Simulation and tracking software for the reference detector

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Outline

- CEPCSW: Key4hep based software
- Simulation software
- Tracking software
- Tracking with ACTS
- Summary

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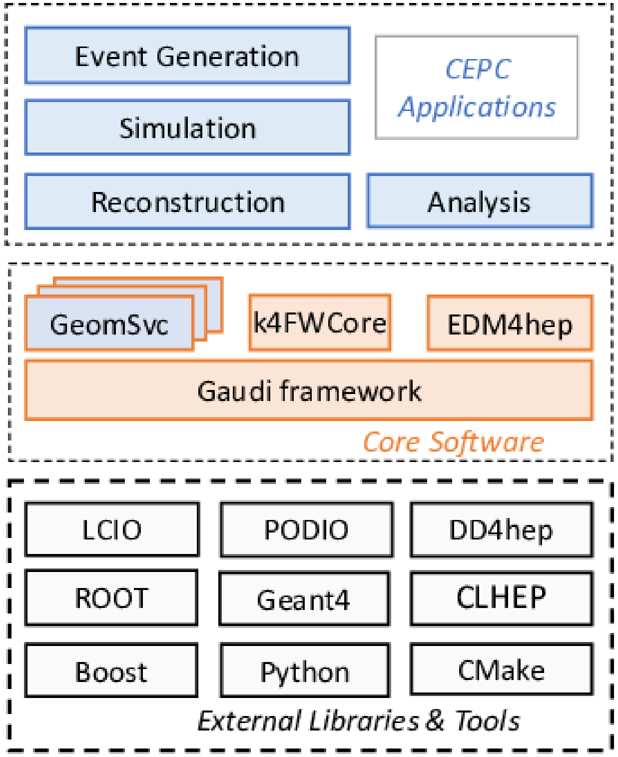
CEPCSW: CEPC Software

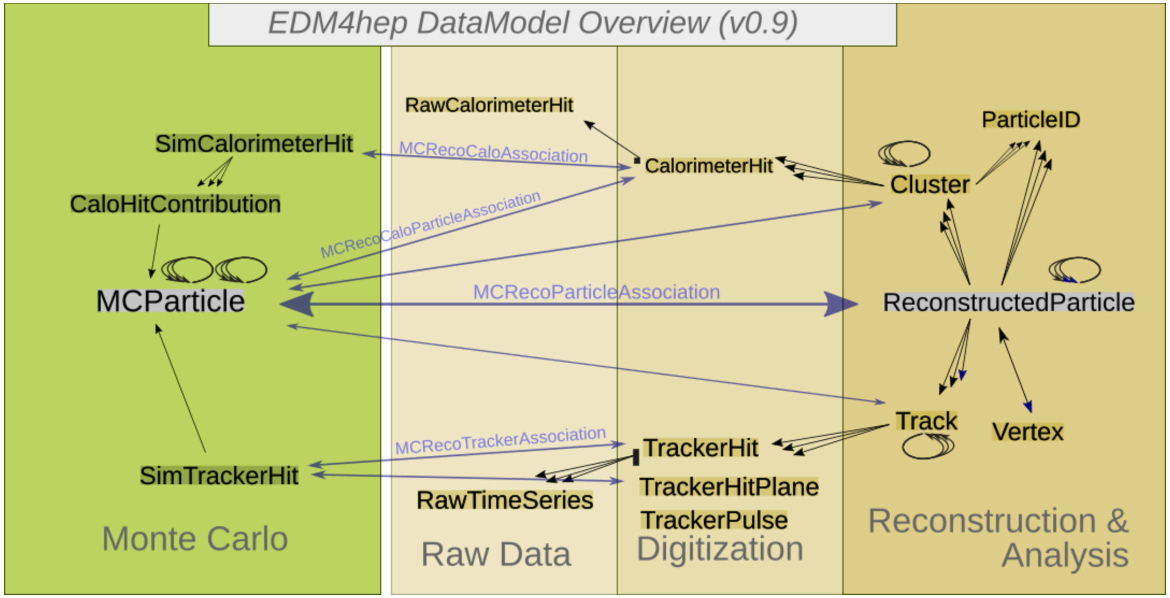
- **The CEPC experiment is among the first to integrate with Key4hep**
  - A common software stack designed for future HEP experiments such as CEPC, CLIC, FCC, and ILC

https://code.ihep.ac.cn/cepc/CEPCSW



- **Multi-layer structure**
  - Applications: simulation, reconstruction, analysis
  - Core software
  - External libraries
- **The key components of core software:**
  - Gaudi: defines interfaces to all software components and manages execution flow
  - EDM4hep: generic event data model
  - DD4hep: unified detector geometry description
  - CEPC-specific components: GeomSvc, simulation framework, RDFAnalysis, beam background mixing, fast simulation, machine learning interface, etc.

