Simulation and track reconstruction in the silicon trackers

FU Chengdong, LI Weidong, LI Zhihao, LIN Tao and ZHANG Yizhou
(on behalf of Software working team)

CEPC Day

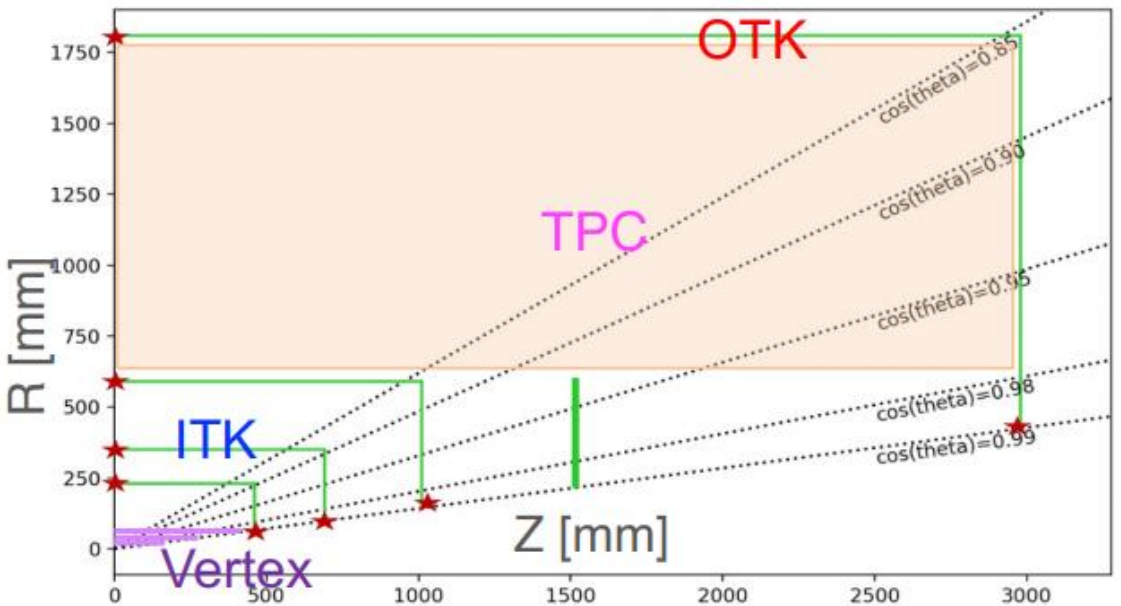
Nov. 27, 2024

Contents

Introduction

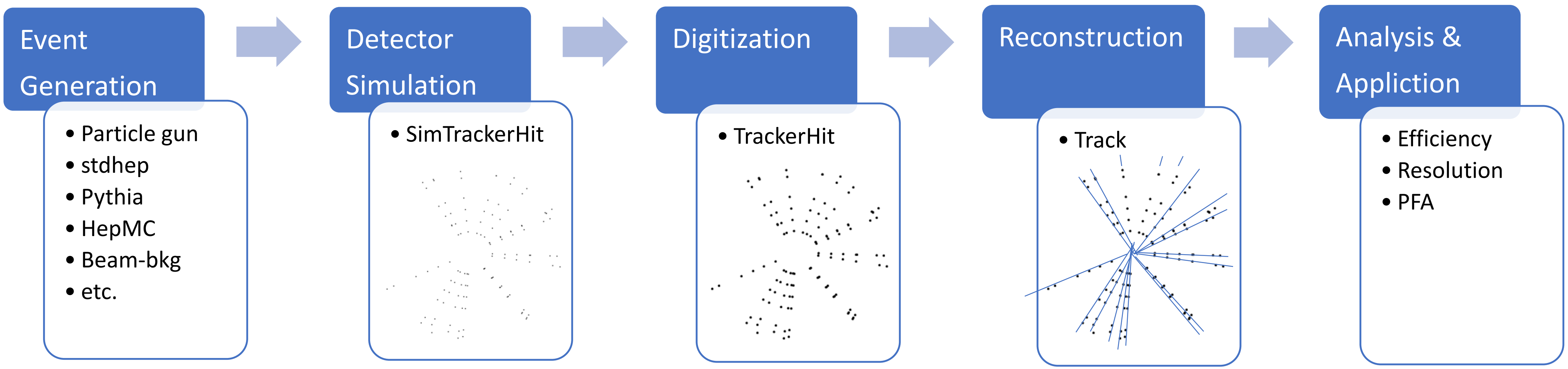
Physics process	Measurands	Requirement on tracker
$ZH, Z\rightarrow e^+e^-(\mu^+\mu^-), H\rightarrow\mu^+\mu^-$	m_H, $\sigma(ZH)$, $BR(H\rightarrow\mu^+\mu^-)$	$\Delta(1/p_T) = 2\times10^{-5} \oplus \frac{0.001}{p(GeV)\sin^{3/2}\theta}$

- The silicon trackers @CEPC will play an important role in detecting high momentum charged particle, be helpful for low momentum region, and unique for those tracks that can not reach TPC.
  - Vertex
  - ITK
  - OTK
- Challenge on application of new technology
  - Stitching vertex
  - LGAD
- On software, requirement on high tracking efficiency and accurate performance of reconstruction
- Application at the TDR stage
  - Simulation to estimation background
  - Track performance for tracker optimization
  - Track objects for PFA, physical analysis



Simulation and Reconstruction Chain

- Full simulation is performed in CEPCSW, and some fast simulation tools for trackers such as LDT, Delphes, tkLayout etc. are applied in standalone.
- The standard chain of MC simulation:

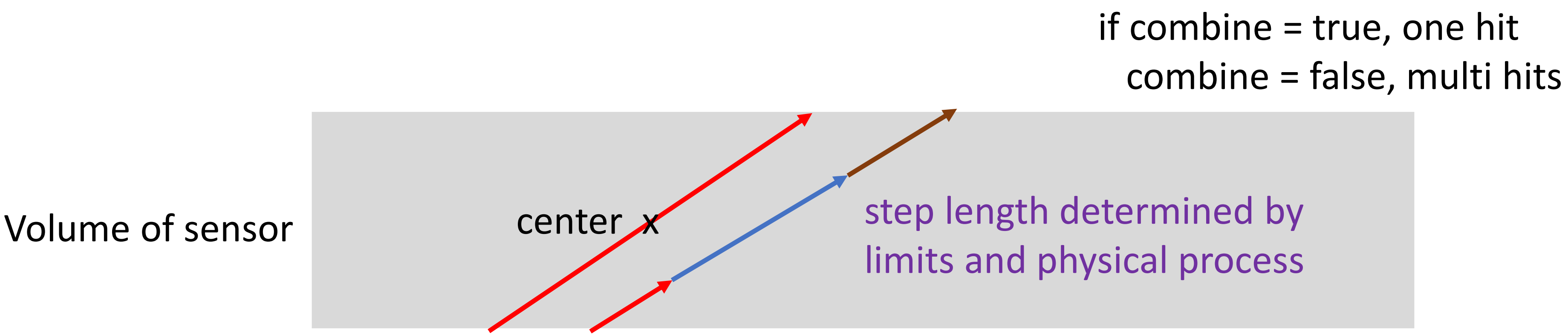


Sensitive Detector

- SD in G4 simulation: G4Step → G4TrackerHit → SimTrackerHit
  - step length through option
    - ✓ <detector name="VXD" … limits="tracker_limits" …>
    - ✓ if not set, use Geant4 default
  - combine steps to one hit
    - ✓ <detector name="VXD" … combineHits="true" …>
    - ✓ if not set, default is false

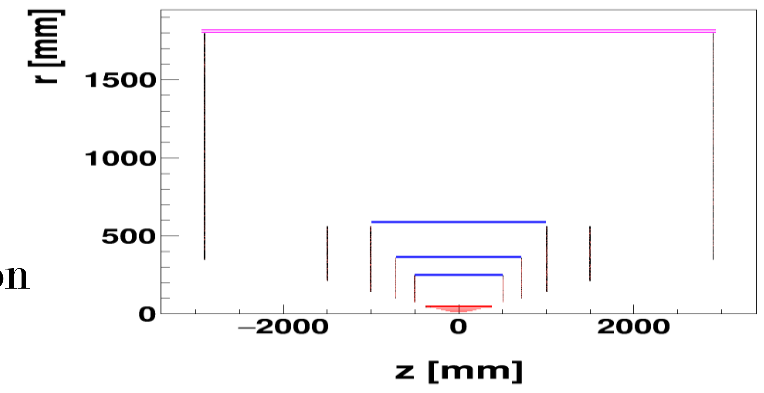
```
<limitset name="tracker_limits">
  <limit name="step_length_max" particles="*" value="5.0" unit="mm" />
</limitset>
<limitset name="detail_limits">
  <limit name="step_length_max" particles="*" value="0.005" unit="mm" />
</limitset>
```

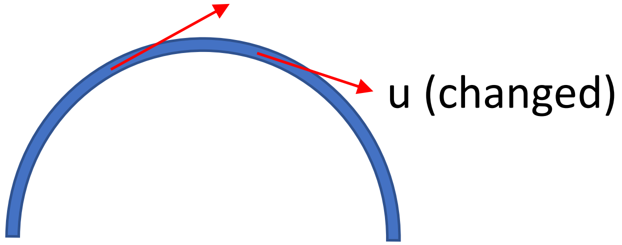
- Save the center position of start and end as the position of SimTrackerHit
- Save the direction from start to end as the direction of momentum of SimTrackerHit



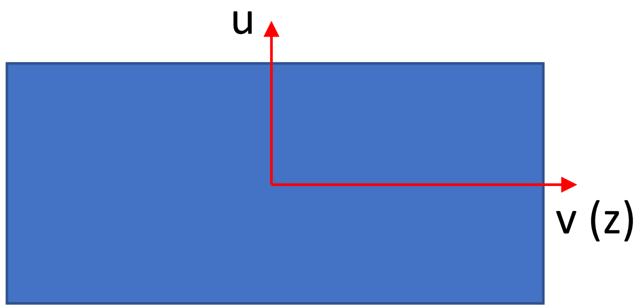
Digitization

- Gaussian smearing on SimTrackerHit at measurement dimension (u,v)
  - pixel: 2D (u,v)
  - strip: 1D (u,0) or (0, v)
- Fixed spatial resolution or Parameterized spatial resolution through option
- Measurement surface at the center plane, consistent with the general simulated hit
- Drop threshold
  - Hit efficiency between [0,1]: current global for each sub-detector, future local option for each sensor, support to make dead for whole sensor
  - Deposited energy in step

