Progress on the IDEA vertex detector implementation in Key4hep full simulation

FCC Week 2023, London

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Thanks to all the people who helped/are helping on the way!

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?

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Goal: Establish feedback-loop

Sensor perf. $\xrightarrow[\text{sim.}]{\text{detector}}$ Subdetector perf. $\xrightarrow[\text{analysis}]{\text{sample}}$ physics perf. $\xrightarrow[\text{input}]{\text{theory}}$ sensor specification

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

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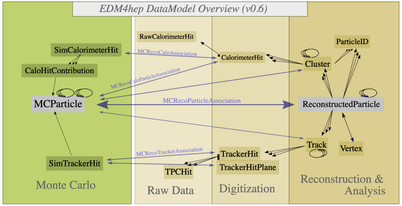
Our software toolkit should be...

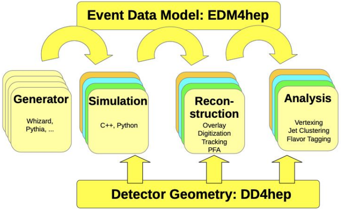
- deploying new software and detector technologies, ease adaption by current experiments
- efficient and easy to learn, use and develop (people with limited time on future colliders)

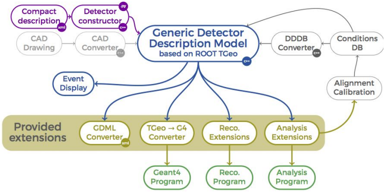
The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis, see also PE&D: Software and Computing / Detectors session

- 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`







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Standalone full simulation of IDEA in Geant4 available

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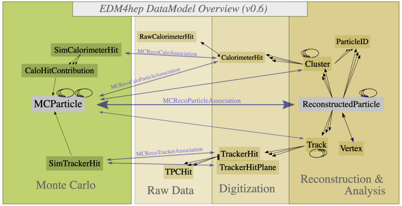

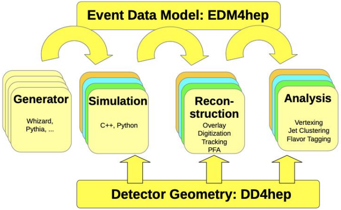

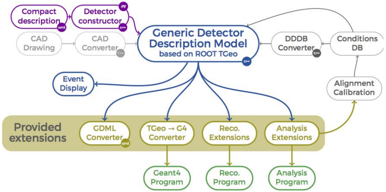

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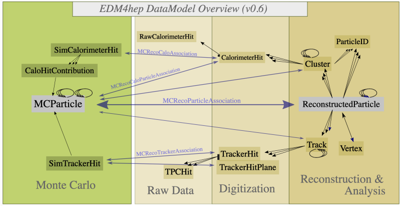
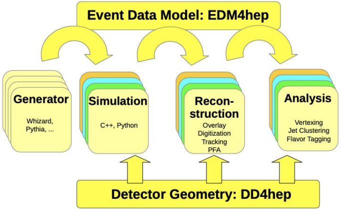
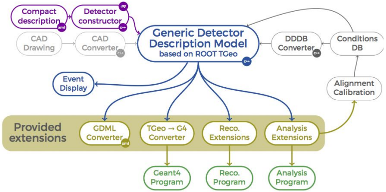
Goal now: Full simulation in Key4hep/DD4hep!







IDEA vertex detector: Layout

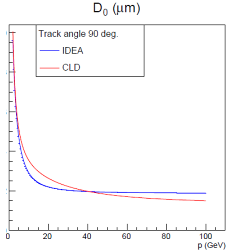
Refer to F. Palla's slides for full layout details

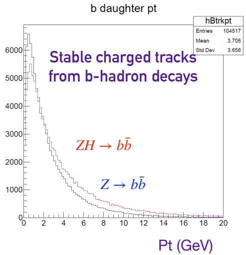
Vertex inner barrel

- 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)

