FCC-ee Vertex Detector: Design and Performance

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In 2012, the last missing piece of the Standard Model (SM) of particle physics, the Higgs boson, was discovered at the Large Hadron Collider (LHC) at CERN in Geneva. Since then, the LHC greatly improved our understanding of the elementary particles of nature and their interactions. The LHC is scheduled to operate until the late 2030's and the particle physics community is now planning for the post-LHC era.

Future Circular Collider (FCC) project

The FCC study [1] envisions a new ~ 100 km long circular collider ring to test the limits of the SM to an unprecedented level. In a first stage, intense collisions of electrons and positrons are produced (FCC-ee). Collision energies of 90–365 GeV at instantaneous luminosities of up to $230 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ make the FCC-ee an electroweak (EW), Higgs and top factory. This for example allows the precise study of the Higgs boson properties and to investigate hints of lepton flavour violation (LFV) recently observed. Later, the FCC would be equipped with 16 T magnets to collide hadrons with energies up to 100 TeV (FCC-hh).

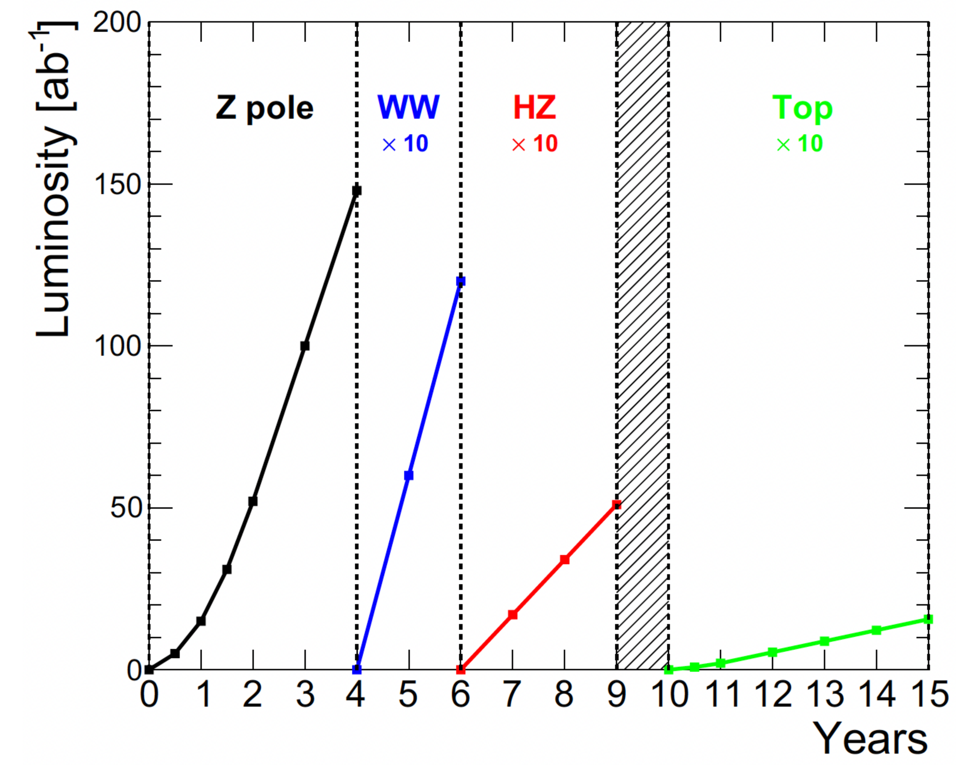

Figure 1: FCC-ee is operated at energies of around 90, 160, 240 and 350–365 GeV [1].

