Application of ACTS to the CEPC Reference Detector

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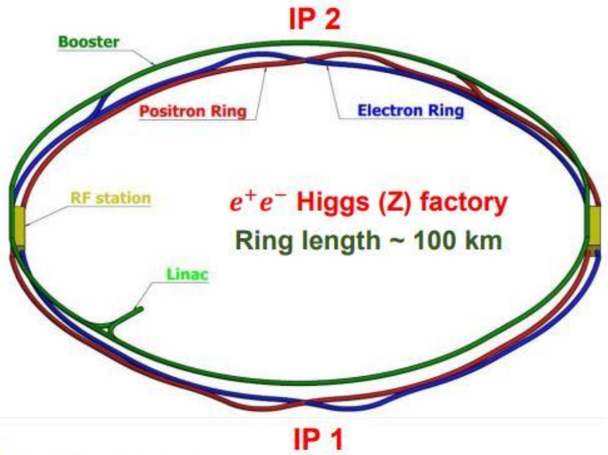
Outline

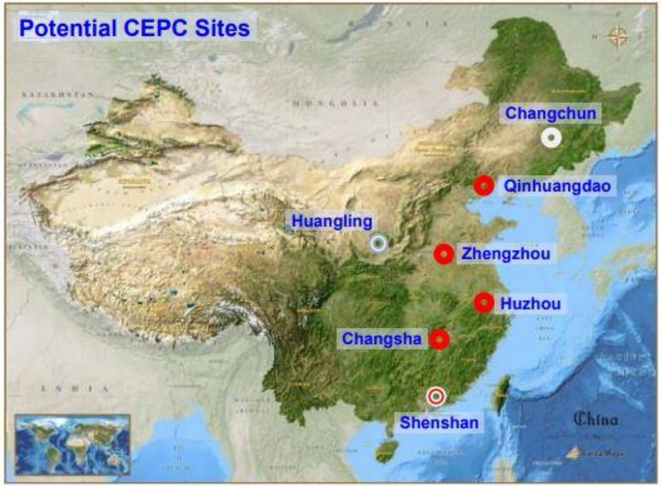
1 Introduction

Circular Electron Positron Collider (CEPC)

- The CEPC was proposed by the Chinese HEP community in 2012 right after the Higgs discovery. It aims to start operation in 2030s, as a Higgs / Z / W factory in China.
- To produce Higgs / W / Z / top for high precision Higgs, EW measurements, studies of flavor physics & QCD, and probes of physics BSM.
- It is possible to upgrade to a *pp* collider (SppC) of $\sqrt{s}$ ~ 100 TeV in the future.



http://cepc.ihep.ac.cn



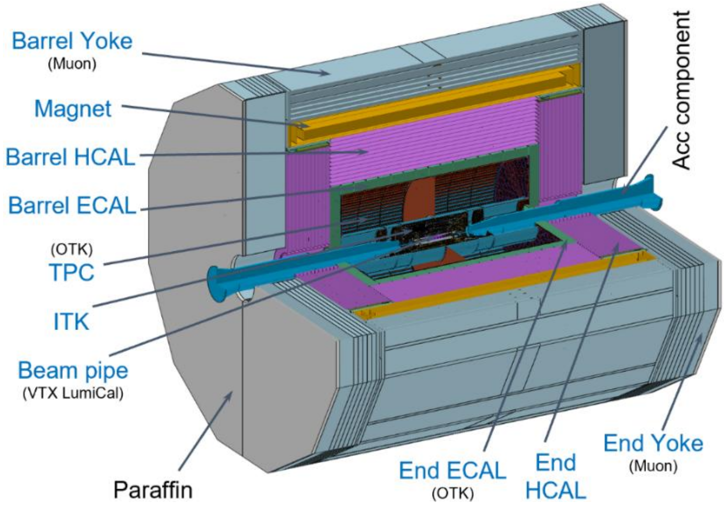
- Accelerator design and technology R&D are approaching maturity, with the TDR completed and progressing into the EDR phase. The TDR for the reference detector is currently in preparation and is expected to be finalized within the year.

1 Introduction

CEPC Detector

CEPC Reference Detector

- VTX: Vertex Detector
- ITK/OTK: Inner Silicon Tracker/Outer Silicon Tracker
- TPC: Time Projection Chamber
- ECAL: Crystal-bar ECAL
- HCAL: Glass Scintillator HCAL
- Muon: Muon Detector



Physics requirements

- Tracking efficiency: Nearly 100%
- Momentum resolution: About 0.1%
- Particle Identification (PID): 2σ separation between pions and kaons for P < ~ 20 GeV/c
- Boson Mass Resolution (BMR): Better than 4%, among other features

Physics process	Measurands	Detector subsystem	Performance requirement
$ZH, Z \to e^+e^-, \mu^+\mu^-$ $H \to \mu^+\mu^-$	$m_H, \sigma(ZH)$ $\mathrm{BR}(H \to \mu^+\mu^-)$	Tracker	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(\mathrm{GeV}) \sin^{3/2}\theta}$
$H \to b\bar{b}/c\bar{c}/gg$	$\mathrm{BR}(H \to b\bar{b}/c\bar{c}/gg)$	Vertex	$\sigma_{r\phi} = 5 \oplus \frac{10}{p(\mathrm{GeV}) \times \sin^{3/2}\theta} (\mu\mathrm{m})$
$H \to q\bar{q}, WW^*, ZZ^*$	$\mathrm{BR}(H \to q\bar{q}, WW^*, ZZ^*)$	ECAL HCAL	$\sigma_E^{\mathrm{jet}}/E =$ $3 \sim 4\%$ at 100 GeV
$H \to \gamma\gamma$	$\mathrm{BR}(H \to \gamma\gamma)$	ECAL	$\Delta E/E = \frac{0.20}{\sqrt{E(\mathrm{GeV})}} \oplus 0.01$

Table 3.3: Physics processes and key observables used as benchmarks for setting the requirements and the optimization of the CEPC detector.

CEPC CDR

CEPC Software: Architecture

The CEPC experiment is among the first to integrate with Key4hep

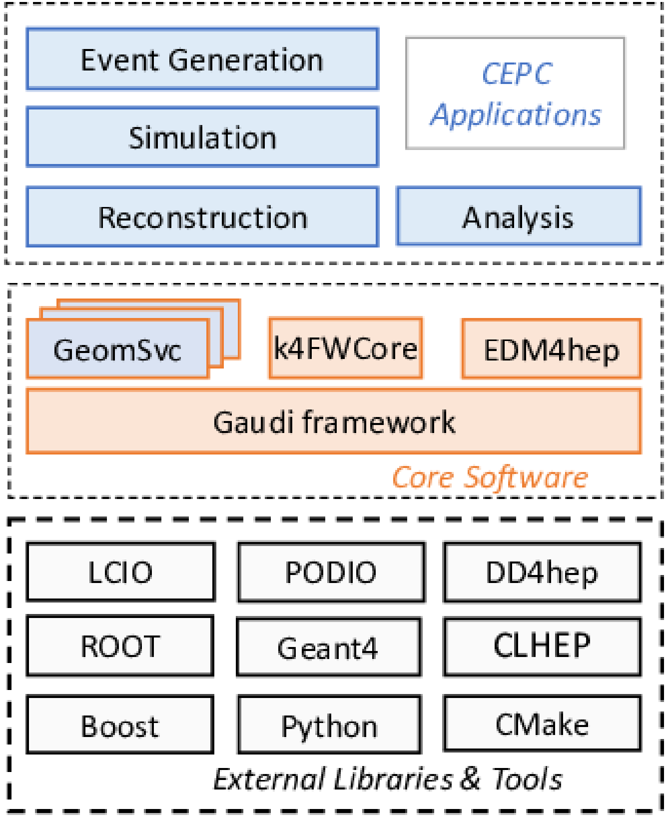
- A common software stack designed for future HEP experiments such as CEPC, CLIC, FCC, and ILC