Vertex outer barrel and vertex disks

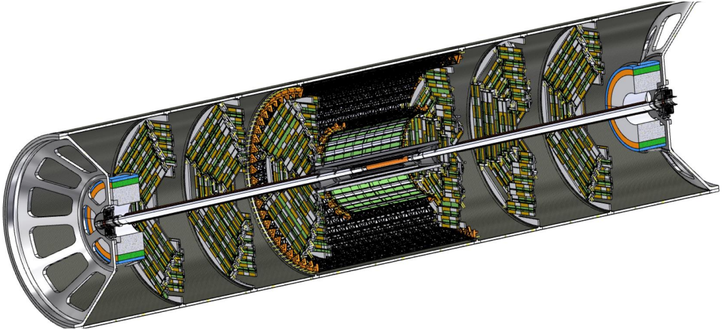
- Quad ATLASPix3 DMAPS with $150 \times 50\,\mu\text{m}^2$ pixels
- **Vertex outer barrel**
  - Intermediate layer at $r = 13$ cm, outer layer at $r = 31.5$ cm
- **Vertex disks**
  - Three disks per side
  - Disks of 8 petals with 4-6 staves going from small to large r



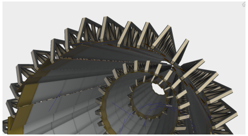


D_0 resolution in IDEA and CLD and p_T of b hadron tracks

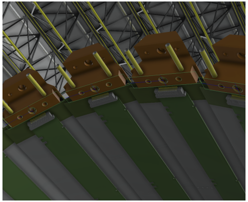
IDEA vertex detector: Design



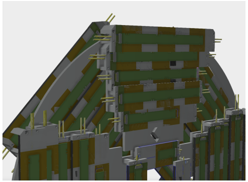
- Vertex detector by F. Palla and F. Bosi (INFN- Pisa)
- Support tube done by F. Fransesini and M. Boscolo (INFN-LNF), see next talk by F. Fransesini. Holding:
  - Luminosity calorimeter
  - Vertex detector
  - Outer tracker
  - Beam pipe
- Rather advanced design, let's implement this in Key4hep full simulation!



Vertex barrel



Outer tracker barrel



Outer tracker end-cap

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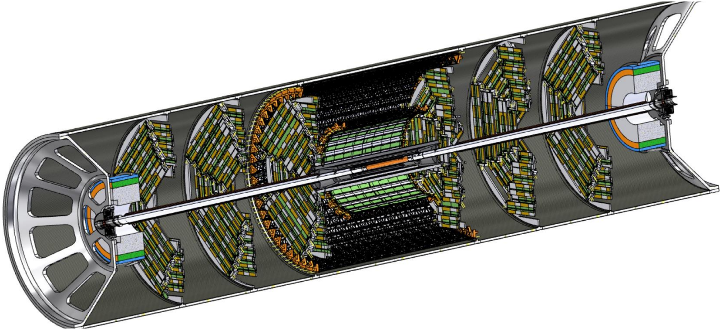

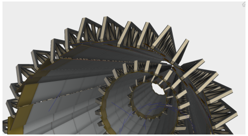

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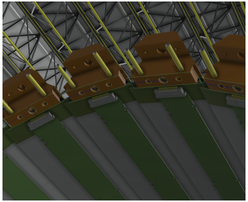

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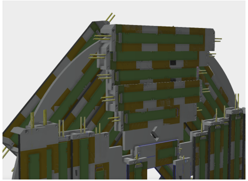

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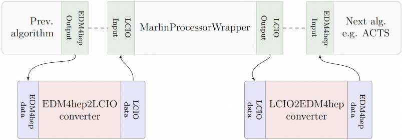
Where to start?

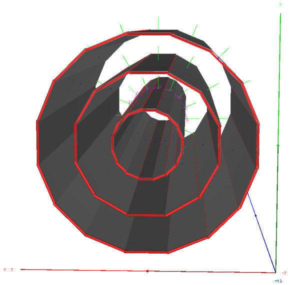
Existing (vertex) full simulation in CLD

Detector model in k4geo/FCCDetectors (smaller beam pipe)

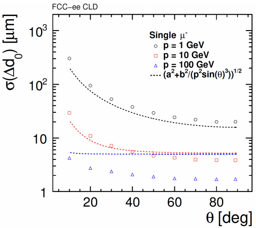
- Linear collider reconstruction (iLCSoft/CLICPerformance)
- Can generate EDM4hep output using k4MarlinWrapper



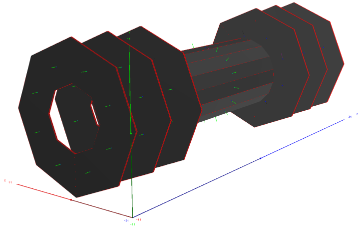
Access to all LC tools: PandoraPFA, LCFI+, etc.



