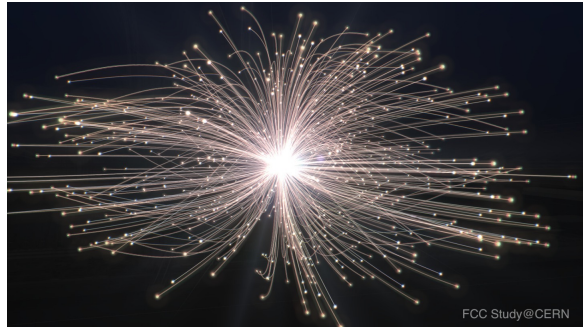
IDEA vertex and silicon wrapper detector simulation

FCC Physics Workshop 2024, Annecy

Armin Ilg

University of Zürich

30.01.2024



University of Zurich[UZH]

FUTURE CIRCULAR COLLIDER

Goal of the FCC feasibility study

A lot of work to be done for the feasibility study...
For the experiments:

- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- What next-gen detector technologies can benefit the FCC-ee physics program? Different detector concepts?

Goal: Establish feedback-loop

Sensor perf. $\overset{\text{detector}}{\underset{\text{sim.}}{\rightarrow}}$ Subdetector perf. $\overset{\text{sample}}{\underset{\text{analysis}}{\rightarrow}}$ physics perf. $\overset{\text{theory}}{\underset{\text{input}}{\rightarrow}}$ sensor specification

Need to perform simulation and analysis of *realistic* detectors at FCC-ee! $\rightarrow$ **Full simulation of complete detectors, using particle flow**

Goal of the FCC feasibility study

A lot of work to be done for the feasibility study...
For the experiments:

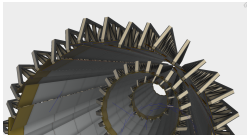
- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- What next-gen detector technologies can benefit the FCC-ee physics program? Different detector concepts?

Goal: Establish feedback-loop

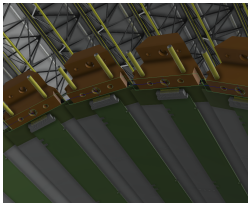
Sensor perf. $\overset{\text{detector}}{\underset{\text{sim.}}{\rightarrow}}$ Subdetector perf. $\overset{\text{sample}}{\underset{\text{analysis}}{\rightarrow}}$ physics perf. $\overset{\text{theory}}{\underset{\text{input}}{\rightarrow}}$ sensor specification

Need to perform simulation and analysis of *realistic* detectors at FCC-ee! $\rightarrow$ **Full simulation of complete detectors, using particle flow**
Today on the menu: IDEA vertex and silicon wrapper and some more exquisite IDEAs

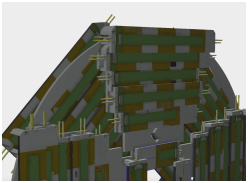
IDEA vertex detector: Design



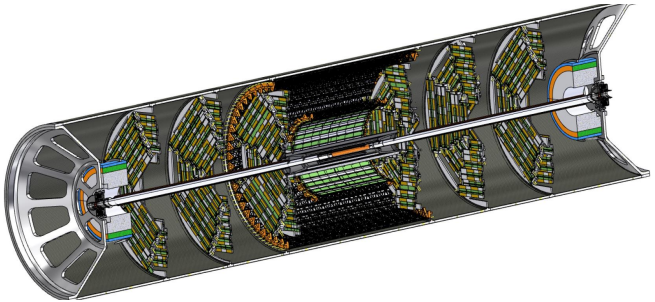
Vertex inner barrel



Vertex outer barrel



Vertex disks

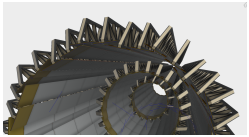


- Vertex detector by INFN Pisa (F. Palla Tue. morning)
- Support tube done by F. Fransesini and M. Boscolo (INFN-LNF). Holding:
  - Luminosity calorimeter
  - Vertex detector
  - Beam pipe ($R_{\text{inner}} = 1\,\text{cm}$)

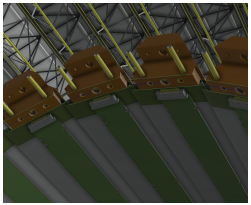
→ Rather advanced design!

