Application of TRACCC seeding to the CEPC vertex detector

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Outline

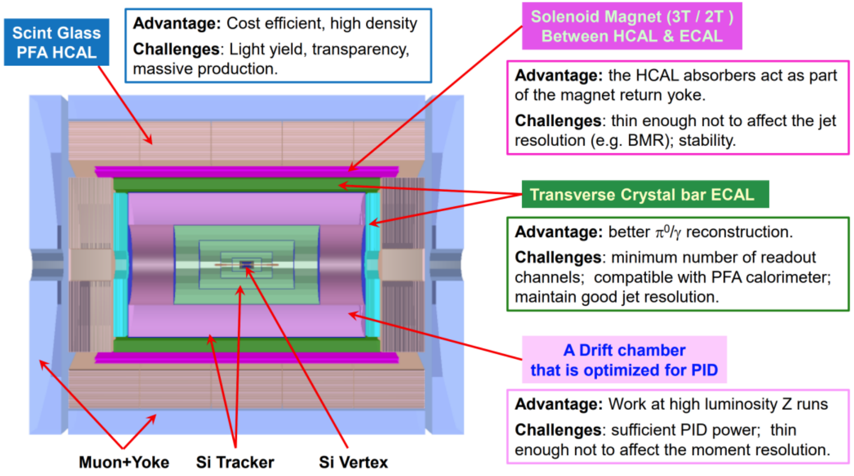
1 Introduction — Circular Electron Positron Collider (CEPC)

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 ($> 4 \times 10^{12}$)

The conceptual design report (CDR) has been completed in Oct. 2018.

- High track efficiency (~100%)
- High momentum resolution (~0.1%)



Schematic view of CEPC's 4th Concept Detector

The 4th conceptual detector was proposed on the basis of the CEPC CDR

- is characterized by a combination of silicon detectors and drift chamber designed to provide both tracking and PID for charged particles

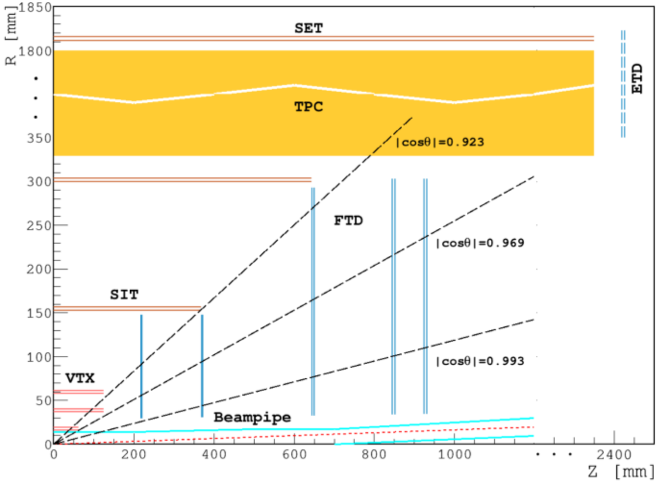
Vertex Detector of CEPC

CEPC Vertex Detector

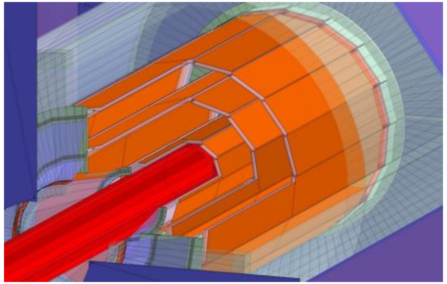
- is the innermost tracker playing a dominant role in determining the vertices of a collision event.
- Covers:
  - ➢ radial range from 16 mm to 60 mm
  - ➢ Z range from -125mm to 125mm

The baseline layout of the Vertex Detector consists of

- 6 concentric cylindrical layers of high spatial resolution silicon pixel sensors.
- Two layers of silicon pixel sensors are mounted on both sides of each of three ladders to provide 6 space points.



Layout of the CEPC baseline tracker
The VTX is located closest to the interaction point.



Schematic view of CEPC Vertex Detector
Only the silicon sensor sensitive region (in orange) is depicted.
The vertex detector surrounds the beam pipe (in red).

	R (mm)	$\|z\|$ (mm)	$\|\cos\theta\|$	σ (μm)
Layer 1	16	62.5	0.97	2.8
Layer 2	18	62.5	0.96	6
Layer 3	37	125.0	0.96	4
Layer 4	39	125.0	0.95	4
Layer 5	58	125.0	0.91	4
Layer 6	60	125.0	0.90	4

Layers of CEPC Vertex Detector

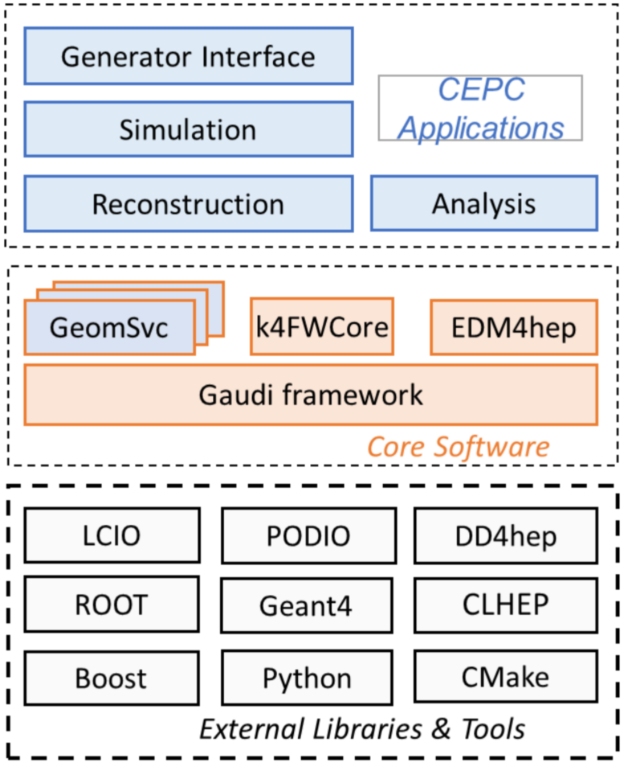
CEPC software (CEPCSW) environment

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/Gaudi Hive: defines interfaces to all software components and controls their execution
- EDM4hep: generic event data model
- k4FWCore: manages the event data
- DD4hep: geometry description
- CEPC-specific components: GeomSvc, detector simulation, beam background mixing, fast simulation, machine learning interface, etc.