CEPCSW is organized as a multi-layer structure

- Applications： simulation, reconstruction and analysis
- Core software
- External libraries

The key components of core software include:

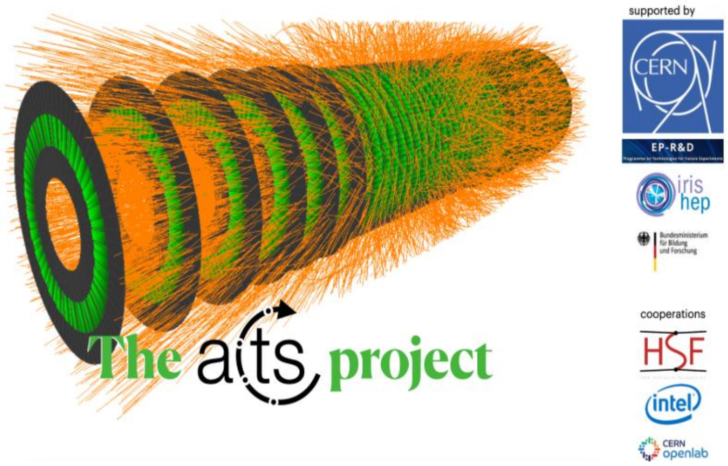
- Gaudi: defines interfaces to all software components
- EDM4hep: generic event data model
- DD4hep: detector geometry description
- CEPC-specific components: GeomSvc, simulation framework, RDFAnalysis, beam background mixing, fast simulation, machine learning interface, etc.



ACTS: Tracking Library

Software development background

- Hardware: Computing is shifting toward multi-core CPUs and diverse accelerators (GPUs, FPGAs).
- ML: Machine learning has become an essential component of high-energy physics experiments.



https://github.com/acts-project

ACTS, A Common Tracking Software

- Open source and experiment-independent toolkit for track reconstruction
- Developed with modern C++ with unit testing and continuous integration

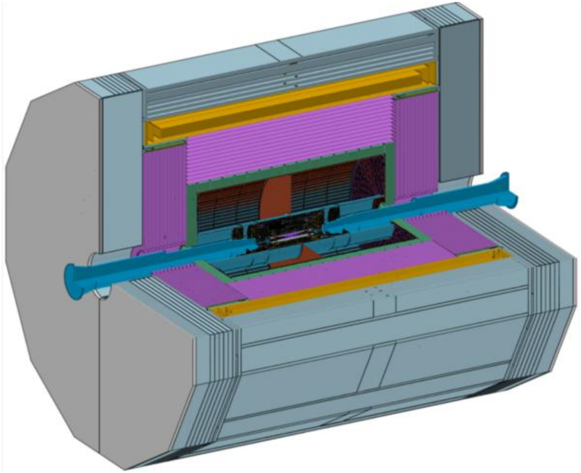
- Several R&D projects within the ACTS ecosystem
  - traccc: GPU R&D line
  - Exa.TrkX: GNN based tracking available
- Four other talks [1][2][3][4] of this workshop also give the applications of acts

Outline

1. Introduction
2. Application of ACTS to CEPCSW
3. Performance
4. R&D

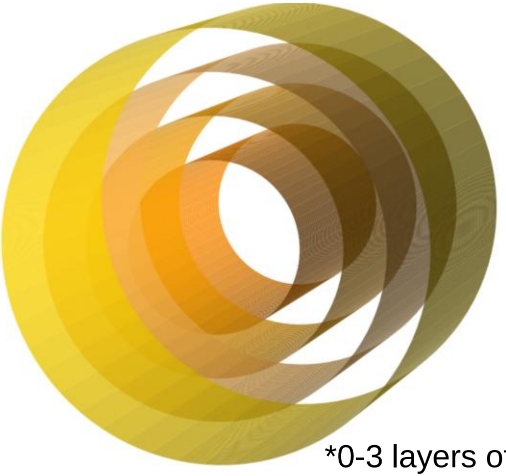
ACTS Geometry Building

- A simplified tracking-optimized geometry is converted from detailed geometry through ACTS' tools.



ACTS material mapping mechanism

acts / Core



*0-3 layers of CEPC VTX

Detailed geometry

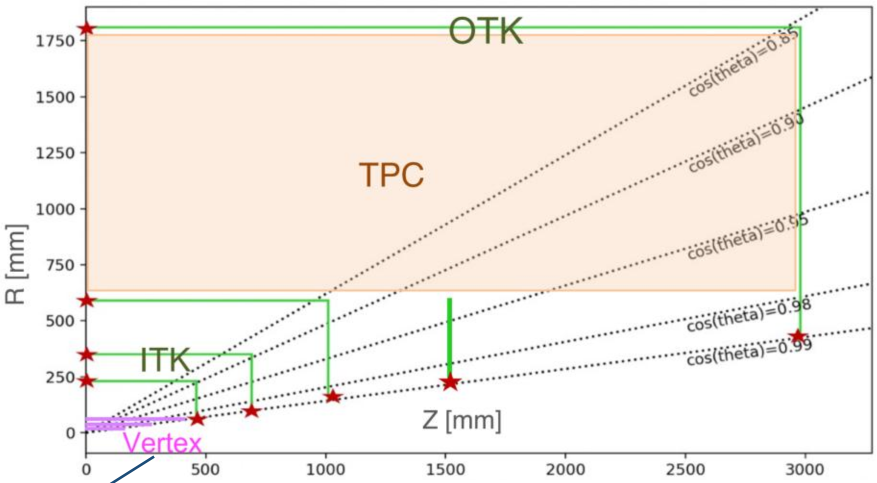
- described by DD4Hep / Tgeo / GeoModel
- Usually interfaced to Geant4
- is unnecessary in track reconstruction

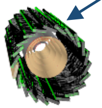
Geometry building in ACTS

- Representing sensitive surfaces
- Simplifying material

ACTS Geometry Building

CEPC Tracking geometry in z-r





Vertex Detector

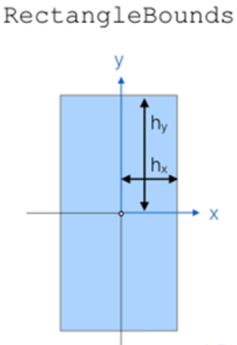
- 4 Cylinder layers
- 1 Double-sided planer layer

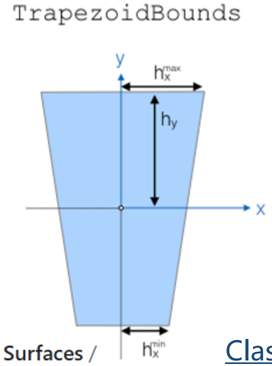
- Vertex Detector
- ITK (Inner Tracker)
- TPC (Time Projection Chamber)
- OTK (Outer Tracker)

Full G4 simulation geometry of CEPCSW is described in DD4hep format

- Convert to ACTS geometry through ACTS TGeo plugin (*DD4hep plugin should also work)
- Barrels (VTX 5th|6th layer & ITK & OTK)
  → Acts::PlaneSurface (RectangleBounds)
- EndCaps (ITK & OTK)
  → Acts::PlaneSurface (TrapezoidBounds)