→ What's its performance?

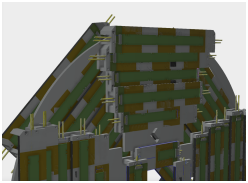
IDEA vertex detector: Design



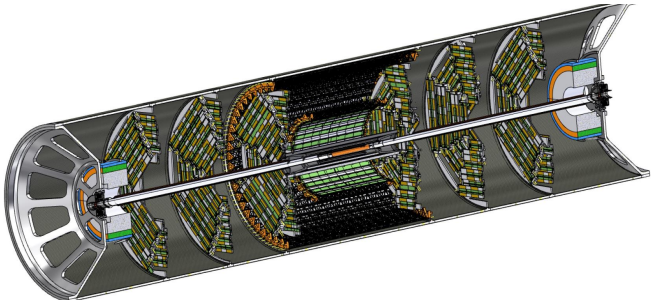
Vertex inner barrel



Vertex outer barrel



Vertex disks



- Vertex detector by INFN Pisa (F. Palla Tue. morning)
- Support tube done by F. Fransesini and M. Boscolo (INFN-LNF). Holding:
  - Luminosity calorimeter
  - Vertex detector
  - Beam pipe ($R_{\text{inner}} = 1\,\text{cm}$)

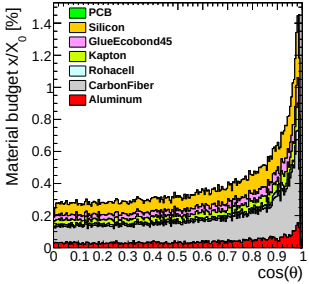
$\rightarrow$ Rather advanced design!

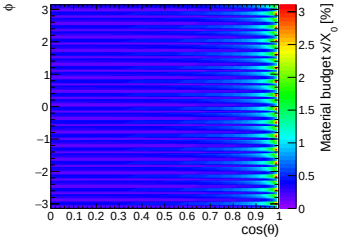
$\rightarrow$ What's its performance?

$\rightarrow$ Implement this in Key4hep *full simulation*!

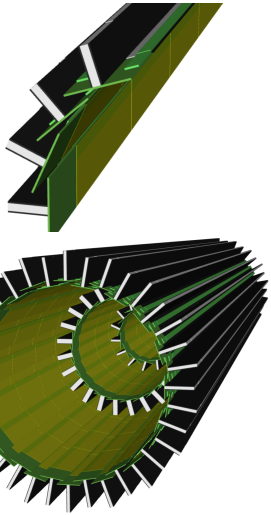
Vertex inner barrel

- Correct material stack, end-of-stave hybrid, insensitive sensor areas, ...
- Inner vertex support imported through DDCAD, but not included in material budget estimation
- Cooling cones not implemented yet, but outside of vertex acceptance
- Material budget in line with 0.3% per layer at $\cos(\theta) = 0$ (CDR assumption)





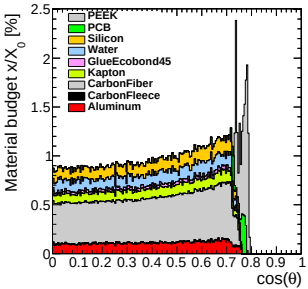
Layer 0, others in backup

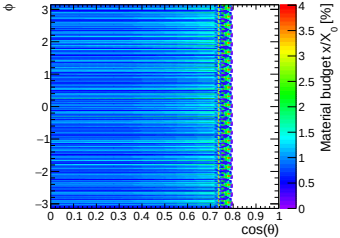


Vertex inner barrel, without support

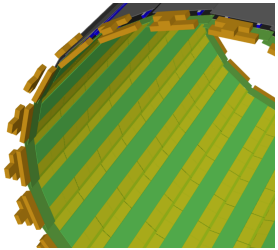
Vertex outer barrel

- Proxy volumes for truss structure and cooling pipes
- Proxy volume for end-of-stave holder (material budget contribution optimised with F. Palla)
- Still significant contribution from PEEK stave holder