CLD vertex barrel



D_0 resolution in CLD [1]



CLD endcap and vertex barrel

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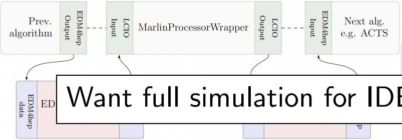
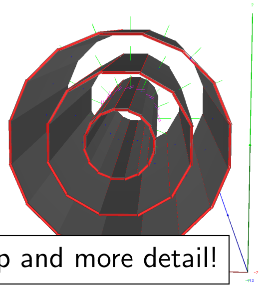


Access to all LC tools:

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



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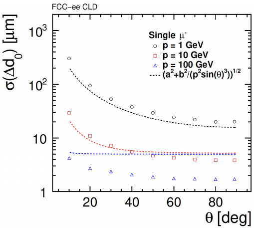

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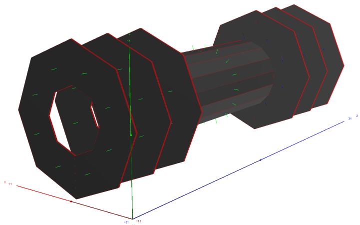
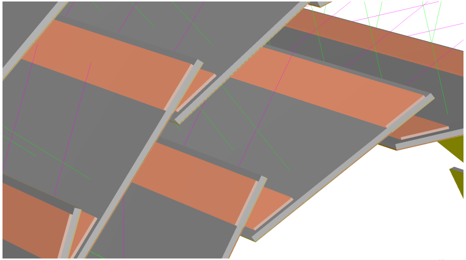
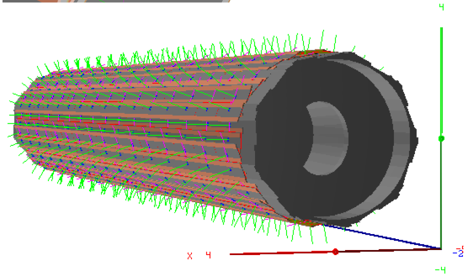


CLD endcap and vertex barrel

IDEA vertex detector in DD4hep

Vertex inner barrel





Adapted CLIC vertex barrel constructor to enable...

- individual sensors along stave, can have insensitive area in $r-\phi$ or z

$\rightarrow$ ARCADIA duals implemented as 6.4 mm active + 2 mm periphery $(r-\phi)\times 32$ mm (z), with 0.2 mm distance between sensors in z

- multiple layers of support and include readout

$\rightarrow$ Support e.g consists of 20 μm of carbon fleece, 120 μm of carbon fiber and 25 μm of paper graphite

- Use DDCAD [2] to import conical vertex support

$\rightarrow$ Don't get correct X/X_0 yet, overlap check fails (investigating...)

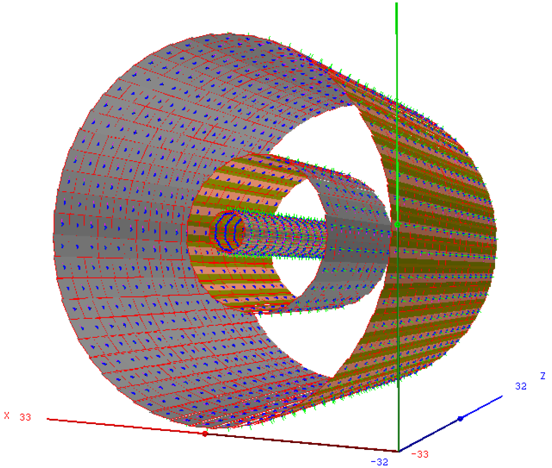
Todo: Add stave holder and end-of-stave structures

Vertex outer barrel

Same detector construction code as inner barrel

- Correct readout flex and stave support material stacks
- Simplified ATLASPix3 periphery (only implemented in $r - \phi$)
- Missing cooling pipes
- Missing lightweight reticular support structure

