Full simulation of the IDEA detector at FCC-ee using the Key4hep framework

LCWS 2023 @ SLAC

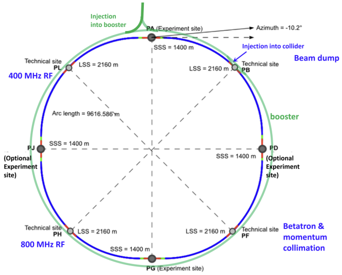
Armin Ilg
on behalf of the FCC Software and IDEA detector concept teams

University of Zürich

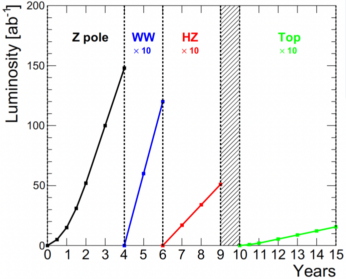
17.05.2023

Thanks to P. Azzi, B. Francois, S. Ko, F. Palla, E. Perez for their help/contribution!

The FCC-ee and its feasibility study



Preliminary FCC-ee layout [1].



Possible run schedule of FCC-ee [2].

EW: $5 \cdot 10^{12}$ Z, 10^8 WW, 10^6 $t\bar{t}$
Higgs: $1.2 \cdot 10^6$ HZ, 75k WW $\rightarrow$ H
Flavour: 10^{12} bb, $1.7 \cdot 10^{11}$ $\tau\tau$
And many more!

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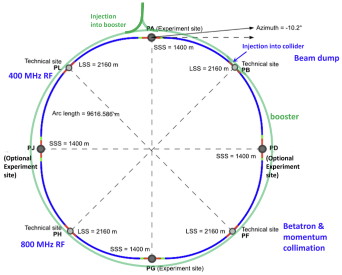

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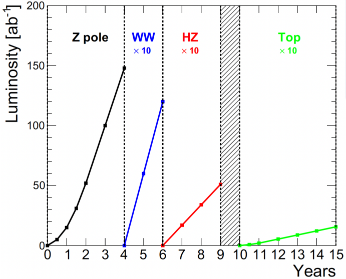

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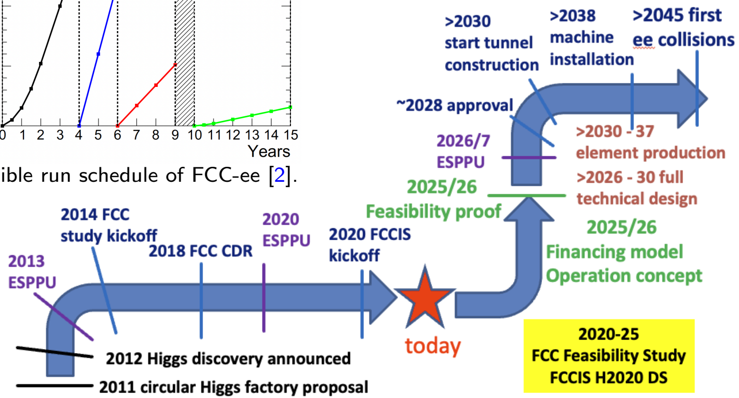

M. Benedikt, FCC Week 2022

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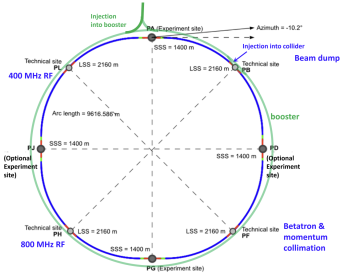

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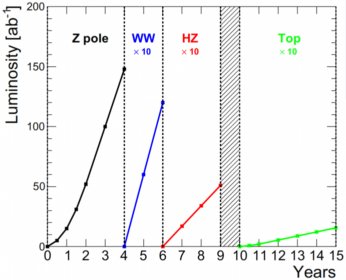

