Software of the Silicon Trackers in CEPCSW

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Silicon Tracker TDR meeting

Mar. 07, 2025

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- Overview of full simulation software
  - Simulation
  - Digitization
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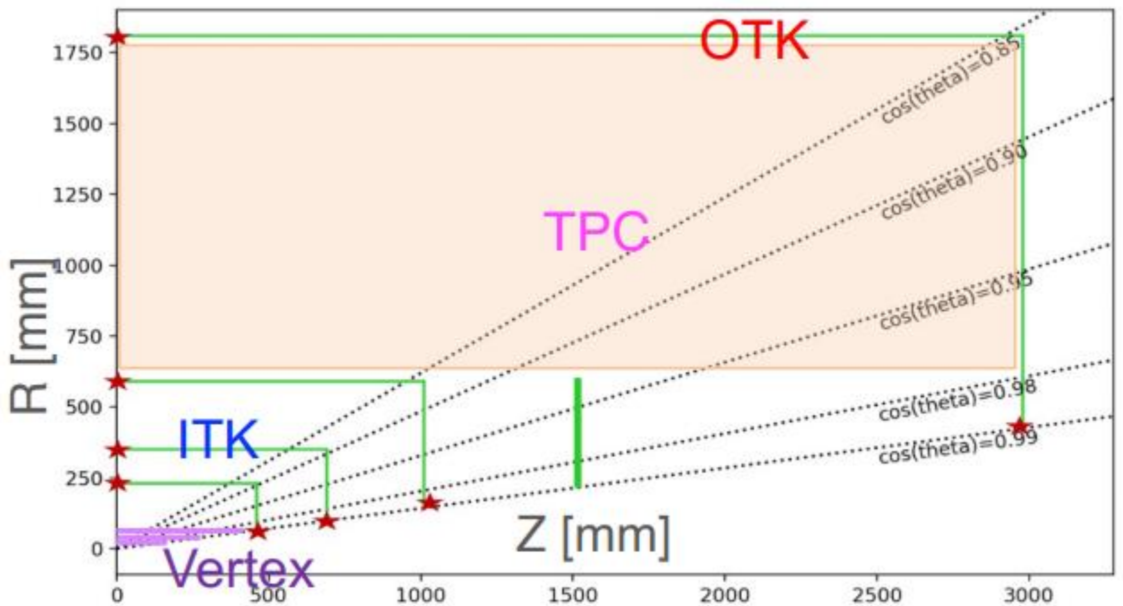
Introduction

Physics process	Measurands	Requirement on tracker
ZH, $Z \to e^+e^-(\mu^+\mu^-)$, $H \to \mu^+\mu^-$	m_H, $\sigma(ZH)$, $BR(H \to \mu^+\mu^-)$	$\Delta(1/p_T) = 2 \times 10^{-5} \oplus \frac{0.001}{p(GeV)\sin^{3/2}\theta}$

- 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:

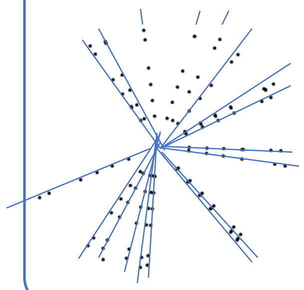
Event Generation → **Detector Simulation** → **Digitization** → **Reconstruction** → **Analysis & Application**

Event Generation
- Particle gun
- stdhep
- Pythia
- HepMC
- Beam-bkg
- etc.

Detector Simulation
- SimTrackerHit

Digitization
- TrackerHit

Reconstruction
- Track

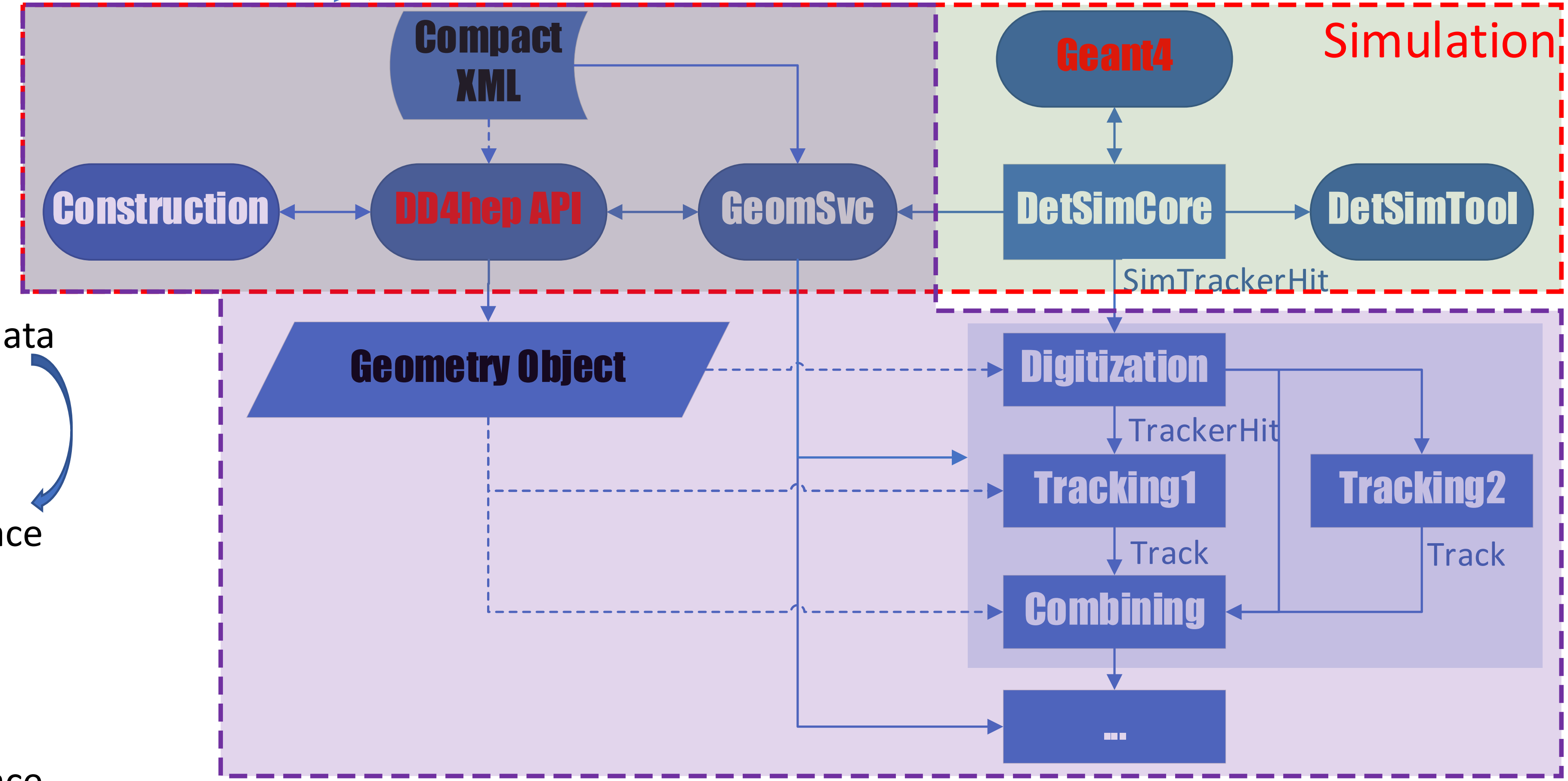


Analysis & Application
- Efficiency
- Resolution
- PFA
- Muon ID

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

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

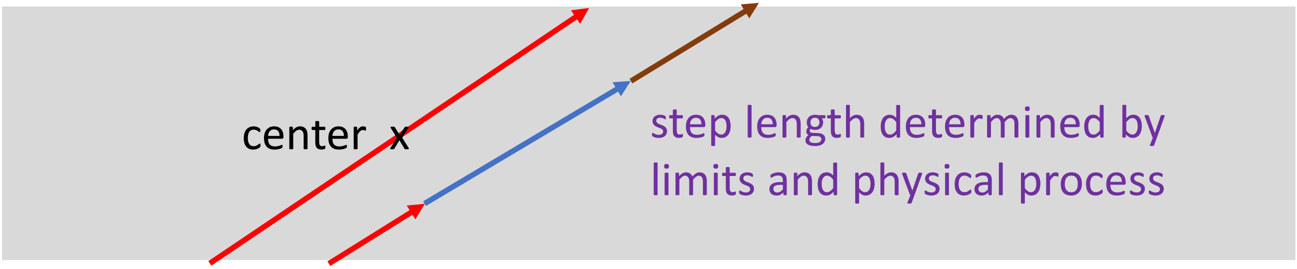
```
<limitset name="tracker_limits">
  <limit name="step_length_max" particles="*" value="5.0" unit="mm" />
</limitset>
<limitset name="detail_limits">
  <limit name="step_length_max" particles="*" value="0.005" unit="mm" />
</limitset>
```