CEPCSW geometry (DD4hep) $\xrightarrow[\text{TGeo plugin}]{\text{ACTS}}$ ACTS geometry

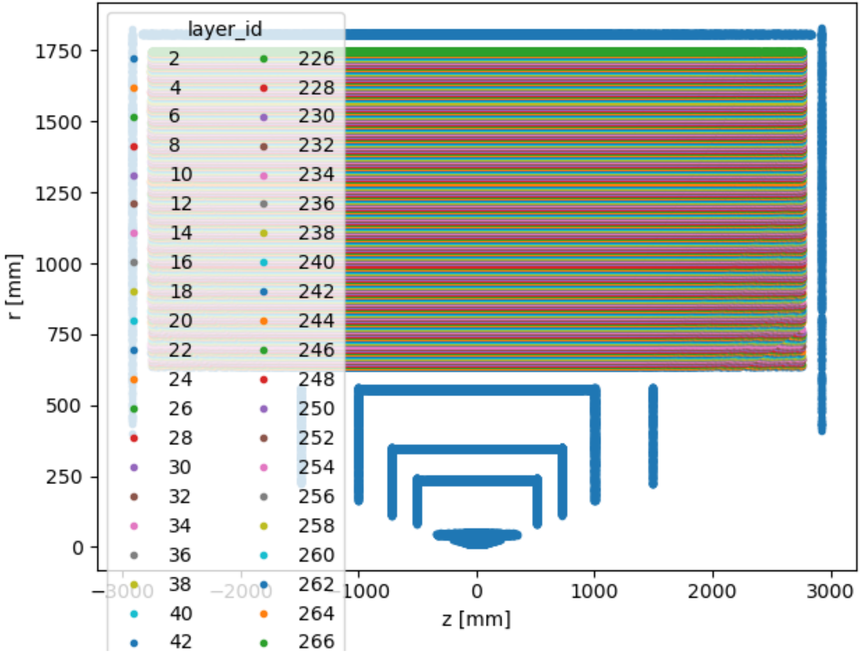




acts / Core / include / Acts / Surfaces /

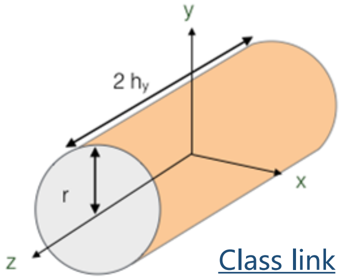
Class link

ACTS Geometry Building



CEPC Tracking geometry in z-r (layer ids in colors)

VTX (1st-4th layers) & TPC
→ Acts::CylinderSurface



Class link

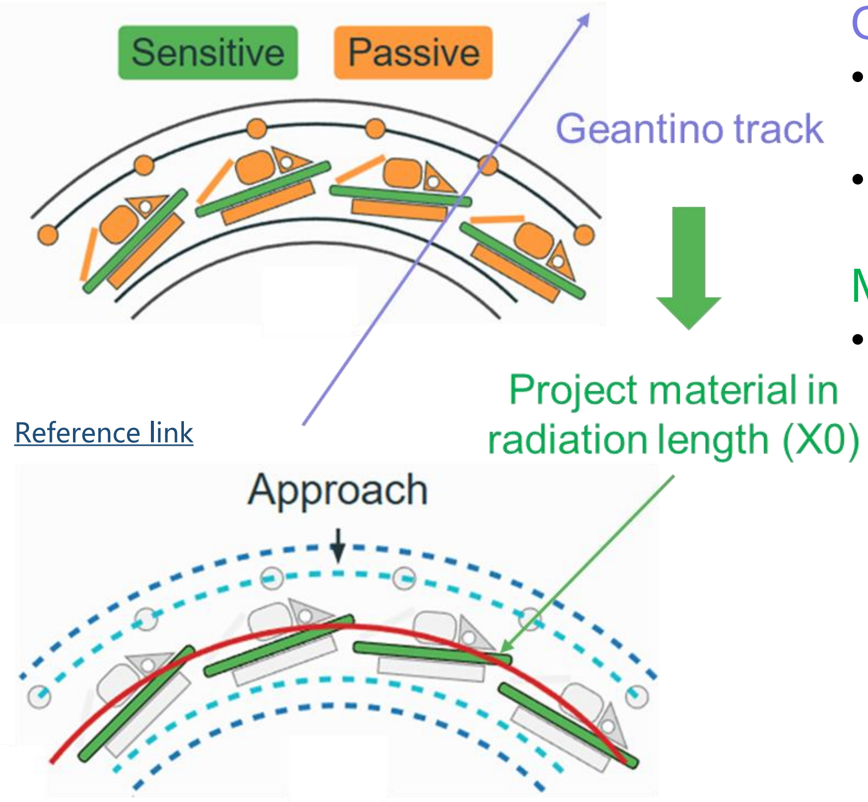
Implementation of ACTS in the TPC (gaseous tracker)

The surfaces required by ACTS are virtually constructed within the TPC gas volume, aligning with the TPC readout layers.

Consists of 223 layers of cylinder surface with a thickness of 5mm

2 Application of ACTS to CEPCSW

Material Mapping



Reference link

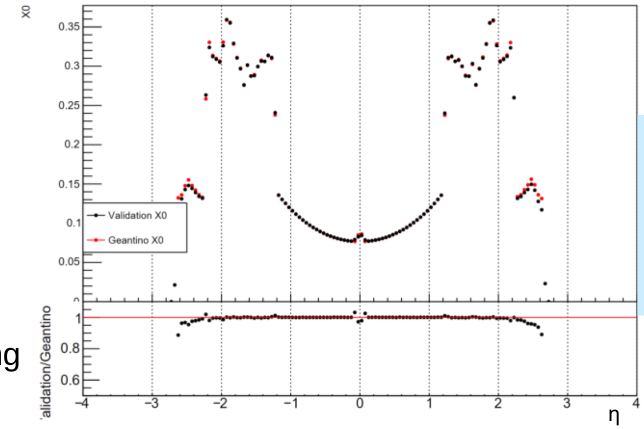
Geant4 simulation using detailed geometry

- The Geant4 simulation employs detailed geometry to simulate particle steps using Geantinos.
- It records the materials traversed by these steps and stores their corresponding radiation lengths (X_0)

Mapping

- Each step is projected onto the nearest sensitive surface, then averaged across multiple events to generate a map.