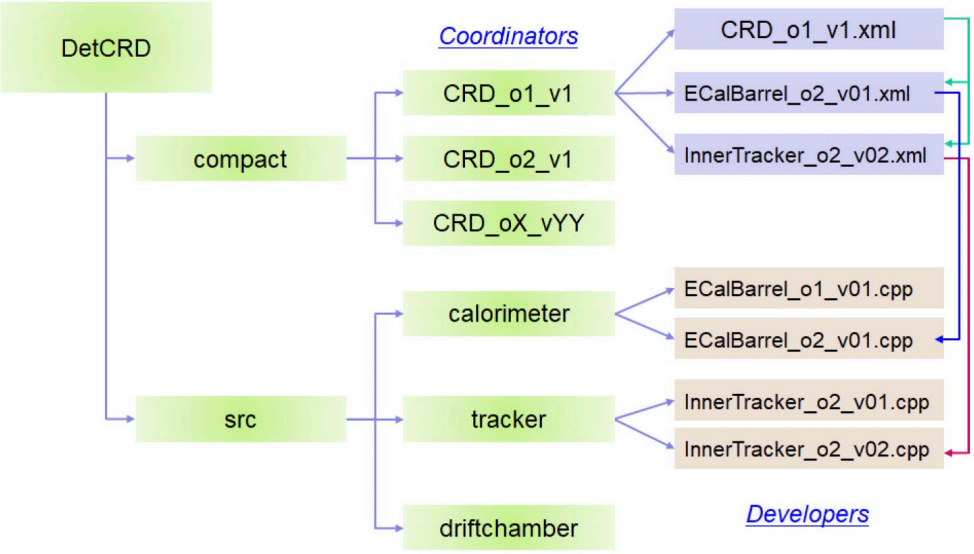
Event Data Model

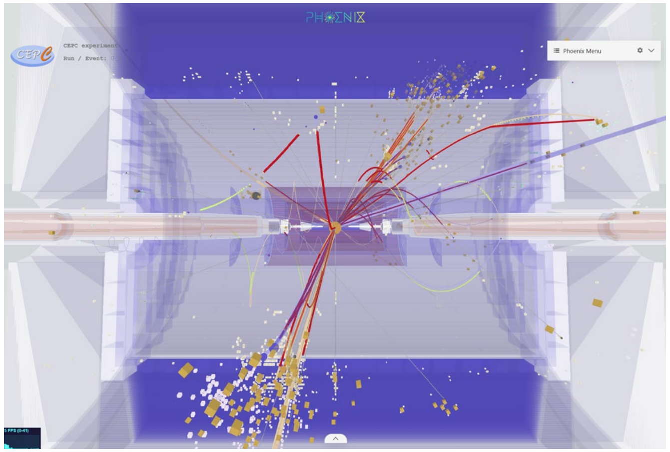


- **EDM4hep has been adopted as the official event data model**
  - provide a unified framework for managing event data across different HEP experiments
  - supports multiple backend data formats, including ROOT and LCIO
- **A number of CEPC-specific classes have been added to EDM4hep**

Detector Description

- **The DD4hep toolkit offers detector information to various applications from a unified source**
  - Each detector element can be created using XML-based compact detector descriptions and C++-based detector constructors
  - Any detector element can be enhanced with extensions, e.g. supplying extra information for reconstruction algorithms
- **A geometry service manages the DD4hep instance in CEPCSW**





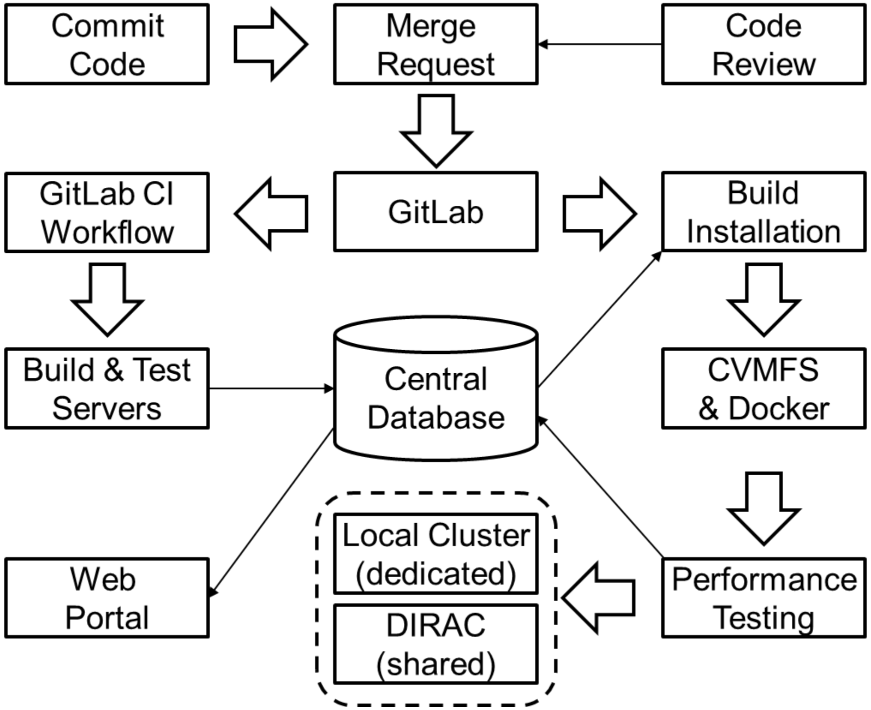
Event display in Phoenix

Software development and validation

- **Modern software development practices are applied in CEPCSW, following best practices from HEP Software Foundation (HSF).**

- **Version control & CI/CD**
  - Git/GitHub/GitLab
  - GitLab Runners
- **Configuration & building**
  - CMake
  - Make and Ninja
- **Software distribution**
  - CVMFS
  - Container: Docker and Apptainer
- **Documentation**
  - Markdown and Sphinx+RTD

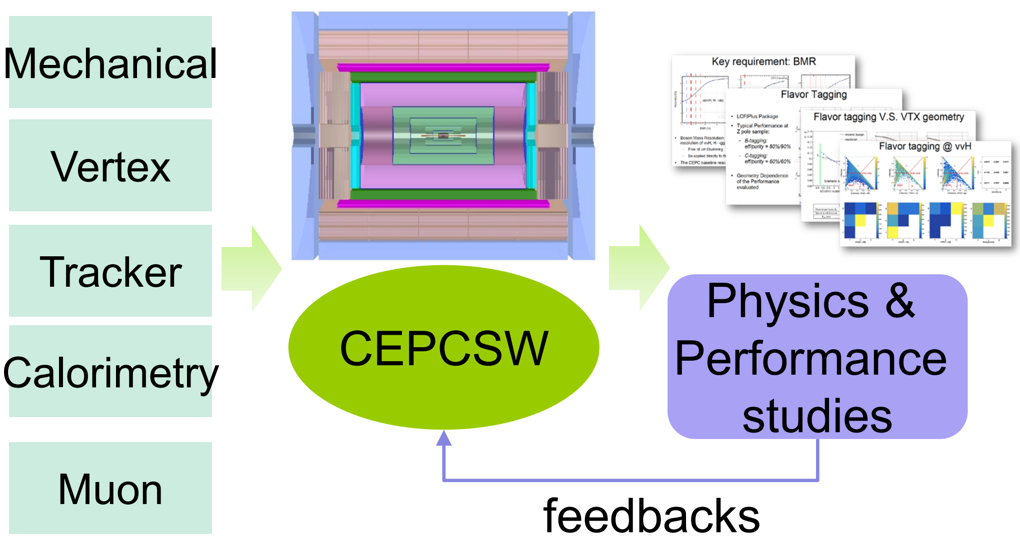
    https://cepcsw-docs.readthedocs.io/en/latest/