- 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

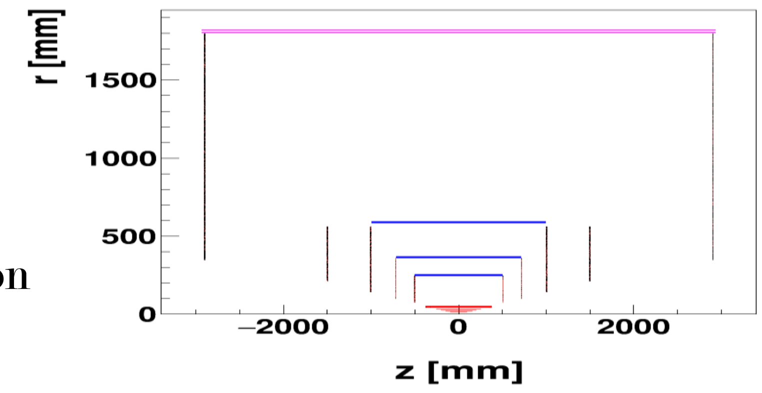
edm4hep::SimTrackerHit
- cell ID
- deposited energy
- time
- path length
- position
- momentum
- MCParticle
- quality

if combine = true, one hit
combine = false, multi hits

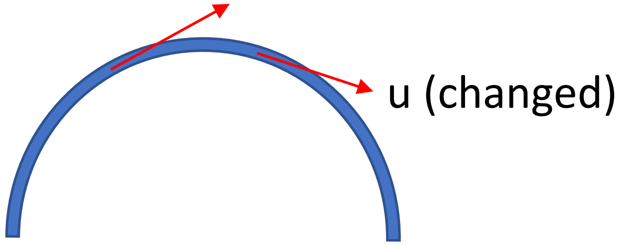
Volume of sensor



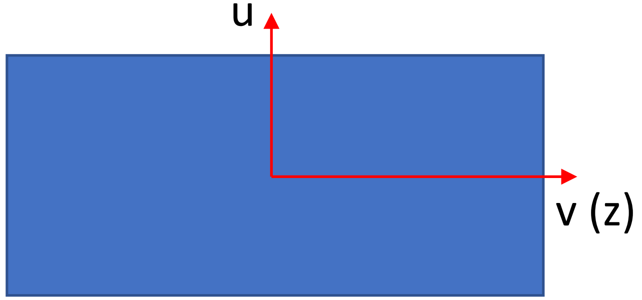
Digitization



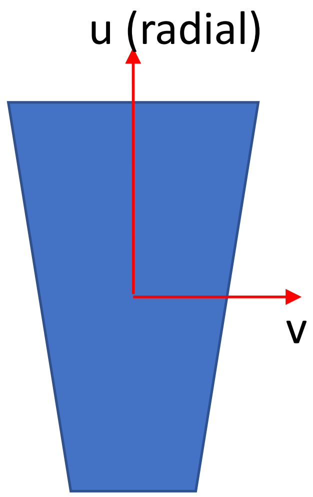
- Gaussian smearing on SimTrackerHit at measurement dimension (u,v)
  - pixel: 2D (u,v)
  - strip: 1D (u,0) or (0, v)
- Fixed spatial resolution or Parameterized spatial resolution through option
  - VXD: 5μm, ITK: 8μm (40μm), OTK: 10μm (1mm), TPC: varied with drift length
- Measurement surface at the center plane, consistent with the general simulated hit
- Drop threshold
  - Hit efficiency between [0,1]: current global for each sub-detector, local option for each sensor, support to make dead for whole sensor
  - Deposited energy in step



Barrel (Cylindric)



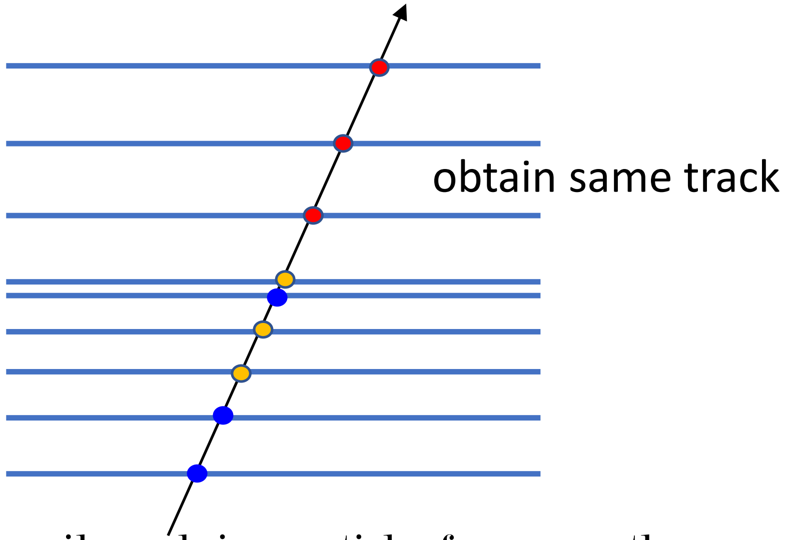
Barrel (Planar)



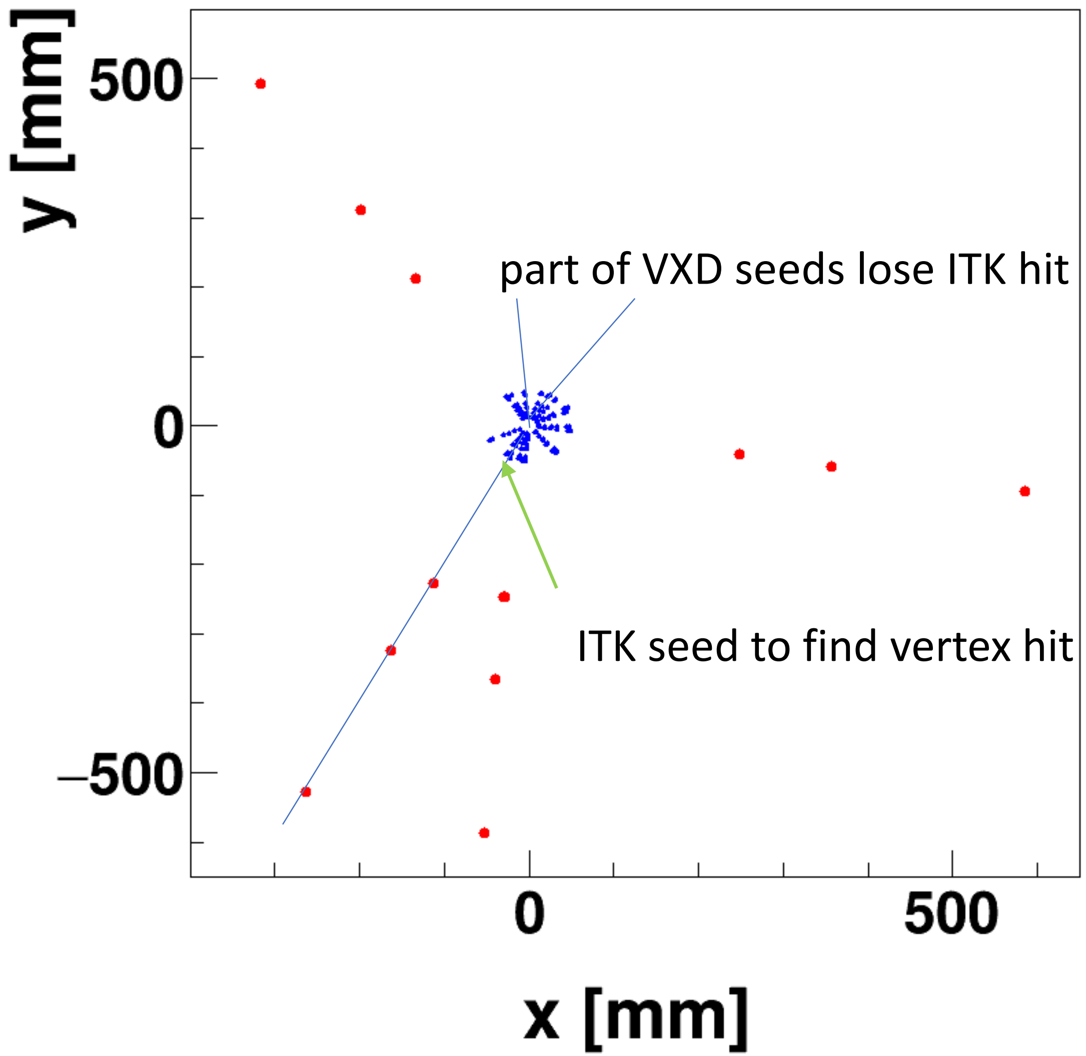
Endcap (Planar)

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

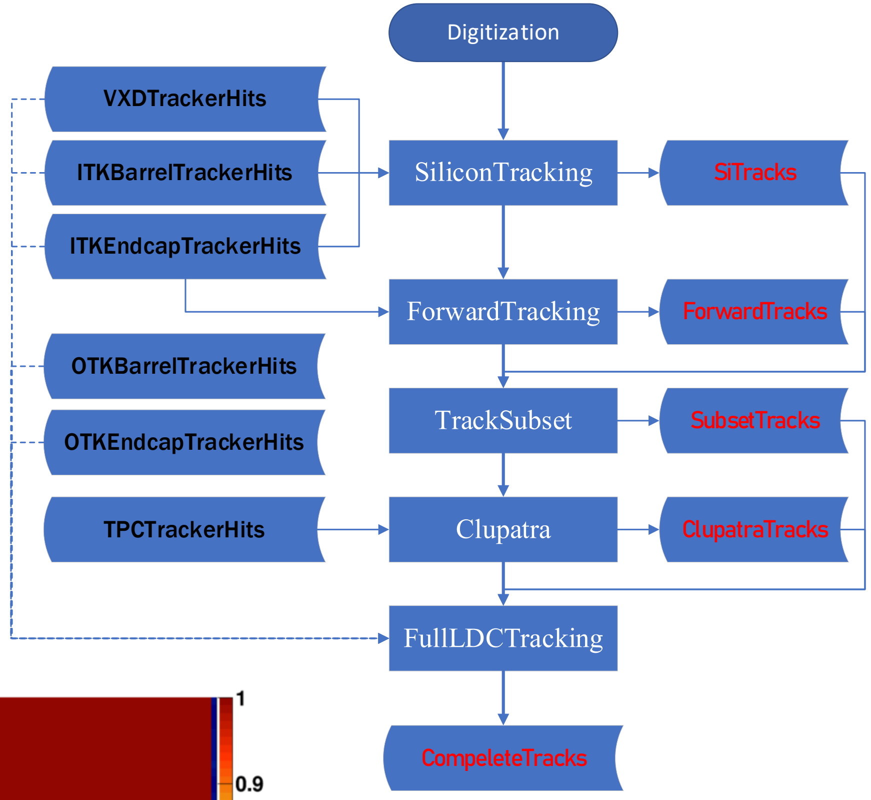


Tracking Options

- A complete reconstruction chain ready
  - Support to reconstruct part of trackers through option sets