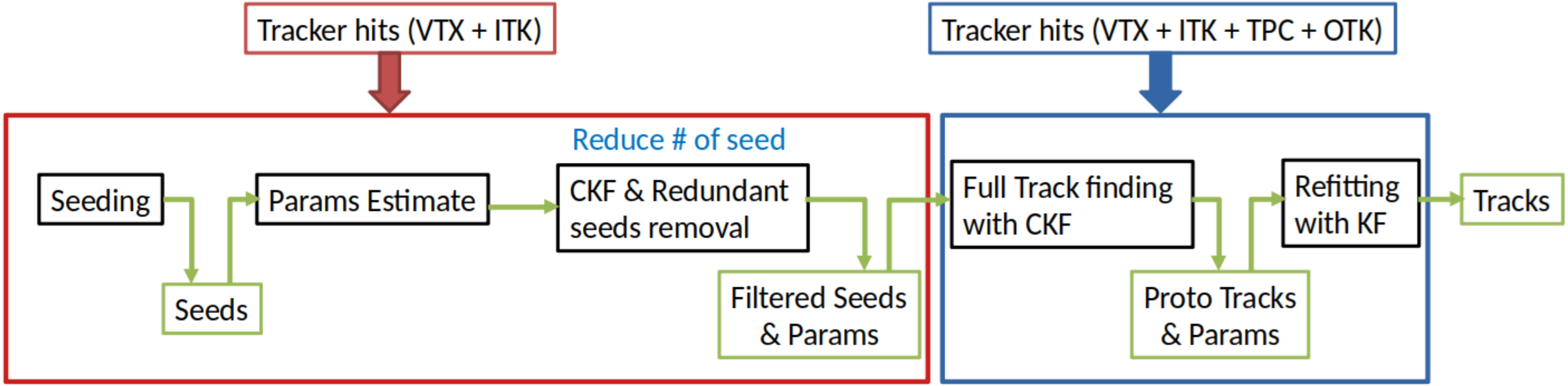
ACTS material mapping allows quasi-exact material modeling



Validation of material mapping for the tracking detector in the CEPC RefDet

2 Application of ACTS to CEPCSW

Tracking chain with ACTS

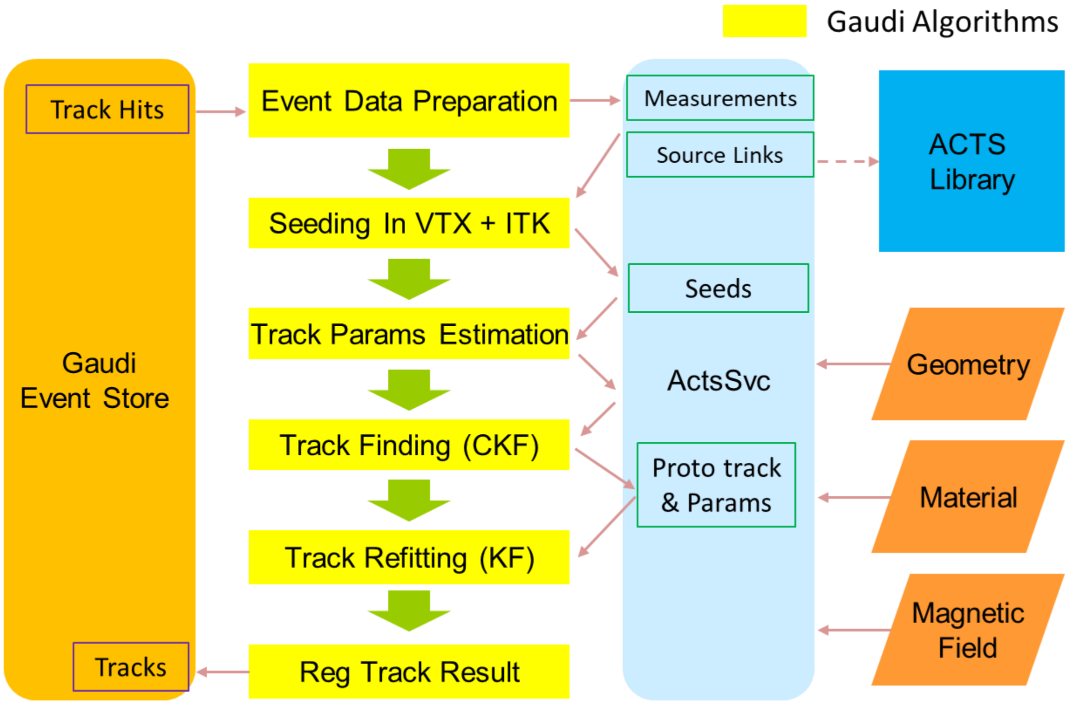


Track finding has two steps

- Silicon Tracking: Track finding in VTX + ITK (reduce # of seed)
  - ACTS forms seeds by combining 3 space points, typically from 3 different detector layers
  - Seeding in VTX + ITK (total 9 layers) will produce ≈ 80 triplets for single track
  - Duplicate seeds are reduced by running CKF and removing the seeds with measurements already associated to found tracks
- Full Tracking: Track finding in VTX + ITK + TPC + OTK
  - With filtered seeds & parameters from silicon tracking

2 Application of ACTS to CEPCSW

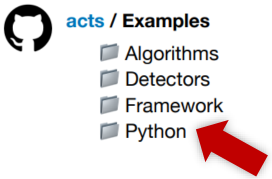
Interface with CEPCSW



Integrate ACTS into the CEPCSW using the Gaudi Algorithms

- Event Data Preparation
  - Retrieves Track Hits from the Gaudi Event Store
  - Convert the hits in EDM4hep format to ACTS' Measurements & Source Links
- Tracking chain algorithms
  - Seeding & params estimation
  - Track finding using ***CKF***
  - Track fitting using ***KF***
- Register tracking results with the Gaudi Event Store

A Gaudi Service ActsSvc was also developed to store the data across the Gaudi Algorithms.



Not intended for production
But showcase how to assemble a track reconstruction chain using the tools from the toolbox