→ Import using DDCAD or adding simplified support



Vertex disks

Most complicated system to implement in DD4hep, based on CLIC vertex endcaps

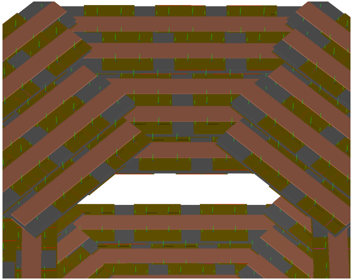
Building the disks:

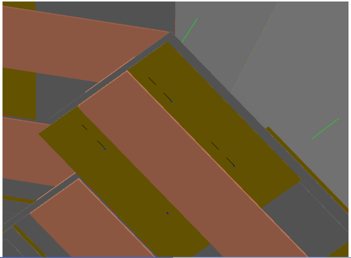
- Build quad sensors out of four sensitive and many insensitive rectangles
- Place quads along stave support structure, add readout
- Place staves with correct number of sensors to build a petal
- Place all petals to form a disk, repeat for all disks

→ Correct orientation and arrangement of all staves/petals

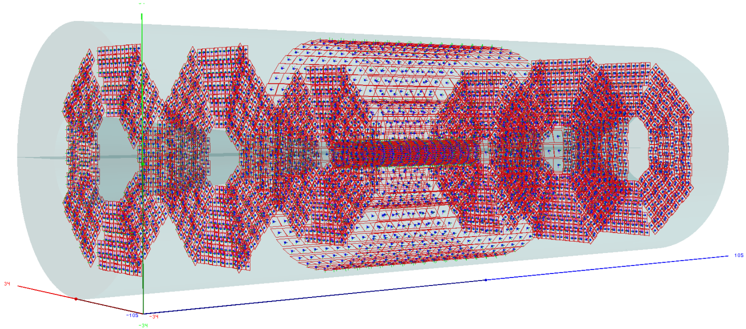
Still missing:

- Non-stave supports and cooling pipes



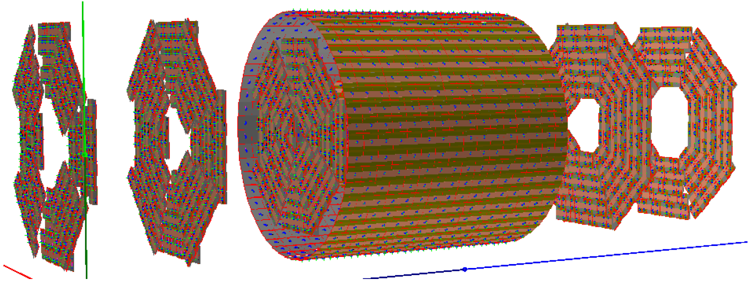


Vertex detector: Overall system



Sensitive surfaces in IDEA vertex implementation in DD4hep

Vertex detector: Overall system



Complete geometry in IDEA vertex implementation in DD4hep

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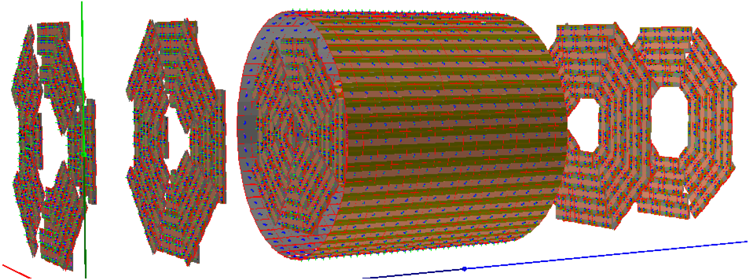
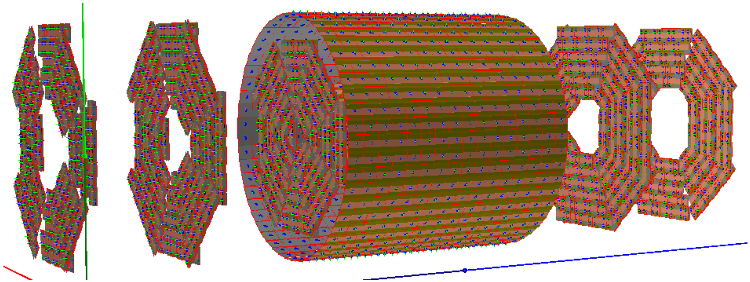


Complete geometry in IDEA vertex implementation in DD4hep

Missing parts:

- Complex support structures and cooling (use DDCAD or simplified shape with equivalent material budget)
- Off-detector cabling (not designed yet)

Vertex detector: Overall system



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Such a detailed geometry description enables...