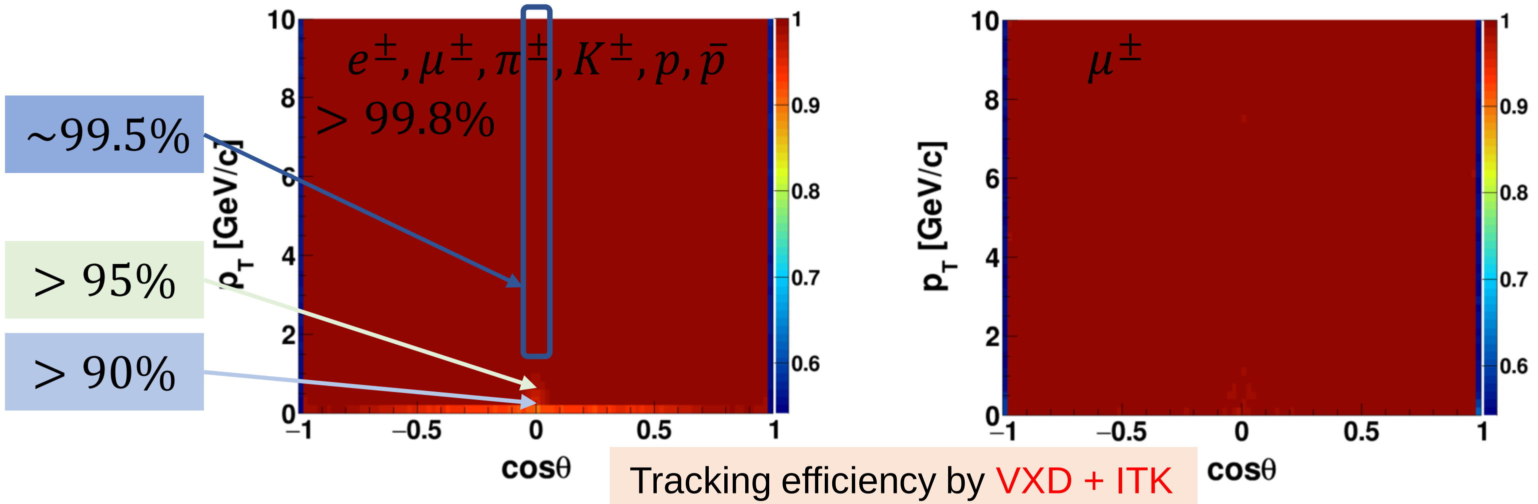
sets of tracking detectors	track objects
VXD only	VXDTracks
VXD + ITK	SiTracks
TPC only	ClupatraTracks (TPCTracks)
VXD + ITK + TPC	InnerTracks
VXD + ITK + OTK	FullSiTracks
ITK + TPC	CenterTracks
ITK + TPC + OTK	OuterTracks
VXD + ITK + TPC + OTK	CompleteTracks

Change input



  - More sets are optional such as ITK + OTK, helpful to study tracker performances for especial tracks (low momentum and decayed)

- Performance estimation by full simulation



Tracking efficiency by VXD + ITK

tdr25.1.2

Output

edm4hep::Track

……

edm4hep::TrackerHit s

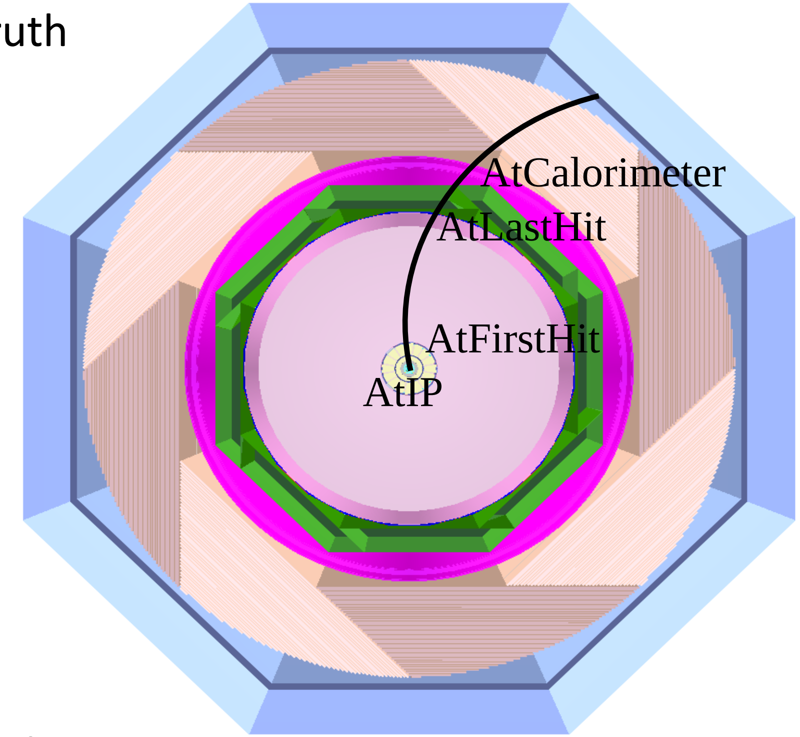
……

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

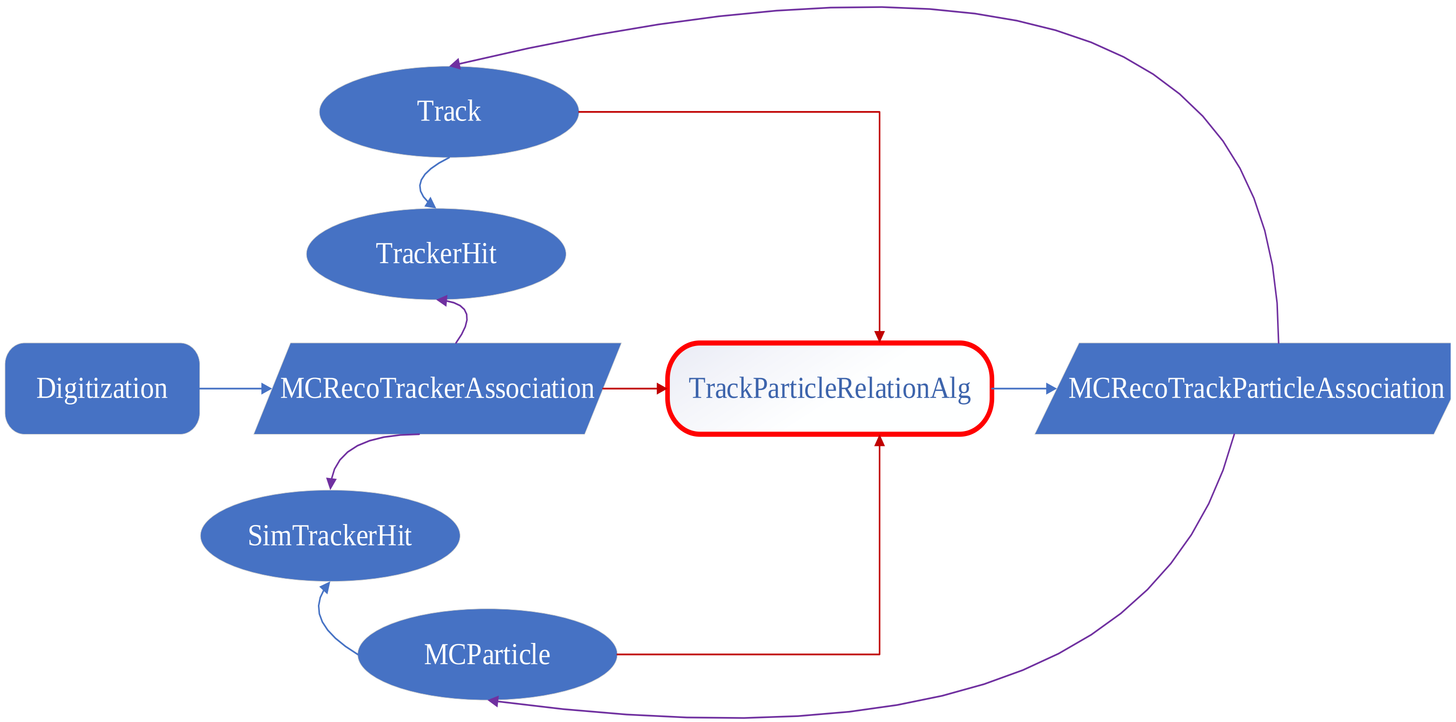


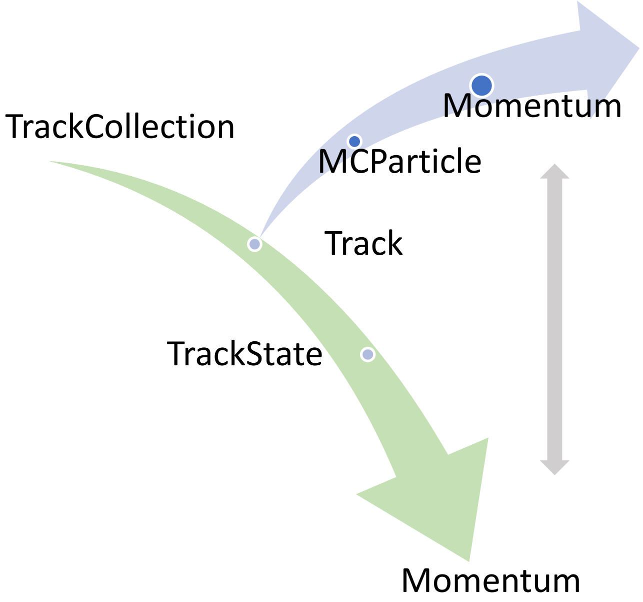
Currently, four TrackStates are in storage:

if(location==edm4hep::TrackState::AtIP)
if(location==edm4hep::TrackState::AtFirstHit)
if(location==edm4hep::TrackState::AtLastHit)
if(location==edm4hep::TrackState::AtCalorimeter)