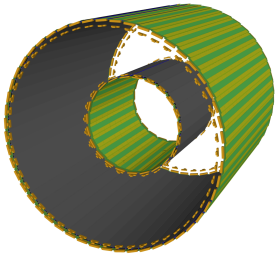




Complete outer barrel



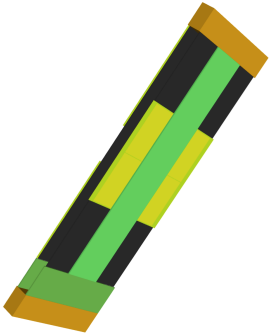
Middle tracker



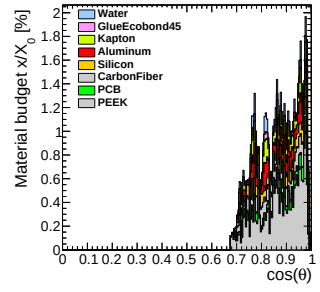
Complete vertex outer barrel system

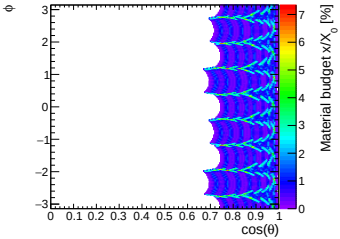
Vertex disks

- Correct placement of all modules in r and z
- Missing vertex disk global support
- Very uneven X_0 distribution

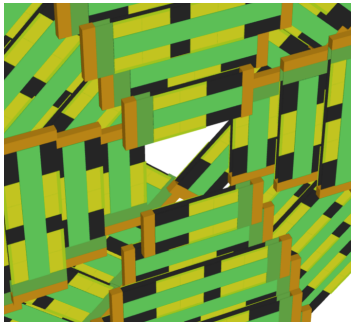


One short stave

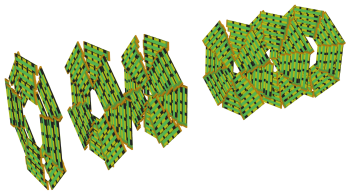




Disk 0

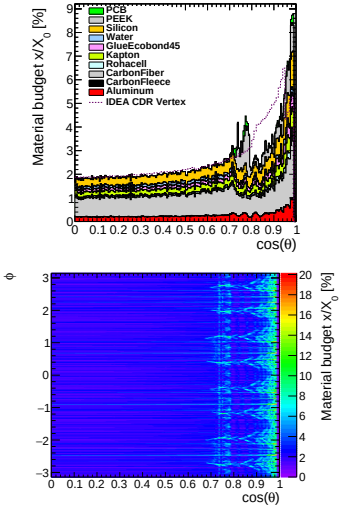


Disk 0 zoom-in



Complete vertex disks system

Complete system



Complete vertex system

- Material budget comparable with CDR estimate
- First working version on k4geo, update imminent with some fixes (getting rid of last overlaps)
- Use it, let me know if you find problems!
- Plan to include last missing volumes using DDCAD (and find a way their material budget is seen using k4SimGeant4 script)
- Look at all material budget evaluations as a lower limit, there's always gonna be more added! (e.g off-detector cabling)

IDEA silicon wrapper: Introduction

A last hurrah of the tracking system before Coulomb scattering takes over

- Momentum resolution thanks to long lever arm
- Extend tracker coverage
- Precise and stable ruler for acceptance definition

Possible technologies:

- DMAPS
- LGADs
- Microstrips
- ...

Needs to be added to DD4hep detector description as well!

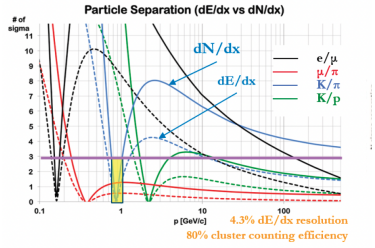
Barrel

Layer	R [mm]	L [mm]	Si eq. thick. [µm]	X0[%]	Pixel size [mm²]	area [cm²]
1	2040	±2400	450	0.5	0.05×100	616K
2	2060	±2400	450	0.5	0.05×100	620K

Endcap

Disk	R^{in} [mm]	R^{out} [mm]	z [mm]	Si eq. thick. [µm]	X0[%]	Pixel size [mm²]
1	350	2020	±2300	450	0.5	0.05×100
2	354	2020	±2320	450	0.5	0.05×100