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

1 Introduction

Challenges for tracking in the CEPC Vertex Detector

1. Piling-up of multiple events

- The size of detector time window (117 pile-up for $t\bar{t}$)is determined by DAQ

2. High beam-related background

- particularly in Z energy region

	Higgs	Z	W	$t\bar{t}$
SR power per beam (MW)	50			
Bunch number	446	13104	2162	58
Bunch spacing (ns)	346.2 (×15)	23.1 (×1)	138.5 (×6)	2700.0 (×117)
Train gap (%)	54	9	10	53
Luminosity per IP (10^{34} cm^{-2} s^{-1})	8.3	192	26.7	0.8

Requirements: Physical Event Rate

3. Reuse of offline tracking algorithm for the purpose of online high level trigger

- Same rec algorithm: offline environment & online Event Filter

Conclusion:

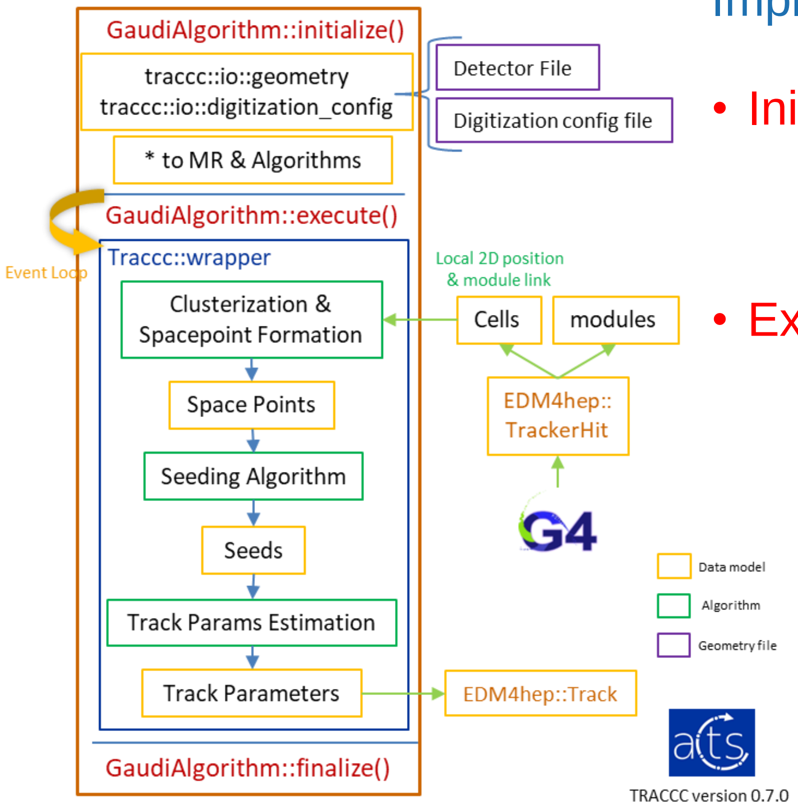
- huge # of hits & background / event:
  - ➢ high demand on track recognition
  - ➢ substantial computational load

→ heterogeneous computing (e.x. TRACCC) and parallelization techniques are required.

* This contribution mainly focuses on:
  - the implementation of seeding algorithm for the vertex detector (VTX), based on TRACCC, in the CEPCSW environment.

Outline

2 Integration of TRACCC with CEPCSW



Gaudi Algorithm using TRACCC reconstruction

Implement a Gaudi algorithm for seeding

- **Initialize():**
  - Read the detector file and digitization config file
  - Initialize the memory resource and the algorithms
- **Execute():**
  - For each event, read hits and run the algorithms
    - ➢ EDM4hep::TrackerHit is converted to Cells & modules
    - ➢ 👆 will only converted to Cells in TRACCC v0.16.0
- Since CEPCSW and TRACCC are using different compilers (Clang, GCC), respectively
  - ➢ Develop a wrapper for TRACCC SYCL algorithms
- Algorithms includes:
  - ➢ Clusterization & Spacepoint Formation (only CPU)
  - ➢ Seeding Algorithm
  - ➢ Track Params Estimation

Outline

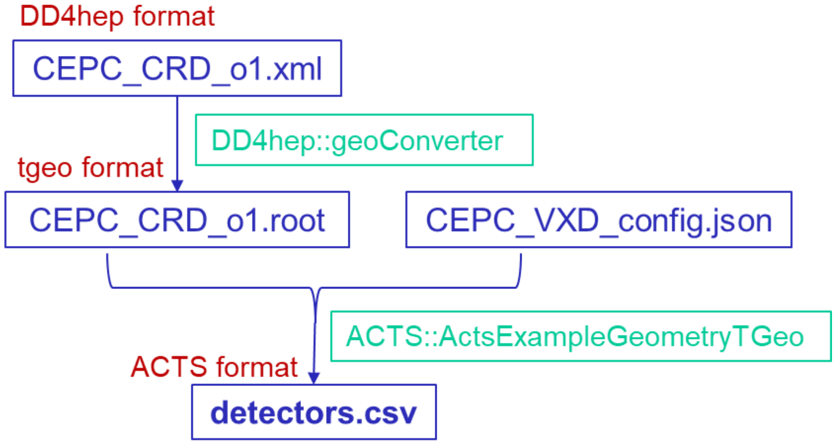
Geometry conversion

Geometry are prepared using various ACTS tools

1. Convert the CEPC VTX geometry file (in DD4hep format) to TGeo format

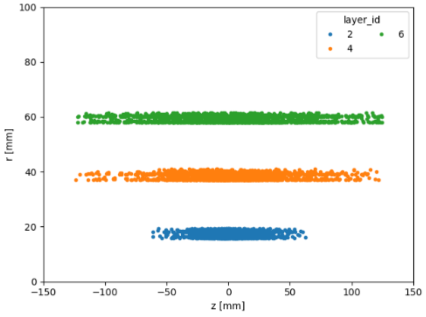
2. The geometry file is translated into Acts::Surface objects using Acts::TGeoLayerBuilder, and is exported to a detector file by Acts::CsvTrackingGeometryWriter.