Association

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





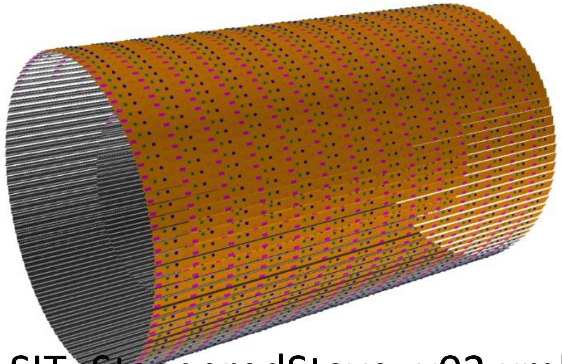
Geometry of ITKBarrel

- Previous version: SIT_StaggeredStave_v02.xml
  - JIANG Xiaojie implemented
  - non-uniform: DC-DC, optical, cooling
- Updated version: ITK_StaggeredStave_v03_01.xml
  - uniform supper layer — to fix issue at low momentum as preliminary
    - ✓ support: truss frame, carbon fleece, graphite foil, cooling pipe, cooling fluid, carbon fiber plate, glue
    - ✓ sensitive: by gaped modules (by gaped sensors with dead side)
    - ✓ flex: FPC, other electronics, glue
  - ladder radius and number: 103→102

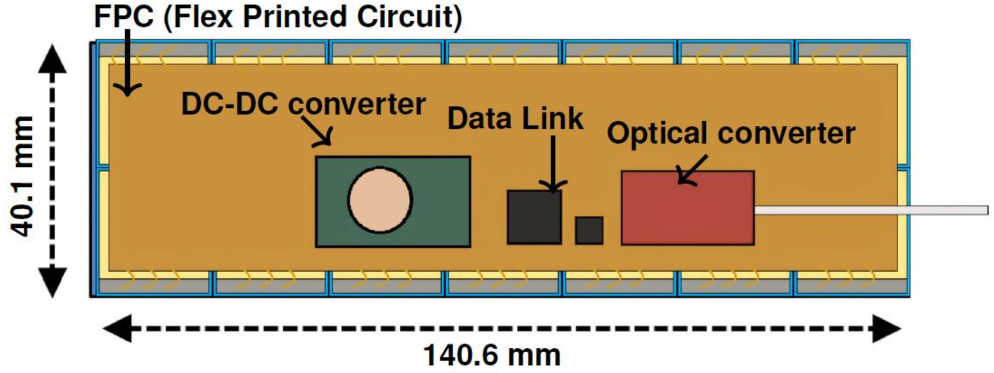
Barrel	Number of staves	Modules per stave	Sensors per module	Total number of sensors	Sensor area [m^2]
ITKB1	44	7	14	4312	1.72
ITKB2	64	10	14	8960	3.58
ITKB3	102	14	14	19992	8.00
Total	210			33264	13.31

Information about staves, modules, and sensors used for 3 ITK barrels construction

Table 5.4: Information about staves, modules, and sensors used for 3 ITK barrels construction.



SIT_StaggeredStave_v02.xml



Barrel Stave:

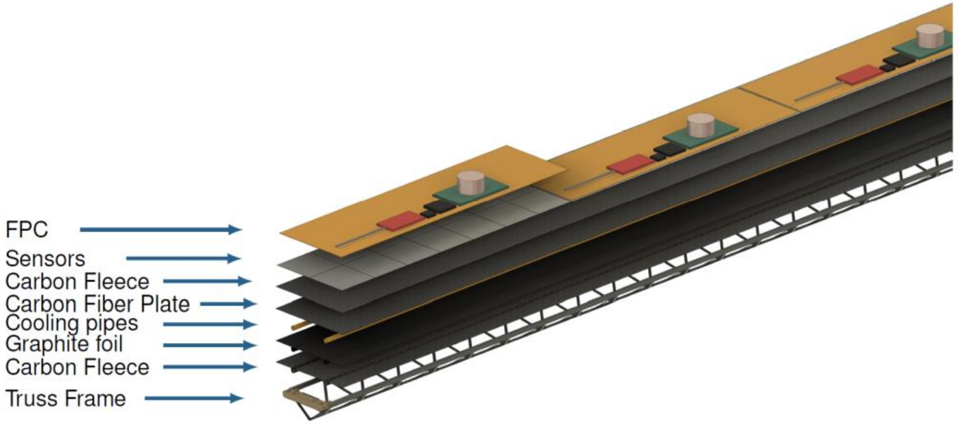
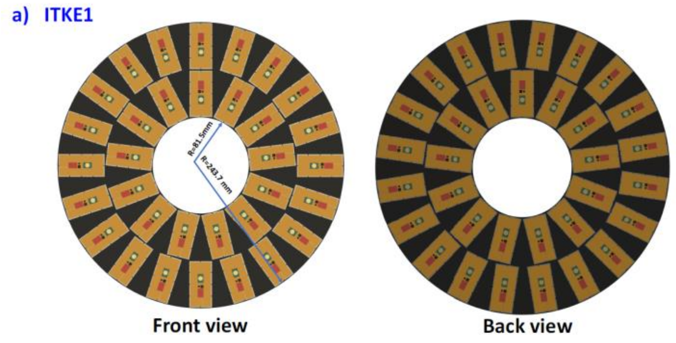
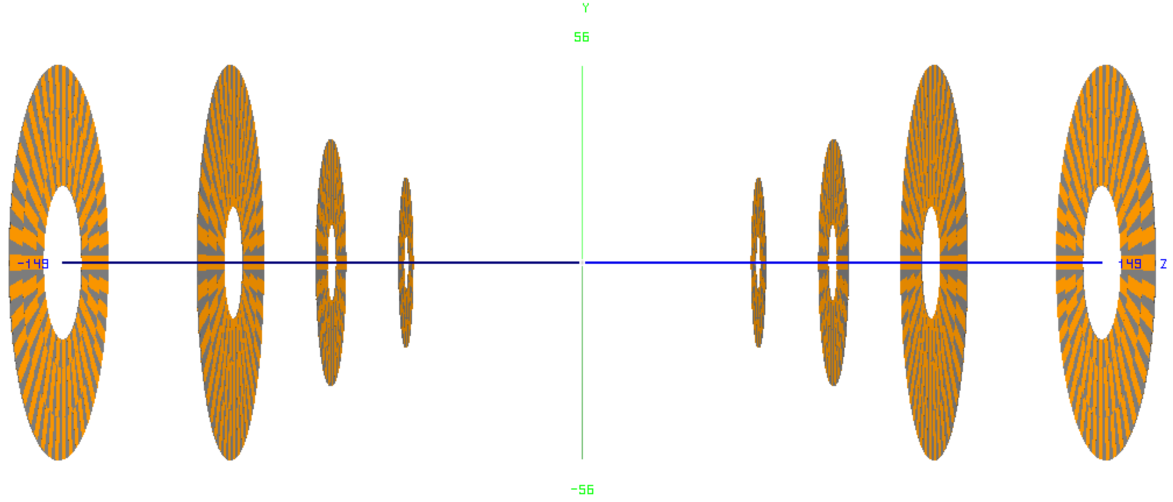


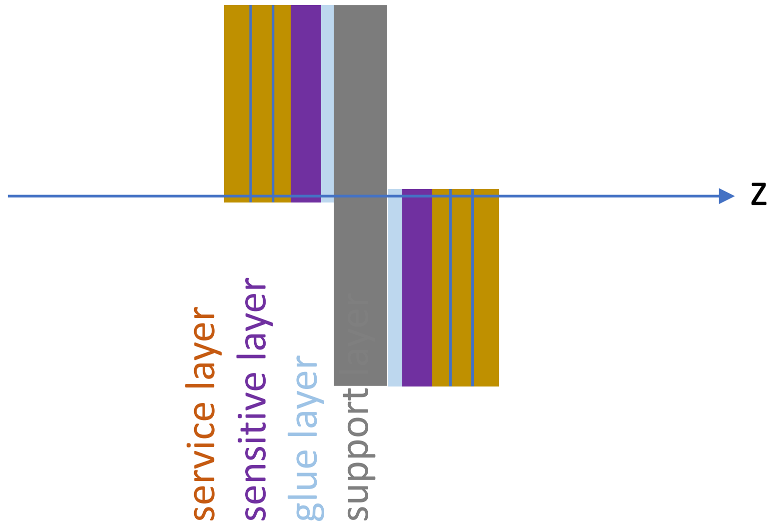
Figure 5.48: ITK barrel mechanics and cooling

Geometry of ITKEndcap

- Previous version: FTD_SkewRing_v01_07.xml
  - 16 trapezoid petals with sensitive layer and support layer
- Updated version: ITK_EndCap_v01.xml (MultiRingsZDisk)
  - support (disk): carbon fiber facesheet, cooling tube wall, cooling fluid, graphite foam+Honeycomb, carbon fiber plate facesheet
  - sensor: petal
    - ✓ glue: glue
    - ✓ sensitive: silicon
    - ✓ service: glue, FPC, other electronics