FCC location

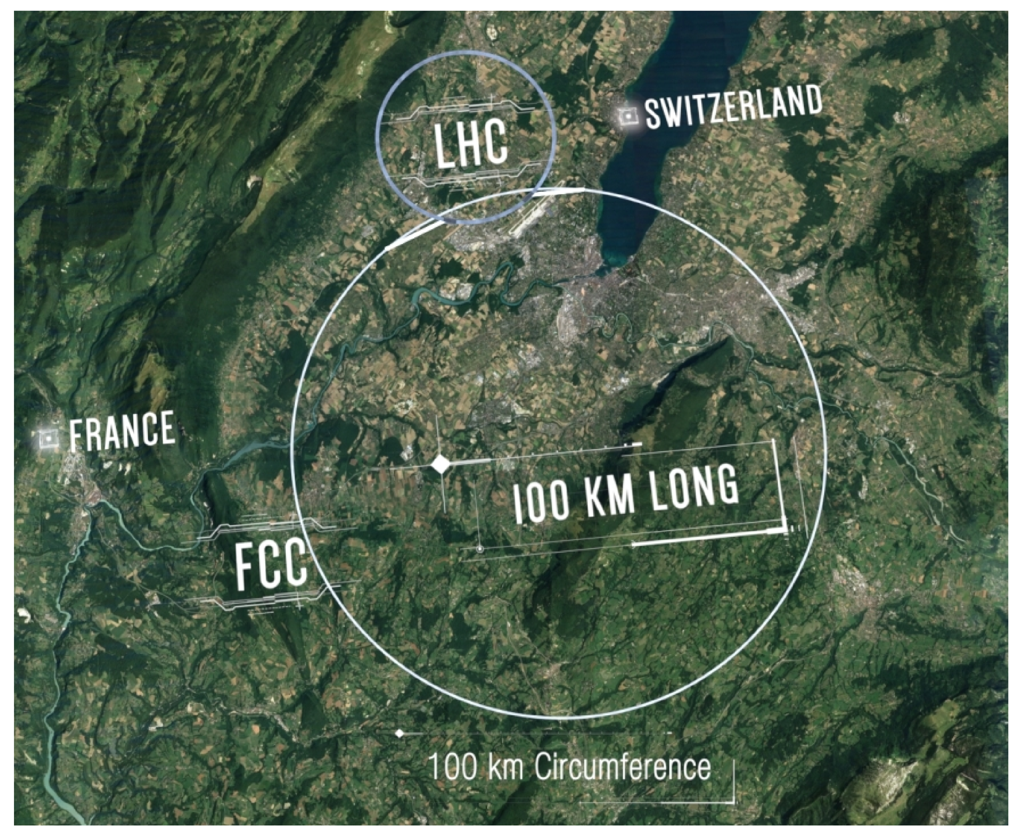

Figure 2: FCC Study@CERN

Physics program at FCC-ee experiments

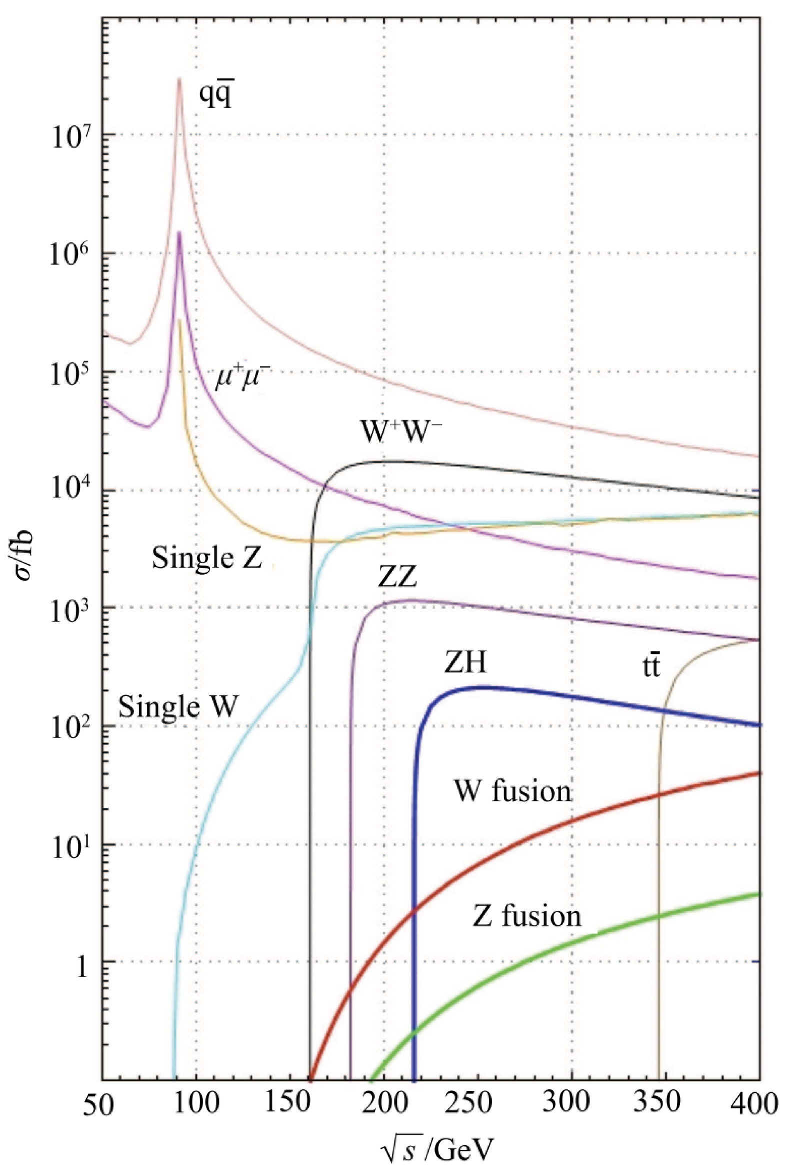

Figure 3: Annihilation cross sections in e^+e^- collisions. Adapted from [2].

EW: $5 \cdot 10^{12}$ Z, 10^8 WW, 10^6 $t\bar{t}$

- 20–50 or more improvement in electroweak quantities [3]
- Indirect sensitivity to new particles up to 10–70 TeV [1]

Higgs: $1.2 \cdot 10^6$ HZ, 75k WW $\to$ H

- Higgs width at 1.6% [1]
- Higgs couplings at percent to sub-percent precision

Flavour: 10^{12} $b\bar{b}$ and $c\bar{c}$, $1.7 \cdot 10^{11}$ $\tau\tau$

- LFV and flavour anomaly searches

And many many more!

FCC-ee detector requirements

e^+ and e^- are **point-like particles** $\to$ 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}
