Vertex Detectors for FCC-ee: Simulation and Sensor R&D

Freya Blekman[1,2] Florencia Canelli [3] Kunal Gautam [3,4]
Armin Ilg [3] Anna Macchiolo [3] Eduardo Plörer [3,4]
[1]DESY, [2]Universität Hamburg, [3]University of Zürich, [4]Vrije Universiteit Brussel,

The particle physics community is preparing for the post-LHC era by investigating the feasibility of the *Future Circular Collider* (FCC, [1]): a 90.6 km circumference collider to serve particle physics until the end of the 21st century. *FCC-ee* will produce intense e^+e^- collisions at energies of 90–365 GeV, making it an EW, Higgs and top factory. Later, the FCC is equipped with 14–20 T magnets to collide hadrons with energies of 80–116 TeV (*FCC-hh*).

Physics programme at FCC-ee experiments

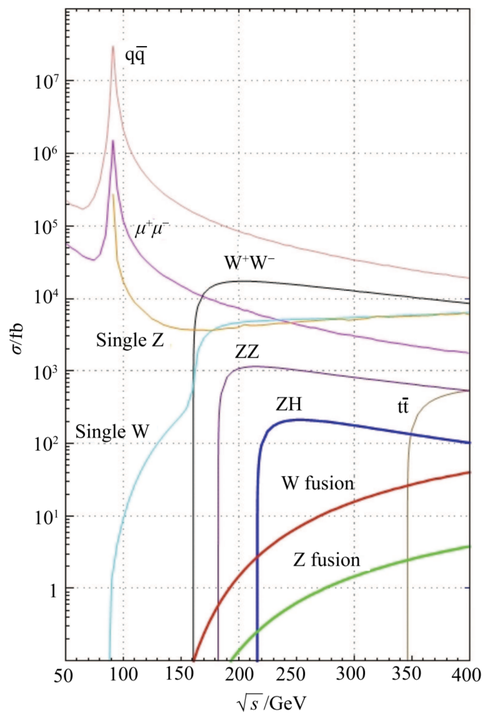


Figure 1: Annihilation cross sections in e^+e^- collisions. Adapted from [2].

EW: $5 \cdot 10^{12}$ Z, 10^8 WW, 10^6 $t\bar{t}$
- 20–50 or more improvement in electroweak quantities
- Indirect sensitivity to new particles up to 10–70 TeV

Higgs: $1.2 \cdot 10^6$ HZ, 75k WW $\rightarrow$ H
- Higgs width at 1.6%
- Higgs couplings at percent to sub-percent precision

Flavour: 10^{12} $b\bar{b}$, $c\bar{c}$, $1.7 \cdot 10^{11}$ $\tau\bar{\tau}$
- $O(10)$ more than Belle-II, not limited to $m(\Upsilon(4S))$

And many many more!

FCC-ee detector requirements

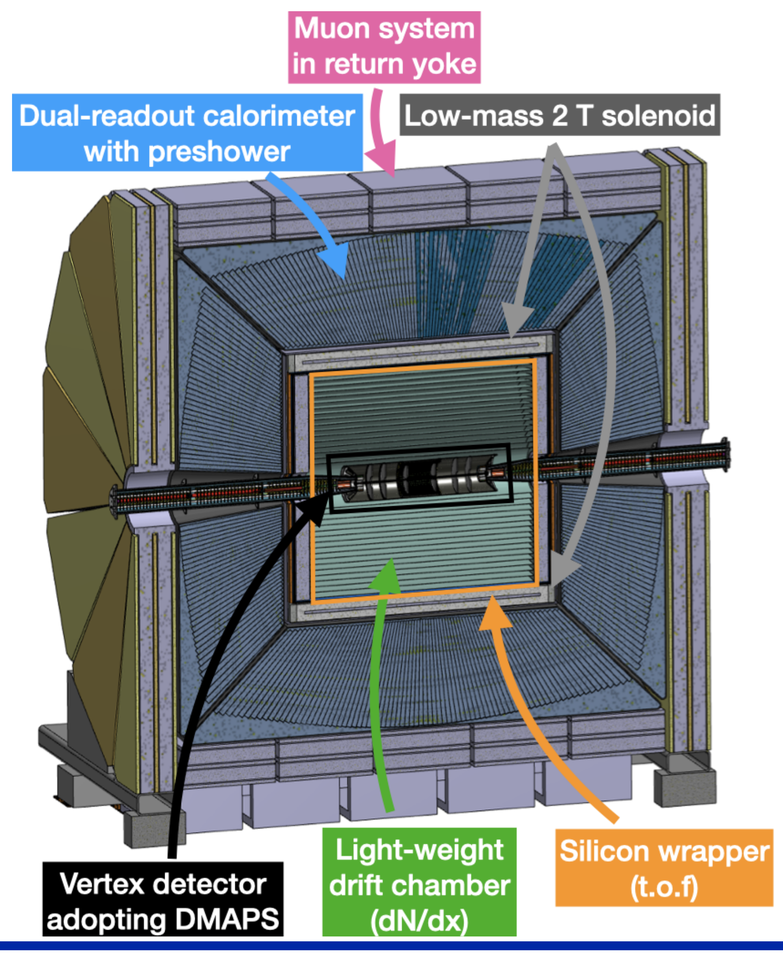
e^+ and e^- are **point-like particles** $\rightarrow$ very different than the LHC!
- Initial E and p known
- Almost no pile-up, no QCD background