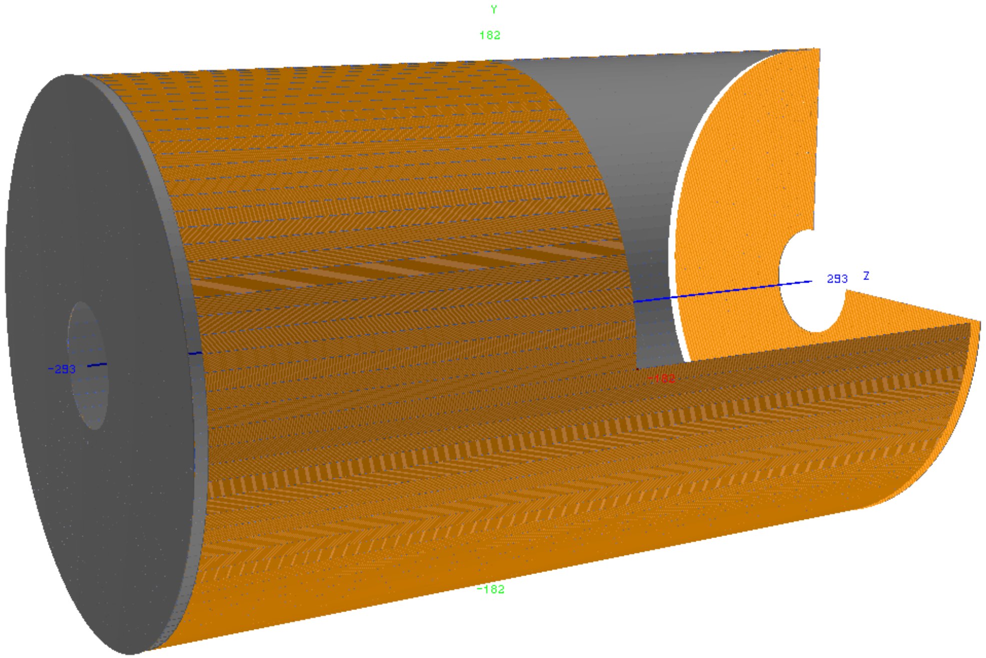
Endcap	Number of module rings	Number of modules per module ring	Number of sensors per module	Total sensors
ITKE1	2	13,20	8,8	264
ITKE2	3	16,24,28	8,8,8	544
ITKE3	3	24,36,44	12,14,14	1408
ITKE4	3	24,36,44	8,14,12	1224
Total				3440

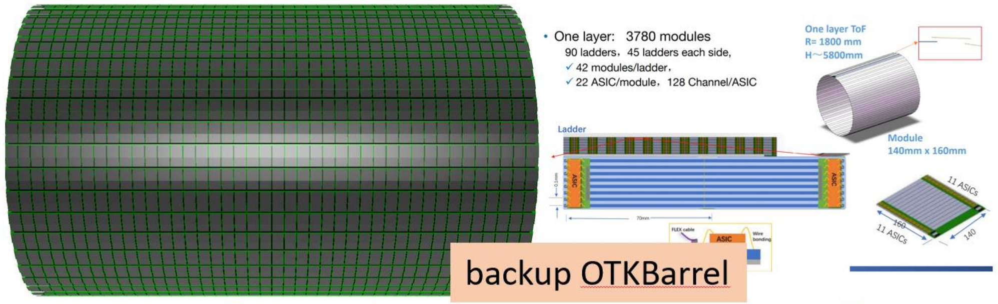
The Module and Sensor Layout of a Single Face of Each ITK Endcap

Table 5.5: The Module and Sensor Layout of a Single Face of Each ITK Endcap

Geometry of OTK

- Previous versions:
  - OTKB: backup (YU Dian implemented)
  - OTKE: 16 trapezoid petals, backup in patch
- Updated versions: baseline (LI Zhihao implemented)
  - OTKB: OTKBarrel_v02.xml
  - OTKE: OTKEndcap_v02.xml






```
<ring name="A1" inner_radius=" 406*mm" outer_radius="( 534-0.2)*mm" repeat="16* 5" aggregation="2"
<ring name="A2" inner_radius=" 534*mm" outer_radius="( 662-0.5)*mm" repeat="16* 5" aggregation="2"
<ring name="B1" inner_radius=" 662*mm" outer_radius="( 790-0.2)*mm" repeat="16* 7" aggregation="2"
<ring name="B2" inner_radius=" 790*mm" outer_radius="( 862-0.2)*mm" repeat="16* 7" aggregation="1"
<ring name="B3" inner_radius=" 862*mm" outer_radius="(1008-0.5)*mm" repeat="16* 7" aggregation="2"
<ring name="C1" inner_radius="1008*mm" outer_radius="(1123-0.2)*mm" repeat="16*10" aggregation="2"
<ring name="C2" inner_radius="1123*mm" outer_radius="(1255-0.2)*mm" repeat="16*10" aggregation="2"
<ring name="C3" inner_radius="1255*mm" outer_radius="(1324-0.2)*mm" repeat="16*10" aggregation="1"
<ring name="C4" inner_radius="1324*mm" outer_radius="(1400-0.5)*mm" repeat="16*10" aggregation="1"
<ring name="D1" inner_radius="1400*mm" outer_radius="(1460-0.2)*mm" repeat="16*14" aggregation="1"
<ring name="D2" inner_radius="1460*mm" outer_radius="(1520-0.2)*mm" repeat="16*14" aggregation="1"
<ring name="D3" inner_radius="1520*mm" outer_radius="(1668-0.2)*mm" repeat="16*14" aggregation="2"
<ring name="D4" inner_radius="1668*mm" outer_radius="(1816-0.2)*mm" repeat="16*14" aggregation="2"
```

Material

```
<flex length="ITKBarrel_ladder_length_1" width="ITKBarrel_module_width" material="Air" vis="SeeThrough">
  <slice name="Glue"          thickness="100*um" material="CER_ITK"          vis="YellowVis"/>
  <slice name="FPCInsulating" thickness="100*um" material="Polyimide_ITK"    vis="YellowVis"/>
  <slice name="FPCMetal"      thickness="100*um" material="G4_Al"            vis="GrayVis"/>
  <slice name="OEComponent1"  thickness=" 25*um" material="Kapton"           vis="YellowVis"/>
  <slice name="OEComponent2"  thickness=" 56*um" material="G4_POLYETHYLENE" vis="GreenVis"/>
  <slice name="OEComponent3"  thickness="  3*um" material="G4_Cu"            vis="RedVis"/>
</flex>
```

Estimation of ITK stave material contributions

Functional unit	Component	Material	Thickness [μm]	X_0 [cm]	Radiation Length [% X_0]
Sensor Module	FPC metal layers	Aluminium	100	8.896	0.112
	FPC Insulating layers	Polyimide	100	28.41	0.035
	Sensor	Silicon	150	9.369	0.160
	Glue		100	44.37	0.023
	Other electronics				0.050
Cooling Plate	Carbon fleece layers	Carbon fleece	40	106.80	0.004
	Carbon fiber plate	Carbon fiber	150	26.08	0.057
	Cooling tube wall	Polyimide	64	28.41	0.013
	Cooling fluid	Water		35.76	0.105
	Graphite foil	Graphite	30	26.56	0.011
	Glue	Cyanate ester resin	100	44.37	0.023
Truss Frame	Carbon rowing				0.080
Total					0.673

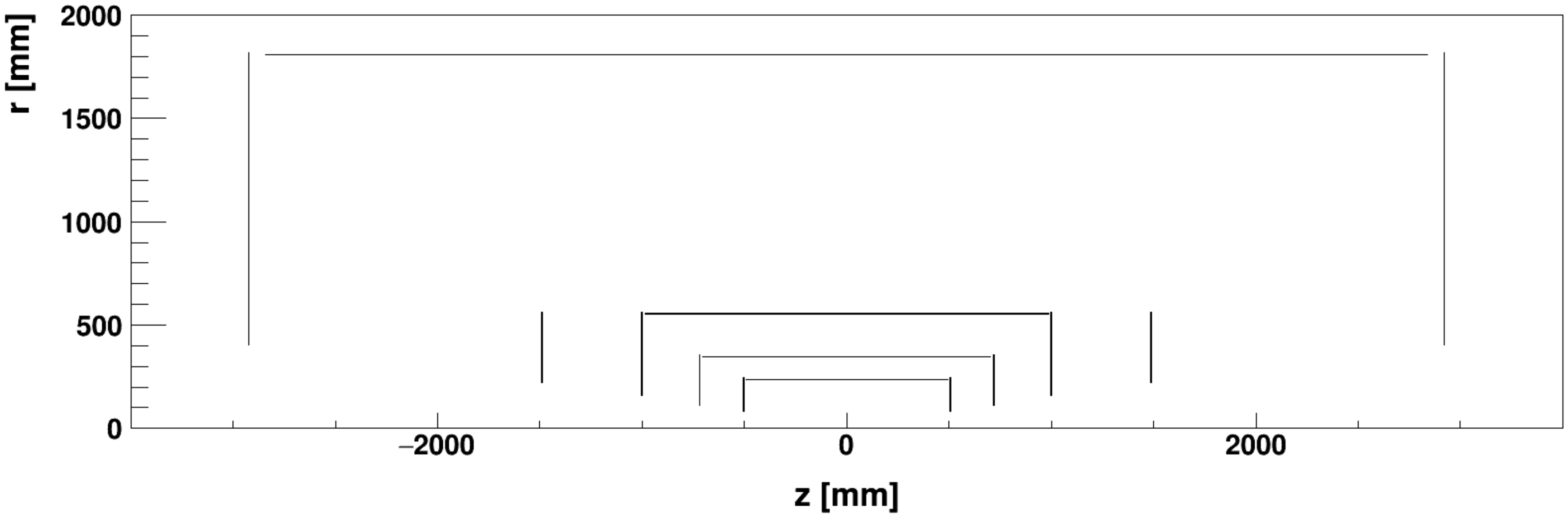
Table 5.9: Estimation of ITK stave material contributions