$\to$ **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:

- Precise vertex determination $\to$ $O(3 \times 3\,\mu\mathrm{m}^2)$ single-hit resolution
- But need to minimise material in the vertex detector to limit multiple scattering and prevent worsening of the momentum resolution ($X_0 \sim 0.3\%$ per layer)

Depleted Monolithic Active Pixel Sensors (DMAPS)

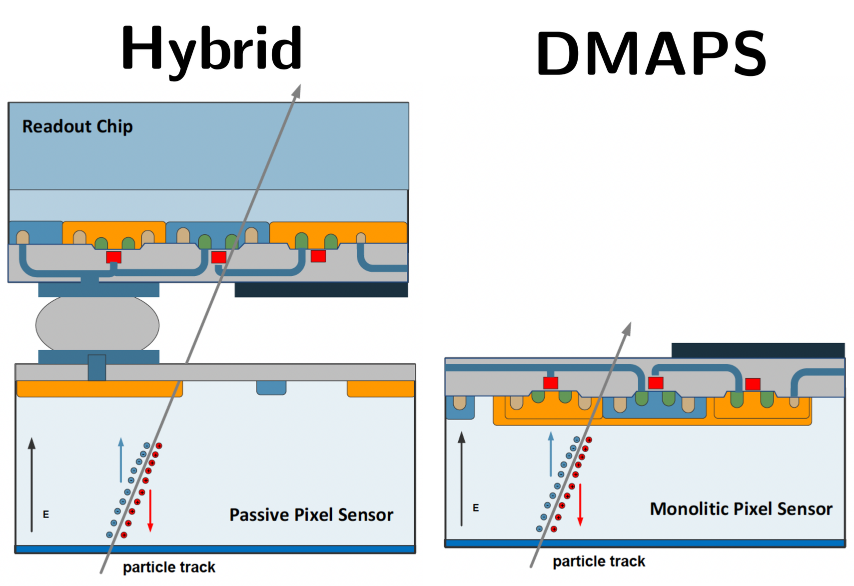

Figure 4: Comparison between hybrid and depleted monolithic active pixel sensors [4].

- Scalable to (very) large sensors
- **Less material** (possibly no support material)
- Simpler assembly
- More cost effective

Only technology feasible for FCC-ee vertex detector

- Similar requirements in ALICE ITS3 and FCC-ee vertex detectors!
- Joined team of ALICE ITS3, CERN R&D, et al.
- Setup at UZH incoming