Automated validation infrastructure

Software release

- **We support the rapid iterations of the reference detector design.**
  - New version scheme based on date: tdr *YY.MM.NN*
  - External libraries are frozen at LCG 105 at AlmaLinux 9



Release	Timeline	Release Count
tdr24.3	March	2
tdr24.4	April	2
tdr24.5	May	1
tdr24.9	Sept	2
tdr24.10	Oct	1
tdr24.12	Dec	1
tdr25.1	Jan	3
tdr25.3	March	8
tdr25.5	May	1
tdr25.6	June	1

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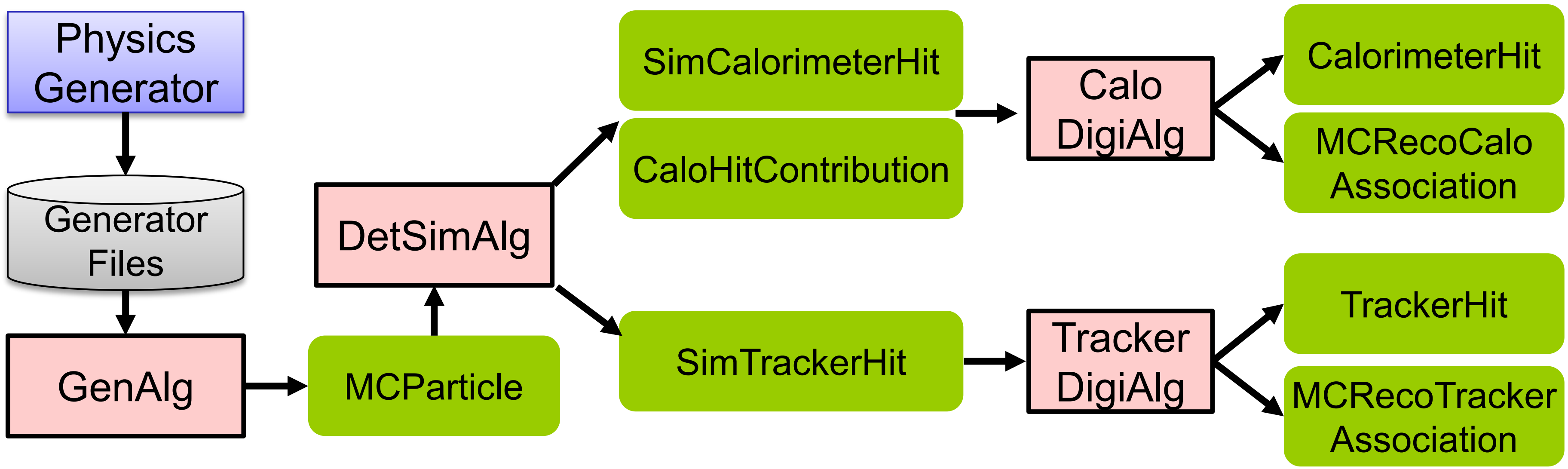
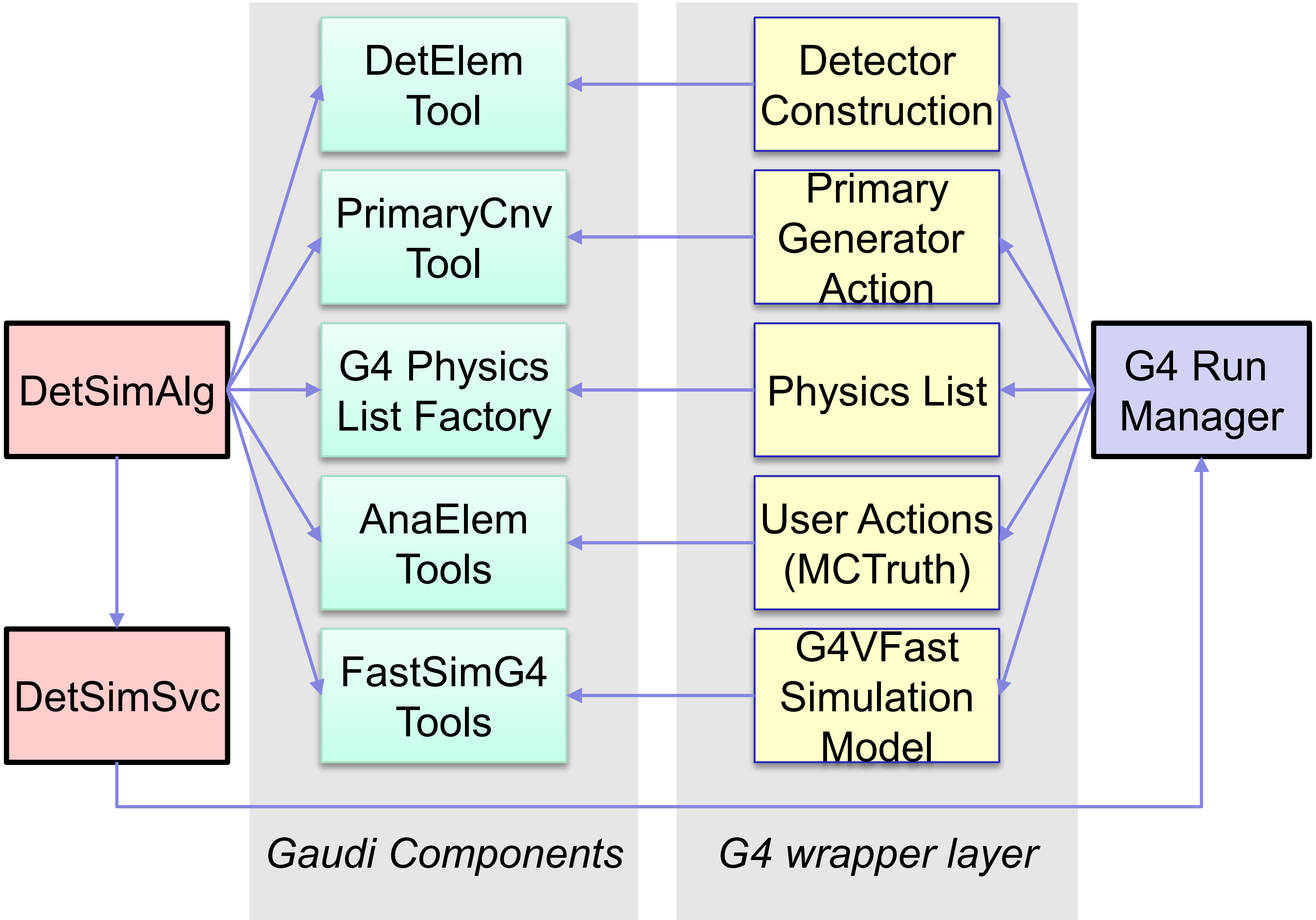
Simulation workflow