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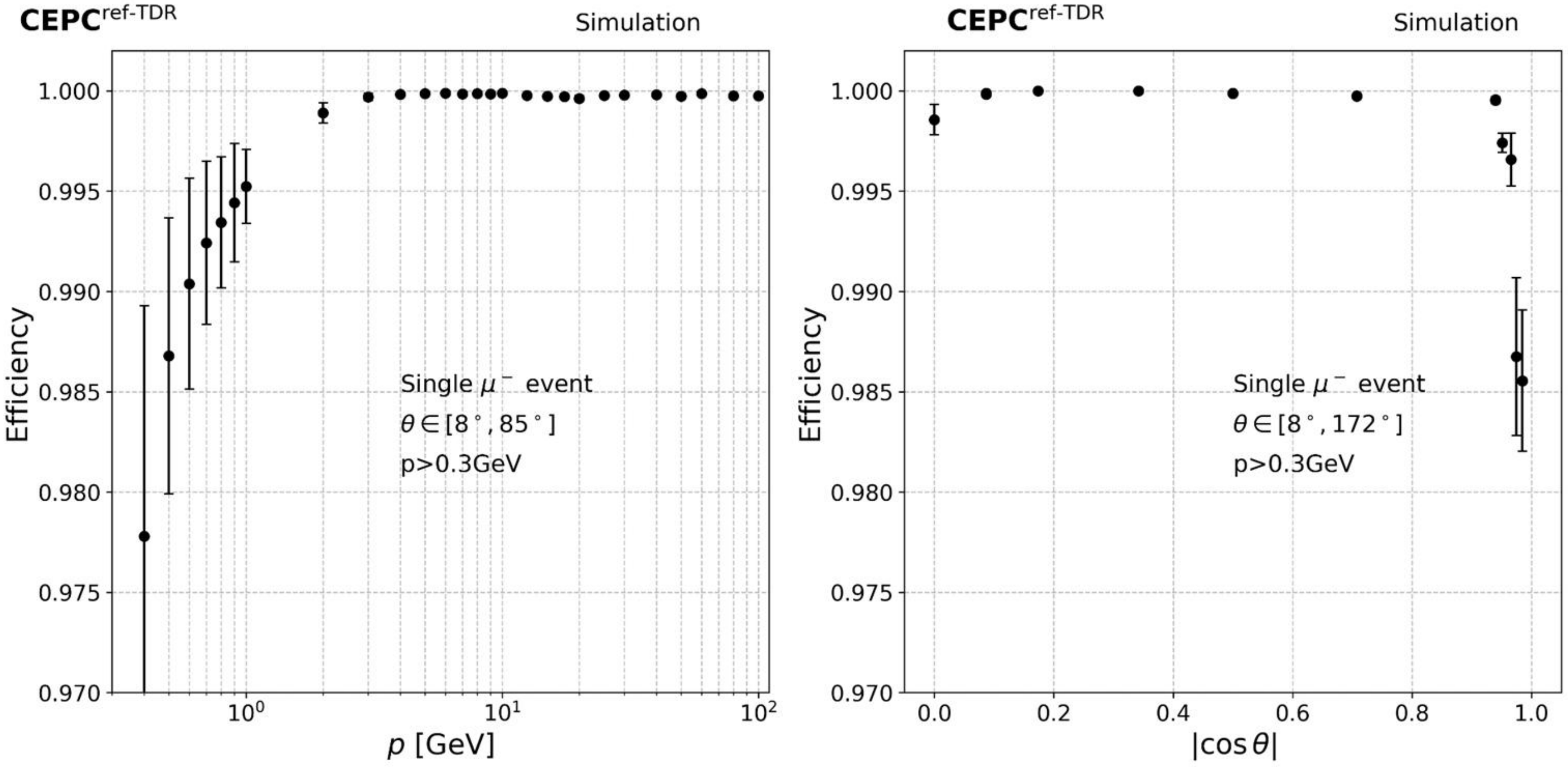
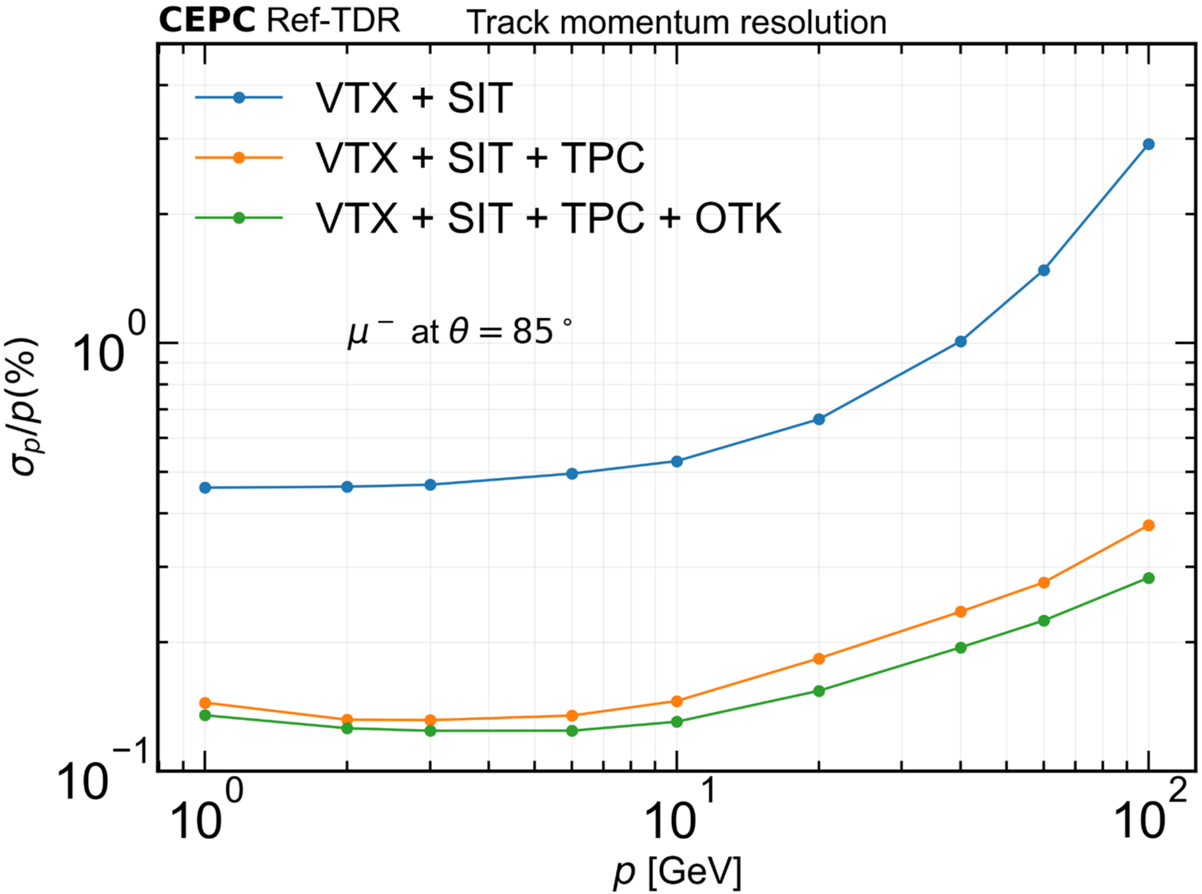
4. R&D

Tracking efficiency



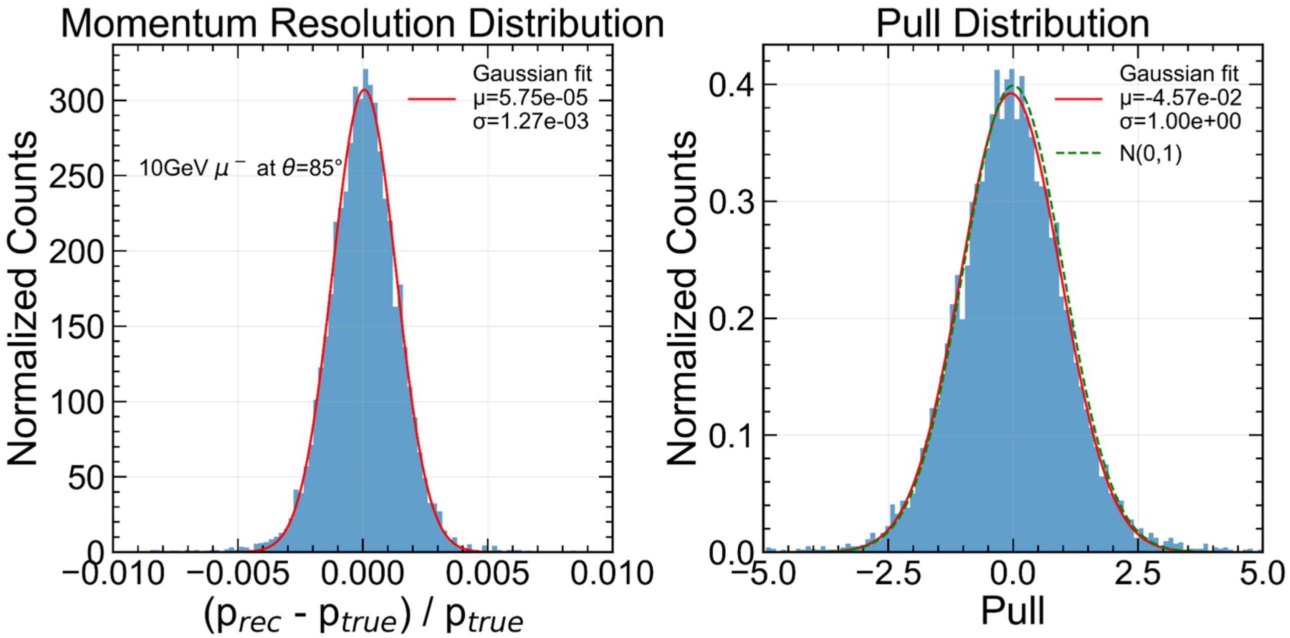
Around the region θ=90°, efficiency drops due to the membrane cathode spanned between two rings in the center of the TPC.