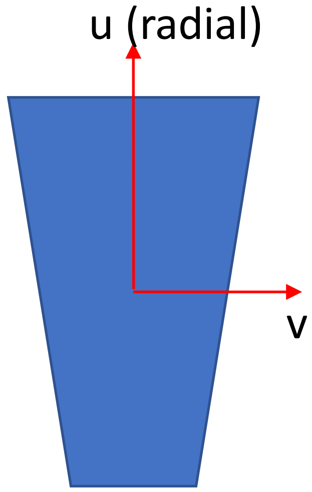




Barrel (Cylindric)



Barrel (Planar)

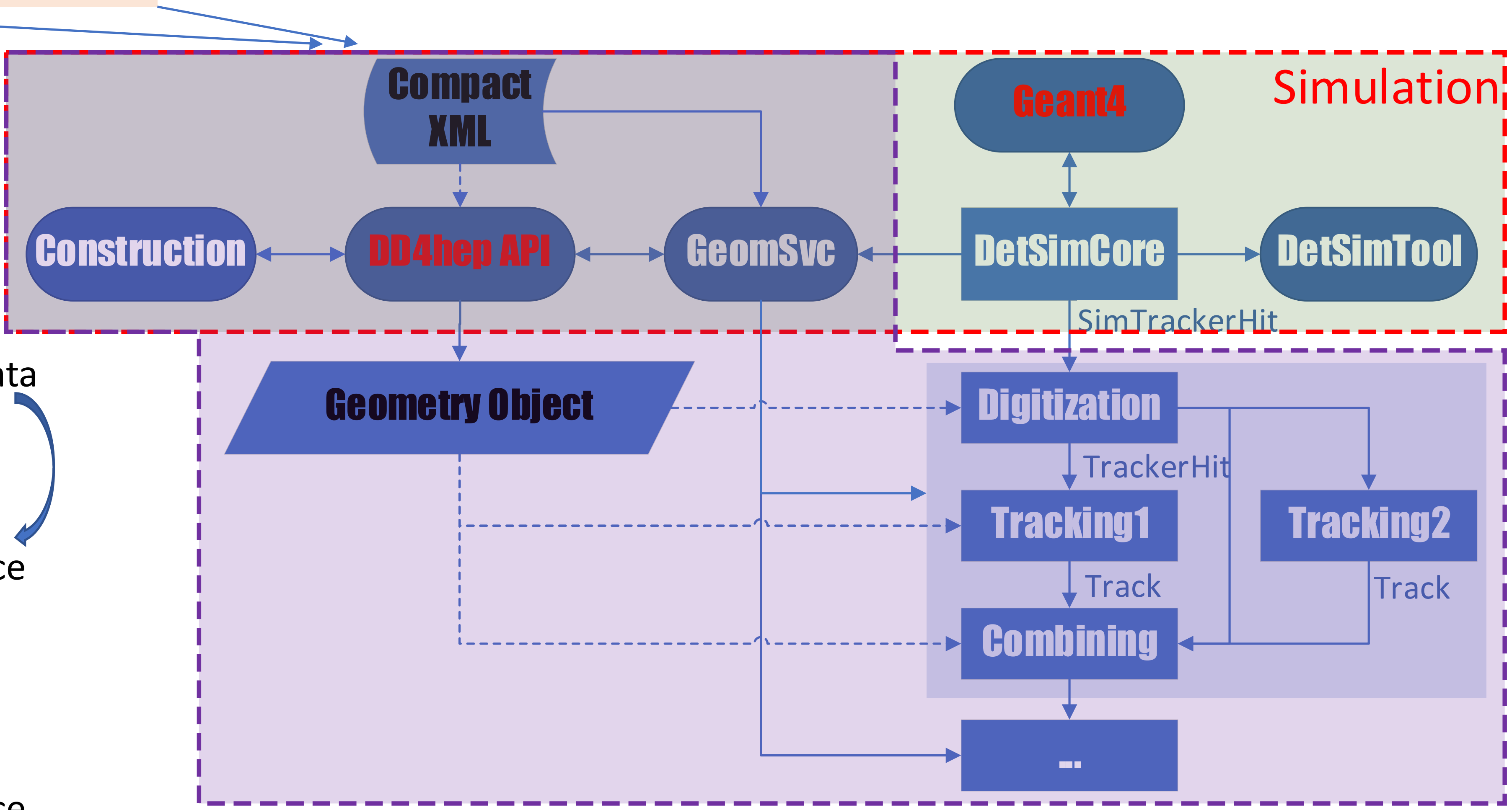


Endcap (Planar)

Implementation and Transmit of Geometry

TDR_o1_v01-onlyTracker.xml

TDR_o1_v01.xml



current:

DD4hep extension data

Gear data

Measurement surface

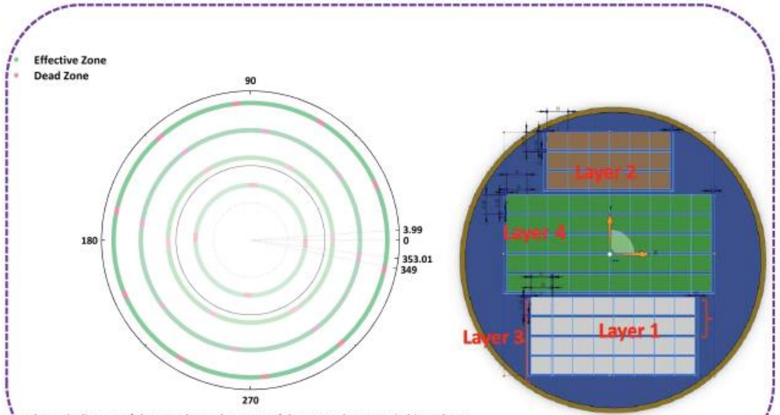
propose:

DD4hep surface

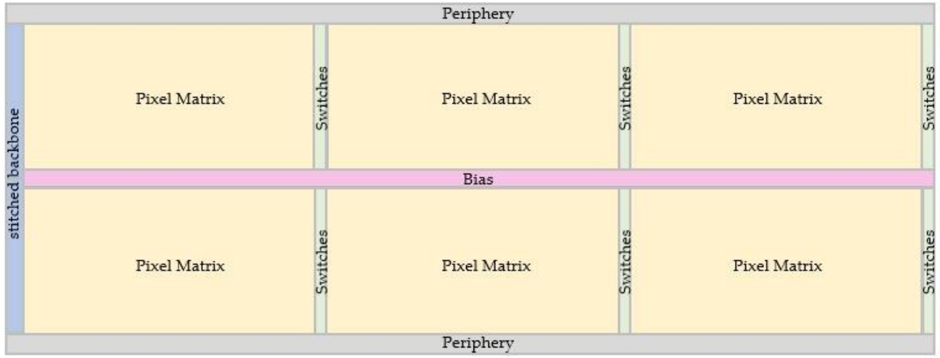
Measurement surface

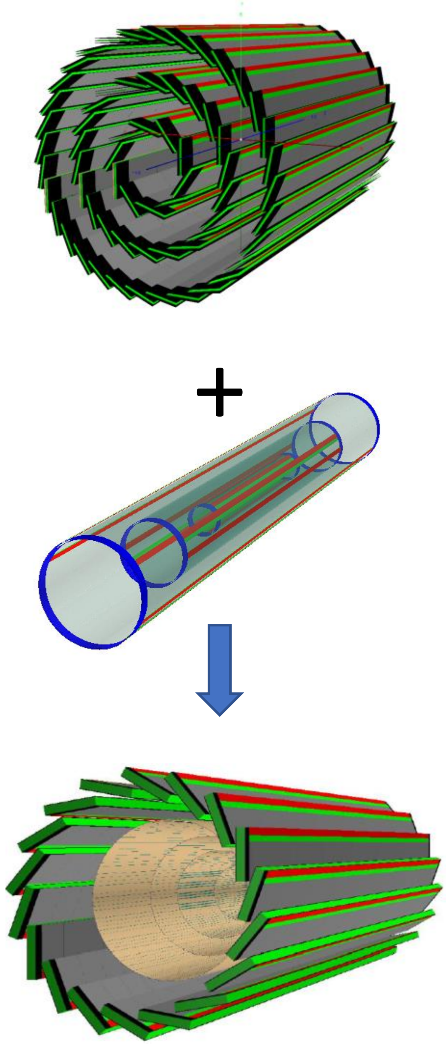
Vertex Detector

- Stitching-planar composite vertex detector implemented
  - Current preliminary layout
  - electronics, readout, driver and dead region between sensors
- Layout optimization is ongoing by vertex group, a baseline design will be updated in this month
- Stitching module will be update
  - More detail on dead region



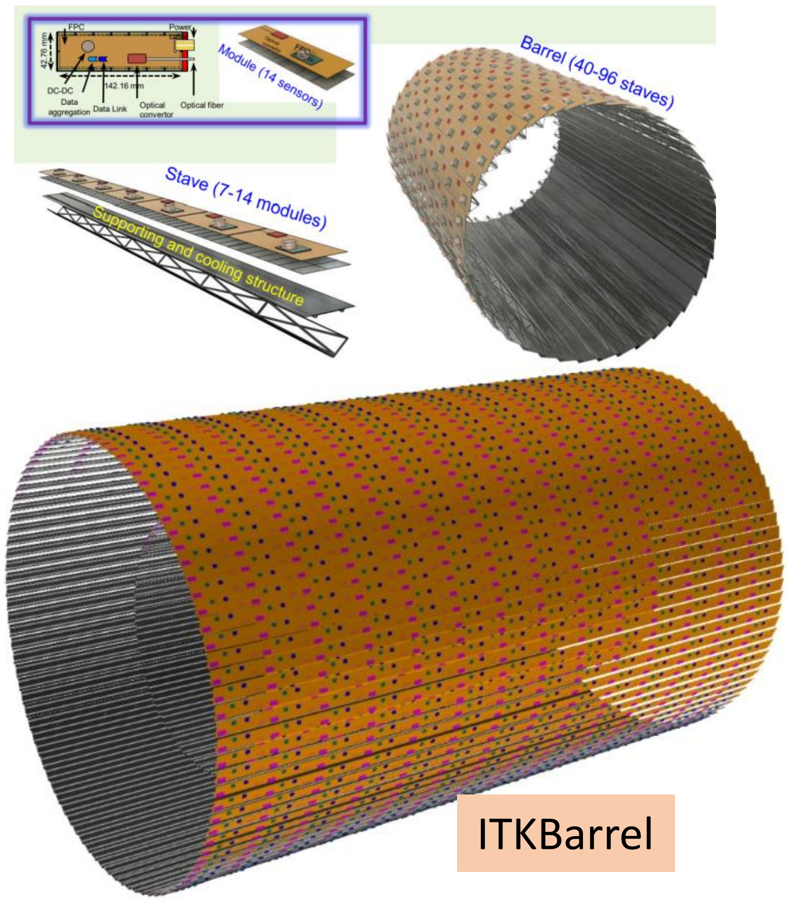
Schematic diagram of the Inner layer placement of the vertex detector stitching scheme.