3. A digitization config file is written to provide the segmentation information of each surface.

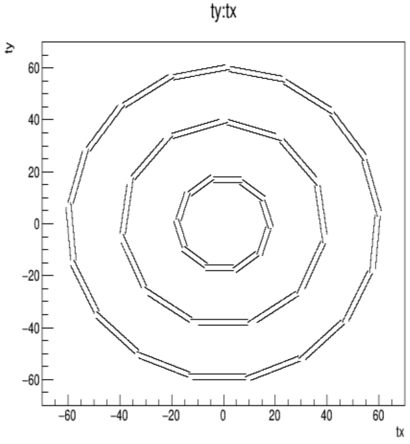


Verification:

Use Fast ATLAS Track Simulation (FATRAS) & ACTS' digitization tool to produce full simulation information and generate cells.



Gid of fatras of ACTS



X-Y projection of VTX

Data model conversion

Cell ID conversion between EDM4hep & TRACCC

- CEPCSW cell id needs to be converted into the TRACCC gid to retrieve correct geometry

CEPCSW cell id:

Layer: {0,1,2,3,4,5} # Indicate 6 layers from inside to outside
Module: { L0: 0-9, L1: 0-9, L2: 0-10, L3: 0-10, L4: 0-16, L5: 0-16}
Indicate ladders in the φ direction
Sensor: 0
Barrelside: 1 for z > 0 else -1
one ladders has 2 sensors separated by z

```
uint64_t barrel_sign = (m_barrelside == 1) ? 1 : 2;
uint64_t acts_volume = VXD_acts_volume_id;
uint64_t acts_boundary = 0;
uint64_t acts_layer = 2 * (m_layer >> 1) + 2;
uint64_t acts_approach = 0;
uint64_t acts_sensitive = VXD_NumOfSensors_per_layer[m_layer >> 1] * (m_layer & 1)
                        + 2 * m_module + barrel_sign;

// set acts geometry identifier
Acts::GeometryIdentifier moduleGeoId;
moduleGeoId.setVolume(acts_volume);
moduleGeoId.setBoundary(acts_boundary);
moduleGeoId.setLayer(acts_layer);
moduleGeoId.setApproach(acts_approach);
moduleGeoId.setSensitive(acts_sensitive);
```

Converter for VXD gid

TRACCC gid:

Volume: {3}
Boundary: 0
Layer: {2, 4, 6} # adjacent layers are treated as the same layers
Approach: 0
Sensitive: {L2: 1-40, L4: 1-44, L6:1-68}
The sensitive counts from z>0 to z<0, then counts in φ direction (the order is same to CEPC), and then counts from inner to outer layers.

Cells local position:

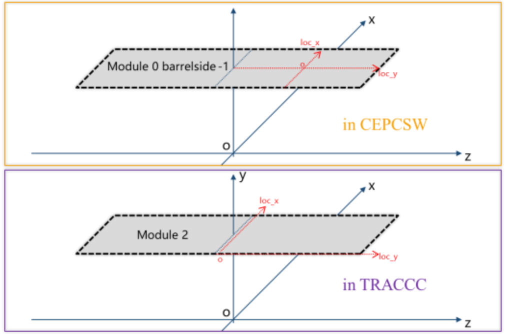
CEPCSW:

- take center point as the origin

TRACCC

- use the lower left corner as the origin.

So the cells' local coordinates need to be modified.



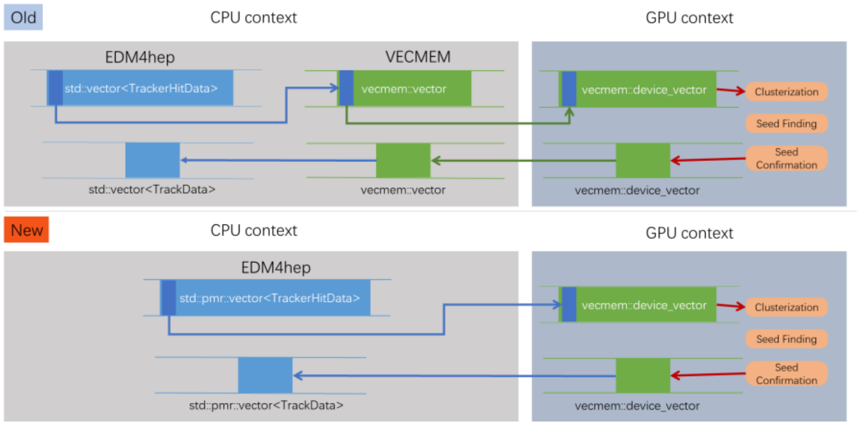
Adjust the local coordinates
for the difference between CEPCSW & TRACCC

3 Geometry & EDM

Common memory for EDM4hep & VecMem

We want TRACCC to use hits data from EDM4hep directly !!

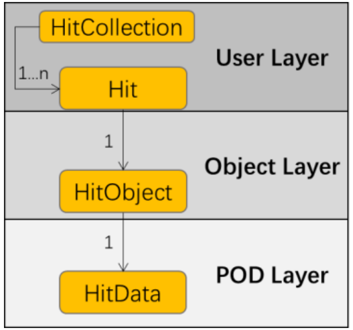
- TRACCC uses VecMem as the vectorised data model across multiple device types.
- EDM4hep and VecMem may use the same storage format (std::pmr::vector), so TRACCC can directly use the hit data with no data-copy.



Modified data transfer process

Modify the data storage format of PODIO

EDM4hep is generated by PODIO, so we modify the DataContainer of PODIO.