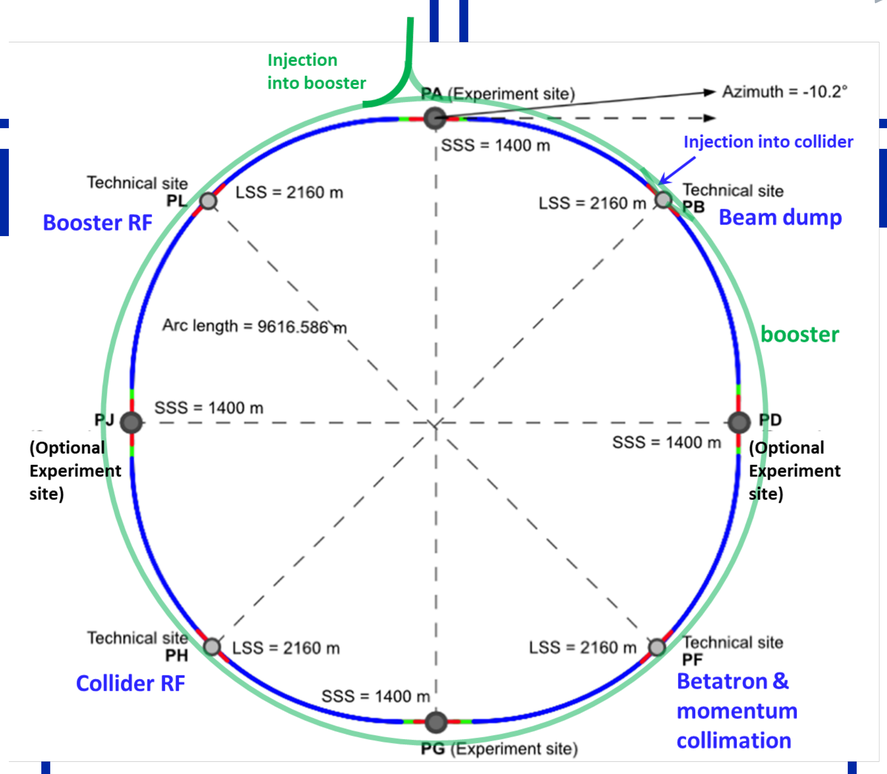
FCC-ee running at the Z pole ($\sqrt{s} = 91.2$ GeV) generates extremely large statistics (*tera-Z factory*).To benefit from this, the systematic uncertainties need to be kept down to 10^{-4}–10^{-5}
$\rightarrow$ **Stringent requirements on FCC-ee detectors**!

Vertex detector to determine the spatial locations of the interactions
- Efficient flavour tagging (b/c/g/**s**)
- Precise flight distance measurements

Vertex detector requirements:
- 3 μm single-hit resolution
  - $\sigma_{p_T}/p_T^2 \simeq 2 \cdot 10^{-5}$/GeV $\rightarrow$ Limit material budget X/X_0 to $\simeq 0.3\%$/layer

The IDEA detector concept for FCC-ee



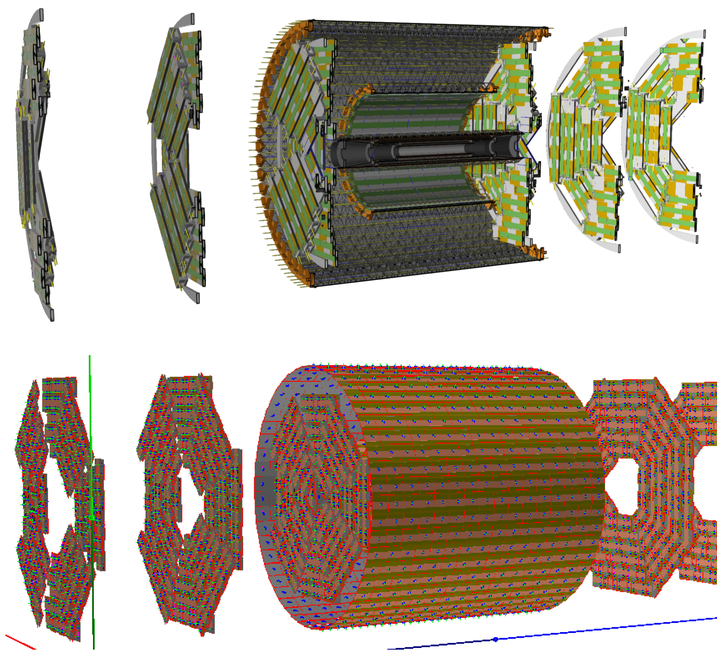


Common software vision: Key4hep

- Adopted by all future collider projects
- From generator to analysis
- EDM4hep+DD4hep+Gaudi