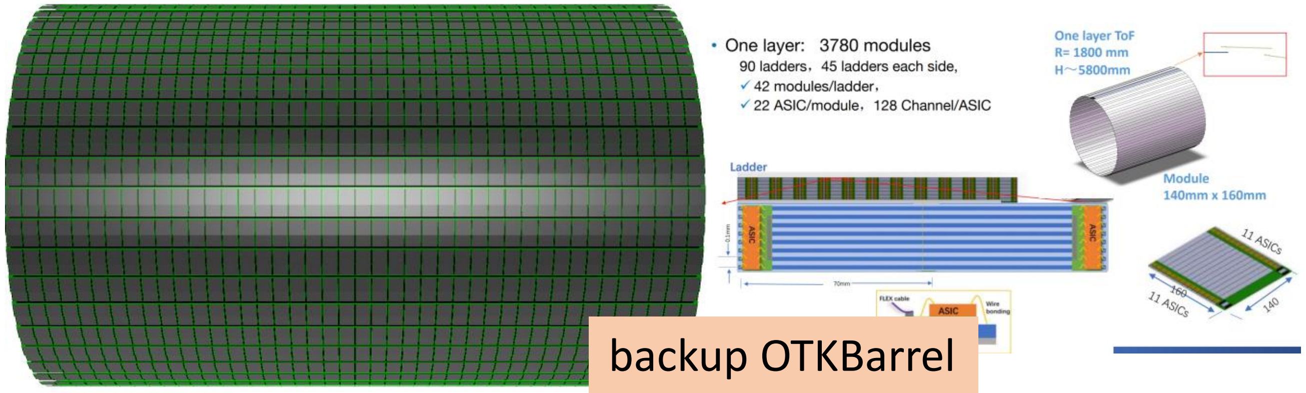


ITK & OTK

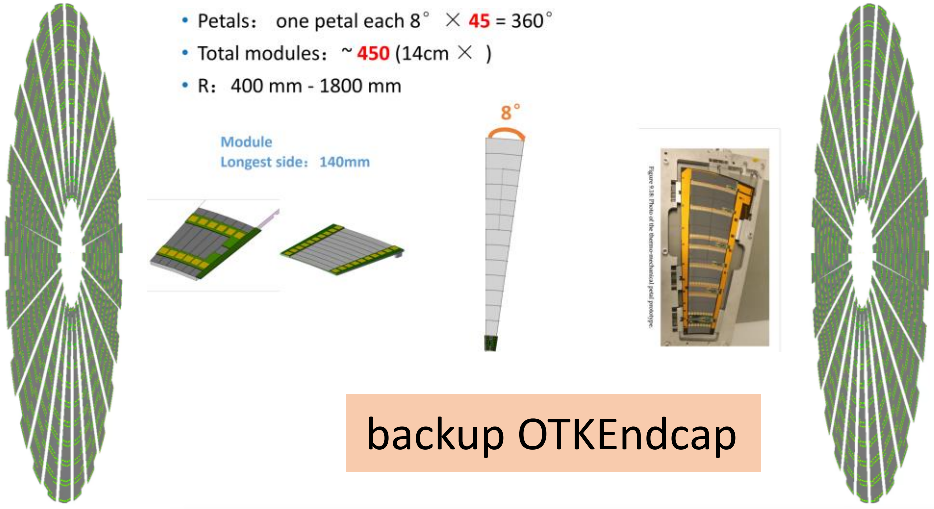
- Full implemented for ITKBarrel: sensor, support, cooling pipe, DC-DC, lpGBTx, optical connector, data aggregation, except truss
- ITKEndcap and baseline OTK: simply as support and sensor, full implementation ongoing