Layout of the PODIO storage format

Add Collection layer interfaces:

```
std::pmr::vector<{{ class.bare_type }}Data> data()
```

Add CollectionData layer interfaces:

```
{{ class.bare_type }}DataContainer getdata();
```

Modify the DataContainer storage format (vector → pmr::vector)

```
using {{ class.bare_type }}ObjPointerContainer = std::deque<{{ class.bare_type }}Obj*>;
using {{ class.bare_type }}DataContainer = std::pmr::vector<{{ class.bare_type }}Data>;
```

We add interfaces to get pmr::vector directly.

3 Geometry & EDM

Customized EDM4hep data collection

- Define a data collection whose member is completely the same as the EDM of TRACCC
- So we can directly use edm4hep::ACTSCells as the input of TRACCC.

```
#------------  ACTSCells
edm4hep::ACTSCells:
  Description: "Cells for reconstruction in TRACCC Project"
  Author: "Yizhou Zhang, IHEP"
  Members:
    - uint32_t channel0        //channel0
    - uint32_t channel1        //channel1
    - float activation         //activation
    - float time               //time
    - uint32_t module_link     //module_link
```

Modified edm4hep.yaml

Verification

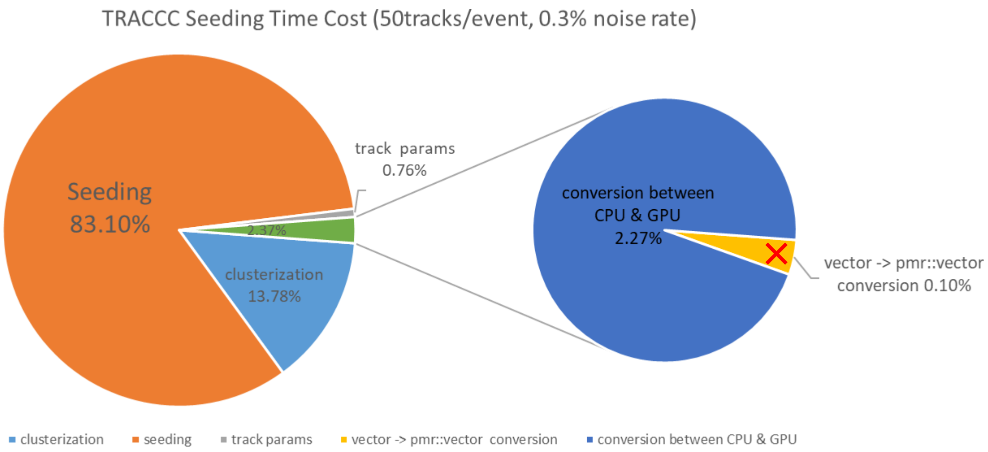
- Now TRACCC can directly read the simulated hits from Geant4 which is stored in EDM4hep format
- No non-essential data-copy is needed

In CEPCSW alg

In TRACCC alg

```
Running Seeding on device: Quadro RTX 8000
Initializing ...
EventLoopMgr      WARNING Unable to locate service "EventSelector"
EventLoopMgr      WARNING No events will be processed from external input.
ApplicationMgr       INFO Application Manager Initialized successfully
ApplicationMgr       INFO Application Manager Started successfully
TracccRun            INFO begin execute TracccRun
TracccRun            INFO reading hits from csv
TracccRun            INFO the size of the csv's cells vector: 199547
TracccRun            INFO creating edm4hep::ACTSCellsCollection
TracccRun            INFO the address of the cells vector: 3963cf0
TracccRun            INFO the size of the cells vector: 199547
TracccRun            INFO running traccc
the address of the cells vector: 3963cf0
the size of the cells vector: 199547
Traccc Success
==>Elapsed times...
             Clusterization (sycl)  5 ms
                   Seeding (sycl)  4 ms
               Track params (sycl)  0 ms
                        Wall time  11 ms
TracccRun            INFO event 0 success
```

The address of pmr::vector does not changed.

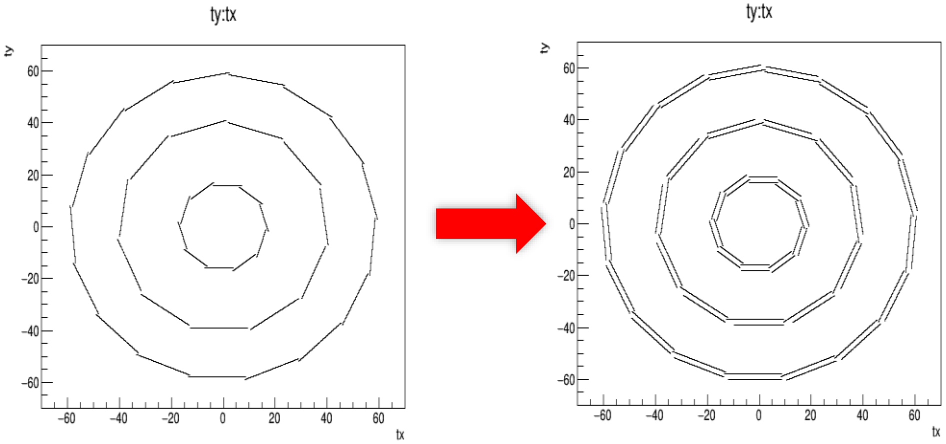


Reduce time overhead of vector → pmr::vector conversion

Outline

4 Extension of seeding algorithm

6-layers seeds finding



CEPC VTX detector:

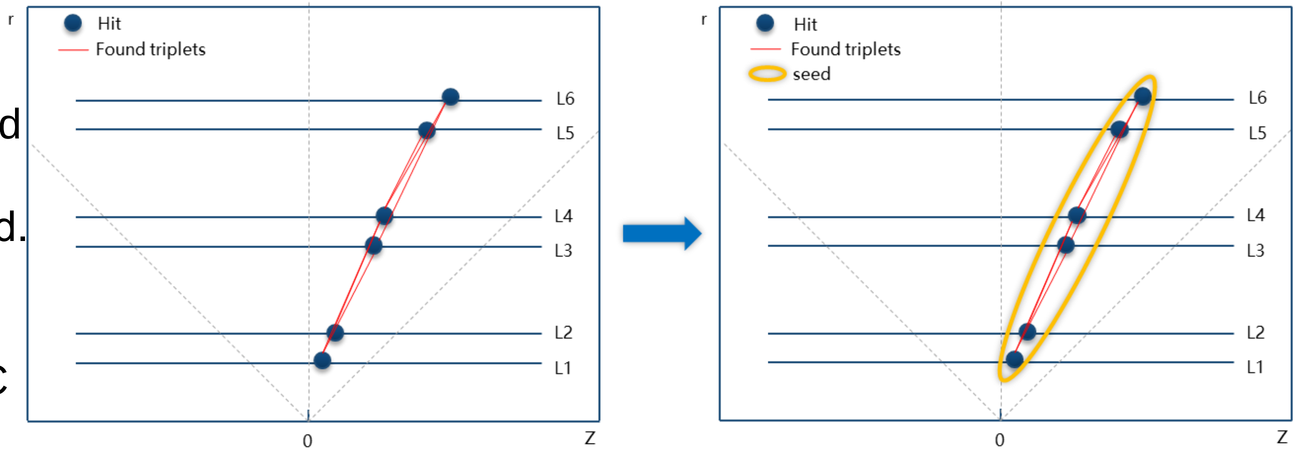
- Two sides of each layer have sensors
- A single seed contains 6 space points

Default TRACCC seeding alg:

- creates 3-space-point seeds

→ The seeding alg needs to be extended for 6-space-points case.

Seed Formation

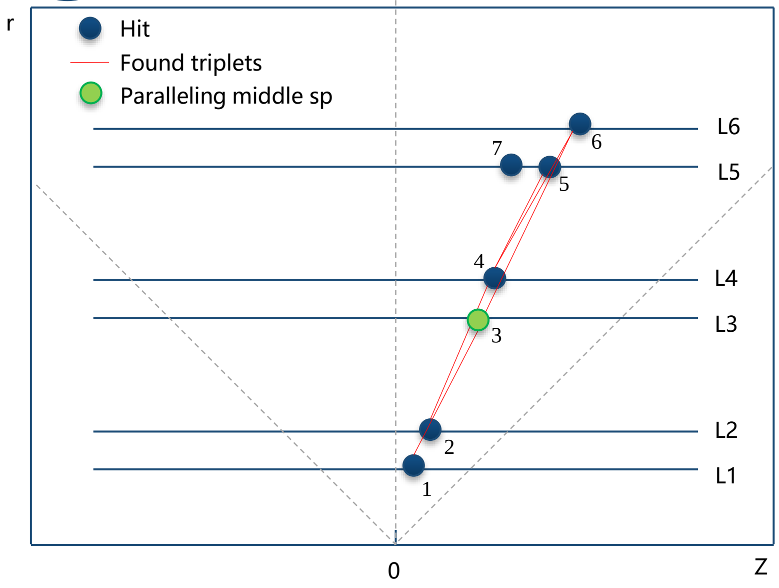


Seed Formation Alg:

After seeding, combine the found triplets that sharing the same space-points into a "bigger" seed.

We have implemented Seed Formation algorithm in TRACCC

4 Extension of seeding algorithm



In GPU

Example:
Paralleling for hit 3 ☞

	bottom	middle	top
	1	3	5
lowest d_0	1	3	6
	1	3	7
	2	3	5
	2	3	6
	2	3	7

Bot_inner	Bot_outer	Mid_inner	Mid_outer	Top_inner	Top_outer
1	2	3	3	5	6

{1, 2}
1.radius() < 2.radius()

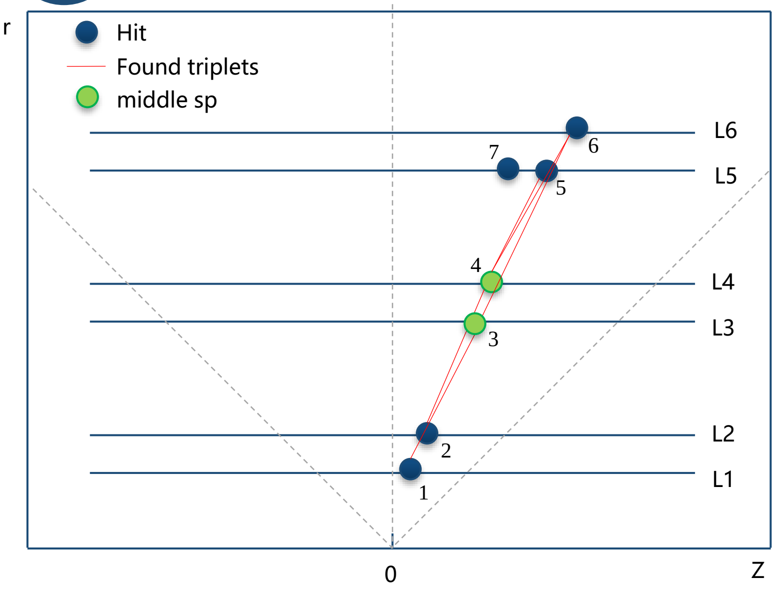
{5, 6} | {7, 6}
5.radius() < 6.radius()

6-layers seeds finding: Seed Formation steps in GPU

For each middle space point in parallel:

1. pick the triplet with lowest impact params (d_0) among all triplets where the middle sp is located
2. find the bottom sp & top sp that are closest to the bottom sp & top sp of the current triplet
3. form a new seed of 5 points and sort them according to their radius

4 Extension of seeding algorithm



In CPU

For hit 3

Bot_inner	Bot_outer	Mid_inner	Mid_outer	Top_inner	Top_outer
1	2	3	3	5	6

For hit 4

\+

Bot_inner	Bot_outer	Mid_inner	Mid_outer	Top_inner	Top_outer
1	2	4	4	5	6

Bot_inner	Bot_outer	Mid_inner	Mid_outer	Top_inner	Top_outer
1	2	3	4	5	6

{3， 4}
3.radius() < 4.radius()