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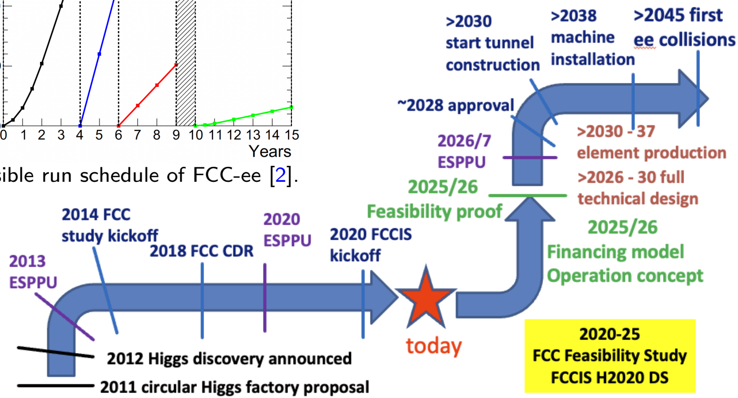
Already been a long journey, but we're still in the beginning!



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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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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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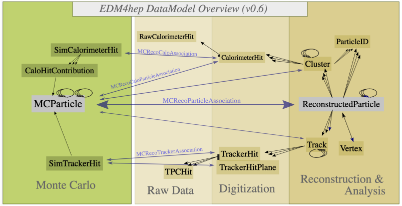
Our software toolkit should be...

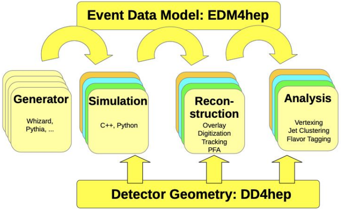
- deploying new software and detector technologies, ease adaption by current experiments
- efficient and easy to learn, use and develop (people with limited time on future colliders)

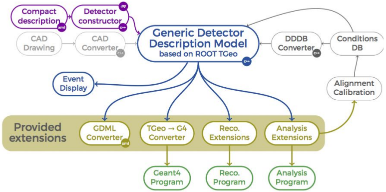
The common software vision: Key4hep

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

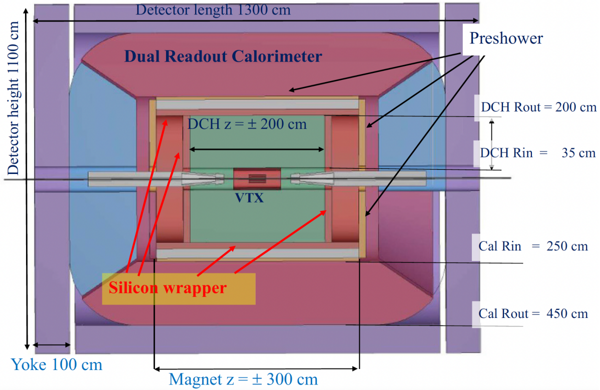
- Event data model: EDM4hep for exchange among framework components
  - Podio as underlying tool, for different collision environments
  - Including truth information
- Data processing framework: Gaudi
- Geometry description: DD4hep, ability to include CAD files
- Package manager: Spack: `source /cvmfs/sw.hsf.org/Key4hep/setup.sh`







IDEA: Innovative Det. for e^+e^- Accelerators



Schematic layout of the IDEA detector concept for FCC-ee [2]

Status of simulation: Full simulation in Geant4
Goal now: Full simulation in native Key4hep!

- Vertex detector adopting DMAPS (depleted monolithic active pixel sensor) to minimise material budget
- Tracker consisting of light-weight drift chamber ($dN_{\text{ionisation}}/dx$) and silicon wrapper with timing information (time-of-flight)
- Dual-readout calorimeter with preshower
- Low-mass 2 T solenoid coil inside calorimeter system
- Muon system composed of μRWell in the return yoke

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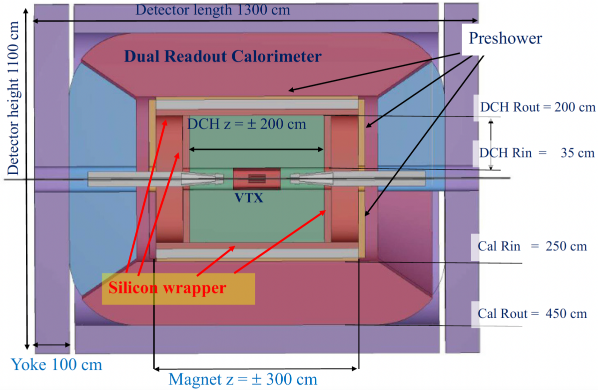