ITKBarrel



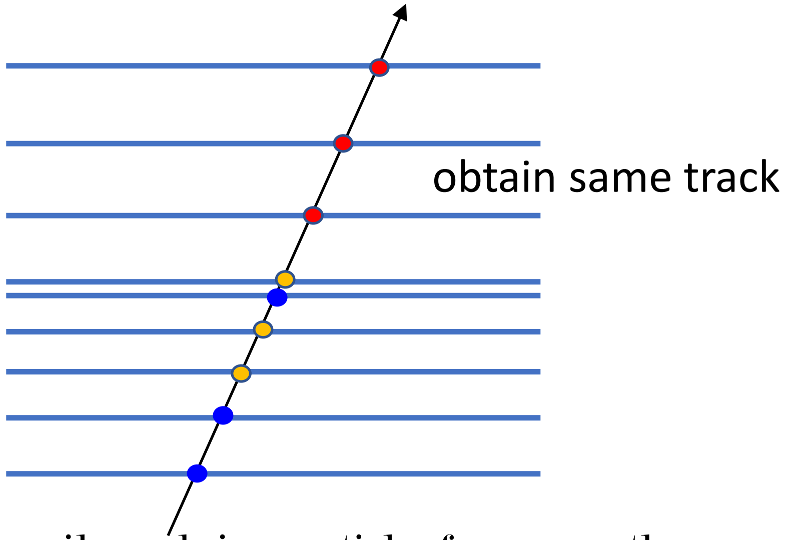
backup OTKBarrel



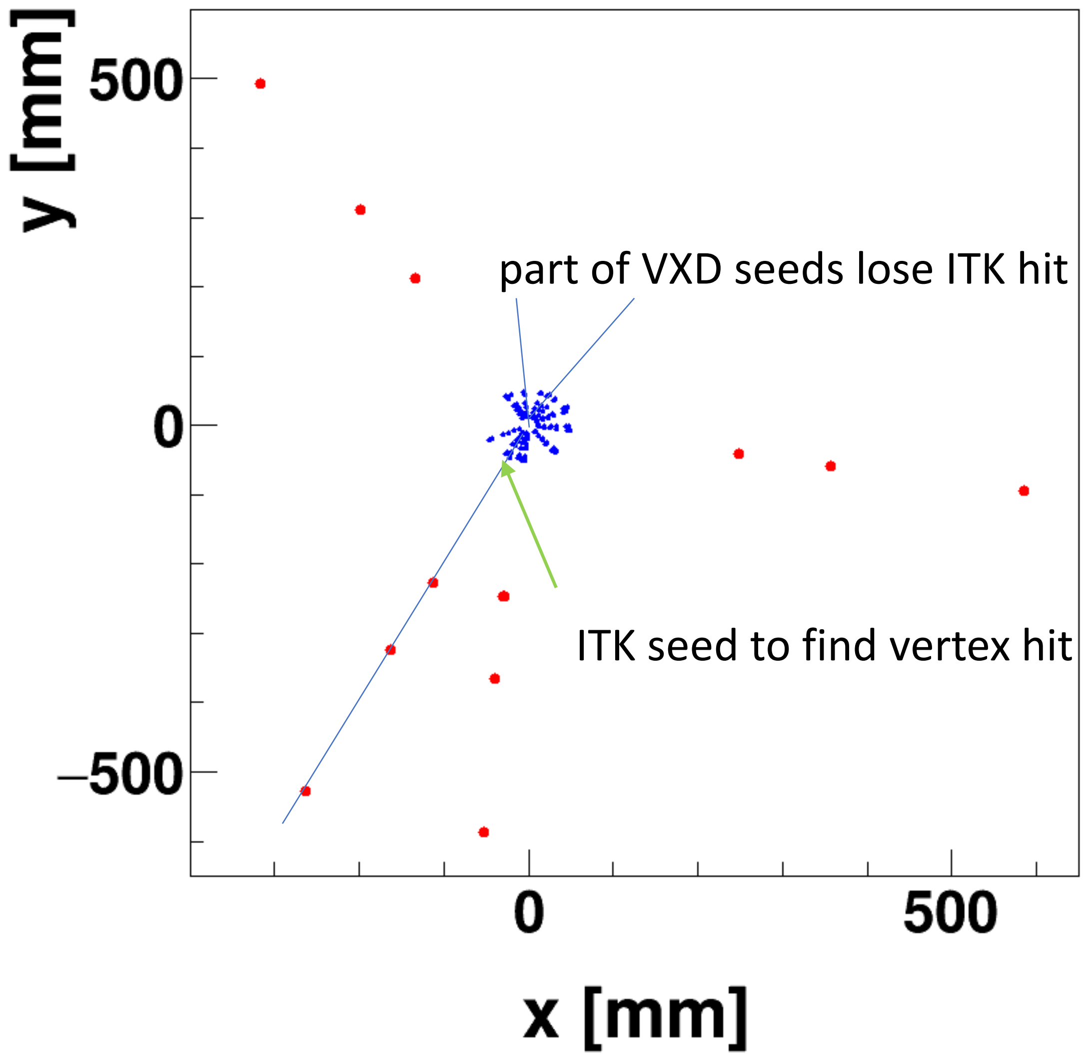
backup OTKEndcap

Track Finding

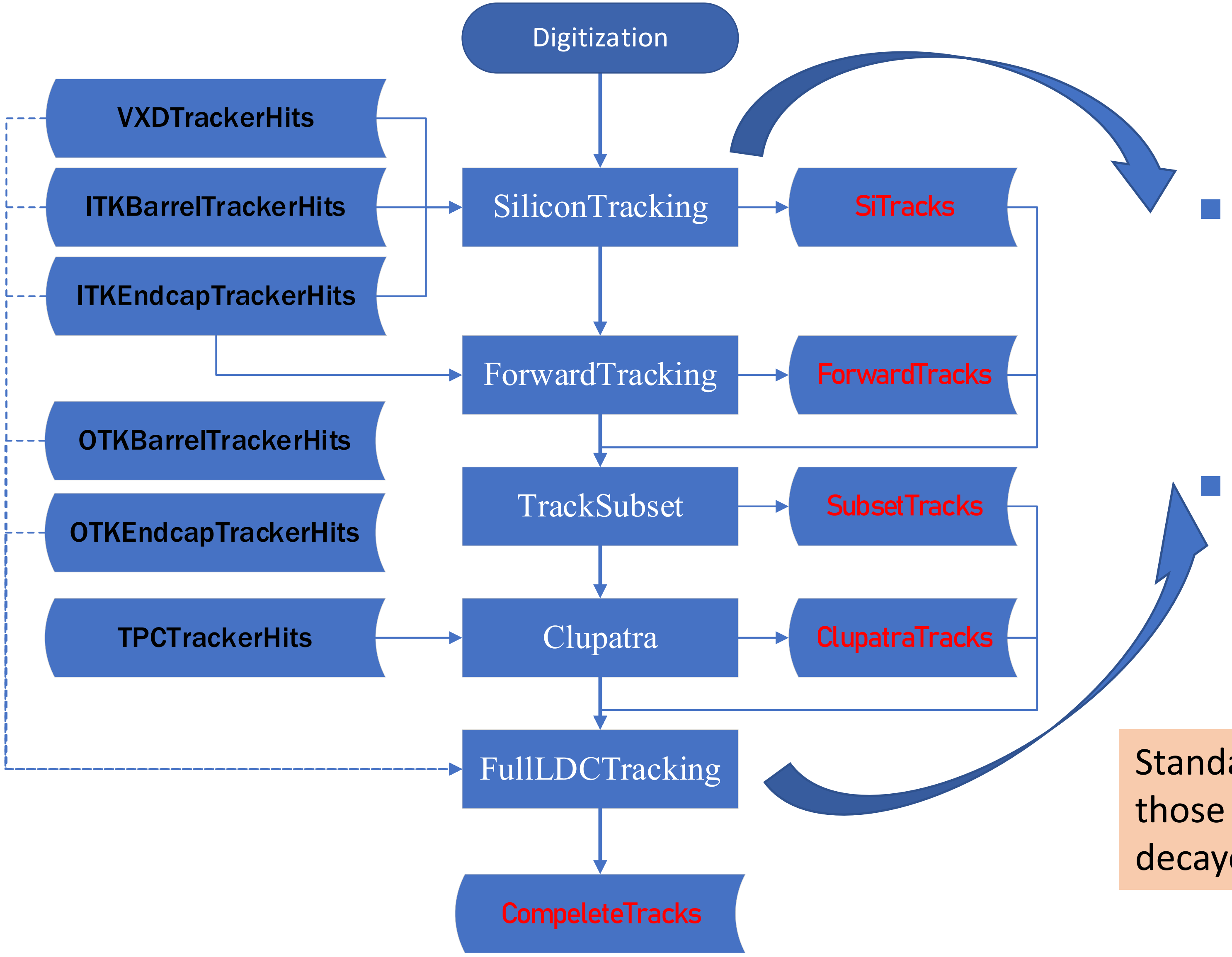
- seed find



- prepare for pile up: bring particles from more than one bunch to vertex
  - VXD seeds
  - ITK seeds
- The track candidates without ITK hit
  - high momentum: drop
  - low momentum can not reach ITK: d0, z0 to remove beam background pT~120MeV



Tracking Option



- Change input collections
  - VXDTracks (VXD hits only)
  - ITKTracks (ITK hits only)

- repeat call algorithm with different input
  - FullSiTracks (remove TPC hits)
  - InnerTracks (remove OTK hits)

Standalone tracking power is helpful for those short tracks (low momentum or decayed)

Output

edm4hep::Track

……

edm4hep::TrackerHit s

……

MCRecoTrackerAssociation

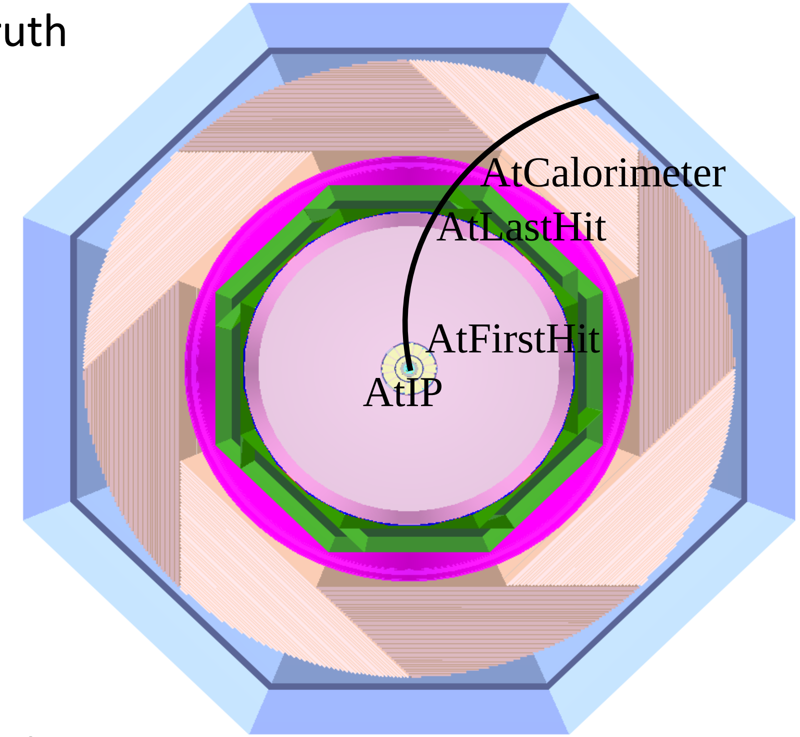
truth

edm4hep::TrackState s

std::int32_t location
float D0
float phi
float omega
float Z0
float tanLambda
float time
edm4hep::Vector3f referencePoint
std::array<float, 21> covMatrix

HelixClass

x0, y0, z0, px, py, pz

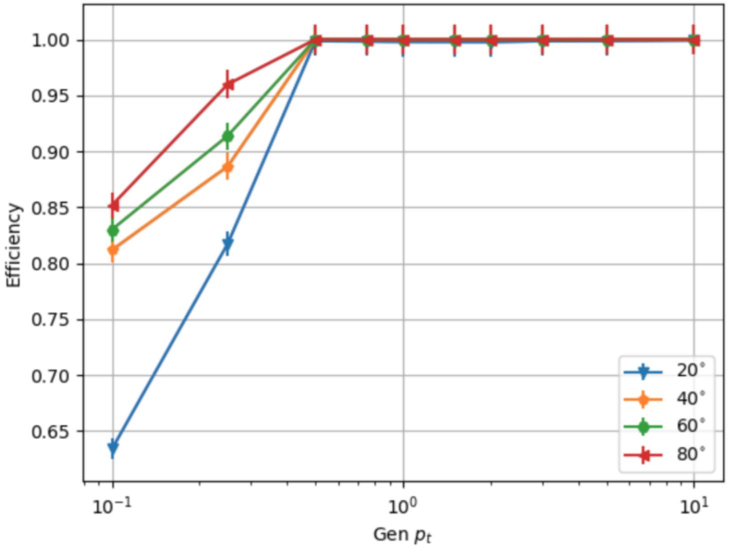


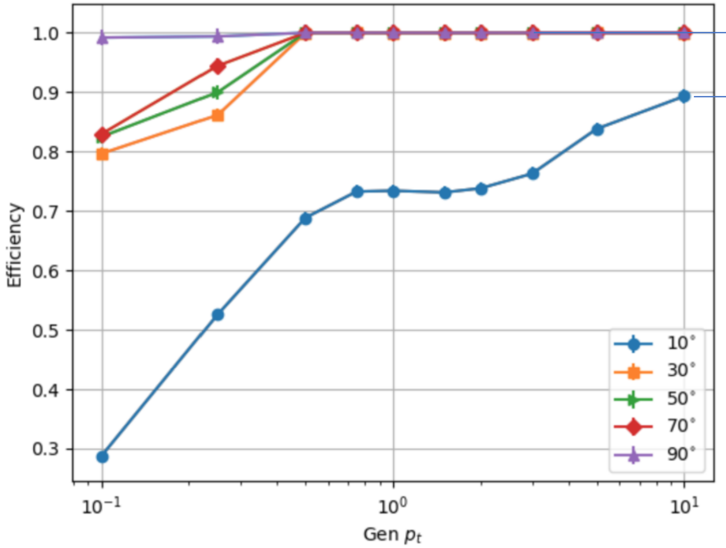
Currently, four TrackStates are in storage:
if(location==edm4hep::TrackState::AtIP)
if(location==edm4hep::TrackState::AtFirstHit)
if(location==edm4hep::TrackState::AtLastHit)
if(location==edm4hep::TrackState::AtCalorimeter)

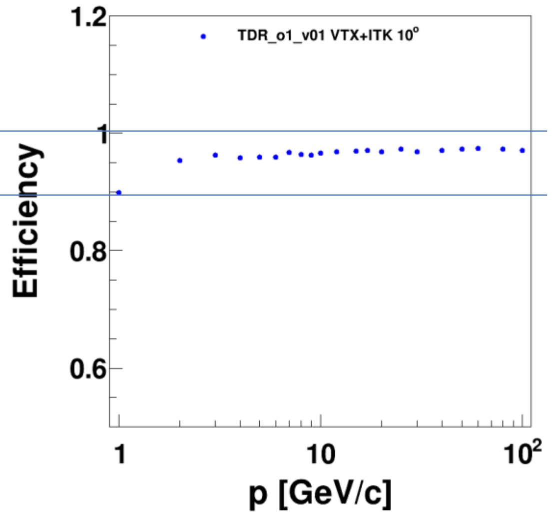
Tracking Efficiency

- Efficiency loss at low pT and small polar angle
  - At small polar angle, coming fix can improve the efficiency observably