6-layers seeds finding: Seed Formation step in CPU

Iterate through all new 5-point seeds:

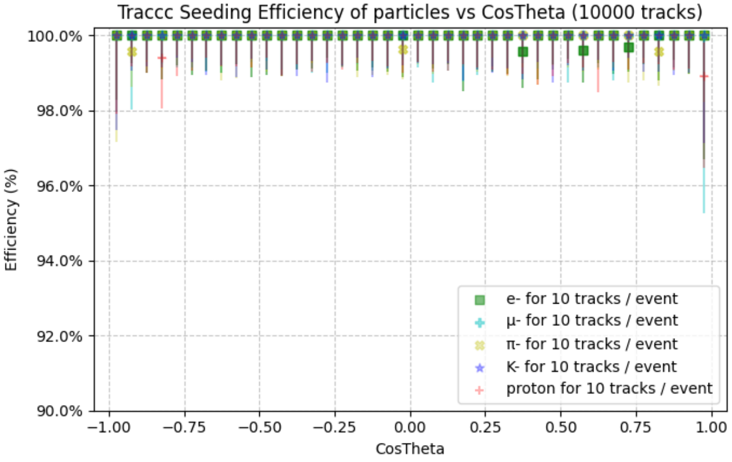
- if two seeds have the same bottom sp & top sp, merge both into hexaplets (6-layer seeds)

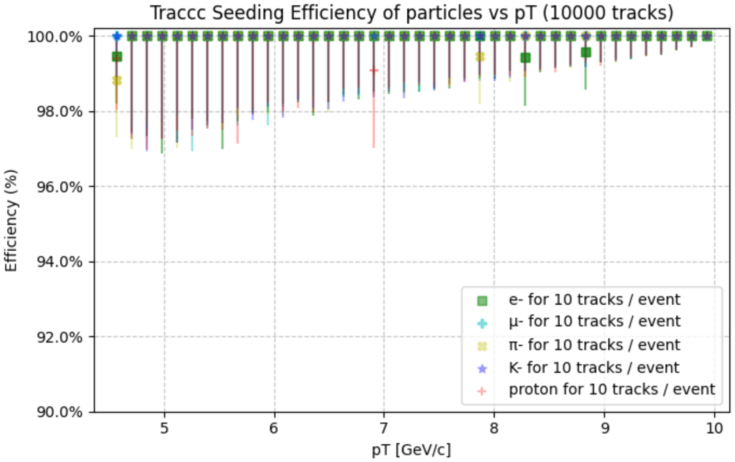
Outline

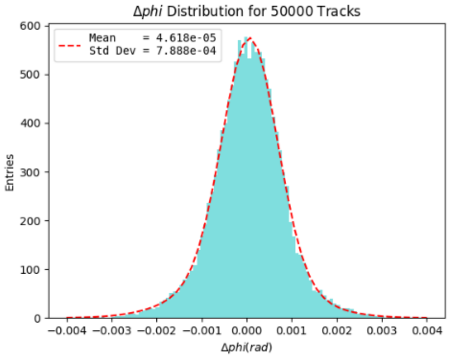
Seeding efficiency with different particles

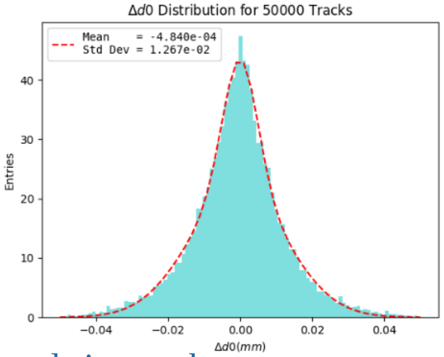
Particle: mu-/pi-/e-/K-/proton   Energy: 10 GeV
Number of events: 1000 Number of tracks per event: 10

- Good seed: half space-points of the seed are from the same particle.
- Pick tracks with polar angle |cosθ| < 0.921 to avoid boundary effects.
- The seeding efficiency is above 99.5% without background for all types of particles
- Resolution of d0/phi is as expected









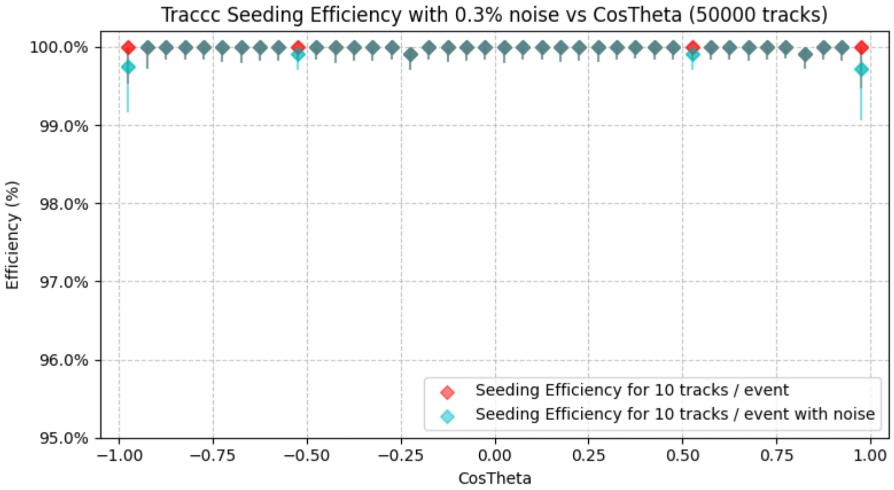
Difference between rec and sim track param