(fcc-ee-detector-full-sim.docs.cern.ch)



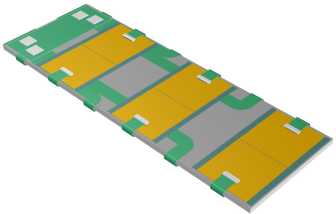
Slide following A. Andreazza FCC Week 2021

IDEA silicon wrapper: Questions

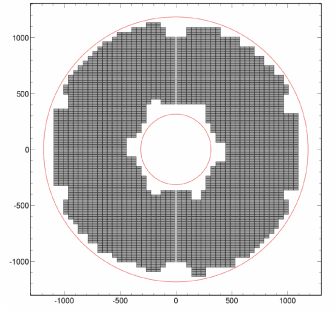
Not engineered yet (anyone interested?). Some assumptions:

- Assume total of $\approx 1\% X/X_0$ in barrel and disks
- Hermeticity
  - Decided to increase disk r_{out} from 2020 to 2040 mm
  - Two barrel layers and two disks, to have at least one silicon hit, but most of the cases we have two silicon hits
- Total area: $\simeq 30\,\text{m}^2$ per barrel layer, $\simeq 13\,\text{m}^2$ per disk $\rightarrow$ $112\,\text{m}^2$ to cover
- Sensor thickness: $50\,\mu$m, resolutions: pitch $0.05 \times 1\,\text{mm}^2$ and 40 ps per hit, don't care about specific sensor technology
  - Assume ATLASPix3-sized modules ($42.2 \times 40.6\,\text{mm}^2$) to construct tiles with 6, 12 or 24 modules each
- Disk design inspired by CMS endcap timing layer

Let's build a first silicon wrapper using vertex constructor codes

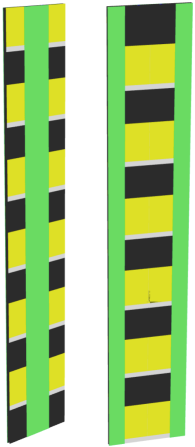


Tile proposed for CEPC [1, 2]

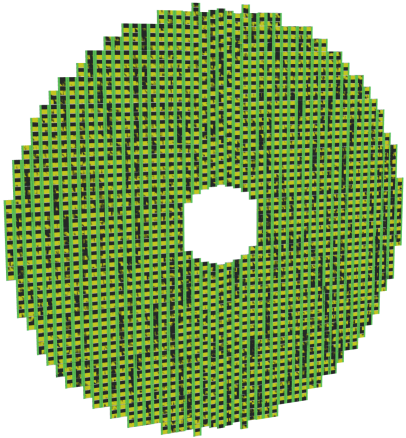


CMS ETL layout [3]