from physical group check

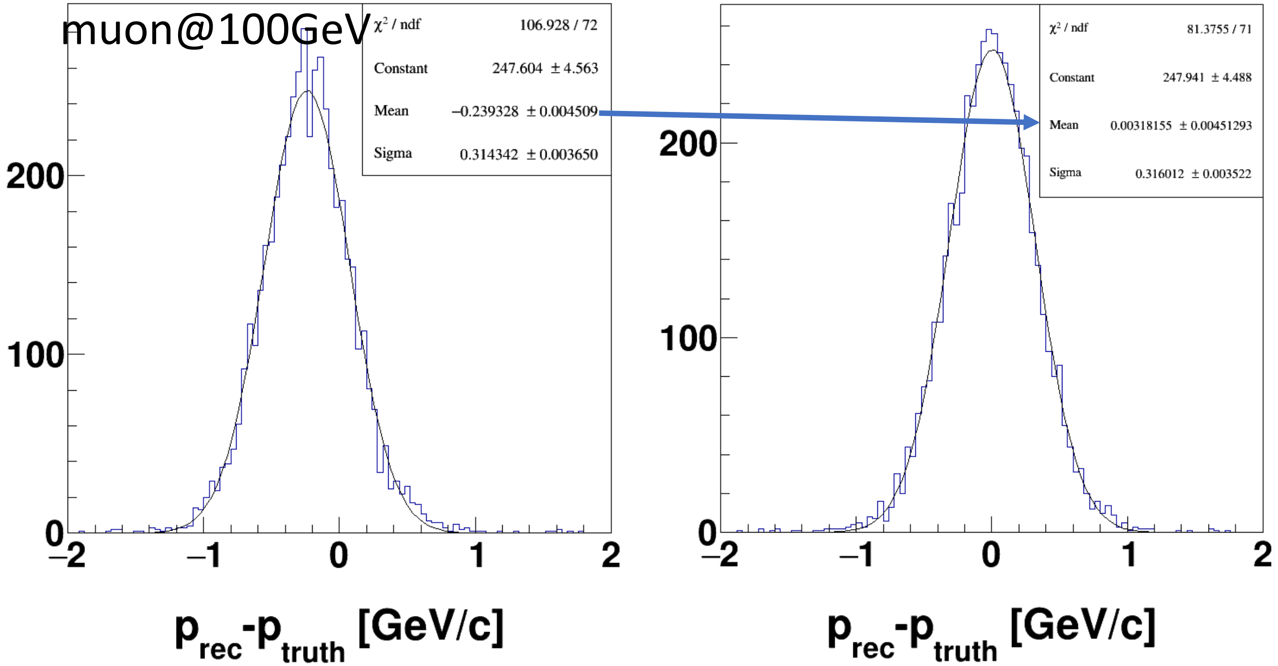




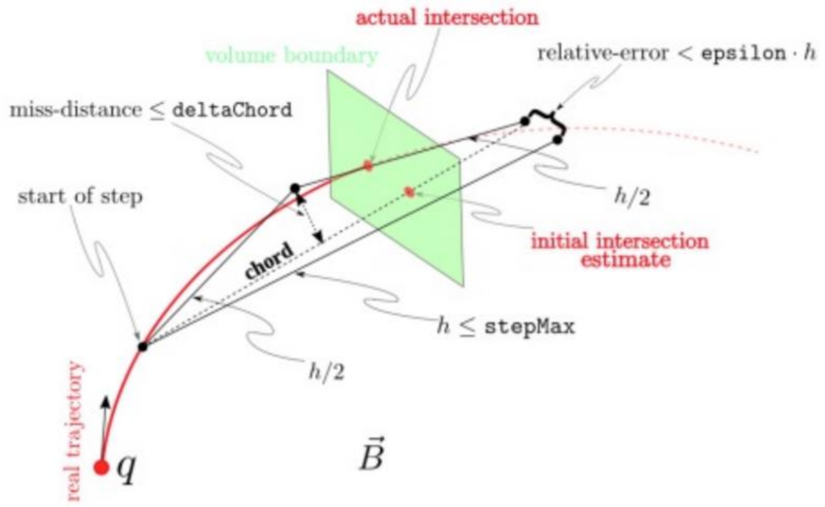


Fix on Momentum Bias

- Reconstructed momentum bias to truth found, larger at high momentum
  - not relative with material effect
  - exists for chargedgeantino
- Position of truth from Geant4 simulation departure from expect, caused by linear chords approximation while tracking in magnetic field, and appropriate setup can fix it
  - Current updated into master, the settings use **the finest precision** acceptable by Geant4.

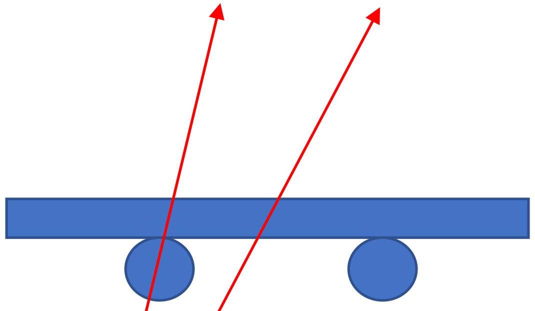



```
fieldManager→SetDeltaIntersection(m_DeltaIntersection.value());
fieldManager→SetDeltaOneStep(m_DeltaOneStep.value());
fieldManager→SetMinimumEpsilonStep( newEpsMin: m_MinimumEpsilonStep.value());
fieldManager→SetMaximumEpsilonStep( newEpsMax: m_MaximumEpsilonStep.value());
```

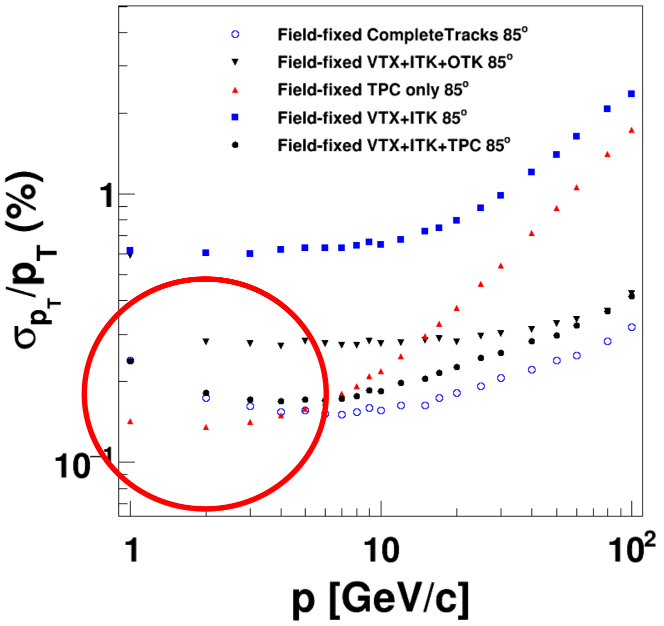


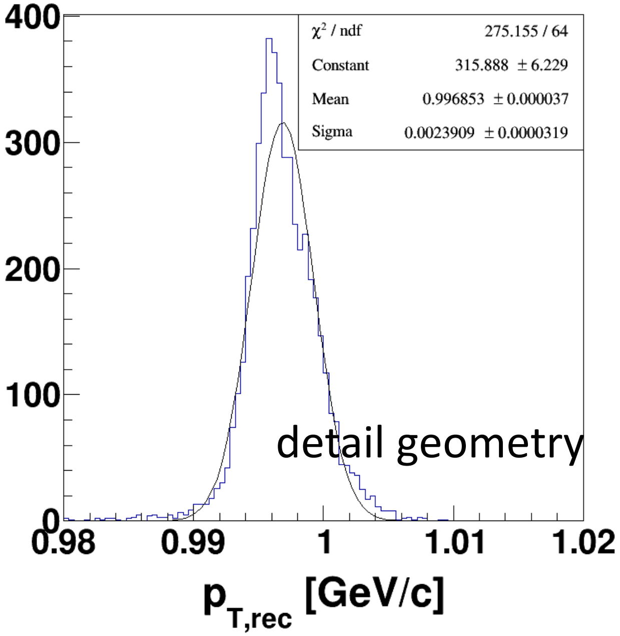
Issue at Low Momentum

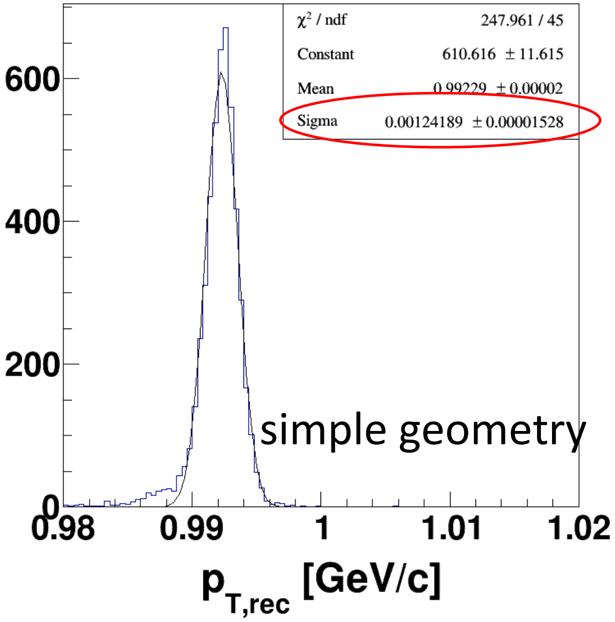
- The resolution of pT from CompleteTracks are worse than TPC-only-Track at low momentum, consistent with physical group check.
- The reason is that the residual distribution has a shoulder structure, whose mean is difference with the center.
- Shoulder structure is believable caused by the material difference between simulation and reconstruction.
  - At fixed ϕ, the shoulder will be not obvious.
  - Recover to previous ITK geometry, the shoulder also disappears, and obtains better resolution than TPC-only (expected)



pass through cooling pipe cause bias of momentum, since it has not been implemented in reconstruction, to fix it

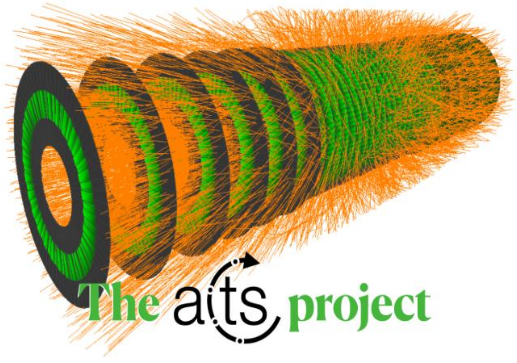


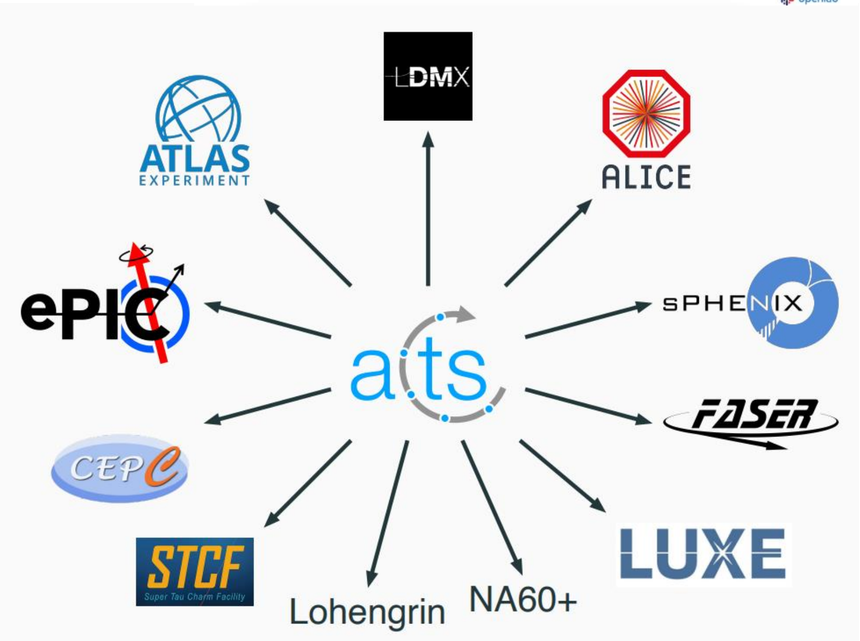




ACTS (A Common Tracking Software)

