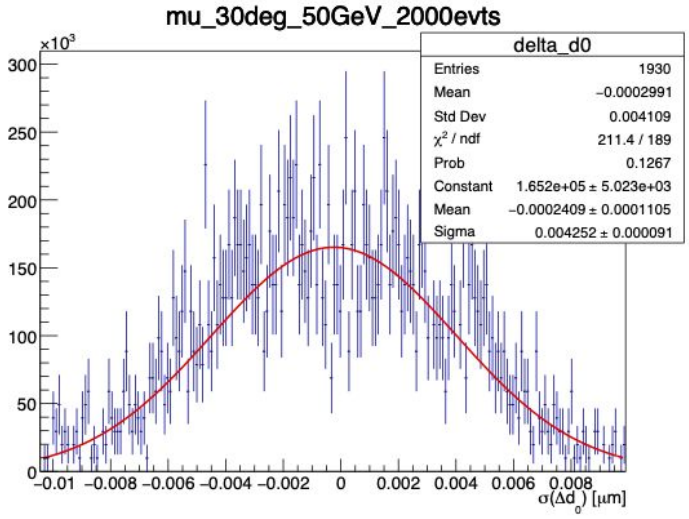
→ **Barrel** : Single hit resolution of **~3.8*μm*** along beampipe and **~5.0*μm*** orthogonal→**Do not reach the 3*μm* goal**
→ A shift of ~1μm along ϕ
= Compatible with charge drift in magnetic field !

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

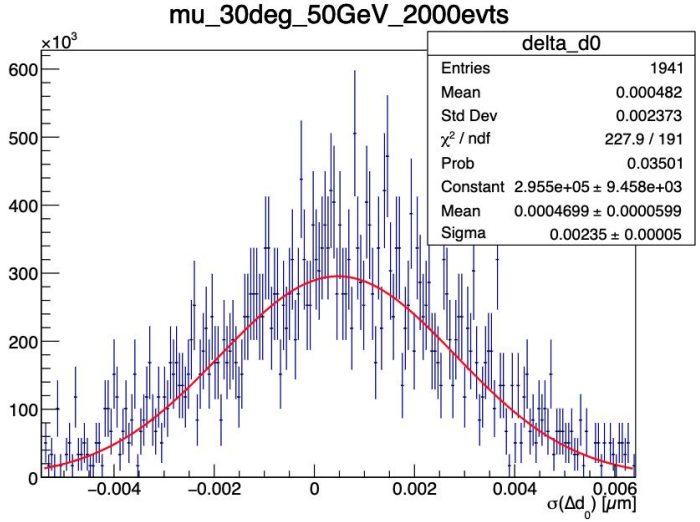
Performance Evaluation: Framework & Methodology

- Analysis Framework : TrackerPerformanceScripts (*Standalone / Non-Gaudi*) and adapted from G. Sadowski's PhD work
  - Match reconstructed tracks directly to simulated (true) particles.

- Resolution Definitions & Fits : Extracted from the width (sigma) of a Gaussian fit



2k - muon - 30° - 50 GeV - Detailed (new) module



2k - muon - 30° - 50 GeV - Parametric module

Results:

❖ Momentum resolution

➢ The relative momentum resolution combines two terms:

- **a** - **multiple scattering**, plateau at low momentum, set by material budget **x/X_0**
- **b** - **single-point measurement term** ∝ **σ_rφ** the point error, the lever arm **$1/L^2$**, the field **1/B** and the number of layers **N** (geometry-fixed)

$$\sigma\left(\frac{\Delta p_T}{p_T^2}\right) = a \oplus \frac{b}{p \sin^{3/2}\theta}$$

θ (°)	a	b
10	7.4×10^{-5}	0.010
30	1.8×10^{-5}	0.005
50	9.2×10^{-6}	0.004
70	8.3×10^{-6}	0.003
89	8.6×10^{-6}	0.003

➢ **Why both digitizers agree as expected:** the digitizers enter only via **σ_rφ** in b, suppressed by **average numbers of N** layers and **L^2**

- **detailed and parametric overlap**

❖ Transverse impact parameter resolution

$$\sigma(d_0) = \sqrt{a^2 + \frac{b^2 \cdot \mathrm{GeV}^2}{p^2 \sin^3(\theta)}}$$

- **a ≅ 5μm**
- **b ≅ 15 μm**

Values and formula are taken from CLD Detector Concept ref. paper

References

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