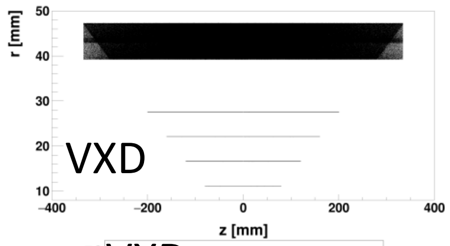
Num. Layer	Material Name	Atomic Number/Z	Mass/A [g/mole]	Density [g/cm3]	Radiation Length [cm]	Thickness [cm]	Integrated X0 [cm]
1	Air	7	14.801	0.0012	30392.1242	3.418	0.000112
2	CF_ITK	6	11.956	1.6088	26.0800	0.021	0.000910
3	CarbonFleece_ITK	6	12.011	0.3998	106.8000	0.002	0.000929
4	Graphite_ITK	6	12.011	1.6076	26.5600	0.003	0.001042
5	Polyimide_ITK	6	12.701	1.4282	28.4100	0.006	0.001267
6	G4_WATER	7	14.322	1.0000	36.0830	0.038	0.002317
7	CF_ITK	6	11.956	1.6088	26.0800	0.015	0.002892
8	CarbonFleece_ITK	6	12.011	0.3998	106.8000	0.002	0.002911
9	CER_ITK	7	13.326	0.8809	44.3700	0.010	0.003137
10	G4_Si	14	28.085	2.3300	9.3661	0.015	0.004738
11	CER_ITK	7	13.326	0.8809	44.3700	0.010	0.004963
12	Polyimide_ITK	6	12.701	1.4282	28.4100	0.010	0.005315
13	G4_Al	13	26.982	2.6990	8.8963	0.010	0.006440
14	Kapton	6	12.701	1.2430	32.6437	0.003	0.006516
15	G4_POLYETHYLENE	5	10.429	0.9400	47.6314	0.006	0.006634
16	G4_Cu	29	63.546	8.9600	1.4356	0.000	0.006843

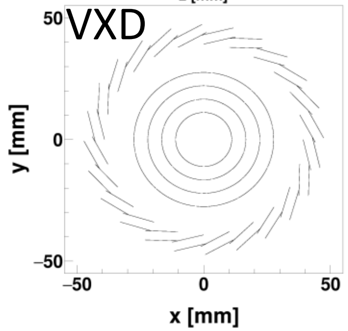
- total 0.006843-0.000112=0.006731 of X0

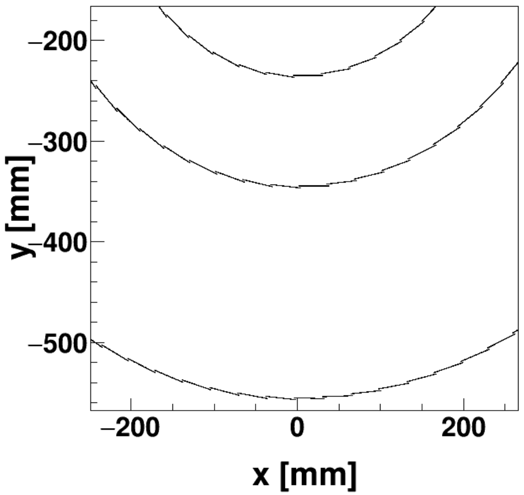
```
<support length="ITKBarrel_ladder_length_1" width="ITKBarrel_module_width" material="Air" vis="SeeThrough">
  <slice name="TrussFrame"   thickness="208*um" width="ITKBarrel_module_width" material="CF_ITK"           vis="LightGrayVis"/>
  <slice name="CarbonFleece" thickness=" 20*um" width="ITKBarrel_module_width" material="CarbonFleece_ITK" vis="LightGrayVis"/>
  <slice name="GraphiteFoil" thickness=" 30*um" width="ITKBarrel_module_width" material="Graphite_ITK"     vis="GrayVis"/>
  <slice name="CoolingTube"  thickness=" 64*um" width="ITKBarrel_module_width" material="Polyimide_ITK"    vis="SeeThrough"/>
  <slice name="CoolingFluid" thickness="379*um" width="ITKBarrel_module_width" material="G4_WATER"         vis="SeeThrough"/>
  <slice name="CFPlate"      thickness="150*um" width="ITKBarrel_module_width" material="CF_ITK"           vis="GrayVis"/>
  <slice name="CarbonFleece" thickness=" 20*um" width="ITKBarrel_module_width" material="CarbonFleece_ITK" vis="LightGrayVis"/>
  <slice name="Glue"         thickness="100*um" width="ITKBarrel_module_width" material="CER_ITK"          vis="GrayVis"/>
</support>
```