- ACTS is an experiment-independent toolkit for track reconstruction
  - derived from the ATLAS track reconstruction software
  - targeting at high quality, generic, modernly designed tracking components
  - has been in development for 10 years
- ACTS core project provides tools including:
  - Components: Detector, Geometry, EventData, Material, Magnetic Field …
  - Algorithms: Clusterization, Seeding, Track Finding, Track Fitting, Vertexing …
  - Fast simulation (Fatras) & Digitalization tools
  - Visualization tools
- ACTS has been used in more than a dozen experiments and conceptual studies
  - including ATLAS, sPHENIX, FASER, and LUXE …
  - has been integrated in ATLAS ITk track reconstruction
  - We joined ACTS project in 2023



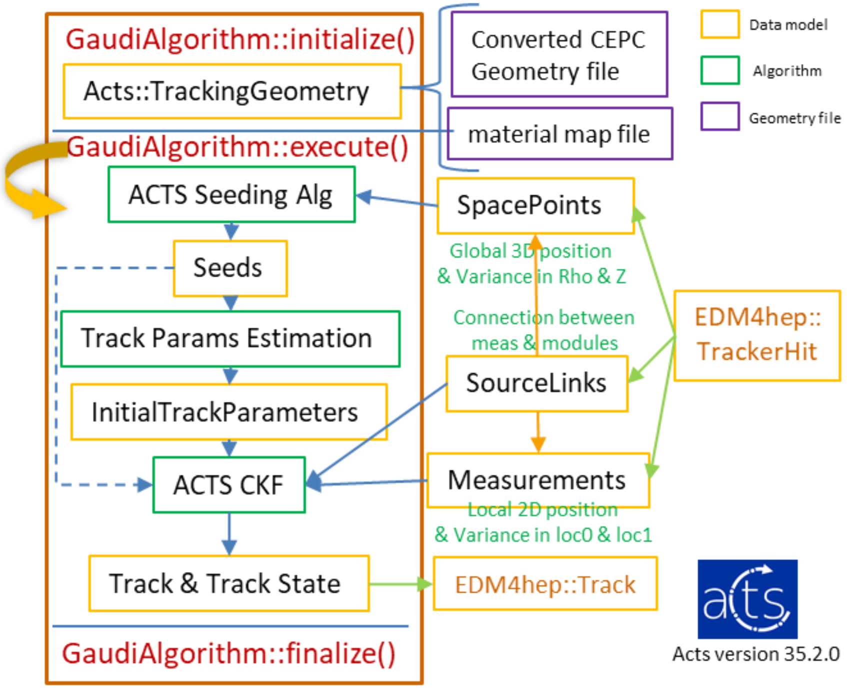


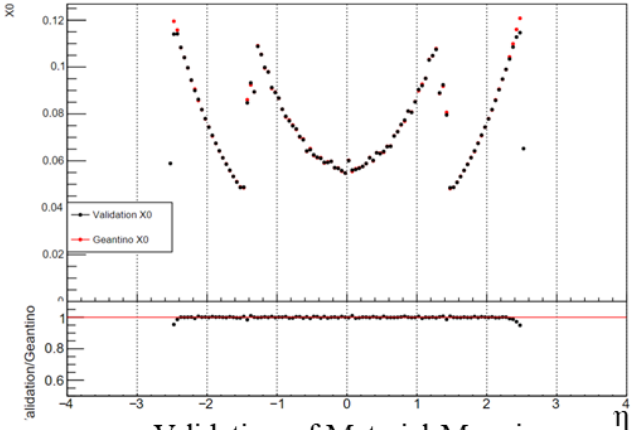
From Paul's 2024 ACTS workshop talk

CEPC silicon Tracking with ACTS

- Convert the CEPC RefDet geometry to ACTS format
  - The CEPC geometry file is translated into Acts::Surface objects using Acts::ILayerBuilder.
  - Completed the conversion of Geometry Id between EDM4hep and ACTS.
  - To simplify the complex material when performing track reconstruction, the material is mapped onto sensitive surfaces in the tracking geometry.

- Developed silicon tracking algorithm of CEPC based on ACTS
  - Developed a Gaudi algorithm applying ACTS reconstruction algorithms
  - Applied ACTS seeding + track params estimation + CKF algorithms

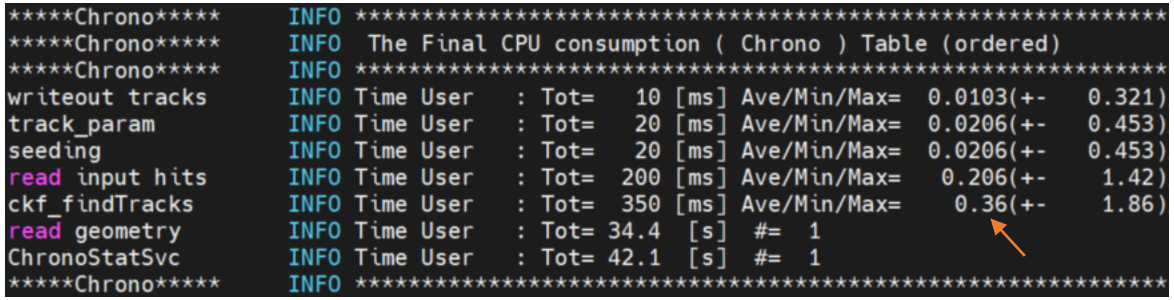




Validation of Material Mapping

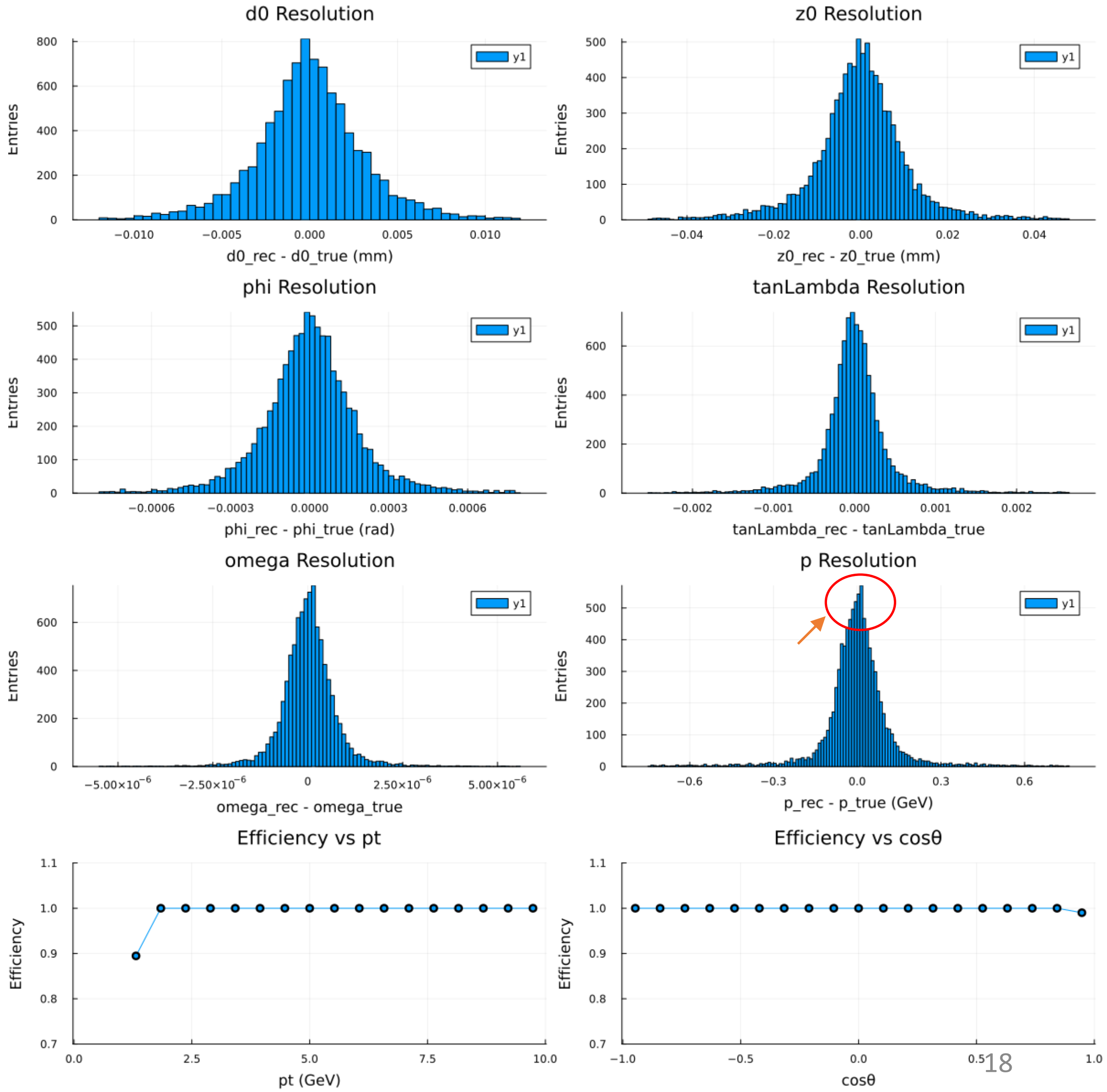
Efficiency of ACTS

- Tracking efficiency of ACTS
  - Shows params & eff of ACTS tracking in the inner tracker of CEPC's RefDet geometry →
  - Particle: mu-, Energy: 10Gev, 10000 events
  - Issue: bias at momentum estimation
- Computing efficiency of ACTS
  - Satisfying computing eff (≈ 0.36 ms/event)
- Plan: Joint reconstruction with origin & ACTS reconstruction algorithm



```
*****Chrono*****      INFO ***************************************************************
*****Chrono*****      INFO  The Final CPU consumption ( Chrono ) Table (ordered)
*****Chrono*****      INFO ***************************************************************
writeout tracks       INFO Time User    : Tot=   10 [ms] Ave/Min/Max=  0.0103(+-    0.321)
track_param           INFO Time User    : Tot=   20 [ms] Ave/Min/Max=  0.0206(+-    0.453)
seeding               INFO Time User    : Tot=   20 [ms] Ave/Min/Max=  0.0206(+-    0.453)
read input hits       INFO Time User    : Tot=  200 [ms] Ave/Min/Max=   0.206(+-     1.42)
ckf_findTracks        INFO Time User    : Tot=  350 [ms] Ave/Min/Max=    0.36(+-     1.86)
read geometry         INFO Time User    : Tot= 34.4  [s]  #=  1
ChronoStatSvc         INFO Time User    : Tot= 42.1  [s]  #=  1
*****Chrono*****      INFO ***************************************************************
```