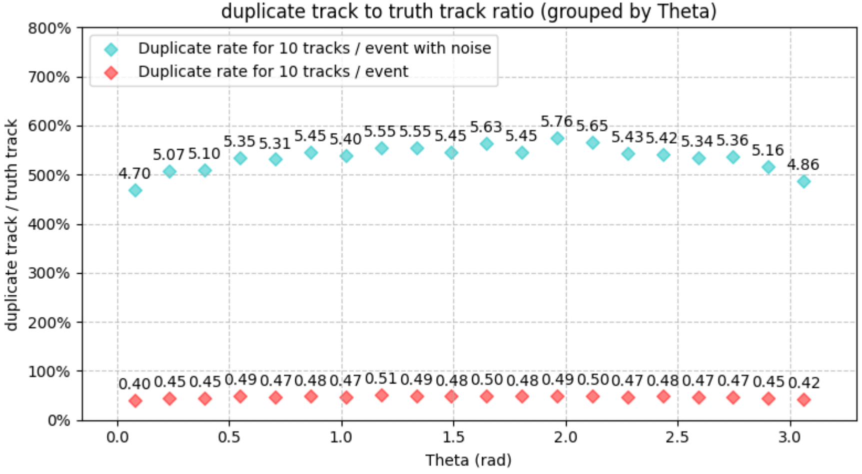
Track parameters include d0, phi (particle: mu-)

Seeding efficiency with background

Particle: mu- Energy: 10 GeV
Number of events: 5000
Number of tracks per event: 10

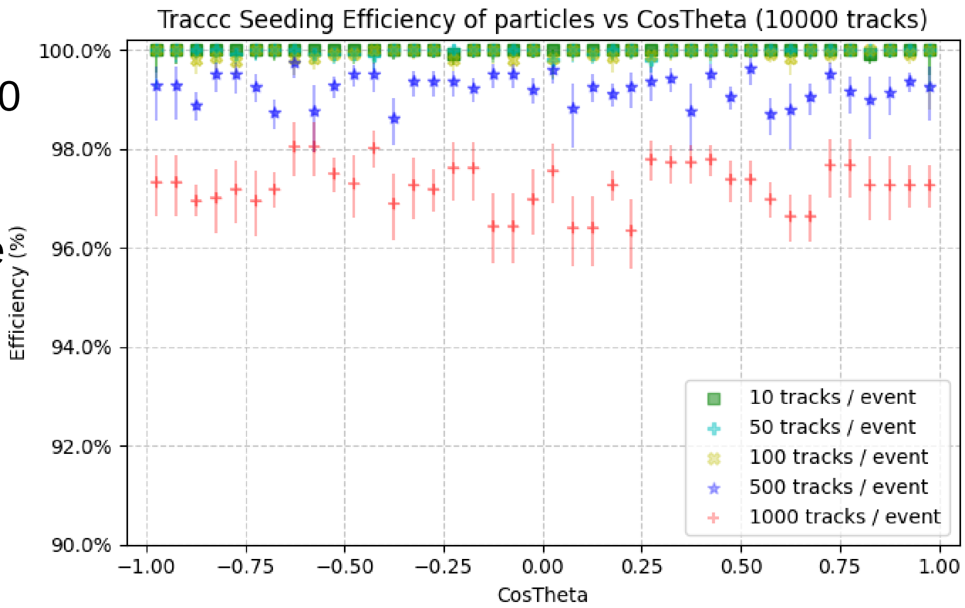
- After adding 0.3% noise, reconstruction efficiency drops slightly.
  - Reason for the decrease in efficiency: If the noise and hit are too close, they may be grouped in the same space-point during clustering, which may result in *wrong position* or *wrong particle id*.
- Higher repetition rate after adding noise.
  - Why no-noise case has ≈30% repetition rate: When processing the Seed Formation algorithm, if there are two triplets from the same track that do not share points at all, a duplicate seed is generated.





Seeding efficiency versus # of track / event

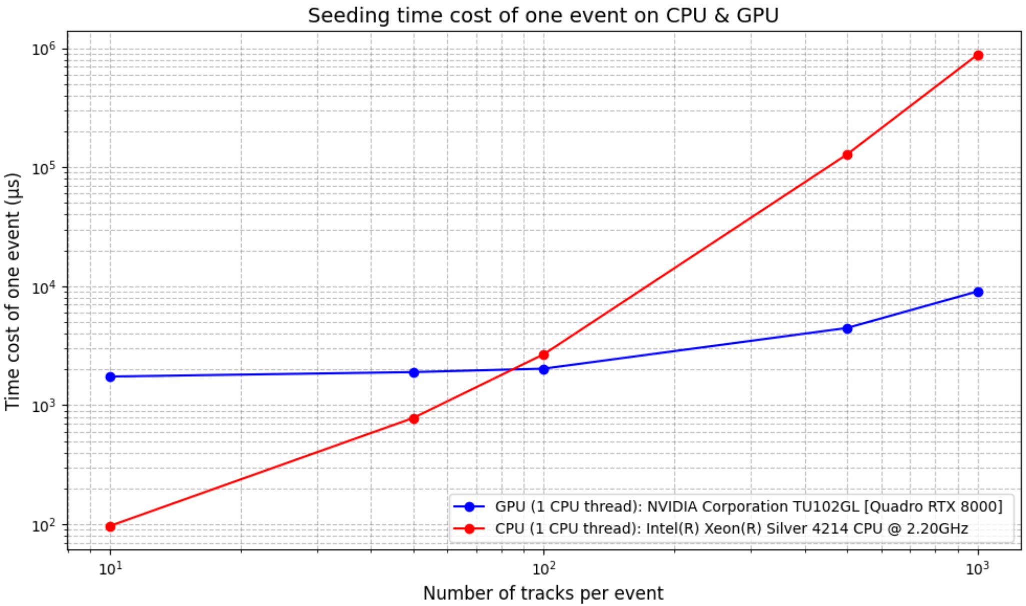
Particle: mu-   Energy: 10 GeV
Total track num: 50000
Number of tracks per event: 10/50/100/500/1000



Conclusion:

- The Seed Formation algorithm may combine two triplets with different particle id into a Seed. And the marked particle id of that is defined as the mode of the particle id of all space-points, which causes the absence of the proper particle id.