Enabling plug-and-play functionality and interface with accelerator components

...and its vertex detector in full simulation



CAD (top) design from INFN-Pisa and DD4hep (bottom) implementation

- Much higher level of detail than other implementations
- Can check for cracks in coverage and assess vertexing performance realistically

Prospects of wafer-scale DMAPS for FCC-ee vertex detectors

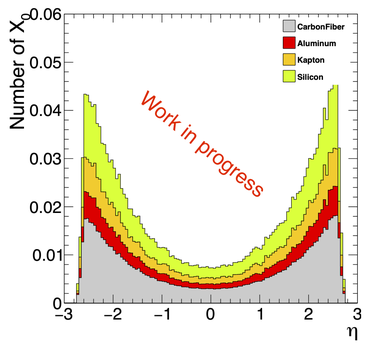
Depleted monolithic active pixel sensors are foreseen by all e^+e^- detector proposals for the vertex detector
- Sensor and readout in one silicon die
- Sensor (silicon) contributes only a small fraction to total material budget

$\rightarrow$ Major improvements in tracking and vertexing if X/X_0 is reduced further

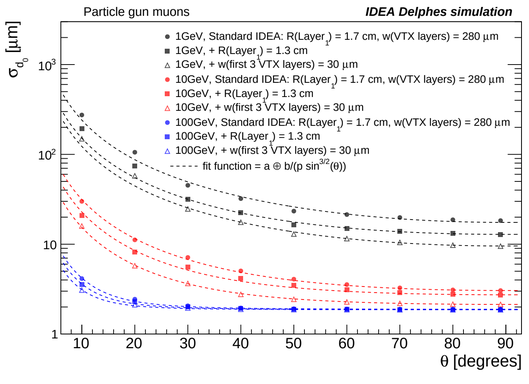
65 nm development for ALICE ITS3:
Wafer-scale curved sensors
- One sensor per half-layer only
- Self-supporting, air cooling

$\rightarrow$ Basically only silicon in vertex

Joined team of ALICE ITS3, CERN R&D and other institutes!



IDEA vertex barrel material budget



Effect of reduced material budget on d_0 resolution in Delphes fast simulation, L. Freitag (BSc. thesis [3])

R&D on 65 nm DMAPS at UZH

Analog pixel test structure (APTS)
- 16 pixels, 10 to 25 μm pitch
- Analogue readout, different processes

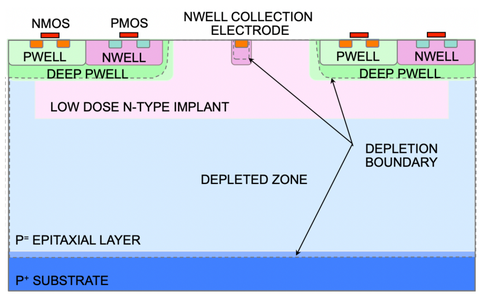
$\rightarrow$ Test beams, lab tests with Fe-55 source and (eventually) X-ray tube

Goal: Compare different p-well and n-well collection electrode designs

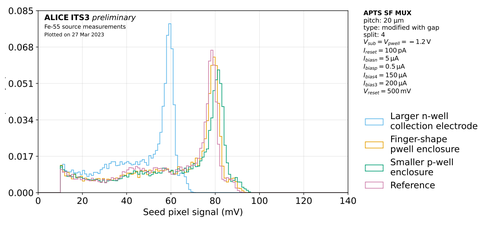
Circuit Exploratoire (CE-65)
- 64x32/48x32 pixels, 15/25 μm pitch
- Digital readout

$\rightarrow$ Test beam this summer, lab test with Fe-55 source

Goal: Long-term development and optimisation towards FCC-ee vertex detectors

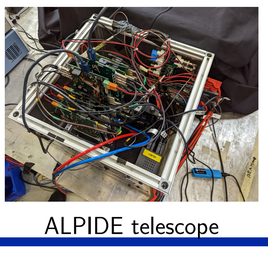


TPSCo 65 nm modified process with gap [4]



Different pixel architectures in APTS

Fe-55 test setup



ALPIDE telescope

[1] FCC Collaboration, *FCC-ee: The Lepton Collider*, The European Physical Journal Special Topics **228** (2019) 261–623.
[2] X. Mo, G. Li, M.-Q. Ruan, and X.-C. Lou, *Physics cross sections and event generation of e^+e^- annihilations at the CEPC*, Chinese Physics C **40** (2016) 033001.
[3] L. Freitag, *Benefits of Minimizing the Vertex Detector Material Budget at the FCC-ee*, 2023. Presented 01 Feb 2023.
[4] W. Snoeys, et al., *Optimization of a 65 nm CMOS imaging process for monolithic CMOS sensors for high energy physics*, in *Proceedings of Pixel2022*.

CHIPP/CHART Workshop on Sustainability in Particle Physics
Sursee, 14-16.06.2023