- **The workflow comprises three stages:**
  - Physics event generation: WHIZARD, Pythia6/8, MDI background, particle gun
  - Detector simulation: Geant4 + DD4hep/DDG4
  - Digitization: silicon tracker, TPC, ECAL, HCAL, Muon
- **Beam-induced background: pre-simulation (particle level mixing), post-simulation (hit level mixing), post-digitization (digi overlay)**

Detector simulation



Within CEPCSW, a lightweight simulation framework has been developed to enable seamless integration of Geant4 into Gaudi framework

MC truth

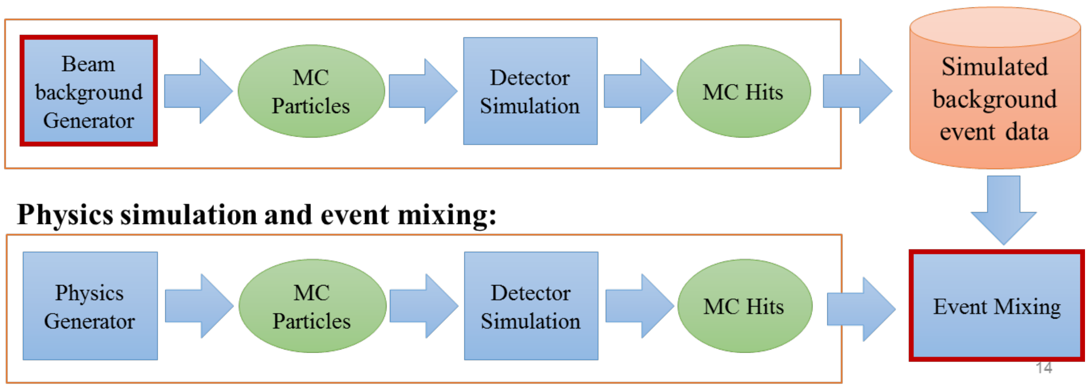
- **MC truth information can help developers and analyzers understand the detailed processes.**
  - Particle – particle relationship at generation and simulation stage
  - Hit – particle relationship at simulation stage

- **Particle – particle relationship**
  - Truth information from physics generators
  - Interesting physics processes in simulation: decay and gamma conversion
  - Part of secondaries created inside the tracker system if the initial kinetic energy of a secondary track is higher than a threshold

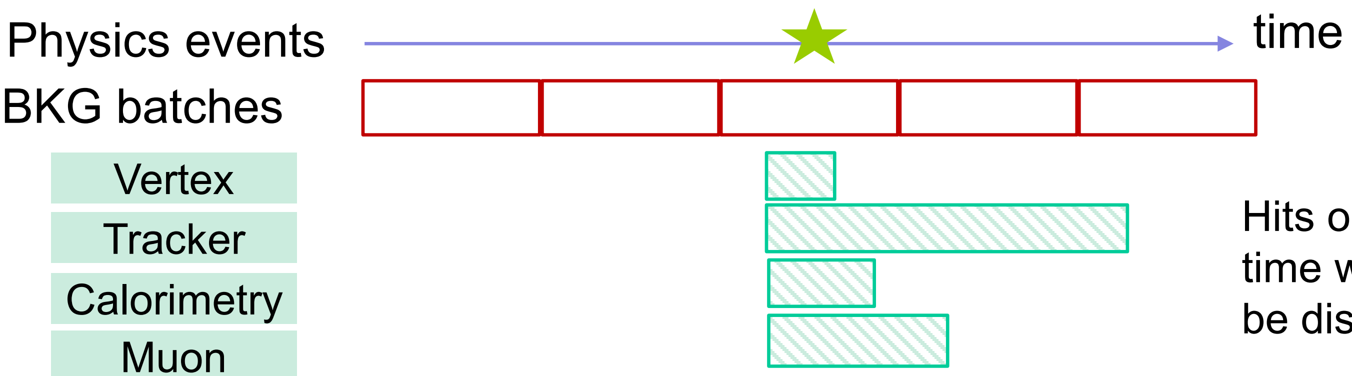
- **Hit – particle relationship**
  - A tracker/calo hit can be associated with a primary track or a secondary track in simulation
  - Easy to know a hit is from signals or backgrounds.

Beam-induced background simulation

- **Two modes of mixing have been implemented**
  - Pre-simulation (particle level): for MDI study
  - Post-simulation (hit level): for performance study



- **For hit level mixing, the background files are prepared in advance.**
- **The time windows are configurable.**



Hits outside the time windows will be discarded.