- Accurate material budget distribution in both θ and ϕ
- Accurate description of angular coverage, #hits in vertex: Are there cracks in the coverage?

Pull request in k4geo

First look at performance...

IDEA vertex detector: First results in DD4hep (preliminary!)

Particle gun to shoot 10 GeV muons, $\theta = 10^{\circ}$

Get Key4hep stack (latest has issues currently):

```
source /cvmfs/sw.hsf.org/spackages6/Key4hep-stack/2022-12-14/
x86_64-centos7-gcc11.2.0-opt/zkjui/setup.sh
```

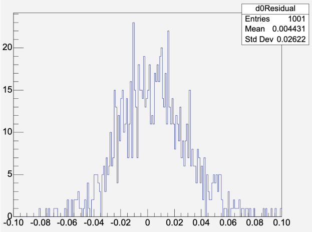
Run simulation on detector compact file (xml), using FCC steering file to generate EDM4hep output:

```
ddsim --compactFile k4geo/FCCee/compact/FCCee_IDEA_o01_v01.xml
--enableGun --gun.thetaMin 9.999 --gun.thetaMax 10.001
--gun.distribution uniform --gun.energy 10*GeV --gun.particle
mu- --steeringFile fcc_steer.py --numberOfEvents 1000
--outputFile ddsim_edm4hep.root
```

Run linear collider reconstruction (iLCSoft/CLICPerformance) using k4MarlinWrapper:

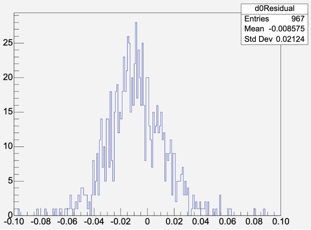
```
k4run fccRec_e4h_input.py --EventDataSvc.input
ddsim_edm4hep.root -n 1000
```

CLD full simulation



D_0 resolution in mm.

...inserting IDEA vertex



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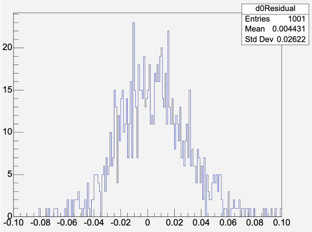
It runs! Performance to be assessed properly... (need IDEA drift chamber)

CLD full simulation



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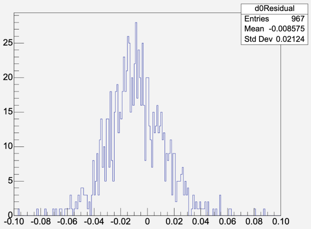

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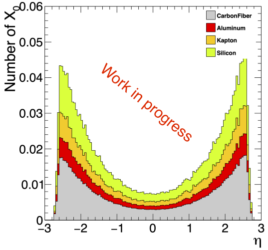
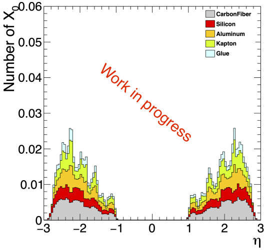
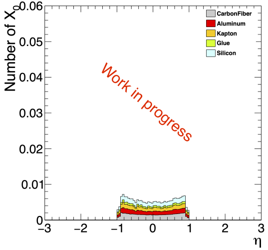
Preliminary (!) material budget estimation



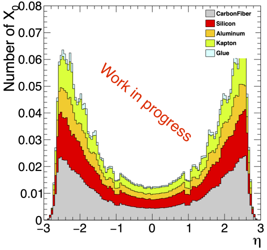
Vertex inner barrel



Vertex disks



Vertex outer barrel



Complete vertex system

Preliminary (!) estimation of the material budget of IDEA vertex in DD4hep

- Best-described detector: Vertex inner barrel

→ F. Palla's slides: $3 \times 0.25\%$ X/X_0 for complete vertex → Roughly agreeing