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Focus on these!
More: P. Azzi @ FCC US Workshop

IDEA vertex detector

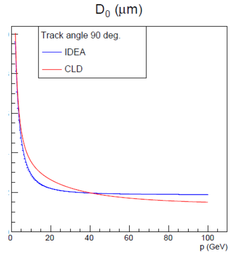
IDEA vertex detector: Layout

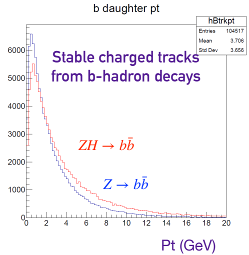
Vertex barrel detector

- Small beam pipe of 10 mm inner radius
- Three barrel layers at 13.7, 22.7 and 33 mm of radius, length 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 tracker

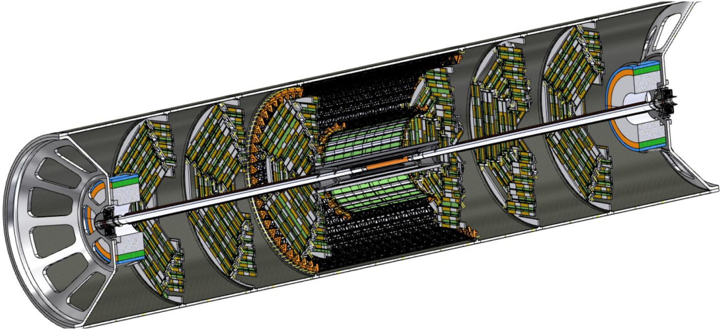
- Quad ATLASPix3 DMAPS with $150 \times 50\,\mu\text{m}^2$ pixels
- **Outer barrel**
  - Intermediate layer at $r = 13$ cm, outer layer at $r = 31.5$ cm
- **Outer end-cap**
  - Three disks per side, at z of 28.5, 62 and 93 cm
  - Disks of 8 petals with 4-6 staves going from small to large r

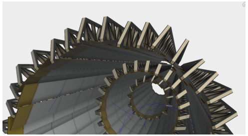


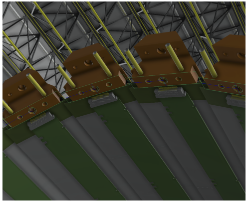


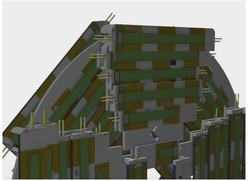
D_0 resolution in IDEA and CLD and p_T of b hadron tracks

IDEA vertex detector: Design




Vertex barrel


Outer tracker barrel


Outer tracker end-cap

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

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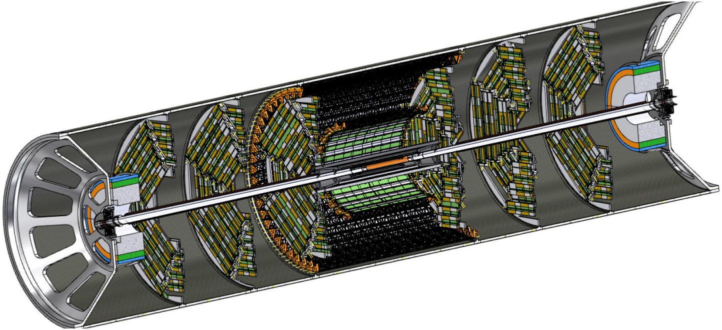

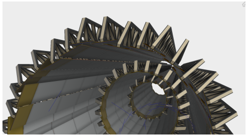

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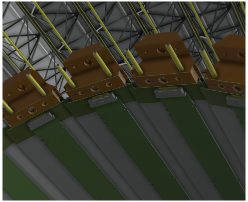

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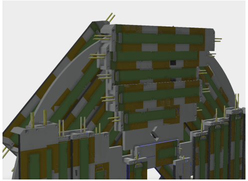

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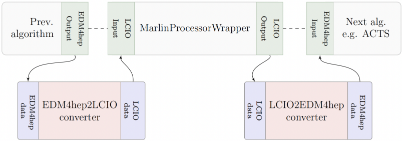
Where to start?