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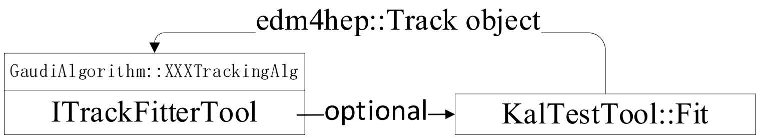
Tracking software



- **iLCSoft-based @Pre-CDR and CDR**
  - Mokka as detector description
  - Marlin as reconstruction framework
- **DD4hep and Gaudi @Ref-TDR**
  - Migrate ILDTracking software for Time Project Chamber + silicon tracker (baseline tracker design)
    - SiliconTracking, Clupatra, ILDFullTracking
    - KalDet, DDKalTest, KalTest
  - Implement Genfit2 for Drift Chamber + silicon tracker
  - Implement ConformalTracking
  - Implement ArborTracking
  - Implement ACTS

→ software backup & developing

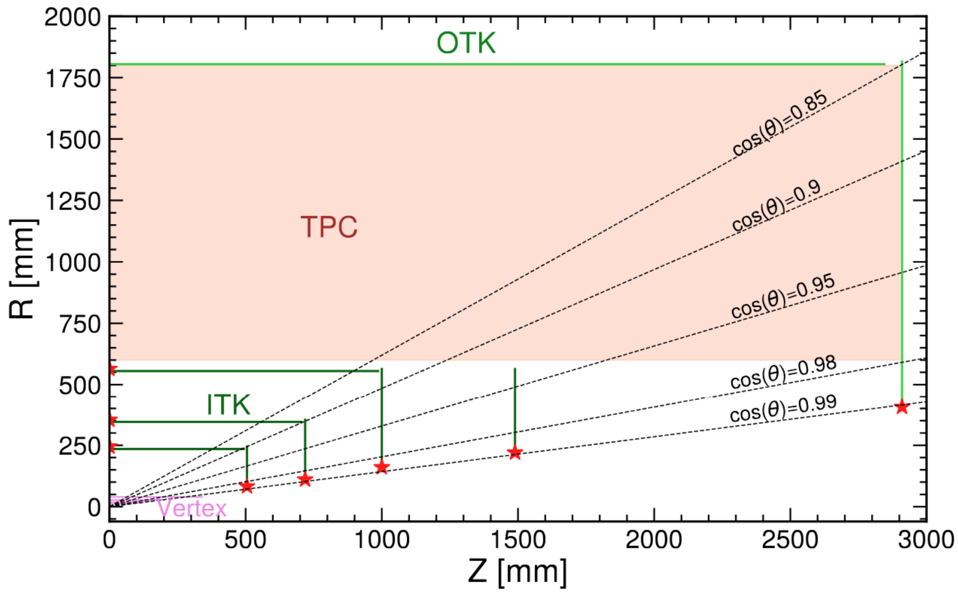
CEPCSW component → ExternalProject

ILDTracking migration: Algorithm + Rec geometry + Fitter tool

framework | data model | CEPC tracker module | data model

Tracking Detector

- **Baseline trackers**
  - Vertex detector (VTX)
    - Stitched sensor (4 layers)
    - Planar sensor (double layer)
  - Inner Tracker (ITK)
    - ITKBarrel (3 layers)
    - ITKEndcap (4 layers)
  - Time Project Chamber (TPC): PID
  - Outer Tracker (OTK): Time of Flight
    - OTKBarrel
    - OTKEndcap



Created simulation geometry & reconstruction measurement surface

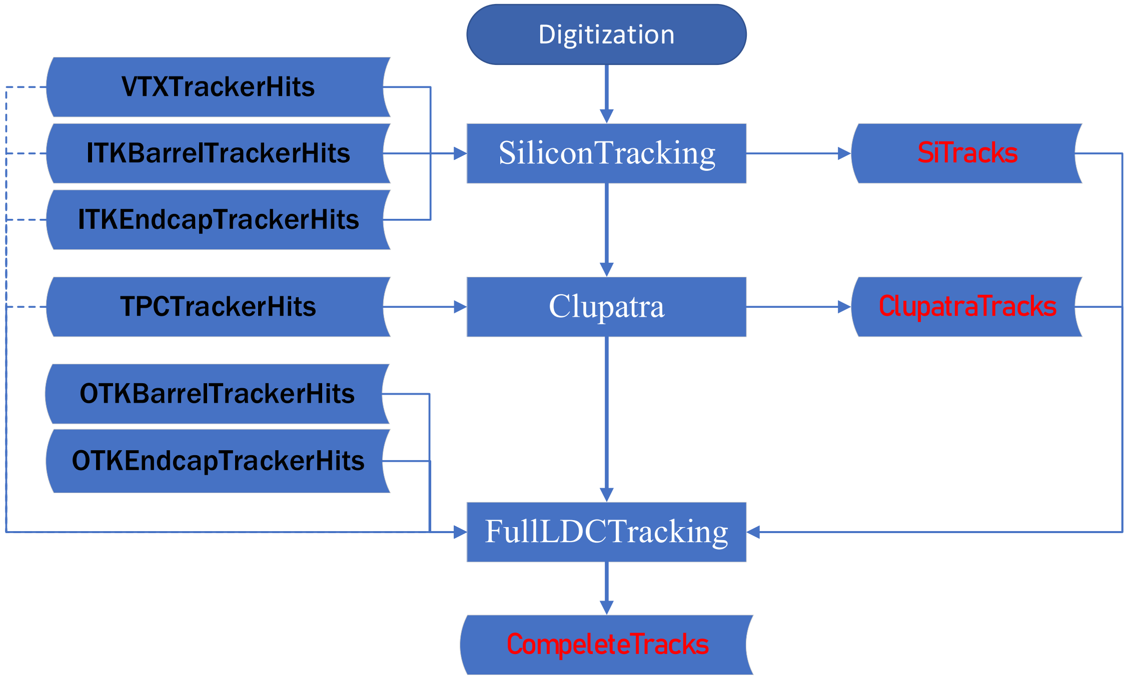
Optional tracker design for optimizing

- **Digitization**
  - Fixed spatial resolution for silicon trackers
  - Parameterized spatial resolution from Garfield simulation for TPC