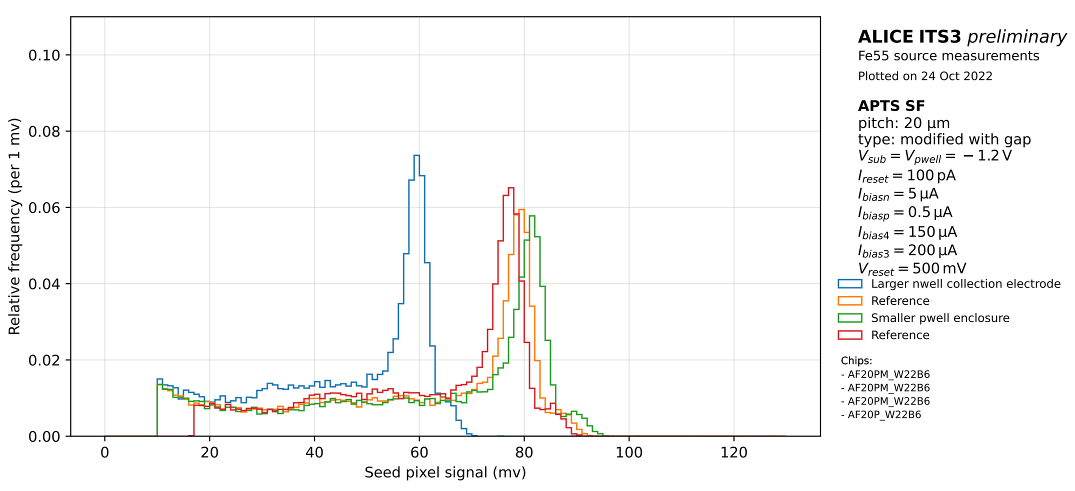

Figure 5: First test of ALICE APTS multiplexer chip.

Characterisation of DMAPS sensors: *Fumble with electronics and sensors and write scripts to analyse data!*

Vertex detector simulation and physics case studies

FCC-ee vertex detector: Implement in full simulation and evaluate performance.

- Optimise vertex detector layout
- Implement ALICE ITS3-like vertex detector in fullSim
- Impact of adding timing measurement at vertex

Build a detector yourself in code and look at what you get out!

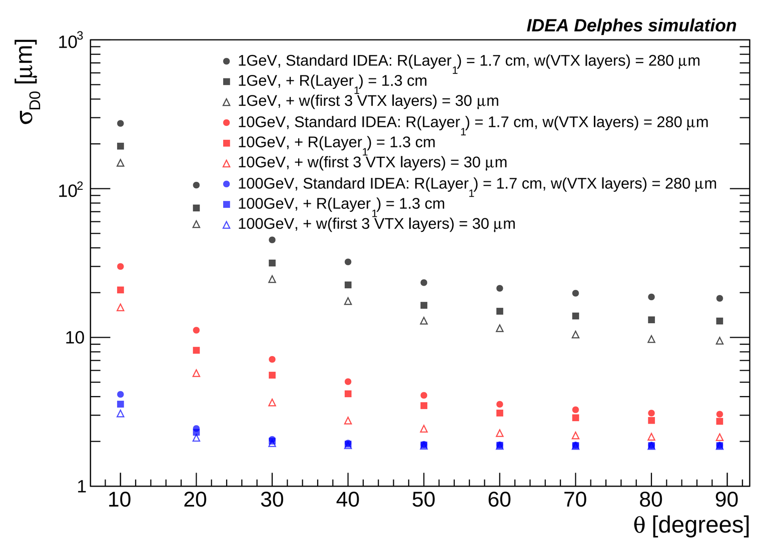

Figure 6: Impact of reduced material budget on impact parameter resolution. Work of Leila Freitag.

Physics case study: Data analysis of simulated FCC-ee collisions to assess potential reach in benchmark physics processes.

- Measure Cabibbo-Kobayashi-Muskawa (CKM) matrix elements V_{cs} and V_{cb} in hadronic W decays
- Measuring the Higgs coupling to the second generation of quarks in $e^+ + e^- \to ZH$, $H \to cc/ss$

Study process in question, apply selections and plot the results! Dependence on vertex performance?

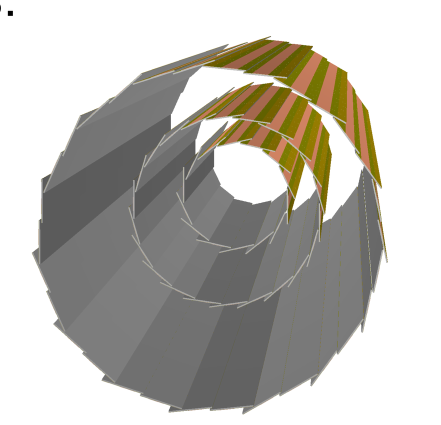

Figure 7: Current IDEA FullSim implementation

[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] FCC Collaboration, *FCC Physics Opportunities*, The European Physical Journal C **79** (2019).
[4] T. Hemperek, *Advances in pixel detectors*, 9, 2021. PSD 2021 workshop.

Open Day 2022
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