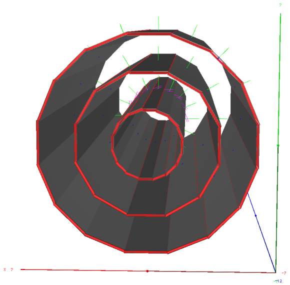
Existing (vertex) full simulation in CLD

Detector model in k4geo/FCCDetectors (smaller beam pipe)

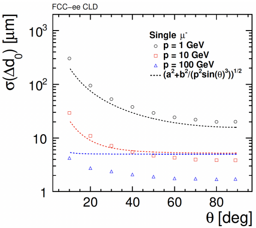
- Linear collider reconstruction (iLCSoft/CLICPerformance)
- Can generate EDM4hep output using k4MarlinWrapper



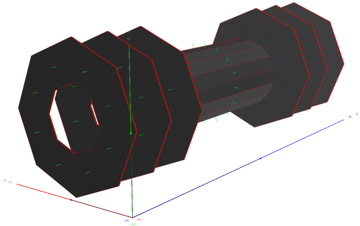
Access to all LC tools: PandoraPFA, LCFI+, etc.



CLD vertex barrel



D_0 resolution in CLD [3]



CLD endcap and vertex barrel

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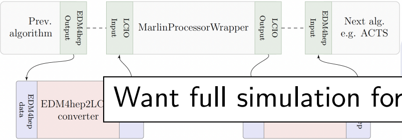

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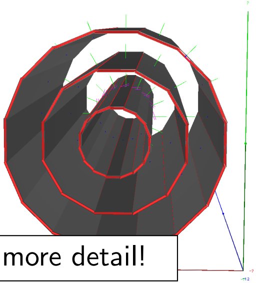
Want full simulation for IDEA, but using native Key4hep and more detail!



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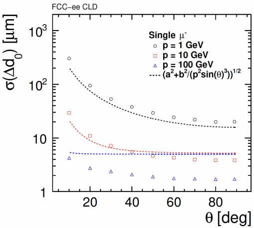

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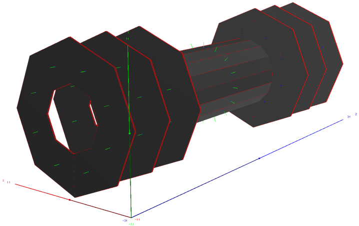
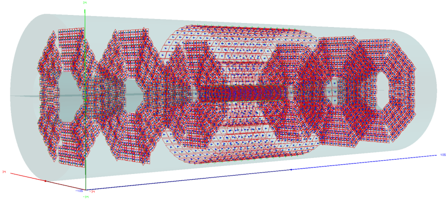


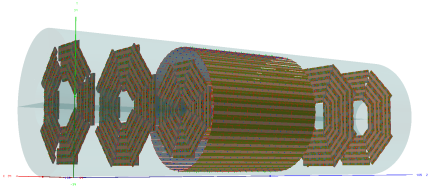
CLD endcap and vertex barrel

IDEA vertex detector: In DD4hep



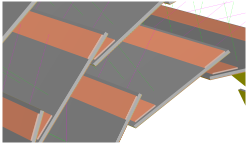
Sensitive surfaces in IDEA vertex implementation in DD4hep

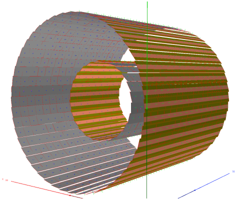
IDEA vertex detector: In DD4hep

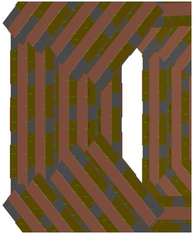


Complete geometry in IDEA vertex implementation in DD4hep

Inner barrel **Outer barrel** **Endcaps**







- Accurate material stack of support, sensor and flex
- Correct orientation and arrangement of all staves/petals
- Outer tracker end-cap quads as four sensitive surfaces with accurate sensor peripheries
- Simplified sensors in barrels currently
- Pull request in FCCDetectors

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

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

Running the code:

Get Key4hep stack:

```
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 $compactFile --enableGun --gun.thetaMin
$thetaMin --gun.thetaMax $thetaMax --gun.distribution uniform
--gun.energy 10*GeV --gun.particle mu- --steeringFile fcc_steer.py
--numberOfEvents 1000 --outputFile ddsim_edm4hep.root
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Run linear collider reconstruction (iLCSoft/CLICPerformance) using k4MarlinWrapper:

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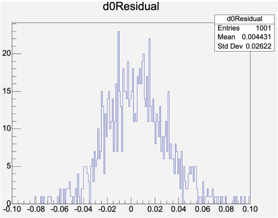
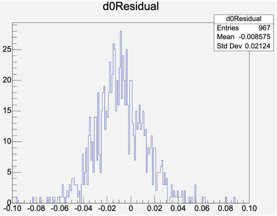

CLD full simulation



D_0 resolution in mm.

... with IDEA vertex



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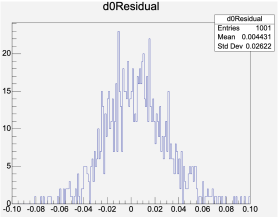

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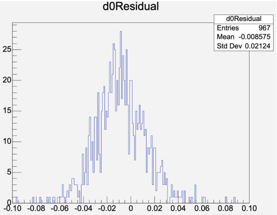


D_0 resolution in mm.

Done

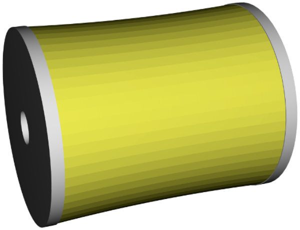
- Representation of the IDEA vertex+outer tracker in DD4hep
- No more overlaps
- Track+vertex reco using iLCSoft with k4MarlinWrapper → It's working!

Next steps

- Complex services and support structures, check material budget
- Accurate sensor periphery description in barrels (done in end-cap)
- Add digitisation inside Key4hep

IDEA drift chamber full simulation in Key4hep *Brieuc Francois*

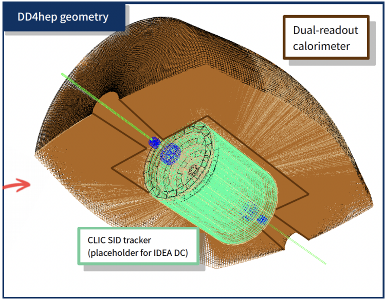
- IDEA DC originally implemented in plain Geant4: link
  - Hits and Track reconstruction output on the GEANT4 description available in EDM4hep format (for validation and studies)
- Geometry description available in DD4hep
  - First implementation available in FCCDetectors: link
  - Currently under validation
- In parallel, working on the Key4hep compliant reconstruction
  - Gaudi algorithm receiving and outputting EDM4hep collections
  - Simple digitzation ongoing
  - Will investigate various external solutions for Tracking
    - Conformal tracking, ACTS, Genfit, . . .



Standalone DRC simulation: HEP-FCC/dual-readout

Key4hep implementation:

- Geometry is implemented in DD4hep
  → Requires a unique DDsegmentation module
- Emulation of SiPM is implemented in Gaudi module
  → Processing signal waveform is vital for digitization
- Full simulation of DRC utilizes a detailed simulation of optical physics
  → Developed fast simulation module to ease intense CPU usage



Also check I. Vivarelli's talk at the FCC US week @ BNL and S. Ko's talk at the last FCC Week

R&D for better detectors

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$\rightarrow$ Estimate possible performance gain of such new technologies using full simulation!

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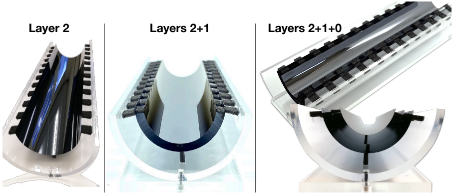
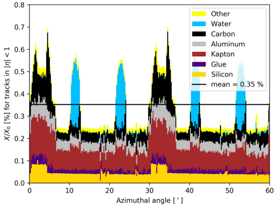