Track Reconstruction

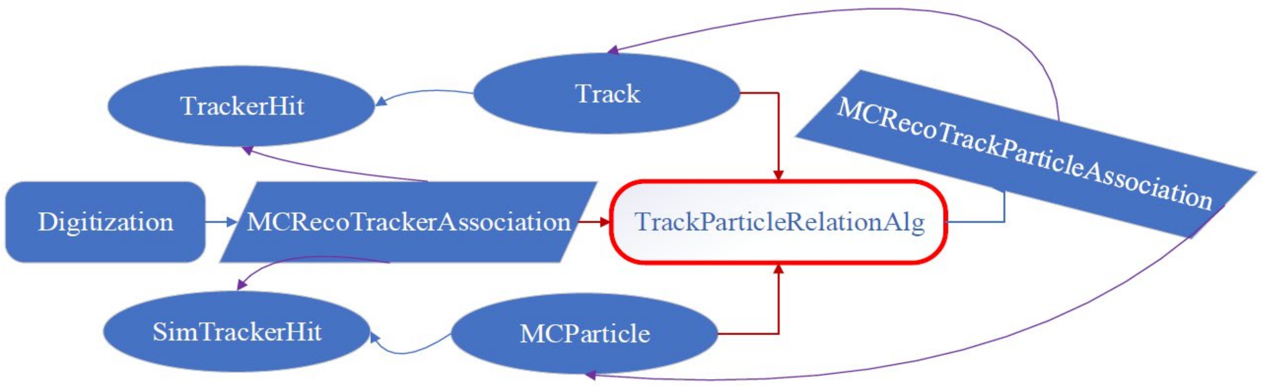
- **Default chain creates CompeleteTracks for all trackers, OTK added as external in FullLDCTracking**
  - TrackCollection → Track → TrackState → momentum

- **More optional reconstruction chains for different set of tracker**
  - such as VTX+ITK, VTX+ITK+TPC, VTX+ITK+OTK, TPC only



Estimation of Performance

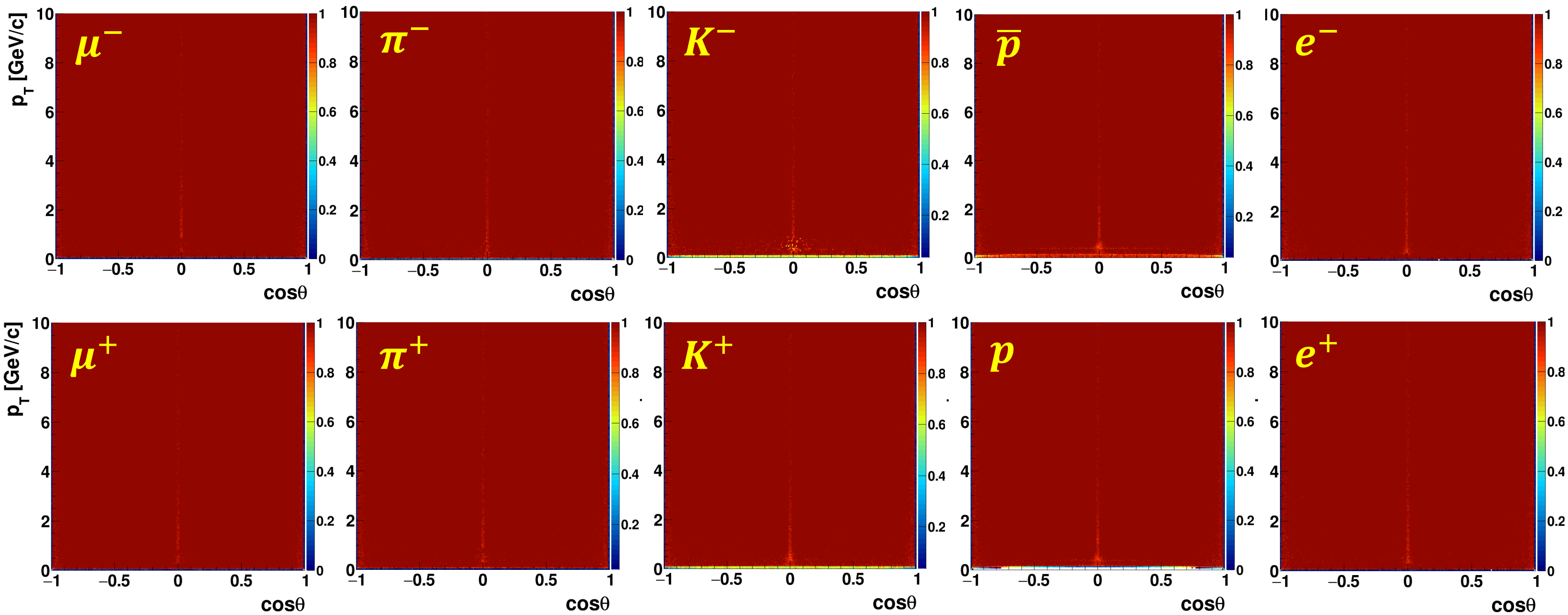
- **Matching between Track (rec) and MCParticle (truth)**
  - Track Particle Relation Alg: shared hit number as weight



- **Standard performance: single particle, multiple particles, physics sample**
  - Select generated MCParticle (N_{MC})
  - Select its relative Track with maximum weight, and condition
    - Weight >4, maximum probability of reconstruction
    - Weight/total hit of MCParticle>80%
    - Additional cut on $\frac{p_{i,rec}-p_{i,MC}}{\sigma_{pi}}$, according to study requirement
  - Calculate performance
    - Count number (N_{rec}) to efficiency $\frac{N_{rec}}{N_{MC}}$
    - Residual of track parameter p_i to resolution