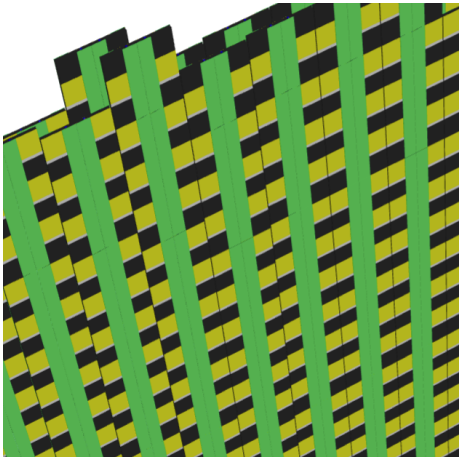
IDEA Silicon wrapper disks



Front Back



One disk

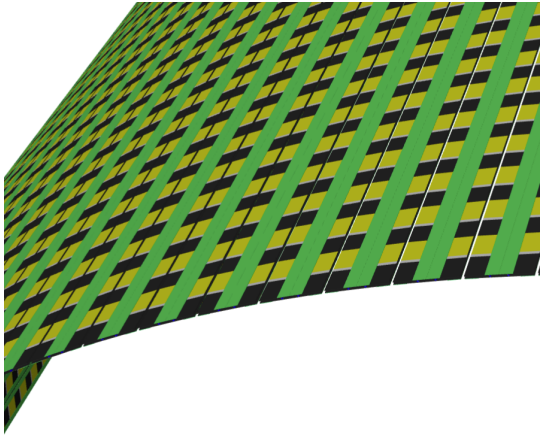


Overlap between two disk layers

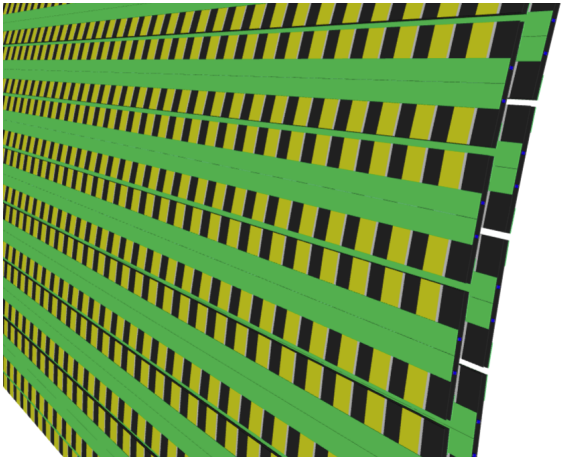
Only inactive area at side of tile

- Tiling the disks with tiles of 6, 12 and 24 modules
- Total of 30432 modules, 51 m^2 of Si

IDEA Silicon wrapper barrel



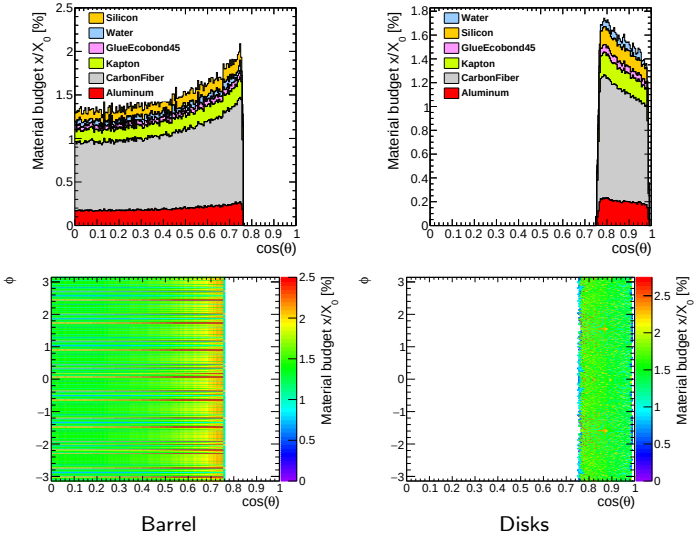
Staves making up the first layer



Two layers to cover gaps

- Each stave is basically an extremely long tile
- Layer made up of 151 staves with 129*2 modules, total of 77916 modules, 132 mm^2 of Si

IDEA Silicon Wrapper material budget



- Flex and cooling pipes (same as in vertex outer barrel and disk), 50 μm silicon, 1.4 mm of carbon fibre
- Adjust material budget when engineered design becomes available

IDEA silicon wrapper: Discussion

University of Zurich[UZH]

Mechanics:

- No engineering design of the silicon wrapper exists – nothing is fixed
  - → Would be a great opportunity to contribute!
- Attach barrel to outer shell of DCH or the solenoid? The disks to the calo pre-shower?

Performance:

- How many silicon hits do we need with what time resolution? 30 ps overall sufficient?
- One hermetic layer of pixels $O(0.2 \times 0.2\,\mathrm{mm}^2)$ or two layers of strips or something else?
- What resolution to use in the disks? Petal-like design or use pixels?
- *Performance metrics*? Two-track confusion, θ and momentum resolution as function of pitch for different momenta?

→ Some of these questions can be answered by using this DD4hep model of the silicon wrapper. Contact me if you're interested in collaborating!