Tracking resolution



The TPC in conjunction with the OTK is able to provide the longest possible radial lever arm for the track fit, improving the resolution at the high momentum region (about 10-20% better than without OTK)

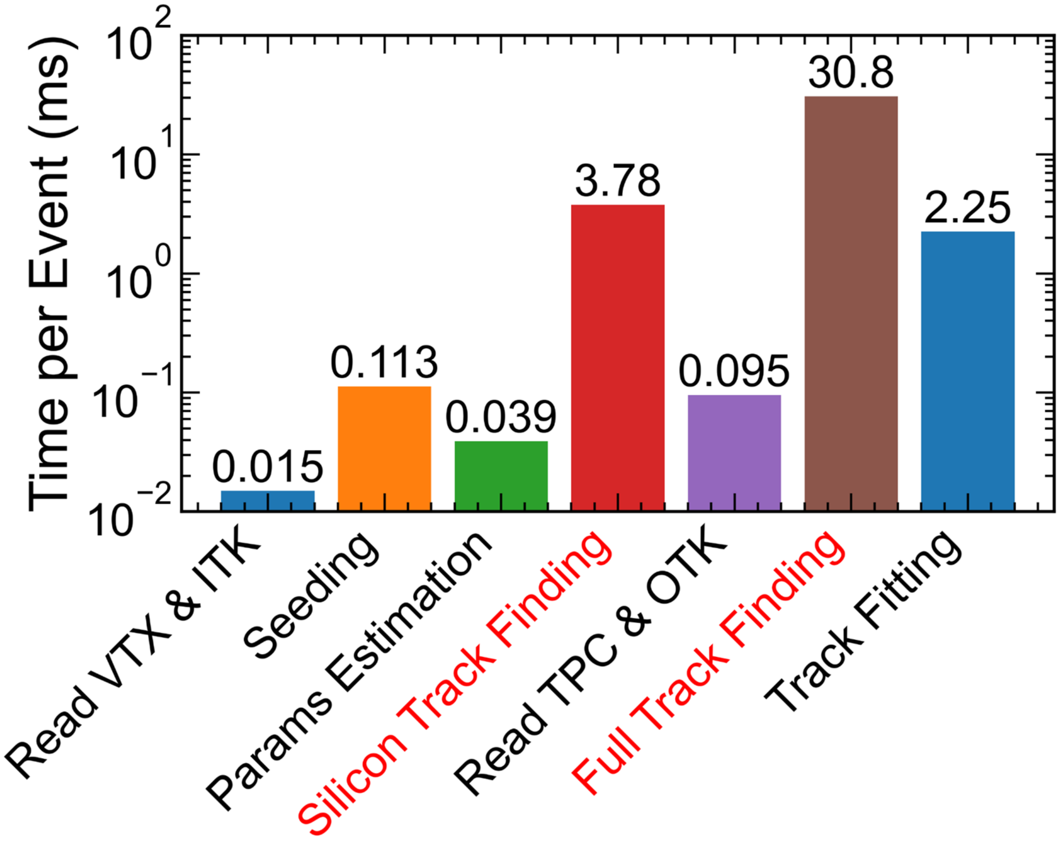
Track fitting validation



Pull distribution shows the uncertainties of momentum provided by ACTS Kalman Fitter (KF) are valid

- The tracking performance achieved with ACTS shows excellent agreement with full detector simulations.

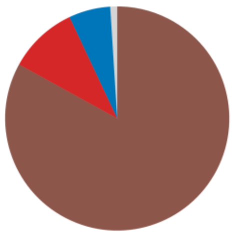
Computing performance



Time cost of reconstruction for single-track events:

- Tested with single thread at:
  - Intel(R) Xeon(R) Silver CPU 4214 @ 2.20GHz

- Total ≈ 37ms/event
- Time cost percentages
  - Full Track Finding 83%
  - Silicon Track Finding 10.2%
  - Track Fitting 6.07%
  - Others 0.73%



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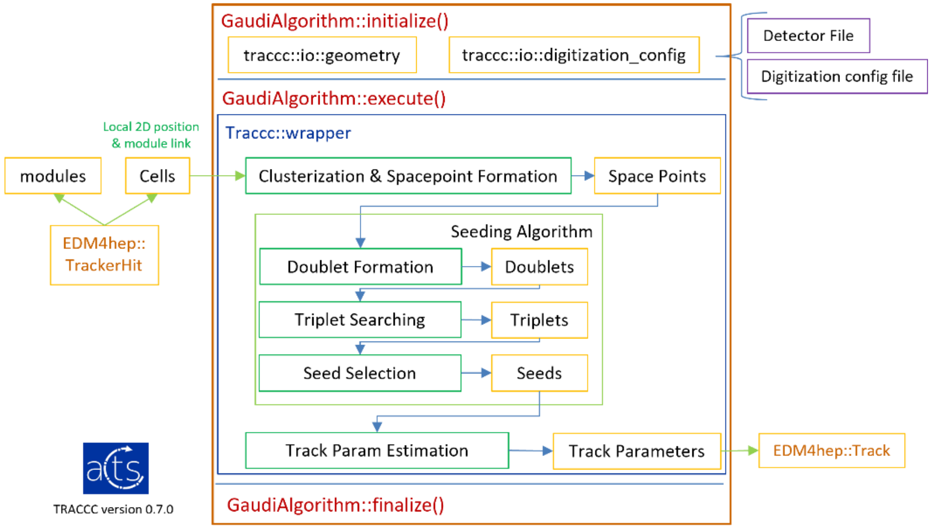
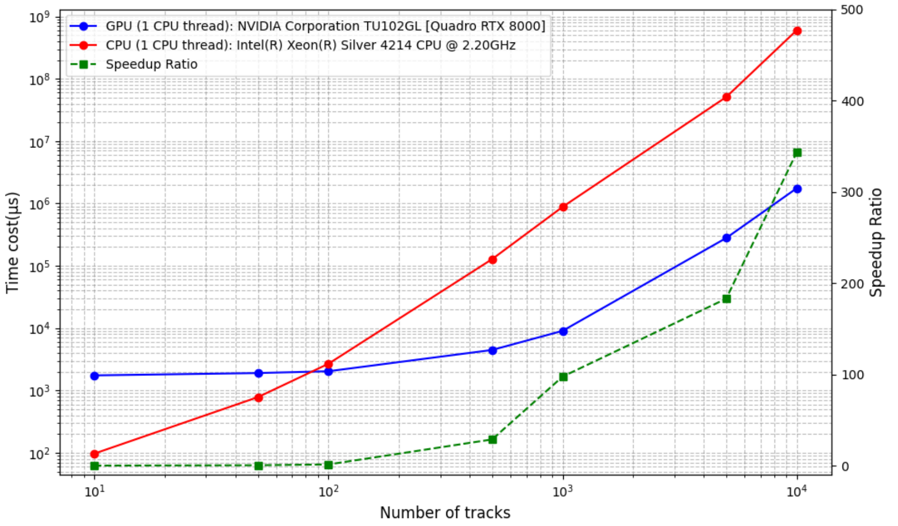
4 R&D