Positions of Hits of Silicon Trackers

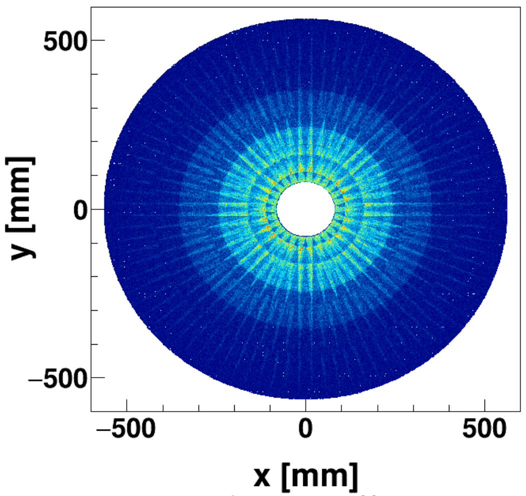




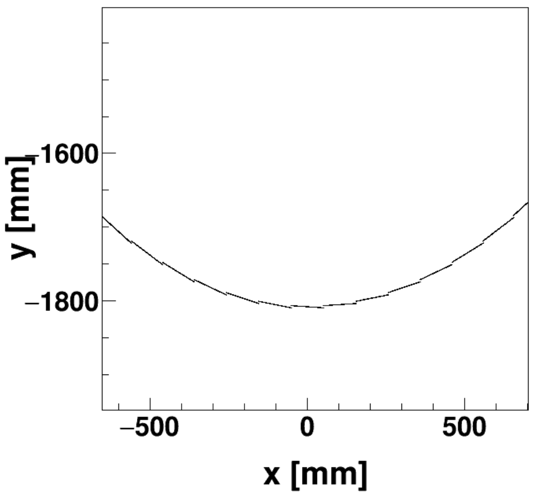




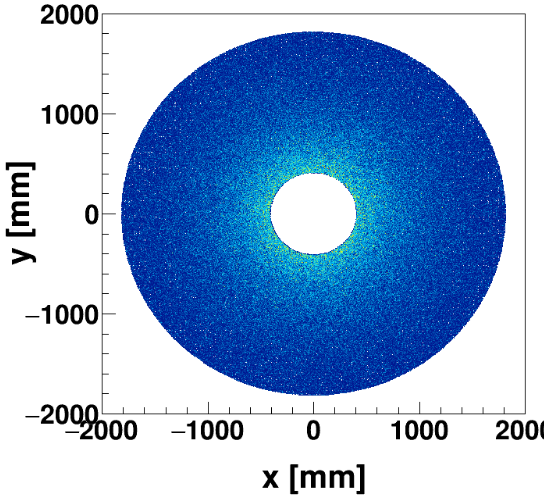
ITKBarrelCollection



ITKEndcapCollection



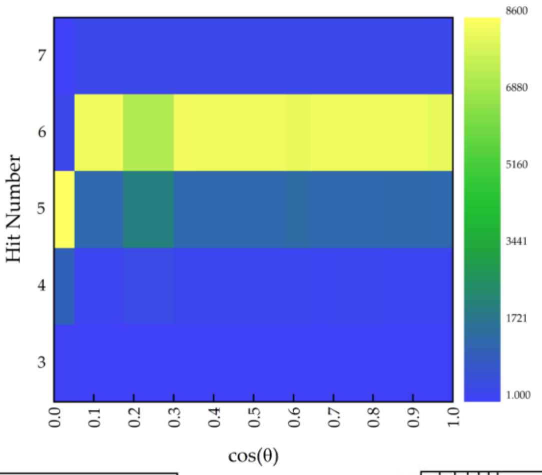
OTKBarrelCollection

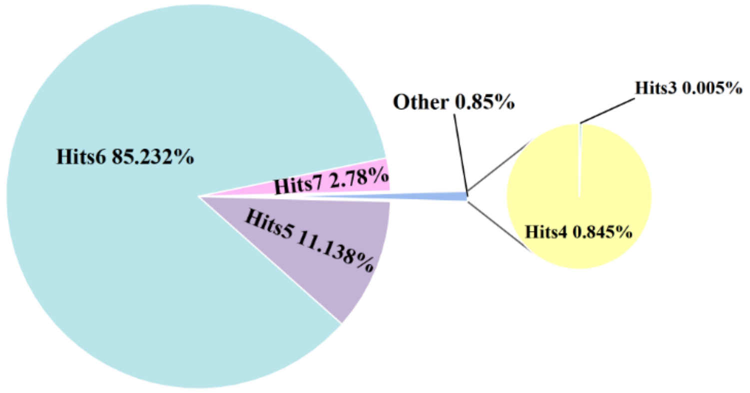


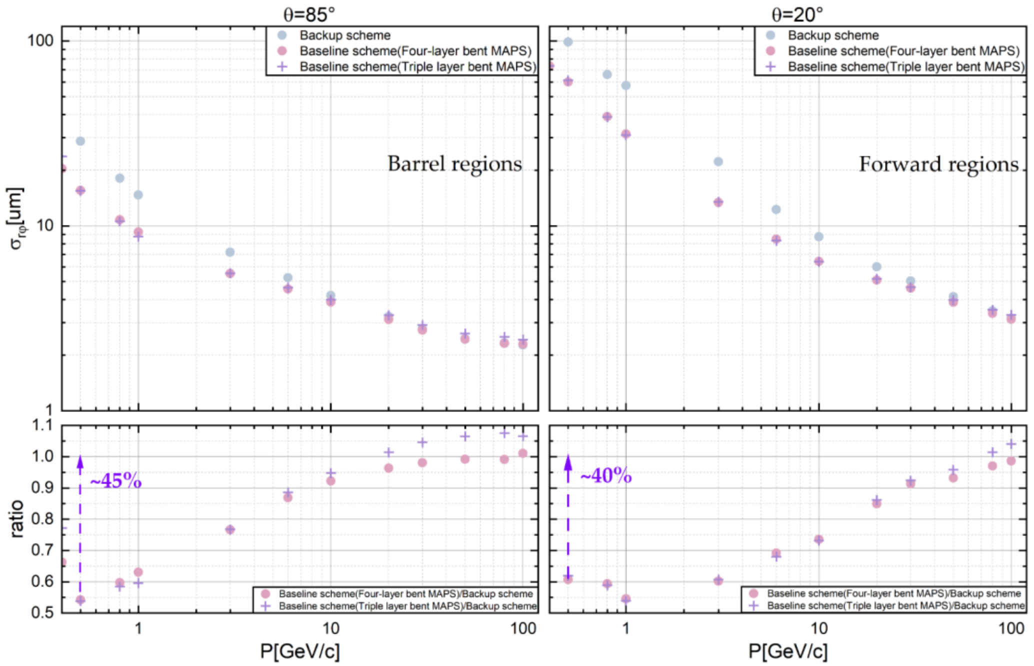
OTKEndcapCollection

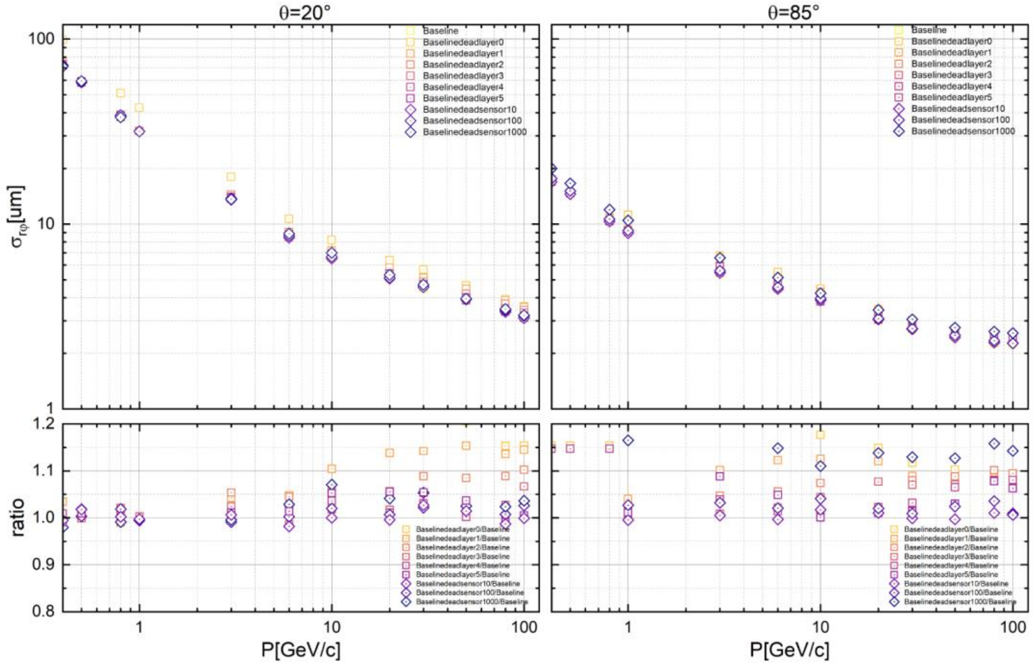
Application on the Vertex Detector

- Perform performance comparison on different case in CEPCSW (ZHANG Tianyuan)
  - Different schemes
  - Hit number
  - Dead sensors, even whole layer