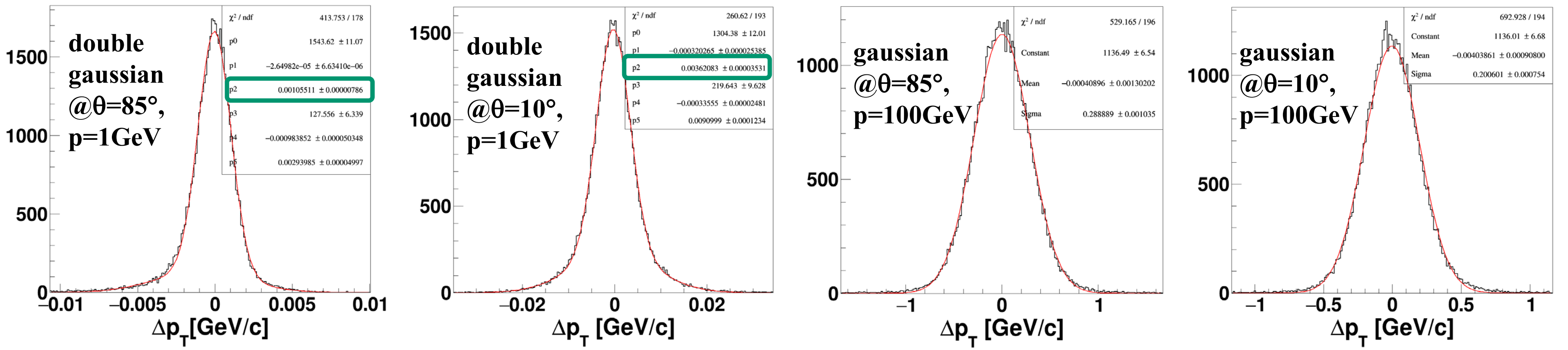
Tracking Efficiency

- **Single particle $p_T \in [0.1,10]$ GeV/c $\phi \in [0, 360°]$ $\theta \in [1°, 179°]$**
  - IP: $\sigma_x = 15\mu m$, $\sigma_y = 36nm$, $\sigma_z = 2.758mm$
  - maximum probability of reconstruction
  - Efficiency drop at $\theta \approx 90°$, caused by silicon sensor gap and TPC cathode plate
- **Close tracking efficiency in multiple particles simulation**

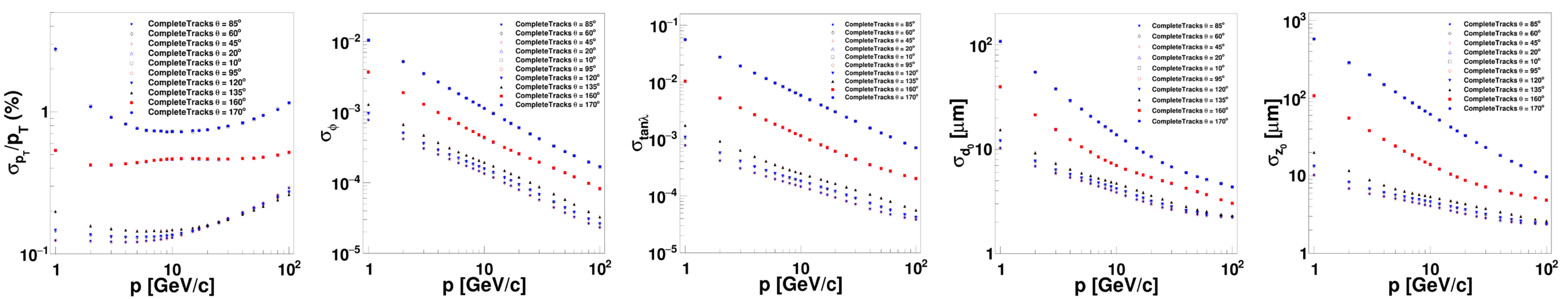


Resolutions

- **At low momentum, the residual distribution of transverse momentum has a tail, and a double Gaussian fit yields better results than a single Gaussian fit.**
- In the future, need more efforts to improve performance.



gaussian fit result:



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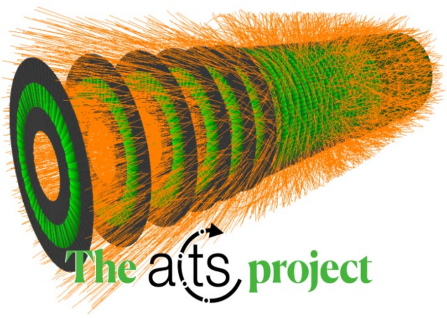
Tracking with ACTS

❖ **Software development background**

- The trend in computing hardware is shifting toward increased CPU cores and more diverse architectures, including GPU, FPGAs, and other accelerators.
- Machine learning has become an essential component of high-energy physics experiments.
- Software development is now focused on efficiently managing concurrent computations while harnessing machine learning techniques.

❖ **ACTS (for details, see the talk by A. Salzburger)**

- designed as a library that contains components for assembling a track reconstruction suite
- traccc: provides high-performance parallel software compatible with complex hardware architectures (e.g., CPU, GPU, FPGA)
- Exa.TrkX plugin: contains a track finding module based on Graph Neural Networks (GNNs) which is developed by the Exa.TrkX team