traccc



Apply traccc seeding algorithm in CEPCSW



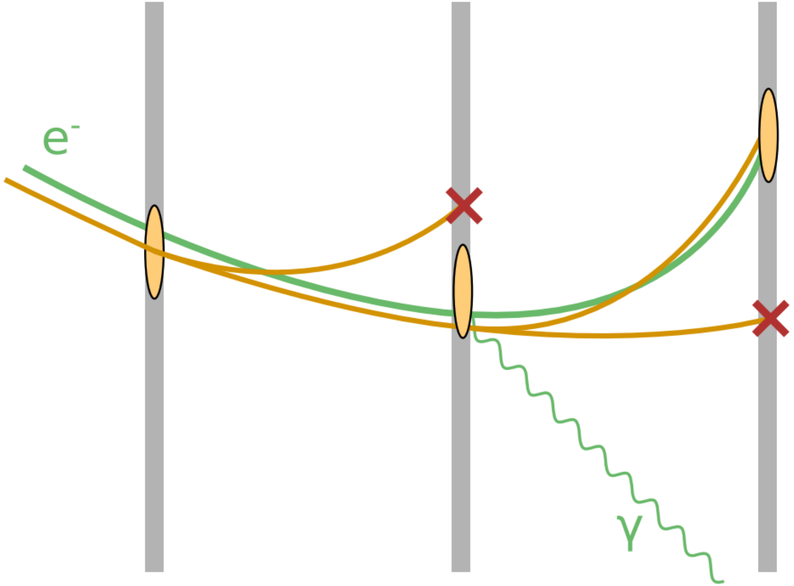
Seeding time comparing CPU & GPU vs # of tracks

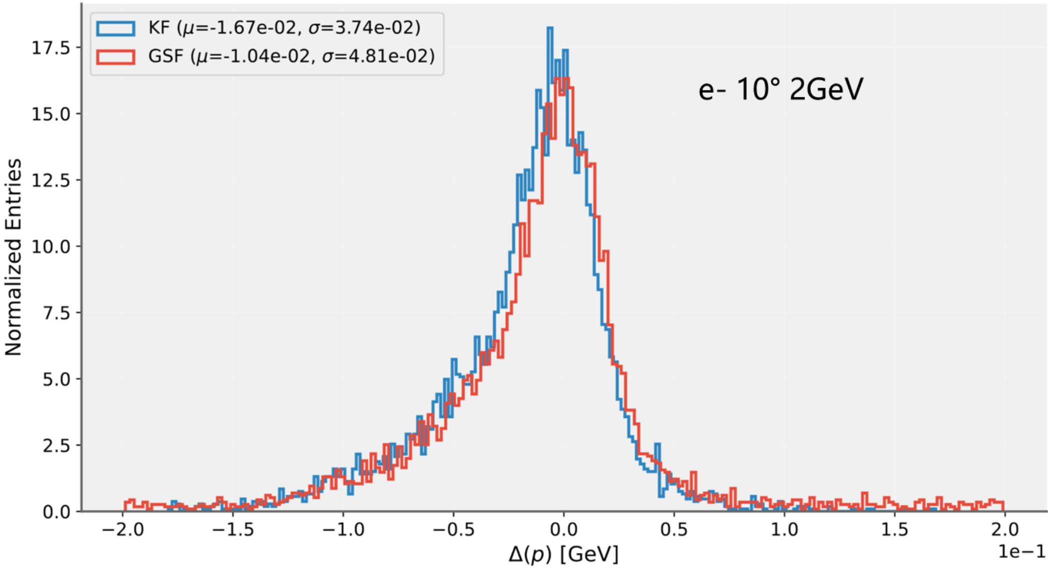
traccc, one of the R&D project of ACTS, provides high-performance parallel tracking software

- Compatible with complex hardware architectures (e.g., CPU, GPU, FPGA)
- Applied in CEPCSW, tested its physical & computing performance, details see link

4 R&D

Gaussian Sum Fitter





p resolution comparison kf & gsf

ACTS provides GSF fitting, an extension of Kalman Filter that can handle non-Gaussian uncertainties

- Models track-state & material effects as Gaussian mixtures

$$f(\vec{x}) = \sum_{i}^{N_{cmp}} w_i p_i(\vec{x})$$

- Used for electron fitting (Brehmsstrahlung is highly non-Gaussian)

Summary

1. ACTS has been successfully integrated into CEPCSW
   - See repository

2. ACTS has been implemented for track reconstruction in the trackers of the ***CEPC RefDet***.
   - Covering a wide range of trackers, e.g. silicon (planar, stitched) and gaseous (TPC)

3. R&D works
   - traccc: implies seeding algorithm in GPU to CEPCSW
   - GSF: implied in electron fitting; no significant improvement due to the thin tracking material

4. Next to do:
   - Further ACTS' GPU & ML implement in CEPCSW

Thank you

Yizhou Zhang[1], Weidong Li[1], Xiaocong Ai[2], Tao Lin[1]

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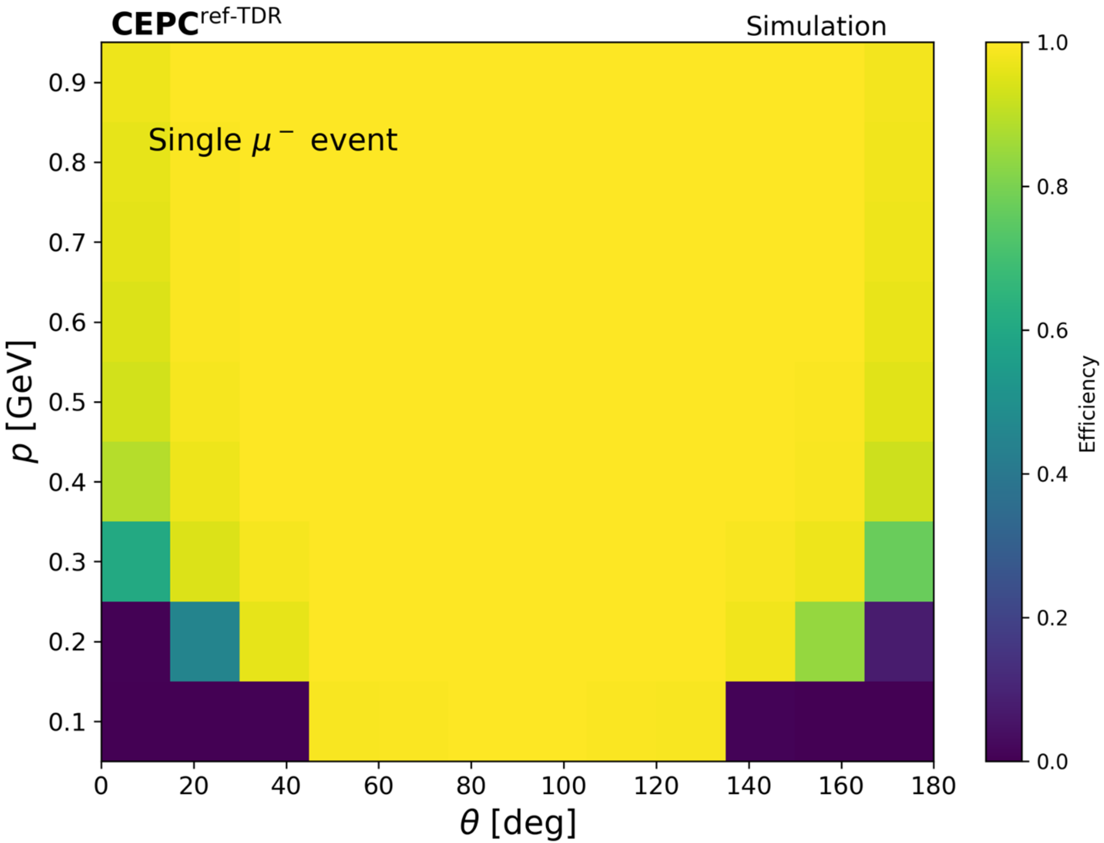
Backup