Computing Eff of ACTS tracking with single CPU thread

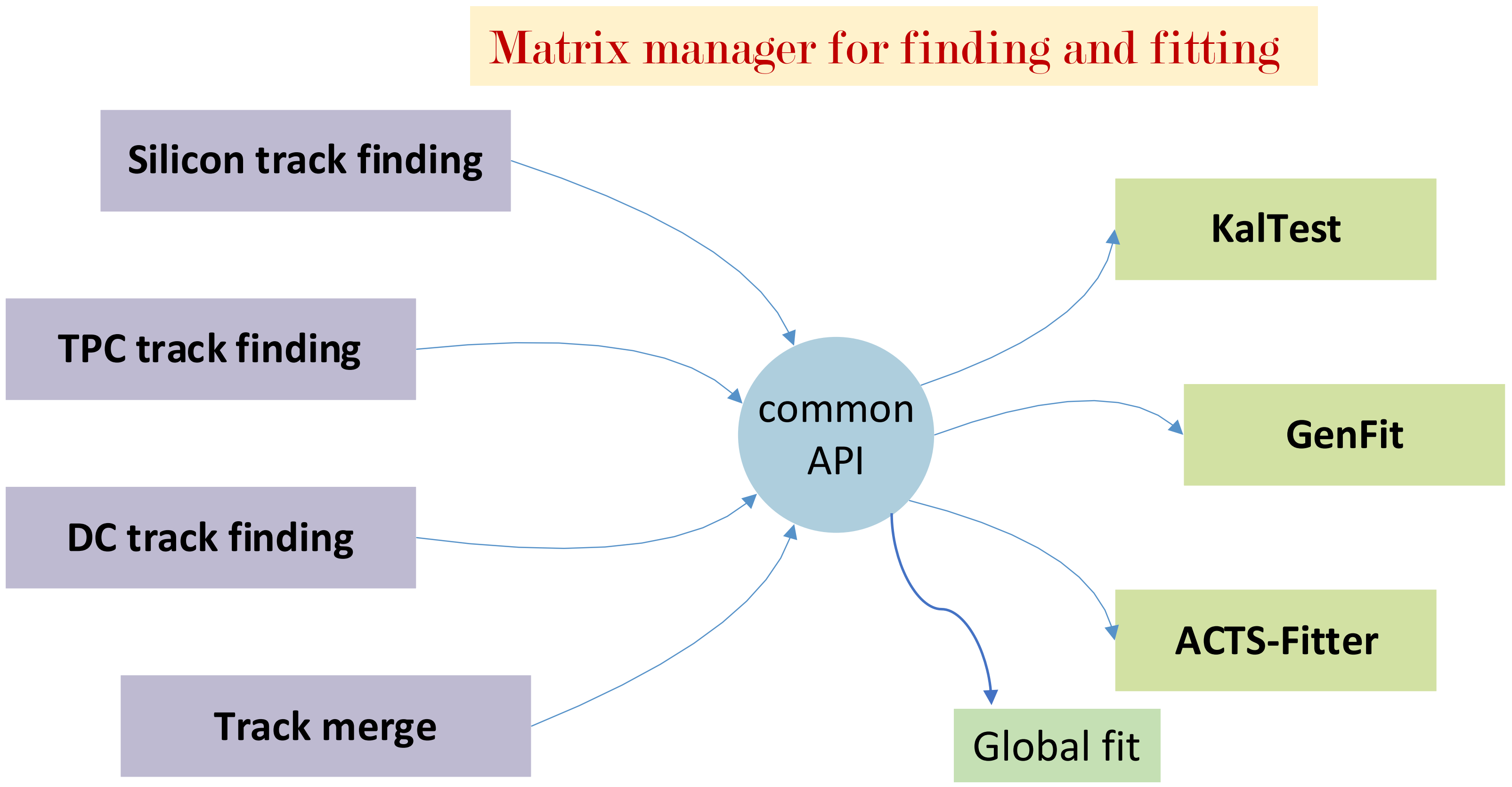


Summary

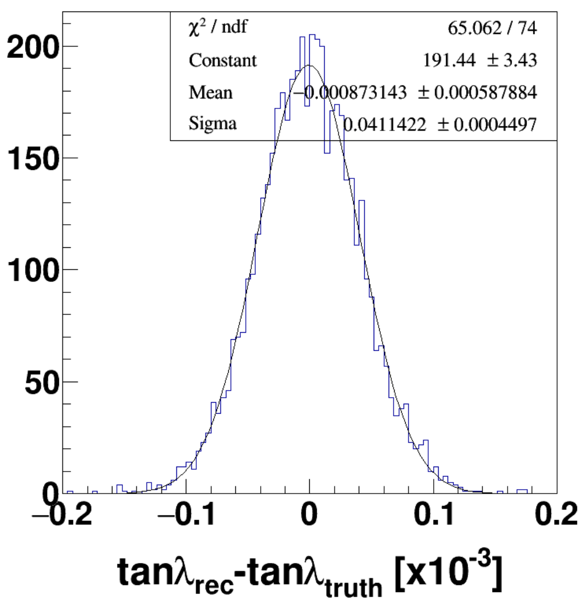
- The silicon trackers have been implemented into CEPCSW, but in different progress
- For current silicon trackers, some fixing on simulation and reconstruction have been performed to improve the performance
- Now, the reconstruction both current and future ACTS is becoming better
- Still there is some issue waiting for fixing, but on understand and plan

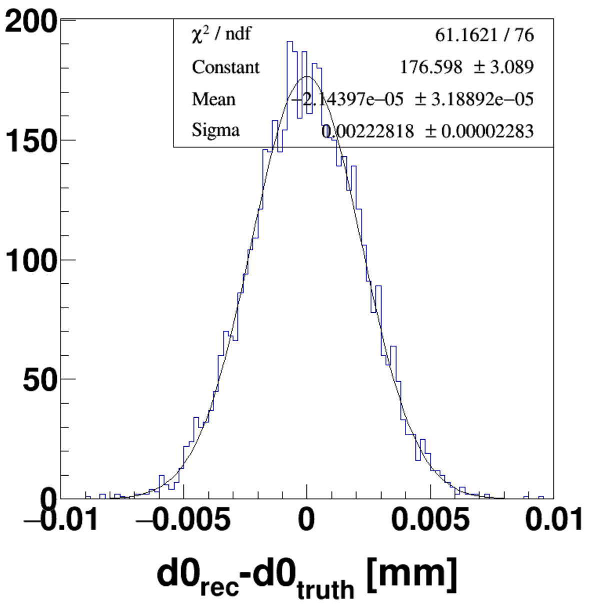
- Towards TDR
  - Implement ITKEndcap and baseline OTK before data production
  - Improve tracking performance before final physical analysis
    - ✓ fix issue at low momentum
    - ✓ update geometry converter
  - Performance study before TDR ready
    - ✓ tracking under background
    - ✓ tracking with non-uniform magnetic field
    - ✓ fast digitization