5 Performance



Computing evaluation of TRACCC seeding

Particle: mu-   Energy: 10 GeV

Run TRACCC in heterogeneous device:

- CPU: Intel(R) Xeon(R) Silver 4214 CPU @ 2.20GHz
- GPU: NVIDIA Corporation TU102GL [Quadro RTX 8000]

We tested the computing efficiency on CPU&GPU with only single CPU thread

- Even in this circumstances, we can beat a single CPU with a single “workstation” GPU at 100 tracks’ event.
- With multiple CPU cores in use, GPU can only “win” at large pipe-up case.

Outline

Summary

1. TRACCC has been applied to the CEPCSW for the first time.
    - The geometry conversion can be easily done by ACTS Tools.
    - The EDM conversion needs careful manually search for one-to-one correspondence
    - The TRACCC's algorithm can be extended for the special detector

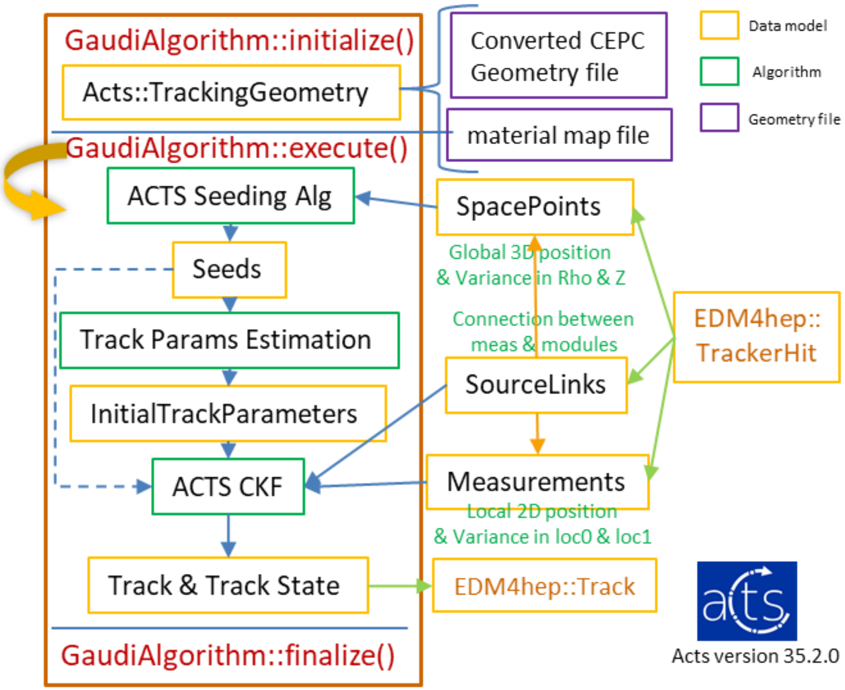
2. For the performance of TRACCC
    - The physical performance of the seeding algorithm is promising
    - GPU shows better computing performance than the CPU for large pile-up events

Ongoing work:

1. Apply ACTS seeding + ACTS CKF at silicon track (VTX+SIT+FTD) of CEPC.

    Previous Report: https://indico.cern.ch/event/1406633/

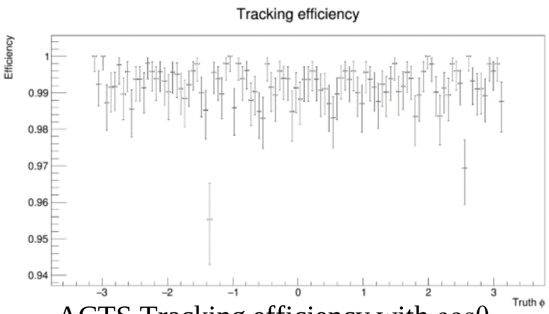
6 Summary & Plan



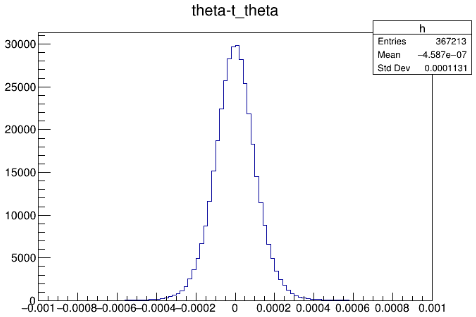
Gaudi Algorithm using ACTS reconstruction

Ongoing work

1. ACTS has been used as one of the tracking methods at CEPC
   - Geometry & EDM conversion is broadly consistent with TRACCC
2. Preliminary performance tests
   - Satisfying tracking performance
   - Faster computing eff (≈ 0.2 ms/event) comparing to CEPC's origin tracking algorithm (≈ 10 ms/event) with single thread
3. Geometry is about to be upgraded to TDR (ongoing)



ACTS Tracking efficiency with cosθ



Distribution of Δθ

Thank You

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Backup

TRACCC: track reconstruction on accelerators

TRACCC

- * TRACCC is one of the ACTS R&D projects, which is developing full track reconstruction algorithms that can run on accelerators.
- Discussions on 20 November:
  - ➢ https://indico.cern.ch/event/1397634/sessions/547939/#20241120
- Is standalone and features a modular architecture
- Has excellent physics and computing performance

Category	Algorithms	CPU	CUDA	SYCL	Alpaka	Kokkos	Futhark
Clusterization	CCL / FastSv / etc.	☑	☑	☑	●	○	☑
	Measurement creation	☑	☑	☑	●	○	☑
Seeding	Spacepoint formation	☑	☑	☑	●	○	○
	Spacepoint binning	☑	☑	☑	☑	☑	○
	Seed finding	☑	☑	☑	☑	○	○
	Track param estimation	☑	☑	☑	☑	○	○
Track finding	Combinatorial KF	☑	☑	●	●	○	○
Track fitting	KF	☑	☑	☑	○	○	○
Ambiguity resolution	Greedy resolver	☑	○	○	○	○	○

☑: exists, ●: work started, ○: work not started yet

Status of TRACCC

SYCL

- SYCL is a high-level C++ programming model. An uniformed written code can run on a variety of platforms.
- * High Portability and Programming Efficiency