PR, making simplified version that loads faster. Currently $O(7\,\mathrm{min})$ to load geo and start sim

Digitisation of silicon hits in Key4hep

Couple of possibilities

- I wrote a simple digitisation of Si hits in k4RecTracker as a Gaudi algorithm

→ Works with IDEA vertex and Si wrapper and all CLD silicon layers

→ Can also project hits onto Si surface, apply simple Gaussian smearing of hits

- Using DDPlanarDigiProcessor.cc from Marlin through k4MarlinWrapper

→ Compatible with IDEA vertex and silicon wrapper implementation

- Port of DDPlanarDigiProcessor as a Gaudi algorithm in k4Reco

→ Work in progress

Outlook

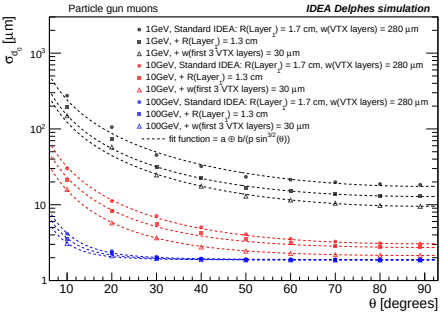
Lots of work ongoing

- IDEA vertex detector DD4hep implementation is mature, can be used
- IDEA silicon wrapper in early development → Looking for feedback and discussion!

Ultra-light vertex detector concept

- Development of conceptual design with INFN Pisa (see F. Palla Tue. morning)
- Already involved in characterisation of 65 nm test chips (see K. Gautam Tue. afternoon)
- Fast DELPHES study of some layer positioning options (à la previous study on the right)
- Full sim study of ultra-light vertex detector concept
- Compare performance between current IDEA vertex detector and ultra-light vertex detector concept

  → *Performance metrics*



L. Freitag (BSc. thesis [4]) and A.I @ Krakow 2023

Thanks!

To all the people who helped, especially Andrea Ciarma, Anna Macchiolo, Attilio Andreazza, Brieuc Francois, Fabrizio Palla and Patrizia Azzi!

References I

[1] T. Jones, *CEPC Silicon /LHCb MT Tile*, 2020.
https://indico.ph.ed.ac.uk/event/65/contributions/814/Presentation at the First UK workshop on HV-CMOS technology for future e+e- colliders, University of Edinburgh.

[2] H. Zhu, *A large tracking system with novel HV-CMOS sensors for the CEPC*, 2021.
https://indico.inp.nsk.su/event/42/contributions/2186/attachments/1355/1777/CEPC_Silicon_Tracker_AFAD.pdfPresentation at the Asian Forum for Accelerators and Detectors (AFAD), BINP.

[3] M. Tornago, *Detector optimization and physics performance of the CMS Phase-2 Endcap Timing Layer*, 2023.
https://cds.cern.ch/record/2848200. Presented 13 Feb 2023.

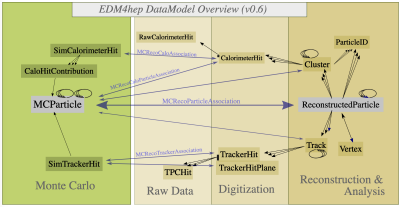
[4] L. Freitag, *Benefits of Minimizing the Vertex Detector Material Budget at the FCC-ee*, 2023.
http://cds.cern.ch/record/2851362. BSc thesis, presented 01 Feb 2023.

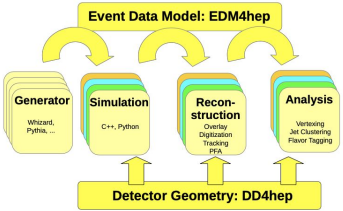
[5] N. Bacchetta, et al., *CLD – A Detector Concept for the FCC-ee*, arXiv:1911.12230 [physics.ins-det].

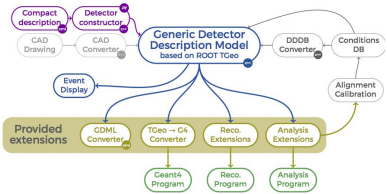
The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis

- Event data model: EDM4hep for exchange among framework components
  - Podio as underlying tool, for different collision environments
  - Including truth information
- Data processing framework: Gaudi
- Geometry description: DD4hep, ability to include CAD files
- Package manager: Spack: `source /cvmfs/sw.hsf.org/Key4hep/setup.sh`



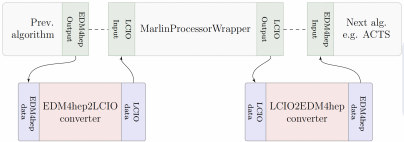




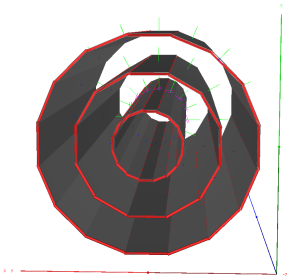
Existing (vertex) full simulation in CLD