- Vertex outer barrel clearly underestimated, expect truss support structure and cooling to have largest X/X_0 contribution

Todo:

- Add missing components or appropriate placeholder
- Remake plot in θ and $\cos(\theta)$, compare with standalone Geant4 description and CLD

Summary

Done

- First implementation of the IDEA vertex detector in DD4hep $\rightarrow$ Can get vertex simHits for other studies
- Track+vertex reconstruction using iLCSoft with k4MarlinWrapper $\rightarrow$ It's working!
- Preliminary material budget estimation

Next steps

- Complex services and support structures, reassess material budget
- Accurate sensor periphery description in barrels (done in disks already)
- Add digitisation inside Key4hep
- Implement silicon wrapper, aim to have complete IDEA description in DD4hep

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What else can we do?

Summary and outlook!

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- Complex services and support structures, reassess material budget
- Accurate sensor periphery description in barrels (done in disks already)
- Add digitisation inside Key4hep
- Implement silicon wrapper, aim to have complete IDEA description in DD4hep

What else can we do?

Goal: Establish feedback-loop

$$\text{Sensor perf.} \xrightarrow[\text{sim.}]{\text{detector}} \text{Subdetector perf.} \xrightarrow[\text{analysis}]{\text{sample}} \text{physics perf.} \xrightarrow[\text{input}]{\text{theory}} \text{sensor specification}$$

R&D for better detectors

Should not close the eyes to new and unproven technologies.
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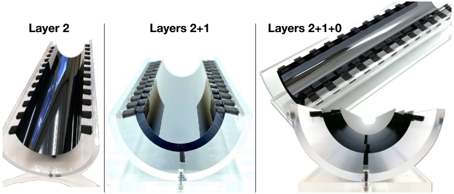
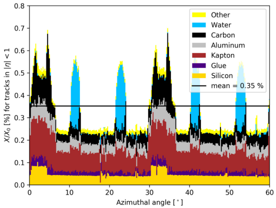
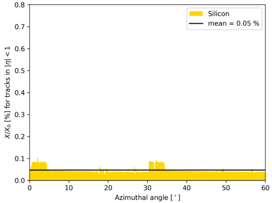
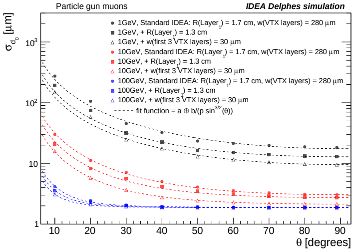


Layer assembly concept for ALICE ITS3 [3]





Material budget in ALICE ITS2 (left, [4]) and silicon only (M. Mager)



L. Freitag (BSc. thesis [5]) and A.I @ Krakow 2023

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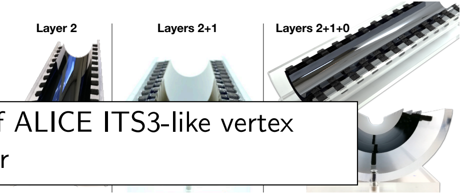
Plan to do *full simulation* performance study of ALICE ITS3-like vertex detector for (parts of) the IDEA vertex detector



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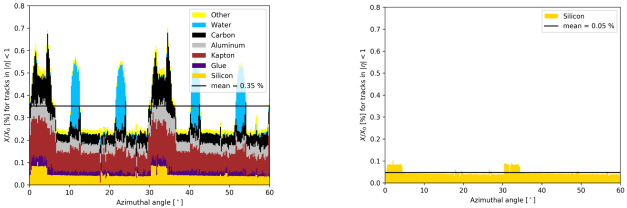

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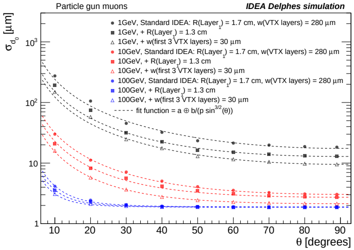

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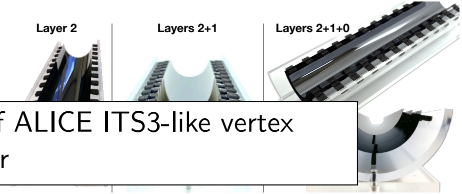