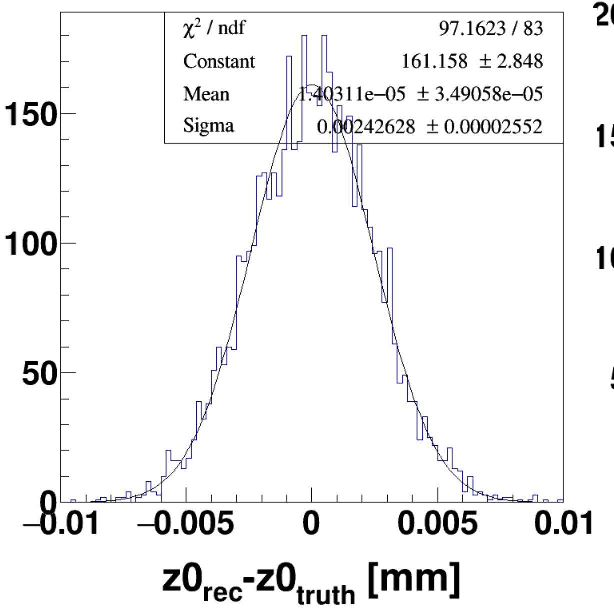
Propose of Tracking Chain

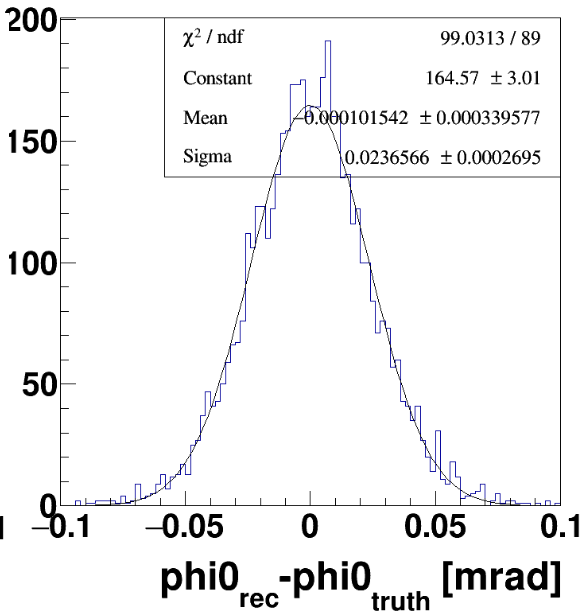


Residual Distribution



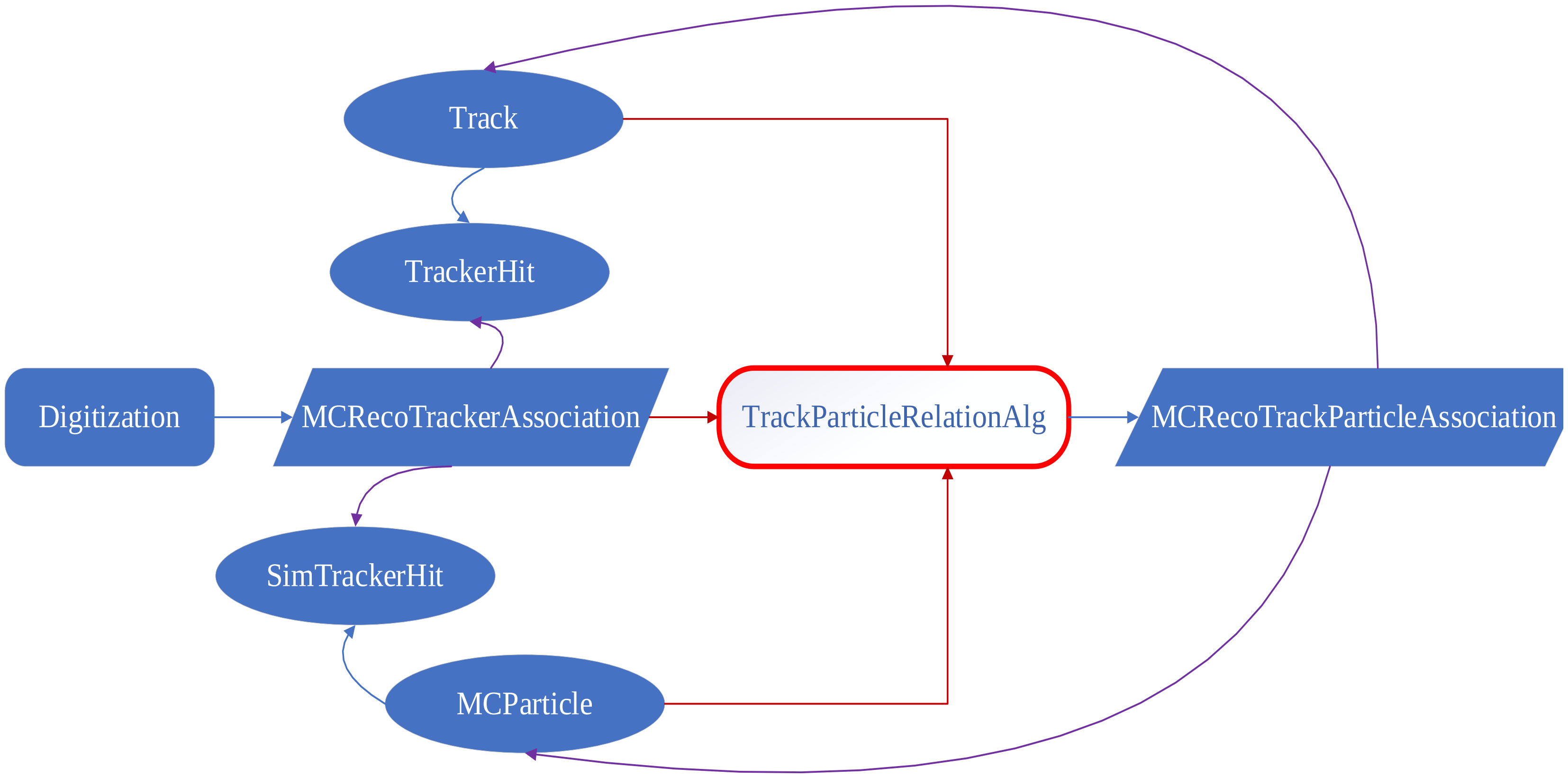






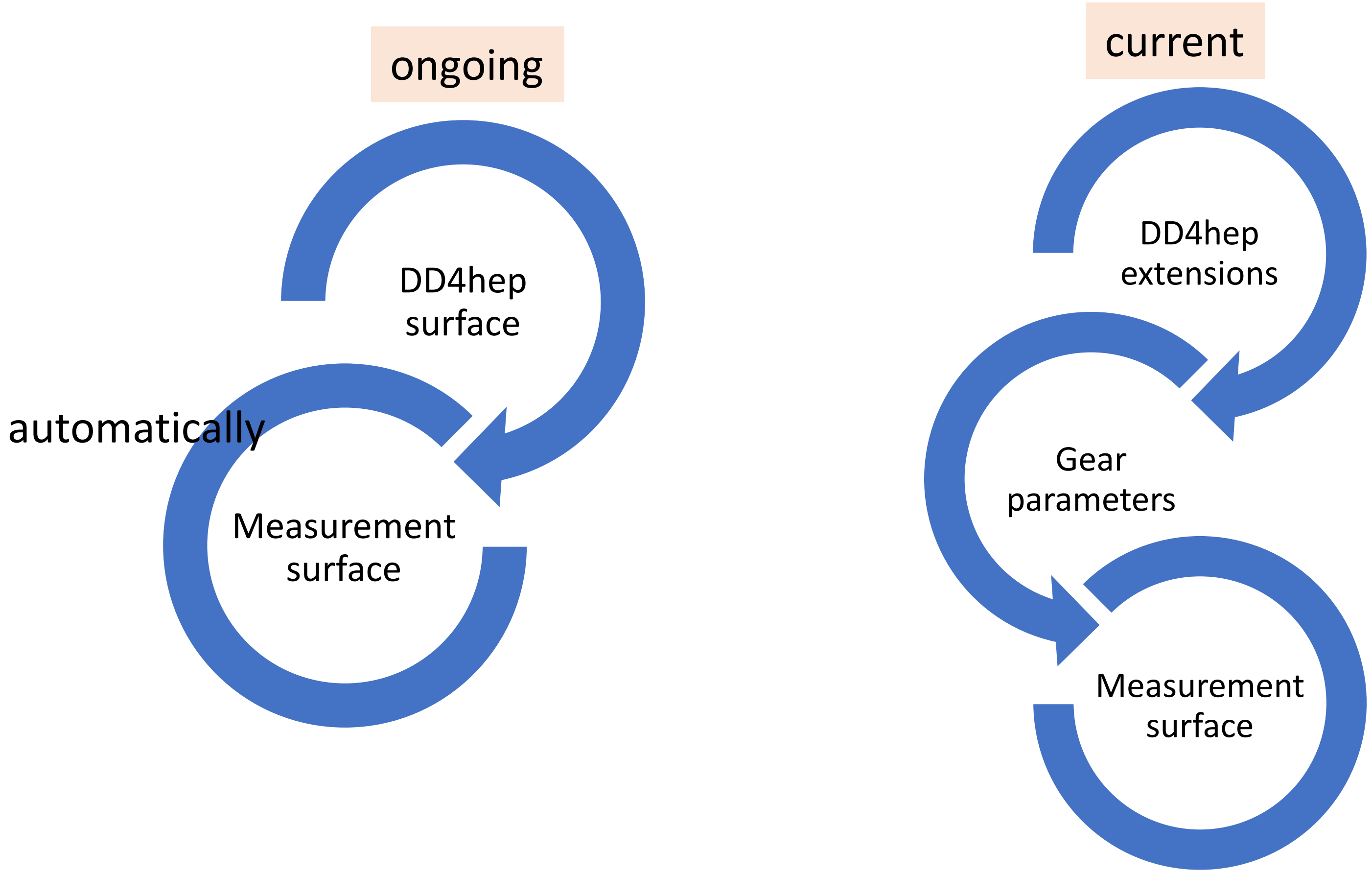
Association

- MCRecoTrackParticleAssociation
  - Track
  - MCParticle
  - weight: number of tracker hit linked between MCParticle and Track (NL), for a particle, found track (minimum requirement: NLmaximum≥4)



Update of Geometry Converter

- Current geometry converter is not suitable for detail geometry

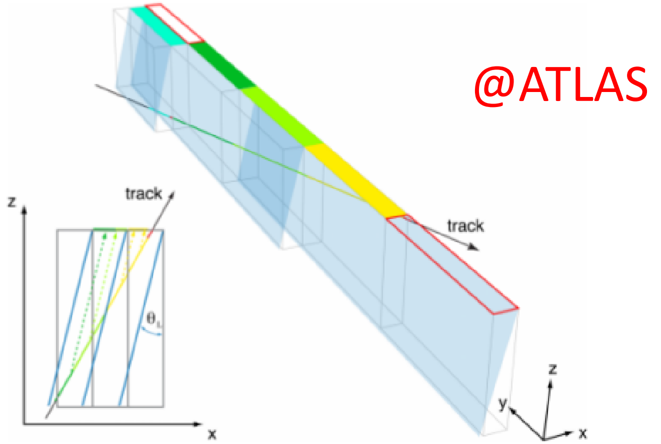


Fast Digitization

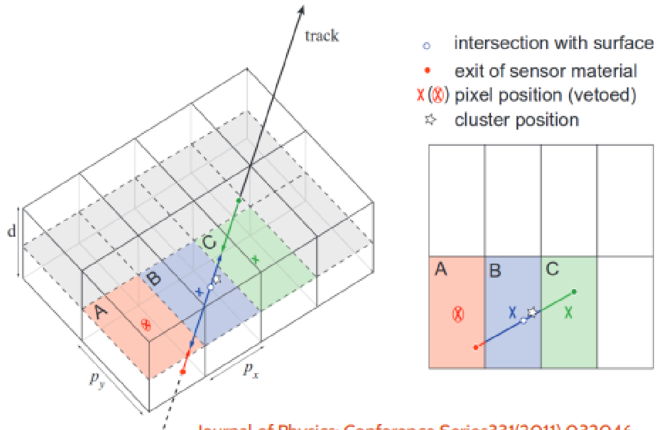
Fast Digitization: Silicon Tracker

Simplified digitization of the signal based on simply geometry projection.

- Local entry and exit point in the detector module from the detector simulation.
- Evaluate the step in each sensor.
- Charge deposited in each pixel proportional to the step.
- Project the charge on the surface taking into account the Lorentz shift (θ_L).



ATL-SOFT-PROC-2013-004



Journal of Physics: Conference Series331(2011) 032046

- Create the clusters directly in digitization step merging all the pixels crossed by a single track
- Set a threshold to path length
- Propagate the truth informations to the reconstruction.