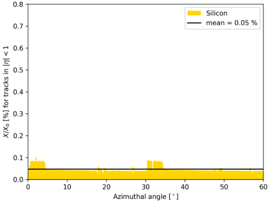
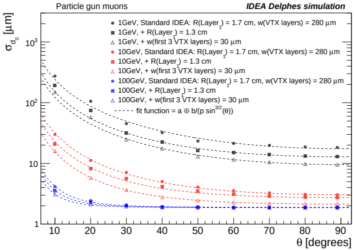


Layer assembly concept for ALICE ITS3 [4]





Material budget in ALICE ITS2 (left, [5]) and silicon only (M. Mager)



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R&D for better detectors

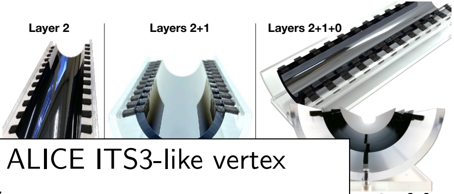
Should not close the eyes to new and unproven technologies.

→ Estimate possible performance gain of such new technologies using full simulation!

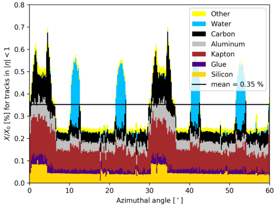
Example: DMAPS in 65 nm TPSCo process

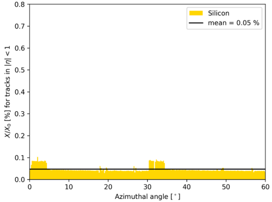
- More logic per cm^2
- Lower power consumption → Air cooling
- Ena
  →

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

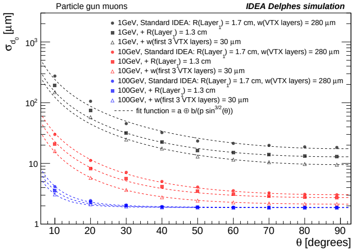


ITS3 [4]





Material budget in ALICE ITS2 (left, [5]) and silicon only (M. Mager)



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Conclusions

Many parts of the IDEA detector concept have already been implemented in Key4hep

Precise implementation of complex detectors in full simulation is time-consuming, but is a must to steer the overall detector design at FCC-ee

Investigating the interplay between various subsystems in particle flow reconstruction will be the next big step towards FCC-ee detector concepts

Conclusions

Many parts of the IDEA detector concept have already been implemented in Key4hep

Precise implementation of complex detectors in full simulation is time-consuming, but is a must to steer the overall detector design at FCC-ee

Investigating the interplay between various subsystems in particle flow reconstruction will be the next big step towards FCC-ee detector concepts

Simulation developments can be transferred from one detector to another and from one collider to another → **A great time to develop (Key4hep) software!**

Thanks!

References I

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[2] FCC Collaboration, *FCC-ee: The Lepton Collider*, The European Physical Journal Special Topics **228** (2019) 261–623.

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

[4] 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.

[5] F. Reidt, *Upgrading the Inner Tracking System and the Time Projection Chamber of ALICE*, Nuclear Physics A **1005** (2021) 121793, https://doi.org/10.1016/j.nuclphysa.2020.121793.

Vertex detector module

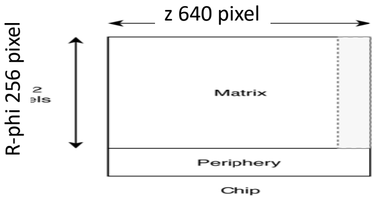
Istituto Nazionale di Fisica Nucleare

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) $50\ \mathrm{mW/cm^2}$



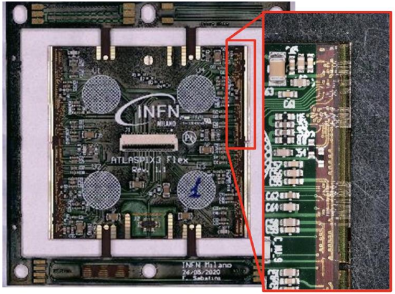
F. Palla , see talk at FCC US week at BNL

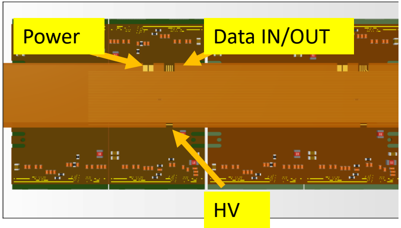
Outer tracker module

- 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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