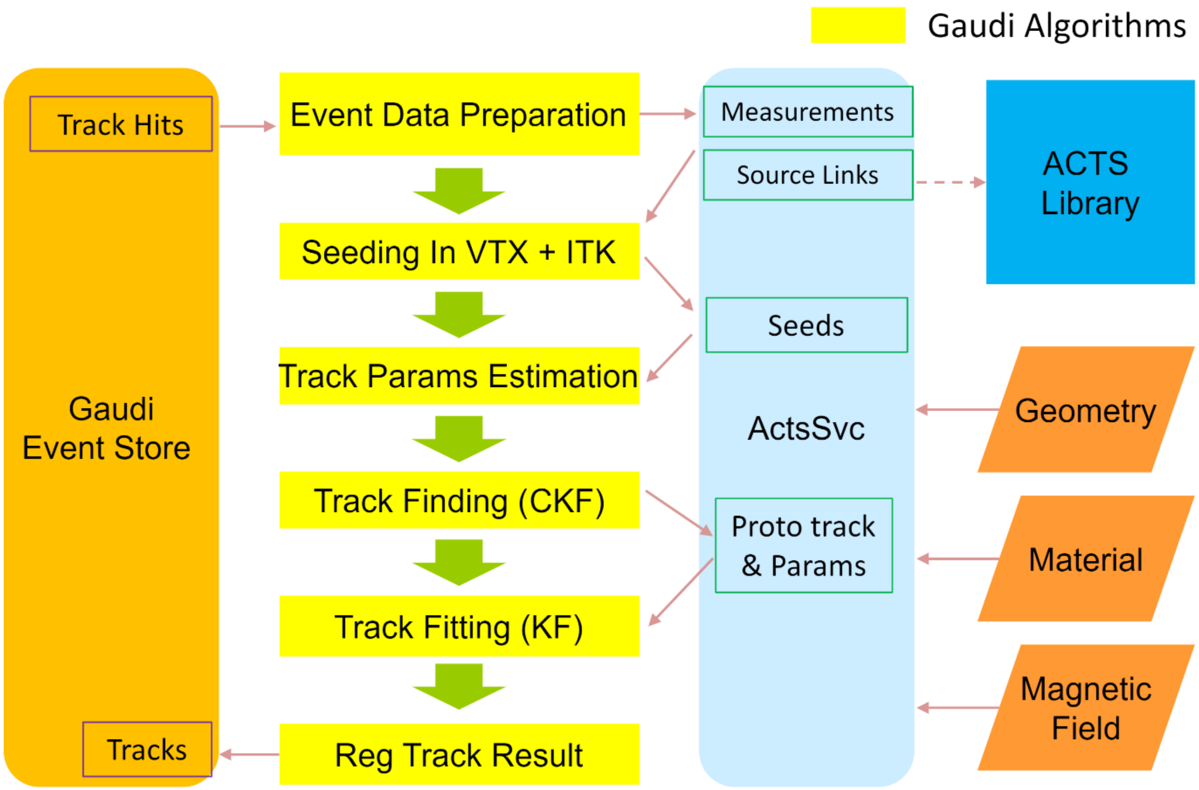


Requirements and Status

- **Tracking Requirements**
  - High-precision measurement places stringent demands on tracking, requiring near 100% tracking efficiency and a momentum resolution of approximately 0.1%.
  - During Z-pole operation at CEPC, the computational workload will be immense, reaching the exa-byte scale.

- **Tracking with ACTS is an R&D project focused on track reconstruction in the trackers of the RefDet. The completed work includes:**
  - To construct the reconstruction flow using ACTS libraries within CEPCSW, detector geometry compatible with ACTS is first prepared.
  - The track reconstruction process, implemented using the Gaudi Algorithm: Event Data Preparation, Seeding and Track parameter Estimation, Track Finding and Track Fitting, Final Registration of results.
  - Implementation of ACTS in the TPC. The surfaces required by ACTS are virtually constructed within the TPC gas volume, aligning with the TPC readout layers.

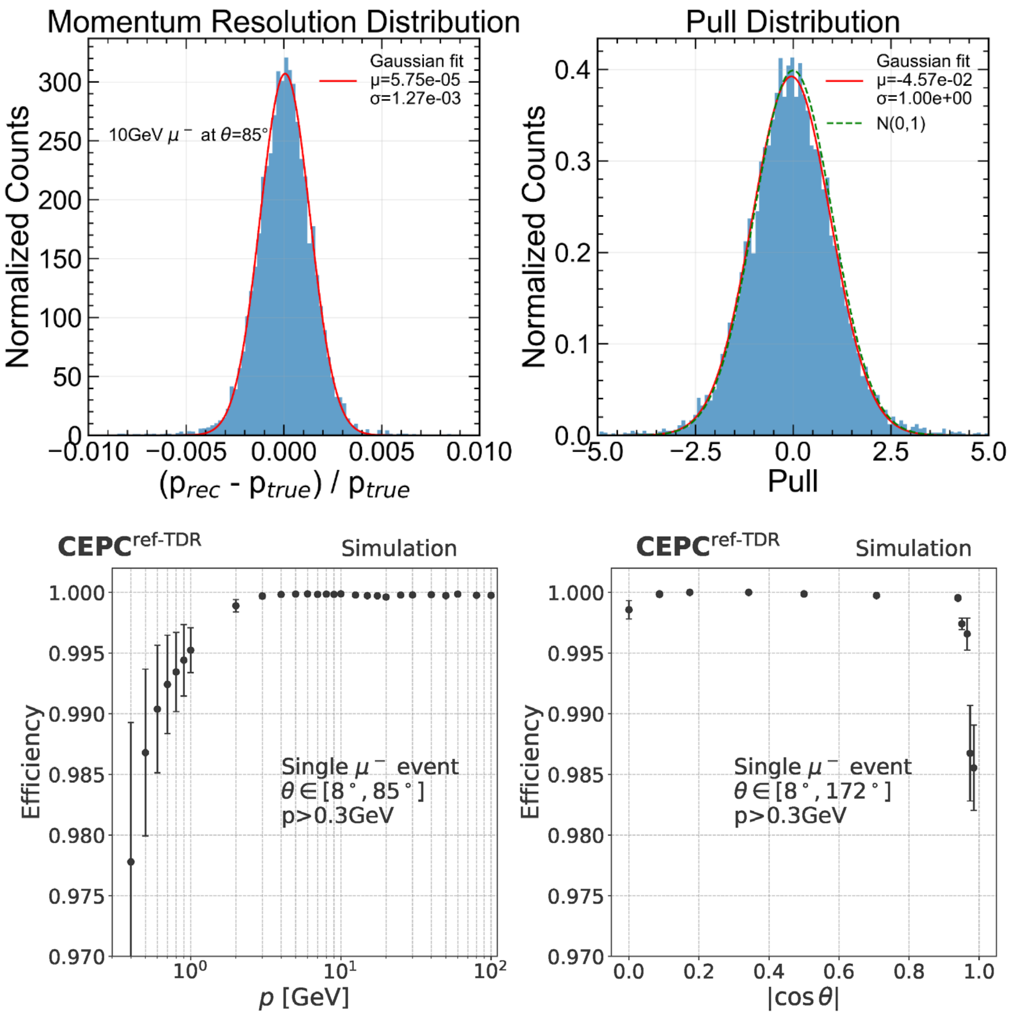
Integration ACTS into CEPCSW



- Each step is implemented as a Gaudi Algorithm.
- Converting the RefDet geometry into the ACTS format
- Mapping Geant4 materials to the ACTS representation

Ongoing work

- **Physics performance**
  - It is consistent with the RefDet TDR performance study.
  - A detailed comparison is still ongoing.
- **Gaussian Sum Filter (GSF) based track fitting**
  - Accurate reconstruction of electron tracks with Gaussian Sum Filter (GSF) track fitting method
- **Roadmap**
  - Only after the ACTS-based implementation has been fully evaluated, the decision on the roadmap of track reconstruction can be made.



Summary

- **The CEPCSW is built upon the Gaudi and Key4hep**
  - reflecting the project's objective to leverage established HEP software, while developing innovative solutions tailored to the experiment's specific needs

- **Simulation and track reconstruction have been developed and being used to**
  - validate the detector design and explore experiment's physics potentials

- **Tracking with ACTS**
  - implements advanced tracking algorithms across all trackers using the ACTS library

Thank you for your attention