Detector model in k4geo/FCCDetectors (smaller beam pipe)

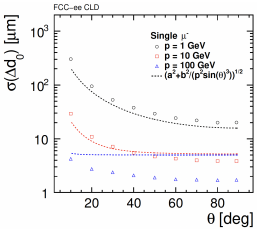
- Linear collider reconstruction (iLCSoft/CLICPerformance)
- Can generate EDM4hep output using k4MarlinWrapper



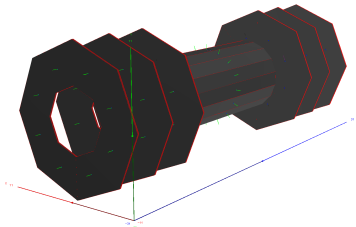
Access to all LC tools: PandoraPFA, LCFI+, etc.



CLD vertex barrel



D_0 resolution in CLD [5]

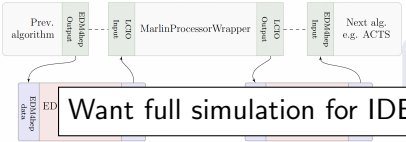


CLD endcap and vertex barrel

Existing (vertex) full simulation in CLD

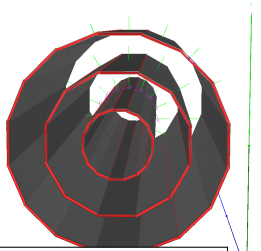
Detector model in k4geo/FCCDetectors (smaller beam pipe)

- Linear collider reconstruction (iLCSoft/CLICPerformance)
- Can generate EDM4hep output using k4MarlinWrapper

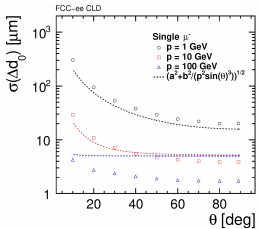


Access to all LC tools:

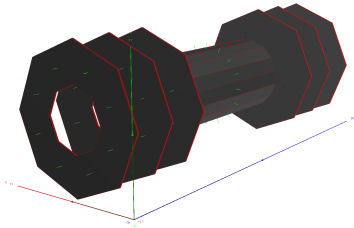
Want full simulation for IDEA, but using native Key4hep/DD4hep and more detail!



CLD vertex barrel



D_0 resolution in CLD [5]



CLD endcap and vertex barrel

IDEA vertex detector: Layout

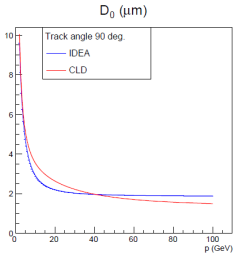
University of Zurich[UZH]

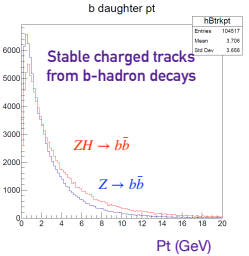
Vertex inner barrel

- Small beam pipe of 10 mm inner radius
- Three barrel layers to cover down to $\theta = 140$ mrad
- Consisting of staves of dual ARCADIA DMAPS, with pixels of $25 \times 25\,\mu\text{m}^2$ ($\sim 3\,\mu$m single point resolution)

Outer Vertex

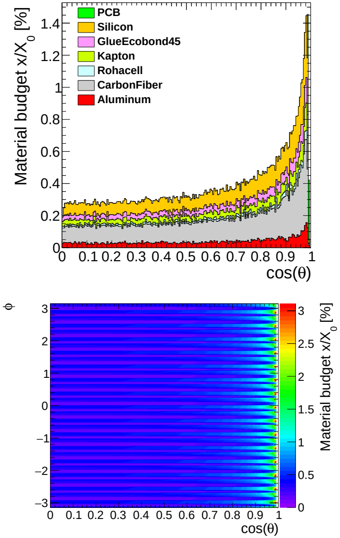
- Quad ATLASPix3 DMAPS with $150 \times 50\,\mu\text{m}^2$ pixels
- **Vertex outer barrel**
  - Intermediate layer at $r = 13$ cm, outer layer at $r = 31.5$ cm
- **Vertex disks**
  - Three disks per side
  - Disks of 8 petals with 4-6 staves going from small to large r