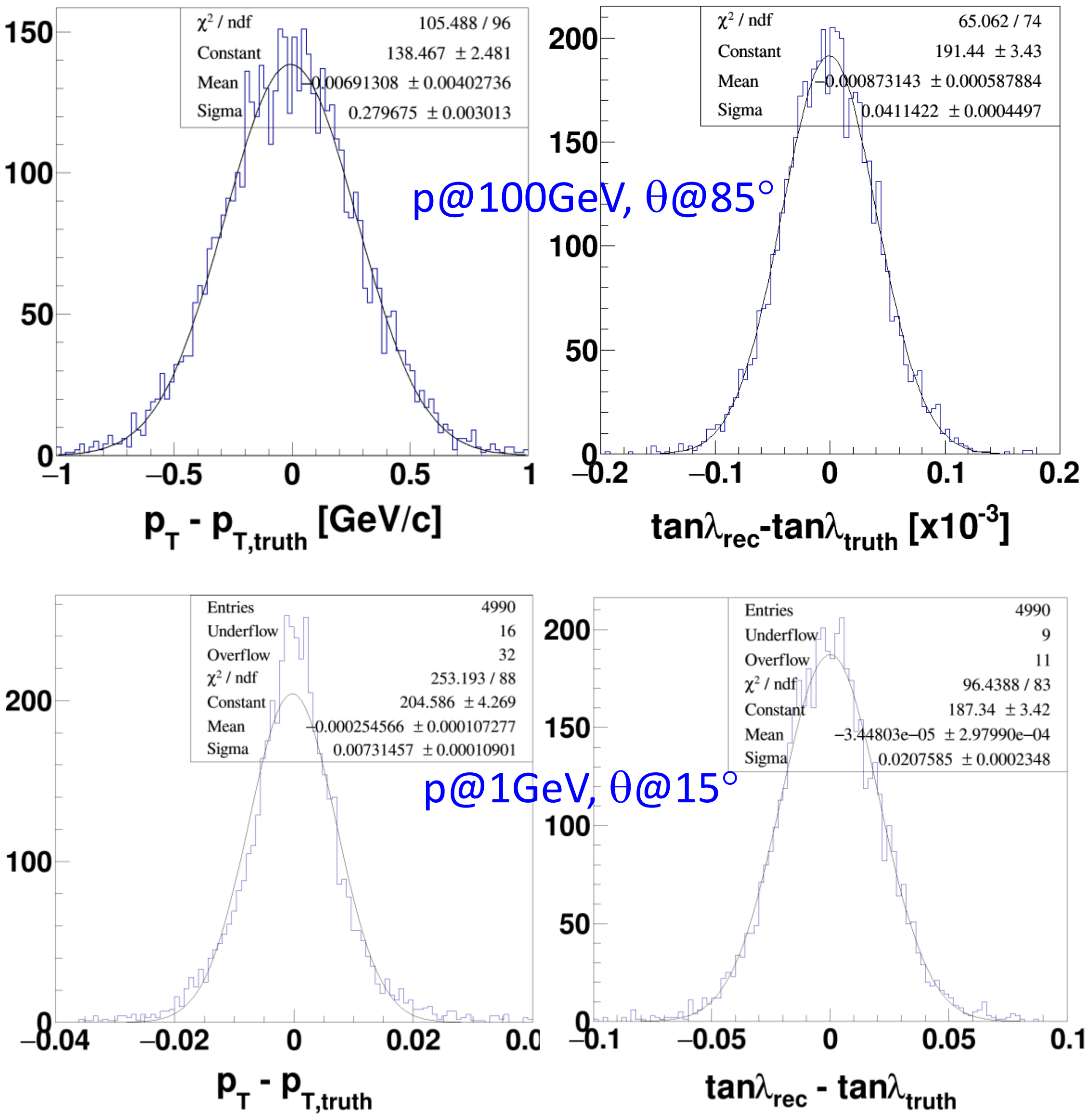


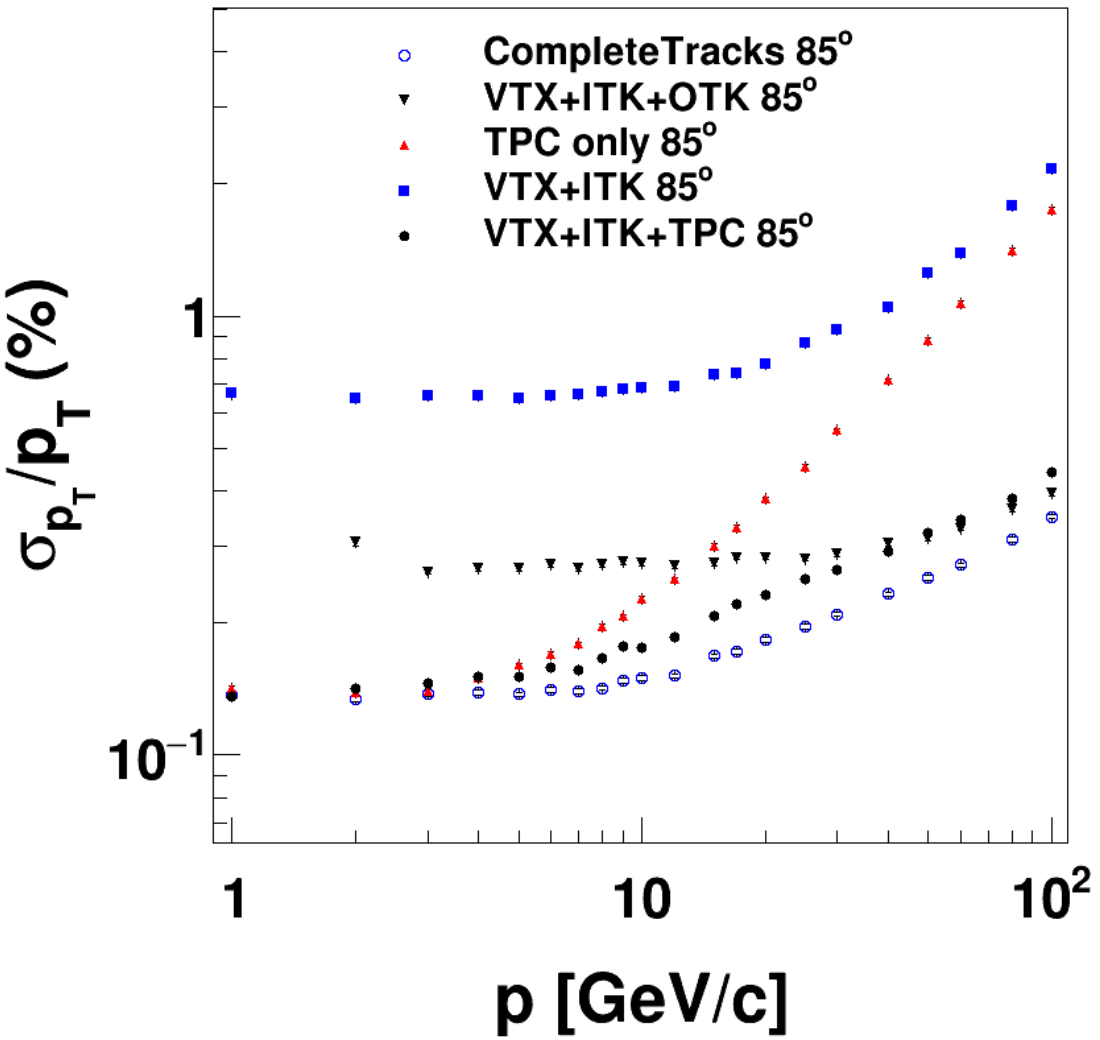






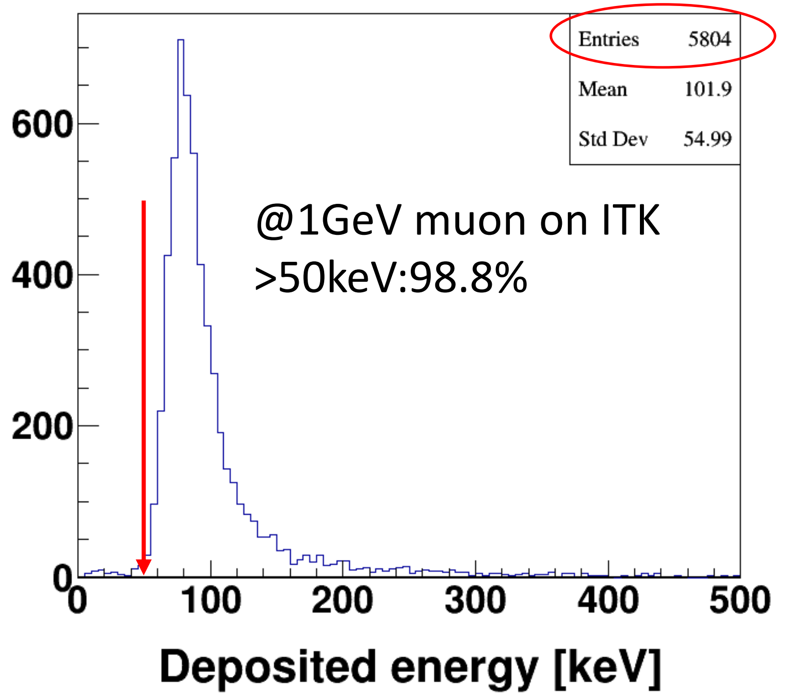
Resolution


χ² / ndf 105.488 / 96
Constant 138.467 ± 2.481
Mean −0.00691308 ± 0.00402736
Sigma 0.279675 ± 0.003013
p_T - p_T,truth [GeV/c]
χ² / ndf 65.062 / 74
Constant 191.44 ± 3.43
Mean −0.000873143 ± 0.000587884
Sigma 0.0411422 ± 0.0004497
tanλ_rec-tanλ_truth [x10^-3]
p@100GeV, θ@85°
Entries 4990
Underflow 16
Overflow 32
χ² / ndf 253.193 / 88
Constant 204.586 ± 4.269
Mean −0.000254566 ± 0.000107277
Sigma 0.00731457 ± 0.00010901
p_T - p_T,truth
Entries 4990
Underflow 9
Overflow 11
χ² / ndf 96.4388 / 83
Constant 187.34 ± 3.42
Mean −3.44803e−05 ± 2.97990e−04
Sigma 0.0207585 ± 0.0002348
tanλ_rec - tanλ_truth
p@1GeV, θ@15°


CompleteTracks 85°
VTX+ITK+OTK 85°
TPC only 85°
VTX+ITK 85°
VTX+ITK+TPC 85°
σ_pT/p_T (%)
p [GeV/c]

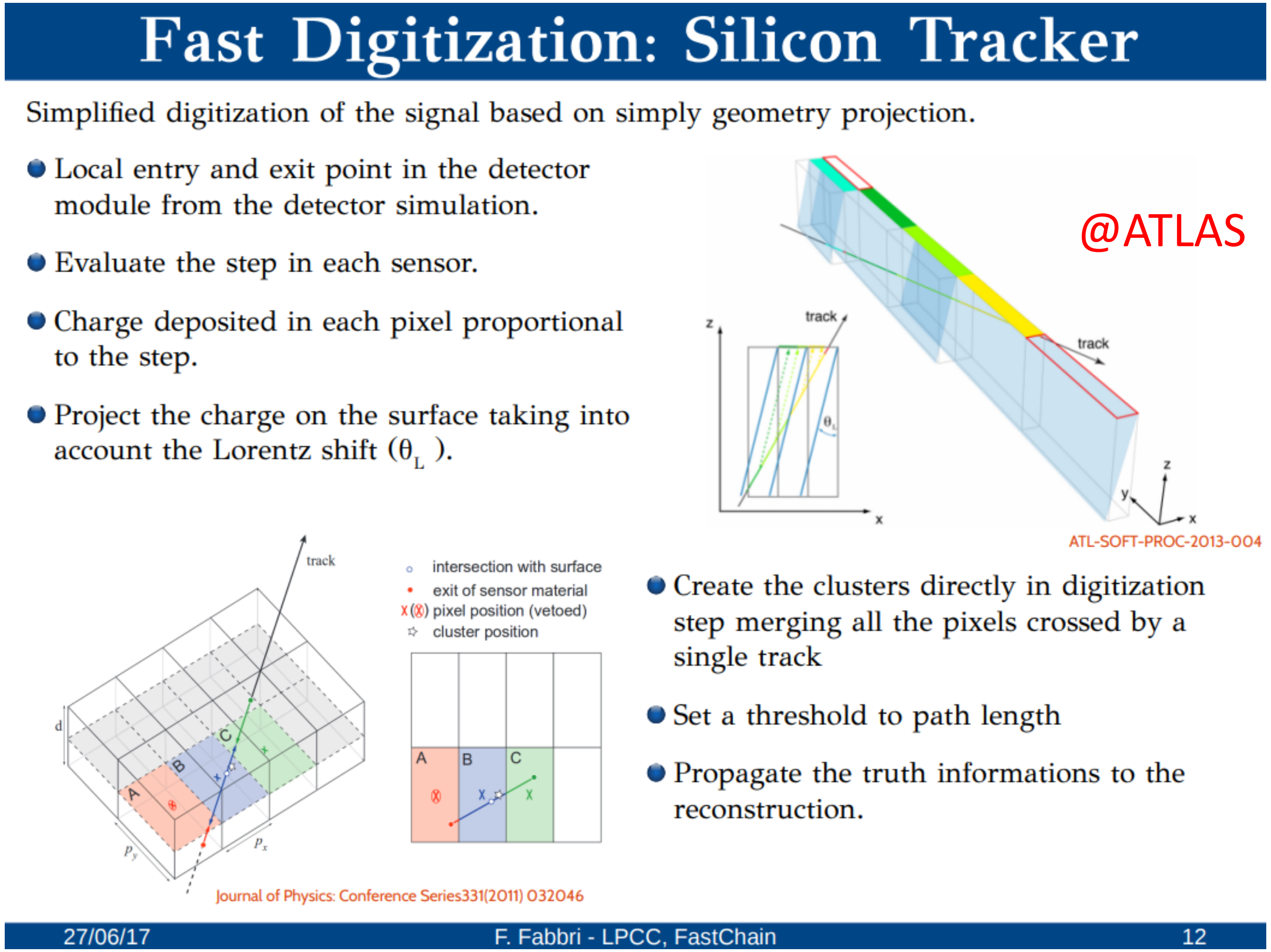
Issues and Plan

- Hit efficiency
  - Not perform threshold now
  - To find out threshold about 99%?
  - Effective thickness?
- Software development
  - Efficiency at low momentum and small polar angle
  - Help tools
  - Alignment
- Performance estimation on special case
  - Dead sensor
    - ✓ Hit drop according to deposited energy or efficiency
    - ✓ Hit drop in whole sensors
  - Background mixing



Fast Digitization

- To create a fast digitization similar with ATLAS
- For vertex detector
  - Without charge amplitude
  - ongoing: by LU Hancen
- For CMOS pixel/strip
  - Charge deposited
- For AC-LGAD
  - Charge deposited
- Estimate hit rate on merged hits while simulation
- Effective thickness?
  - Charge collected



Summary

- Full simulation chain for tracker has been created in CEPCSW
  - Output edm4hep SimTrackerHit, TrackerHit, Track and association
  - Helix tool to obtain momentum
  - Apply on performance study and PFA, muon ID ongoing
- Baseline silicon trackers has been implemented: ITKB, ITKE, OTKB, OTKE
  - TDR baseline detector geometry TDR_o1_v01 close to forezen
- Towards TDR
  - Tracking under dead sensors
  - Tracking under background
- Future
  - Fast digitization
  - Alignment