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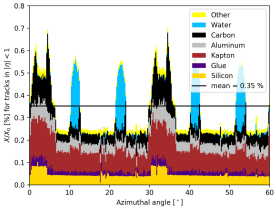
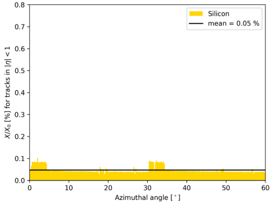
Plan to do *full simulation* performance study of ALICE ITS3-like vertex detector for (parts of) the IDEA vertex detector

Contributing to testing of 65 nm test structures as well





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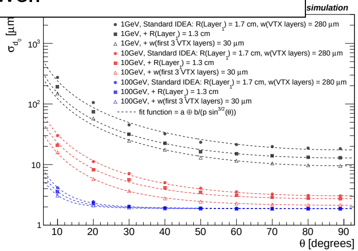

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Thanks!

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[2] M. Frank, F. Gaede, M. Petrič, and A. Sailer, *CAD support and new developments in DD4hep*, in *EPJ Web of Conferences*, p. , 03015, EDP Sciences. 2021.

[3] M. Mager, *On the "bendable" ALPIDE-inspired MAPS in 65 nm technology*, 11, 2021. https://indico.ihep.ac.cn/event/14938/session/6/contribution/196. 2021 International Workshop on High Energy Circular Electron Positron Collider.

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Vertex detector module

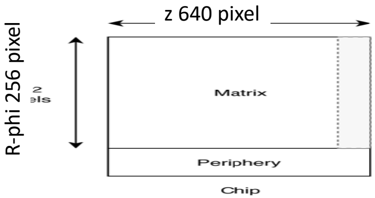
Istituto Nazionale di Fisica Nucleare

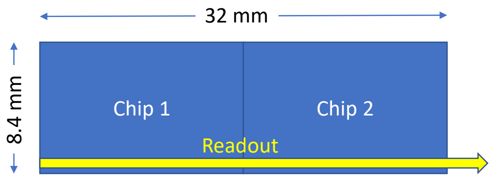
Module concept inspired by ARCADIA INFN R&D

- Depleted Monolithic Active Pixel Detectors (DMAPS) sensor and back-side processing already tested on silicon
- Pixel size 25x25 μm^2 , 50 μm thick
- Active area 640 pixel (16 mm) in z and 256 pixels (6.4 mm) in $\mathrm{r} - \varphi$
- Chip periphery plus an inactive zone: total of 2 mm in $\mathrm{r} - \varphi$
- Chips are side-abuttable in z

Composed of 2 pixelated parts: total of 8.4 mm $(\mathrm{r} - \varphi)$ × 32 mm (z)

- Power budget not established yet: assume (reasonably) $50\ \mathrm{mW/cm^2}$





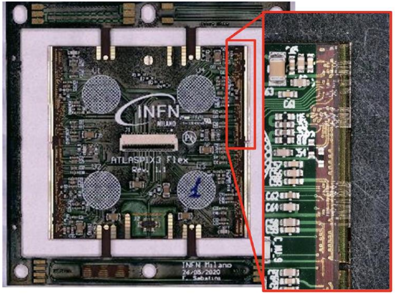
F. Palla , see talk at FCC US week at BNL

Outer tracker module

- Based on ATLASPIX3 R&D
  - DMAPS
  - 50 x 150 μm^2
  - Up to 1.28 Gb/s downlink
  - TSI 180 nm process
  - 132 columns of 372 pixels

  - Active (total) length (r-phi x z)
    - 18.6 (21) mm x 19.8 (20.2) mm
  - Module is made of 2x2 chips – total length:
    - size 42.2 mm x 40.6 mm

  - Power budget not established yet:
    assume $100\ \mathrm{mW/cm^2}$



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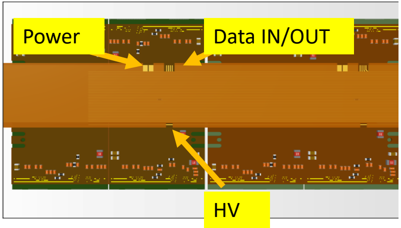

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