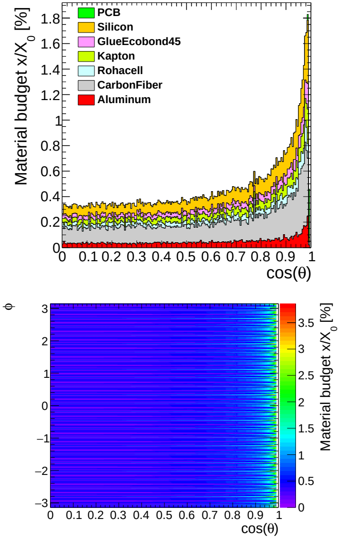


D_0 resolution in IDEA and CLD and p_T of b hadron tracks

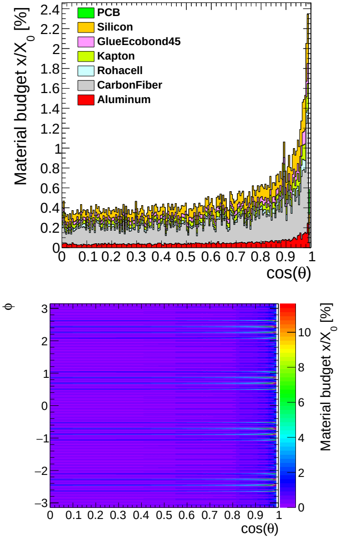
Material budget in inner vertex barrel



Layer 0

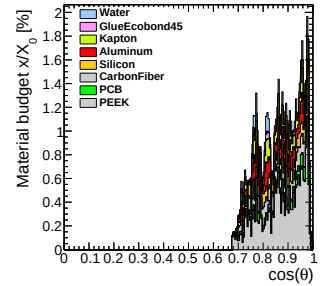


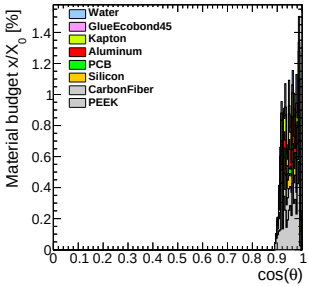
Layer 1

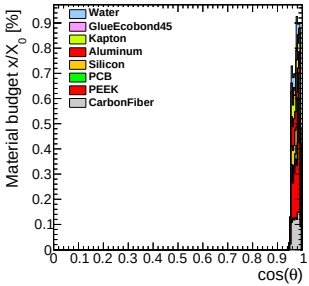


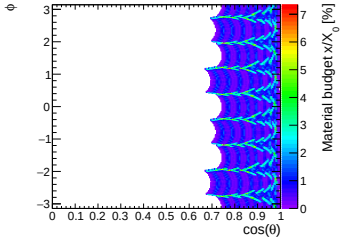
Layer 2

Material budget in vertex disks

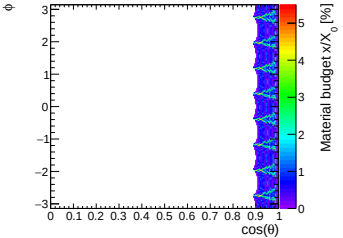




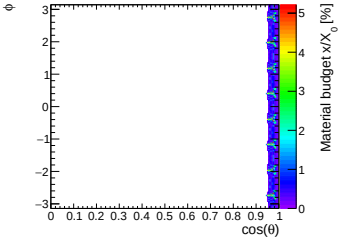




Layer 0



Layer 1



Layer 2

IDEA silicon wrapper: Some further questions

University of Zurich[UZH]

- Stability of $2 \times 2.4\,\text{m}$ long staves? Need another "support tube" holding the silicon wrapper? Or sequence of rings?
- Petal or ring design in the disks? Need better resolution than in barrel due to DCH being more massive in the endcap?
- What's the typical multiple scattering error after the drift chamber? This will define the needed spatial resolution in the Si wrapper
- How hermetic does it need to be?