Tracking efficiency

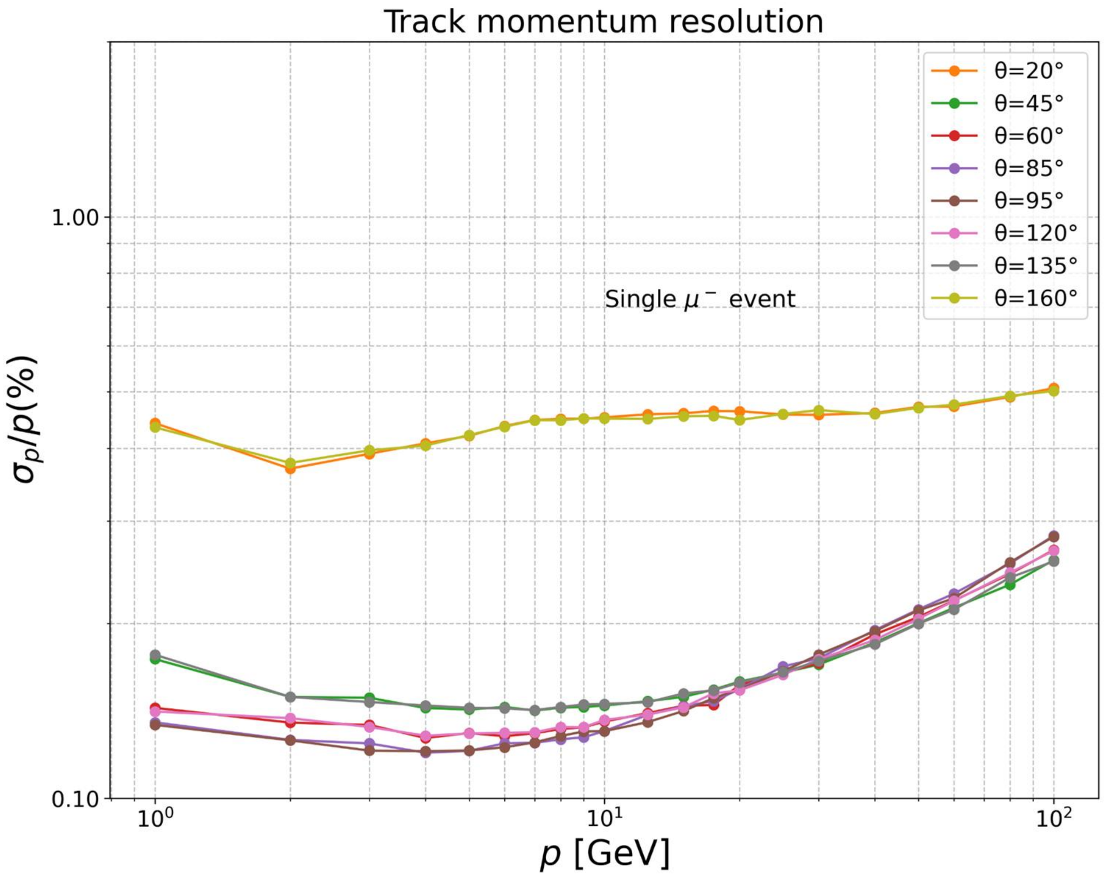


Good efficiency for low momentum tracks as well

- The efficiency of each bin is analysed with fixed p and theta.

3 Performance

Tracking resolution



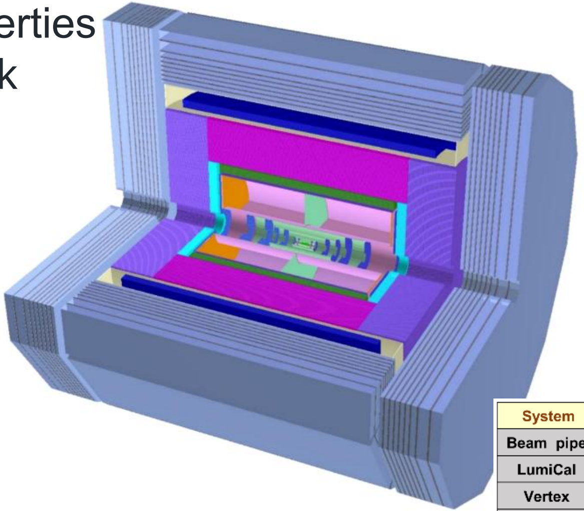
With a theta of 20° or 160°, track hits are mainly distributed on EndCaps.

Momentum resolution is not gaussian distributed at low momentum (≈ 1 GeV)

Circular Electron Positron Collider (CEPC)

The CEPC is a 100 km circular electron-positron collider aiming to

- Precisely measure the Higgs boson's properties
- Study electroweak physics at Z-boson peak
- Will produce:
  - At 250 GeV: Higgs bosons (4×10^6)
  - At 160 GeV: W bosons $(> 10^8)$
  - At 90 GeV: Z bosons $(> 4 \times 10^{12})$



CEPC

System	Technologies		
Beam pipe	Φ20 mm		
LumiCal	SiTrk+Crystal		
Vertex	CMOS+Stitching	CMOS Pixel	SOI
Tracker	SPD ITrk		
	Pixelated TPC	PID Drift Chamber	
	AC-LGAD OTrk	SSD OTrk	SPD OTrk
		LGAD ToF	
ECAL	4D Crystal Bar	Stereo Crystal Bar	
	GS+SiPM	PS+SiPM+W	SiDet+W
HCAL	GS+SiPM+Fe	PS+SiPM+Fe	RPC+Fe
Magnet	LTS	HTS	
Muon	PS Bar+SiPM	RPC	
TDAQ	Conventional	Software Trigger	
BE electr.	Common	Independent	

R

Baseline | For Comparison

Software development background

- Hardware: Computing is shifting toward multi-core CPUs and diverse accelerators (GPUs, FPGAs).
- ML: Machine learning has become an essential component of high-energy physics experiments.

Acts: A Common Tracking Software

Open source and experiment-independent toolkit for track reconstruction

- https://github.com/acts-project

- Developed with modern C++ with unit testing and continuous integration

supported by

cooperations

- Several R&D projects within the ACTS ecosystem
  - traccc: GPU R&D line
  - Exa.TrkX: GNN based tracking available
  - …

- Four [other talks] that can be found also intro the application of acts

CEPC tracker parameters setup

The truth hits are smeared by tentative tracker resolution for now:

Vertex Detector

- **1st-4th layer** RPhi, Z = [5 µm, 5 µm]
- **5th & 6th layer** U, V = [5 µm, 5 µm]

ITK (Inner Tracker)

- **Barrel** U, V = [8 µm, 40 µm]
- **Endcap** U, V = [8 µm, 40 µm]

TPC (Time Projection Chamber)

- RPhi, Z = [144 µm, 40 µm]

OTK (Outer Tracker)

- **Barrel** U, V = [10 µm, 1 mm]
- **Endcap** U, V = [10 µm, 1 mm]

Tracking Requirements

High-precision measurement places stringent demands on tracking, requiring

- near ***100%*** tracking efficiency
- momentum resolution of approximately ***0.1%***.